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

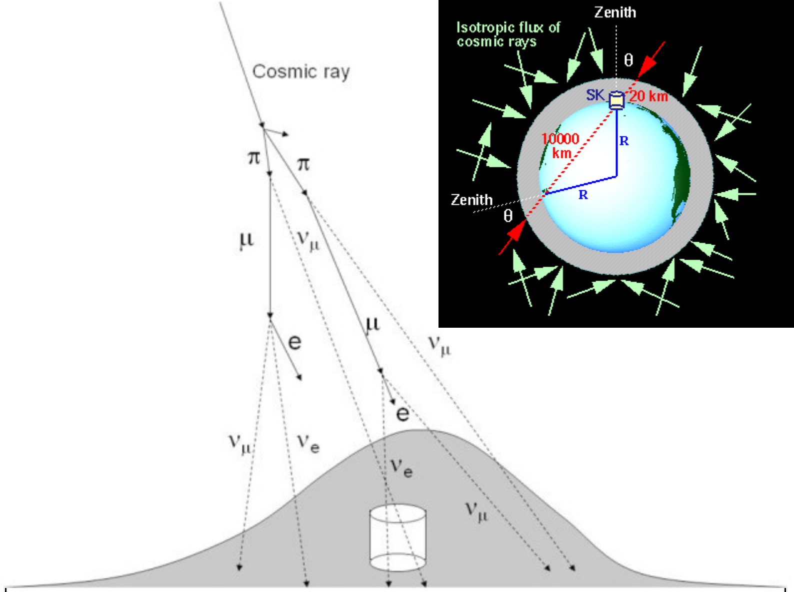
Pablo F. for the Super-Kamiokande Collaboration

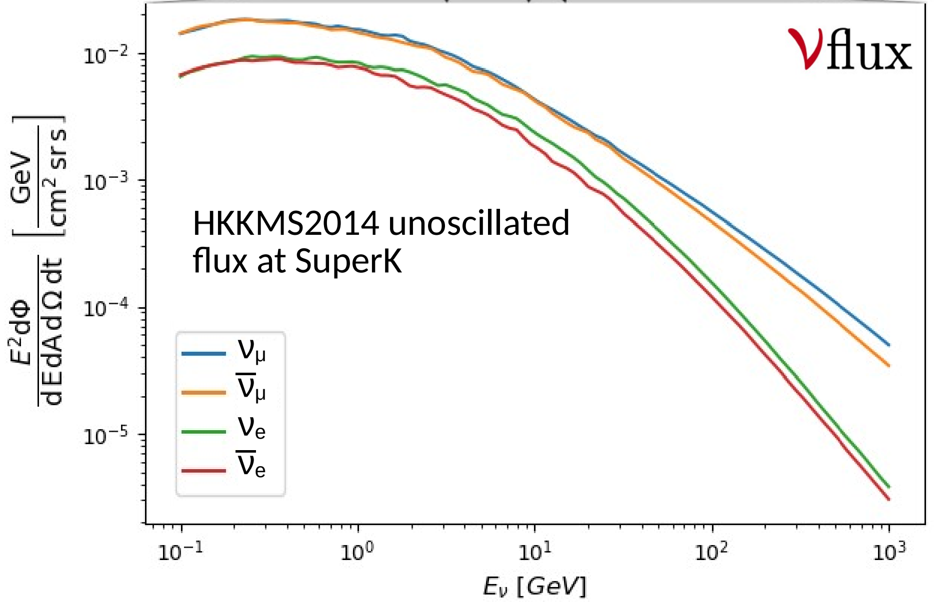
37th International Cosmic Ray Conference
– The Astroparticle Conference –

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 100s 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



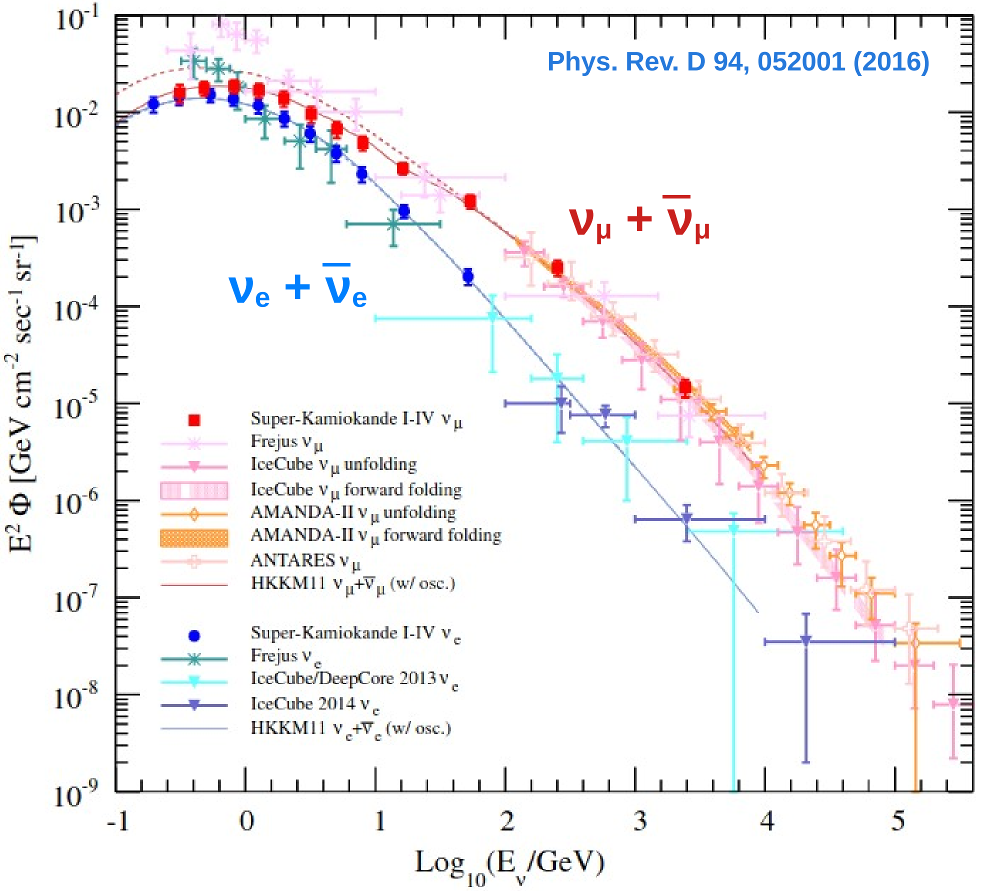


Atmospheric Neutrino Flux

- 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, $\boldsymbol{\nu_\tau}$

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

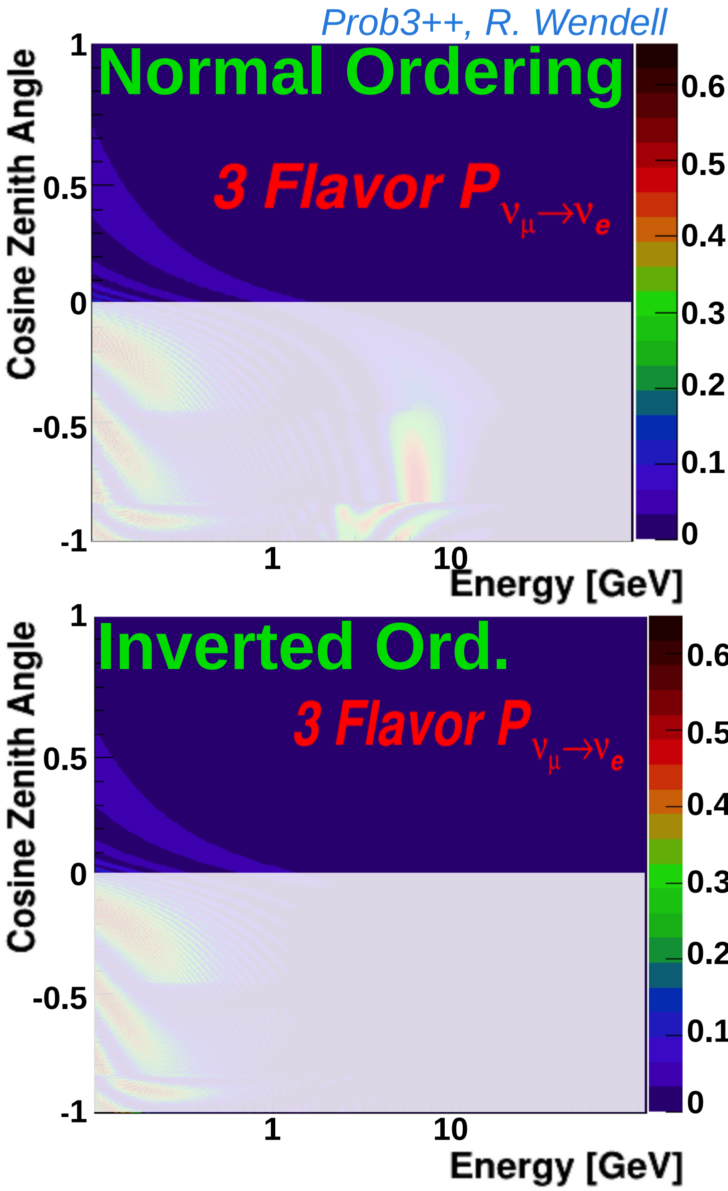


Atmospheric Neutrino Oscillations

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

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

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



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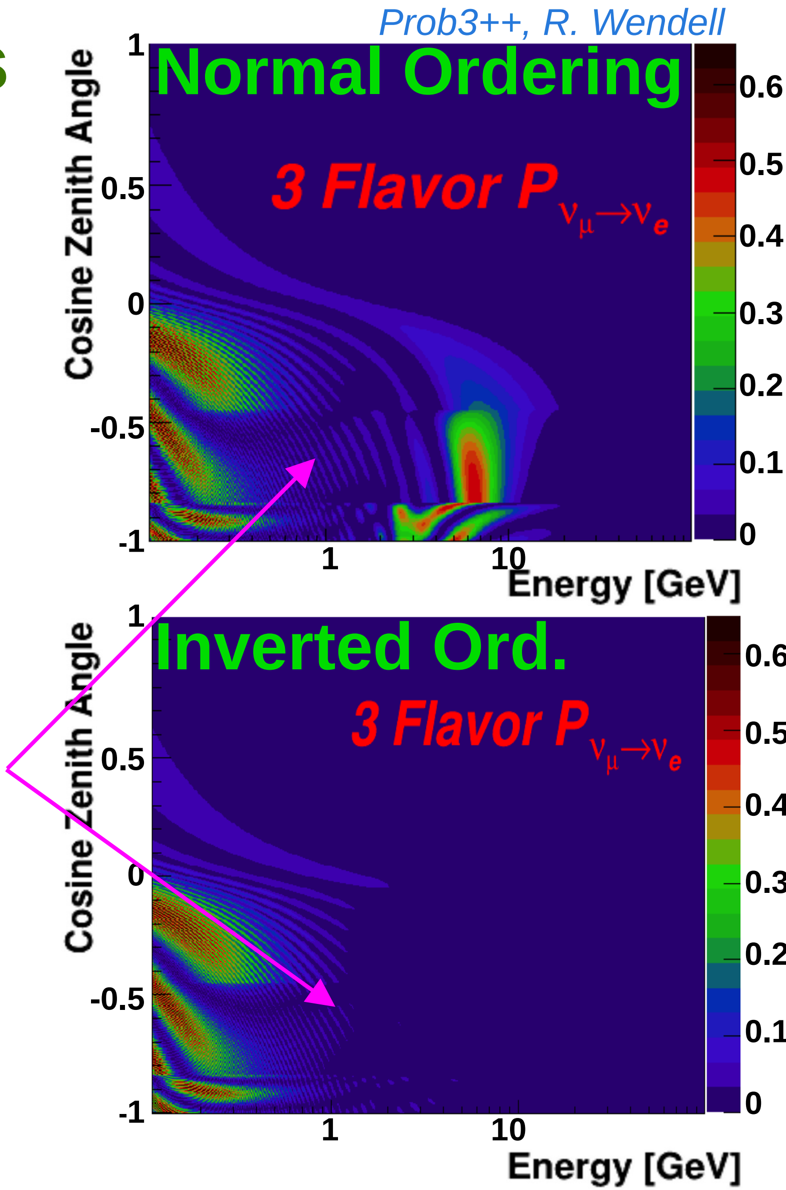
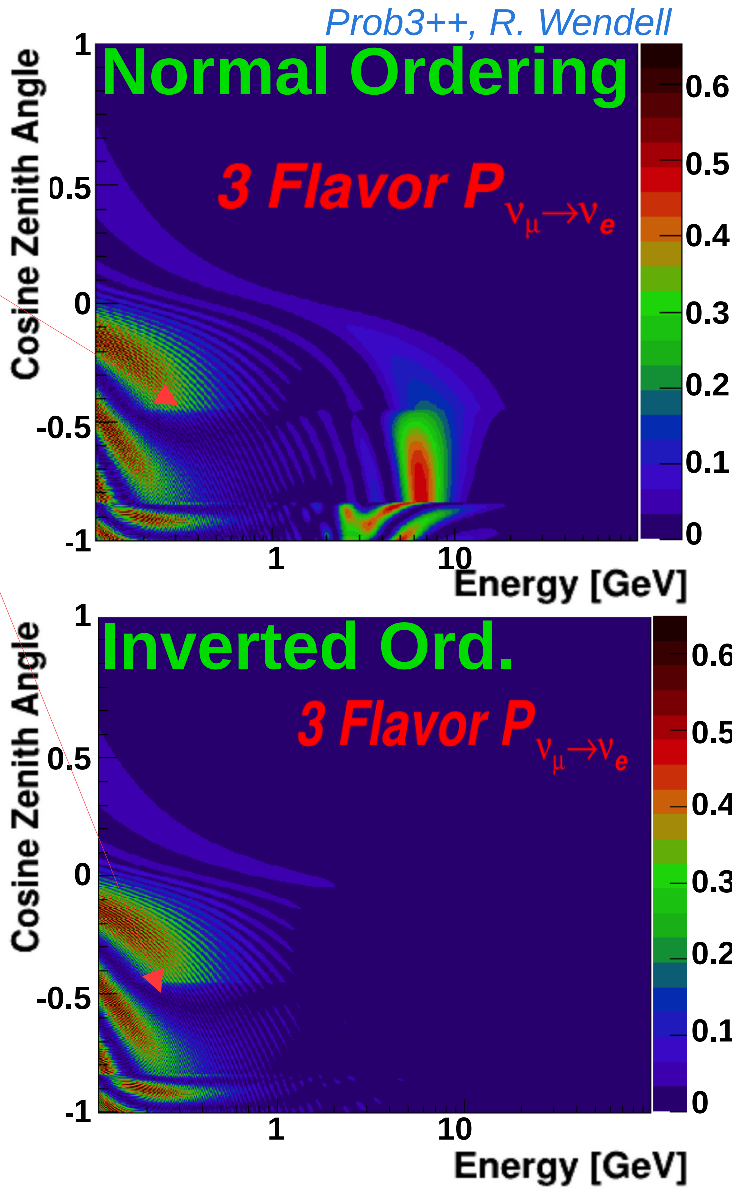
Neutrinos coming from below $(\cos(\theta_{zen})<0)$, pass through the Earth changing the effective Hamiltonian and thus, the neutrino propagation

