Looking for New Physics with Neutrinos

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Neutrino oscillations

- consistent picture of three flavor oscillations from many experiments: solar, atmospheric , reactor, accelerator neutrinos

$$U = R_{23}\, K\, R_{13}\, K^*\, R_{12}$$

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

$\theta_{12} = \theta_{sol}$ $\theta_{13} = \theta_{reactor}$ $\theta_{23} = \theta_{atm}$ δ

$\Delta m^2_{21} = \Delta m^2_{sol}$ $\Delta m^2_{32} = \Delta m^2_{atm}$

- with some possible “anomalies”: LSND, MiniBooNE, Reactor, Gallium

NuFIT 2.0 (2014)

	Normal Ordering ($\Delta\chi^2 = 0.97$)		Inverted Ordering (best fit)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.270 \to 0.344$	$0.304^{+0.013}_{-0.012}$	$0.270 \to 0.344$	$0.270 \to 0.344$
$\theta_{12}/^\circ$	$33.48^{+0.78}_{-0.75}$	$31.29 \to 35.91$	$33.48^{+0.78}_{-0.75}$	$31.29 \to 35.91$	$31.29 \to 35.91$
$\sin^2\theta_{23}$	$0.452^{+0.052}_{-0.028}$	$0.382 \to 0.643$	$0.579^{+0.025}_{-0.037}$	$0.389 \to 0.644$	$0.385 \to 0.644$
$\theta_{23}/^\circ$	$42.3^{+3.0}_{-1.6}$	$38.2 \to 53.3$	$49.5^{+1.5}_{-2.2}$	$38.6 \to 53.3$	$38.3 \to 53.3$
$\sin^2\theta_{13}$	$0.0218^{+0.0010}_{-0.0010}$	$0.0186 \to 0.0250$	$0.0219^{+0.0011}_{-0.0010}$	$0.0188 \to 0.0251$	$0.0188 \to 0.0251$
$\theta_{13}/^\circ$	$8.50^{+0.20}_{-0.21}$	$7.85 \to 9.10$	$8.51^{+0.20}_{-0.21}$	$7.87 \to 9.11$	$7.87 \to 9.11$
$\delta_{\mathrm{CP}}/^\circ$	306^{+39}_{-70}	$0 \to 360$	254^{+63}_{-62}	$0 \to 360$	$0 \to 360$
$\dfrac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.50^{+0.19}_{-0.17}$	$7.02 \to 8.09$	$7.50^{+0.19}_{-0.17}$	$7.02 \to 8.09$	$7.02 \to 8.09$
$\dfrac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.457^{+0.047}_{-0.047}$	$+2.317 \to +2.607$	$-2.449^{+0.048}_{-0.047}$	$-2.590 \to -2.307$	$\left[\begin{array}{c}+2.325 \to +2.599\\ -2.590 \to -2.307\end{array}\right]$

Gonzalez Garcia, Maltoni, Schwetz, http://www.nu-fit.org

JHEP 11 (2014) 052 [arXiv:1409.5439]

Neutrinos in the Standard Model and beyond

- Neutrino mass and mixing: physics beyond SM.
- Non-trivial extension:
  - add right handed neutrino to SM (like for other SM fermions)
  - add Yukawa coupling to Higgs $Y_\nu \bar{L} H N_R$
    (like for other SM fermions)
  - BUT Majorana mass term $M_R \overline{N_R^c} N_R$ allowed by SM symmetries
    (unlike for other SM fermions)

Need to consider at least:

new implications of Majorana neutrinos

or

new symmetry to forbid Majorana mass term

-> new interactions, new phenomena, etc.

Neutrino mass

Simplest scenario:

right-handed neutrino

Majorana mass $M > v$ $\longrightarrow$ see-saw mechanism

$$m_1 \sim M \qquad m_2 \sim \frac{Y^2 v^2}{M}$$

$$Y_t \sim 1 \qquad M \sim M_{GUT}$$

$$Y_e \sim 10^{-6} \qquad M \sim TeV$$

Other scenarios:

see-saw like: $m \sim \dfrac{Y'^2 v'^2}{M'}$

v' and M' can both be much smaller

Different scenarios

KeV, MeV, GeV discussed in different contexts

(hidden sectors, dark matter connections, etc.)

flavor symmetries, etc.

Learning about neutrinos

- We want to measure

Neutrino oscillations

- ▸ hierarchy (sign of Δm^2_{32})
- ▸ CP violating phase δ
- ▸ θ_{23} octant
- ▸ higher precision for all angles/mass differences

Other (neutrino) observations

- ▸ absolute mass scale
- ▸ Majorana vs. Dirac
- ▸ Majorana phases

A lot more!

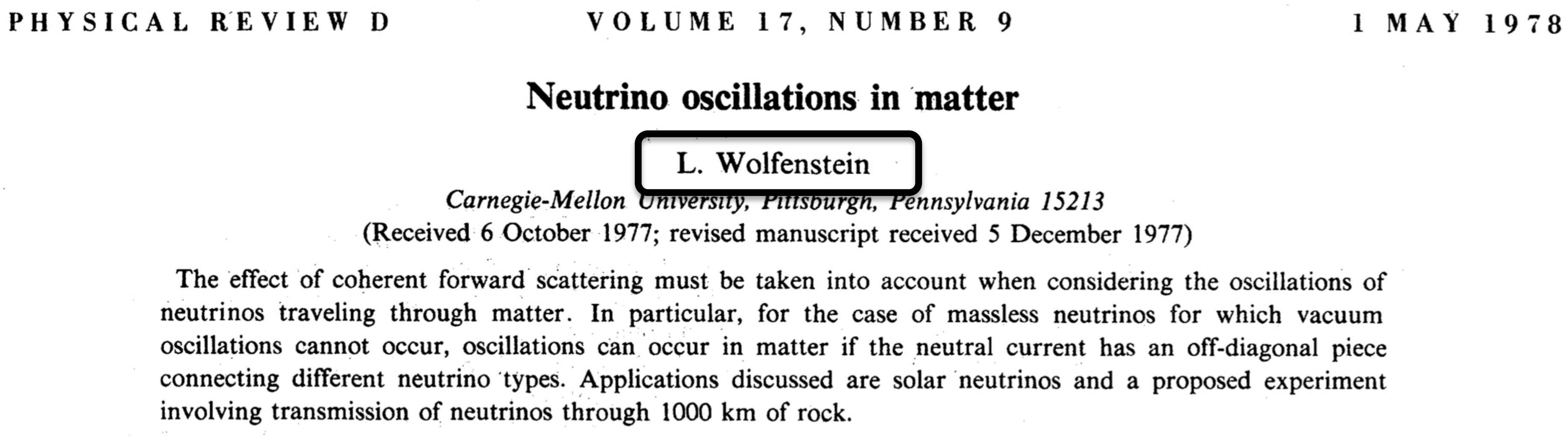
Searching for new physics

- The new physics is there! (somewhere)
- How do we find it/understand it?
- Different scenarios have different observational consequences
- We know a lot more about neutrinos than we did 20 years ago, but we do not yet know for sure what to look for and where

→ need to keep looking everywhere

- Many approaches:
  - Explicit model building
  - Effective theories/operators, general parametrizations
  - Measure everything you can and maybe something comes up
  - Some combinations of these
  - Detailed studies of sensitivities for specific experiments (design a better experiment)
  - Study how to combine data from different experiments or look at completely new set of observables and connections to other physics (e.g collider, astrophysics, cosmology) (get more from the data you have/can get)

Non-Standard neutrino Interactions (NSI)



PHYSICAL REVIEW D VOLUME 17, NUMBER 9 1 MAY 1978

Neutrino oscillations in matter

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(Received 6 October 1977; revised manuscript received 5 December 1977)

The effect of coherent forward scattering must be taken into account when considering the oscillations of neutrinos traveling through matter. In particular, for the case of massless neutrinos for which vacuum oscillations cannot occur, oscillations can occur in matter if the neutral current has an off-diagonal piece connecting different neutrino types. Applications discussed are solar neutrinos and a proposed experiment involving transmission of neutrinos through 1000 km of rock.

$$\mathcal{L} = -2\sqrt{2}G_F\epsilon_{\alpha\beta}^{fP}(\bar{\nu}_\alpha\gamma^\rho\nu_\beta)(\bar{f}\gamma_\rho P f)$$

Non-Standard neutrino Interactions (NSI)

- Standard Model can be treated as an effective low energy theory of some high energy completion at scale M
- Write down all effective higher-dimensional operators involving SM fields and respecting SM symmetries
- Dimension 5 ($1/M$) : Majorana mass
- Dimension 6 ($1/M^2$): lots of operators, with and without Higgs
- new neutrino interactions, smaller than SM ones

→ (suppressed by high scale M)

can be parametrized as $\epsilon_{\alpha\beta}$

$$\mathcal{L} = -2\sqrt{2} G_F \epsilon_{\alpha\beta}^{fP} (\bar{\nu}_\alpha \gamma^\rho \nu_\beta)(\bar{f} \gamma_\rho P f)$$

- Effective low-energy parametrization in terms of $\epsilon_{\alpha\beta}$ very general: can come from different types of underlying physics
- E.g.: effects of a sterile neutrino at energies much lower than its mass look like $\epsilon_{\alpha\beta}$; leptoquarks
- If you can constrain general $\epsilon_{\alpha\beta}$, many models can map their parameters onto $\epsilon_{\alpha\beta}$

Neutrino Telescopes

- Present: IceCube(+DeepCore), SuperKamiokande
  Future: extensions (PINGU, HyperKamiokande)
  + new experiments/techniques

- High energy neutrinos from astrophysical sources detected!
  - Want to understand:
    - astrophysics:
      - origin, source characteristics, relation to cosmic rays, gamma rays, etc.
    - physics:
      - sensitivity to new interactions
      - tests of fundamental symmetries (Lorentz, etc.)

