Atmospheric Neutrino Results mostly from Super-Kamiokande

John Learned
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and

Roger Wendell of ICRR, U. Tokyo
mostly based on his Nu2014 Boston talk

And with thanks to the SuperK Collaboration

KITP Neutrino Workshop, 3 November 2014

Introduction

- Some Introductory Material

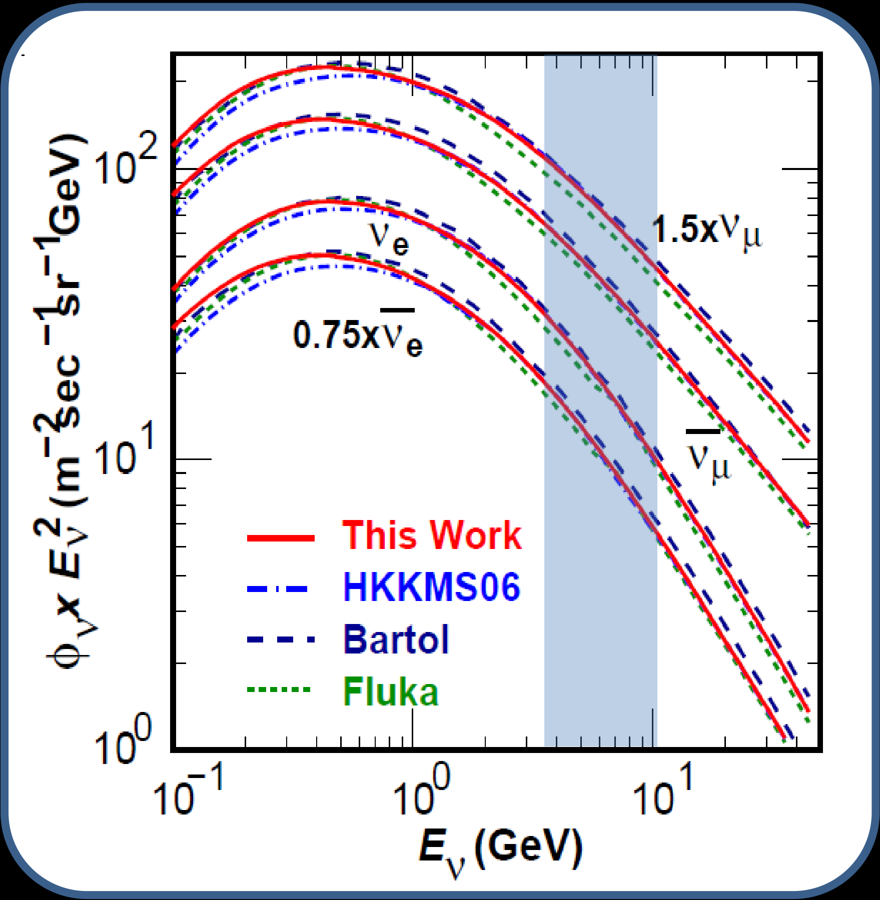
- Atmospheric neutrinos as **signal**
  - Search for ν_τ Appearance
  - Standard MNS Oscillation Analysis
  - Search for $\Delta m_s \sim eV^2$ scale sterile neutrinos
  - Search for Lorentz invariance violation

- Atmospheric neutrinos as **background**
  - Search for WIMP-induced neutrinos from the galactic center
  - Search for WIMP-induced neutrinos from the sun

- Summary

Atmospheric Neutrinos As Signal

Atmospheric Neutrino Generation



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

$P + A \rightarrow N + \pi+ + x$

$\mu+ + \nu\mu \rightarrow e+ + \nu e + \bar{\nu}\mu$

Primary cosmic rays Isotropic about Earth
νs 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

R.Wendell (ICRR)

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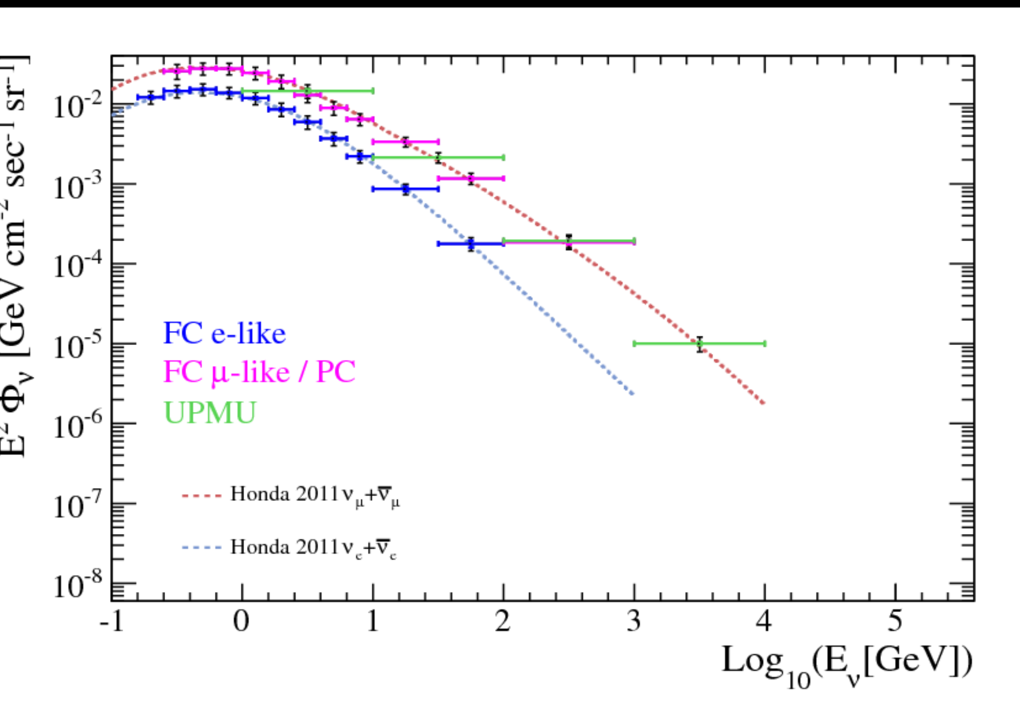

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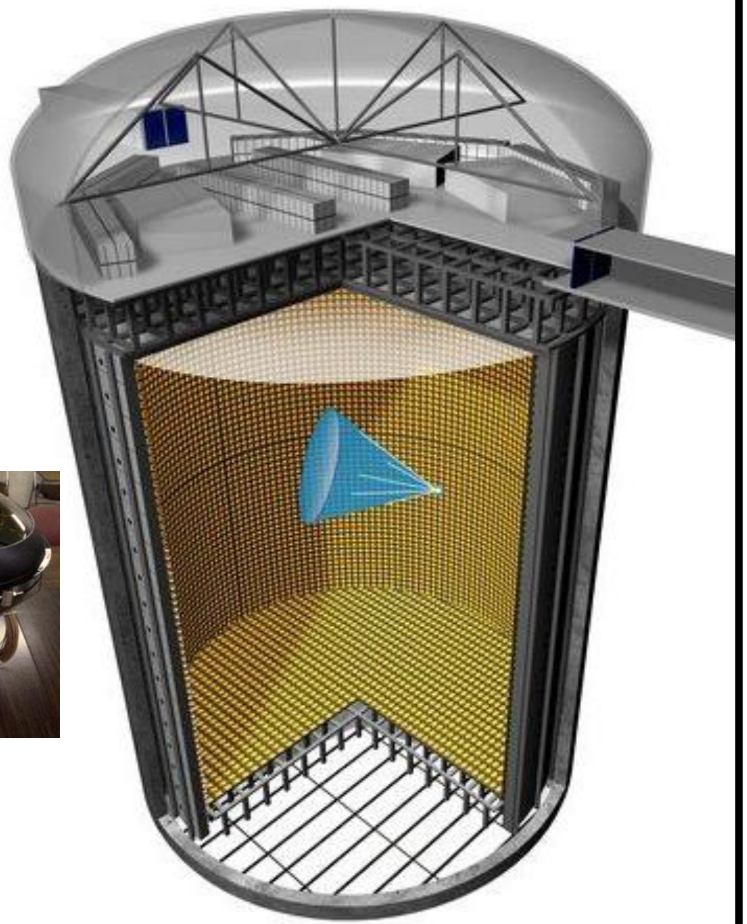
Super-Kamiokande: Introduction



Four Run Periods:
SK-I (1996-2001)
SK-II (2003-2005)
SK-III (2005-2008)
SK-IV (2008-Present)

- 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 (μ-like)
  - < 1% MIS ID at 1 GeV

- Today: 4581 days of atmospheric neutrino data
  - 40,000 Events
  - Statistics limited

- Multipurpose machine
  - Solar and Supernova Neutrinos
  - **Atmospheric Neutrinos (this talk)**
  - Nucleon Decay
  - Far detector for T2K
  - And More (CR Anisotropy, Monopole search…)

SuperK Particle ID

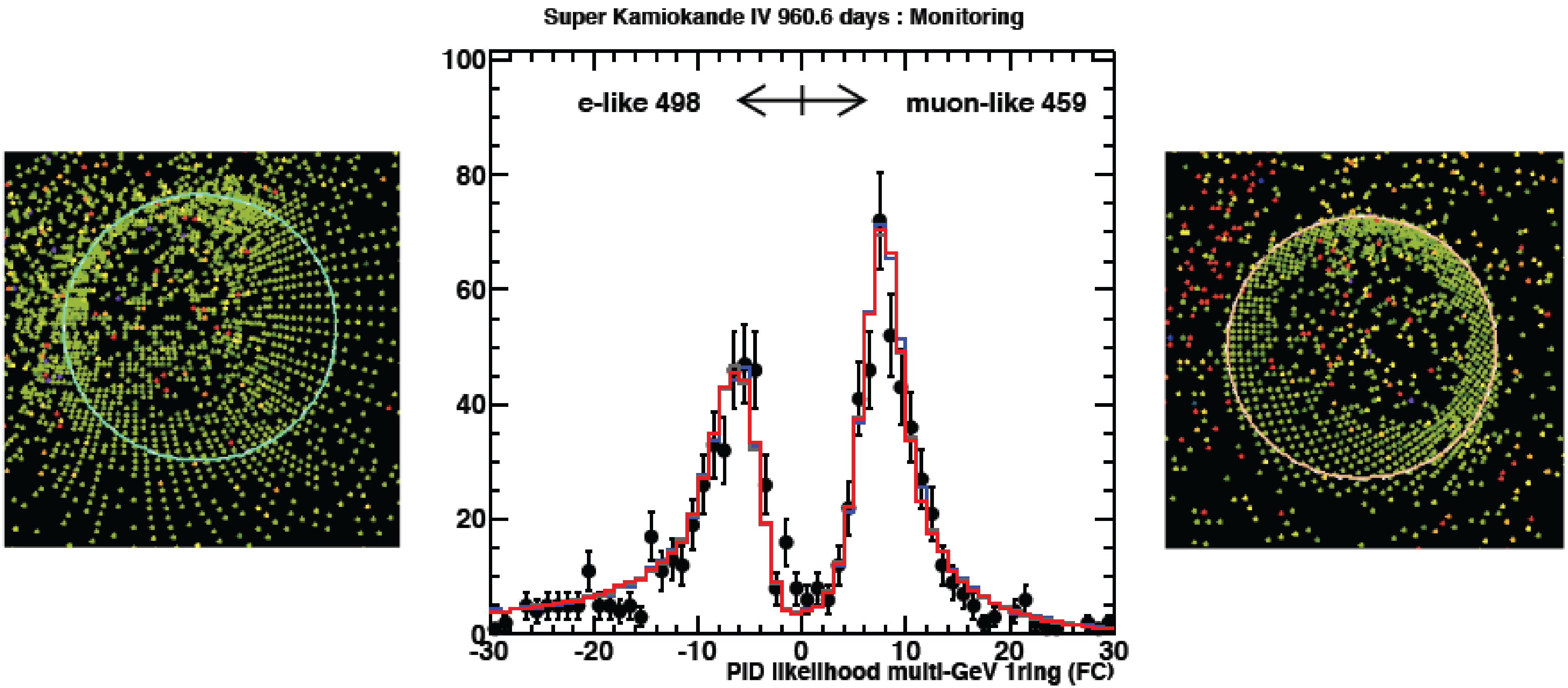
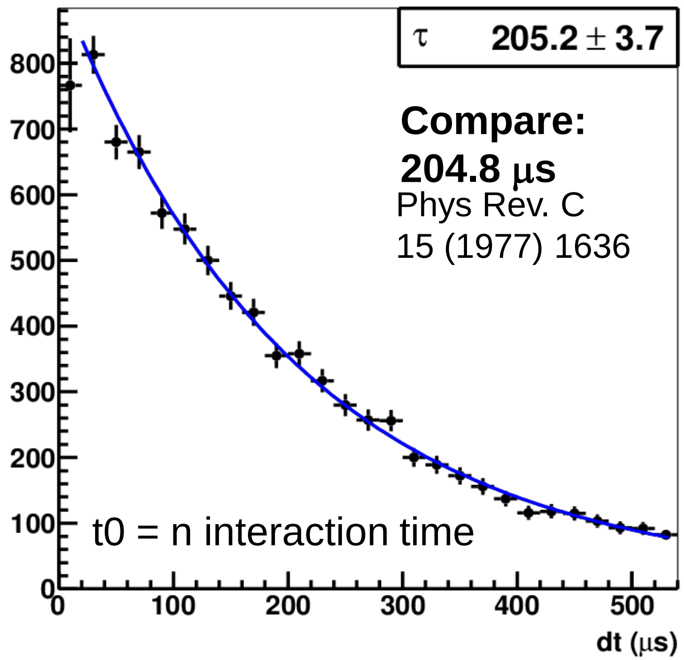
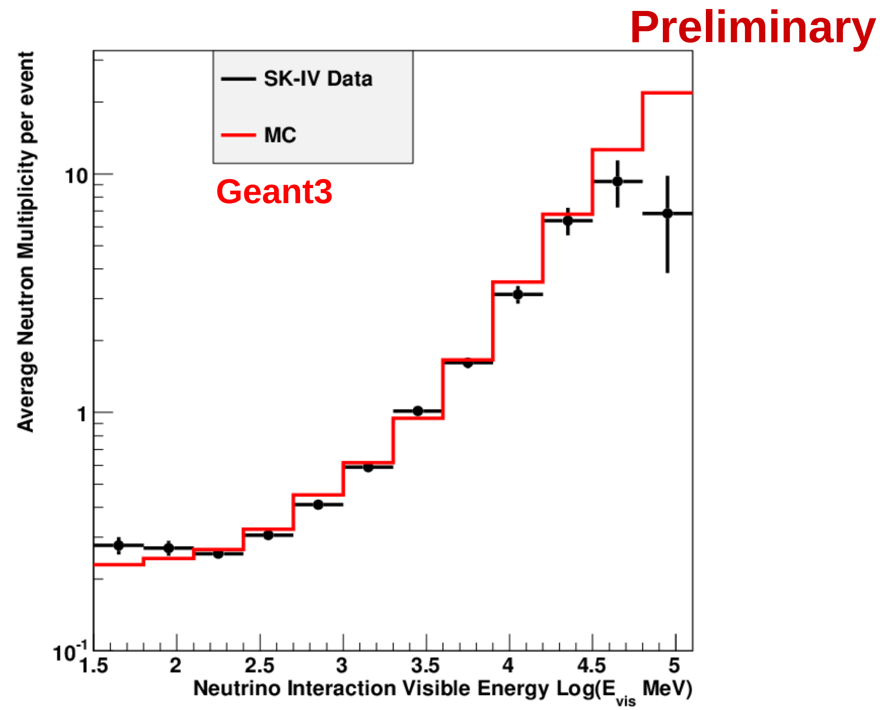


FIGURE 1. The distribution of the likelihood parameter used to separate electron-like and muon-like rings with an example electron-like ring to the left and an example muon-like ring to the right.

