Neutrino NSI:
old beyond-the-SM physics at NOνA and beyond

Alexander Friedland

LANL

Project-X workshop

Fermilab, June 20, 2012

LBNE science roadmap
(Y.-K. Kim, LBNE reconfiguration workshop, Apr 2012)

- Beam neutrino physics:
  - CPV
  - Mass hierarchy
    - Known angles and splittings
- Nucleon decay
- Supernova

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Bread and butter physics

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- Beam neutrino physics:
  - CPV
  - Mass hierarchy
  - Known angles and splittings
  - New Physics?

Bread and butter physics

Analogy

- Imagine the LHC would present its case as just a search to measure one parameter (the mass of the SM Higgs)
    - Would this have captured the imagination of the world?
    - ... and O($10B) of funding?
- We don’t know what to expect at the full 14 TeV LHC. However, to gauge the reach of various searches, it is useful to have a framework like the MSSM.
- Similarly to the 5 points of MSSM, to gauge the sensitivity of NOvA, LBNE, T2K, Hyper-K, etc to possible New Physics, we need a (toy) framework.

A good abstract for a paper:

The effect of coherent forward scattering must be taken into account when considering the oscillations of neutrinos traveling through matter. In particular [..]. 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.

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PHYSICAL REVIEW D VOLUME 17, NUMBER 9 1 MAY 1978

Neutrino oscillations in matter

L. Wolfenstein

Carnegie-Mellon University, Pittsburgh, Pennsylvania 15213

(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.

Maximally minimal extension

- Let's assume "New New physics" modifies the MSW potential
  - Assume a new physics contribution to neutrino-quark interactions
- Interactions of the tau neutrino are particularly poorly known
- For the purpose of setting up a deliberately simplistic framework
  - a just single term: a flavor changing $qq\nu_e\nu_\tau$ interaction
  - subdominant to the SM weak interactions

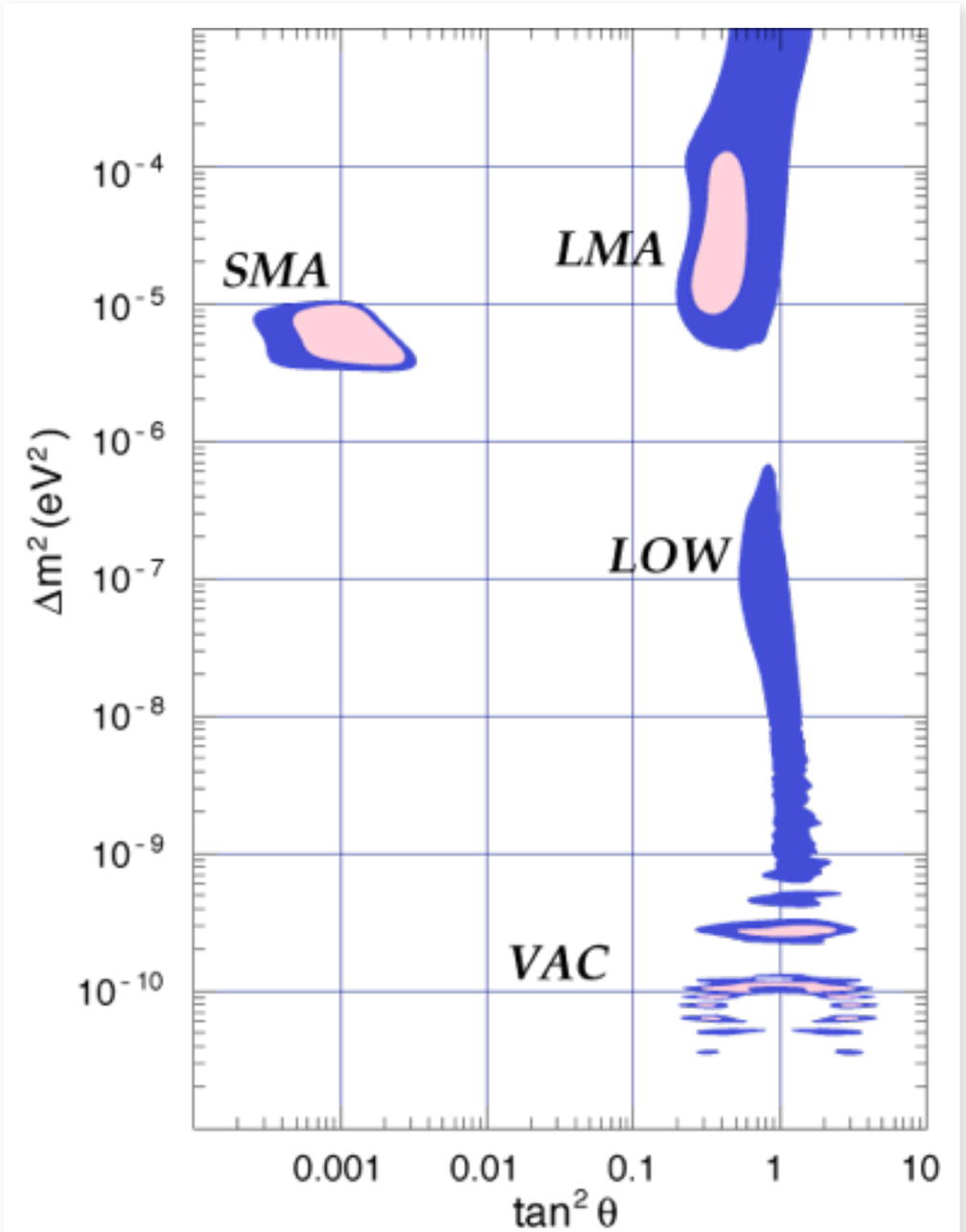
$$H_{mat}^{flav} = \sqrt{2} G_F n_e \begin{pmatrix} 1 & 0 & |\varepsilon_{e\tau}|\, e^{-i\delta_\nu} \\ 0 & 0 & 0 \\ |\varepsilon_{e\tau}|\, e^{i\delta_\nu} & 0 & 0 \end{pmatrix}$$

Let’s see where things stand with Wolfenstein’s proposal now

- Solar neutrinos
- Experiments involving 1000 km of rock
- Other measurements that didn’t exist in the 1970s

Solar neutrinos

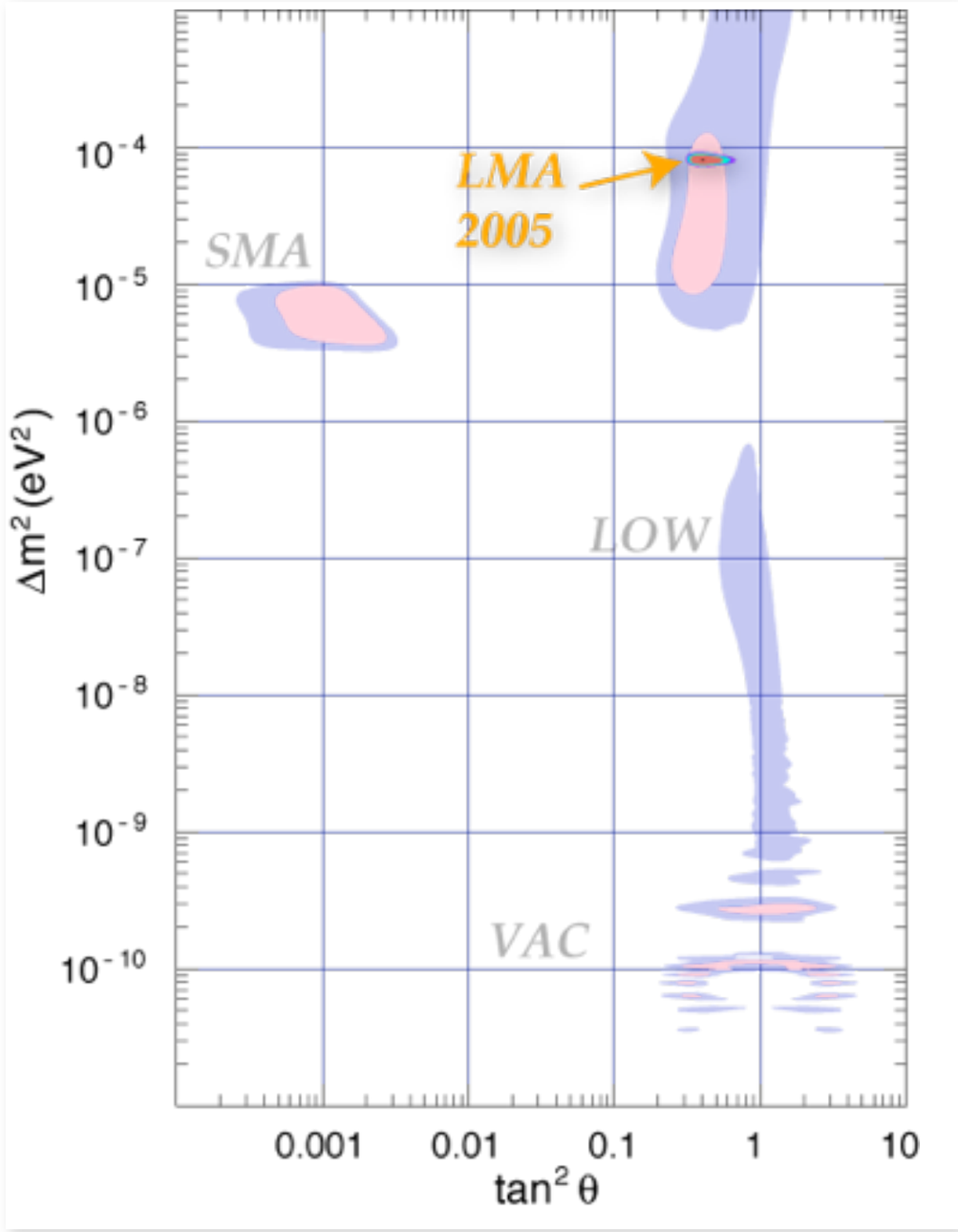
- Things have improved significantly in the last ~ 10 years!



Solar neutrinos

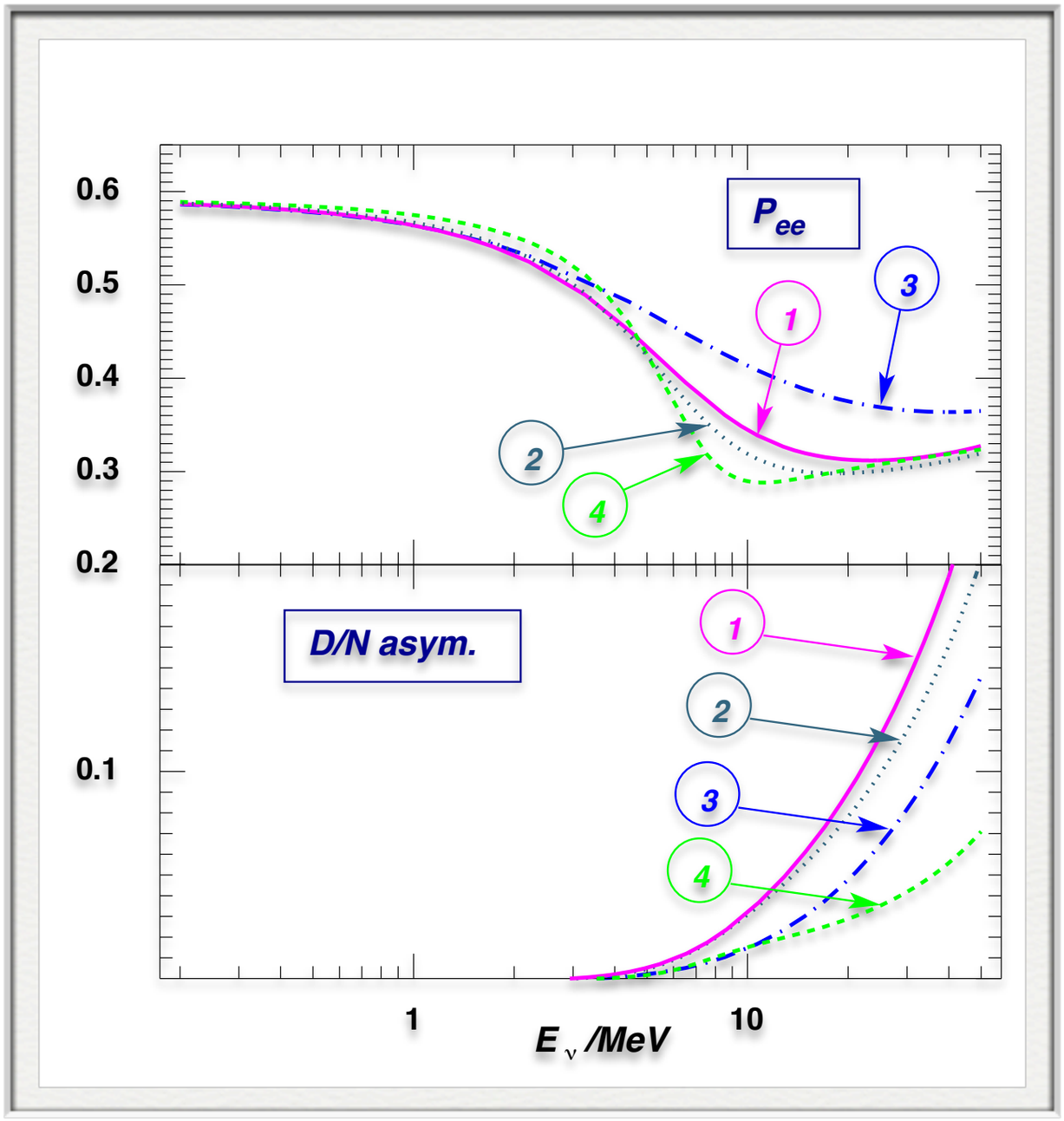
- We now know that the dominant mechanism of solar flavor transformations is not due to flavor-changing matter effects in the Sun

- But how about probing new physics at subdominant levels?