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



Atmospheric Neutrino Oscillations

The dominant effect is the oscillation of muon to tau neutrinos (disappearance) and modulated by θ_{23}, especially at low energies



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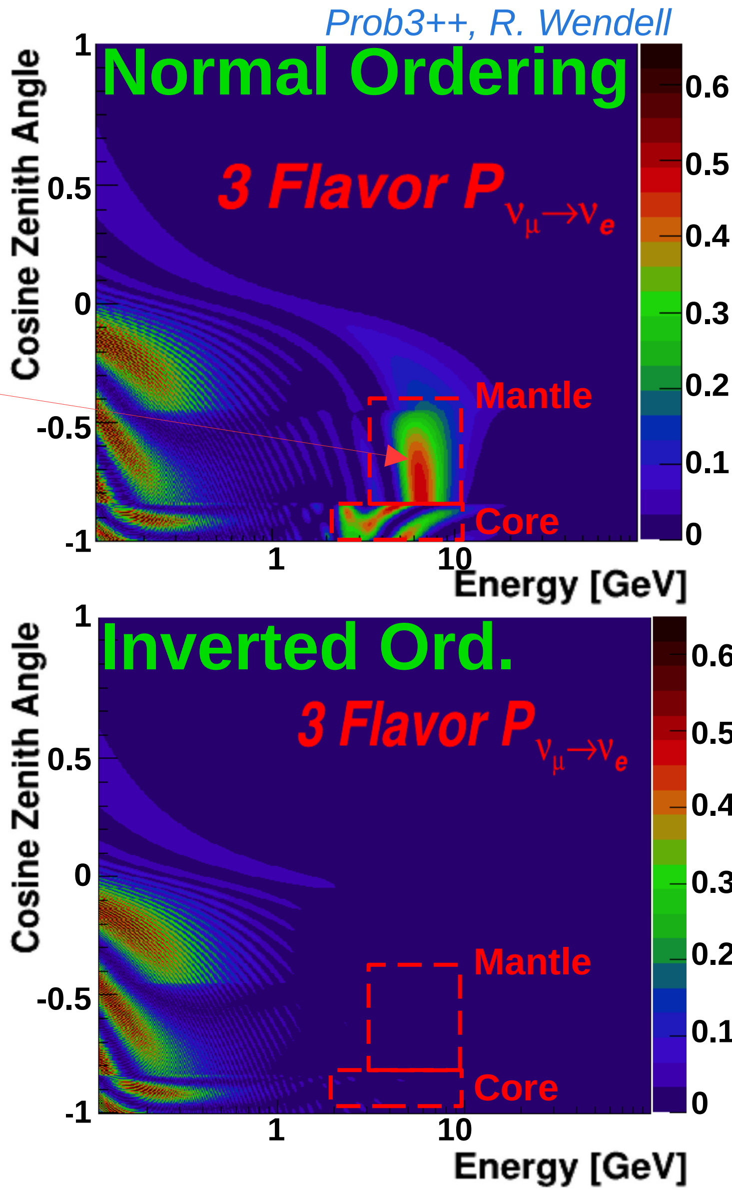
The non-zero value of θ_{13} enables the matter-effect (mantle and core) resonances



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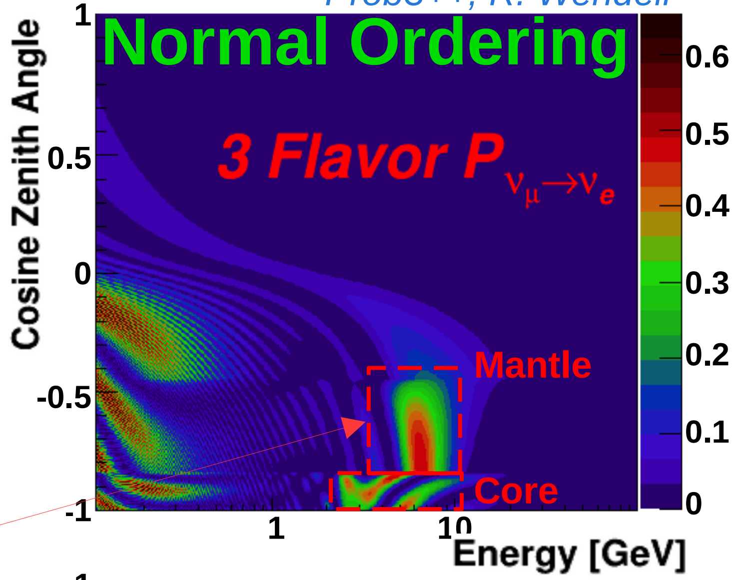
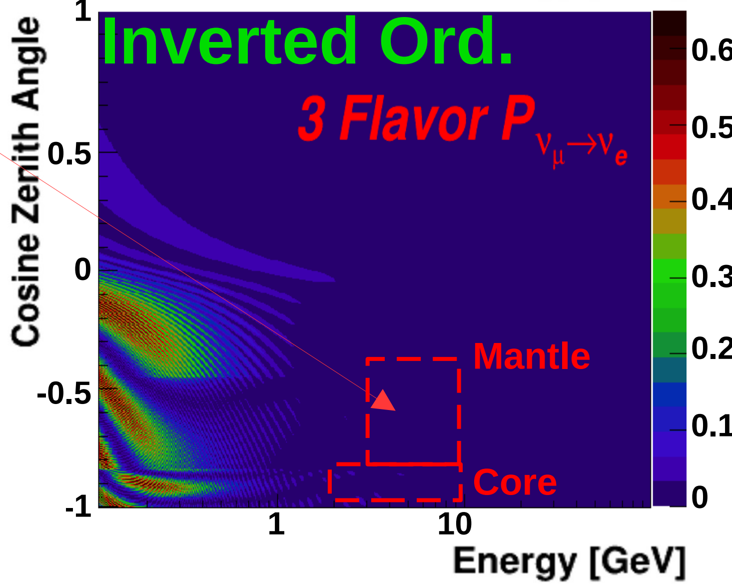
Prob3++, R. Wendell





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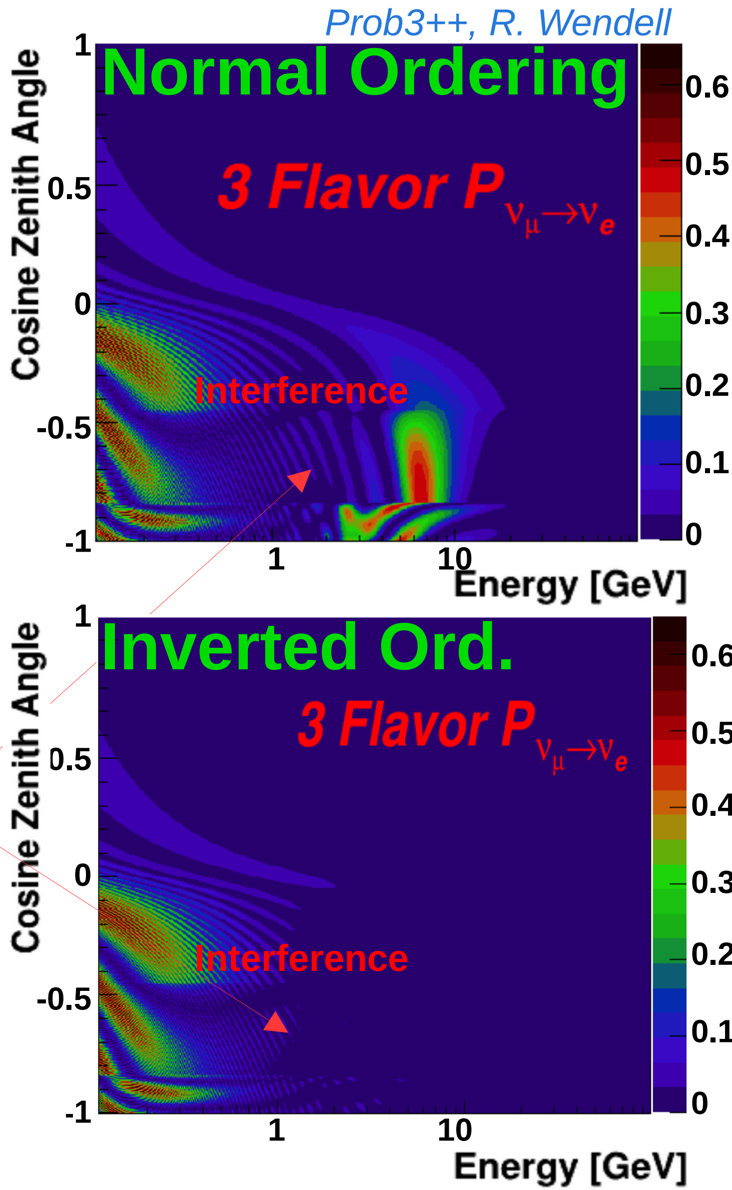

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While waiting for more statistics…
Distiguishing neutrinos from antineutrinos would enhance the sensitivity to the mass ordering and δ_{CP}

