Atmospheric neutrino oscillations with Super-Kamiokande and prospects for SuperK-Gd

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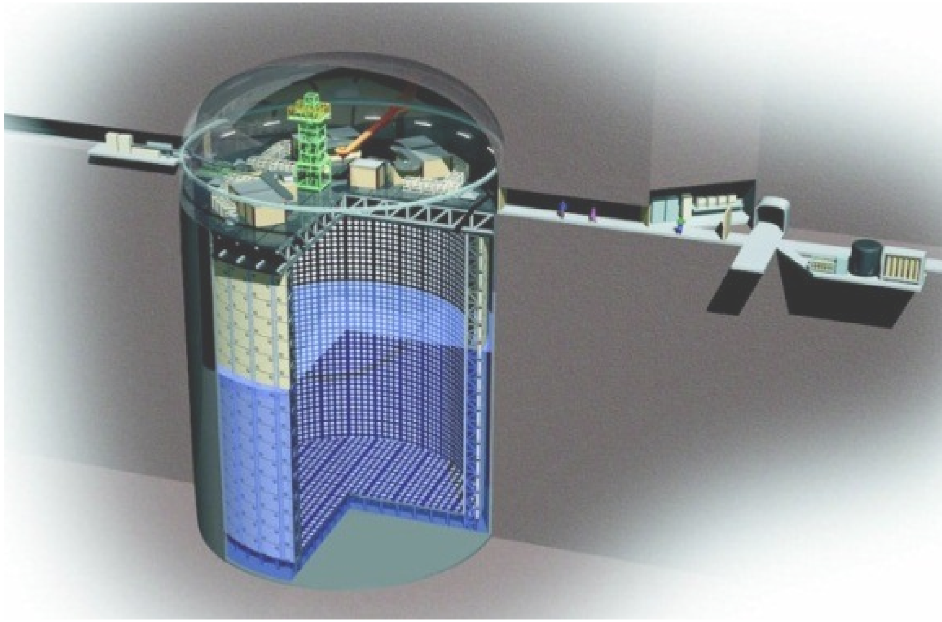
The Super-Kamiokande (SK) Experiment

- Water-Cherenkov detector
- Located in Kamioka, Japan
- Under Mt. Ikenoyama
- Overburden 1km of rock
- Total of 50 kton of ultra-pure water, and **22.5 kton fiducial volume**
- Optically divided into inner (ID) and outer (OD) detectors, instrumented with
  - **ID:** ~11000 20”-PMTs → 40% photo-coverage
  - OD: ~2000 8”-PMTs mainly used as veto

The Super-Kamiokande Experiment

- More than 20 years of operation and data taking

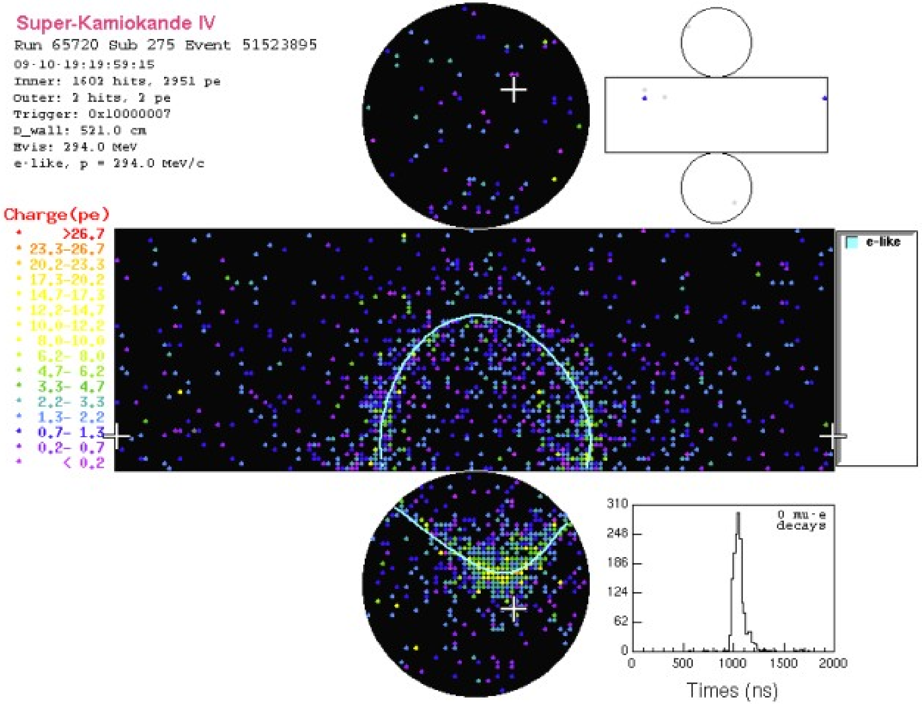
	Period	Event
SK-I	1996 to 2001	Start
SK-II	2003 to 2005	20% PMT coverage after accident
SK-III	2006 to 2008	Resume 40% PMT coverage
SK-IV	2008 to 2018	Electronics upgrade
SK-V	2019 to 2020	Upgrade for Gd-loading
SK-Gd1	2020 to...	Largest Gd-doped WC detector



