Long-Baseline Neutrino Experiments

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Outline

- Neutrino Oscillations
- Open Questions for Long-Baseline Beams
- Long-Baseline Neutrino Experiments
- Recent Results
- Future Experiments

Standard Model of Particles

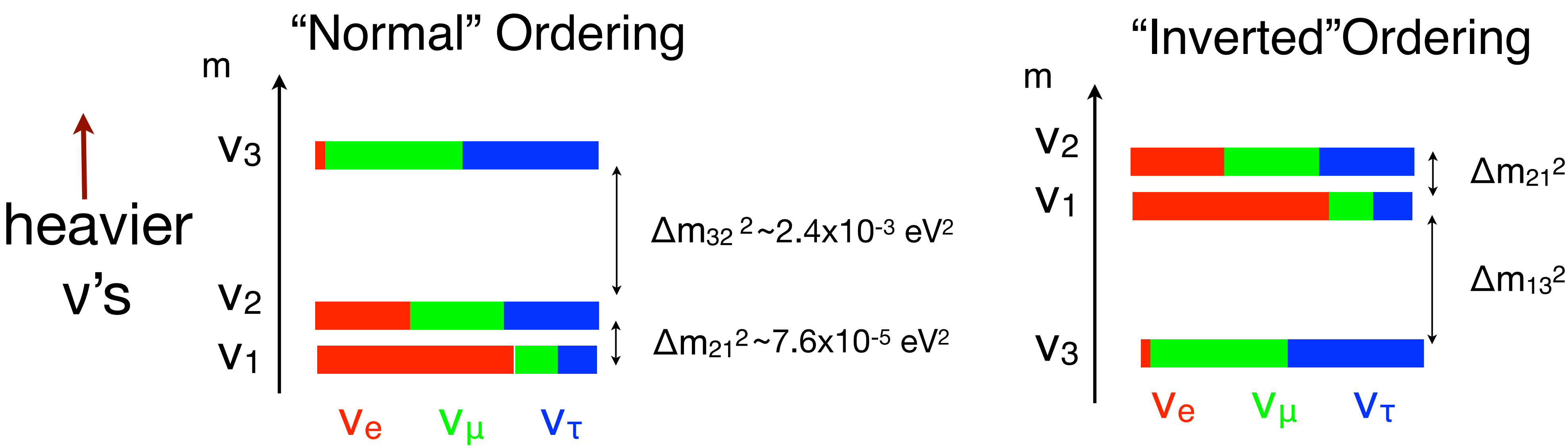
	Quarks		Leptons	
charge → / mass →	+2/3 u 3 MeV	-1/3 d 7 MeV	-1 e 0.5 MeV	0 ν_e ~0 MeV
	+2/3 c 1.2 GeV	-1/3 s 120 MeV	-1 μ 105 MeV	0 ν_μ ~0 MeV
	+2/3 t 174 GeV	-1/3 b 4.3 GeV	-1 τ 1.8 GeV	0 ν_τ ~0 MeV
	Strong, EM, Weak forces		EM, Weak forces	Weak force

Heavier Masses (?)

- Each particle also has a corresponding anti-particle, eg e^+ and $\bar{\nu}_e$

Neutrino Masses

- Two different mass difference scales



- Sign of Δm_{21} is known due to effects in the Sun, but sign of Δm_{31} isn't, so two possible orderings of masses

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Neutrino Mixing

- Unitary PMNS matrix relates mixing between flavor and mass states

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \times \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \times \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

where $s_{ij} = sin(\theta_{ij})$ and $c_{ij} = cos(\theta_{ij})$

- Anti-ν depend on U*

Neutrino Mixing

- Unitary PMNS matrix relates mixing between flavor and mass states

θ_{23} and Δm^2_{32}
Atmospheric/ Accelerator neutrinos
θ_{23}~45°

δ, θ_{13} and Δm^2_{31}
reactor anti-neutrinos and accelerator neutrinos
θ_{13}~9°

θ_{12} and Δm^2_{21}
Solar neutrinos/ long distance reactor anti-neutrinos
θ_{12}~34°

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \times \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \times \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

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Mixing in Vacuum with δ=0

- L/E scale relevant for recent accelerator beams oscillation effects are dominated by $m_3 \leftrightarrow m_2$ and $m_3 \leftrightarrow m_1$ mixing
- ν_μ Disappearance in a ν_μ Beam

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - \sin^2 2\theta_{23} \cdot \sin^2 (\Delta m^2_{32} L/4E)$$

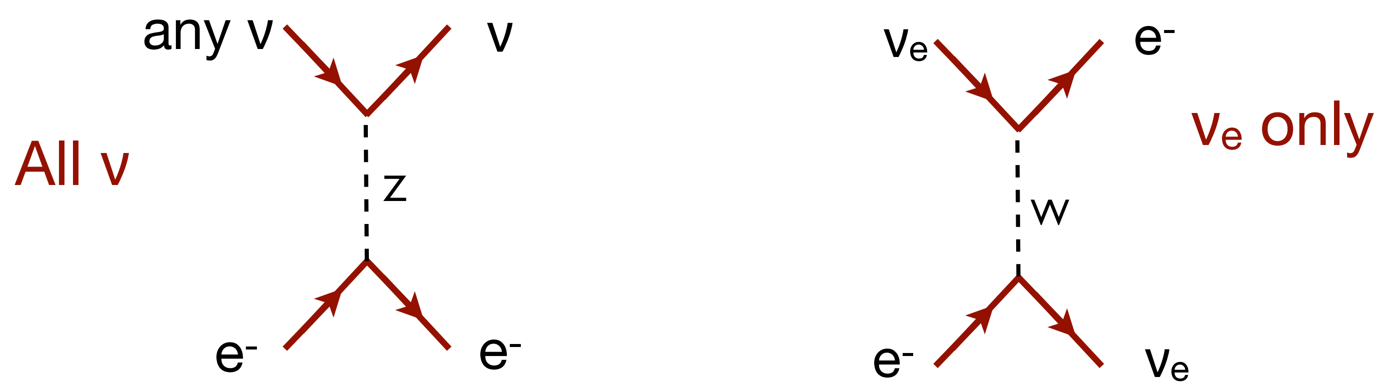
- ν_e Appearance in a ν_μ Beam

$$P(\nu_\mu \to \nu_e) \simeq \sin^2 2\theta_{13} \cdot \sin^2 \theta_{23} \cdot \sin^2 (\Delta m^2_{31} L/4E)$$

- Precision measurements require 3 flavor fits

Neutrino Oscillations in Matter

- Matter has e^-, and no μ^- or τ^-
- Additional processes for ν_e and anti-ν_e scattering on e^-



- Modifies apparent oscillation probabilities

$$P(\nu_\mu \to \nu_e) \simeq \sin^2 2\theta_{13} \cdot \frac{\sin^2\theta_{23}}{(A-1)^2} \cdot \sin^2\left((A-1)\Delta m^2_{31} L/4E\right)$$

$$\text{where } A = \sqrt{2} G_F N_e \frac{2E}{\Delta m^2_{31}}$$

Sign depends on hierarchy

- Effect varies with E

Matter Effects

$$P(\nu_\mu \to \nu_e) \simeq \sin^2 2\theta_{13} \cdot \frac{\sin^2\theta_{23}}{(A-1)^2} \cdot \sin^2\left((A-1)\Delta m^2_{31} L/4E\right)$$

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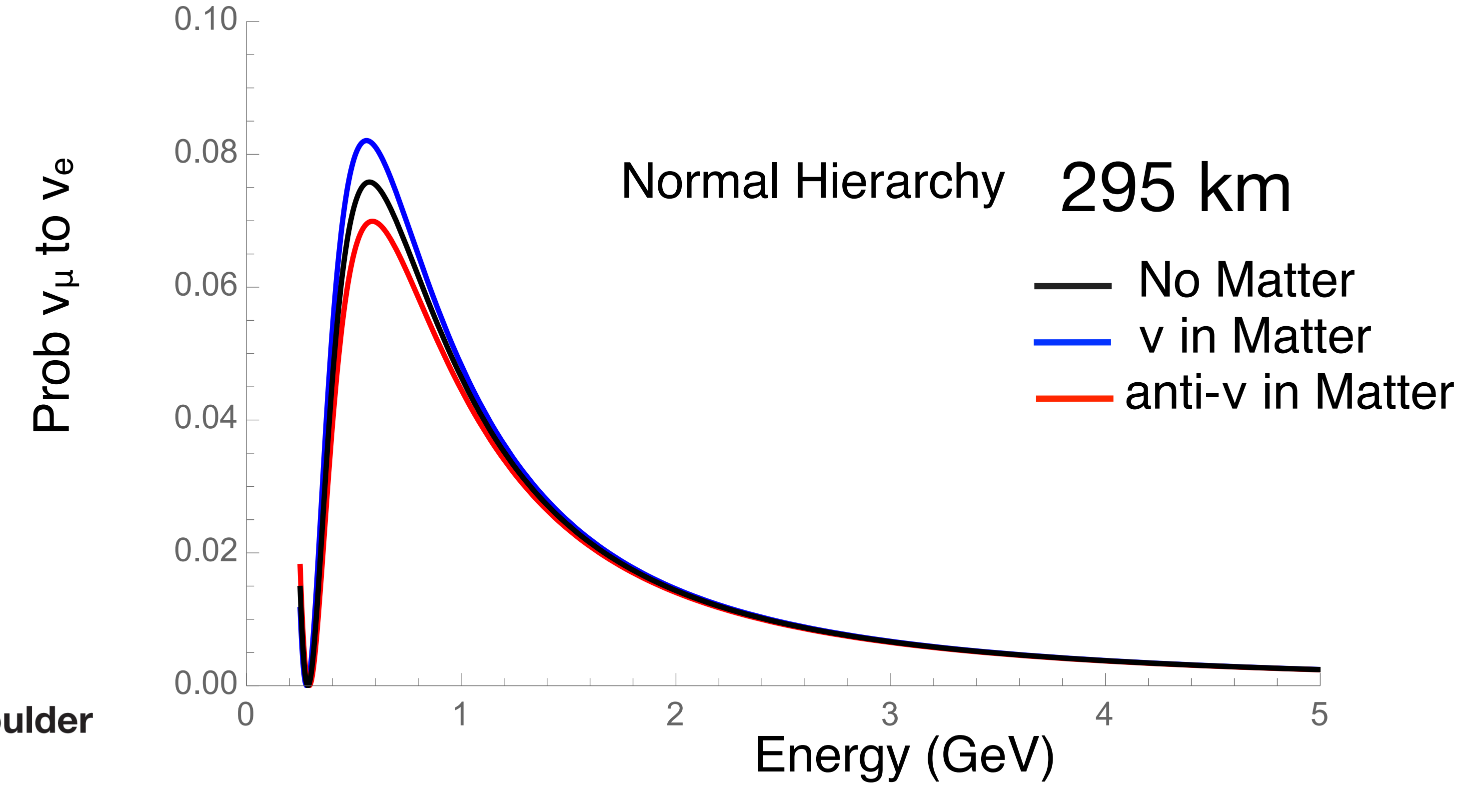
- Additionally A changes sign for anti-neutrinos
- So in the normal hierarchy the appearance probability increases for neutrinos and decreases for anti-neutrinos.



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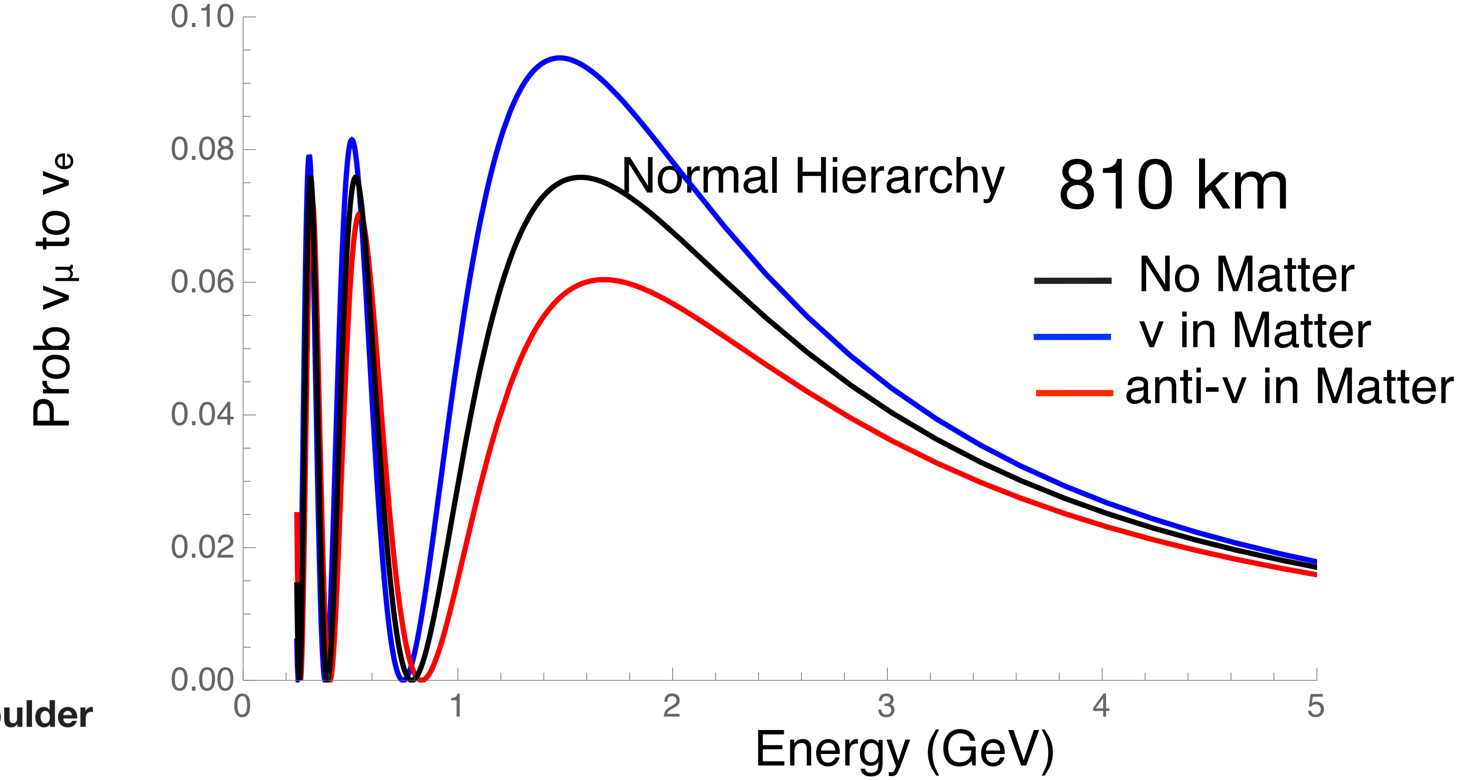

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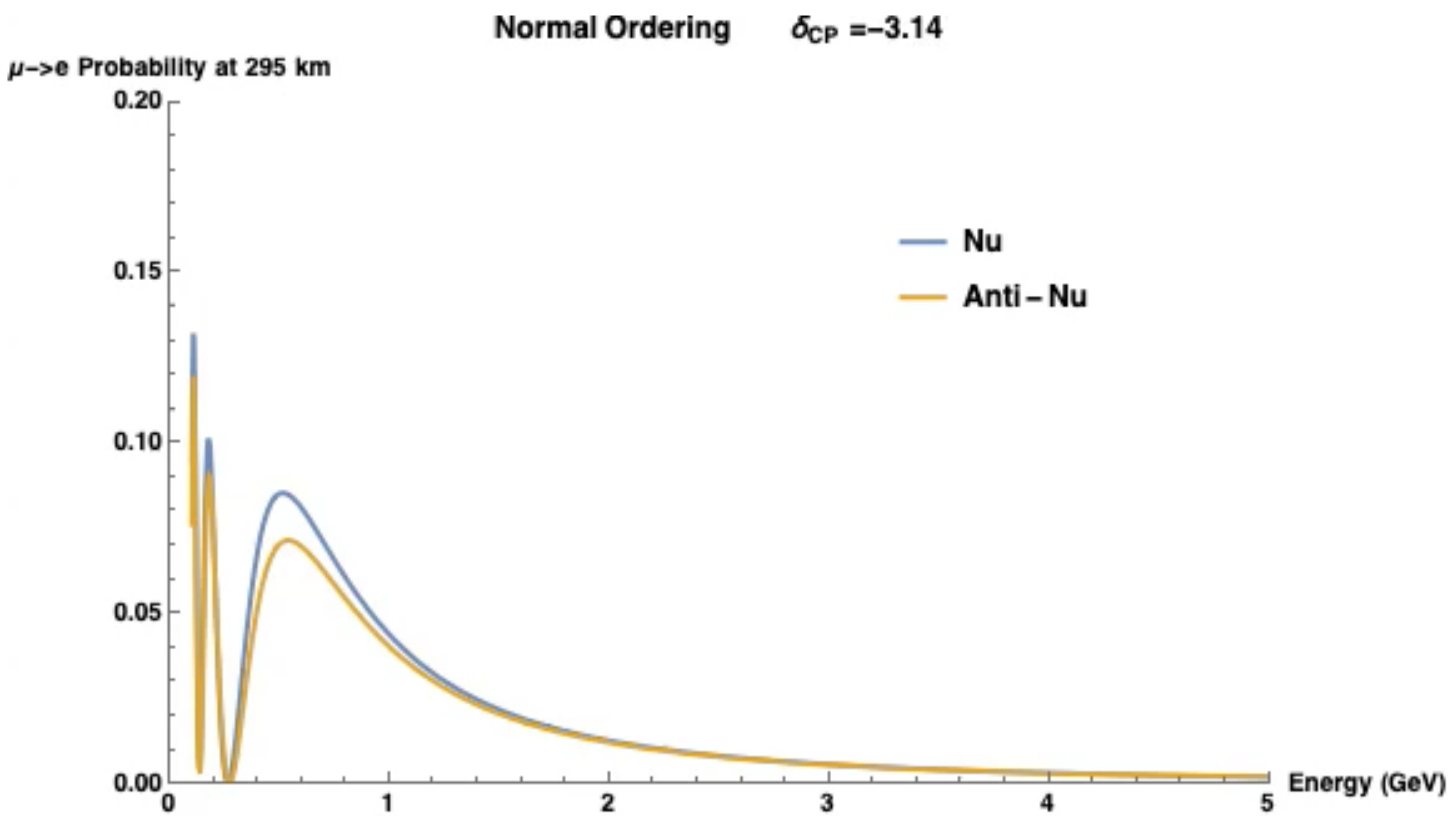
δ≠0

