Physics | Lancaster University

# Atmospheric neutrino oscillation physics with Liquid Argon detectors

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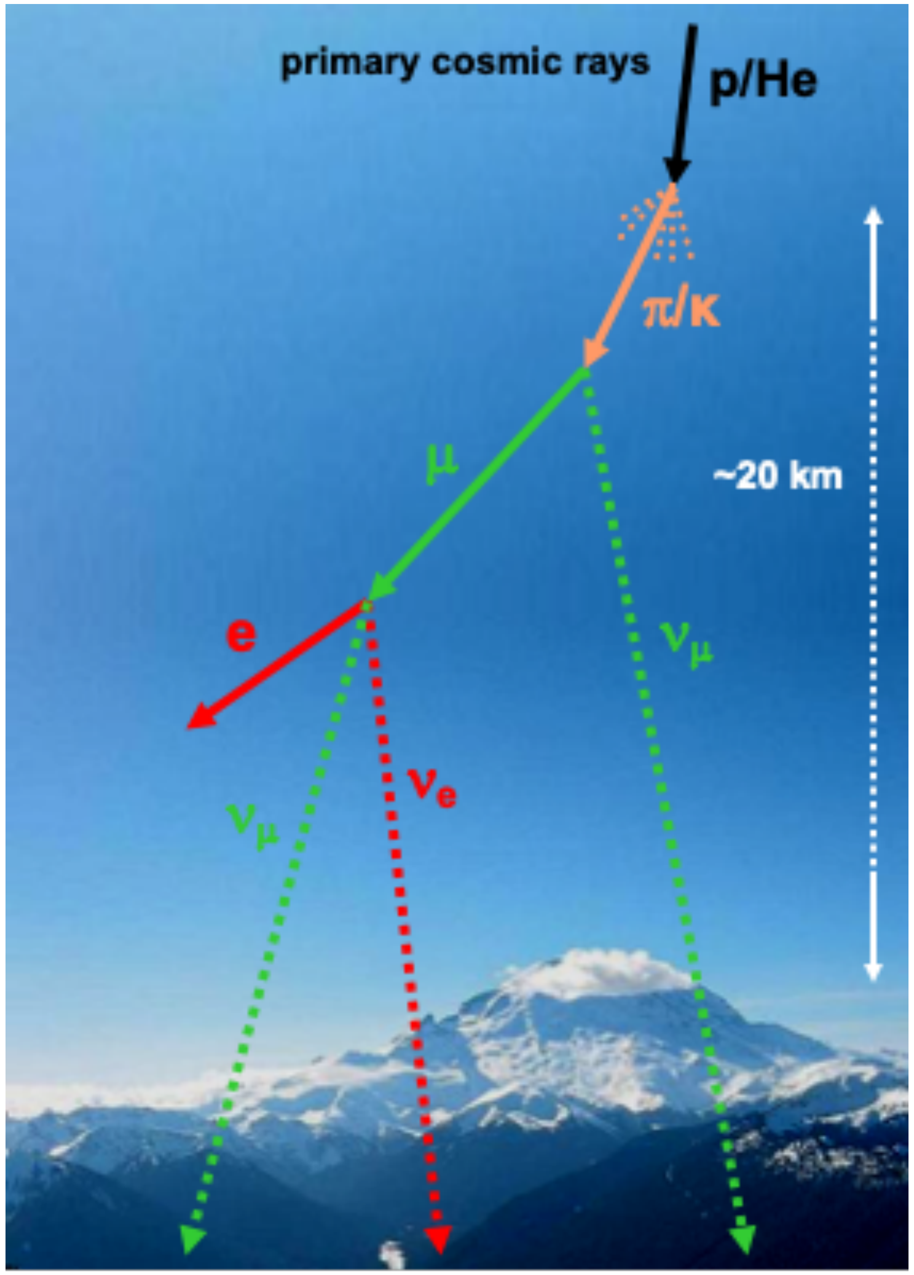
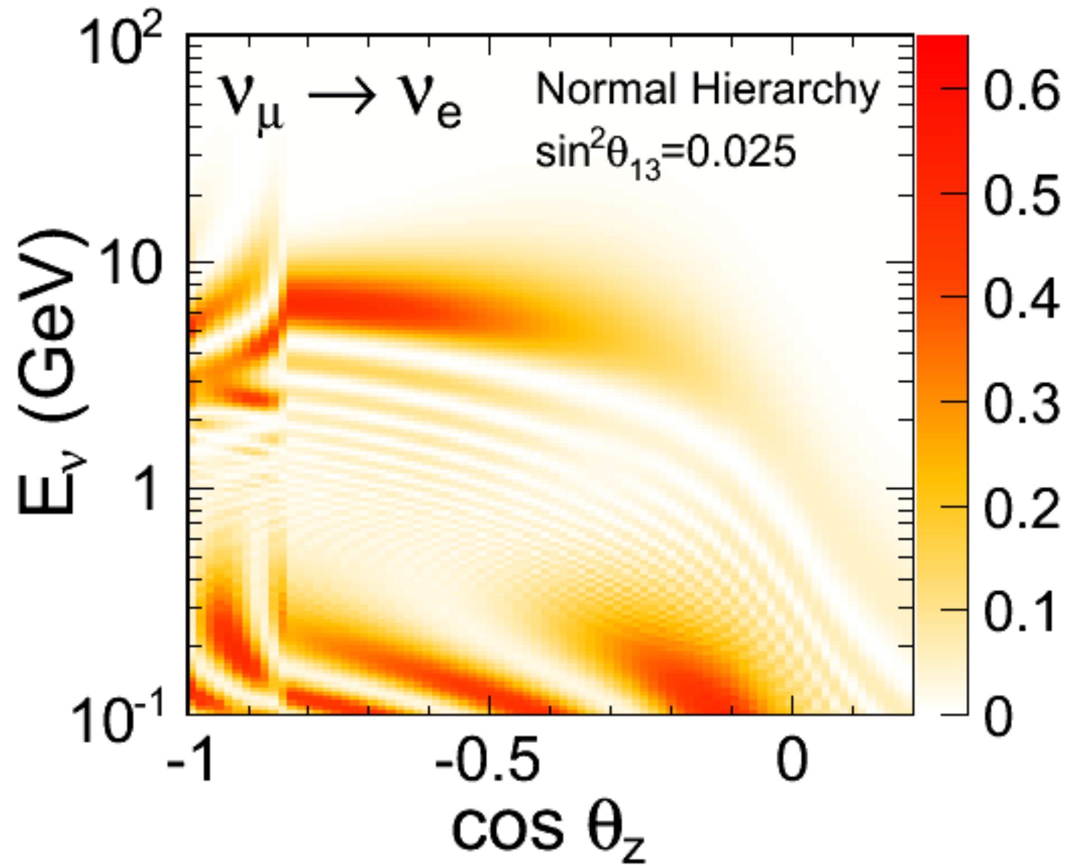
# Atmospheric Neutrinos

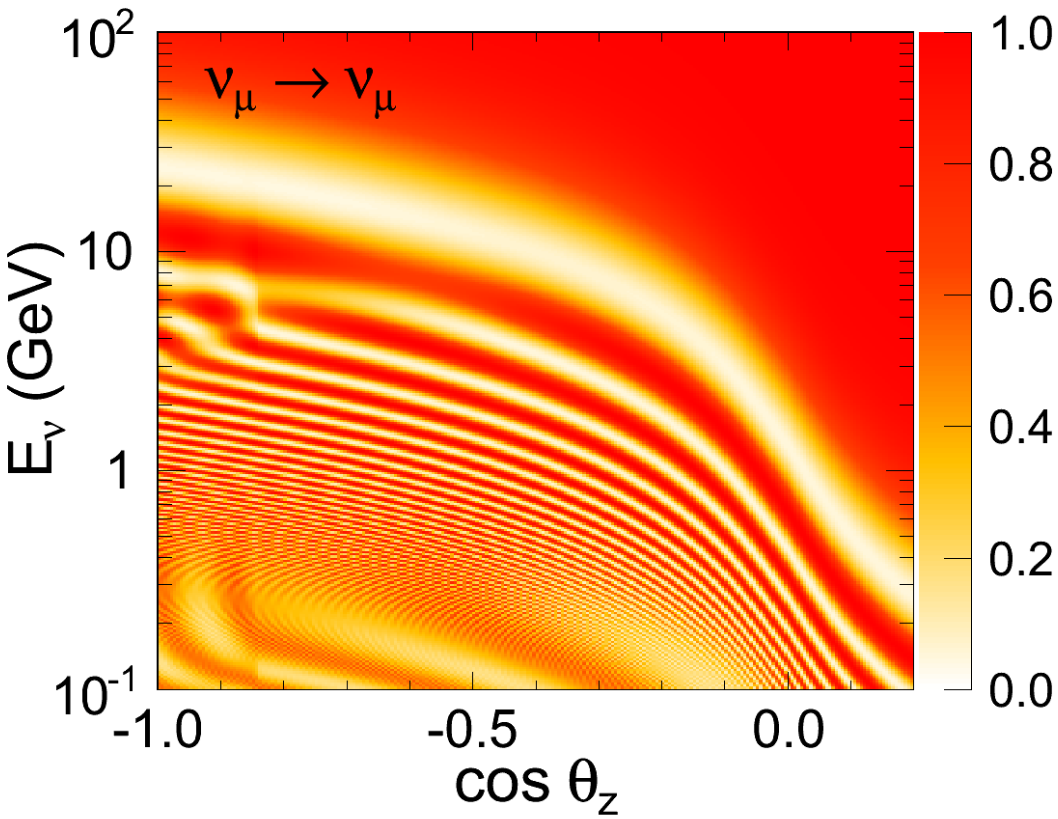
- **Atmospheric neutrinos offer a unique probe of neutrino oscillations.**
  - ➢ All flavours of neutrinos and antineutrinos, generating **multiple oscillation modes**.
  - ➢ Wideband coverage of neutrino energies and baselines, enabling tests of oscillations over **multiple wavelengths**.
  - ➢ Upward-going multi-GeV neutrinos are sensitive to matter effects via **MSW resonance**.
- **Complementary with beam neutrinos.**
  - ➢ Stand-alone and powerful probe of oscillation phenomena.
  - ➢ Atmospheric neutrino data can help to resolve ambiguities that arise in beam-only analyses.