Neutron Tagging



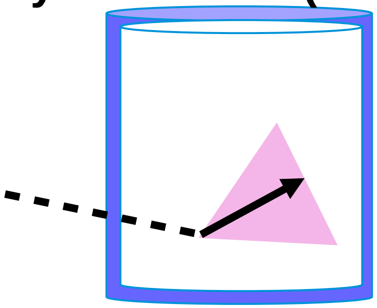


- Upgraded detector electronics in SK-IV store all PMT hits in a 500 μsec window after a physics trigger
  - Search for the 2.2 MeV gamma from p(n,γ)d
- Search is performed using a neural network built from 16 variables
  - Data and MC show good agreement on atmospheric neutrino sample
- **Future**: Implement neutron tagging to help distinguish ν/ν-bar interactions and to reduce proton decay backgrounds

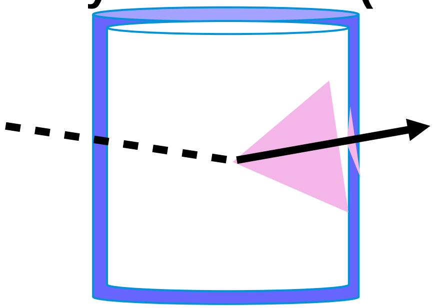
2.2 MeV γ Selection	
Efficiency	**20.5%**
Background / Event	**0.018**

Super-K Atmospheric ν Event Topologies

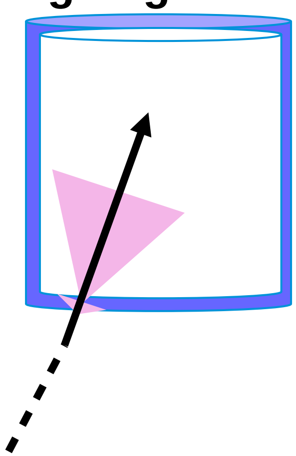
Fully Contained (FC)

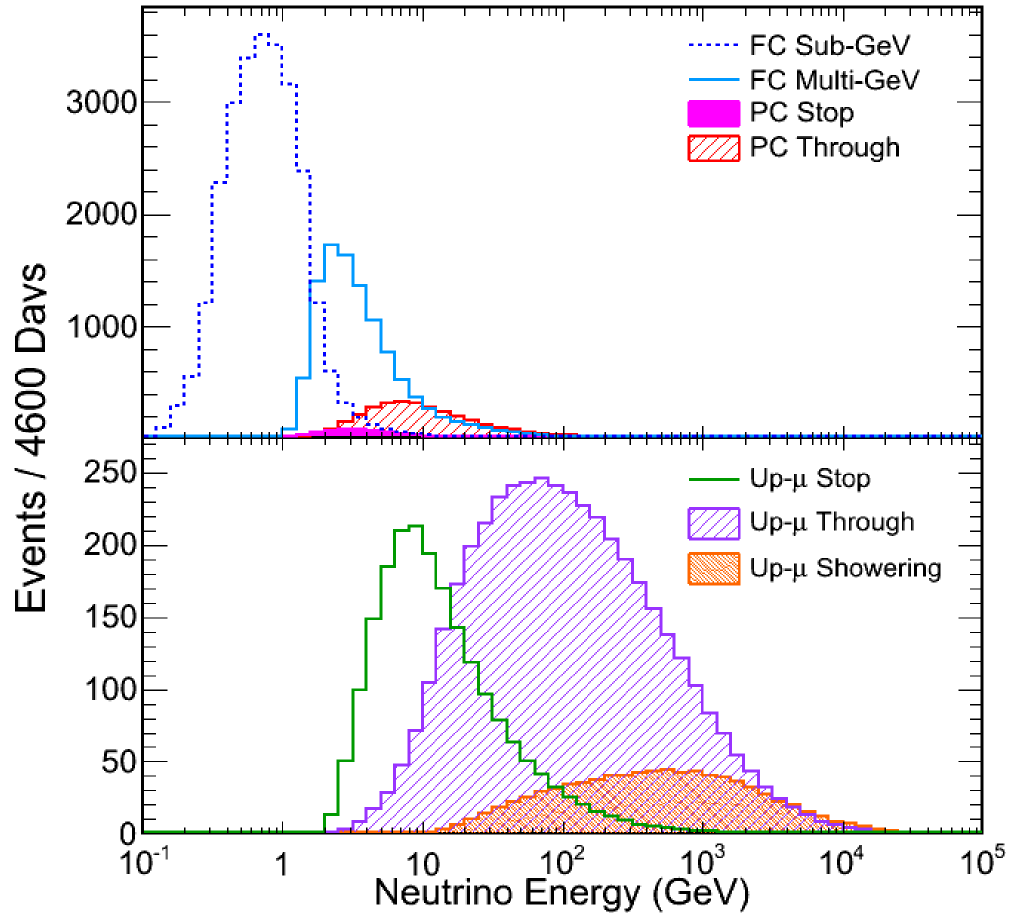


Partially Contained (PC)



Upward-going Muons (Up-m)

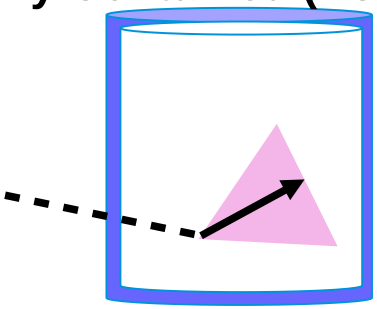




- Average Atm neutrino source energies
  - FC: ~1 GeV ,
  - PC: ~10 GeV,
  - UpMu:~ 100 GeV

Super-K Atmospheric ν Analysis Samples

Fully Contained (FC)



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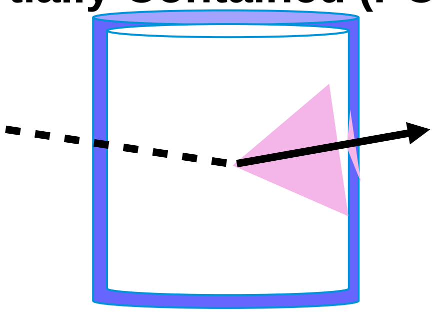
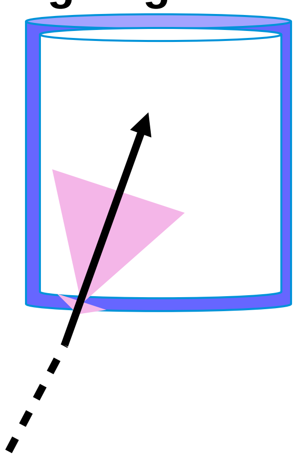
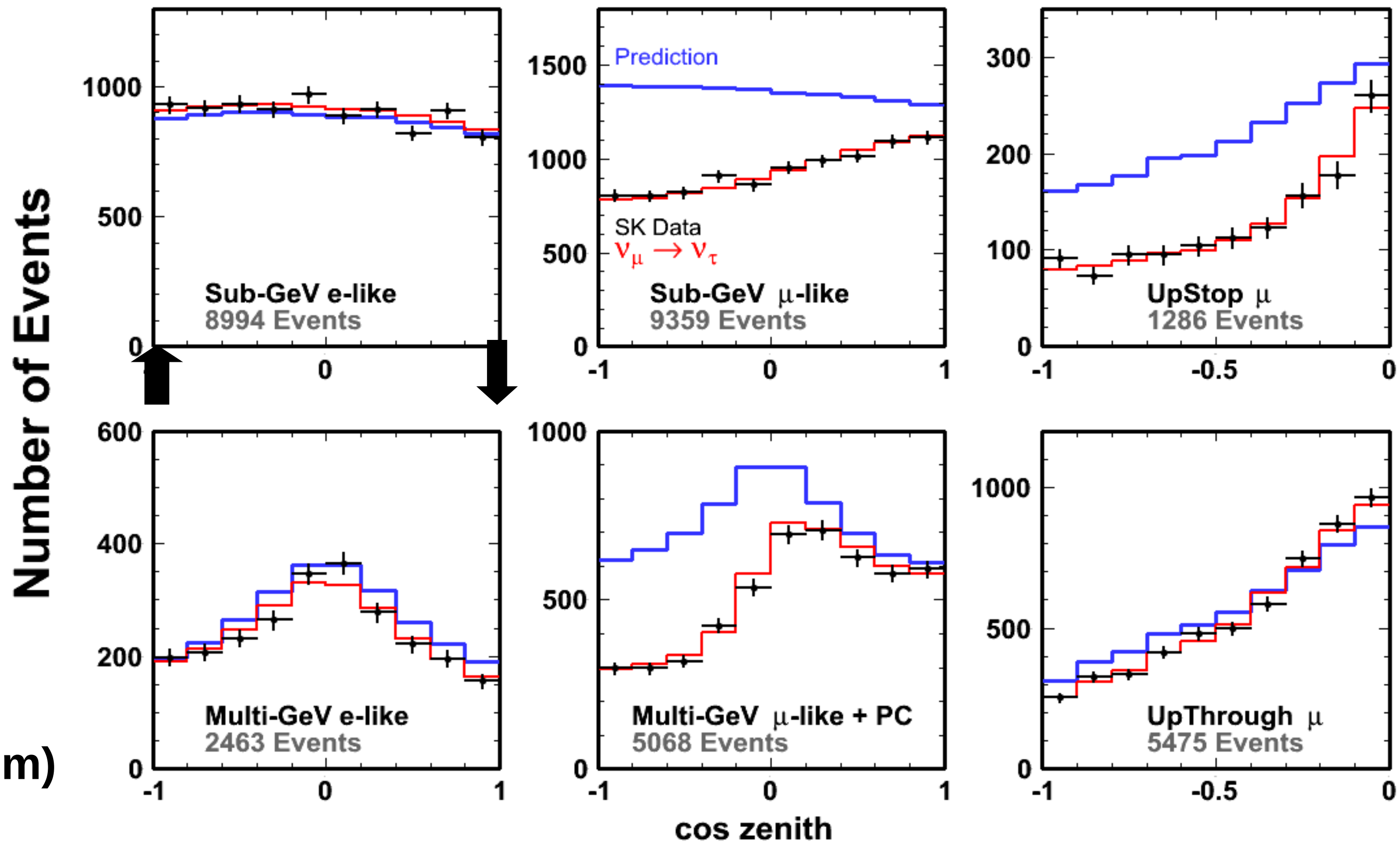


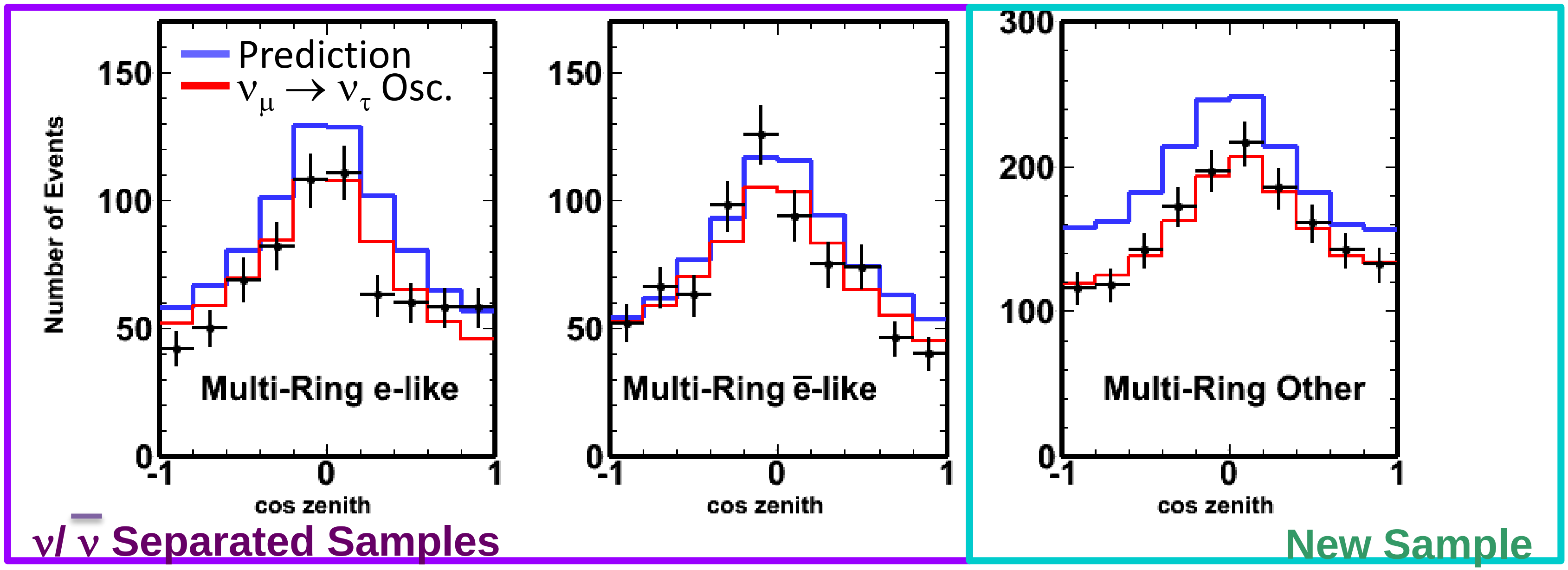
Upward-going Muons (Up-m)





