

Atmospheric Neutrino Oscillations at Super-Kamiokande



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For the Super-Kamiokande Collaboration

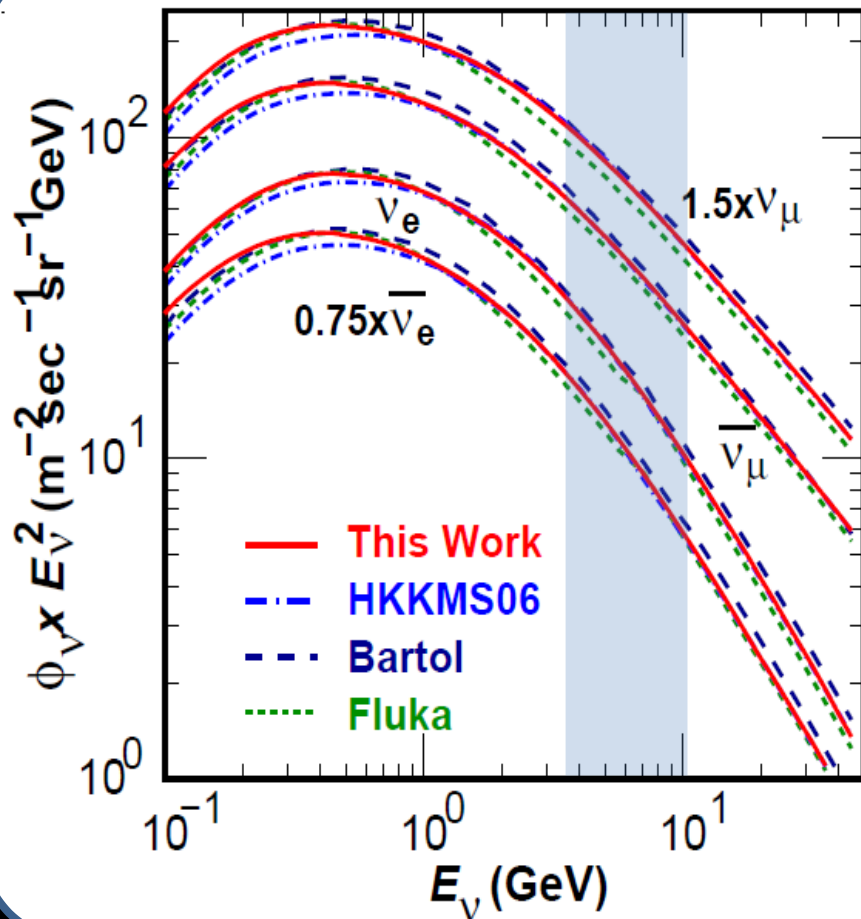
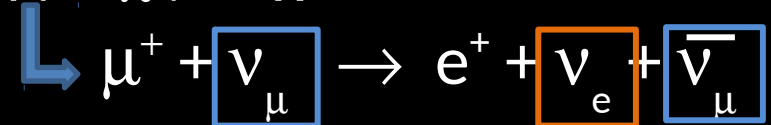
2015.08.06

ICRC 2015, The Hague

- Atmospheric neutrino oscillation results
 - Standard MNS Oscillation Analysis
 - Search for $\Delta m_s \sim \text{eV}^2$ scale sterile neutrinos
 - Search for Lorentz invariance violation
- Summary

Atmospheric Neutrino Generation

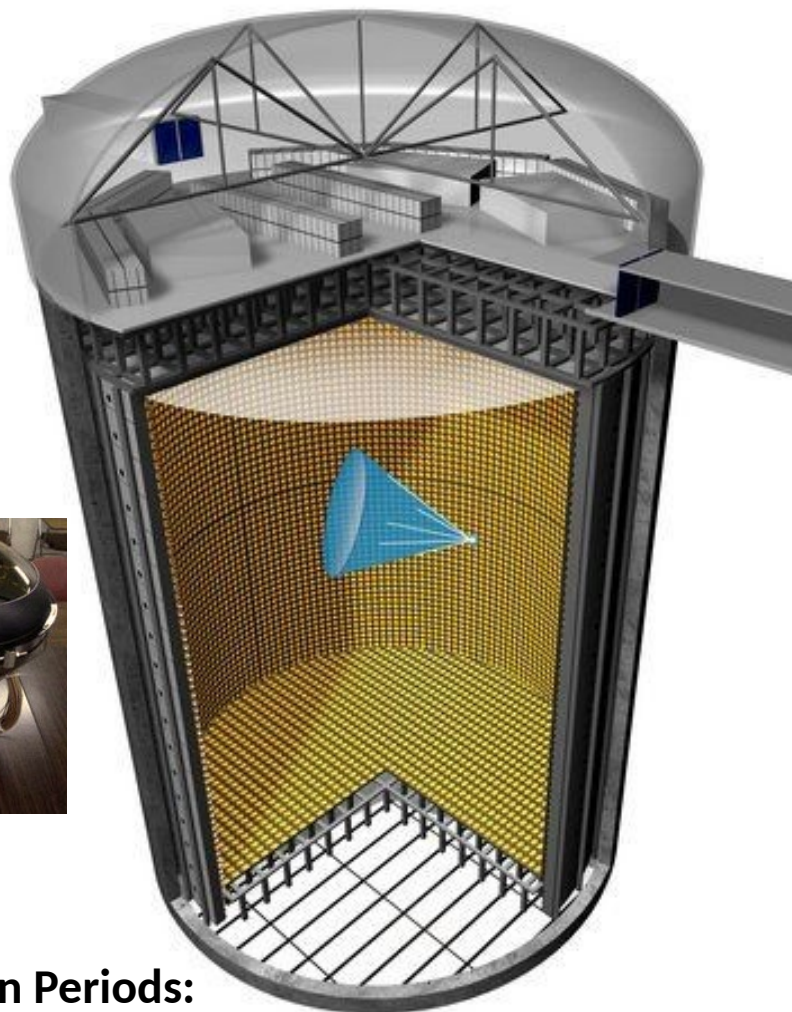
- Cosmic rays strike air nuclei and the decay of the out-going hadrons gives neutrinos



- Primary cosmic rays Isotropic about Earth
- ν s travel 10 – 10,000 km before detection
- Both neutrinos and antineutrinos in the flux
 - ~ 30% of final analysis samples are antineutrinos
- Flux spans many decades in energy ~100 MeV – 100TeV+
- Excellent tool for broad studies of neutrino oscillations
 - Access to sub-leading effects with high statistics

Super-Kamiokande: Introduction

4



Four Run Periods:

SK-I (1996-2001) SK-II (2003-2005)

SK-III (2005-2008) **SK-IV (2008-Present)**

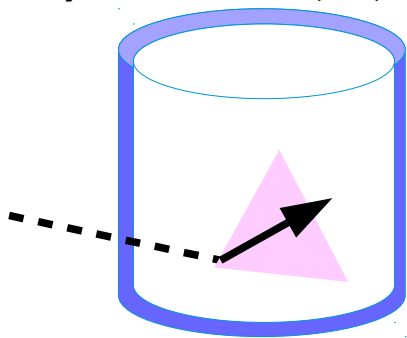
Proton Decay Results (M. Miura)
Solar Neutrino Measurements (Y. Nakano)
Atmospheric Neutrino Flux (E. Richard)

- 22.5 kton fiducial volume
- Optically separated into
 - Inner Detector 11,146 20" PMTs
 - Outer Detector 1885 8" PMTs
- No net electric or magnetic fields
- Excellent PID between showering (e-like) and non-showering (m-like)
 - $< 1\%$ MIS ID at 1 GeV
- Today: 4972 days of atmospheric neutrino data
 - 51,000 Events
 - Statistics limited
- Multipurpose machine
 - Solar and Supernova Neutrinos
 - **Atmospheric Neutrinos (this talk)**
 - Nucleon Decay
 - Far detector for T2K

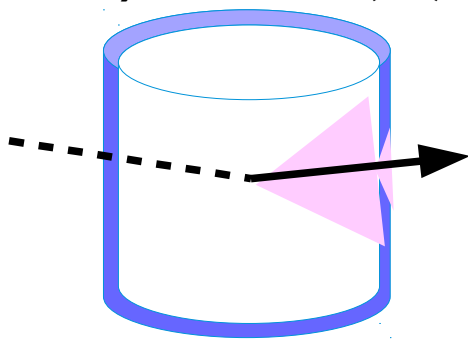
Super-K Atmospheric ν Analysis Samples

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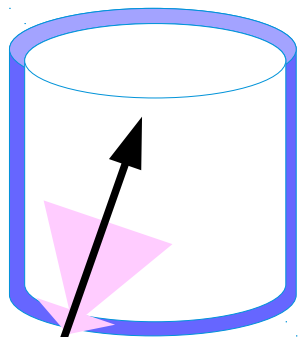
Fully Contained (FC)