- For δ≠0, there are additional terms that **depend on -sin(δ)** for neutrinos.
- **Depends on +sin(δ)** for anti-ν. So this will lead to differences in $P(\nu_\mu \to \nu_e)$ compared to $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ in vacuum

Includes matter effects, assuming normal ordering



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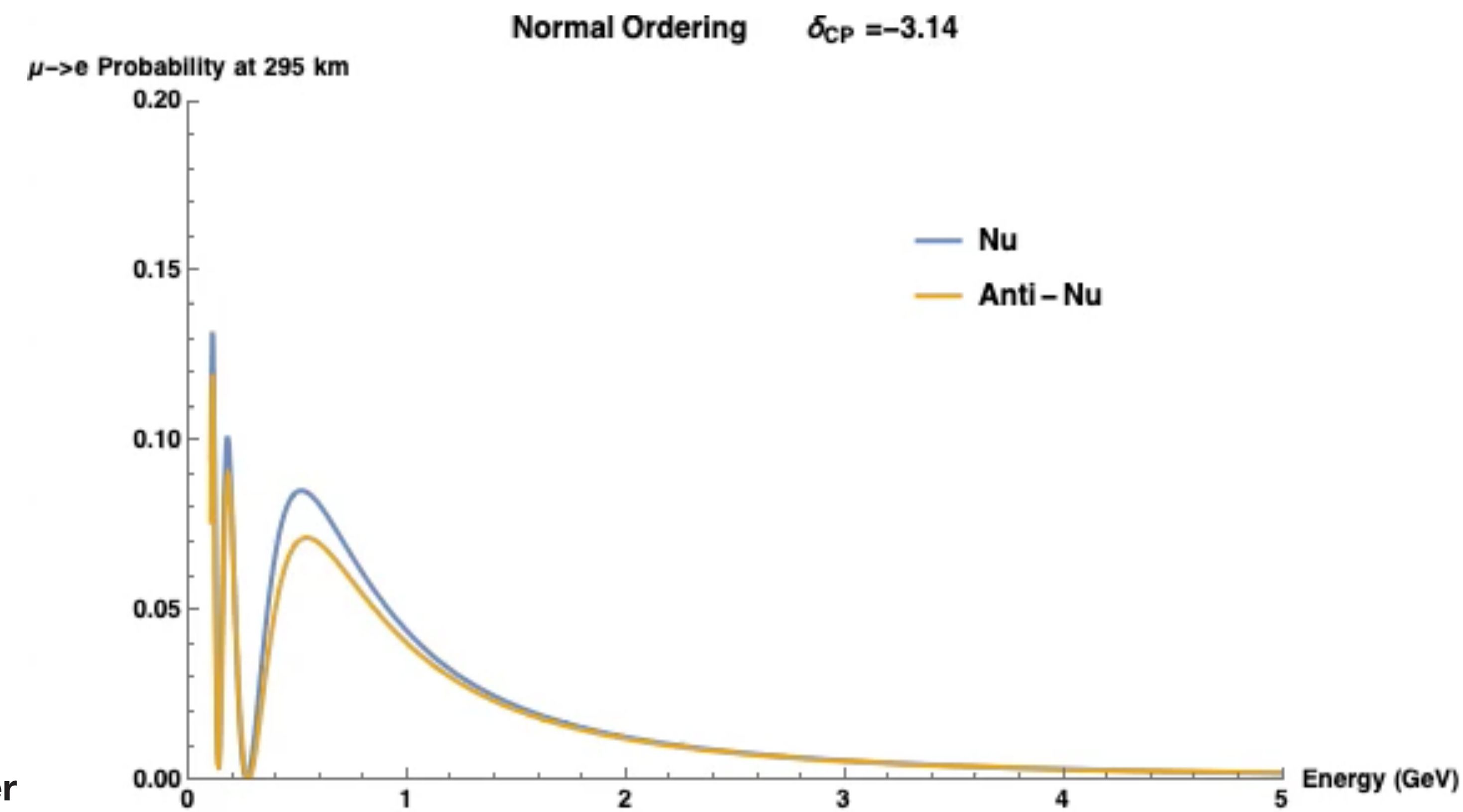

Important Questions to Answer with Long-Baseline Beams

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- What are **more precise** values of the mixings and mass differences?
  - θ_{13} and θ_{12} known fairly well
  - Is θ_{23} exactly 45 degrees?

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- What are **more precise** values of the mixings and mass differences?
  - θ_{13} and θ_{12} known fairly well
  - Is θ_{23} exactly 45 degrees?
- Is the mass **ordering** normal or inverted?
- Is the mixing matrix different for neutrinos and anti-neutrinos?
  - Is **sin(δ)=0**?
  - CP Violation w leptons?

Long-Baseline Neutrino Beams

First Neutrino Beam Experiment

Phys. Rev. Lett **9** 39 (1962)

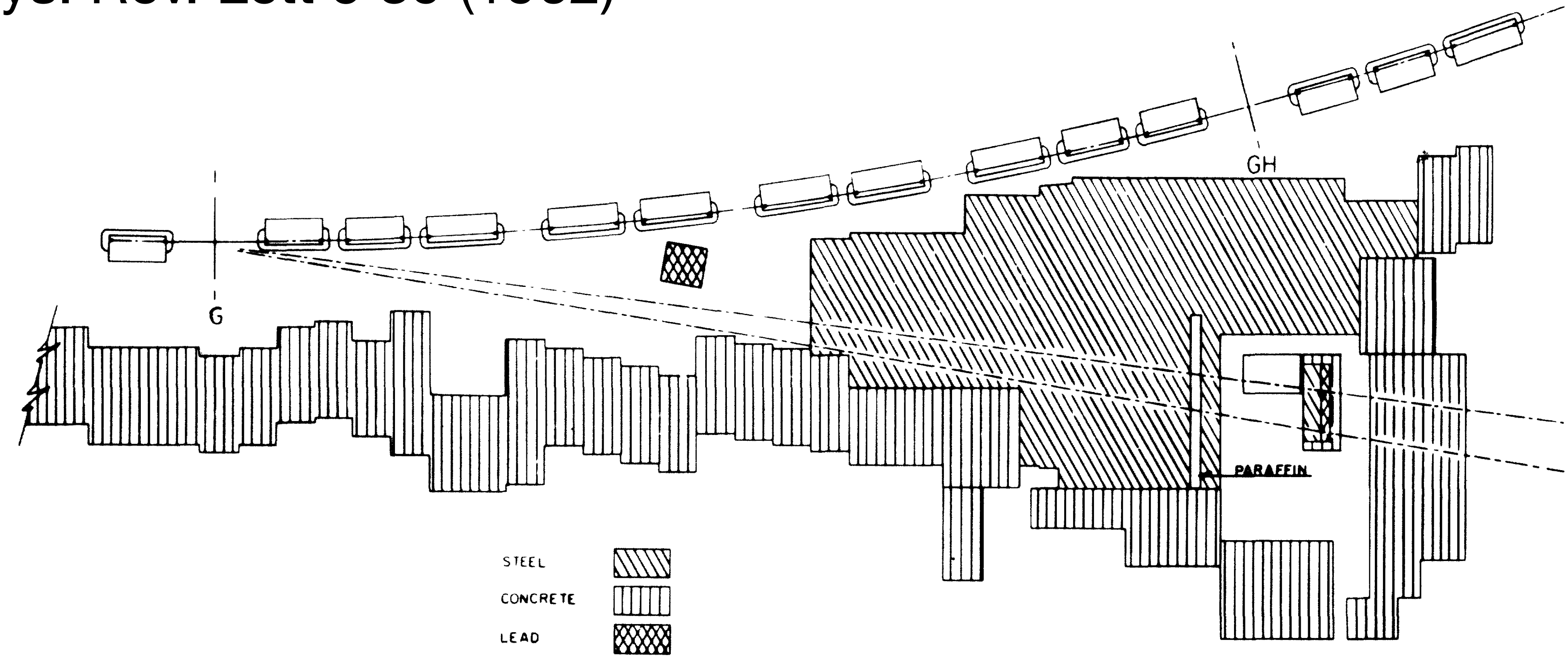
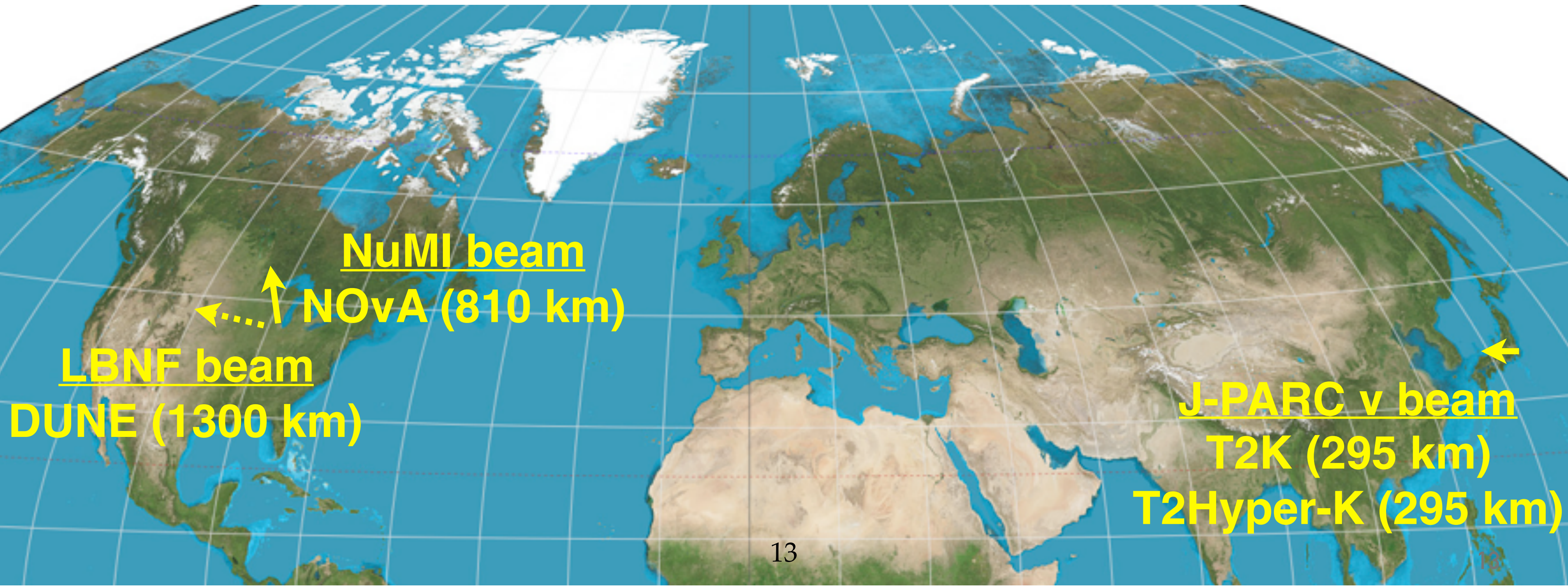


FIG. 1. Plan view of AGS neutrino experiment.

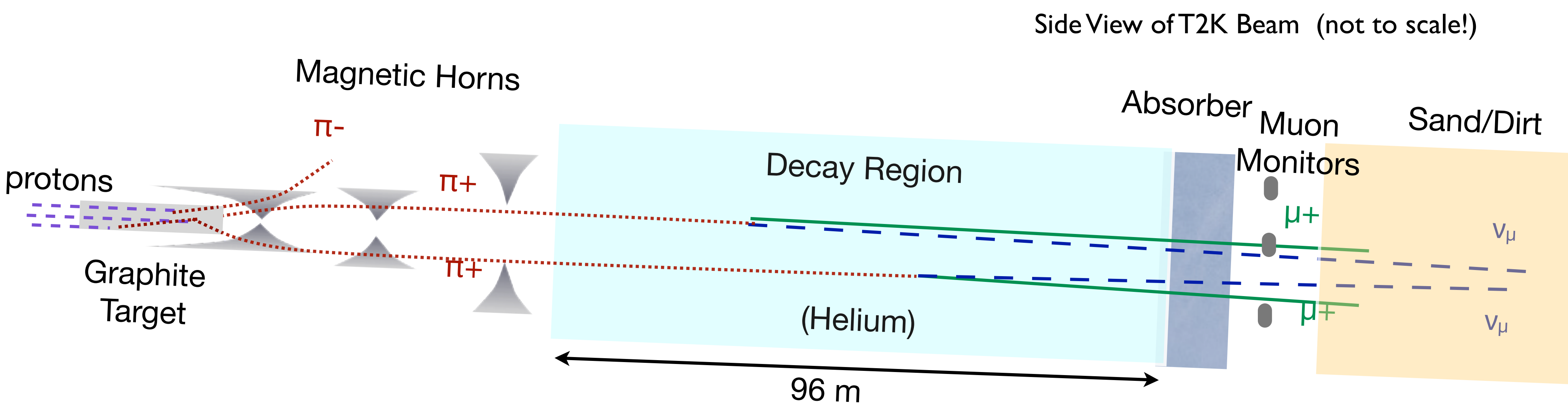
- ν_μ discovered using 15 GeV protons in the BNL AGS
  - Used a Be target and a ~21 m decay region

Current and Planned Long-Baseline Beams

- Two currently running long-baseline neutrino beams are serving experiments with baselines on the order of hundreds of km

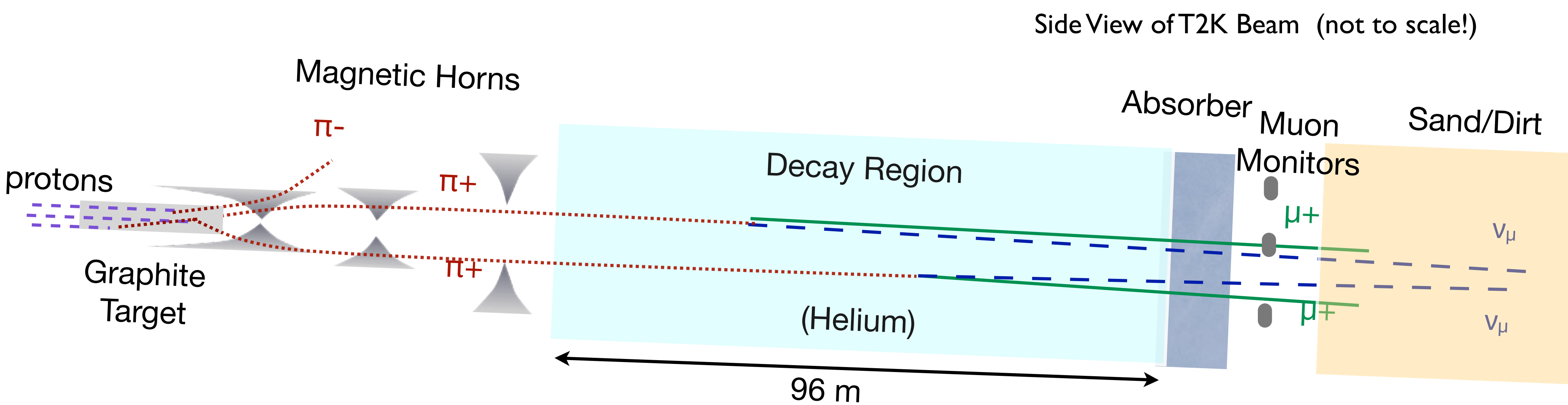


How to Make ν Beam



How to Make ν Beam

- High-energy p's strike target, producing π's and K's



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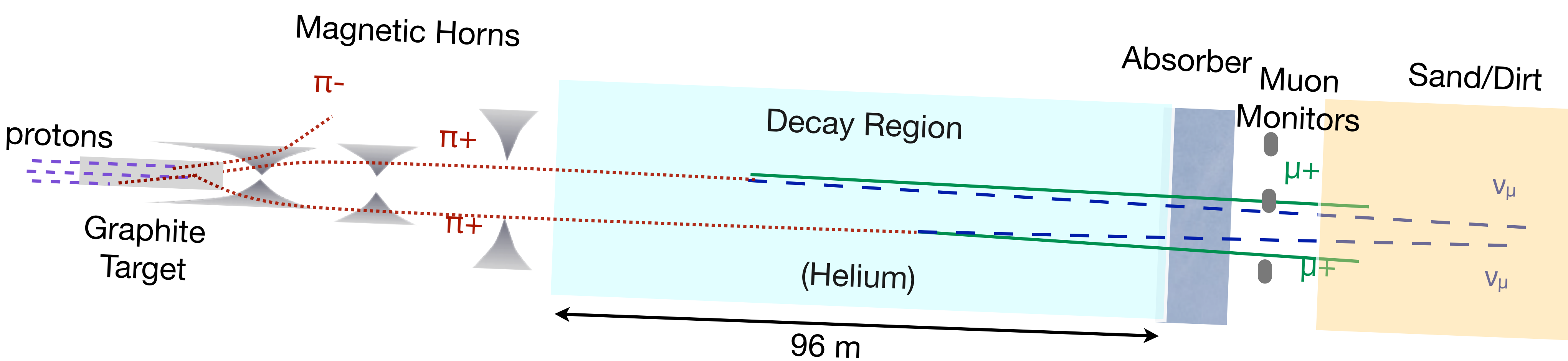
How to Make ν Beam

- High-energy p's strike target, producing π's and K's
- Magnetic horns focus π^+ and K^+ in desired direction

Side View of T2K Beam (not to scale!)