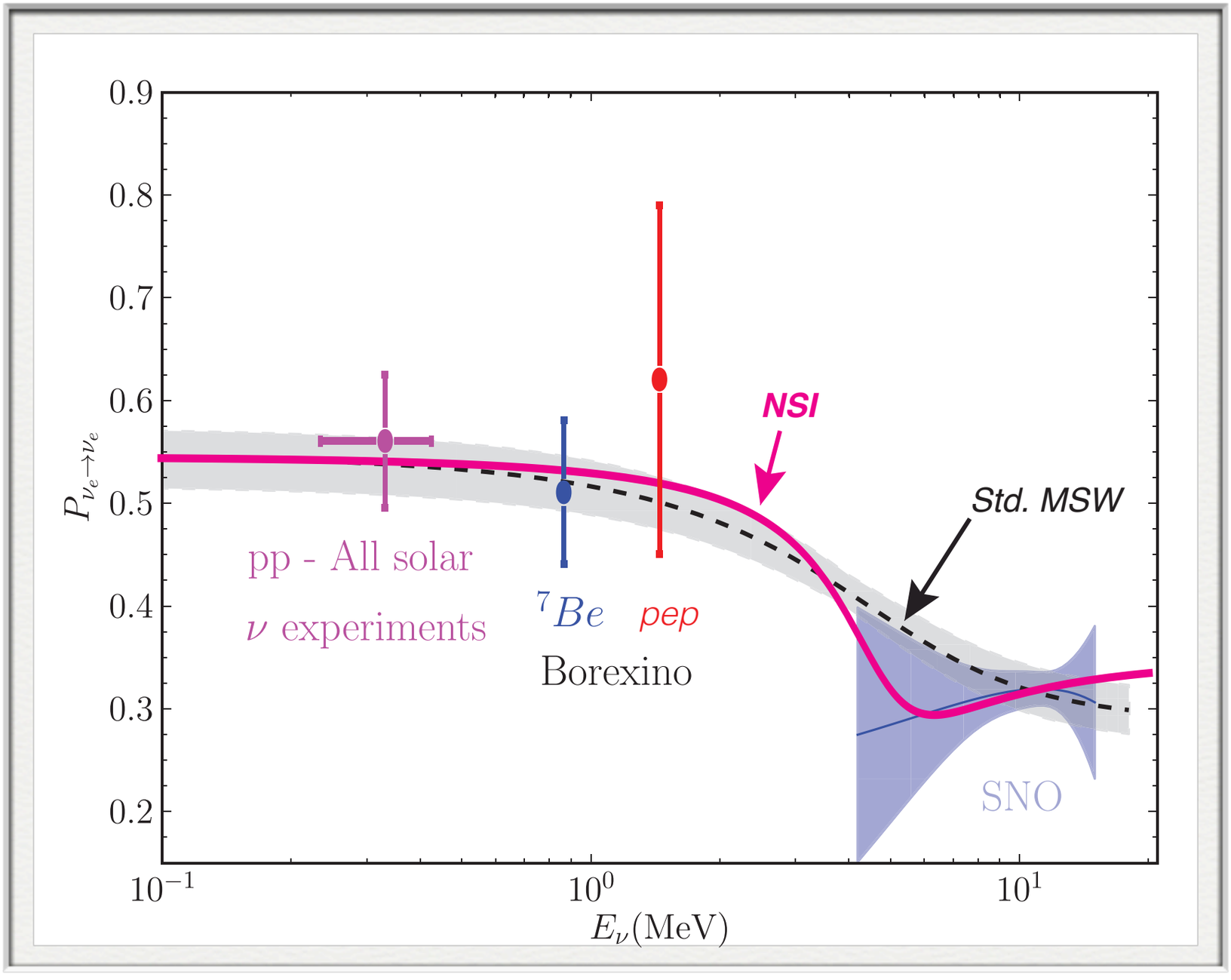
Solar neutrinos

- Small NSI change the energy dependence of the solar neutrino survival probability
  - mostly in the vacuum/matter transition regime
- Also change the D/N asymmetry
- All one has to do is observe the upturn of the survival probability



Friedland, Lunardini, Peña-Garay, PLB (2004)

Solar neutrinos, 2012



SNO 3-phase analysis 2011; our fit

Similar story with Borexino, SuperK; see Palazzo, PRD 2011

Other bounds: atmospheric neutrinos

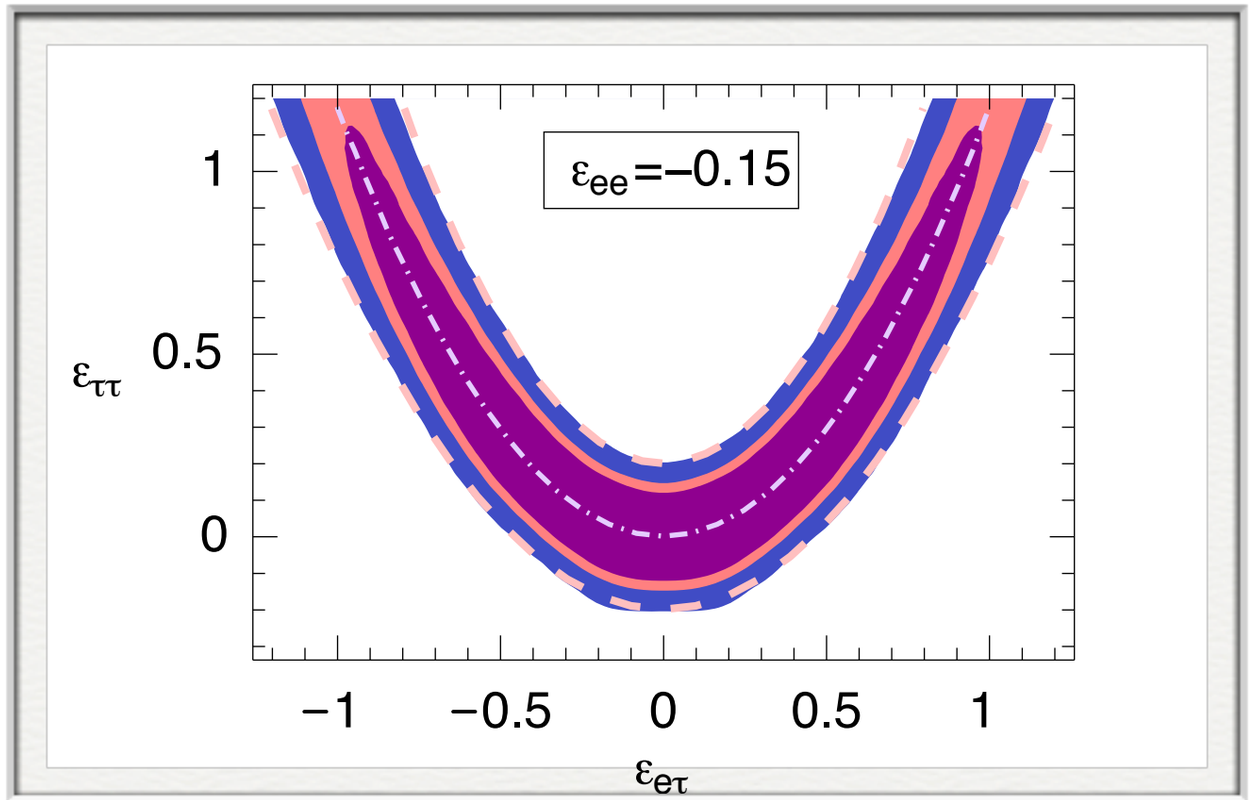
- Friedland, Lunardini, Maltoni, PRD 2004; Friedland, Lunardini, PRD 2005

- Same e-τ NSI are also probed by atmospheric neutrinos

  - Atmospheric neutrinos probe oscillations over 5 decades in energy! Fit well by vac. osc.

  - Yet, even without special cancellations $\varepsilon_{e\tau}$ up to ~0.5 allowed

    - Weaker than solar



See Gonzalez-Garcia, Maltoni, Salvado, arXiv:1103.4365v2 for a recent update

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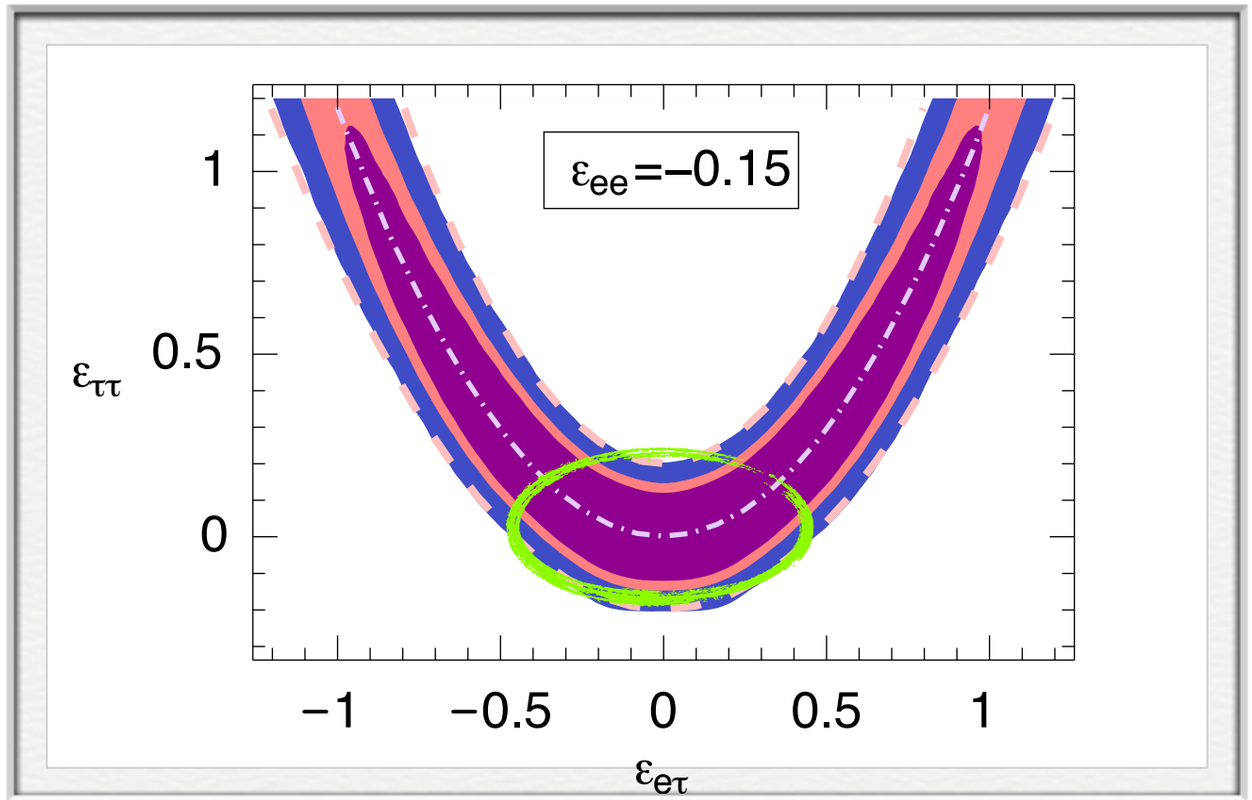

