Experimental Neutrino Physics

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Overview

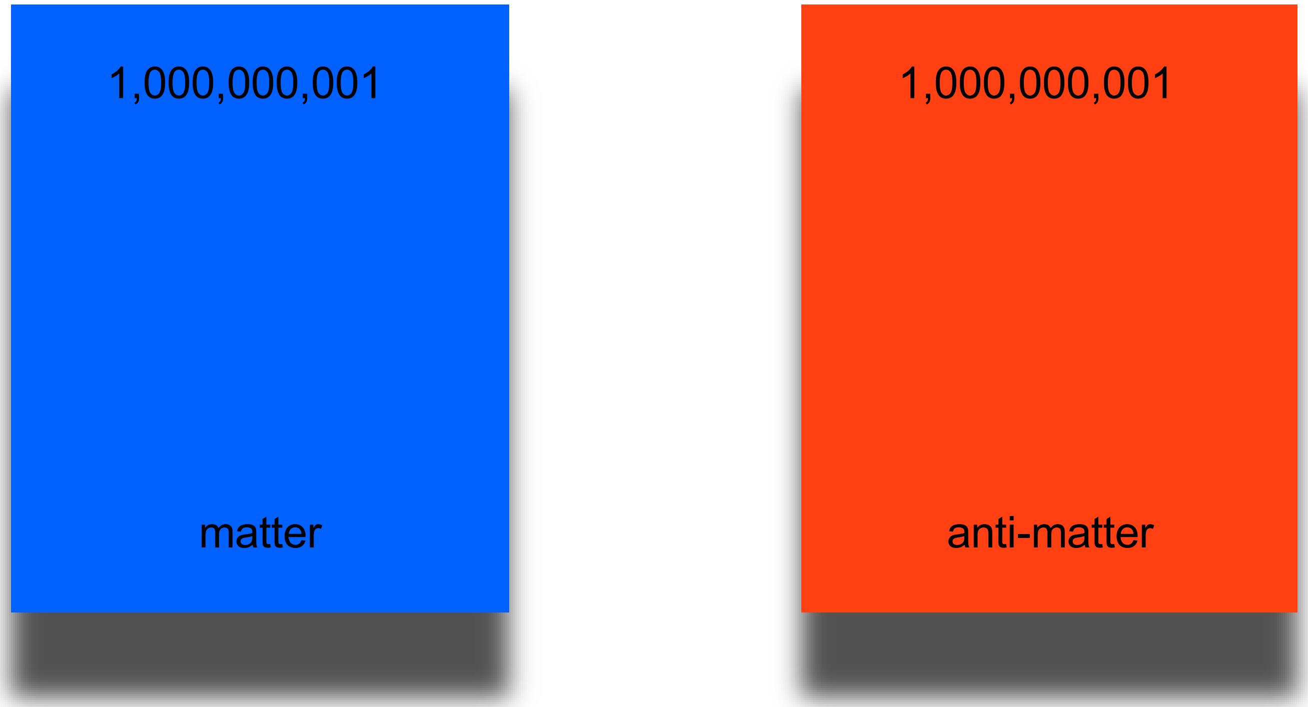
- "Experimental Neutrino Physics" is a very broad topic
  - Impossible to cover everything related to that title in 2 lectures
- For these lectures, I'll be focusing on neutrino oscillation physics
  - Part 1: A broad overview of (PMNS) oscillation experiments
  - Part 2: Deep dive into long-baseline neutrino physics
    - More details on the largest experiments within the field for the next decade+
- There are many other interesting topics in neutrino physics that I won't be able to cover, such as
  - Neutrino-nucleus scattering measurements
  - Neutrino astronomy
  - Searches for Beyond the Standard Model (BSM) physics (including sterile searches)
    - Although, in some sense, neutrino oscillations are already BSM physics…
- To begin, I'll briefly recap a few of the key topics presented earlier this week

We are made of matter

(and not anti-matter)

Adapted from Hitoshi Murayama

But just after the big bang, there should have been an equal amount of equal matter and anti-matter



If it stayed that way, all the matter and anti-matter would annihilate and there would be no matter left

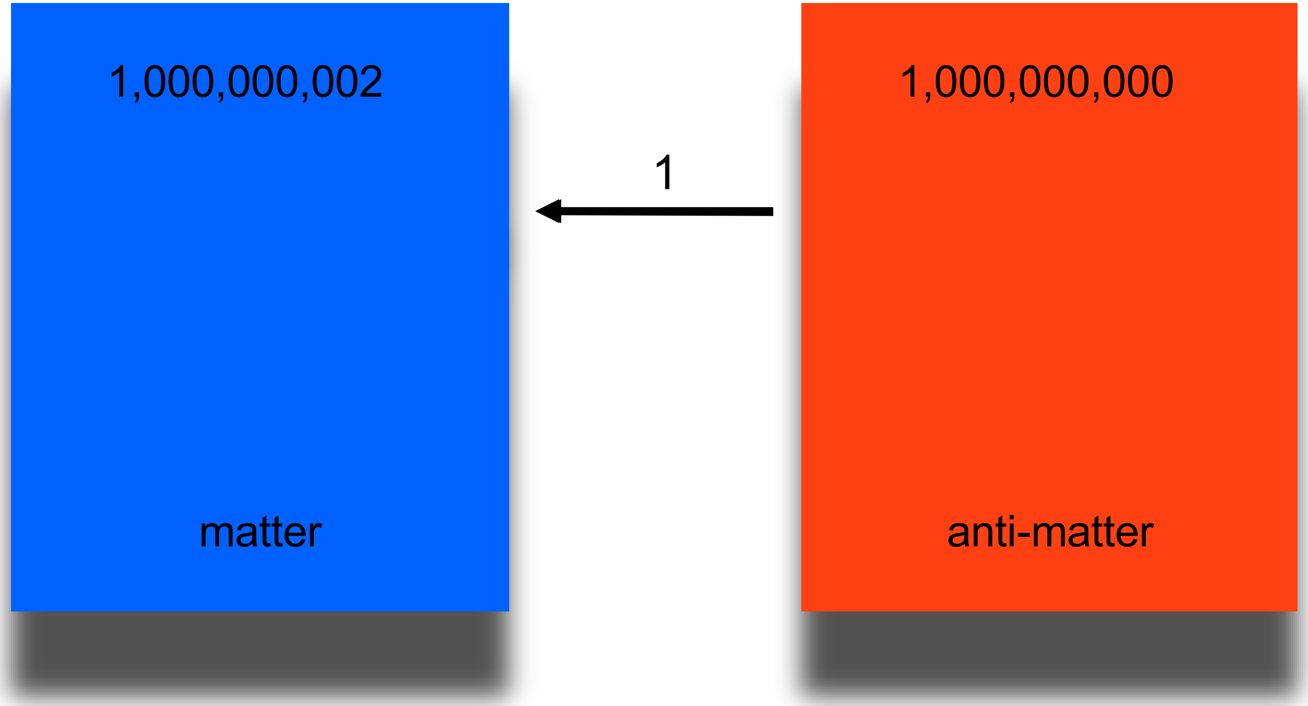
We would not exist!

We are made of matter

Adapted from Hitoshi Murayama

(and not anti-matter)

Fortunately, there was some process that (very quickly!) made a little extra matter



So when the matter and anti-matter annihilated, there was a little bit of matter left over

That's why we exist!

Our Matter Filled Universe

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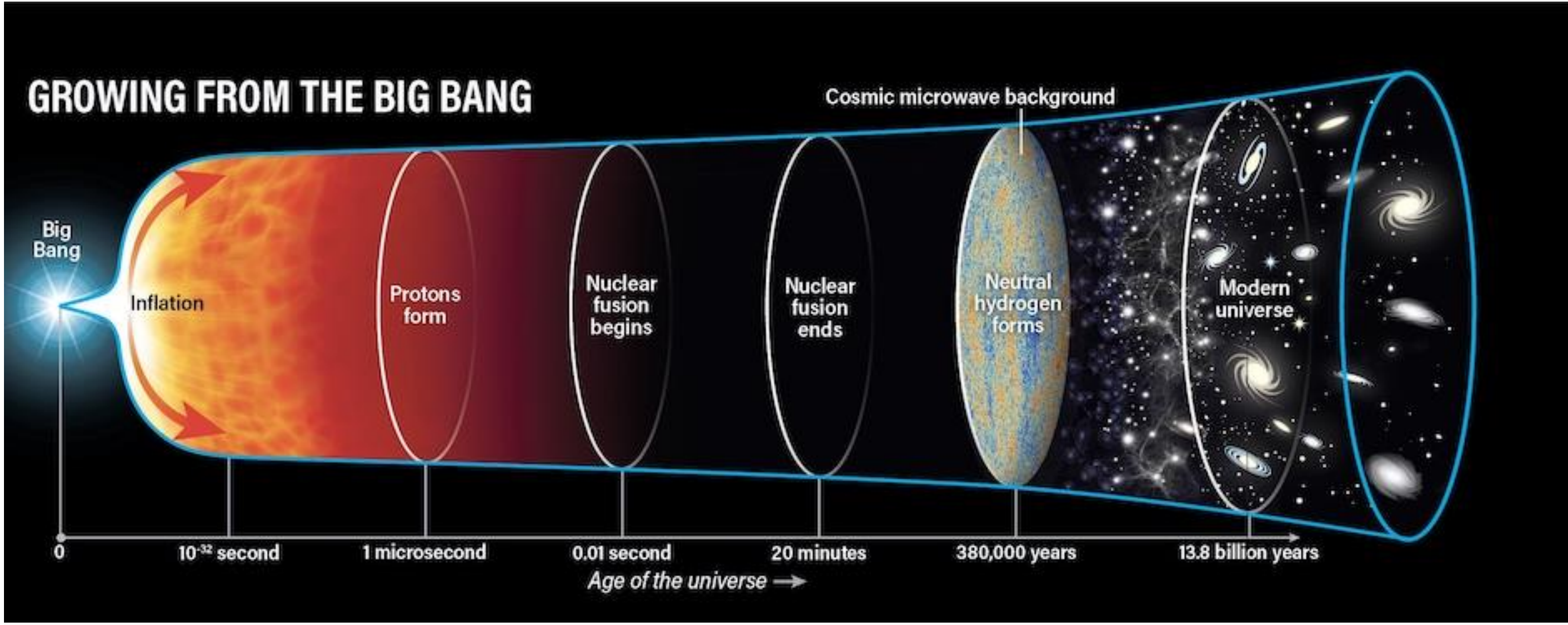
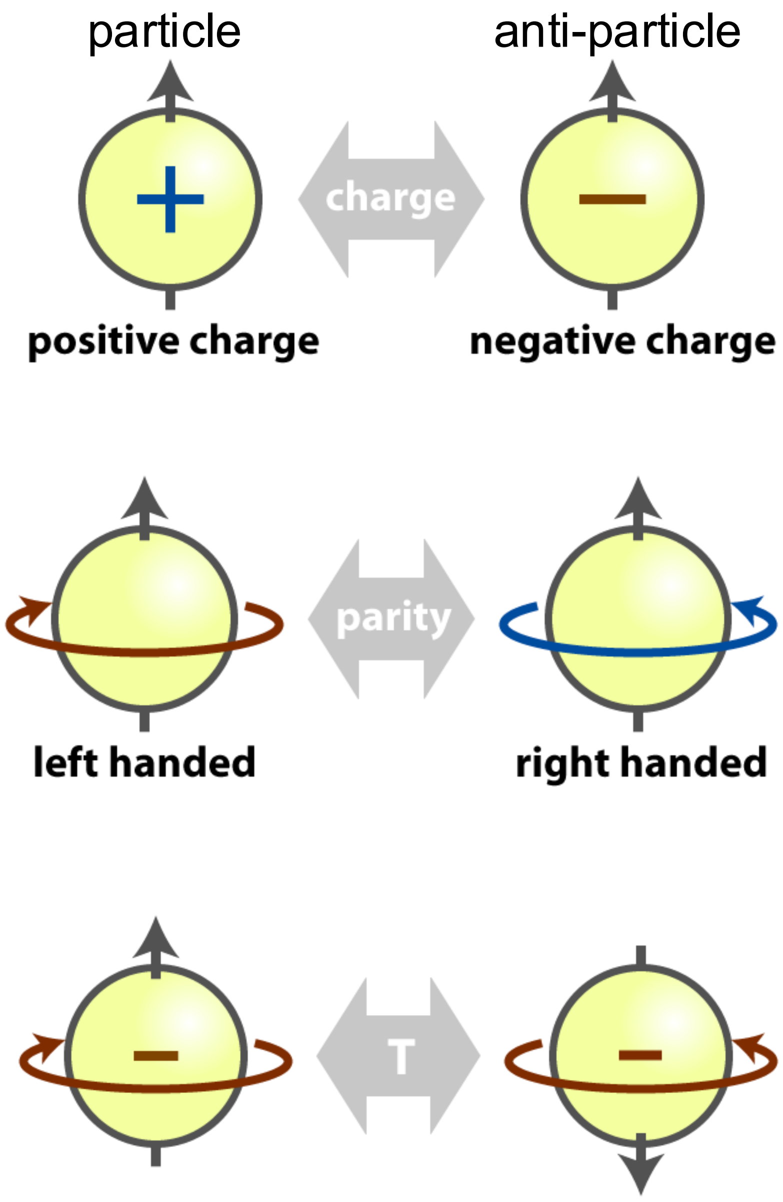


- Observationally, the universe appears to be composed of matter (and not anti-matter)
- To generate a matter/antimatter asymmetry in the very early universe, must satisfy the Sakharov Conditions:
  - A baryon (or lepton) number violating process must exist
  - A "sufficient amount" of C- and CP-violation must exist (next slide)
  - These process must be able to occur outside of thermal equilibrium

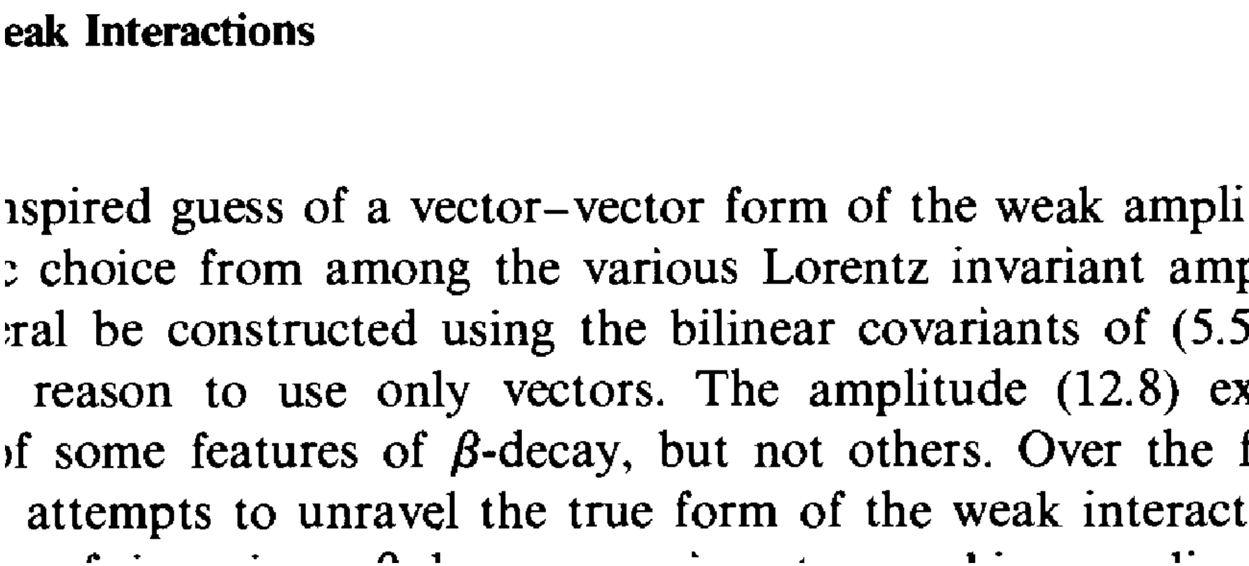
Discrete Symmetries

- Matter and anti-matter behave in a very similar manner
  - If we lived in an anti-matter galaxy, we would (almost) not notice any difference!
- It was once thought that physics was invariant under 3 discrete transformations:
  - Charge (C): Replace all particles with anti-particles (and vice versa)
  - Parity (P): Replace a physical process with its mirror image
    - i.e. flip the particle spins relative to the particle directions)
  - Time (T): Flip the direction of time for a physical process
    - i.e. inputs → outputs = outputs → inputs



Parity (P) Violation

- If parity is a good symmetry, then, in every process, we should be able to flip the spins of the particles and get the same rate:
  - i.e. in beta decay: $\Gamma(^{60}Co \rightarrow e_L^- \, \bar{\nu}_{e,R}) = \Gamma(^{60}Co \rightarrow e_R^- \, \bar{\nu}_{e,L})$


eak Interactions

ıspired guess of a vector–vector form of the weak ampli
: choice from among the various Lorentz invariant amp
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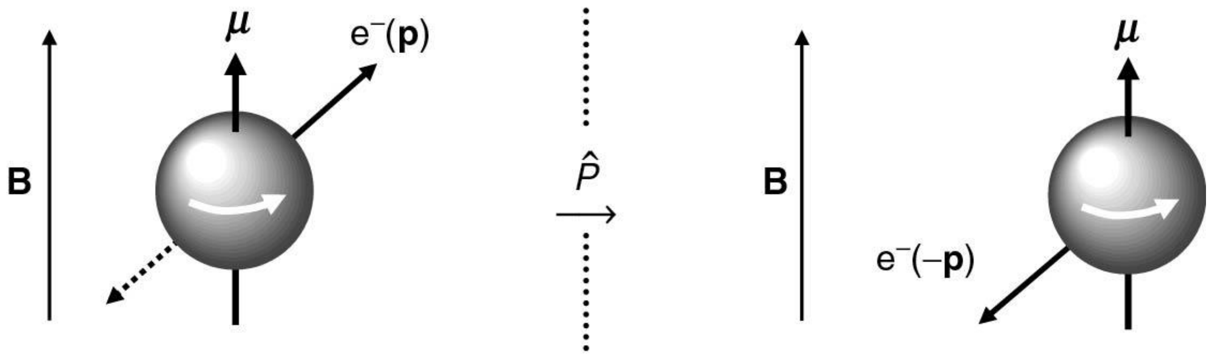
reason to use only vectors. The amplitude (12.8) ex
ɔf some features of β-decay, but not others. Over the f
attempts to unravel the true form of the weak interact

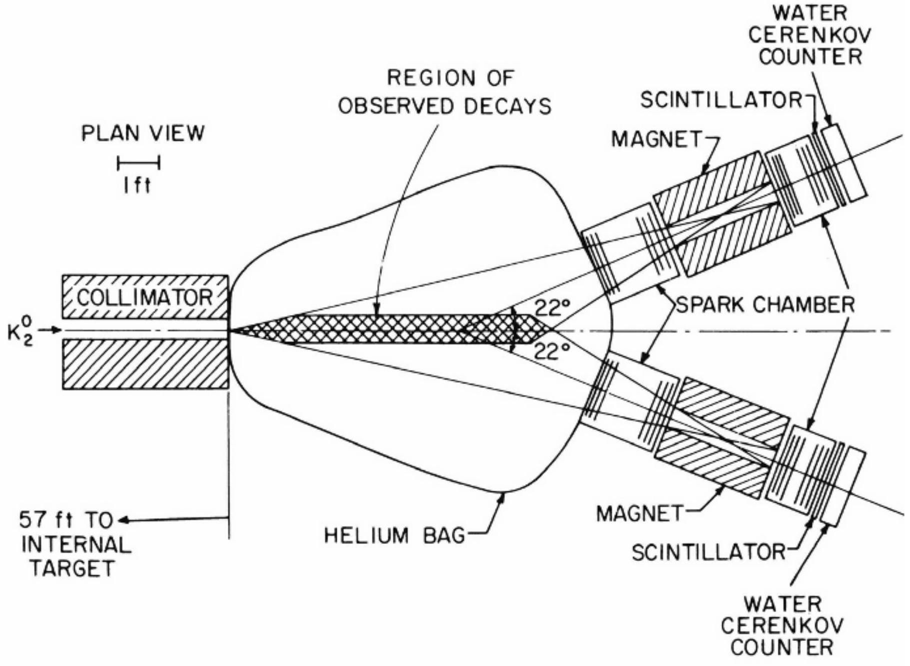
- Wu experiment (1956): Align the spins of cobalt atoms with a magnetic field, and measure the distribution of emitted electrons
  - If parity is conserved, “upward” and “downward” electron motion relative to the B-field should both be allowed
- The result? Electrons were preferentially produced in the direction opposite of the magnetic field!
  - Parity is ~maximally violated in weak interactions:
  - $\Gamma(^{60}Co \rightarrow e_L^- \, \bar{\nu}_{e,R}) \neq \Gamma(^{60}Co \rightarrow e_R^- \, \bar{\nu}_{e,L}) = 0$

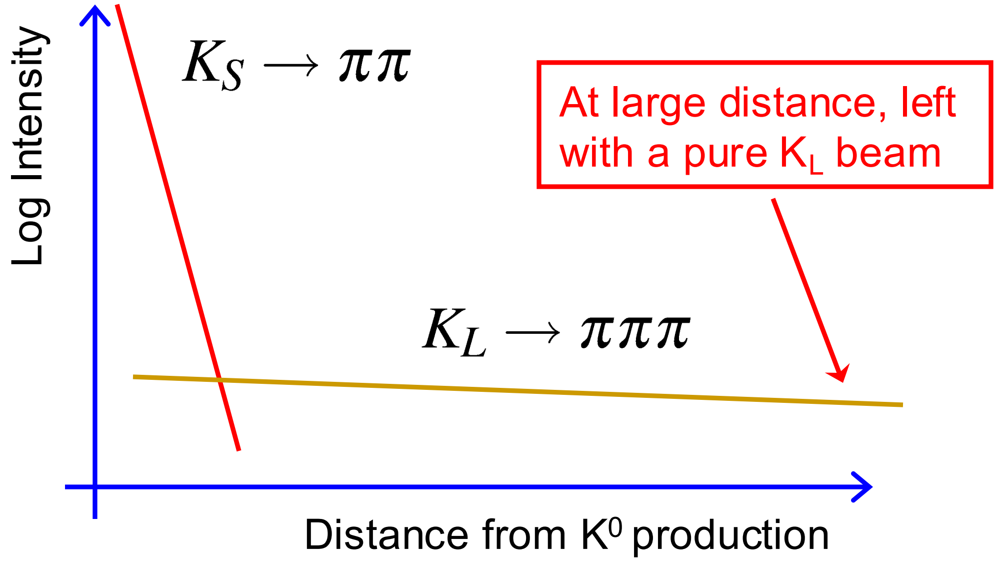


- (anti-)neutrinos are ~always produced (right-) left-handed!
- C.N. Yang and T.D. Lee (theorists) win 1957 Nobel Prize (but not Chien-Shiung Wu…)

Charge-Parity (CP) Violation

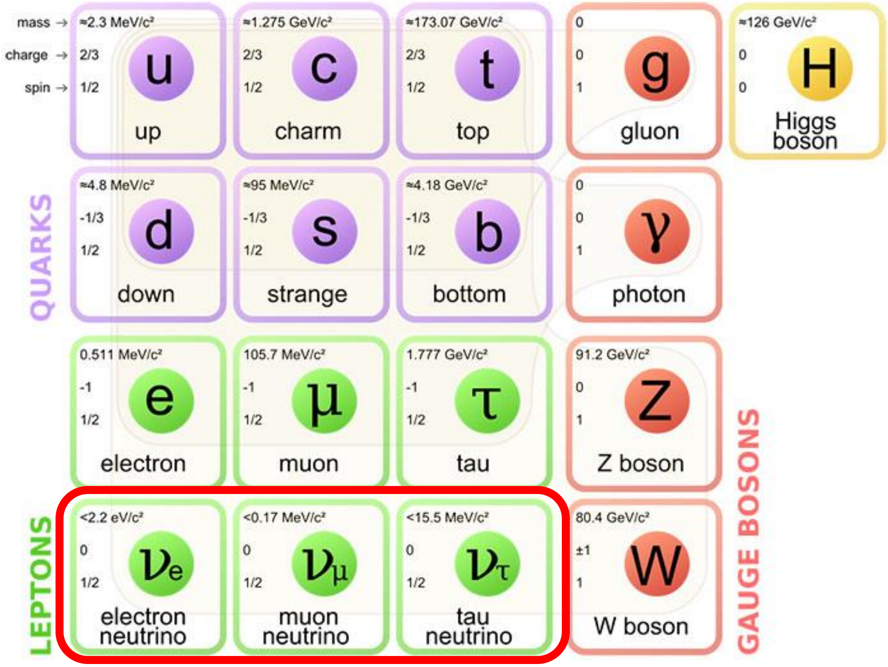
- Since (anti-)neutrinos are always produced (right-) left-handed, C & P together may still be a good symmetry
  - $\Gamma({}^{60}Co \to e_L^- \bar{\nu}_{e,R}) = \Gamma({}^{60}\overline{Co} \to e_R^+ \nu_{e,L})$?
  - Unfortunately, it's not easy to make ${}^{60}\overline{Co}$
- Instead, in 1964, Cronin and Fitch used neutral kaons
  - CP even: K_S (short-lived) → π π
  - CP odd: K_L (long-lived) → π π π
- At long distances (after all the K_S decayed), they observed $K_L \to \pi^+ \pi^-$
  - CP is also violated! Matter and anti-matter behave (slightly) differently!
  - 1980 Nobel Prize
- However, this mechanism for CP violation (in quarks) is far too small to account for the matter/anti-matter asymmetry of the universe
  - What about leptons?





Neutrino Properties

- Neutrinos only participate in the weak interaction (no EM charge, no strong (color) charge)
  - *VERY* rarely interacts with other particles
  - The "Ghost Particle" (named "neutrino" by Enrico Fermi)
  - Wolfgang Pauli (1930): "I have done a terrible thing. I have postulated a particle that cannot be detected"
- If you hold your thumb toward the sun, 100 billion neutrinos pass through your thumbnail every second (during the daytime or nighttime)
  - However, only a few solar neutrinos will interact in your body over your lifetime
- The flavor states (e, μ, τ) do not need to correspond to the 3 mass states
  - Neutrinos can be produced in a superposition of mass states
  - Each mass state can then propagate with a different phase
- So, when the neutrino is later observed (via the weak interaction), the flavor state can be different
  - **Neutrino oscillations!**



Flavor State | Mixing Matrix | Mass State

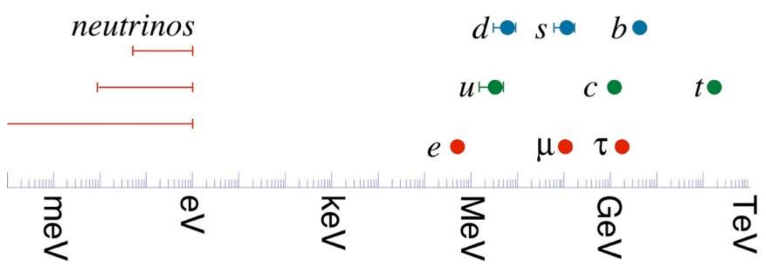
$$|\nu_\alpha(\tau)\rangle = \sum_{i=1}^{3} U_{\alpha i} e^{-i(m_i \tau)} |\nu_i\rangle$$

$$\alpha = e, \mu, \tau$$

How Do We Explain Neutrino Masses?

- In 1998, we discovered that neutrinos oscillate! (More details about this later)
  - Neutrinos have mass!
  - First physics beyond the standard model!
- We could, in the standard model, just add an absurdly small coupling to the Higgs
  - (as discussed last week by S. Gori)
- However, something qualitatively different appears to be happening to produce neutrino masses
  - Orders of magnitude lighter than the other matter particles
- This strongly suggests a new mechanism to generate such small, but non-zero masses

Fermion Mass Spectrum



$$\mathcal{L}_{Dirac} = -f \langle \phi \rangle_0 \bar{\nu}_L \nu_R + h.c.$$

$$m_\nu = f \langle \phi \rangle_0 \sim 0.2\text{eV}$$

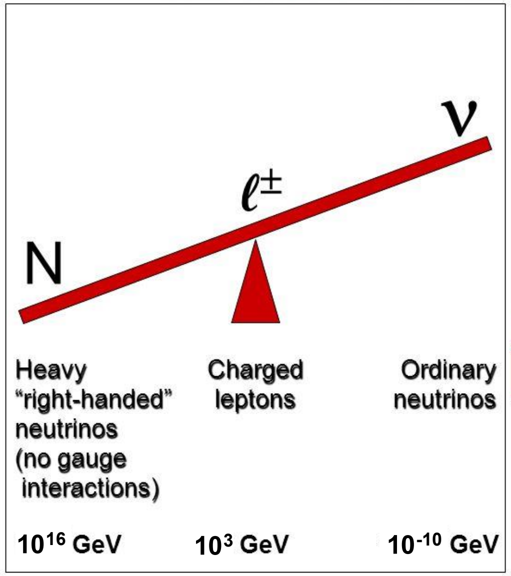
& $$\langle \phi \rangle_0 \sim 200\text{GeV}$$

$$\boxed{f \sim 10^{-12}}$$

Why Are (Very) Small Neutrino Masses Interesting?

- Neutrinos are special, since they don't have electric charge
  - This means it's possible that neutrinos are their own antiparticles
  - If so, they would be expected to have additional "Majorana mass" terms (unless some additional symmetry is added to forbid such terms)
- If a new right-handed **Majorana neutrino state (N_R)** is introduced, it would be unconstrained by standard model symmetries, and can naturally have a very high mass
  - e.g. at the energies where the forces unified, known as the Grand Unified Theory (GUT) scale
  - These N_R fields would mix with the ν_L fields and produce a mass matrix → diagonalize to determine physical particle masses
- If we choose a "regular" (Dirac) mass around the other matter particles (~1 TeV), and a GUT-scale N_R mass (~10^{16} GeV), the resulting light neutrino masses (0.1 eV) **come out about right!**
- **Summary**: a very light (but non-zero) neutrino masses suggests the existence of a new (potentially) GUT-scale particle!

See-Saw Model for Neutrino Masses



Light Majorana mass

$$(\bar{\nu}_L\ \bar{N}_R)\begin{pmatrix} \frac{g_\nu^2\langle\phi\rangle^2}{M} & 0 \\ 0 & M \end{pmatrix}\begin{pmatrix} \nu_L \\ N_R \end{pmatrix}$$

- **Interesting side-effect**: these N_R particles would have been prevalent in the early universe
  - If decays of N_R violate CP (like neutral kaons), this could give rise to the matter/anti-matter asymmetry of the universe (leptogenesis)

Neutrino Mixing

Note: $c_{ij} = \cos(\theta_{ij})$, $s_{ij} = \sin(\theta_{ij})$

Flavor States →

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} e^{i\alpha_1}/2 & 0 & 0 \\ 0 & e^{i\alpha_2}/2 & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

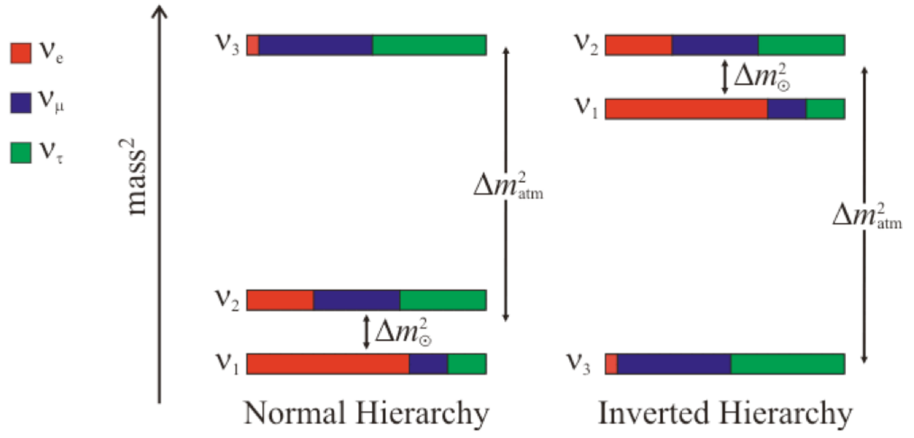
← Mass States

“Atmospheric ν”	“Reactor ν?”	“Solar ν”	Majorana phases;
(Super-K, T2K, NOvA, MINOS)	(Daya Bay, T2K, NOvA)	(Super-K, SNO, KamLAND)	Not yet observed
θ_{23} = 45°±6° (90% C.L.)	θ_{13} = 9.0°±0.5°	θ_{12} = 33.9°±1.0°	(no effect on oscillation experiments)

- In the light neutrinos, the unitary transformation between flavor and mass states contains 3 angles and 1 phase
    - If neutrinos are Majorana particles, we can have 2 more phases that are, sadly, inaccessible in oscillation experiments
    - All 3 angles have been measured with increasing precision over the past 1-3 decades
    - CP violation is controlled by δ_{CP} (the last unknown parameter of the “neutrino-extended” standard model)
- Unfortunately, CP violation in light leptons is not simply related to leptogenesis
    - However, it may be suggestive in an “archaeological sense” – Boris Kayser, Fermilab
- In any case, GUTs require unification of quarks and leptons, and precise measurements of all “fundamental parameters” (masses and mixings) will provide valuable constraints

Neutrino Oscillations

- Oscillations are sensitive to m^2 differences
  - We do not know whether $\Delta m^2_{31}>0$ or $\Delta m^2_{31}<0$
  - **Neutrino Mass Hierarchy**
- Flavor composition oscillates as a function of distance, L
  - Wavelength $\propto E/\Delta m^2$
- Amplitude of the oscillation is given by the mixing angles
- Oscillation probabilities can be greatly simplified by expanding in small parameters
  - $\Delta m^2_{21}/\Delta m^2_{31}$ (≈1/30)
  - $\sin^2\theta_{13}$ (≈1/10)



$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{i>j}\Re\left[U_{\beta i}U^*_{\alpha i}U^*_{\beta j}U_{\alpha j}\right]\sin^2\left(\frac{\Delta m^2 L}{4E}\right)_{ij} + 2\sum_{i>j}\Im\left[U_{\beta i}U^*_{\alpha i}U^*_{\beta j}U_{\alpha j}\right]\sin\left(\frac{\Delta m^2 L}{2E}\right)_{ij}$$

Expand in ($\Delta m^2_{21}/\Delta m^2_{31}$) and $\sin^2\theta_{13}$

LBL ν_μ disappearance

$$P_{\mu\to\mu} \approx 1 - \sin^2 2\theta_{23}\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right)$$

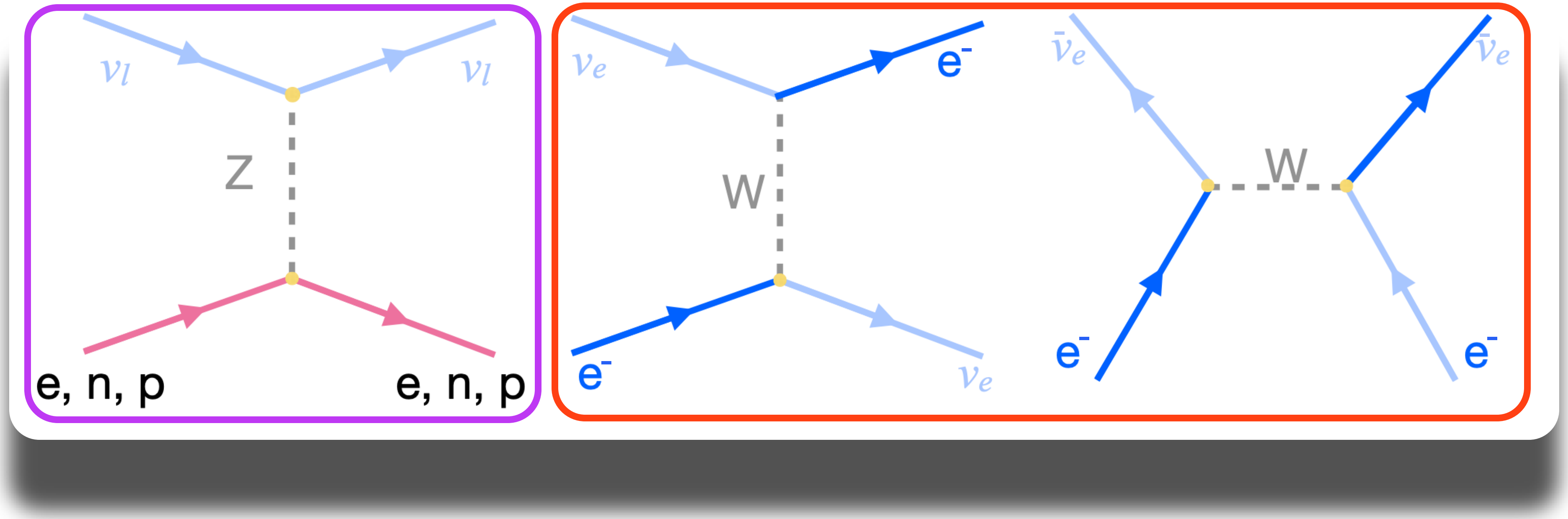
LBL ν_e appearance

$$P_{\mu\to e} \approx \sin^2 2\theta_{13}\sin^2\theta_{23}\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right)$$

MSW Effect

For more details, see talk from S. Li earlier this week

- When neutrinos travel through matter, ν_e can undergo an additional interactions with electrons relative to ν_μ & ν_τ



- Contributes an additional potential to the free space Hamiltonian
  - Opposite effect for neutrinos and anti-neutrinos

$$V_M = \pm\sqrt{2}G_F n_e$$

+ for ν_e

- for $\bar{\nu}_e$

Things Can Get Complicated (Accelerator ν Example)

The "Simplified" Form for Long-Baseline ν_e appearance

$$P(\nu_\mu \rightarrow \nu_e) \cong \sin^2 2\theta_{13}\, T_1 \; - \; \alpha \sin 2\theta_{13}\, T_2 \; + \; \alpha \sin 2\theta_{13}\, T_3 \; + \; \alpha^2\, T_4$$

$$T_1 = \sin^2\theta_{23} \sin^2[(1-x_\nu)\Delta] / (1-x_\nu)^2$$

$$T_2 = \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \sin\Delta \sin(x_\nu\Delta) / x_\nu \sin[(1-x_\nu)\Delta] / (1-x_\nu)$$

$$T_3 = \cos\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \cos\Delta \sin(x_\nu\Delta) / x_\nu \sin[(1-x_\nu)\Delta] / (1-x_\nu)$$

$$T_4 = \cos^2\theta_{23} \sin^2 2\theta_{12} \sin^2(x_\nu\Delta) / x_\nu^2$$

$$\Delta \equiv \Delta m^2_{31} L/4E_\nu, \quad \alpha \equiv \Delta m^2_{21}/\Delta m^2_{31} \sim 1/30, \quad x_\nu \equiv 2\sqrt{2}\, G_F N_e E_\nu / \Delta m^2_{31}$$

- δ_{CP} flips sign for neutrinos and anti-neutrinos
  - Can measure CP violation

$$P(\nu_\alpha \rightarrow \nu_\beta) - P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)$$

- x_ν flips sign for different mass orderings
  - Can measure the neutrino mass hierarchy

$$\Delta m^2_{31} > 0?$$

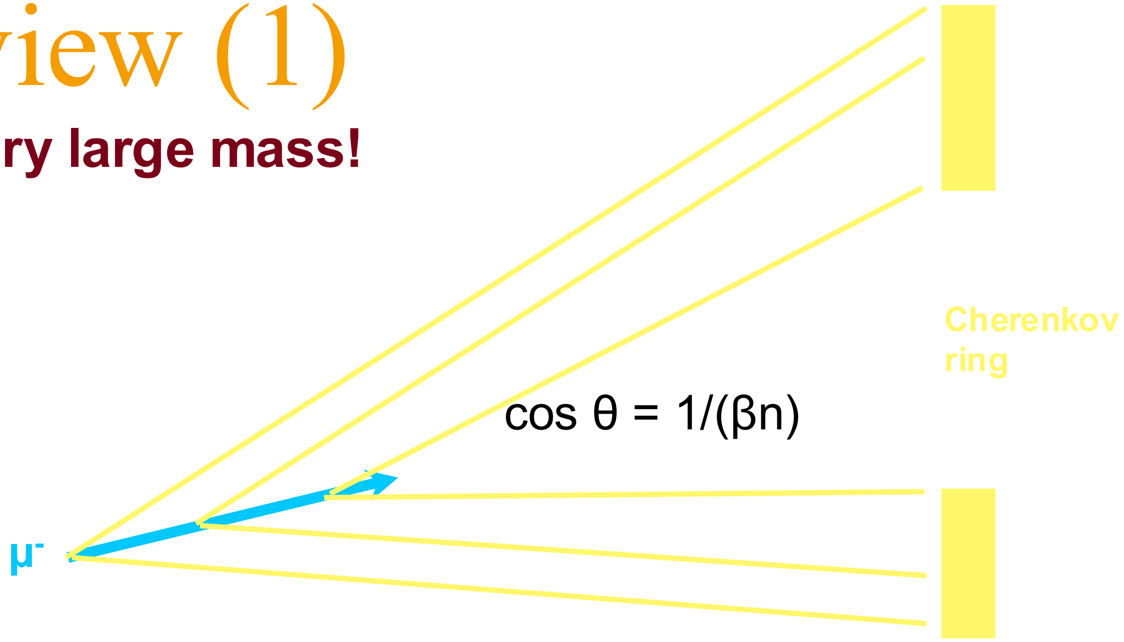
Detector Technology Overview (1)

Required: A very large mass!