- Dark matter annihilation

Neutrino Telescopes

- Present: IceCube(+DeepCore), SuperKamiokande
  Future: extensions (PINGU, HyperKamiokande)
  + new experiments/techniques (radio,etc.)

  - Atmospheric neutrinos
    - lots of them; “background”, but useful!
    - physics:
      - “short term”: could get to mass ordering first
      - “long term”: can measure mass ordering
        - crucial consistency check in
          - testing framework
          - search for new physics
    - astrophysics:
      - atmospheric neutrino production in cosmic ray interaction
      - better understanding of background for astrophysical searches

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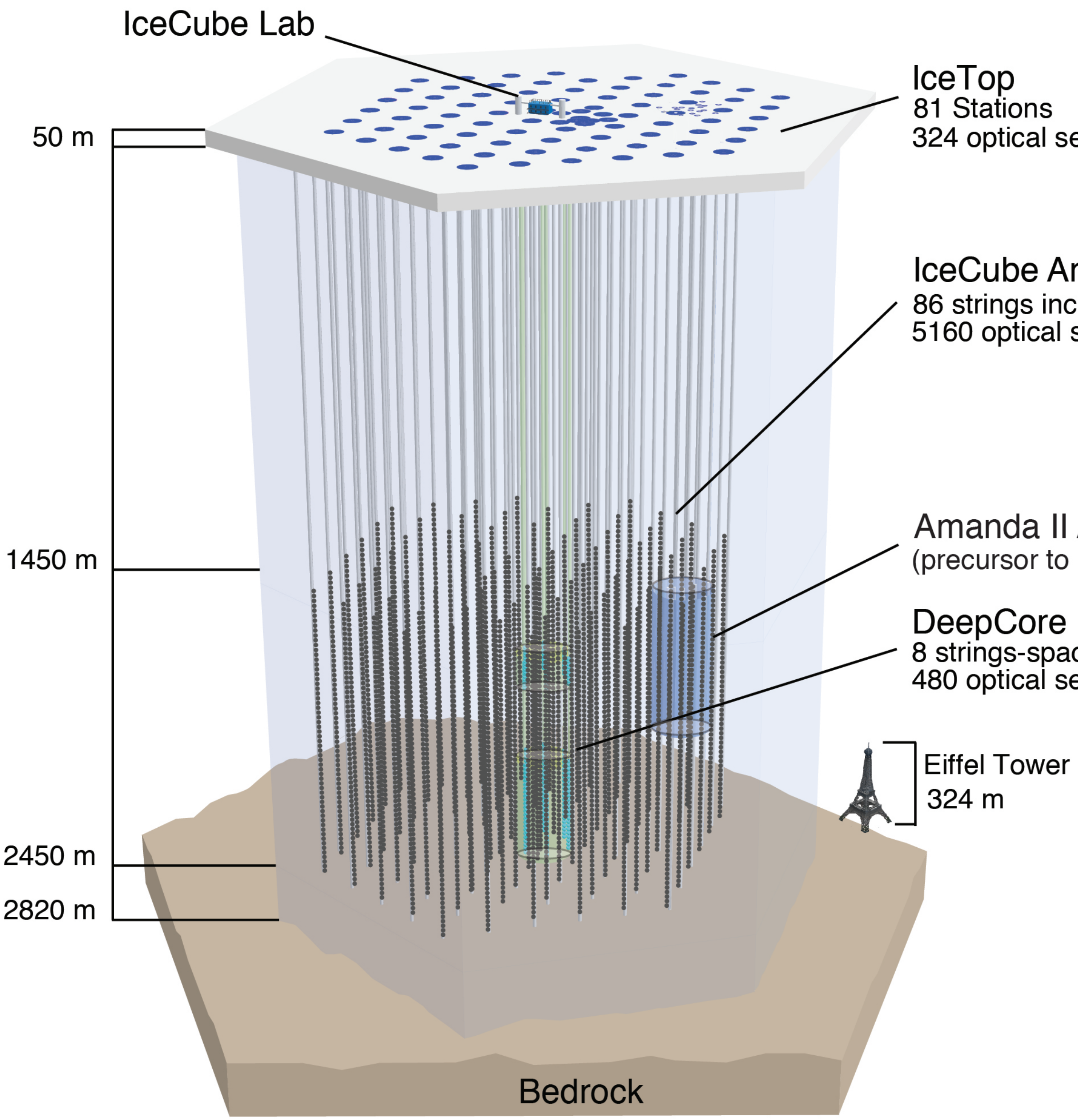
The IceCube Neutrino Observatory



IceCube Lab

IceTop
81 Stations
324 optical sensors

IceCube Array
86 strings including 8 DeepCore strings
5160 optical sensors

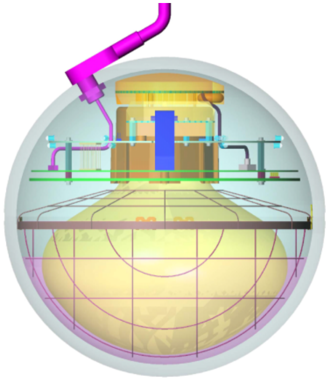
Amanda II Array
(precursor to IceCube)

DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors

Eiffel Tower
324 m

Configuration chronology

2006: IC9
2007: IC22
2008: IC40
2009: IC59
2010: IC79
2011: IC86

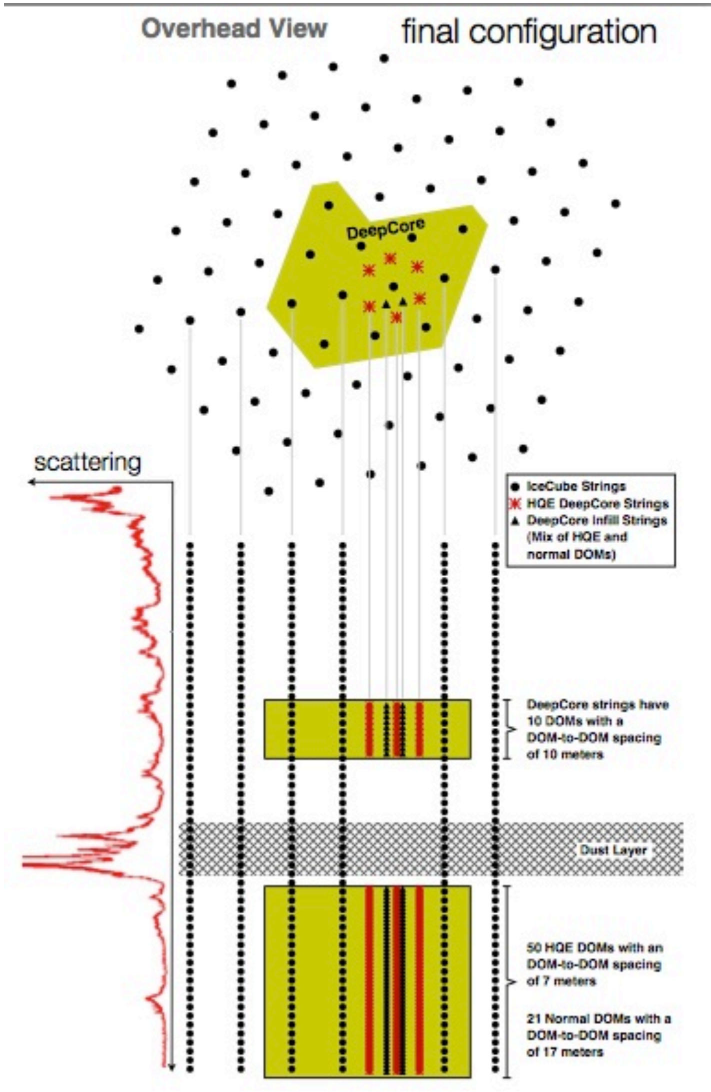


Digital Optical Module (DOM)

