UNIVERSITY OF LIVERPOOL

Atmospheric neutrino oscillations with Super-Kamiokande

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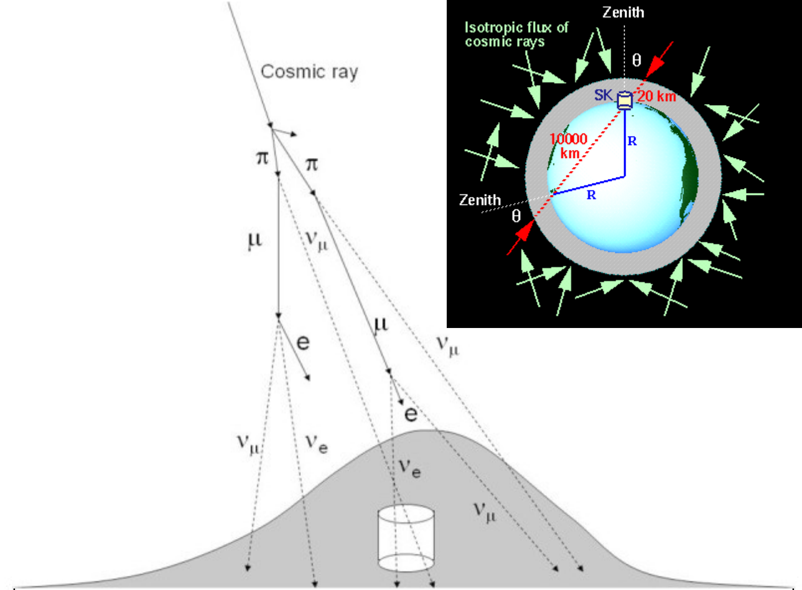
for the Super-Kamiokande Collaboration

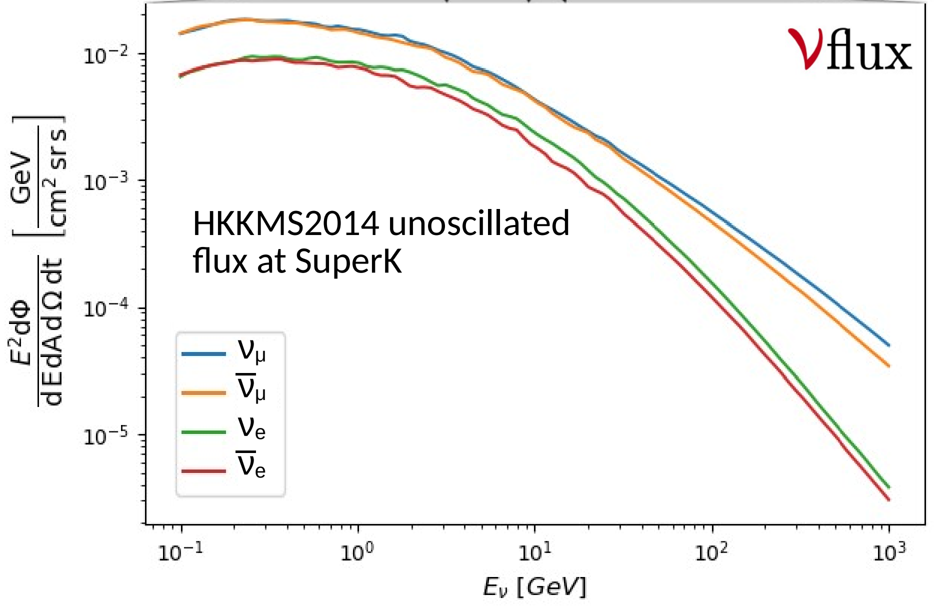
NuFact 20|21
The 22nd International Workshop on neutrinos from accelerators

Atmospheric Neutrino Flux

- Neutrinos produced in the interaction of cosmic rays (*p, α...*) with Earth's atmosphere

- Large statistics spread over
  - wide range of energies
    - from 10s of MeV and well beyond the TeV scale
  - wide range of baselines
    - produced at 10s of km above surface
    - coming from all directions
    - travel distance ~defined by zenith angle, from $\mathcal{O}(10^1\text{ km})$ to $\mathcal{O}(10^4\text{ km})$
  - flavoured
    - $\nu_\mu/\nu_e \simeq 2$, below 1 GeV
    - $\nu_\mu/\nu_e > 2$, above 1 GeV



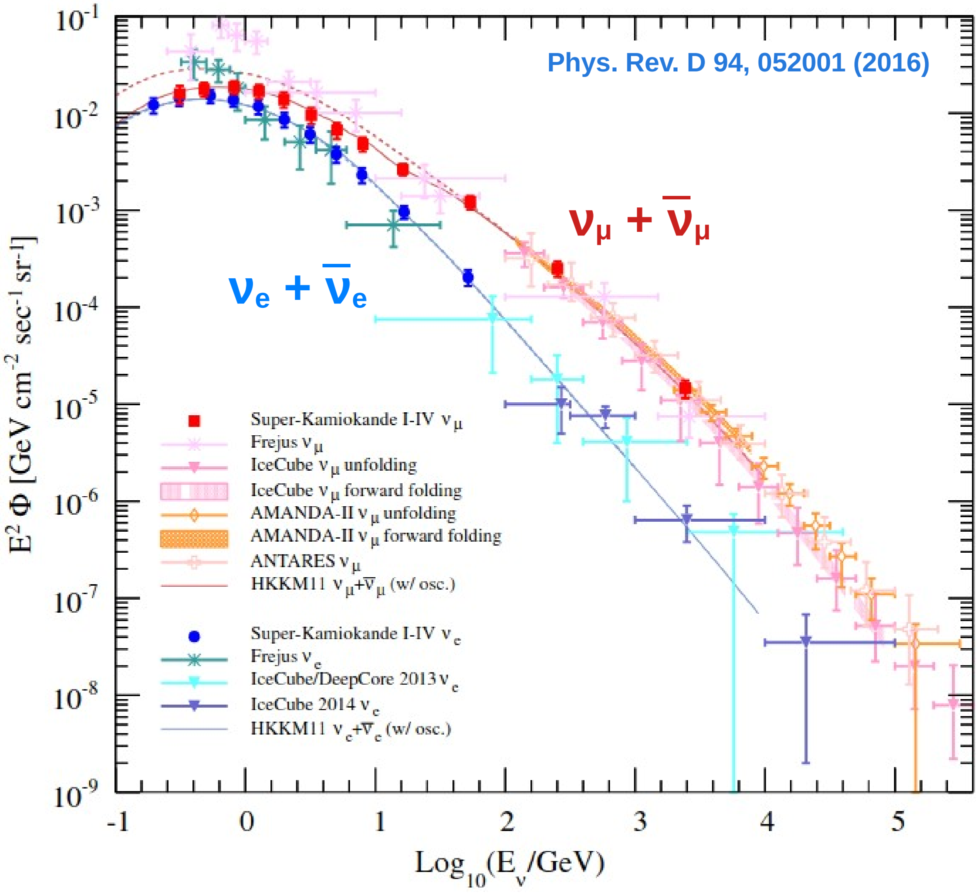


Atmospheric Neutrino Flux

- Detailed simulations are required to compute the neutrino flux taking into account **cosmic ray flux**, complex **hadron interactions**, **geomagnetic field**, **solar activity**, etc…

- On top of that, **oscillations**
  - ➔ complicated matter effects of neutrinos travelling through Earth
  - ➔ appearance of the third kind of neutrinos, ν_τ

- Neutrino oscillations were first discovered by SK measuring the deficit of upward going atmospheric muon neutrinos (Nobel 2015)