Water Cherenkov (e.g. Super-Kamiokande)

- Particles moving faster than light (in water) emit light
  - Analogous to a sonic boom in air
- Cherenkov "rings" are imaged on the wall

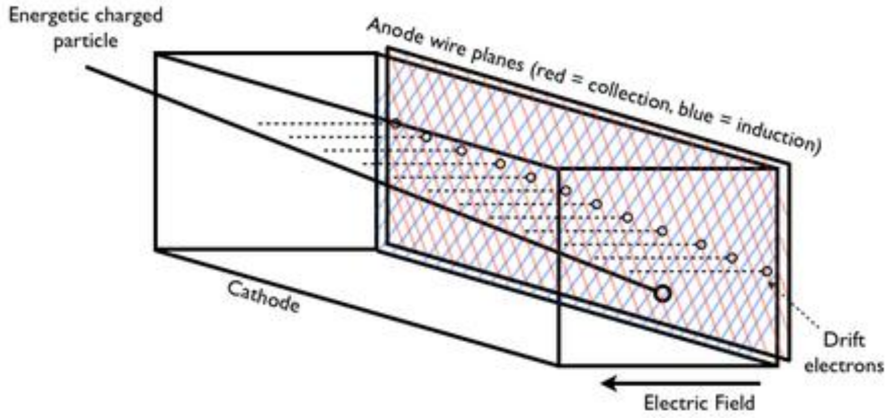
Cannot detect particles below Cherenkov threshold (e.g. outgoing protons)

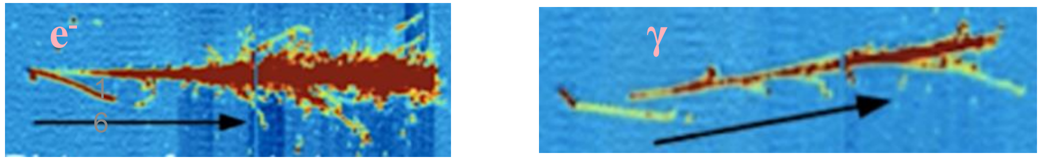


Time Projection Chambers (TPCs) (e.g. DUNE)

- Ionized electrons drift to the readout plane to provide 3D track images

Missing energy due to nuclear binding energy and escaping neutrons (incomplete hadronic calorimetry)



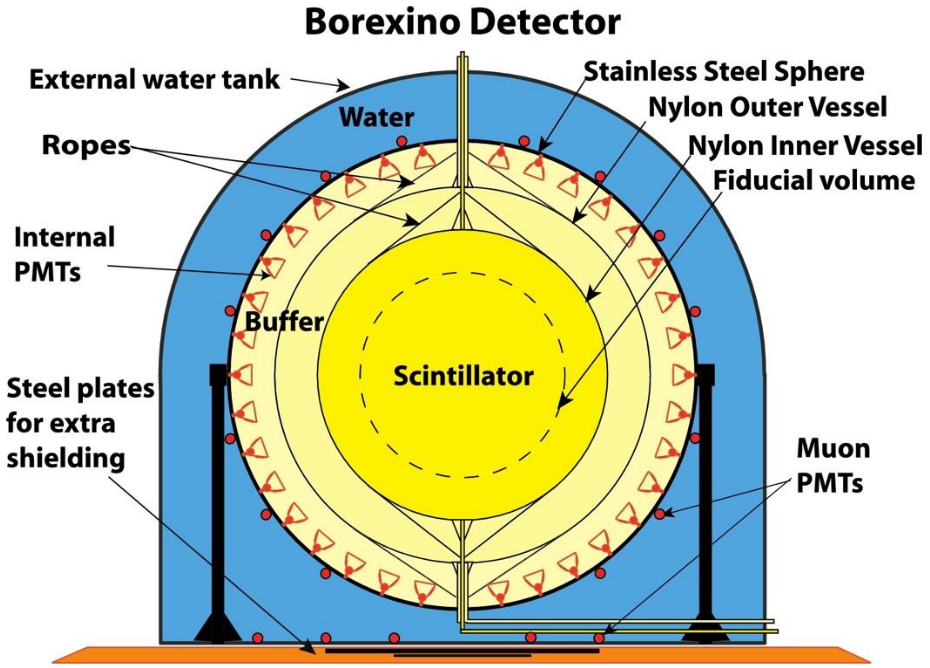


Detector Technologies (2)

Monolithic Scintillator Detectors (e.g. Borexino)

- Well suited to low energy physics
- High light yield (~500 pe/MeV)
- Good energy resolution (~5% / $\sqrt{E}$)

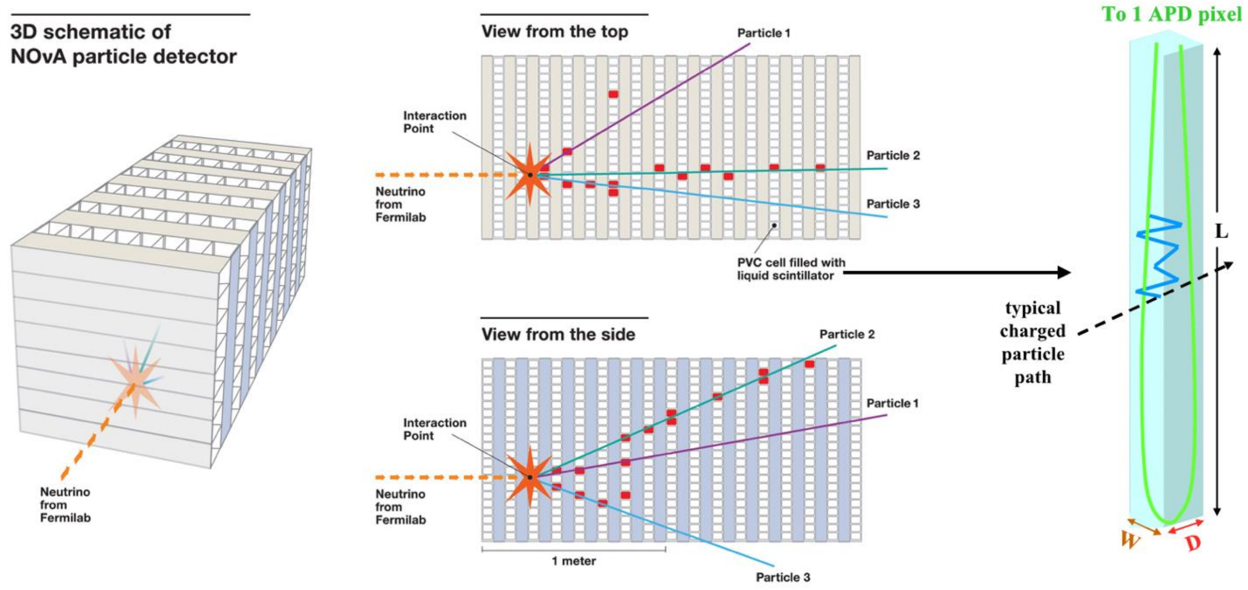
Not well suited to measuring particle direction or multi-particle states



Scintillator cells (e.g. NOvA, T2K ND)

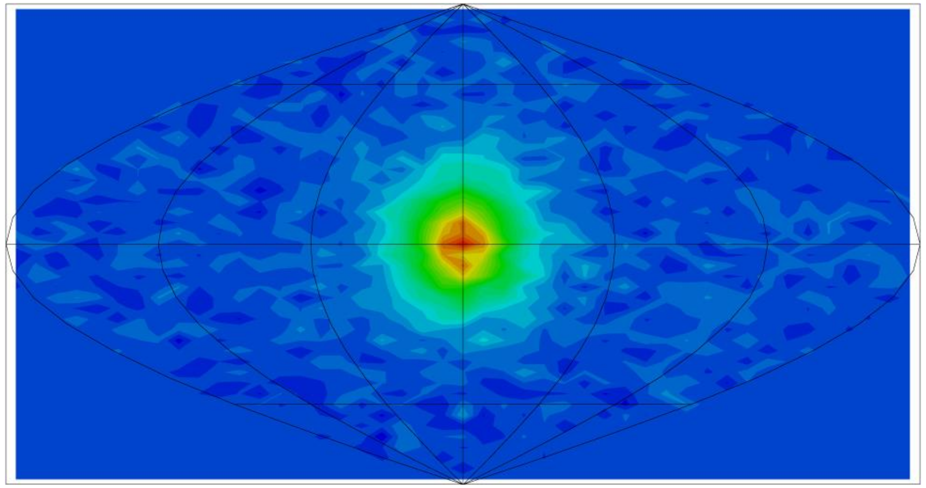
- Tracking through hits on bars
- Potential for neutron detection (due to free H)

Better suited for longer tracks (depends on granularity)

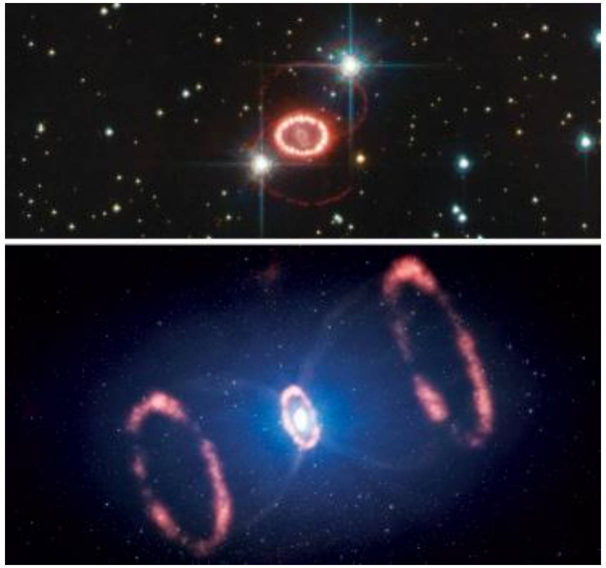


Neutrino Sources

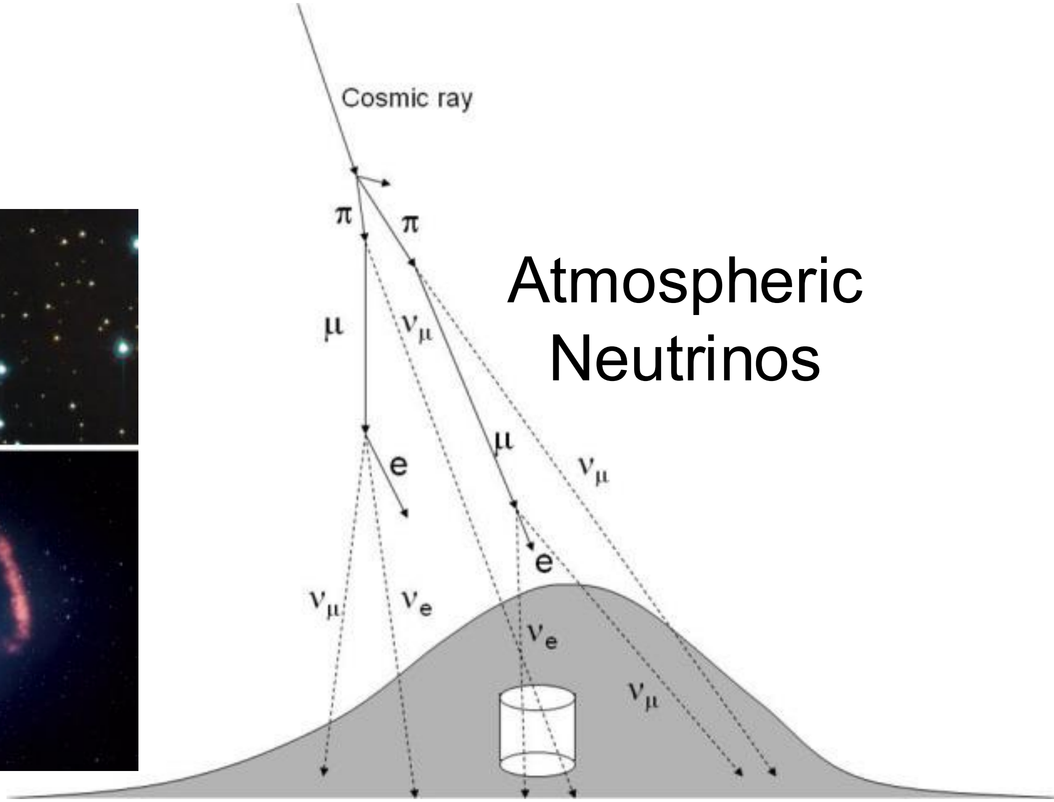
Solar Neutrinos



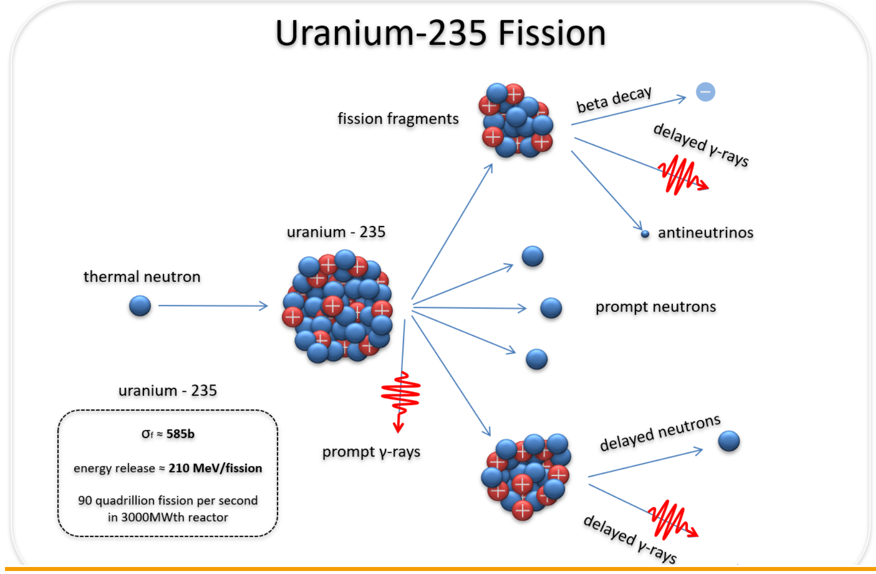
Supernova Neutrinos



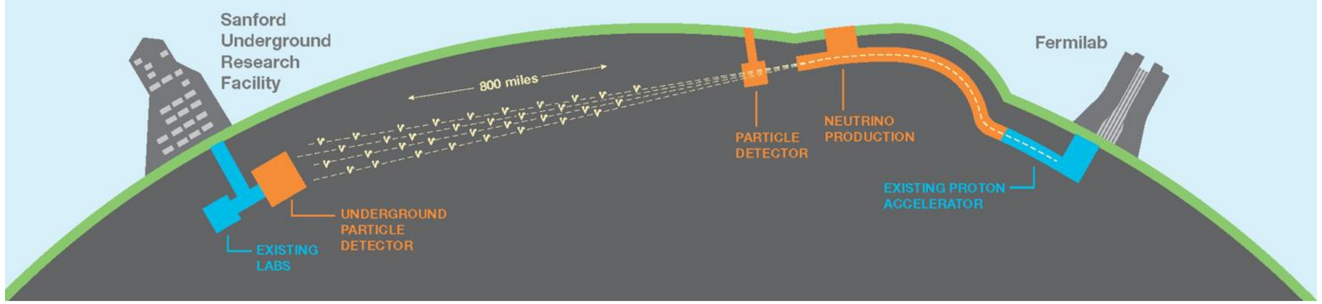
Atmospheric Neutrinos



Reactor Neutrinos

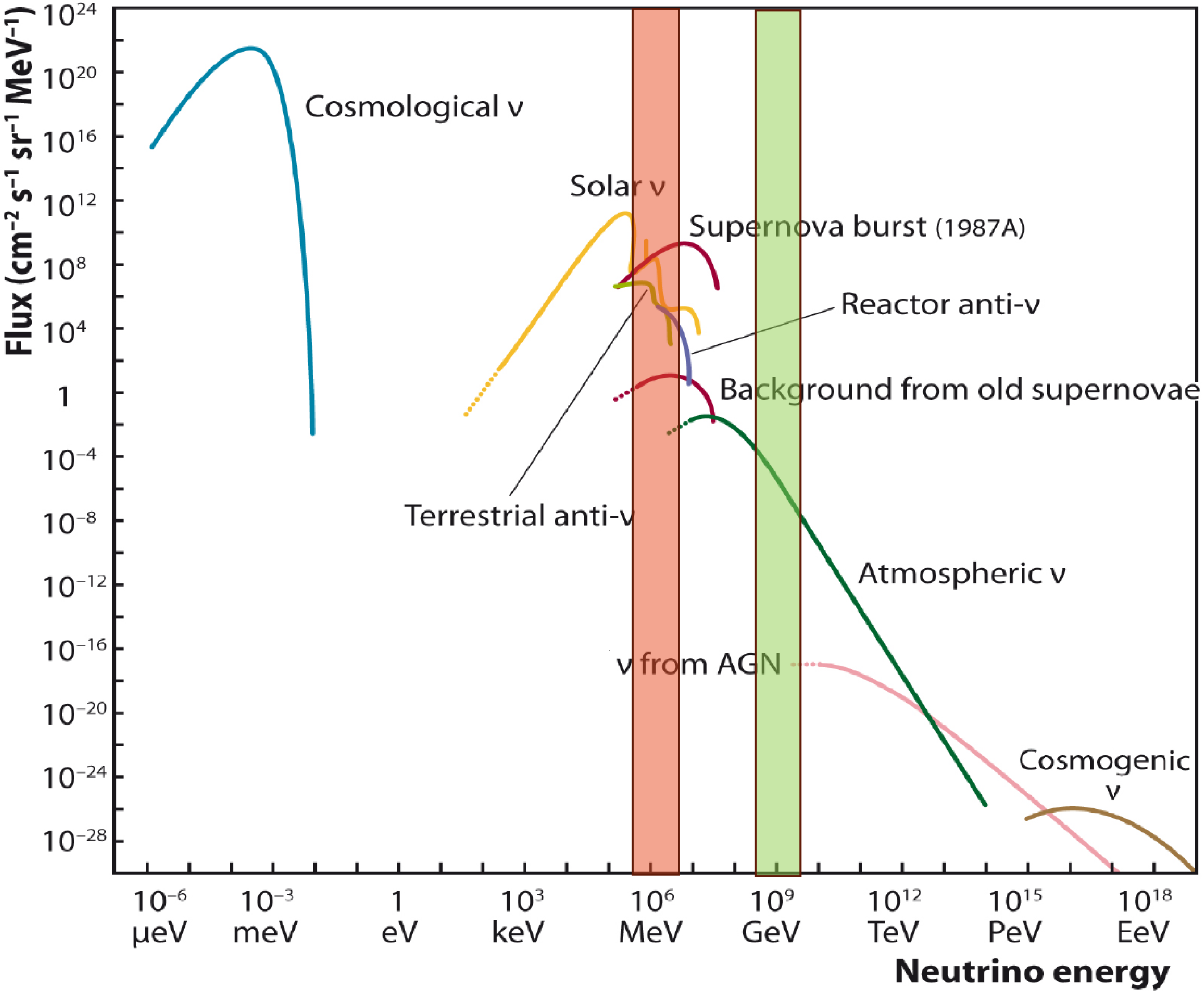


Accelerator Neutrinos



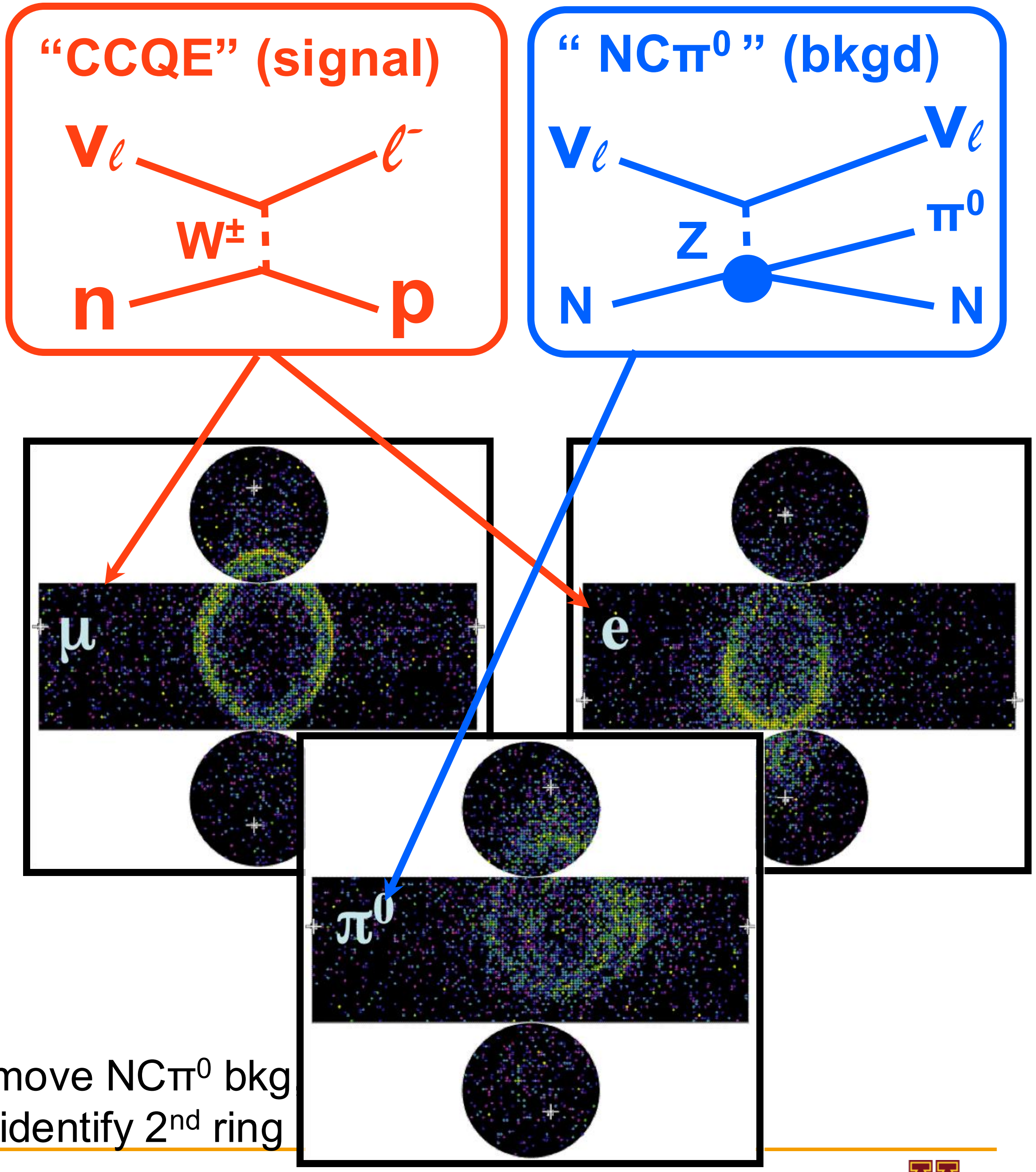
Neutrino Sources

- For oscillation physics, there are 2 regimes
- MeV-scale:
  - Solar neutrinos
  - Reactor neutrinos
  - Supernova neutrinos
  - Geoneutrinos
- GeV-scale:
  - Atmospheric neutrinos
  - Accelerator neutrinos (not pictured)



Super-Kamiokande

- 50 kton water Cherenkov detector
  - 39.3m diameter, 41.4m height, 11k 20” PMTs
- At the GeV scale, e/μ particle ID is based on scattering
  - $e^{\pm}$ -> more scattering, fuzzy rings ($\mu^{\pm}$ produces sharp rings)
- At the MeV scale, all events are e-like, and the key issues are energy threshold and radioactive backgrounds



To remove $NC\pi^0$ bkg must identify 2nd ring

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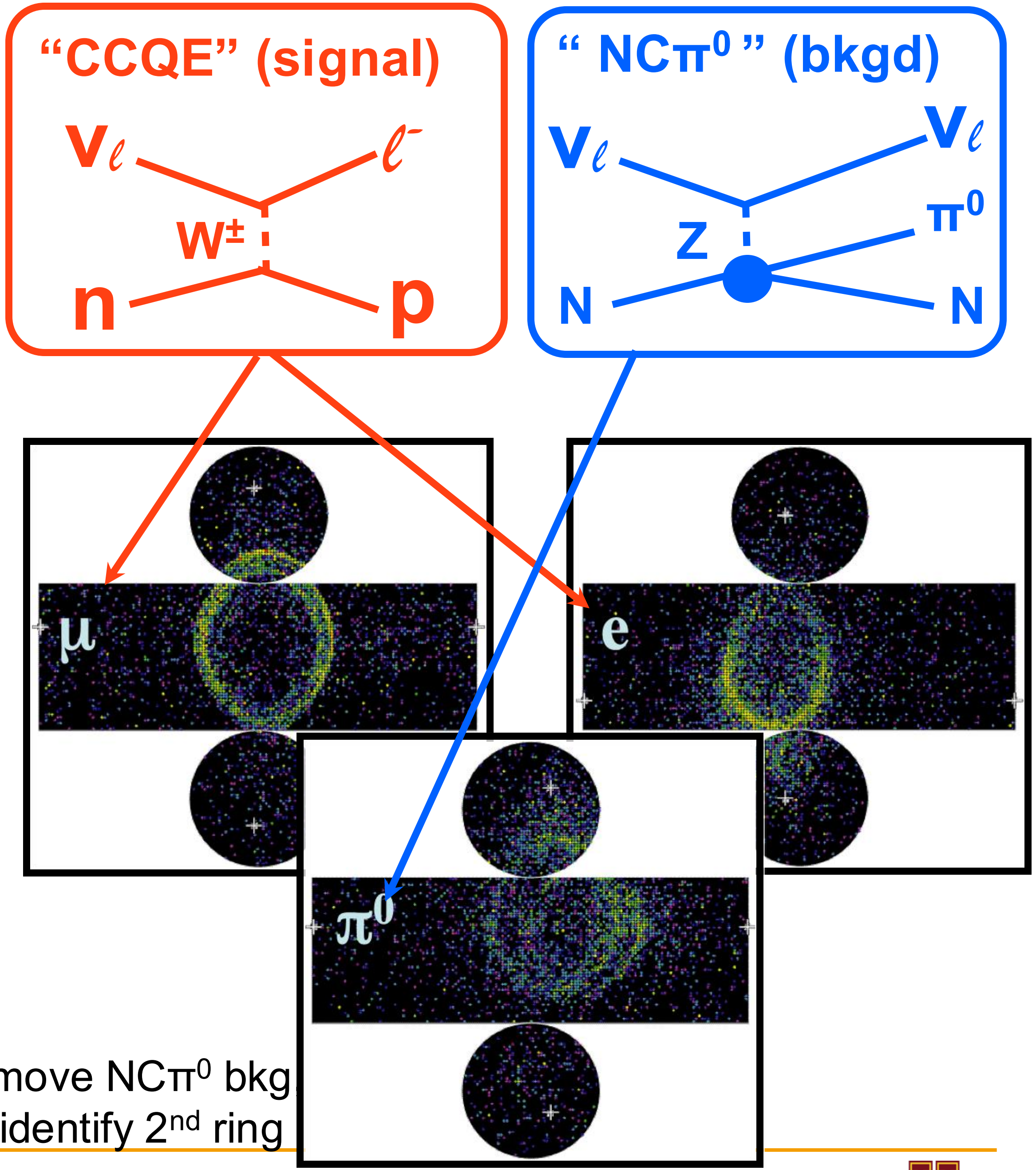

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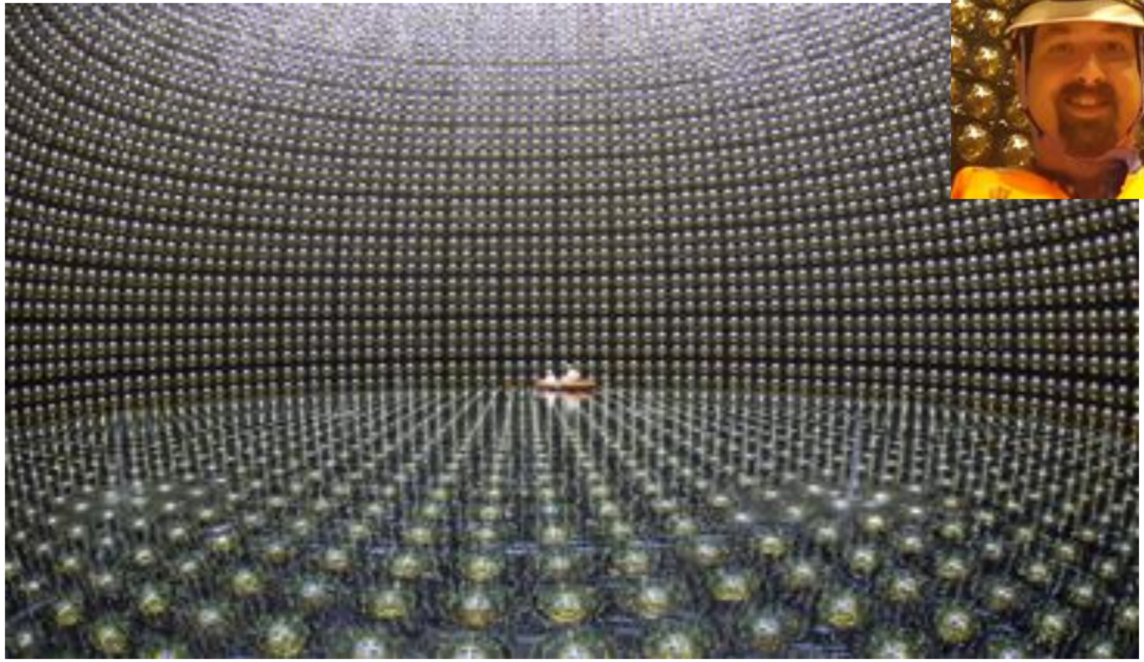

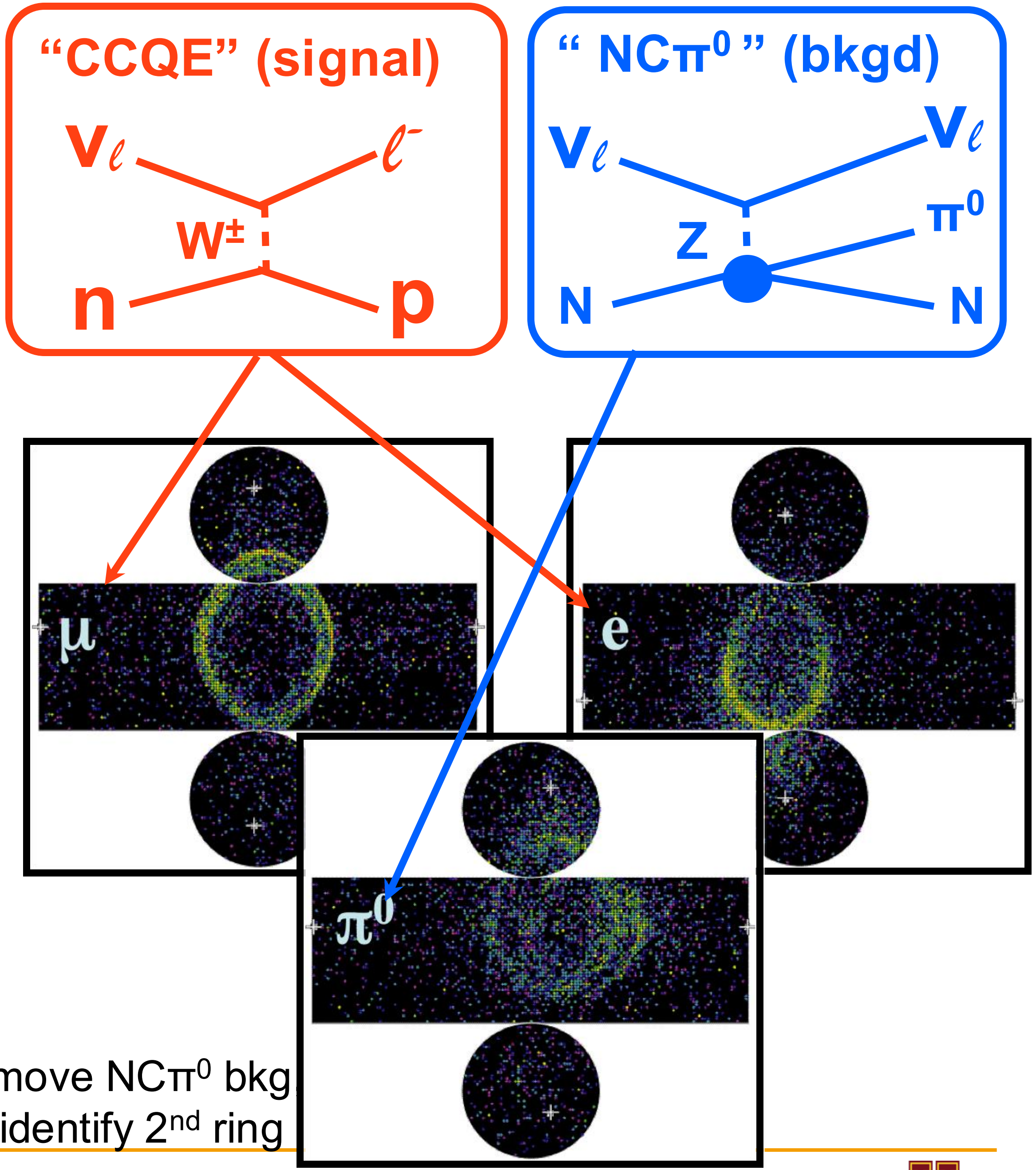

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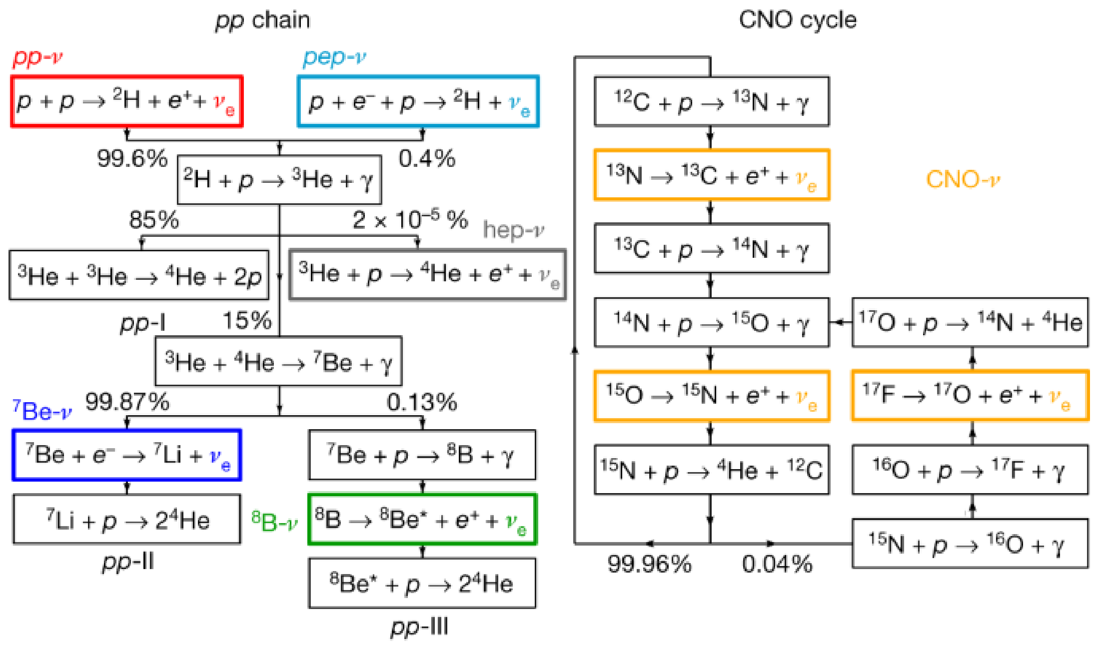
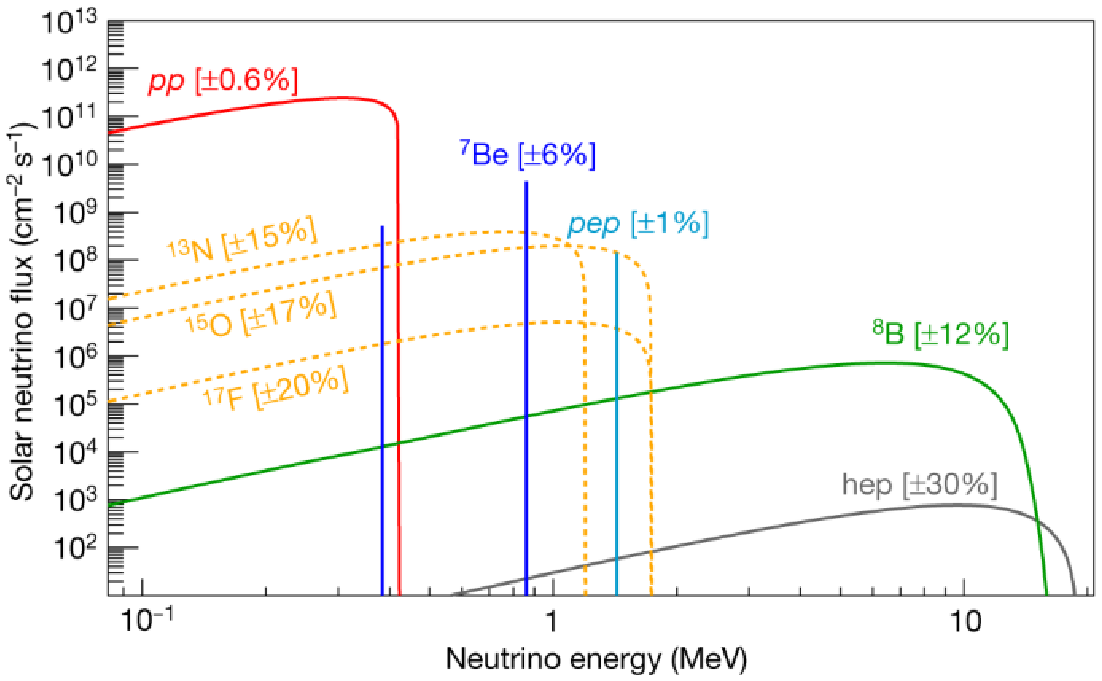
To remove $NC\pi^0$ bkg must identify 2nd ring