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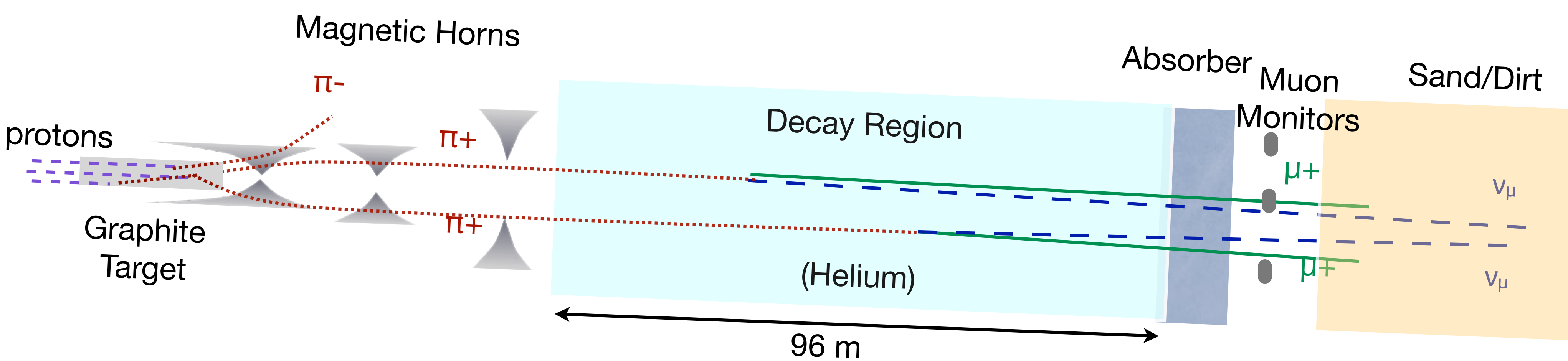

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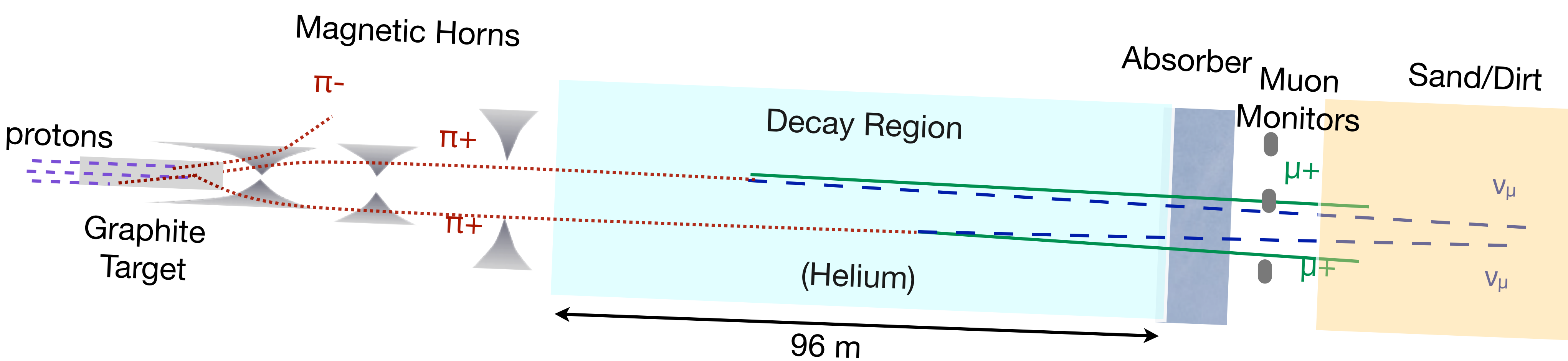

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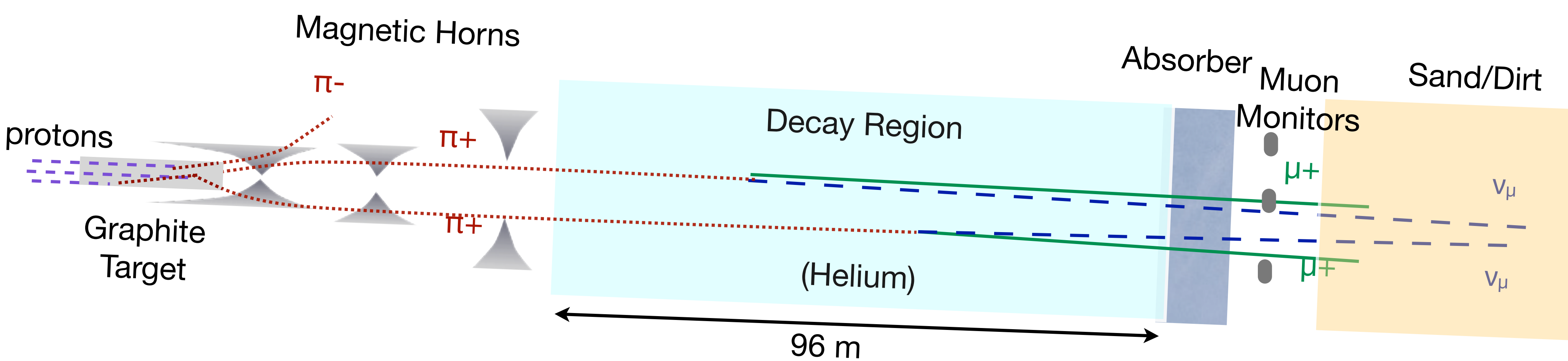
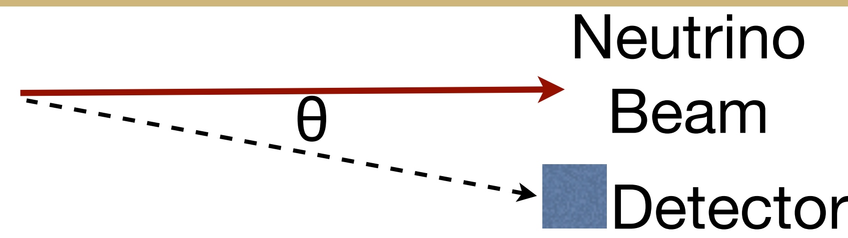
- High-energy p's strike target, producing π's and K's
- Magnetic horns focus π^+ and K^+ in desired direction
- π's and K's to decay to μ's and ν's
- Dirt/rock will stop μ's; ν's continue through the earth
- Can make a $\bar{\nu}_\mu$ beam by reversing direction of horn current

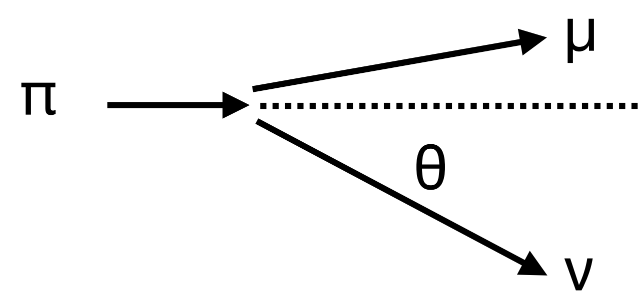


“Off-Axis” Beam

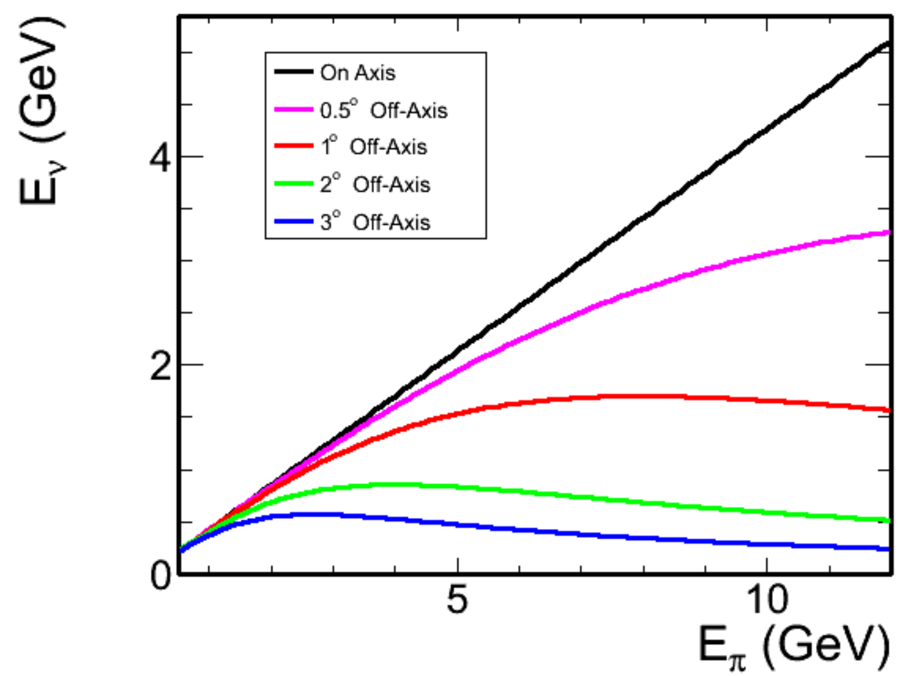


- The T2K and NOvA detectors are slightly off of the ν beam axis

$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2(E_\pi - p_\pi \cos\theta_\nu)}$$



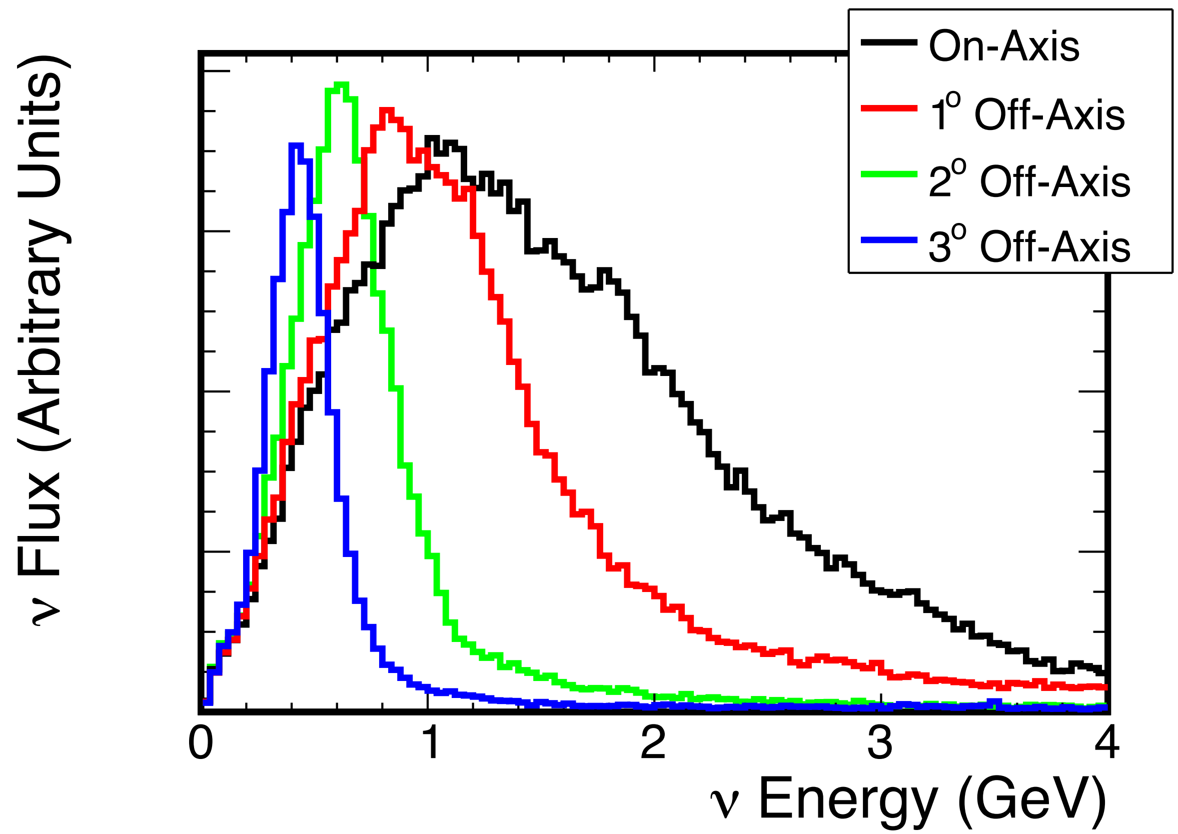
- In kinematics of pion decay, at a small angle away from the pion axis, the neutrino energy becomes nearly independent of the energy of its parent pion.