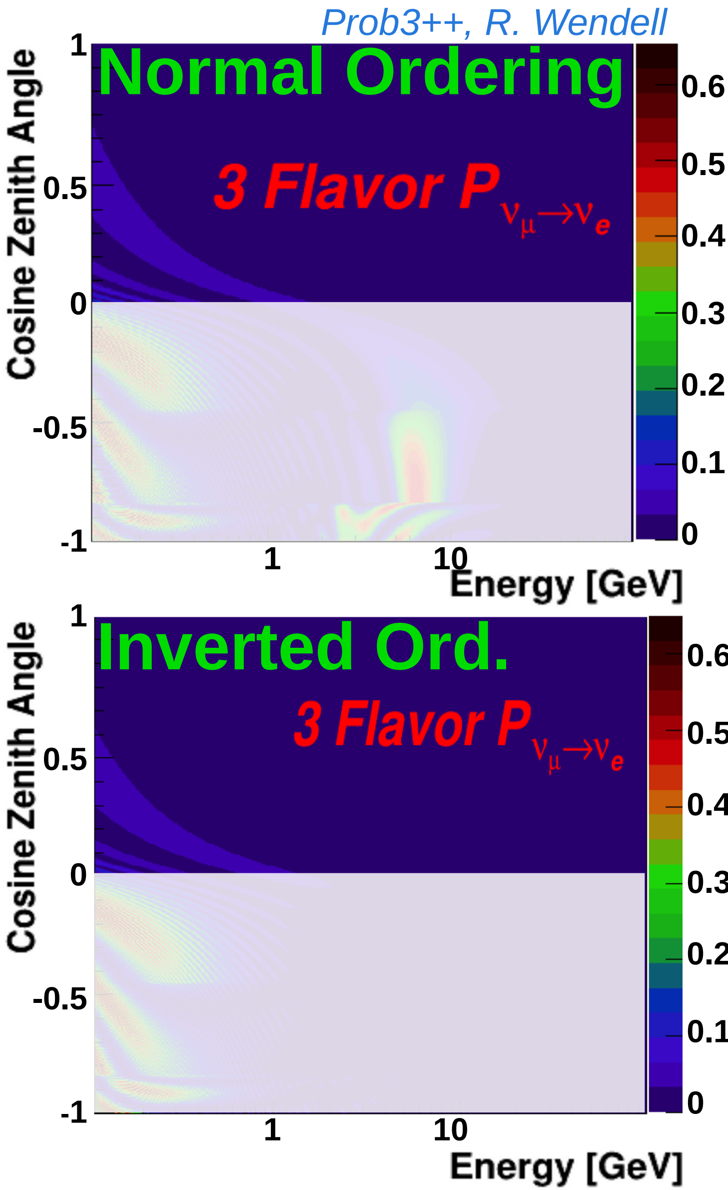


Standard Neutrino Oscillations

Vacuum oscillations: neutrinos coming from above $(\cos(\theta_{zen}) > 0)$

$$|\overline{\nu}_l\rangle = \sum_l U_{PMNS}^{li} |\overline{\nu}_i\rangle$$

$$U_{PMNS} = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{23}s_{13}c_{12}e^{i\delta} & c_{23}c_{12} - s_{23}s_{13}s_{12}e^{i\delta} & s_{23}c_{13} \\ s_{23}s_{12} - c_{23}s_{13}c_{12}e^{i\delta} & -s_{23}c_{12} - c_{23}s_{13}s_{12}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$



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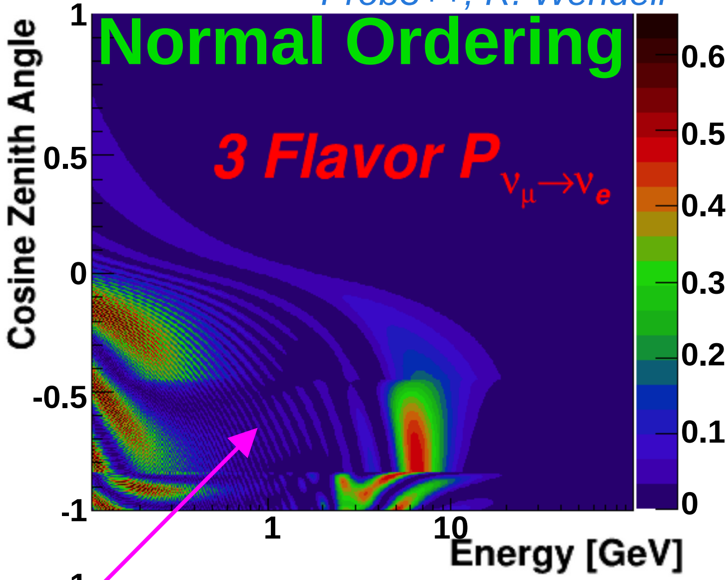
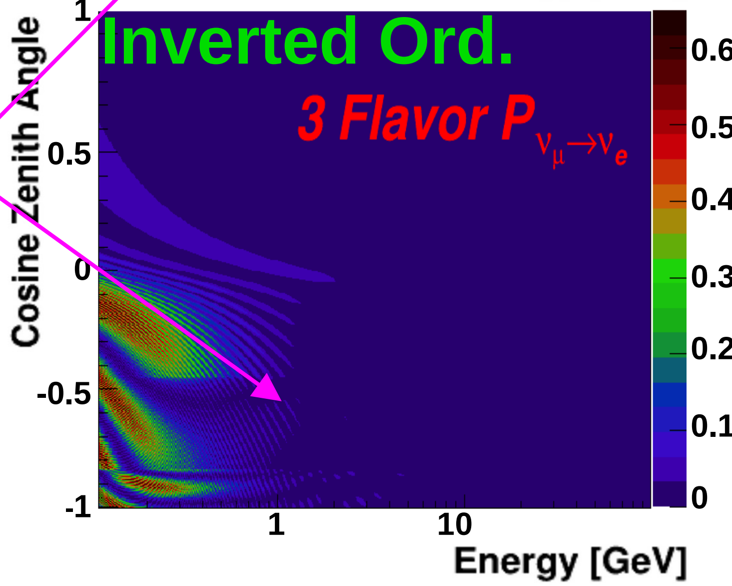
Neutrinos coming from below ($\cos(\theta_{zen})<0$), pass through the Earth changing the effective Hamiltonian and thus, the neutrino propagation

$$H_{eff} = H_0 + H_{CC} = H_0 \pm \overbrace{\sqrt{2}G_F N_e \mathrm{diag}(1,0,0)}^{V_{MSW}}$$

Producing opposite effects each mass ordering between neutrinos and antineutrinos

Prob3++, R. Wendell





Non-Standard Interactions in Neutrino Oscillations

Non-standard interactions (NSI) are motivated by some GUT models, where the existence of heavy (~TeV) bosons allow flavour-changing neutrino interactions

- This changes the hamiltonian thus, the propagation of neutrinos through matter and the neutrino-mixing

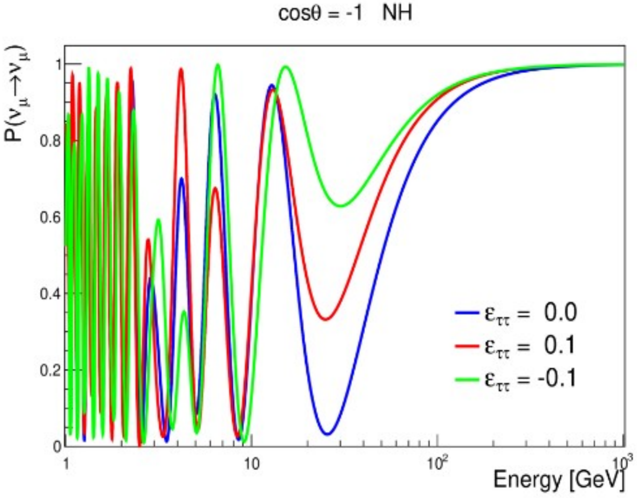
Vacuum oscillations **Matter oscillations**

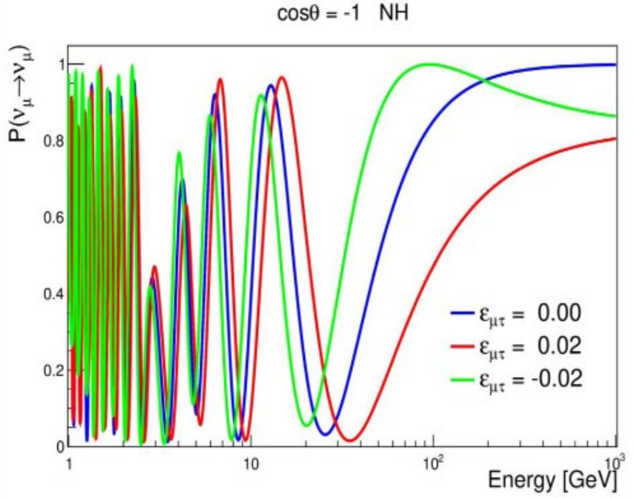
$$H_{\alpha\beta} = \frac{1}{2E} U_{\alpha j} \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} (U^\dagger)_{k\beta} + V_{\text{MSW}} + \sqrt{2} G_F N_f(\vec{r}) \begin{pmatrix} \varepsilon_{ee} & \varepsilon^*_{e\mu} & \varepsilon^*_{e\tau} \\ \varepsilon_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon^*_{\mu\tau} \\ \varepsilon_{e\tau} & \varepsilon_{\mu\tau} & \varepsilon_{\tau\tau} \end{pmatrix}$$

Standard oscillations **NSI**

Atmospheric neutrinos are very well suited to the search of non-standard interactions:

- large matter effects νs go through Earth ($\cos(\theta_{zen}) \simeq -1$)
- significant effects at high energies ($E_\nu > 20\, GeV$)

