“Nonstandard” neutrino interactions

Alexander Friedland

Los Alamos

Outline

- Possible new neutrino interactions and oscillations
  - Solar
  - Atmospheric
  - Long-baseline
- Collider constraints
- Other considerations: stars

Time permitting

Generalizing Fermi

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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.

$$\mathcal{L}_{\rm NSI} = -2\sqrt{2}G_F\,\epsilon^{fP}_{\alpha\beta}(\overline{\nu}_\alpha\gamma^\rho\nu_\beta)(\overline{f}\gamma_\rho P f)$$

Neutrino Flavor

f =SM fermion
P=L,R

Laid the foundation for the MSW effect and pointed out that NSI can modify neutrino propagation.

- Lots of NSI papers since
  - Hundreds in the last ten years alone
- The motivation here is to outline some physics arguments, not to give a complete review of the subject

Simplifying framework

- Following Wolfenstein, let's suppose new flavor-changing interactions
  - For clarity, just a single term: a flavor changing $qq\nu_e\nu_\tau$ interaction

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

  - subdominant to the SM weak interactions
  - Effective low-energy interaction, can be due to many different kinds of underlying physics

Solar neutrinos, 2004

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Solar neutrinos as probes of neutrino–matter interactions

Alexander Friedland [a], Cecilia Lunardini [b], Carlos Peña-Garay [b]

[a] *Theoretical Division, T-8, MS B285, Los Alamos National Laboratory, Los Alamos, NM 87545, USA*
[b] *School of Natural Sciences, Institute for Advanced Study, Einstein Drive, Princeton, NJ 08540, USA*

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Solar neutrinos, 2004

where level jumping can take place is narrow, defined by $A \simeq \Delta$ [21]. A neutrino produced at a lower density evolves adiabatically, while a neutrino produced at a higher density may undergo level crossing. The probability P_c in the latter case is given to a very good accuracy by the formula for the linear profile, with an appropriate gradient taken along the neutrino trajectory,

$$P_c \simeq \Theta(A - \Delta) e^{-\gamma(\cos 2\theta_{\rm rel}+1)/2}, \qquad (12)$$

where $\Theta(x)$ is the step function, $\Theta(x) = 1$ for $x > 0$ and $\Theta(x) = 0$ otherwise. We emphasize that our results differ from the similar ones given in [5,22] in three important respects: (i) they are valid for all, not just small values of α (which is essential for our application), (ii) they include the angle ϕ, and (iii) the argument of the Θ function does not contain $\cos 2\theta$, as follows from [21]. We stress that for large values of α and $\phi \simeq \pi/2$ adiabaticity is violated for large values of θ.

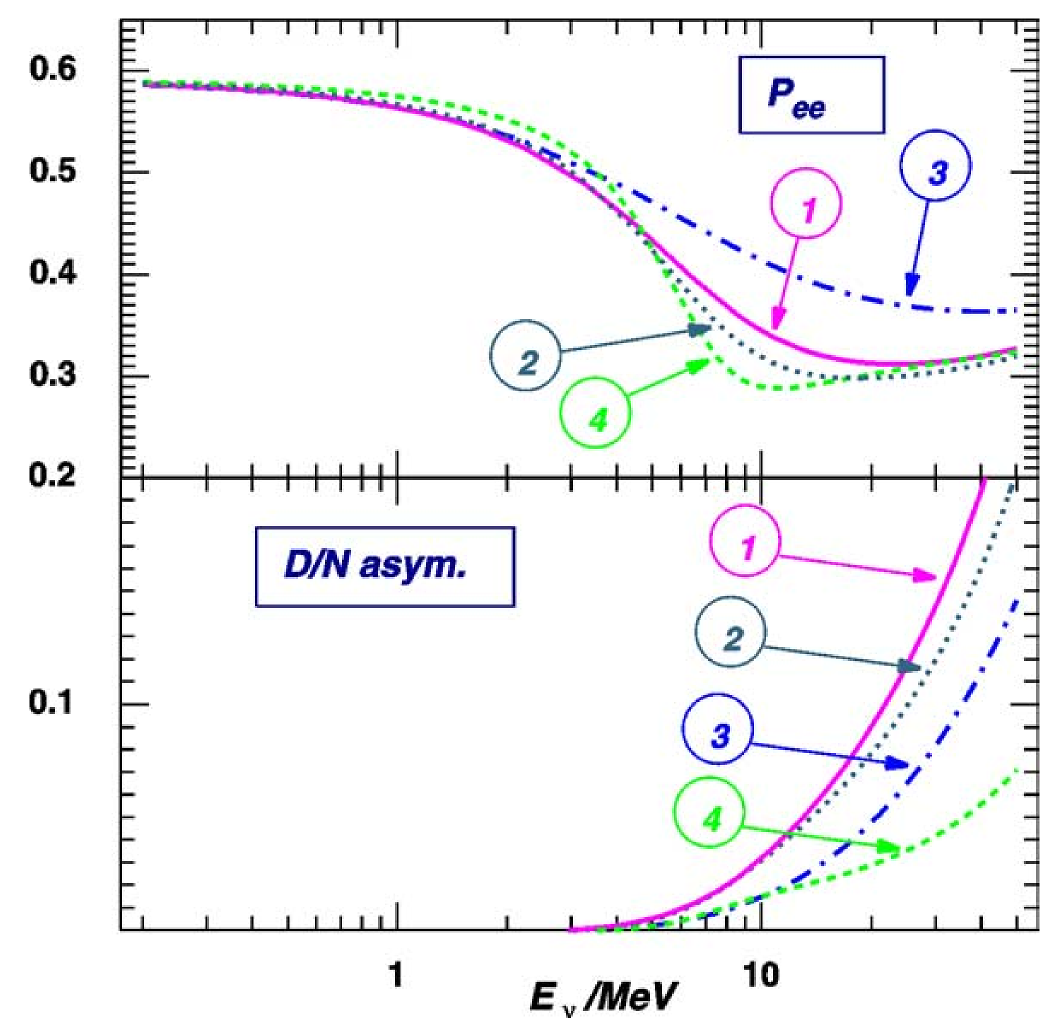
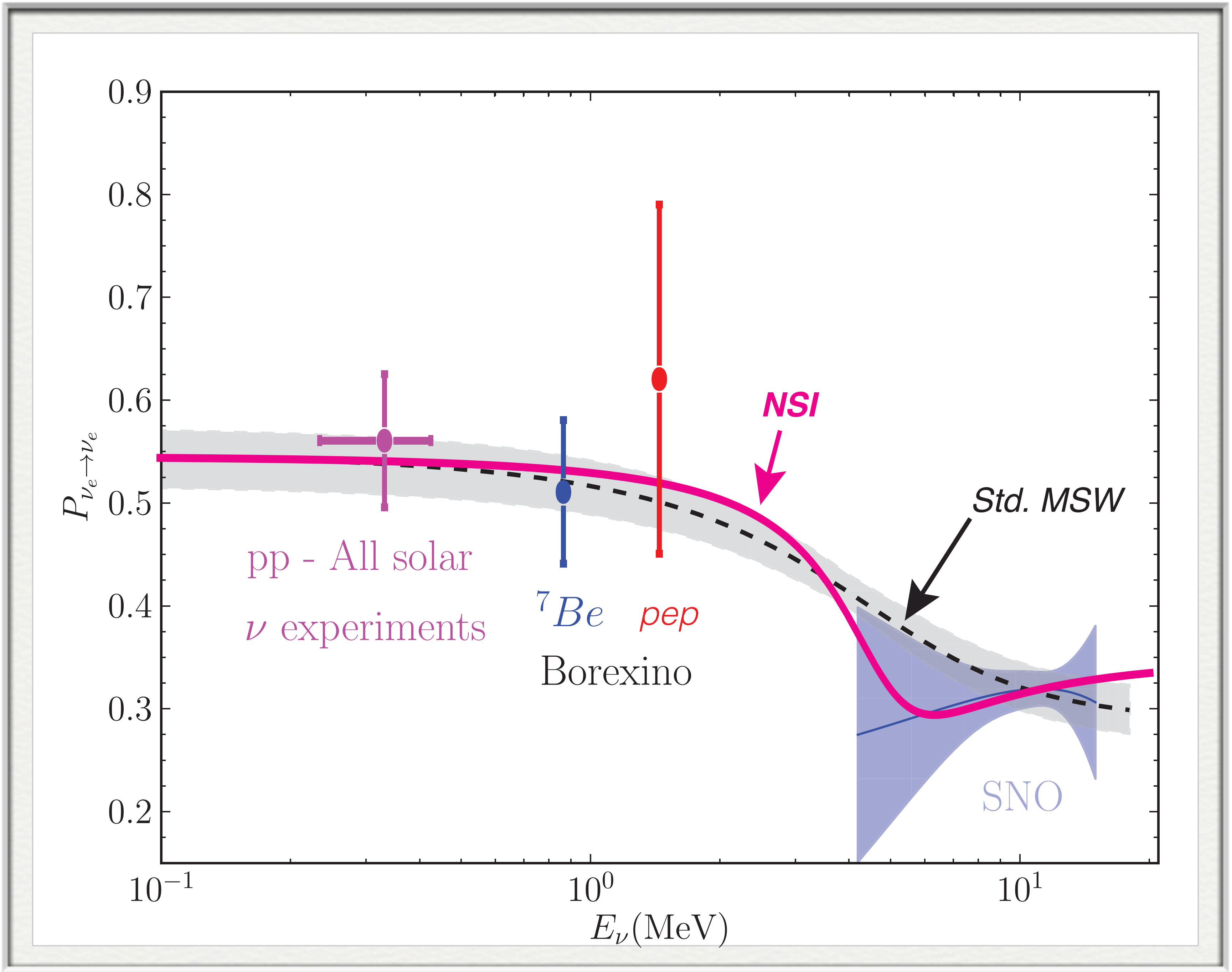