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

Changes and Updates to Oscillation Analyses



- Addition of a new analysis sample
- Multi-Ring e-like Inclusive (Fully Contained)
  - Events that fail multi-ring e-like selection

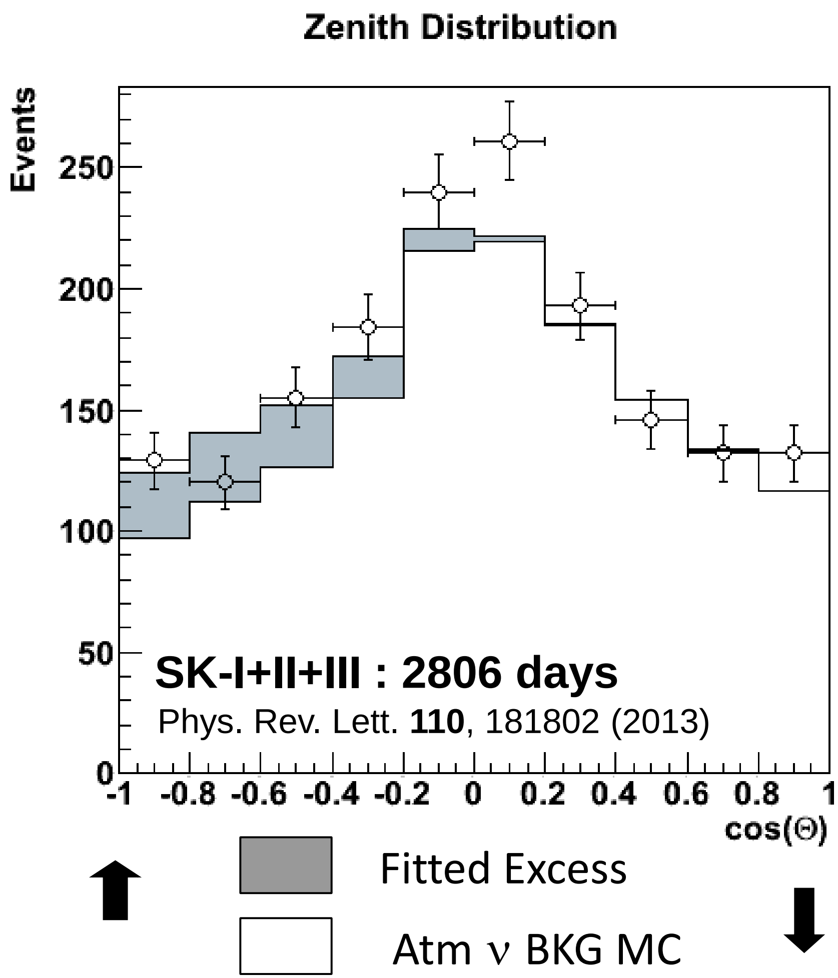
- Improved systematic error treatments
  - Updates to cross-section, FSI, detector systematics, 2p-2h (MEC) uncertainties

- 1775 days of SK-IV data: 4581.4 days total (282.2 kton yrs)

Multi-Ring e-like Sample Purities

Purity	CC ν_e	CCν_μ	CCν_τ	NC
ν-like	72.2%	8.3%	3.2%	16.1%
$\bar{\nu}$-like	75.0%	6.5%	2.8%	15.6%
other	30.9%	33.4%	5.1%	30.5%

Evidence for ν_τ CC interaction at Super-K



- Search for events consistent with hadronic decay of τ lepton
  - Multi-ring e-like events, mostly DIS interactions
- Negligible primary ν_τ flux so ν_τ must be oscillation-induced: **upward-going**
- Event selection performed by neural network
  - Total efficiency ~60%

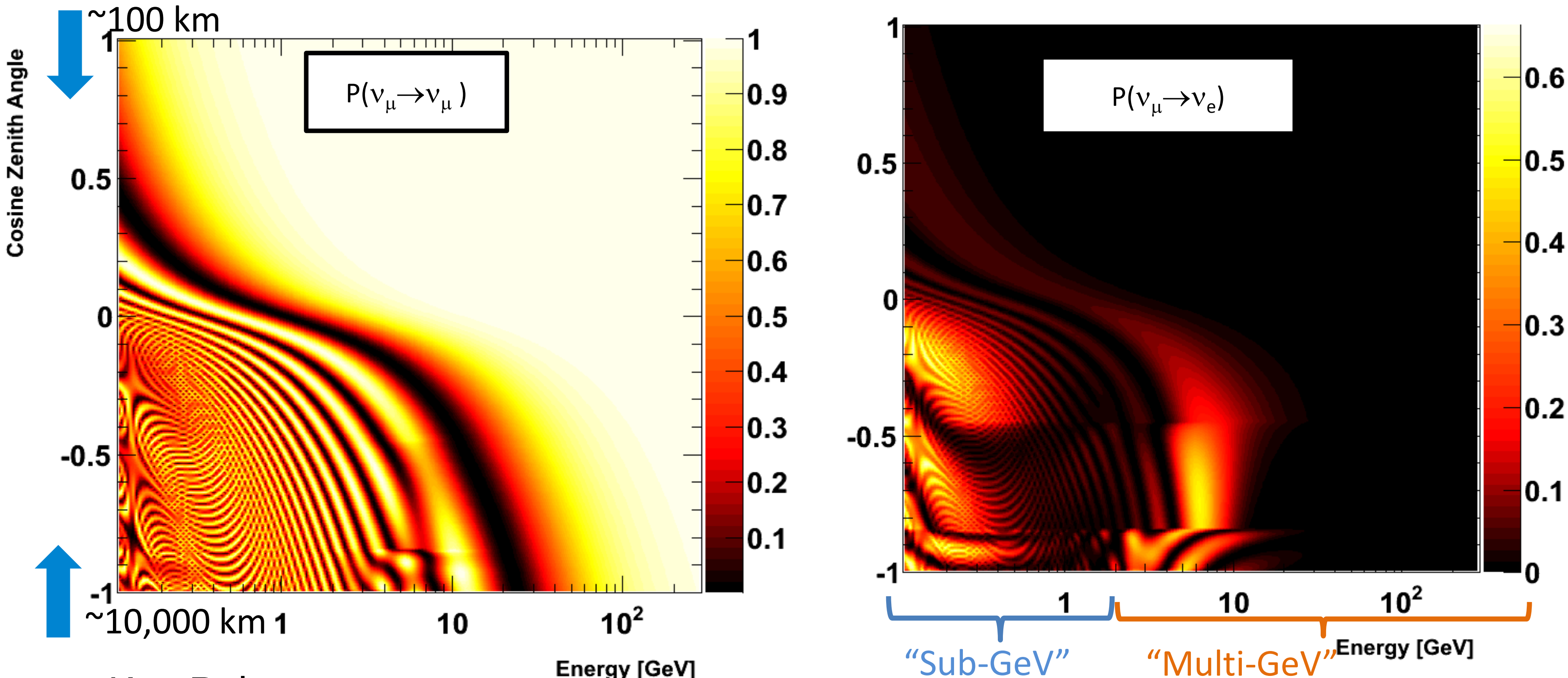
$\beta = 0$: no ν_τ

$$Data = \alpha(\gamma) \times bkg + \beta(\gamma) \times signal$$

Result	Background	DIS (γ)	Signal
SK-I+II+III	0.94 ± 0.02	1.10 ± 0.05	**1.42 ± 0.35**

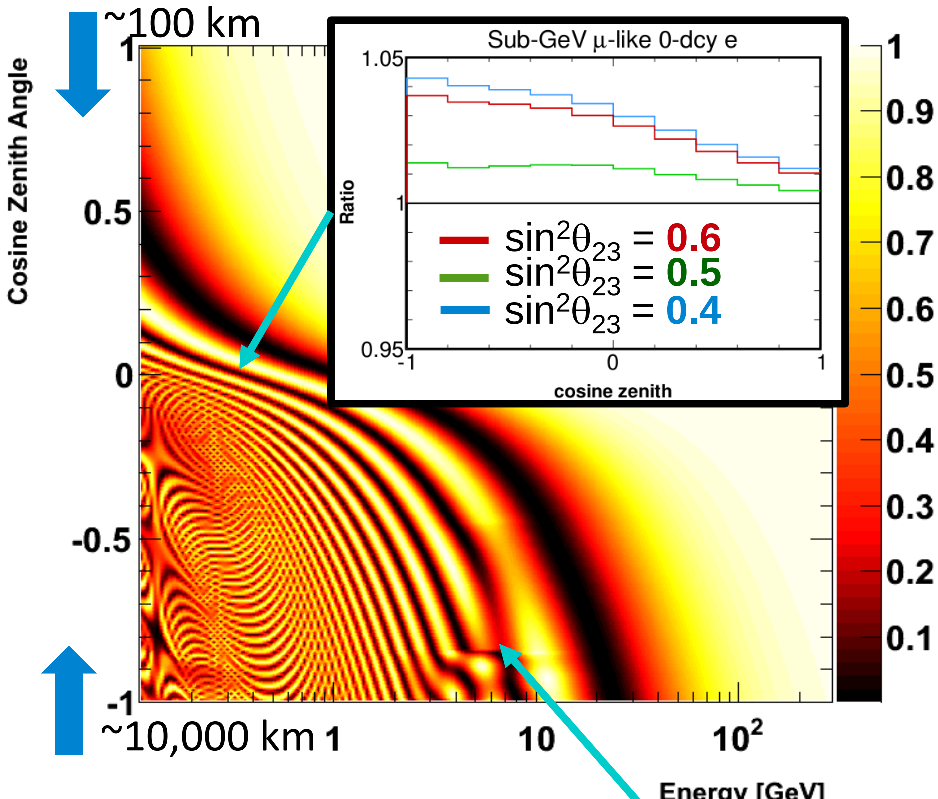
This corresponds to **180.1** ±44.3 (stat) +17.8-15.2 (sys) events, a **3.8 σ** excess (Expected 2.7 σ significance)

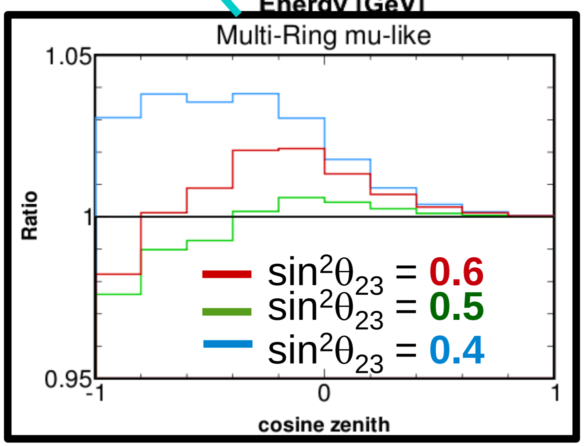
Searching for Three-Flavor Effects: Oscillation probabilities

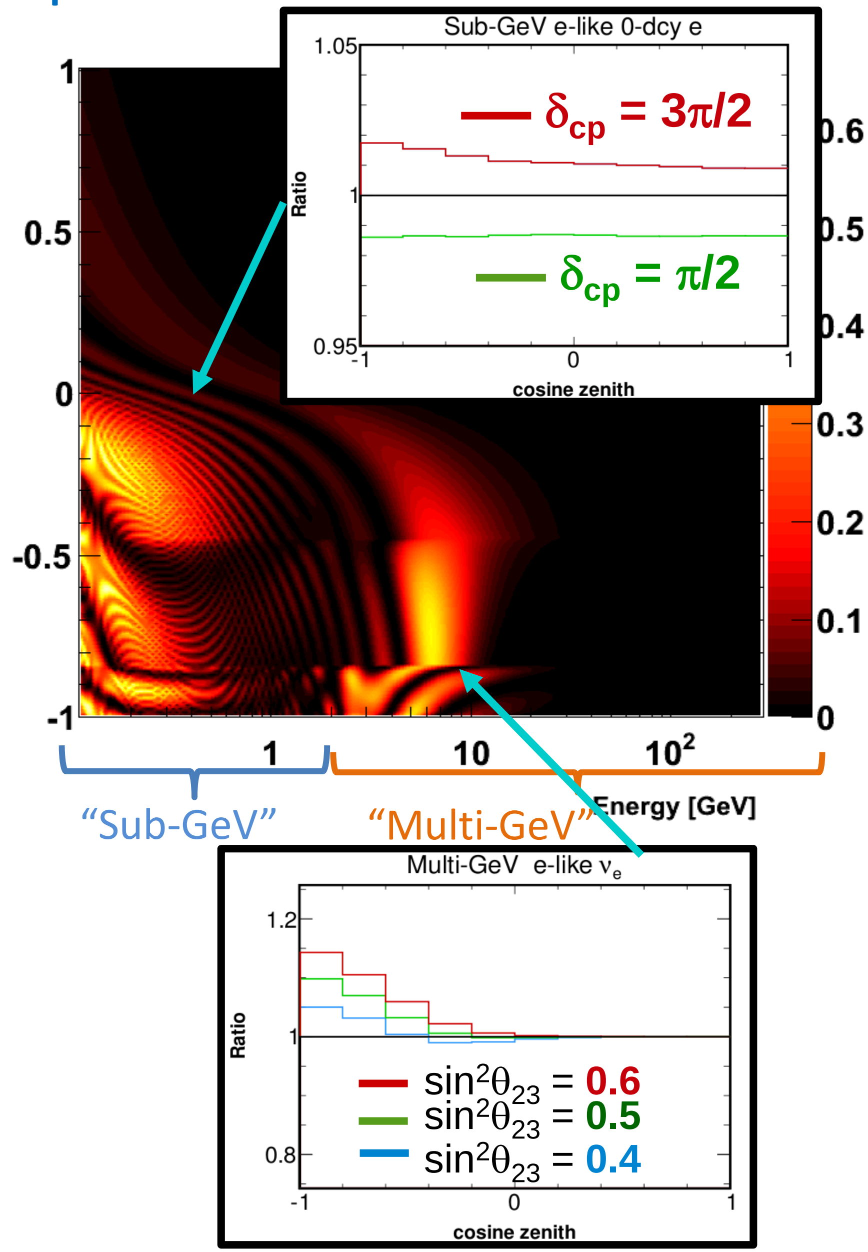


- Key Points
  - No $\nu_\mu \rightarrow \nu_e$ Appearance above ~20 GeV,
  - Resonant oscillations between 2-10 GeV (for ν or $\bar{\nu}$ depending upon MH)
  - No oscillations above 200 GeV
  - No oscillations from downward-going neutrinos above ~5 GeV
  - Expect effects in most analysis samples, largest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