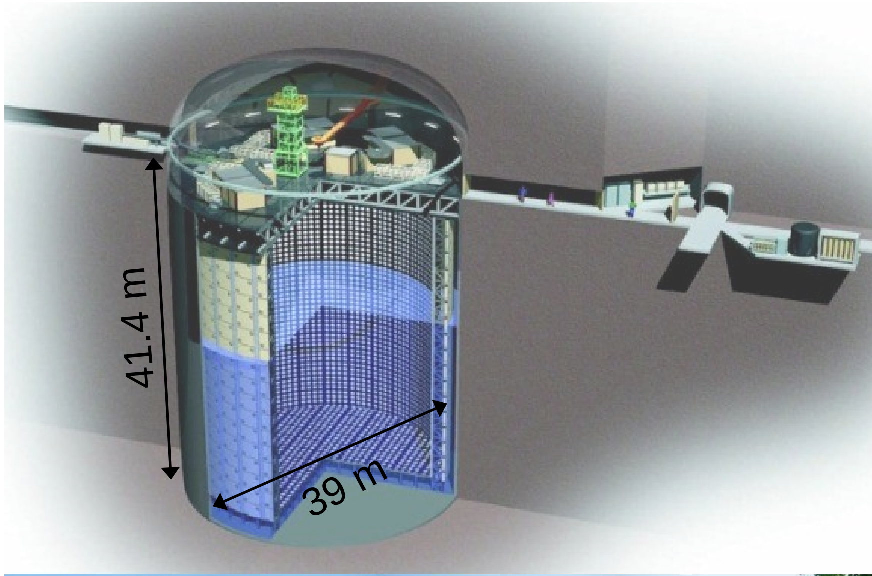




The Super-Kamiokande Experiment

- Water-Cherenkov detector
- Located in Kamioka, Japan
- Under Mt. Ikenoyama, overburden 1km of rock
- Total of 50 kton of ultra-pure water
  - ➔ Currently doped with **Gd sulfate**
- Optically divided into inner (ID) and outer (OD) detectors, instrumented with
  - **ID:** ~11000 20”-PMTs → 40% photo-coverage
  - **OD**: ~1900 8”-PMTs primarily used as veto

25 years since its start and still has a lot to teach!



The Super-Kamiokande Experiment

- Covers a wide variety of fundamental physics over a wide range of energies:
  - Solar, **atmospheric**, LBL, SN and astrophysicsal νs, proton decays, etc.

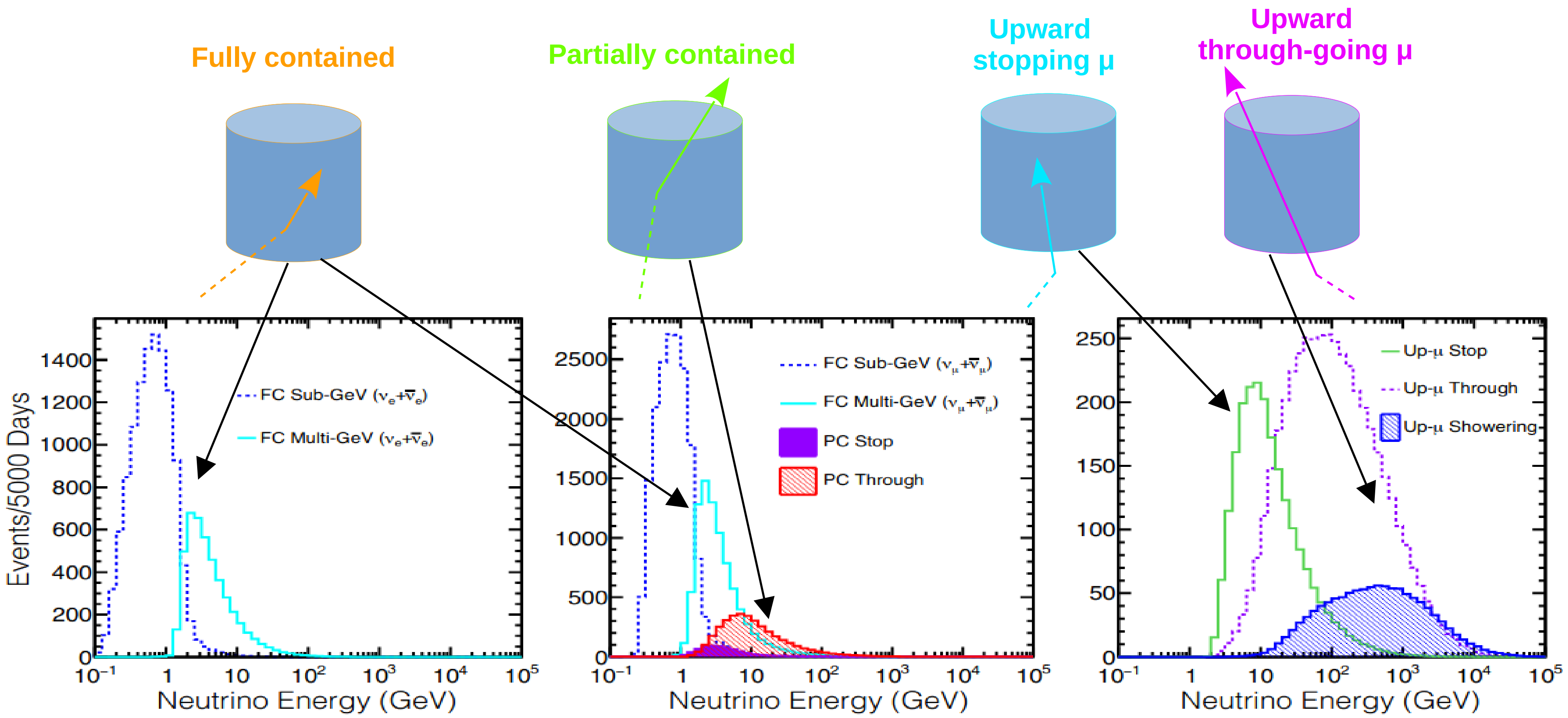
	Period	Event
SK-I	1996 to 2001	Start
SK-II	2003 to 2005	20% PMT coverage after accident
SK-III	2006 to 2008	Resume 40% PMT coverage
SK-IV	2008 to 2018	Electronics upgrade
SK-V	2019 to 2020	Upgrade for Gd-loading
SK-VI	2020 to ...	0.01% Gd-doped WC detector

- Still at the forefront of neutrino physics with the latest upgrade (still ongoing), **SuperK-Gd**
  - Eventually reaching a concentration of 0.1% of Gd, detecting 90% of neutrons

- Even richer physics capabilities:
  - First measurement of Diffuse SN Background
  - Background reduction for proton-decay
  - Improved distinction of νs and $\bar{\nu}$s at low (~MeV) higher energies (~GeV)
  - Search for solar antineutrinos

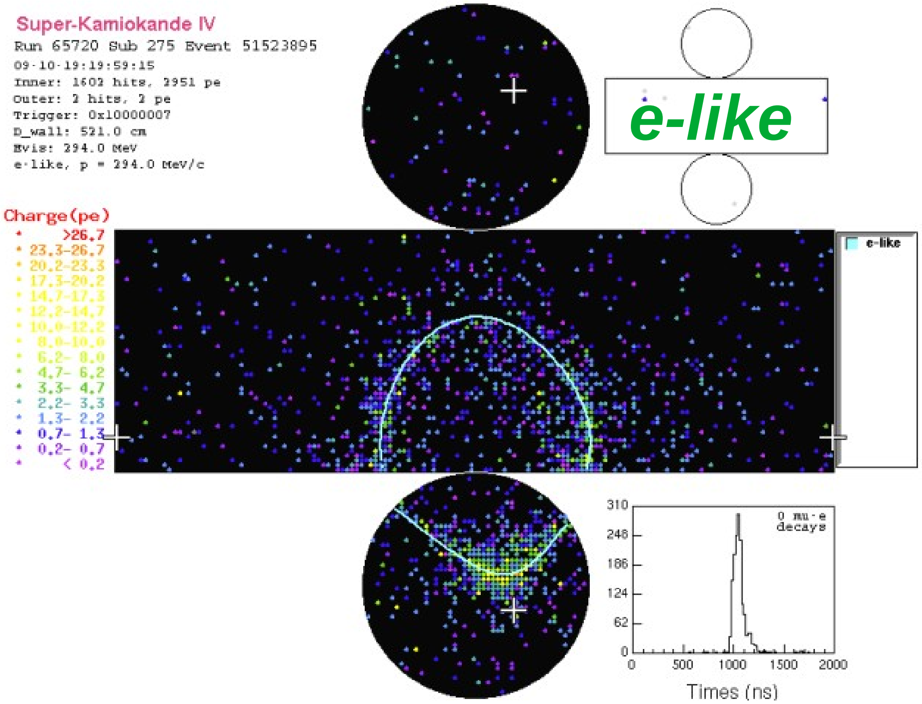
SK Atmospheric Neutrino Event Classification