Off-Axis Spectra

- Smaller ν flux, but more low energy flux, and νs are in a very narrow energy range
- Oscillations depend on L/E so a narrow energy range is preferable
- Reduces background from high-energy NC interactions

J-PARC Flux



Ingredients for a Long-baseline Analysis

Flux prediction
(From simulations with constraints or tuning from other measurements)

Near Detector Data

Cross Sections
Model predictions and constrains from other experiments

Predicted unoscillated spectrum

Far Detector Data and Uncertainties

Oscillation Parameter Fit

Neutrino Interactions

- In charge-current interactions, lepton flavor and charge sign identify the neutrino type

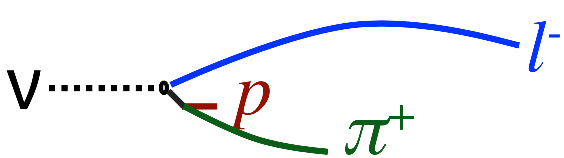
CC Quasi-elastic

$$\nu_l + n \rightarrow l^- + p \qquad \bar{\nu}_l + p \rightarrow l^+ + n$$

- Other charged-current interactions can occur too including

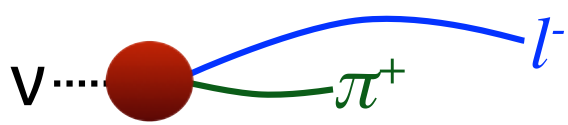
CC 1π Resonance

$$\nu_\mu + p \rightarrow N^* + \mu^-$$
$$N^* \rightarrow p + \pi^+$$



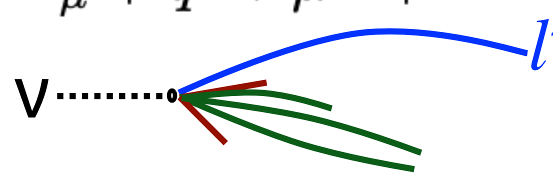
Coherent Pion Production

$$\nu_\mu + A \rightarrow \mu^- + A + \pi^+$$



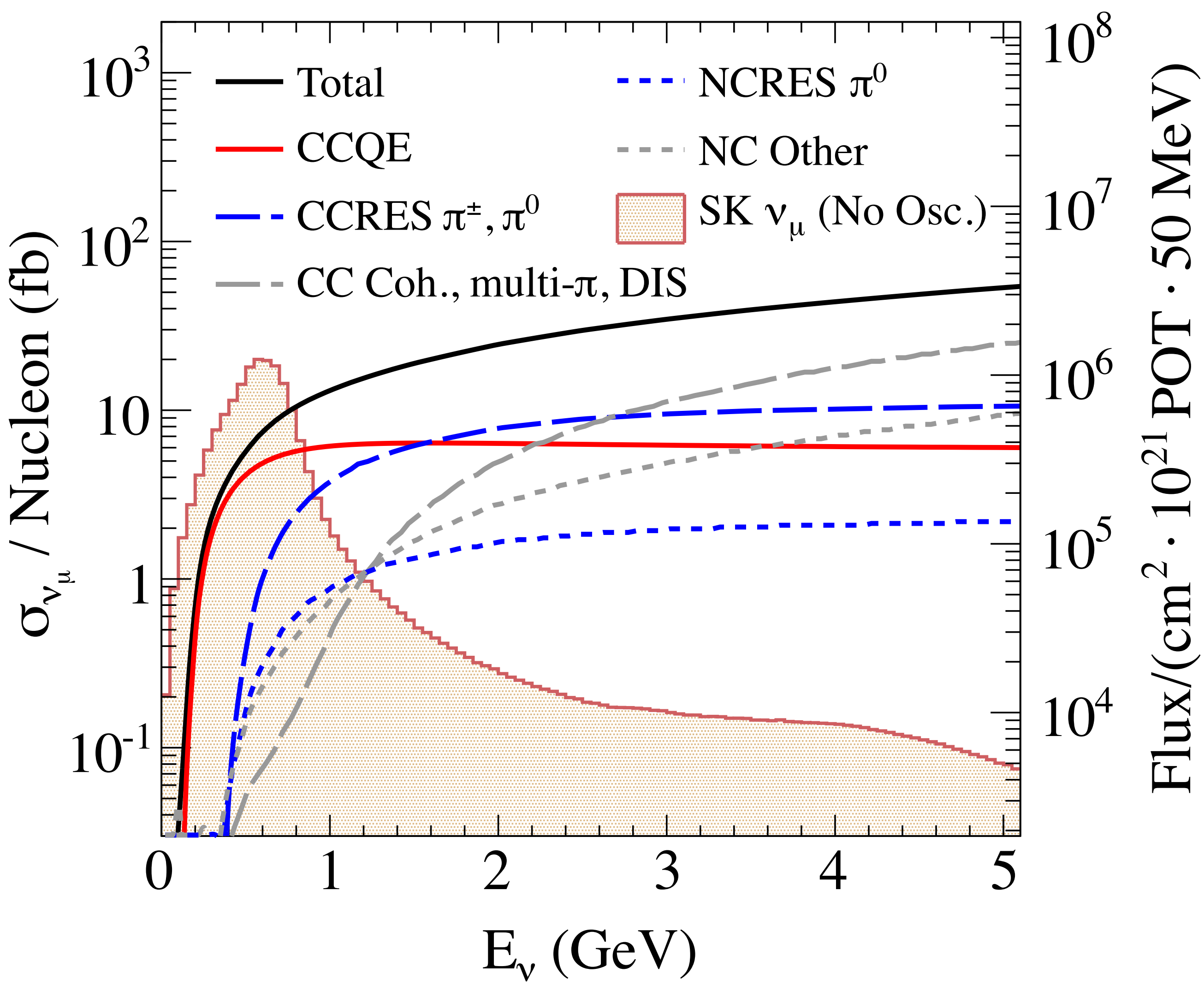
Deep Inelastic Scattering

$$\nu_\mu + q \rightarrow \mu^- + X$$



- And neutral current interactions too

Neutrino Cross sections



- NEUT generator predictions per nucleon on ^{16}O

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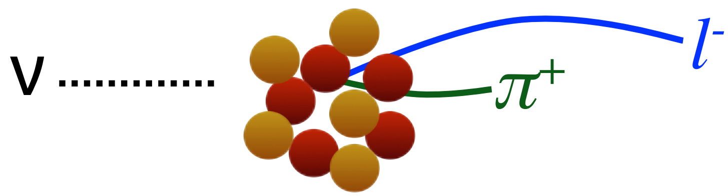
Neutrino Interaction Models

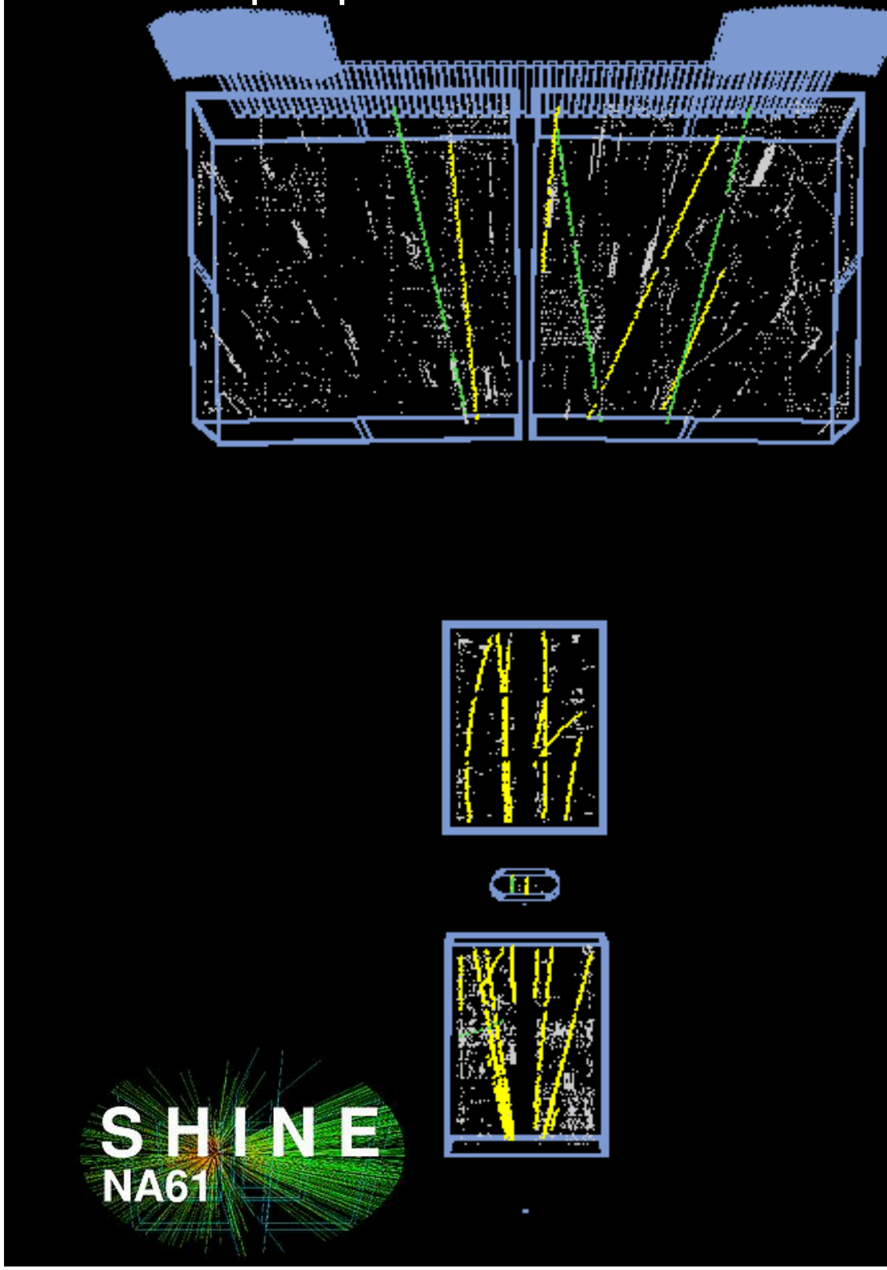


- Not just interactions with a single free nucleon.
  - Often a relativistic Fermi gas model is used to describe nucleons, and maybe additional models like the random-phase approximation or spectral function models.
- Also need to consider interactions on **correlated nucleon pairs**
- Also need to consider **final state interactions** of particles. Hadrons can scatter, charge-exchange, or be absorbed while exiting the nucleus
- Data from **precision near detectors** and **dedicated cross section experiments** like MINERvA are necessary to constrain and improve models

Hadron Production Measurements

- Simulations of the hadrons that are generated in neutrino beamlines have large uncertainties
- Fixed target experiments like **NA61/SHINE** and **EMPHATIC** can **directly measure the production of hadrons** off of beamline materials to better predict the neutrino flux
  - NA61 data of T2K target will reduce flux uncertainties to <5%

Example p+C event at 120 GeV

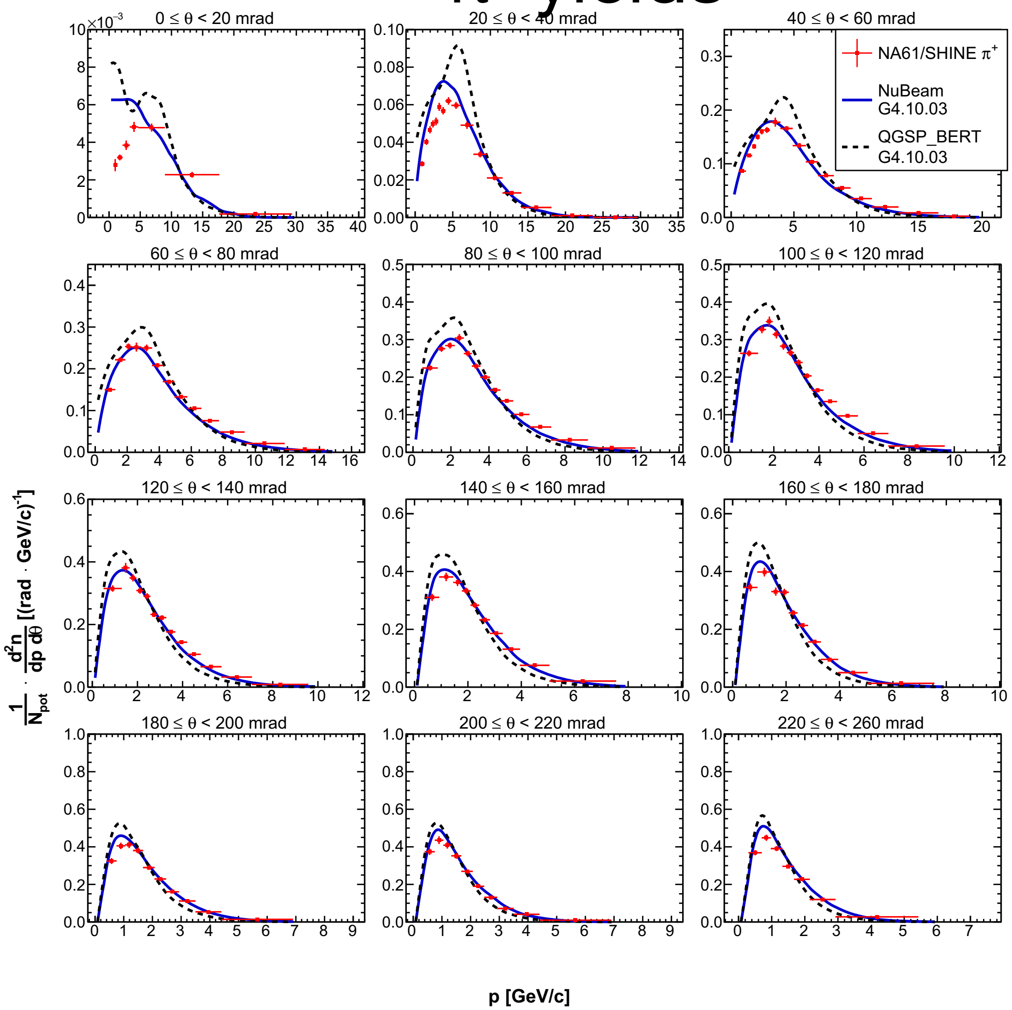


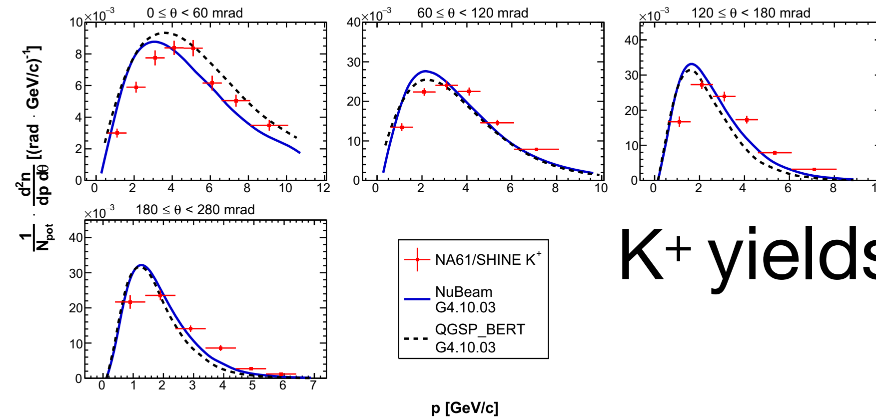
Hadron Production Data

Eur. Phys. J. C (2019) **79**: 100

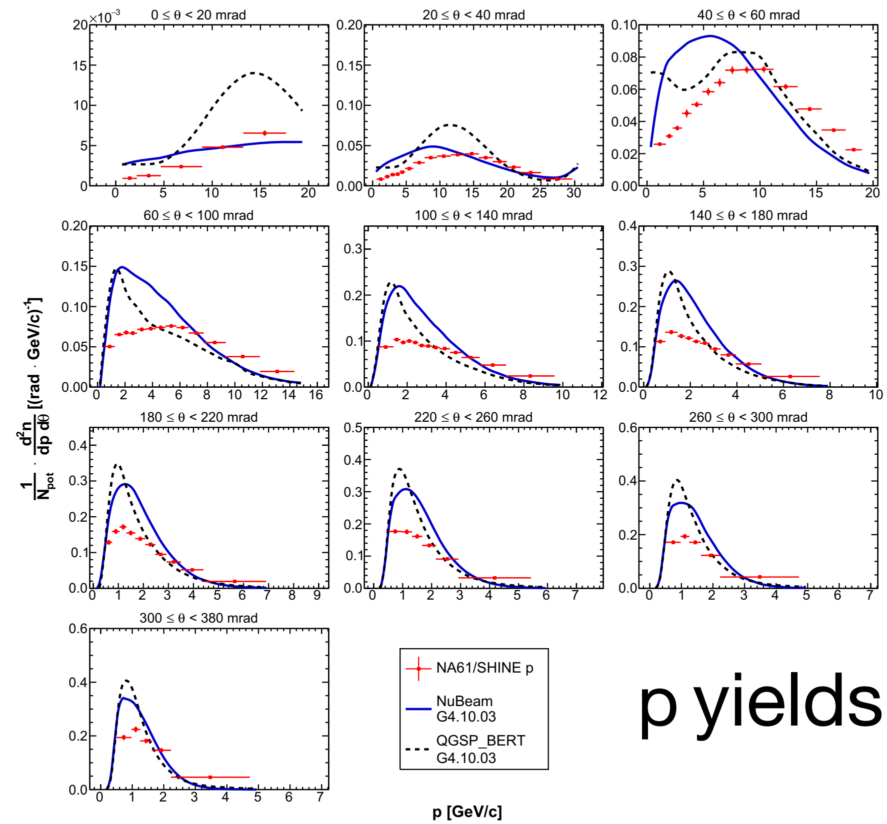
For a slice in the middle of the T2K target