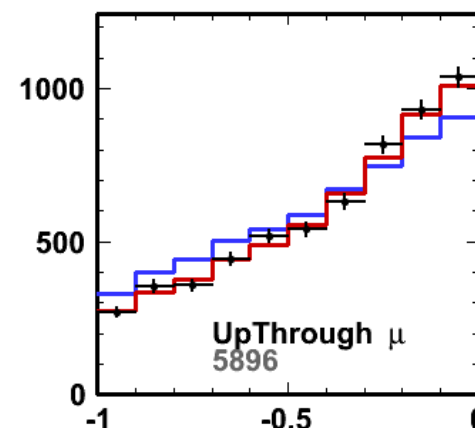
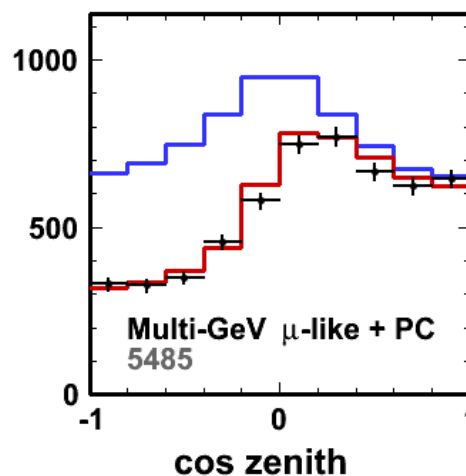
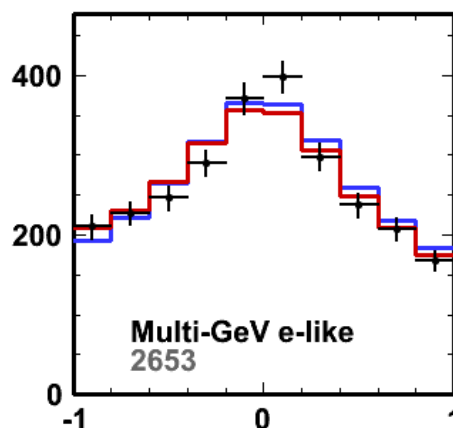
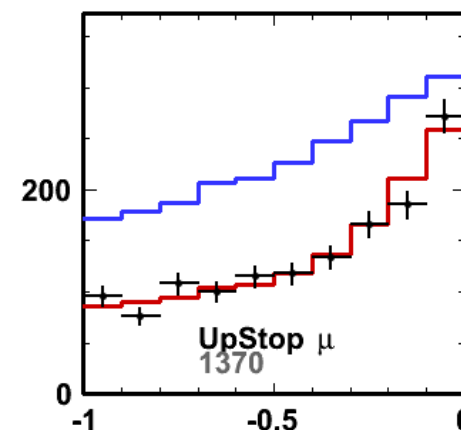
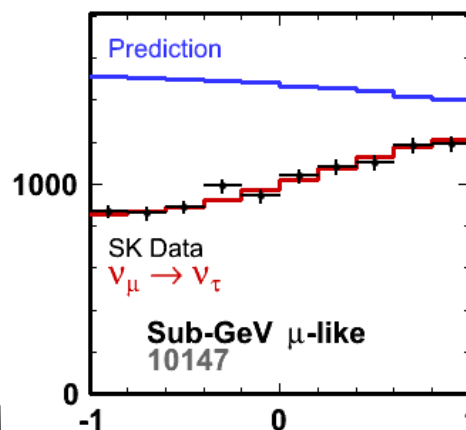
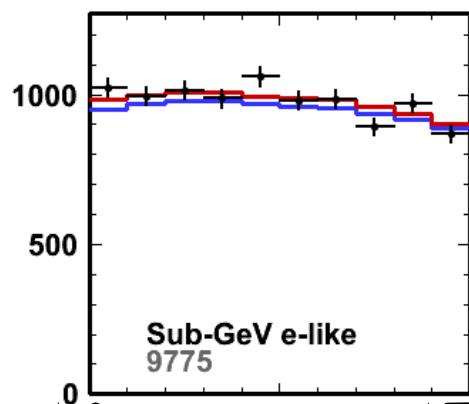
Partially Contained (PC)



Upward-going Muons (Up- μ)

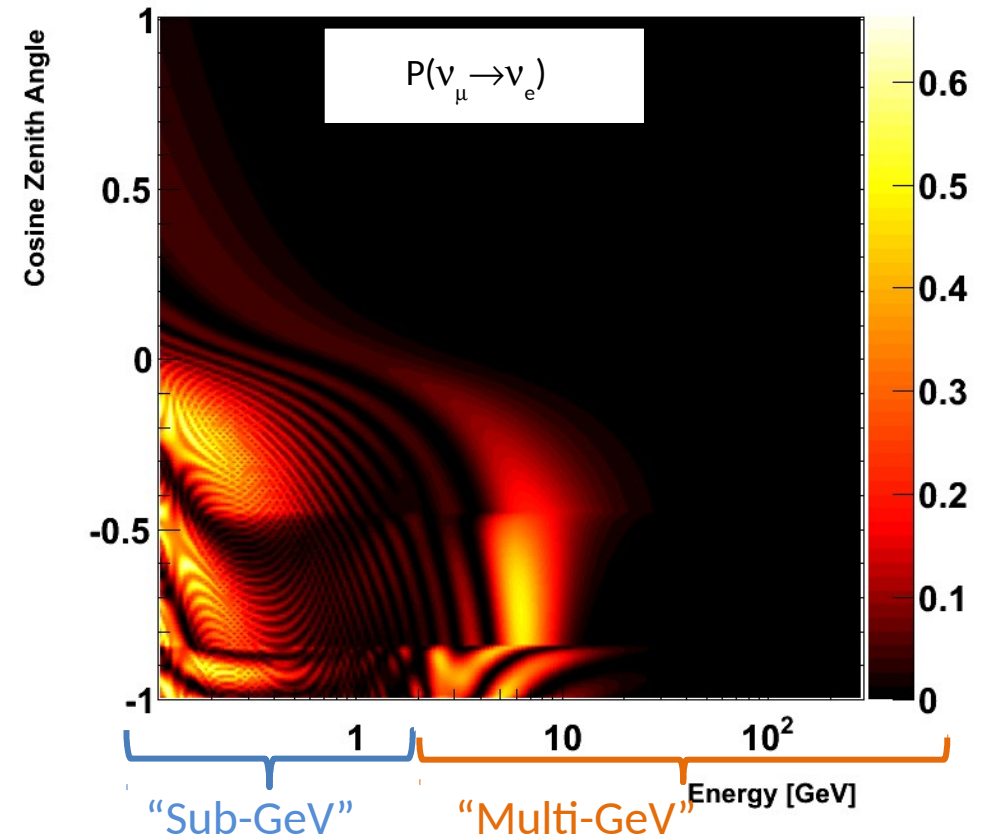
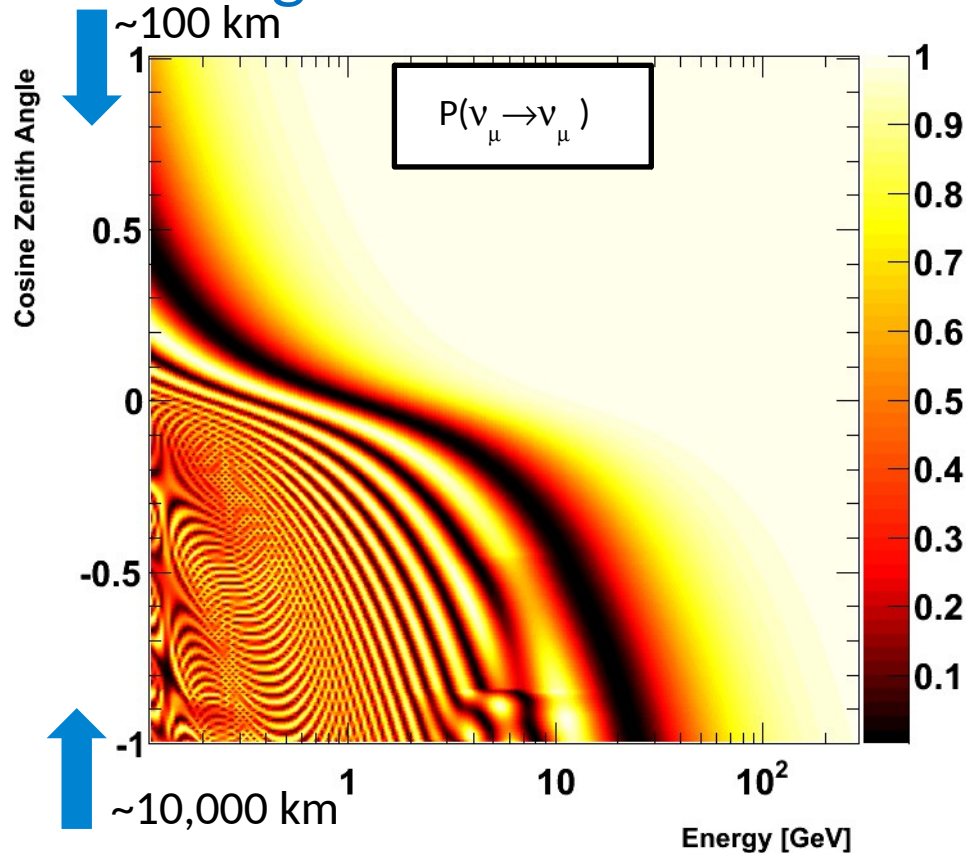


Number of Events



- In total **19** analysis samples: multi-GeV e-like samples are divided into ν -like and $\bar{\nu}$ -like subsamples
- Dominated by $\nu_\mu \rightarrow \nu_\tau$ oscillations
- Interested in subdominant contributions to this picture
 - le three-flavor effects, Sterile Neutrinos, LIV, etc.

Searching for Three-Flavor Effects: Oscillation probabilities



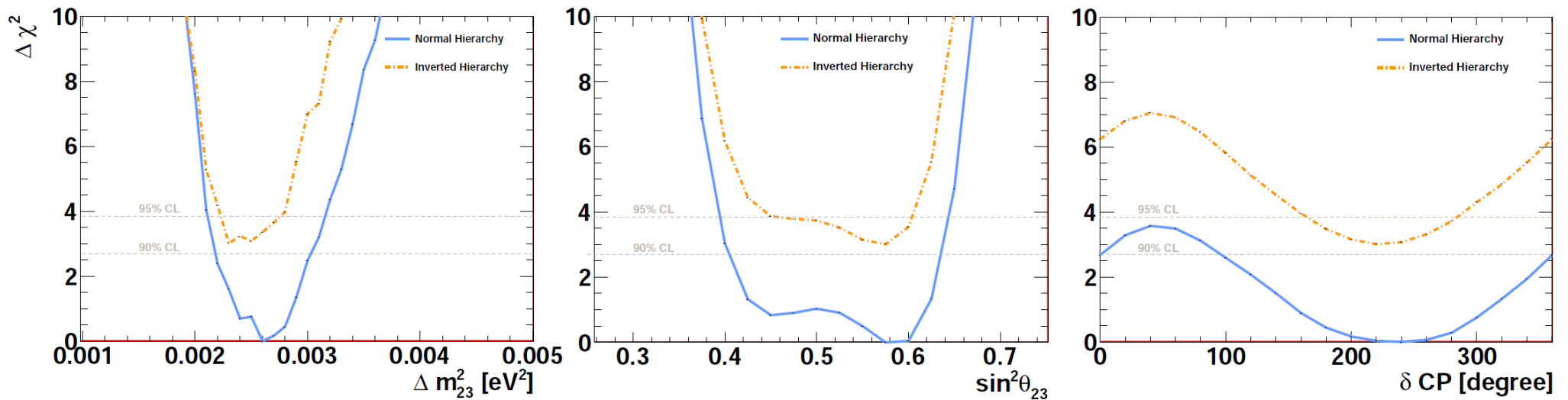
Key Points

- No $\nu_\mu \rightarrow \nu_e$ Appearance above ~ 20 GeV,
- Resonant oscillations between 2-10 GeV (for ν or $\bar{\nu}$ depending upon MH)
- No oscillations above 200 GeV
- No oscillations from downward-going neutrinos above ~ 5 GeV
- Expect effects in most analysis samples, largest in upward-going ν_e
- Sensitive to most of the MNS mixing parameters