Fig. 1. The electron neutrino survival probability and the day/night asymmetry as a function of energy for $\Delta m^2 = 7 \times 10^{-5}$ eV^2, $\tan^2\theta = 0.4$ and several representative values of the NSI para-

Solar neutrinos, 2012



SNO 3-phase analysis 2011; our fit

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

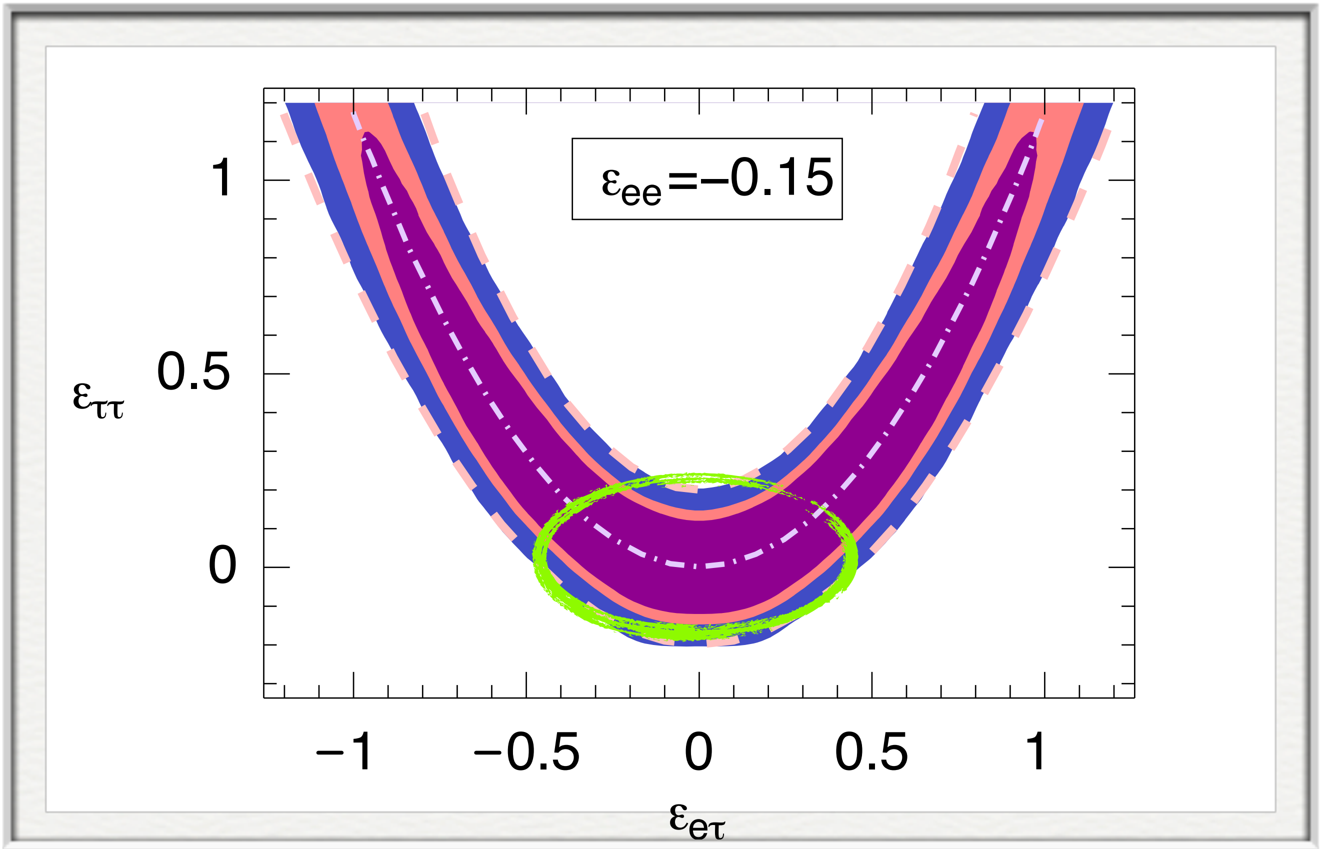
Atmospheric neutrinos

- A.F., Lunardini, Maltoni, PRD 2004;
  A.F., Lunardini, PRD 2005

- The same e-τ NSI shows up in atm. neutrinos at SuperK

- Data over 5 decades in energy! But energies not well-resolved

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



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

Long Baseline

- arXiv:1207.6642

LA-UR-12-22243

Searching for Novel Neutrino Interactions at NOνA and Beyond in Light of Large θ_{13}