Oscillation Effects on Analysis Subsamples







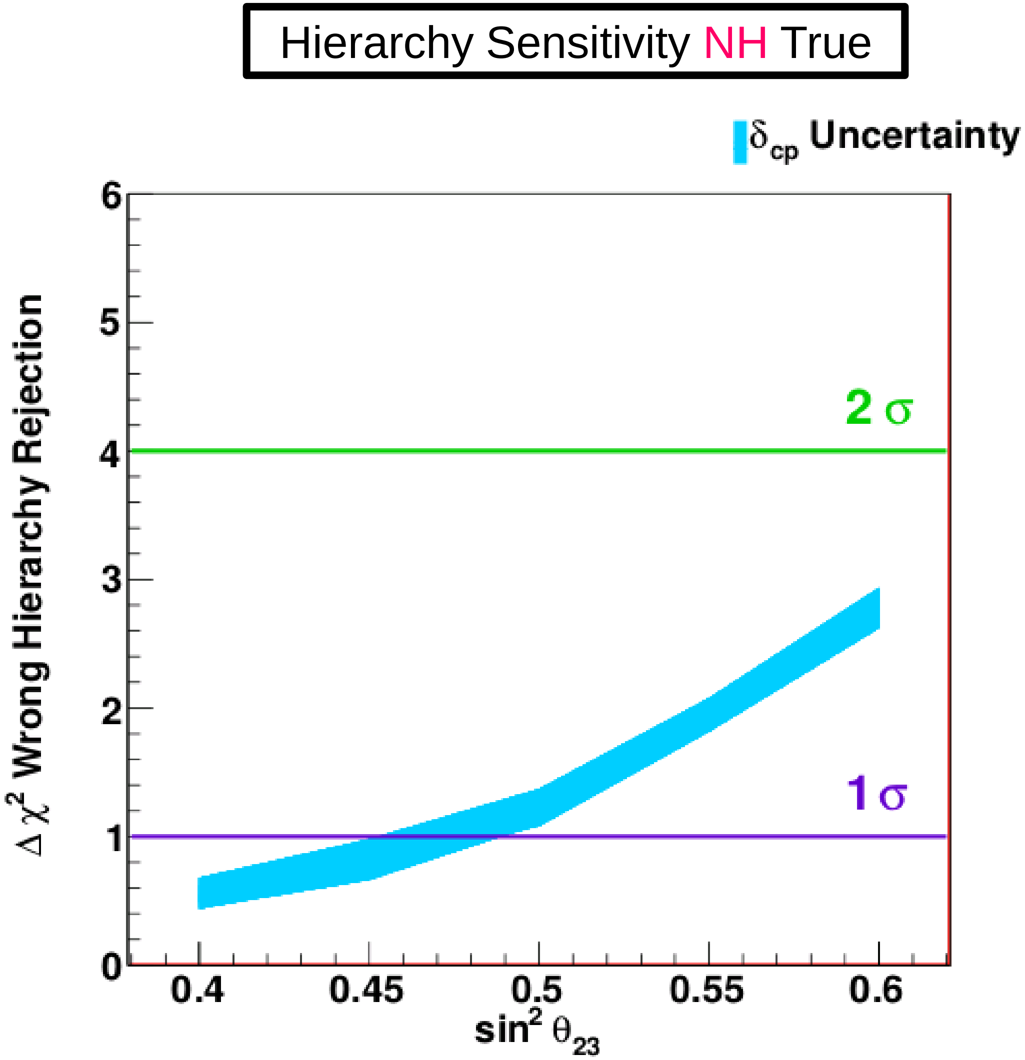
Ratio to two-flavor oscillations

Appearance effects are roughly halved for the inverted hierarchy

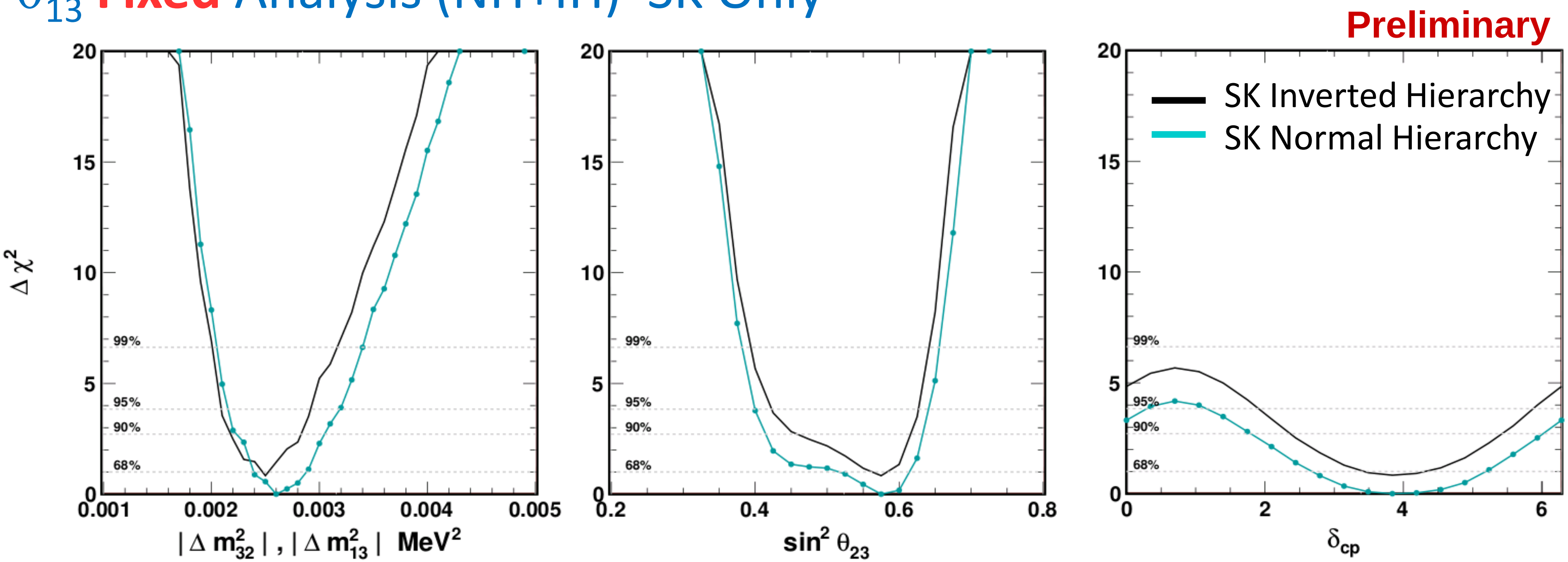
Expected Hierarchy Sensitivity

- As a result, the sensitivity to the mass hierarchy is a rather strong function of the other oscillation parameters

- As a function of the true value of $\sin^2\theta_{23}$ this plot shows the ability to reject the inverted mass hierarchy hypothesis assuming the normal hierarchy



θ_{13} **Fixed** Analysis (NH+IH) SK Only

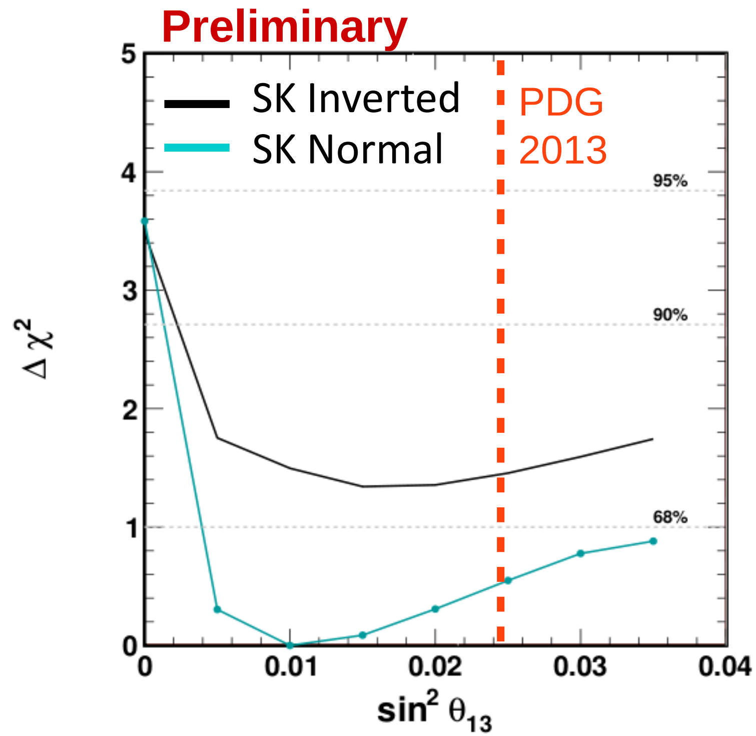


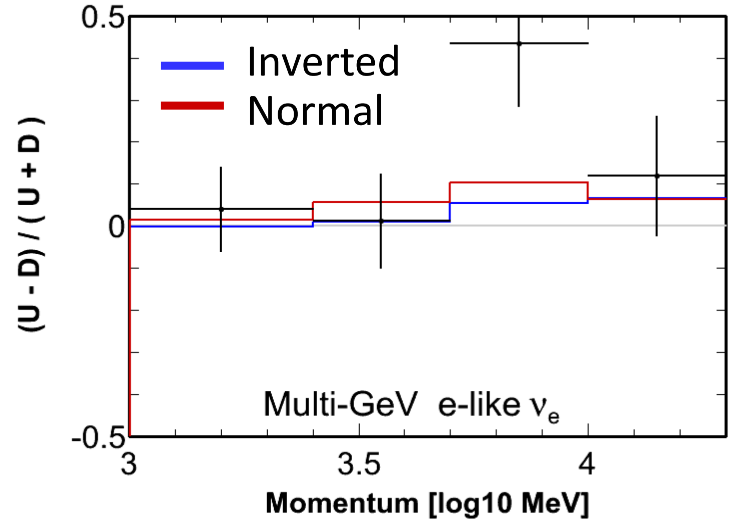
Fit (517 dof)	$\chi 2$	θ_{13}	δ_{cp}	θ_{23}	Δm_{23} (x10^{-3})
SK (NH)	559.8	0.025	3.84	0.57	2.6
SK (IH)	560.7	0.025	3.84	0.57	2.5

- θ_{13} fixed to PDG average, but its uncertainty is included as a systematic error
- Offset in these curves shows the difference in the hierarchies

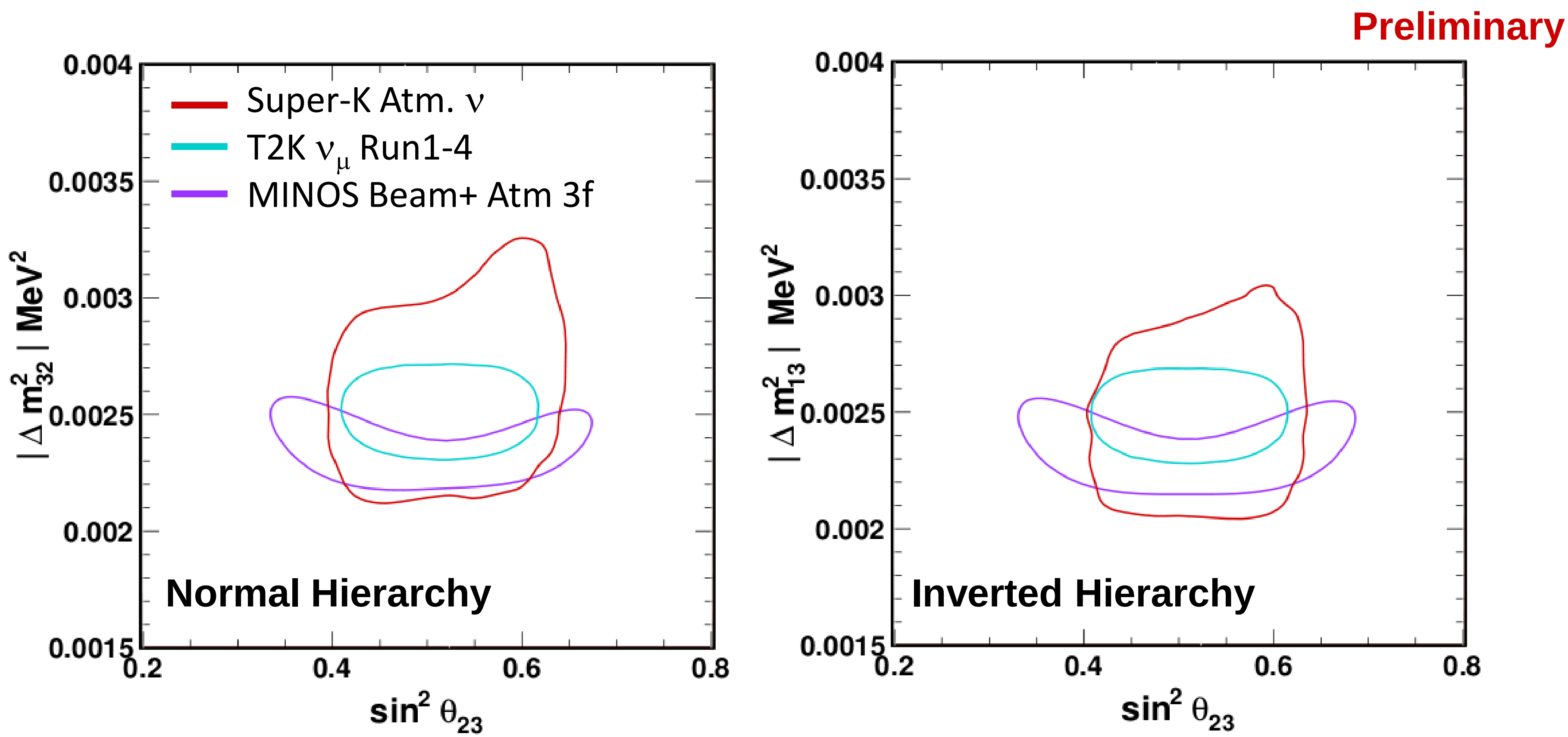
About These Results

- **Normal** hierarchy favored at:
  - $\chi^2_{IH} - \chi^2_{NH} =$ **-0.9**
  - Not a significant preference
  - Previous results (2013 Summer) favored inverted hierarchy by $\Delta\chi^2 \sim$ **1.5**
- 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 $\theta_{13} > 0$
- Rejection of $\delta_{cp} \sim 60^o$ driven by excess in Sub-GeV electron events
  - Constraint is consistent with sensitivity