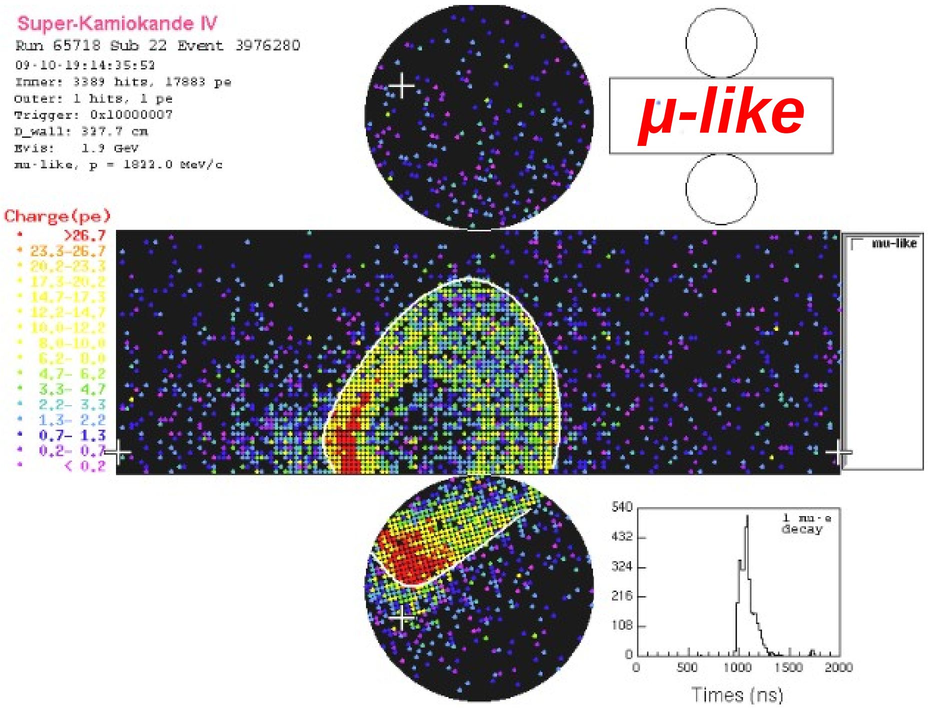
- Depending on the topology and the ID and OD activities



SK Atmospheric Neutrino Event Classification

- Further, events can be split into e-like and μ-like taking into account the features of the Cherenkov rings



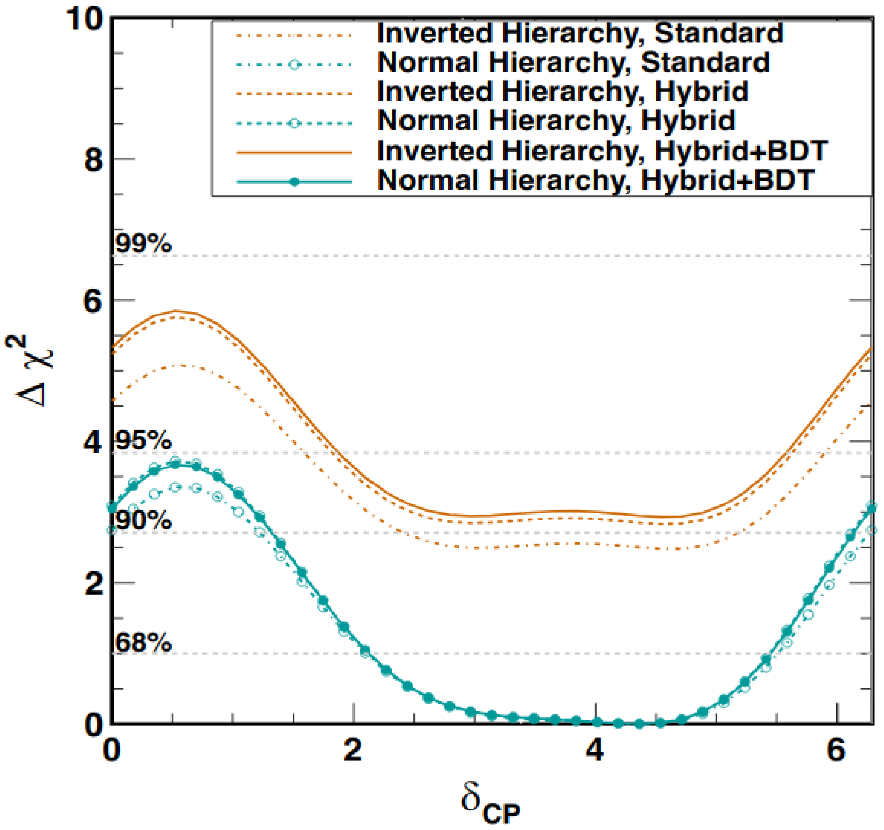


- In addition, depending on kinematics, number of rings and other features fully contained events are classified into 14 subsamples (Phys.Rev.D97,072001(2018))

SuperK Atmospheric Neutrinos

Updates:

- *Sample definition for **SK-IV** based on **H-neutron tagging** (hybrid) improving the distinction between neutrinos and antineutrinos*
- *Employ machine learning (BDT) to better classify **multi-ring events***
- *New Monte-Carlo using **NEUT 5.4.0** with updated cross-section models*
- *Updated and additional systematic errors included*
- *Changed **zenith binning** to better target the matter effects*

