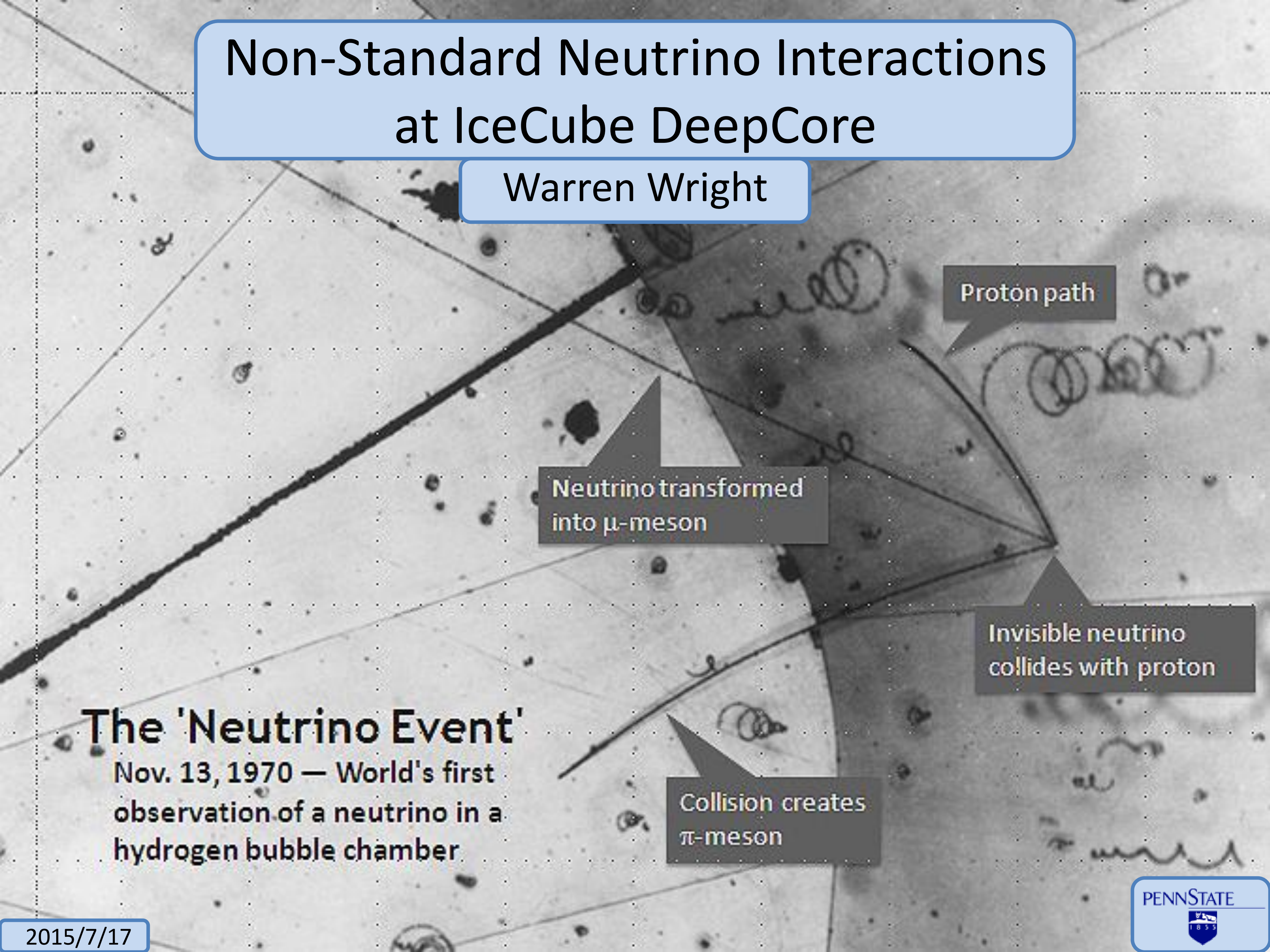
Non-Standard Neutrino Interactions at IceCube DeepCore

Warren Wright



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2015/7/17

Outline

1. Neutrino Introduction **- SKIP**
2. Standard Oscillation Framework
3. Open Questions
4. Non Standard Interactions
5. One NSI Parameter
6. Many NSI Parameters
7. Next Steps

2. Standard Oscillation Framework

$$i\frac{d}{dL}\begin{pmatrix}\nu_e(L)\\ \nu_\mu(L)\\ \nu_\tau(L)\end{pmatrix} = \left(\frac{1}{2E}UMU^\dagger + H_I\right)\begin{pmatrix}\nu_e(L)\\ \nu_\mu(L)\\ \nu_\tau(L)\end{pmatrix}$$

$$M = \begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m^2_{21} & 0\\ 0 & 0 & \Delta m^2_{31}\end{pmatrix}$$

$$H_{I,SI} = V_{cc}\begin{pmatrix}1 & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{pmatrix}$$

$$V_{CC} = \sqrt{2}G_F N_e = 7.6\times 10^{14} Y_e \rho$$

$G_F =$ the Fermi constant

$N_e =$ the electron number

$Y_e =$ the electron fraction

$\rho =$ the density

3. Open Questions

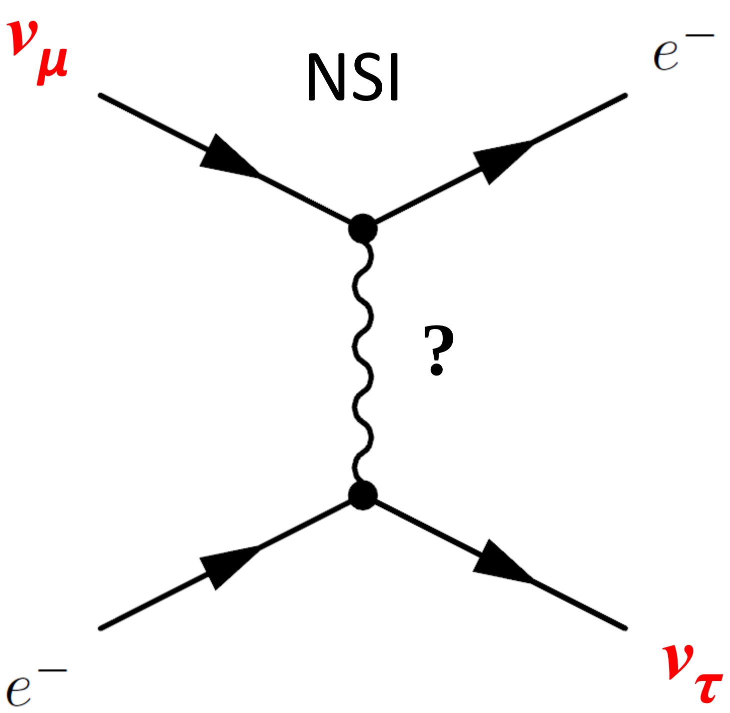
- Precision: $\theta_{12}, \theta_{13}, \theta_{23}, \Delta m^2_{21}, |\Delta m^2_{31}|, \ldots \quad ?$
- Determination: $m_k, \delta_{cp}, \theta_{23} <> \pi/4, \Delta m^2_{31} <> 0, \ldots \quad ?$
- Fundamental: $m_4, \delta_{maj}, \epsilon_{\alpha\beta}, \ldots \quad ?$

<u>My Focus: NSI and MH</u>

$\Delta m^2_{31} > 0$ Normal Hierarchy (**NH**)

$\Delta m^2_{31} < 0$ Inverted Hierarchy (**IH**)

4. Non-Standard Interactions



4. NSI: Motivation

- Reasons to study NSI:
  - Sub-Leading Phenomena
    - Does the SM explain everything we see?
  - The Standard Model is an Effective theory
    - NSI is Beyond the SM physics
    - The quest for new physics and fundamental answers
- Methods to study NSI:
  - Model Building
    - Seesaw, Zee-Babu, …
  - Phenomenological / Effective Theory

4. NSI: Formalism

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

$$\alpha, \beta = e, \mu, \tau$$

$$i, j = e, u, d$$

$$\epsilon \propto \frac{m_W^2}{m_X^2}$$

$$\therefore m_X \sim 1(10)\ \mathrm{TeV}\ \Rightarrow \epsilon \sim 10^{-2}(10^{-4})$$

Wolfenstein. Phys. Rev. D17, 2369 (1978)

4. NSI: Formalism

$$i\frac{d}{dL}\begin{pmatrix}\nu_e(L)\\ \nu_\mu(L)\\ \nu_\tau(L)\end{pmatrix} = \left(\frac{1}{2E}UMU^\dagger + H_I\right)\begin{pmatrix}\nu_e(L)\\ \nu_\mu(L)\\ \nu_\tau(L)\end{pmatrix}$$

$$M = \begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m^2_{21} & 0\\ 0 & 0 & \Delta m^2_{31}\end{pmatrix}$$

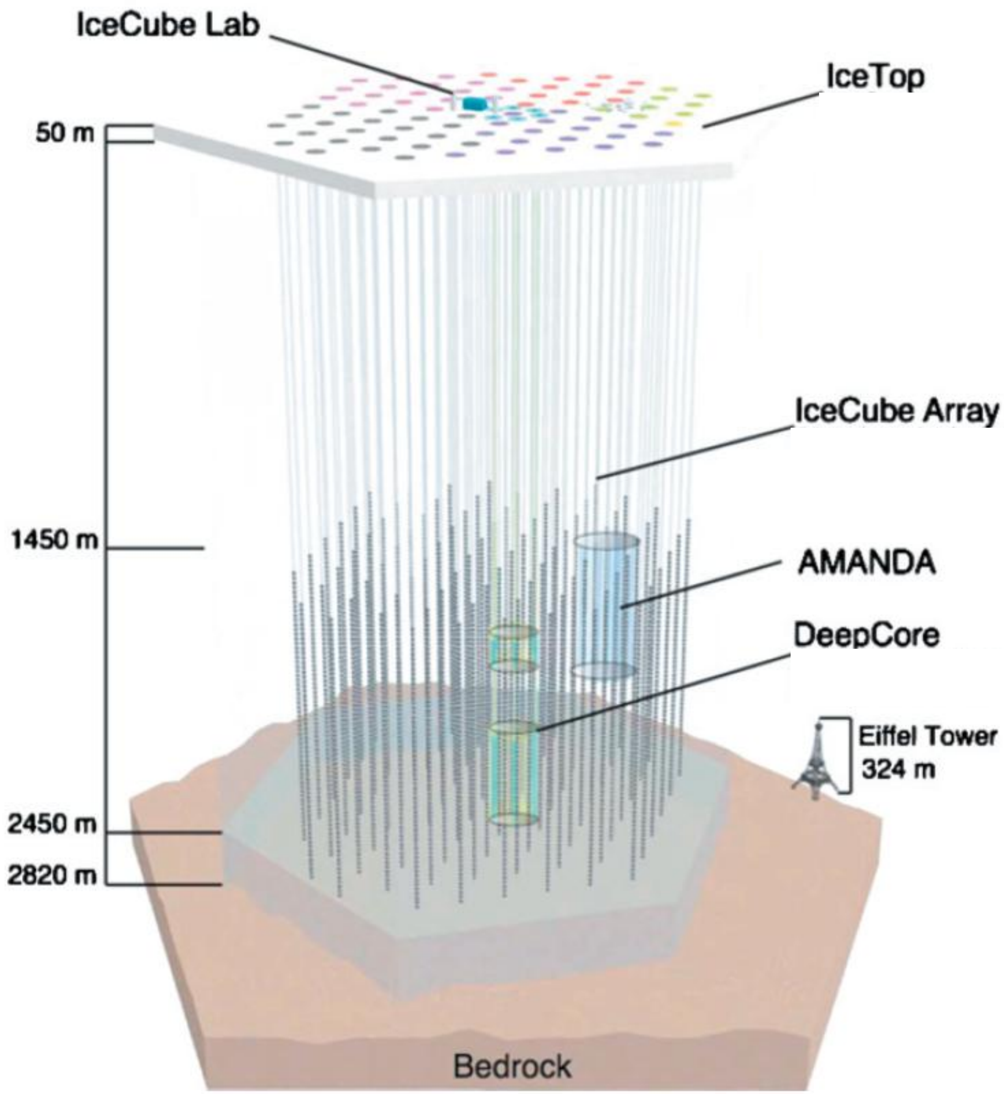
$$H_{I,NSI} = V_{cc}\begin{pmatrix}1+\epsilon_{ee} & |\epsilon_{e\mu}|e^{i\delta_{e\mu}} & |\epsilon_{e\tau}|e^{i\delta_{e\tau}}\\ |\epsilon_{e\mu}|e^{-i\delta_{e\mu}} & \epsilon_{\mu\mu} & |\epsilon_{\mu\tau}|e^{i\delta_{\mu\tau}}\\ |\epsilon_{e\tau}|e^{-i\delta_{e\tau}} & |\epsilon_{\mu\tau}|e^{-i\delta_{\mu\tau}}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