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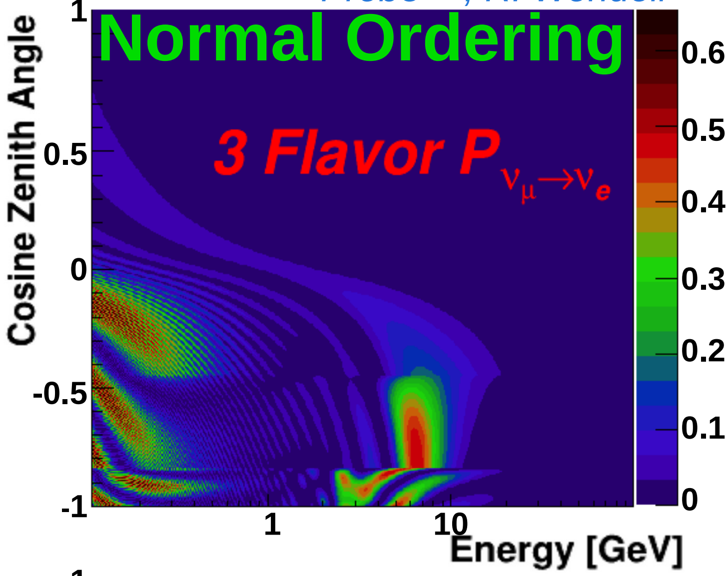
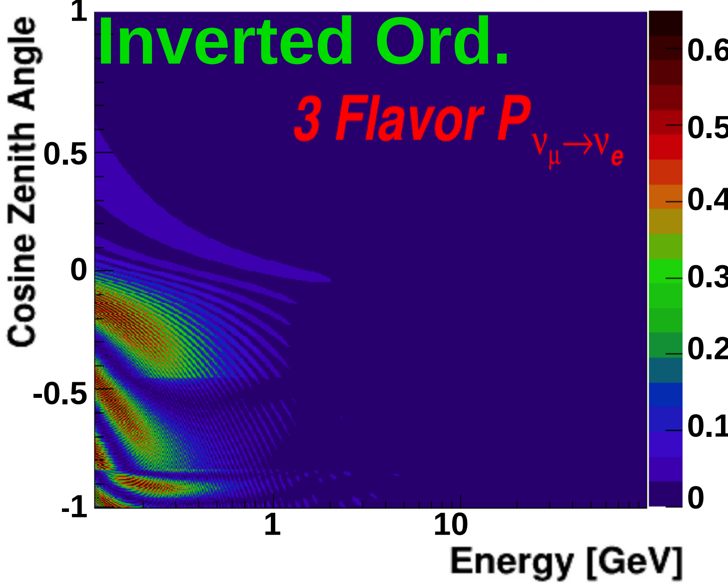
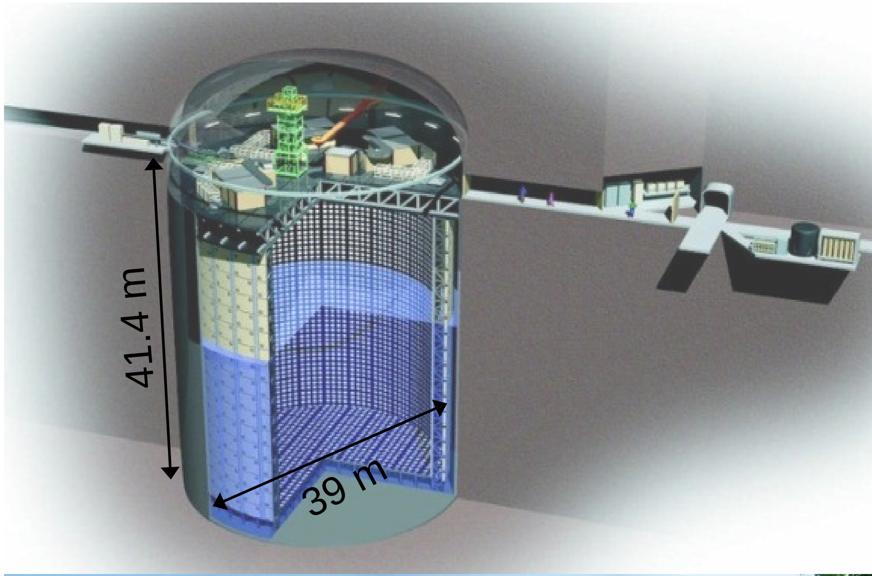




The Super-Kamiokande Experiment

- 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.

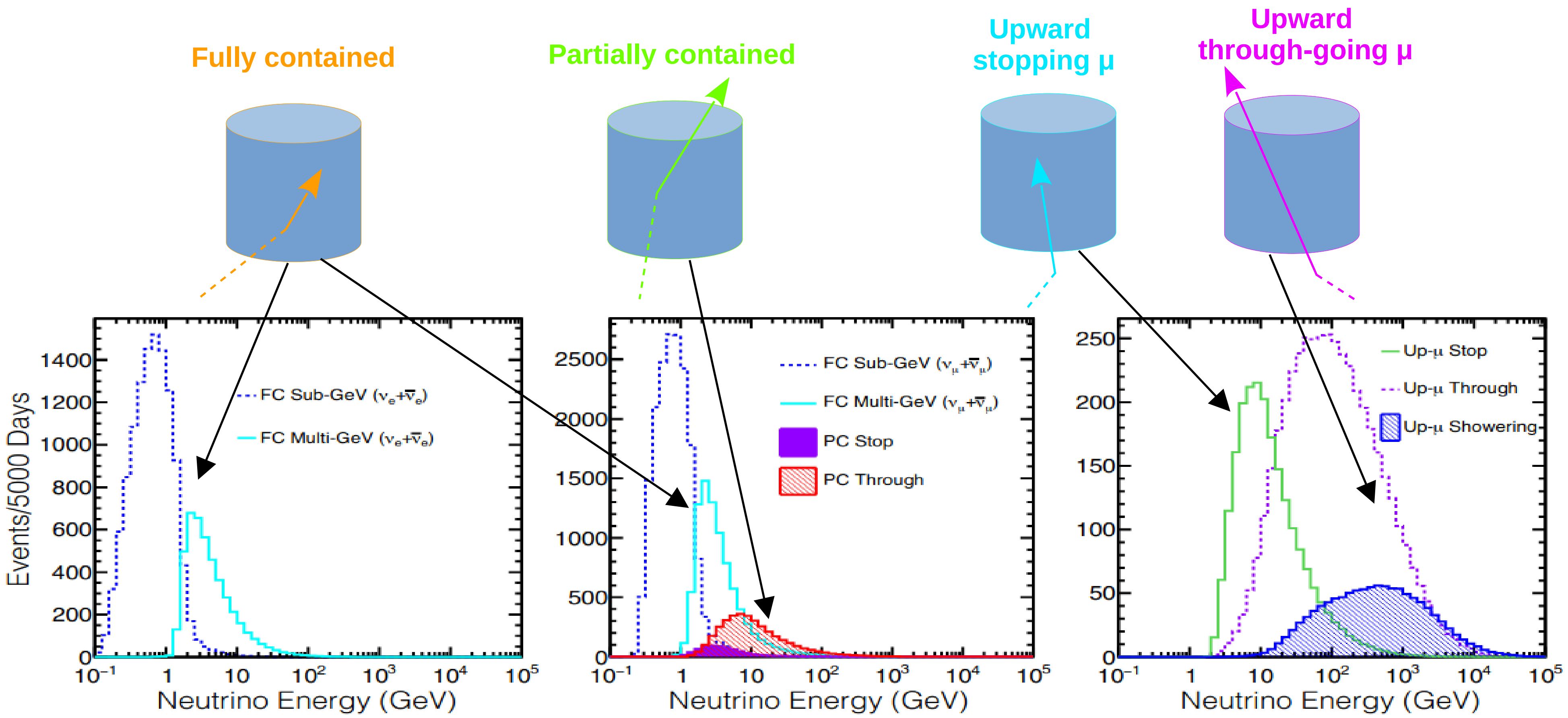
- Still at the forefront of neutrino physics with the latest upgrade (still ongoing), **SuperK-Gd**
  - Eventually reaching a concentration of 0.1% of Gd, detecting 90% of neutrons

	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

- 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

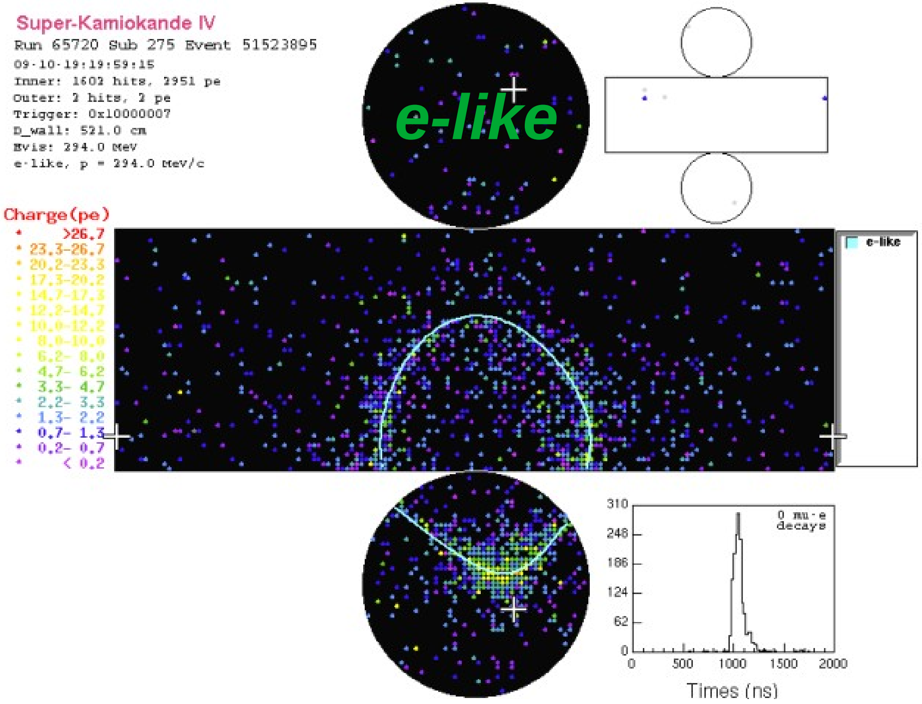
SK Atmospheric Neutrino Event Classification

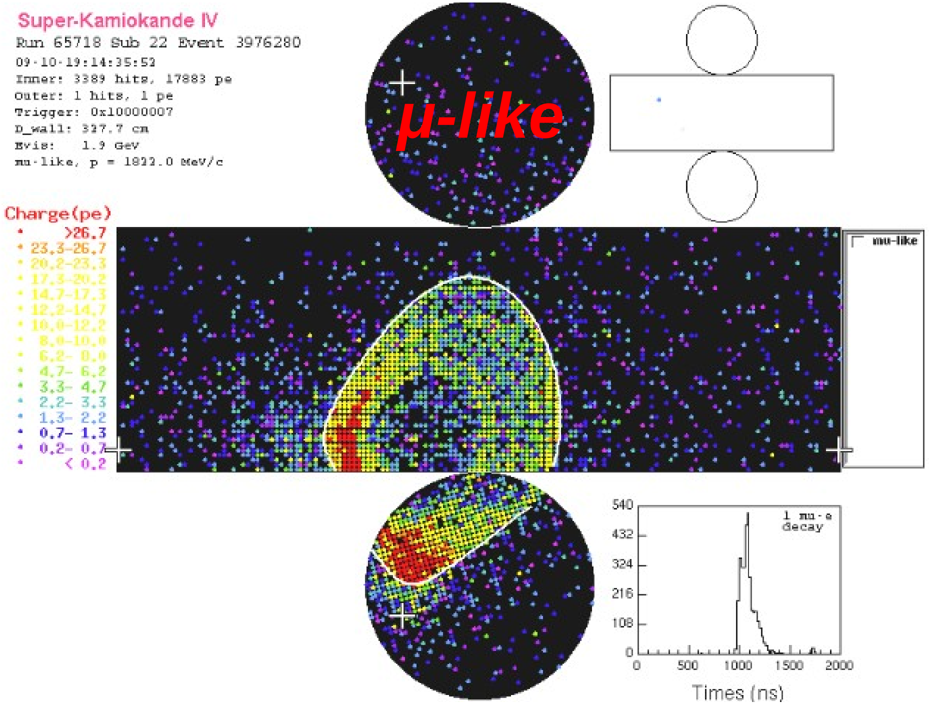
- Depending on the topology and the ID and OD activities



SK Atmospheric Neutrino Event Classification

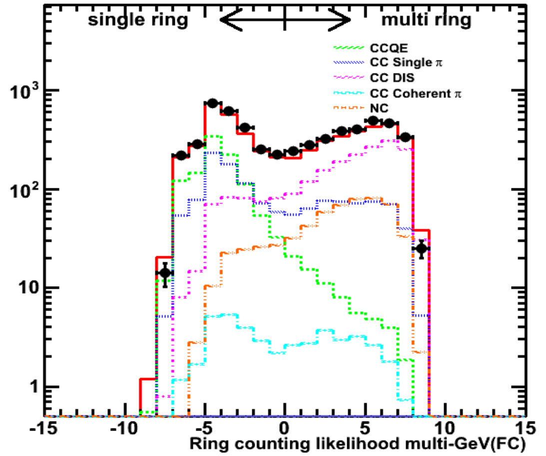
- Further, events can be split into e-like and μ-like taking into account the features of the Cherenkov rings