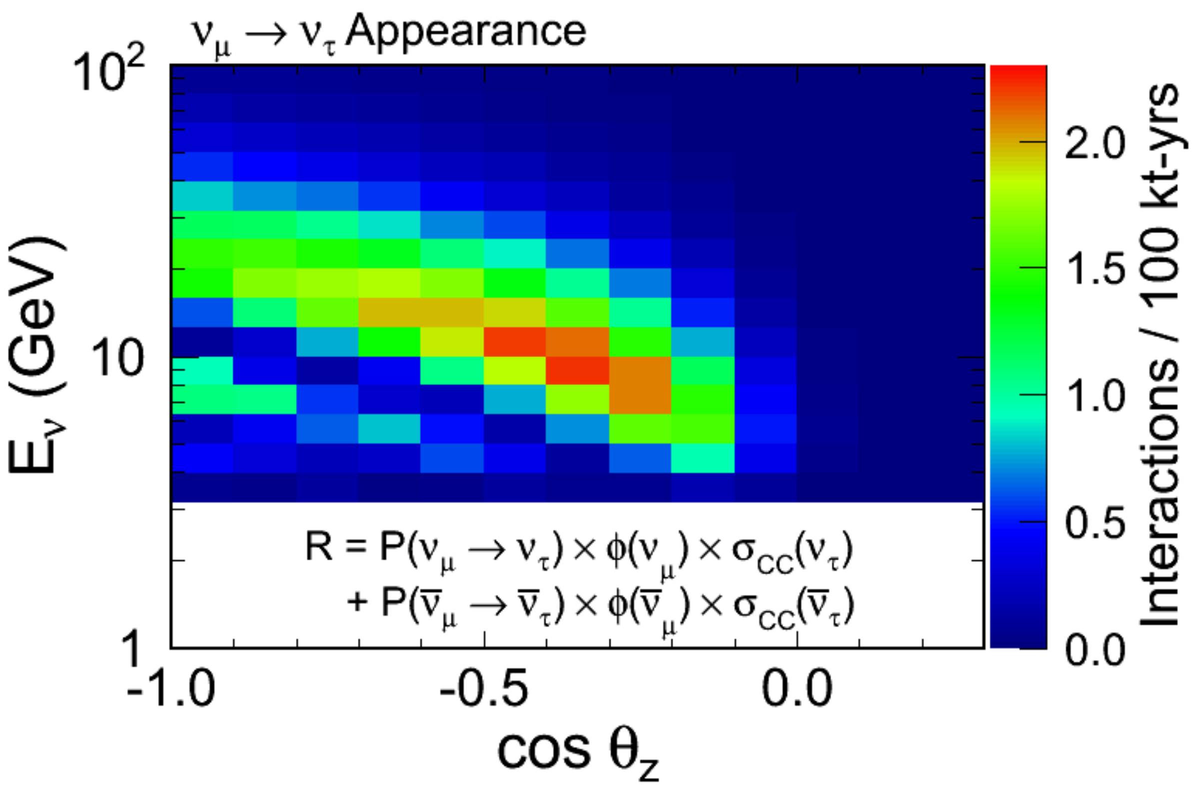


Atmospheric neutrino production

# Oscillation Physics



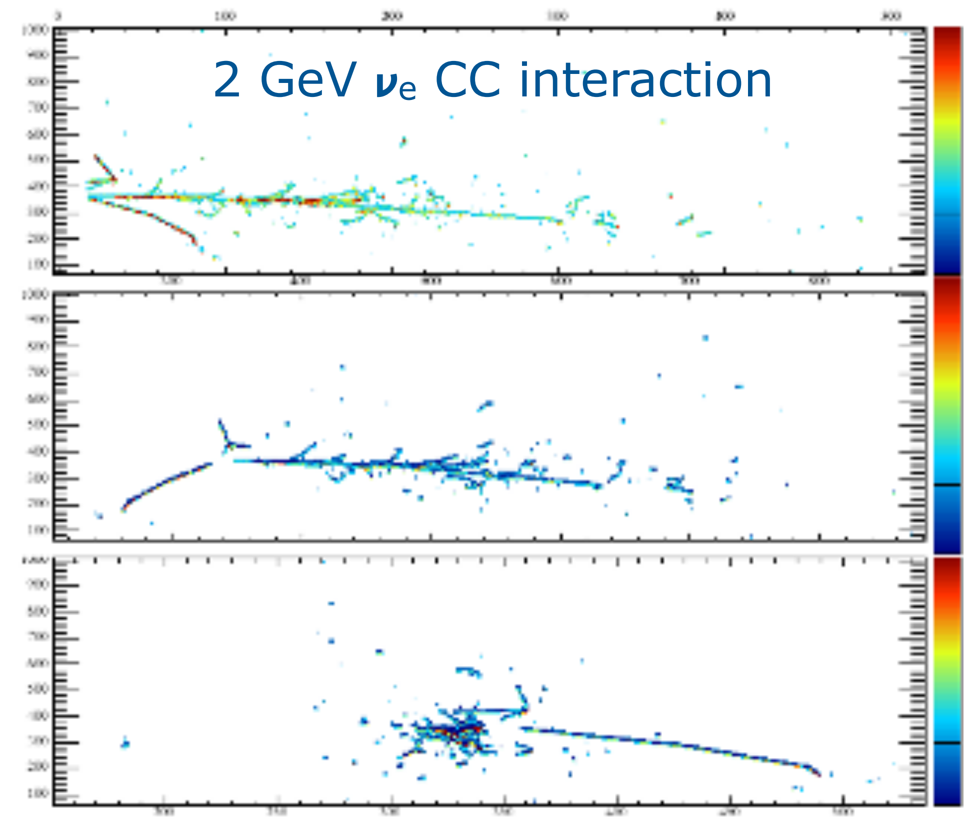



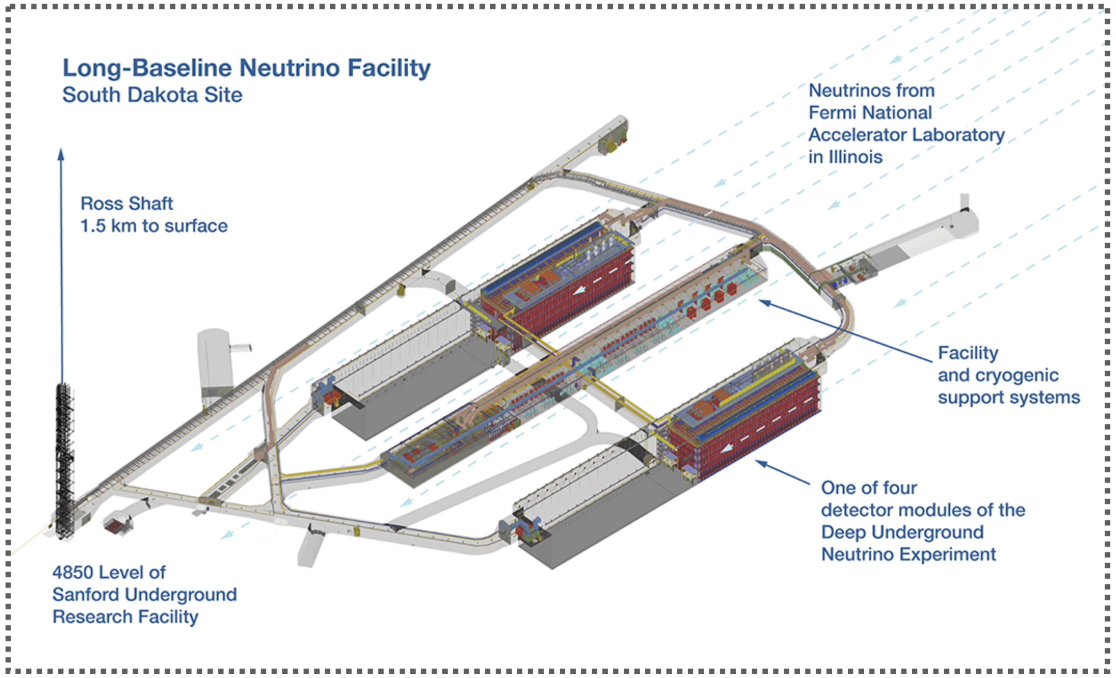

- **Atmospheric neutrino oscillations exhibit rich structure in a range of channels!**
  - Strong enhancement of $\boldsymbol{\nu_e}$ appearance due to matter effects.
  - Beautiful $\boldsymbol{\nu_\mu}$ disappearance fringes!
  - Significant levels of $\boldsymbol{\nu_\tau}$ appearance

# Liquid Argon Detectors

- **The use of LAr-TPC technology offers many advantages in the study of atmospheric neutrino oscillations.**
  - ➢ Excellent spatial and calorimetric resolution will enable precise measurements of energy and angle.
  - ➢ Excellent particle ID capabilities
  - ➢ Moderate discrimination between neutrinos and antineutrinos.