Solar Neutrinos

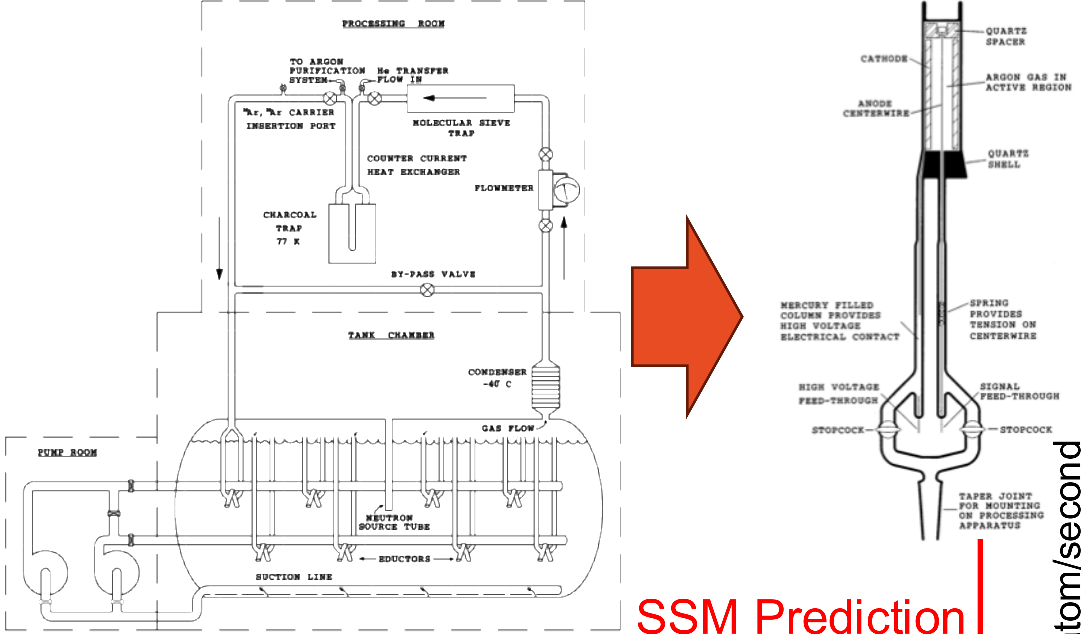
- Neutrinos are produced in fusion reactions in the sun
- Standard solar model: relates mass, luminosity, radius, etc. to neutrino production
- Solar neutrino problem: observed ν_e flux was ~30% of solar model prediction
- Most solar neutrino experiments measure ^8B
  - Highest energy (other than subdominant hep)
- Lower energy spectrum is much more difficult to measure precisely
  - Most precise measurements in this range are from Borexino

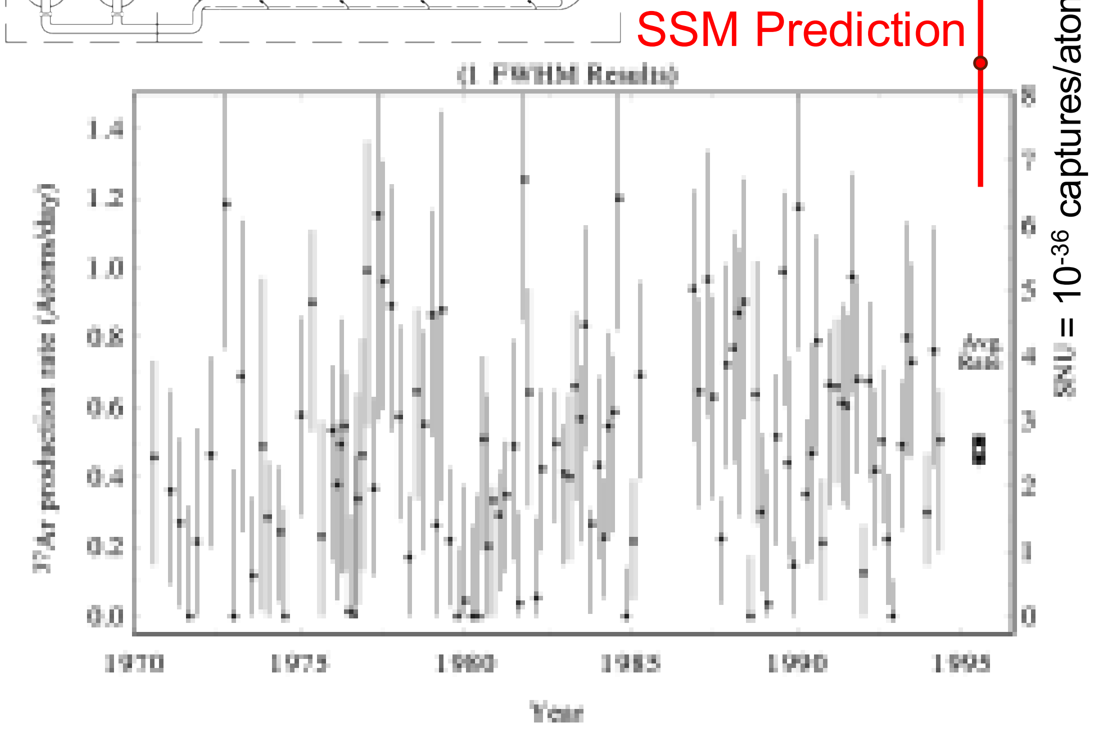




Solar Neutrino Problem

- Standard Solar Model (SSM) predicts the neutrino flux based on the observed photon luminosity
- In the 1960s, Ray Davis, et al. filled a tank full of dry cleaning fluid (C_2Cl_2) to measure the SSM flux
  - Each neutrino interaction converted ^{37}Cl → ^{37}Ar (half life of 35 days)
  - Every 2 weeks, He was bubbled through the tank to extract the ^{37}Ar
  - The extracted ^{37}Ar was then counted as it decayed back into ^{37}Cl
- Only ~30% of the neutrinos predicted by the SSM were observed
- (Fun fact: The Homestake mine, where this experiment took place, is where DUNE is now being built; 4 new huge caverns now exist!)

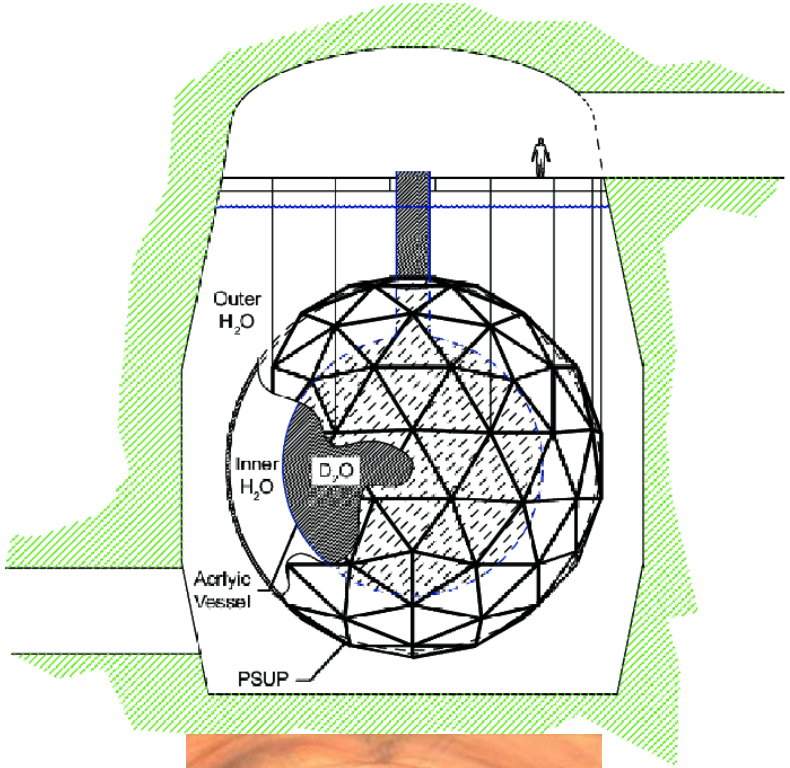




B.T. Cleveland et al., Astrophys. J. 496, 505 (1998)

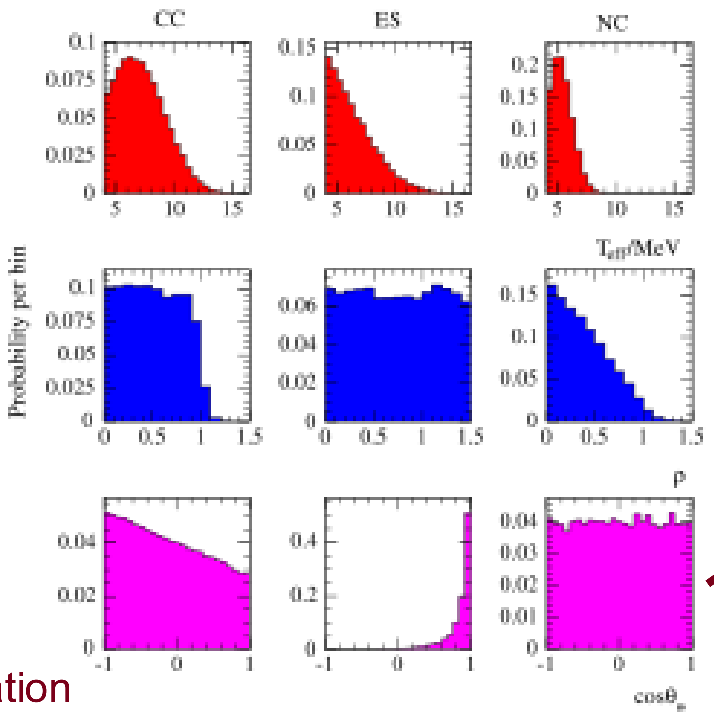
SNO Experiment

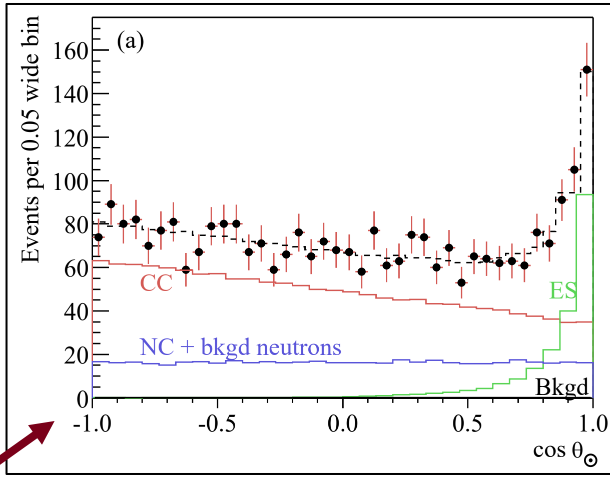
- Cavity at SNOLAB was 34 m high x 22 m diameter
  - Lined with a water- and radon-impermeable Urylon plastic
- Inner detector medium was heavy water D_2O
  - Worth about 300M Canadian dollars
  - Deuterium (^2H) was important for 2 reasons:
    - Provided a neutron target to allow for CC-ν_e interactions
    - Neutron capture on D produces a 6.25 MeV photon
      - Neutron capture on H produces a 2.2 MeV photon
      - Later phases of SNO used Cl (NaCl salt) and ^{3}He neutron counters
- 9438 inward-facing 20” PMTs w/ light concentrators (54% photocoverage)
  - 94 outward-facing PMTs (no concentrators) used as a veto

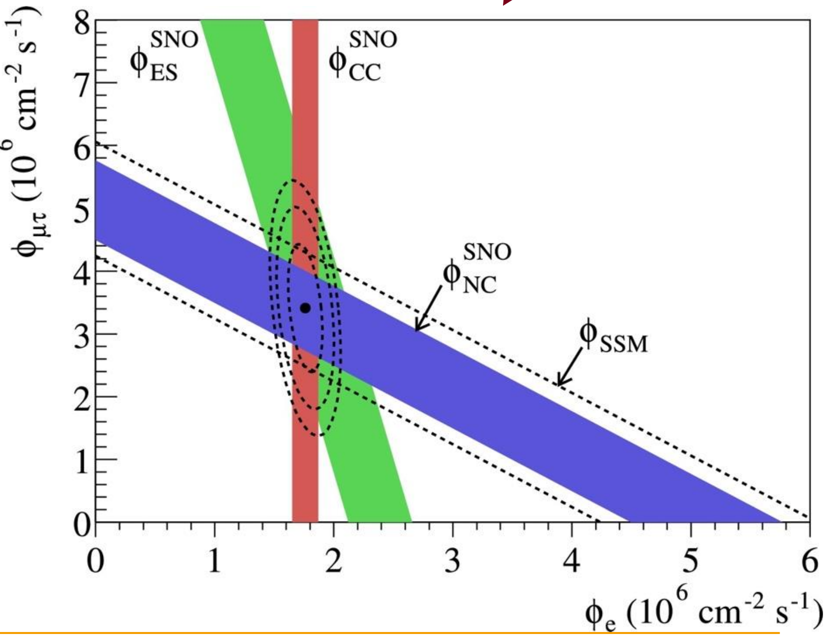


SNO Results

- 3 measured ν-interaction processes were:
- CC: $\nu_e + d \rightarrow p + p + e^-$
  - Only sensitive to ν_e ($\mu^\pm$ & $\tau^\pm$ are too heavy)
- NC: $\nu_x + d \rightarrow n + p + \nu_x$
  - Equally sensitive to all 3 neutrino flavors
    - Measures total neutrino flux, regardless of oscillation
- ES: $\nu_x + e^- \rightarrow \nu_x + e^-$
  - Electron cross section is 6 times higher (due to W-exchange diagrams)
- All 3 processes produced a single e/γ Cherenkov ring
  - Must be statistically separated by energy, vertex ρ, and θ_{sun}
  - Phase 3 used dedicated ^{3}He neutron counters
- Total measured rate (via NC) is consistent with the standard solar model (SSM); missing ν_e due to mixing/oscillations







Borexino

- While SNO and Super-Kamiokande measure ^{8}B neutrinos, Borexino has mapped out the lower energy spectrum
  - ~250 keV threshold due to high scintillator light yield (~500 pe/MeV)
- Controlling radioactive backgrounds is critical at these energies
- They were able to measure many of the solar spectrum components:
  - pp (11%), ^{7}Be (5%), pep (21%), CNO (39%)

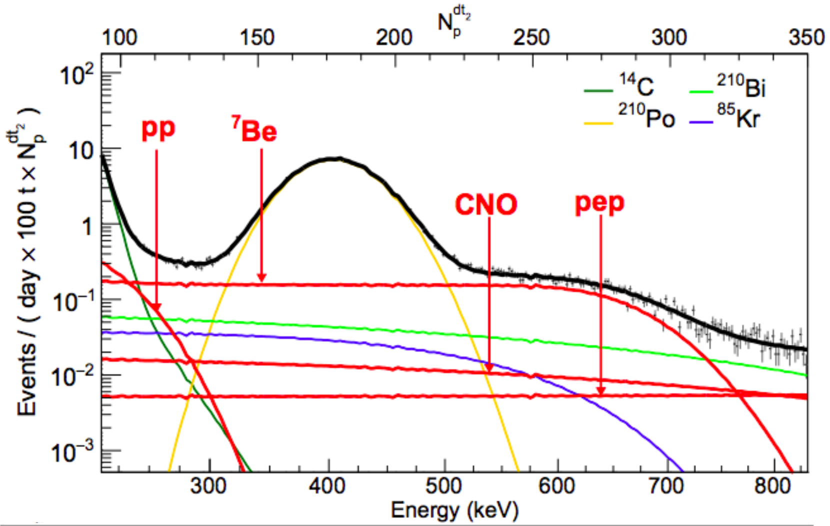


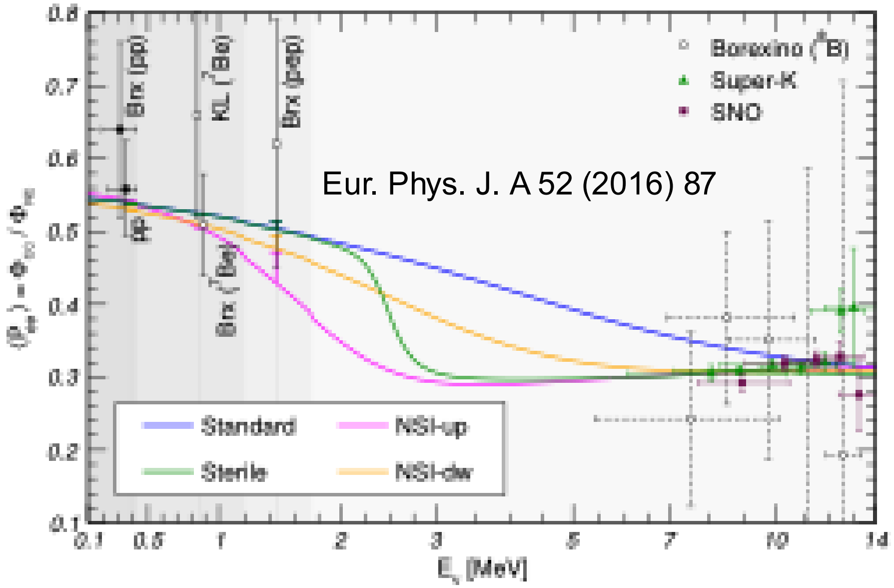
Table 1. The radiopurity in the Borexino scintillator, gases and water used for the radio-purification (g/g = grams of contaminants over grams of material; cpd = counts per day).

Radio-isotope		Concentration or flux		Final
Name	**Source**	**Typical**	**Required**	**Achieved**
^{14}C	Intrinsic scintillator	~10^{-12} $^{14}C/^{12}C$	~10^{-18} $^{14}C/^{12}C$	~2×10^{-18} $^{14}C/^{12}C$
^{238}U	Dust, particulate,	10^{-5}–10^{-6}g/g	<10^{-16}g/g	(5.0±0.9)10^{-18}g/g
^{232}Th	All materials			(3.0±1.0)10^{-18}g/g
^{7}Be	Cosmogenic	~3×10^{-2}Bq/t	<10^{-6}Bq/t	not observed
^{40}K	Dust, PPO	~2×10^{-6}g/g (dust)	<10^{-18}g/g	not observed
^{210}Po	Surface contamination	Decaying with a half time of ~138 days	<700 cpd/100 t	May 2007:500 cpd/100 t May 2009: 15 cpd/100 t
^{222}Rn	Emanation from materials, rock	10 Bq/l air, water 100–1000 Bq/kg rock	<10 cpd/100 t	<1 cpd/100 t
^{39}Ar	Air, cosmogenic	17 mBq/m^3 (air)	<1 cpd/100 t	≪1 cpd/100 t
^{85}Kr	Air, nuclear weapons	~1 Bq/m^3 (air)	<1 cpd/100 t	30±5cpd/100t

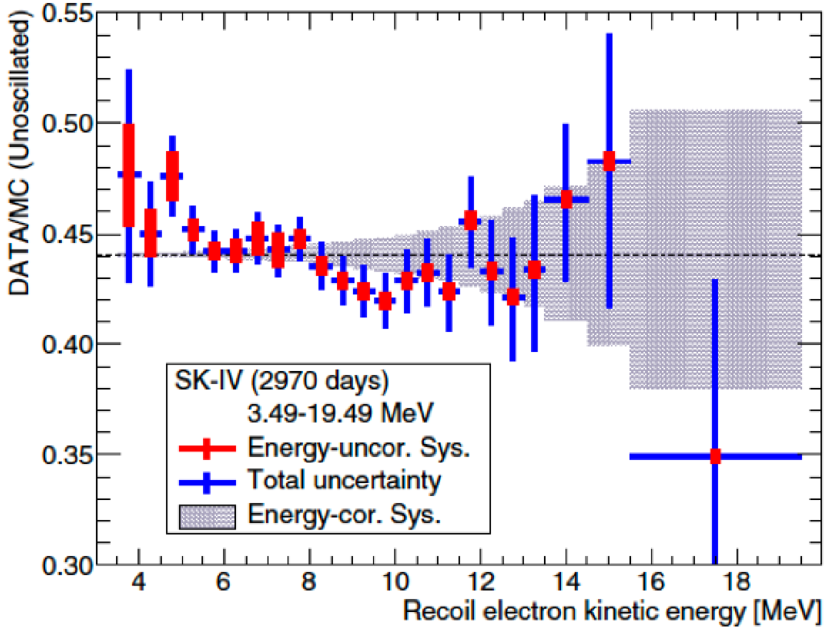
Nucl. Phys. B. 908, 178 (2016)
Phys. Rev. D **108**, 102005 (2023)

Solar Neutrinos, Next Steps

- Observe MSW effect in the sun
  - "Upturn" of solar spectrum as the neutrino energy decreases below SNO/SK threshold
  - SK may be seeing some hints already
- Observe MSW effect in the earth
  - Day/night asymmetry
    - Measured via reconstructed zenith angle
    - Neutrinos directly from the sun vs neutrinos passing through earth first
- SNO+ is taking data now and working to lower energy thresholds
- Hyper-Kamiokande: 5σ upturn measurement if E_{thresh} -> 3.5 MeV
- DUNE: Promising for first measurement of hep neutrinos
- JUNO: Should be able to improve on Borexino low energy measurements (^{7}Be, pep, CNO)

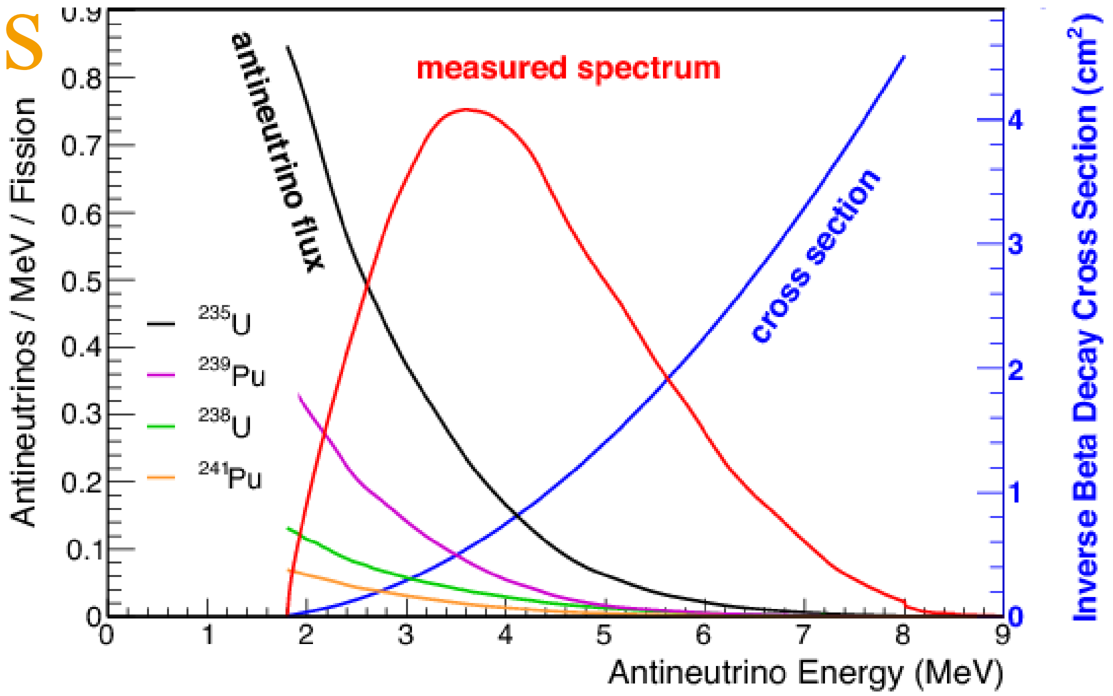


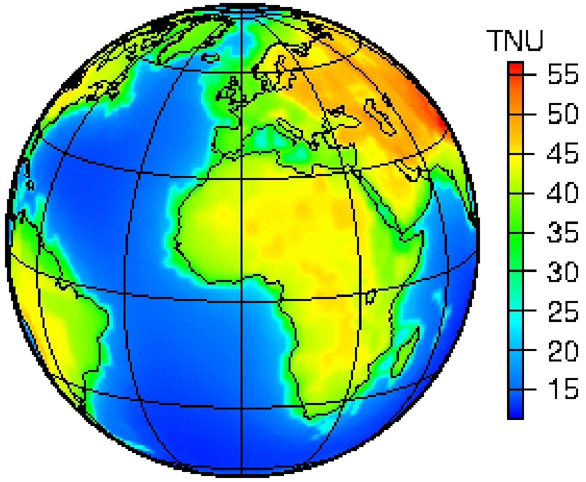
Phys.Rev.D 109 (2024) 9, 092001

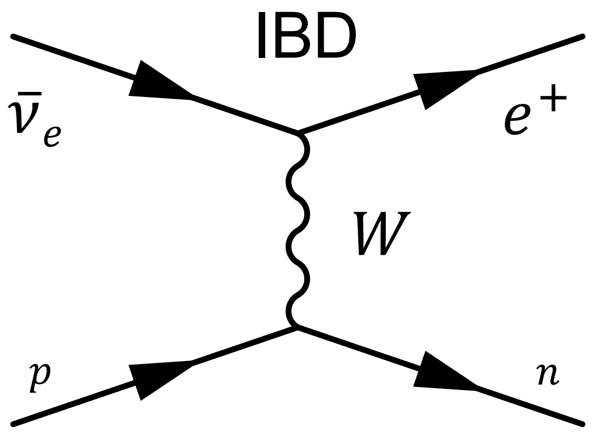


Reactor (and Geo-) Neutrinos

- Beta decays of reactor isotopes (largely anti-ν_e)
  - >99.7% flux from ^{235,238}U and ^{239,241}Pu
- "Point-source" allows for a near/far measurement strategy for oscillations
- Low energy source (like solar neutrinos) mainly detector through inverse beta decay (IBD)
- Similar for geoneutrinos
  - uranium, thorium, and potassium in the earth's crust and mantle

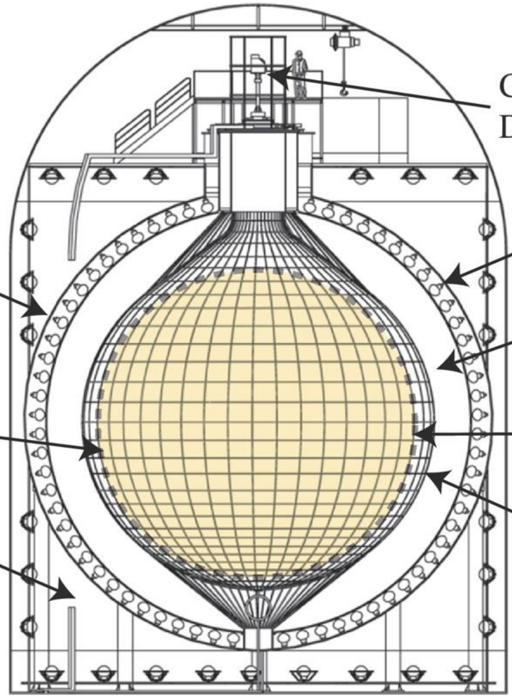




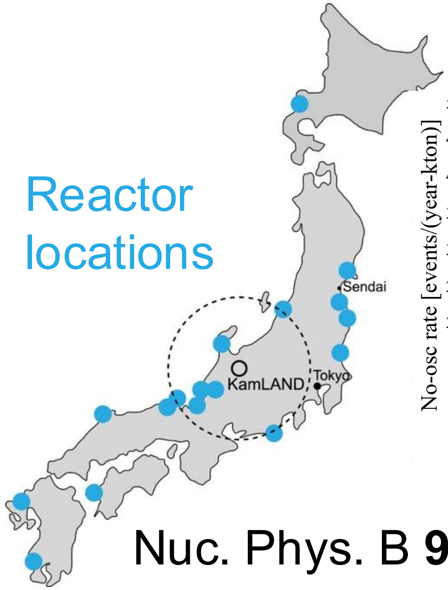


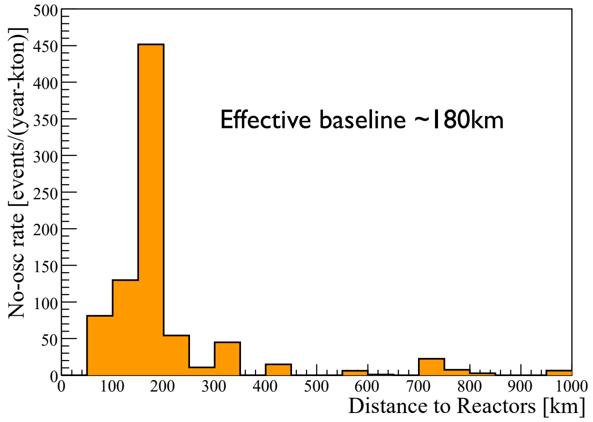
Reactor Experiments: KamLAND

- Located in the same mine a Super-K
- 13-m-diameter spherical balloon full of liquid scintillator
- Signal is Inverse Beta Decay (IBD)
  - $\bar{\nu}_e + p \rightarrow e^+ + n$
    - E_ν threshold is 1.806 MeV (extra mass in final state)
  - "Prompt" energy from e^+ KE & e^+/e^- annihilation to 2 photons (0.511 MeV each)
    - $E_{\nu,rec} = E_{vis} + 0.784$ MeV
  - "Delayed" energy is from neutron capture
    - 2.2 MeV γ if capture on a p
    - 4.9 MeV γ cascade if captured on ^{12}C
    - Occurs ~200 μs after the prompt signal



Reactor locations

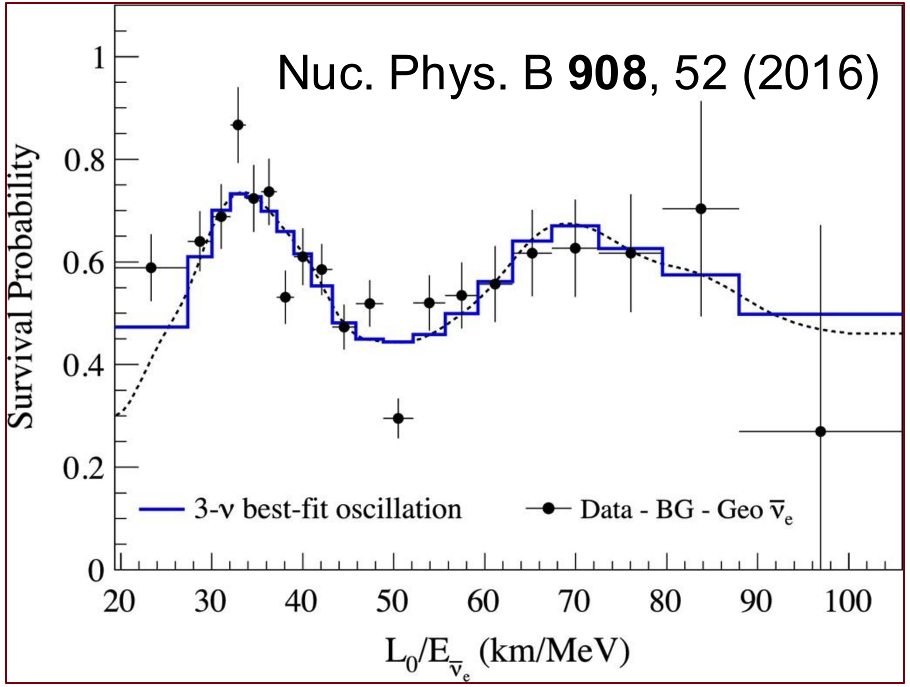


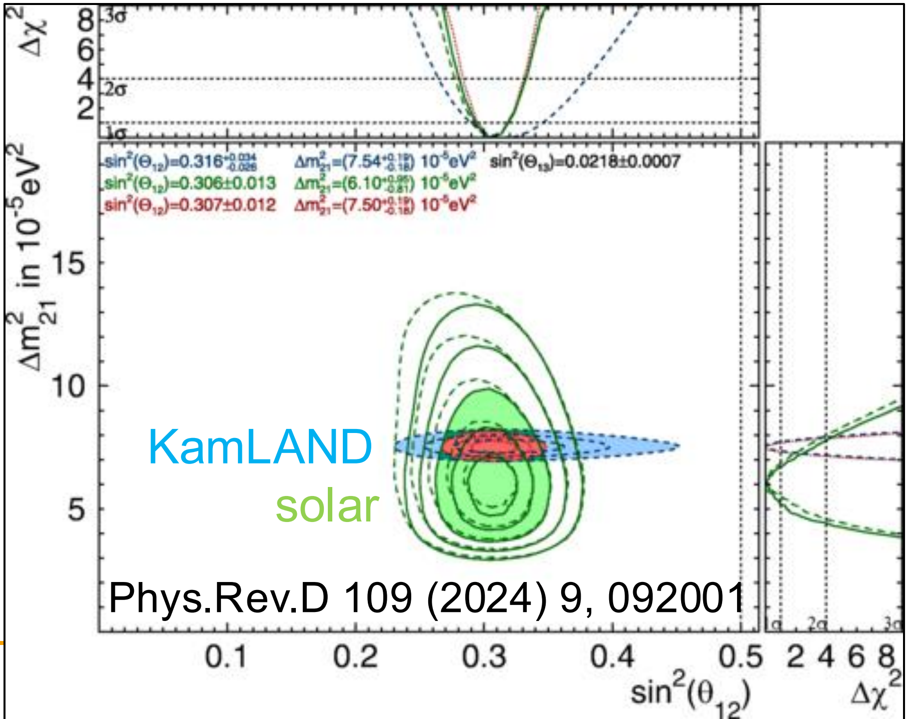


Nuc. Phys. B **908**, 52 (2016)

KamLAND Results

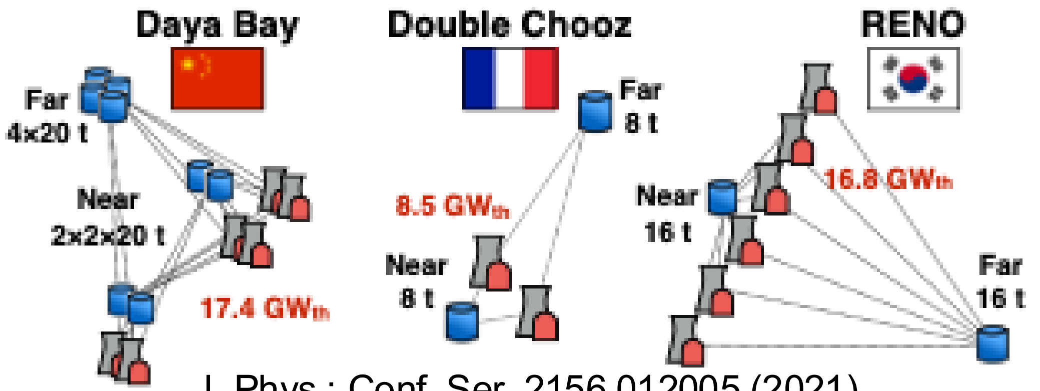
- When the data is plotted vs L/E, almost 2 oscillation periods can be seen
  - Most precise determination of Δm_{21}^2
- These results can be compared with a global fit of solar neutrino data
  - ~1.5 σ “tension” between the results
- One of the main goals of the next generation of solar & reactor experiments is to investigate this plot (more later)



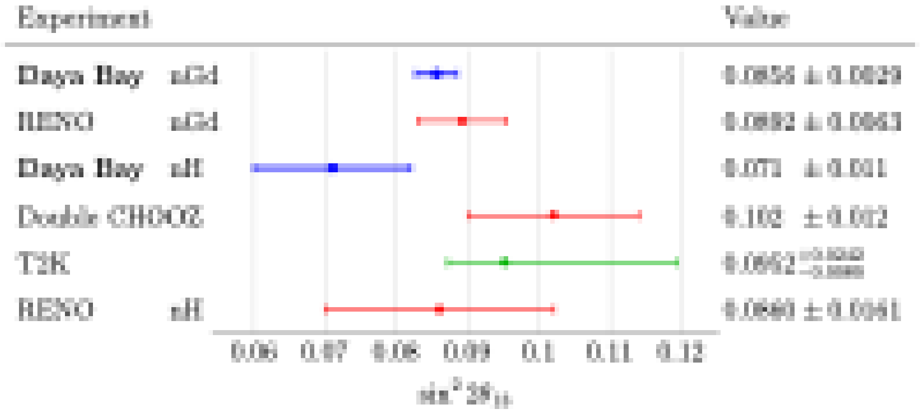


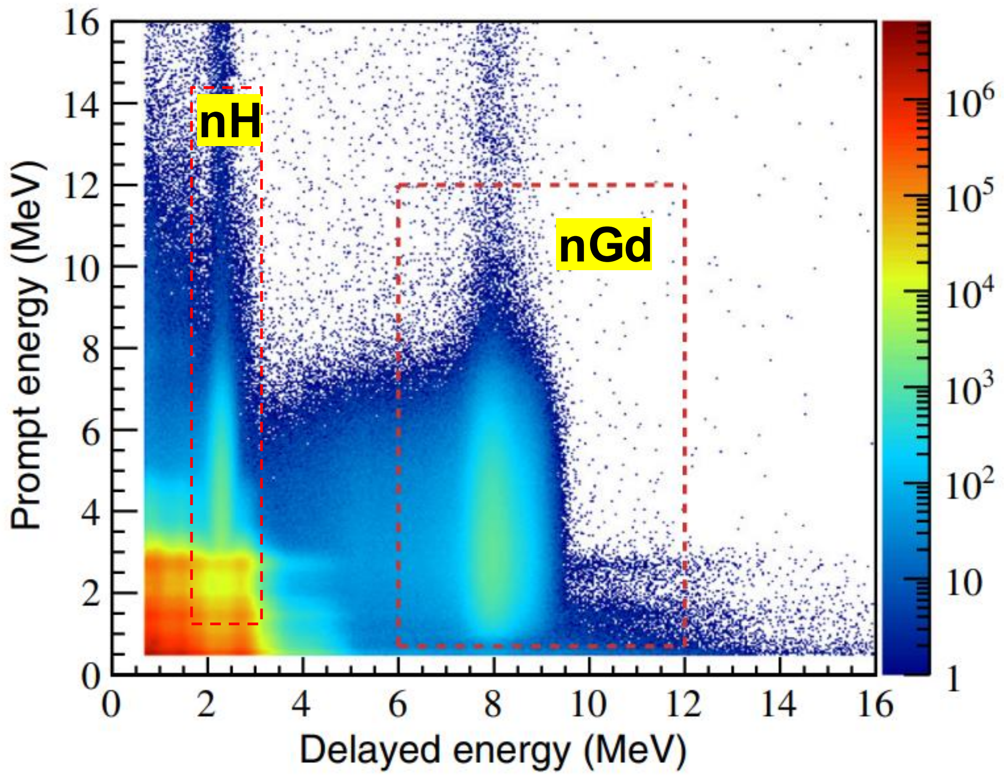
Recent Reactor Experiments

- The last unknown mixing angle, θ_{13}, is now the best-known mixing angle
- Measured by Daya Bay, RENO, & Double Chooz
  - Each experiment doped the inner detector LS volume with Gd