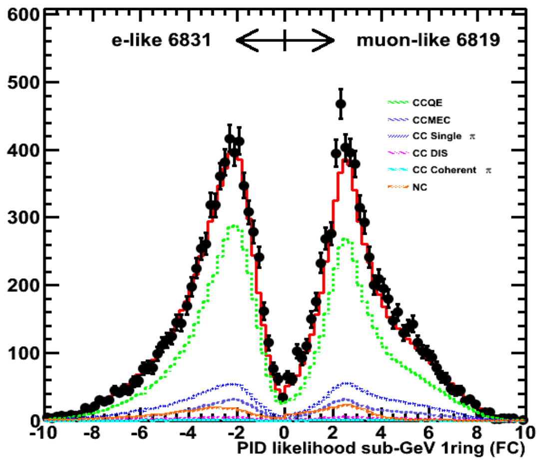


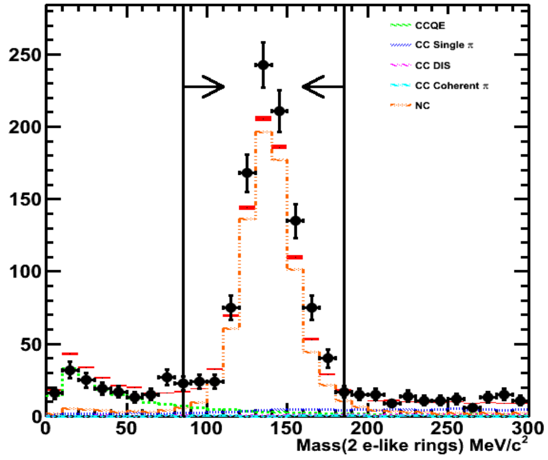


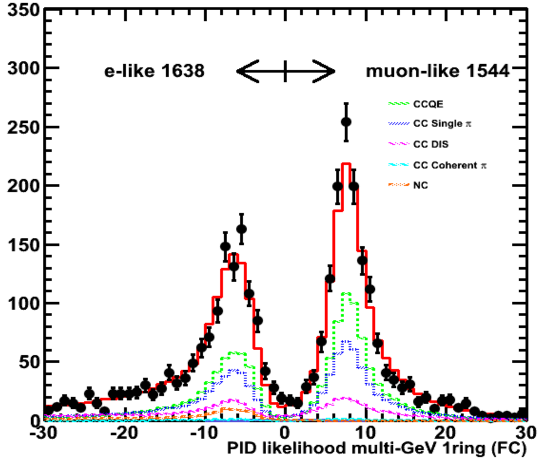
SK Atmospheric Neutrino Event Classification

- Fully contained (22.5 kton FV) events are classified into 14 subsamples:
  - Single or multi ring
  - Particle ID of brightest ring (e/μ)
  - Reconstructed neutrino energy larger/smaller(SubGeV/ Multi-GeV) than 1.33 GeV
  - Other criteria such as:
    - Number of <u>decay electrons</u> in Sub-GeV samples
    - <u>π^0-likelihood</u> cut for removing NCπ^0 events
    - <u>Neutrino-antineutrino likelihood</u> for e-like samples









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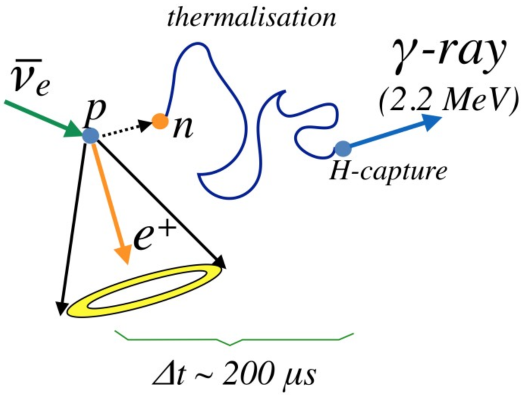
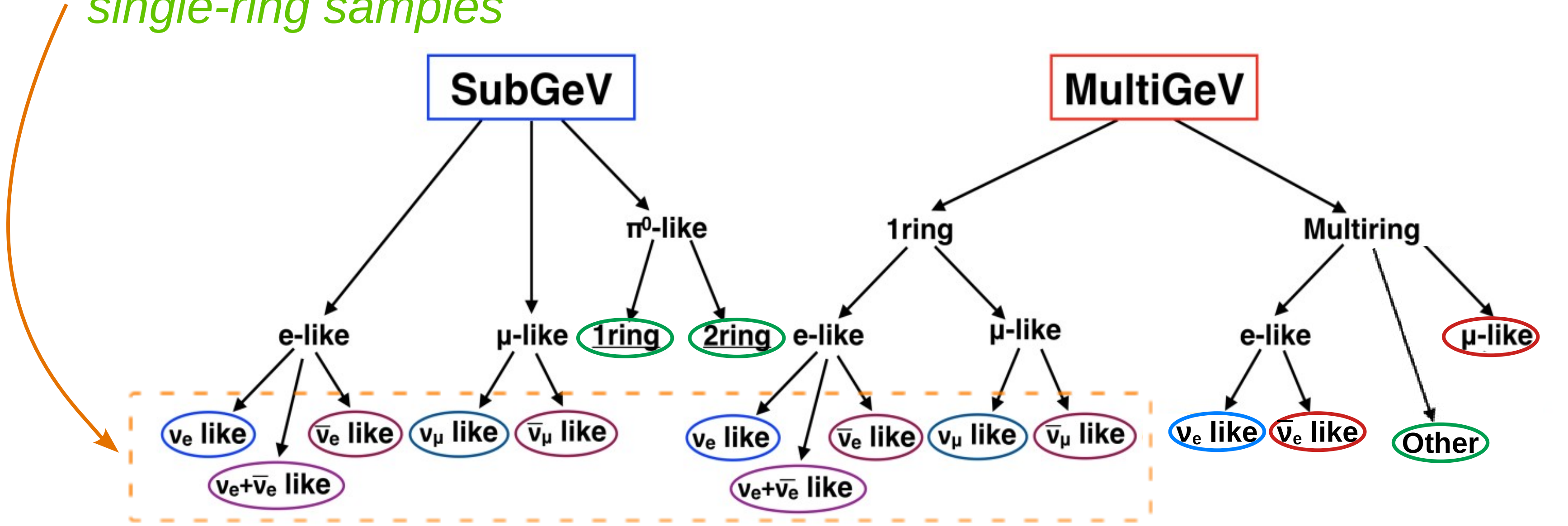


Updates for this analysis:

- Sample definition for **SK-IV** based on neutron tagging (*hybrid*)
  - Electronics allow the detection of neutrons captured on hydrogen, achieving an efficiency of 25%
  - Antineutrinos tend to produce more neutrons than neutrinos
    - *Make use of neutron and decay-e to separate neutrinos from antineutrinos in single-ring samples*



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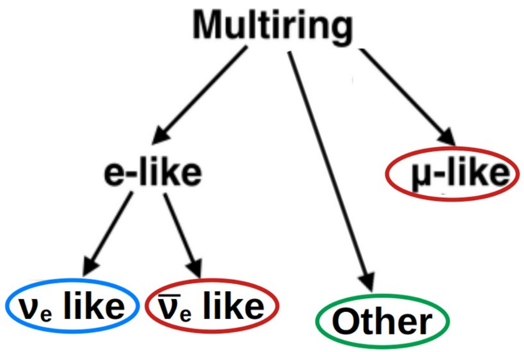


Updates for this analysis:

- New approach for classifying **multi-ring** events
  - BDT to classify all multi-ring events into 4 categories
  - Improves efficiency as compared to the previous method
    - *Better discern between CCν_e, CC$\bar{\nu}_e$, CC$\overset{(-)}{\nu}_\mu$ and NC and tau (other) events*

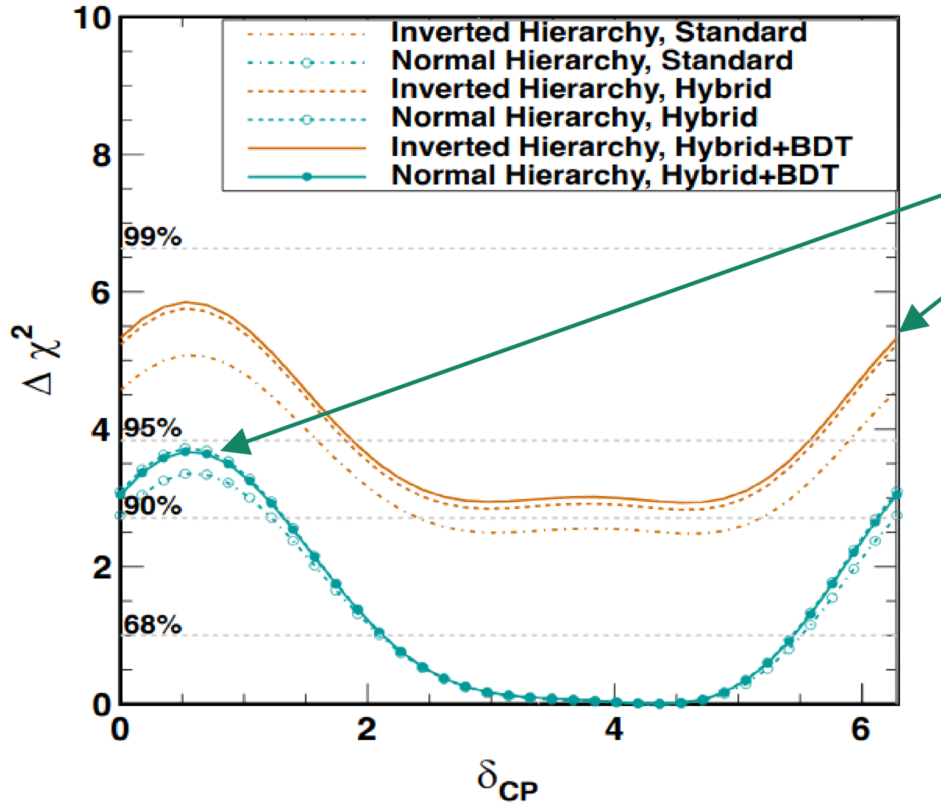
inputs	Definition
N_{ring}	# of rings
E_{vis}	Visible energy
T_{mom}	Total transvers momentum / E_{vis}
F_{mom}	amome of the most energic ring / E_{vis}
$N_{\text{decay }e}$	# of decay electron
$L_{\text{decay }e}$	Largest distance between decay e vertex and primary vertex
PID	PID likelihood(μ-like - e-like)

Efficiency of ν_e-like sample increased by 36%, keeping the same purity

	Previous method	New BDT classification
MultiRing ν_e-like	34.4% of CCν_e	46.7% of CCν_e

SK Atmospheric Neutrino Event Classification

Impact of the updates:



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

SK Atmospheric Neutrino Event Classification

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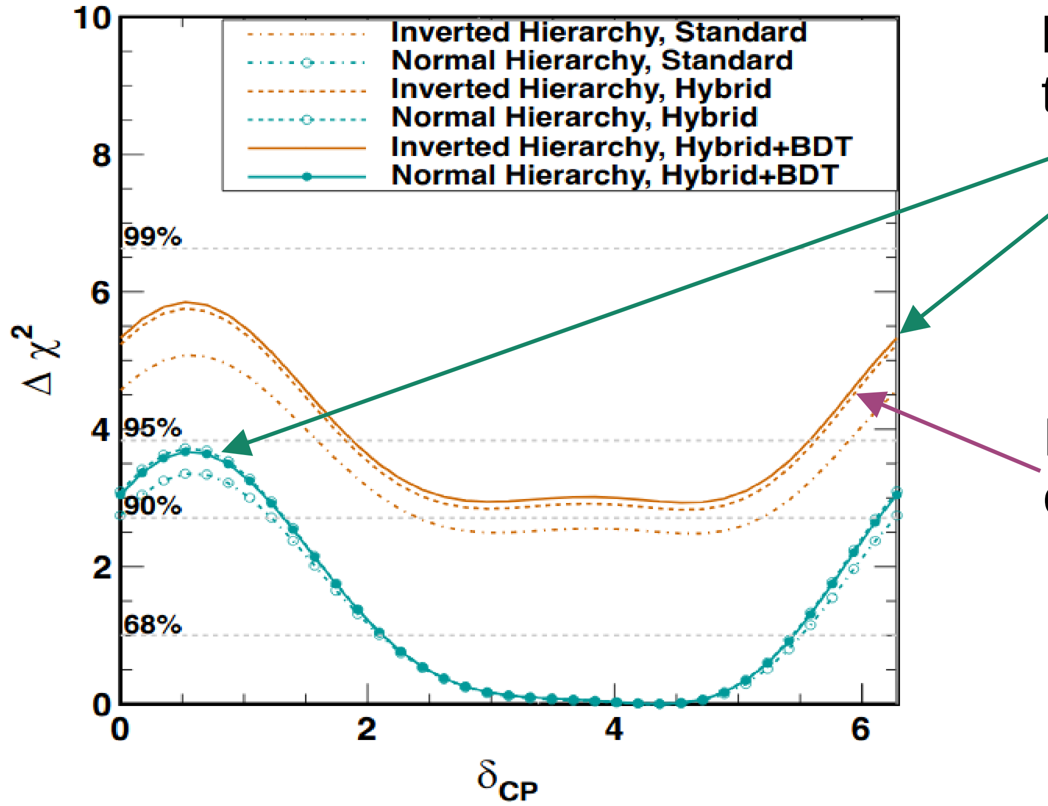