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

4. NSI: Bounds

- 3 Types of Bounds:
  - Indirect (G_F, CKM unitarity, Pion decay, …)
    - $0.068 < |\epsilon_{\alpha\beta}| \quad \text{to} \quad |\epsilon_{\alpha\beta}| < 21$ — Biggio *et al.* arXiv:0907.0097 [hep-ph]
  - Simplified, one NSI/one experiment analysis (SuperK, Minos, …)
    - $0.033 < |\epsilon_{\alpha\beta}| \quad \text{to} \quad |\epsilon_{\alpha\beta}| < 0.2$ — Adamson *et al.* arXiv:1303.5314 [hep-ex]; Mitsuka *et al.* arXiv:1109.1889 [hep-ex]
  - Global Fit To Oscillation Data (3σ)
    - $0.03 < |\epsilon_{\alpha\beta}^{u,d}| \quad \text{to} \quad |\epsilon_{\alpha\beta}^{u,d}| < 0.71$ — Gonzalez-Garcia *et al.* arXiv:1307.3092 [hep-ph]
- NSI are constrained at the **1% to 10%** level
  - Believable (not too big)
  - Experimentally reachable (not too small)

4. NSI: Experimental Context: ICDC



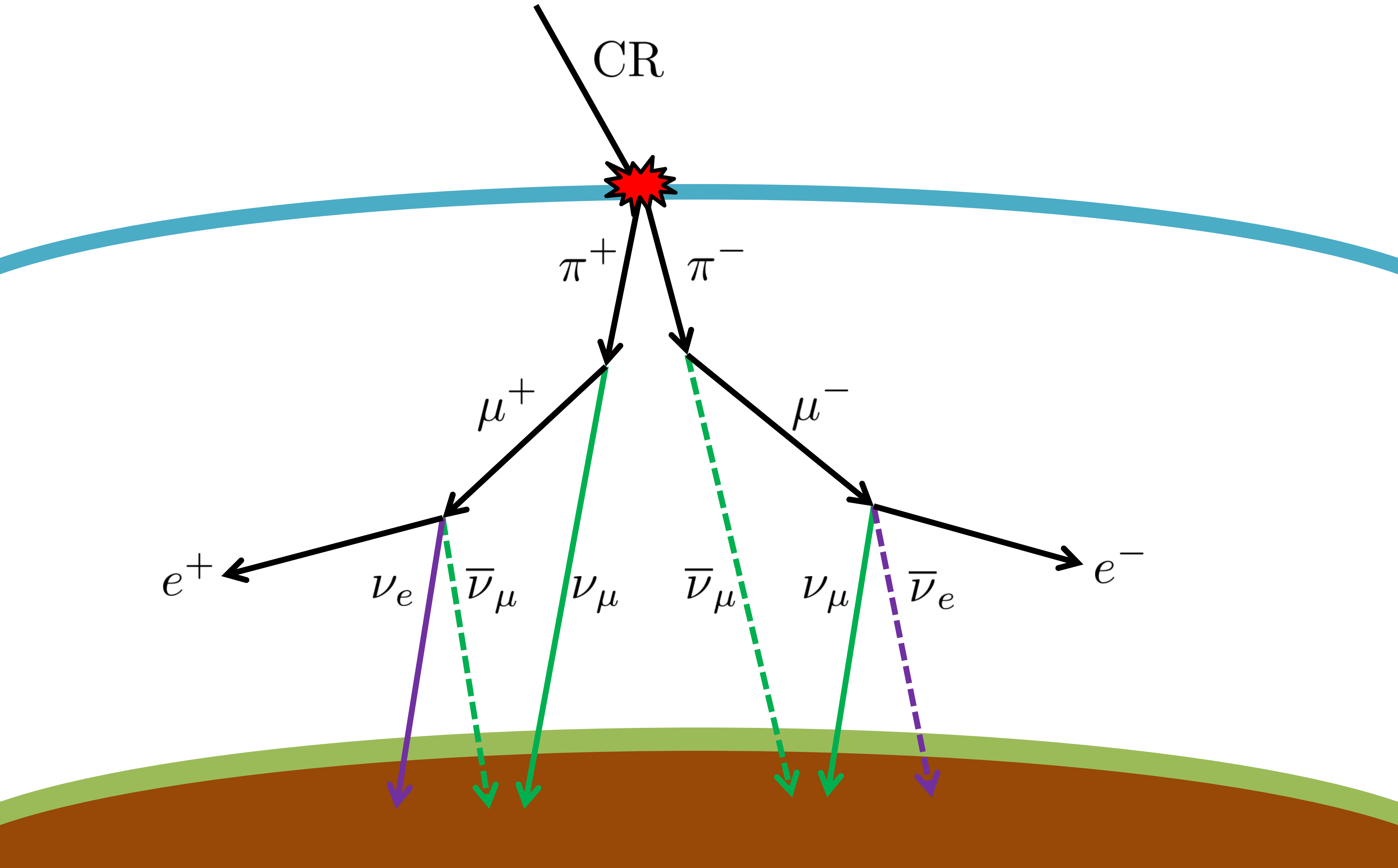
High Statistics

Muon tracks

E>6GeV

IceCube Science Team - Francis Halzen, Dept of Physics, University of Wisconsin

4. NSI: ICDC – Atmospheric Neutrinos



4. NSI: ICDC – Number of Muons

$$N_\mu\left(\Delta E_\mu, \Delta\theta\right) =$$

$$2\pi t N_A \int_{E_{\mu,i}}^{E_{\mu,f}} dE_\mu \int_{\theta_i}^{\theta_f} \sin\theta d\theta \int_{E_\mu}^{\infty} dE_\nu M\left(E_\nu\right) \frac{\partial\sigma_{\nu_\mu}^{CC}}{\partial E_\nu}\left(E_\nu, E_\mu\right)$$

$$\times\left(\frac{\partial^2\phi_{\nu_\mu}\left(E_\nu,\theta\right)}{\partial E_\nu \partial\theta} P_{\mu\mu}\left(E_\nu,\theta\right) + \frac{\partial^2\phi_{\nu_e}\left(E_\nu,\theta\right)}{\partial E_\nu \partial\theta} P_{e\mu}\left(E_\nu,\theta\right)\right)$$

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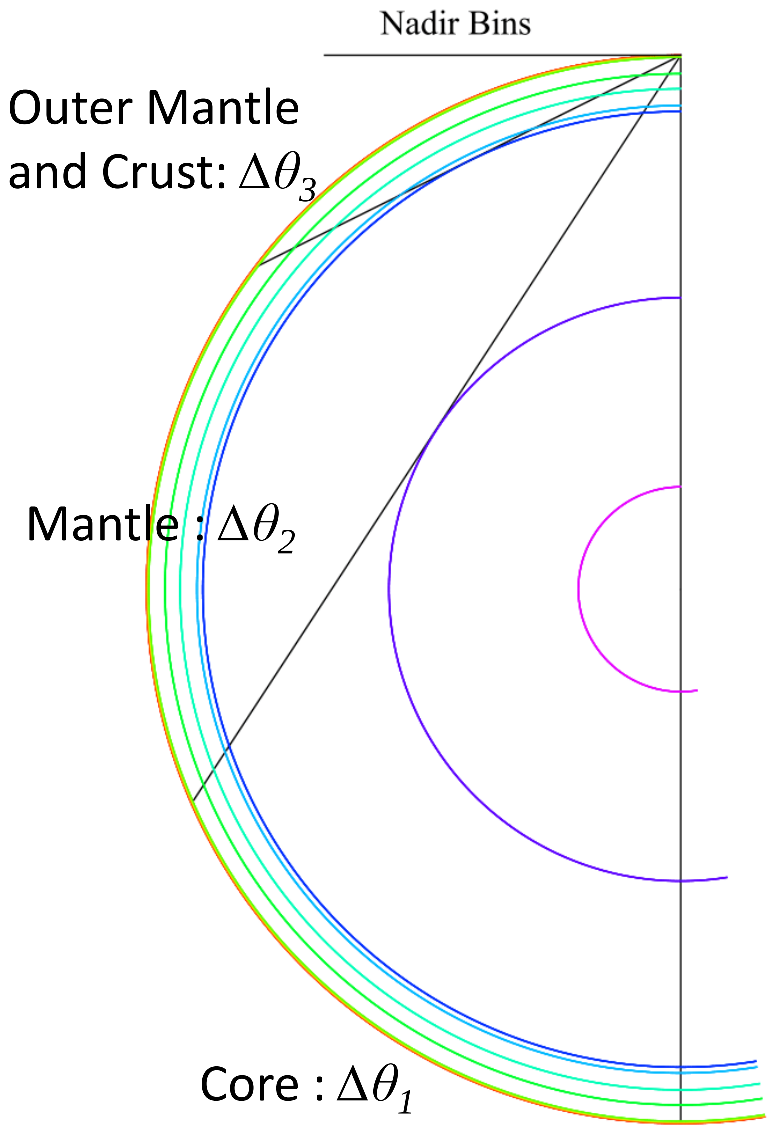
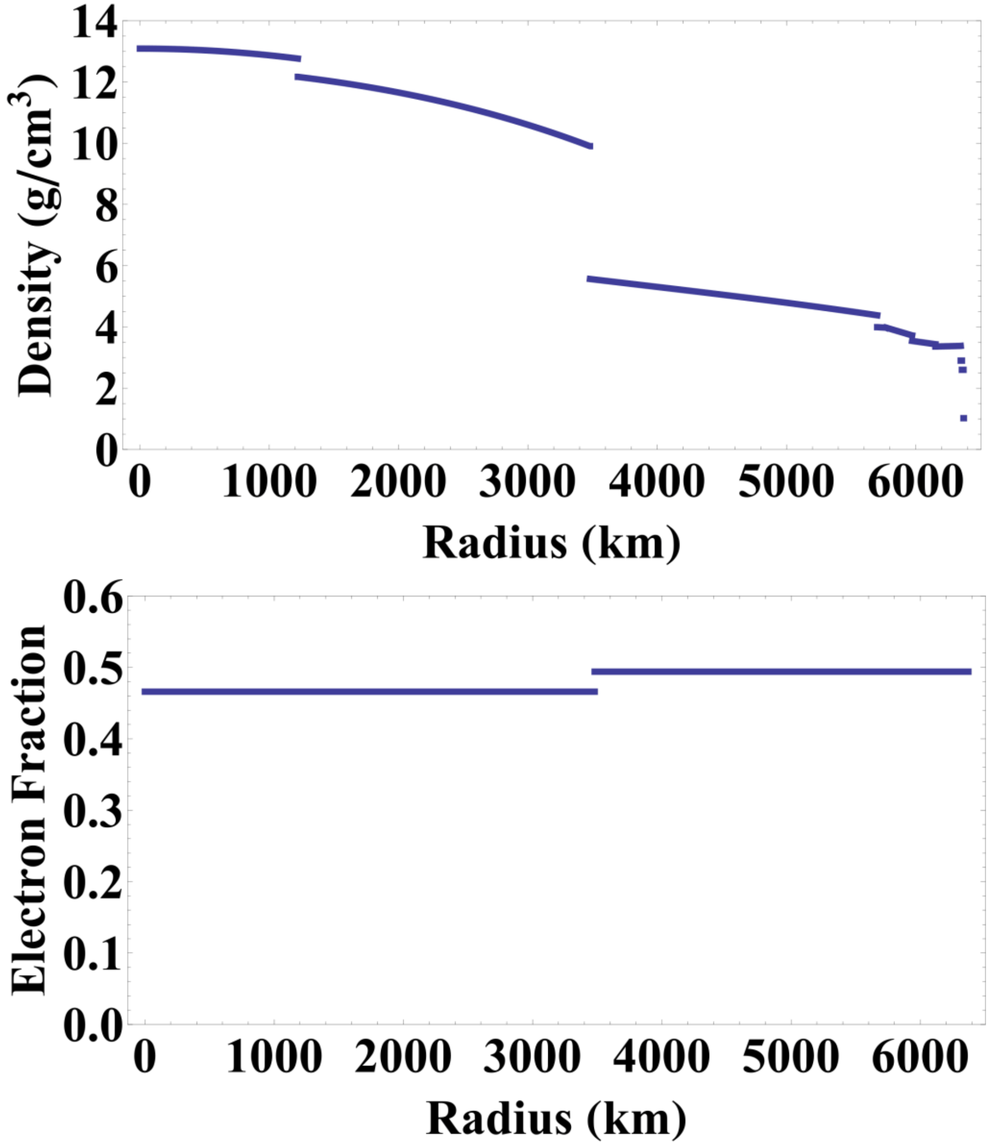
- <u>Detector mass:</u>
  IceCube Collaboration. arXiv:1109.6096 [astro-ph]
- <u>Cross Section:</u>
  GQRS. arXiv:9512364 [hep-ph]
- <u>Atmospheric Neutrino Flux:</u>
  Honda *et al.* arxiv:0611418 [astro-ph]