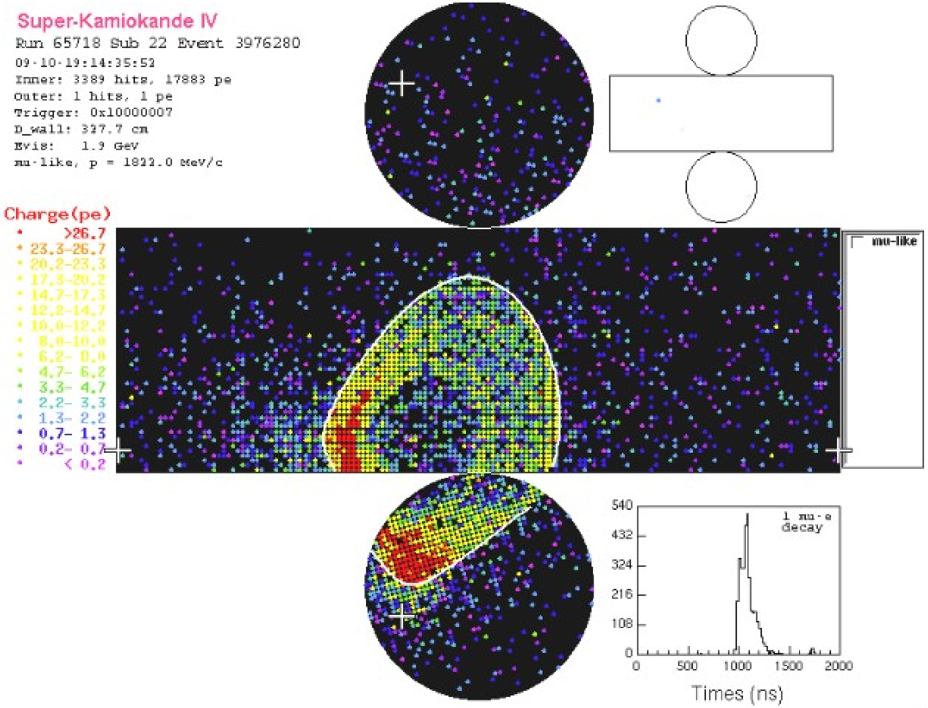
- Wide variety of fundamental physics over a wide range of energies:
  - Solar, **atm.**, LBL, SN and astrophysicsal νs, proton and exotic nucleon decays, dark matter
- Still at the forefront with its latest upgrade, **SuperK-Gd**
  - Will eventually reach a concentration of 0.2% of Gd, capturing 90% of the neutrons
- Even richer physics capabilities:
  - First measurement of DSNB
  - Background reduction for proton-decay
  - Search for solar antineutrinos
  - Improved distinction of νs and $\overline{\nu}$s at higher energies

The Super-Kamiokande Experiment

e-like



μ-like



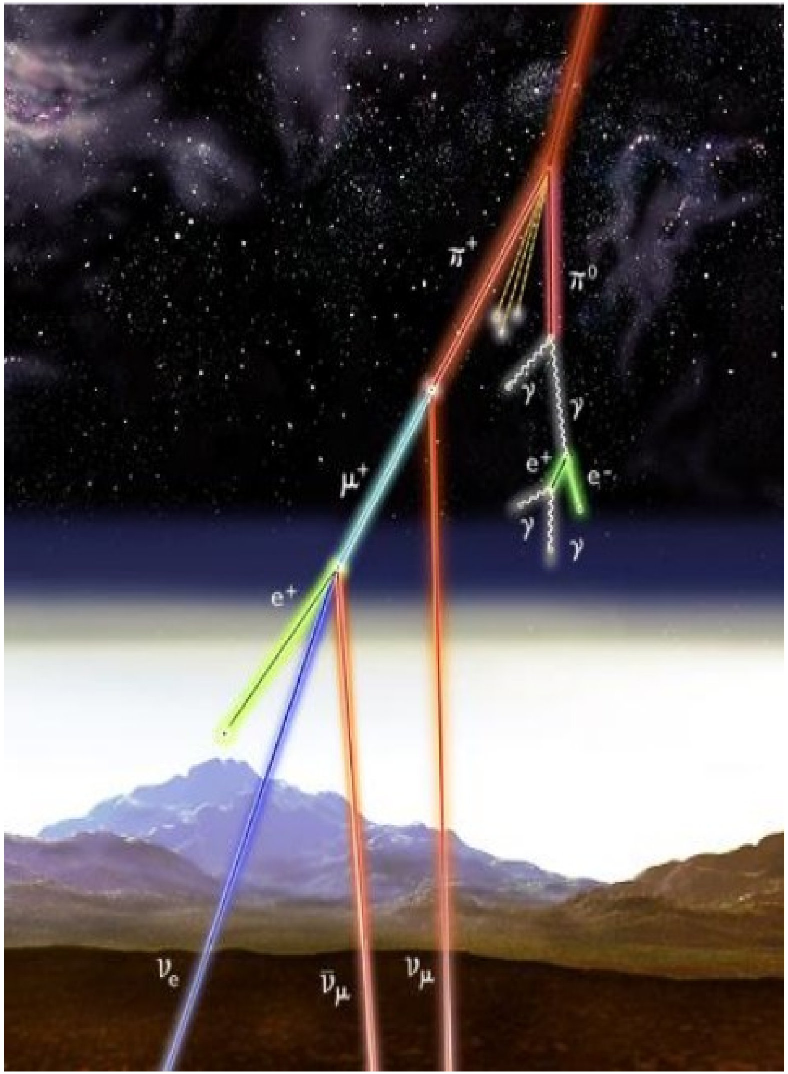
Atmospheric Neutrinos

- Neutrinos produced due to the interaction of cosmic rays and Earth's atmosphere

- Large statistics, but not enough yet
  - wide range of energies: $\mathcal{O}(10^{-1})$ GeV to $\mathcal{O}(10^{2})$ GeV
  - wide range of baselines: $\mathcal{O}(10)$ km to $\mathcal{O}(10^{4})$ km, half of them through the Earth

- Detailed and specific simulations are required to compute the neutrino flux

- SK discovered the **atmospheric neutrino oscillations** (Nobel 2015)



Atmospheric Neutrino Oscillations

Vacuum oscillations: neutrinos coming from above

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

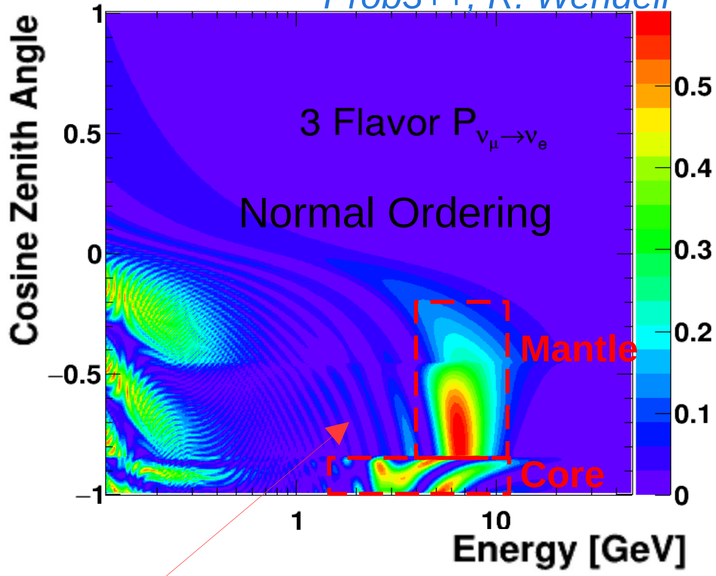
$$U_{PMNS} = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{23}s_{13}c_{12}e^{i\delta} & c_{23}c_{12} - s_{23}s_{13}s_{12}e^{i\delta} & s_{23}c_{13} \\ s_{23}s_{12} - c_{23}s_{13}c_{12}e^{i\delta} & -s_{23}c_{12} - c_{23}s_{13}s_{12}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