Neutron tagging improves the sensitivty to the mass hierarchy and the CP-phase

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

SuperK Atmospheric Neutrino Analysis

Some more updates in this analysis:

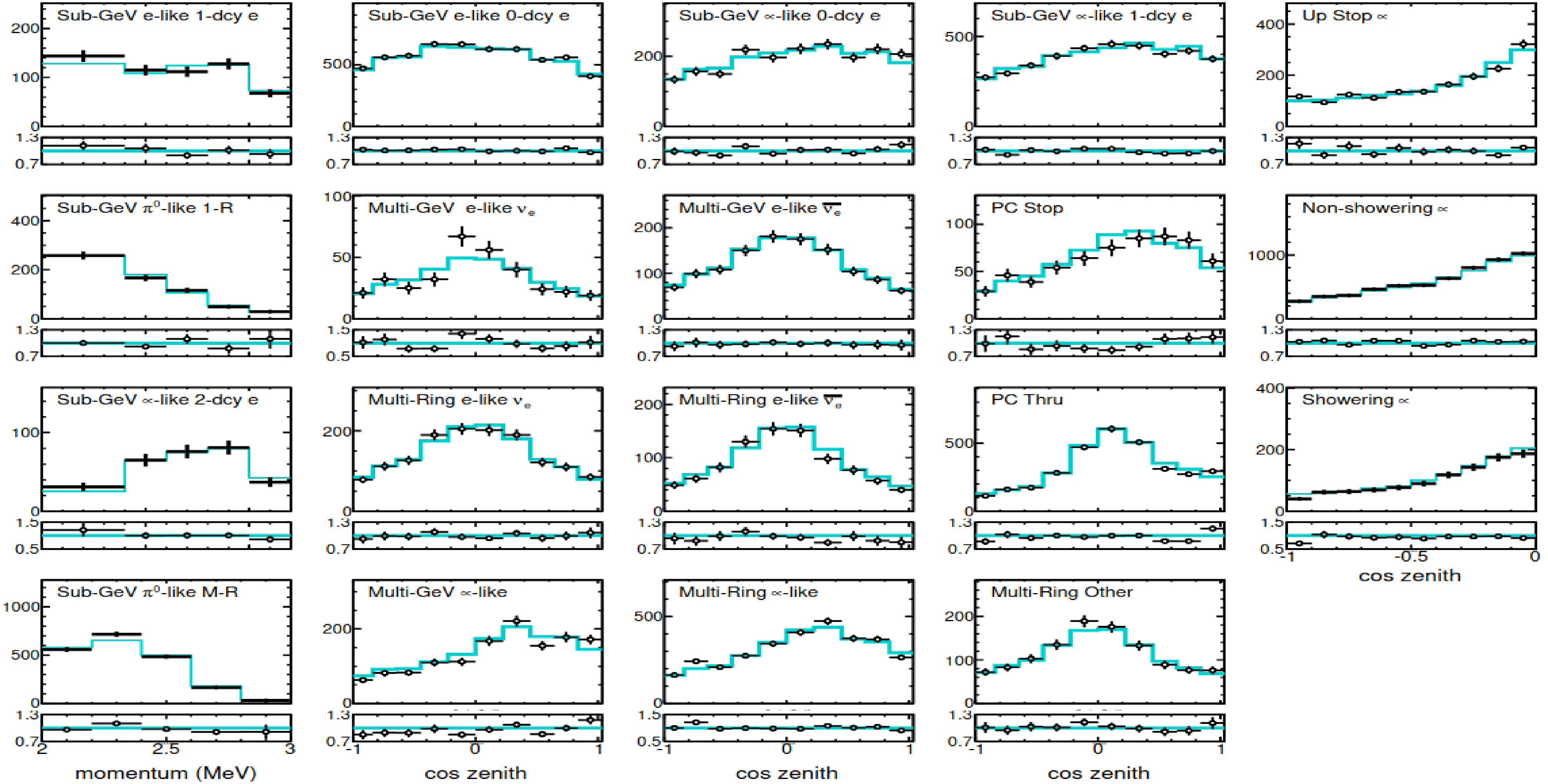
- *New Monte-Carlo using **NEUT 5.4.0** with updated cross-section models*
- *Updated and additional systematic errors included*
- *Changed **zenith binning** to better target the matter effects*

Analysis of the whole atm. data collected from SK-I to SK-IV: **>6000 days** (~16.5 years)

Results assume standard 3-flavour oscillations and have fixed the solar parameters (i.e. θ_{13} is unconstrained)

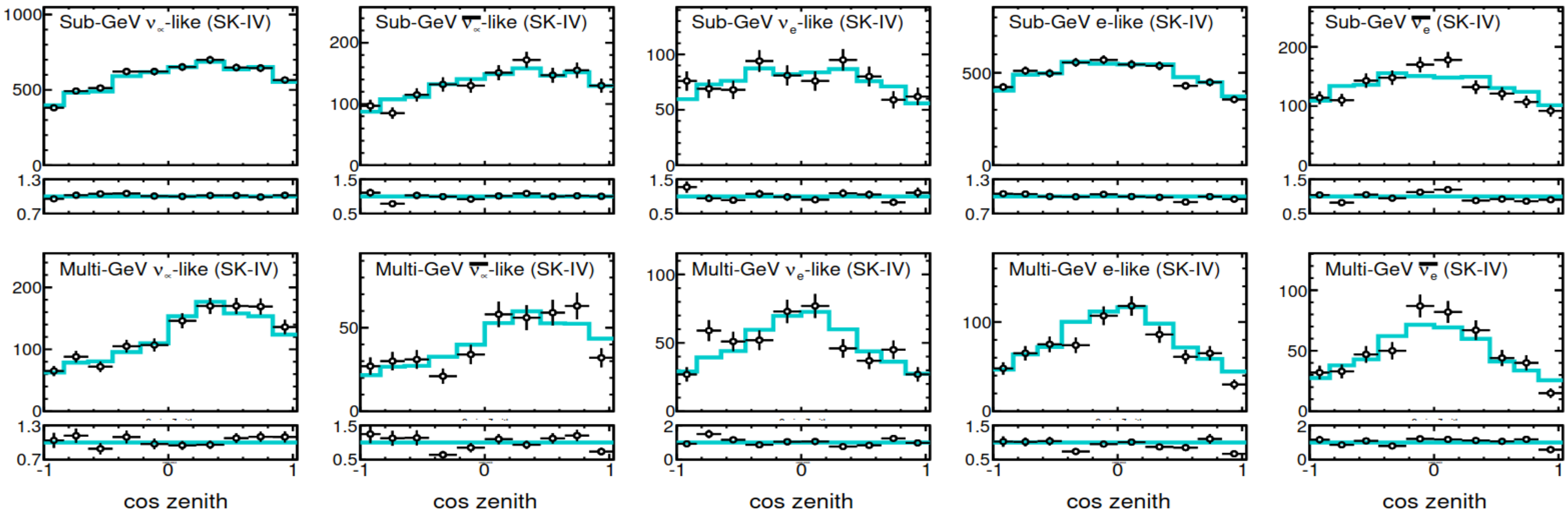
SuperK Atmospheric Neutrino Analysis

Data and best fit prediction for SK-I to SK-III and common samples of all data periods