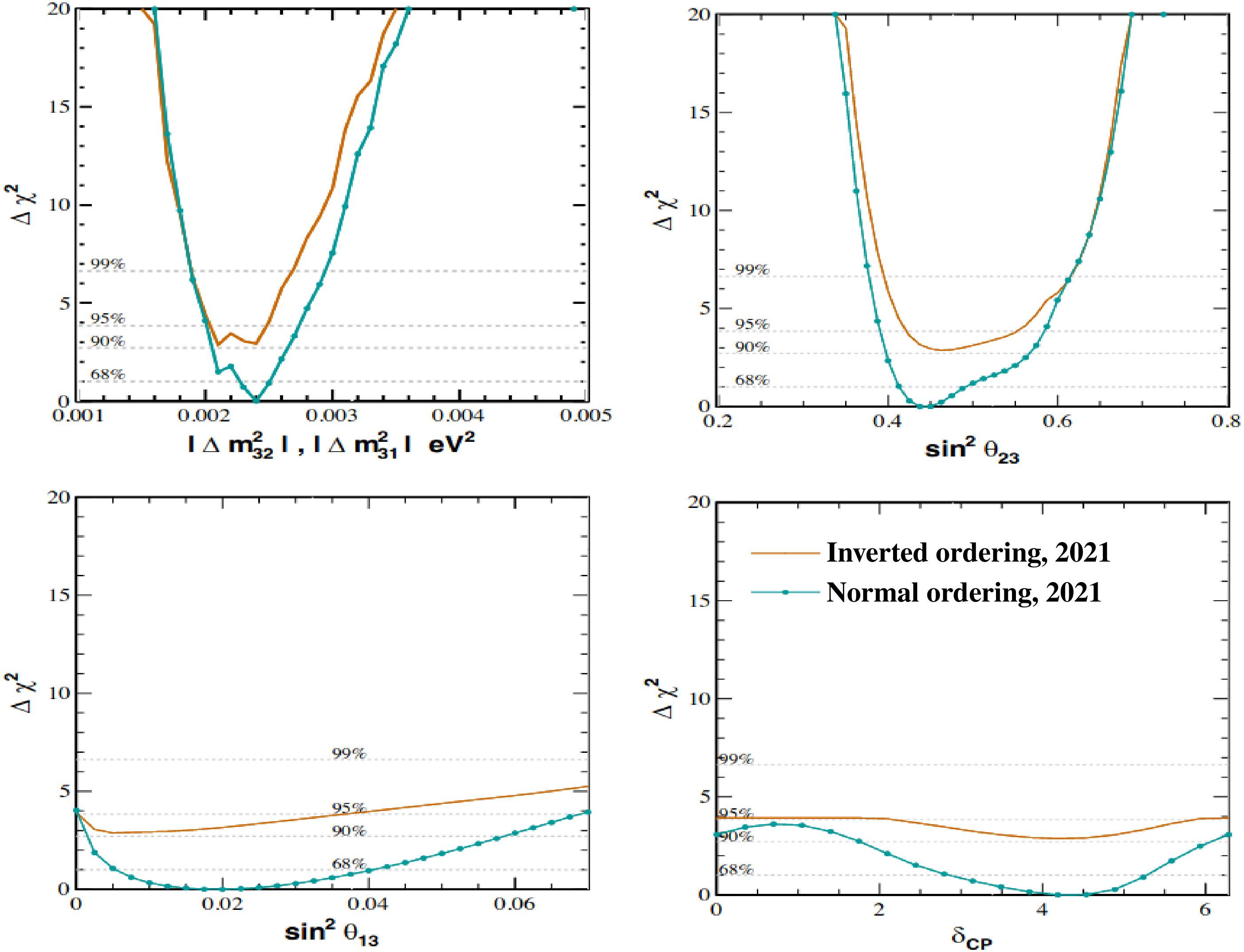


SK Atm. Neutrinos Results: Standard oscillations

Analysis of the whole atm. data collected from SK-I to SK-IV: ~16.5 years

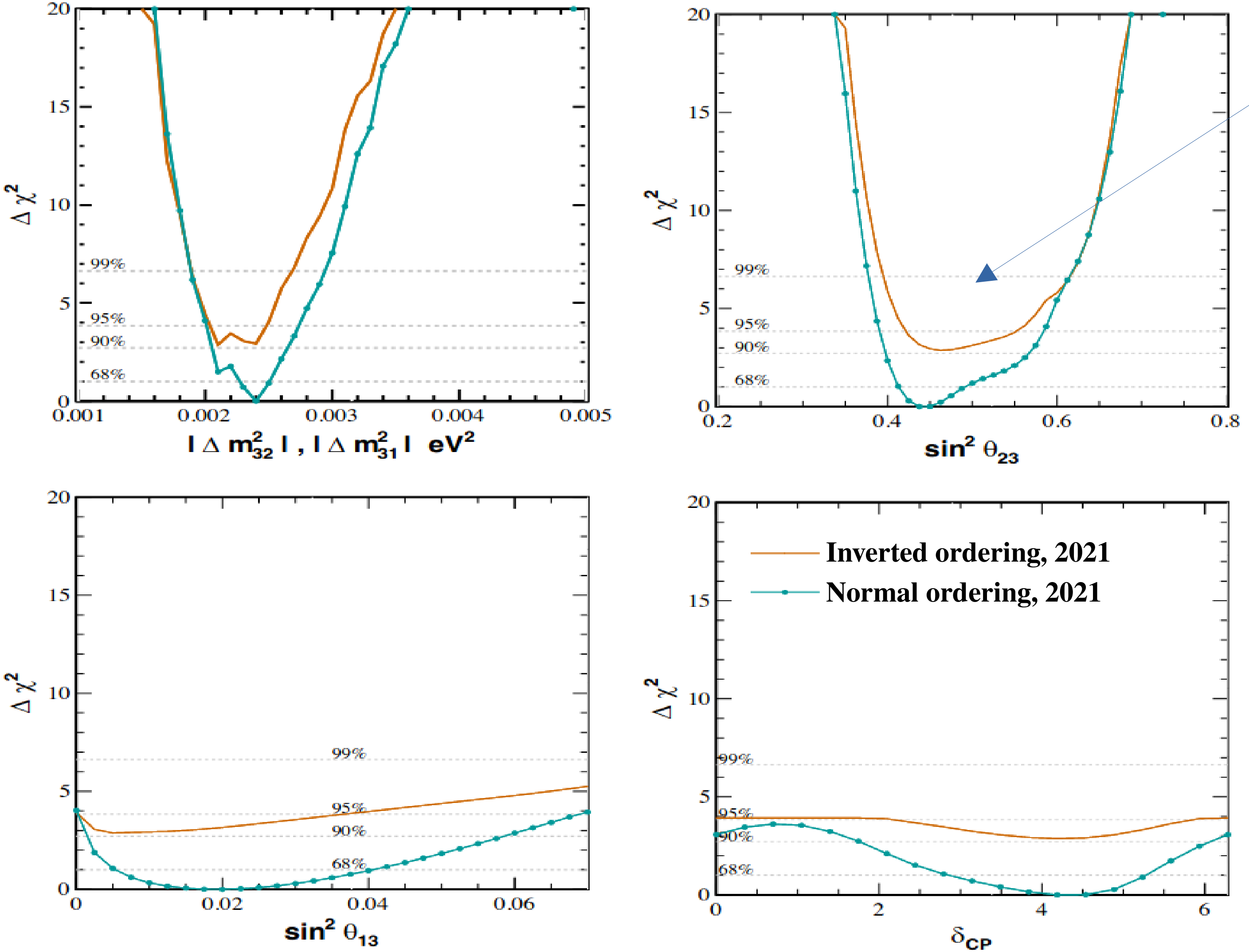
Results have fixed the solar parameters and θ_{13} unconstrained

SK Atm. Neutrinos Results: Standard oscillations



- Results prefer θ_{23} to be in the first octant
- Normal mass ordering is still prefered at $\Delta\chi^2(IH) - \Delta\chi^2(NH) = 2.8$
- δ_{CP} best fit value agrees with that of T2K
- Some constraining power over θ_{13} and consistent with reactor and LBL experiments

SK Atm. Neutrinos Results: Standard oscillations



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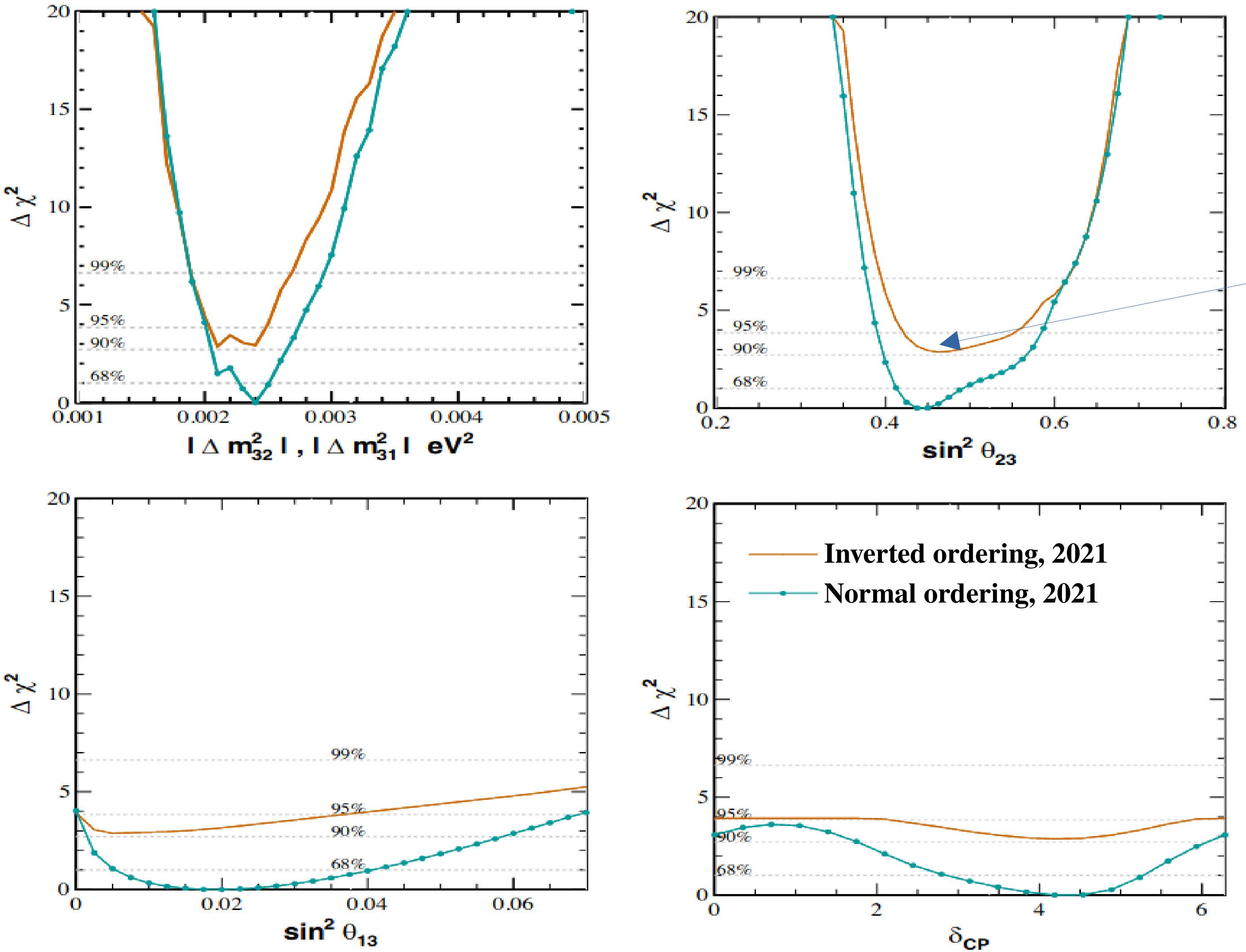