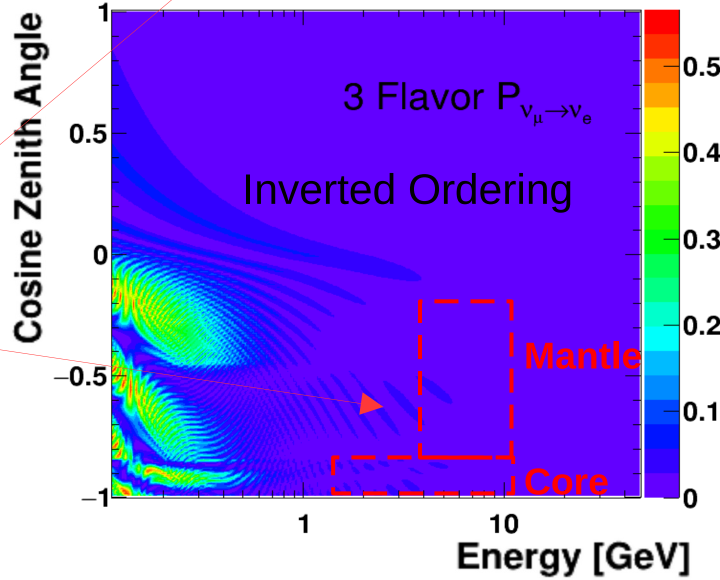
Neutrino coming from below, pass through the Earth changing the effective Hamiltonian and thus, the neutrino propagation

$$H_{eff} = H_0 + H_{CC} = H_0 \underline{+} \sqrt{2}G_F N_e \mathrm{diag}(1,0,0)$$

- matter potential is opposite for $\overline{\nu}$s
- mass ordering changes the matter (MSW) effects between νs and $\overline{\nu}$s

Prob3++, R. Wendell





SK Atmospheric Neutrino Oscillation Analysis

Atmospheric neutrinos are sensitive to crucial oscillation parameters:

- Neutrino mass ordering: e-like, > 1 GeV
- Leptonic δ_{CP} phase: < 1 GeV
- Octant of θ23: > 1 GeV

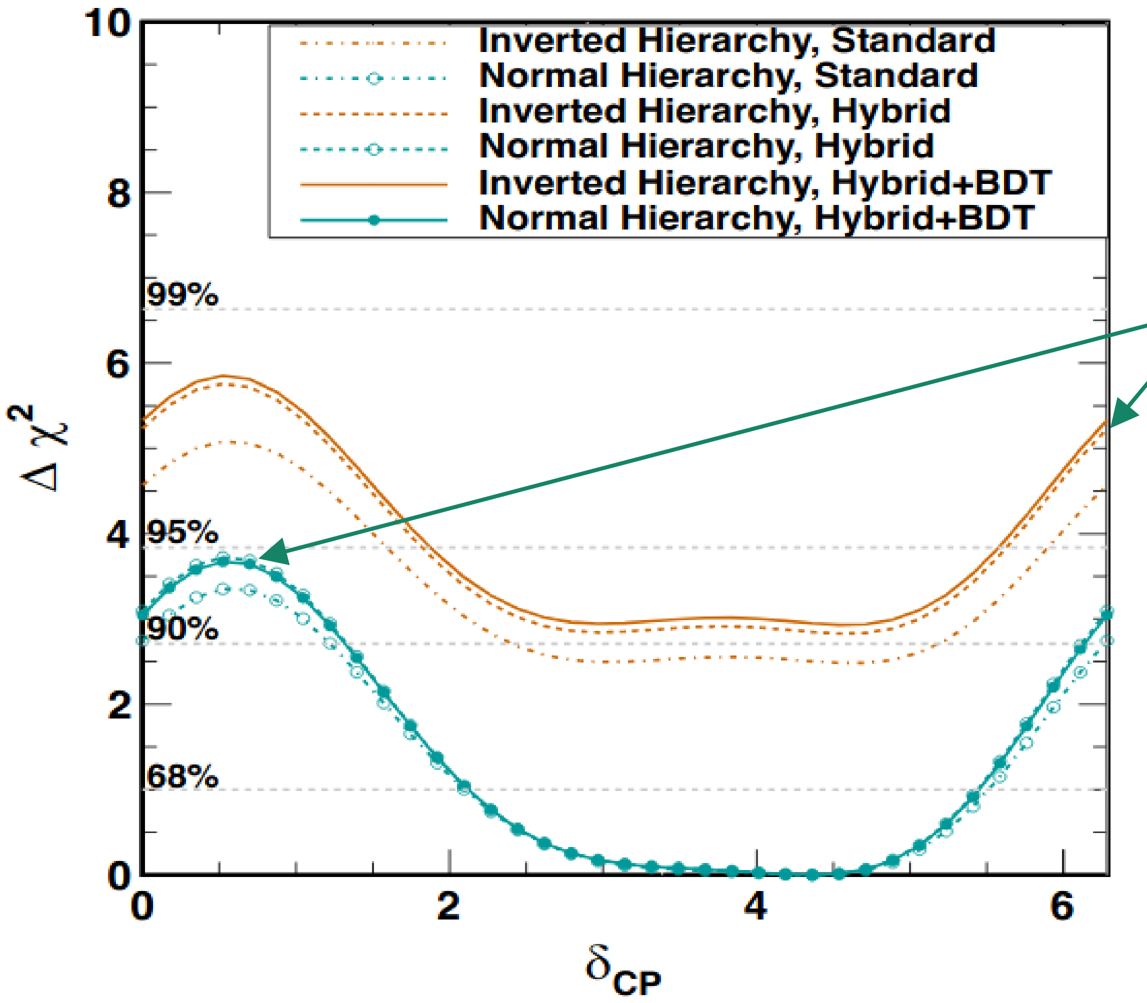
Separation of ν and $\bar{\nu}$ is crucial