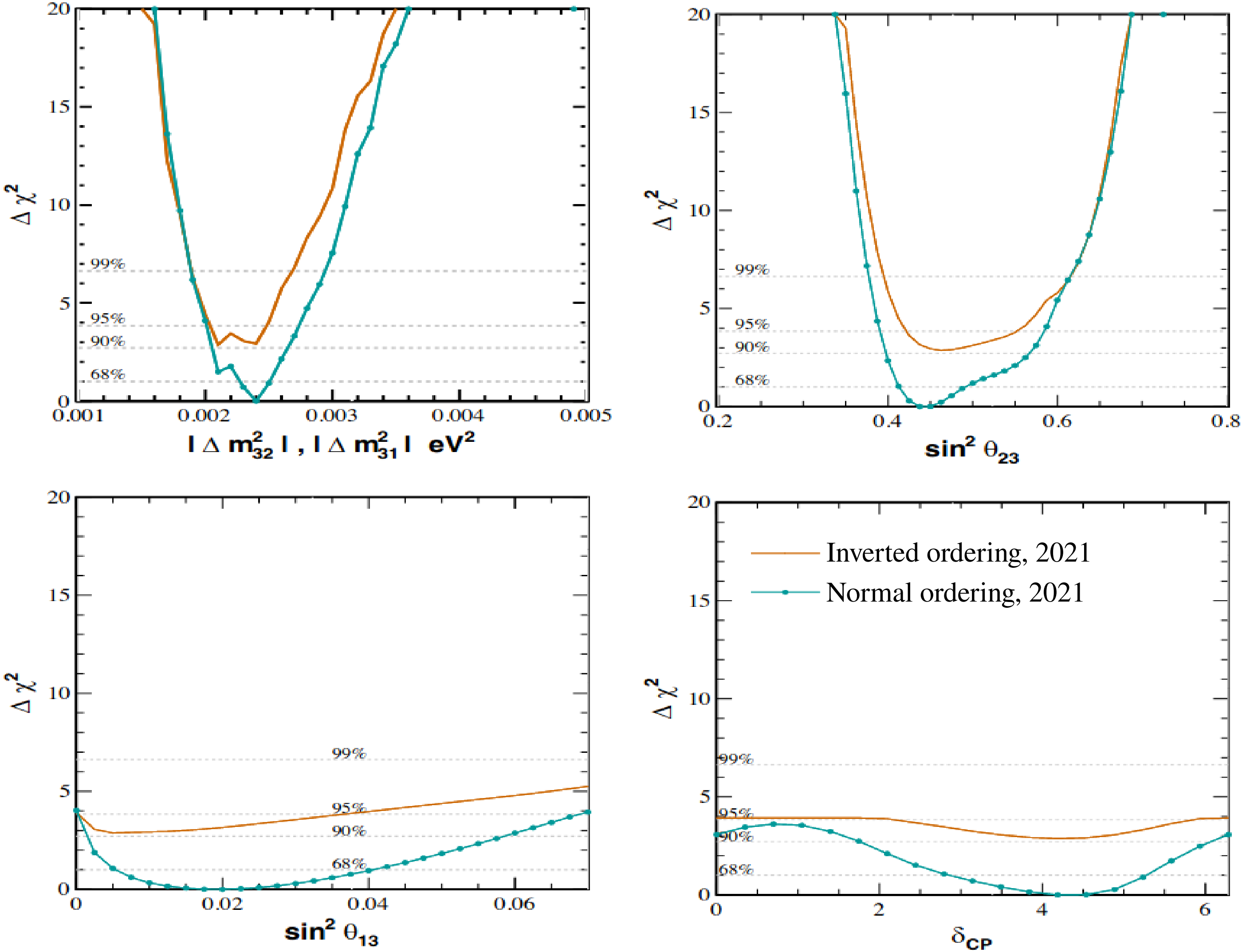


SuperK Atmospheric Neutrino Analysis

Data and best fit prediction for SK-IV new samples

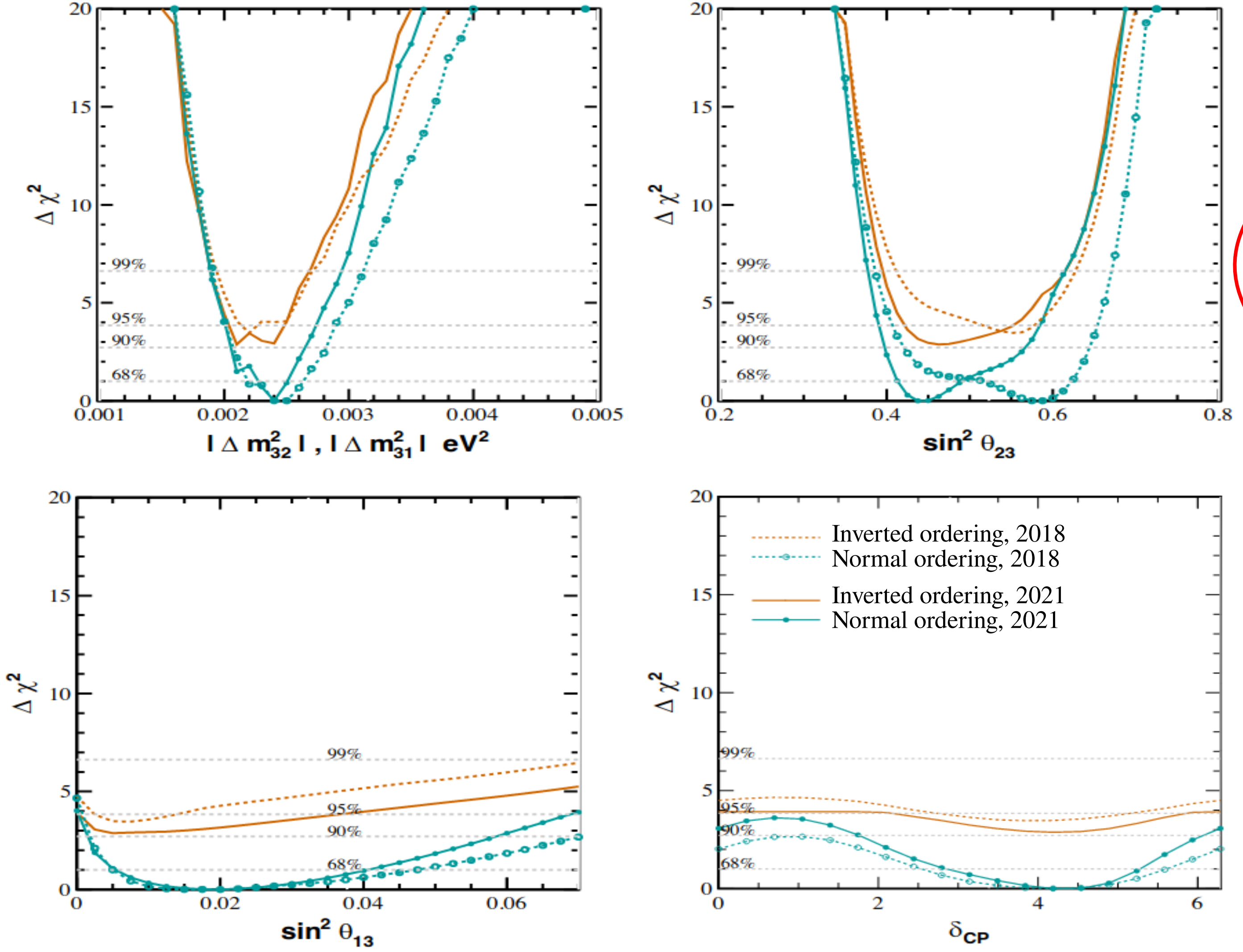


Results from the SK Atm. Neutrino Osc. Analysis



- 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

Results compared to previous SK Atm. ν Osc. Analysis



Comparing latest results with Phys.Rev.D97,072001(2018)

- Change θ_{23} octant preference and quite smaller 1σ interval
- Normal ordering prefered, but at lower significance *(previous, $\Delta\chi^2(IH)=3.5$)*
- Significantly improved sensitivity to δ_{CP} and θ_{13}

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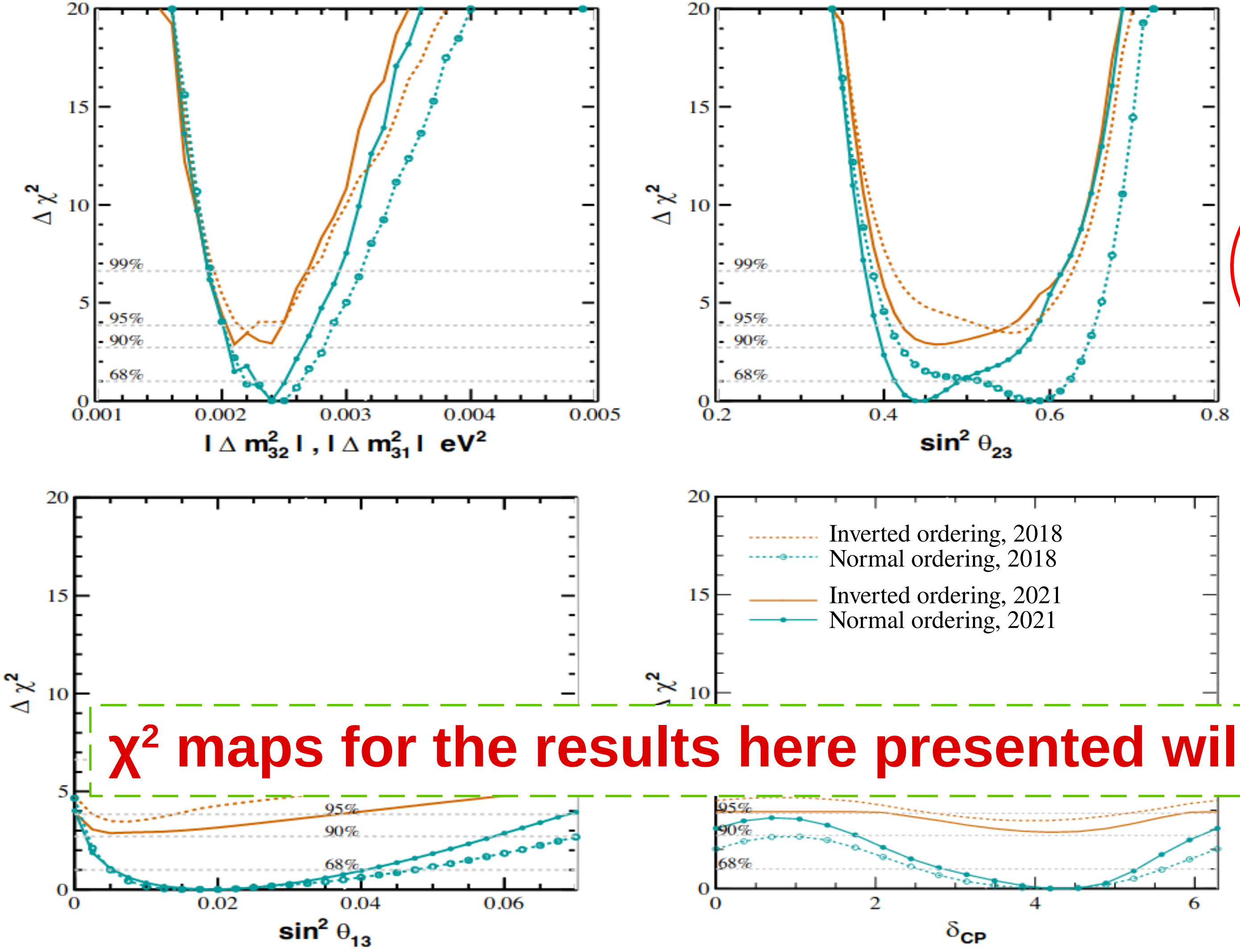

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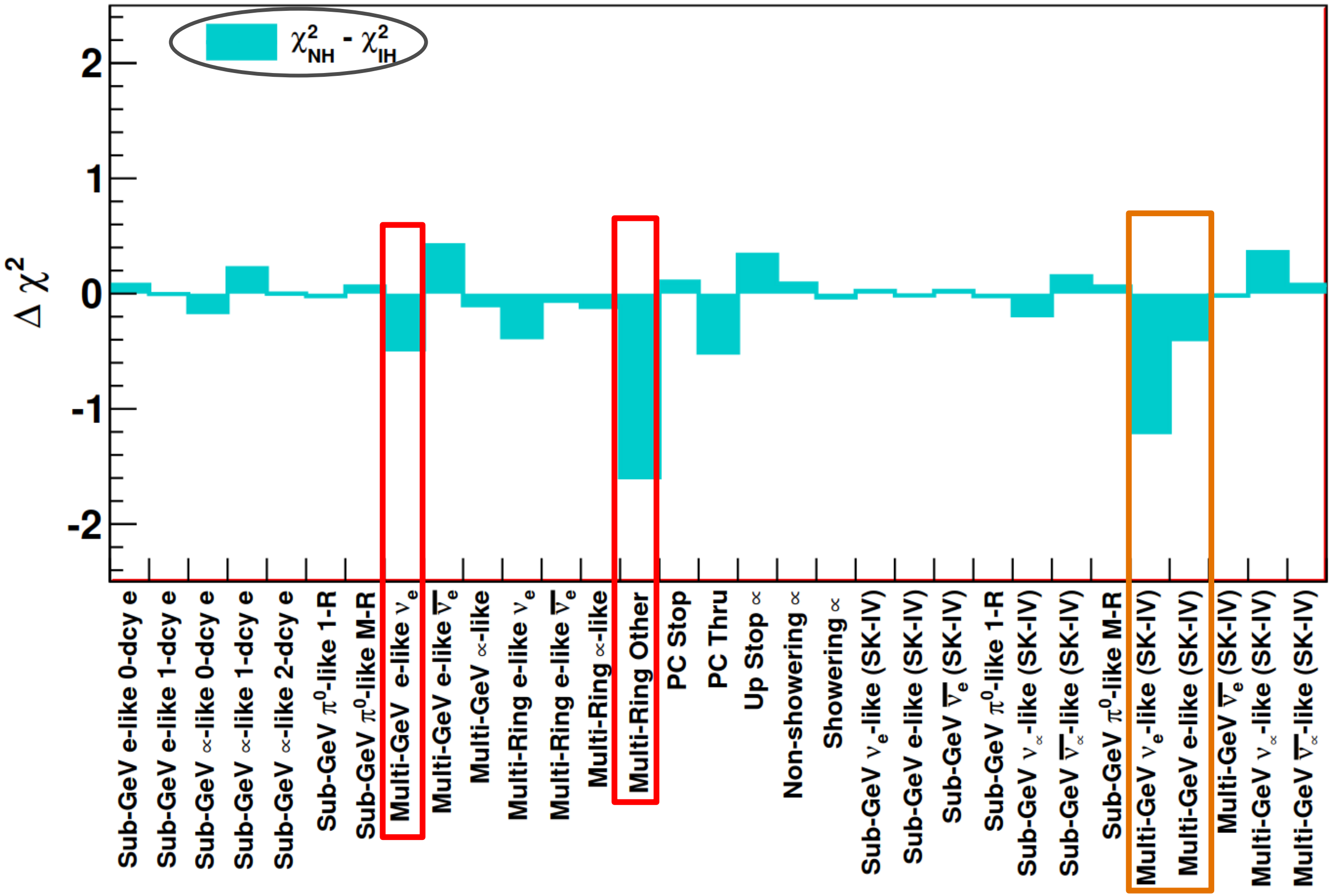
χ^2 maps for the results here presented will be released soon!