θ_{13} Fixed Analysis (NH+IH) SK Only

7

Preliminary

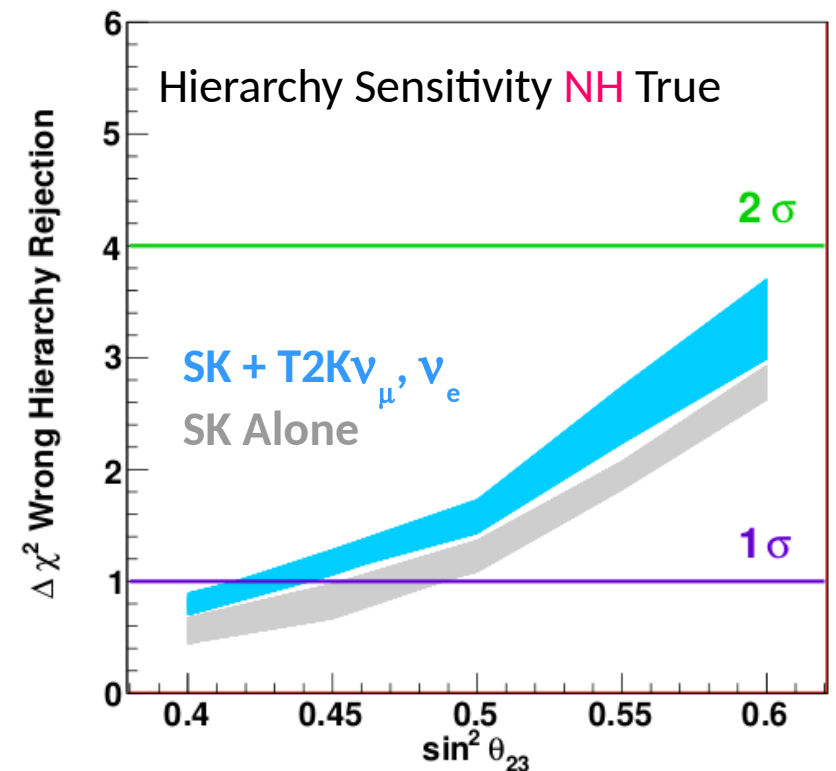
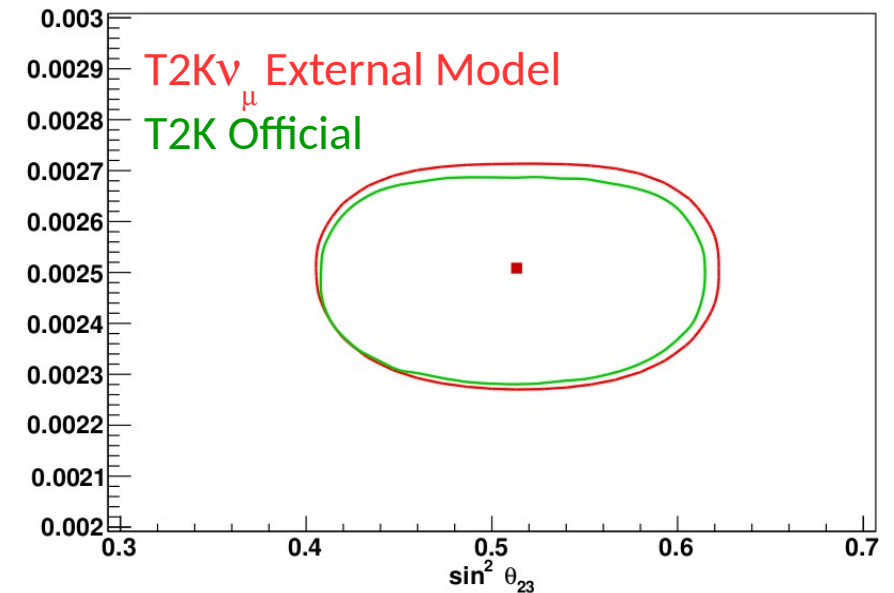


| Fit (517 dof) | χ^2 | θ_{13} | δ_{cp} | θ_{23} | $\Delta m_{23} (x10^{-3})$ |
|---------------|----------|---------------|---------------|---------------|----------------------------|
| SK (NH) | 582.4 | 0.0238 | 4.19 | 0.575 | 2.6 |
| SK (IH) | 585.4 | 0.0238 | 3.84 | 0.575 | 2.3 |

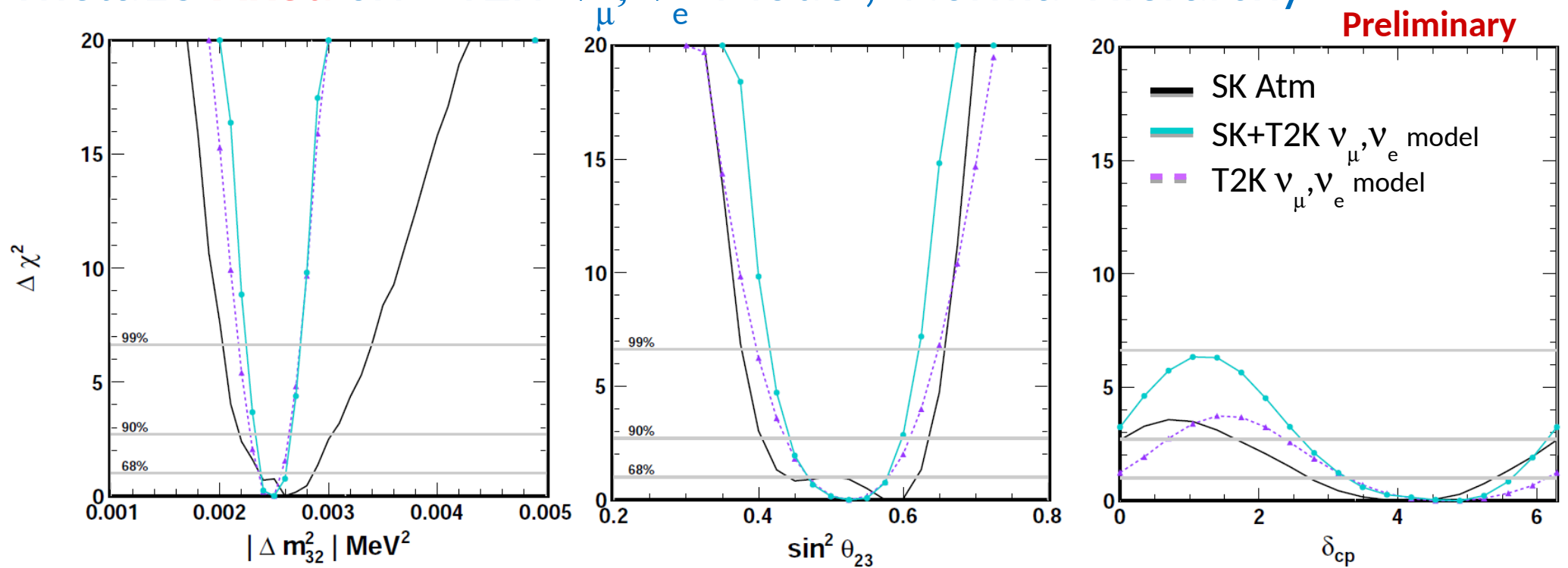
- Offset in these curves shows the difference in the hierarchies
- **Normal** hierarchy favored at: $\chi^2_{NH} - \chi^2_{IH} = -3.0$, not significant
 - Preference for matter over vacuum oscillations at $\sim 1 \sigma$ (82% C.L.)

Introduction of External Constraint

- Restricting the allowed values of Δm^2 and $\sin^2 \theta_{23}$ available to the atmospheric neutrino fit can help improve sensitivity to the mass hierarchy
 - Include these constraints as external data sets in the SK fit
- Goal: Fit the T2K ν_μ and ν_e data sets with SK
 - Same detector, generator and reconstruction: systematic error correlations incorporated easily
 - Build external models by reweighting atmospheric neutrino MC to T2K beam
 - Fit is based on **publicly available** T2K information and results
 - Simulate T2K using SK tools
 - (not a joint result of the T2K and SK collaborations)



Theta13 Fixed SK + T2K ν_μ, ν_e Model, Normal Hierarchy



| Fit (585 dof) | χ^2 | θ_{13} | δ_{cp} | θ_{23} | $\Delta m_{23} (\times 10^{-3})$ |
|---------------|----------|---------------|---------------|---------------|----------------------------------|
| SK + T2K (NH) | 651.5 | 0.0238 | 4.89 | 0.525 | 2.5 |
| SK + T2K (IH) | 654.7 | 0.0238 | 4.19 | 0.550 | 2.4 |

■ $\chi^2_{\text{NH}} - \chi^2_{\text{IH}} = -3.2$ (-3.0 SK only)

■ CP Conservation ($\sin \delta_{cp} = 0$) allowed at (at least) 90% C.L. for both hierarchies