Alexander Friedland* and Ian M. Shoemaker†
Theoretical Division T-2, MS B285, Los Alamos National Laboratory, Los Alamos, NM 87545, USA
(Dated: July 27, 2012)

We examine the prospects of probing nonstandard interactions (NSI) of neutrinos in the $e-\tau$ sector with upcoming long-baseline $\nu_\mu \rightarrow \nu_e$ oscillation experiments. First conjectured decades ago, neutrino NSI remain of great interest, especially in light of the recent ^8B solar neutrino measurements by SNO, Super-Kamiokande, and Borexino. We observe that the recent discovery of large θ_{13} implies that long-baseline experiments have considerable NSI sensitivity, thanks to the interference of the standard and new physics conversion amplitudes. In particular, in some parts of NSI parameter space, the upcoming NOνA experiment will be sensitive enough to see $\sim 3\sigma$ deviations from the SM-only hypothesis. On the flip side, NSI introduce important ambiguities in interpreting NOνA results as measurements of CP-violation, the mass hierarchy and the octant of θ_{23}. In particular, observed CP violation could be due to a phase coming from NSI, rather than the vacuum Hamiltonian. The proposed LBNE experiment, with its longer $\sim$ 1300 km baseline, may break many of these interpretative degeneracies.

PACS numbers: 14.60.Pq,26.65.+t, 25.30.Pt,13.15.+g,14.60.St

Interference of amplitudes

A.F. ,C. Lunardini, PRD (2006); A.F., I. Shoemaker, arXiv:1207.6642

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

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

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

- 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 CV-violating phase; interference depends on the relative phases!***

Relevant scales

- Assuming $E_\nu = 2$ GeV, $\theta_{23} = \pi/4$, and $\theta_{13} = 8.7^\circ$

$$
\begin{aligned}
\Delta \sin 2\theta_{13} &= 0.87 \times 10^{-13} \text{ eV}, \\
\sqrt{2} G_F n_e \cos\theta_{23} &= 0.76 \times 10^{-13} \text{ eV}, \\
\Delta_\odot \sin 2\theta_{12} &= 0.09 \times 10^{-13} \text{ eV}.
\end{aligned}
$$

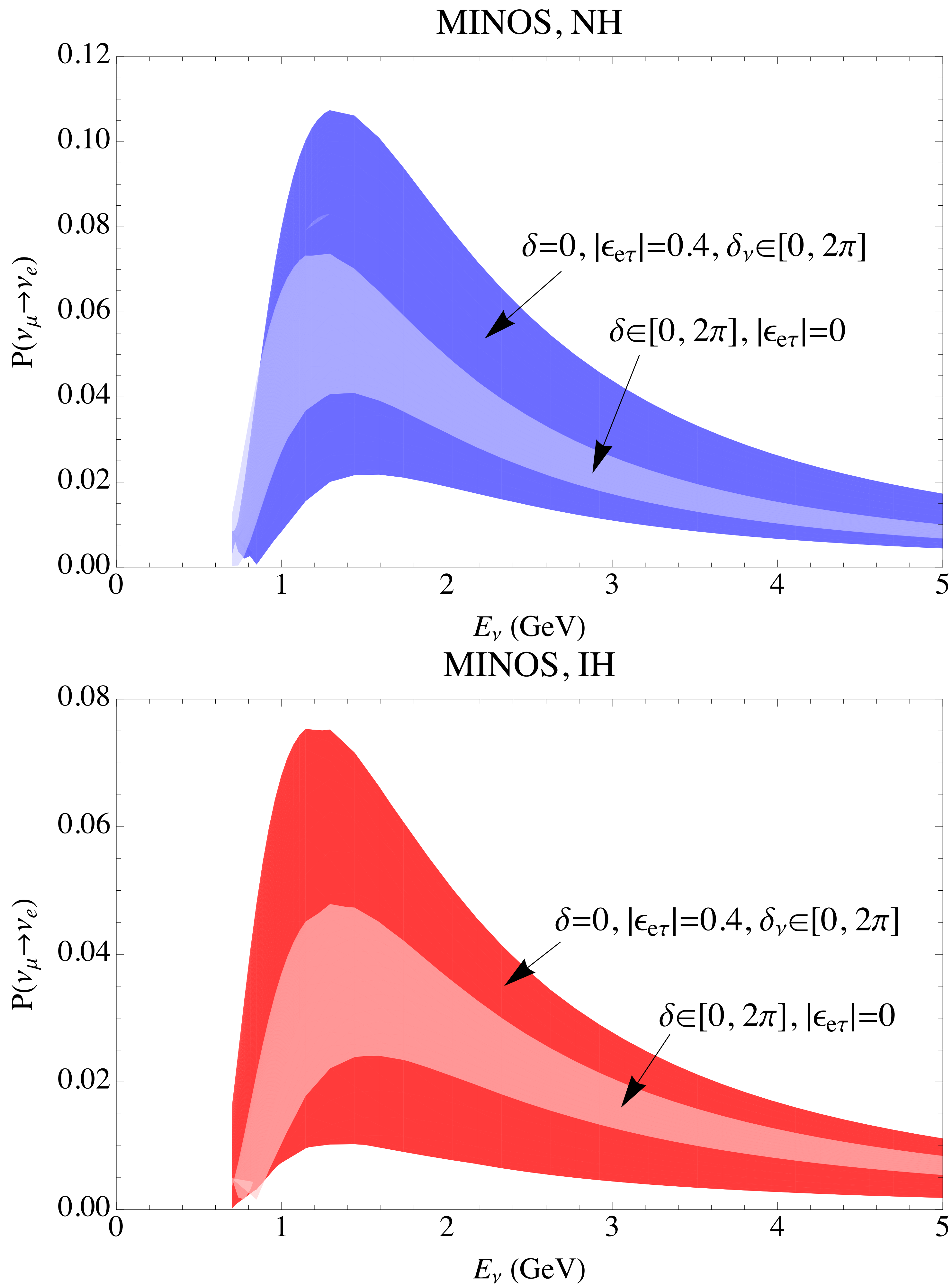
- For standard physics, the solar term is 0.1 of atm. Upon interference, ~20% modulation (hence, search for CP requires precision)

- Assuming NSI $\varepsilon_{e\tau}$ ~0.2, roughly motivated by the solar spectral data, we have