Analysis updates since last publication *[Phys. Rev. D 97, 072001]*

- SK-IV electronics allows for neutron tagging on hydrogen, with an efficiency of 25%
  - New samples in SKIV for better single-ring ν/$\bar{\nu}$ separation
  - Usual sample scheme for SKI-III

  Hybrid analysis
- **New event selection for Multi-Ring** events based on Boosted Decision Tree
- New Monte-Carlo using **NEUT 5.4.0** with updated cross-section models and systematics
- Changed **zenith binning** to better target the **matter effects**
- Total of 3244.4 days

SK Atmospheric Neutrino Oscillation Analysis



Neutron tagging improves the sensitivty to the mass hierarchy and the CP-phase

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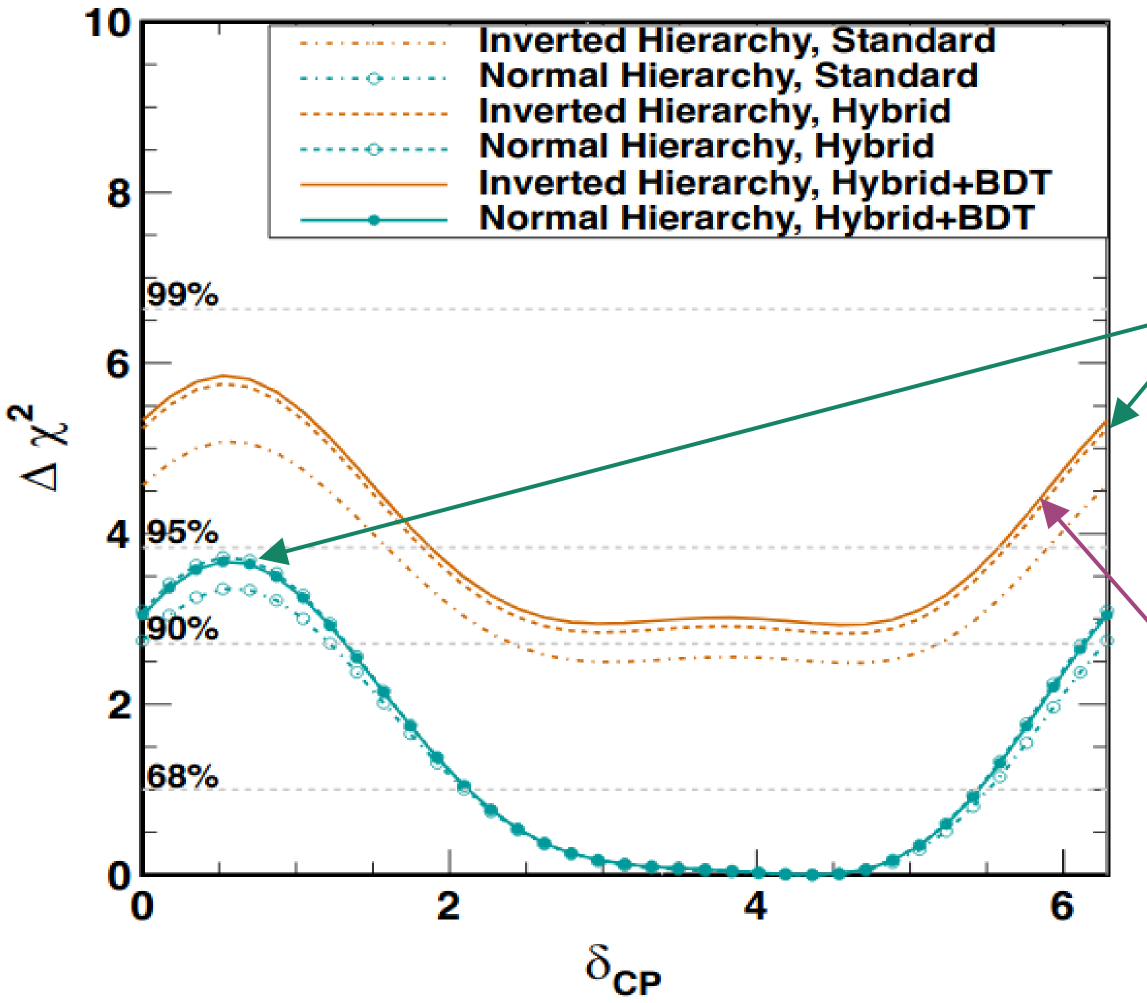
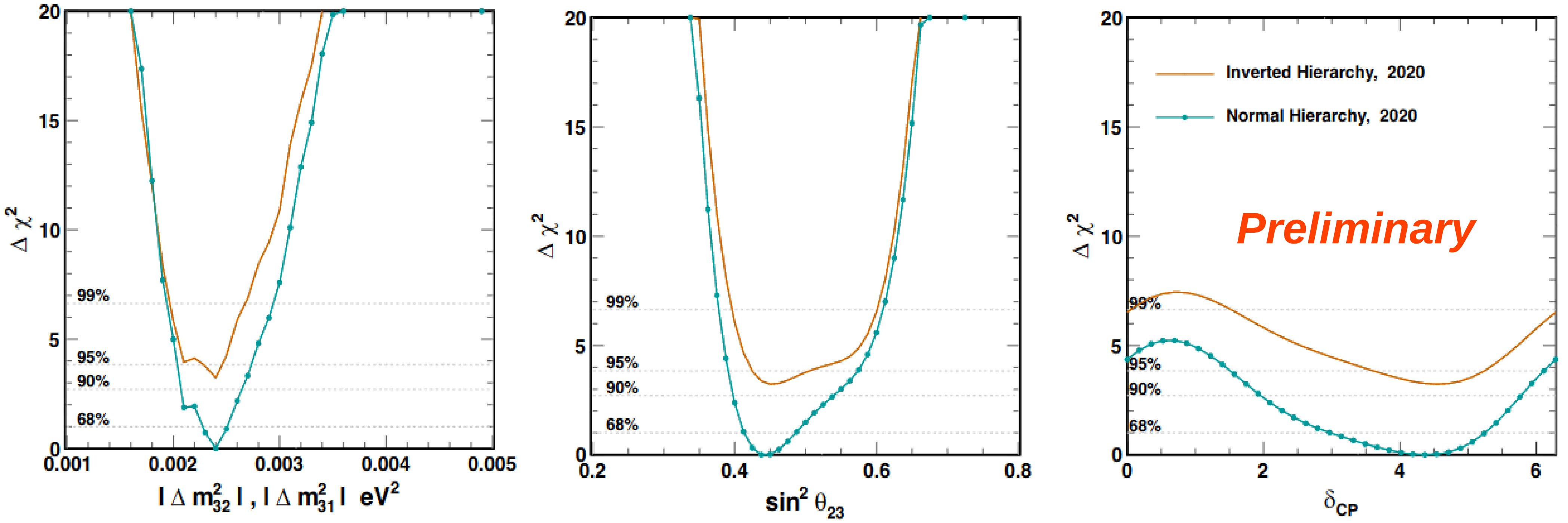