4. NSI: ICDC – PREM



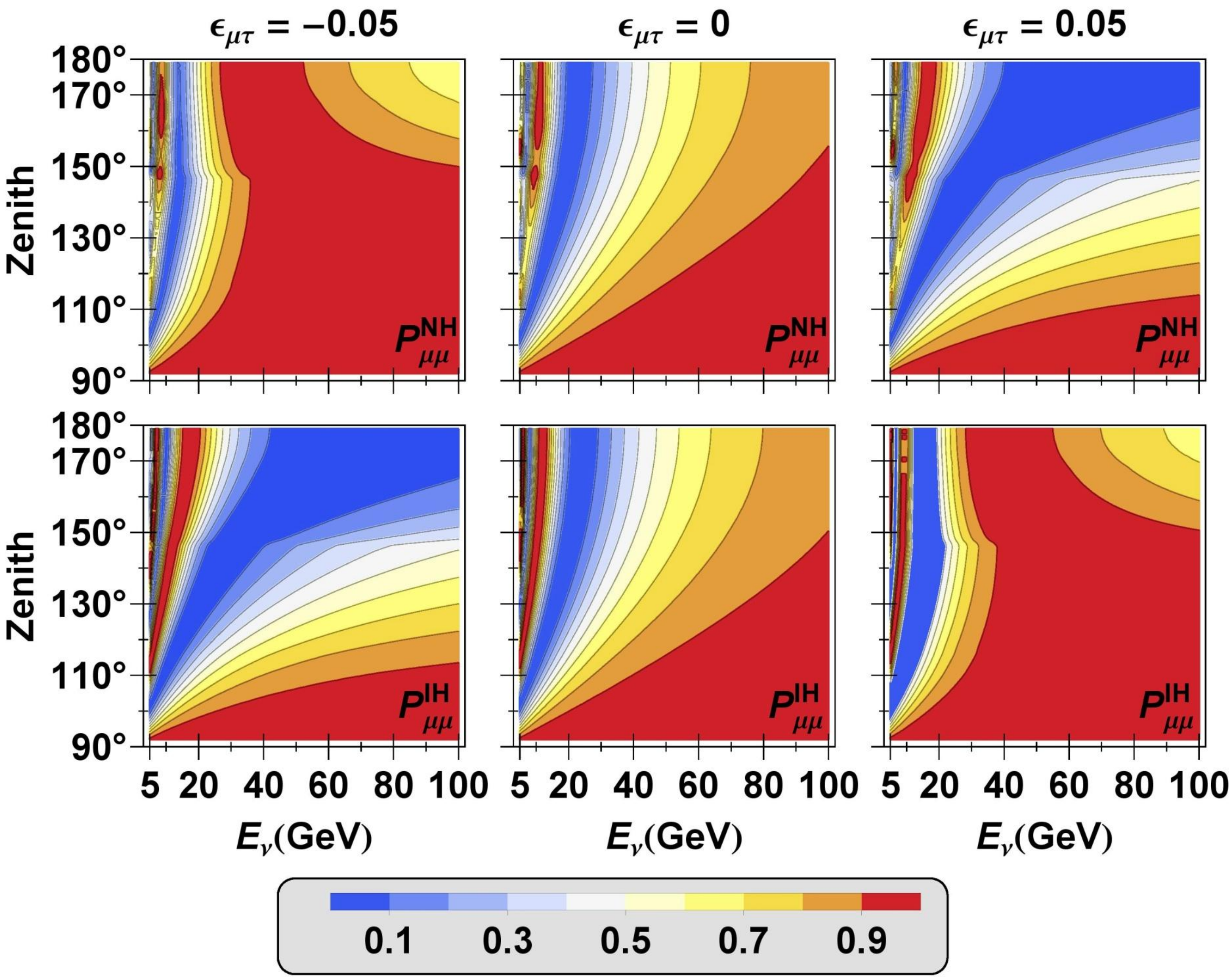


Dziewonski *et al.* Phys. Earth Planet. Inter., **25** (1981), 297

Outline: One NSI

1. Neutrino Introduction
2. Standard Oscillation Framework
3. Open Questions
4. Non Standard Interactions
5. **One NSI Parameter**
6. Many NSI Parameters
7. Next Steps

5. One NSI: Oscillation Probability



I. Mocioiu & W. Wright. arXiv: 1410.6193 [hep-ph]

5. One NSI: Analytics

$$\begin{aligned}
\Delta m^2_{21} &= \theta_{12} = \theta_{13} = \delta_{cp} = \epsilon_{\alpha\beta\neq\mu\tau} = \delta_{\mu\tau} = 0 \\
\theta_{23} &= \pi/4 \\
H &= \begin{pmatrix} V_{cc} - \frac{\Delta m^2_{31}}{4E_\nu} & 0 & 0 \\ 0 & 0 & \frac{\Delta m^2_{31}}{4E_\nu} + V_{cc}\epsilon_{\mu\tau} \\ 0 & \frac{\Delta m^2_{31}}{4E_\nu} + V_{cc}\epsilon_{\mu\tau} & 0 \end{pmatrix} \\
P_{\mu\mu} &= \cos^2\left(L\left(\frac{\Delta m^2_{31}}{4E_\nu} + V_{cc}\epsilon_{\mu\tau}\right)\right)
\end{aligned}$$

5. One NSI: Analytics

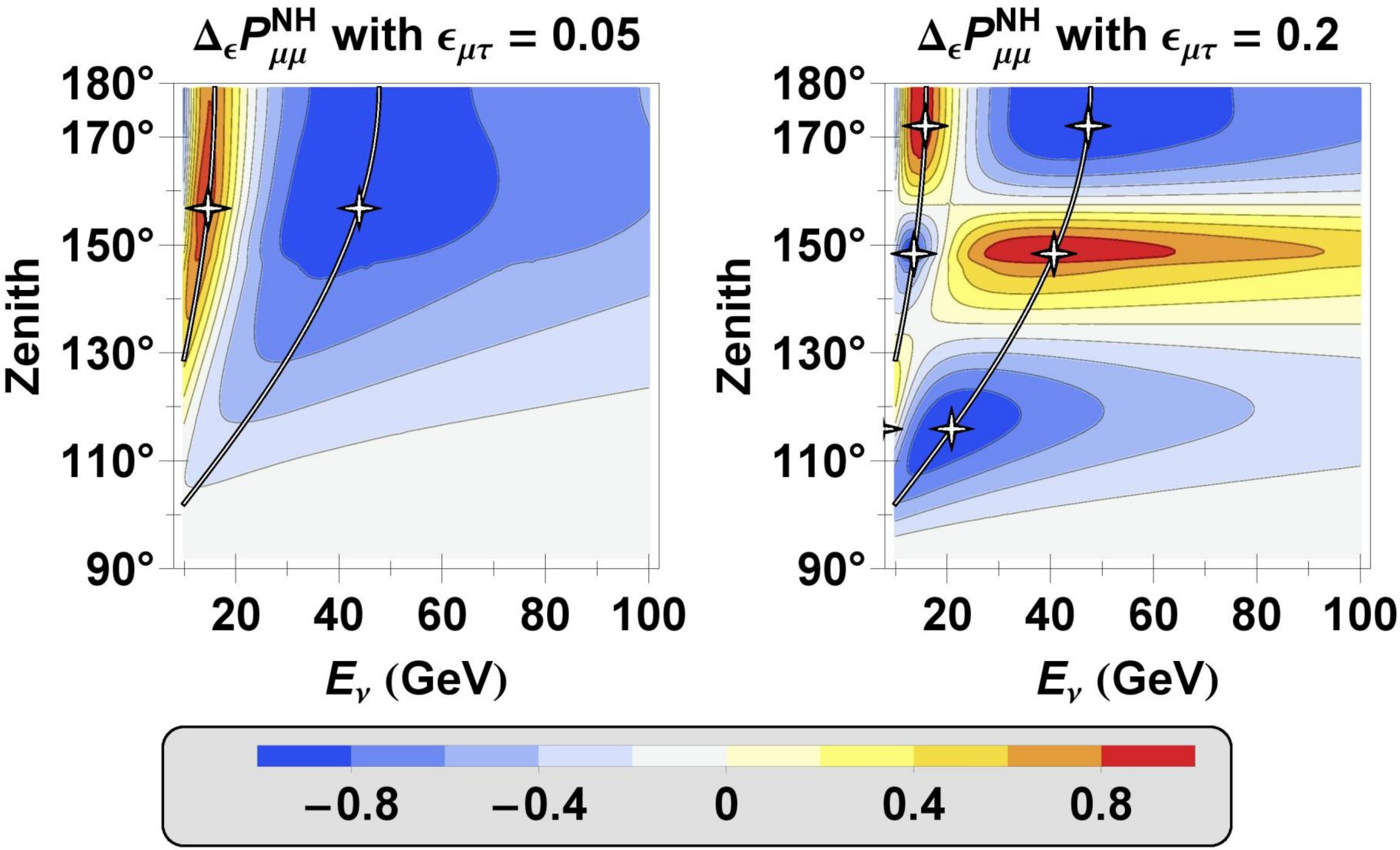
$$\Delta_\epsilon P_{\mu\mu} = P_{\mu\mu}\left(\epsilon_{\mu\tau}\right) - P_{\mu\mu}\left(-\epsilon_{\mu\tau}\right)$$

$$E_\nu = \left(\frac{2m+1}{2n+1}\right)\frac{\Delta m^2_{31}}{4V_{cc}\epsilon_{\mu\tau}}$$