  - Atm > NSI > solar

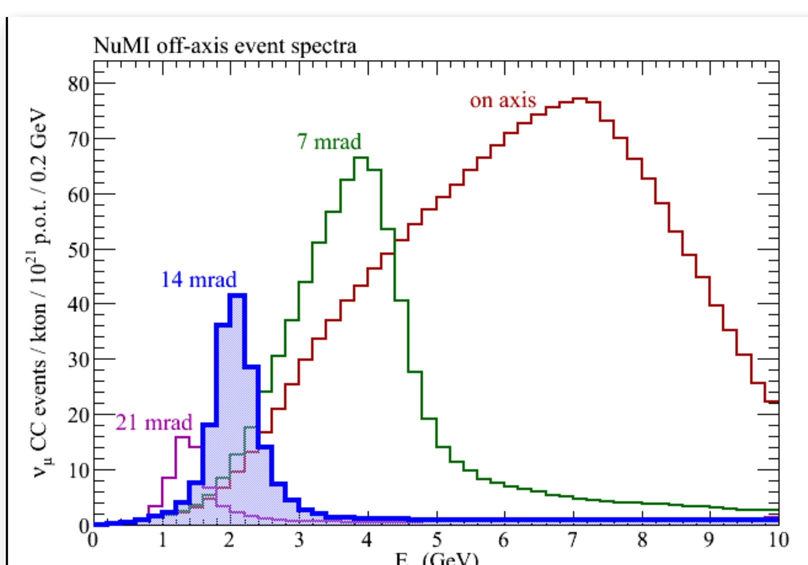
MINOS and “solar-inspired” NSI

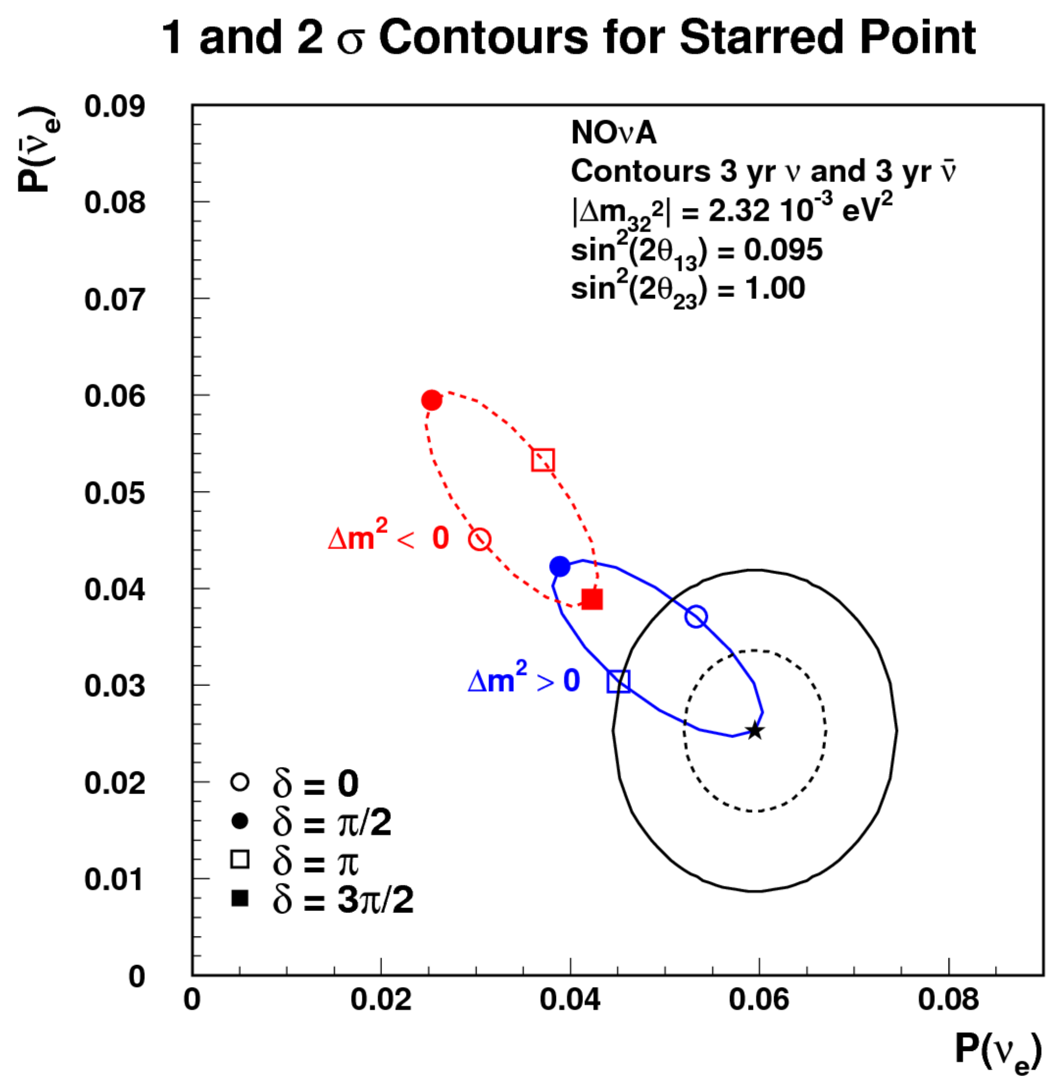
- Interference makes for a pretty large effect
    - Useful constraint already possible
    - On the other hand, NSI can confuse the hierarchies
- Need more sensitivity. NOvA?