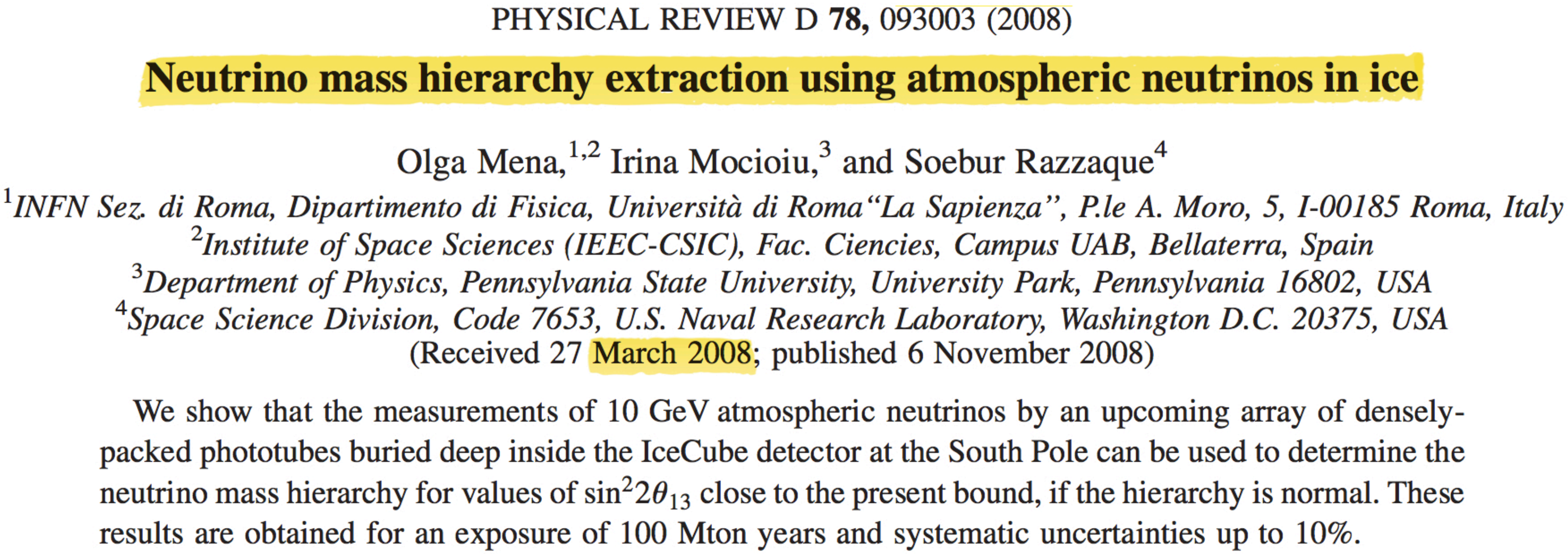
IceCube Deep Core

- motivation: look for neutrinos from galactic sources, dark matter annihilation
  - galactic center is above horizon at South Pole
  - need to reduce large cosmic muon background
- 4π coverage
  look at down-going events,
  study galactic sources, galactic center

- 8 special strings, 72m IS, 7m DOM spacing
- ~ 5x higher effective photocathode density
- ~ 20Mton
- IceCube's top and outer layers: active veto



- Up to 100,000 events/year! Use them!
- Energy range 10-40 GeV great for oscillation physics
- Statistics compensate for systematics for many issues
  - Use energy and angular distributions sensitive to physics
  - Normalizations can be determined from data



PHYSICAL REVIEW D **78,** 093003 (2008)

Neutrino mass hierarchy extraction using atmospheric neutrinos in ice

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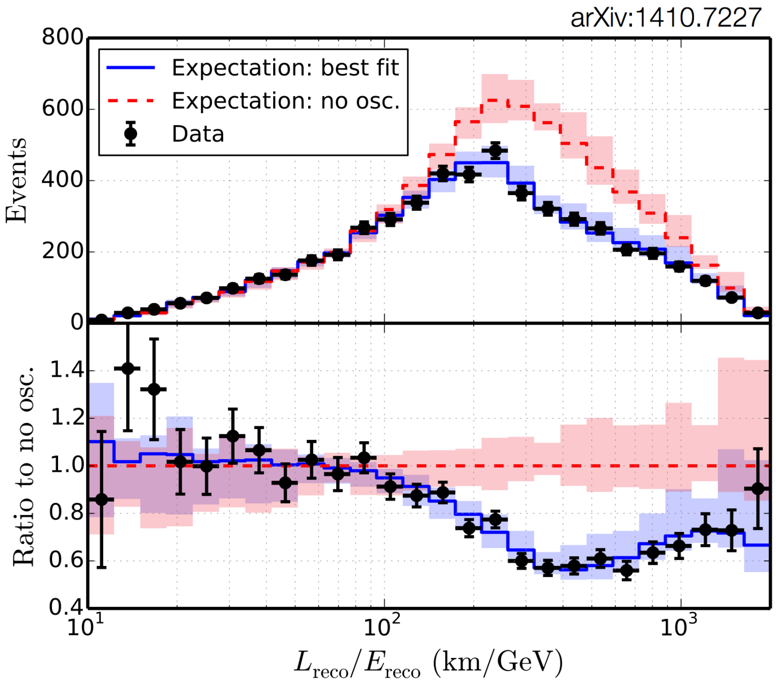
(Received 27 March 2008; published 6 November 2008)

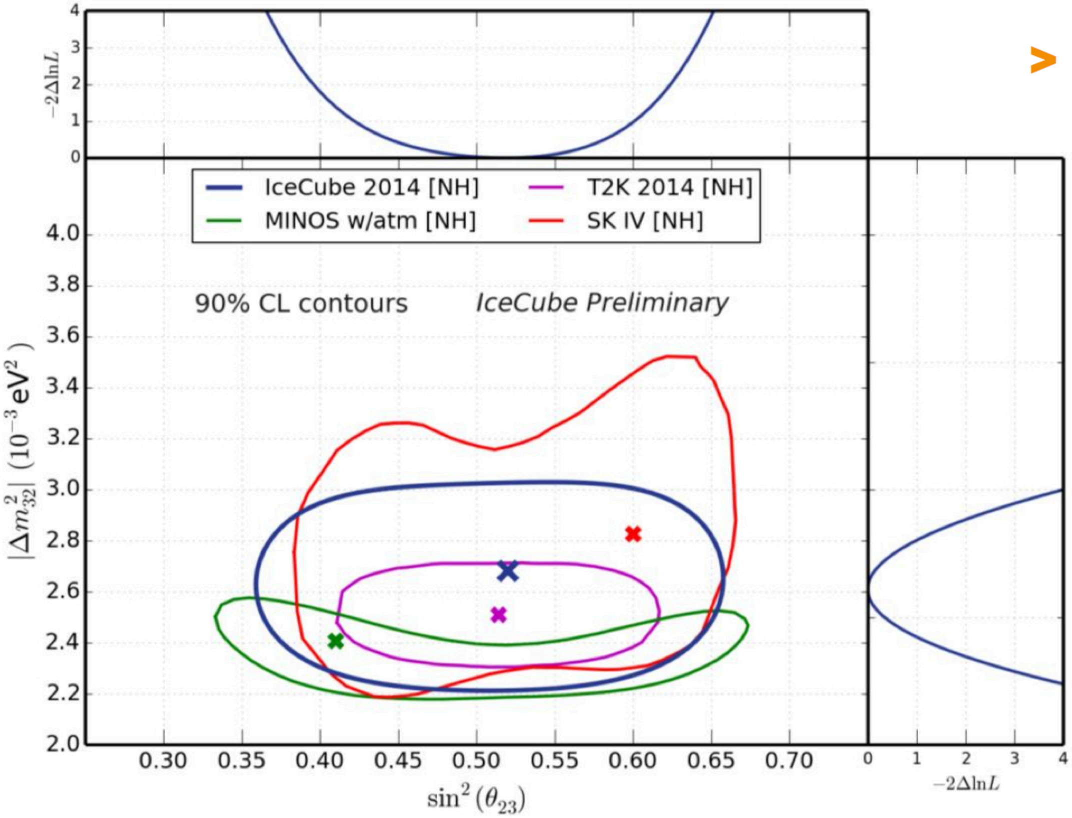
We show that the measurements of 10 GeV atmospheric neutrinos by an upcoming array of densely-packed phototubes buried deep inside the IceCube detector at the South Pole can be used to determine the neutrino mass hierarchy for values of $\sin^2 2\theta_{13}$ close to the present bound, if the hierarchy is normal. These results are obtained for an exposure of 100 Mton years and systematic uncertainties up to 10%.