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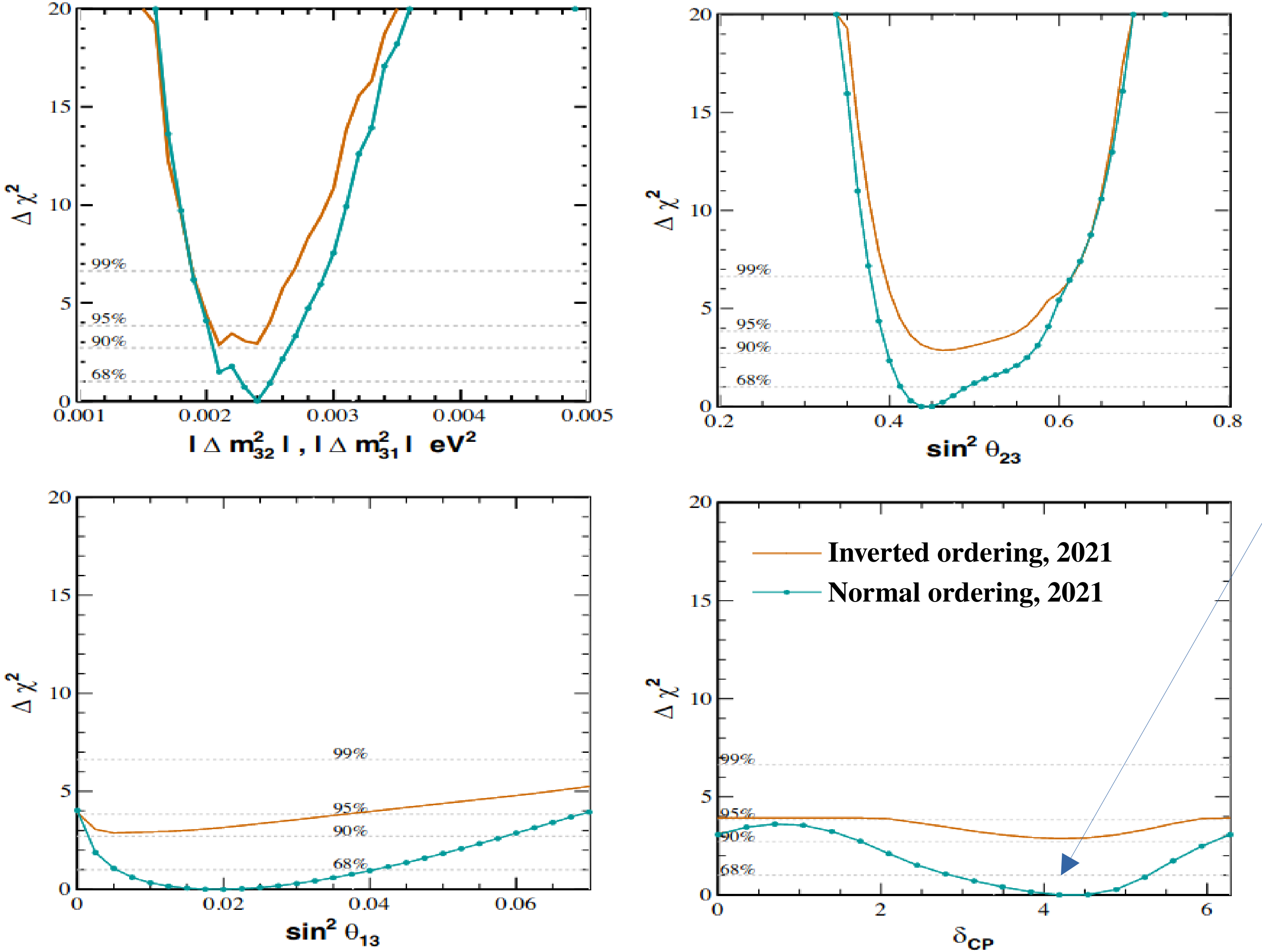

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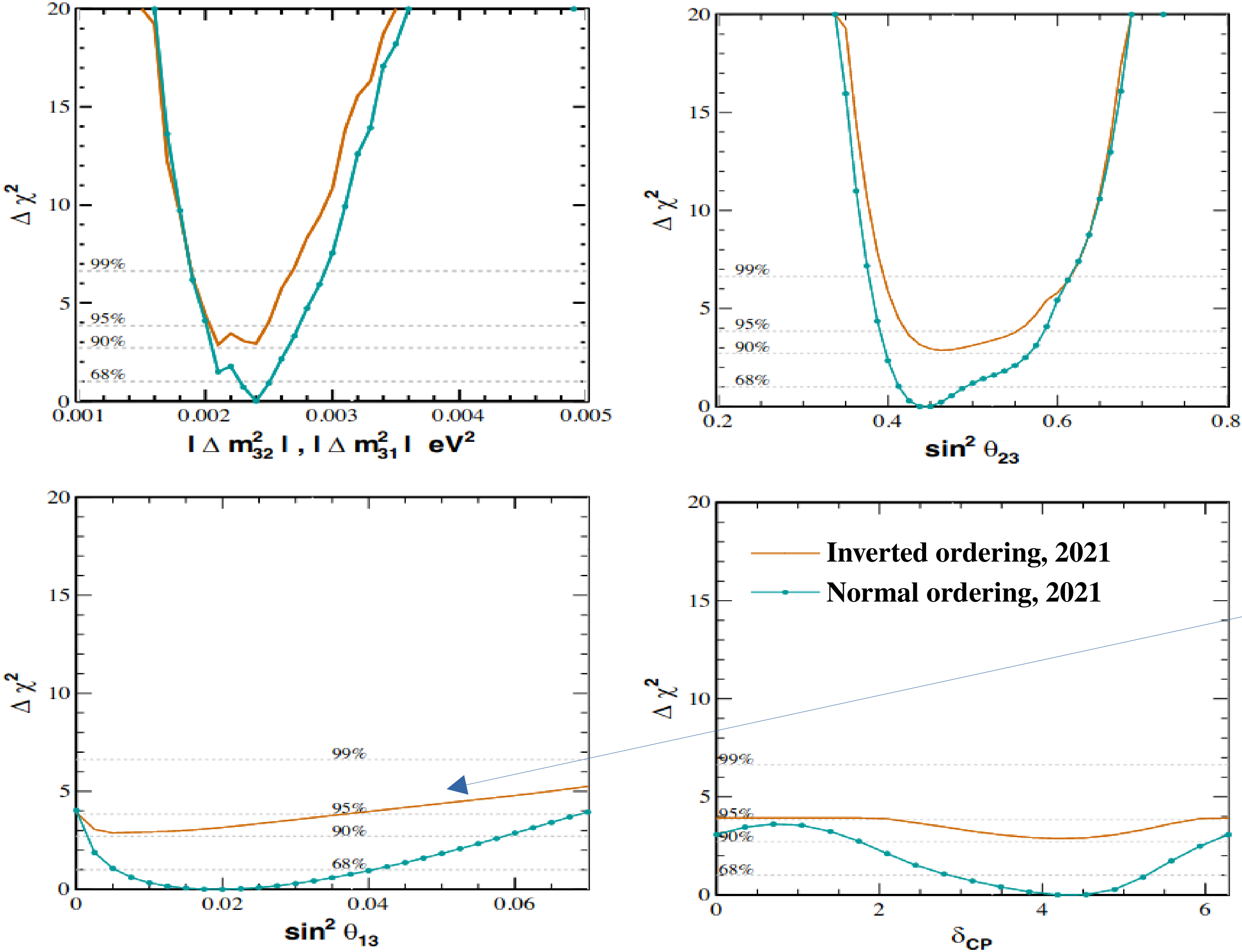