Sterile Neutrino Oscillations in Atmospheric Neutrinos

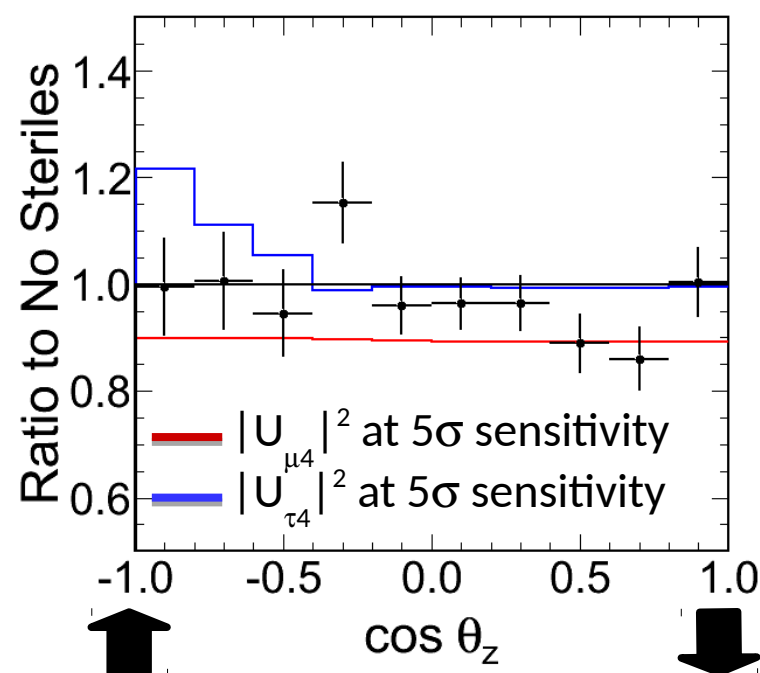
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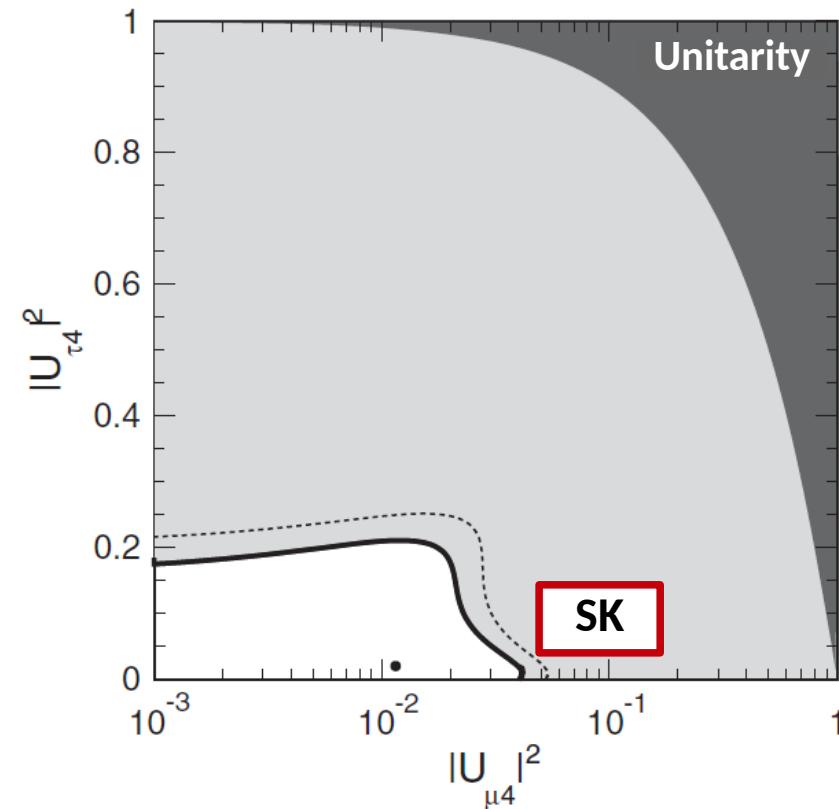
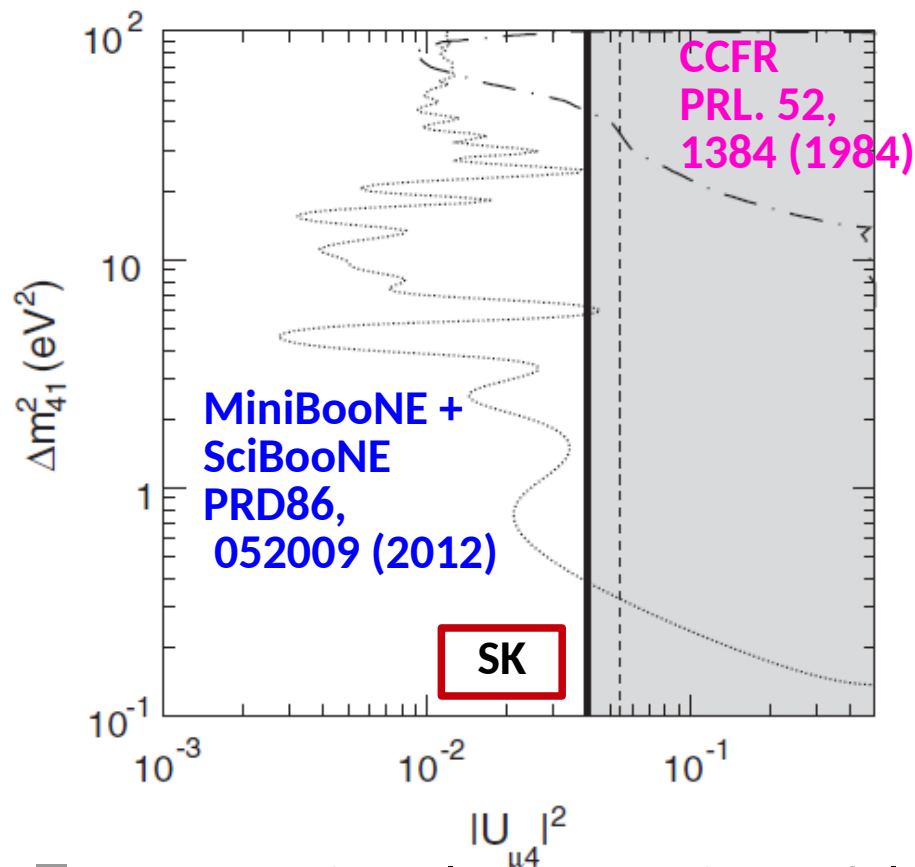
- Sterile Neutrino searches at SK are independent of the sterile Δm^2 and the number sterile neutrinos
 - 3+1 and 3+N models have the same signatures in atmospheric neutrinos
 - For $\Delta m_s^2 \sim 1 \text{ eV}^2$ oscillations appear fast: $\langle \sin^2 \Delta m^2 L/E \rangle \sim 0.5$

$$U = \begin{pmatrix} \begin{matrix} \text{MNS} & \text{Sterile} \end{matrix} \\ \begin{matrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & \cdots \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} & \cdots \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} & \cdots \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} & \cdots \end{matrix} \\ \begin{matrix} \vdots & \vdots & \vdots & \vdots & \ddots \end{matrix} \end{pmatrix}$$

- $|U_{\mu4}|^2$
 - Induces a decrease in event rate of μ -like data of all energies and zenith angles
- $|U_{\tau4}|^2$
 - Shape distortion of angular distribution of higher energy μ -like data

PC Through





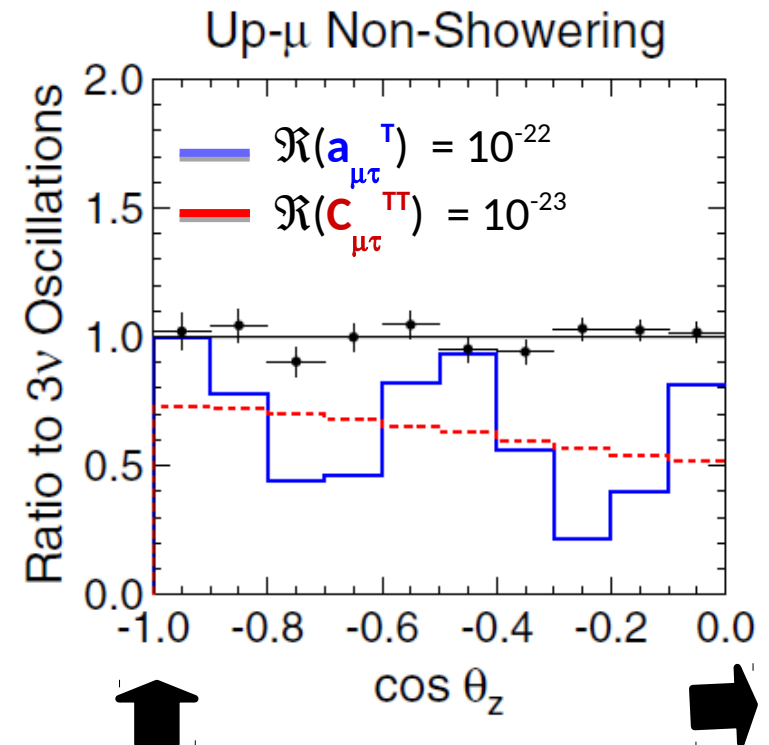
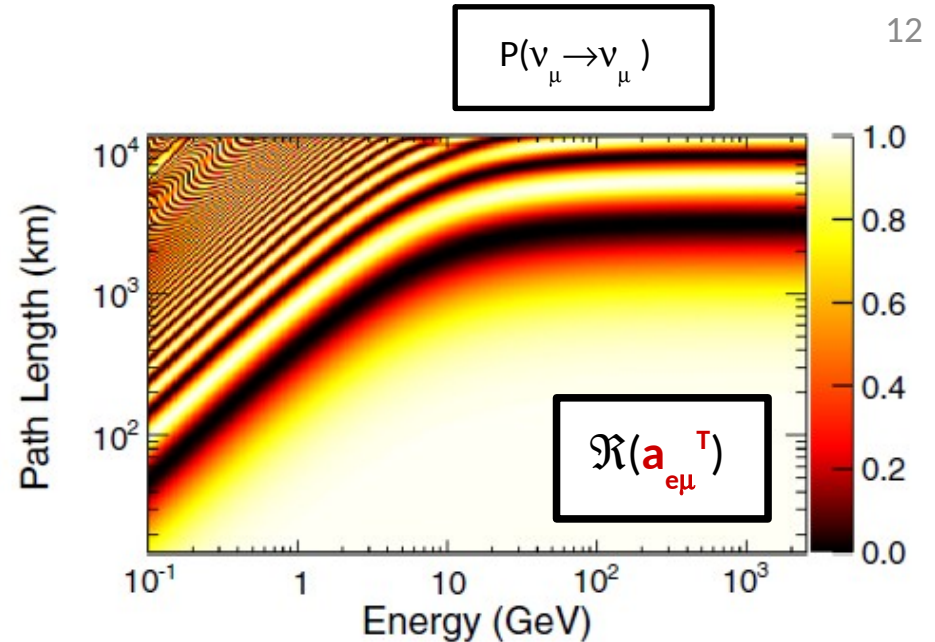
- Turning off sterile matter effects while preserving standard three-flavor oscillations provides a pure measurement of $|U_{\mu 4}|^2$
- Using sterile matter effects, but decoupling ν_e oscillations provides a joint measurement of $|U_{\mu 4}|^2$ and $|U_{\tau 4}|^2$, with a slightly biased estimate of the former
- Using SK-I+II+III+IV data (4438 days)
 $|U_{\mu 4}|^2 < 0.041$ at 90% C.L. $|U_{\tau 4}|^2 < 0.18$ at 90% C.L.