Neutron tagging improves the sensitivty to the mass hierarchy and the CP-phase

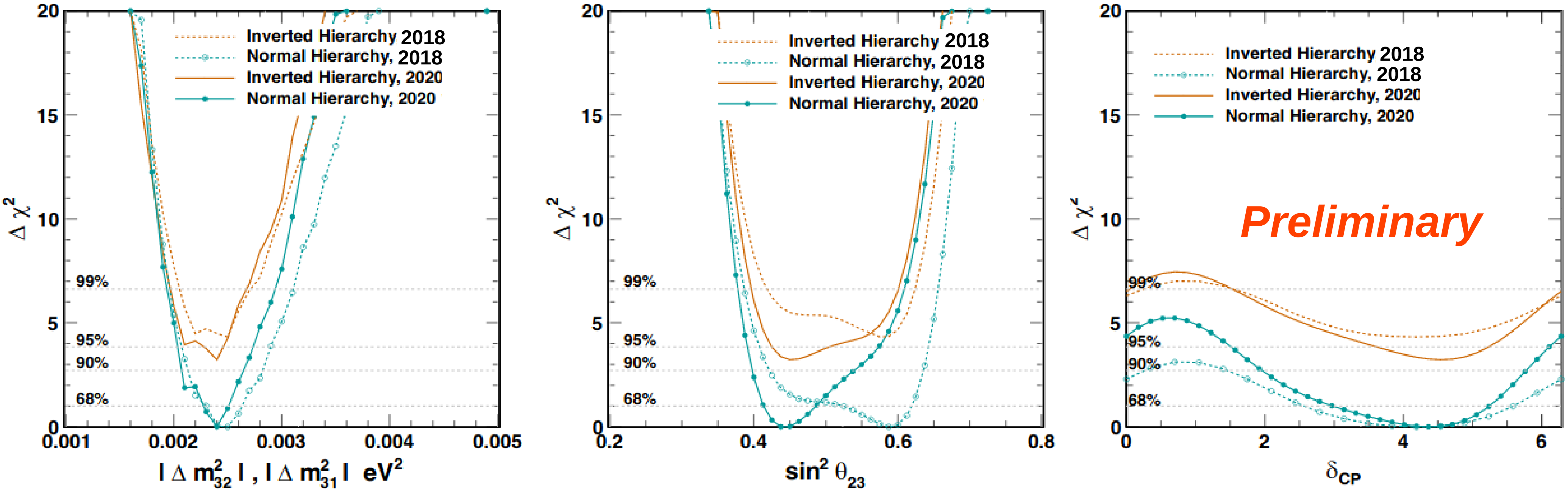
Improved **Multi-Ring** event classification enhances the sensitivity to the ordering

Results from the SK Atm. Neutrino Osc. Analysis



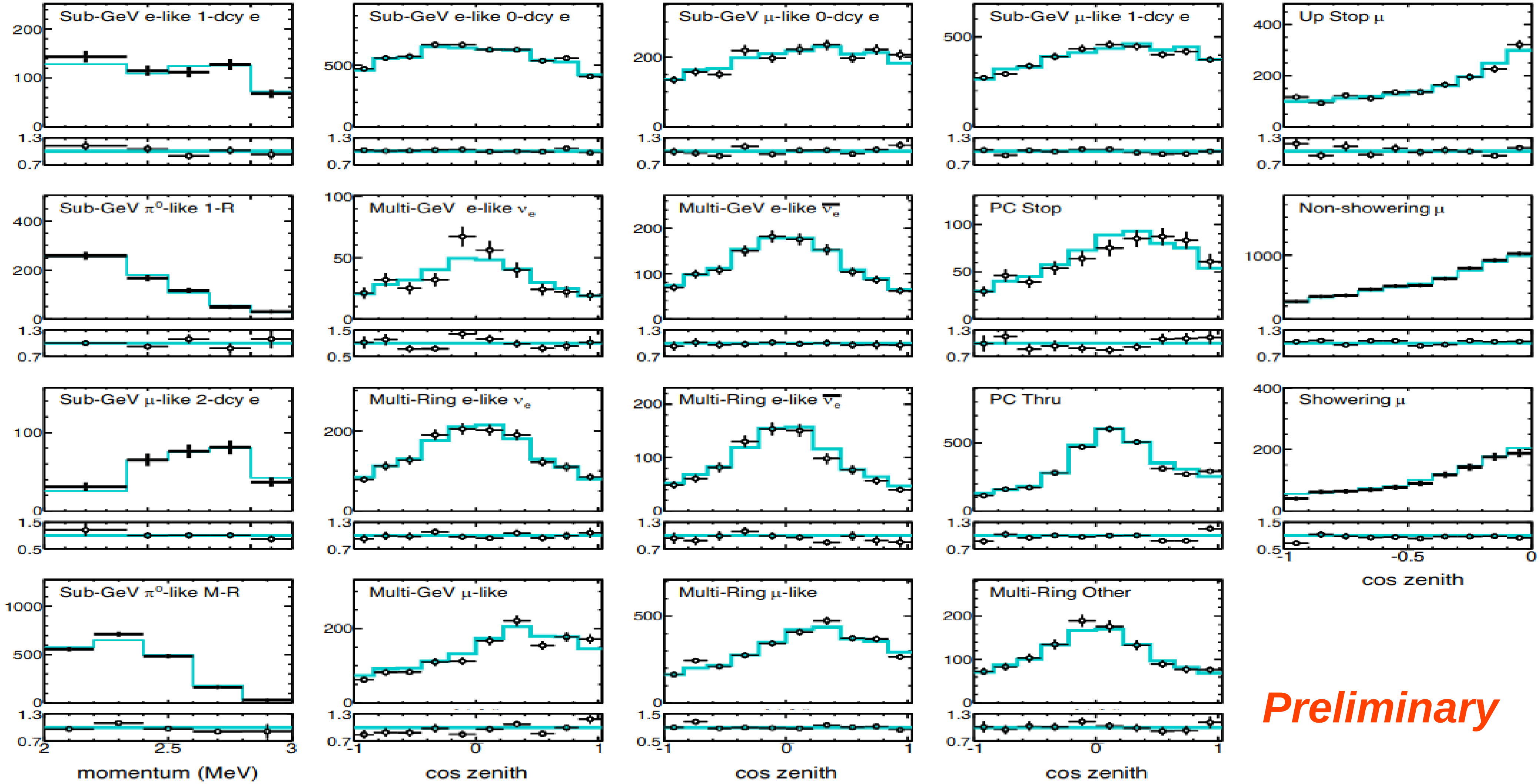
930 bins	χ2	θ_{13} (reac.)	δ_{CP}	θ_{23}	Δm_{23} ($\times10^{-3}$)
SK (NH)	1037.5	0.0218	$4.36^{+0.88}_{-1.39}$	$0.44^{+0.05}_{-0.02}$	$2.40^{+0.11}_{-0.12}$
SK (IH)	1040.7	0.0218	$4.54^{+0.88}_{-1.32}$	$0.45^{+0.09}_{-0.03}$	$2.40^{+0.09}_{-0.32}$