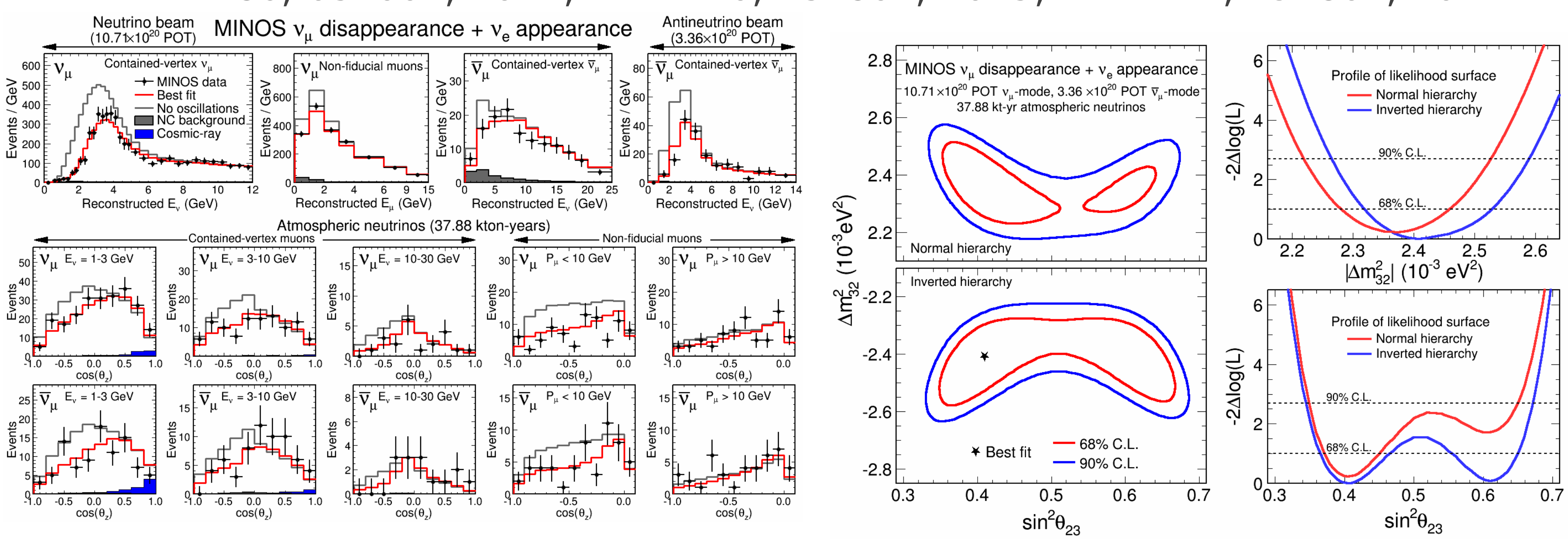

- **The DUNE experiment promises to deliver an exciting programme of atmospheric neutrino physics!**
  - ➢ Large fiducial mass (40kton) will provide high event rates.
  - ➢ Large rock overburden (4850 feet) will shield against cosmic-ray backgrounds.



# Physics Studies

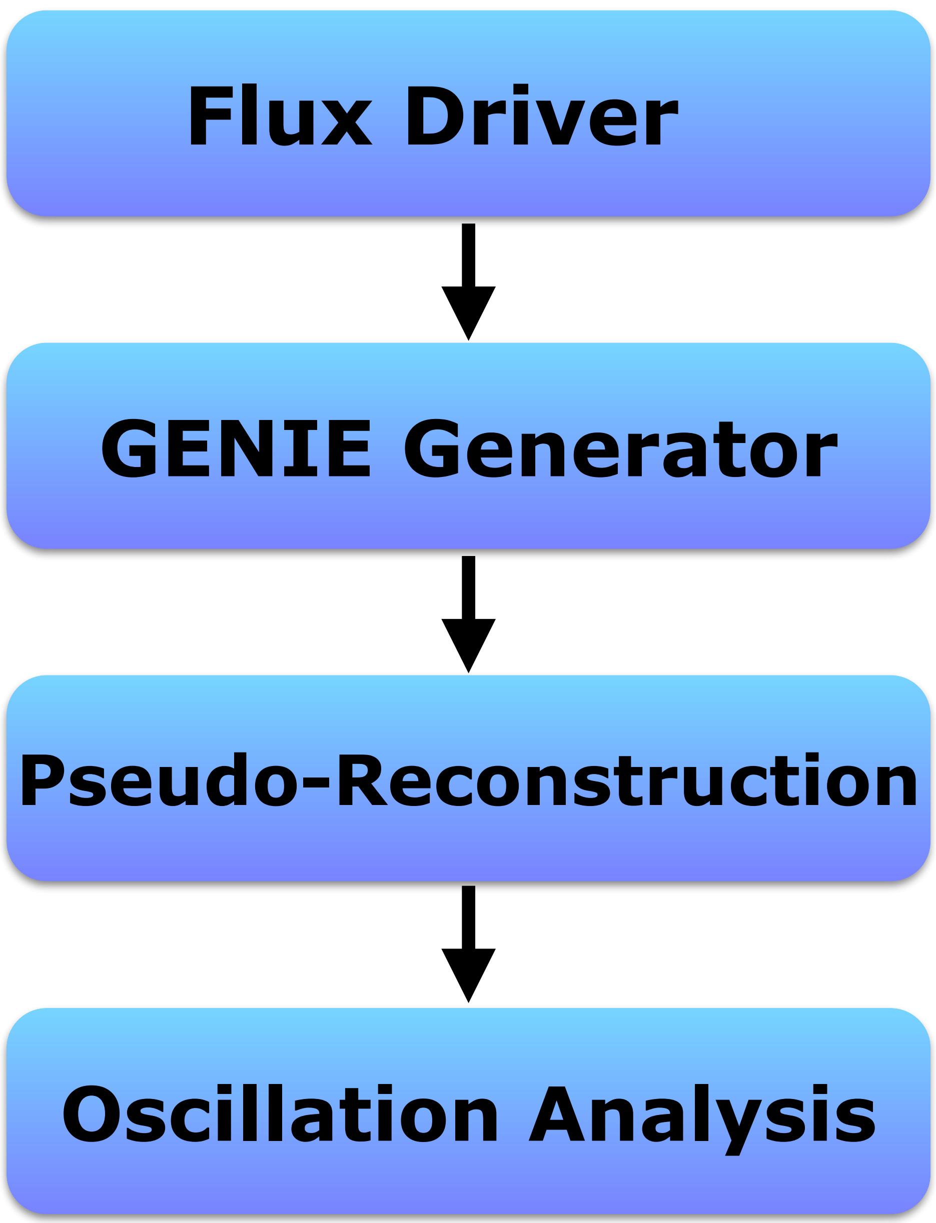
- **To investigate the oscillation sensitivity of a large LAr-TPC experiment like DUNE, I developed a fast Monte Carlo simulation:**
  - ➢ GENIE event generator.
  - ➢ Parameterised reconstruction (will be superseded by full reconstruction!)
  - ➢ Oscillation fitting framework based on MINOS long-baseline experiment.

PRD 86, 052007, 2012;  PRL 110, 251801, 2013;  PRL 112, 191801, 2014




- **Focus on standard oscillation physics with atmospheric neutrinos:**
  - ➢ Combined analysis of $\nu_\mu$ disappearance and $\nu_e$ appearance.
  - ➢ Sensitivities to mass hierarchy, CP violation, $\theta_{23}$ octant.

# Fast Simulation (1)




**Fast Monte Carlo simulation:**

- **GENIE event generator**:
  Use GENIE to simulate atmospheric neutrino interactions on Argon.
  - Bartol 3D flux (Soudan mine).
  - Neglect cosmic-ray backgrounds and neutrino interactions in rock.
- **Pseudo-reconstruction**:
  Simulate LAr-TPC detector performance by smearing final-state four-vectors.
  - Parameterised thresholds, resolutions, particle ID, etc
  - Separation of fully/partially contained events using realistic geometry.
- **Multivariate fitting framework**:
  Fit oscillation parameters plus a suite of systematics.

# Fast Simulation (2)

- **The pseudo-reconstruction categorises simulated events according to their final-state particles:**
  - ➢ **Flavour tag**: $\nu_\mu$-like or $\nu_e$-like, based on final-state lepton.
  - ➢ **Containment**: fully contained (FC) or partially contained (PC).
  - ➢ **Kinematics**: Each event is assigned a leptonic and hadronic four momentum, based on a smearing of the Monte Carlo truth.
- **The detector performance is described by a suite of parameters:**