Tests of Lorentz Invariance

$$H = U M U^\dagger + V_e + H_{LV}$$

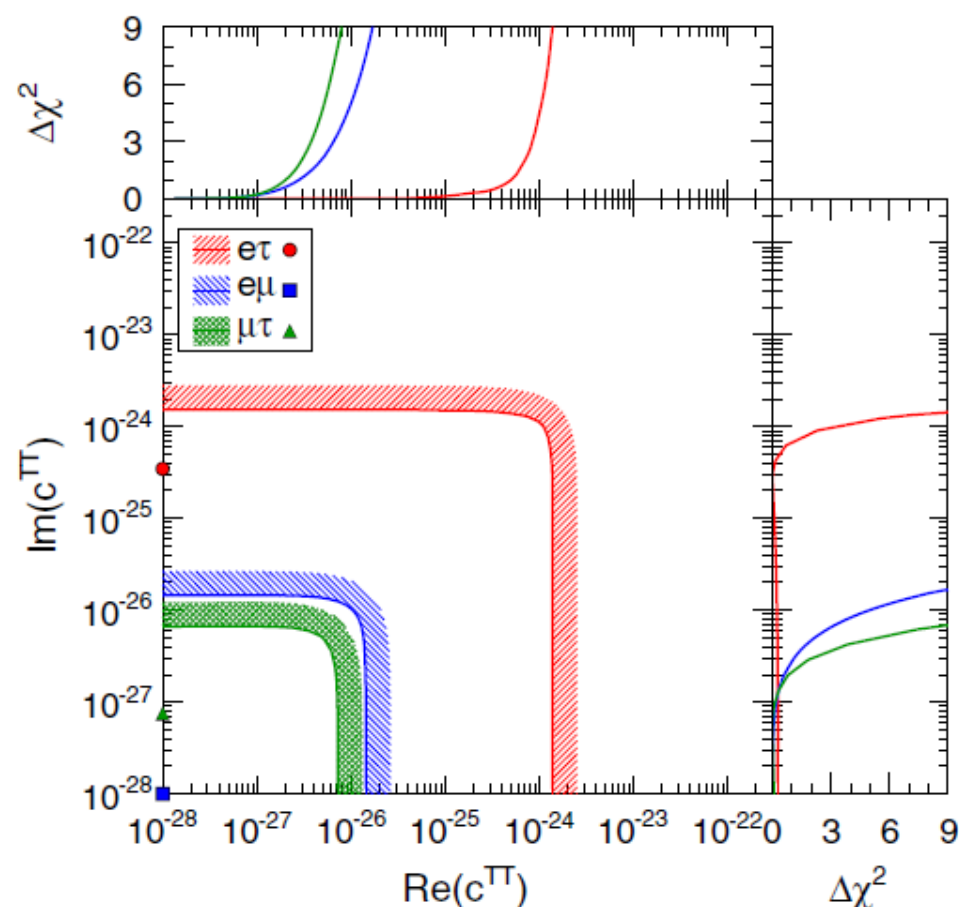
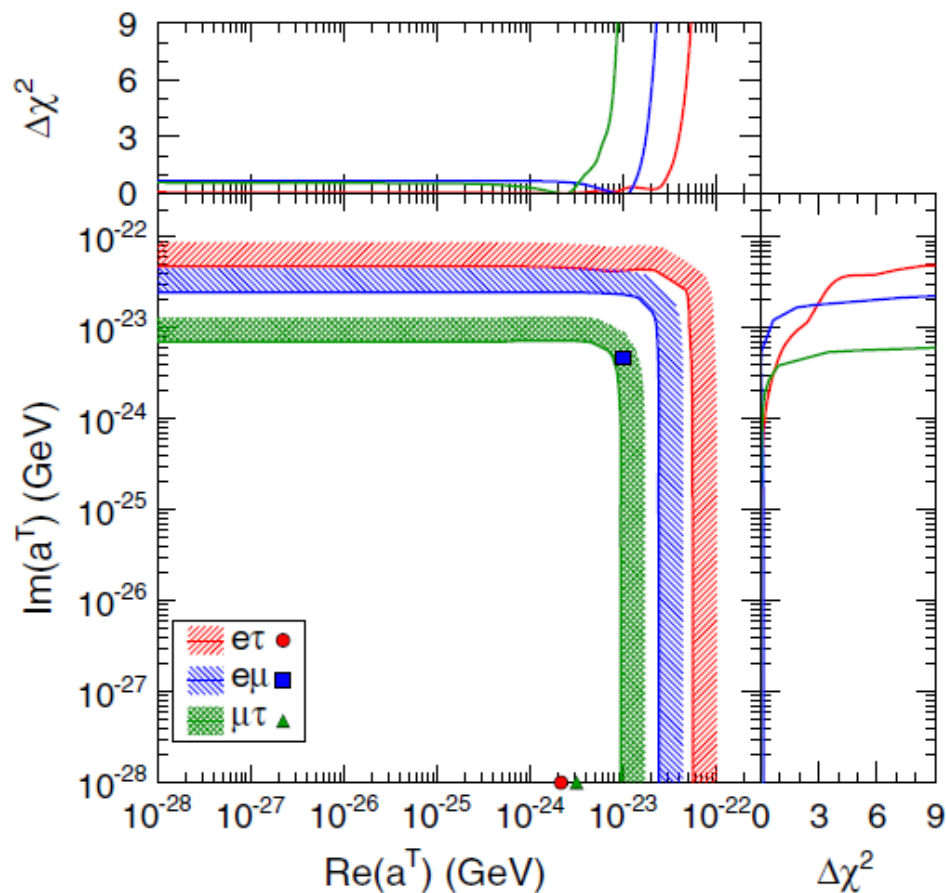
$$\pm \begin{pmatrix} 0 & a_{e\mu}^T & a_{e\tau}^T \\ (a_{e\mu}^T)^* & 0 & a_{\mu\tau}^T \\ (a_{e\tau}^T)^* & (a_{\mu\tau}^T)^* & 0 \end{pmatrix} - E \begin{pmatrix} 0 & c_{e\mu}^{TT} & c_{e\tau}^{TT} \\ (c_{e\mu}^{TT})^* & 0 & c_{\mu\tau}^{TT} \\ (c_{e\tau}^{TT})^* & (c_{\mu\tau}^{TT})^* & 0 \end{pmatrix}$$

- Lorentz invariance violating effects can be probed using atmospheric neutrinos
 - Focus here on **isotropic** effects
 - (sensitive to sidereal effects as well...)
- Analysis using the Standard Model Extension (SME)
 - **Not a perturbative** calculation
 - Effects computed using full solutions of the Hamiltonian
- Effects of LIV controlled by two sets of complex parameters
 - $\mathbf{a}_{\alpha\beta}^T$ dim = 3 induces oscillation effects $\sim L$
 - $\mathbf{c}_{\alpha\beta}^{TT}$ dim = 4 induces oscillation effects $\sim L \times E$



Constraints on Lorentz Invariance Violating Oscillations: 90% C.L.

13



PRD.91.052019 (2015)

- SK-I+II+III+IV : 4438 days of data
- Perform separate fits on both hierarchy assumptions for each coefficient and each sector : $e\mu$, $e\tau$, $\mu\tau$
- No indication of Lorentz invariance violation
 - Limits placed on the real and imaginary parts of **6 parameters** $\leq O(10^{-23})$
 - New limits on $\mu\tau$ sector, improvements by **3 to 7** orders of magnitude over existing limits

■ Three-Flavor Analysis

- Using 4972 days of data, there is a $\sim 1 \sigma$ ($\Delta\chi^2 = 3.0$) preference for the NH, and second octant

■ No indication of oscillations into sterile states

- For 3+N models $|U_{\mu 4}|^2 < 0.041$ and $|U_{\tau 4}|^2 < 0.18$ 90% C.L.