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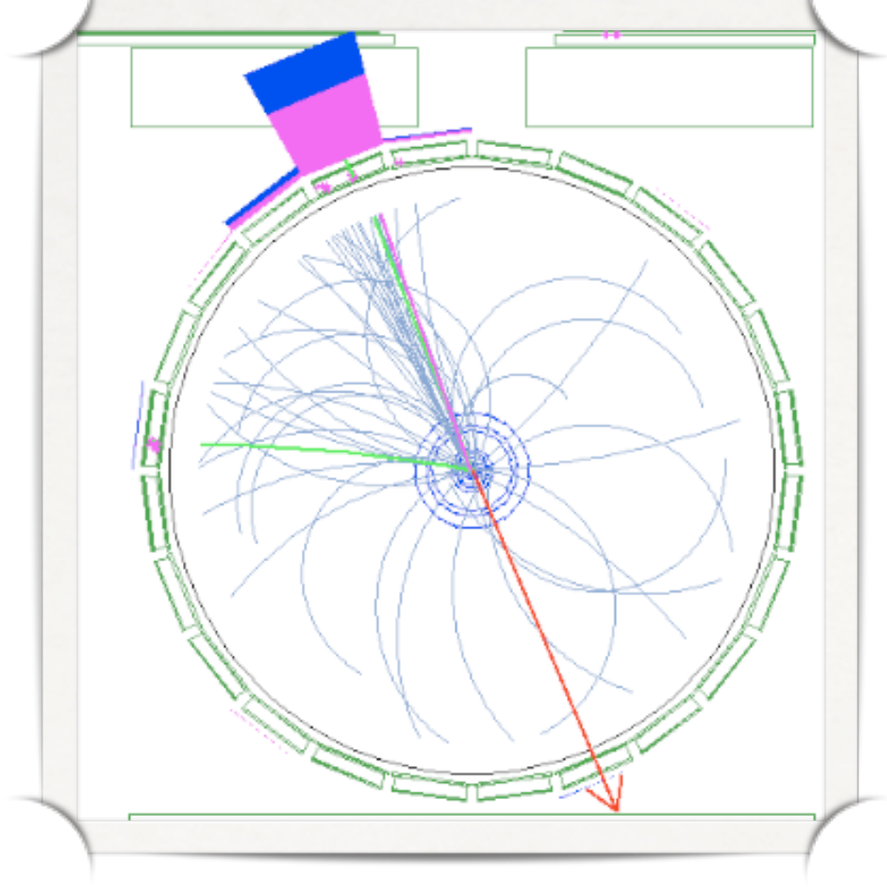
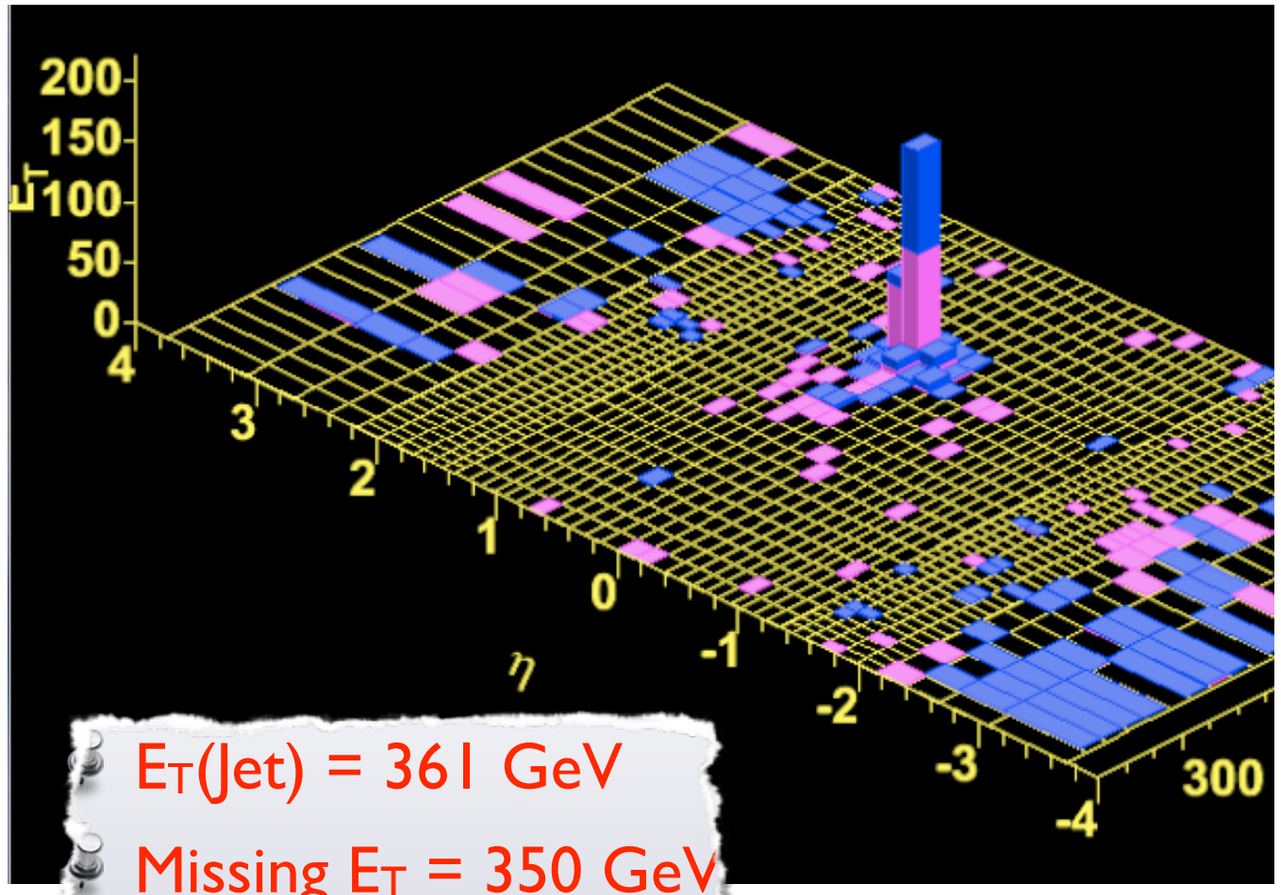
Other bounds: LHC Monojet searches

- “monophoton” or “monojet” events recoiling against “nothing”
- “nothing” could be, e.g., dark matter particles, extra-dim KK gravitons, etc



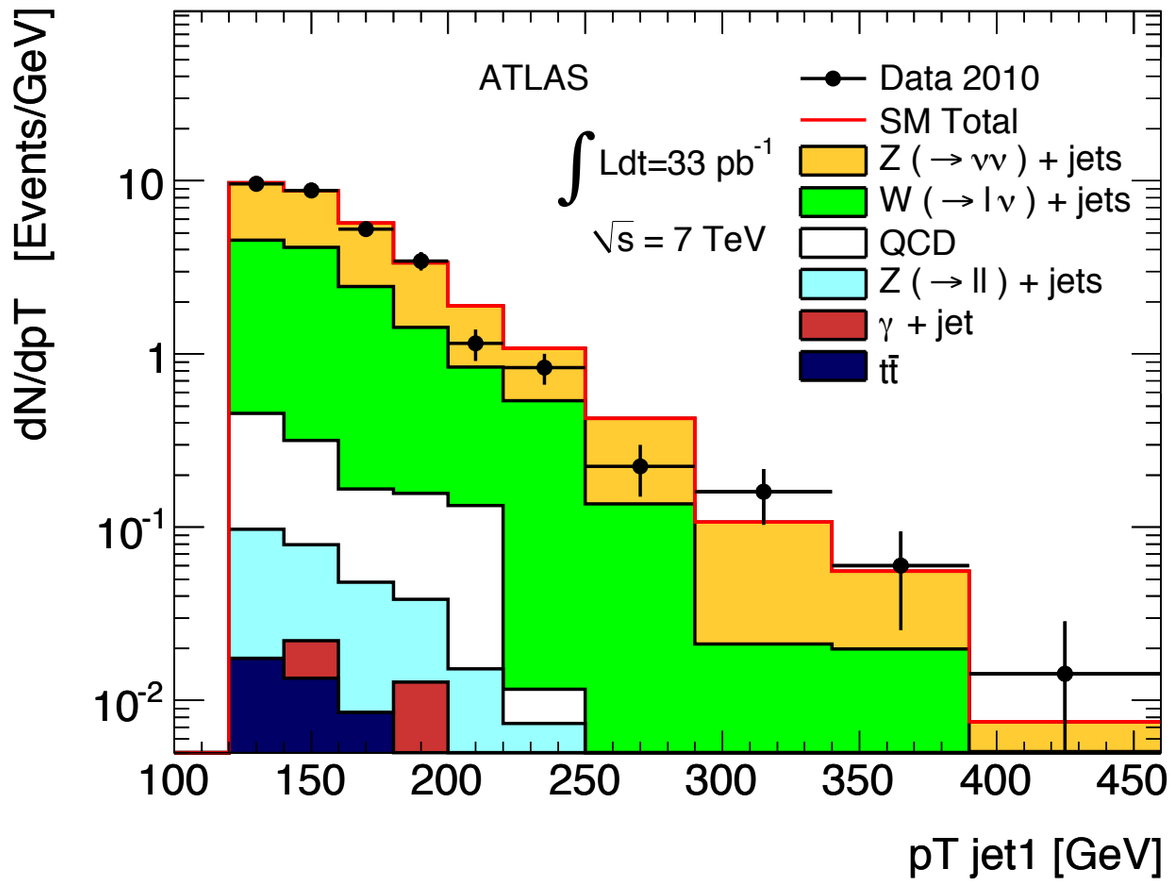


Some of the (many) papers on these searches

- Large extra dimensions (ADD):
  - Mirabelli, Perelstein, Peskin, PRL 1999
  - Vacavant & Hinchliffe, J. Phys. G 2001
  - CDF Collaboration, PRL 2006, PRL 2008
- DM:
  - Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu, PLB 2011; PRD 2011
  - Bai, Fox, Harnik, JHEP 2010
  - Rajaraman, Shepherd, Tait, Wijangco, arXiv:1108.1196
  - Fox, Harnik, Kopp, Tsai, arXiv:1109.4398

Neutrinos are Backgrounds

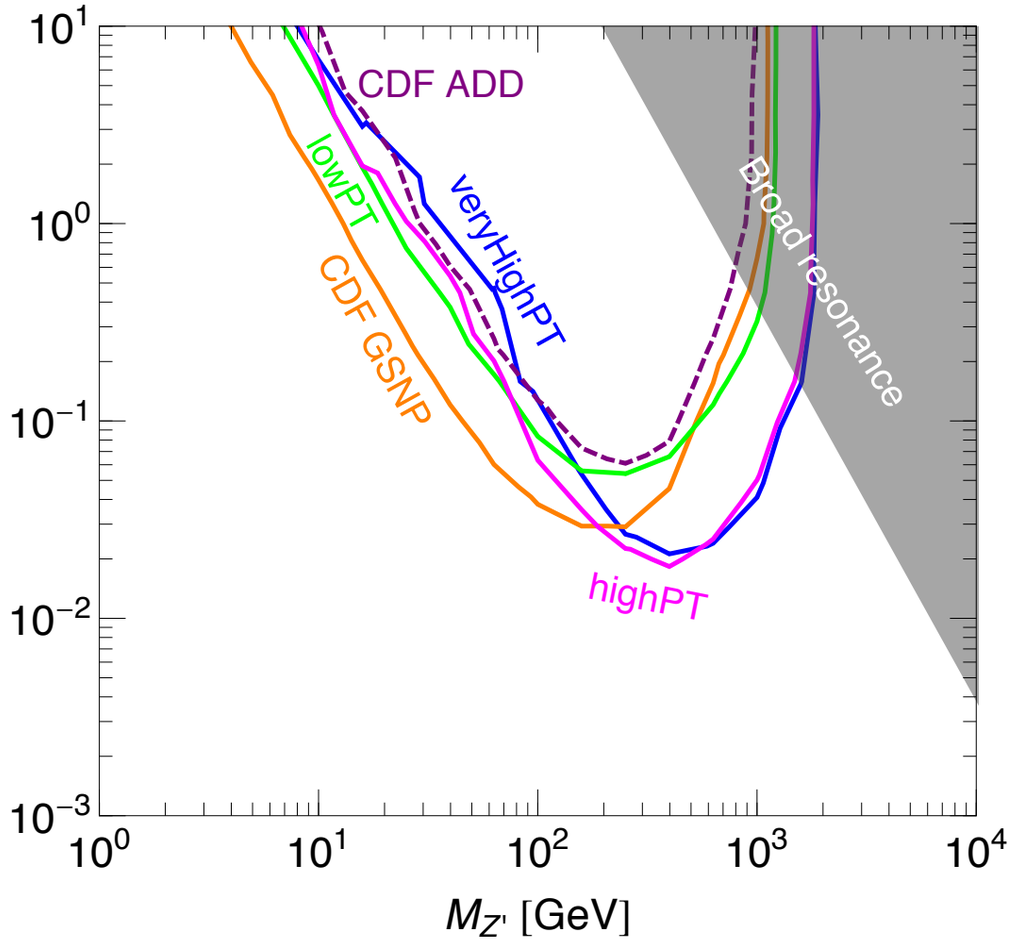
- Standard Model physics that leads to monojet events
- jet + Z → jet + νν-bar
- jet + W → jet + eν
  - → jet + μν
  - → jet + τν
- NSI modify BG rate
- May fake DM/KK states



ATLAS, arXiv:1106.5327, Phys. Lett. B 2011

Constraints on neutrino NSI

- Neutrino NSI modify the rate of monojet events
  - look like dark matter or extra dimensions
- Monojet data from the Tevatron and LHC provide a useful constraint, especially if the new physics scale is in the hundred GeV range (s-channel), but weaker if it's above or below
  - Systematics limited, already with 1 fb^{-1} of data (last July)



A. F., Graesser, Shoemaker, Vecchi, arXiv:1111.5331

Neutrinos vs. DM

- If we see an anomaly in monojet events, is it a signature of extra dimensions, dark matter, or neutrino NSI?