J. Phys.: Conf. Ser. 2156 012005 (2021)

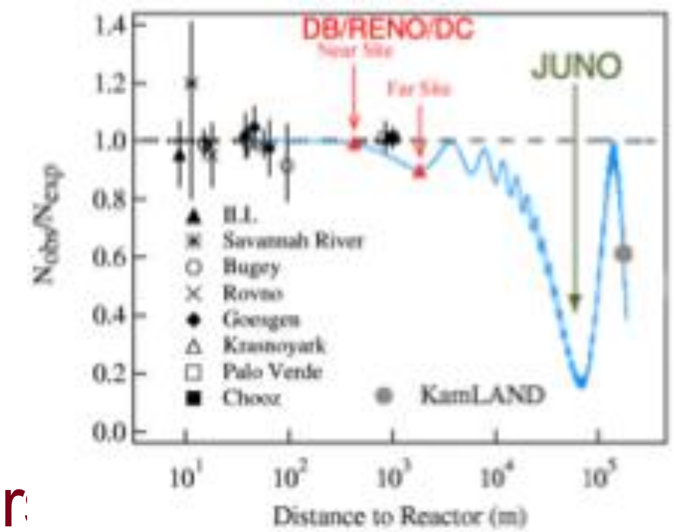


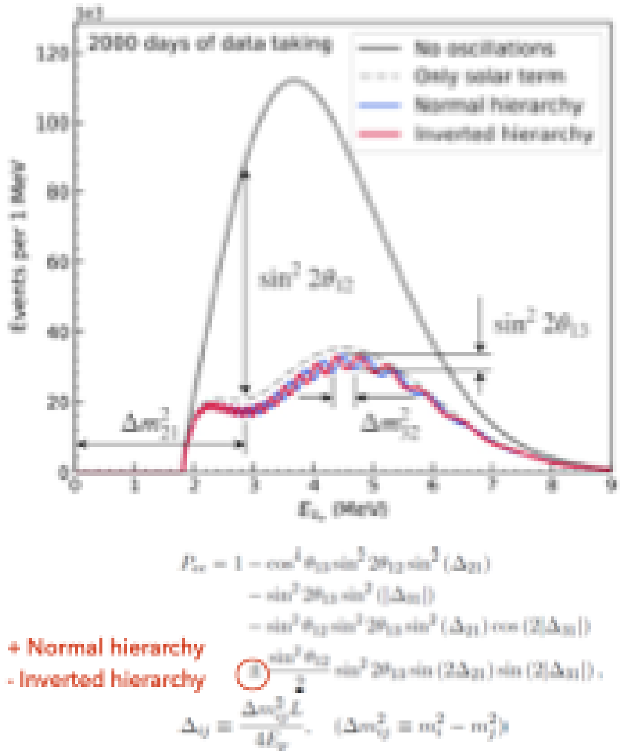


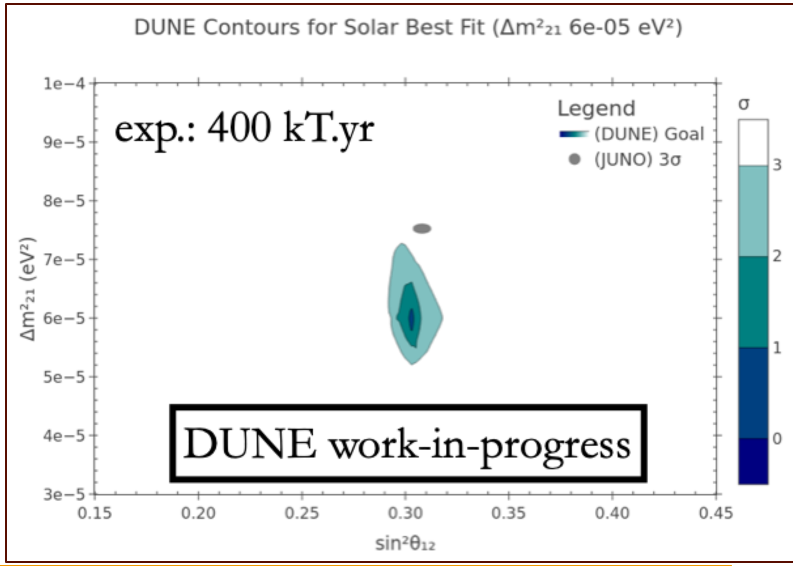
Daya Bay, PHYSICAL REVIEW D 95, 072006 (2017)

JUNO

- Jiangmen Underground Neutrino Observatory (JUNO) is a 20 kt LS detector (~10x Borexino)
- It is positioned (53 km from 2 reactor is sensitive to both the solar and atmospheric mixing angles and m^2's
- Stated goal is to try to measure the neutrino mass hierarchy
  - Requires ~3% energy resolution at 1 MeV
    - LS will produce 1100 pe/MeV (2x Borexino)
- However, even if the mass hierarchy proves too difficult, it will substantially improve the precision of θ_{12} & Δm_{21}^2

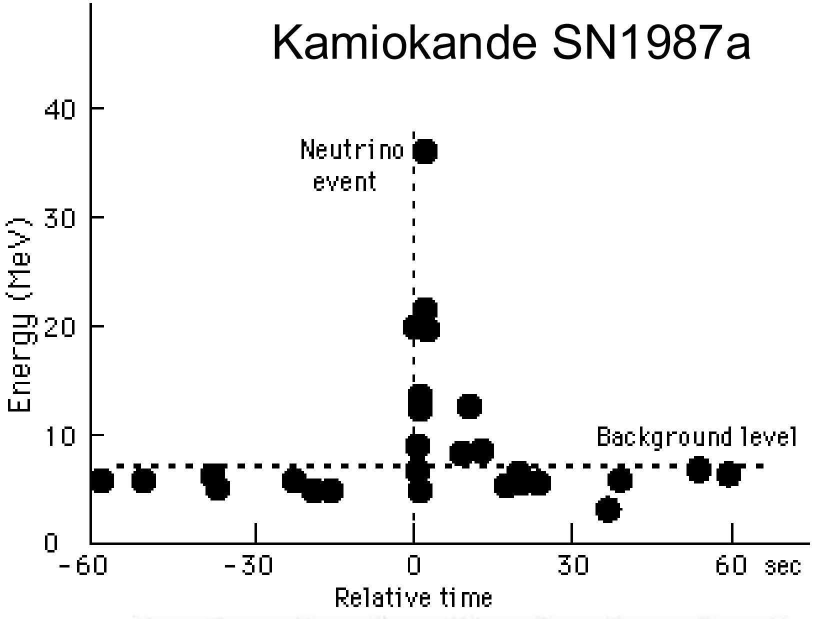


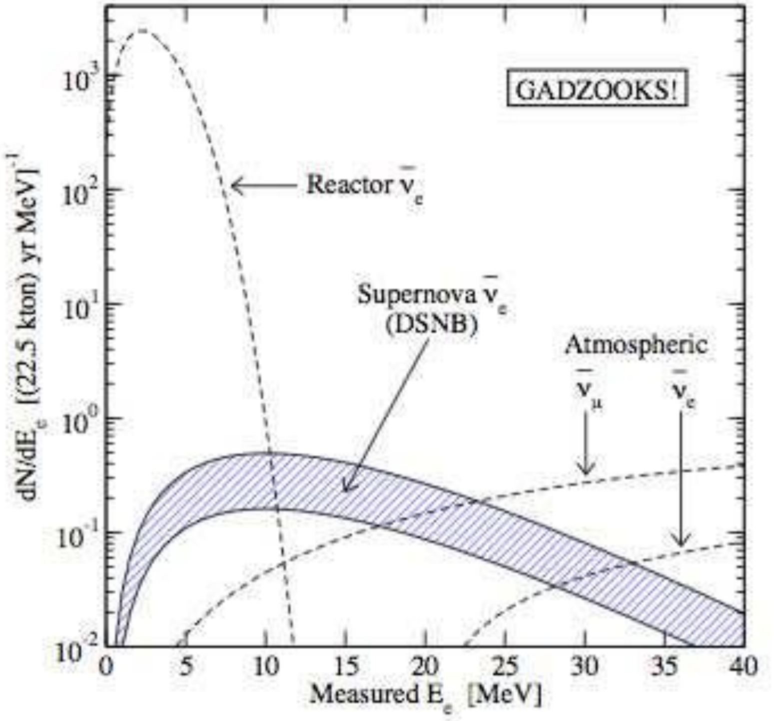




Supernova Neutrinos

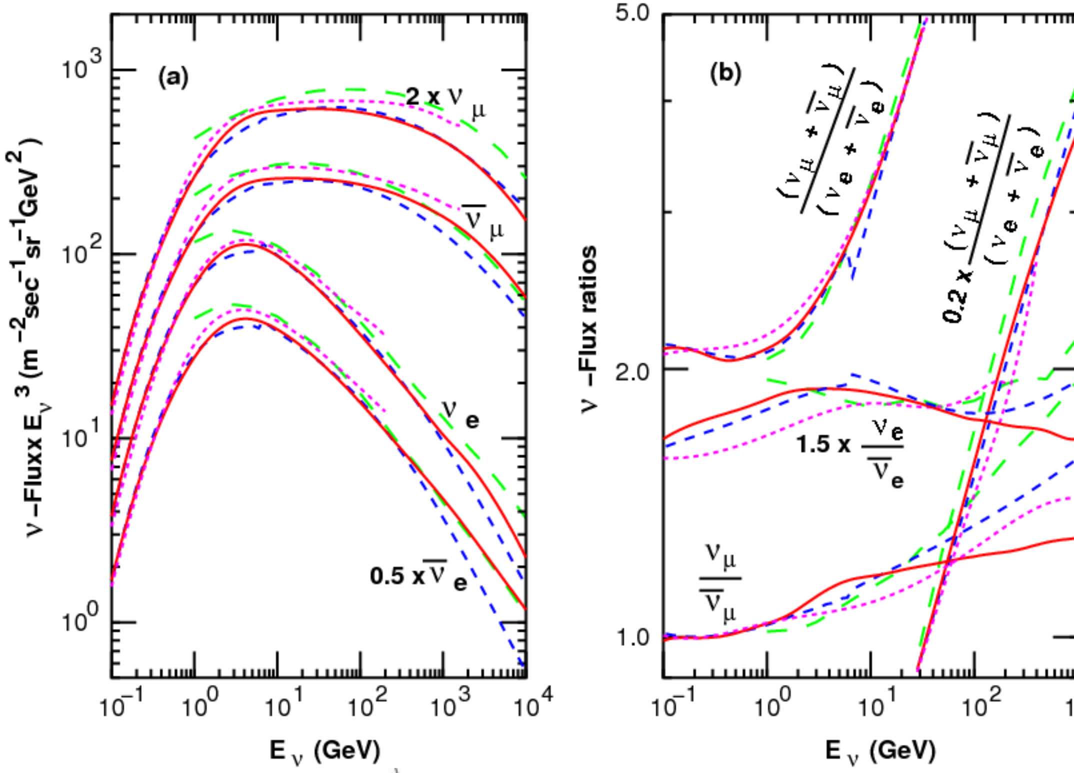
- 99% of the energy released in a supernova is carried by neutrinos
- A galactic supernova would produce O(10k) events in Super-Kamiokande:
  - Neutrinos arrive hours before optical signal
  - Goal of SNEWS is to report direction of the supernova within an hour (for telescope observation)
- In addition, we can search for the "Diffuse Supernova Neutrino Background" (DSNB)
  - The ambient neutrinos from all Supernovas that have ever happened (~10/cm^2/s)
  - Small window for observation between the reactor and atmospheric neutrino background

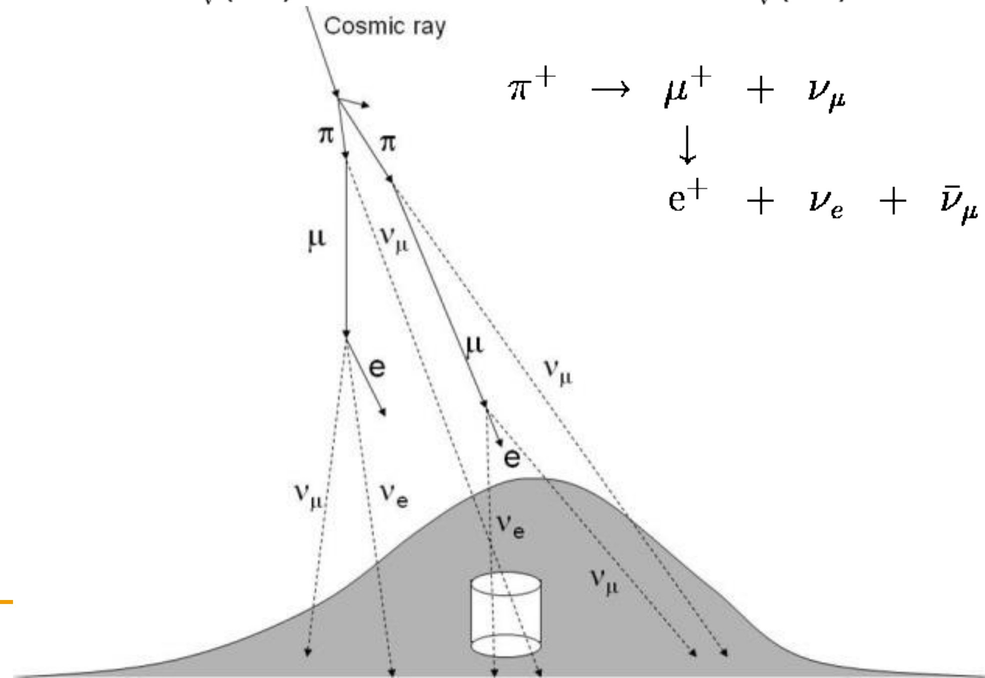




Atmospheric Neutrinos

- Earth is constantly bombarded with high energy cosmic rays
  - 90% protons, the rest mostly alphas
- Interactions in the upper atmosphere (N_2, O_2) produce hadrons
- π^+ are the most prevalent ν producer (especially at low energies)
  - Due to helicity suppression, pions decay to a muon and a muon neutrino 99.99% of the time
  - The muon decays to an electron and 2 neutrinos
- At low energies, we see $\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} \approx 2$
  - As the energy increase, muons begin reaching the ground before decaying
- So, in the region around 1 GeV, from just the flux, we would expect to measure a 2:1 ratio of ν_μ to ν_e (if we don't distinguish ν from $\bar{\nu}$)



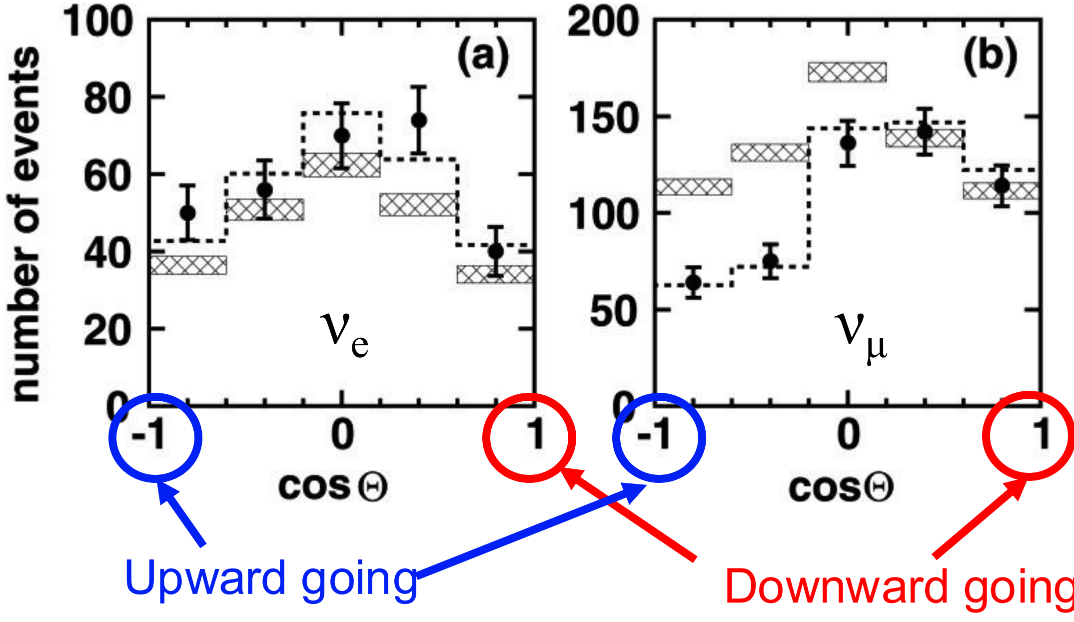


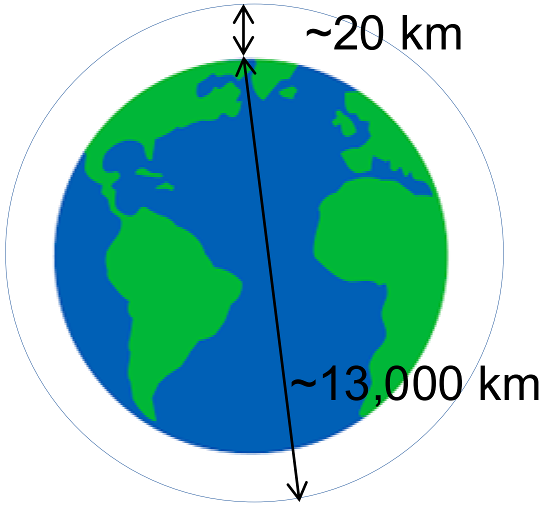
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

Discovery of "Neutrino Oscillations"

"hashed" = default MC
"dotted" = oscillated

- For downward going muon neutrinos, Super-K saw the expected 2:1 ratio of ν_μ to ν_e
  - (Consistent with default MC – hashed boxes)
- For upward-going neutrinos, the ratio was 1:1!
  - Not possible from the atmospheric neutrino flux, since that should always produce *at least* a 2:1 ratio (higher at higher energies)
- Neutrinos are oscillating!
  - … to tau neutrinos, which are (mostly) too low in energy to make tau leptons
  - … so, we mostly observe ν_μ disappearance
- 2015 Nobel Prize

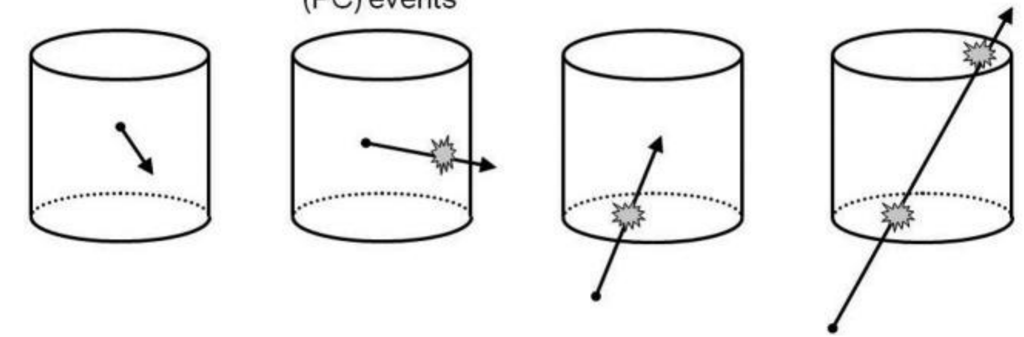




Phys.Rev.Lett. 81 (1998) 1562-1567.

More Recent SK ATM Results

- These days, we use many more event samples
  - Still mostly e-like & mu-like
  - Single-ring & multi-ring
  - Sub-GeV & multi-GeV
  - Different numbers of “decay electrons” (d.e.) to identify decays of stopped π^+ & $\mu^\pm$



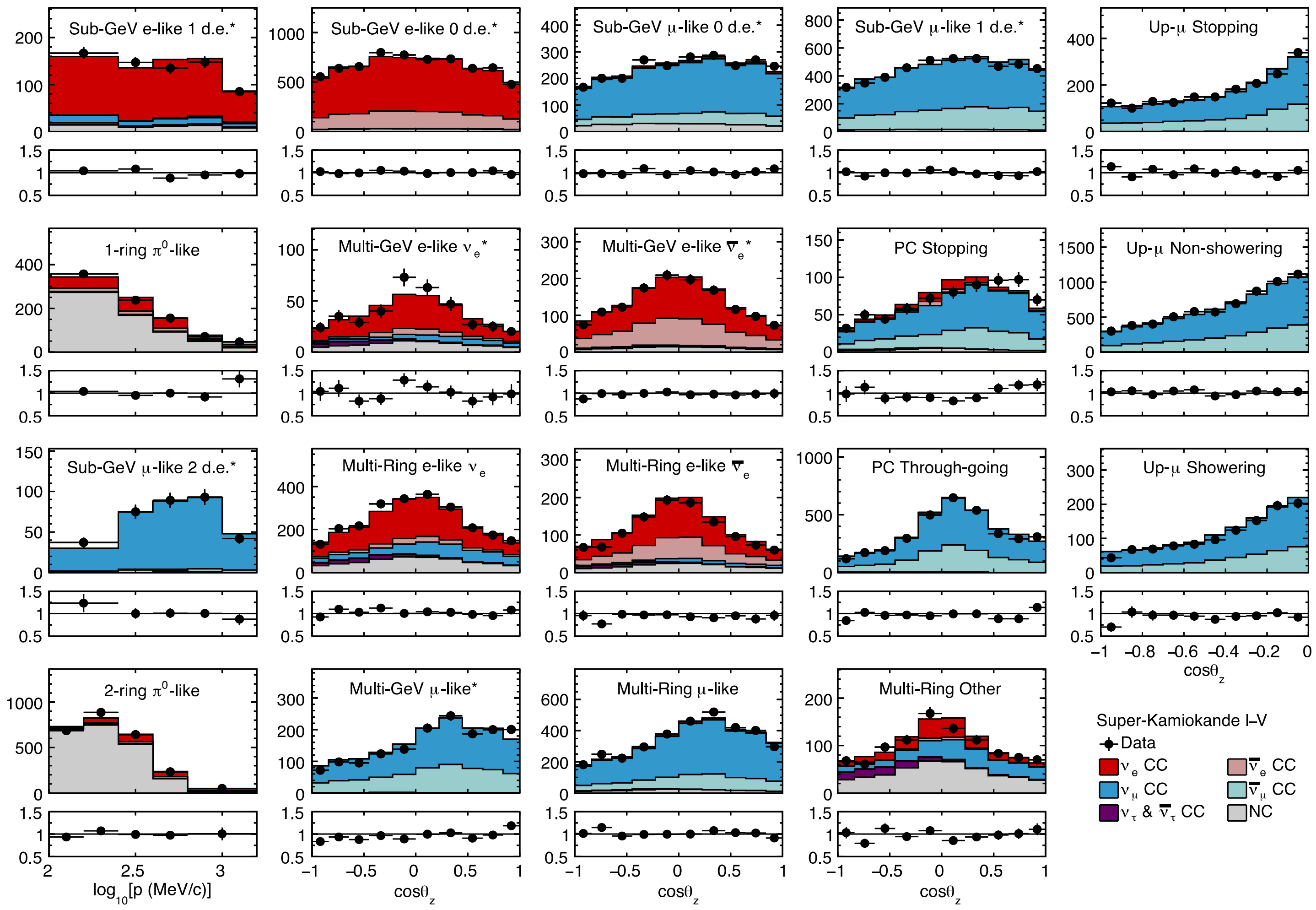


FIG. 5. Zenith angle or momentum distributions for the 19 analysis samples without neutron tagging. The first column shows the momentum bins for samples which are not also binned by zenith angle, while the second through fifth columns show the 1D zenith angle distributions for samples which use 2D momentum-and-zenith-angle binning. The MC distributions are shown at the best-fit point in the normal ordering, cf. Tab. IV with best-fit systematic pulls applied. Different colors in the MC histograms correspond to the true neutrino flavors present in each sample. Panels beneath each distribution show the data-MC ratio, and all error bars are statistical. FC (non-PC and non-Up-μ) sub-GeV and multi-GeV single-ring samples, marked with an asterisk (*), contain events from only SK I–III, while the corresponding events from SK IV–V are separated into samples using tagged neutron information, shown in Fig. 6.

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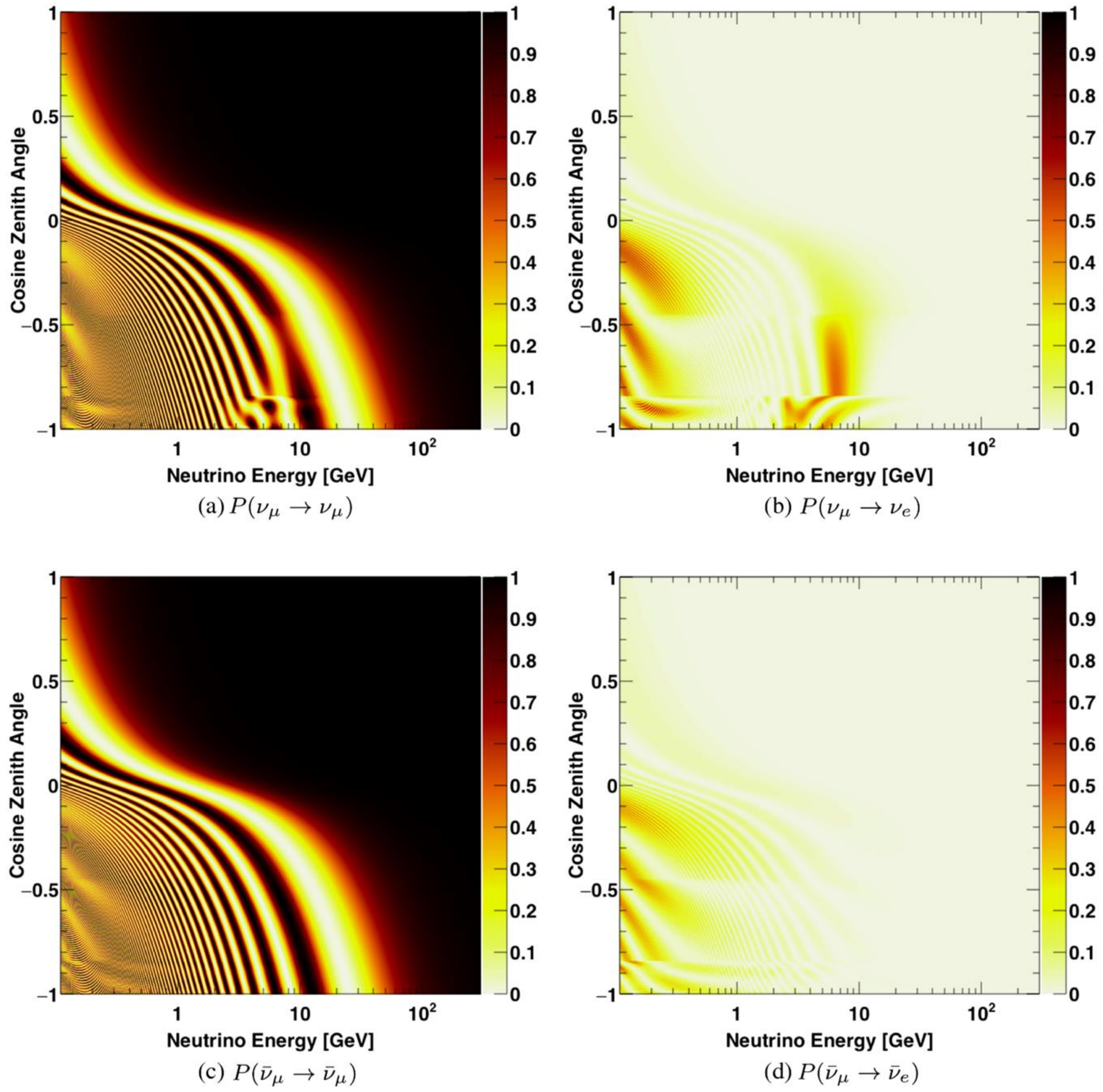
Atmospheric Oscillogram

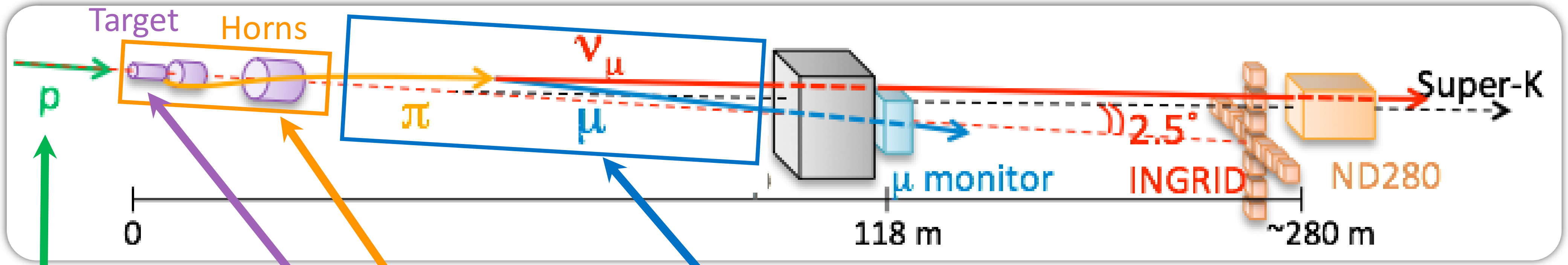
- The direction of the incoming neutrino determines how much earth it passes through before reaching the detector
  - Pathlength, L, determines oscillation probability
- No oscillations at the “top” of the plots (downward-going)
  - As the zenith angle decreases, L gets longer, and the first oscillation maximum makes a broad S-shape
  - Moving from the outer band to the inner bands is stepping through higher oscillation maxima
  - Eventually, the oscillations become too fast to resolve
- The MSW effect in the earth produces a resonance at ~6 GeV in neutrinos (antineutrinos) if the mass ordering is normal (inverted)
  - Resonances also appear in the sub-GeV region, which could be exploited with sufficient energy/angular resolution

Normal Hierarchy Case



Accelerator Neutrinos

Example: T2K beamline

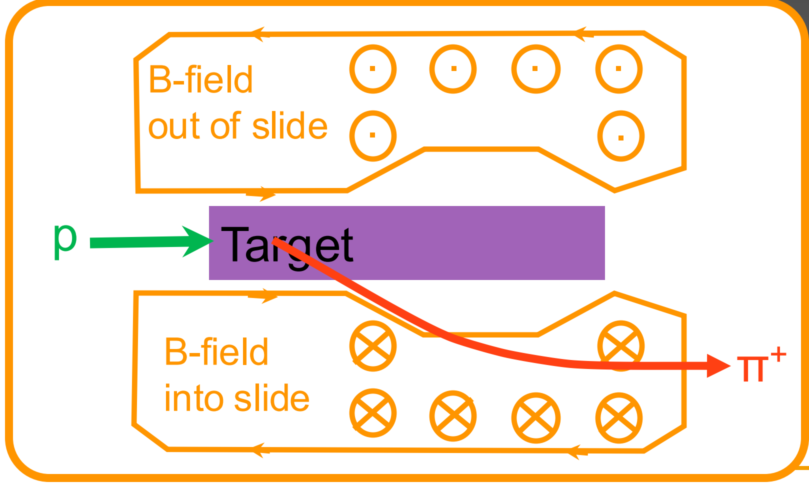


30 GeV protons from the J-PARC Accelerator

Protons interact in a 90cm graphite target

Resulting Pions are forward-focused by the toroidal B-field within 3 "horns"

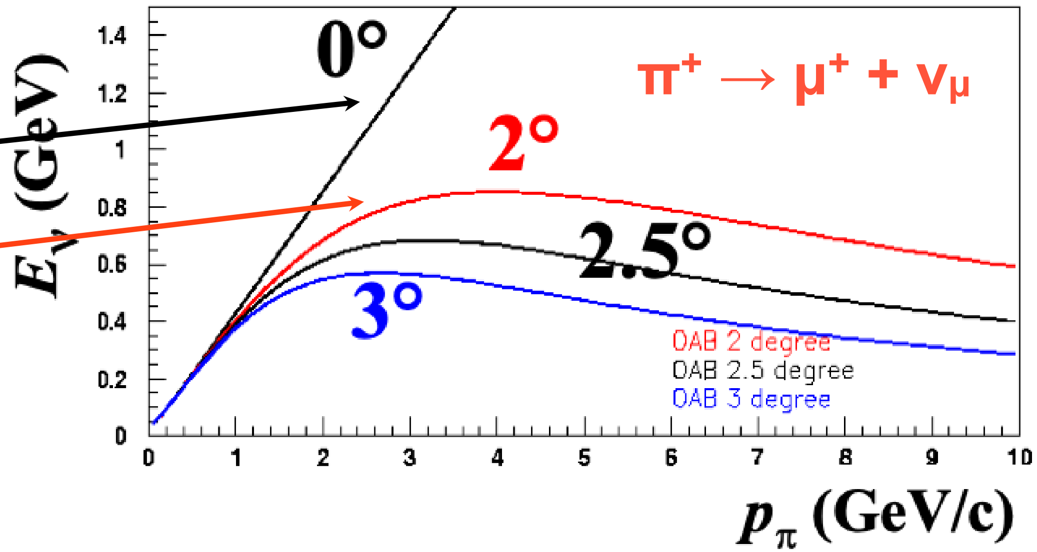
Pions decay to μ and ν_μ within a 100m decay volume

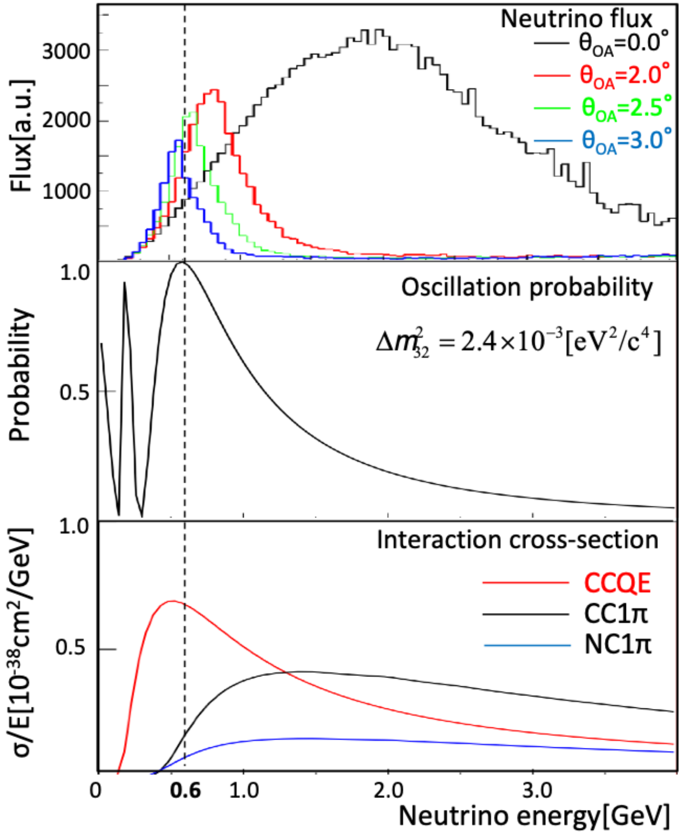


- Goal is to reproduce the atmospheric neutrino mechanism
  - But with more precise control
- Mostly pure ν_μ beam is useful to search for $\nu_\mu \rightarrow \nu_e$ oscillations

Off-Axis Neutrino Beams

- The current experiments (T2K & NOvA) do not point their beams directly at their far detector!
- Along the beam direction, $E_\nu \propto p_\pi$
- By pointing the beam slightly off-axis, $E_\nu \approx$ constant (above some p_π)

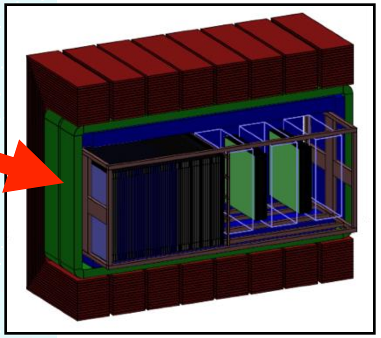


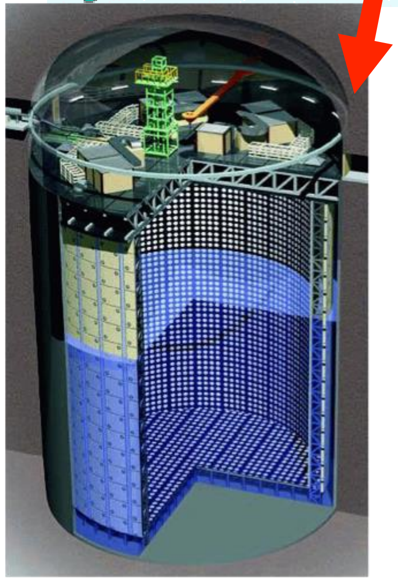


- Can tune ν energy peak by varying the off-axis angle
  - Optimize for oscillation maximum
  - Reduces the high E_ν tail
  - Less background from higher energy neutrino interactions
- The off-axis effect is key to the latter portions of these lectures

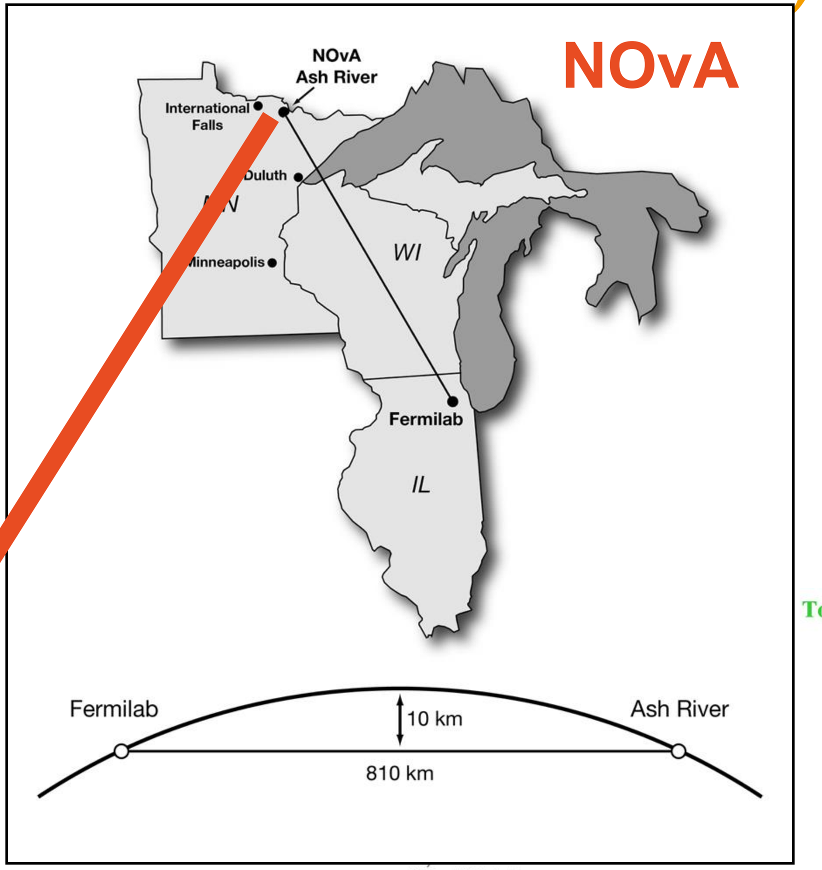
Long-Baseline Experiments (Current Generation)