π+ yields





K+ yields



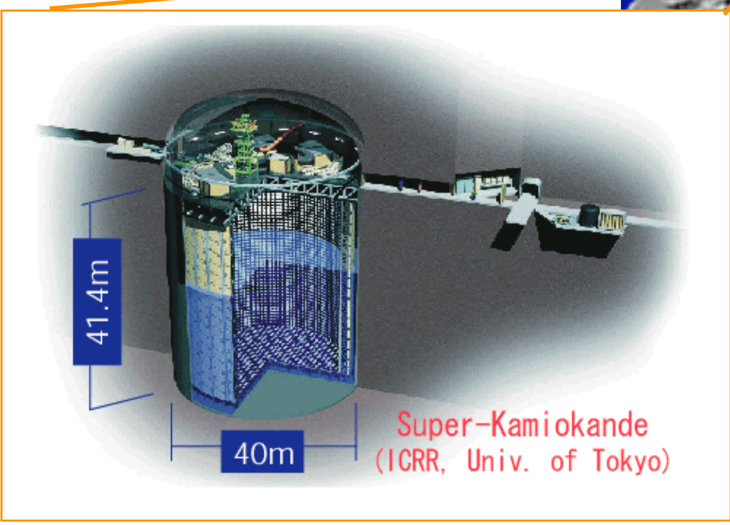
p yields

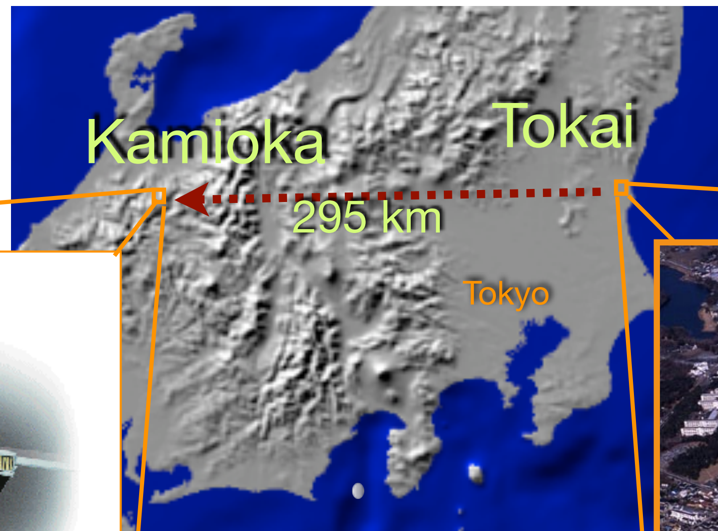
Recent Results

T2K: Tokai-to-Kamioka

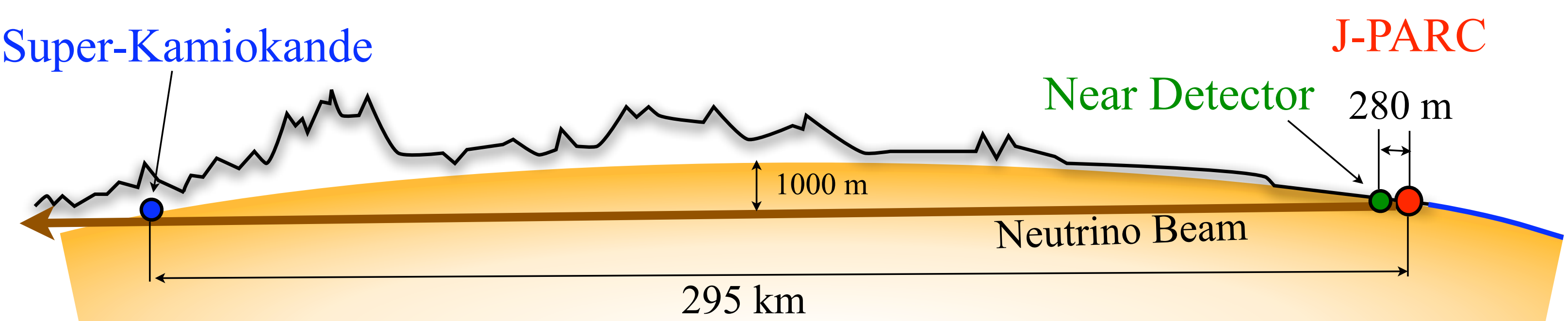
Super-Kamiokande Detector

J-PARC Facility (Tokai) Accelerator+Near Detector

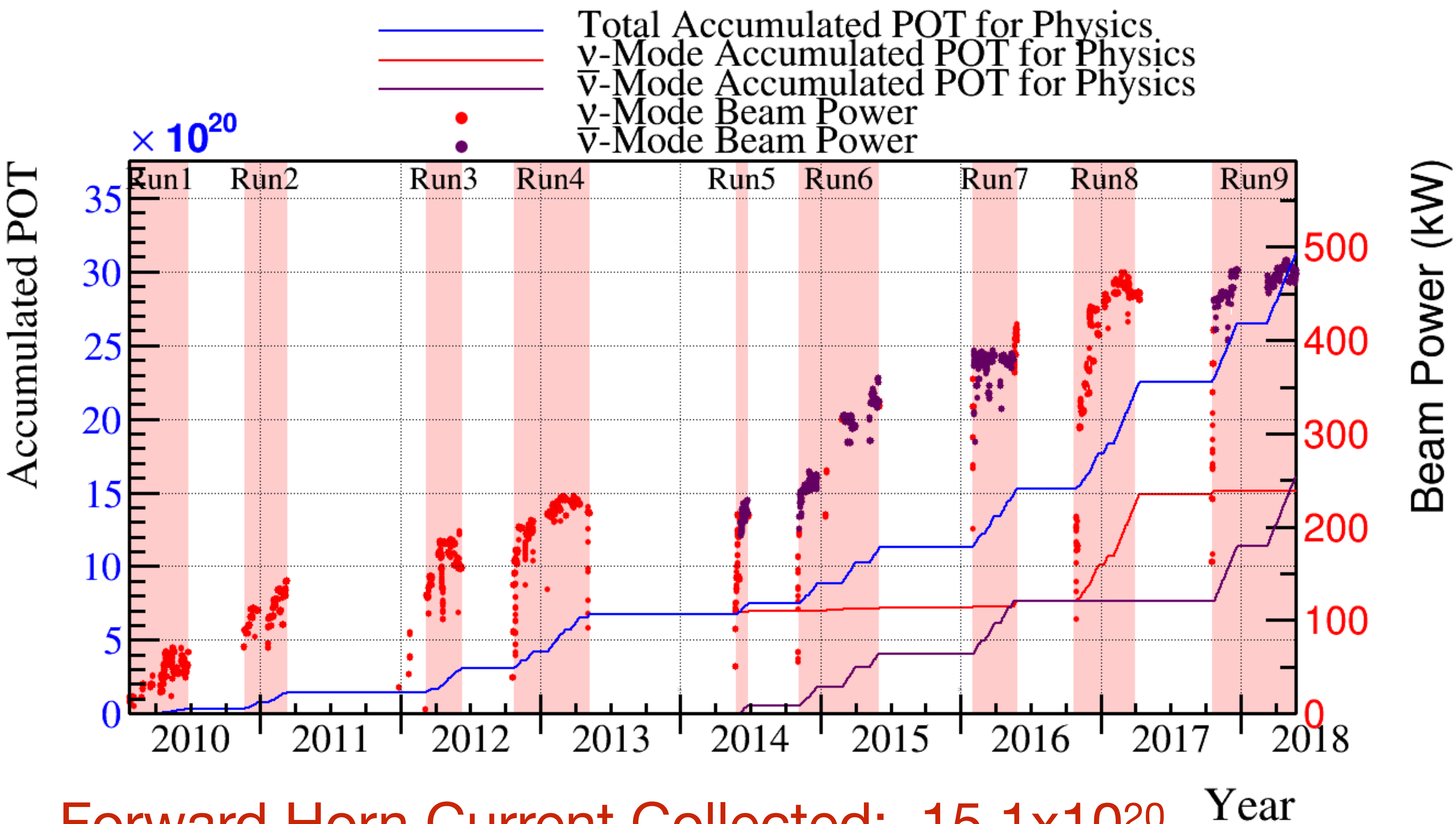




- Long-baseline neutrino experiment in Japan with 295 km baseline



T2K Beam Running



Forward Horn Current Collected: 15.1×10^{20}

Reverse Horn Current Collected: 16.5×10^{20}

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- Only ~50% of total dataset T2K expects to collect

Selected Events

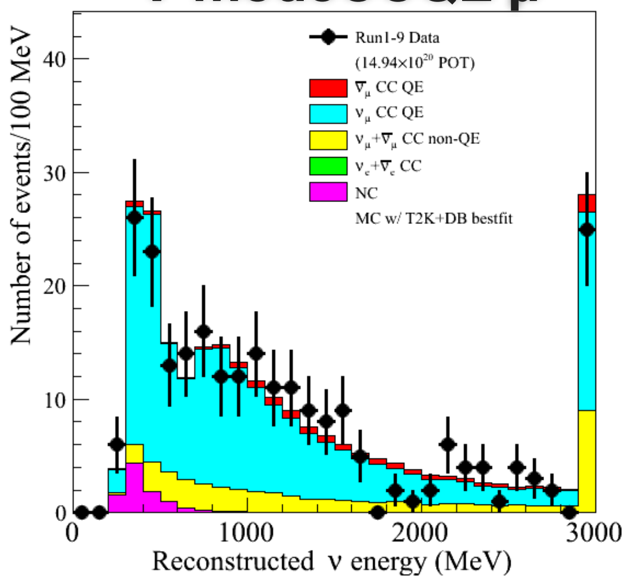
Predicted Event Numbers

Sample	$\delta_{CP}=\pi/2$	$\delta_{CP}=-\pi/2$	$\delta_{CP}=0$	Observed
ν_μ CCQE	272	272	271	243
ν_e CCQE	51	75	62	75
ν_e CC1π e	5	7	6	15
$\bar{\nu}_\mu$ CCQE	140	140	139	140
$\bar{\nu}_e$ CCQE	22	17	20	15

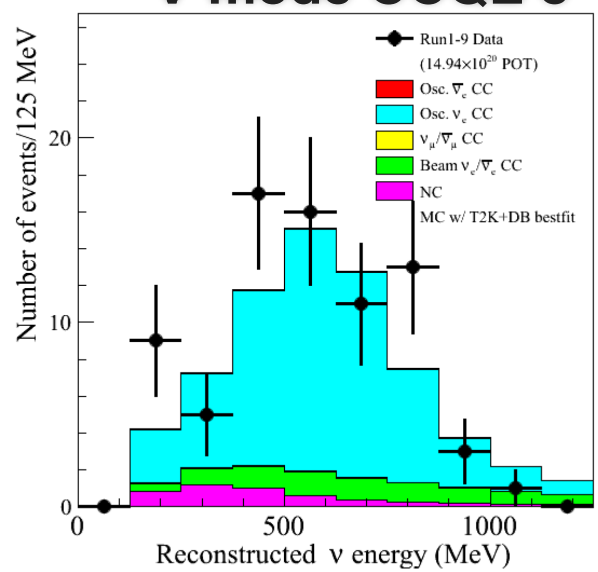
- Notice that in neutrino mode, see an excess of ν_e events, while in anti-neutrino mode see fewer anti-ν_e events than expected for $\delta_{CP}=0$

