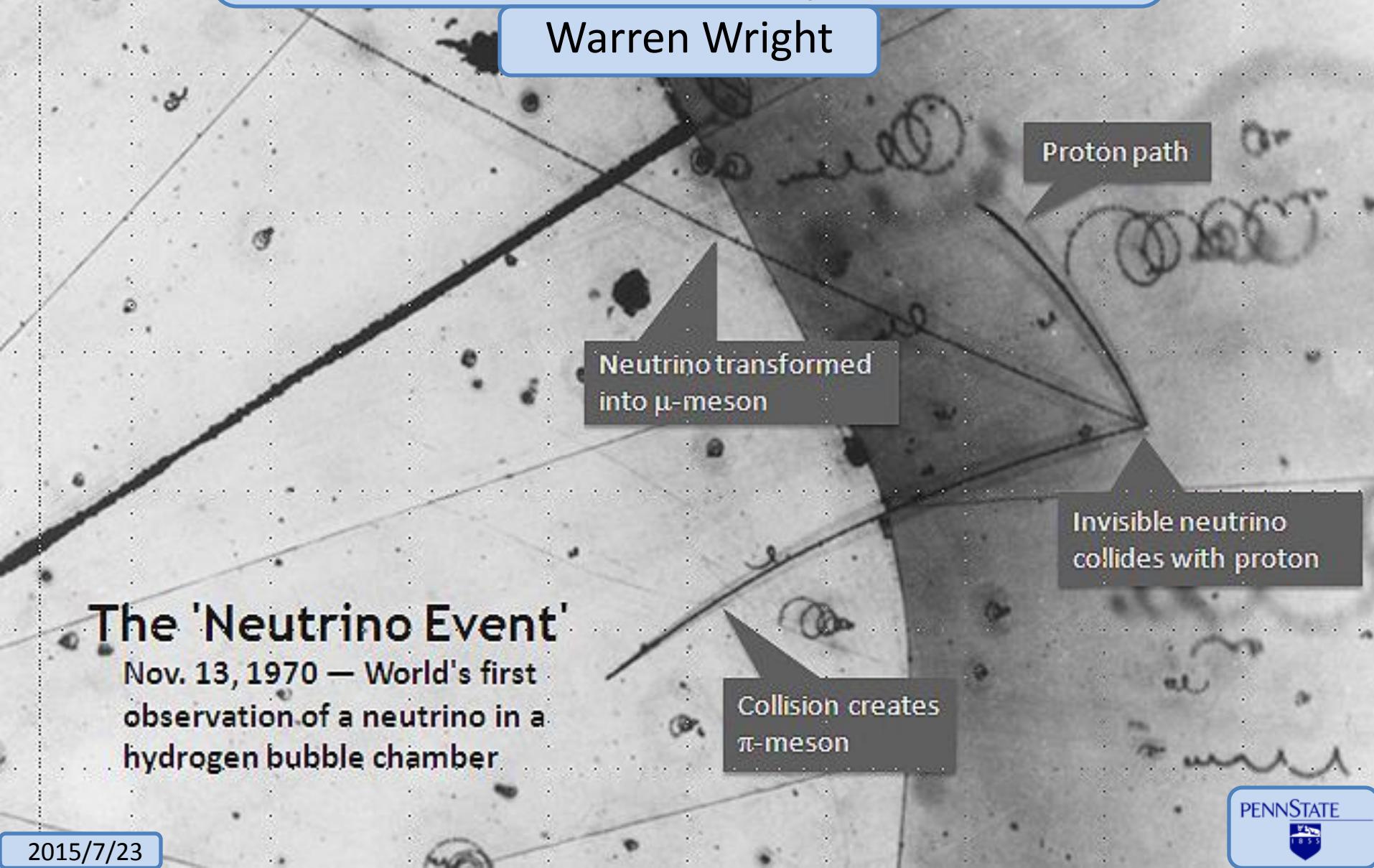


Non-Standard Neutrino Interactions at IceCube DeepCore

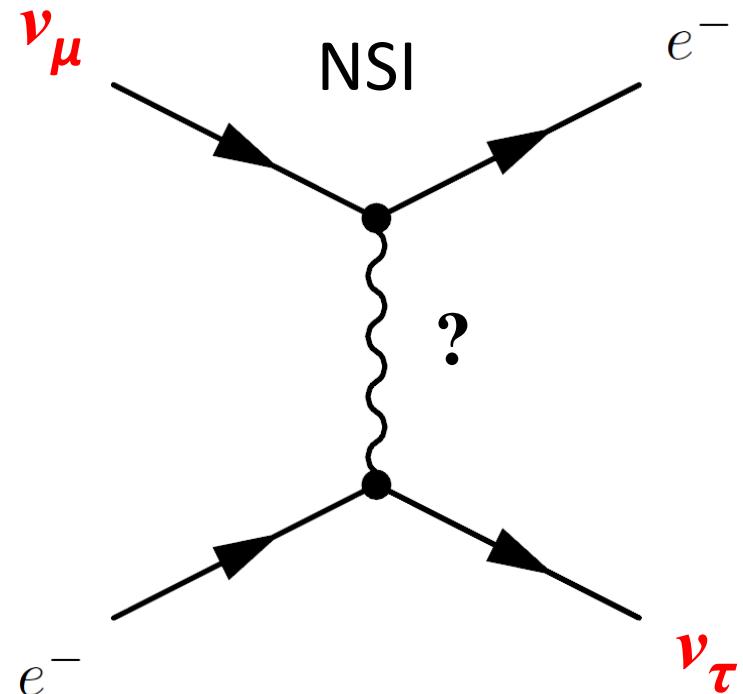
Warren Wright



The 'Neutrino Event'

Nov. 13, 1970 — World's first observation of a neutrino in a hydrogen bubble chamber

Non-Standard Interactions



- 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:

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

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

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

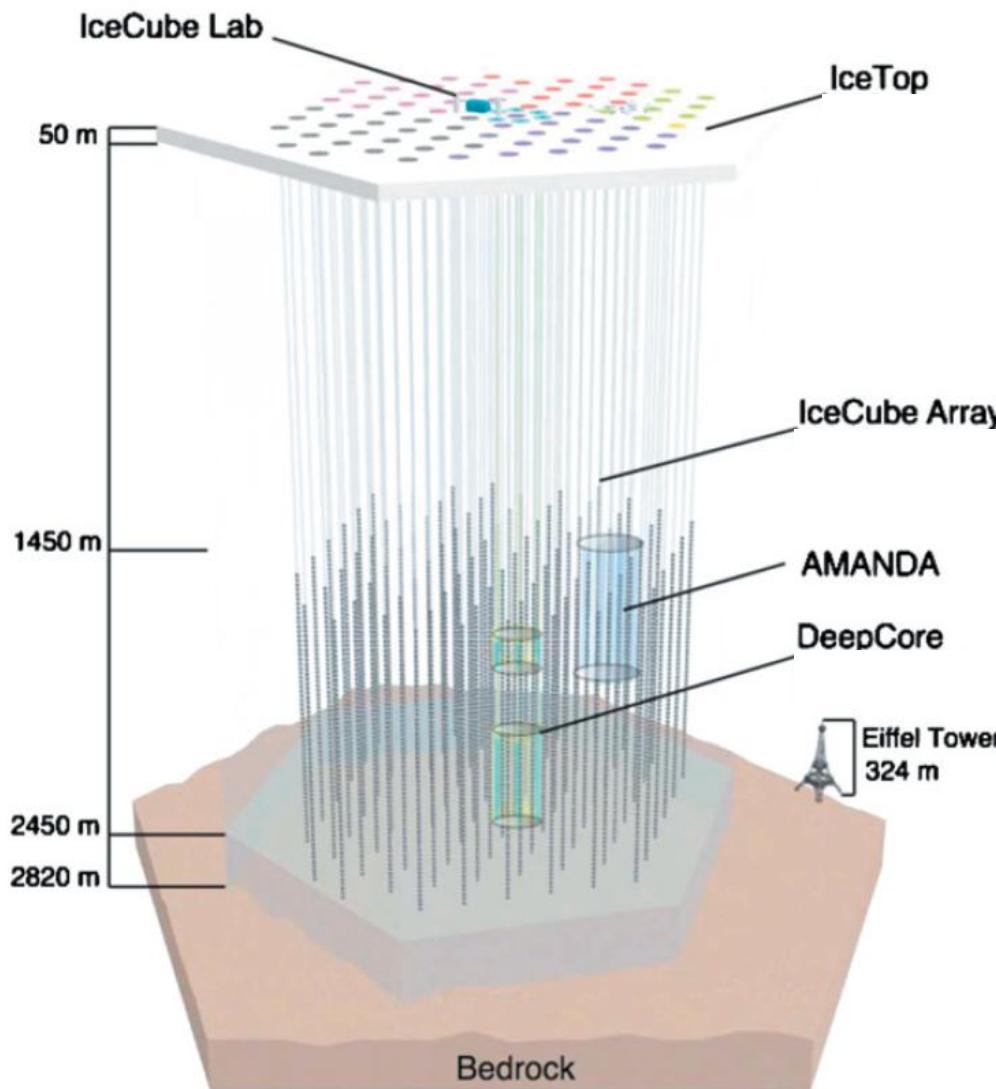
$$M = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{pmatrix}$$

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

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

- 3 Types of Bounds:
 - Indirect (G_F , CKM unitarity, Pion decay, ...)
 - $0.068 < |\epsilon_{\alpha\beta}|$ to $|\epsilon_{\alpha\beta}| < 21$ Biggio *et al.* arXiv:0907.0097 [hep-ph]
 - Simplified, one NSI/one experiment analysis (SuperK, Minos, ...)
 - $0.033 < |\epsilon_{\alpha\beta}|$ to $|\epsilon_{\alpha\beta}| < 0.2$ Adamson *et al.* arXiv:1303.5314 [hep-ex]
Mitsuka *et al.* arXiv:1109.1889 [hep-ex]
 - Global Fit To Oscillation Data (3σ)
 - $0.03 < |\epsilon_{\alpha\beta}^{u,d}|$ to $|\epsilon_{\alpha\beta}^{u,d}| < 0.71$ 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)