Comparison with Official Results from T2K and MINOS



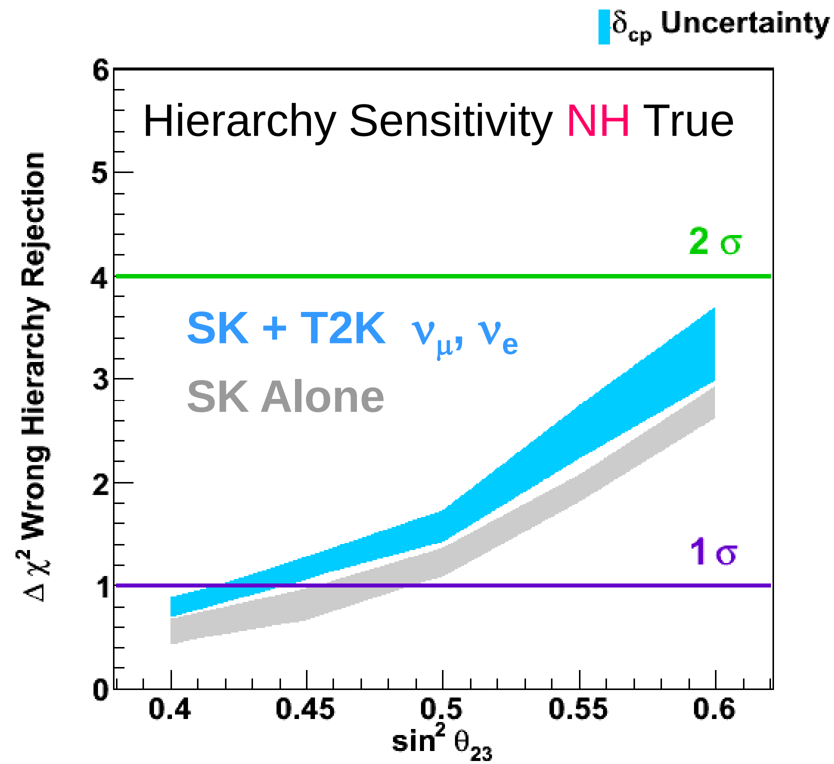
- Though consistent with long-baseline measurements, atmospheric neutrinos allow more of the mixing parameter space
- SK's sensitivity can be improved by incorporating constraints from these measurements

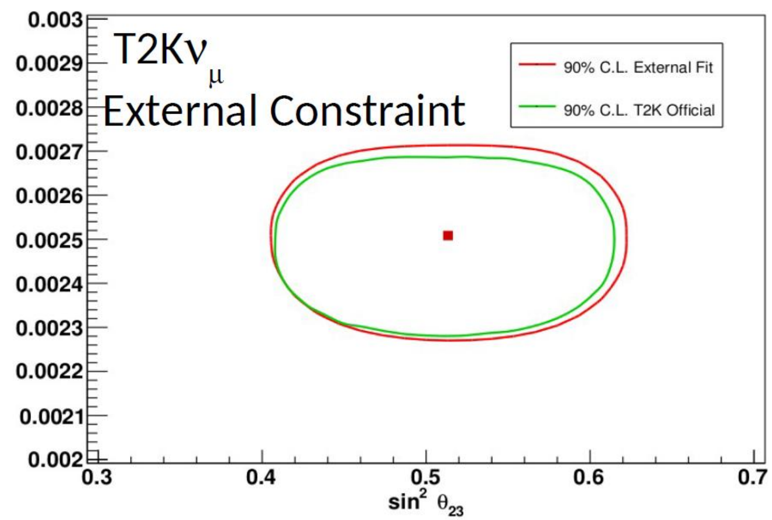
Introduction of External Constraint

- 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

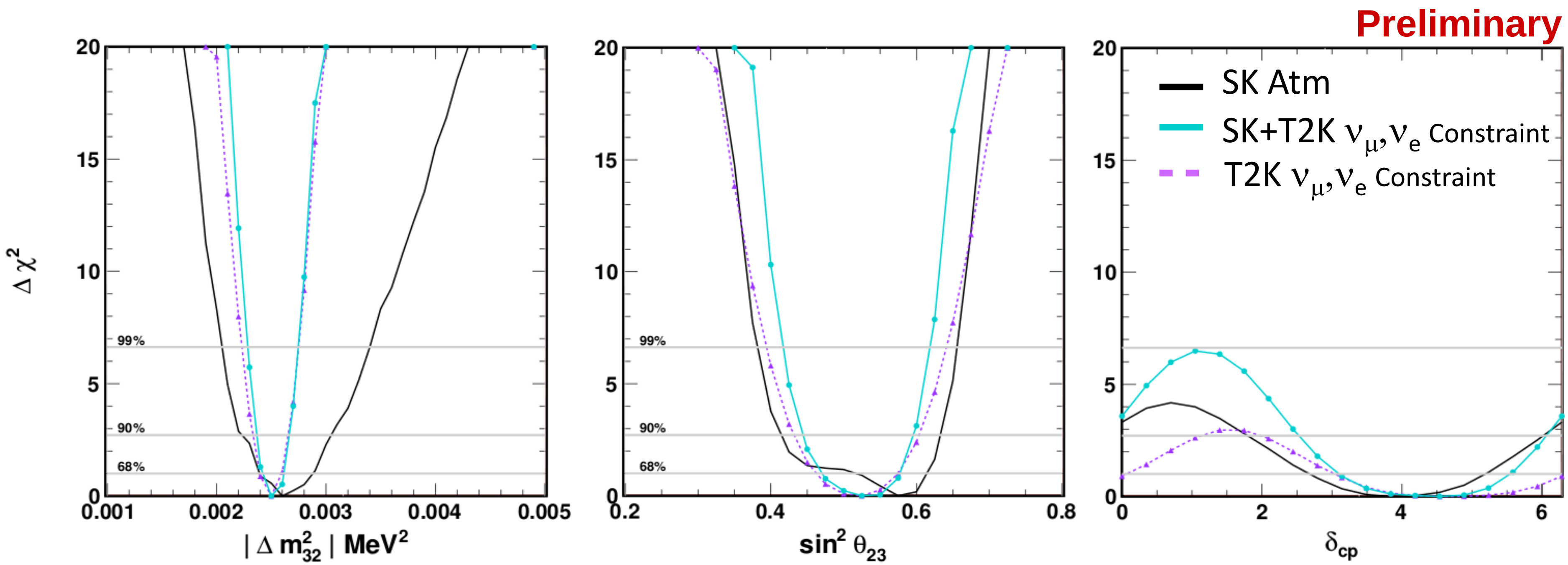
- Fit the T2K ν_μ and ν_e data sets with SK
  - Same detector, generator and reconstruction: systematic error correlations incorporated easily
  - Fit is based on **publicly available** T2K information and results
  - Simulate T2K using SK tools
    - (*not a joint result of the T2K and SK collaborations*)

- MINOS constraint is similarly important but harder to model accurately (so far...)





θ_{13} **Fixed** SK + T2K ν_μ, ν_e (External Constraint) Normal Hierarchy



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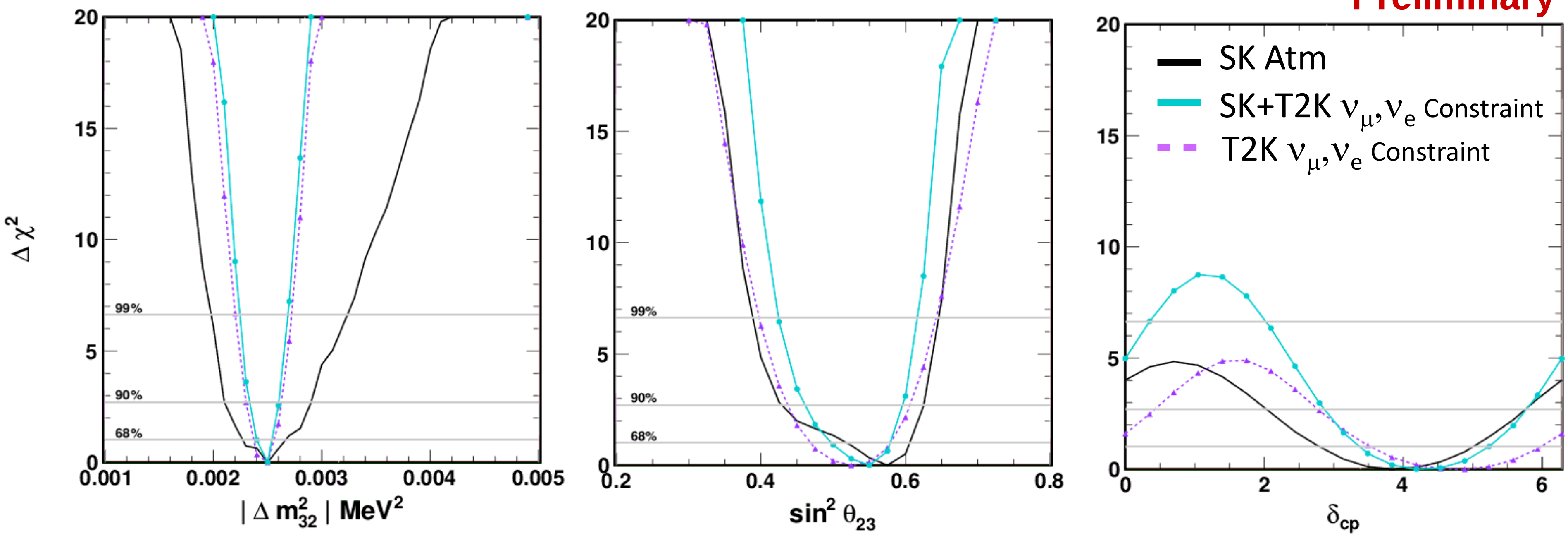
SK + T2K (NH)	578.2	0.025	4.19	0.55	2.5
SK + T2K (IH)	579.4	0.025	4.19	0.55	2.5

- $\chi^2_{IH} - \chi^2_{NH}$ = **-1.2** (-0.9 SK only)
- **CP** Conservation ($\sin\delta_{cp}$ = 0) allowed at (at least) 90% C.L. for both hierarchies

$\theta 13$ **Fixed** SK + T2K ν_μ, ν_e (External Constraint) **Inverted** Hierarchy

Preliminary



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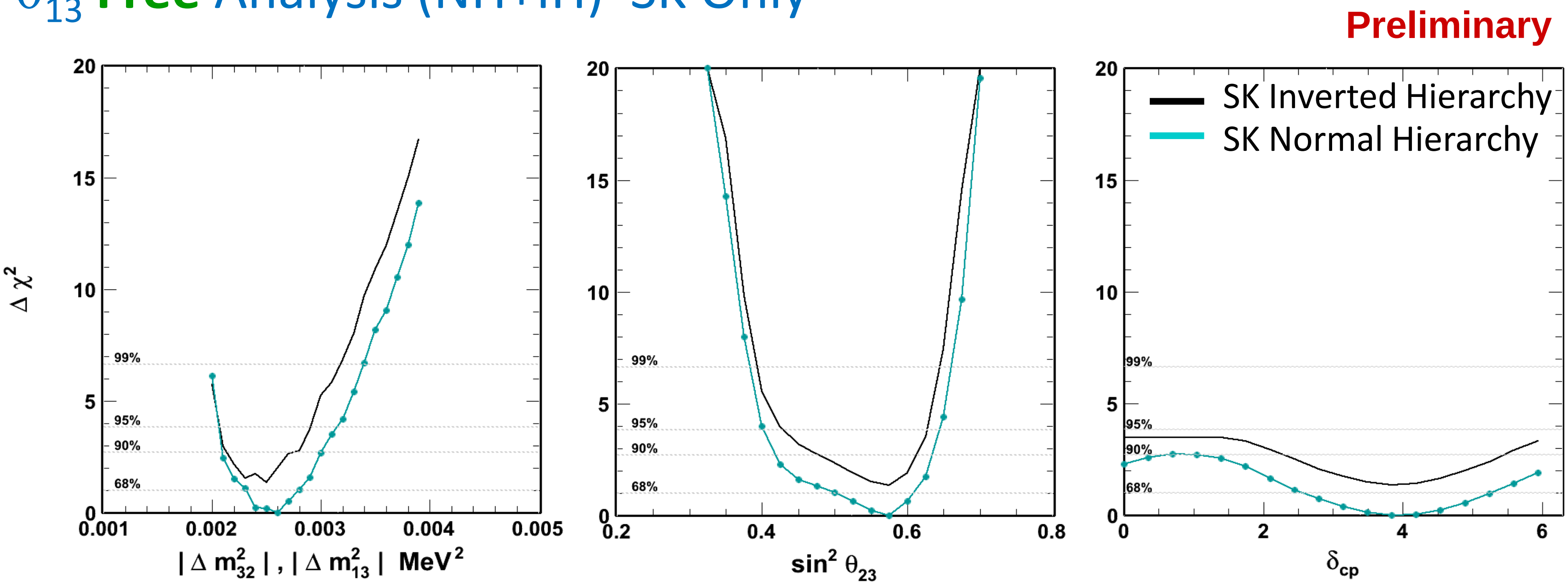

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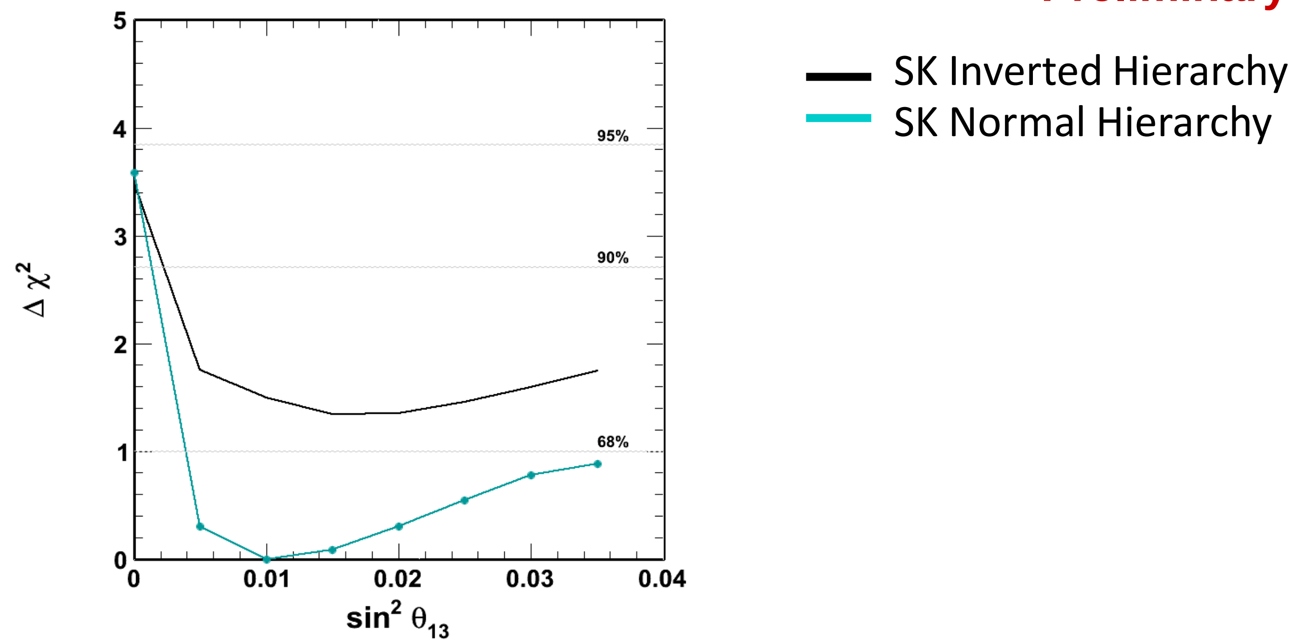