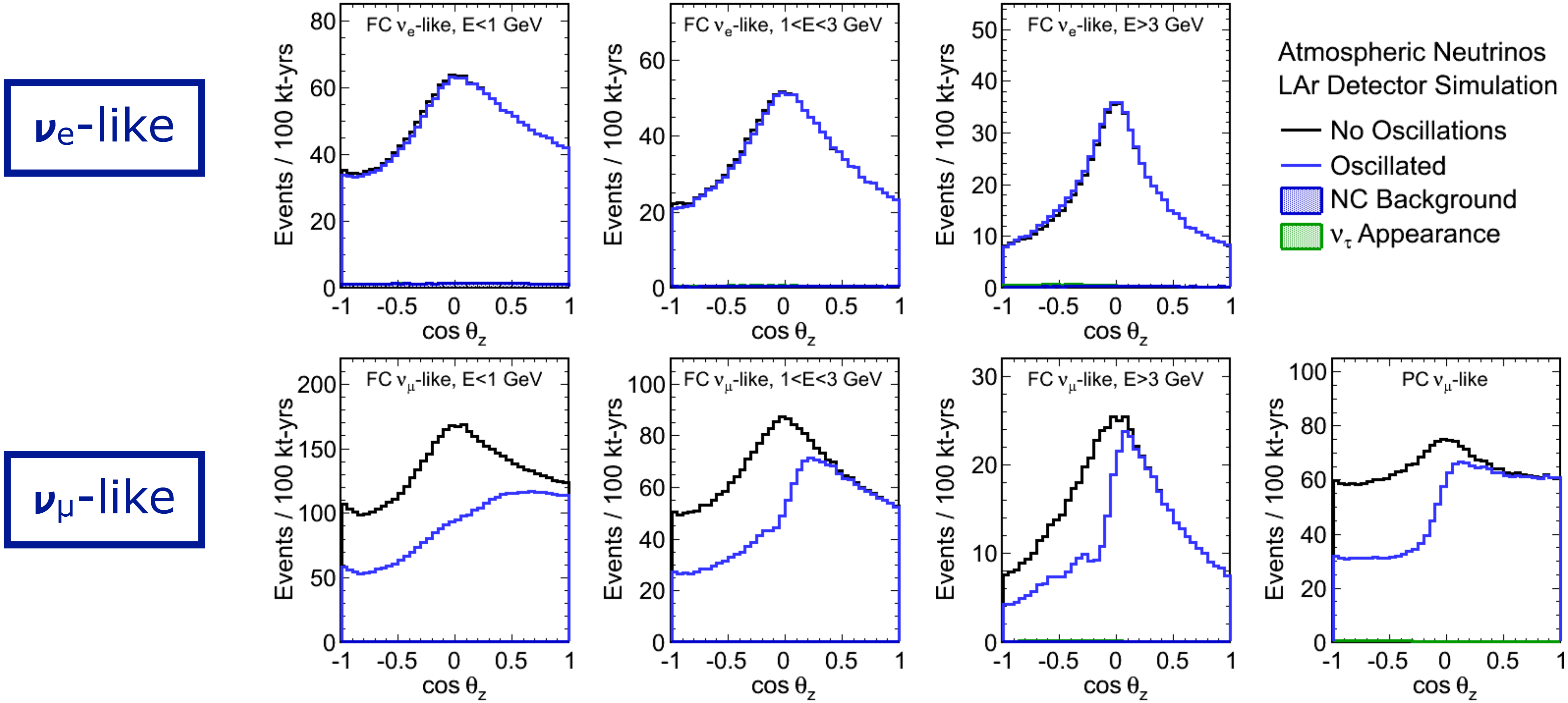
| | | |
|---|---|---|
| Angular Resolution | Electron | 1° |
| | Muon | 1° |
| | Hadronic system | 10° |
| Energy Resolution | Stopping muon | 3% |
| | Exiting muon | 15% |
| | Electron | $1\%/\sqrt{E} + 1\%$ |
| | Hadronic system | $30\%/\sqrt{E}$ |
| Signal Acceptance | Electrons | 90% |
| | Muons | 100% |
| Background Rejection | e-like ($\pi^0$, $\gamma$) | 95% |
| | μ-like ($\pi^+$, $\pi^-$) | 99% |

**Sources**:

- ➢ ICARUS, JINST 6, 07011 (2011)
- ➢ LBNE, arXiv:1307.7335 (2013)
- ➢ Four-vector studies using GENIE and GEANT4

# Event Distributions (1)

- **Fast simulation produces a realistic zenith angle distribution:**

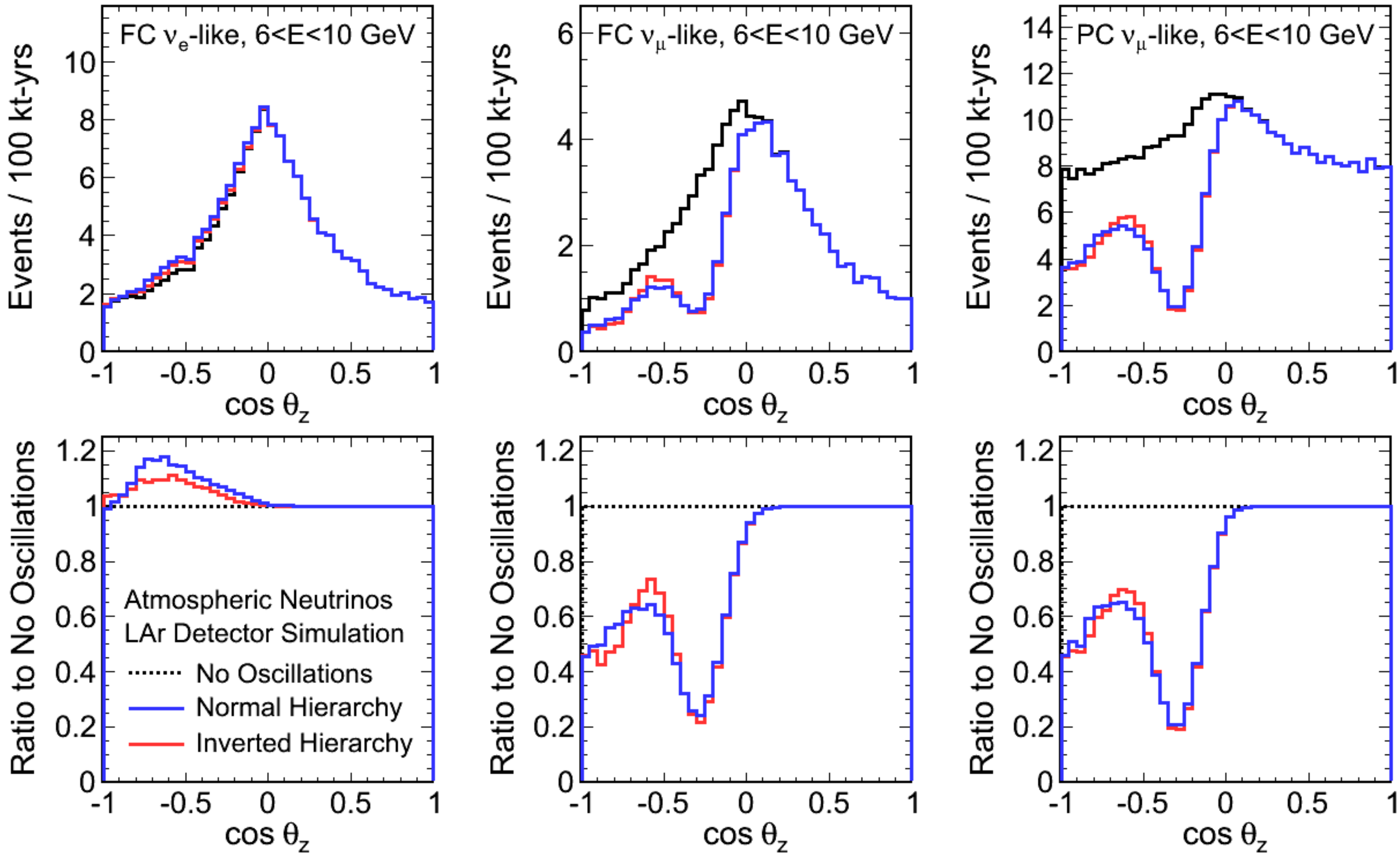



➢ Predicted event yields in 350 kton-yrs exposure:

| | |
|---|---|
| Fully-contained $\nu_e$-like sample | 14,053 |
| Fully-contained $\nu_\mu$-like sample | 20,853 |
| Partially-contained $\nu_\mu$-like sample | 6,871 |

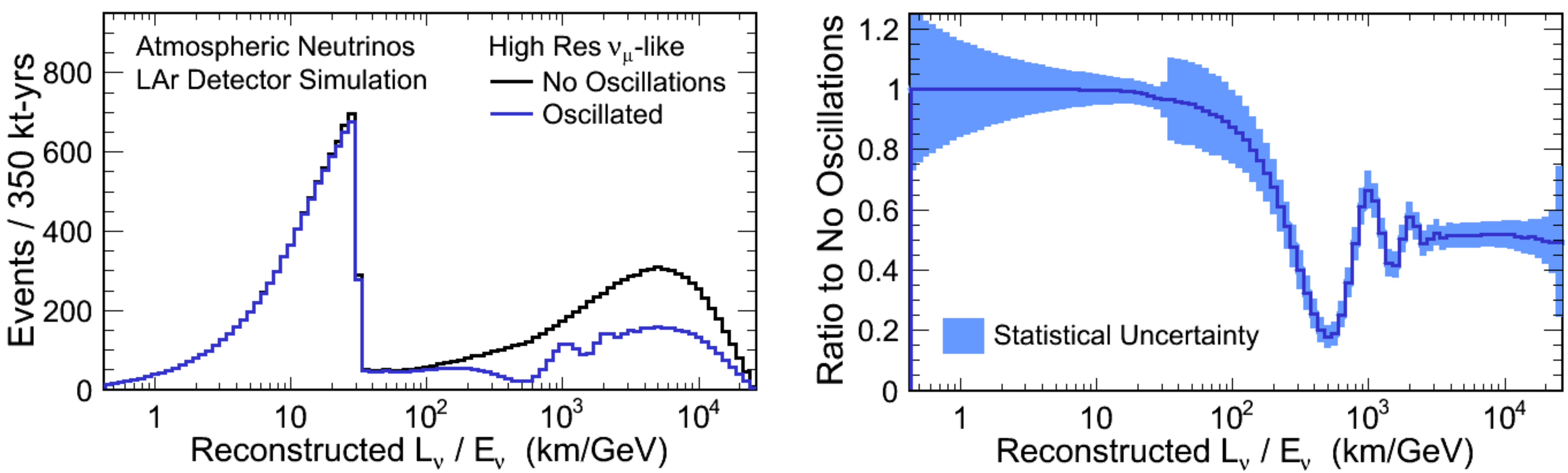
# Event Distributions (2)

- **Sensitivity to mass hierarchy from both $\nu_\mu$-like and $\nu_e$-like channels:**



# Event Distributions (3)

- **We can perform an L/E analysis by selecting "high-resolution" events.**
  - ➢ High-resolution sample is obtained by cutting out low-energy events around the horizon (can imagine more sophisticated methods).
- **The first, second and third oscillation maxima can be resolved in the high-resolution L/E distributions!**
  - ➢ Unique capability for atmospheric neutrinos in LAr-TPC detectors.



# $\nu$/anti-$\nu$ Enhancement

- **The fast simulation provides an environment for developing tools to statistically separate neutrinos and antineutrinos.**
  - ➢ Sensitivity to mass hierarchy can be enhanced if atmospheric neutrinos and antineutrinos can be separated.