- Data already there: need the right tools to analyze it

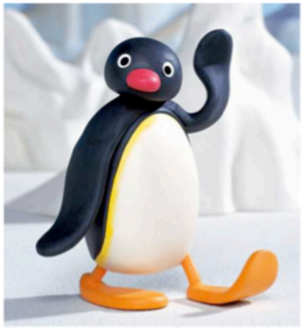
IceCube Deep Core Neutrino Oscillation Results



Phys. Rev. D 91, 072004 (2015)



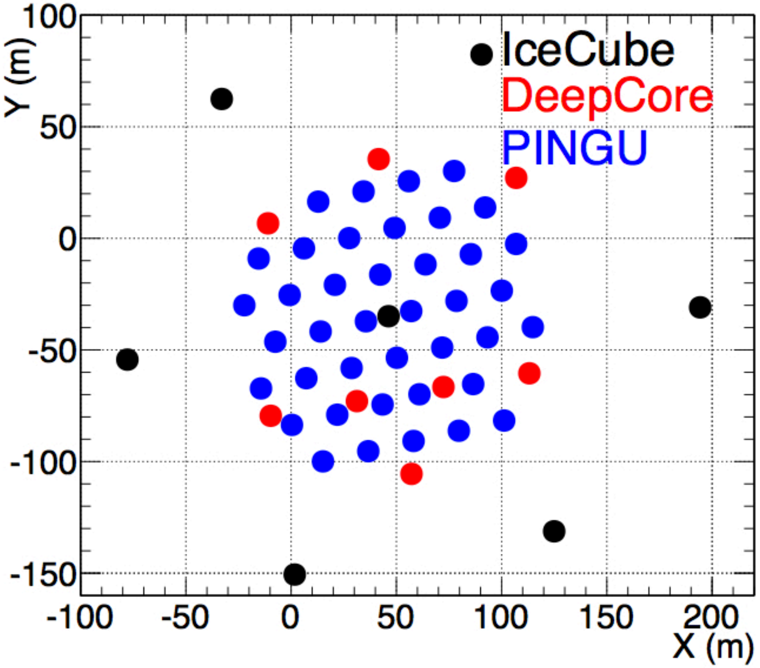
PINGU



PRECISION ICECUBE NEXT GENERATION UPGRADE

- Baseline detector consists of 40 additional strings of 60 Digital Optical Modules each, deployed inside the DeepCore volume
  - Geometry optimization underway – additional DOMs have relatively low incremental cost – final proposal likely 80-96 DOMs/string
  - 20-22 m string spacing (cf. 125 m for IceCube, 72 m for DeepCore)
  - ~25x higher photocathode density
  - Additional in situ calibration devices will better control detector systematics (not included in projected performance)
- Engineering issues and cost of deploying instrumentation are well understood from IceCube experience
  - Can install ≥20 strings per season once underway

Top view of the PINGU new candidate detector



Ty DeYoung

ICDC/PINGU

- mass hierarchy (O.Mena, I.Mocioiu, S.Razzaque, Phys. Rev. D78(2008) 093003)
- precision on all parameters (G. Giordano, O.Mena, I.Mocioiu, Phys. Rev. D82 (2010) 093001)
- tau neutrino appearance (G. Giordano, O.Mena, I.Mocioiu, Phys. Rev. D81 (2010) 113008)

- new physics in neutrino sector
    - large range of energies
    - large range of distances
    - high densities: matter effects

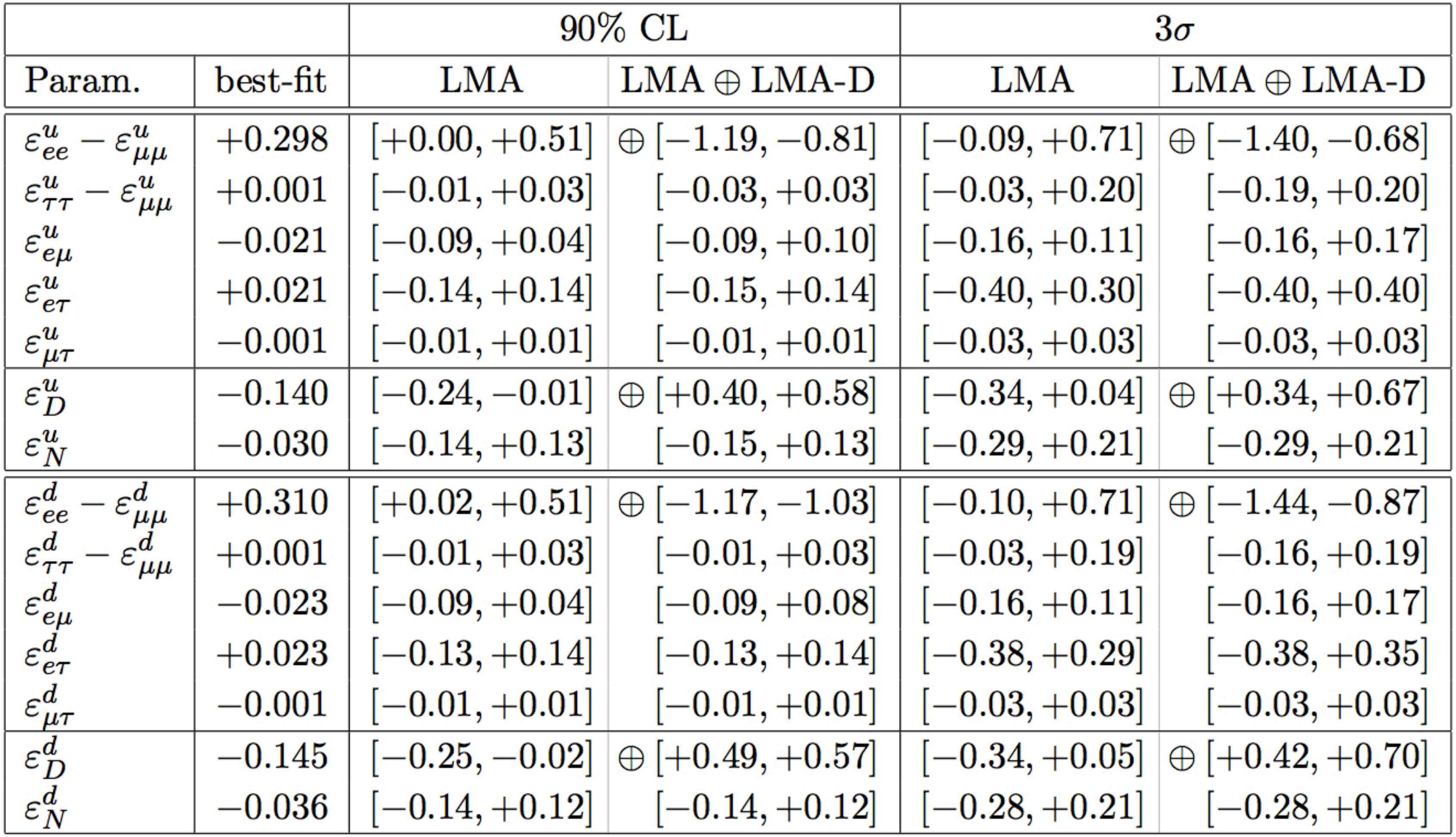
NSI: matter effect

$$H_{I,NSI} = V_{cc} \begin{pmatrix} 1+\epsilon_{ee} & |\epsilon_{e\mu}|e^{i\delta_{e\mu}} & |\epsilon_{e\tau}|e^{i\delta_{e\tau}} \\ |\epsilon_{e\mu}|e^{-i\delta_{e\mu}} & \epsilon_{\mu\mu} & |\epsilon_{\mu\tau}|e^{i\delta_{\mu\tau}} \\ |\epsilon_{e\tau}|e^{-i\delta_{e\tau}} & |\epsilon_{\mu\tau}|e^{-i\delta_{\mu\tau}} & \epsilon_{\tau\tau} \end{pmatrix}$$

$$\epsilon_{\alpha\beta} \equiv \sum_{\substack{f=e,u,d \\ P=L,R}} \epsilon_P^{\alpha\beta,ff} \frac{n_f}{n_e}$$

$$\mathcal{L}_{NSI} = -2\sqrt{2}G_F \bar{\nu}_\alpha \gamma_\mu \nu_\beta \left(\epsilon_L^{\alpha\beta,ij} \bar{f}_L^i \gamma^\mu f_L^j + \epsilon_R^{\alpha\beta,ij} \bar{f}_R^i \gamma^\mu f_R^j \right) + h.c.$$