NSI: Experimental Context: ICDC



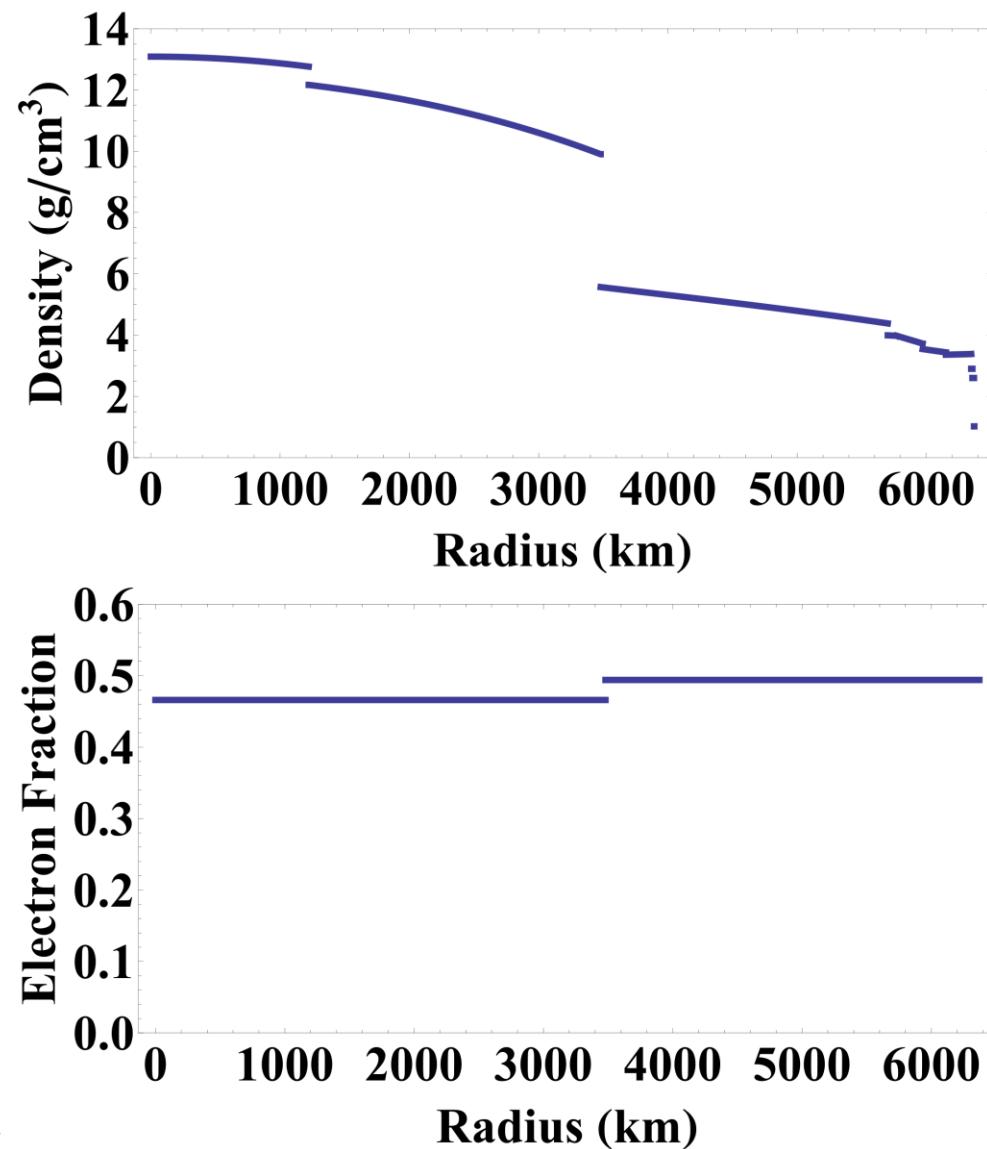
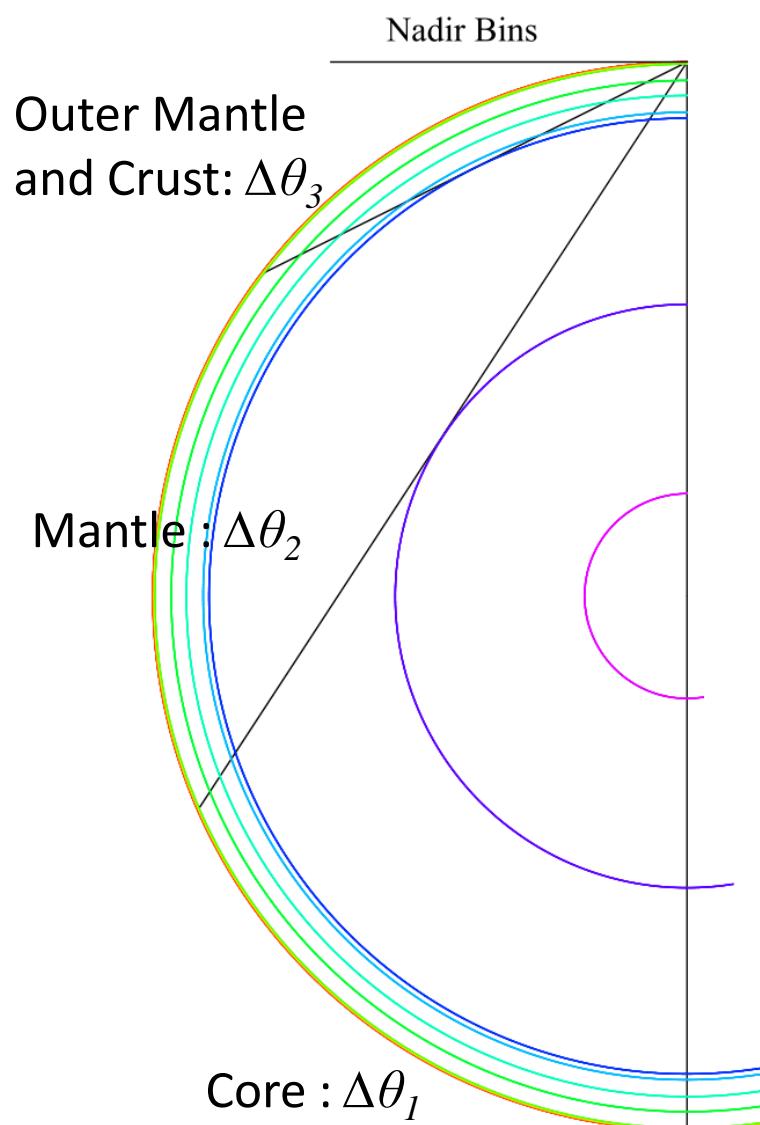
High Statistics

Muon tracks

$E > 6\text{GeV}$

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

NSI: ICDC – PREM



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

Many NSI: Analytics

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

$$H = \begin{pmatrix} V_{cc}(1 + \epsilon_{ee}) + 2\Delta s_{13}^2 & \Delta s_{2.13}s_{23} & V_{cc}\epsilon_{e\tau} + \Delta s_{2.13}c_{23} \\ \Delta s_{2.13}s_{23} & V_{cc}\epsilon_{\mu\mu} + 2\Delta c_{13}^2 s_{23}^2 & V_{cc}\epsilon_{\mu\tau} + \Delta c_{13}^2 s_{2.23} \\ V_{cc}\epsilon_{e\tau} + \Delta s_{2.13}c_{23} & V_{cc}\epsilon_{\mu\tau} + \Delta c_{13}^2 s_{2.23} & V_{cc}\epsilon_{\tau\tau} + 2\Delta c_{13}^2 c_{23}^2 \end{pmatrix}$$

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

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

$$n=0 \Rightarrow \tan(2\beta) = \frac{2(V_{cc}\epsilon_{e\tau} + \Delta s_{2.13}c_{23})}{V_{cc}(1 + \epsilon_{ee} - \epsilon_{\tau\tau}) + 2\Delta(s_{13}^2 - c_{13}^2 c_{23}^2)}$$