SK Atm. Neutrino Osc. Analysis. Mass Ordering



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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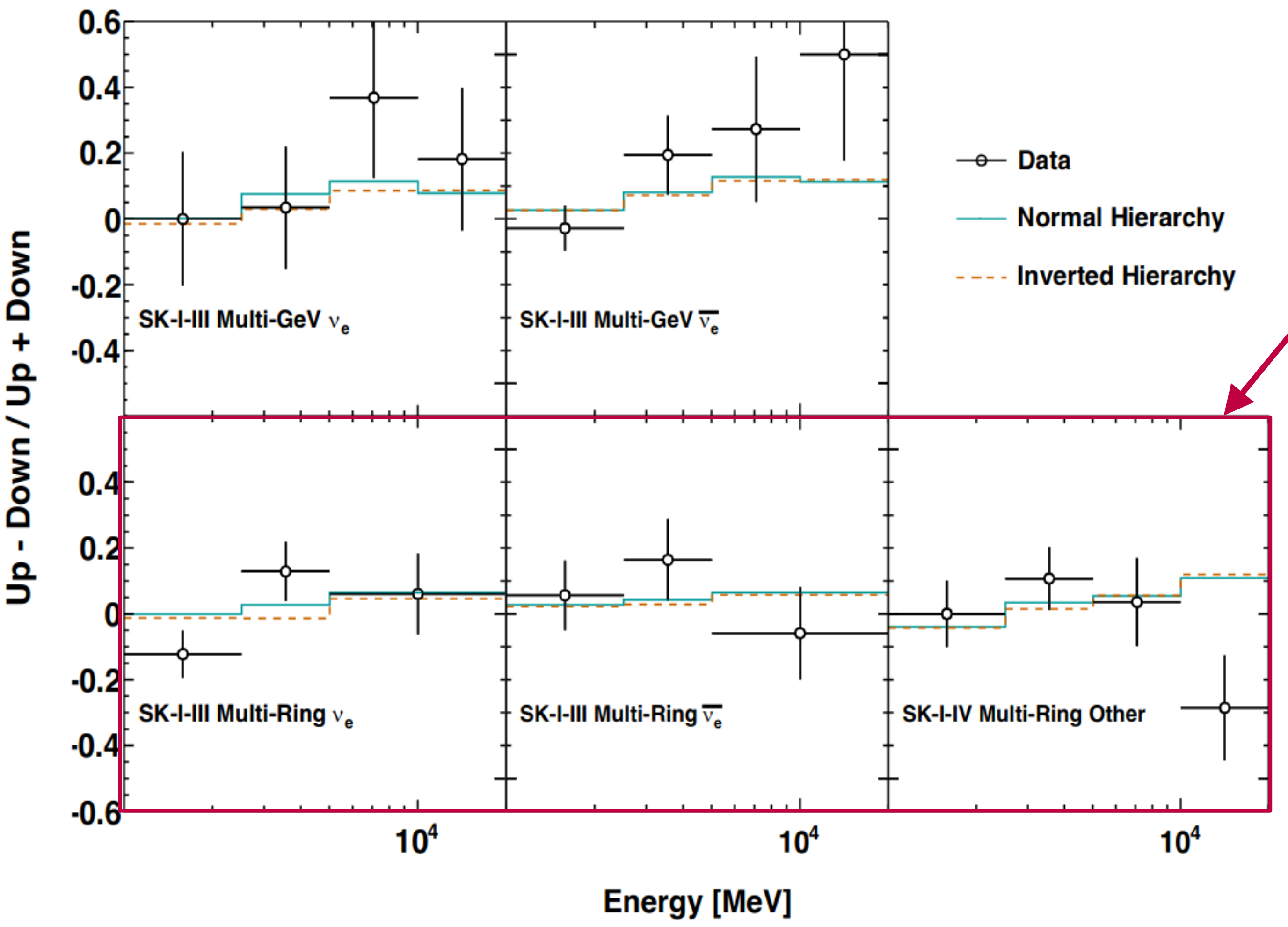

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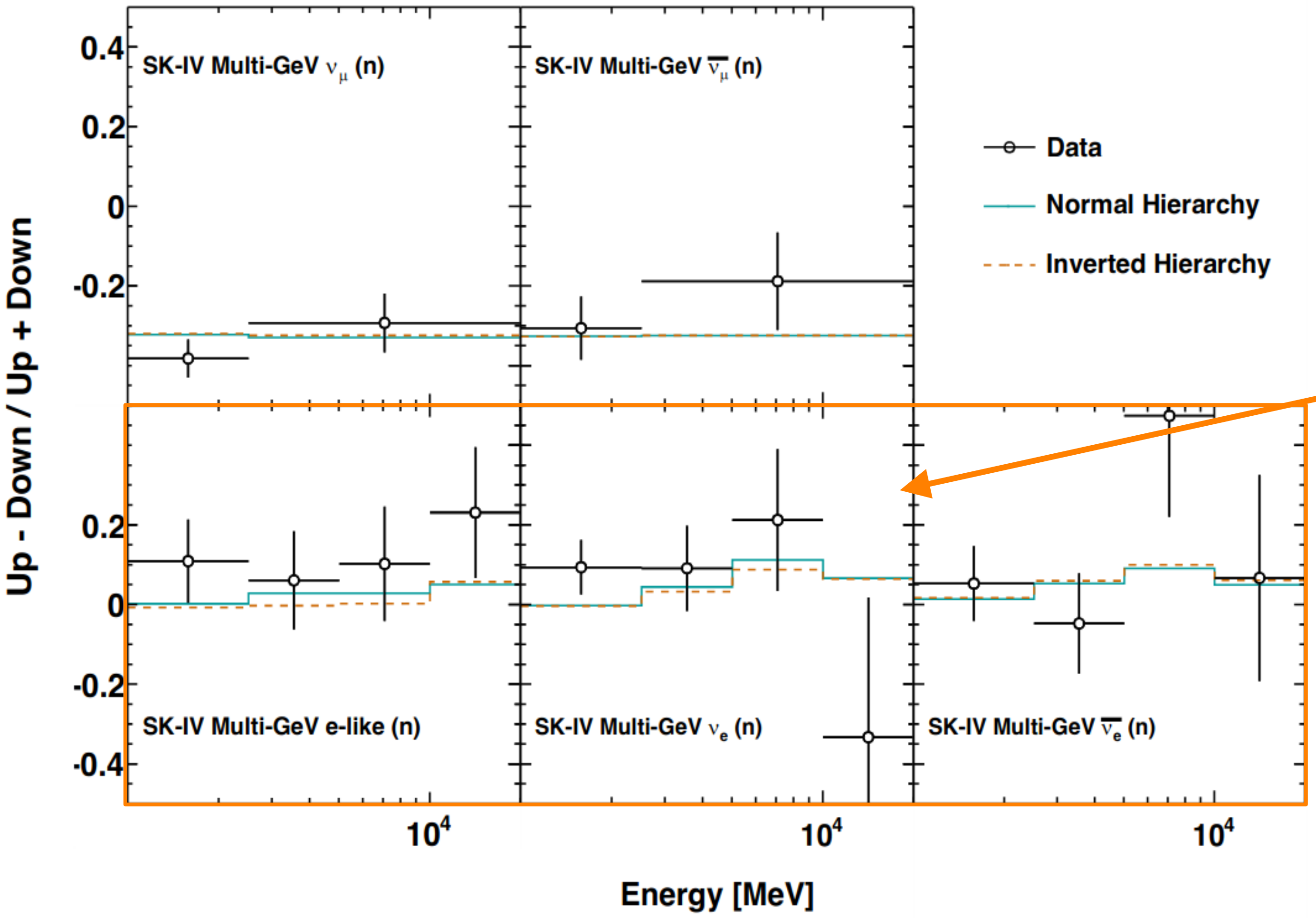

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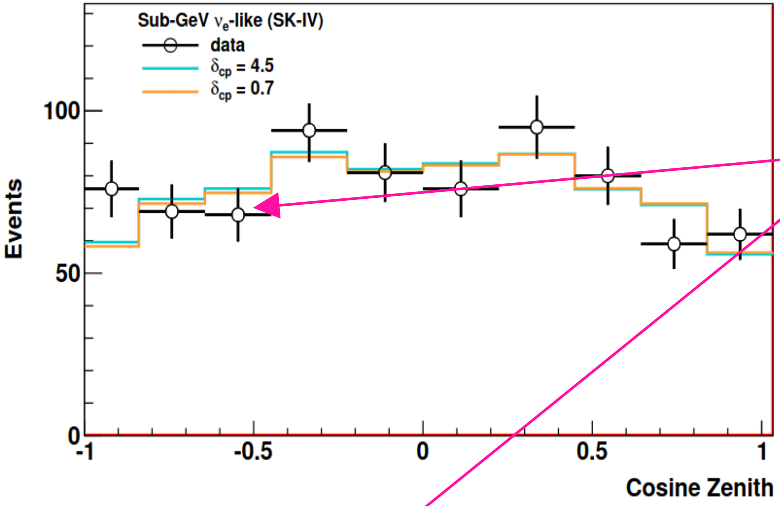
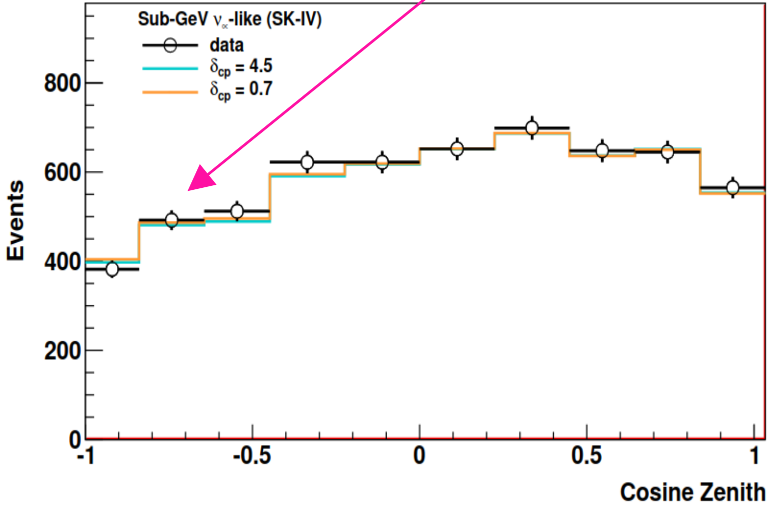
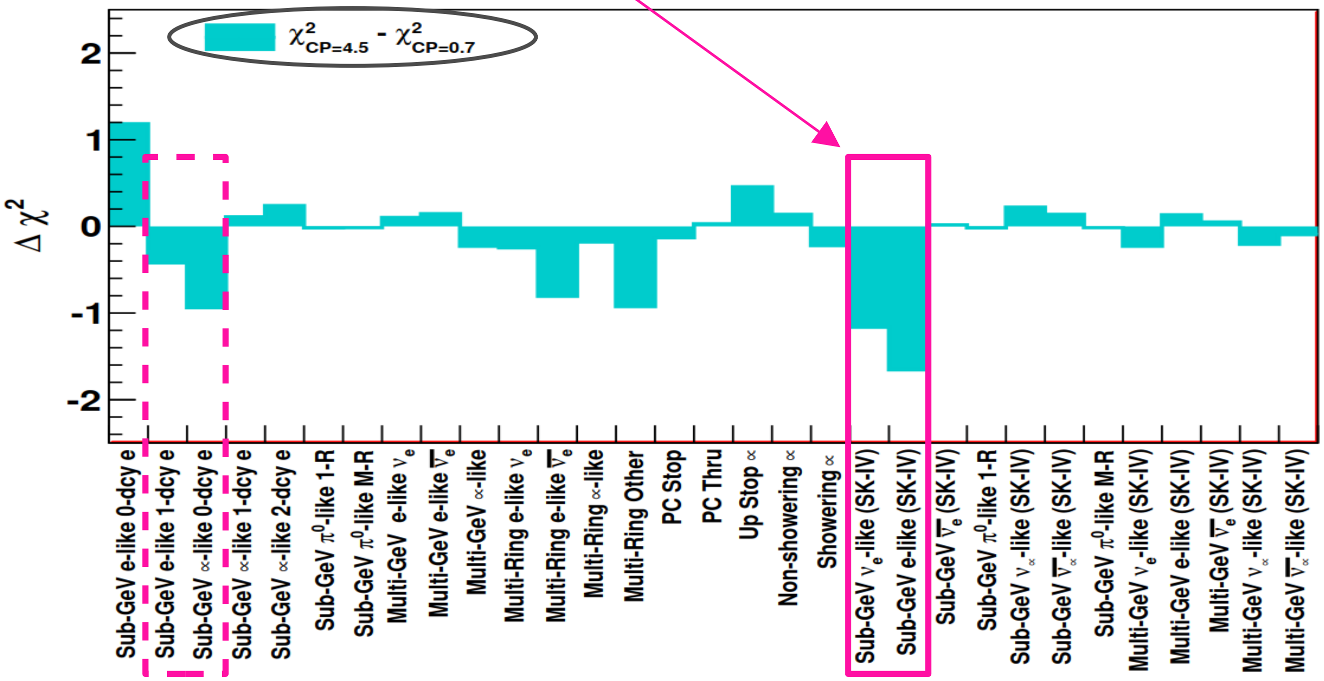
SK Atm. Neutrino Osc. Analysis. CP phase





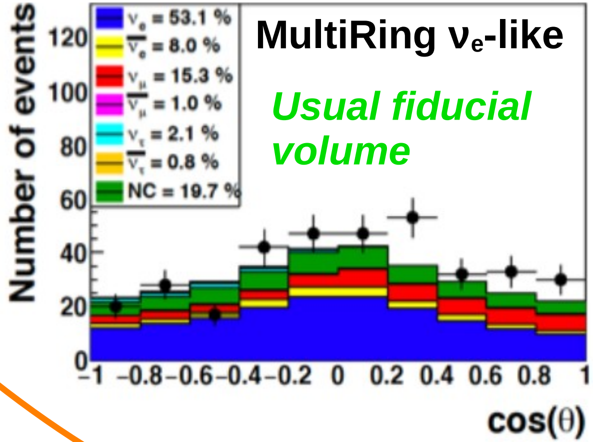
Significance comes from the SubGeV samples