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

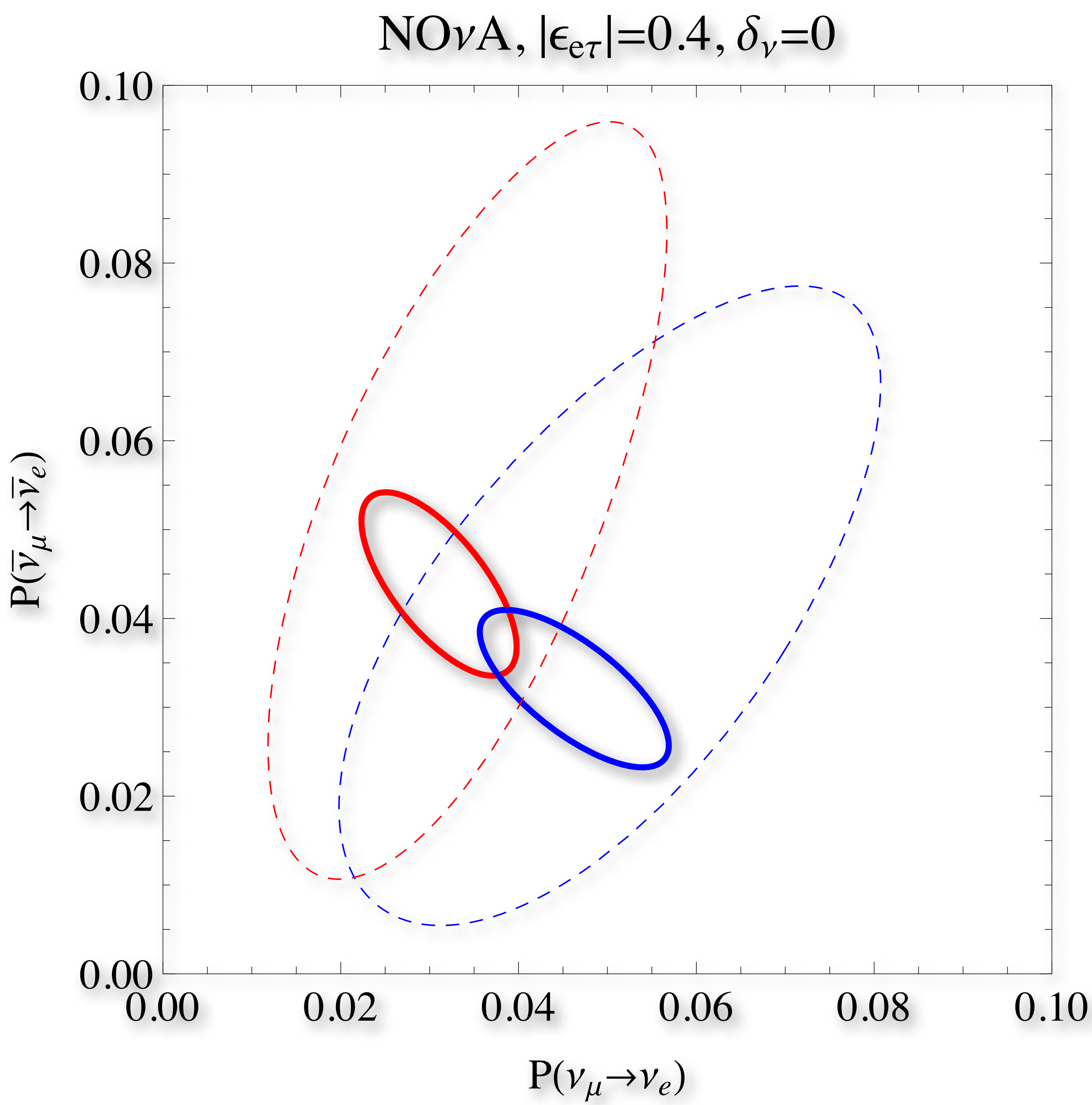




Ryan Patterson, NU 2012

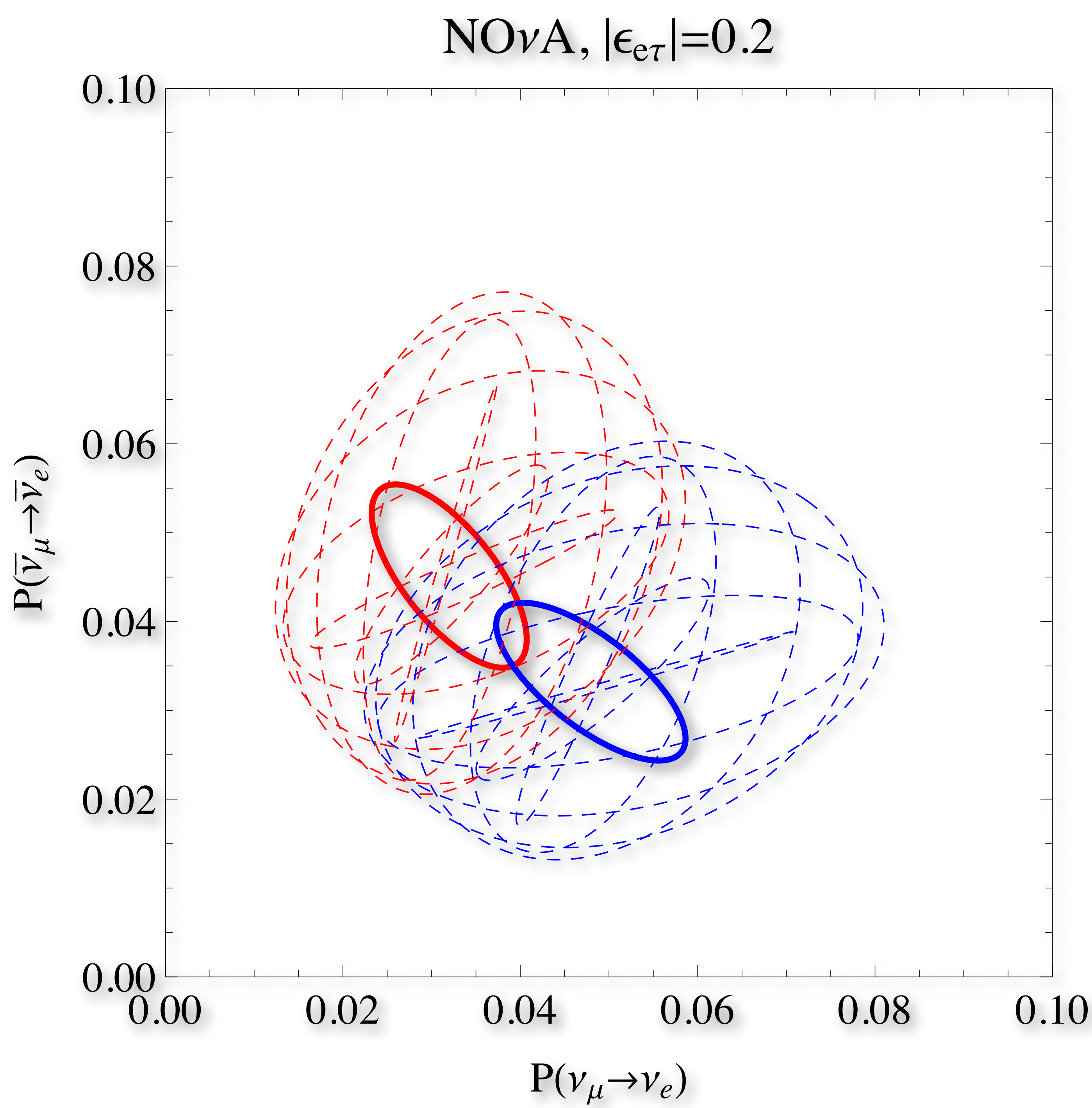
But what if there are also NSI?

- Let's take $\varepsilon_{e\tau}$ = +0.4, as in the earlier solar plot



Next step: vary the NSI phase

- Let's take a different approach: we don't care about solar data, just trying to constrain NSI.
- Take small $|\varepsilon_{e\tau}| \sim 0.2$, vary its phase freely
- The result is big regions in the bi-probability space