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Sterile Neutrino Oscillations in Atmospheric Neutrinos

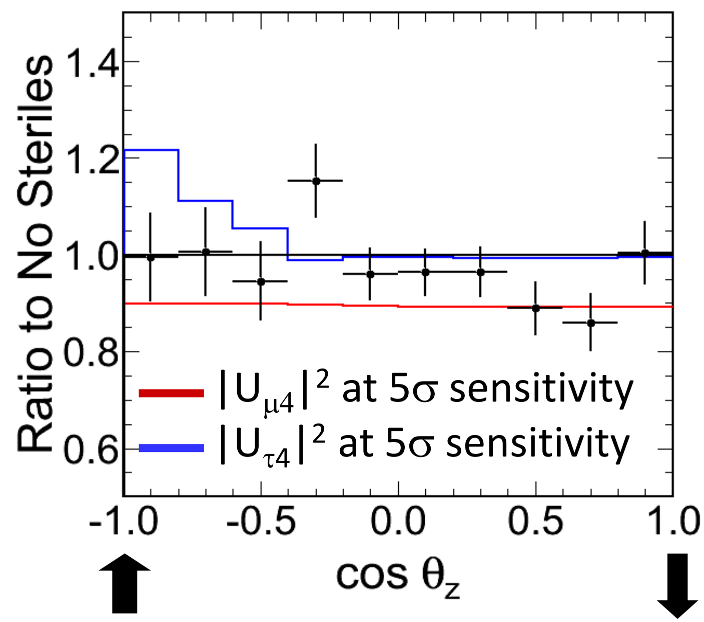
- Sterile Neutrino searches at SK are independent of the sterile Δm^2 and the number sterile neutrinos
  - 3+1 and 3+N models have the same signatures in atmospheric neutrinos
  - For $\Delta m_s^2 \sim 1$ eV^2 oscillations appear fast: $< \sin^2 \Delta m^2 L/E > \sim 0.5$

MNS — Sterile

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & \cdots \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & \cdots \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

- **$|U_{\mu 4}|^2$**
  - Induces a decrease in event rate of μ-like data of all energies and zenith angles
- **$|U_{\tau 4}|^2$**
  - Shape distortion of angular distribution of higher energy μ-like data

PC Through



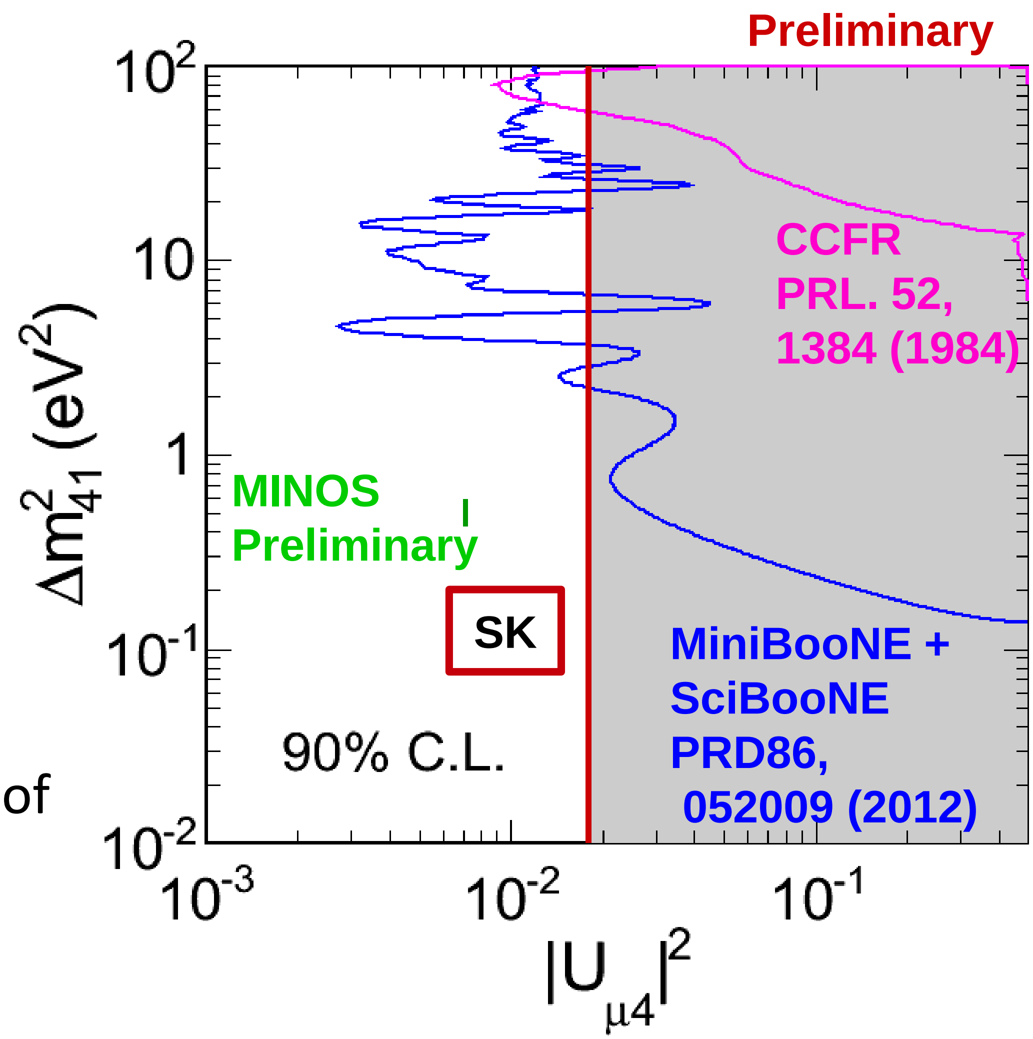
See Maltoni & Schwetz, Phys.Rev. D76, 093005, (2007)

"Hydrogen Earth" Approximation

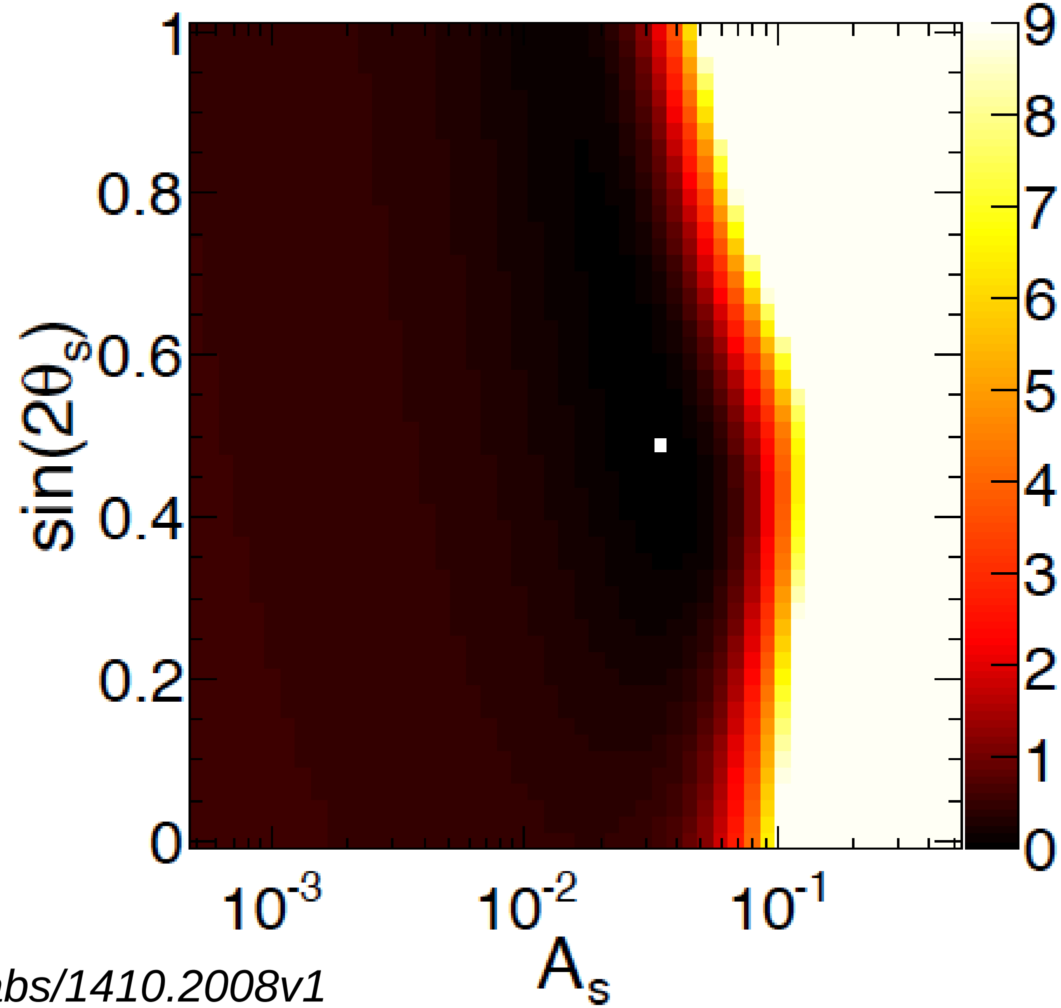
- Turning off sterile matter effects while preserving standard three-flavor oscillations provides a pure measurement of $|U_{\mu 4}|^2$

- Using SK-I+II+III+IV data (4438 days)
- $|U_{\mu 4}|^2 < 0.022$ at 90% C.L.

- Limit is valid for $\Delta m_{41}^2 > 0.01$ eV2
- For smaller values, the assumption of fast oscillations is invalid



Limits on A_s



See SK paper http://lanl.arxiv.org/abs/1410.2008v1

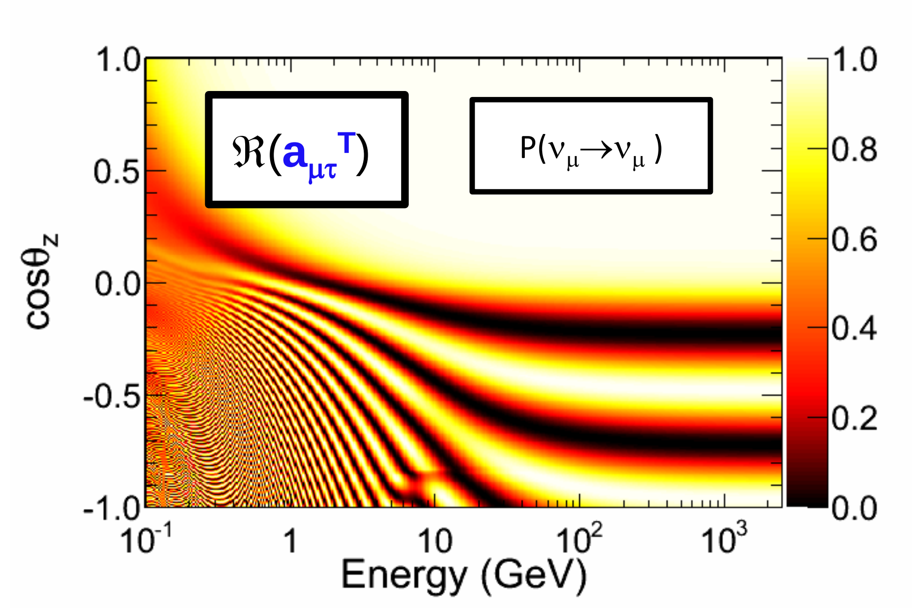
FIG. 8. The $\Delta\chi^2$ from the fit to the atmospheric neutrino data in the no-ν_e approximation, plotted versus the two effective parameters, A_s and $\sin(2\theta_s)$, with the third free parameter, d_μ, profiled out.