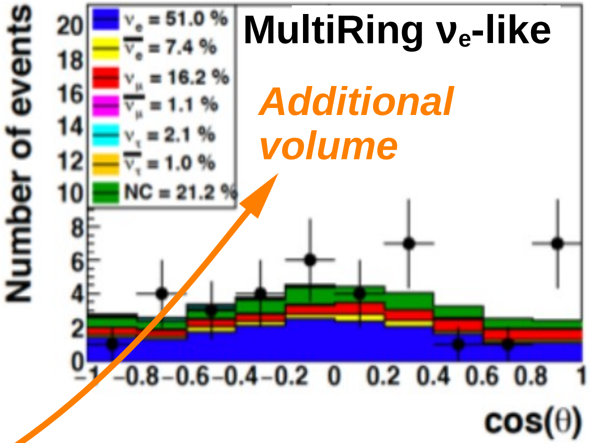
→ With improved efficiency and purity in SKIV using **neutron tagging**



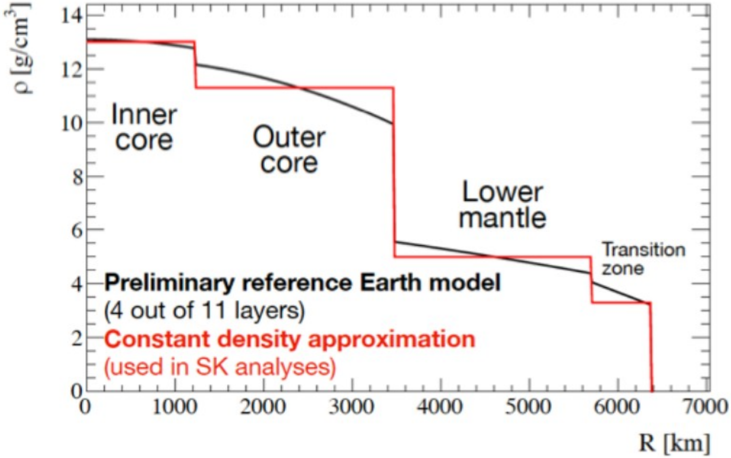
Next-to-come upgrades in SK Atm. Osc. Analysis

- Expansion of SK fiducial volume for all SK periods:
  - ➔ Distance vertex-wall: from >2*m* to ***>1m***
  - ➔ **20% increase** of **statistics**





- Add **data from SKV** (period after refurbishment and before Gd-loading)
- Include **tau selection** neural network to the oscillation analysis (tau-rich sample)
- Constraints from **T2K** with **improved model**
- Implement polynomial-based average density oscillation calculation



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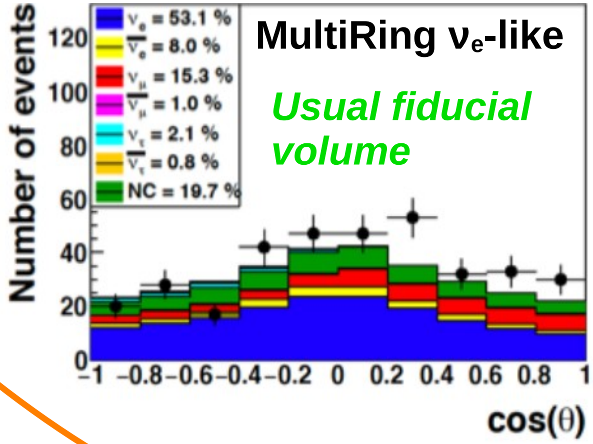

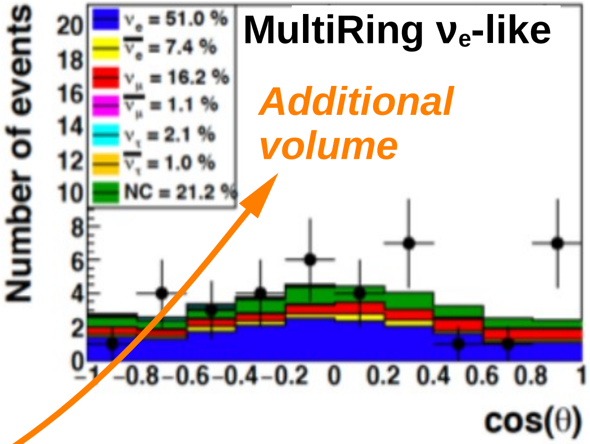

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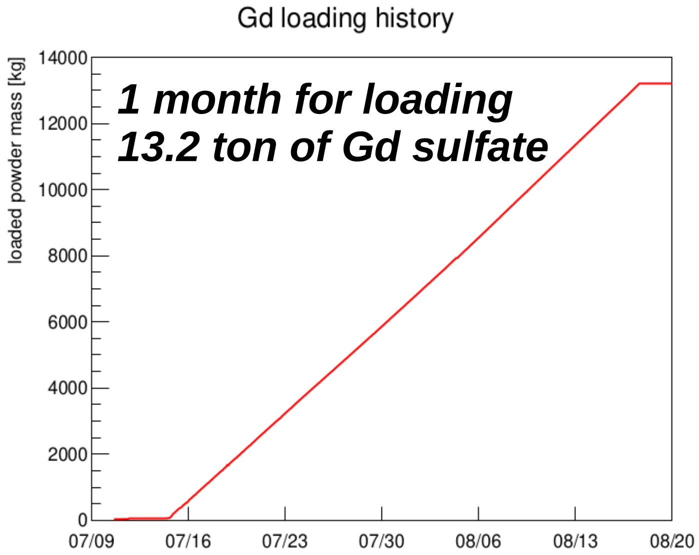
...and working very hard to analyze the first **SK data with Gd**

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

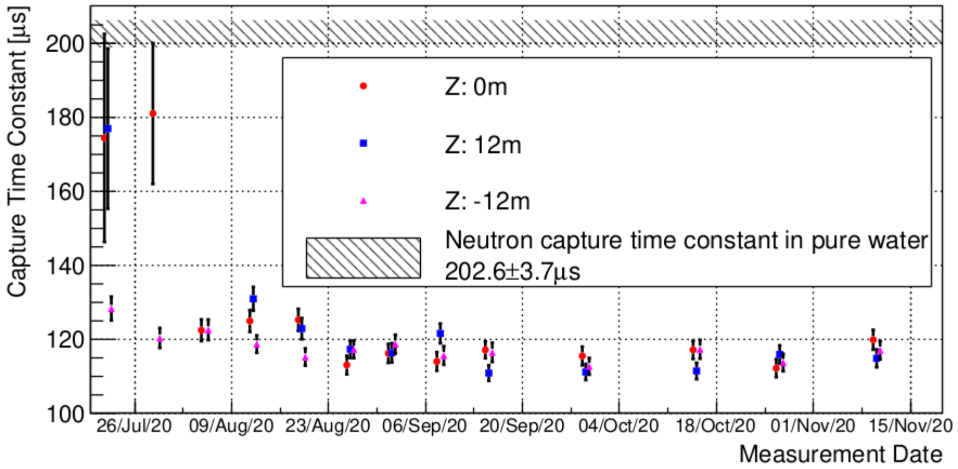
The **SuperK-Gd** upgrade has finally started in July 2020

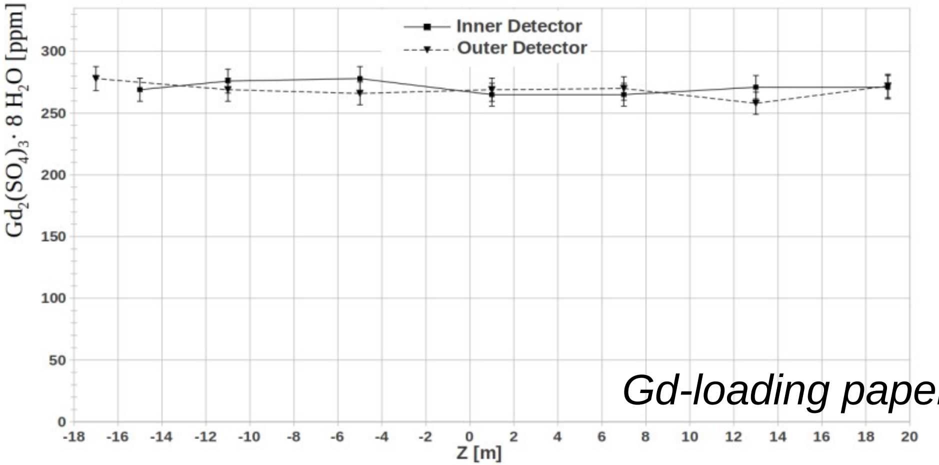
The detector is fully operational and acquiring data with **0.011% Gd concentration**

- ~50% of neutron tagging efficiency (x2 H-tagging eff.)
- *reduced neutron capture time from 200 to 116 μs*



Concentration and thus, neutron capture time, **stable since the start and throughout the whole detector**

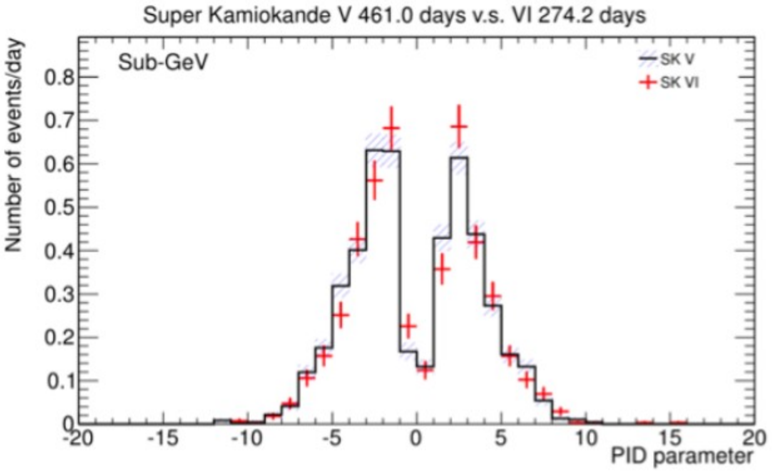


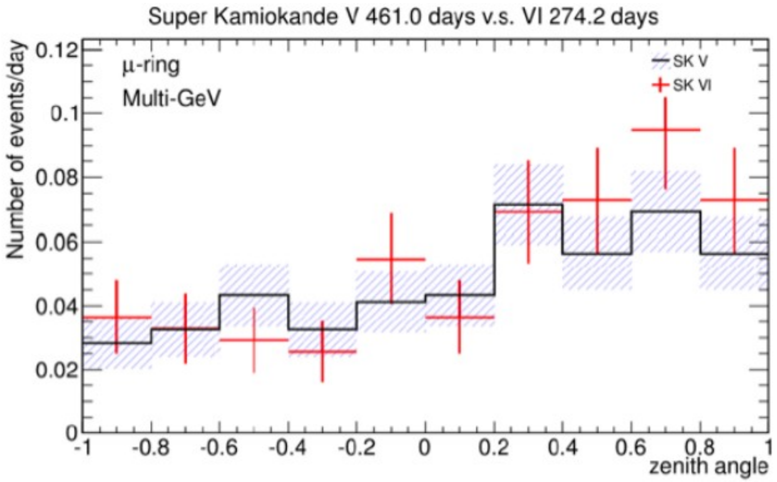


Gd-loading paper soon

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

Atmospheric neutrino data from **SKVI(Gd)** looks consistent with previous periods





Neutron tagging plays an important role 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 Cherenkov-invisible energy
- Provide additional power in discriminating CC events from NC and ν_τ events

Much work needed to fully exploit the information provided by neutron tagging

Conclusions

- After 25 years since the beginning, SK has rejuveneted once again to stay at the forefront of ν physics with **SuperK-Gd**
- **Upgraded atmospheric neutrino analysis:**
  - Neutron tagging for ν-$\bar{\nu}$ separation
  - Multi-ring BDT classification
  - Improved interaction models
  - Updated systematics
- **Results:**
  - 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 for this analysis to be released soon!

- Still more to come soon with additional data and important analysis upgrades
- **SuperK-Gd** is running stably, providing the first atmospheric neutrino data with **50% neutron tagging**

➔ Looking forward to the next loading from **0.01% to 0.03%** in spring 2022, increasing the Gd-capture efficiency to **~75%**