Comparison with previous results



- Preference for normal mass ordering at C.L. 86%
- Stronger rejection of small values of CP-phase
- Data prefers first octant and the contours for θ_{23} are significantly more constraining

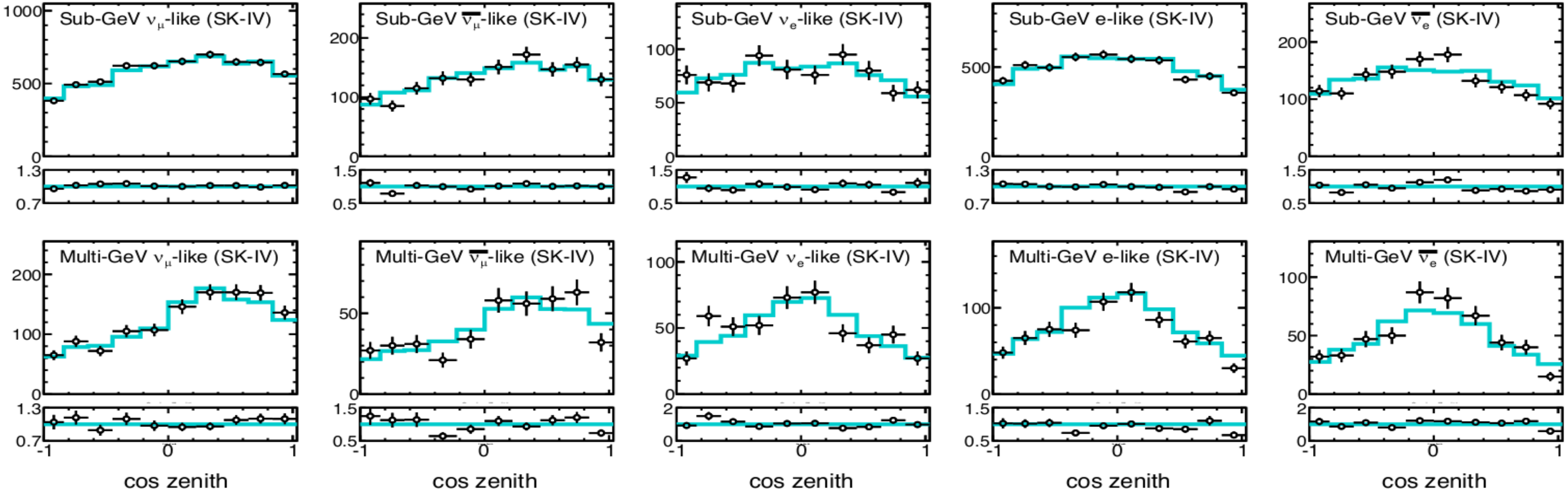
Explicit fit to the data *(traditional SK atm. samples)*