- Neutrino NSI could be potentially distinguished by their companion multilepton events (SU(2) symmetry)

  - qq -> WW ll

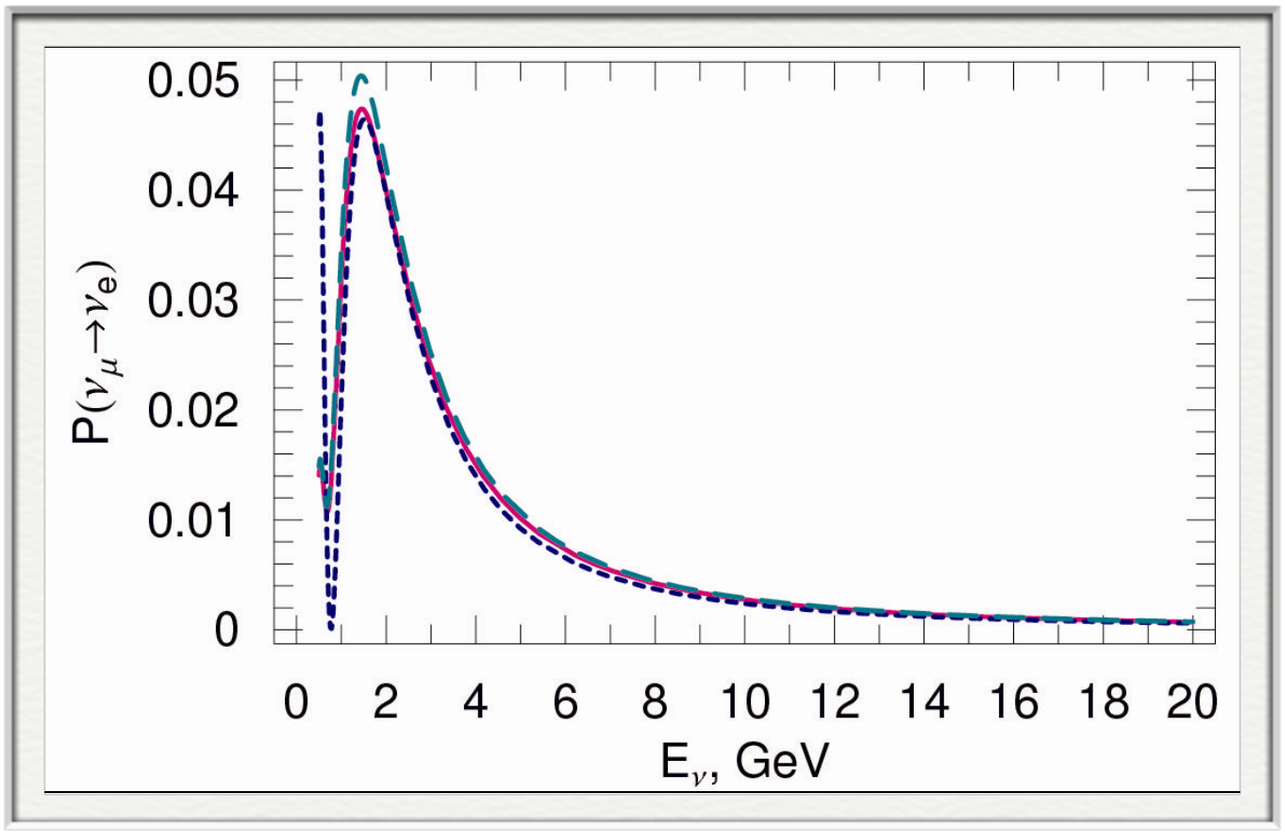
- Turns out that 3-lepton events at the LHC (latest published 5 fb^{-1} sample) come close to the sensitivity of monojets, but don't beat them

  - the case of contact dimension-8 interactions

A. F., Graesser, Shoemaker,
Vecchi, arXiv:1111.5331v2

Finally, 1000 km of rock: MINOS

- The flavor-changing NSI cause small nu-e appearance
- This could fake the effect of theta13 pretty closely
- One might think that only large NSI (same size at the SM weak interactions) can be probed...



$\sin^2 2\theta_{13} = 0.07$ or

$\sin^2 2\theta_{13} = 0$ + NSI $\varepsilon_{e\tau} \sim 1$

Friedland, Lunardini, PRD 2006

Interference of amplitudes

A.F. ,C. Lunardini, PRD (2006)

$$P(\nu_\mu \to \nu_e) \simeq \left| G_1 \sin\theta_{23} \frac{\exp(i\Delta_1 L) - 1}{\Delta_1} - G_2 \cos\theta_{23} \frac{\exp(i\Delta_2 L) - 1}{\Delta_2} \right|^2 ,$$

$$G_1 \simeq \sqrt{2} G_F N_e |\epsilon_{e\tau}| e^{i\delta_\nu} \cos\theta_{23} + \Delta \sin 2\theta_{13} e^{i\delta} ,$$

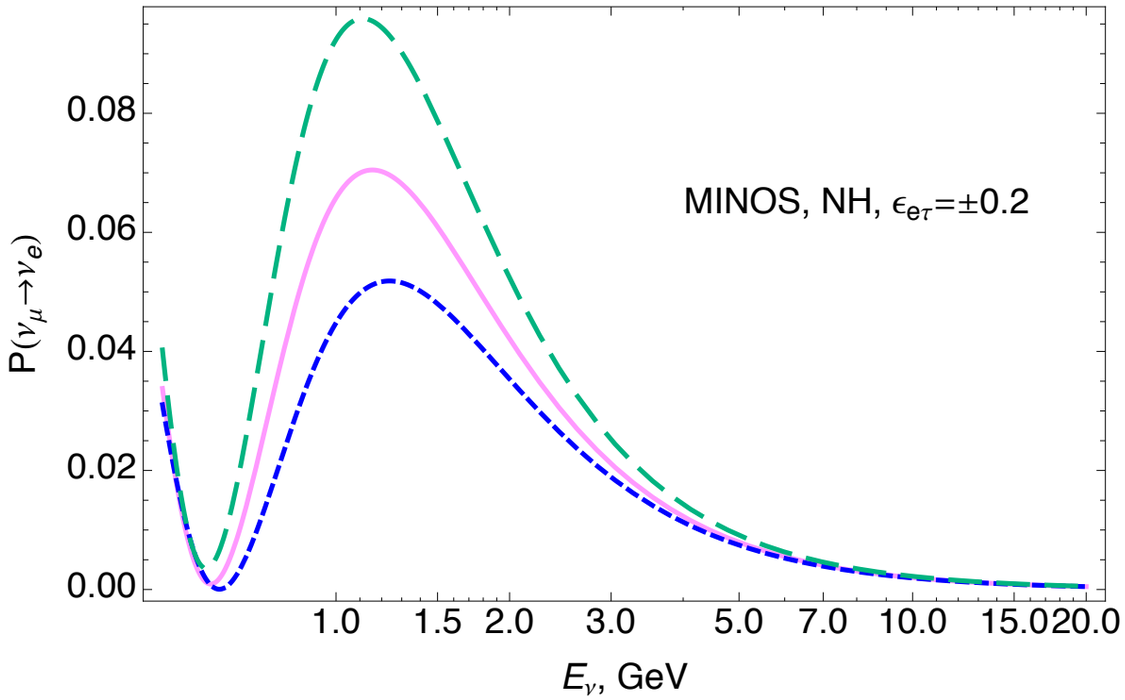
$$G_2 \simeq \sqrt{2} G_F N_e |\epsilon_{e\tau}| e^{i\delta_\nu} \sin\theta_{23} - \Delta_\odot \sin 2\theta_{12} .$$

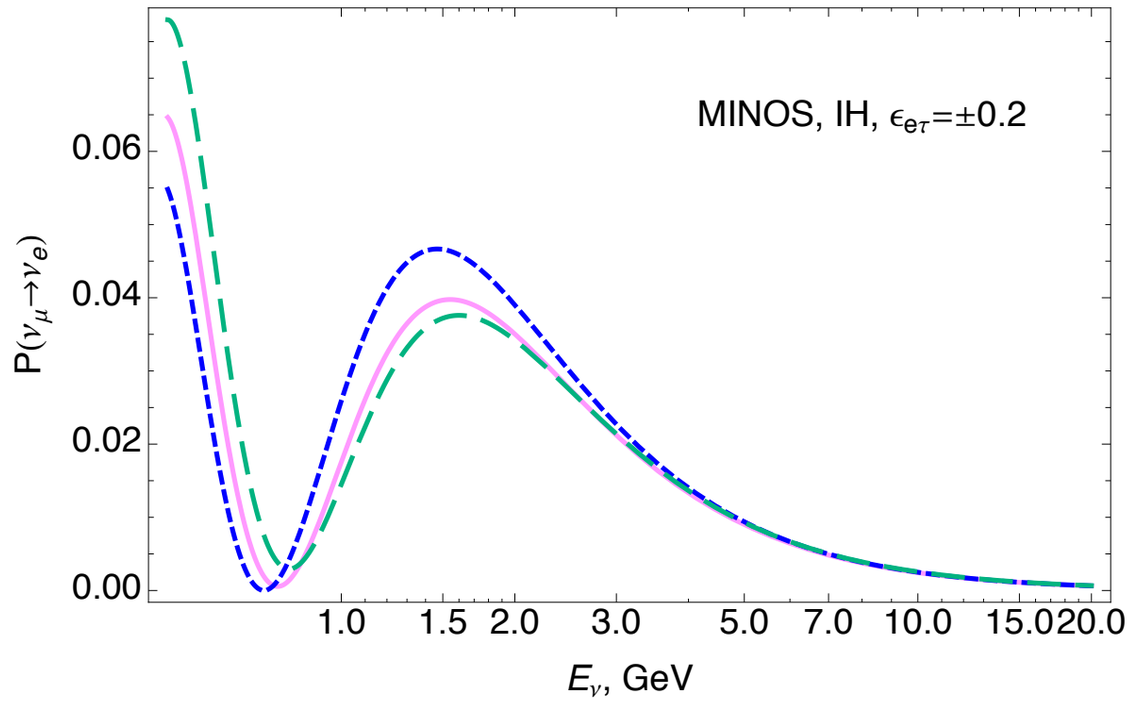
- Two channels, solar and atmospheric; NSI amplitude appears in both

Interference of the large theta13 term with the NSI term dramatically enhances the sensitivity!

- ***NSI has its own phase; interference depends on the relative phases!***

MINOS and “solar-inspired” NSI

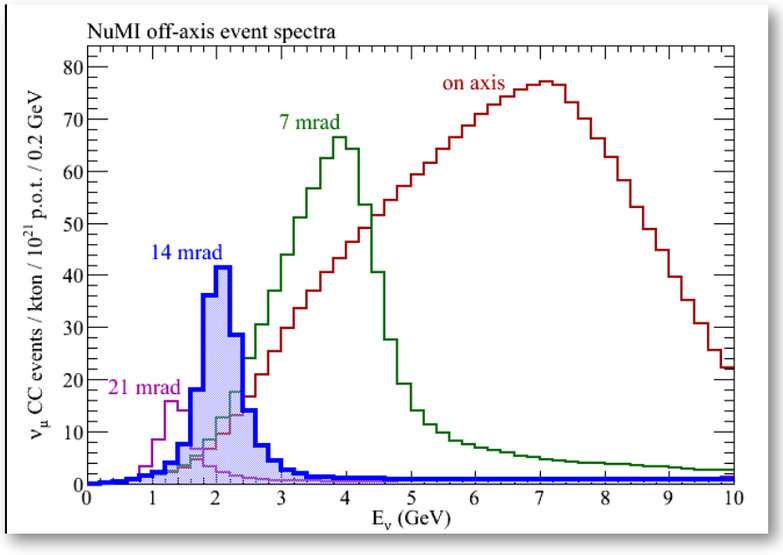


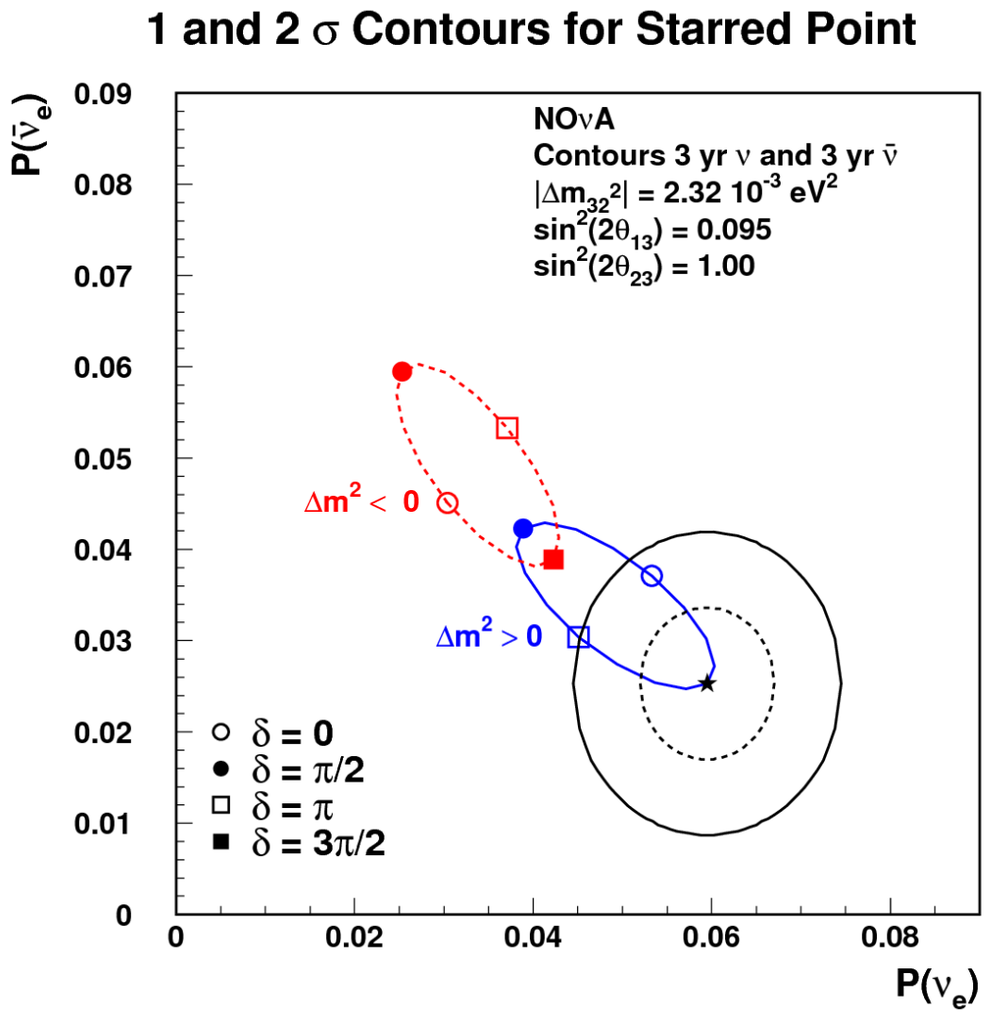


- Interference makes for a pretty large effect
  - Useful constraint already possible
  - On the other hand, NSI can confuse the hierarchies
- Not enough sensitivity at MINOS. NOvA?