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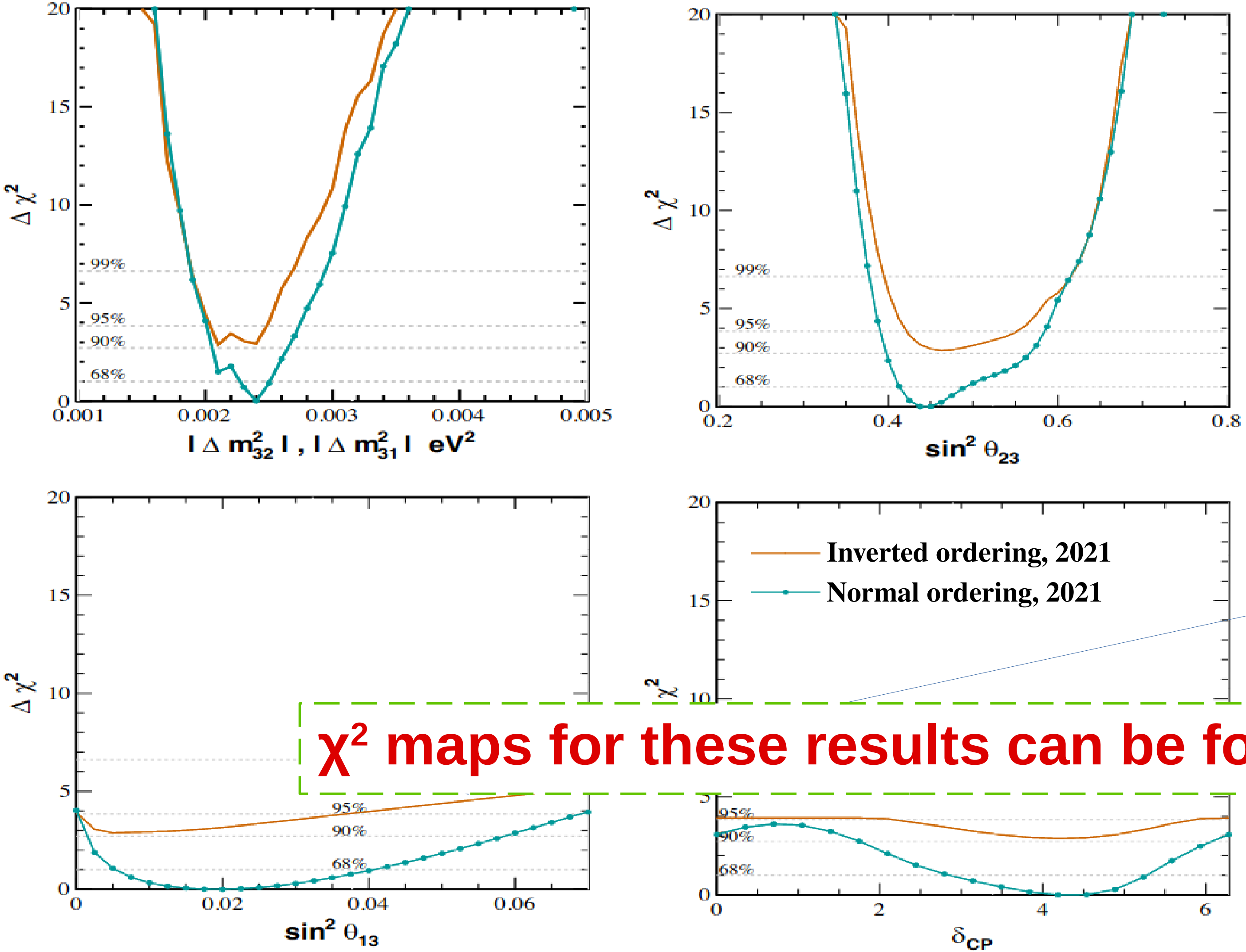

χ^2 maps for these results can be found here

- Results prefer θ_{23} to be in the first octant
- Normal mass ordering is still prefered at <u>$\Delta\chi^2(IH) - \Delta\chi^2(NH) = 2.8$</u>
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- Some constraining power over θ_{13} and consistent with reactor and LBL nts

SK Atmospheric Neutrinos: NSI oscillations

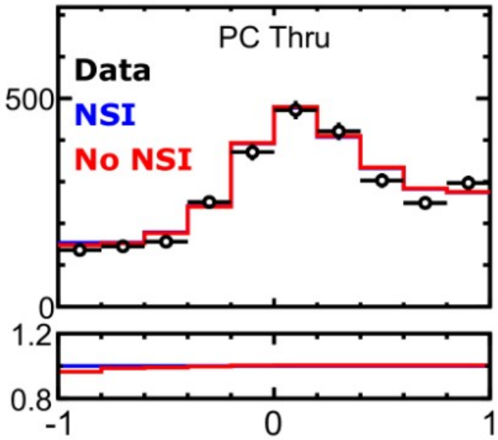
Analysis of ~15 years of atm. data collected from SK-I to SK-IV

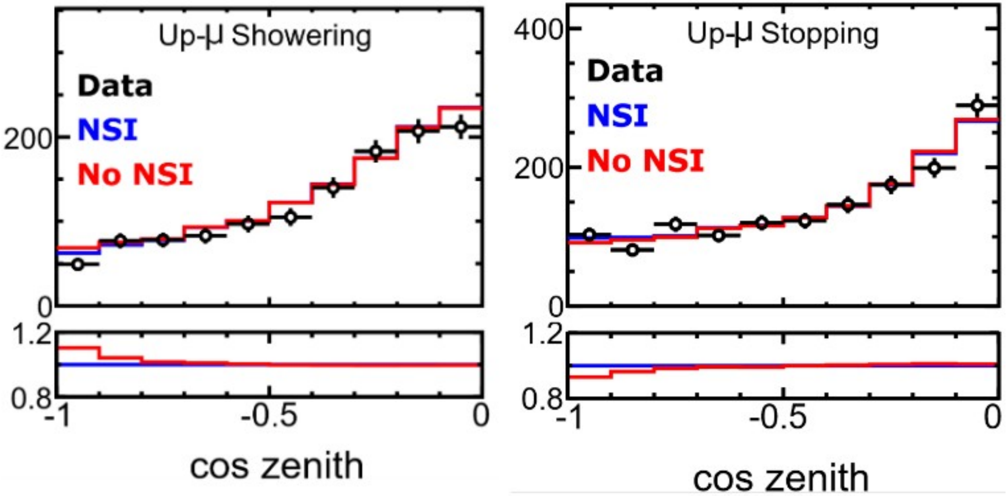
Results assume standard oscillation parameters fixed to SK best fit

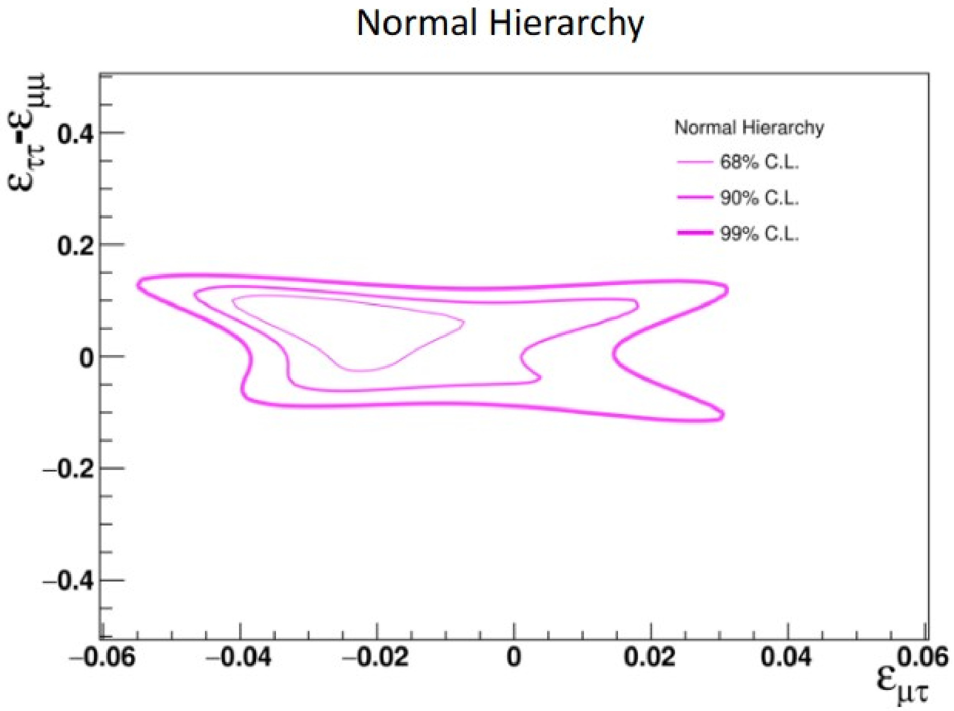
SK Atmospheric Neutrinos: NSI oscillations

Fit to the μ-τ sector

All $\varepsilon_{e\alpha}$ set to 0







SK1-4 (90%C.L):

$-4.5\times10^{-2} < \varepsilon_{\mu\tau} < 1.9\times10^{-2}$

$-5.1\times10^{-2} < \varepsilon_{\tau\tau} - \varepsilon_{\mu\mu} < 1.4\times10^{-1}$