Many NSI: Analytics

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

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

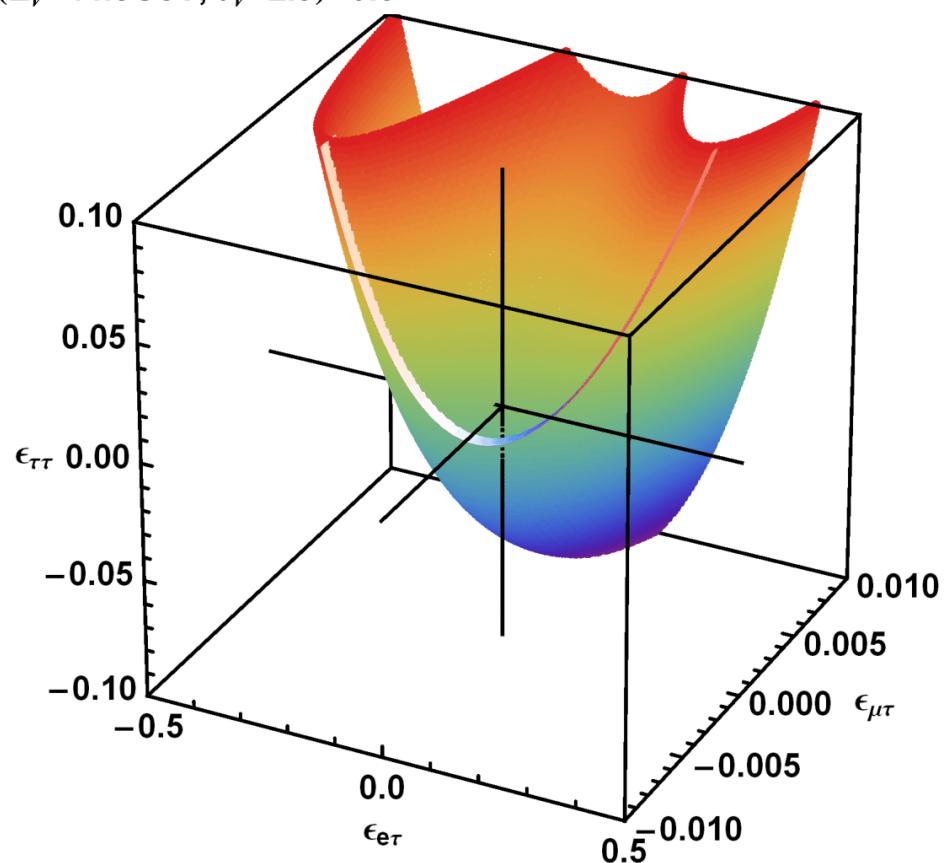
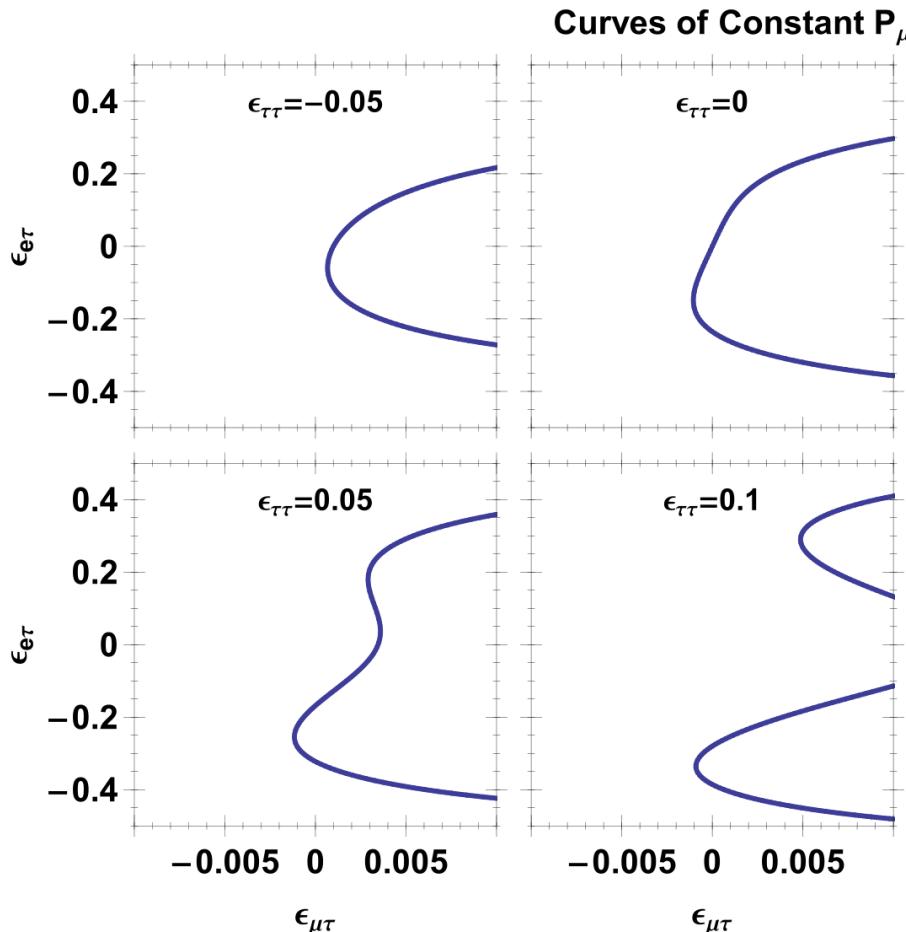
$$P_{\nu_\mu \rightarrow \nu_\mu} = 1 - \sin^2 \left(\sqrt{b^2 + g^2} L \right) \frac{b^2}{b^2 + g^2}$$

$$b = V_{cc} \epsilon_{\mu\tau} c_\beta + \Delta (c_{13}^2 s_{2.23} c_\beta - s_{23} s_{2.13} s_\beta)$$