5 Data Samples with Best Fit

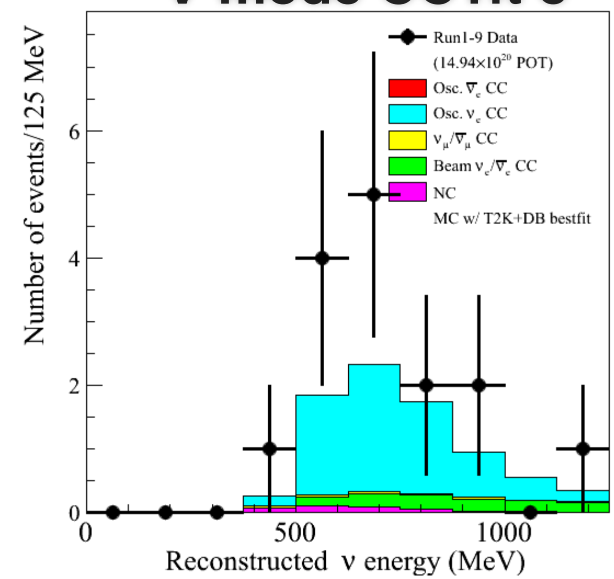
ν-modeCCQE μ



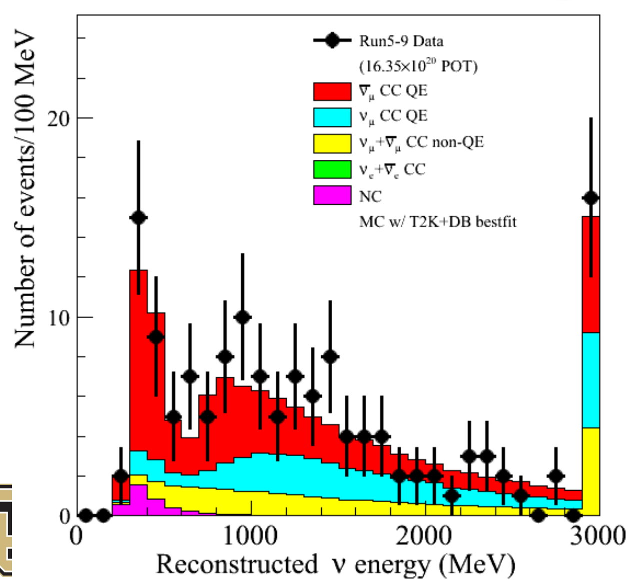
ν-mode CCQE e



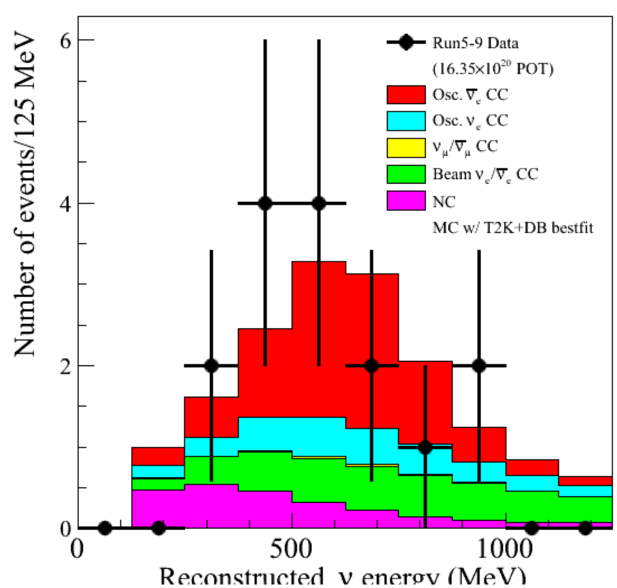
ν-mode CC1π e



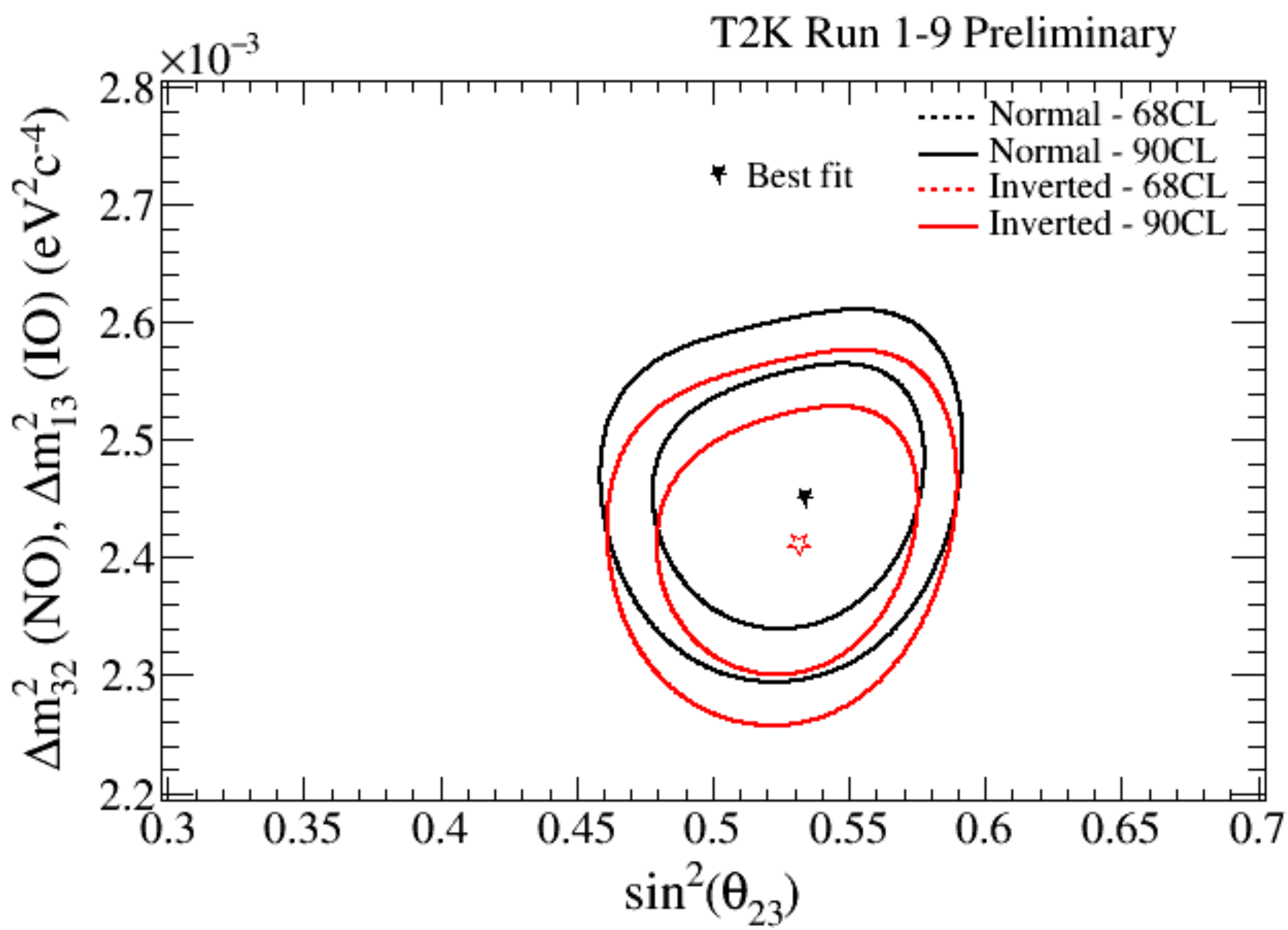
antiν-mode CCQE μ



antiν-mode CCQE e

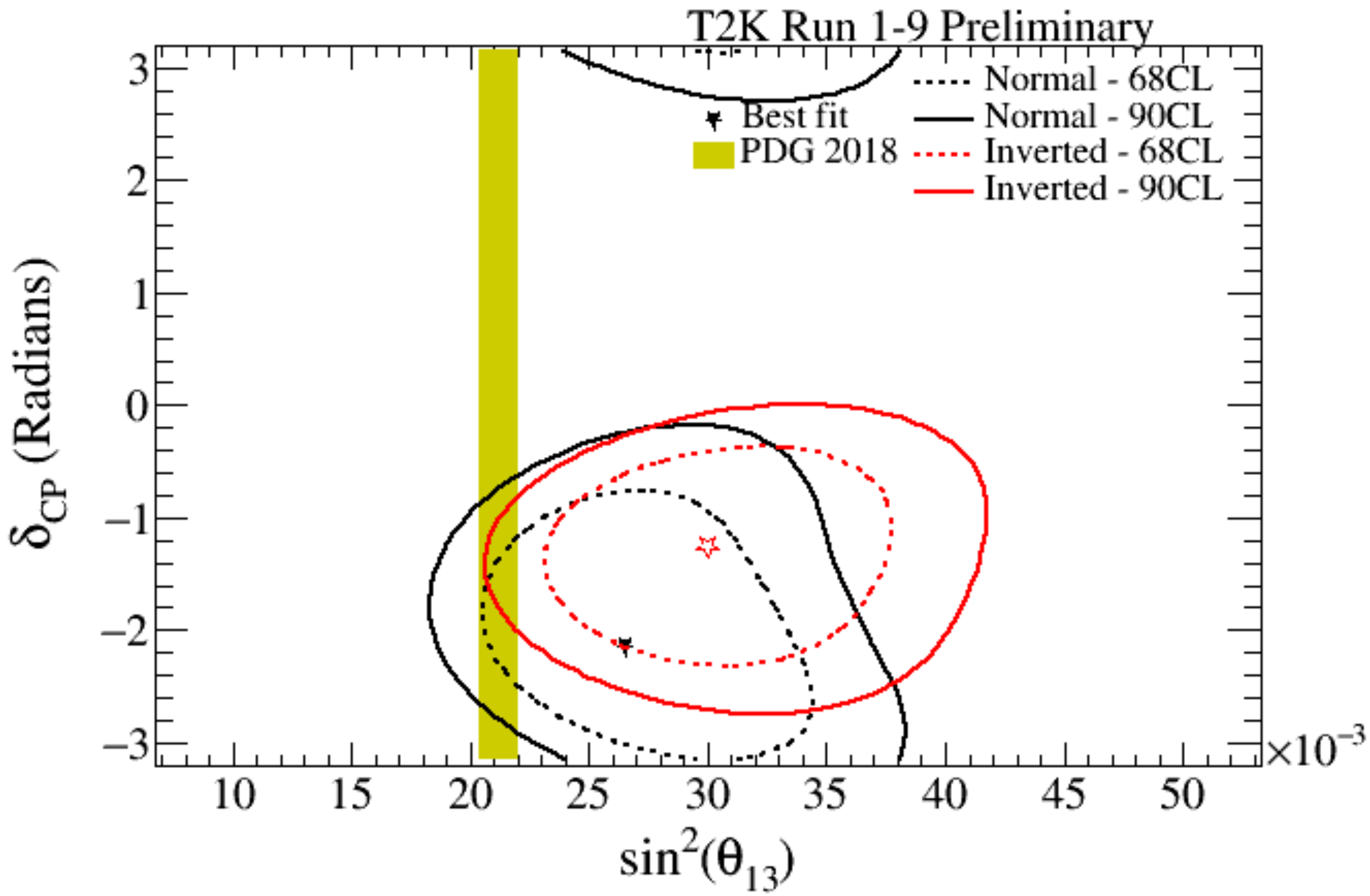


Measurement of Δm_{23}^2 and $\sin^2\theta_{23}$



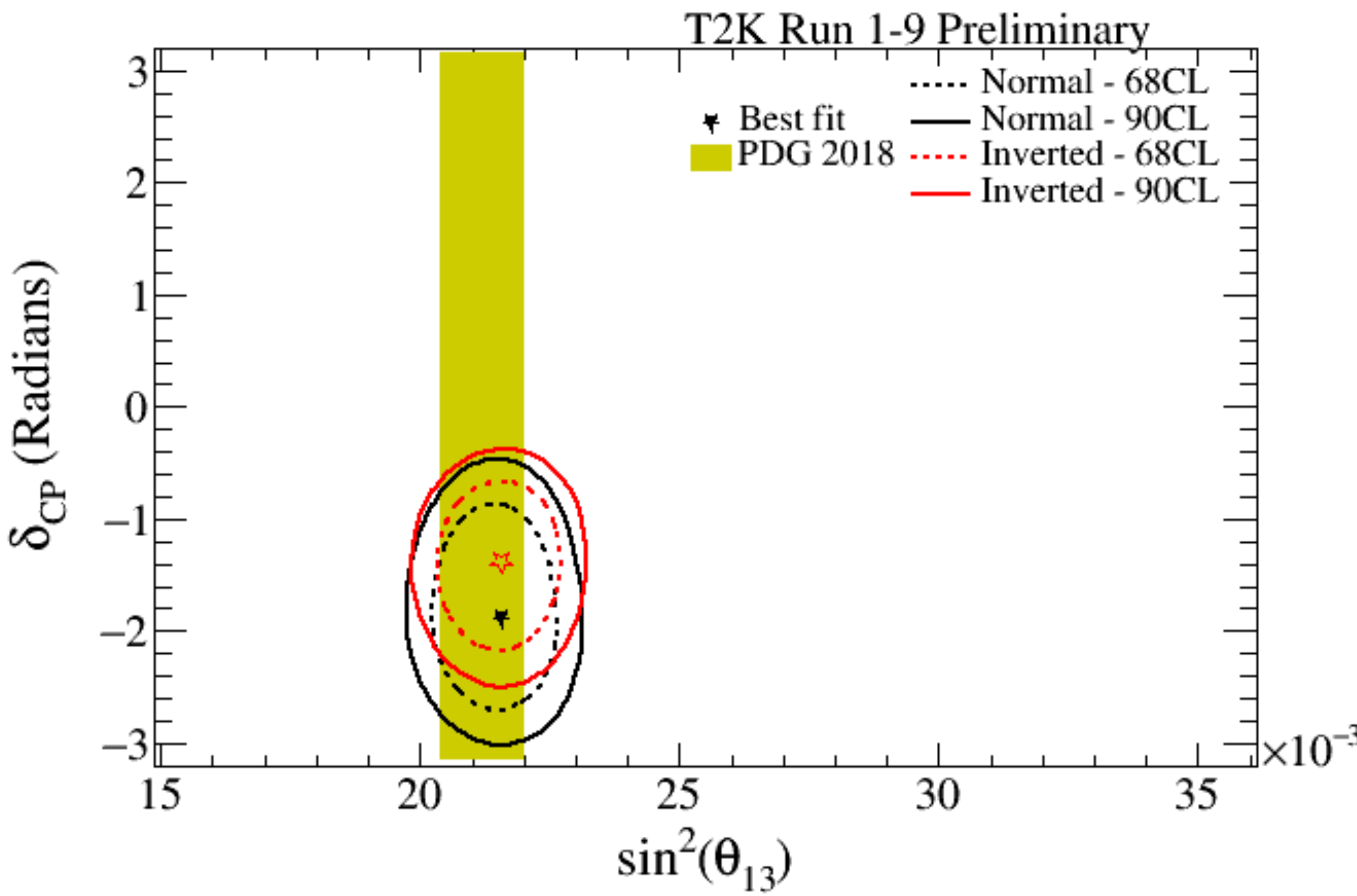
- T2K Favors a large mixing angle, close to 45°

Fits for δ_{CP}



T2K only

Fits for δ_{CP}

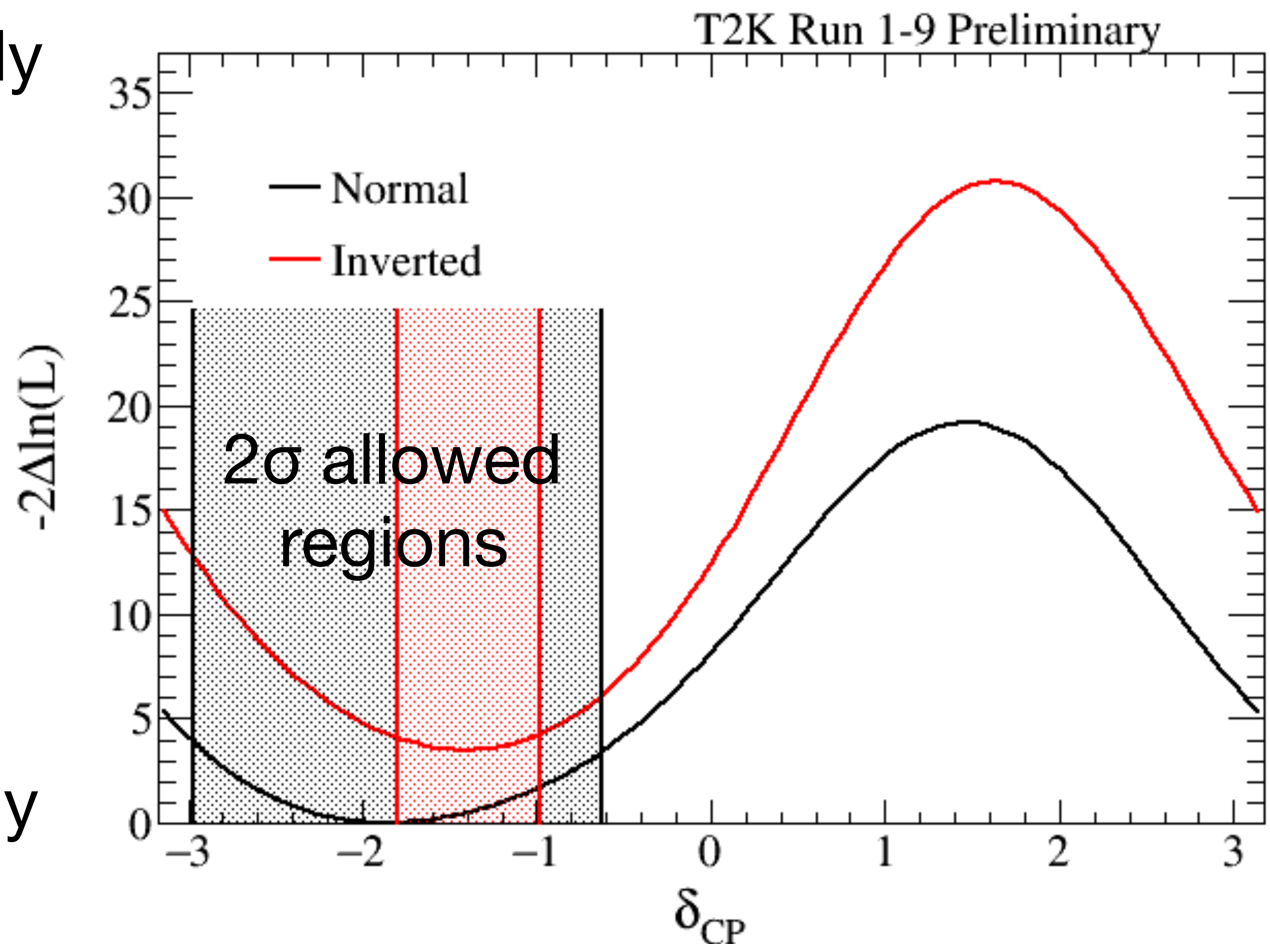


T2K + Reactor Data

- Excludes δ_{CP}=0 or π at more than 95% CL

δ_{CP}

Less Likely

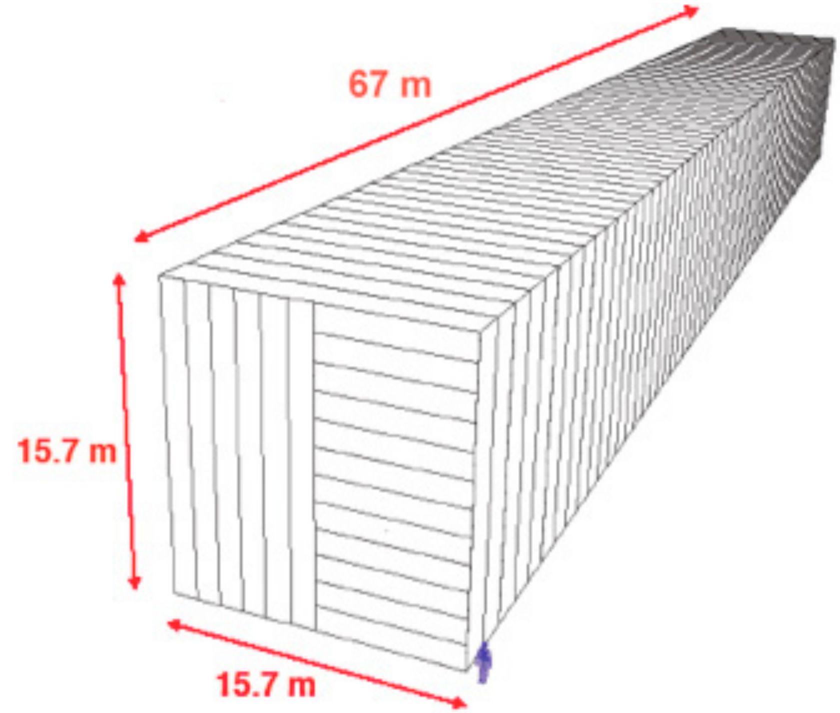


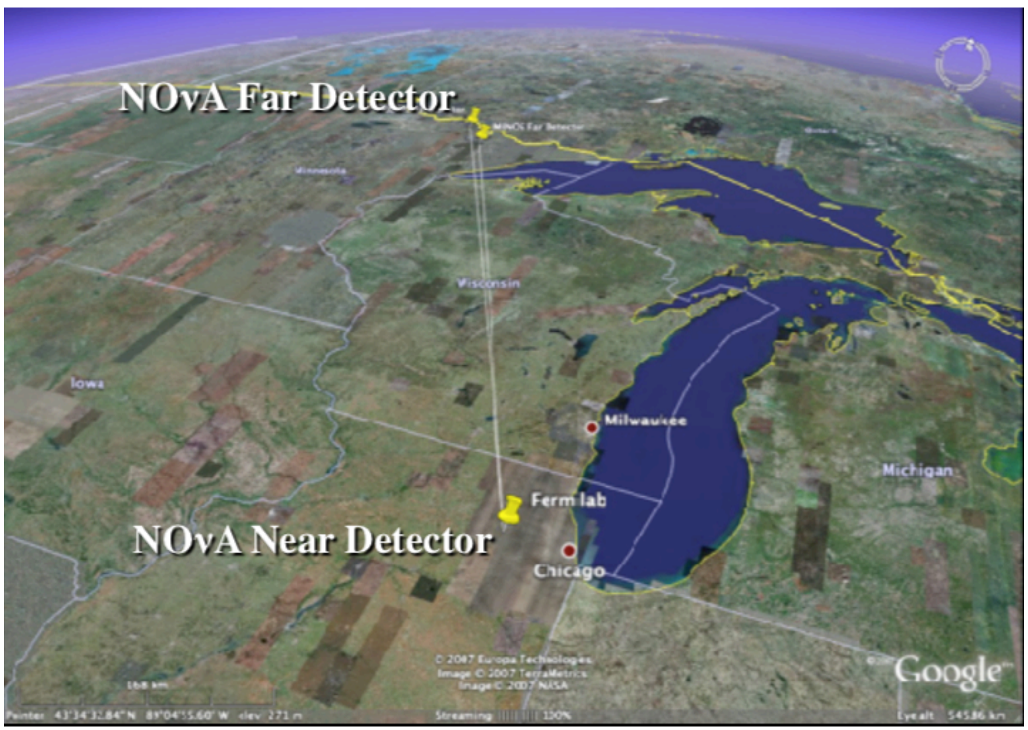
More Likely

- Data prefers a value of δ_{CP} around -π/2
- **CP conserving values** of δ_{CP}=0 and δ_{CP}=π **excluded** for both hierarchies at more than **95% CL**

NOvA Neutrino Experiment

- Using NuMI beam from Fermilab
- Longer L (810 km) and larger E than T2K, larger matter effects