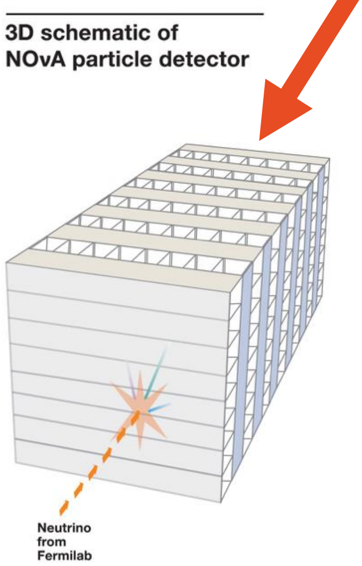
ND280
(Scintillator
bar target)



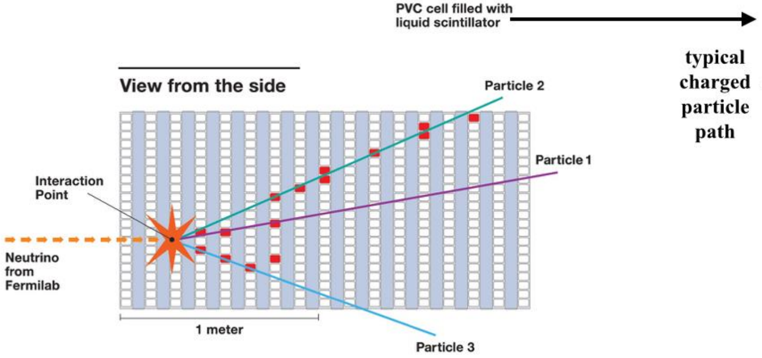


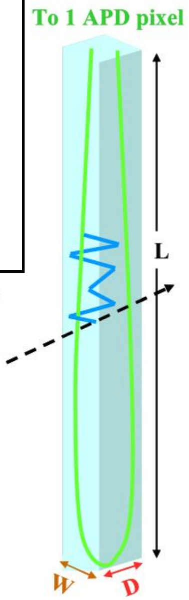
Super-Kamiokande
(Water Cherenkov)





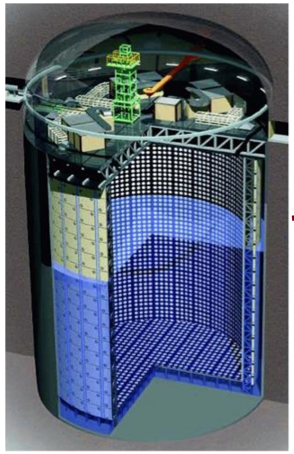
Liquid Scintillator

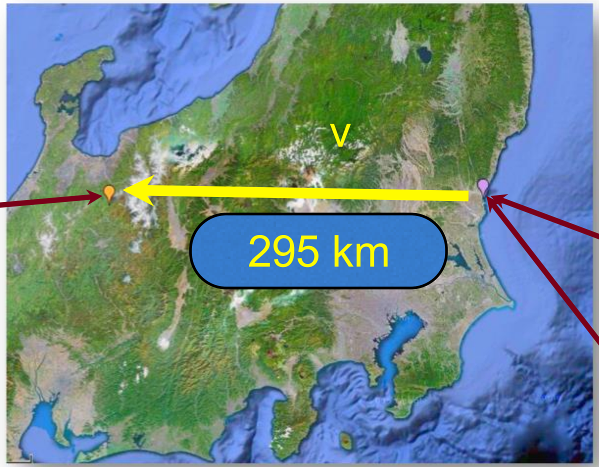




The T2K Experiment

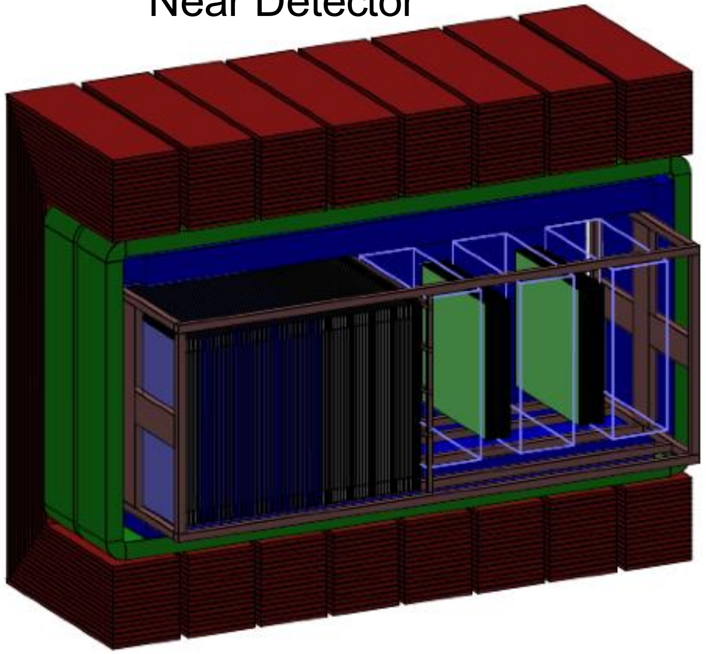
Super-K Detector





J-PARC Accelerator

Near Detector



- The T2K experiment searches for neutrino oscillations in a high purity ν_μ beam
- A near detector located 280 m downstream of the target measures the unoscillated neutrino spectrum
- The neutrinos travel 295 km to the Super-Kamiokande water Cherenkov detector
- Search for **appearance of ν_e** (to measure θ_{13}, δ_{CP})
- Search for **disappearance of ν_μ** (to measure θ_{23}, Δm^2_{31})
- CP violation is seen in the difference of ν_e & anti-ν_e appearance rates:

$$P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)$$

How to Measure Neutrino Oscillations

Neutrino Beam
(nearly pure ν_μ)

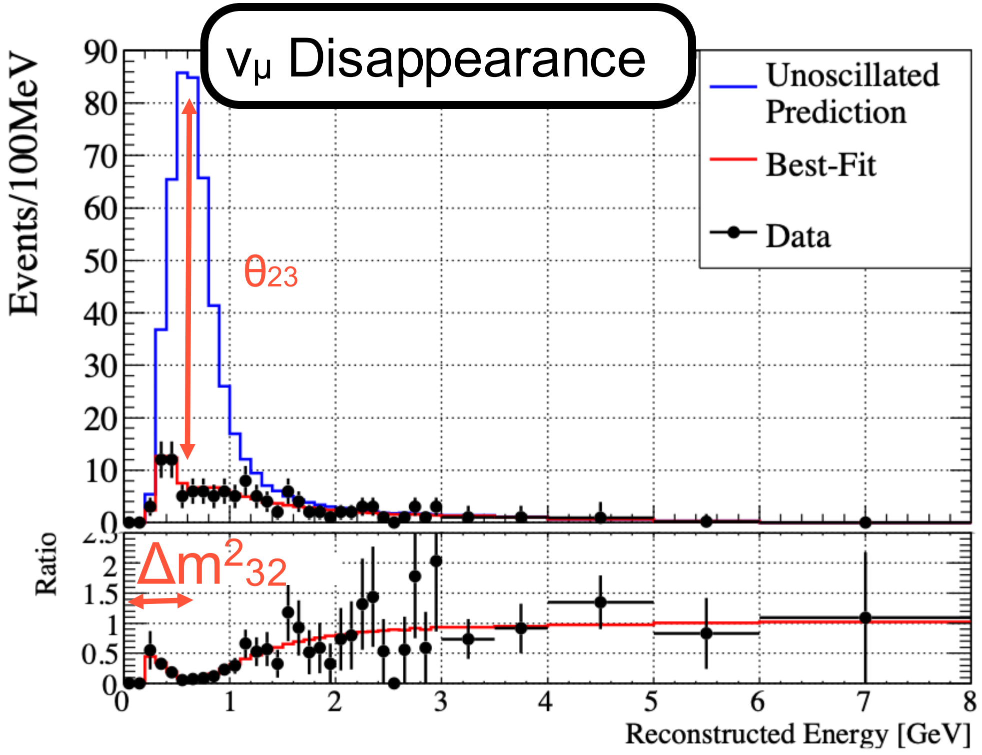
→

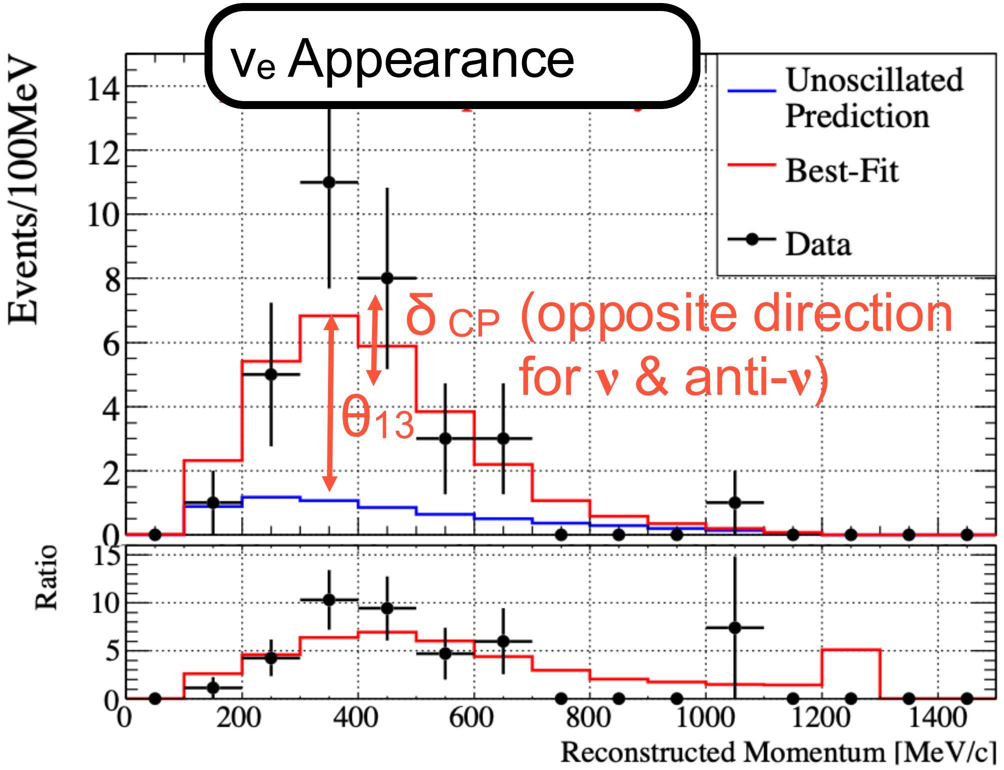
Near Detector Measures:
- unoscillated ν_μ spectrum
- small amount of beam ν_e

→

Far Detector Measures:
- ν_μ disappearance (vs E_ν)
- ν_e appearance (vs E_ν)

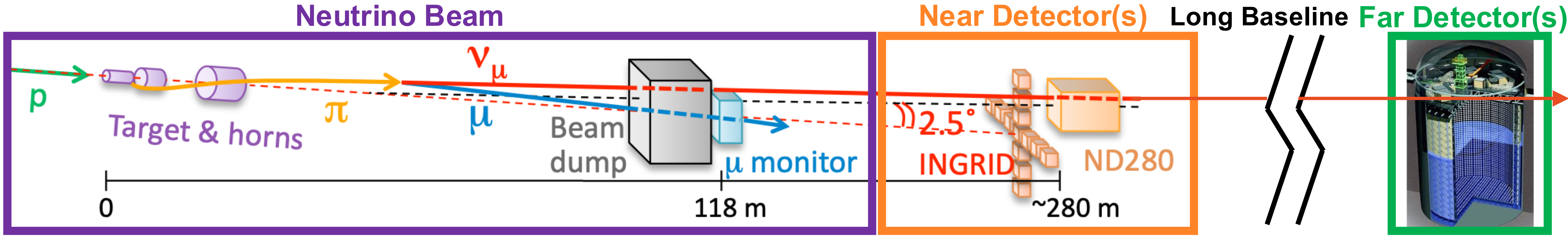
T2K E_ν Spectra:





- Note that the near & far energy spectra are VERY different!
  - Any uncertainties that affect E_ν shape will not cancel in a near/far ratio

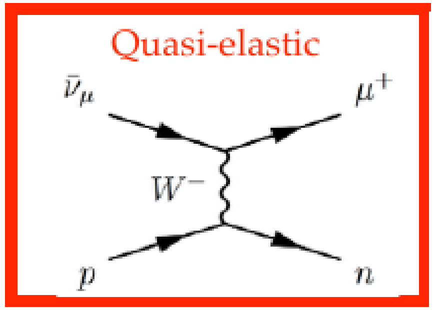
How Long-Baseline Experiments Work

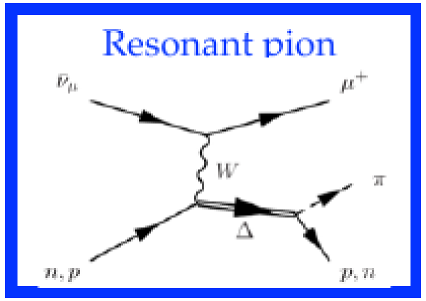


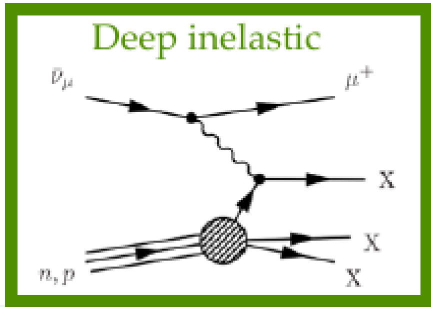
- Three main sources of systematic uncertainties: Flux, XSec, & Detector
  - **Flux**: **hadron production** (p + target → π^+/K^+/etc.) & **focusing** (horns, decay pipe, …)
  - **XSec**: **ν-nucleus** interaction modeling (CCQE, CCRes, SIS, DIS, Nuclear effects, …)
  - **Detector**: **Low level** (light absorption, charge readout, …) & **High level** (particle identification distributions, reconstructed kinematics, …)
- Each of these sources has a corresponding model, and all of the uncertainty is captured in individual **model parameters**
- The near detector (ND) data are used to constrain these **parameters**, which reduces the model uncertainty in the predicted far detector (FD) E_ν spectrum
  - Smaller FD prediction error = stronger constraints on θ_{23}, Δm^2_{32}, δ_{CP} , …

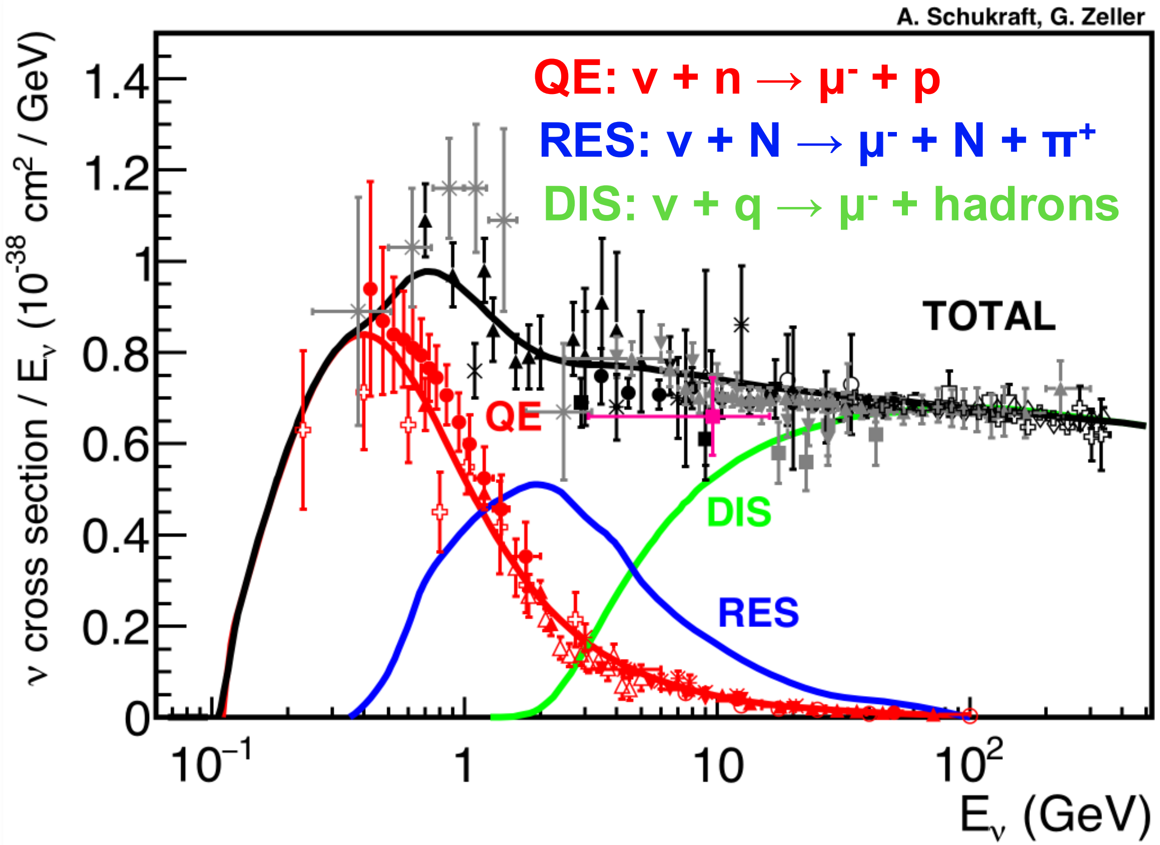
Charged Current Neutrino-Nucleon Scattering

- In charged current interactions, neutrinos produce charged leptons (which tag the neutrino flavor)
- At low energies, a single nucleon is present in the initial and final state (CCQE: Charged Current Quasi-Elastic)
  - In principle, this is the best interaction mode for neutrino oscillation searches
  - Tags the (anti-)neutrino flavor, and energy is reconstructed in simple 2-body scattering kinematics
    - But, complicated by nuclear effects…
- As the energy increases, nucleon resonances are produced (e.g. Δ, N*)
  - Generally produce charged or neutral pions in the final state
  - A missed pion will produce a biased neutrino energy
  - NC-RES interactions are often the main background
- At higher energies, Deep Inelastic Scattering (DIS) begins to dominate
  - Neutrino-quark scattering
  - Many hadrons in the final state



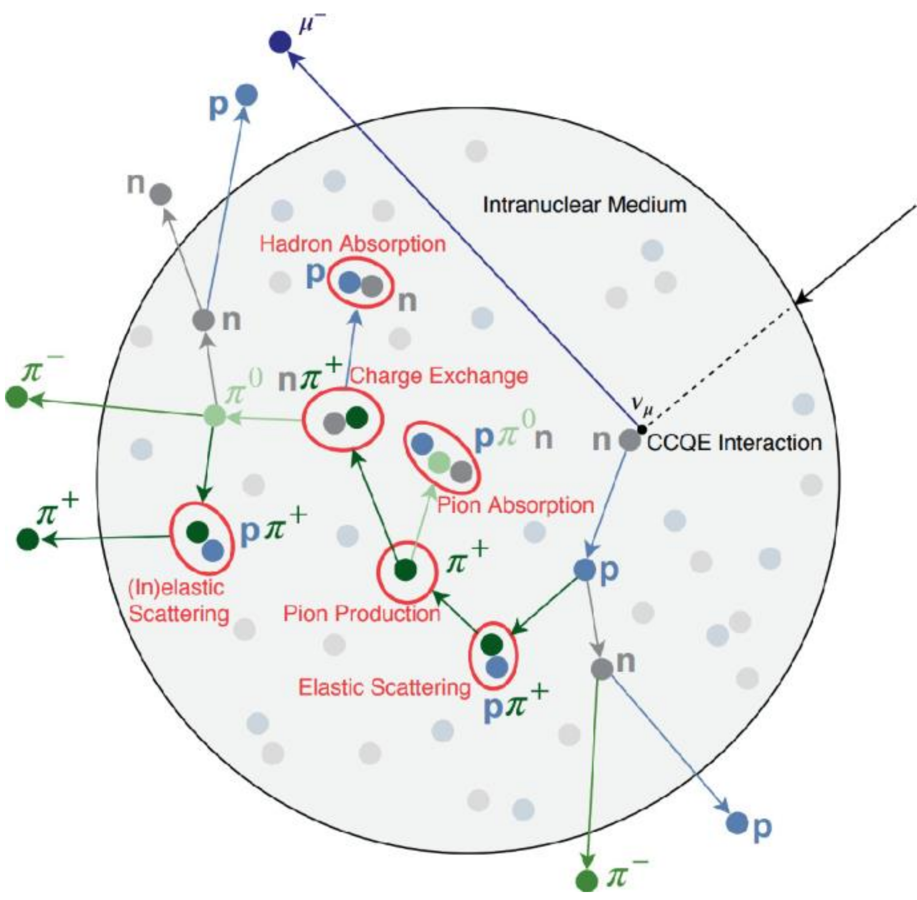






Neutrino-Nucleus Scattering

- In accelerator beam physics, nuclear targets are always used (no H-only detectors)
- Neutrino-nucleon interactions determine the initial state
  - They are also modified in the nuclear medium, e.g. Pauli blocking, off-shell effects, etc.
  - Struck nucleons often share short-range correlations with other nucleons (multi-nucleon effects)
- Initial state particles then traverse the nucleus, interacting with other nuclei
- Modeling all of this correctly is very difficult



https://doi.org/10.1007/978-3-031-19572-3_3

Cross Section Modeling

DUNE TDR Cross Section Model (Eur. Phys. J. C 80, 978 (2020))

- Example: DUNE LBL Analysis
- All of the uncertainty in ν-Ar modeling is captured in these ~30 parameters
  - The LBL analysis implicitly assumes that every other part of the xsec model is correct
  - e.g. the shapes of the distributions modified by these parameters are assumed to be correct; they need only be scaled by a correct parameter value
- The ND fit can strongly constrain these parameters
  - DUNE ND will collect >10M events per year
- It turns out to be very easy to constrain xsec errors beyond the level at which we trust our models (see later slides)
  - Non-zero xsec errors are achieved by choosing minimum-allowed values for detector errors

GENIE Xsec Parameters

Description	1σ
Quasielastic	
M_A^{QE}, Axial mass for CCQE	$^{+0.25}_{-0.15}$ GeV
QE FF, CCQE vector form factor shape	N/A
p_F Fermi surface momentum for Pauli blocking	±30%
Low W	
M_A^{RES}, Axial mass for CC resonance	±0.05 GeV
M_V^{RES} Vector mass for CC resonance	±10%
Δ-decay ang., θ_π from Δ decay (isotropic → R-S)	N/A
High W (BY model)	
A_{HT}, higher-twist in scaling variable ξ_w	±25%
B_{HT}, higher-twist in scaling variable ξ_w	±25%
C_{V1u}, valence GRV98 PDF correction	±30%
C_{V2u}, valence GRV98 PDF correction	±40%
Other neutral current	
M_A^{NCRES}, Axial mass for NC resonance	±10%
M_V^{NCRES}, Vector mass for NC resonance	±5%

GENIE FSI Parameters

Description	1σ
N. CEX, Nucleon charge exchange probability	±50%
N. EL, Nucleon elastic reaction probability	±30%
N. INEL, Nucleon inelastic reaction probability	±40%
N. ABS, Nucleon absorption probability	±20%
N. PROD, Nucleon π-production probability	±20%
π CEX, π charge exchange probability	±50%
π EL, π elastic reaction probability	±10%
π INEL, π inelastic reaction probability	±40%
π ABS, π absorption probability	±20%
π PROD, π π-production probability	±20%

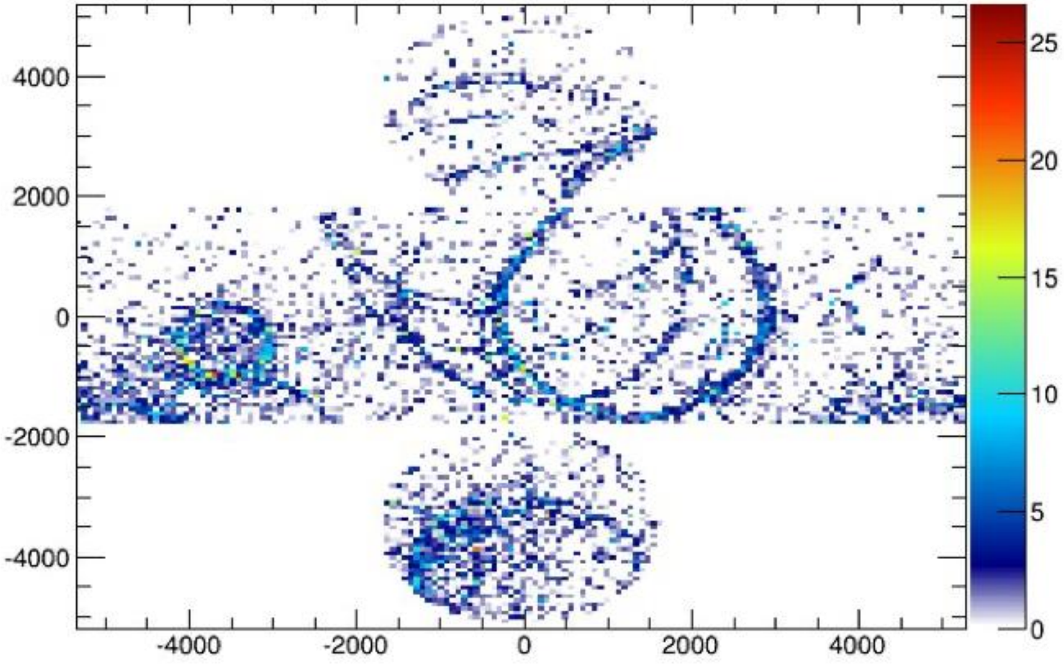
Additional Xsec Parameters

Uncertainty	Mode
BeRPA [A,B,D]	$1p1h$/QE
ArC2$p2h$ [ν,$\bar{\nu}$]	$2p2h$
E_{2p2h} [A,B] [ν,$\bar{\nu}$]	$2p2h$
NR [ν,$\bar{\nu}$] [CC,NC] [n,p] [1π,2π,3π]	Non-res. pion
ν_e PS	ν_e,$\bar{\nu}_e$ inclusive
$\nu_e/\bar{\nu}_e$ norm	ν_e,$\bar{\nu}_e$ inclusive
NC norm.	NC

Event Reconstruction

- How do we extract the underlying particle information (4-momentum, 4-vertex, & particle ID) for every particle in an event?
- In the monolithic, multi-PMT detectors often used in neutrino physics, this sounds like a job for machine learning
  - 11k charges + 11k times = all the recorded information for an event
    - Seems like we should use a CNN for this
  - And we are working on it!
    e.g. N. Prouse, Phys.Sci.Forum 8 (2023) 1, 63
    - However, many difficulties arise in creating such physics-guided networks
- In the meantime, most experiments use likelihood-based reconstruction algorithms (Super-K, Hyper-K, Daya Bay, JUNO, …)
  - The following few slides show how this works

Super-Kamiokande Event Display



(It may be the case that a hybrid ML+Likelihood solution will be the first upgraded algorithm to be employed)

The FiTQun Reconstruction Algorithm

- For each Super-K event we have, for every hit PMT
  - **A measured charge**
  - **A measured time**
- For a given event topology hypothesis, we produce a charge and time PDF **for each PMT**

$$L(\mathbf{x}) = \prod_{\text{unhit}} P(i\text{unhit};\mathbf{x}) \prod_{\text{hit}} P(i\text{hit};\mathbf{x}) f_q(q_i;\mathbf{x}) f_t(t_i;\mathbf{x})$$

Charge PDF

Consists of 2 components:

- **Predicted Charge (μ):** How many photons hit the PMT? (depends on detector geometry)
- **PMT Charge Response P(Q|μ):** What PMT pulse is produced? (depends only on PMT properties)

Time PDF

What is the arrival time of the first photon?

Calculated using:

- “Direct” μ
- Scattered/Reflected μ

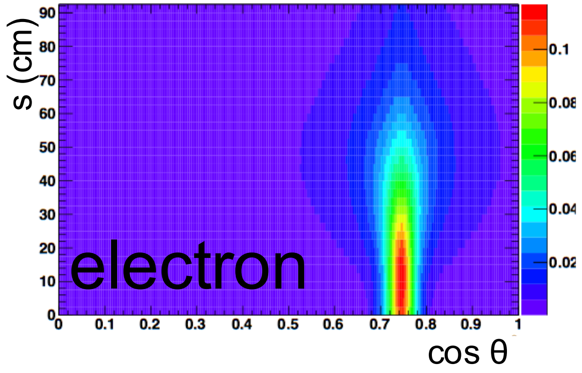
- Framework can handle any number of reconstructed tracks
- Event hypotheses are distinguished by comparing best-fit likelihoods
  - electron vs muon
  - 1-ring vs 2-ring vs 3-ring ...
- FiTQun is a **complete, self-contained** reconstruction package (does not employ a multi-step approach for vertex, direction, PID, etc.)

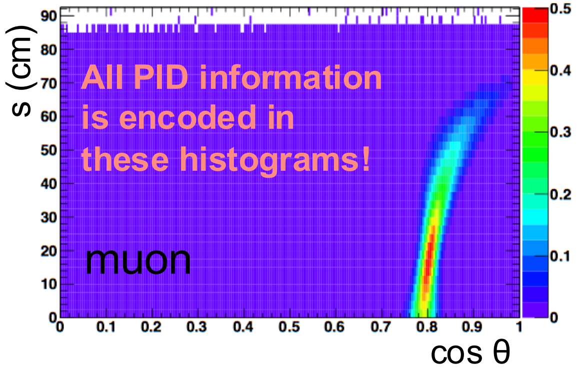
Predicted Charge (μ)

$$\mu = \Phi(p)\int ds\; g(s, cos\theta)\Omega(R)T(R)\epsilon(\eta)$$

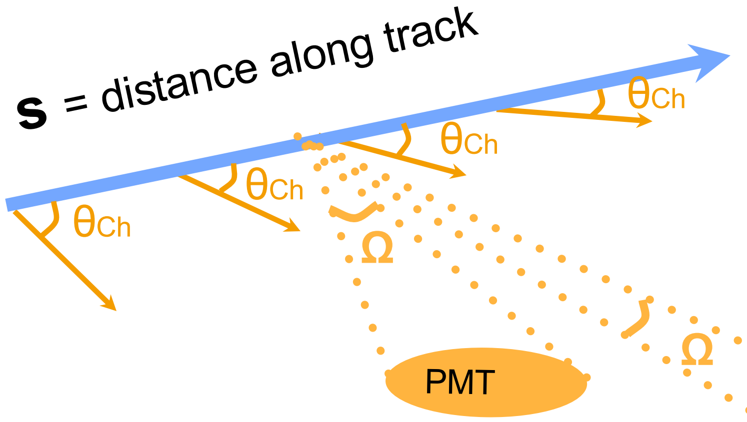
- $\Phi(p)$: Light Yield (normalization)
- $\int ds$: Integral over track length
- $g(s, cos\theta)$: Cherenkov light emission profile
- $\Omega(R)$: PMT solid angle
- $T(R)$: Water attenuation
- $\epsilon(\eta)$: PMT angular response

Cherenkov light emission profile





Particle Track
($e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, p)

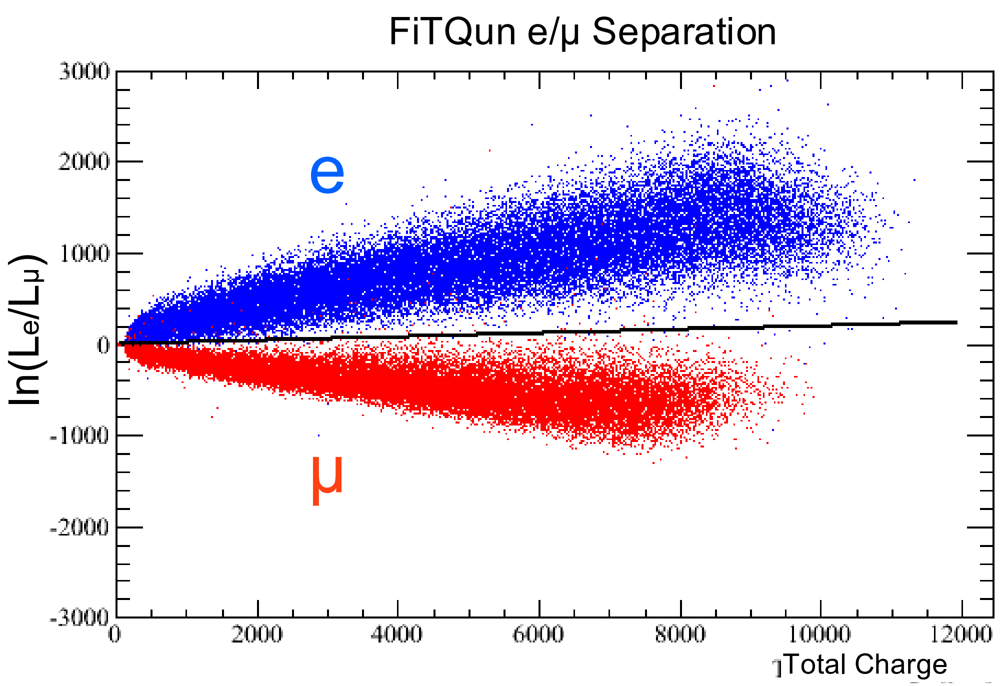


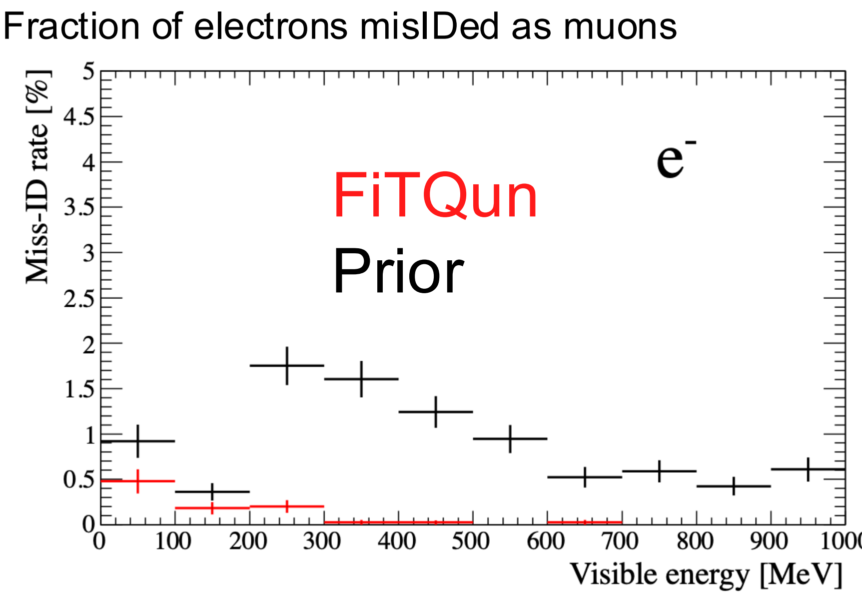
μ = amount of charge seen by a PMT

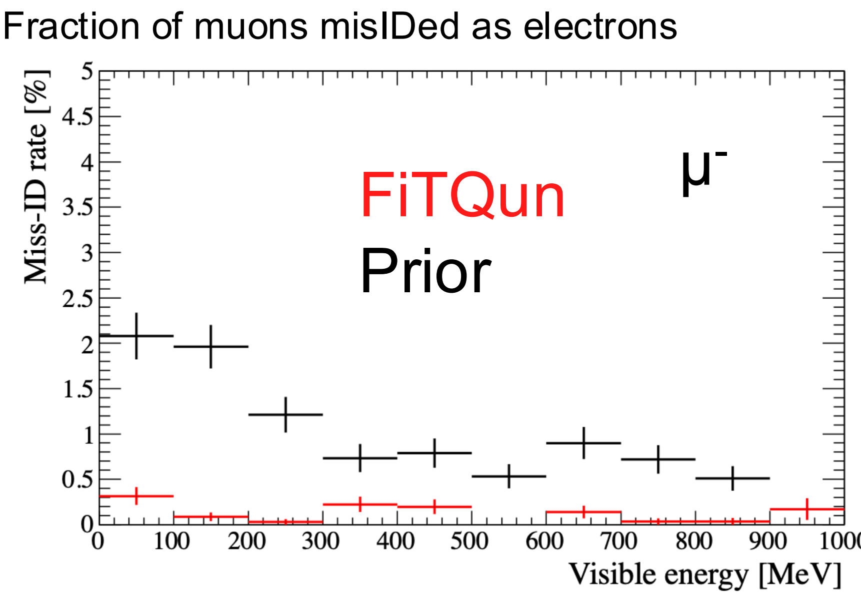
- These integrals can approximated as quadratic functions of s, and performed in advance
- For multi-particle states, predicted charges are summed
- Scattered and reflected light is treated separately (and more crudely: tabulation)

Single Track Particle ID

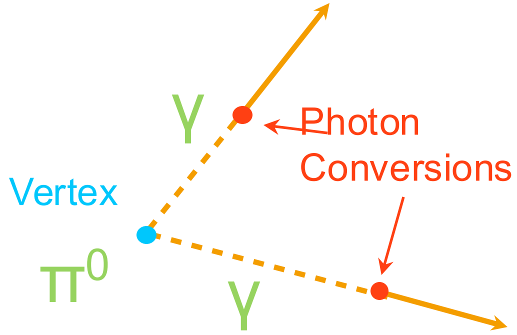
- By comparing best fit likelihoods of different fit hypotheses (e.g. e & μ), we can achieve particle identification
  - Fit the event with an electron hypothesis (i.e. fuzzy ring)
  - Fit the event with a muon hypothesis (i.e. sharp ring)
  - Then ask, which hypothesis gives the better fit?
- As the energy increases, there is more information, so the separation improves