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

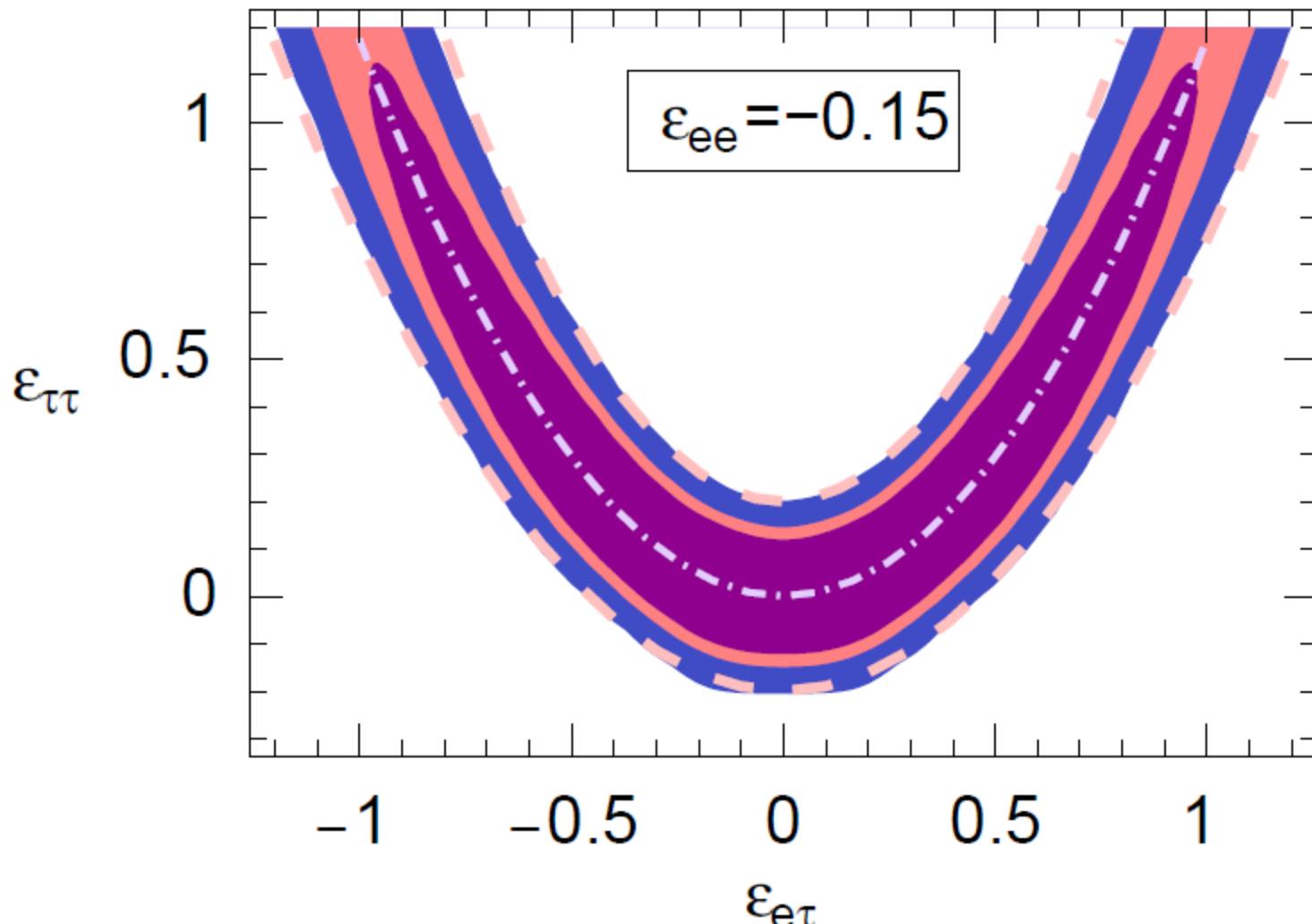
$$+ \Delta (c_{13}^2 s_{23}^2 - (c_{13} c_{23} c_\beta - s_{13} s_\beta)^2)$$