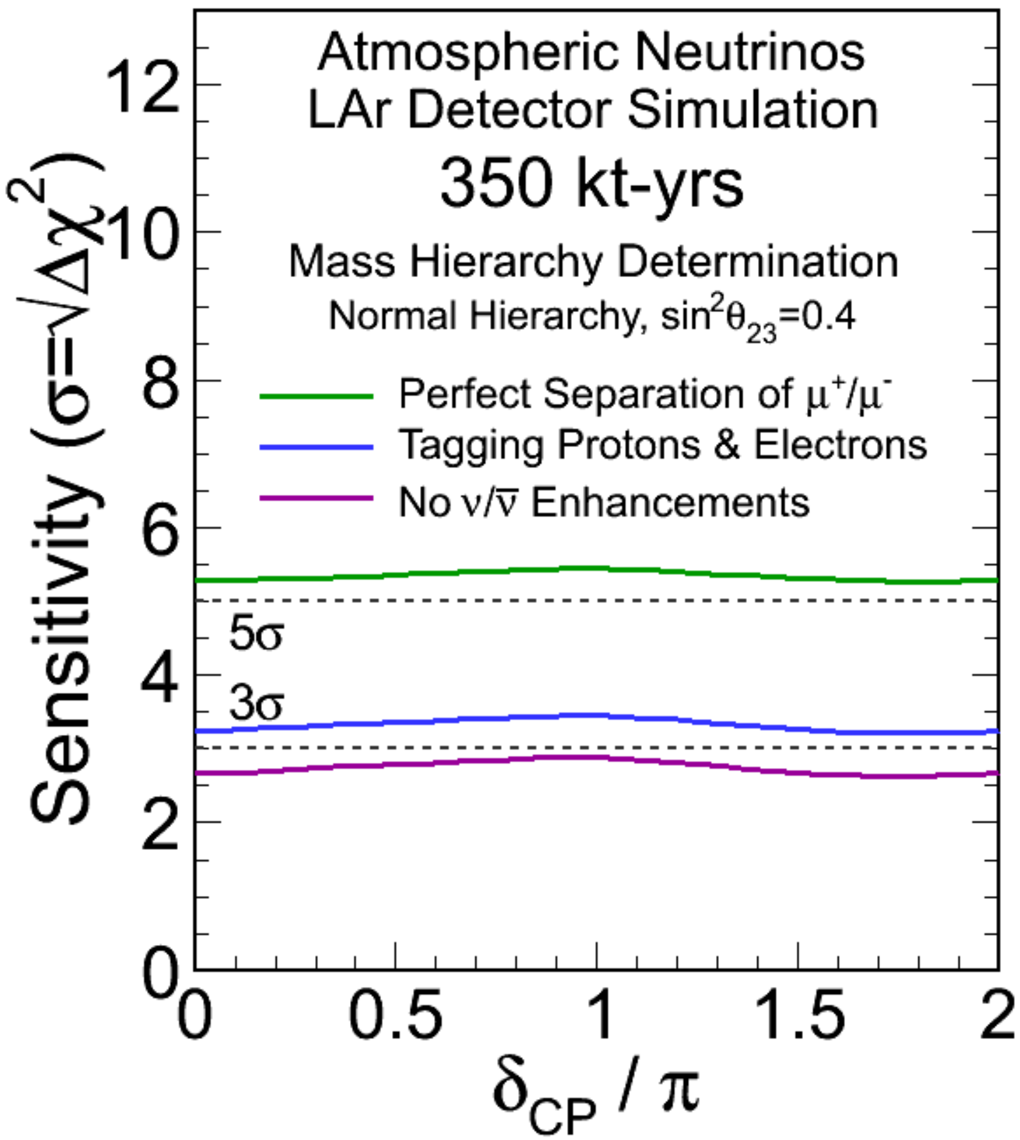
- **Currently simulate three methods of $\nu$/anti-$\nu$ enhancement:**
  - ➢ **Tagging final-state protons**:
    - Assume perfect efficiency for proton reconstruction if KE>50 MeV.
    - Proton-tagging yields a 10% enhancement in the neutrino fraction.
  - ➢ **Tagging Michel electrons**:
    - Exploit large asymmetry of $\mu^-$ and $\mu^+$ decay vs capture in Argon.
    - Electron-tagging yields a 25% enhancement in the antineutrino fraction.
    - Non-tagged sample is entirely composed of neutrinos.
  - ➢ **Perfect charge separation**:
    - For comparison, also simulate perfect separation of $\mu^-$ and $\mu^+$ events.

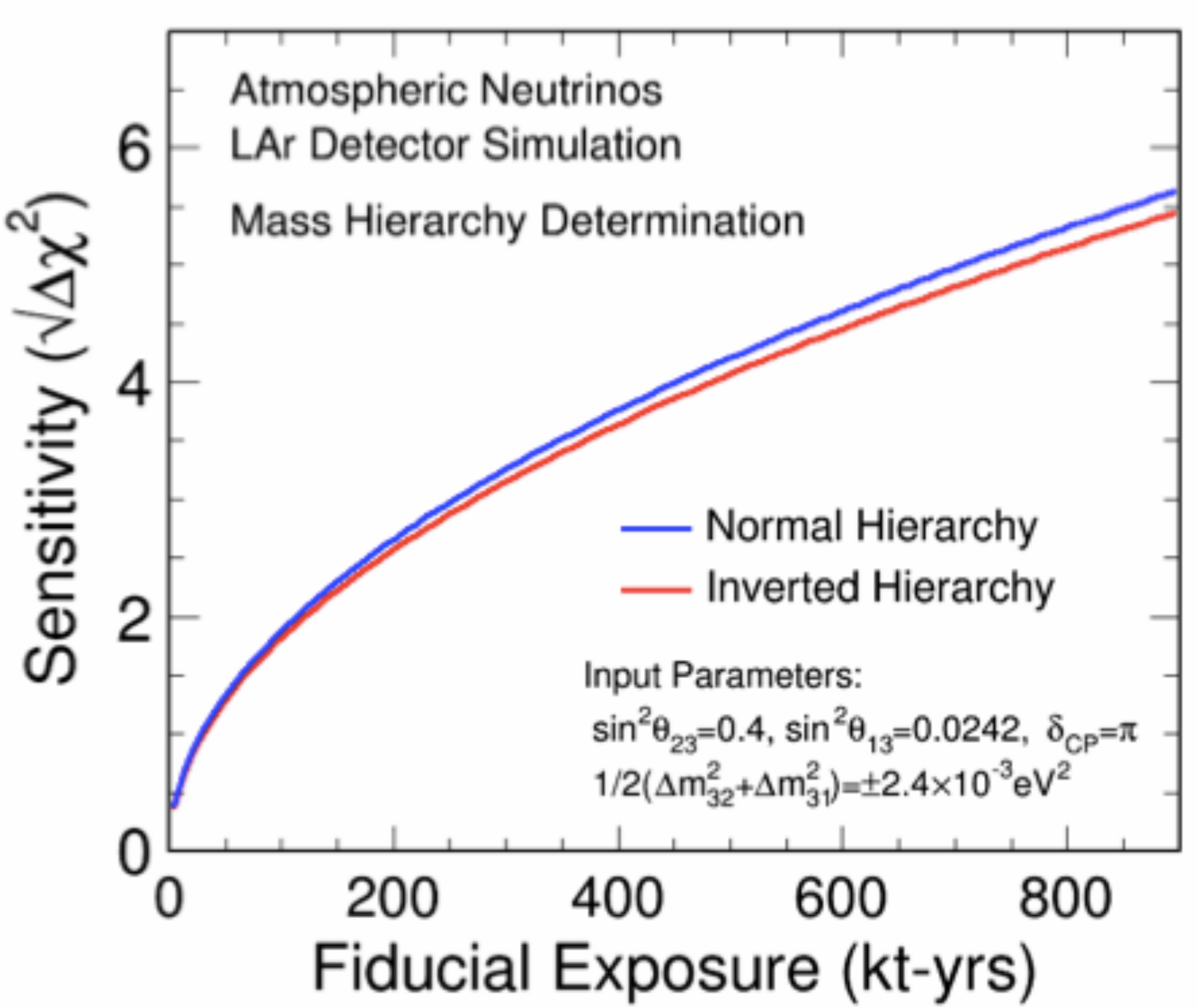
# Oscillation Sensitivities

- **To calculate oscillation sensitivities, we apply a joint log-likelihood fit to the $\nu_\mu$-like or $\nu_e$-like event samples.**
  - ➢ Each sample is binned by reconstructed energy and angle.
- **The following parameters are allowed to float in the oscillation fit:**
  - ➢ Oscillations:
    - 3 parameters included in the fit: $\theta_{23}$, $\delta_{CP}$, sign($\Delta m^2$).
  - ➢ Systematics:
    - 18 parameters included in the fit covering normalisation, flux ratios, neutral-current backgrounds, spectral indices, and energy scales.
    - Implemented as nuisance parameters with penalty terms.
- **Determine the sensitivity to mass hierarchy, $\theta_{23}$ octant and CP violation using $\sigma=\sqrt{\Delta\chi^2}$ as a simple estimate of the significance.**