$$L = \frac{(2m+1)\,\pi}{4V_{cc}\epsilon_{\mu\tau}}$$

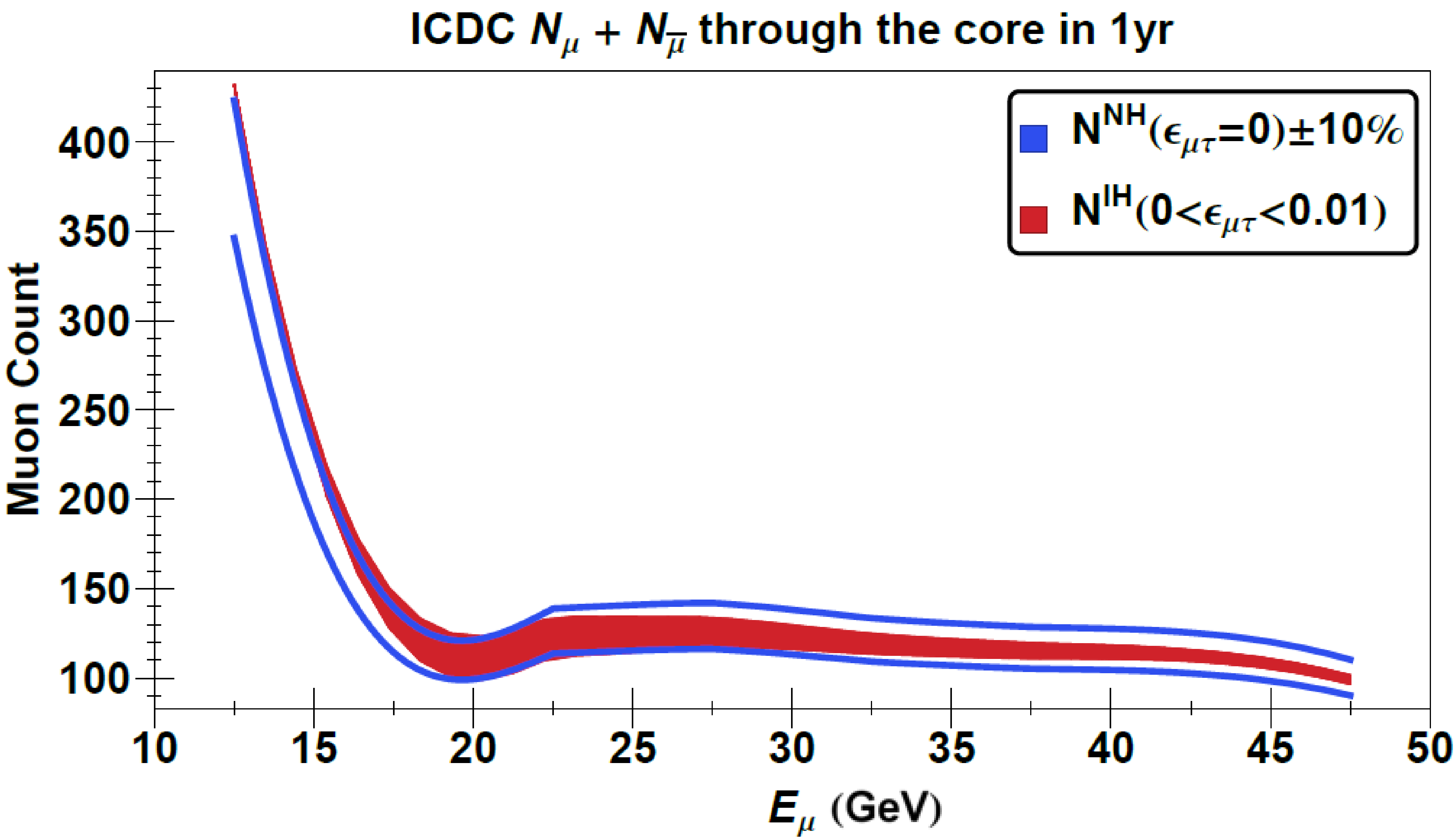
$$\frac{L}{E_\nu} = \frac{(2n+1)\,\pi}{\Delta m^2_{31}}, \text{ Where } n, m \in \mathbb{Z} \text{ and } n \geq 0$$

5. One NSI: Analytical vs. Numerical



I. Mocioiu & W. Wright. arXiv: 1410.6193 [hep-ph]

5. One NSI: Mass Hierarchy Implications



I. Mocioiu & W. Wright. arXiv: 1410.6193 [hep-ph]

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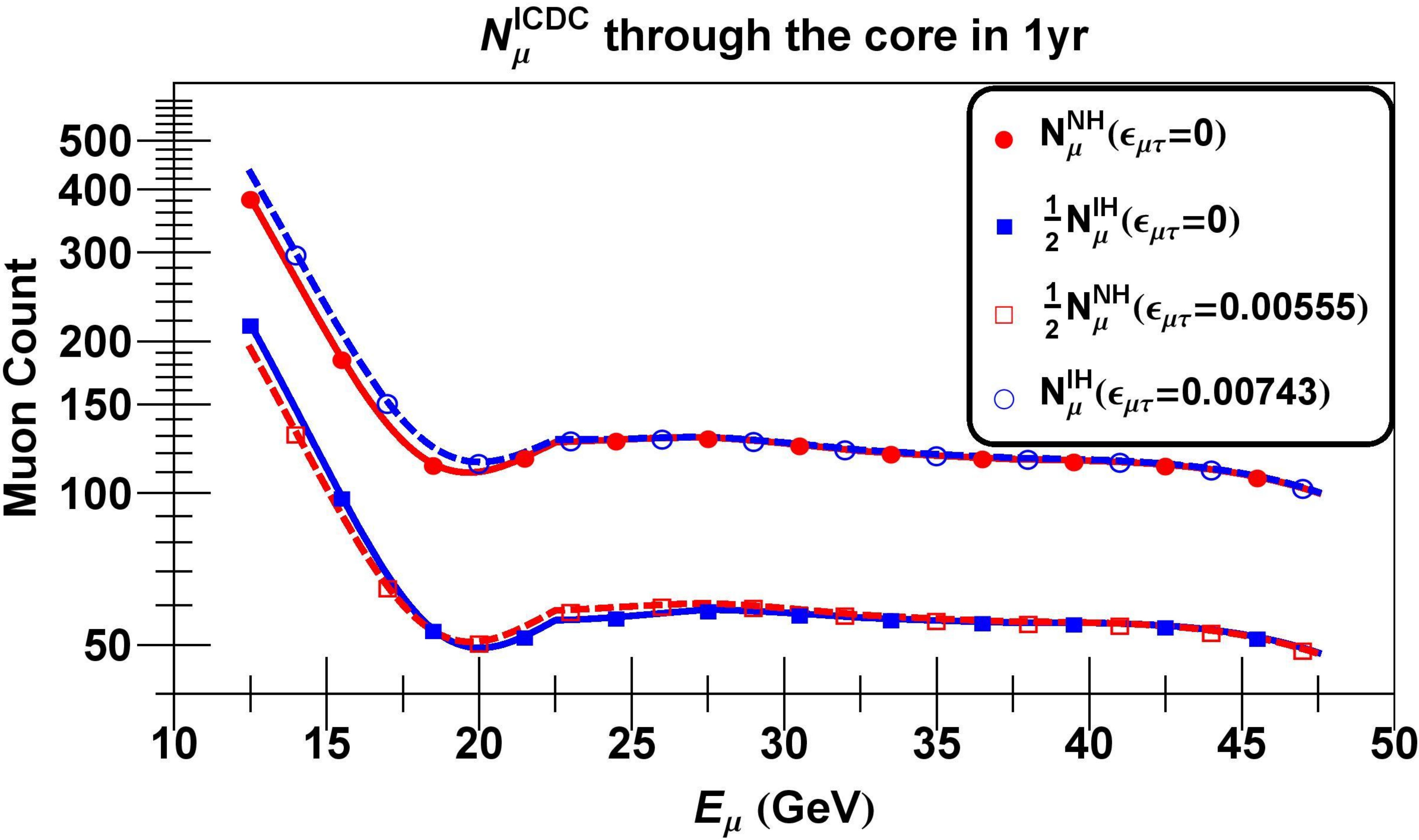
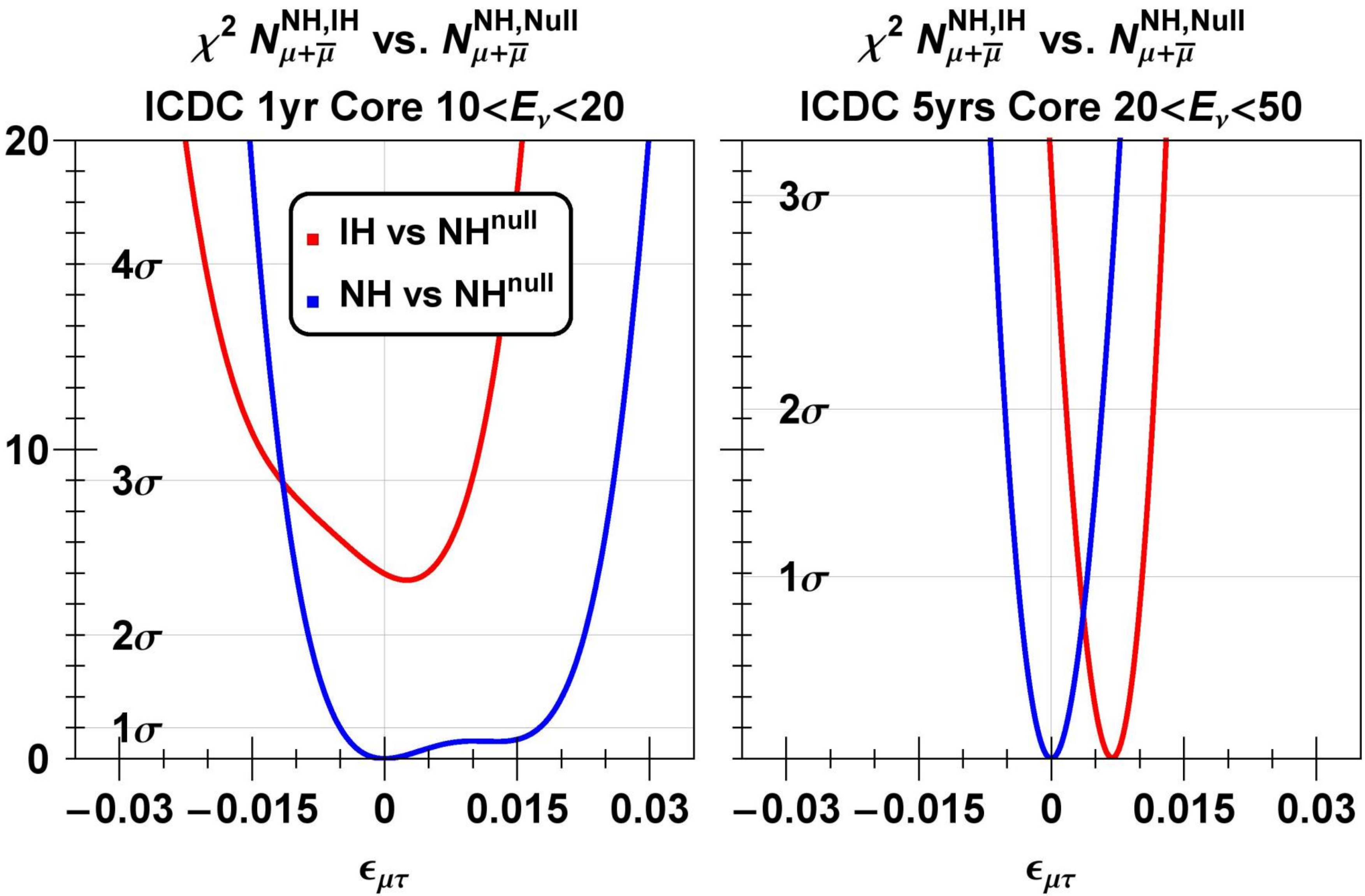