Many NSI: Oscillation Probability



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

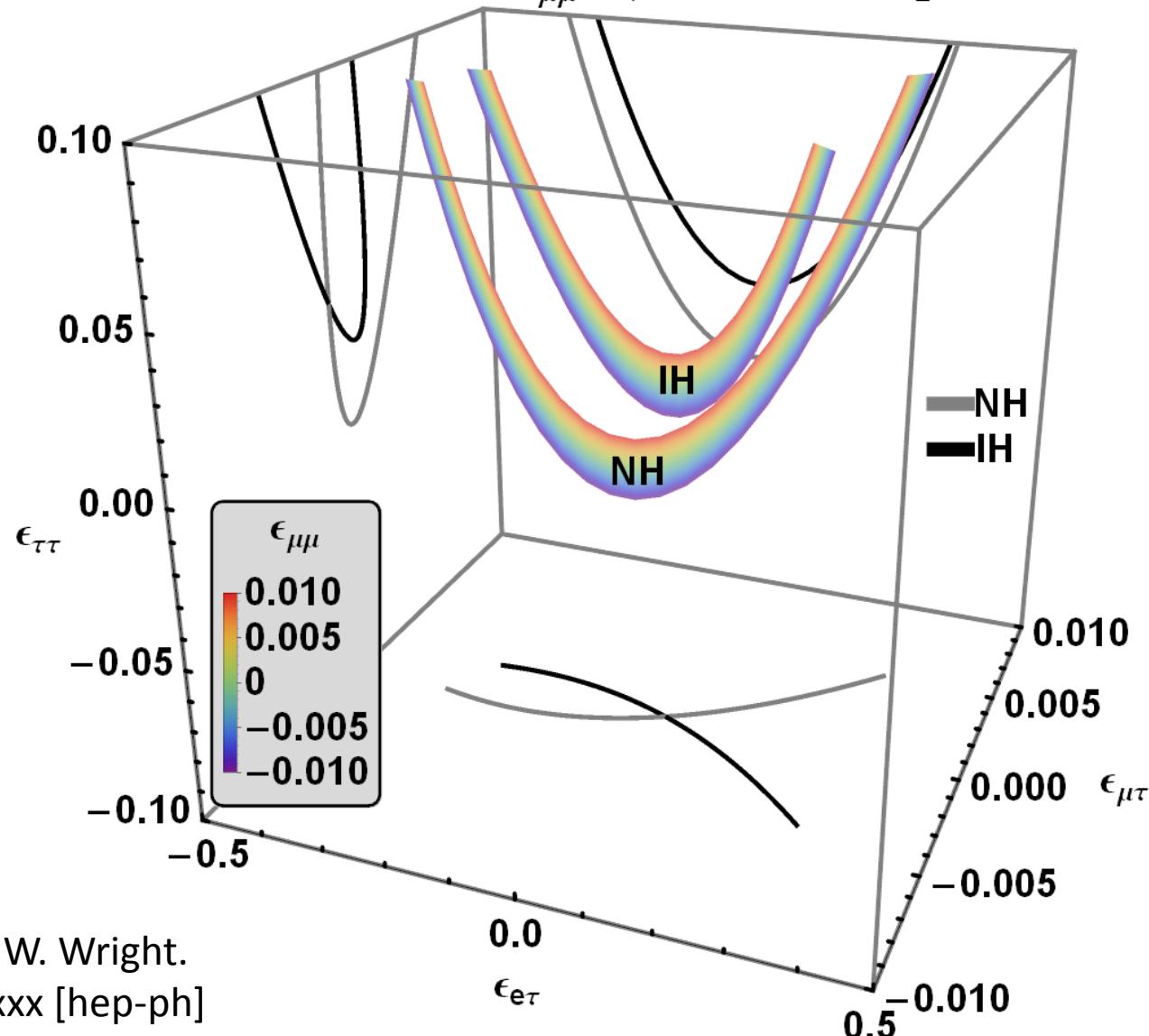
Many NSI: Oscillation Probability



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

Many NSI: Parameter Selection

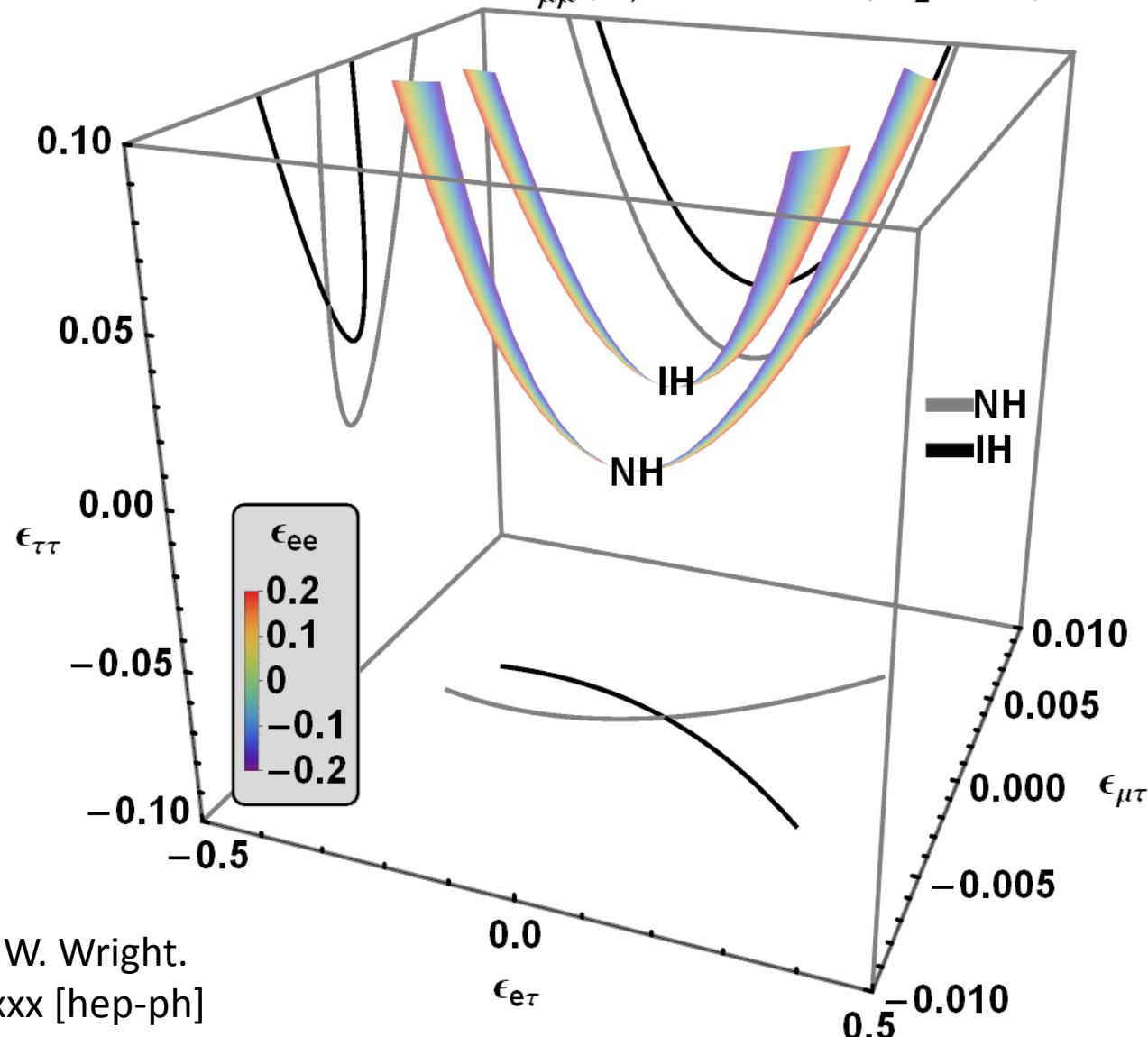
Curves of Constant $P_{\mu\mu}(E_\nu=44.8\text{GeV}, \theta_z=2.9)=0.5$