# Mass Hierarchy

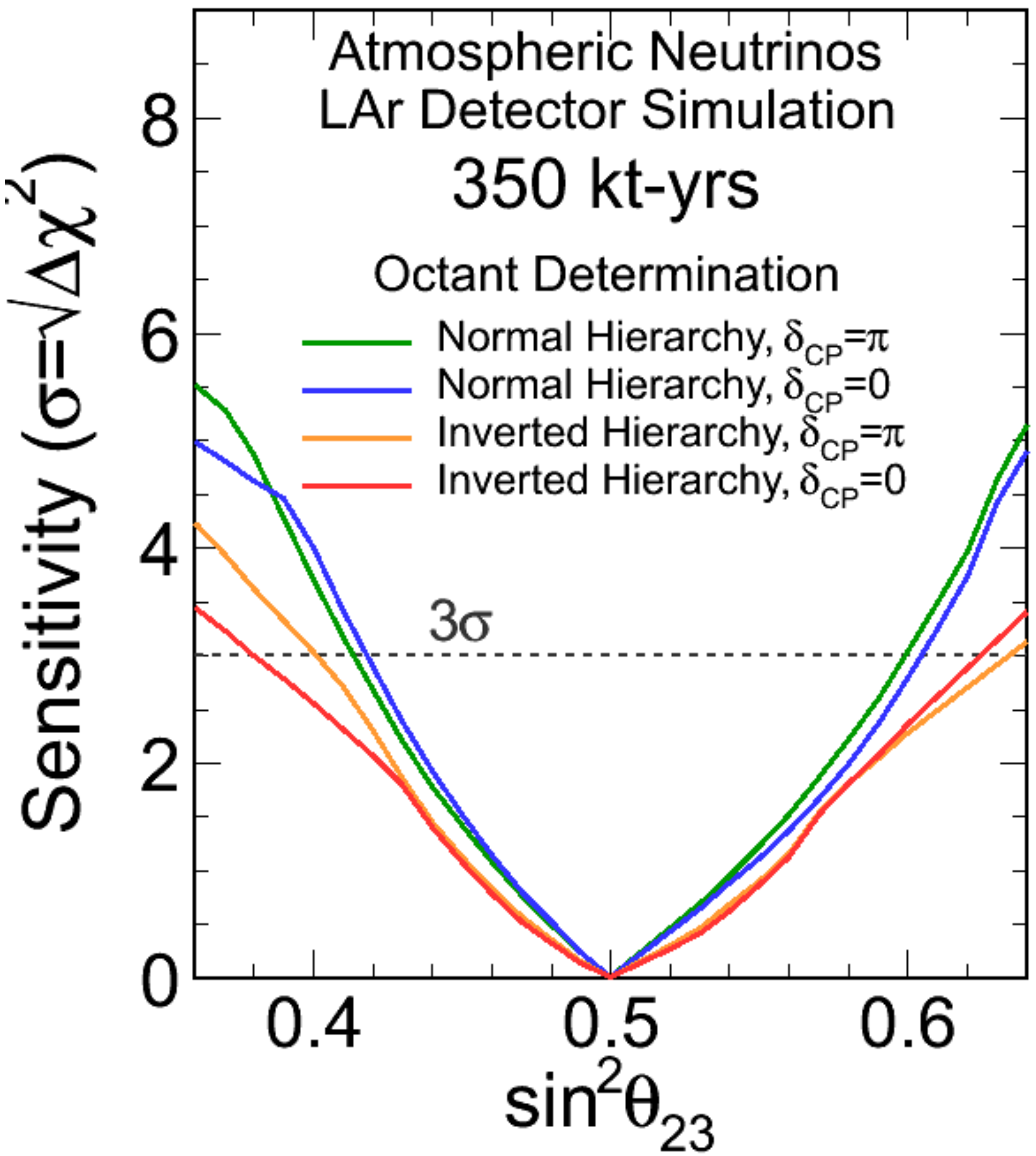
- **Mass hierarchy capability looks promising with atmospheric neutrinos!**
  - ➢ Require ~300 kt-yr exposure to achieve “3$\sigma$” determination of hierarchy.
  - ➢ Sensitivity to hierarchy is almost independent of the value of the **δ**CP phase.
  - ➢ Proton and electron tags yield a moderate improvement in sensitivity.

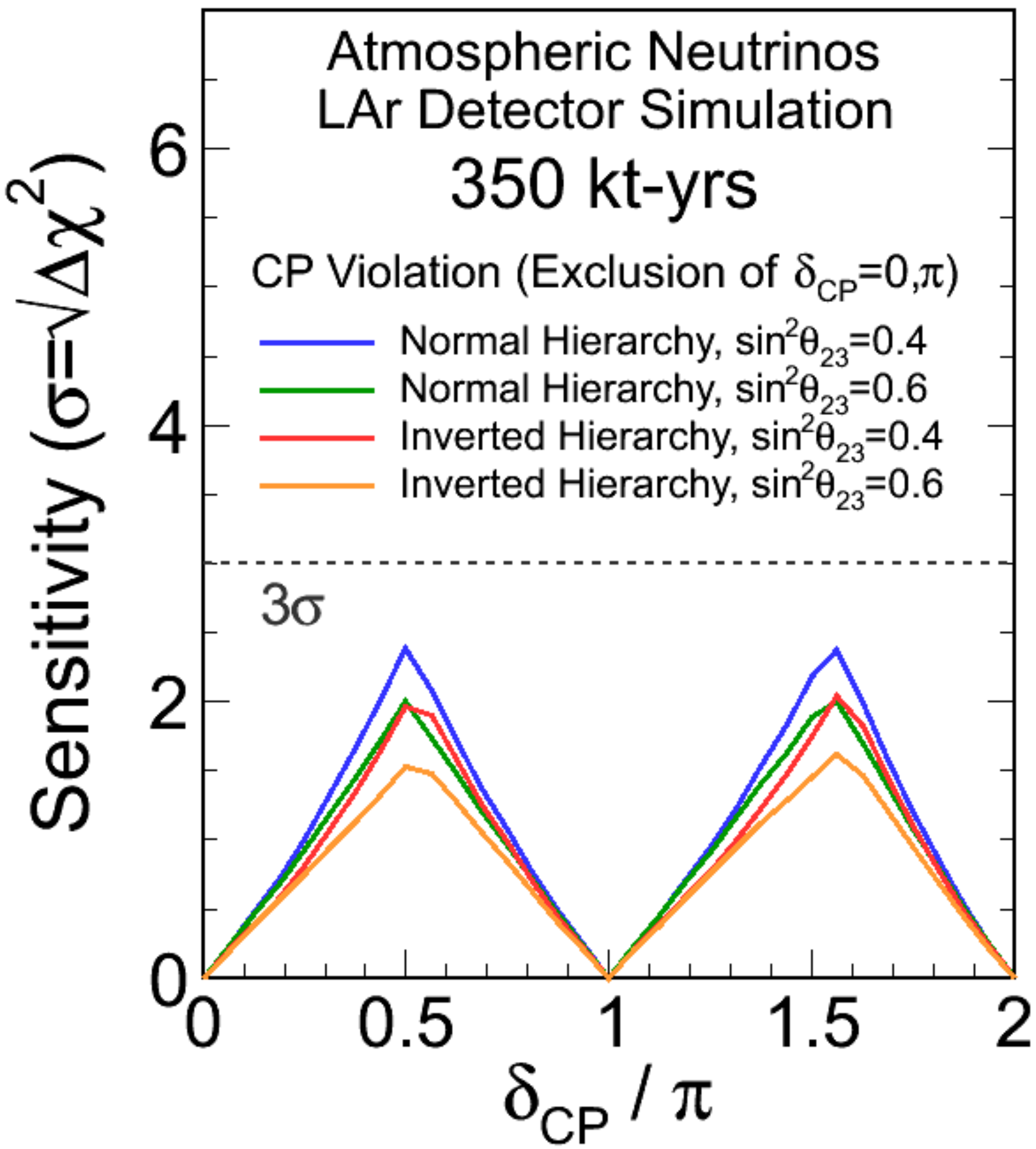


# $\theta_{23}$ Octant and CP Violation

- **Moderate sensitivity to $\theta_{23}$ octant and $\delta_{CP}$ (although weaker than beam):**

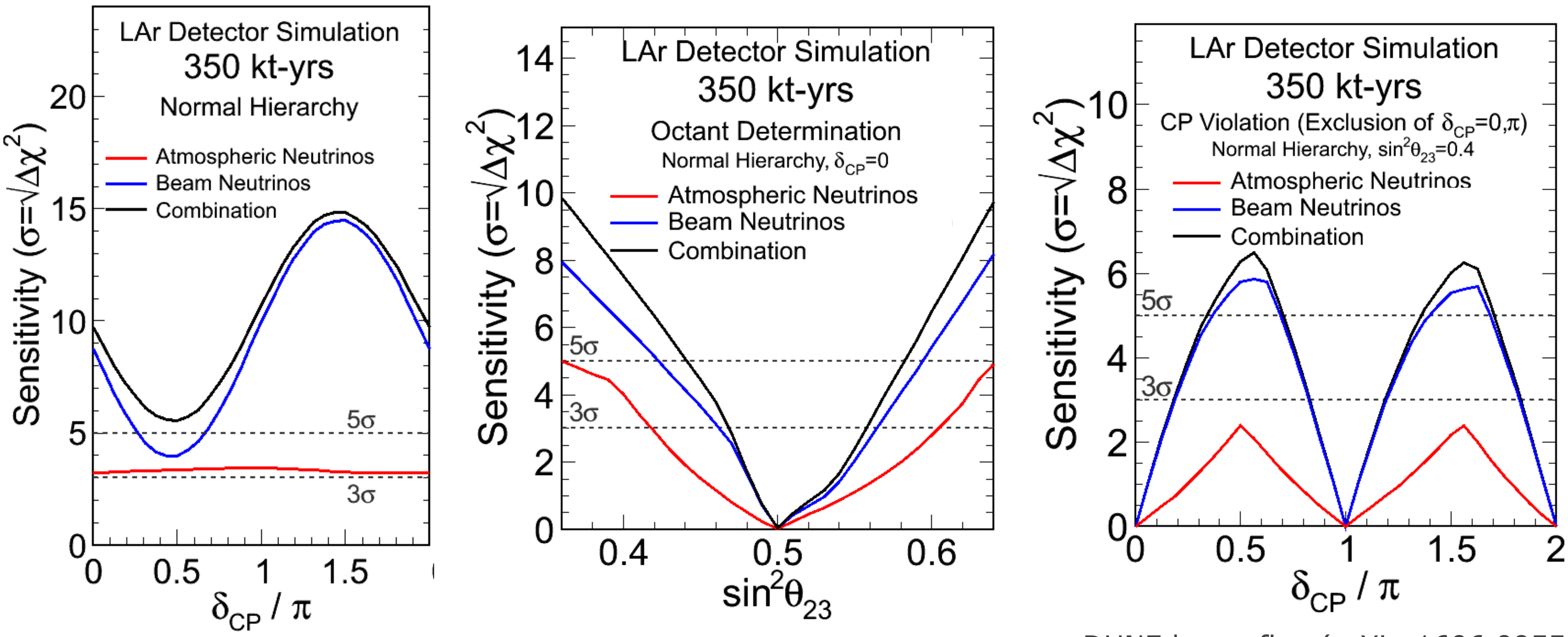



(However, atmospheric data can help to break degeneracies in oscillation analyses)

# Combined Beam and Atmospherics

- **For context, we can compare the atmospheric neutrino sensitivities to representative beam sensitivities calculated using the same method.**
  - ➢ Beam dominates average sensitivity, but atmospherics are complementary, and significantly contribute to the mass hierarchy sensitivity.
  - ➢ In DUNE, atmospheric neutrinos will also provide a crucial data set for detector understanding.