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NOvA Data

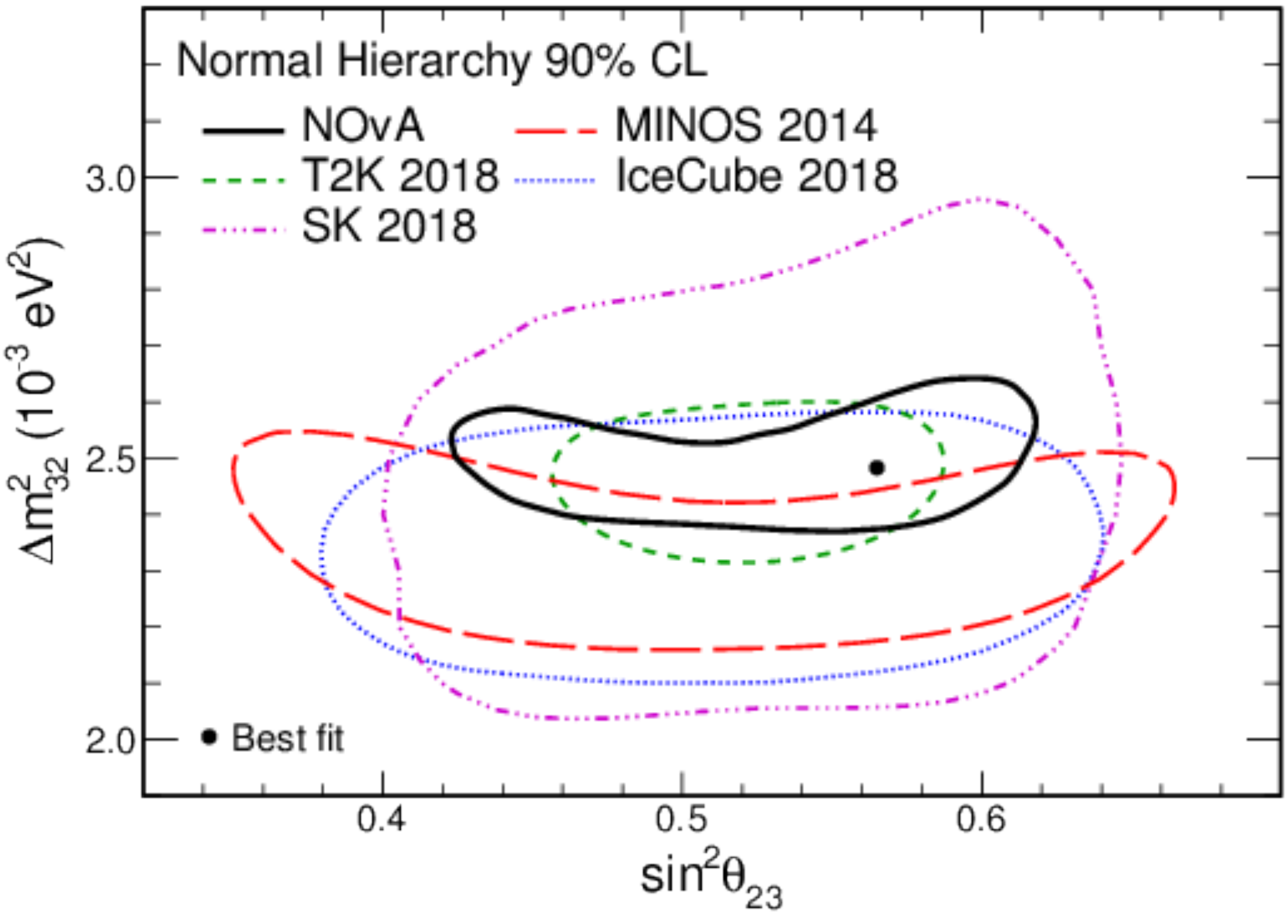
- 8.85×10^{20} protons on target in neutrino mode; 12.33×10^{20} protons on target in anti-neutrino mode,

Predicted Event Numbers (NH, upper octants)

Sample	$\delta_{CP}=\pi/2$	$\delta_{CP}=3\pi/2$	$\delta_{CP}=0$	Observed
ν_μ	121	121	121	113
ν_e	52	70	62	58
$\overline{\nu}_\mu$	96	96	96	102
$\overline{\nu}_e$	28	22	26	27

T2K vs NOvA on θ_{23}

arXiv:1906.04907

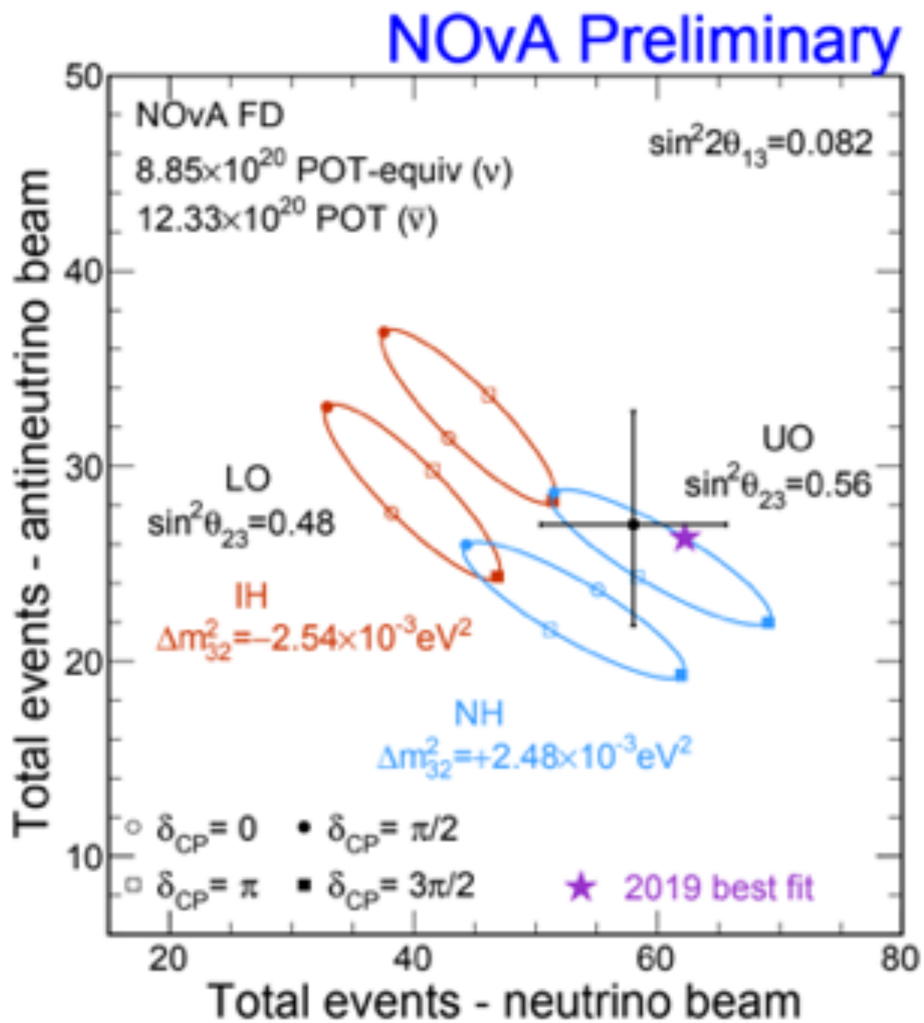


- NOvA prefers an angle above 45° at the >1σ level

NOvA ν_e and $\bar{\nu}_e$ Appearance Results

J. Wolcott, JETP seminar,
FNAL June 2019

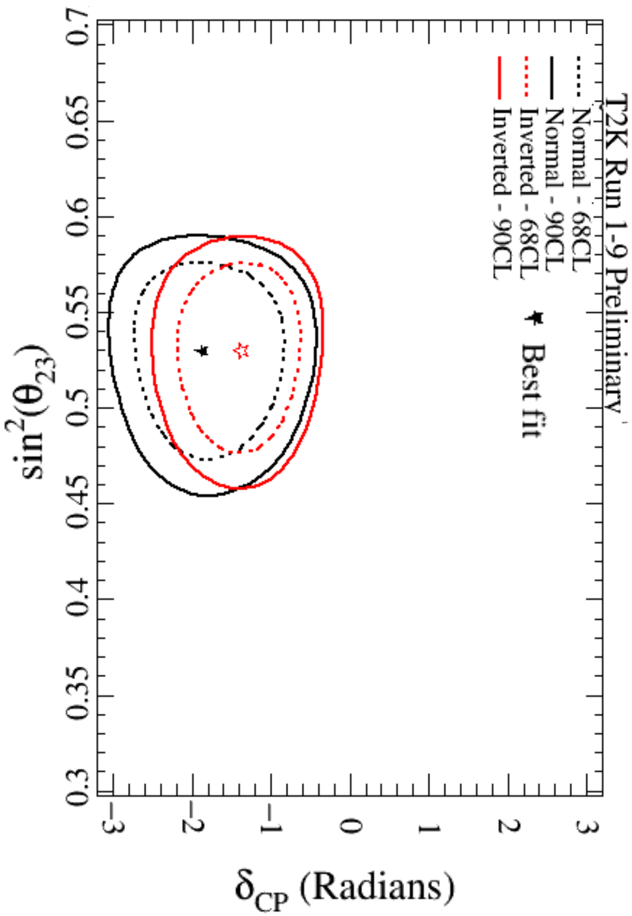
Observed: 27 $\bar{\nu}_e$

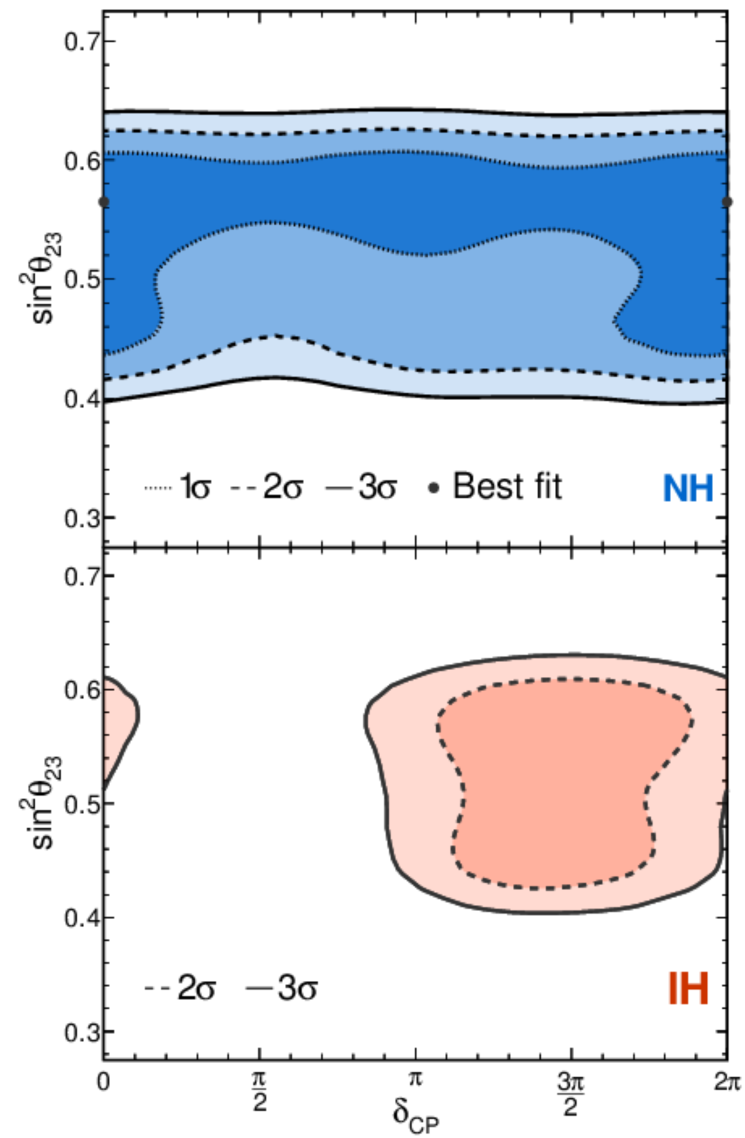


Observed: 58 ν_e

T2K vs NOvA on δ_{CP}

arXiv:1906.04907





- Note: T2K plots δ over -π to π
- NOvA plots δ over 0 to 2π

Future running

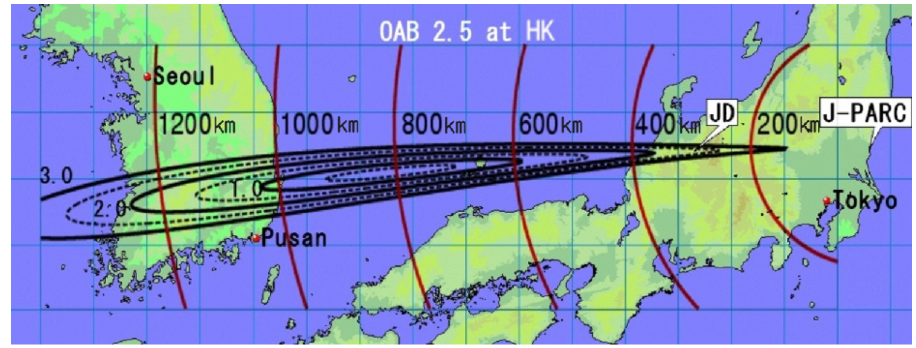
- Both T2K and NOvA expect to continue running
  - T2K approved for 2x more PoT (7.8×10^{21}) thru 2021
  - T2K-II proposes to extend this to 20×10^{21} PoT thru 2026
  - NOvA aiming for 7.2×10^{21} by 2025
- T2K should reach **3σ exclusion of CP conservation** if δ_{CP} is close to the current T2K best fit value
- NOvA could reach **3-5σ** sensitivity to the hierarchy depending on δ_{CP}, and future modeling improvements could increase this

Future Long-Baseline Neutrino Experiments

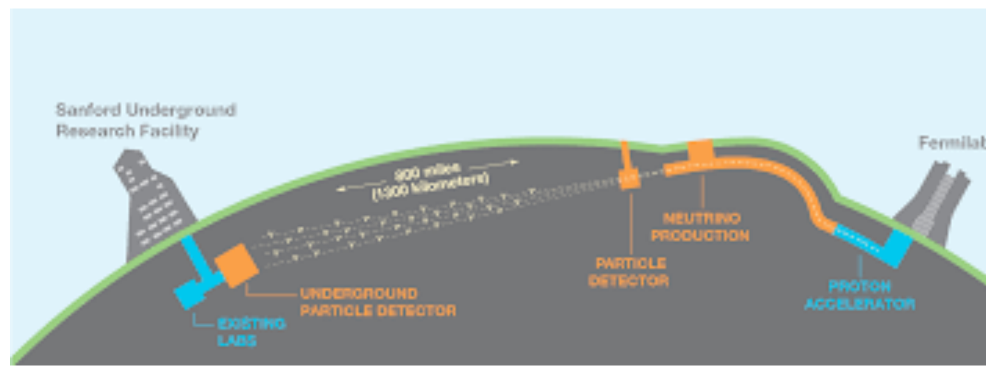
Future Long-Baseline Neutrino Experiments

- Hyper-Kamiokande:
  - J-PARC to Kamioka beamline
  - 295 km baseline
  - Possibility for other off-axis detectors at longer-baselines

PTEP 2018 (2018) no.6, 063C01

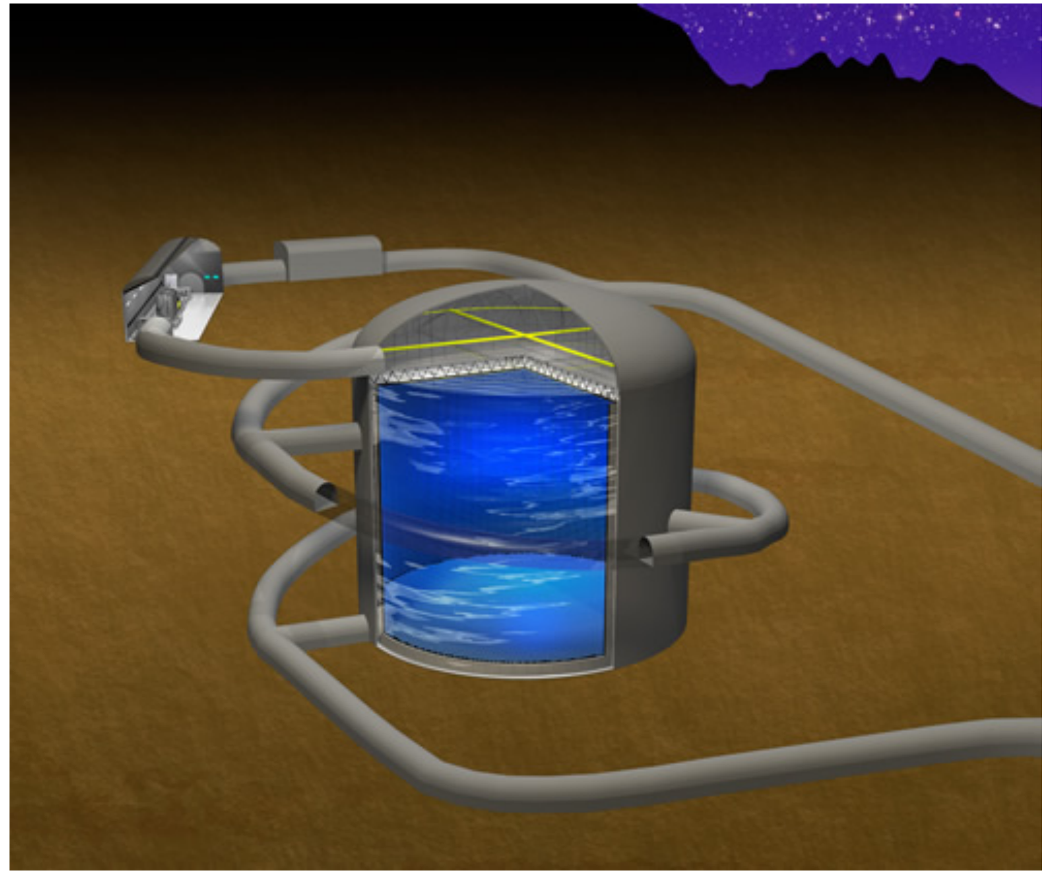


- Deep Underground Neutrino Experiment (DUNE)
  - New LBNF beamline from Fermilab to SURF in Lead,SD
  - 1300 km baseline