Tests for Lorentz Violation

Tests of Lorentz Invariance

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

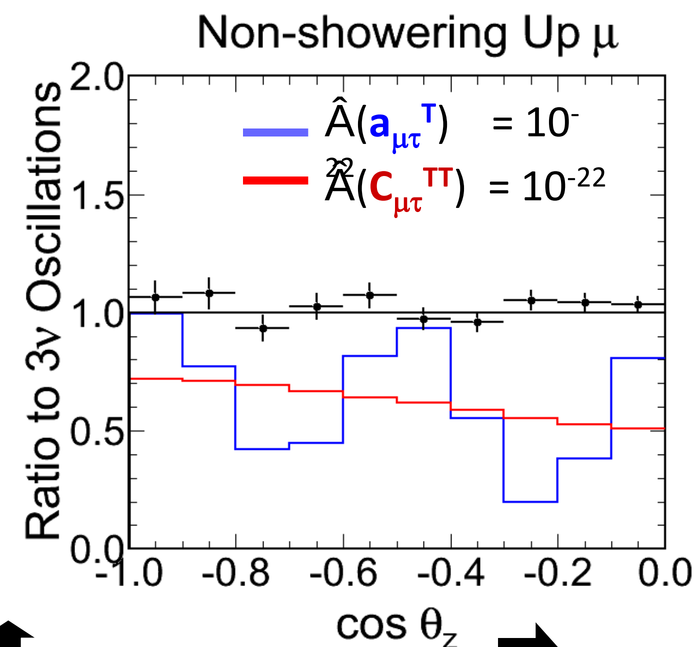
$$\pm \begin{pmatrix} 0 & a^T_{e\mu} & a^T_{e\tau} \\ (a^T_{e\mu})^* & 0 & a^T_{\mu\tau} \\ (a^T_{e\tau})^* & (a^T_{\mu\tau})^* & 0 \end{pmatrix} - E \begin{pmatrix} 0 & c^{TT}_{e\mu} & c^{TT}_{e\tau} \\ (c^{TT}_{e\mu})^* & 0 & c^{TT}_{\mu\tau} \\ (c^{TT}_{e\tau})^* & (c^{TT}_{\mu\tau})^* & 0 \end{pmatrix}$$



- Lorentz invariance violating effects can be probed using atmospheric neutrinos
  - Focus here on **isotropic** effects
  - (sensitive to sidereal effects as well…)

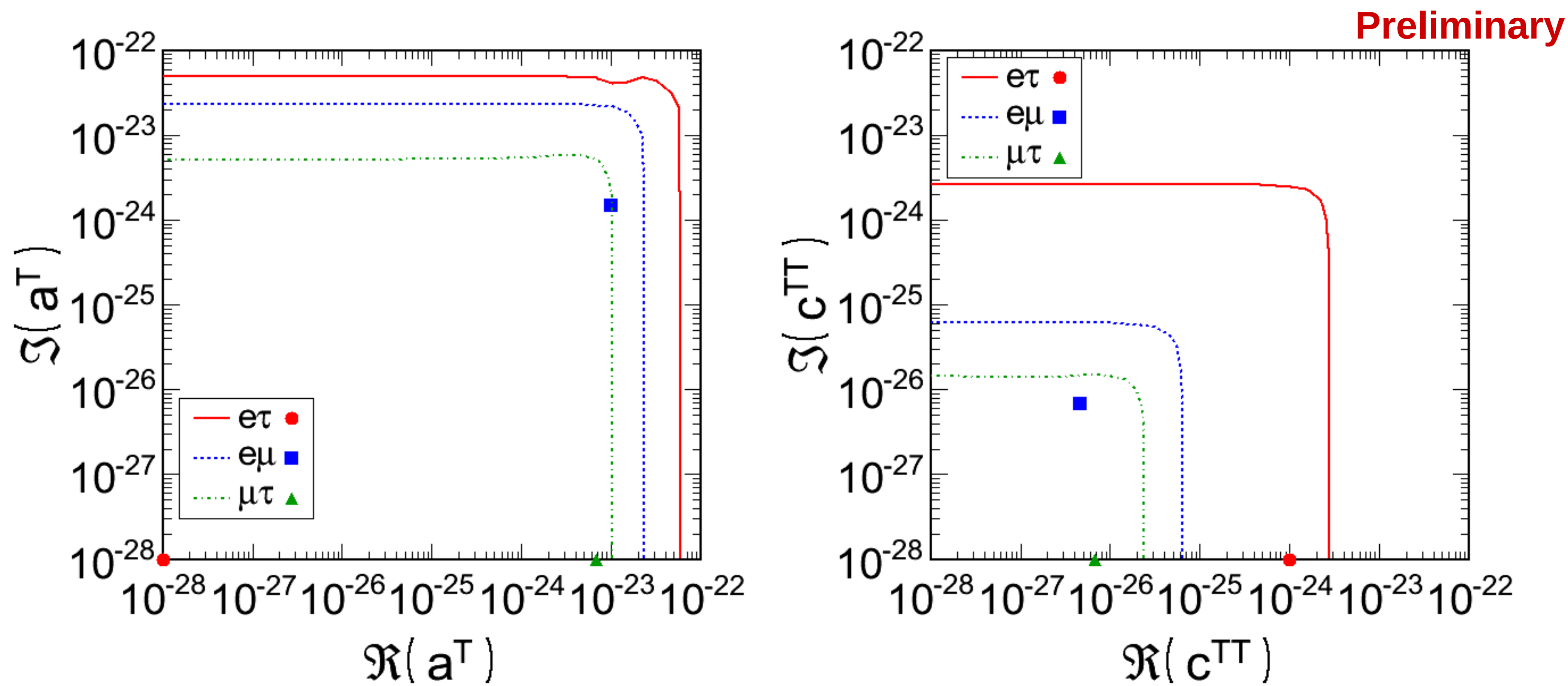
- Analysis using the Standard Model Extension (SME)
  - **Not a perturbative** calculation
  - Effects computed using full solutions of the Hamiltonian

- Effects of LIV controlled by two sets of complex parameters
  - $a^T_{\alpha\beta}$ dim = 3 induces oscillation effects ~ **L**
  - $c^{TT}_{\alpha\beta}$ dim = 4 induces oscillation effects ~ **L × E**



See: arXiv:1410.4267v1 [hep-ex] 16 Oct 2014,
Formulation from D. Colladay and V. A. Kostelecky,
Phys.Rev. D55, 6760 (1997), arXiv:hep-ph/9703464 [hep-ph], et seq.

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



- SK-I+II+III+IV : 4438 days of data
- Perform separate fits on both hierarchy assumptions for each coefficient and each sector : eμ , eτ, μτ
- No indication of Lorentz invariance violation
  - Limits placed on the real and imaginary parts of **6 parameters** ≤ O(10^{-23})

Lorentz Invariance Violating Oscillation Limits : **90% C.L.**

Preliminary

	$e\mu$	$e\tau$	$\mu\tau$		$e\mu$	$e\tau$	$\mu\tau$
$\Re(a^T)$ (GeV)	4×10^{-20} MiniBooNE	8×10^{-20} Double Chooz	-	$\Im(a^T)$ (GeV)	4×10^{-20} MiniBooNE	8×10^{-20} Double Chooz	-
	2×10^{-23}	4×10^{-23}	8×10^{-24}		2×10^{-23}	2×10^{-23}	4×10^{-24}

	$e\mu$	$e\tau$	$\mu\tau$		$e\mu$	$e\tau$	$\mu\tau$
$\Re(c^{TT})$	1×10^{-19} MiniBooNE	1×10^{-17} Double Chooz	-	$\Im(c^{TT})$	1×10^{-19} MiniBooNE	1×10^{-17} Double Chooz	-
	4×10^{-26}	2×10^{-24}	2×10^{-26}		4×10^{-26}	2×10^{-24}	2×10^{-26}

- Established new limits in the $\mu\tau$ sector for both $a^{T}_{\alpha\beta}$ and $c^{TT}_{\alpha\beta}$ coefficents
- Improvements on existing limits between **3** and **7** orders of magnitude!

Atmospheric Neutrinos As Background

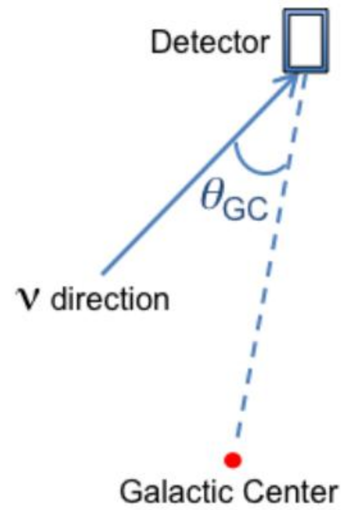
Search for WIMP Annihilations in the Galactic Center and Sun

- Search for a signal of WIMP annihilation from the Galactic Halo or solar interior assuming several branching modes
  - $\nu\bar{\nu}$, $b\bar{b}$, $\tau^{+}\tau^{-}$, $W^{+}W^{-}$

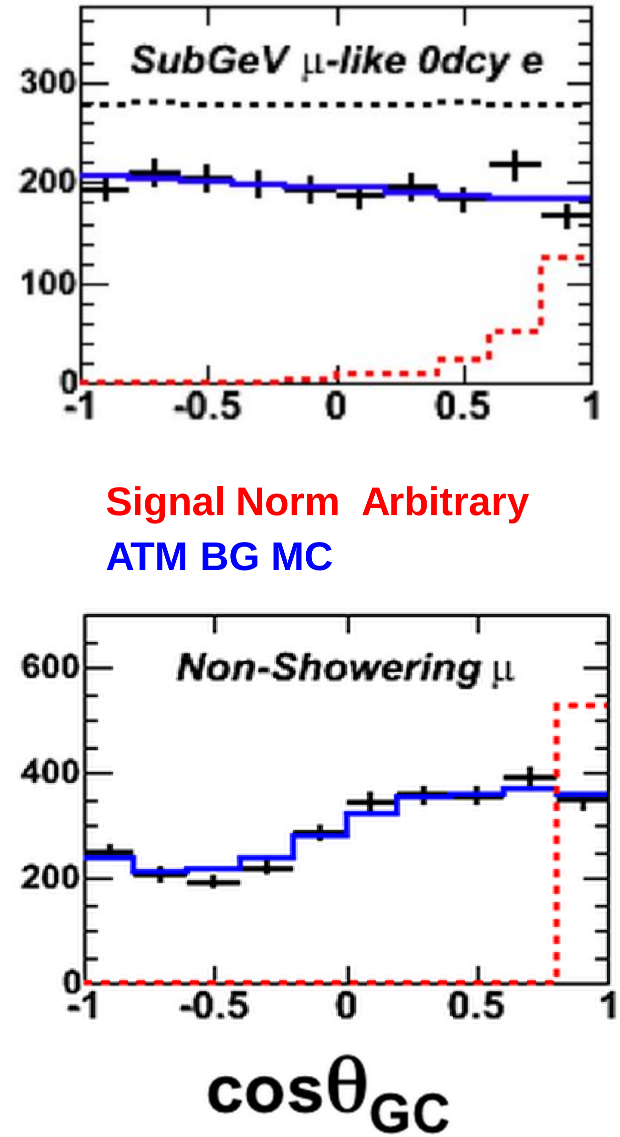
- Signal would appear atop the ATM ν background, peaked towards either the **galactic center** or towards the **sun**

- Simulate signal and detector response for all ν flavors

- Same analysis samples as oscillation analyses but binned in angle toward the galactic center (or sun)
  - Use **all** samples
  - Previous analyses used only Up μ samples
  - Allows probe of both low O(GeV) and high O(TeV) WIMP masses

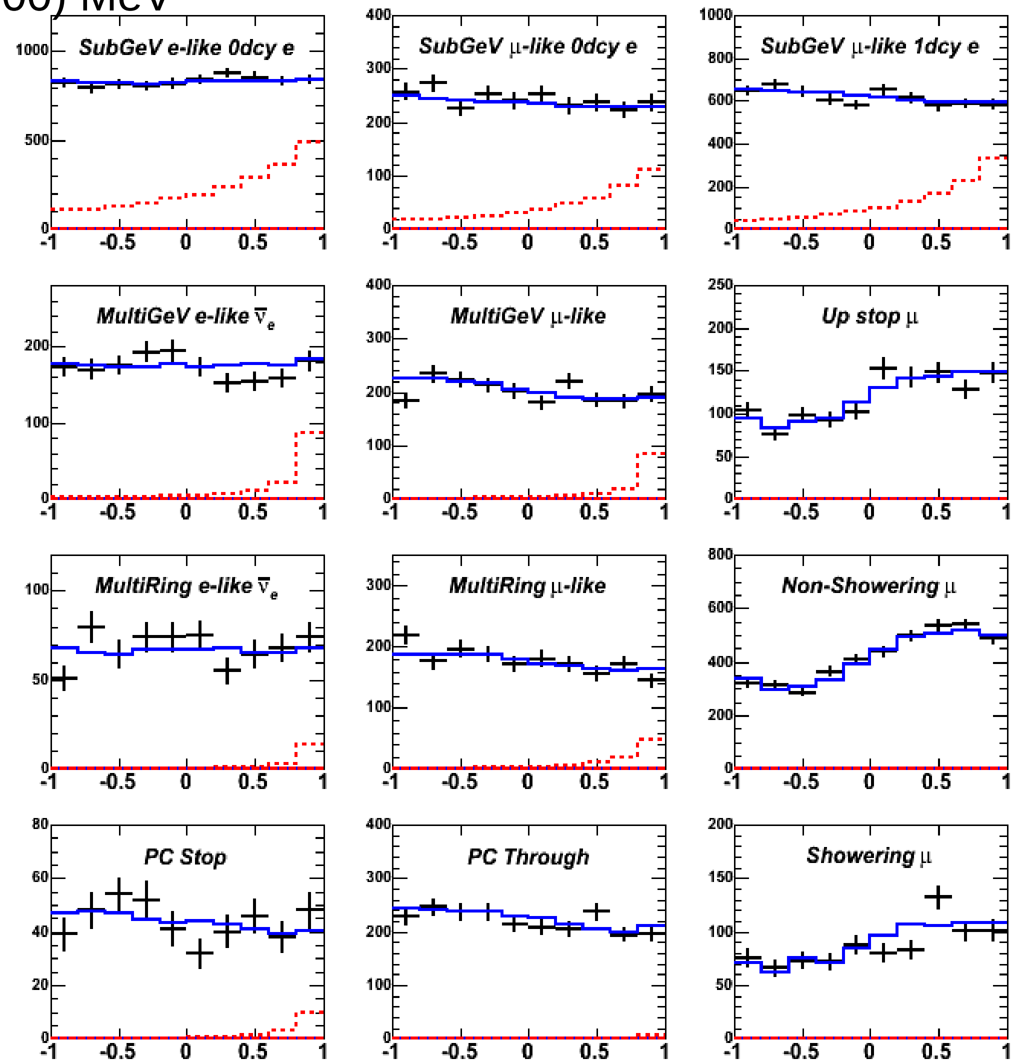


(Or Sun)



Search for WIMP Annihilations : Signal Demonstration

O(100) MeV



O(10)–O(100⁺) GeV

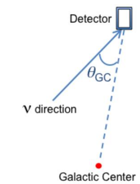
cos (θ_{GC})