I. Mocioiu & W. Wright. arXiv: 1410.6193 [hep-ph]

5. One NSI: Chi Squared



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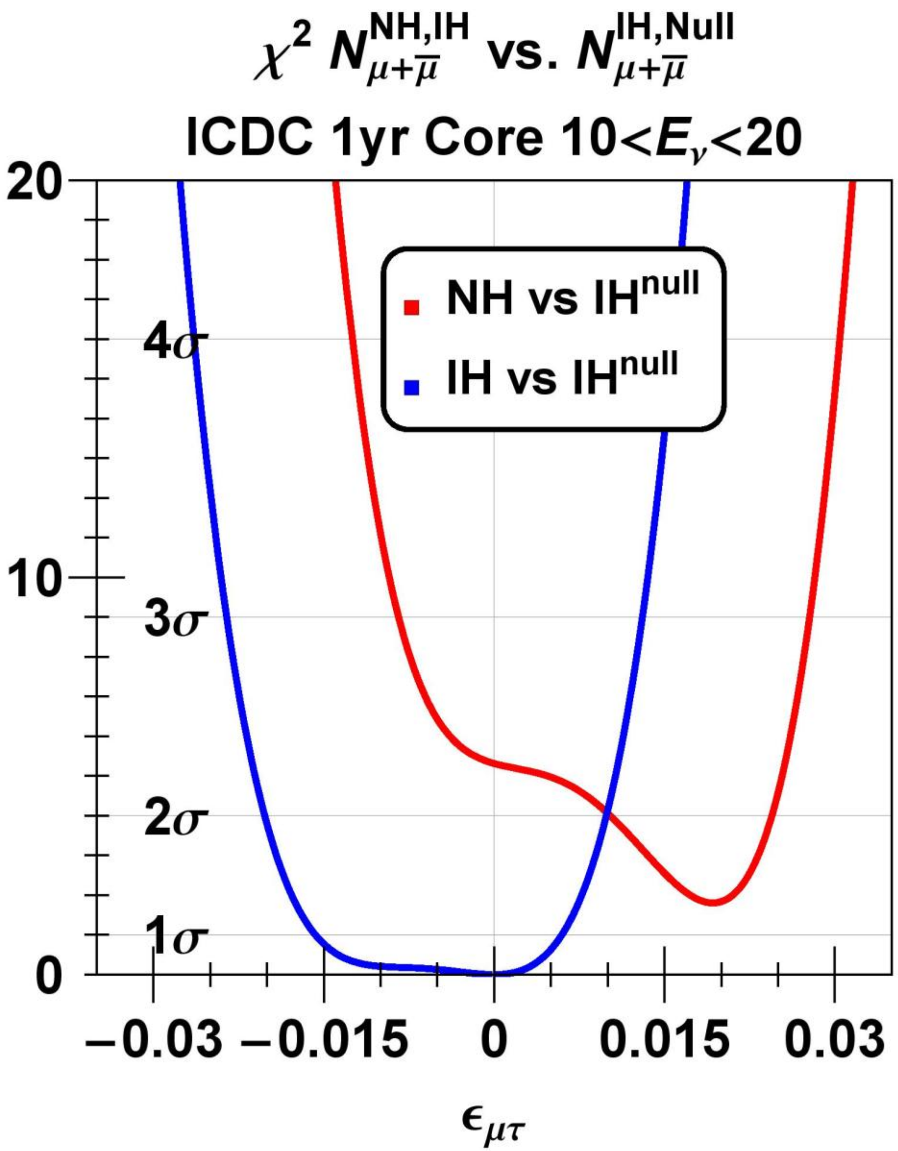

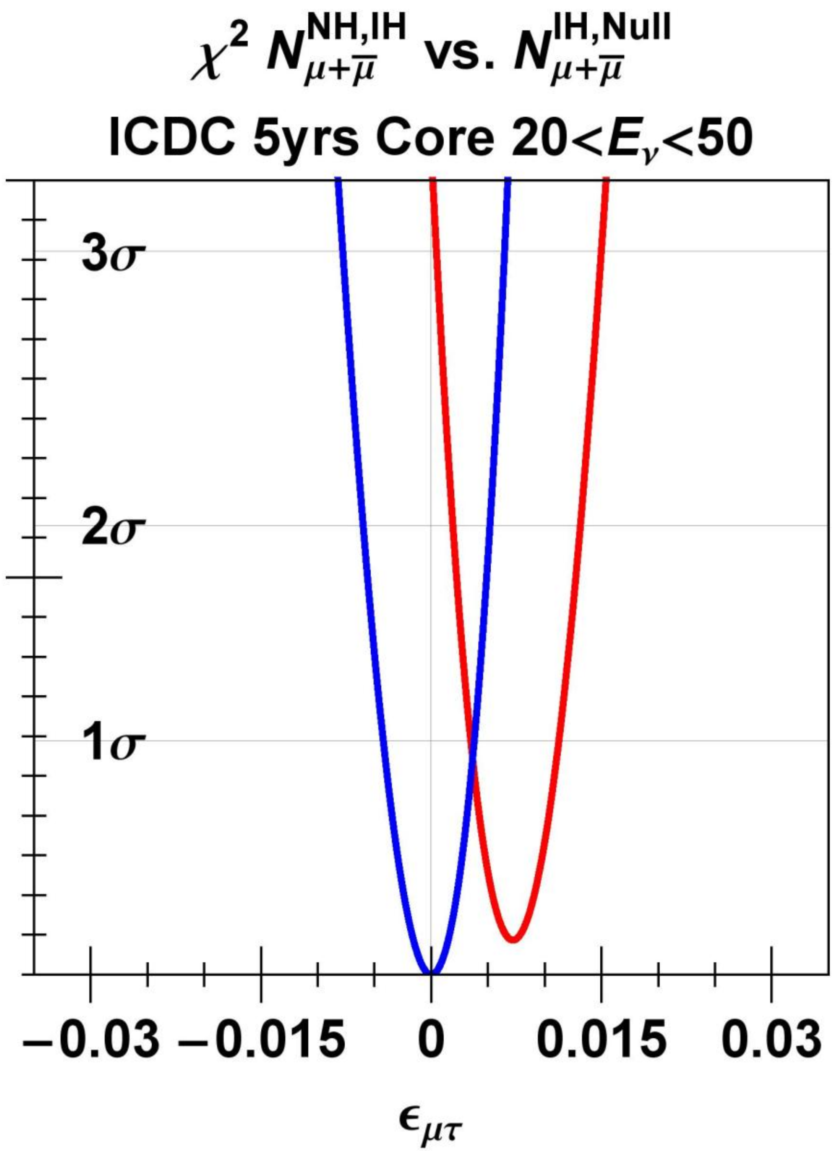

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5. One NSI: Summary

- Non standard neutrino interactions:
  - are important for the investigation of new physics
  - have significant effects on Neutrino Oscillation
- $\epsilon_{\mu\tau}$ is sign asymmetric (unlike other NSI)
  - Seen in numerical results
  - Well described by analytical solutions
- This asymmetry has mass hierarchy implications
  - Partial degeneracy between $\epsilon_{\mu\tau}$ and mass hierarchy
  - Potential for Hierarchy misidentification
  - Can separate effects with careful energy bin choices

Outline: Many NSI

1. Neutrino Introduction
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6. **Many NSI Parameters**
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6. Many NSI: Analytics

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

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

$$T = \begin{pmatrix} c_\beta & 0 & -s_\beta \\ 0 & 1 & 0 \\ s_\beta & 0 & c_\beta \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 0 & \frac{-1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

$$H' = \begin{pmatrix} H'_{11} & m-n & m+n \\ m-n & a-b & g \\ m+n & g & a+b \end{pmatrix}$$

$$n = 0 \Rightarrow \tan(2\beta) = \frac{2\left(V_{cc}\epsilon_{e\tau} + \Delta s_{2\cdot 13} c_{23}\right)}{V_{cc}\left(1 + \epsilon_{ee} - \epsilon_{\tau\tau}\right) + 2\Delta\left(s^2_{13} - c^2_{13} c^2_{23}\right)}$$

6. Many NSI: Analytics

$$H'_{11} \gg m \Rightarrow$$

$$H' = \begin{pmatrix} H'_{11} & 0 & 0 \\ 0 & a-b & g \\ 0 & g & a+b \end{pmatrix}$$

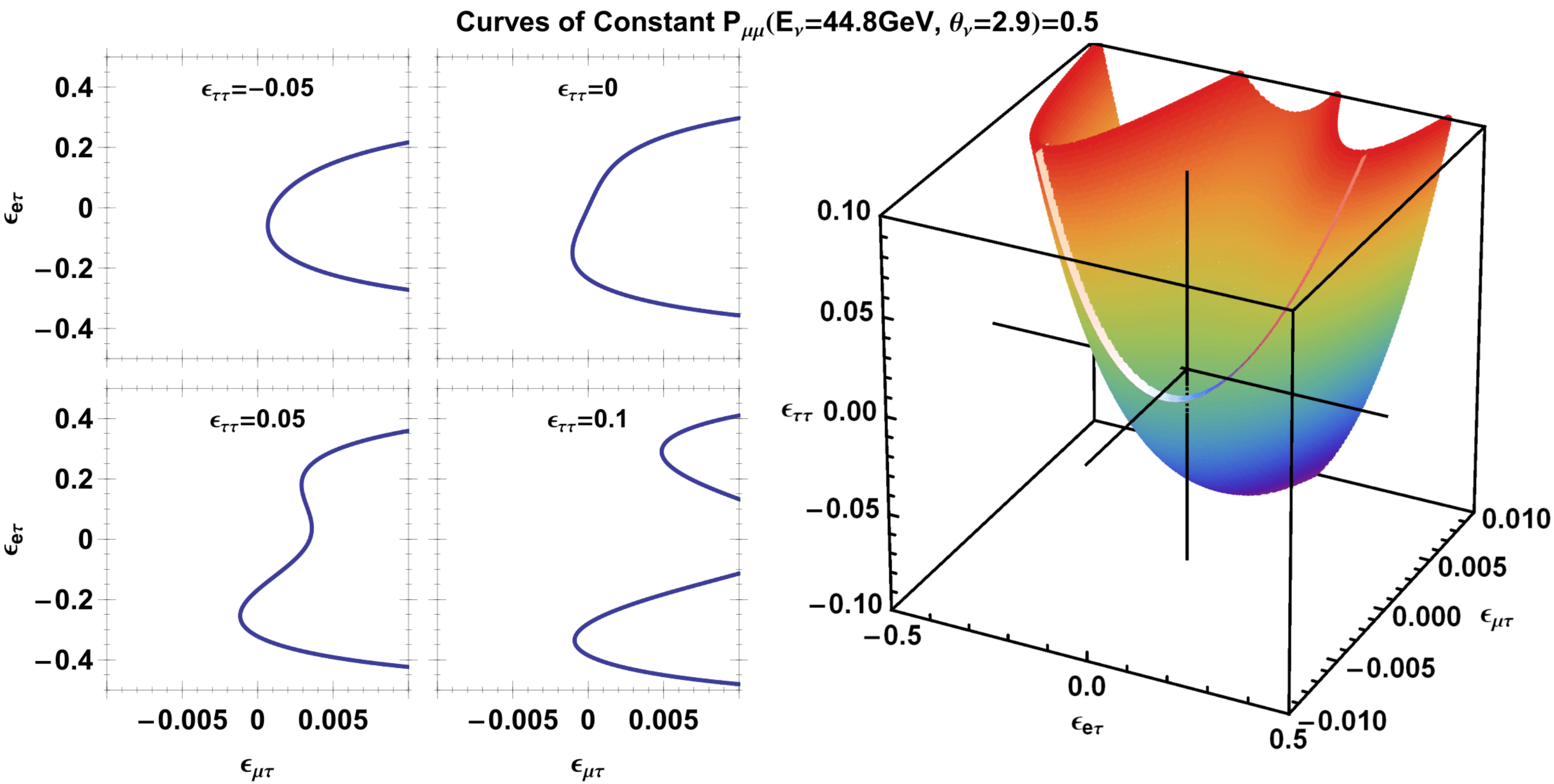
$$P_{\nu_\mu \to \nu_\mu} = 1 - \sin^2\left(\sqrt{b^2+g^2}L\right)\frac{b^2}{b^2+g^2}$$

$$b = V_{cc}\epsilon_{\mu\tau}c_\beta + \Delta(c_{13}^2 s_{2\cdot 23}c_\beta - s_{23}s_{2\cdot 13}s_\beta)$$

$$g = \frac{1}{2}V_{cc}\left(\epsilon_{\mu\mu} - (1+\epsilon_{ee})s_\beta^2 - \epsilon_{\tau\tau}c_\beta^2 + \epsilon_{e\tau}s_{2\beta}\right)$$