NSI: constraints

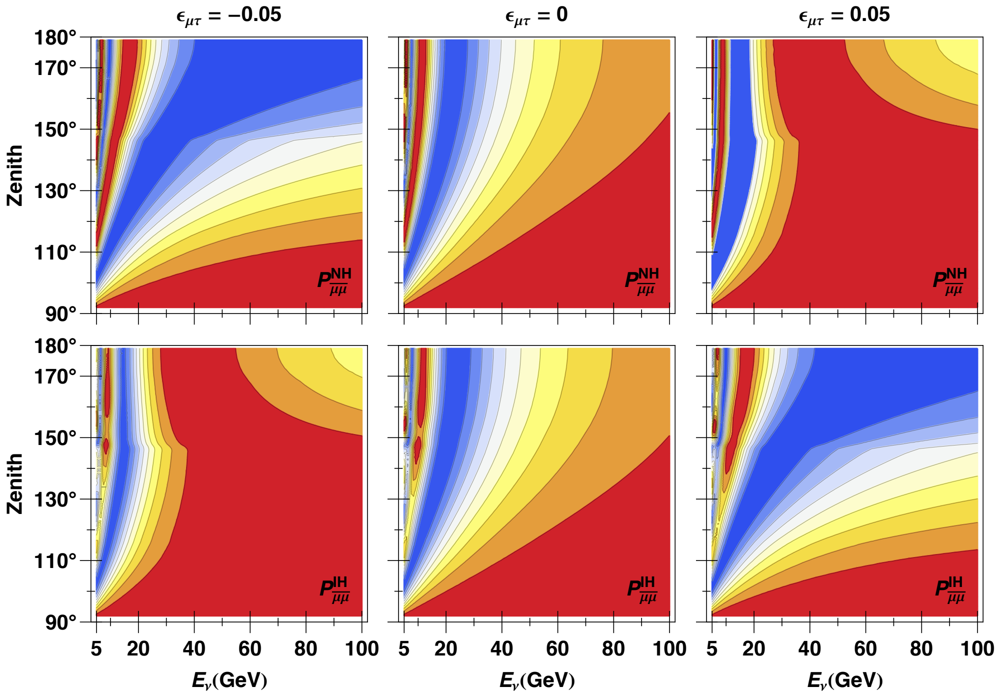


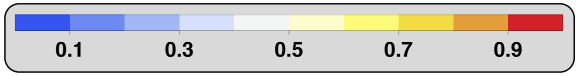
		90% CL		3σ	
Param.	best-fit	LMA	LMA $\oplus$ LMA-D	LMA	LMA $\oplus$ LMA-D
$\varepsilon^u_{ee} - \varepsilon^u_{\mu\mu}$	$+0.298$	$[+0.00, +0.51]$	$\oplus\ [-1.19, -0.81]$	$[-0.09, +0.71]$	$\oplus\ [-1.40, -0.68]$
$\varepsilon^u_{\tau\tau} - \varepsilon^u_{\mu\mu}$	$+0.001$	$[-0.01, +0.03]$	$[-0.03, +0.03]$	$[-0.03, +0.20]$	$[-0.19, +0.20]$
$\varepsilon^u_{e\mu}$	-0.021	$[-0.09, +0.04]$	$[-0.09, +0.10]$	$[-0.16, +0.11]$	$[-0.16, +0.17]$
$\varepsilon^u_{e\tau}$	$+0.021$	$[-0.14, +0.14]$	$[-0.15, +0.14]$	$[-0.40, +0.30]$	$[-0.40, +0.40]$
$\varepsilon^u_{\mu\tau}$	-0.001	$[-0.01, +0.01]$	$[-0.01, +0.01]$	$[-0.03, +0.03]$	$[-0.03, +0.03]$
ε^u_{D}	-0.140	$[-0.24, -0.01]$	$\oplus\ [+0.40, +0.58]$	$[-0.34, +0.04]$	$\oplus\ [+0.34, +0.67]$
ε^u_{N}	-0.030	$[-0.14, +0.13]$	$[-0.15, +0.13]$	$[-0.29, +0.21]$	$[-0.29, +0.21]$
$\varepsilon^d_{ee} - \varepsilon^d_{\mu\mu}$	$+0.310$	$[+0.02, +0.51]$	$\oplus\ [-1.17, -1.03]$	$[-0.10, +0.71]$	$\oplus\ [-1.44, -0.87]$
$\varepsilon^d_{\tau\tau} - \varepsilon^d_{\mu\mu}$	$+0.001$	$[-0.01, +0.03]$	$[-0.01, +0.03]$	$[-0.03, +0.19]$	$[-0.16, +0.19]$
$\varepsilon^d_{e\mu}$	-0.023	$[-0.09, +0.04]$	$[-0.09, +0.08]$	$[-0.16, +0.11]$	$[-0.16, +0.17]$
$\varepsilon^d_{e\tau}$	$+0.023$	$[-0.13, +0.14]$	$[-0.13, +0.14]$	$[-0.38, +0.29]$	$[-0.38, +0.35]$
$\varepsilon^d_{\mu\tau}$	-0.001	$[-0.01, +0.01]$	$[-0.01, +0.01]$	$[-0.03, +0.03]$	$[-0.03, +0.03]$
ε^d_{D}	-0.145	$[-0.25, -0.02]$	$\oplus\ [+0.49, +0.57]$	$[-0.34, +0.05]$	$\oplus\ [+0.42, +0.70]$
ε^d_{N}	-0.036	$[-0.14, +0.12]$	$[-0.14, +0.12]$	$[-0.28, +0.21]$	$[-0.28, +0.21]$

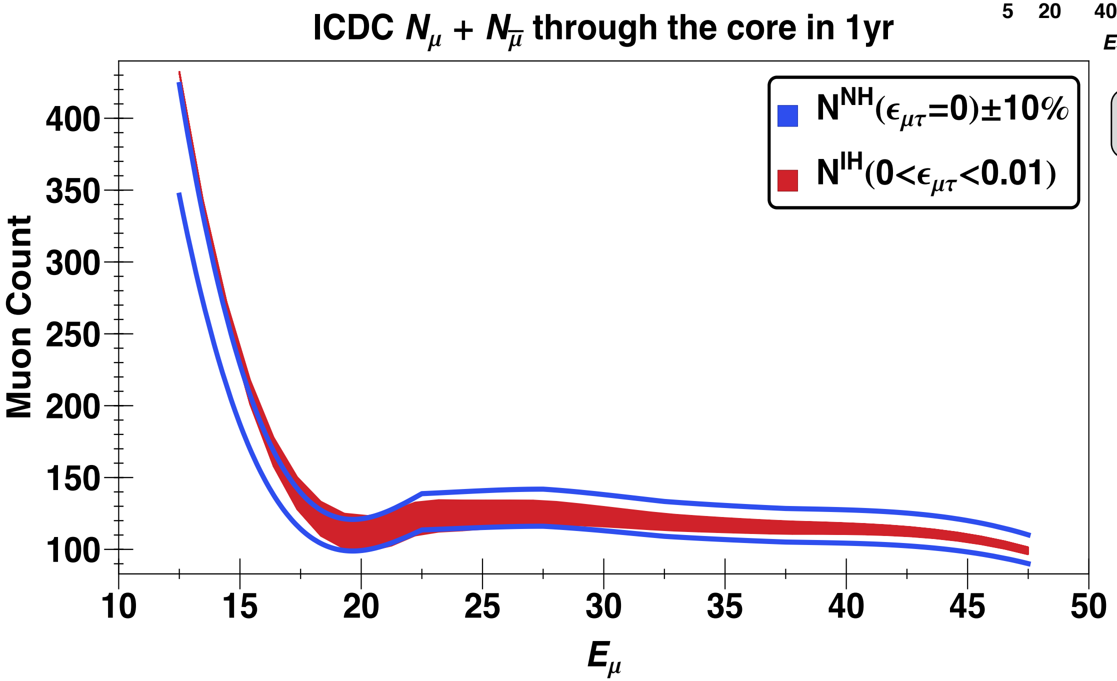
M.C. Gonzalez-Garcia, M. Maltoni, JHEP 1309 (2013) 152