NOvA bi-probability: standard case

- Interference between solar and atm. terms depends on the phase
- Instead of plotting the energy spectrum people often show the “bi-probability” plot (Minakata, Nunokawa, JHEP 2001).
- Esp. useful for NOvA, since it’s a narrow band off-axis beam with E ~ 2 GeV

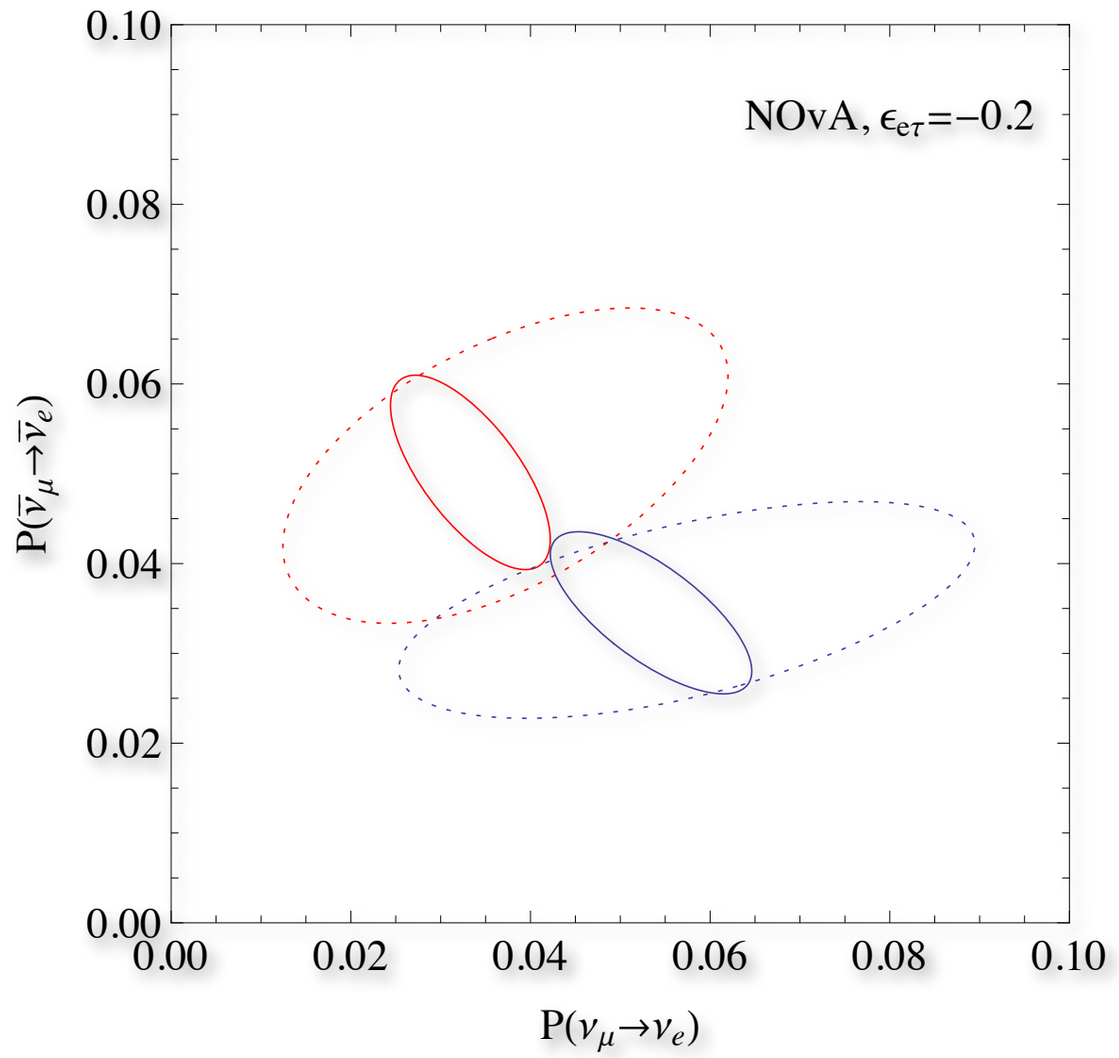




Ryan Patterson, NU 2012

But what if there is also NSI?

- Let's take $\varepsilon_{e\tau}$ ~0.2, roughly motivated by the solar spectral data
  - From here on, Friedland & Shoemaker, arXiv:1206.xxxx
- Choose a phase of $\varepsilon_{e\tau}$



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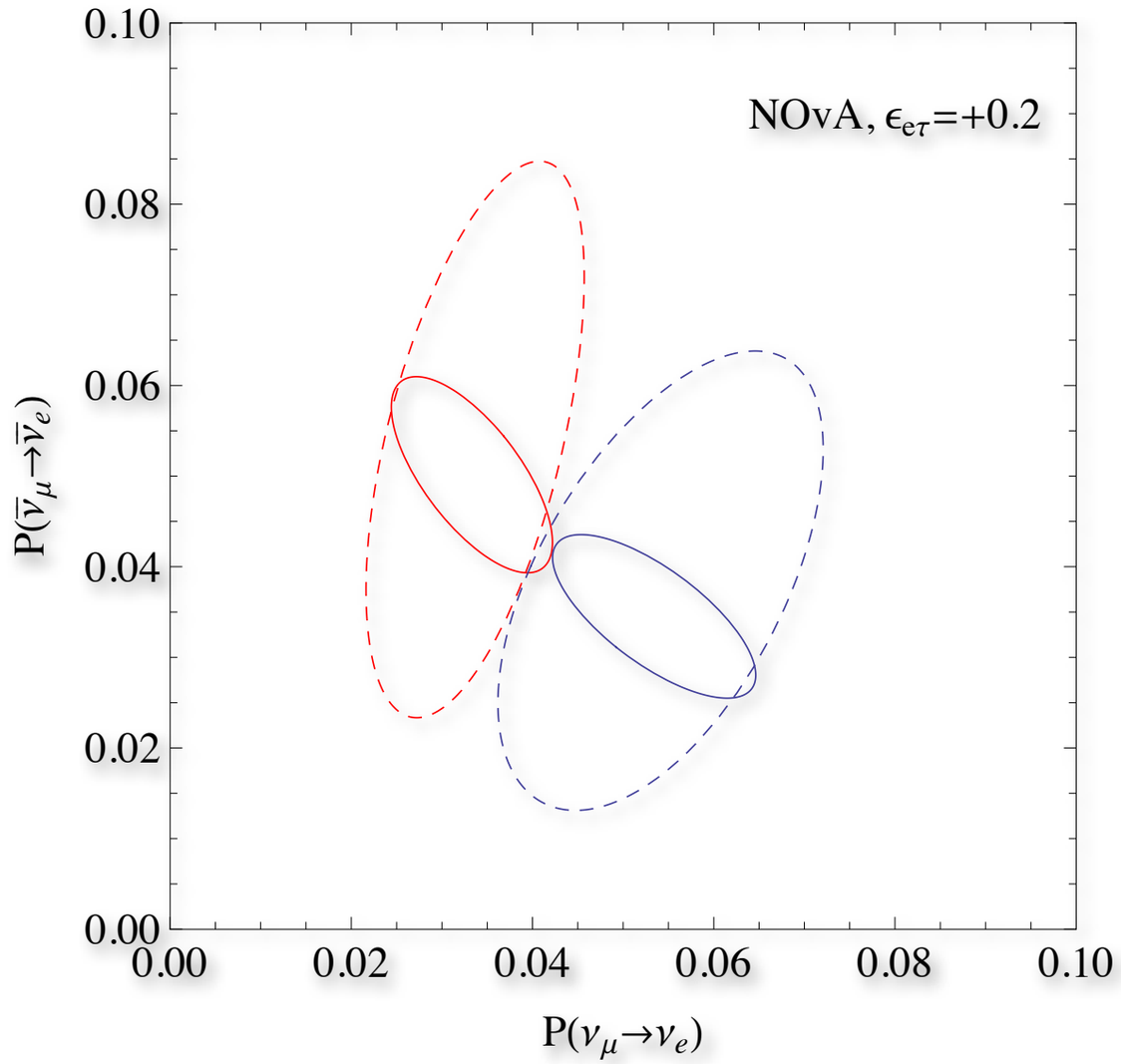
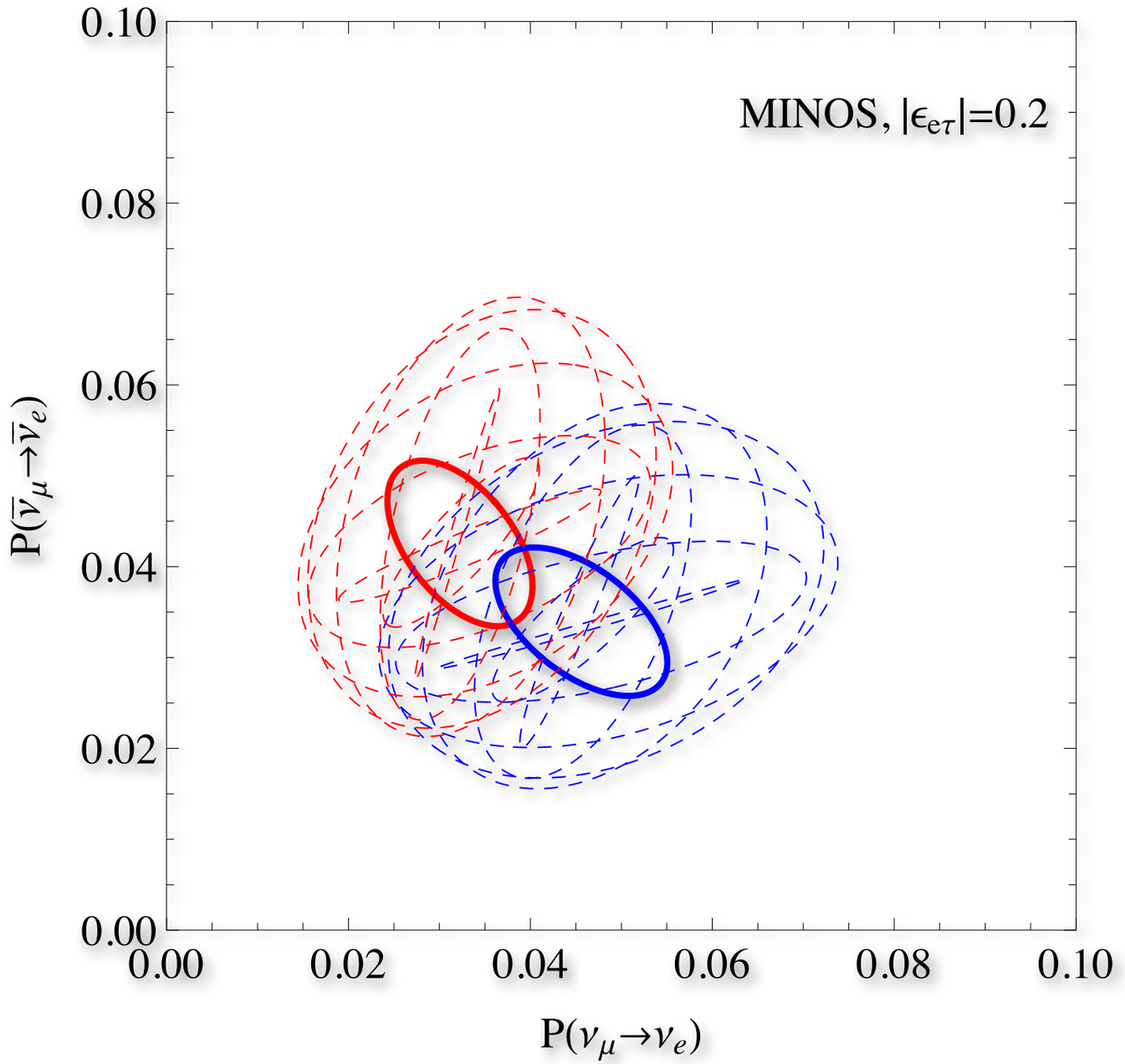