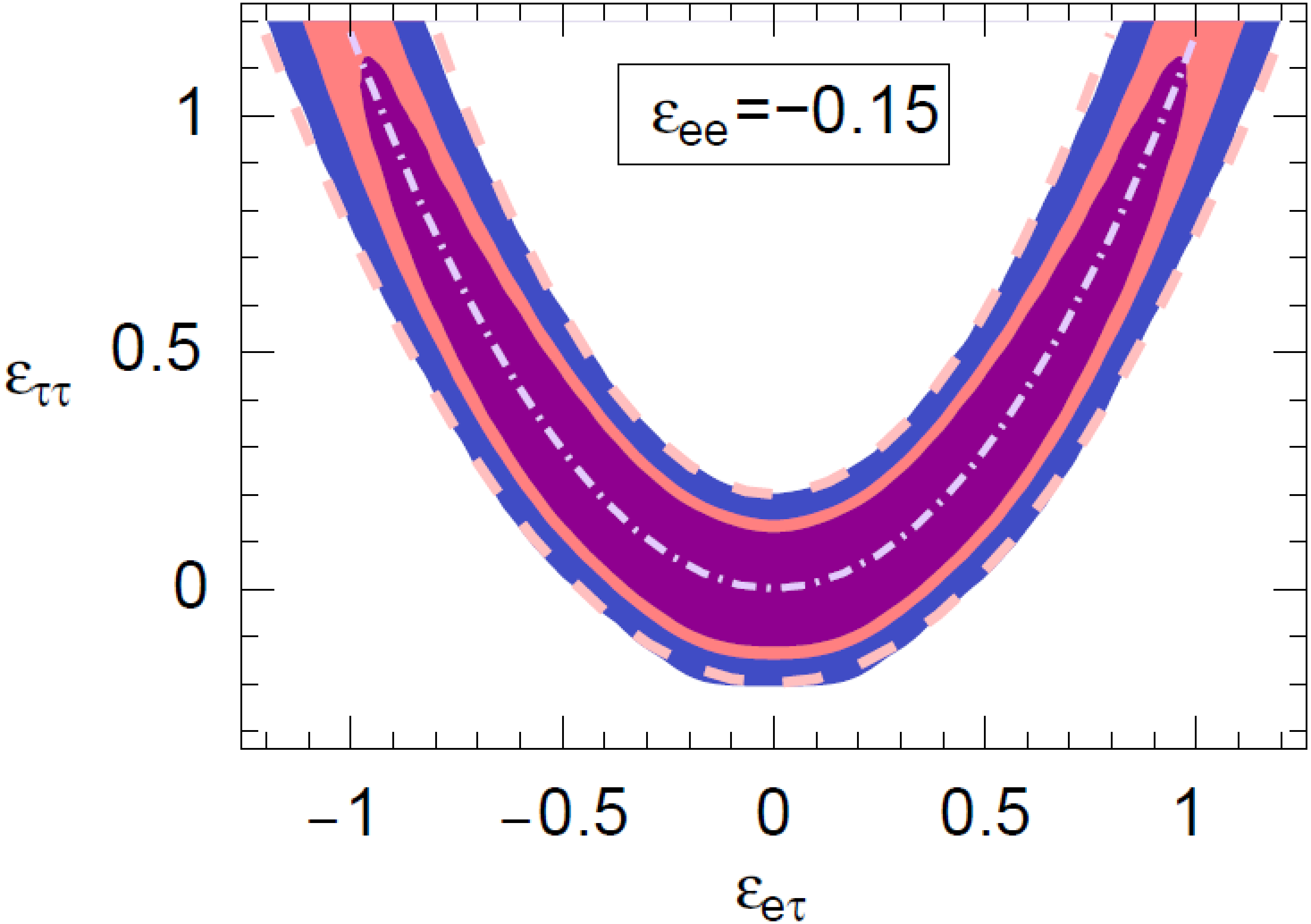
$$+ \Delta\left(c_{13}^2 s_{23}^2 - (c_{13}c_{23}c_\beta - s_{13}s_\beta)^2\right)$$

6. Many NSI: Oscillation Probability



I. Mocioiu & W. Wright. arXiv: 1508.xxxx [hep-ph]

6. Many NSI: Oscillation Probability



Friedland, Lunardini & Maltoni arXiv:hep-ph/0408264v2

6. Many NSI: Analytics: Extrema

MSW resonance at $g = 0 \Rightarrow$

$$\epsilon_{\tau\tau} \approx \frac{\left(\epsilon_{e\tau} + \ldots\right)^2}{\epsilon_{ee} - \epsilon_{\mu\mu} + \ldots} + \epsilon_{\mu\mu} + \ldots$$

$$\ldots = \text{Terms made up of: } \Delta, V_{cc}, \theta_{13} \& \theta_{23}$$

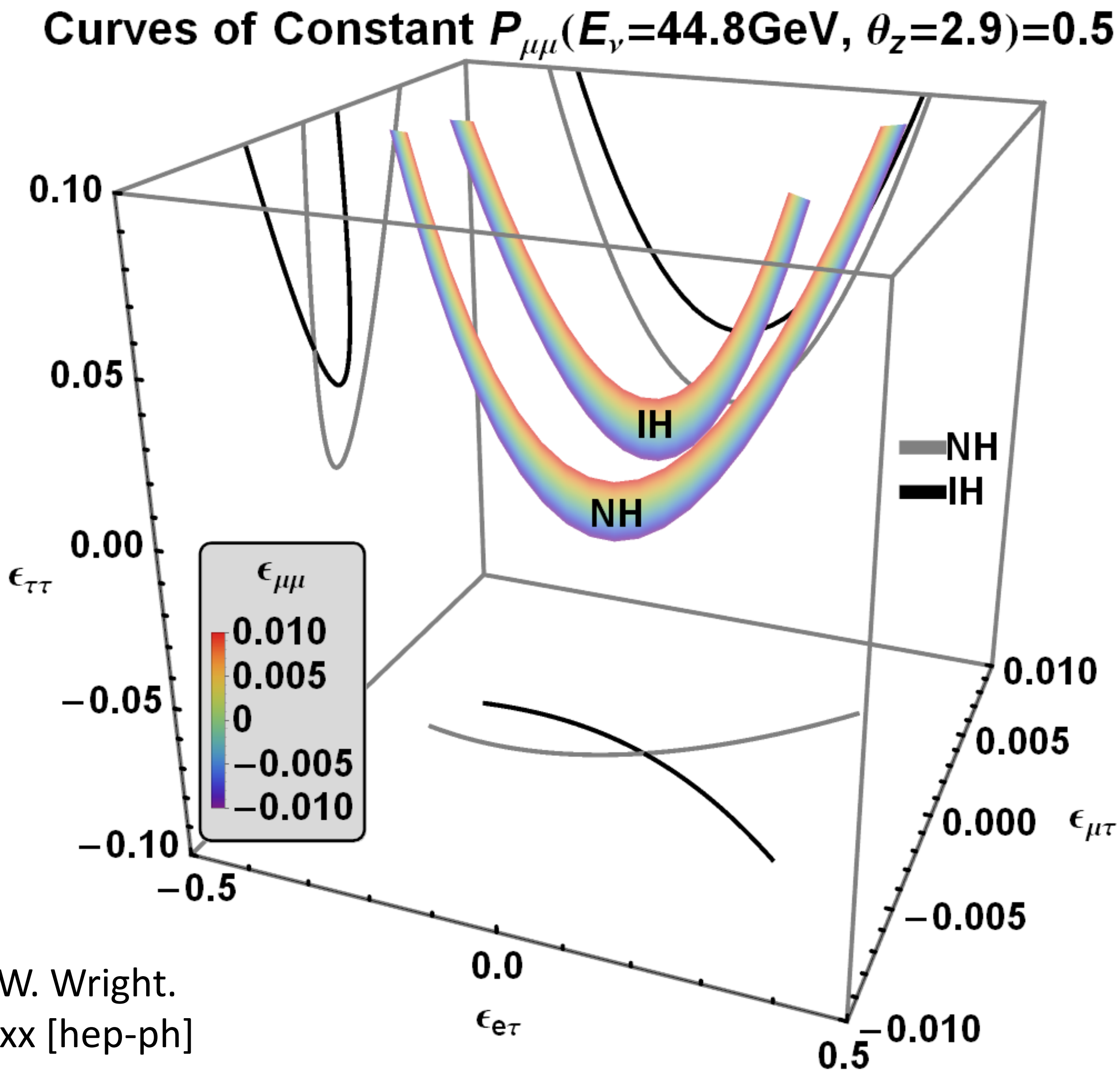
$$P_{\nu_\mu \to \nu_\mu} = 1 - \sin^2(bL) = 1 - \sin^2(\Phi) \quad \therefore b = \Phi/L \Rightarrow$$

$$\epsilon_{\mu\tau} \approx \frac{\epsilon_{e\tau} + \ldots}{\epsilon_{ee} - \epsilon_{\mu\mu} + \ldots}(\ldots) \pm \frac{\Phi}{L}\sqrt{1 + \left(\frac{\epsilon_{e\tau} + \ldots}{\epsilon_{ee} - \epsilon_{\mu\mu} + \ldots}\right)^2}$$

$$\Phi = \sin^{-1}\left(\sqrt{1 - P_{\mu\mu}\left(E_\nu, \theta_\nu, \text{All } \epsilon = 0\right)}\right)$$

$$\therefore \text{ for given } \left(E_\nu, \theta_\nu, \epsilon_{ee}, \epsilon_{\mu\mu}\right) : \vec{\Gamma}\left(\epsilon_{e\tau}\right) = \left\{\epsilon_{e\tau}, \epsilon_{\mu\tau}, \epsilon_{\tau\tau}\right\}$$

6. Many NSI: Parameter Selection



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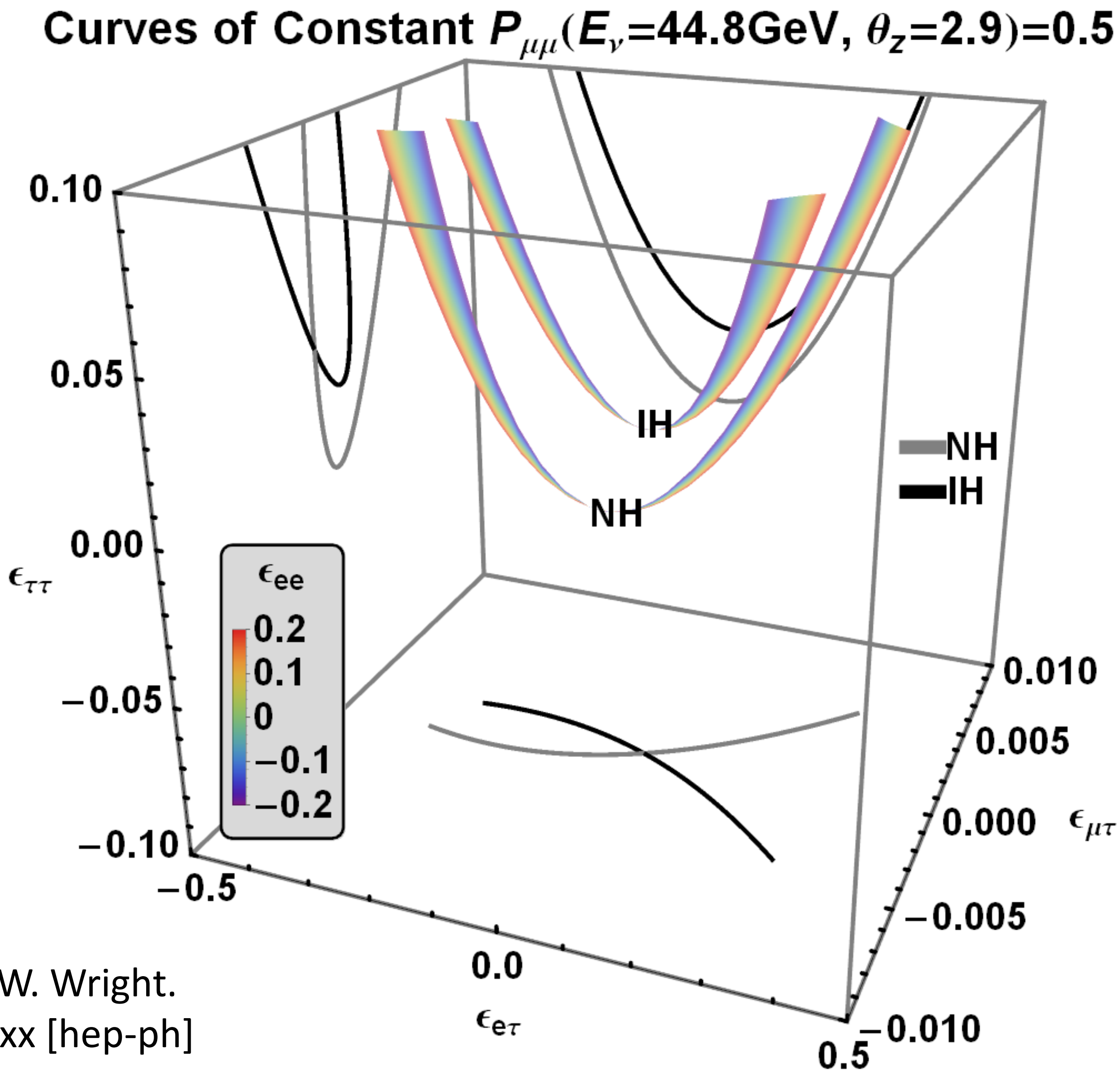