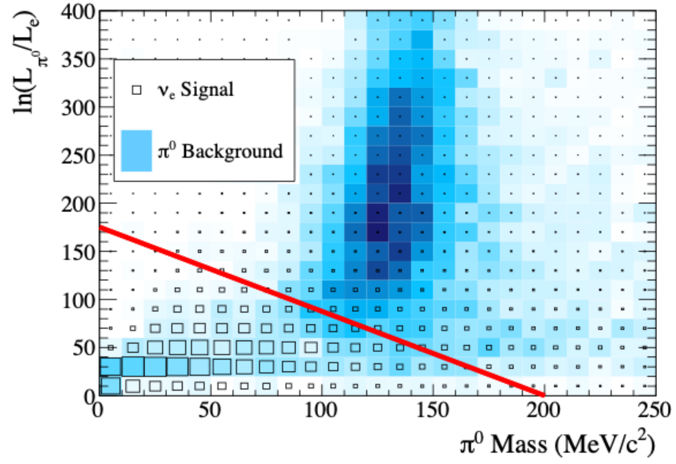


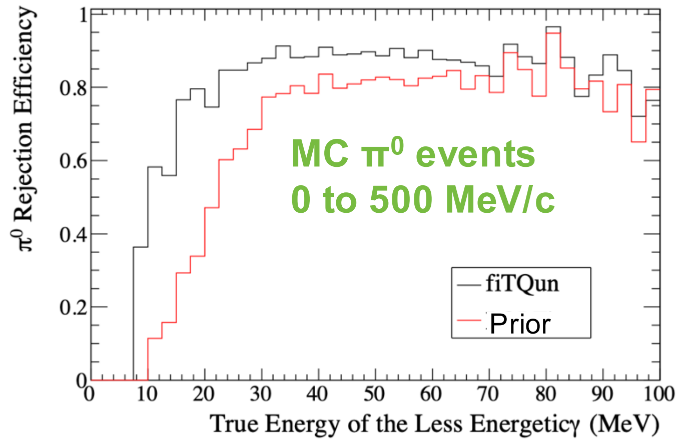


NC π^0 Rejection

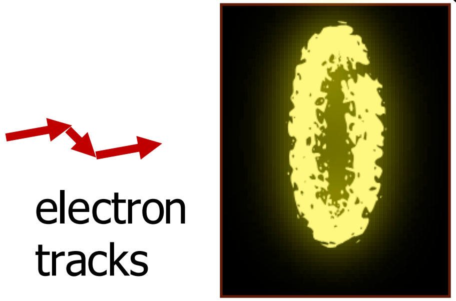


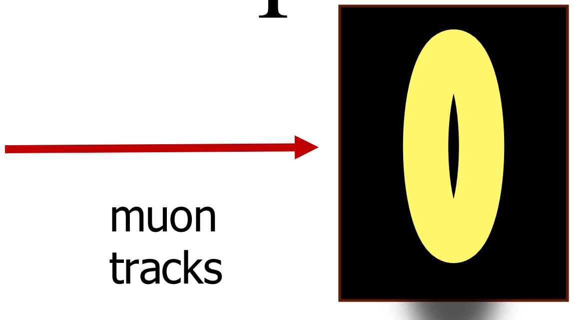
- FiTQun performs a simultaneous fit for 2 photon-like rings from a common vertex
  - To reject π^0 events, we can compare the **best fit likelihoods** for π^0 and single-e- fits
    - (and the reconstructed π^0 mass)
- This technique allows us to identify a **low-E photon** in the presence of a **high-E photon**
- 70% of the largest removal background NCπ^0, is removed by this fit
  - Substantial improvement in sensitivity is possible with improved reconstruction techniques

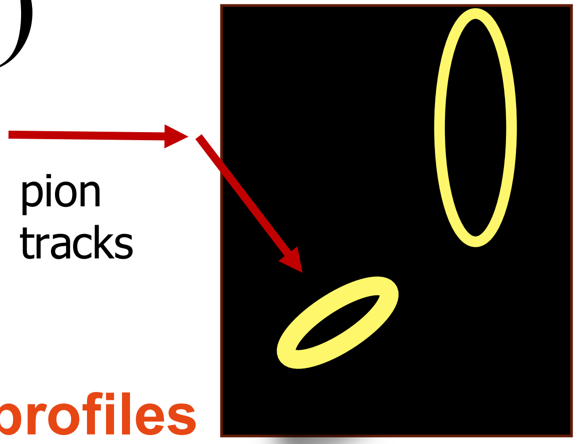




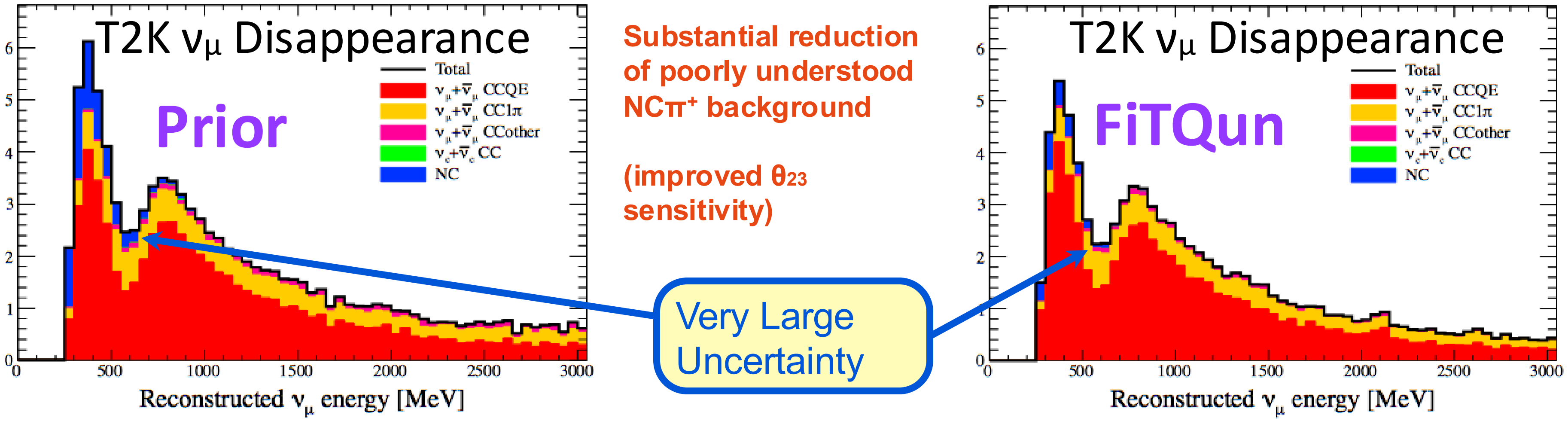
π^+ Fitter (μ^-/π^+ Separation)





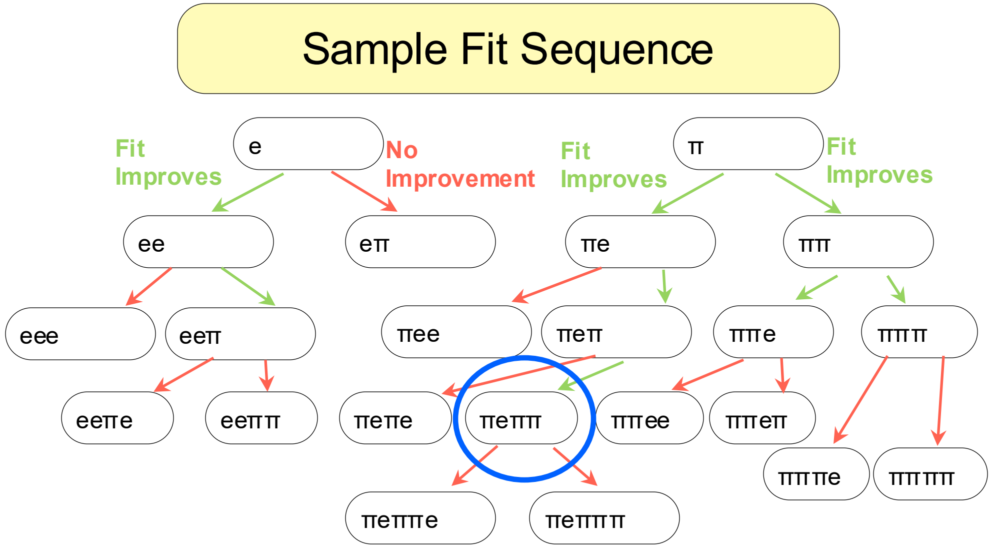


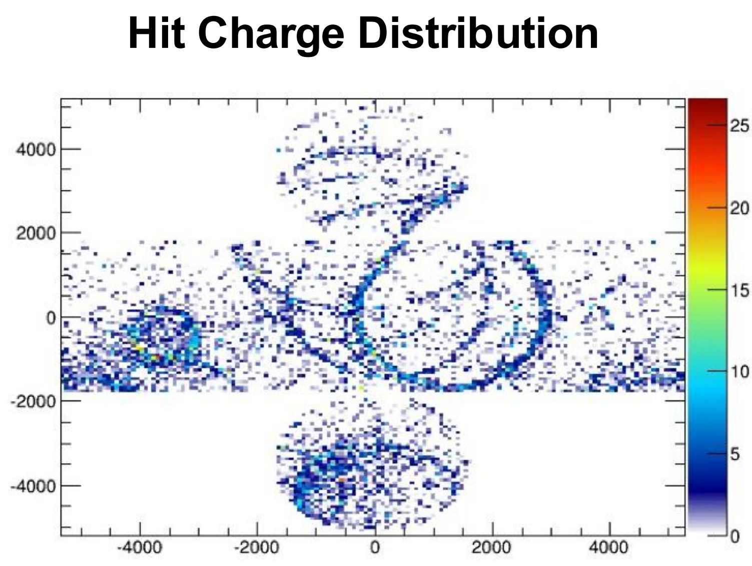
- Pions and muons have **very similar Cherenkov profiles**
  - The main difference is the **hadronic interactions** of pions
- The observed ring pattern is a **thin ring** with the center portion missing
- We are now able to **separate π^+ & μ^-** for the first time at Super-K

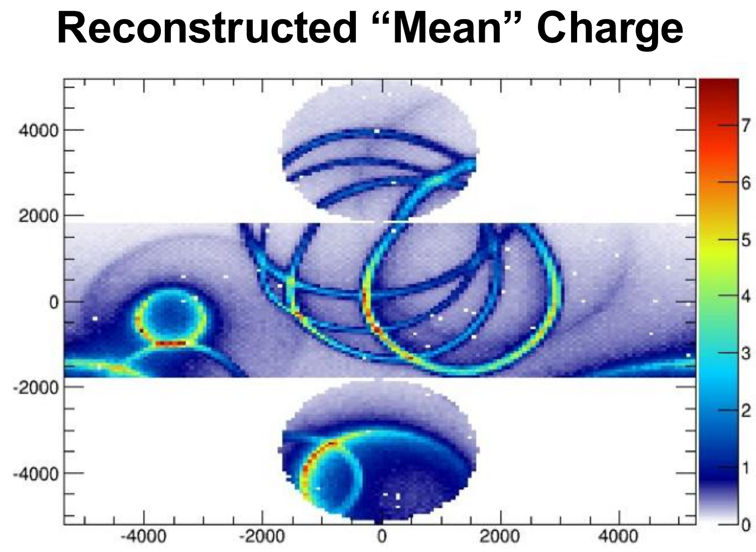


Multi-Ring Events

- FiTQun can reconstruct up to 6 rings in a staged approach
  - Each step sequentially adds a "track-like" (μ/π^+) or "shower-like" (e) ring
  - The chain terminates when adding a ring does not sufficiently improve the fit
- Ring counting & PID are significantly improved
- It may be possible to upgrade the likelihood function using machine learning while keeping the multi-ring algorithm: (M. Jia, et al., Front. Big Data **5** (2022))

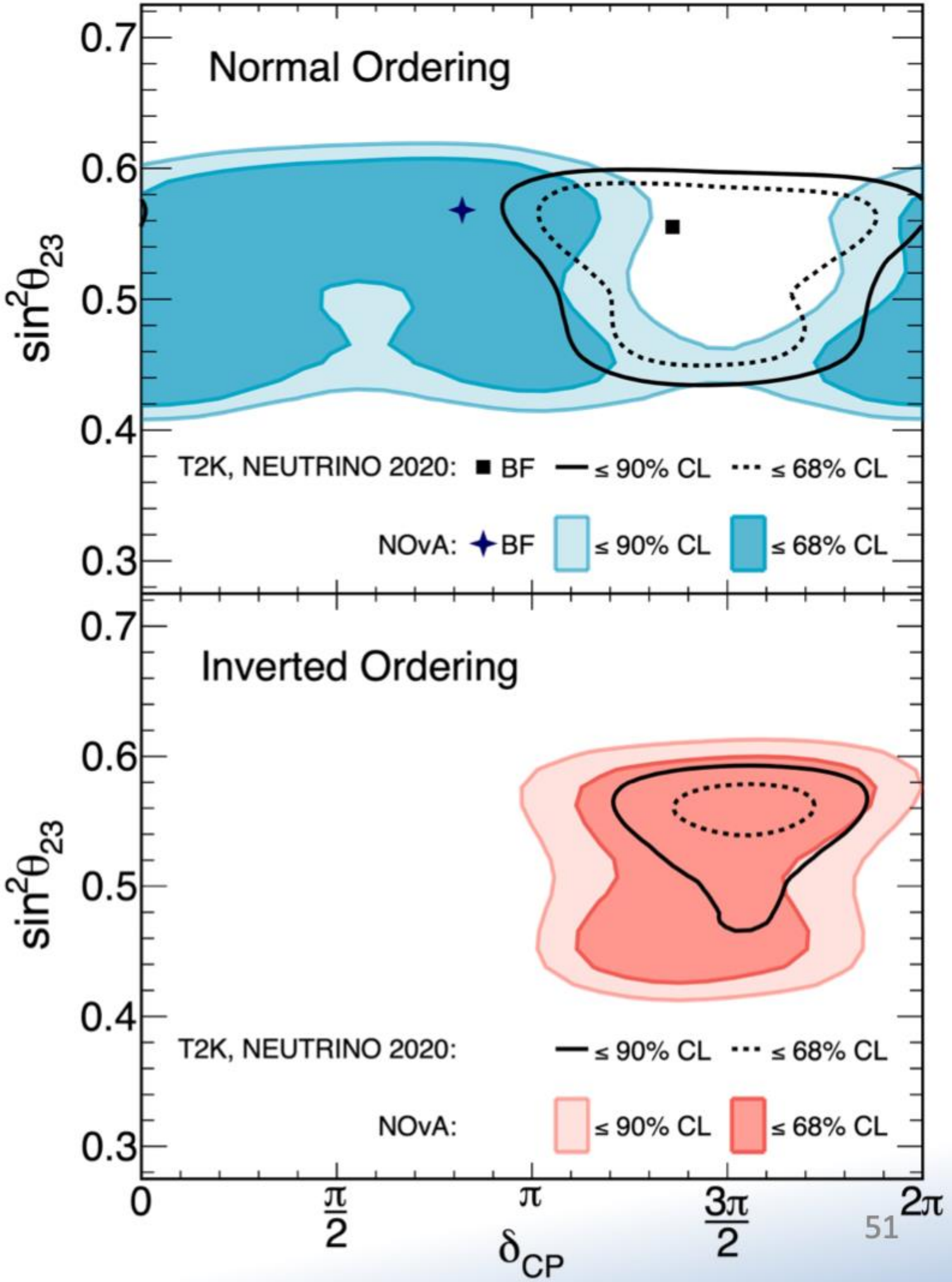






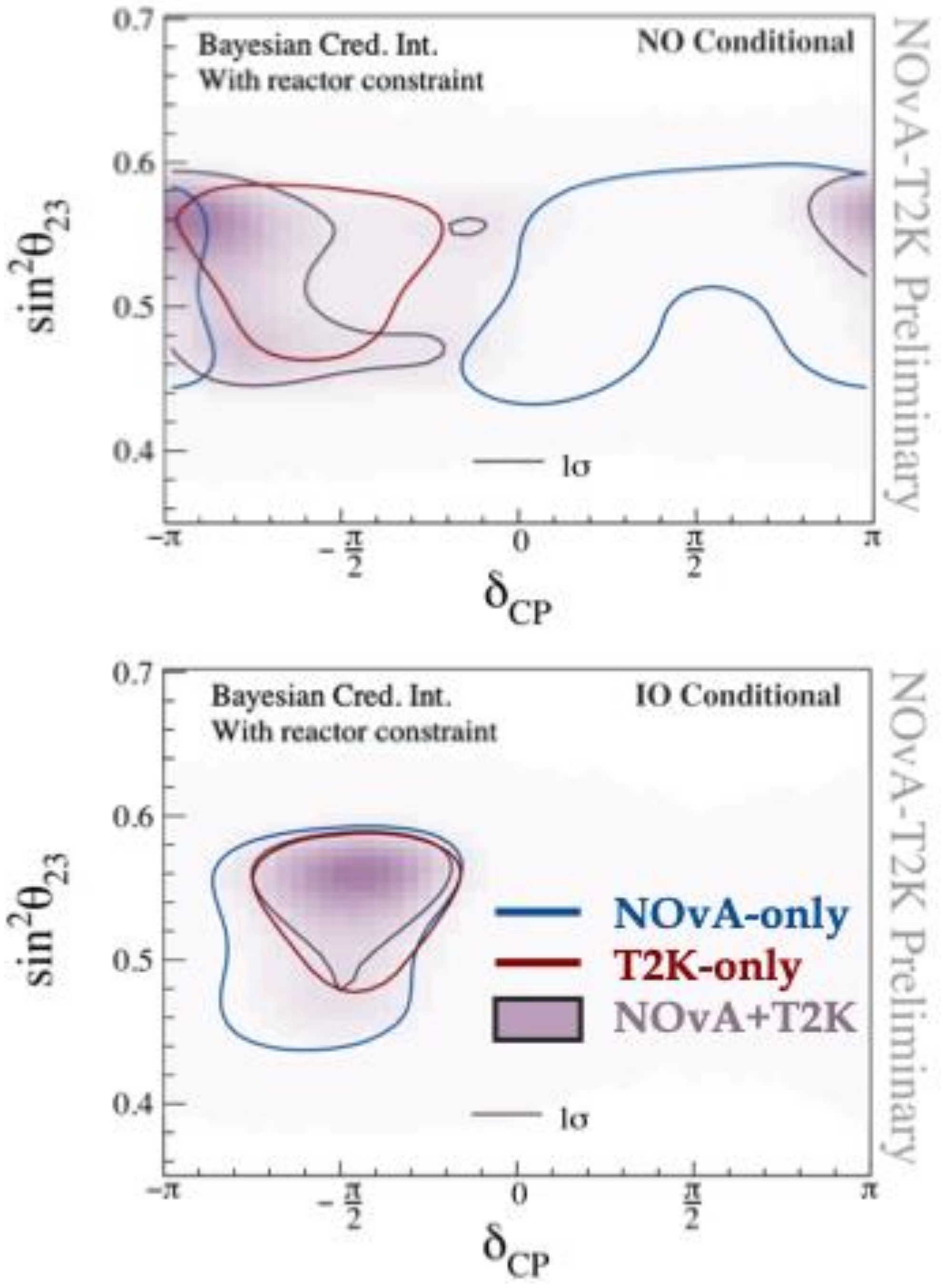
T2K and NOvA Results

- Both experiments slightly prefer Normal Hierarchy (NOvA @ ~1σ)
- However, different regions of δ_{CP} preferred for Normal Hierarchy
  - NOvA's observed ν_e and anti-ν_e event rates are consistent with CP-conservation
  - T2K sees excess of ν_e, deficit of anti-ν_e
- The top plot may look scary, but this is less than a 1σ "tension" between the experiments
  - What if we could fit the data from both experiments together in a single analysis?



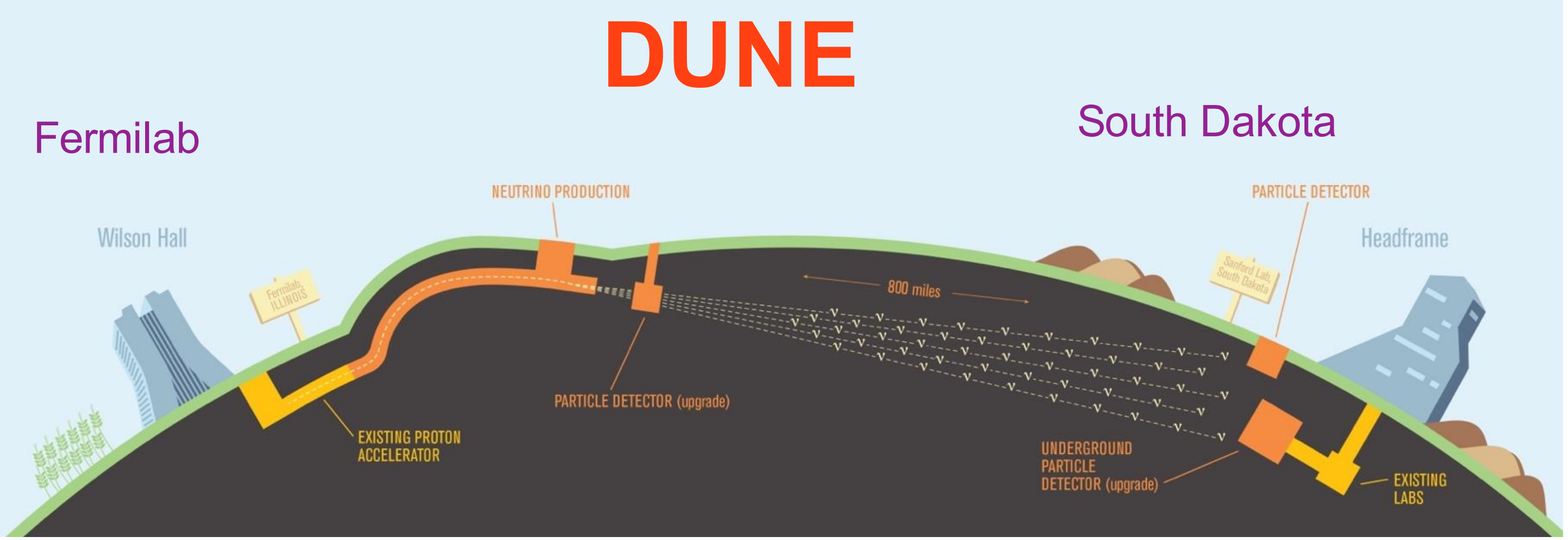
T2K + NOvA Joint Fit

- The T2K & NOvA spent several years working together to produce a framework to fit both experiments together
  - Main challenge is how, and to what extent, systematic uncertainties can/should be correlated
    - Several studies demonstrated that correlated systematic
- This situation is likely to only be fully resolved with more statistics and more precise systematic uncertainties
  - Next-generation experiments will be important



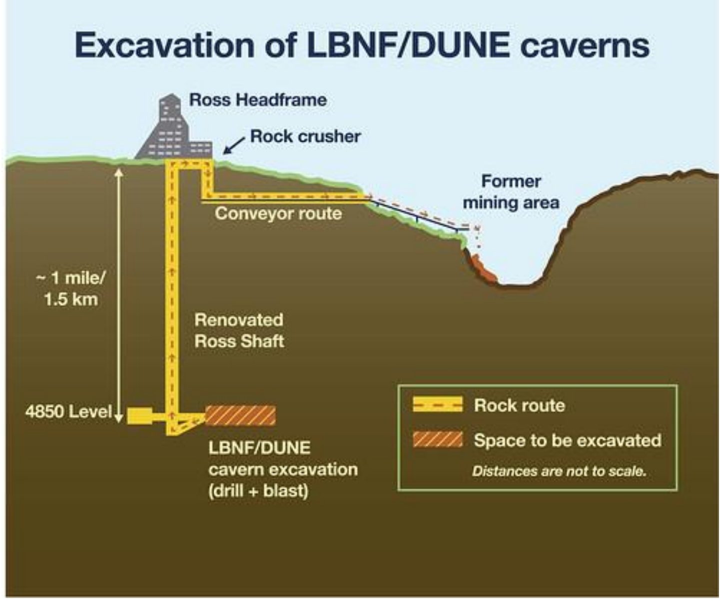
The Next Generation

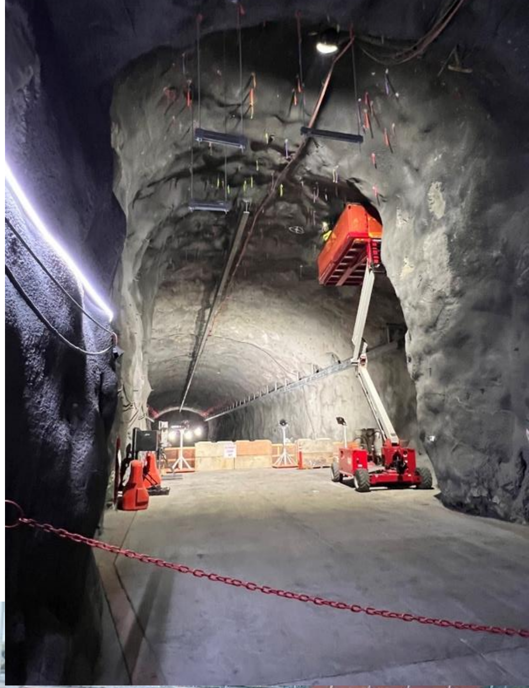
- Order of magnitude enhancement in statistics
- Requires percent-level systematic uncertainties
- **Primary challenge**: Neutrino-nucleus interactions



DUNE Far Detectors

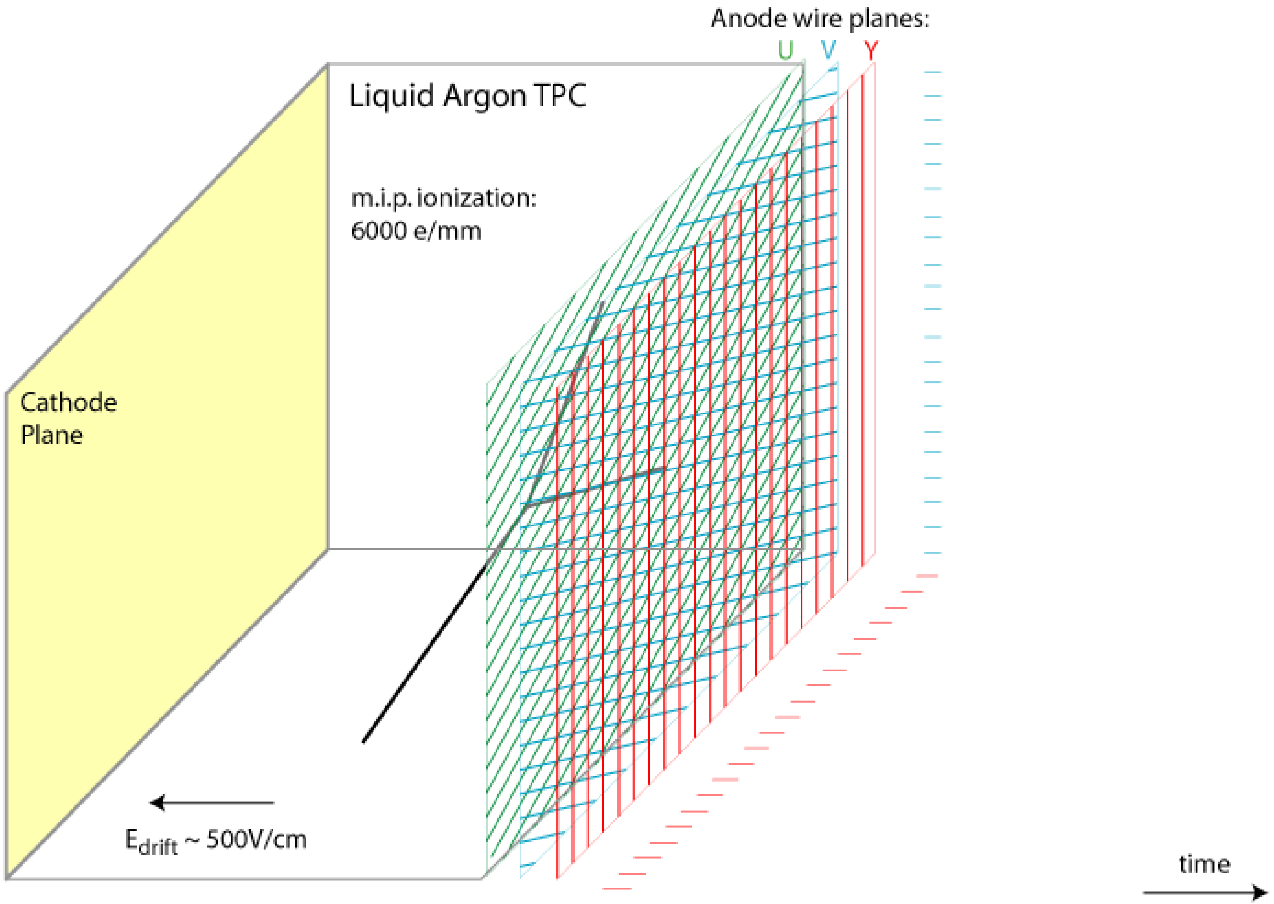
- Liquid Argon Time Projection Chambers (LAr-TPCs) are contained in insulated steel boxes (“cryostats”), each 66m x 12m x 12m
- The cryostats will be located a mile underground at the Sanford Underground Research Facility (SURF)
  - In order to reduce the number of muons showering down through the detector
- SURF is a refurbishment of the old Homestake Gold Mine
  - Site of Ray Davis’ solar neutrino experiment, which discovered the “solar neutrino problem” (ν deficit due to oscillations) → 2002 Nobel Prize
- Cavern excavation is complete, and outfitting is underway





Detection Principle

- Liquid Argon (LAr) is a noble liquid
  - Electrons can move relatively freely
- When a charged particle travels through LAr, it ionizes the atoms (kicks out electrons)
  - These electrons are like breadcrumbs that show us the precise path of the particle
- We impose a strong electric field to pull the electrons toward the readout wires (3 views)
  - 3D track reconstruction (2D hit position, 3rd dimension given by hit time)
- The affected argon atoms also “scintillate” (i.e. give off photons / light)
  - Light detection gives us precise timing (but with less precise position)
    - Light detection helps separate particles from different interactions



High Precision Physics

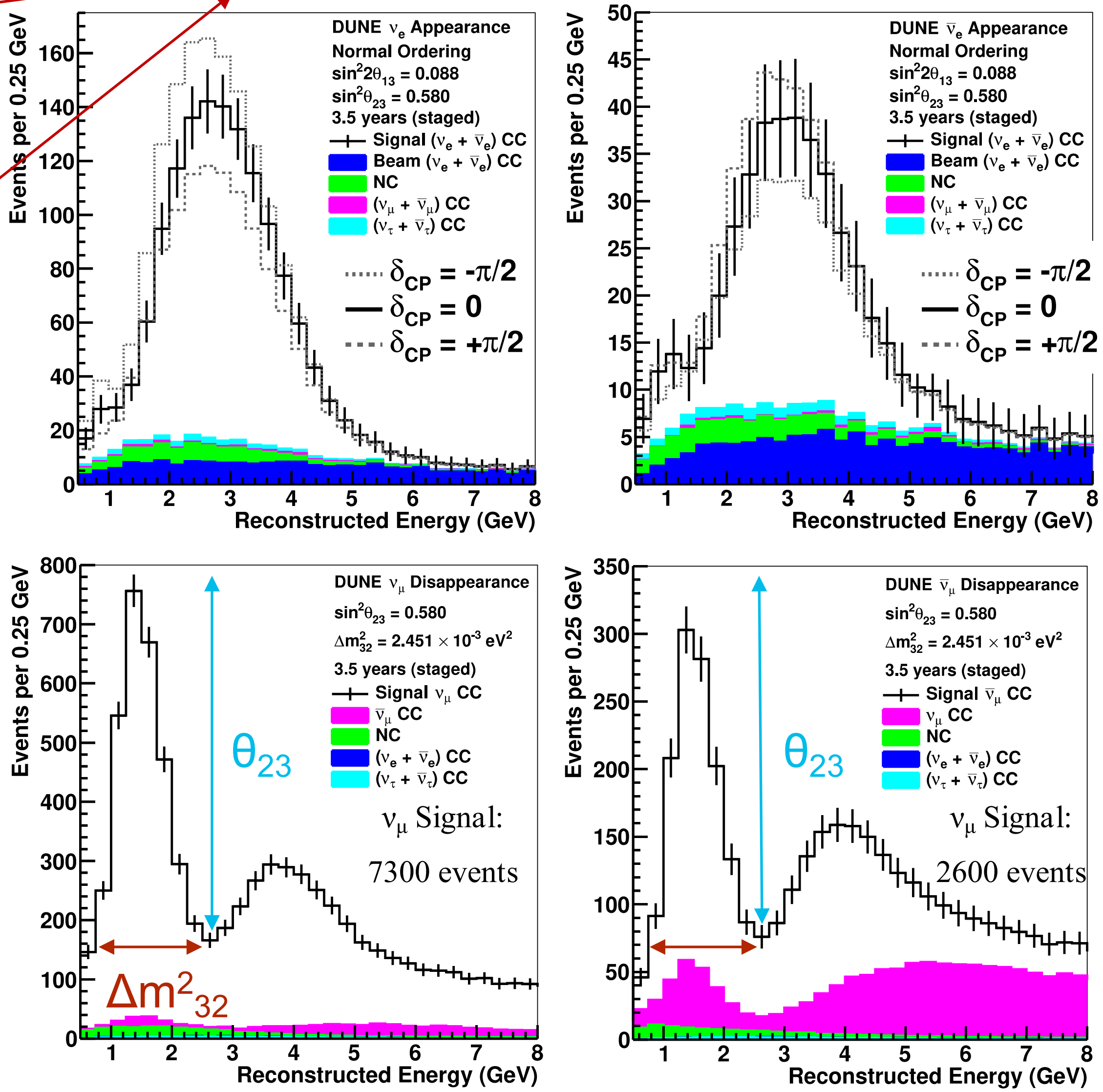
- >1k ν_e events for 3.5 years of nu-mode running (if NO)
- Very high purity (beam ν_e is largest background)
  - Wrong-sign background is important in anti-nu mode
- Mass Hierarchy (MH) effect is enormous (factor of 2)
  - Eventually MH will be known to >10σ regardless of other parameters & all plausible uncertainty scenarios
- δ_{CP} effect is smaller than MH (~20% from 0 to -π/2)
  - Systematics on event rate are important
- E_ν shape determines δ_{CP} resolution near ±π/2 and disappearance parameter precision (Δm^2_{32}, θ_{23})
- This requires a precise understanding of reconstructed energy
  - (driven by the interaction between ν–Ar cross section uncertainties and detector uncertainties)

Expected Events

	$\delta_{CP}=0$		$\delta_{CP}=-\frac{\pi}{2}$	
	NO	IO	NO	IO
Oscillated ν_e	1155	526	1395	707

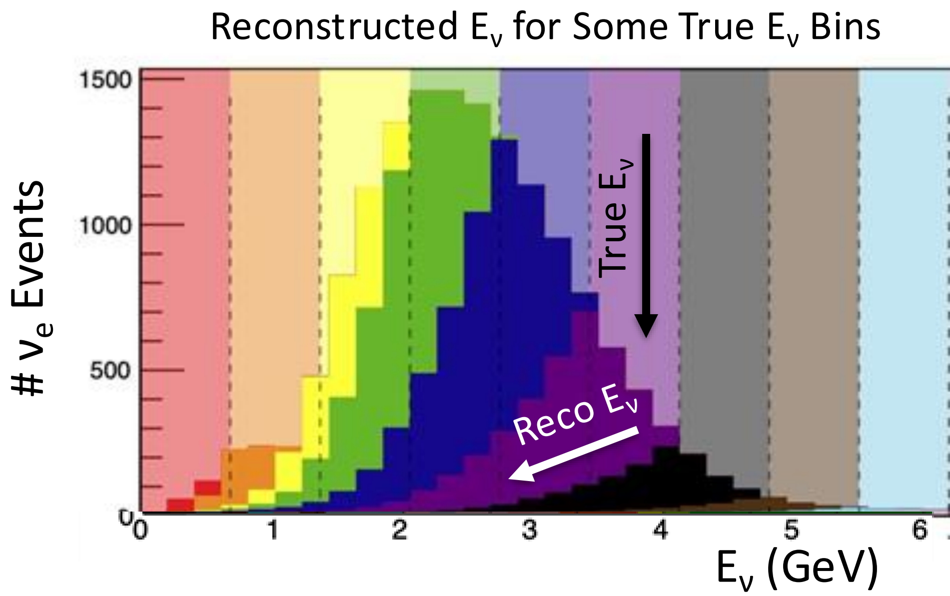
Expected Events

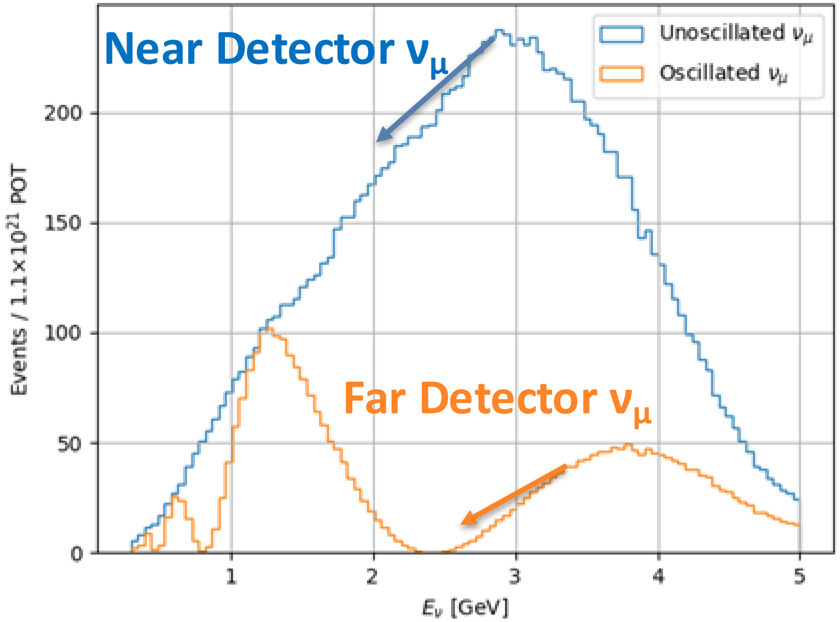
	$\delta_{CP}=0$		$\delta_{CP}=-\frac{\pi}{2}$	
	NO	IO	NO	IO
Oscillated $\bar{\nu}_e$	236	492	164	396



The E_ν Measurement Problem

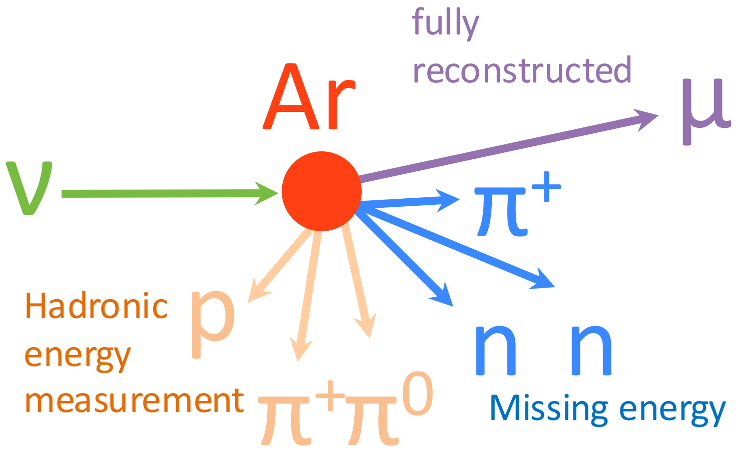
- The observed energy in the detector is always less than the incident neutrino energy
  - e.g. nuclear binding energy is unobserved, most of the energy carried by neutrons is not observed, untagged π^+ lose energy to neutrino daughters, …
- The "feed-down" of E_{reco} in each E_{true} bin "fills-in" the oscillation dip(s) at the far detector, but is difficult to constrain in an on-axis near detector
  - (due to the lack of features in the ND energy spectrum)
  - The shape of the feed down is strongly dependent on neutrino-nucleus interaction modeling