DUNE beam flux (arXiv:1606.09550)

# Summary

- **Atmospheric neutrinos provide a rich source of oscillation physics!**

- **The use of Liquid Argon TPC detectors offers many benefits in the study of atmospheric neutrino oscillations.**
  - ➢ Detectors have exquisite spatial and calorimetric resolution.

- **DUNE will collect copious atmospheric data , enabling precision measurements of neutrino oscillations.**

- **Physics studies based on a fast Monte Carlo simulation indicate that DUNE has excellent sensitivity to sub-dominant oscillation phenomena, particularly the mass hierarchy.**
  - ➢ Oscillation measurements with atmospheric neutrinos are complementary to the accelerator programme.
  - ➢ Atmospherics will also help to resolve ambiguities in beam-only analyses.

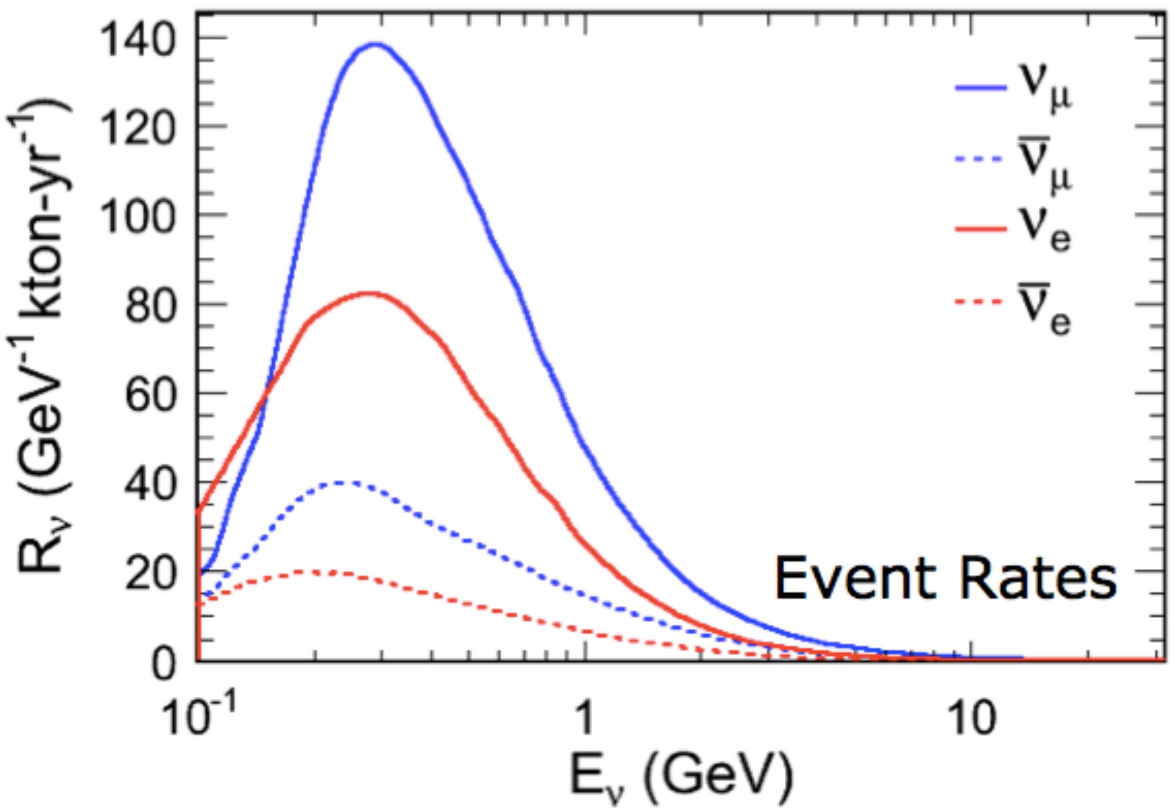
- **Fast simulation can be used to study optimisations of the analysis, such as $\nu$/anti-$\nu$ enhancement.**

# BACKUP

# GENIE Simulation

- **Use Bartol 3D flux calculation at Soudan mine (solar maximum).**
  - Published PRD 70, 023006, 2004.

- **Normalise sample by integrating flux times cross-section.**



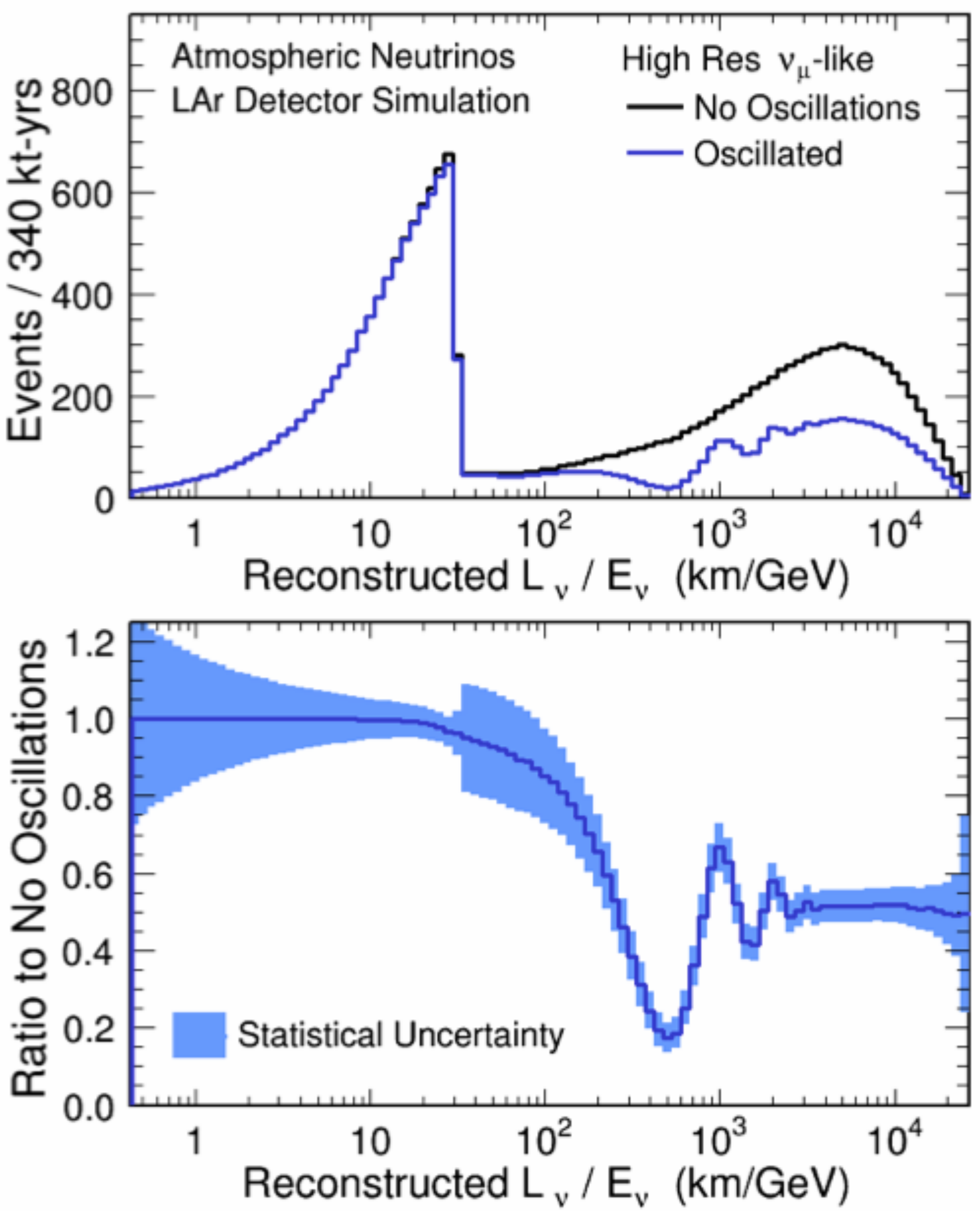

Interaction rates per 100 kt-yrs:

| | CC | NC | Total |
|---|---|---|---|
| $\nu_\mu$ | 10069 | 4240 | 14309 |
| anti-$\nu_\mu$ | 2701 | 1895 | 4596 |
| $\nu_e$ | 5754 | 2098 | 7852 |
| anti-$\nu_e$ | 1230 | 782 | 2012 |
| **Total** | 19754 | 9015 | 28769 |

solar max: 288 interactions / kt-yr

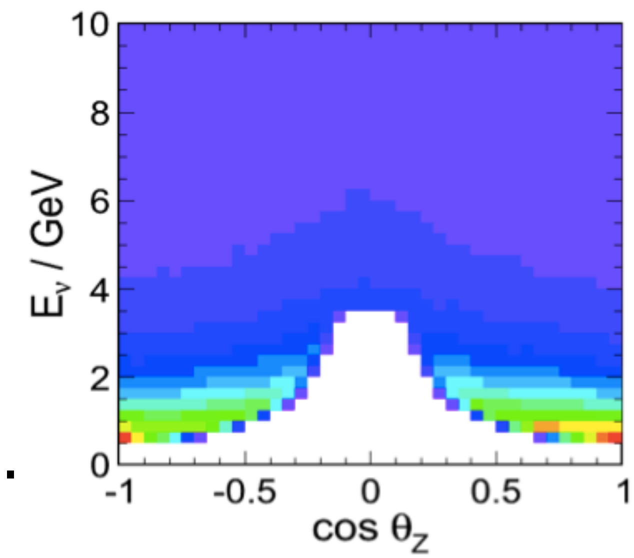
*[solar min: 328 interactions / kt-yr]*

# L/E Analysis




- **Can perform L/E analysis by selecting "high resolution" atmospheric neutrinos.**

- Need to select high resolution events, even in Liquid Argon experiment.
- Select shaded area of $E_\nu$-$\cos\theta_z$ (right):
- Can imagine more sophisticated ways of selecting events (e.g. arXiv:1208.2899).