J-PARC to Hyper-Kamiokande

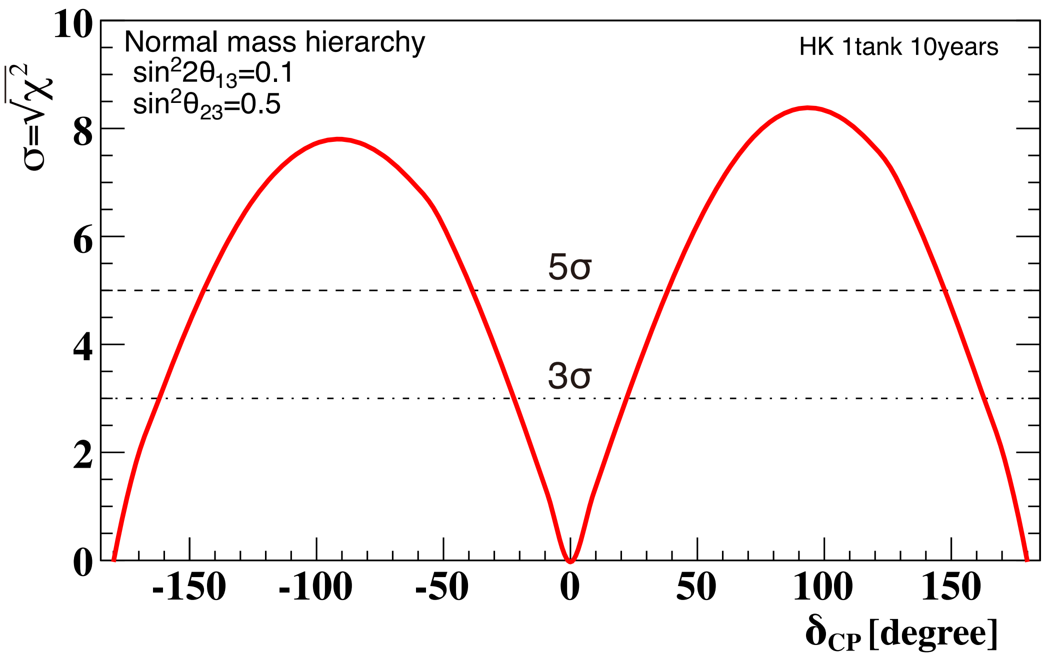
arXiv:1805.04163

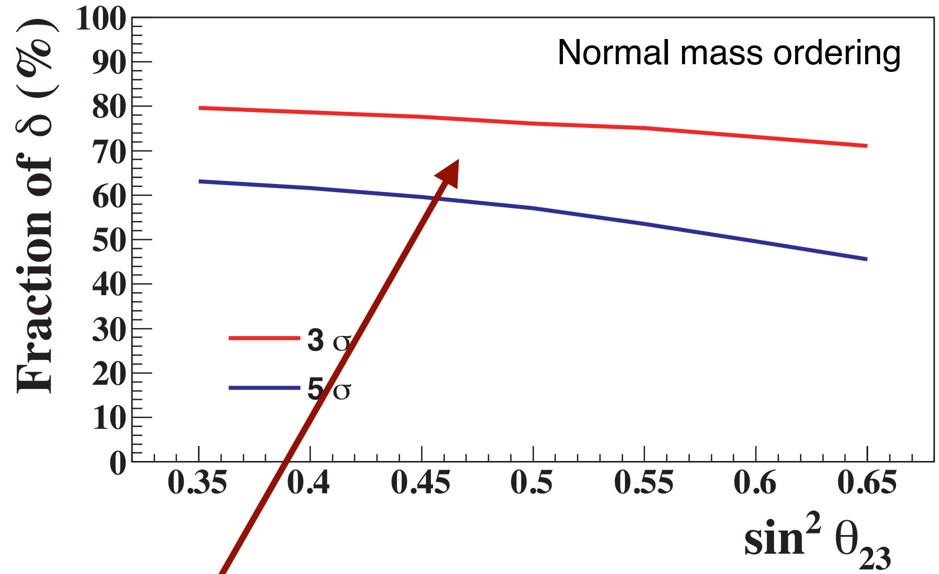


- Hyper-Kamiokande: New far detector
  - 260 kt water Cherenkov
  - 40% photocathode coverage
  - Fiducial volume is ~10x SK
- New intermediate detector: NuPRISM
  - Movable water Cherenkov detector

Hyper-Kamiokande Sensitivity

arXiv:1805.04163

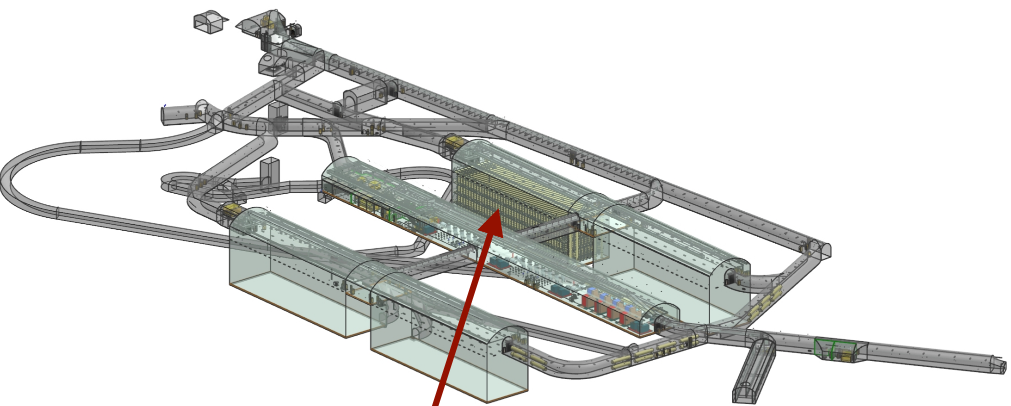




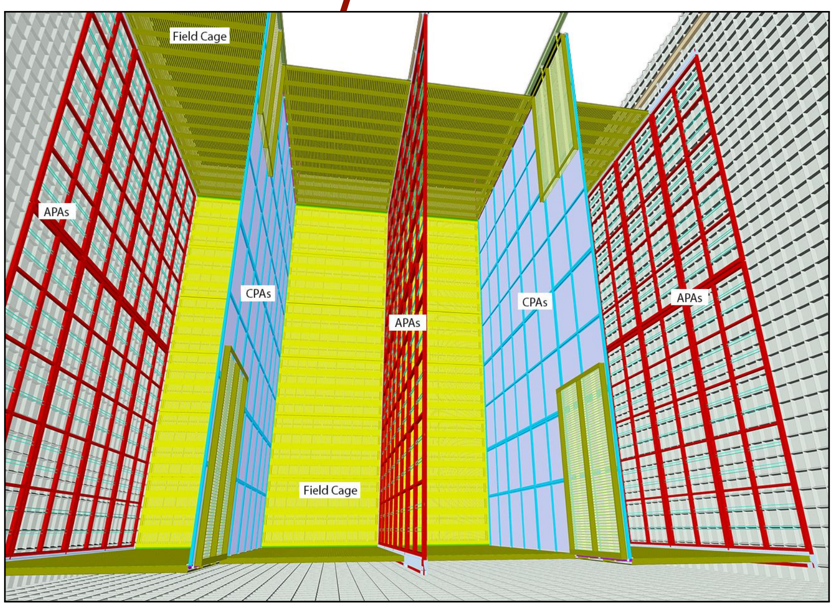
- Can exclude $\delta_{CP}=0$ at 3σ for ~80% of the range of possible δ_{CP} values

DEEP UNDERGROUND NEUTRINO EXPERIMENT

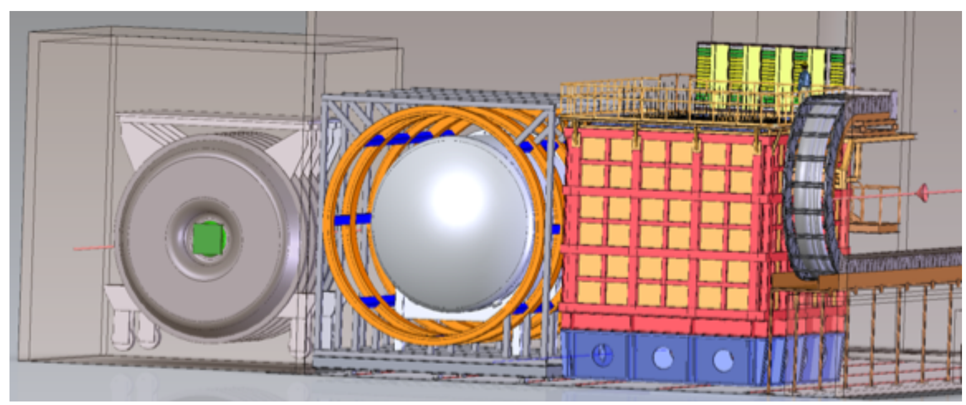
arXiv:1807.10334



arXiv:1807.10327

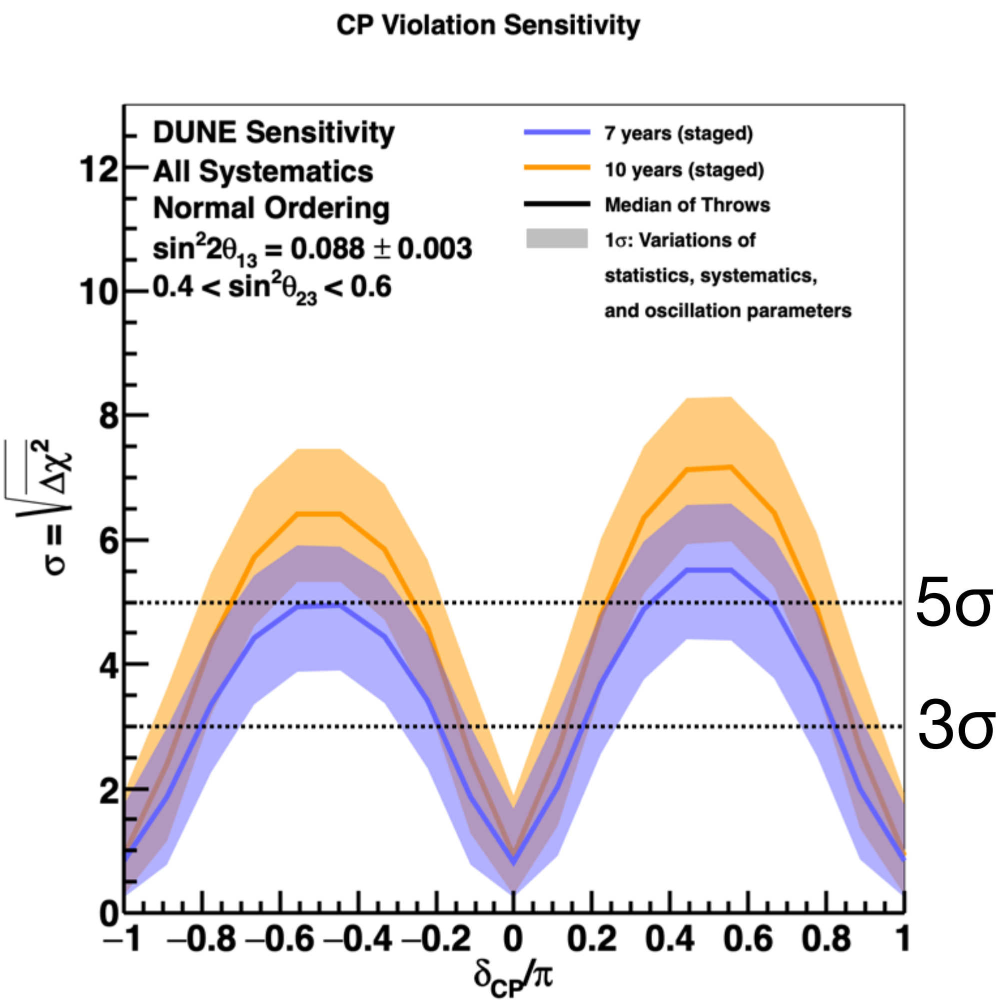


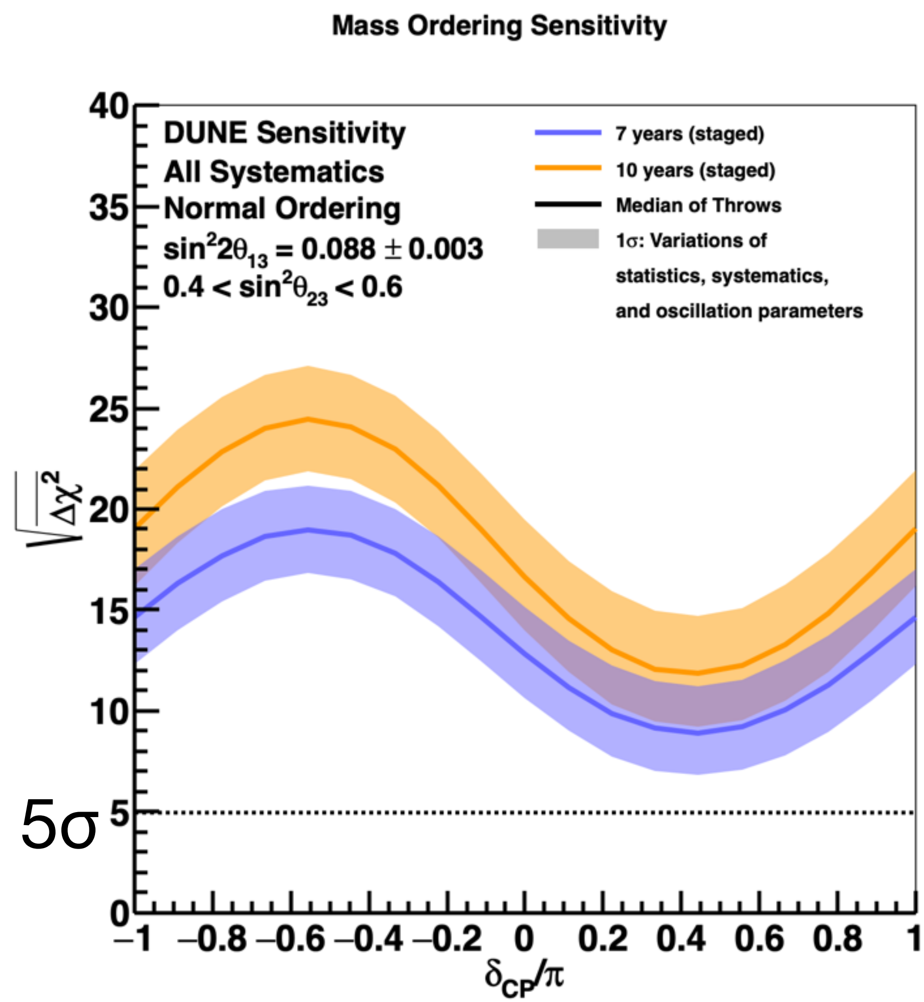
- Far Detector is four 10k ton detector modules detectors
  - Mixture of single-phase and dual-phase liquid argon TPCs
- Near detector concept has several subsystems including a movable liquid argon TPC+gaseous argon TPC, and an on-axis beam monitor



University of Colorado **Boulder**

DUNE Sensitivity





- Can resolve the mass ordering at >5σ for all values of δ_{CP}

Conclusions

- Long-baseline neutrino experiments addressing one of the biggest unanswered questions in neutrino physics:
  - Do **neutrinos** and **anti-neutrinos** have same mixing properties?
- **More data** to come from current experiments
- **Larger detectors** and **more intense beams** coming in the 2020's
- By the mid-2030's we will definitively know the **ordering of neutrino masses** and should have **strong indications** of CP violation in the neutrino sector if it is more than 20^{o} from 0 or π

- Stay tuned!

Thank you

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