SK Atmospheric Neutrinos: NSI oscillations

Fit to the μ-τ sector

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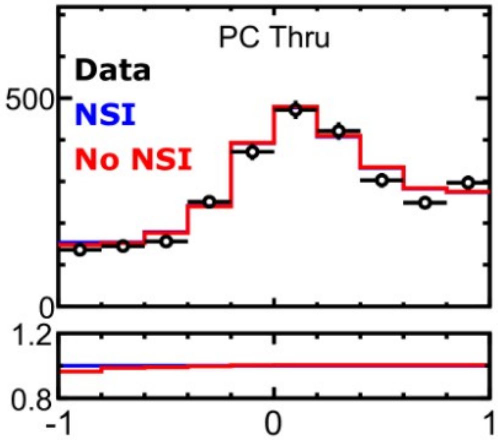

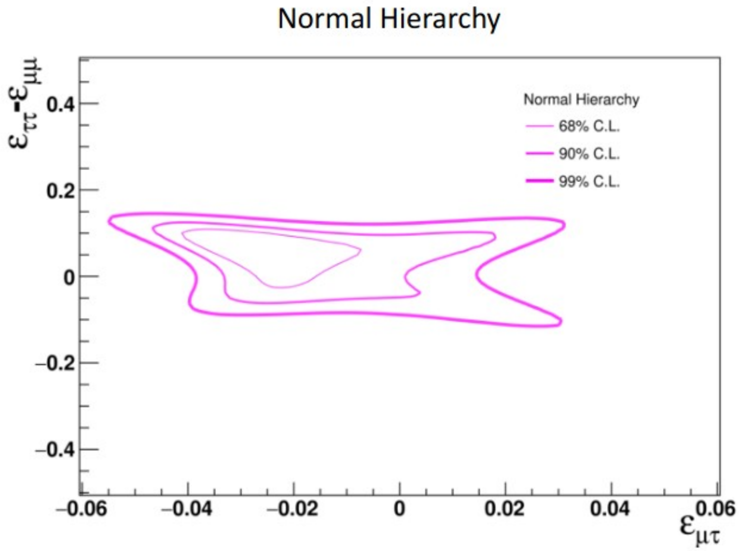

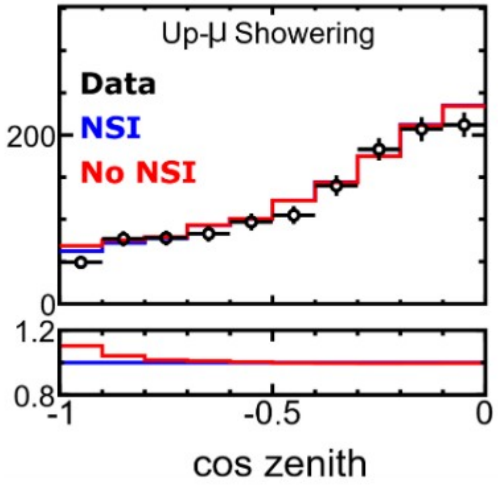

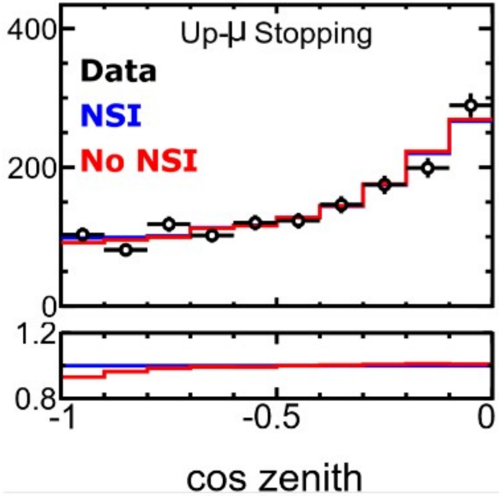

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Consistent with the latest published results from DeepCore (90%CL)

$$-6.7 \times 10^{-3} < \varepsilon_{\mu\tau} < 8.1 \times 10^{-3}$$

Phys. Rev. D 97, 072009

SK Atmospheric Neutrinos: NSI oscillations

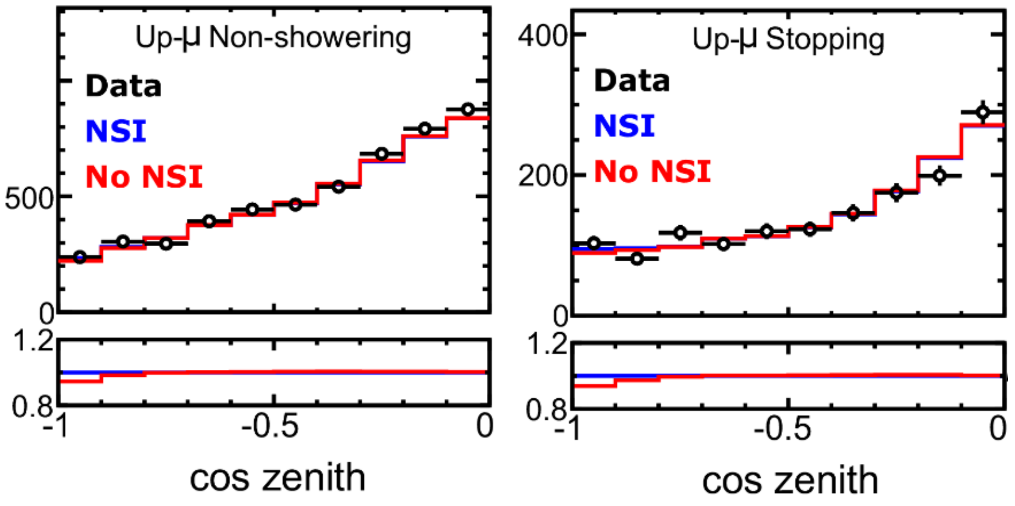
Fit to the e-τ sector

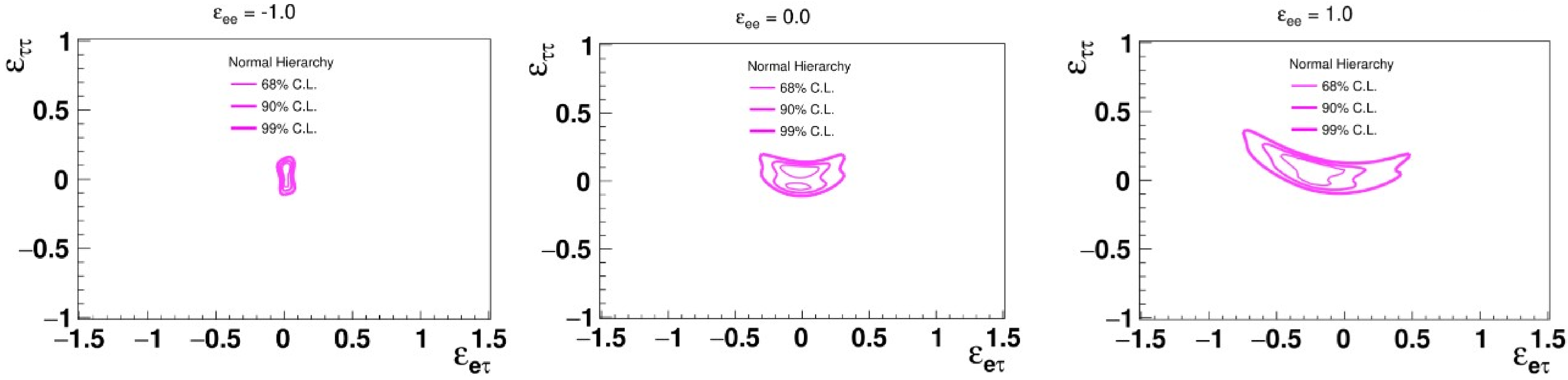
Atmospheric νs tightly constrain $\varepsilon_{\tau\tau}$

For $\varepsilon_{\mu\alpha} = 0$, the NSI parameters follow

$$\varepsilon_{\tau\tau} = \frac{|\varepsilon_{e\tau}|^2}{1+\varepsilon_{ee}}$$

Various analyses are performed depending on the ε_{ee} scenario





Conclusions

- **Upgraded and updated atmospheric neutrino oscillation analysis:**
  - Neutron tagging for ν-$\bar{\nu}$ separation
  - Multi-ring BDT classification
  - Improved interaction models
  - Updated systematics

- **Results for standard neutrino oscillations:**
  - Preference for large (~3π/2) CP-phase values, agreeing with LBL experiments
  - Preference for normal mass ordering
  - Preference for first octant of θ_{23}

  χ^2 maps available at https://indico-sk.icrr.u-tokyo.ac.jp/event/5517/

- **Results for neutrino oscillations with NSI:**
  - Consistent with no NSI in both e-*τ and μ-τ sectors*