Next step: vary the NSI phase

- NSI with $|\varepsilon_{e\tau} \sim 0.2|$ result in bigger regions in the bi-probability space



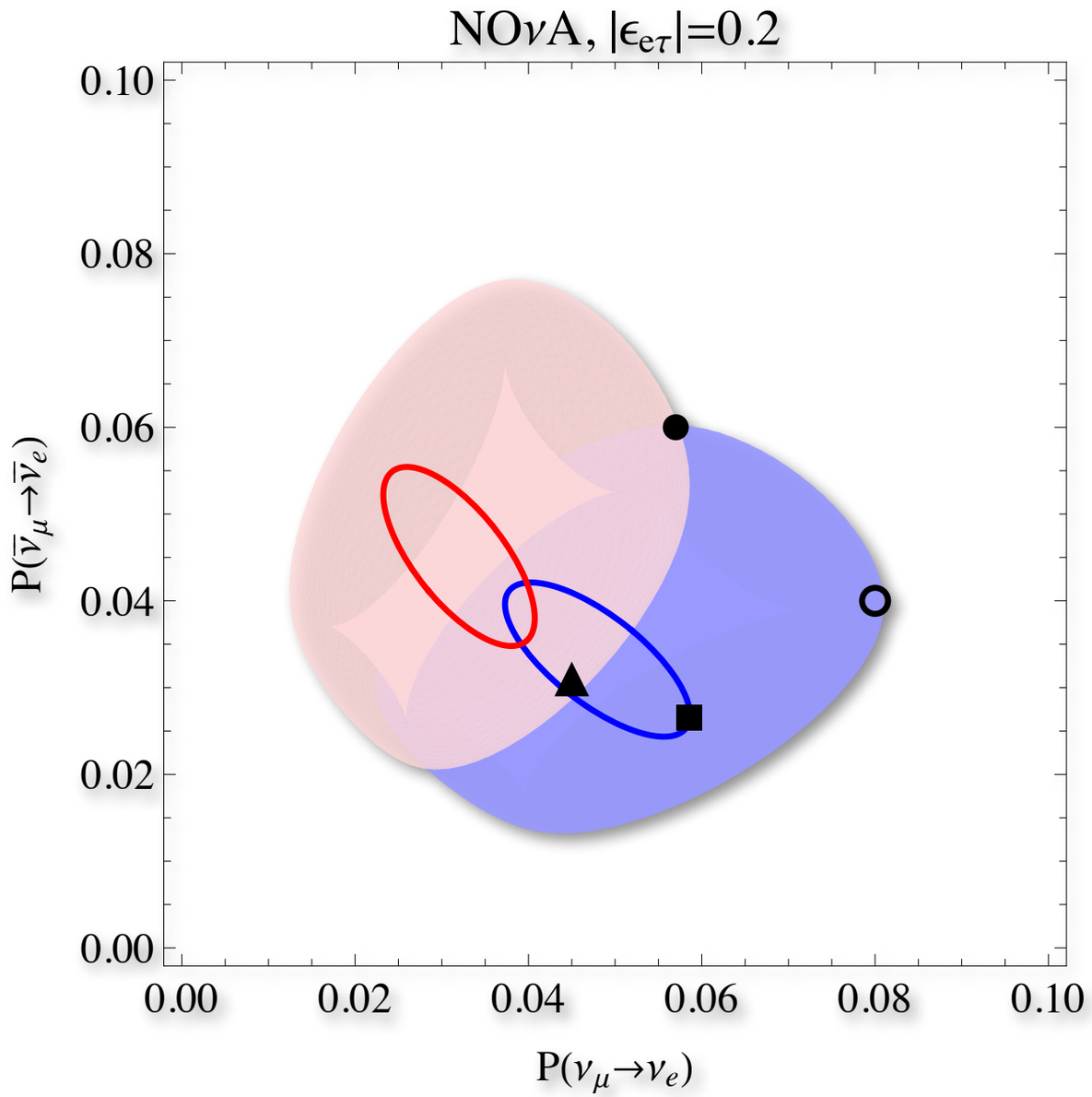
Qualitatively different possibilities

1. Large deviation from the standard ellipses: detection of new physics + mass hierarchy!

2. Large deviation from the standard ellipses: detection of new physics, but mass hierarchy is confused

3. Mass hierarchy measured, but no don't know if NSI or not

4. Complete confusion



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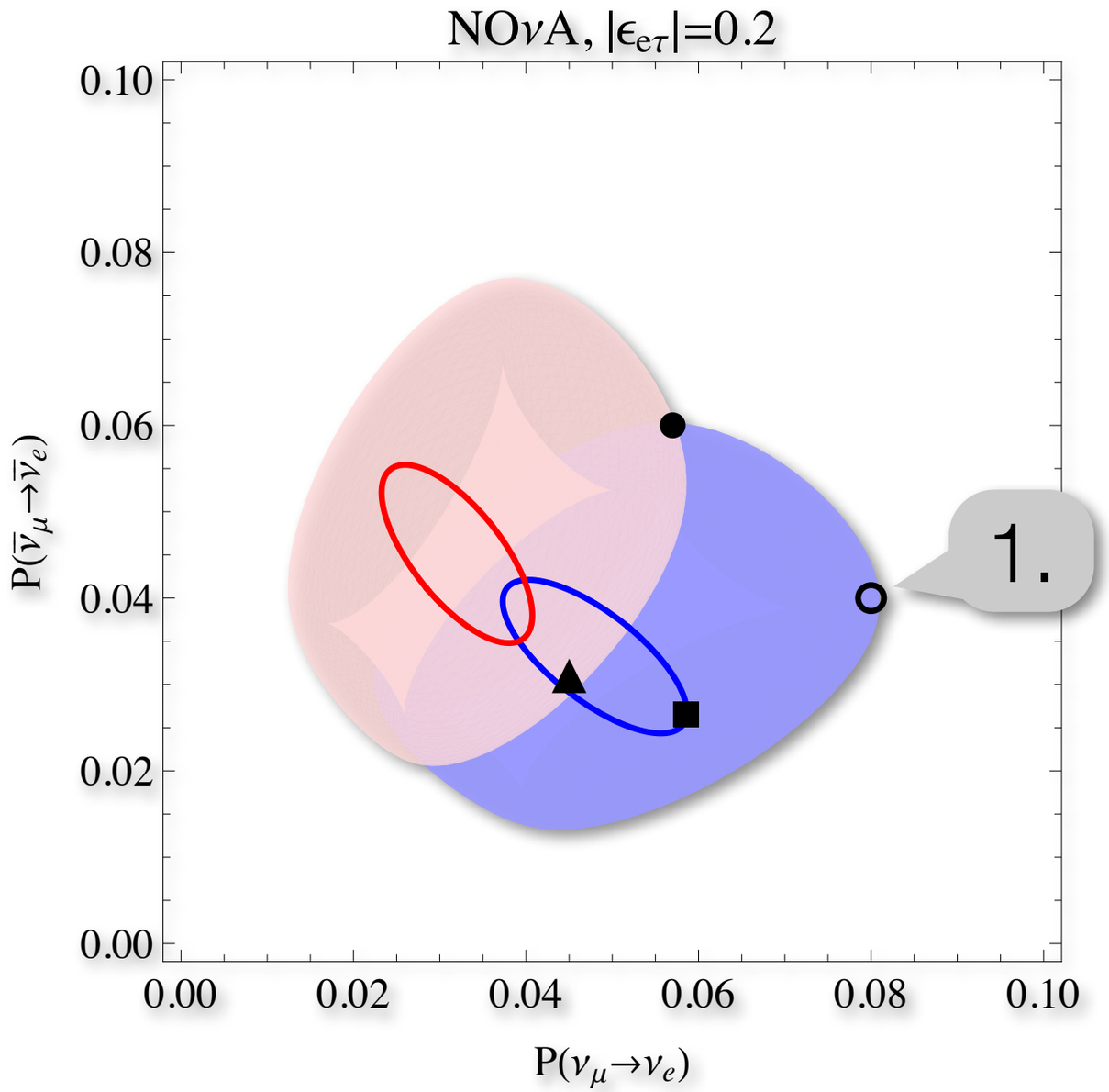

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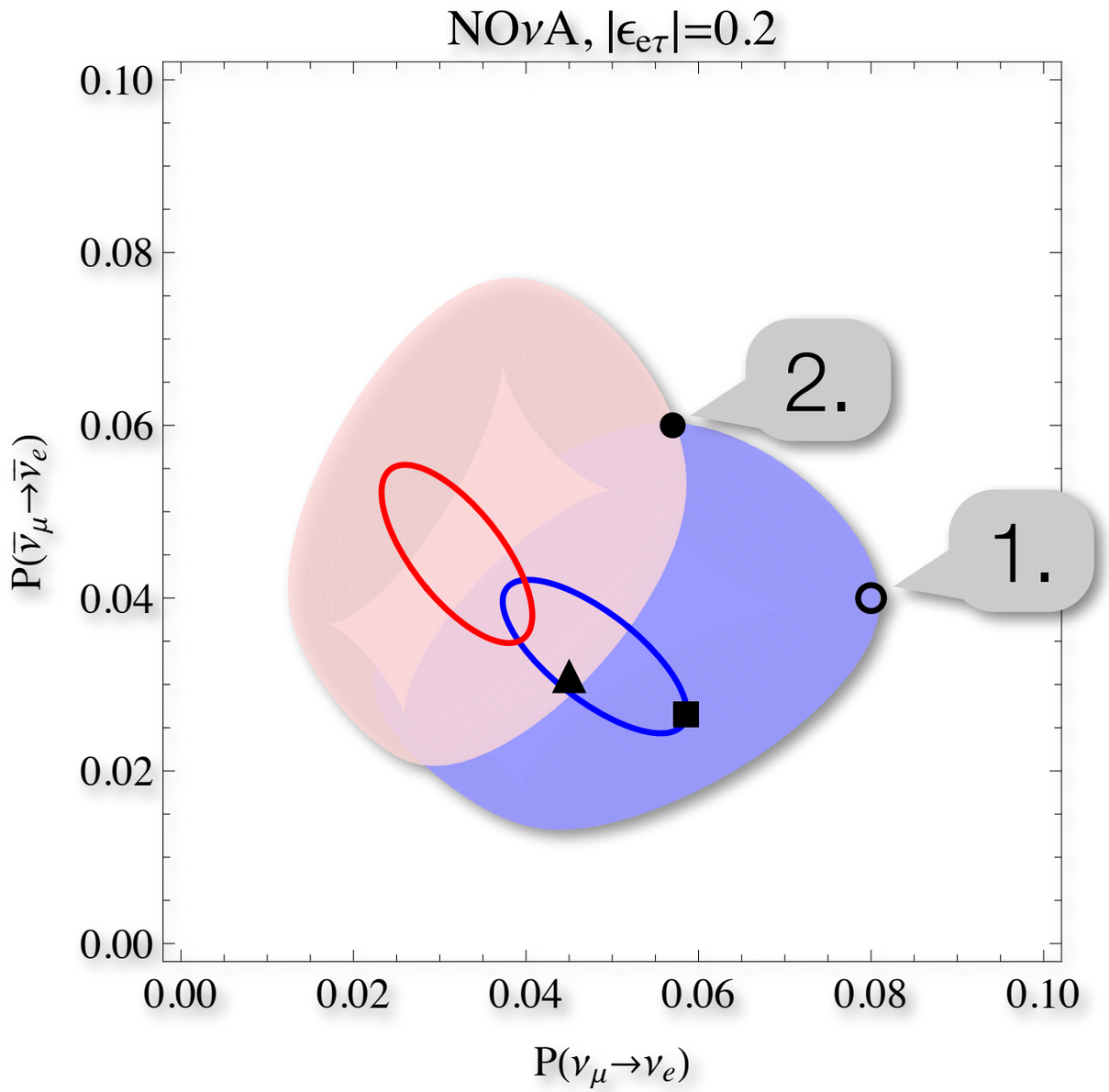