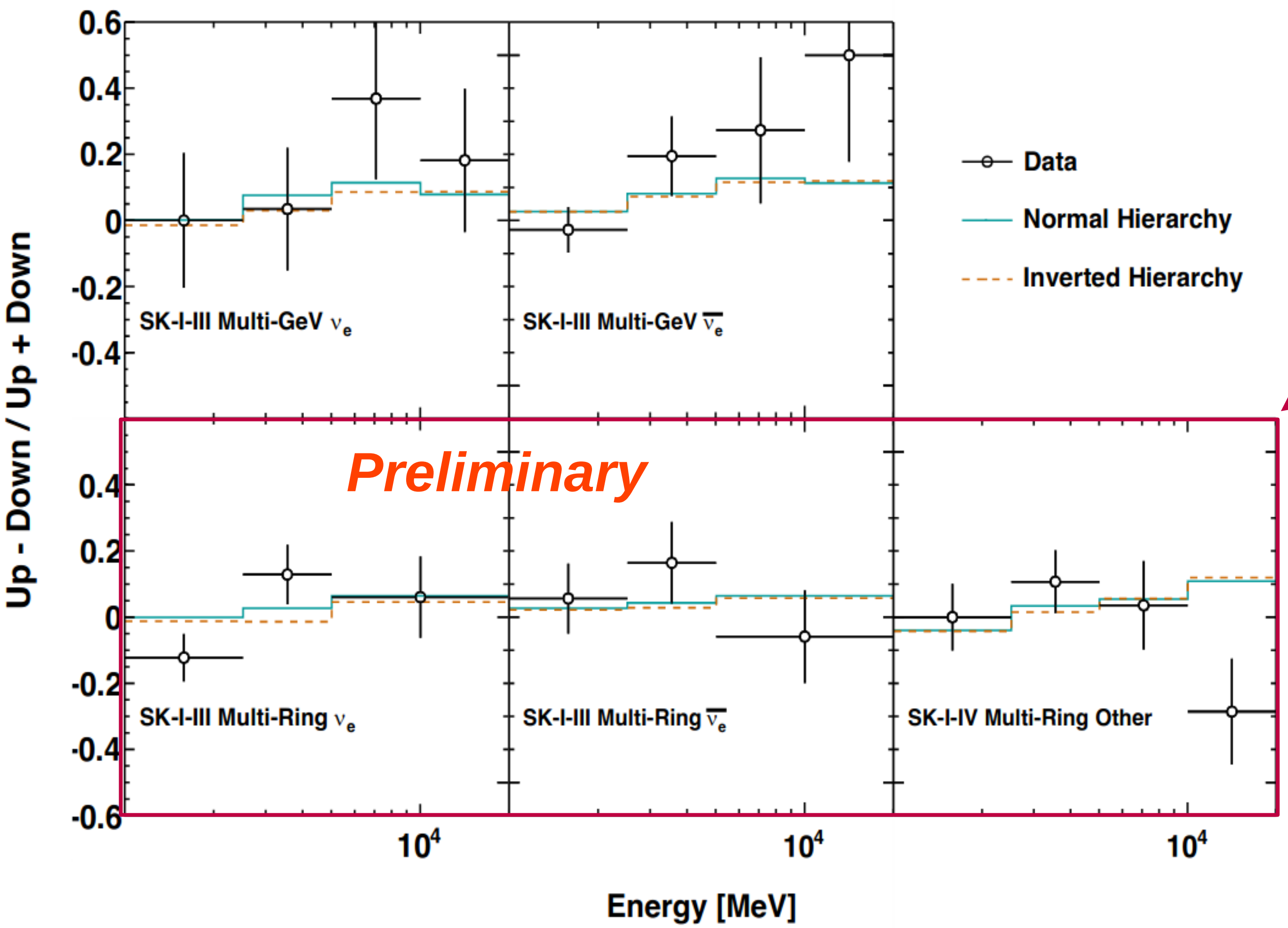
Preliminary

Explicit fit to the data *(neutron-tagging SK atm. samples)*

Preliminary



The hierarchy preference, a closer look



Significance resides mainly in the purity of ν_e-like samples

→ Improved in **Multi-Ring** with new event selection

→ Improved in Single-Ring with new sample definition using neutrons

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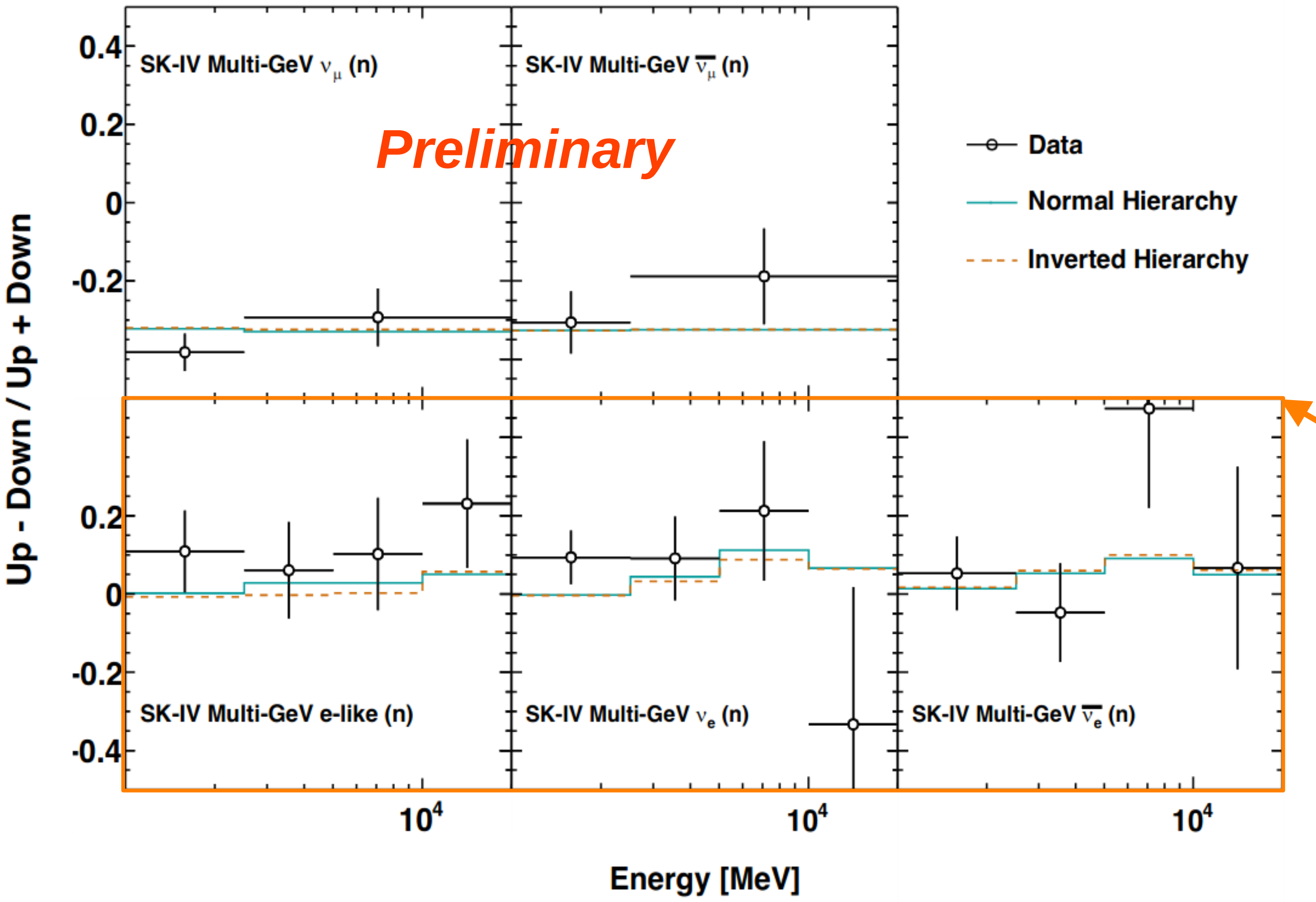