■ No indication of Lorentz invariance violation

- New limits set and others improved by 3 to 7 orders of magnitude

Thank you

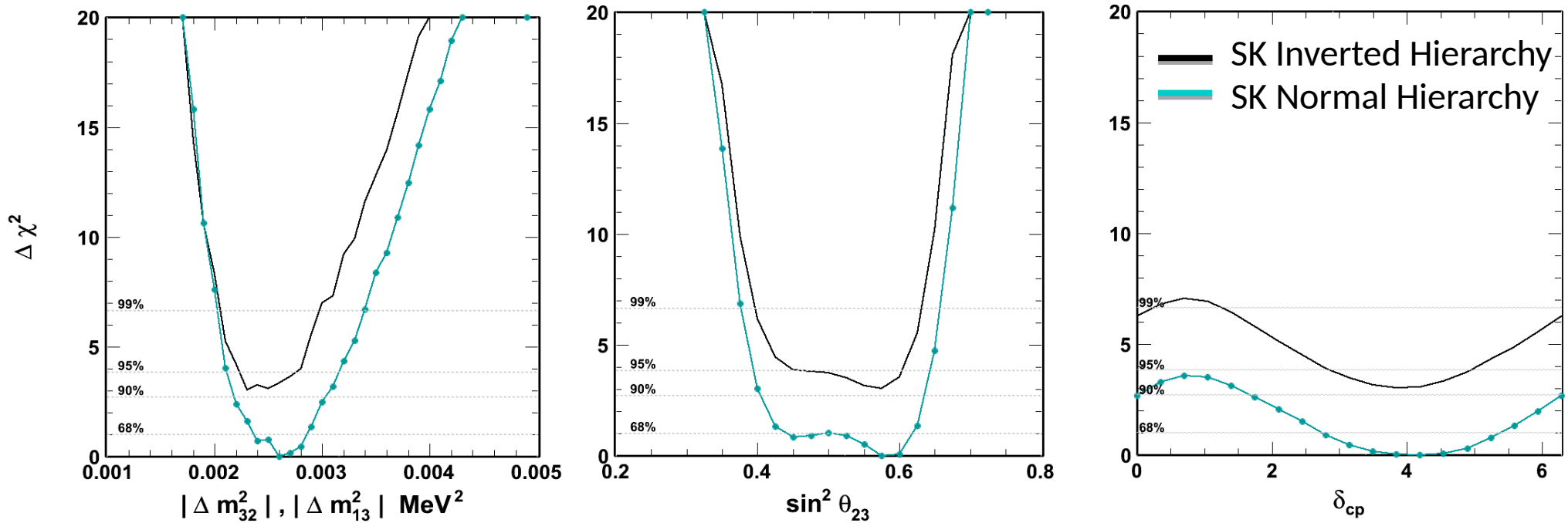
Supplements

Three-Flavor

θ_{13} Fixed Analysis (NH+IH) SK Only

17

Preliminary



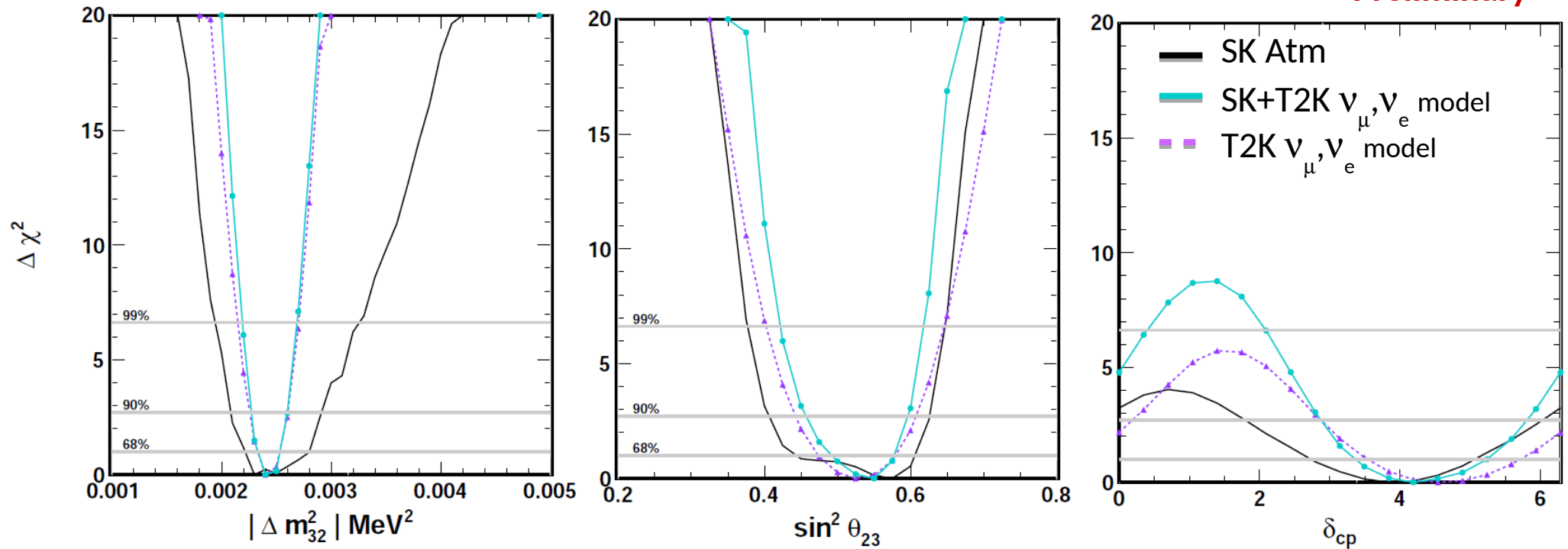
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Theta13 Fixed SK + T2K ν_μ, ν_e Model, Inverted Hierarchy

Preliminary



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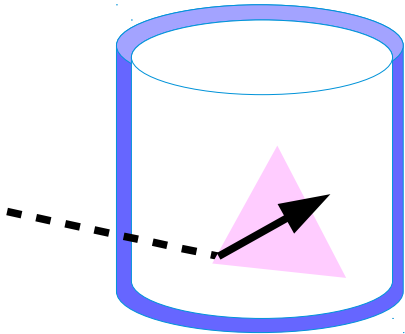
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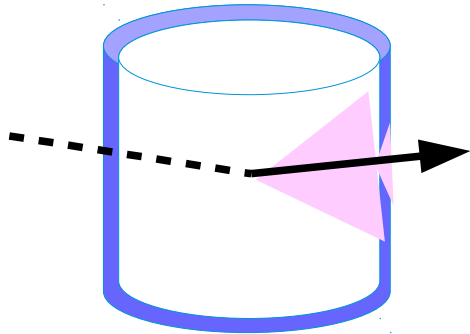
Super-K Atmospheric ν Event Topologies

19

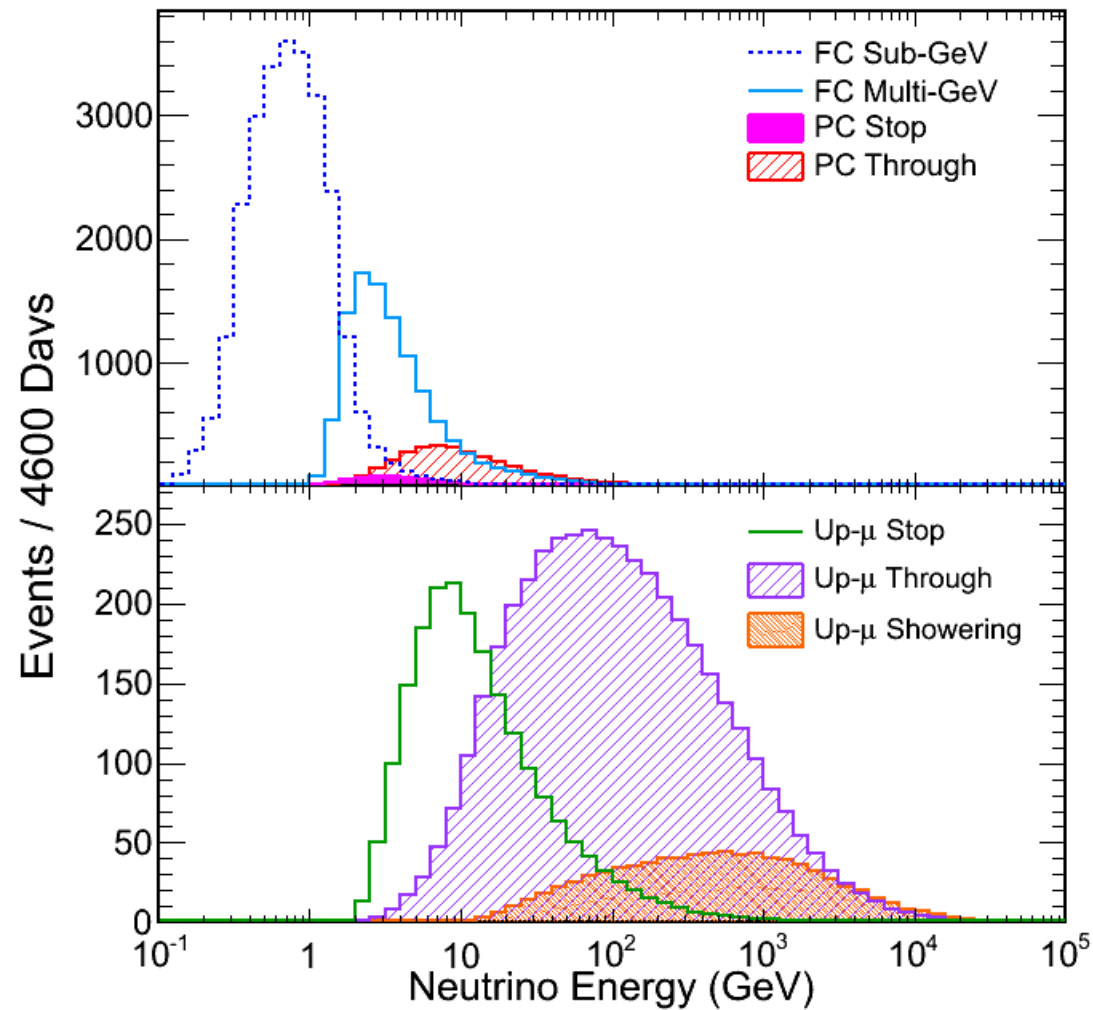
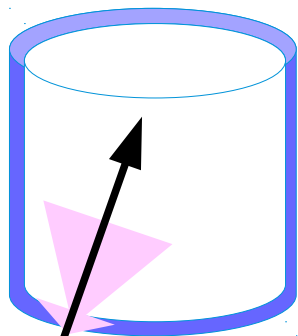
Fully Contained (FC)



Partially Contained (PC)



Upward-going Muons (Up- μ)