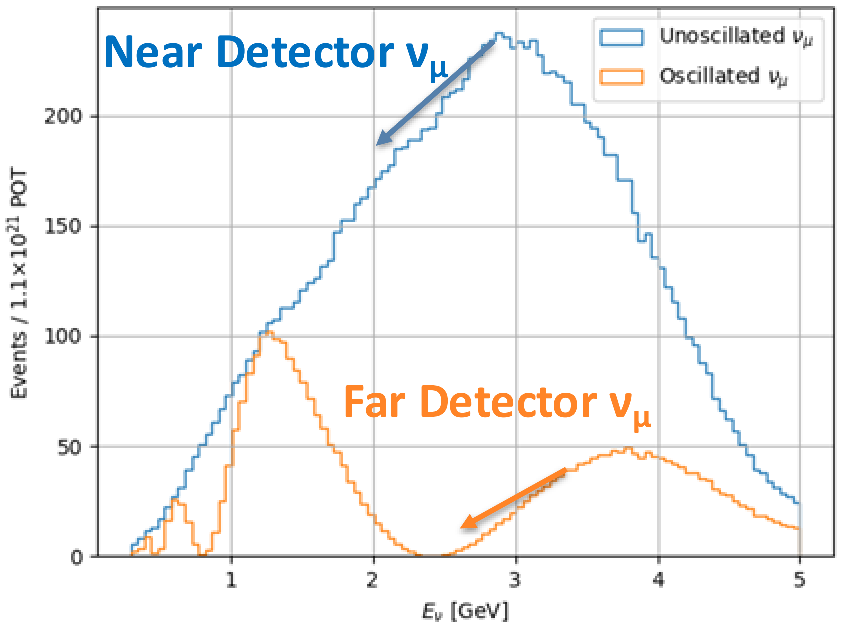




Cross Section Model Adjustments

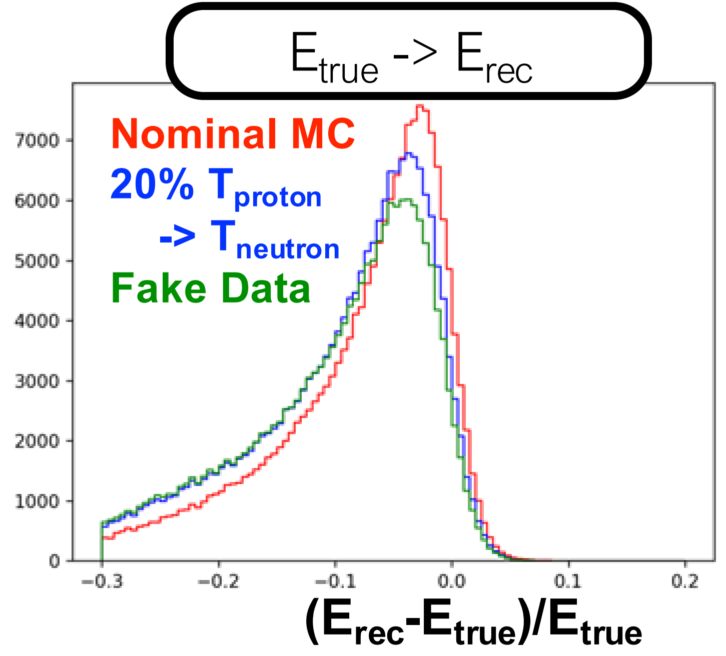
- If we knew our cross section model were correct, even with a large number of uncertain parameters, our high-statistics, on-axis ND sample would precisely (and correctly) constrain all model parameters
- However, when LBL experiments compare their out-of-the-box models (trained on other experiments) to ND data, **no choice of parameters** produces data/MC agreement
  - In practice, the neutrino flux and cross section model **must always be "tuned"** to make the near detector MC match the ND data
- **The problem**: there are many degenerate choices for cross section model adjustments that can produce agreement in an on-axis ND (even if the flux prediction is perfect)
  - If we choose the wrong cross section model modifications, we can introduce large biases at the far detector, even if the ND model agrees with the data in ~all observable distributions!
    - (Again, this is due to the lack of sharp oscillation features in the ND spectra)

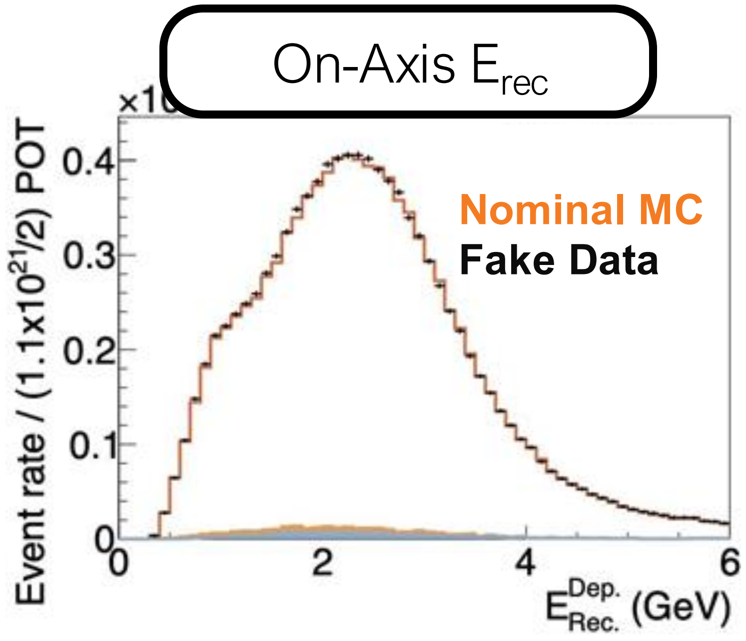




Missing Proton KE Fake Data

- To demonstrate the problems of inaccurate cross section modeling, a fake dataset was produced in which the sharing of energy between final state protons and neutrons was modified
  - 20% of the proton KE was transferred to unseen neutron energy
- The cross section model was then (incorrectly) adjusted to produce agreement in on-axis ND observables (via multi-dimensional reweighting of the model parameters)
  - This process is meant to demonstrate the effect of (incorrect) model tuning
- The result is a fake dataset that provides model agreement with datain an on-axis near detector (by design), but does ***NOT*** contain the same $E_{true} \rightarrow E_{rec}$ relationship as assumed by the model





Missing Proton KE Fake Data

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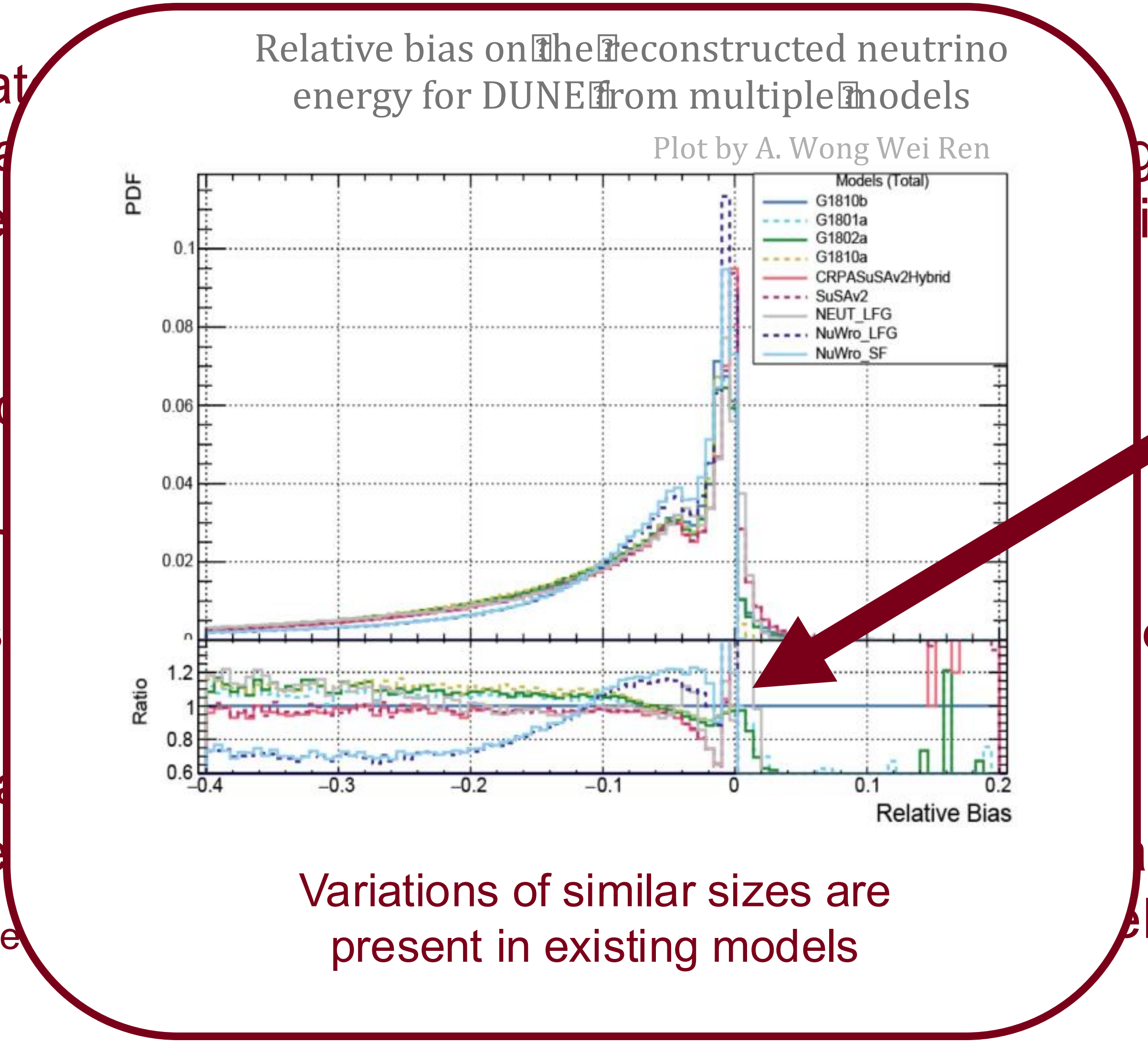
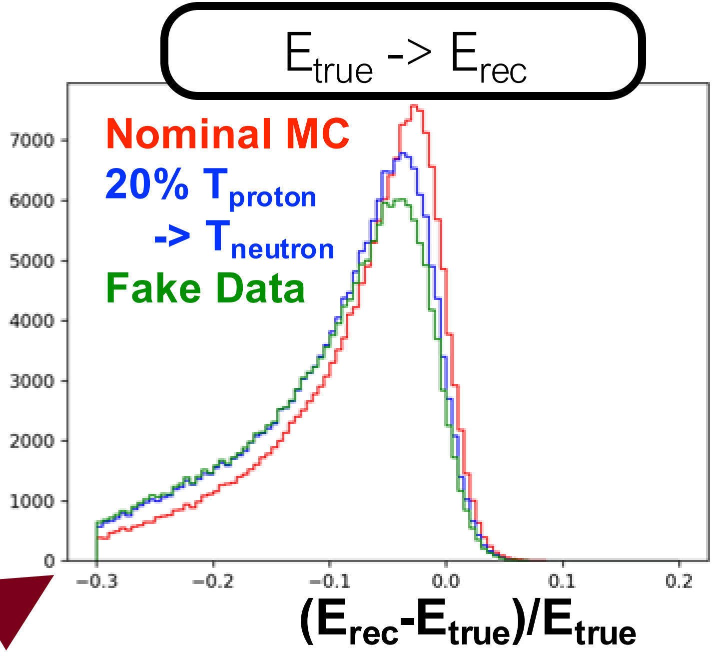
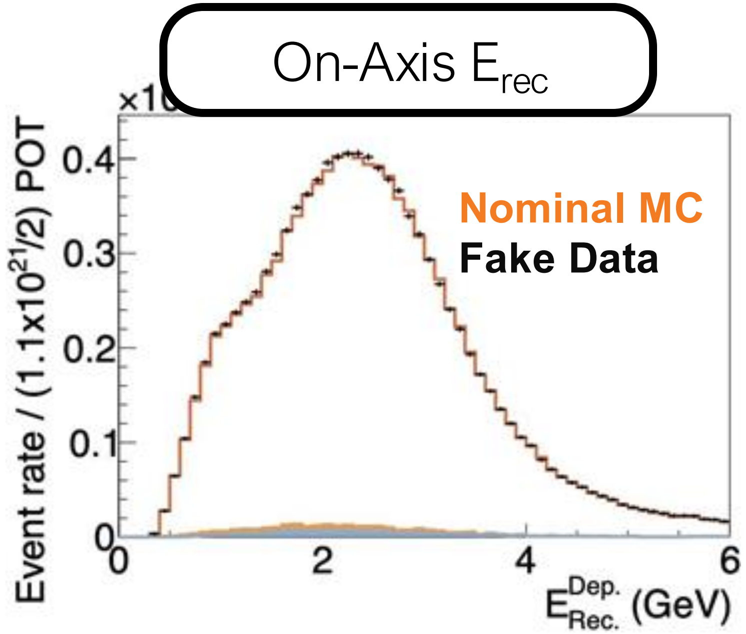
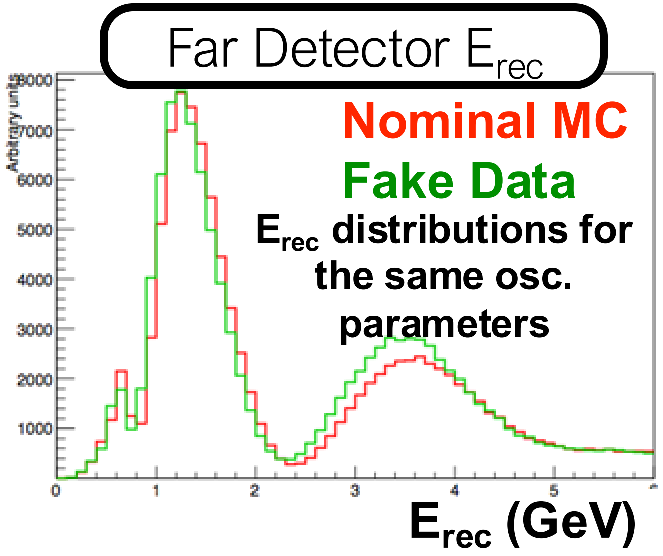


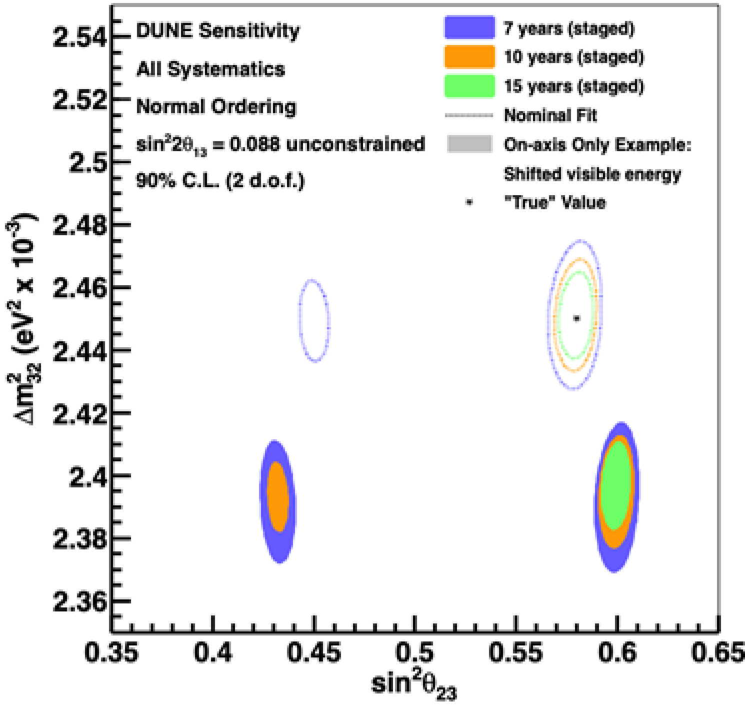


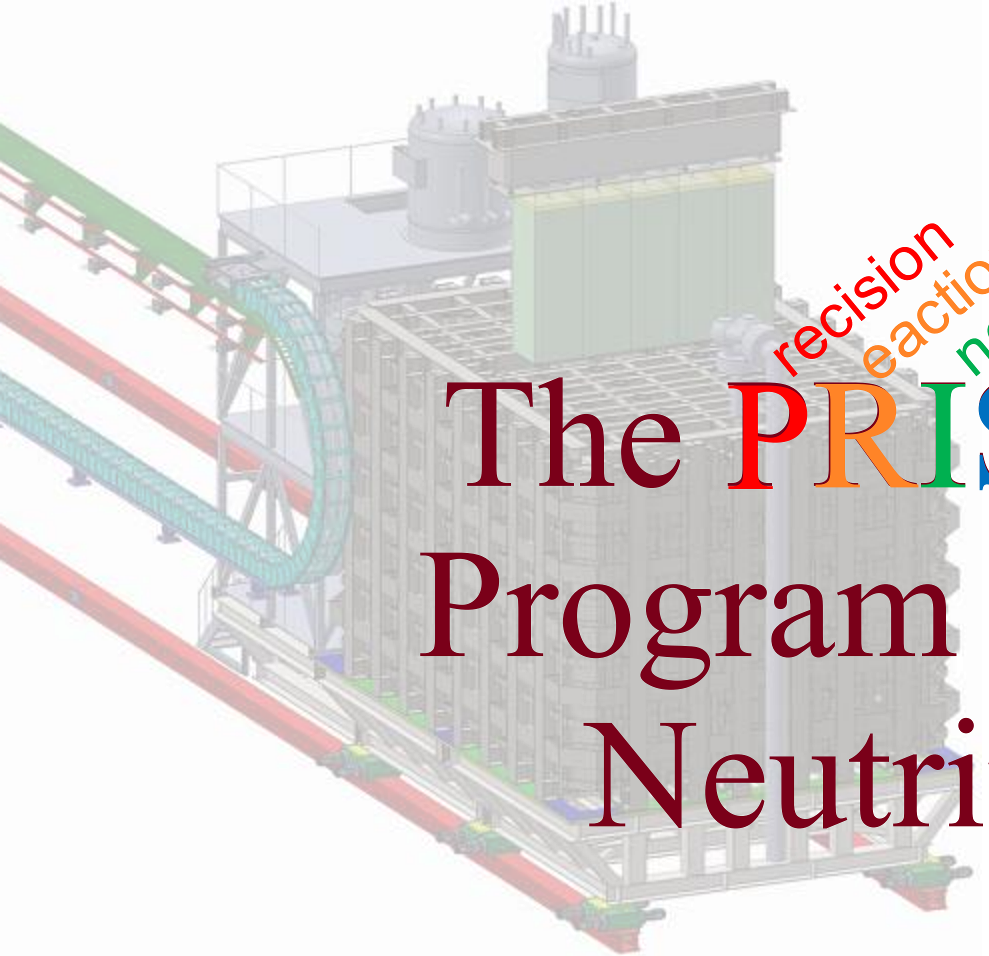


Oscillation Parameter Bias

- Despite good agreement in the ND, the bias is clearly apparent in the oscillated FD spectrum
  - The same oscillation parameters produce a different FD E_{rec} shape in the nominal MC and the fake data
- A full near + far detector fit of the fake data results in a biased measurement of oscillation parameters (well outside of 90% C.L. contours)
  - The fit quality is very good, since there is E_{rec} agreement (by design) in the high-statistics, on-axis near detector
- With only an on-axis near detector, DUNE could get the wrong answers for neutrino oscillation parameters with no evidence that anything was wrong
  - Can anything be done experimentally to address this problem?







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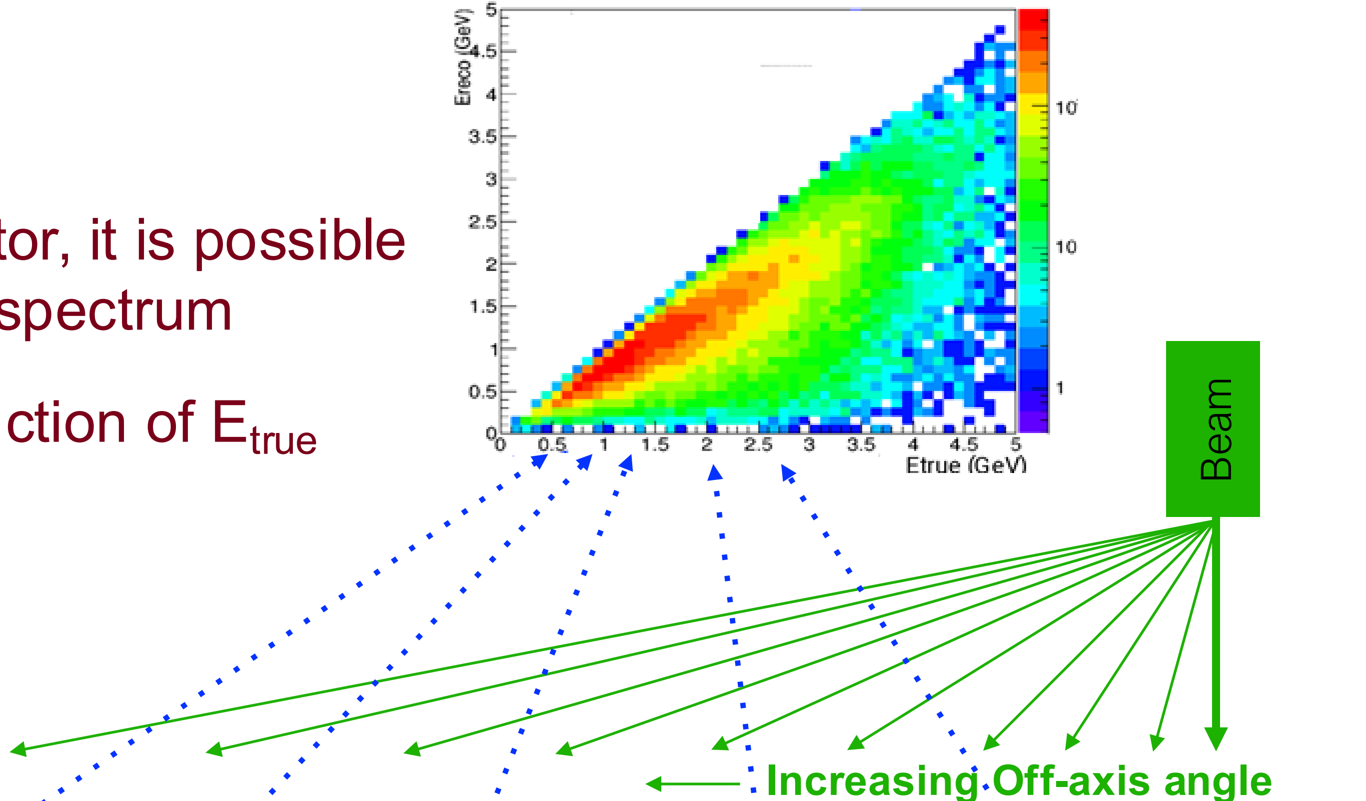
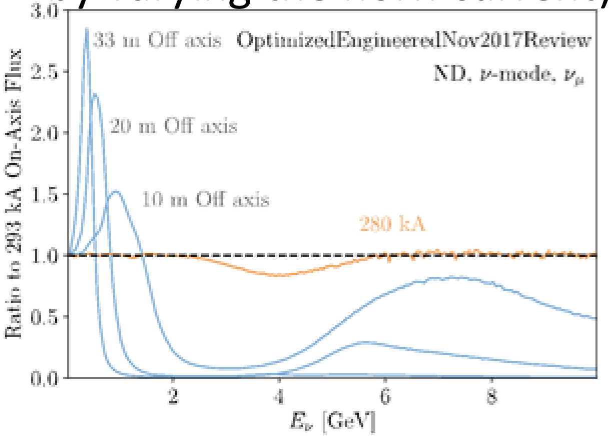
The PRISM Near Detector Program for Long-Baseline Neutrino Experiments

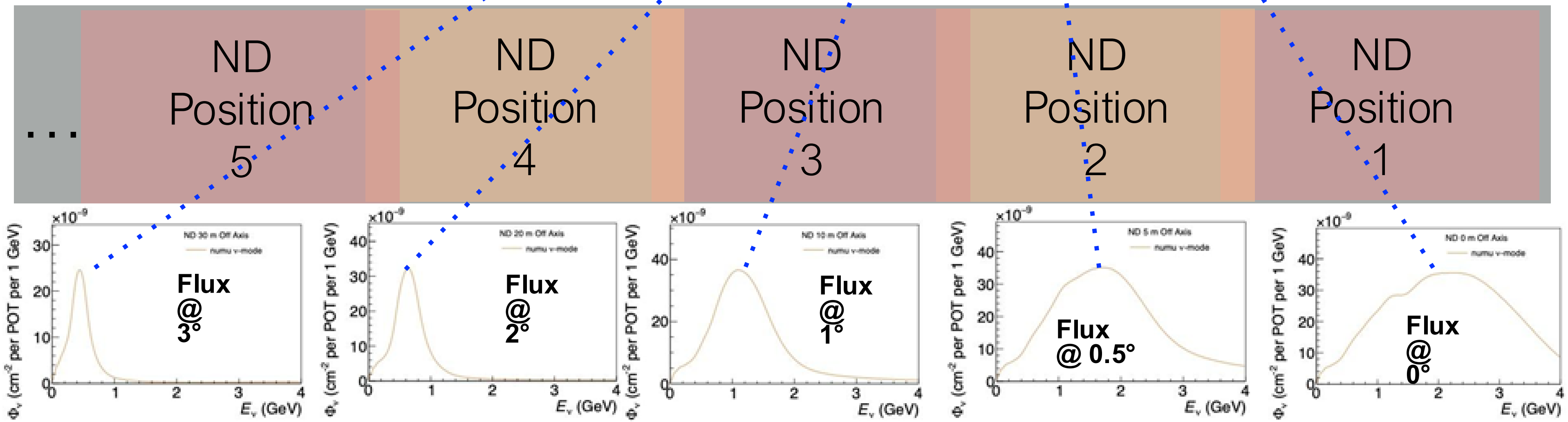
The PRISM Concept

- By changing the off-axis angle of the detector, it is possible to sample a continuously changing energy spectrum
- This provides a "calibration" of E_{rec} as a function of E_{true}
  - Each off-axis location provides an independent "neutrino test beam" measurement with a different incident neutrino energy spectrum



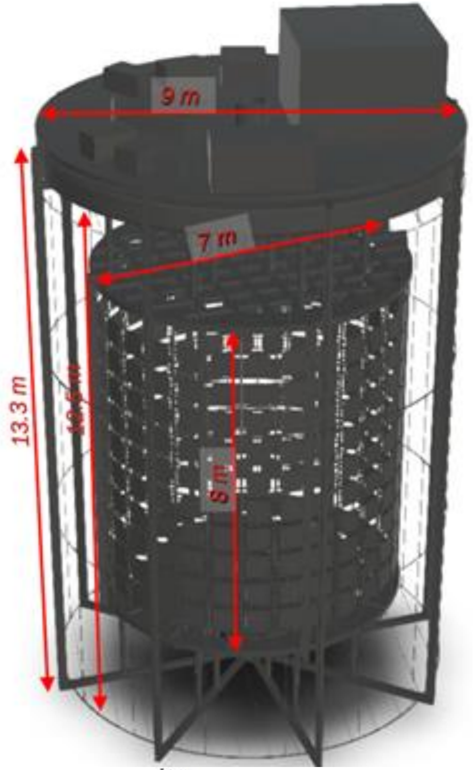
(An additional flux is obtained by varying the horn current)

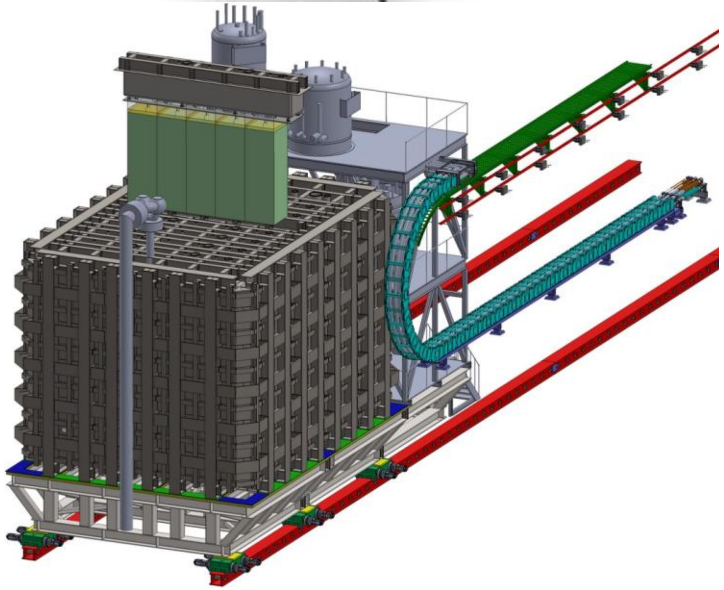




Overview of PRISM Detectors

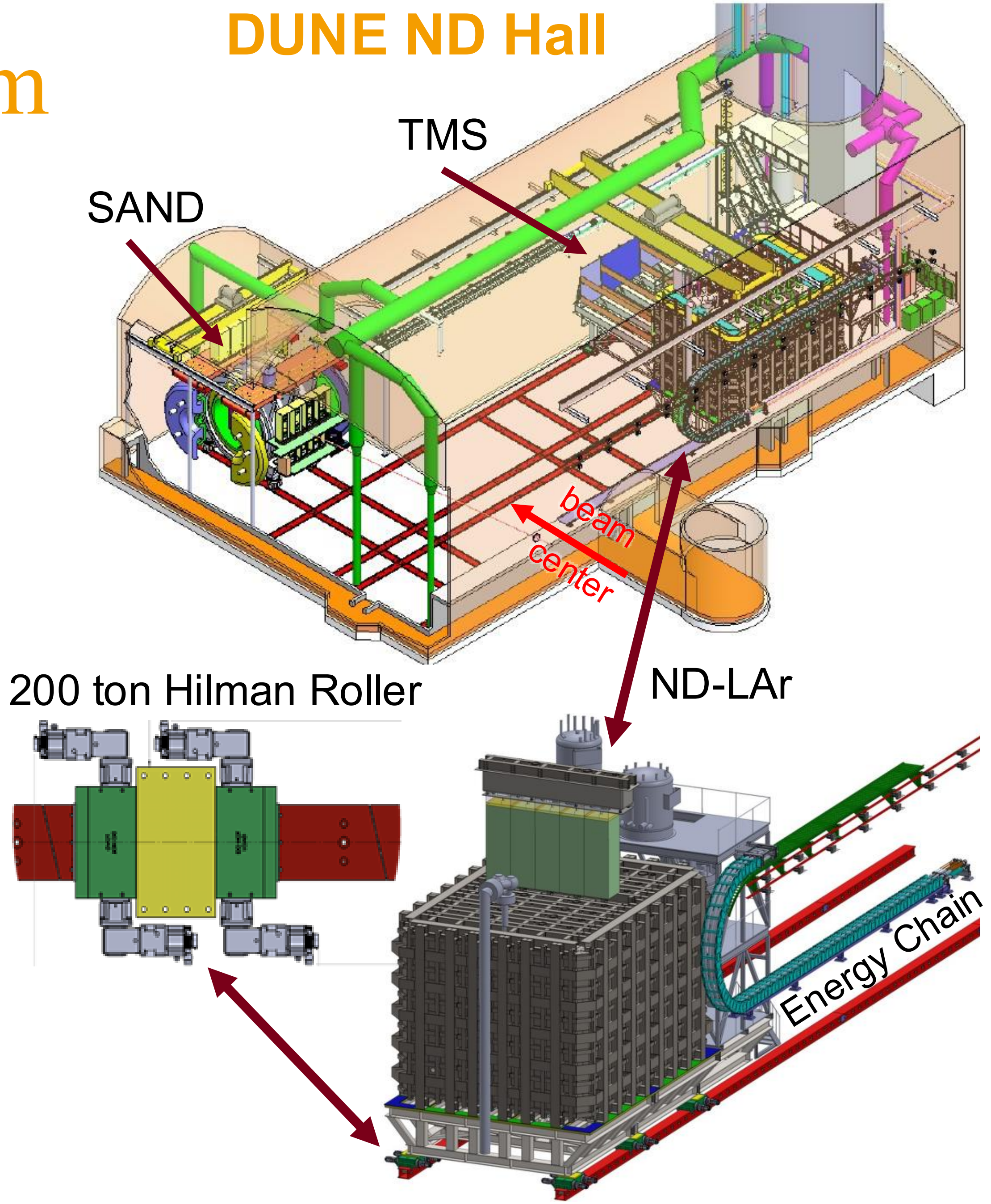
- We first proposed NuPRISM for the J-PARC neutrino beam in 2013
  - Letter of Intent submitted to J-PARC PAC in 2014 (https://arxiv.org/abs/1412.3086)
  - In 2016, this became the Intermediate Water Cherenkov Detector (IWCD) for Hyper-K
- The DUNE-PRISM effort began in 2017 and was selected for the DUNE Near Detector Complex in 2019 (ratified by the EC in 2020)
  - The DUNE-PRISM detector movement system is a separate ND design element, with separate designs for the 2 detectors that move
  - The system is now under design, with installation set to begin in 2028



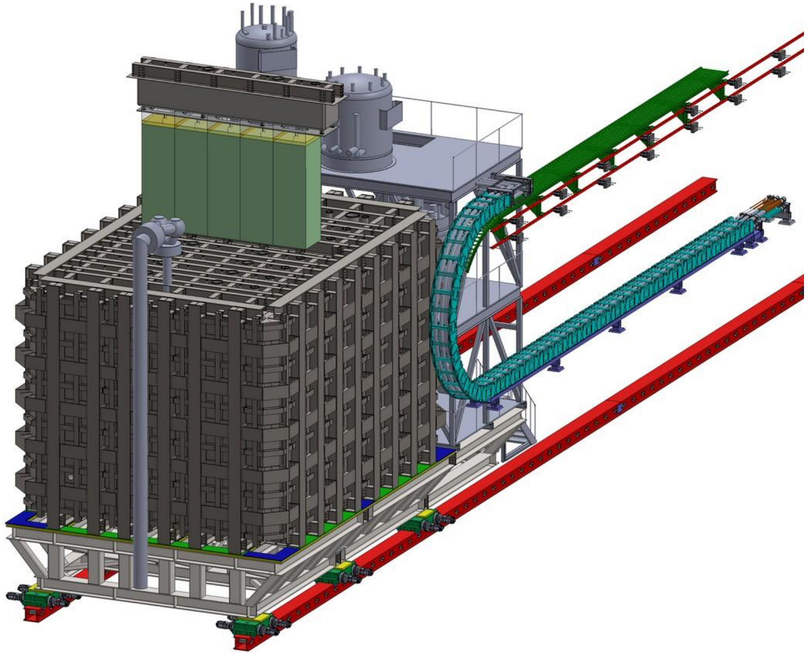


DUNE-PRISM Movement System

- The DUNE ND Hall will house 3 detectors
  - ND-LAr: a modular array (7x5) of LAr TPCs
  - TMS: a magnetized steel/scintillator sandwich for muon range measurements
  - SAND: on-axis beam monitor
- Both ND-LAr and TMS will move together to take data up to ~30 m off-axis
  - Each detector weighs ~1000 tons, and is moved by a set of 6 powered Hilman rollers
  - All detector utilities (cryogenic liquids, power, data) are routed through an energy chain
    - Allows the detector to be placed in an arbitrary off-axis location



DUNE-PRISM Capabilities



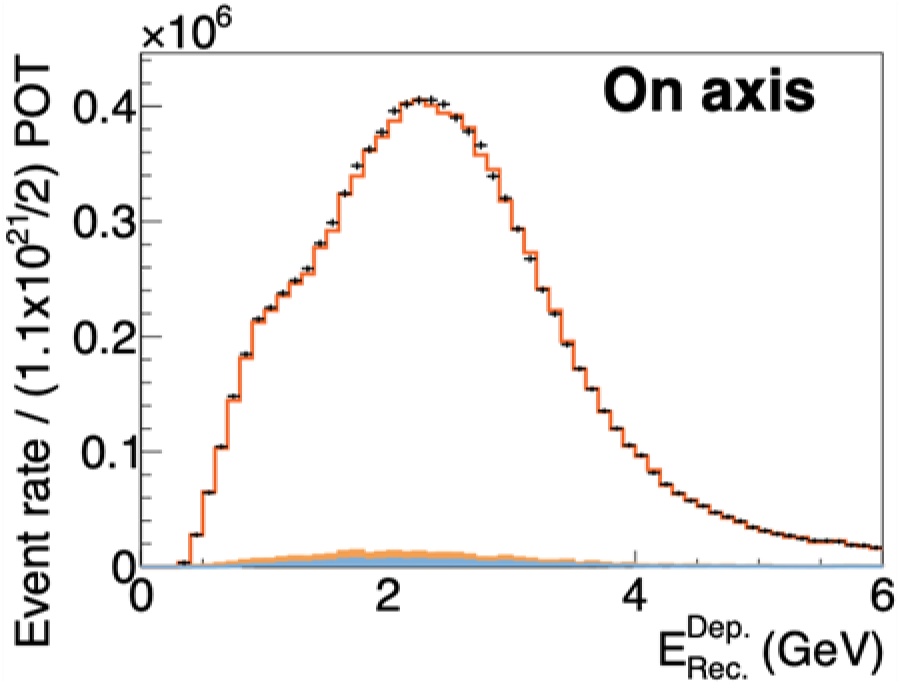
- The system is designed to allow for weekly detector movements
- Detectors can move between 2 arbitrary off-axis positions in < 8 hours
  - ~1 cm positioning accuracy (~1 mm position monitoring accuracy)
- Can frequently return on-axis to monitor detector (and beam) stability
- A full suite of off-axis measurements can be made in a yearly beam run

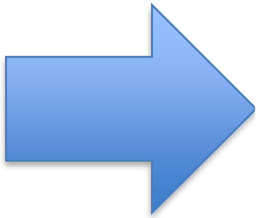
Example (Unoptimized) Run Plan

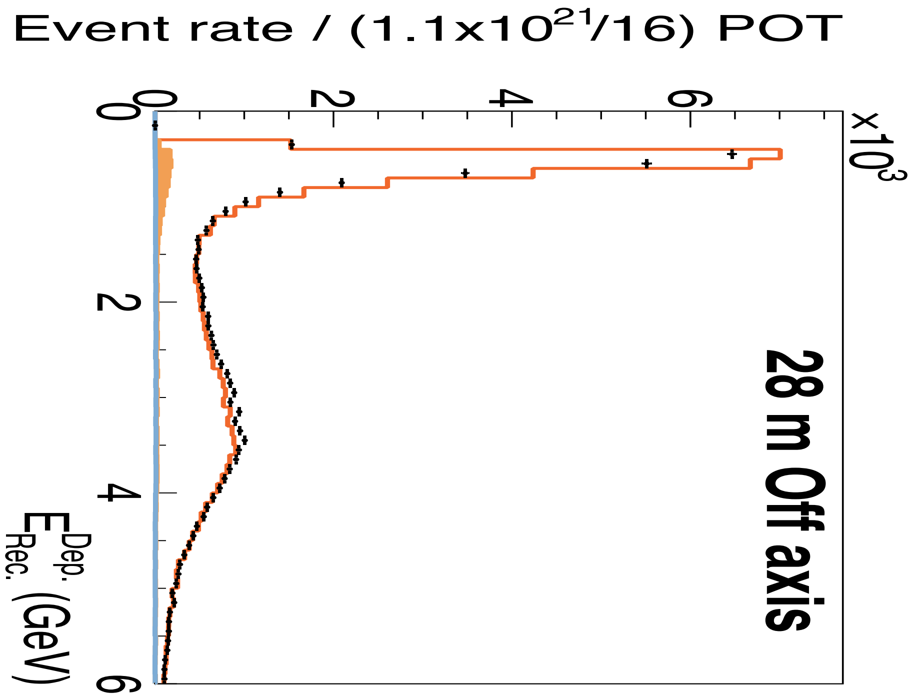
		ND-LAr			
		All int.	Selected		
Stop	Run duration	$N_{\nu_\mu CC}$	N_{Sel}	WSB	NC
On axis (293 kA) m	14 wks.	21.6M	10.1M	0.2%	1.3%
On axis (280 kA) m	1 wk.	1.5M	690,000	0.3%	1.3%
4 m off axis m	12 dys.	2.3M	1.2M	0.3%	1.0%
8 m off axis m	12 dys.	1.3M	670,000	0.5%	0.9%
12 m off axis m	12 dys.	650,000	330,000	0.8%	0.7%
16 m off axis m	12 dys.	370,000	190,000	1.1%	0.7%
20 m off axis m	12 dys.	230,000	120,000	1.3%	0.7%
24 m off axis m	12 dys.	150,000	75,000	1.8%	0.7%
28 m off axis m	12 dys.	110,000	50,000	2.1%	0.8%