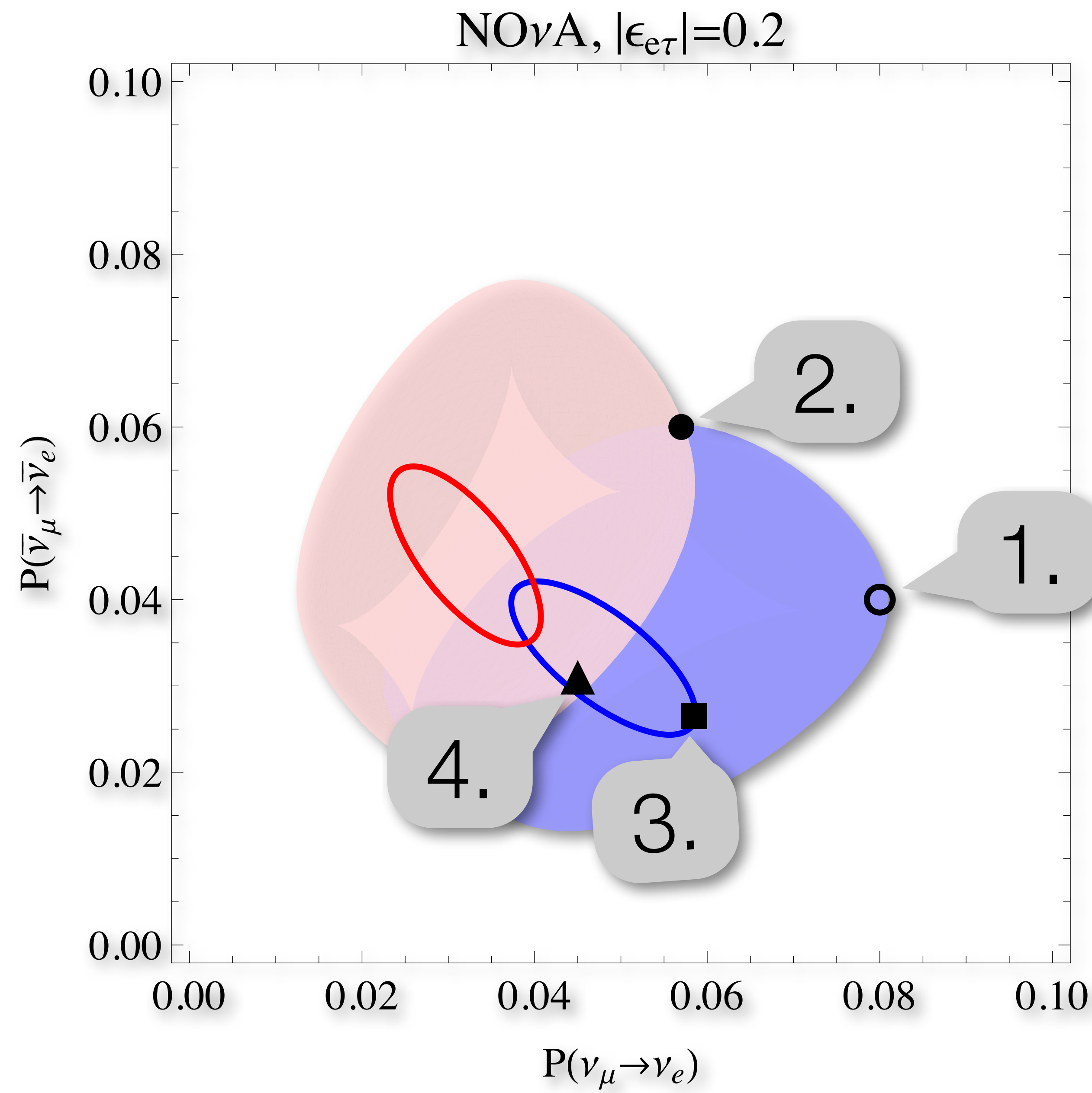
Qualitatively different possibilities

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

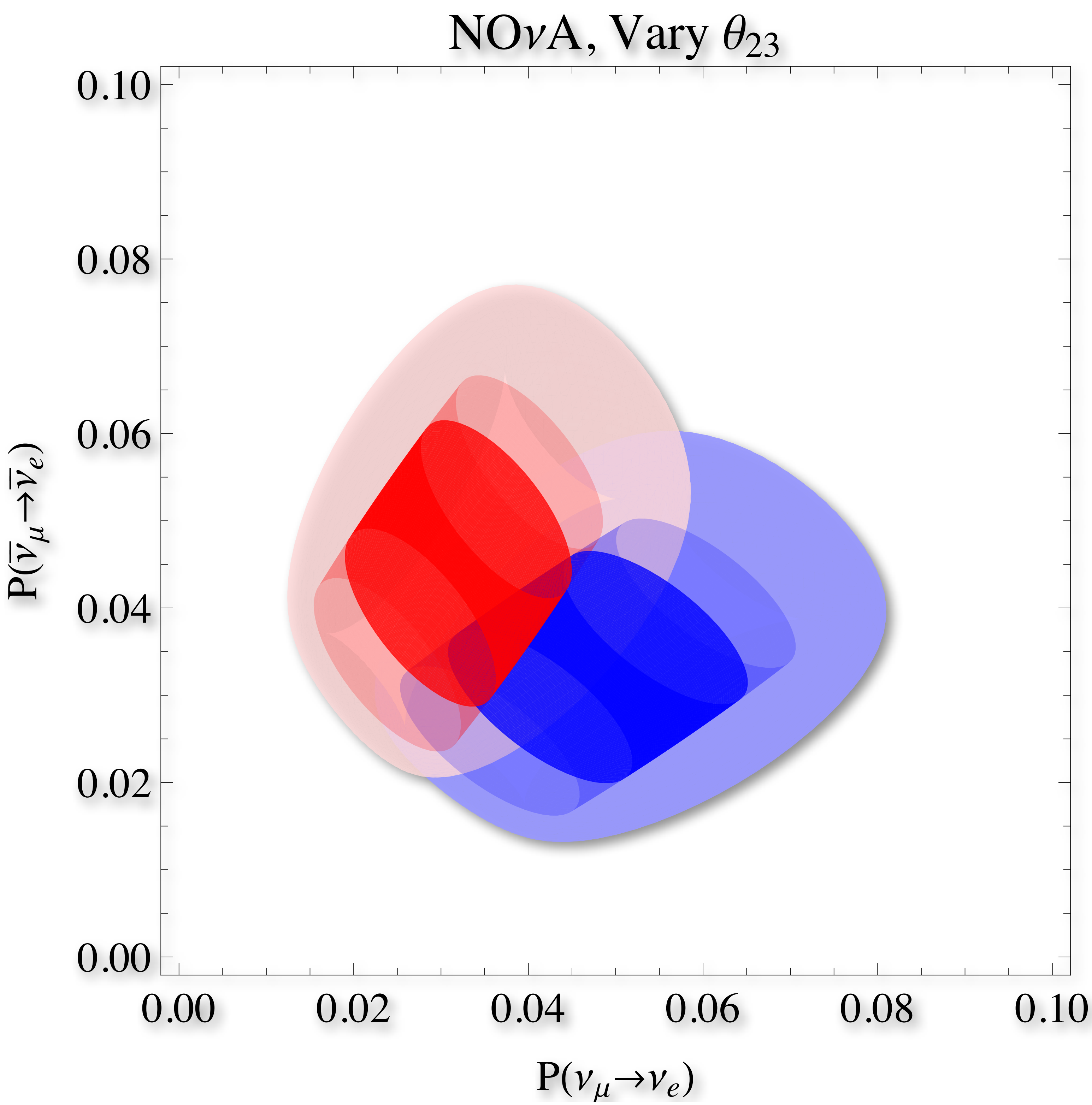
2. Large deviation from the standard ellipses: detection of new physics, but mass hierarchy is confused