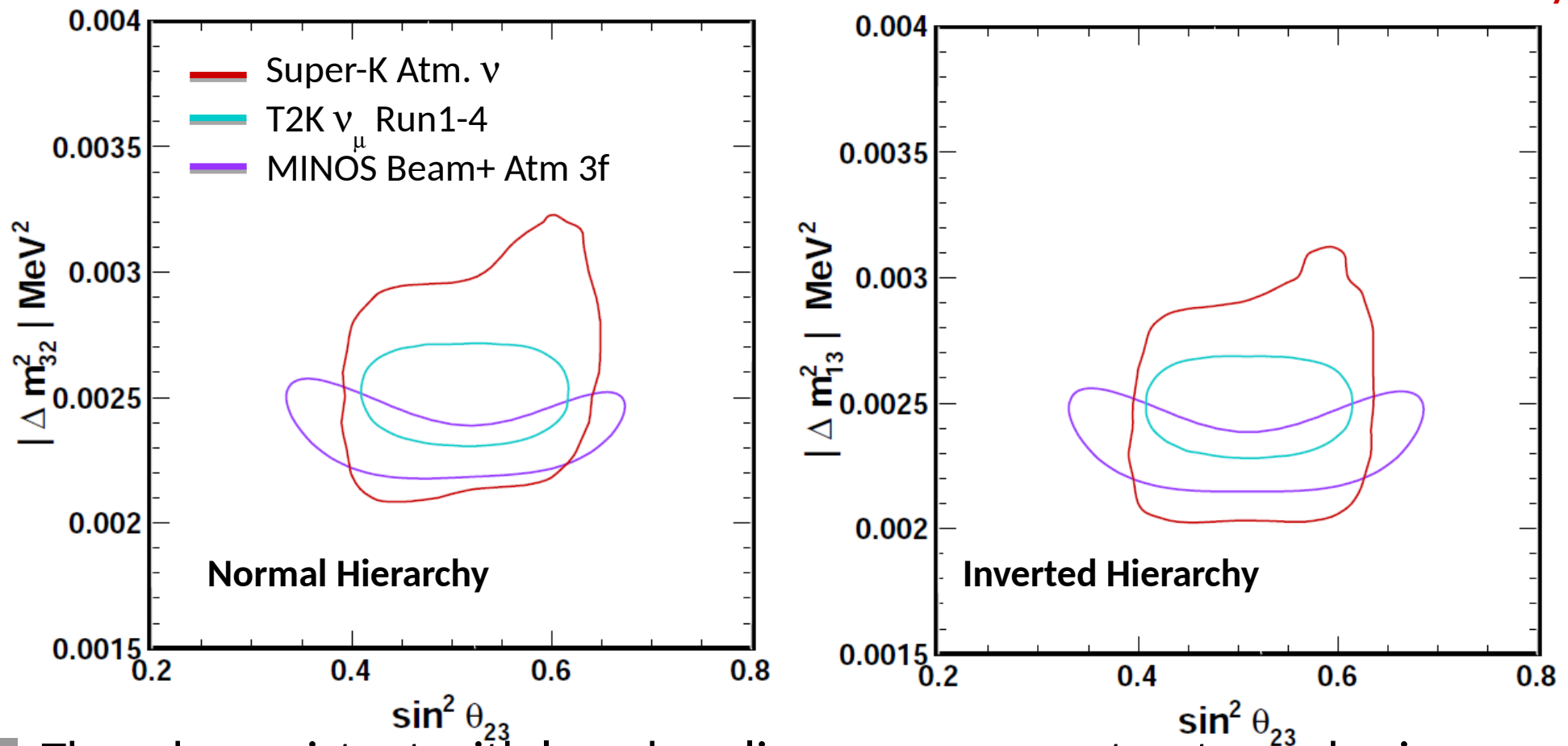


■ Average energies

- FC: ~ 1 GeV , PC: ~ 10 GeV, UpMu: ~ 100 GeV

Comparison with Official Results from T2K and MINOS

Preliminary



- Though consistent with long-baseline measurements, atmospheric neutrinos allow more of the mixing parameter space
- SK's sensitivity can be improved by incorporating constraints from these measurements

About These Results

■ Normal hierarchy favored at:

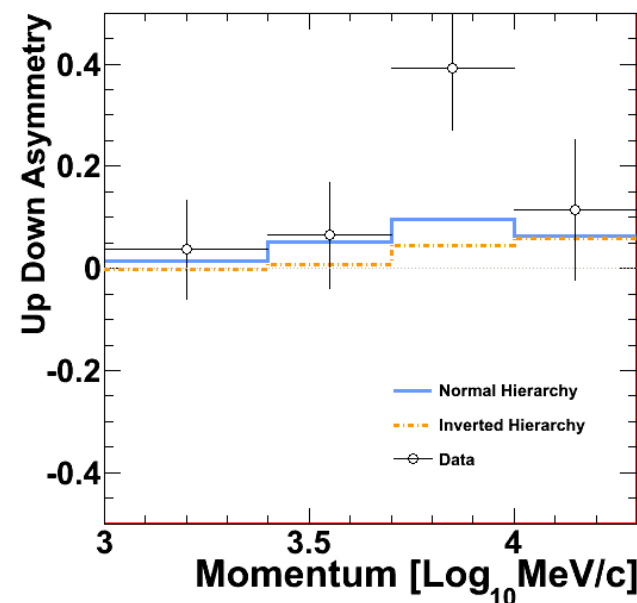
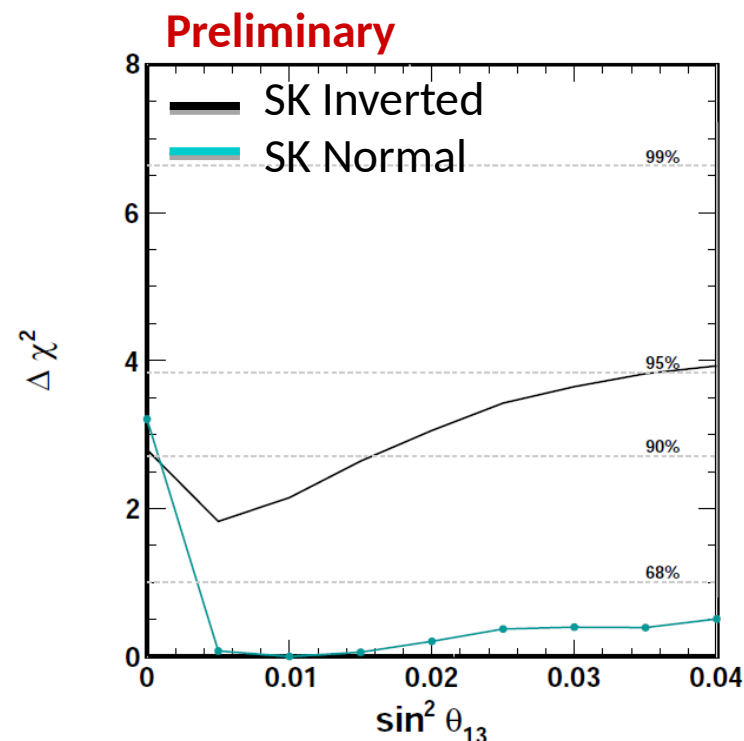
- $\chi^2_{\text{NH}} - \chi^2_{\text{IH}} = -3.0$
- Not a significant preference
- Previous results (2014 Summer) favored normal hierarchy by $\Delta\chi^2 \sim 0.9$

■ Driven by excess of upward-going e-like events consistent with the effects of θ_{13}

- Primarily in SK-IV data
- New multi-ring e-like sample also pulls the fit towards the NH
- Fit for θ_{13} now weakly favors $\theta_{13} \neq 0$

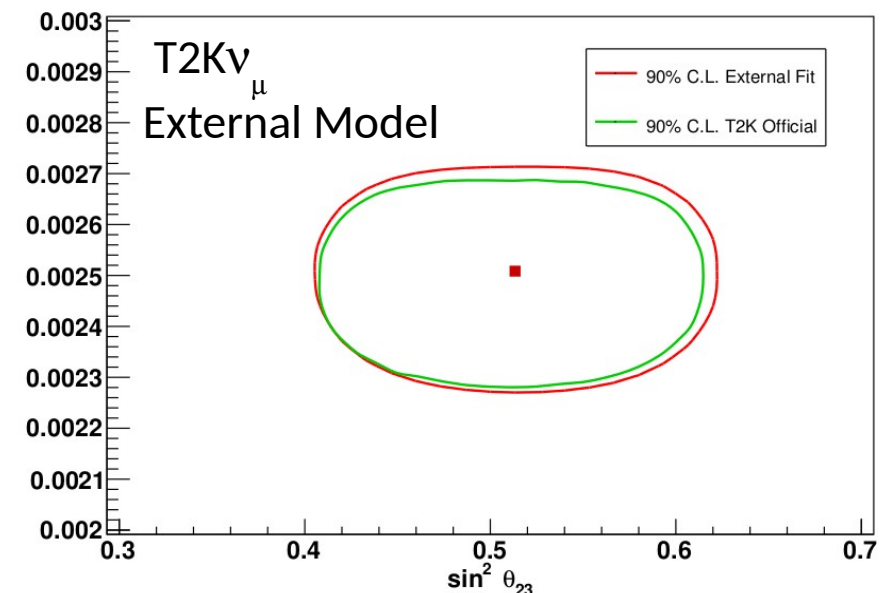
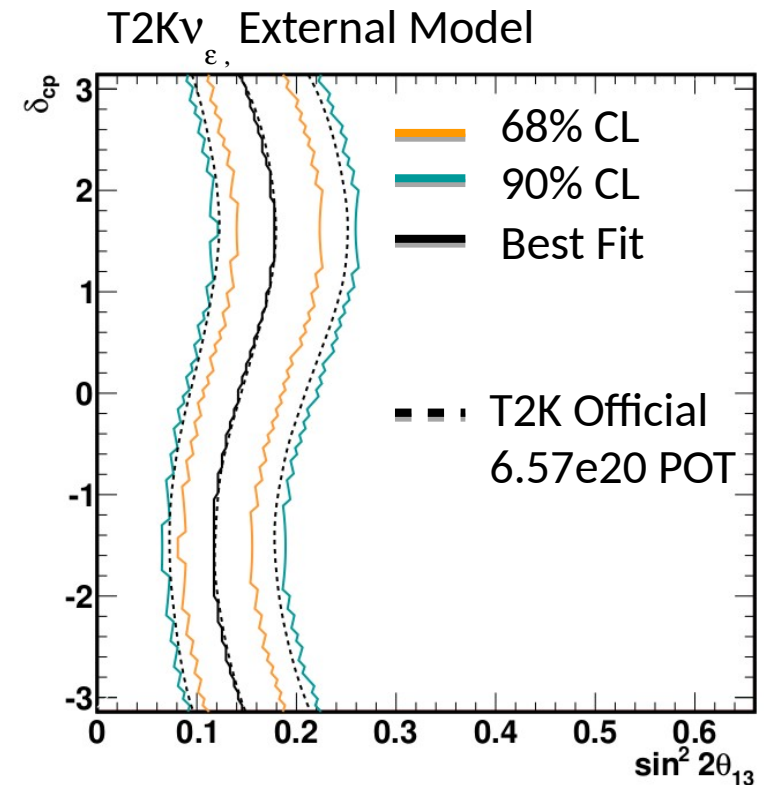
■ Rejection of $\delta_{\text{cp}} \sim 60^\circ$ driven by excess in SubGeV electron events