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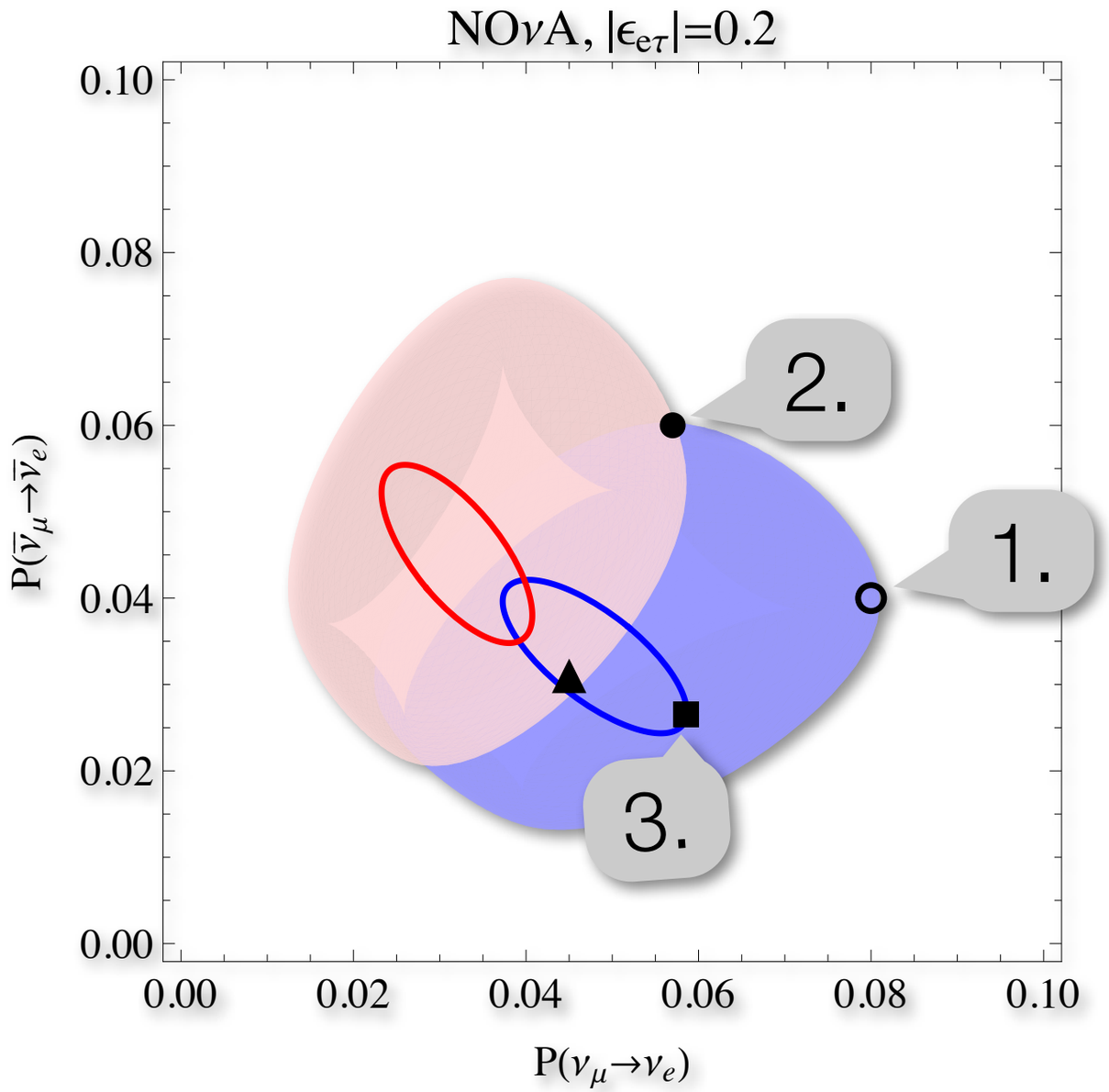

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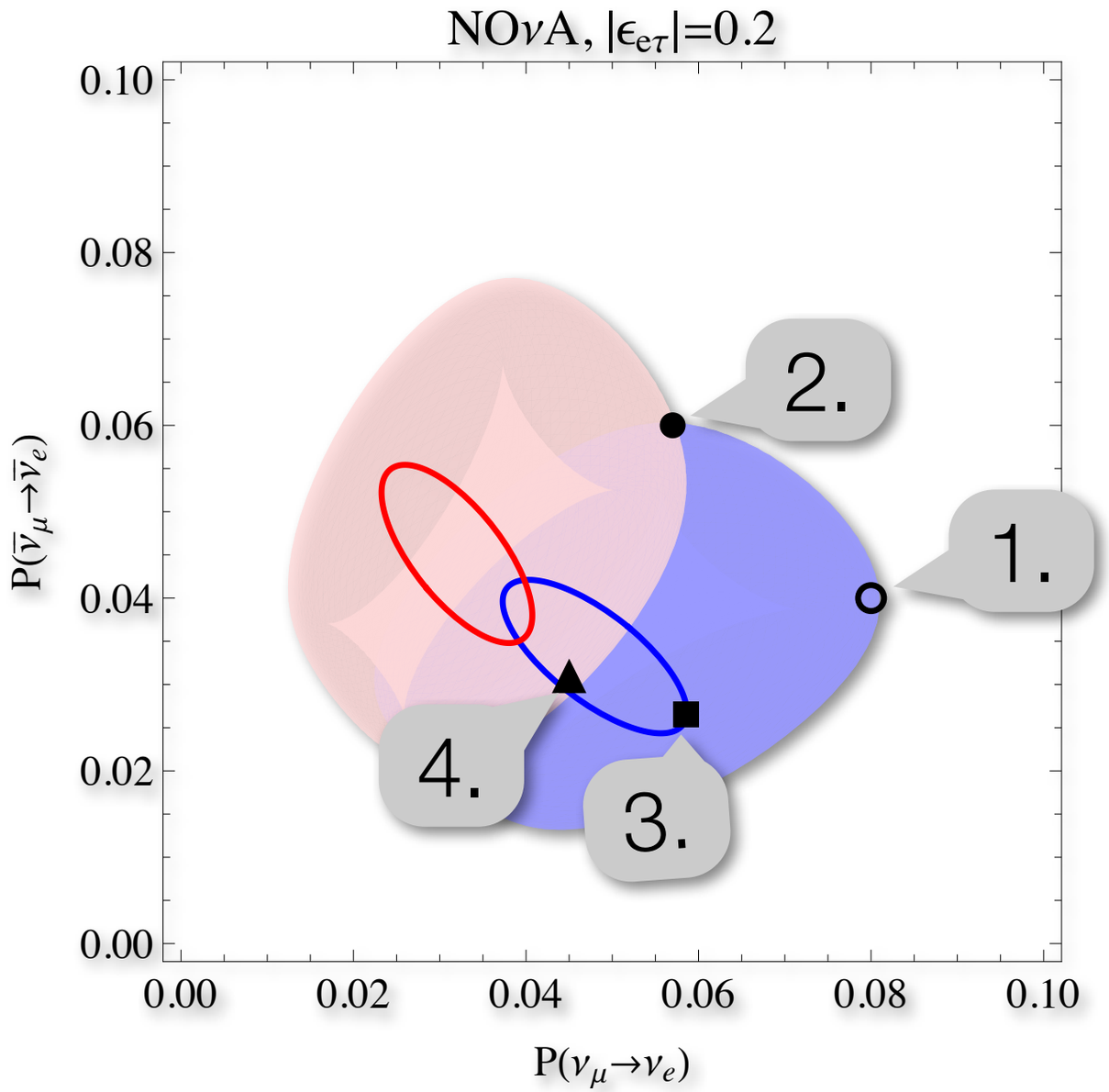
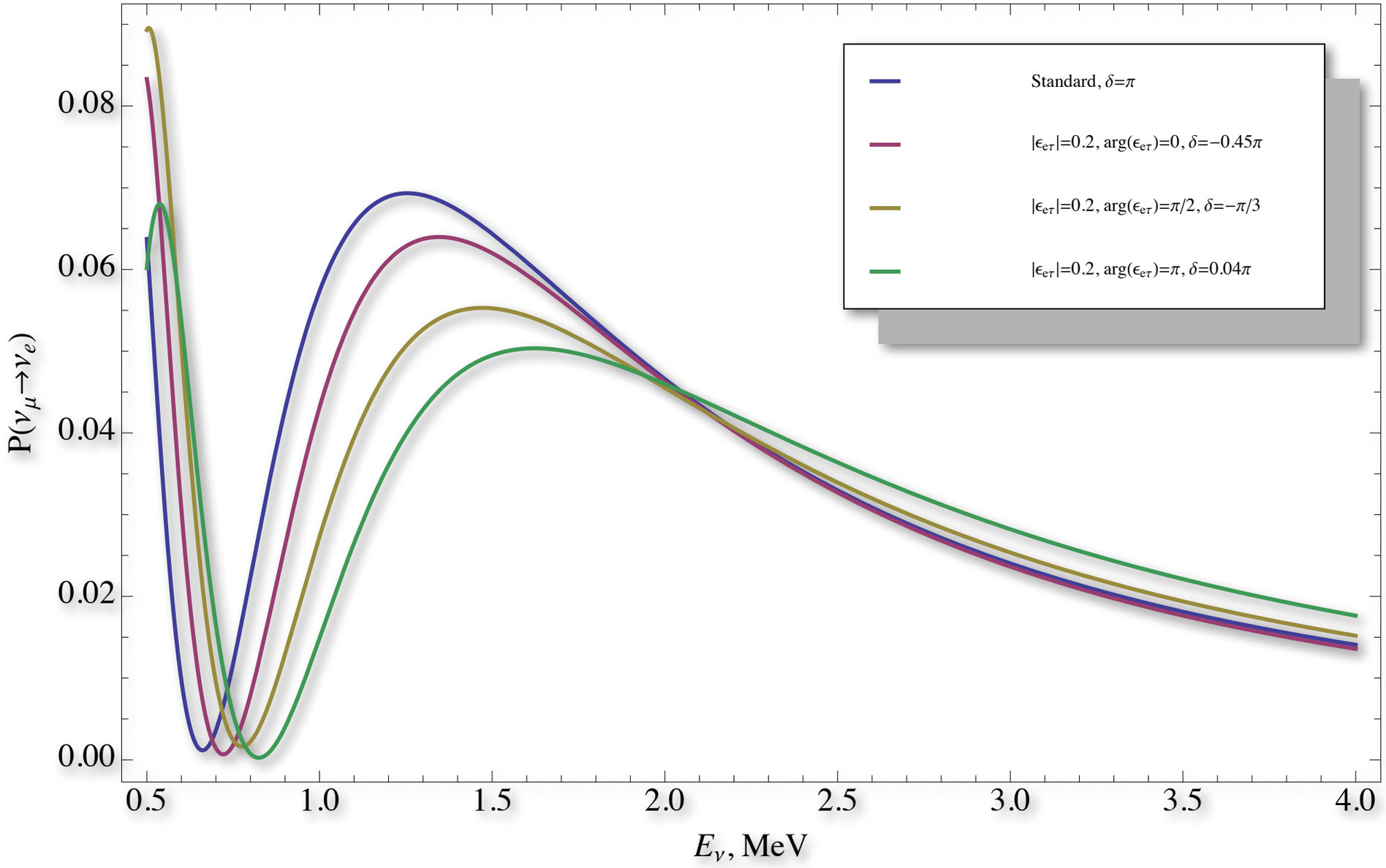
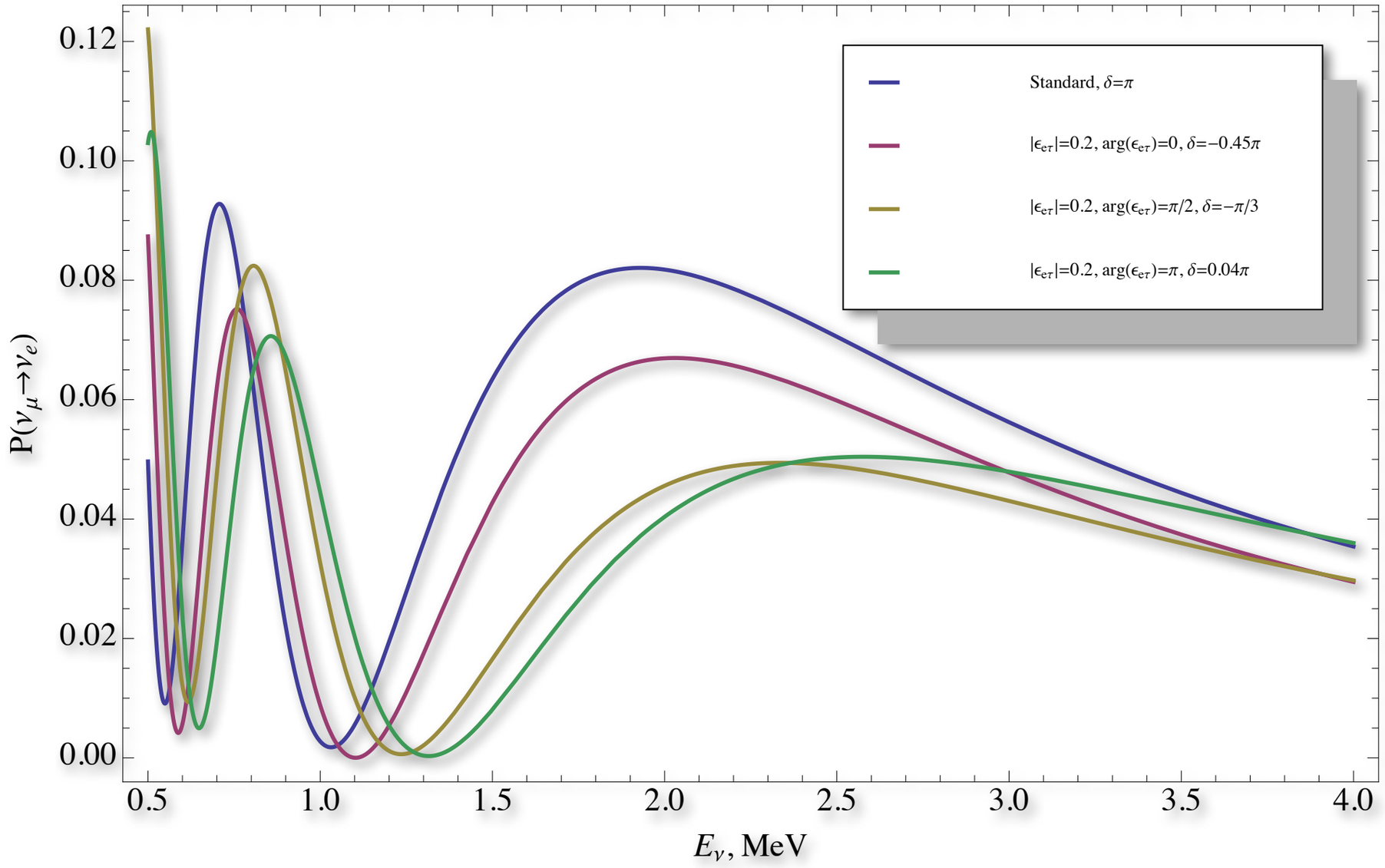