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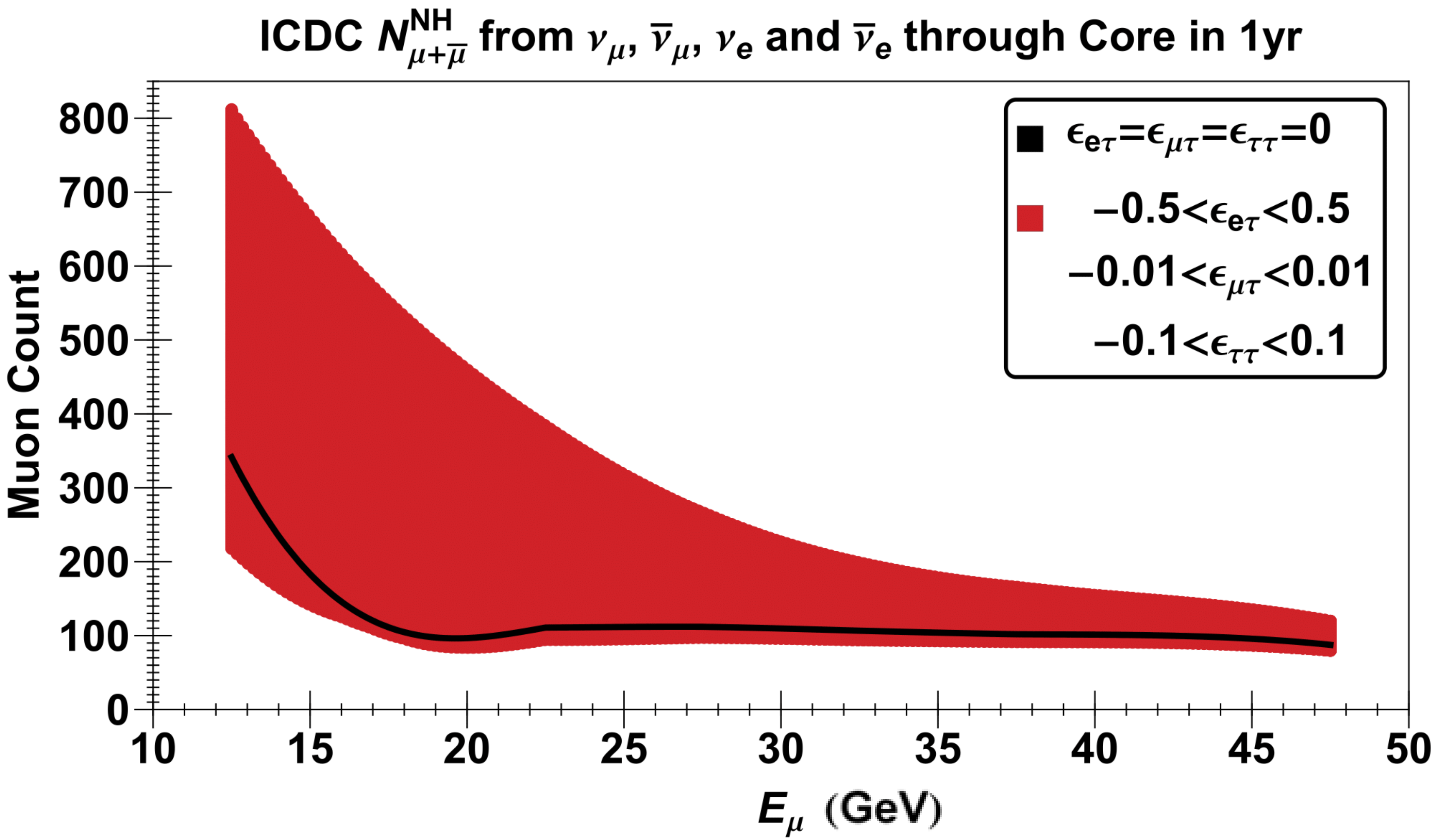
6. Many NSI: Muons at ICDC



I. Mocioiu & W. Wright. arXiv: 1508.xxxx [hep-ph]

6. Many NSI: Chi Squared

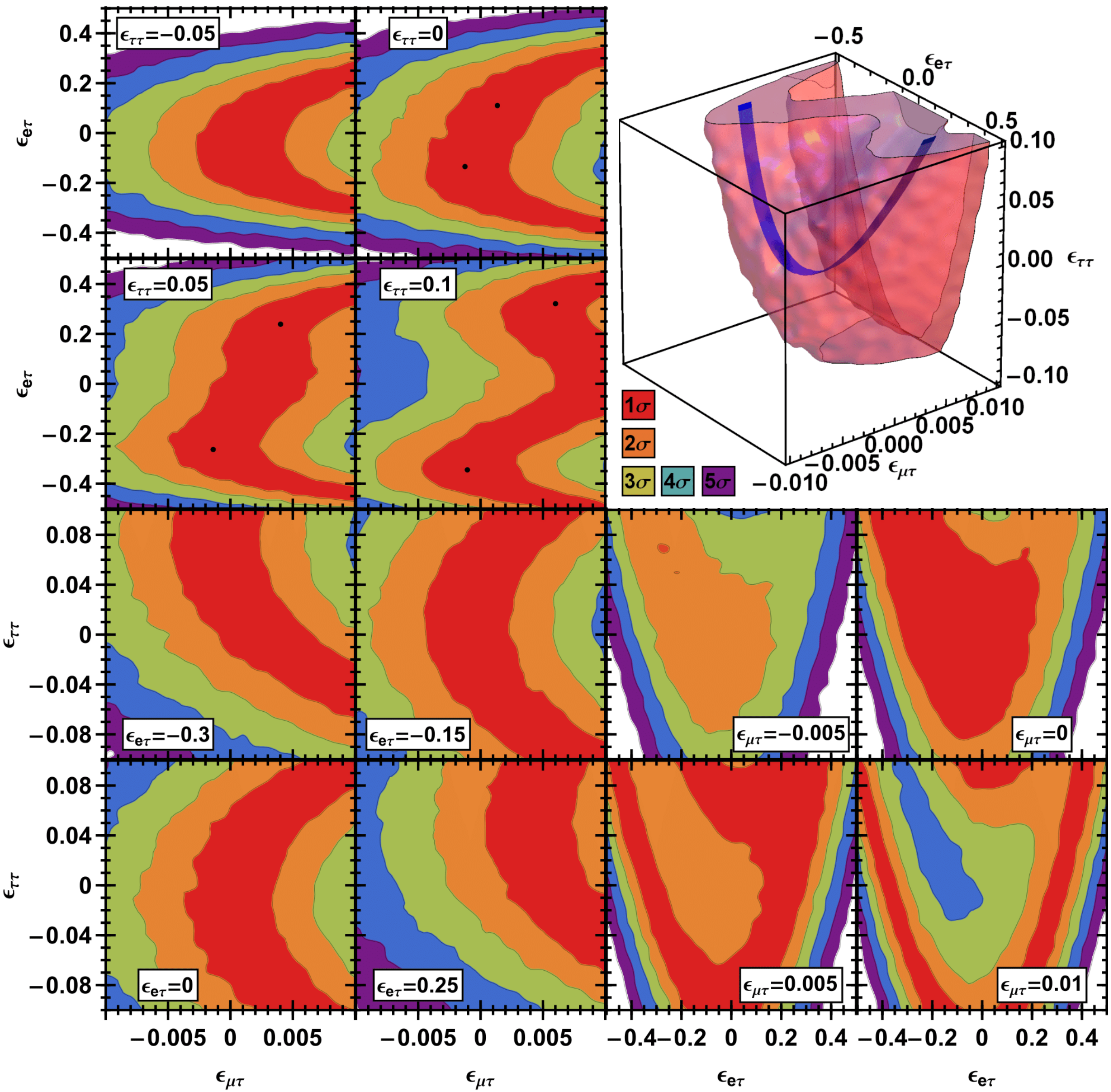
$$\chi^2\left(\epsilon_{e\tau},\epsilon_{\mu\tau},\epsilon_{\tau\tau}\right)=\sum_{E_\mu}\frac{\left(N_{\mu+\overline{\mu}}\left(E_\mu,\epsilon_{e\tau},\epsilon_{\mu\tau},\epsilon_{\tau\tau}\right)-N^{\text{Null}}_{\mu+\overline{\mu}}\left(E_\mu\right)\right)^2}{N^{\text{Null}}_{\mu+\overline{\mu}}\left(E_\mu\right)}$$

$$\chi^2_{\text{low}}:E_\mu\in\{20,35\}\ \text{GeV}\ (3\ \text{bins})$$

$$\chi^2_{\text{high}}:E_\mu\in\{35,50\}\ \text{GeV}\ (3\ \text{bins})$$

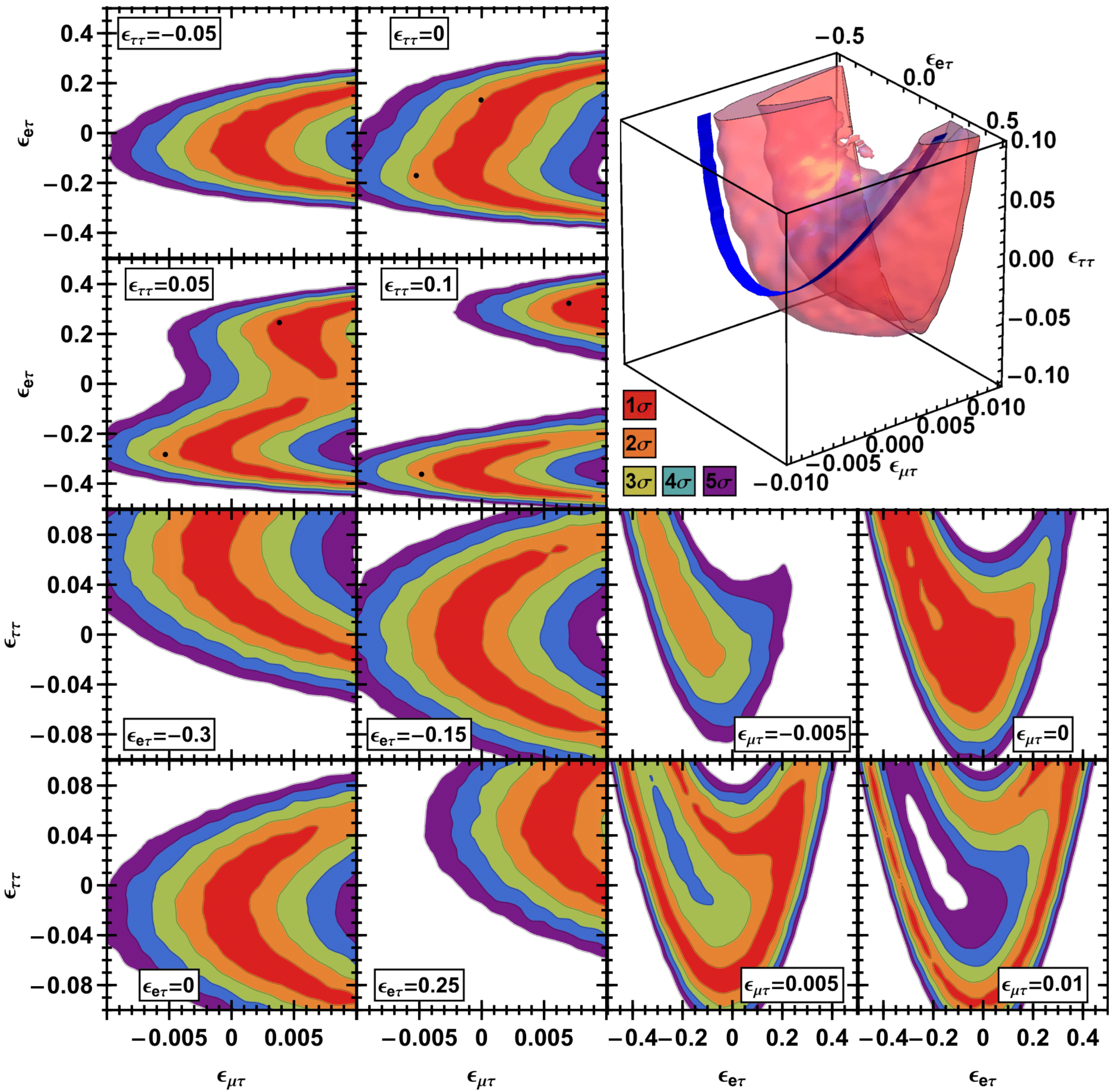
χ^2 from ICDC $N_\mu^{NH,null}$ vs. N_μ^{NH} for High energy ν_μ through Core. Source: $P_{\mu\mu}$ only.