- Constraint is consistent with sensitivity



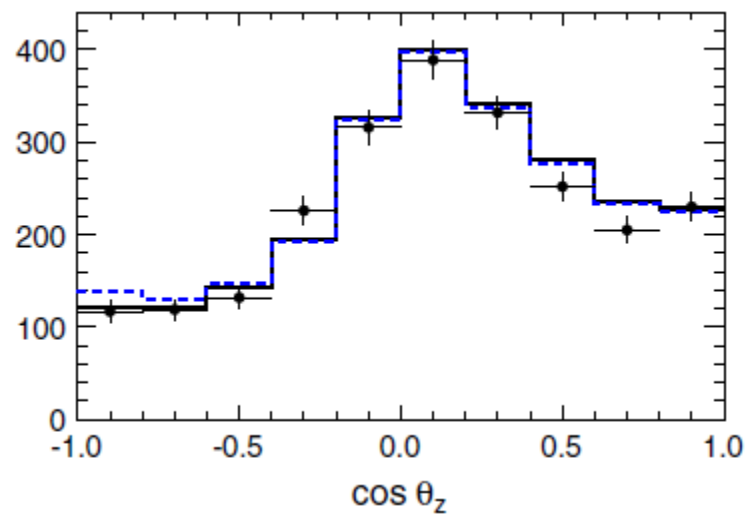
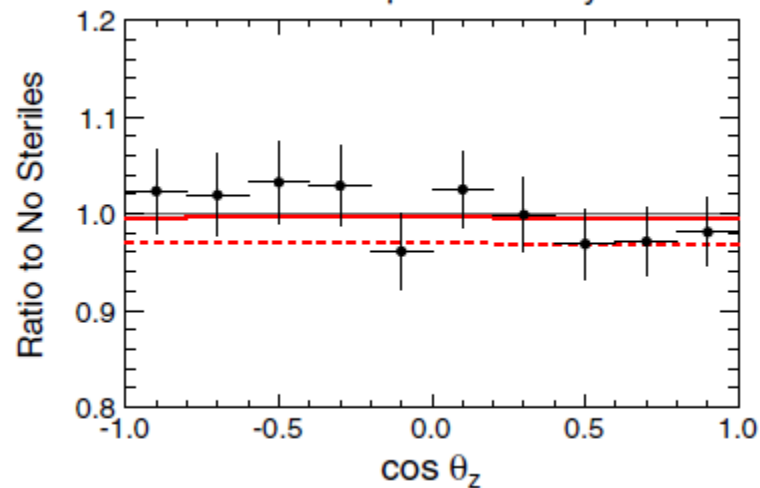
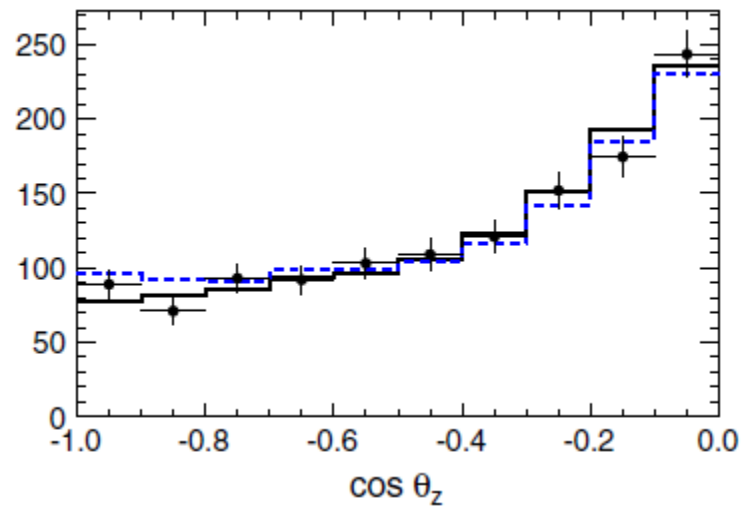
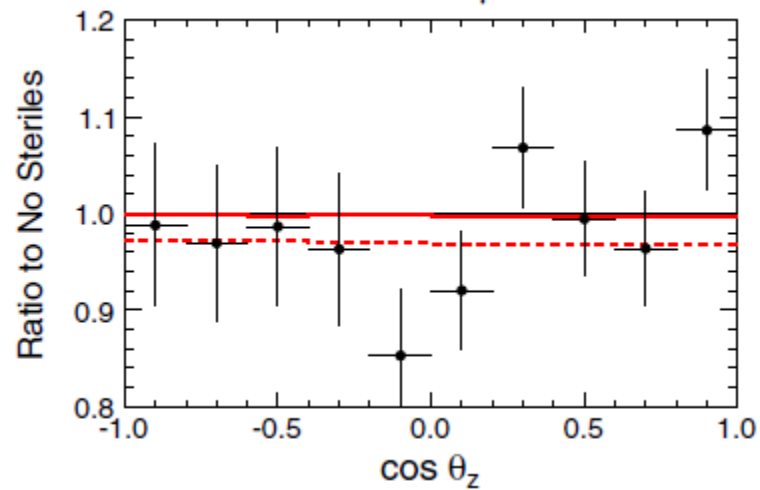
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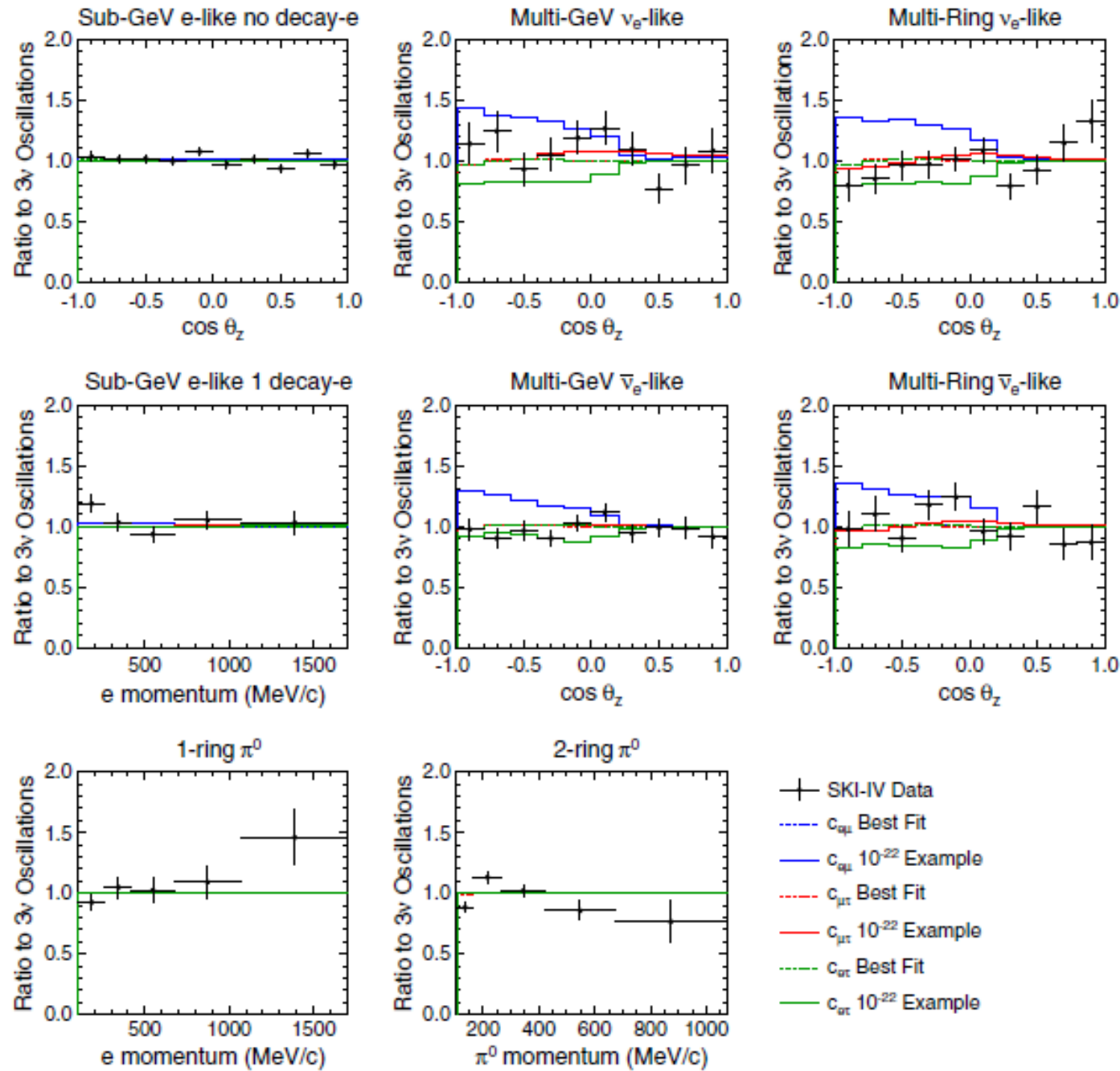


Sterile

PC Through-going

Sub-GeV μ -like 1 decay-eUp- μ StoppingMulti-GeV μ -like

LIV



| LV parameter | | Limit at 95% C.L. | Best fit | No LV $\Delta\chi^2$ | Previous limit |
|--------------|---------------------|---------------------------|---------------------------|----------------------|--------------------------------|
| $e\mu$ | $\text{Re}(a^T)$ | 1.8×10^{-23} GeV | 1.0×10^{-23} GeV | 1.4 | 4.2×10^{-20} GeV [61] |
| | $\text{Im}(a^T)$ | 1.8×10^{-23} GeV | 4.6×10^{-24} GeV | | |
| | $\text{Re}(c^{TT})$ | 8.0×10^{-27} | 1.0×10^{-28} | 0.0 | 9.6×10^{-20} [61] |
| | $\text{Im}(c^{TT})$ | 8.0×10^{-27} | 1.0×10^{-28} | | |
| $e\tau$ | $\text{Re}(a^T)$ | 4.1×10^{-23} GeV | 2.2×10^{-24} GeV | 0.0 | 7.8×10^{-20} GeV [62] |
| | $\text{Im}(a^T)$ | 2.8×10^{-23} GeV | 1.0×10^{-28} GeV | | |
| | $\text{Re}(c^{TT})$ | 9.3×10^{-25} | 1.0×10^{-28} | 0.3 | 1.3×10^{-17} [62] |
| | $\text{Im}(c^{TT})$ | 1.0×10^{-24} | 3.5×10^{-25} | | |
| $\mu\tau$ | $\text{Re}(a^T)$ | 6.5×10^{-24} GeV | 3.2×10^{-24} GeV | 0.9 | ... |
| | $\text{Im}(a^T)$ | 5.1×10^{-24} GeV | 1.0×10^{-28} GeV | | |
| | $\text{Re}(c^{TT})$ | 4.4×10^{-27} | 1.0×10^{-28} | 0.1 | ... |
| | $\text{Im}(c^{TT})$ | 4.2×10^{-27} | 7.5×10^{-28} | | |