NSI: understanding degeneracies

- Mu-Tau sector







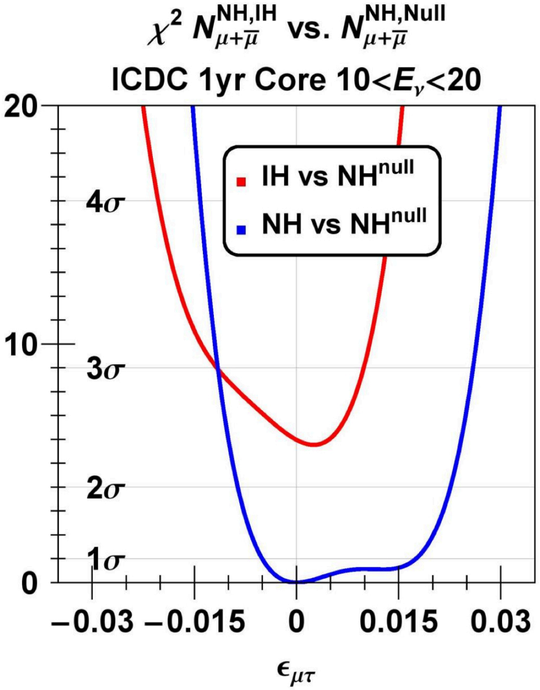
I.Mocioiu, W.Wright, arXiv:1410.6193,
Nucl.Phys. B893 (2015) 376-390

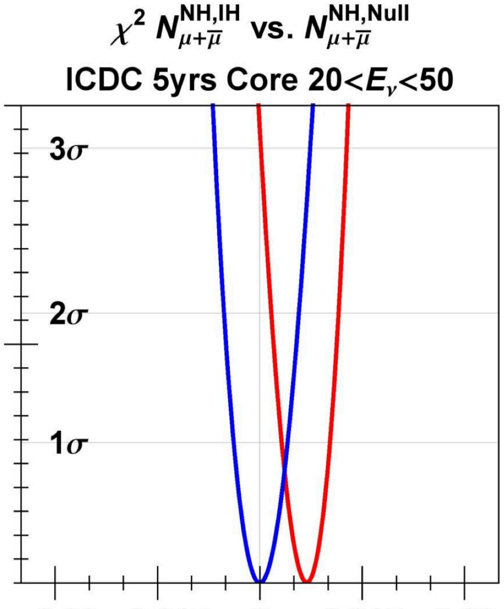
NSI: understanding degeneracies

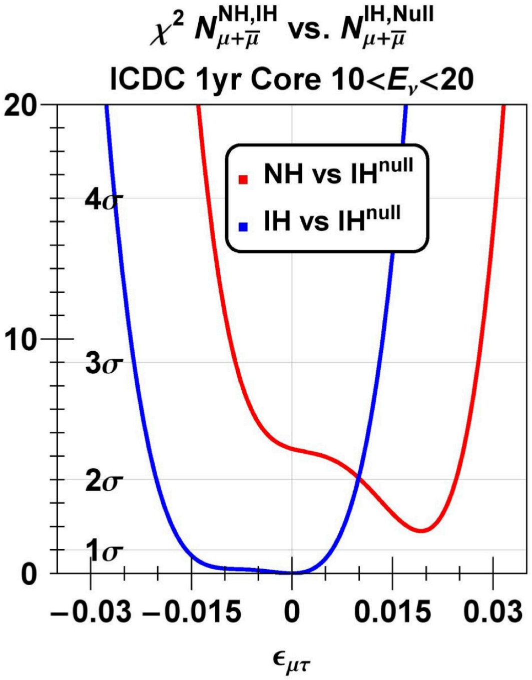
$$\Delta m^2_{21} = \theta_{12} = \theta_{13} = \delta_{cp} = \epsilon_{\alpha\beta\neq\mu\tau} = \delta_{\mu\tau} = 0 \quad \theta_{23} = \pi/4$$

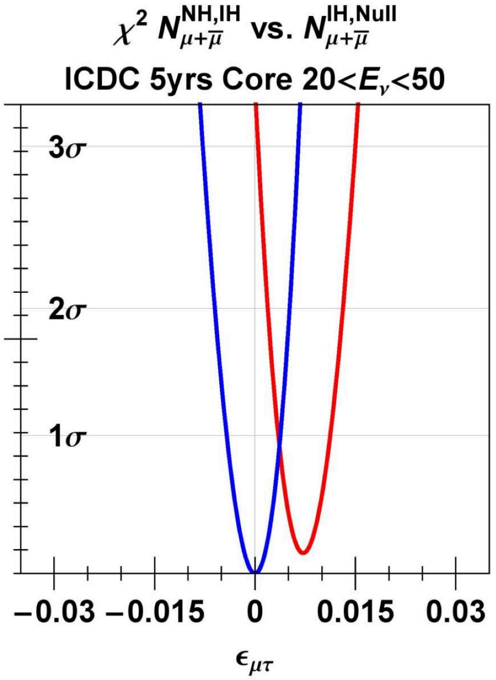
$$P_{\mu\mu} = \cos^2\left(L\left(\frac{\Delta m^2_{31}}{4E_\nu} + V_{cc}\epsilon_{\mu\tau}\right)\right)$$

NSI: breaking degeneracies









NSI: breaking degeneracies

- need multiple observables/
  independent measurements of hierarchy
  - ICDC/PINGU: ν_μ survival
    large matter effect, good sensitivity to $\epsilon_{\mu\tau}$, high statistics
    energy distribution
  - NOVA/DUNE (LBNE): ν_e appearance
    matter effect, little sensitivity to $\epsilon_{\mu\tau}$
  - JUNO (other long baseline reactor) : $\bar{\nu}_e$ disappearance
    interference of mass scales, no matter effect/NSI
  - Neutrinoless double beta decay, cosmology, etc.