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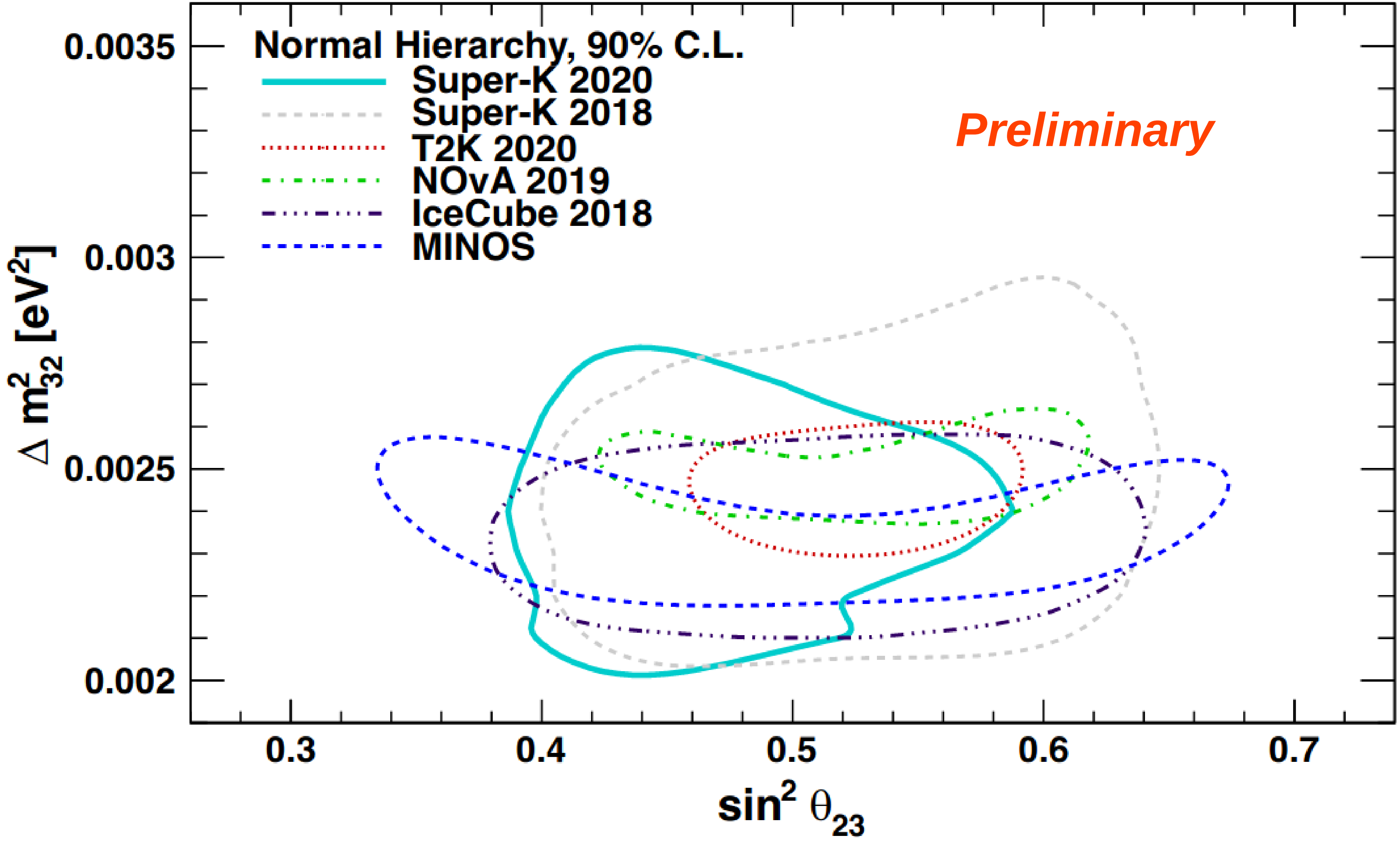
Results in context

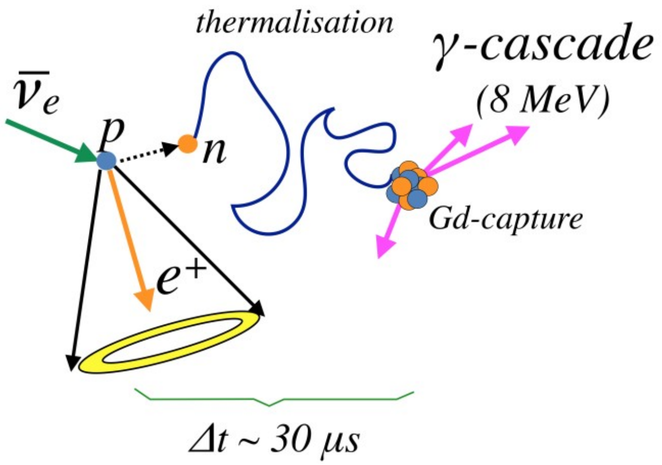


Prospects for the SuperK-Gd Atm. ν Osc. Analysis

The **SuperK-Gd** upgrade has finally started in July 2020

The detector is fully operational and acquiring data with its present Gd concentration. 0.011% Gd

- ~50% of neutron tagging efficiency (double the H-tagging eff.)



In addition to its impact to low energy physics, we have already seen the **importance of neutron tagging in the atm. ν analysis**

With greater neutron tagging efficiency:

- Much better classification of neutrinos and antineutrinos
- Improve the neutrino energy reconstruction, as they carry information about the invisible energy
- Provide additional power in discriminating CC events from NC events

Complementary studies and measurements will be needed, especially for the two last items as they rely on large neutron multiplicities (>10)

Conclusions

- After 25 years since the beginning, SK has rejuveneted once again to stay at the forefront of ν physics → **SuperK-Gd**

- Discovery of neutrino oscillations in 1998 and currently providing some of the most precise measurements of the oscillation parameters

- **Updated and upgraded atmospheric neutrino analysis**
  - Preference for large (~3π/2) CP-phase values, agreeing with LBL experiments
  - Preference for normal mass ordering at 86% C.L.
  - Preference for first octant of θ_{23}

- Expecting still improved performance and results from SuperK-Gd data and from the acquired experience over the years