I. Mocioiu & W. Wright. arXiv: 1508.xxxx [hep-ph]

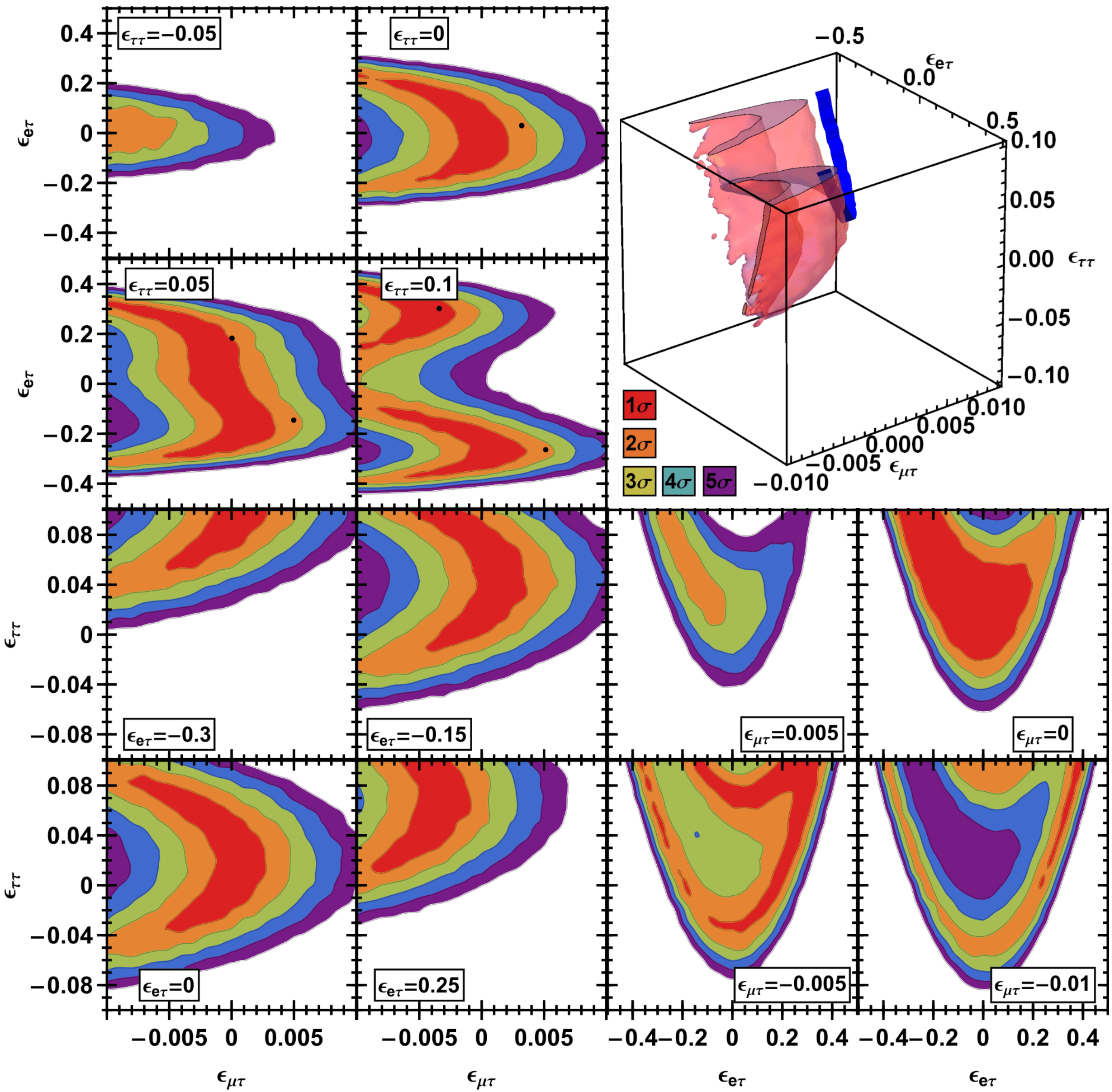


χ^2 from ICDC $N_\mu^{NH, null}$ vs. N_μ^{NH} for low energy ν_μ through Core. Source: $P_{\mu\mu}$ only.

I. Mocioiu & W. Wright. arXiv: 1508.xxxx [hep-ph]



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



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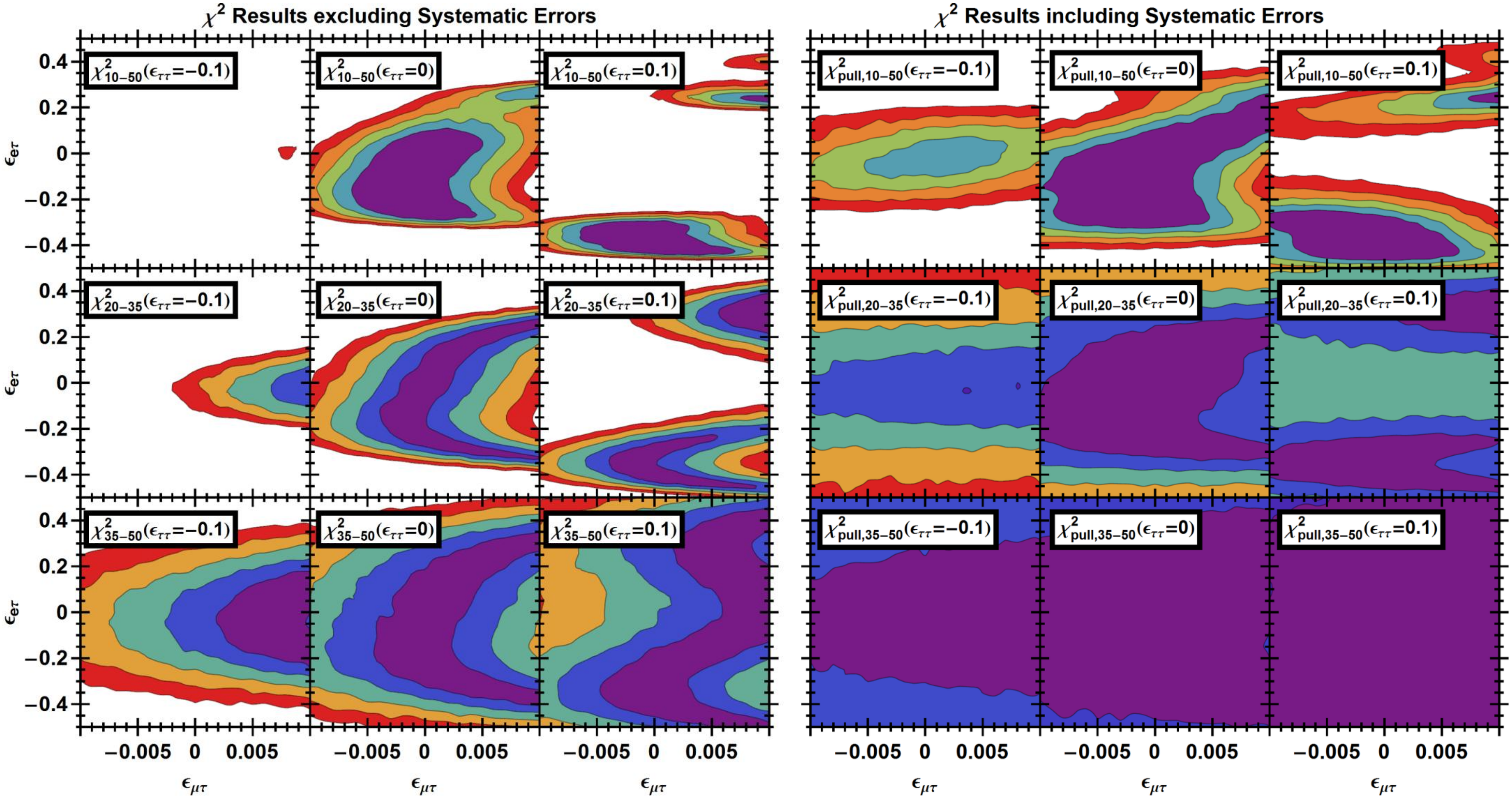
6. Many NSI: Chi Squared

$$\chi^2_{\text{pull}}\left(\epsilon_{e\tau},\epsilon_{\mu\tau},\epsilon_{\tau\tau}\right) = \min_{\{\xi_k\}}\left(\sum_{i=1}^{n}\left(\frac{\left(N^{\text{model}}_{\mu,i}\left(1+\sum_{j=1}^{m}\pi_{ij}\xi_j\right)-N^{\text{null}}_{\mu,i}\right)^2}{N^{\text{null}}_{\mu,i}}\right)+\sum_{j=1}^{m}\xi_j^2\right)$$

$$N^{\text{model}}_{\mu,i} \equiv N^{\text{model}}_{\mu}\left(\epsilon_{e\tau},\epsilon_{\mu\tau},\epsilon_{\tau\tau},\Delta E_{\mu,i}\right)$$

$$N^{\text{null}}_{\mu,i} \equiv N^{\text{null}}_{\mu}\left(0,0,0,\Delta E_{\mu,i}\right).$$

1. **Energy Dependant Flux Uncertainty:** $\pi_{i1} \approx 11\%$ to 17%.
2. **Zenith Dependant Flux Uncertainty:** $\pi_{i2} \approx 5\%$
3. **Normalization Flux Uncertainty:** $\pi_{i3} = 20\%$
4. **Normalization Cross Section Uncertainty:** $\pi_{i4} = 10\%$
5. **Detector Uncertainty:** $\pi_{i5} = 5\%$



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6. Many NSI: Summary

PENNSTATE 1855

- Many NSI introduce complicated degeneracies:
  - In particular, there are regions in NSI parameter space that predict the same muon signal as a “no NSI” theory.
- Degenerate region:
  - Derived via approximate analytical solution
  - Characterized by parametric curve
  - In agreement with numerical results

8: Next Steps

- Improve analysis of this potential new physics by:
  - Better Chi Squared from:
    - Multiple data sources and observables
- Extend analysis by:
  - Explore NSI impact on CP phase discovery
  - Investigate effects of NSI phases

Thank you – Questions?