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

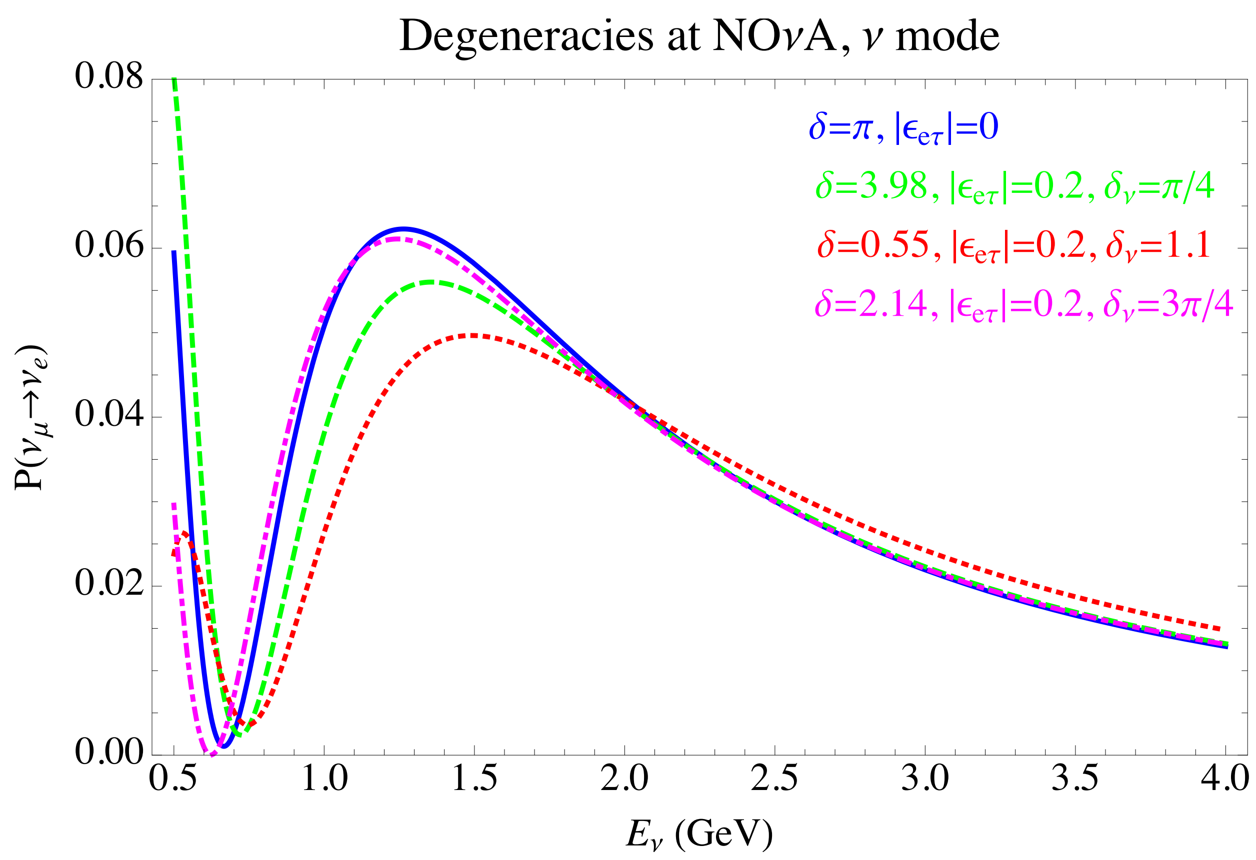
4. Complete confusion

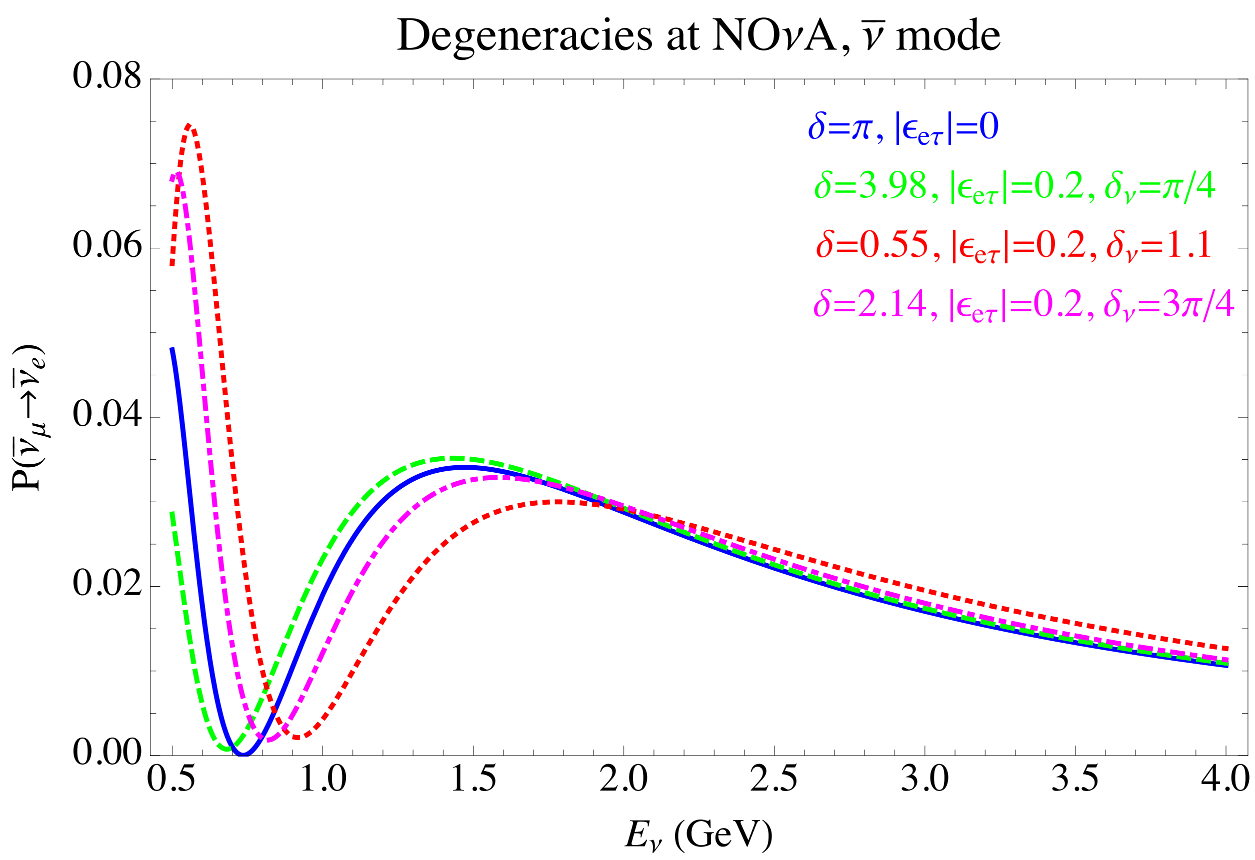


theta23 confusion: octant measurement?