$\chi\chi \rightarrow b\bar{b}$

M(χ) = 5 GeV / c^2

WIMP Signal, **Best Fit × 15**

ATM ν Background + WIMP



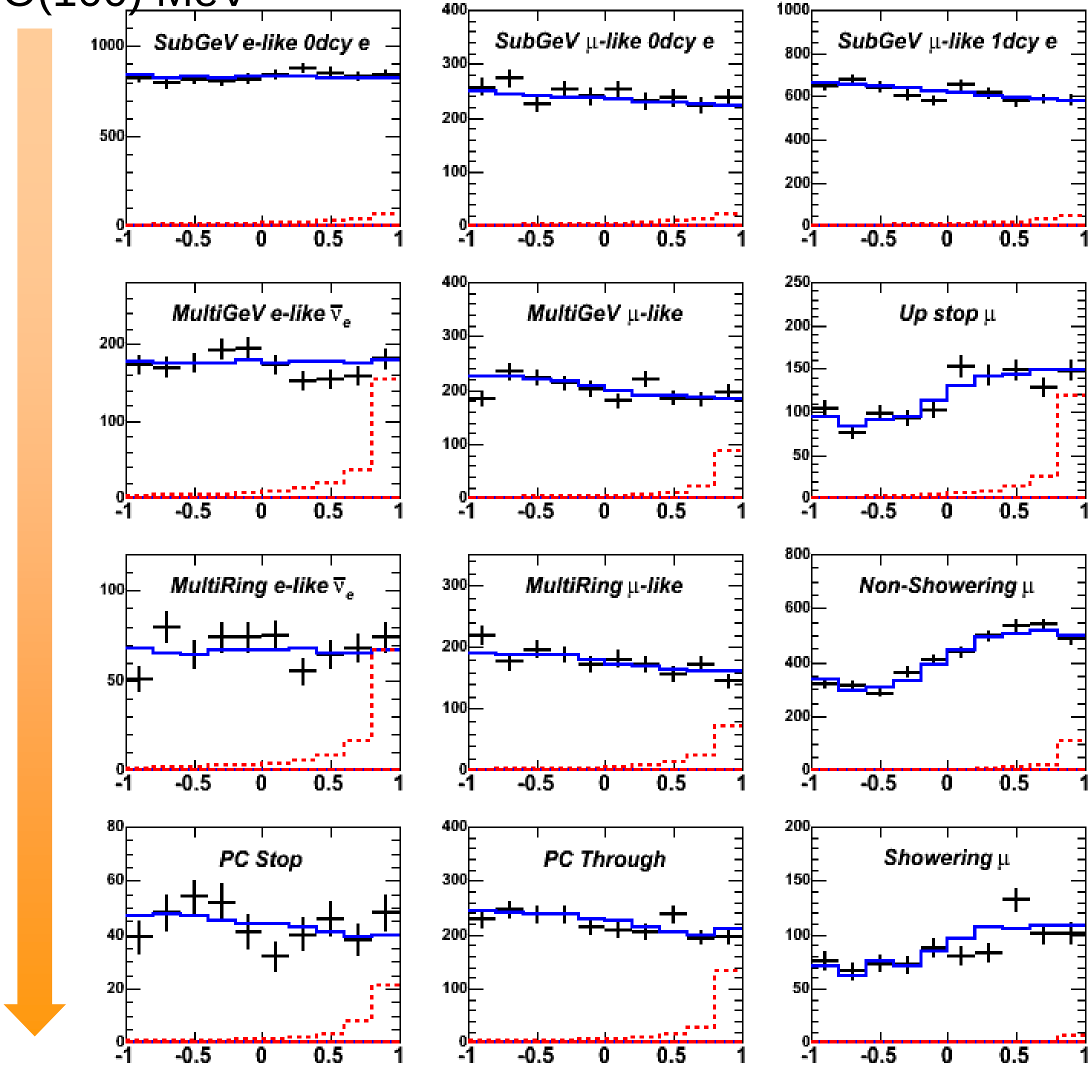
- Analysis uses all available data
- Previous analyses used only the upward-going muons

- 100% branching fraction assumed for each tested annihilation channel

- Equal fluxes at detection
  - $\phi(\nu_e) = \phi(\nu_\mu) = \phi(\nu_\tau)$

Search for WIMP Annihilations : Signal Demonstration

O(100) MeV



O(10)–O(100⁺) GeV

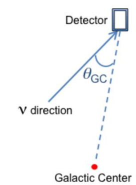
cos (θ_{GC})

$\chi\chi \rightarrow b\bar{b}$

M(χ) = 100 GeV / c^2

WIMP Signal, **Best Fit × 15**

ATM ν Background + WIMP

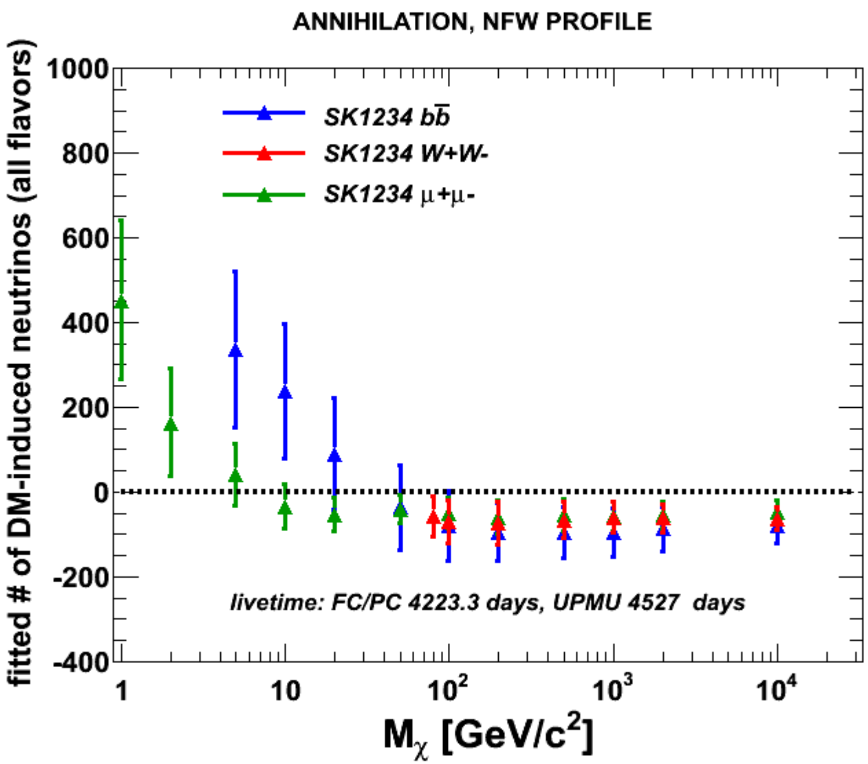


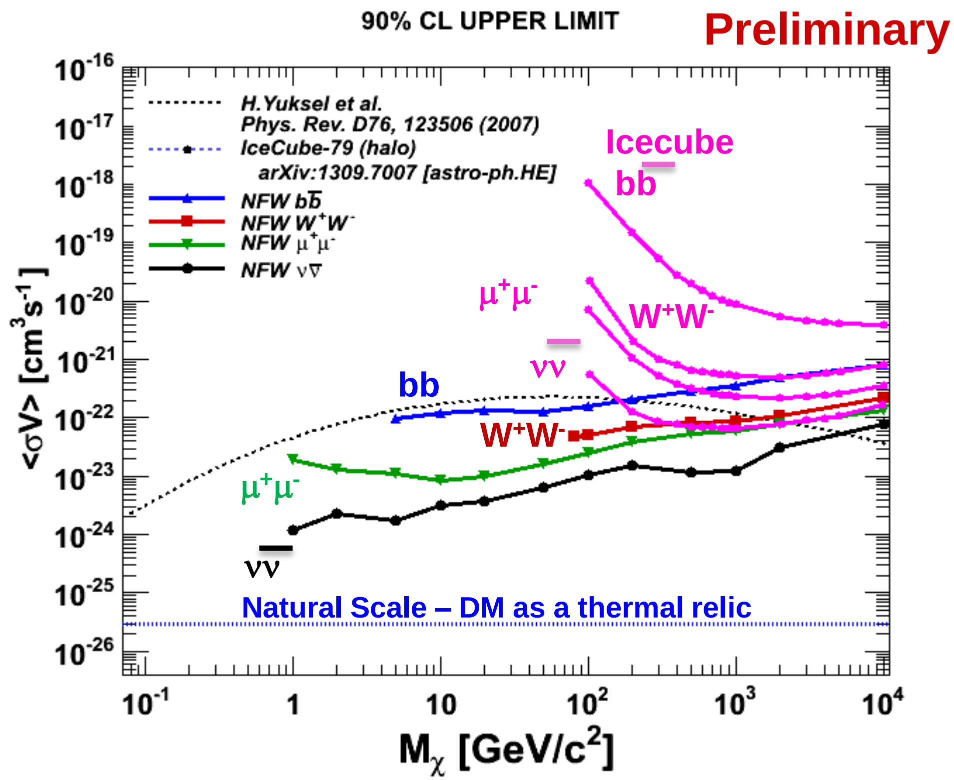
- Analysis uses all available data
- Previous analyses used only the upward-going muons

- 100% branching fraction assumed for each tested annihilation channel

- Equal fluxes at detection
  - $\phi(\nu_e) = \phi(\nu_\mu) = \phi(\nu_\tau)$

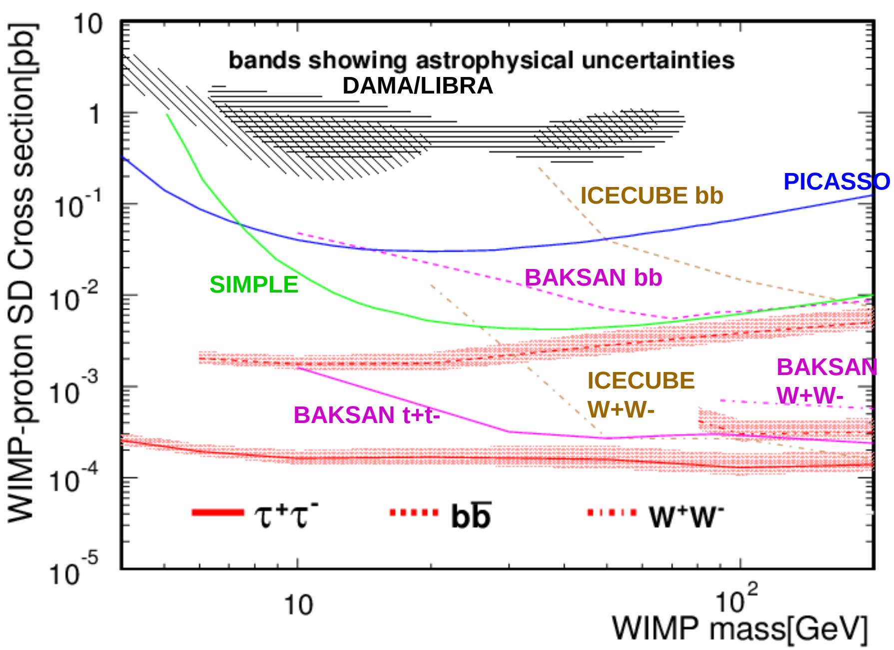
Search for WIMP Annihilations in the **Galactic Center**: Results

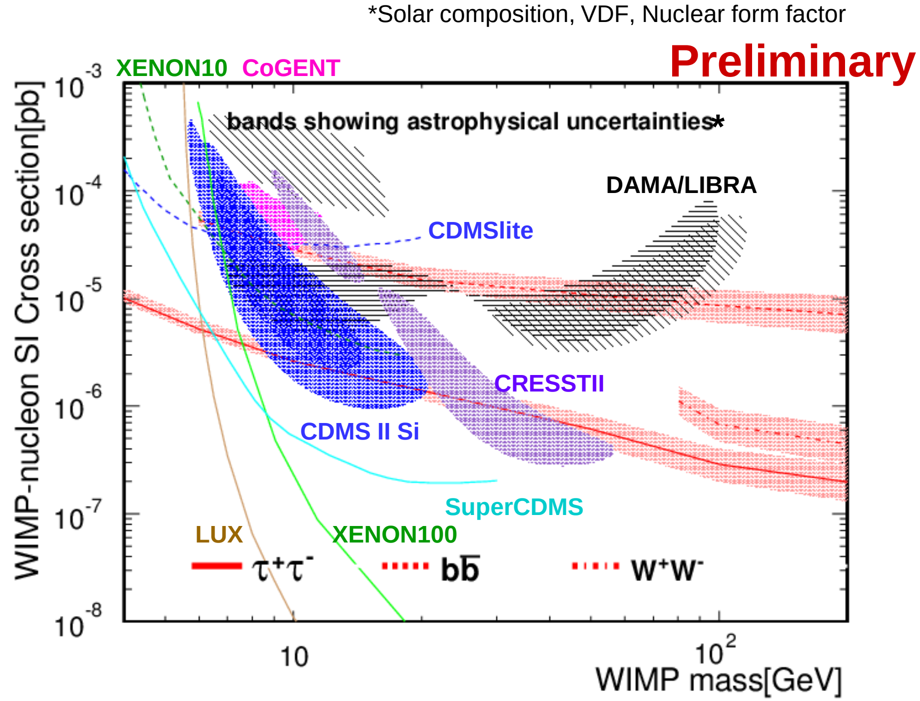




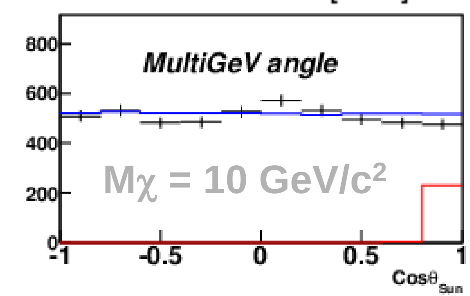
- No evidence for event excess on top of the atmospheric neutrino background
  - N.B. ~300 events allowed at 5 GeV test point are distributed over several analysis bins
- Stringent limits placed on the velocity-averaged annihilation cross section down to WIMP masses of 1 GeV / χ^2 ($\chi\chi \rightarrow \nu\nu$)

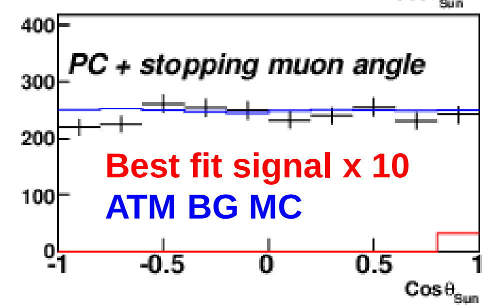
Search for WIMP Annihilations in the Sun





- Similar analysis can be performed when looking towards the center of the Sun
- No indication of an event excess in the data
- Spin-dependent cross section limits well below the allowed regions for DAMA/LIBRA
- Spin-independent limits in tension with some allowed regions, but not as constraining as LUX or XENON100





Summary

- ν_τ appearance seen at 3.8σ significance

- Three-Flavor Analysis
  - Using 4538 days of data, there is a ~1 σ preference for the NH, and second octant

- No indication of oscillations into sterile states
  - For 3+N models $|U_{\mu 4}|^2 < 0.022$ at 90% C.L.

- No indication of Lorentz invariance violation
  - Limits set or improved by 3 to 7 orders of magnitude

- So far no indication of indirect dark matter annihilation into neutrinos from either the sun or galactic center

Thank you, and I thank Roger and all of SK Collaboration

End