→ measure hierarchy and $\epsilon_{\mu\tau}$ in consistent global fit

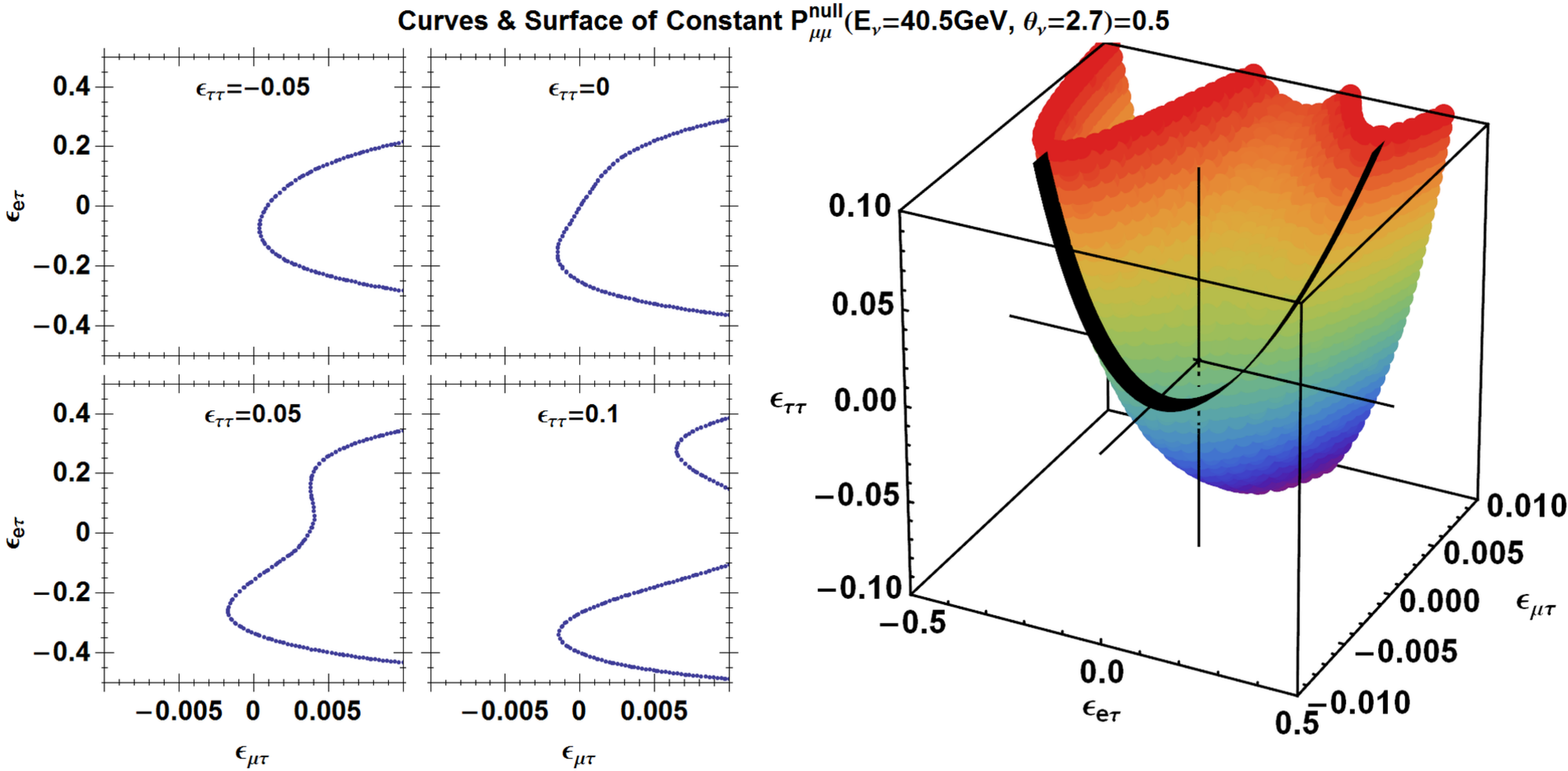
NSI: understanding degeneracies

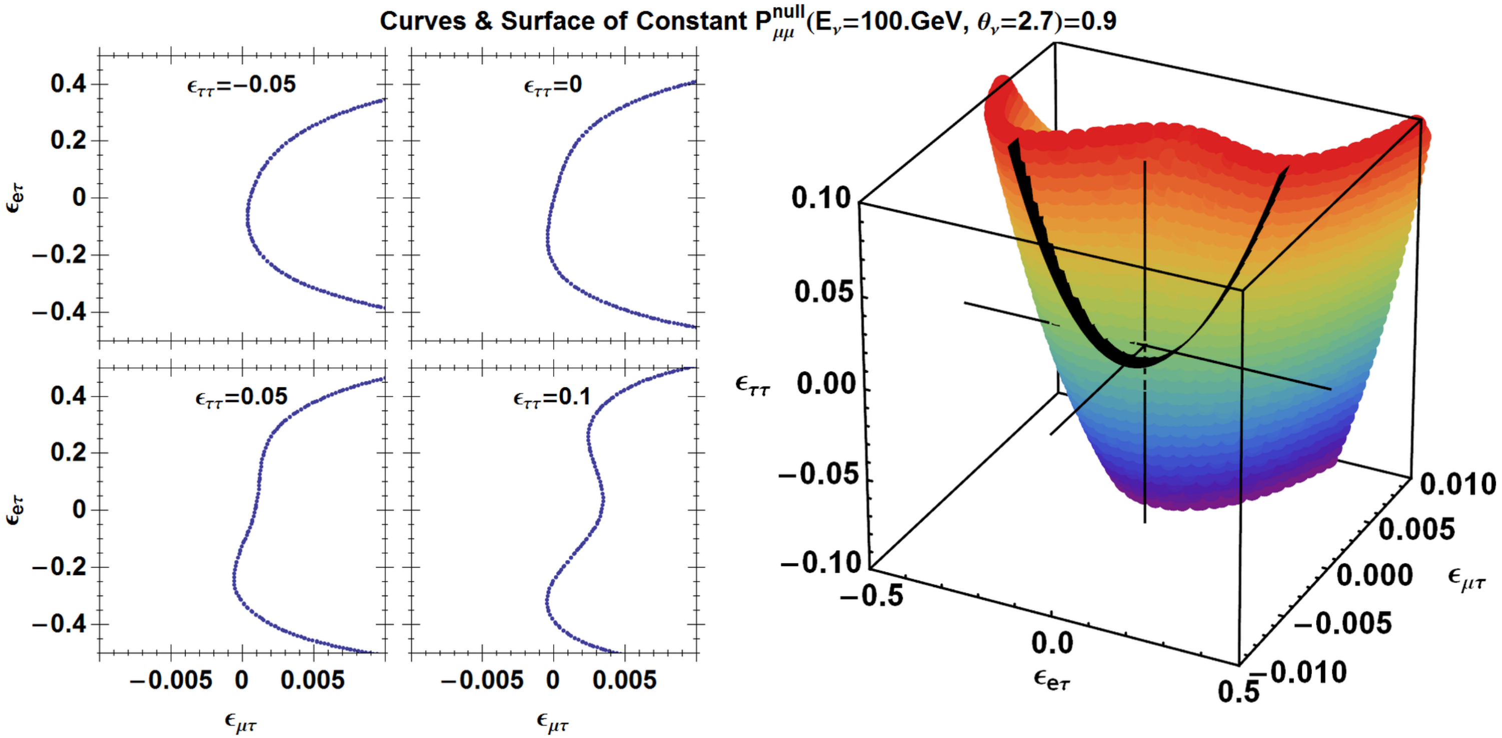
$$\text{All } \delta = 0,\ \Delta m_{21}^2 = \epsilon_{e\mu} = 0 \text{ and } \Delta = \Delta m_{31}^2 / (4E_\nu)$$

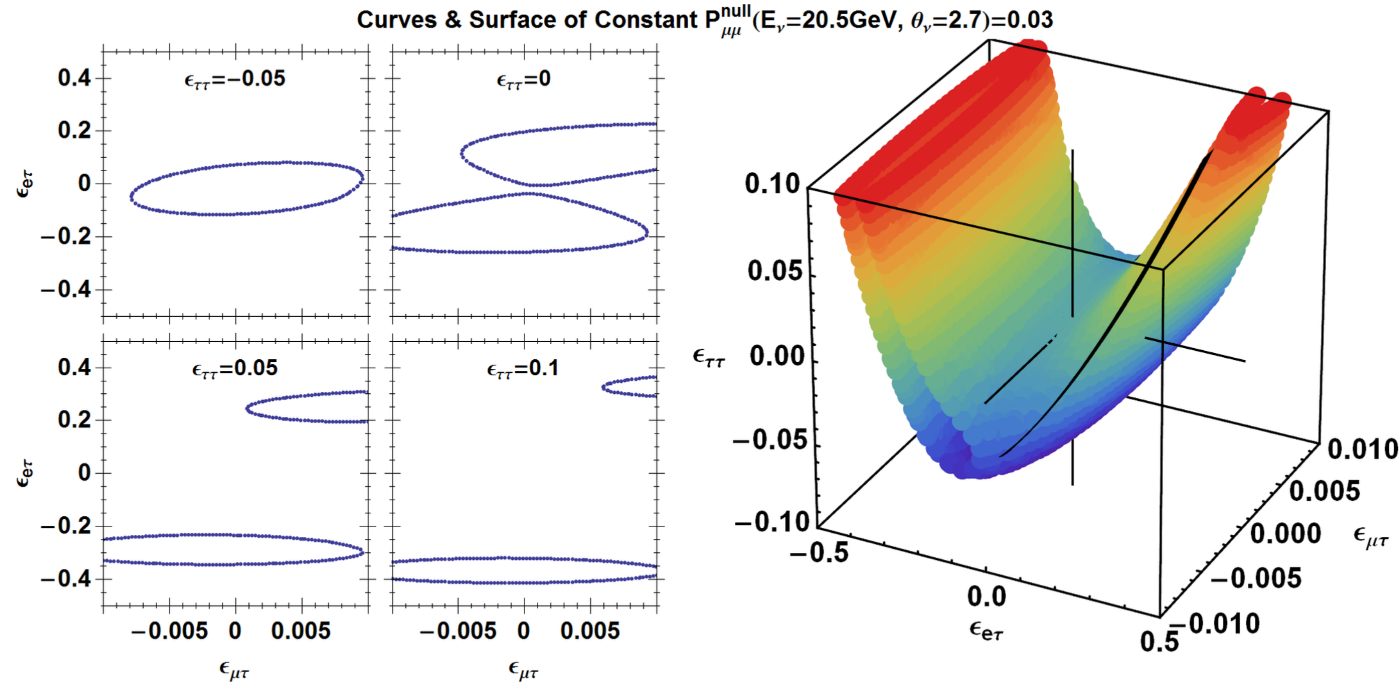
$$H = \begin{pmatrix} V_{cc}\left(1 + \epsilon_{ee}\right) + 2\Delta s_{13}^2 & \Delta s_{2\cdot 13} s_{23} & V_{cc}\epsilon_{e\tau} + \Delta s_{2\cdot 13} c_{23} \\ \Delta s_{2\cdot 13} s_{23} & V_{cc}\epsilon_{\mu\mu} + 2\Delta c_{13}^2 s_{23}^2 & V_{cc}\epsilon_{\mu\tau} + \Delta c_{13}^2 s_{2\cdot 23} \\ V_{cc}\epsilon_{e\tau} + \Delta s_{2\cdot 13} c_{23} & V_{cc}\epsilon_{\mu\tau} + \Delta c_{13}^2 s_{2\cdot 23} & V_{cc}\epsilon_{\tau\tau} + 2\Delta c_{13}^2 c_{23}^2 \end{pmatrix}$$