Identifying Modeling Issues

- With PRISM, the missing proton KE fake data can be compared to nominal MC at many different off-axis positions
- The previously "hidden" modeling problems can clearly be seen off-axis
  - ND off-axis spectra span the FD E_ν spectrum, so modeling can be verified within the E_ν range relevant for DUNE oscillation physics

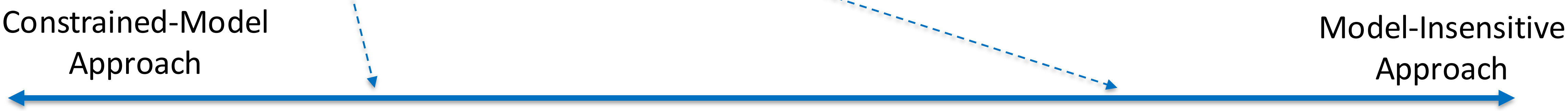






Oscillation Analysis Design

- Constrained-Model Approach: use ND data to constrain flux and cross section model parameters
  - Then use this constrained model to produce predictions for oscillated far detector data
- Model-Insensitive Approach: propagate ND measurements to a FD prediction in a manner that is insensitive to flux and cross section model parameters
  - i.e. the model parameters do not get constrained by the fit
  - In this case, the fit results do not rely on the model details (GOOD!), but this only works if all reasonable model choices are unable to bias the fit results (HARD!)
- Any real analysis will lie on the continuum between these 2 approaches
  - Goal is to only constrain parameters using models that we really believe (e.g. ν–e scattering, beamline monitoring) and avoid constraining parameters in models with large uncertainties (e.g. ν–Ar scattering, beam hadron production)

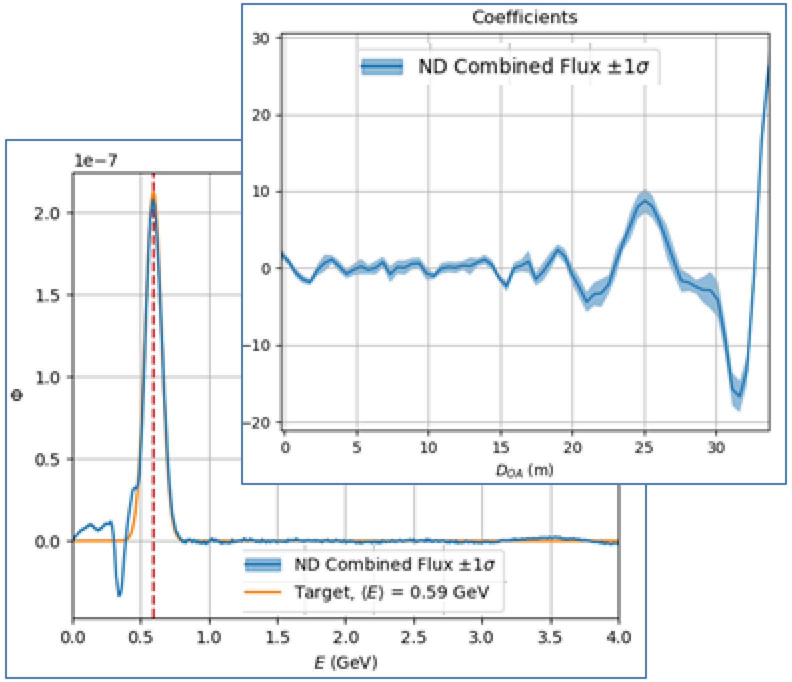


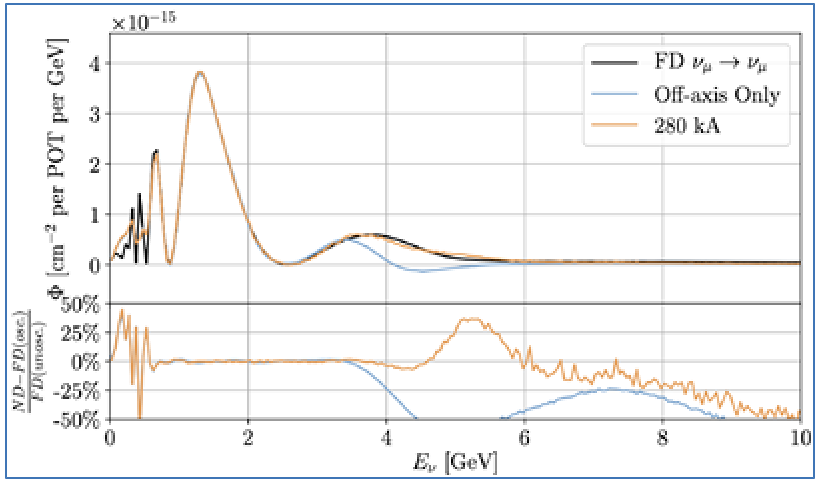
Toward a More Model-Insensitive Approach:

The DUNE-PRISM Linear Combination Analysis

Flux Matching (ND Linear Combinations)

- The flux predictions at each off-axis position can be linearly combined to match any user-defined flux
  - The same combination can then be applied to any observable distribution (e.g. E_{rec})
- 2 types of fluxes are of particular interest:
  - A Pseudo-monoenergetic flux (e.g. Gaussian)
    - Can be used to measure a reconstructed distribution for a known true energy (similar to electron scattering)
    - e.g. it is now possible to measure neutral current interactions vs E_ν
  - A far detector oscillated flux
    - We can now produce oscillated fluxes at the ND!
    - Allows for a direct measurement of the oscillated FD E_{rec} distribution at the ND (for any choice of oscillation parameters)

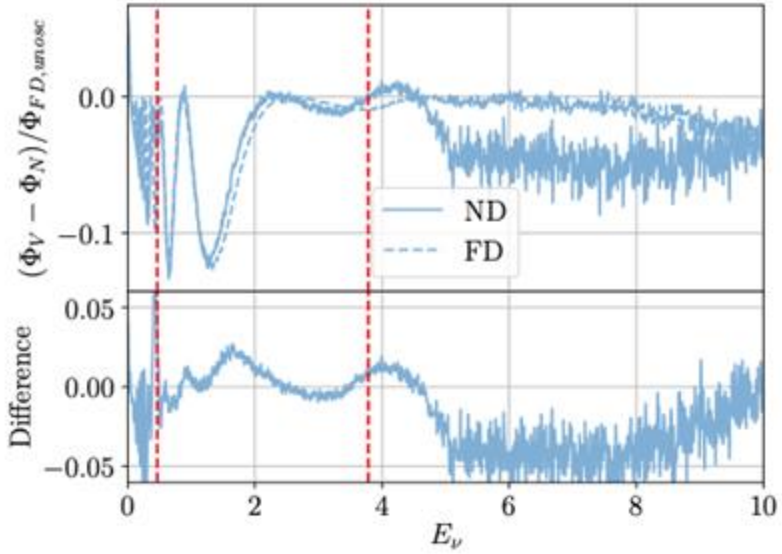




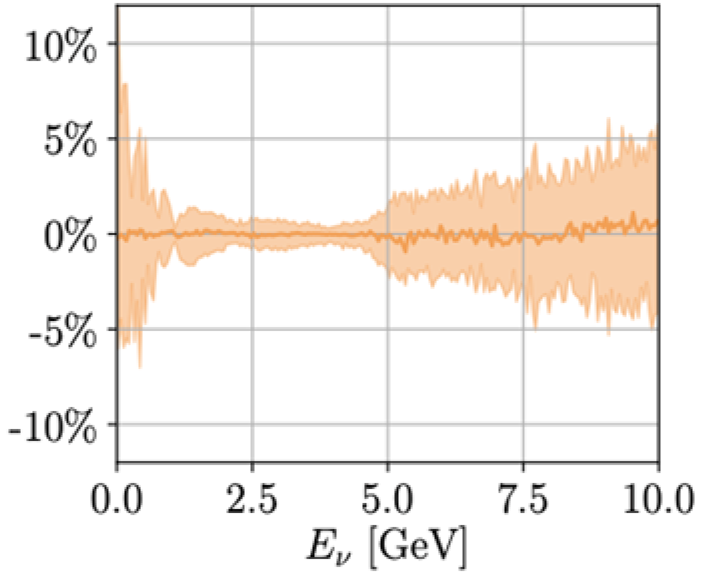
Flux Error Cancelation

- Since the ND fluxes and the FD flux both come from the same beam, there is significant error cancelation
  - ND linear combination variations are very similar to FD flux variations
- Top plot: a single (large) variation of a hadron production uncertainty
  - The effect in ND linear combination and FD is almost identical
  - Resulting error is the residual difference
- Repeating this procedure for all flux variations results in a very small residual error (~1% in the oscillation region)
  - Hadron production is (currently) not the dominant uncertainty in the linear combination analysis

Effect of 1 hadron production variation on the ND linear combination & FD



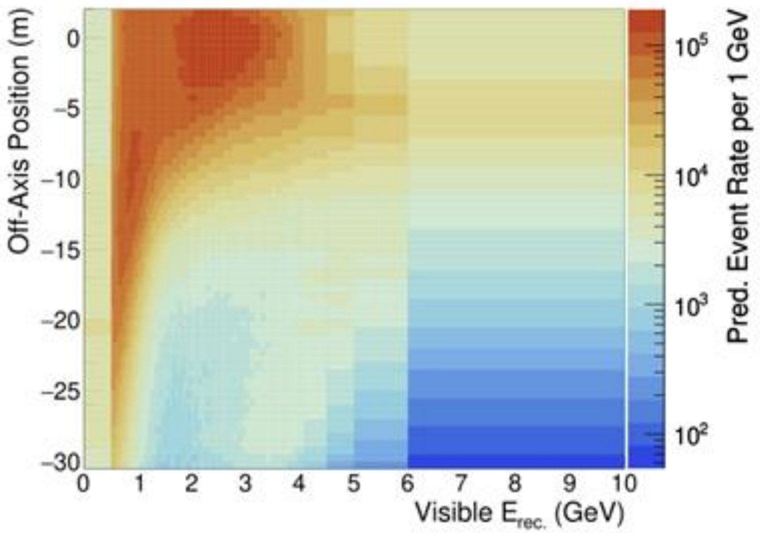
Total Uncertainty from Hadron Production

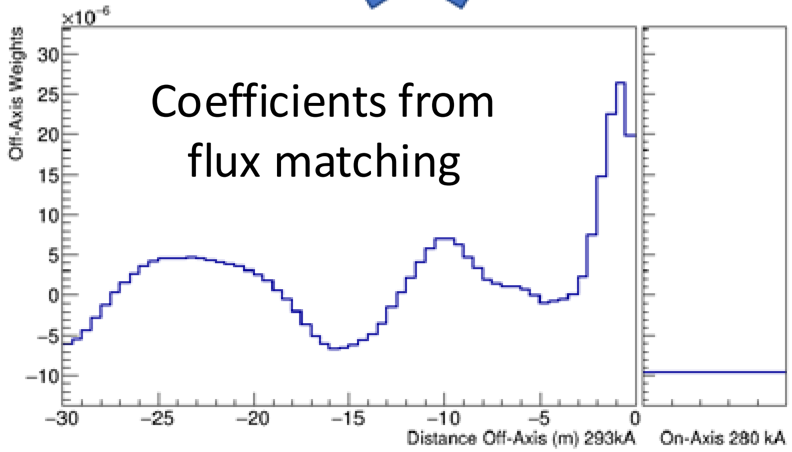


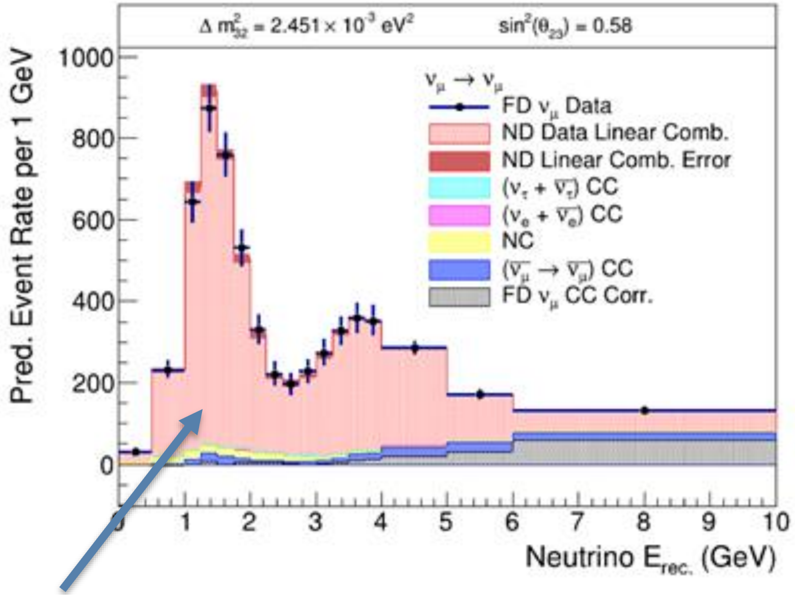
FD Event Rate Prediction

- The off-axis coefficients derived from the flux matching are applied to the ND data
- This produces a data-driven prediction of the far detector oscillated data
- The analysis variable is chosen to minimize dependence on missing energy
  - Reconstructed E_ν is not used
  - ”E_{vis}” excludes energy from neutrons and binding energy
    - Should mainly be sensitive to detector effects (rather than cross section modeling)

Measured ND ν_μ Events

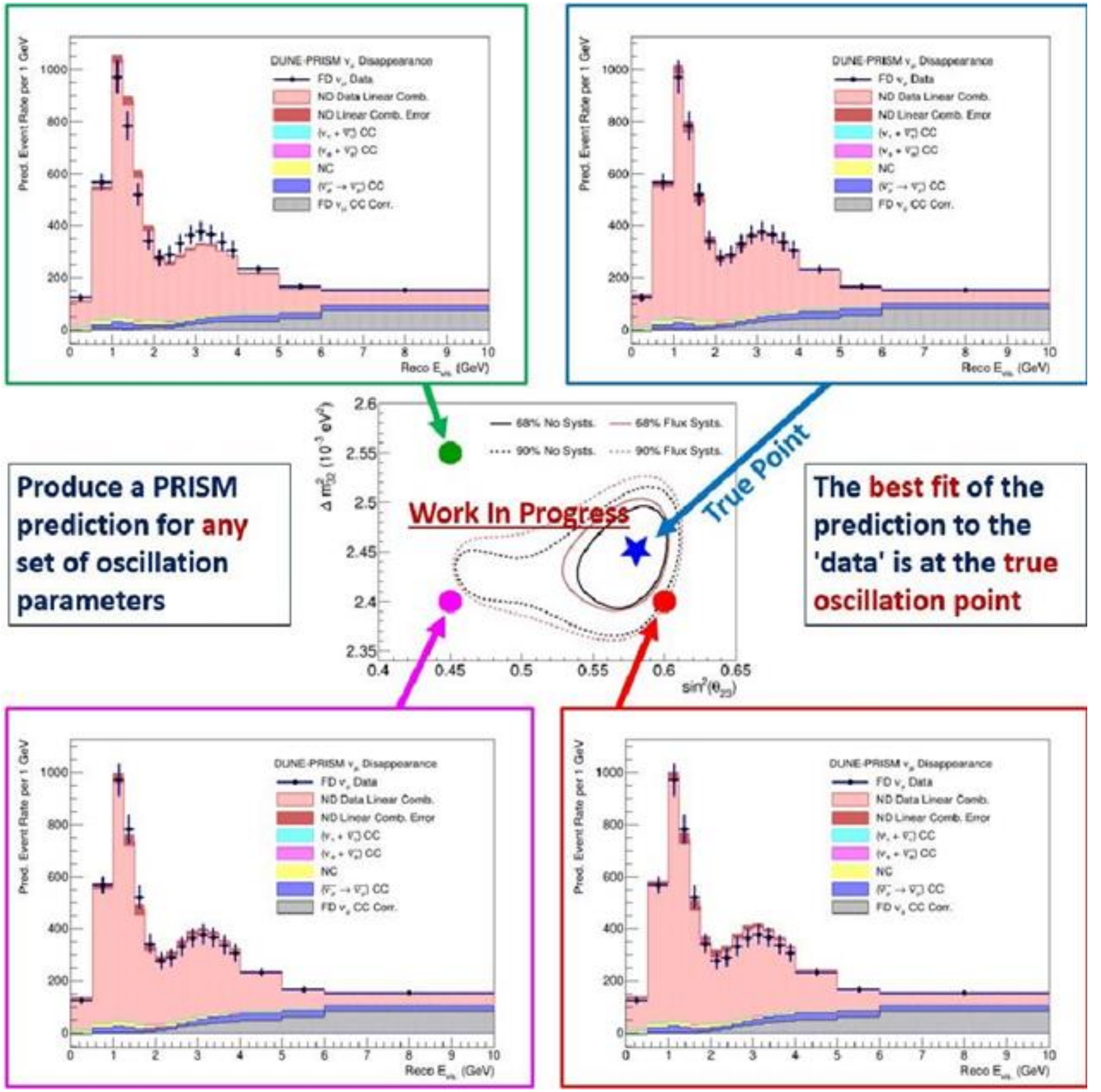






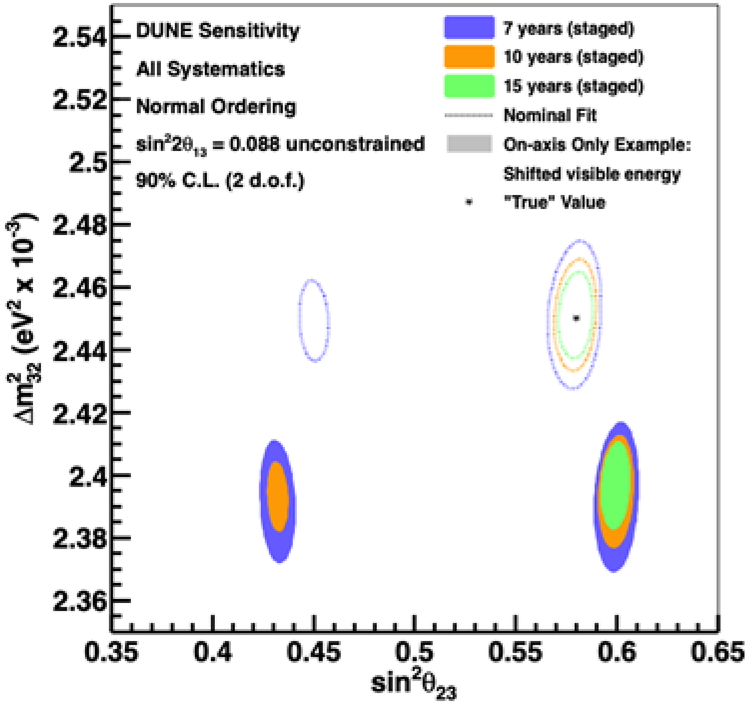
Oscillation Fits

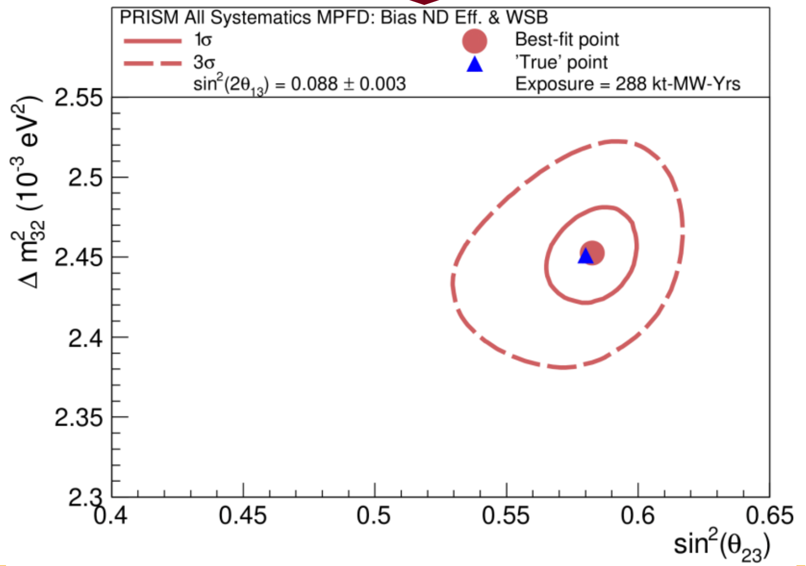
- For each choice of oscillation (and systematic error) parameters, the translation of ND data to FD prediction is repeated
  - Each new prediction is compared to FD data to calculate the likelihood
  - The ND and FD data always remain unchanged throughout this process
- Systematic error (nuisance) parameters are constrained very little during the fit
  - Constraint comes from FD statistics
  - Non-data-driven components of the prediction incur the full flux & cross section uncertainties



Missing Proton KE Fake Data

- We can now return to the missing proton fake data study from earlier
- Using the DUNE-PRISM Linear Combination analysis, there is no longer a bias in the measured oscillation parameters relative to the true parameters
    - The contour is wider due to:
        - Lower total exposure
        - Remaining uncertainties in the ND efficiency correction
            - This is currently being addressed by a novel “geometric efficiency correction”
        - Crude ND “unfolding” and FD “smearing”
            - Will be replaced with an under-development machine-learning ND to FD event translation
- Summary: the Linear Combination removes the bias in the measured oscillation parameters!
    - Next steps are to improve control of systematic uncertainties





Particle Physics Project Prioritization Panel (P5) Report

- The US particle physics community recently completed a multi-year planning exercise to determine funding priorities for the next decade
  - DUNE Phase 1 is fully supported
  - DUNE FD3 is supported
    - We are awaiting a new DOE project to fund this detector
  - DUNE ND upgrade is supported
    - Upgrade to a Gas Ar TPC
      - Lower particle thresholds, less hadronic interactions
  - DUNE FD4 technology will be reevaluated
    - But another LAr detector seems unlikely, given the report

https://www.usparticlephysics.org/2023-p5-report/

Recommendation 1: As the highest priority independent of the budget scenarios, complete construction projects and support operations of ongoing experiments and research to enable maximum science.

b. The first phase of DUNE and PIP-II to determine the mass ordering among neutrinos, a fundamental property and a crucial input to cosmology and nuclear science

Recommendation 2: Construct a portfolio of major projects that collectively study nearly all fundamental constituents of our universe and their interactions, as well as how those interactions determine both the cosmic past and future.

b. Re-envisioned second phase of DUNE with an early implementation of an enhanced 2.1 MW beam—ACE-MIRT—a third far detector, and an upgraded near-detector complex as the definitive long-baseline neutrino oscillation experiment of its kind (section 3.1).

⋮

3.1.4 – Future Opportunities: DUNE FD4, the Module of Opportunity

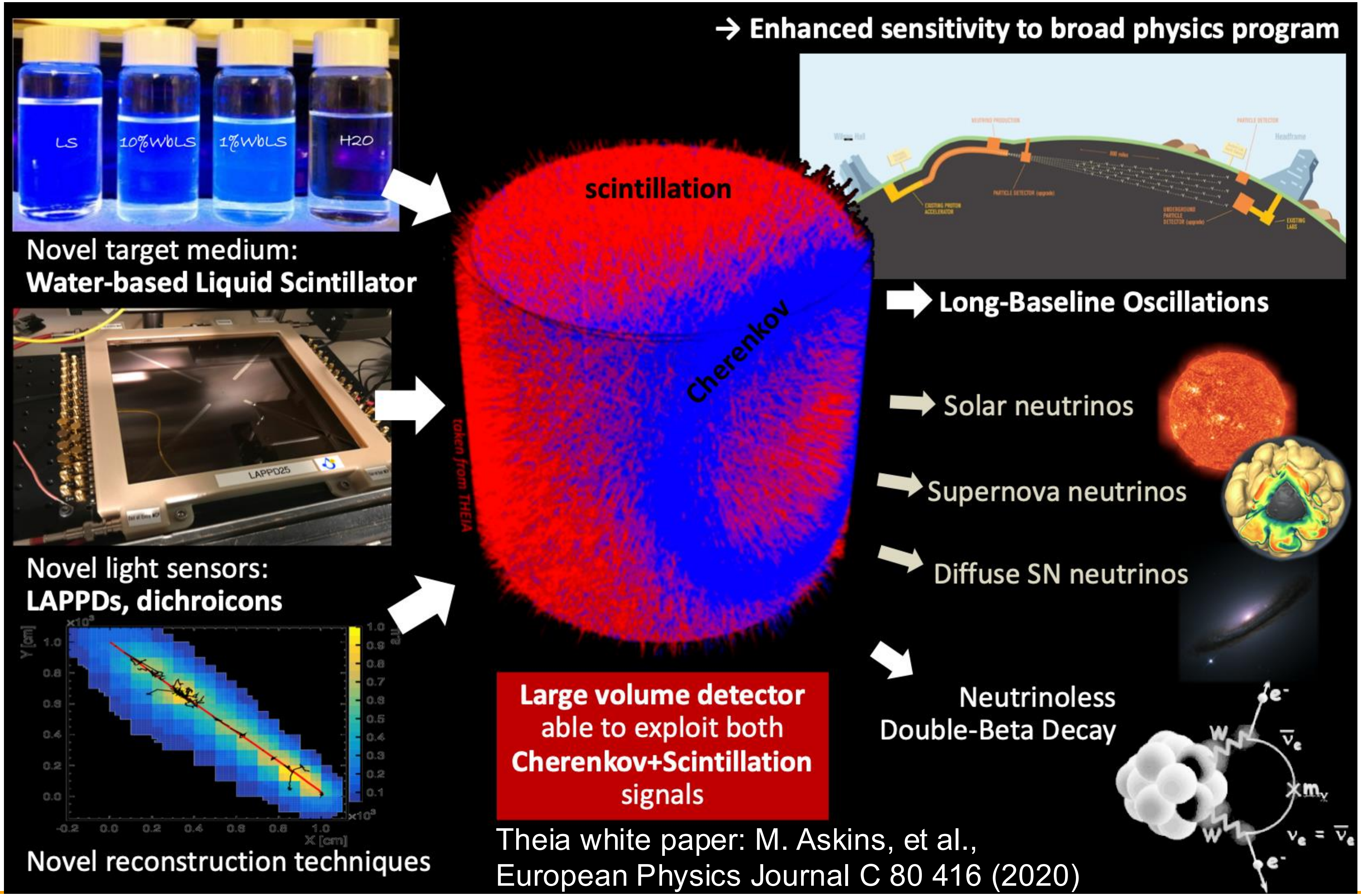
A range of alternative targets, including low radioactivity argon, xenon-doped argon, and novel organic or water-based liquid scintillators, should be considered to maximize the science reach, particularly in the low-energy regime. Increased radiochemical purity

⋮

matter searches, and expanded sensitivity to solar neutrinos. R&D for advanced detector concepts should be supported.

the physics potential will require input from all stakeholders: DUNE collaboration, US funding agencies, and the international community. A decision-making process led by DOE, inclusive of the entire community and driven by all stakeholders, will ensure that the full potential of the FD4 is realized. The timeline should be driven by the most promising scientific opportunities and must be inclusive of the long baseline science program (Recommendation 4d).

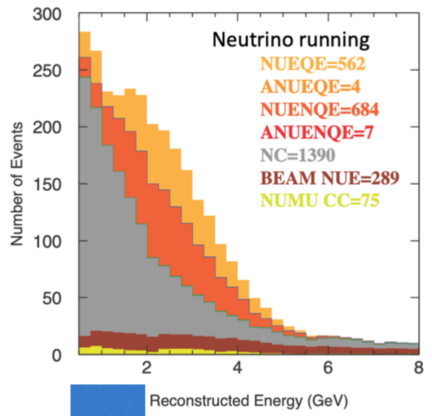
Theia: a Water-based Liquid Scintillator Detector Designed for Low-Energy Physics

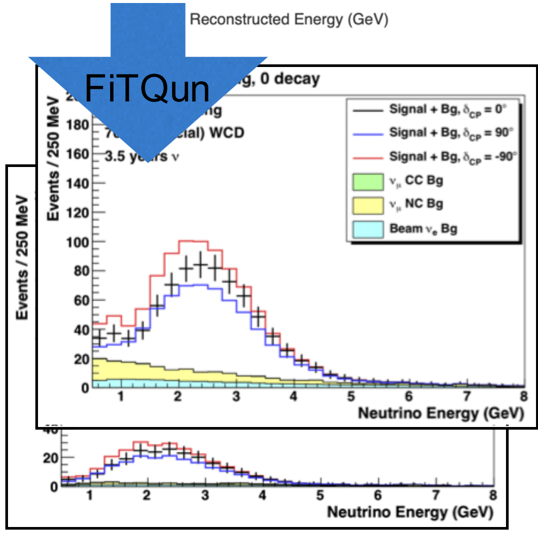


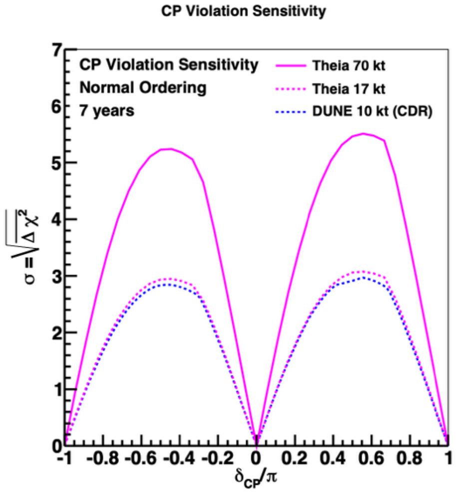
slide from
M. Wurm

Theia Beam Physics

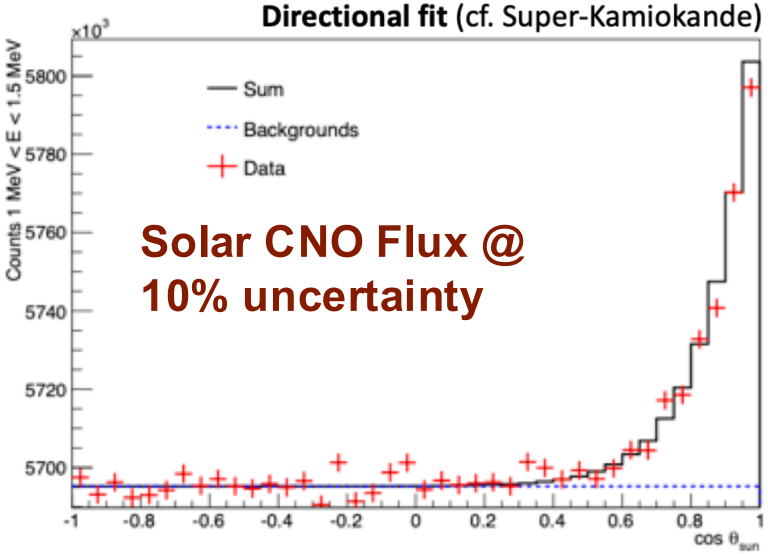
- But can Theia do high energy beam physics (δ_{CP}, θ_{23}, etc.)?
- Prior to DUNE, the LBNE collaboration studies the relative sensitivities of water Cherenkov and LAr detectors
  - They concluded that a water detector would need 6 times the mass of a LAr detector for equivalent sensitivity to δ_{CP}
  - This was based on old SK reconstruction tools that produced a large neutral current (π^0) background
- We updated this analysis using a simple FiTQun selection, and found the 6:1 ratio is now closer to 1.7:1
- **A Theia detector at SURF can produce beam physics sensitivities similar to a LAr detector**
- Next for Theia LBL working group: full simulation + reconstruction, ND + FD oscillation analysis (decisions to be made in 2027-2028)



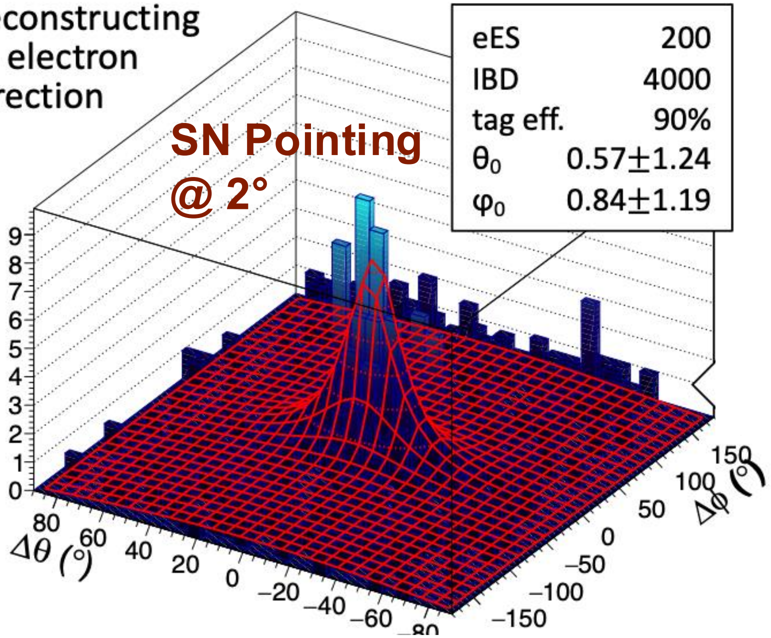




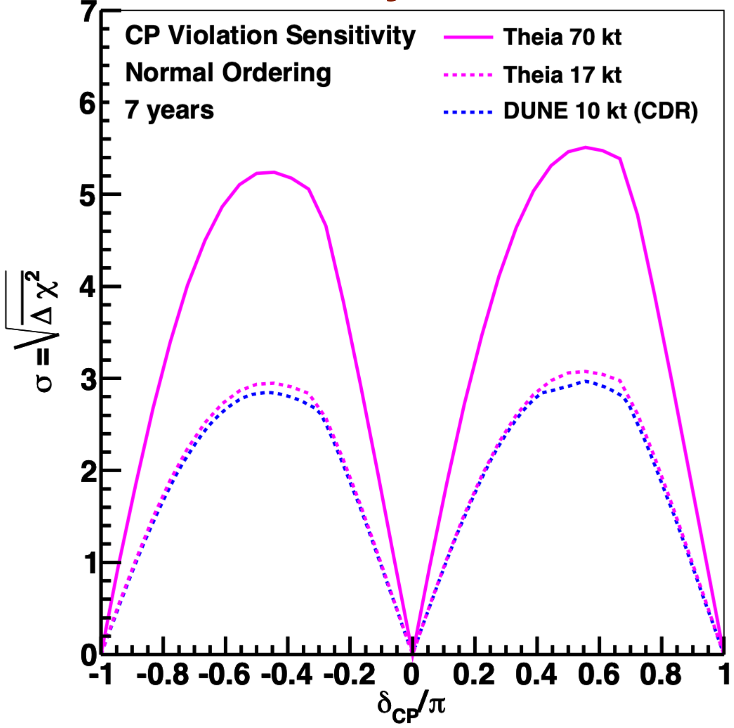
A Theia Detector at Homestake Would Provide Unique Physics Capabilities

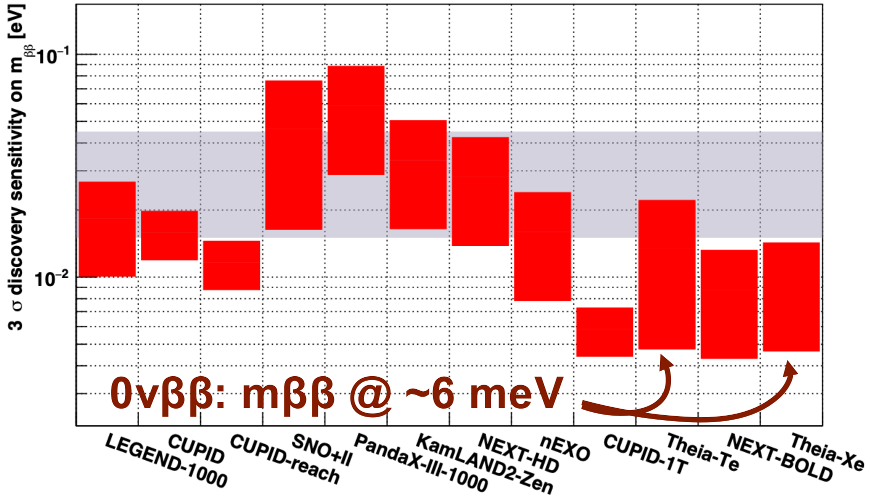


Reconstructing ES electron direction

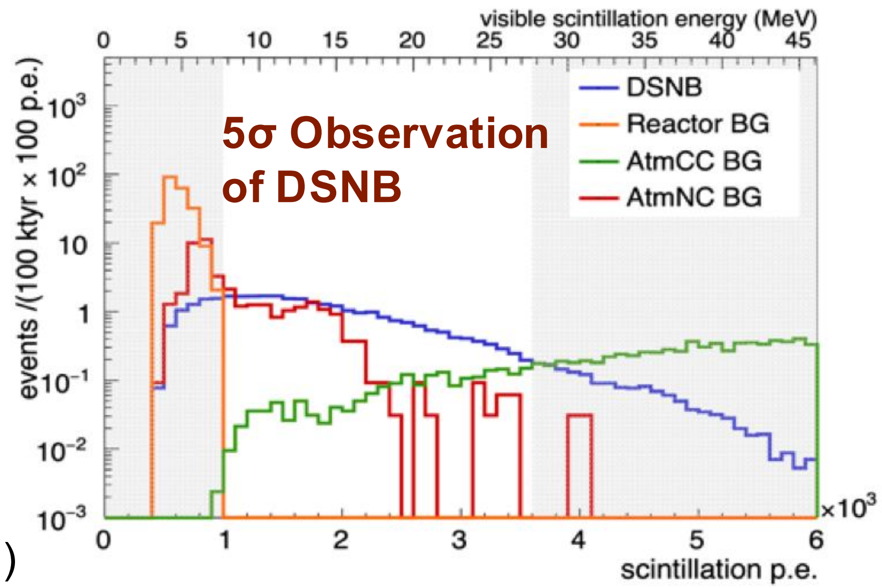


Confirm CPV w/ different systematics





Signal/BG spectra and observation window



Theia white paper: M. Askins, et al., European Physical Journal C 80 416 (2020)