- **Can clearly resolve multiple oscillation wavelengths in L/E distributions!**

(Unique capability for atmospheric neutrinos in LAr-TPC detectors).

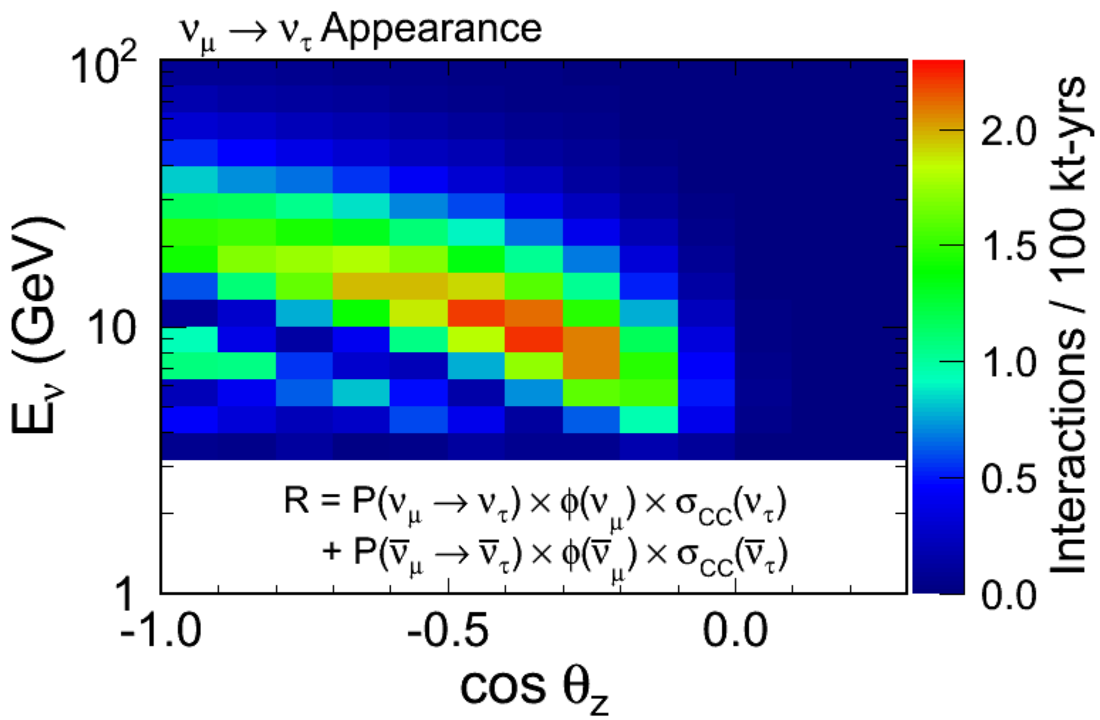
# Oscillation Analysis

- **Oscillation sensitivities: apply joint fit to e-like and $\mu$-like event samples ($\mu$-like events separated into FC and PC).**
  - Samples are binned by reconstructed energy and angle.
  - By default, atmospheric events are also separated according to proton and electron tags (provides some $\nu$/anti-$\nu$ enhancement).
- **Oscillation analysis includes following parameters:**
  - Systematics: 14 parameters, covering overall normalisation, flux, NC background and energy scales [see overleaf].
  - Oscillations: Fix $\theta_{12}$, $\Delta m^2_{21}$, and $\Delta m^2 = 1/2\ (\Delta m^2_{32} + \Delta m^2_{31})$. Fit $\theta_{23}$, $\theta_{13}$, $\delta_{CP}$, sign($\Delta m^2$) [2% constraint on $\theta_{13}$].
  - Use the following representative input oscillations:
    - ◇ $\Delta m^2_{21} = 7.54 \times 10^{-5} eV^2$, $\sin^2\theta_{12} = 0.307$, $\sin^2\theta_{13} = 0.0242$.
    - ◇ $\sin^2\theta_{23} = 0.40$, $\Delta m^2 = 1/2(\Delta m^2_{32} + \Delta m^2_{31}) = \pm 2.40 \times 10^{-3} eV^2$
- **Calculate sensitivity to hierarchy, octant and CP violation, using $\sigma = \sqrt{\Delta\chi^2}$ as measure of sensitivity.**

# Systematics

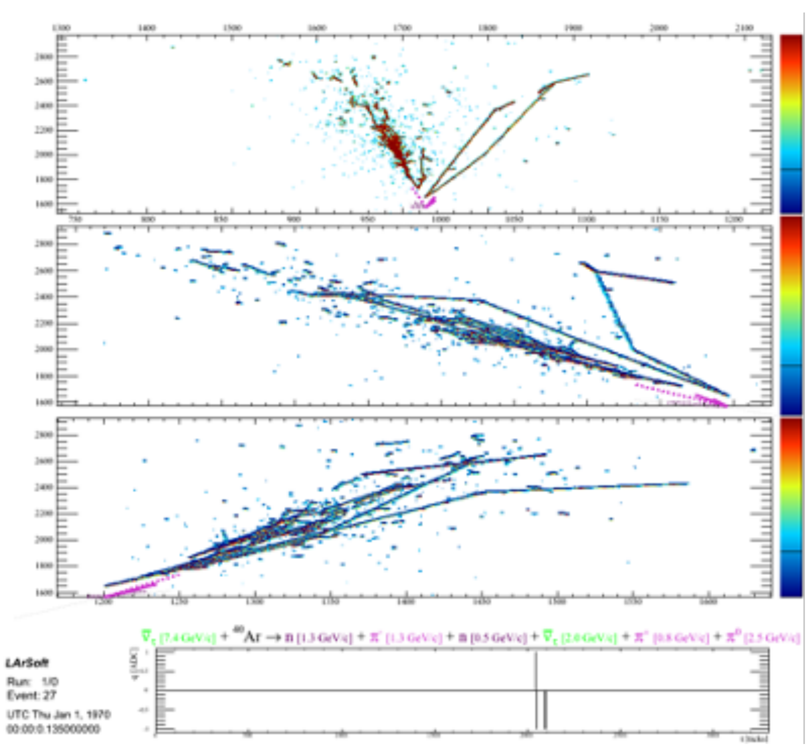
| | Atmospheric | Beam (Assume ND) |
|---|---|---|
| Normalisations | Overall (15%) | $\mu$-like (1%)<br>e-like (1%) |
| NC Backgrounds | (No ND decomposition for atmos $\nu$)<br>e-like (10%) | $\mu$-like (10%)<br>e-like (5%) |
| Spectrum Ratios | up/down (2%)<br>$\nu_e/\nu_\mu$ (2%)<br>anti-$\nu_\mu/\nu_\mu$ & anti-$\nu_e/\nu_e$ (5%) | } Flux ratios cancel strongly, so these are estimated detector uncertainties |
| Spectrum Shape | Apply separate functions for $\nu_\mu$, $\nu_e$, anti-$\nu_\mu$, anti-$\nu_e$ } | $f(E<E_0)=1+\alpha(E-E_0)/E_0$<br>$f(E>E_0)=1+\alpha\log(E/E_0)$<br>where $\sigma_\alpha=5\%$ |
| Energy Scales (Correlated) | Muons (stopping 1%, exiting 5%)<br>Electrons (1%)<br>Hadronic system (5%) | |

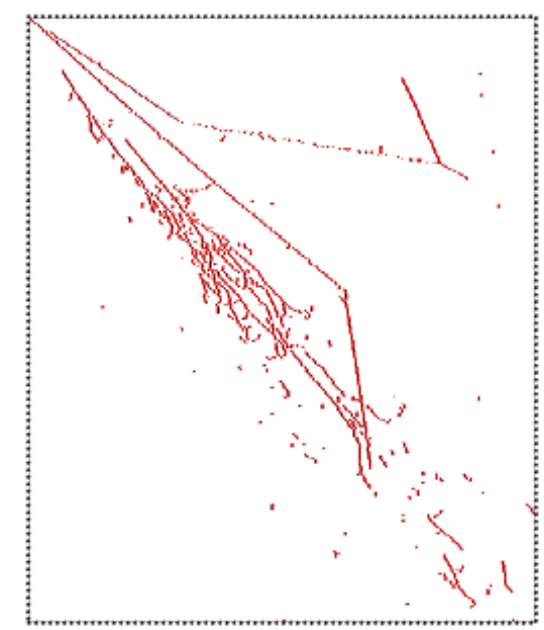
# Tau neutrinos




- Expect ~1 $\nu_\tau$ interaction per kton-year from tau neutrino appearance.

- Events have complex topologies! Need to develop complete chain of simulation and reconstruction.





7 GeV $\nu_\tau$ CC interaction