- Matter resonance at multiple energies, depending on NSI parameters

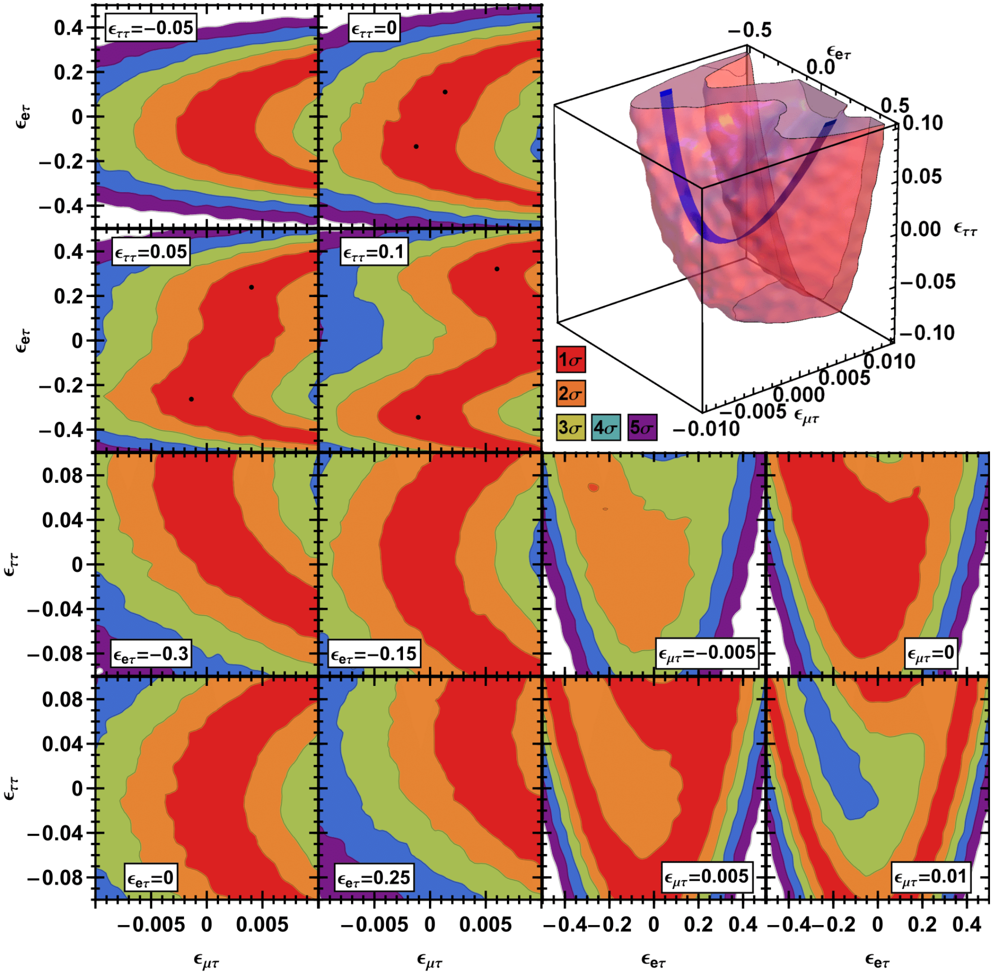
NSI: understanding degeneracies




Curves & Surface of Constant $P^{\text{null}}_{\mu\mu}(E_\nu=100.\text{GeV}, \theta_\nu=2.7)=0.9$
$\epsilon_{\tau\tau}=-0.05$
$\epsilon_{\tau\tau}=0$
$\epsilon_{\tau\tau}=0.05$
$\epsilon_{\tau\tau}=0.1$
$\epsilon_{e\tau}$
$\epsilon_{\mu\tau}$
0.4
0.2
0
−0.2
−0.4
−0.005
0
0.005
$\epsilon_{\tau\tau}$
0.10
0.05
0.00
−0.05
−0.10
−0.5
0.0
0.5
$\epsilon_{e\tau}$
0.010
0.005
0.000
−0.005
−0.010
$\epsilon_{\mu\tau}$

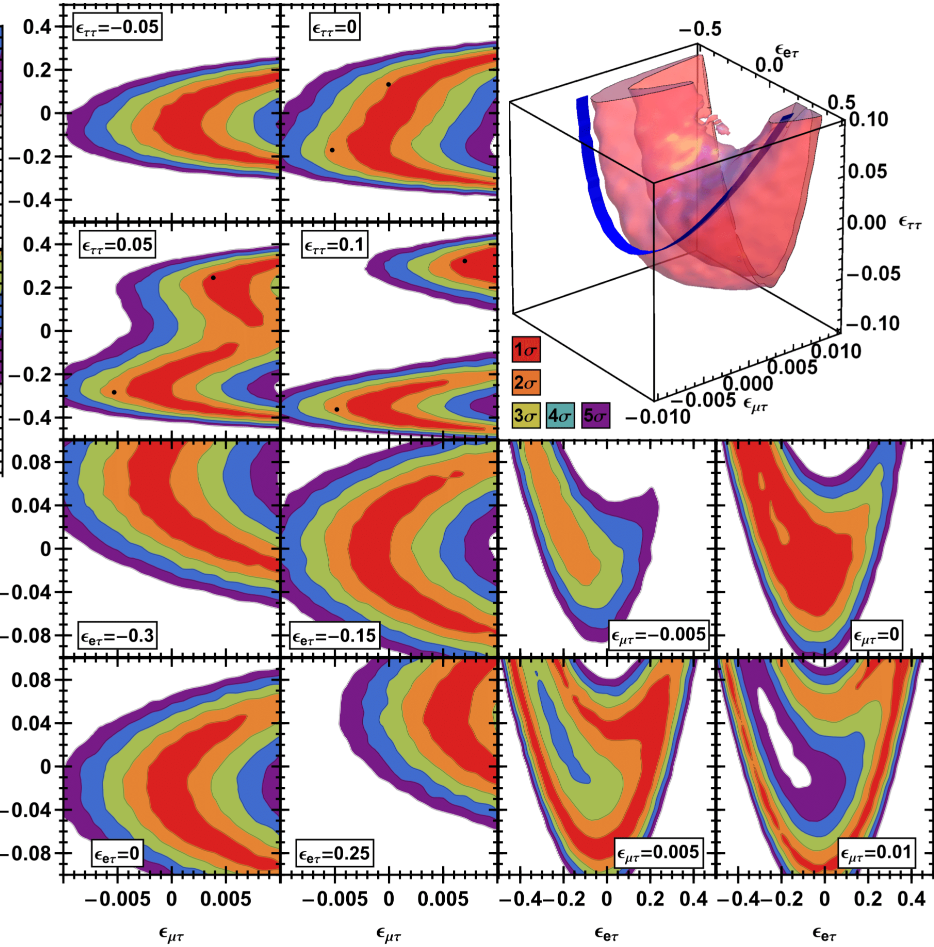

Curves & Surface of Constant $P^{\text{null}}_{\mu\mu}(E_\nu=20.5\text{GeV}, \theta_\nu=2.7)=0.03$
$\epsilon_{\tau\tau}=-0.05$
$\epsilon_{\tau\tau}=0$
$\epsilon_{\tau\tau}=0.05$
$\epsilon_{\tau\tau}=0.1$
$\epsilon_{e\tau}$
$\epsilon_{\mu\tau}$
0.4
0.2
0
−0.2
−0.4
−0.005
0
0.005
$\epsilon_{\tau\tau}$
0.10
0.05
0.00
−0.05
−0.10
−0.5
0.0
0.5
$\epsilon_{e\tau}$
0.010
0.005
0.000
−0.005
−0.010
$\epsilon_{\mu\tau}$

χ^2 from ICDC $N_\mu^{NH,\,null}$ vs. N_μ^{NH} for High energy ν_μ through Core. Source: $P_{\mu\mu}$ only.



NSI
e-tau
mu-tau
tau-tau

χ^2 from ICDC $N_\mu^{NH,\,null}$ vs. N_μ^{NH} for low energy ν_μ through Core. Source: $P_{\mu\mu}$ only.



Neutrino Telescopes

- Atmospheric neutrinos
  - High statistics
  - physics:
    - “short term”: could get to mass ordering first
    - “long term”: can measure mass ordering
      - could measure octant
      - could get tau neutrino appearance
      - crucial consistency check in
        - testing framework
        - search for new physics

- To get physics optimize (PINGU):
  - energy resolution
  - some directional reconstruction
  - energy threshold: more physics vs systematics at low energy

Neutrinos and New Physics

- Model Building
  - explicit theoretical models that generate large NSI and are consistent with all other constraints
- NSI in other contexts
  - matter effects only probe vector-like interactions
  - what about others?
  - scattering experiments (high precision or high energy) can probe other NSI structures.
  - back to pre-SM tests at 1% of weak interaction!
  - tests at highest energy (e.g. IceCube astrophysical nus)

    hidden source matter effect: Mena, Mocioiu, Razzaque (2007)

    Smirnov et. Aal. , Winter et. al. (2010)
  - supernovae + other astrophysics
- Other manifestations of new physics in the neutrino sector
  - astrophysics
  - cosmology