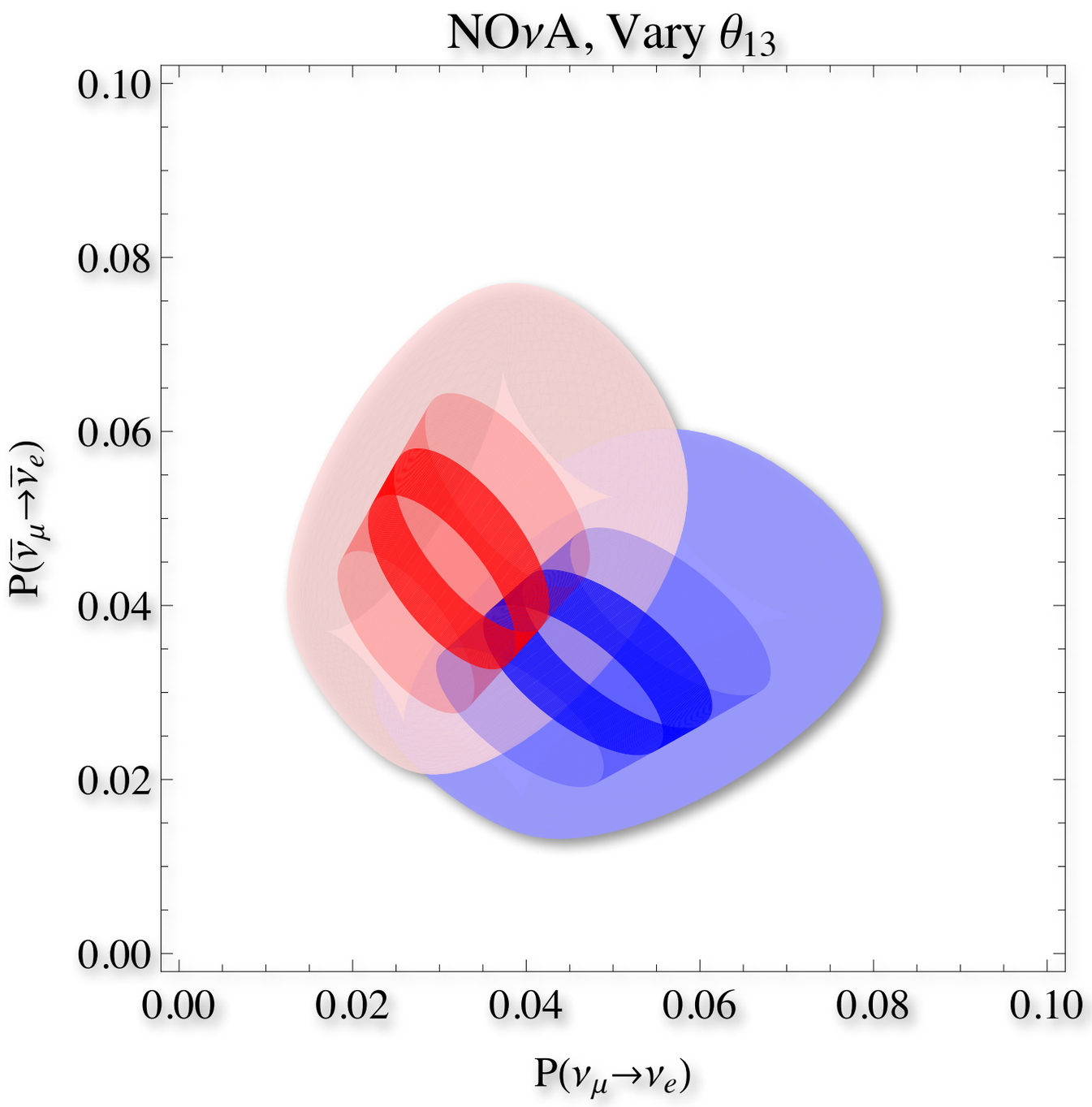
Degeneracies: spectra information



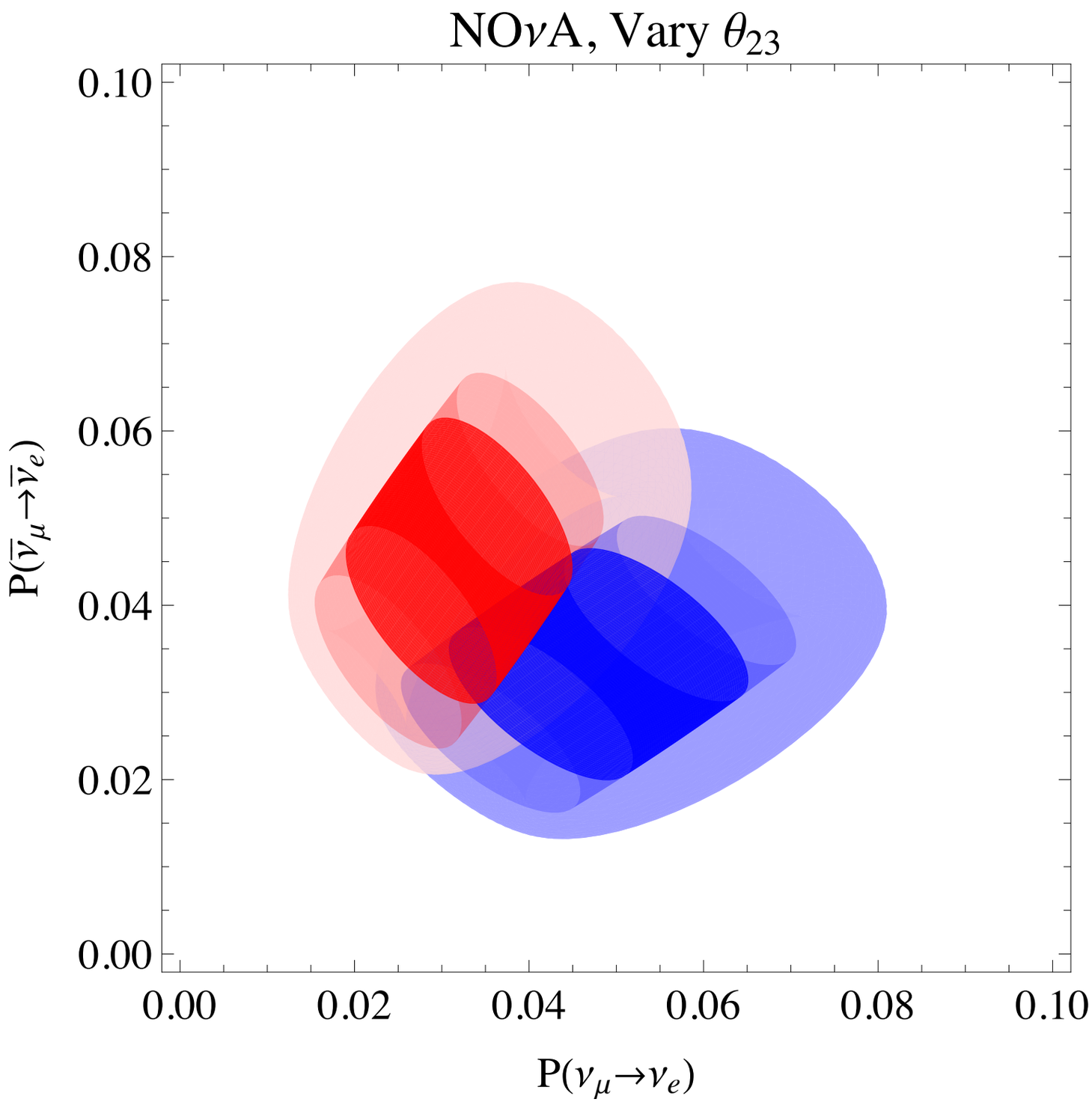
Degeneracies: Go to a different baseline (1300 km)



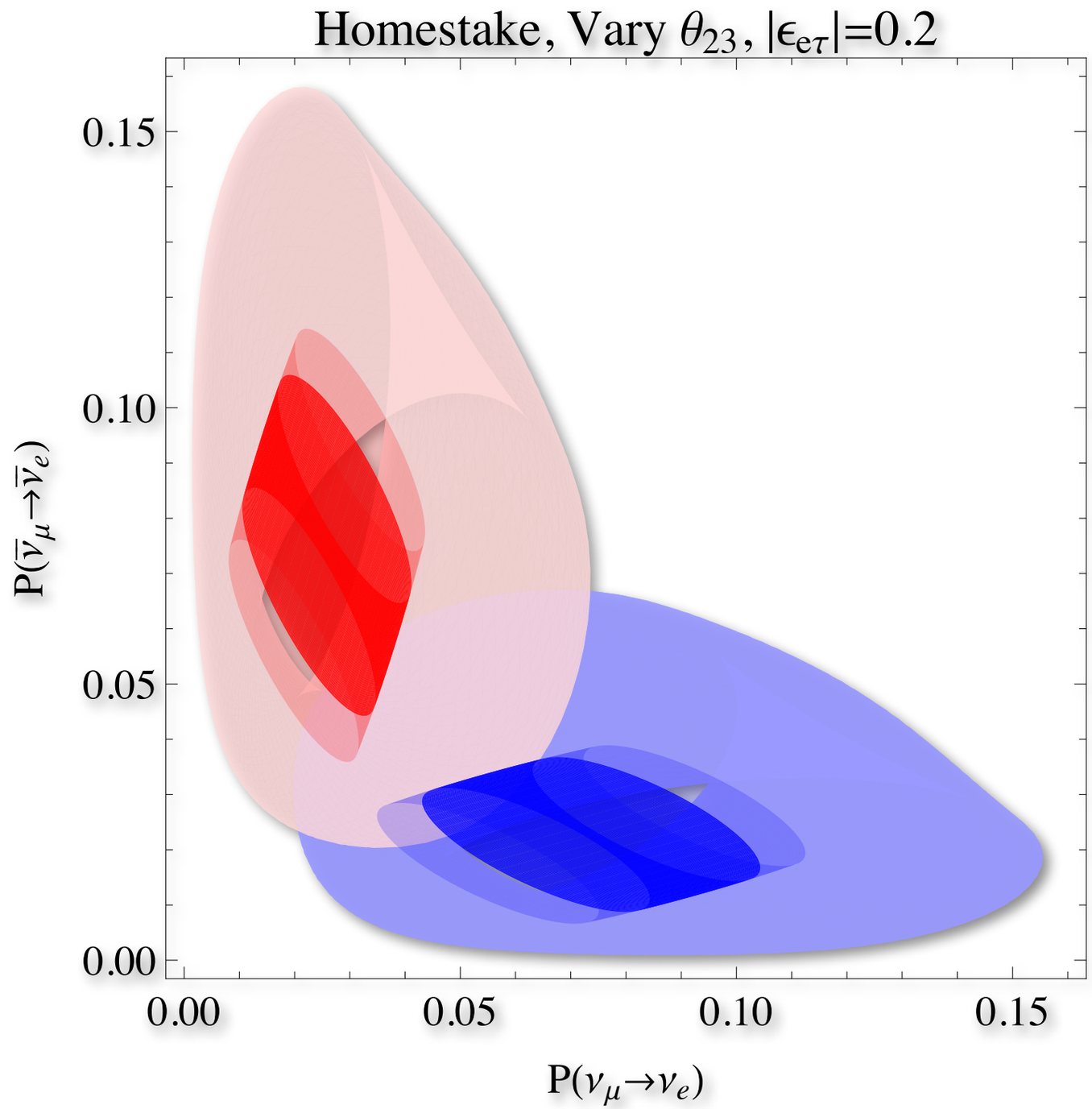
More degeneracies: theta13



More degeneracies: theta23 (dominant!)



Again: go to longer baseline!



Conclusions

- Simple NSI framework that illustrates many of the important physics points and could be used to gauge the reach of different experiments

- Minimalistic; based on the classical idea by Wolfenstein

- Solar neutrinos may be providing a hint. Not excluded by other experiments.

- Sensitivity of long-baseline experiments is much greater, thanks to large theta13 (interference!)

- Additional source of CP-violation! What have you measured

- Multiple baselines, spectral information needed to correctly interpret data and understand the degeneracies