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

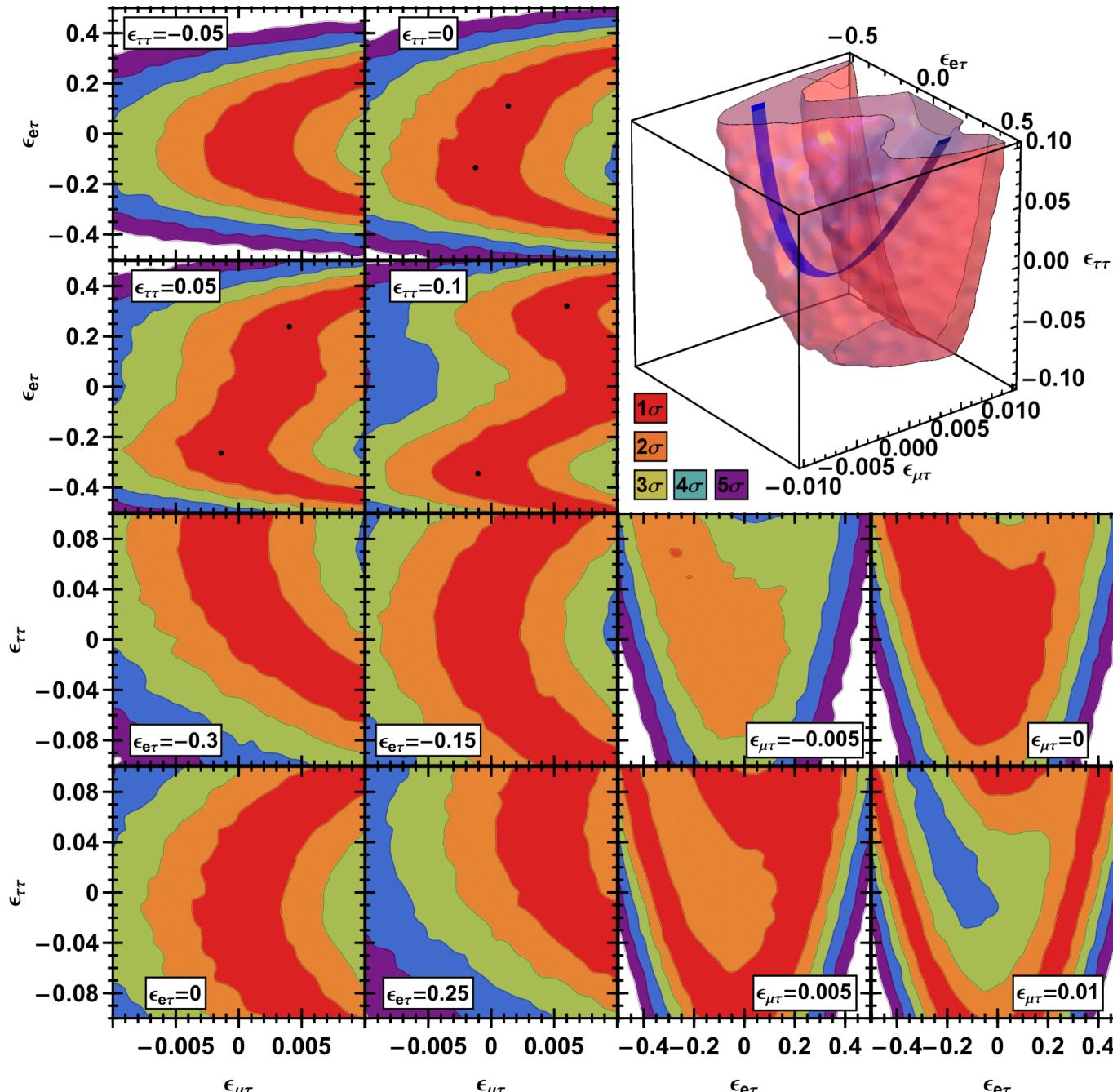
Many NSI: Parameter Selection

Curves of Constant $P_{\mu\mu}(E_\nu=44.8\text{GeV}, \theta_z=2.9)=0.5$

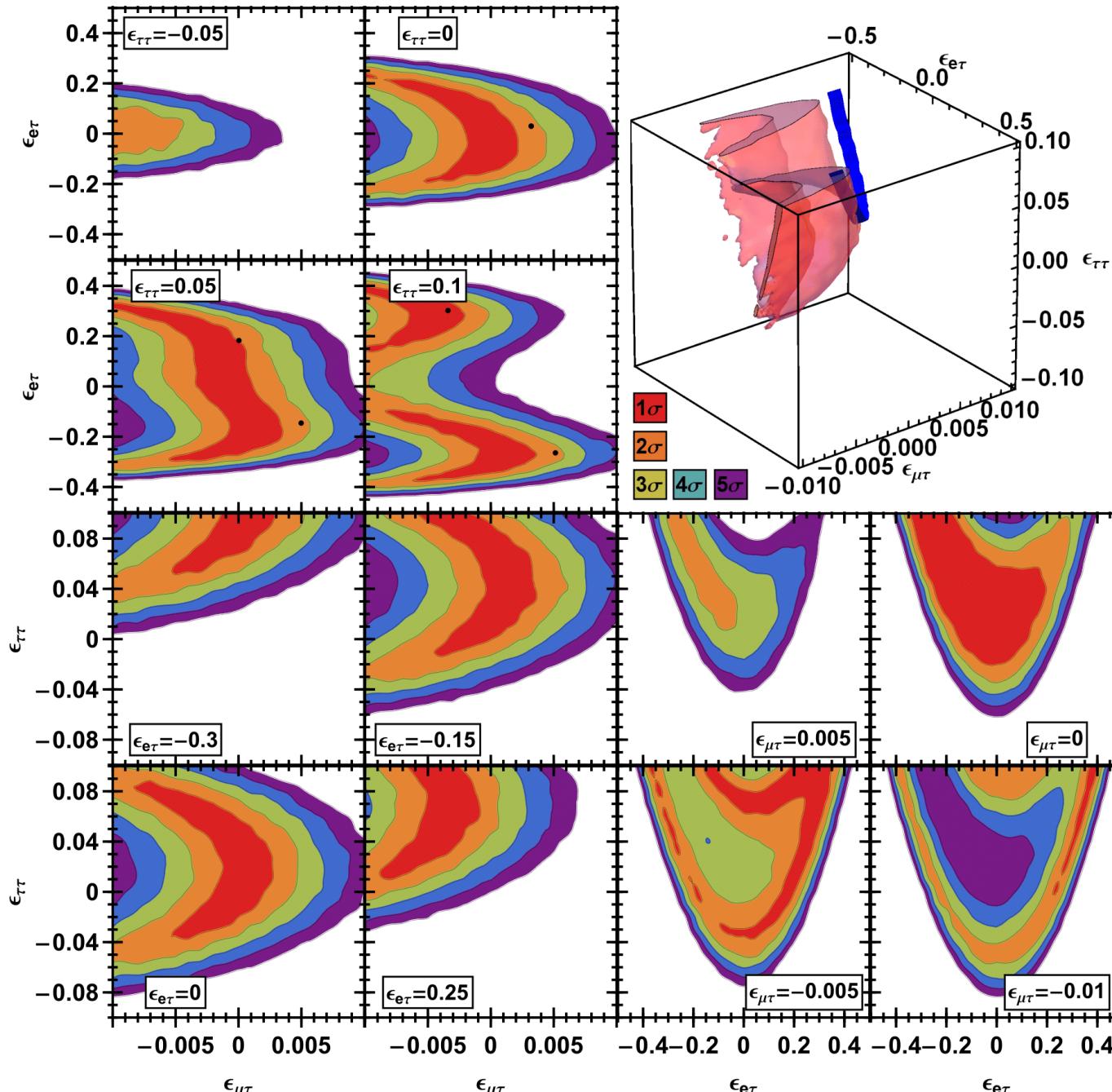


I. Mocioiu & W. Wright.
arXiv: 1508.xxxx [hep-ph]

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



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



Many NSI: Chi Squared

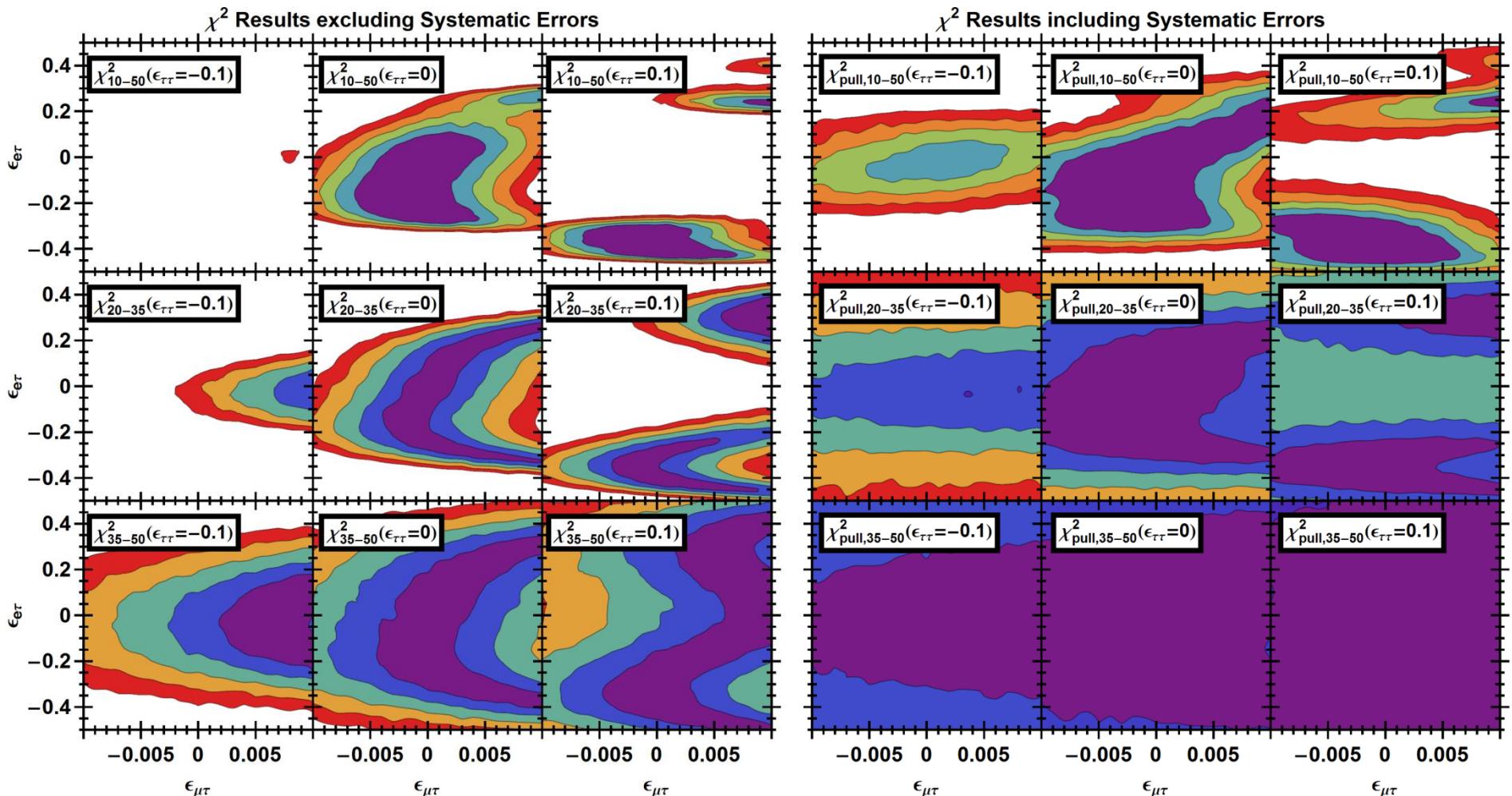
$$\chi^2_{\text{pull}}(\epsilon_{e\tau}, \epsilon_{\mu\tau}, \epsilon_{\tau\tau}) = \min_{\{\xi_k\}} \left(\sum_{i=1}^n \left(\frac{\left(N_{\mu,i}^{\text{model}} \left(1 + \sum_{j=1}^m \pi_{ij} \xi_j \right) - N_{\mu,i}^{\text{null}} \right)^2}{N_{\mu,i}^{\text{null}}} \right) + \sum_{j=1}^m \xi_j^2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

$$N_{\mu,i}^{\text{model}} \equiv N_{\mu}^{\text{model}}(\epsilon_{e\tau}, \epsilon_{\mu\tau}, \epsilon_{\tau\tau}, \Delta E_{\mu,i})$$

$$N_{\mu,i}^{\text{null}} \equiv N_{\mu}^{\text{null}}(0, 0, 0, \Delta E_{\mu,i}).$$

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:** $\pi_{i5} = 5\%$

Many NSI: Chi Squared



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

- 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

Thank you – Questions?