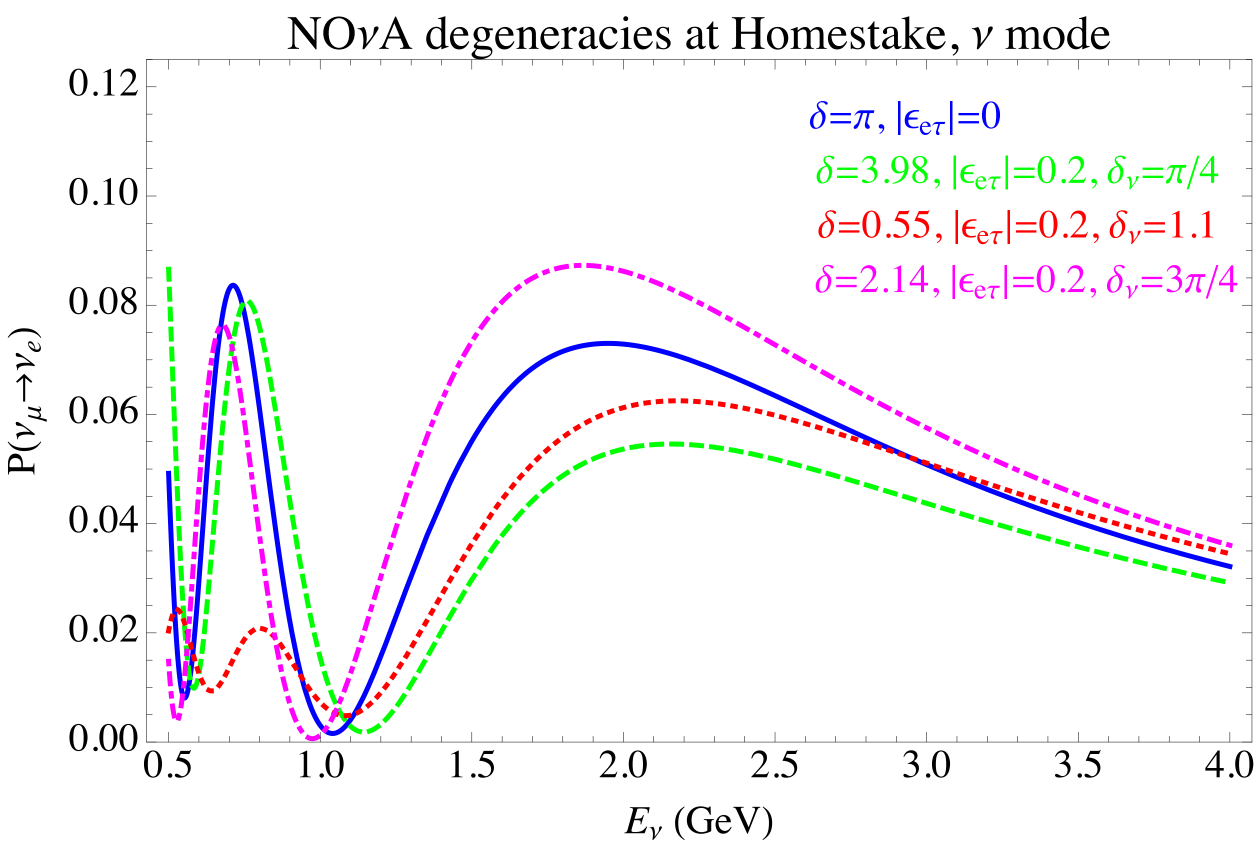


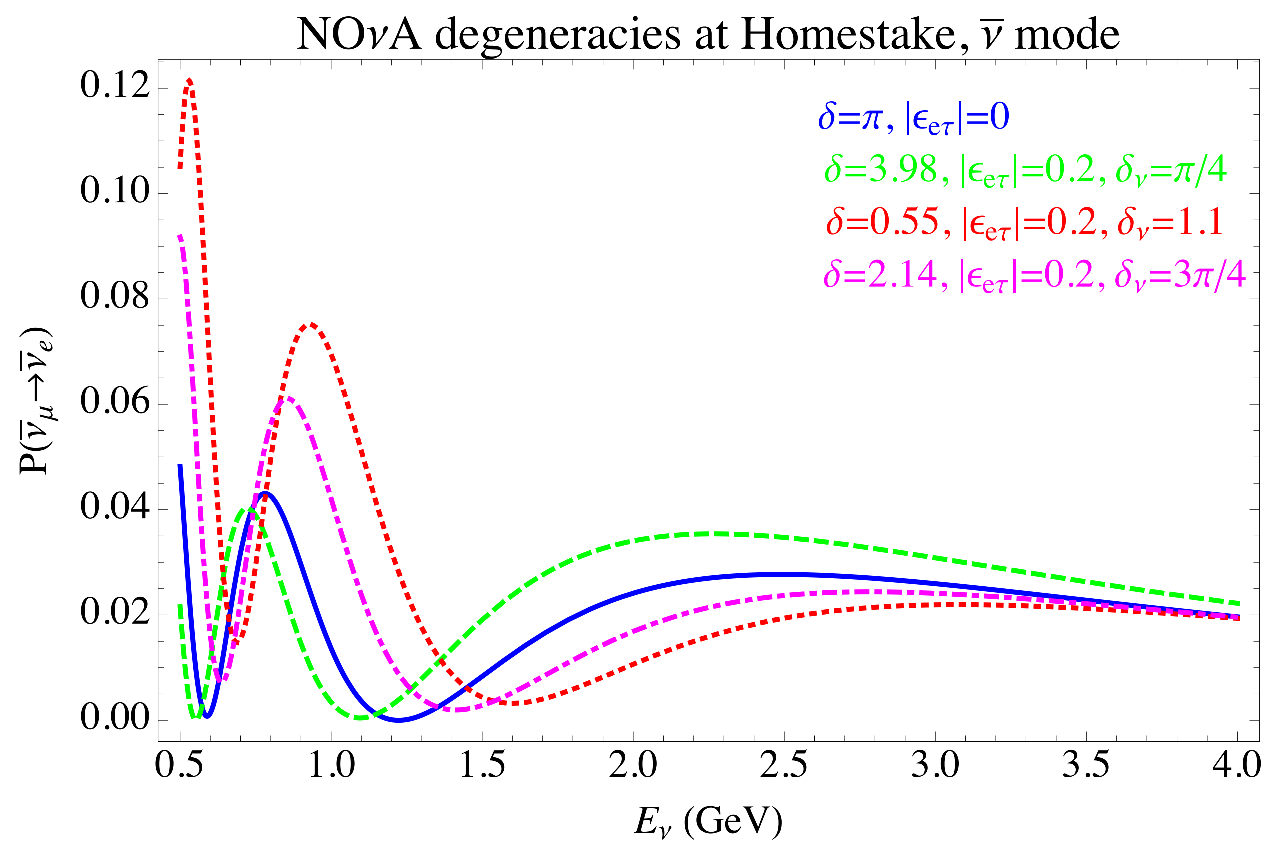
Degeneracies for point 4



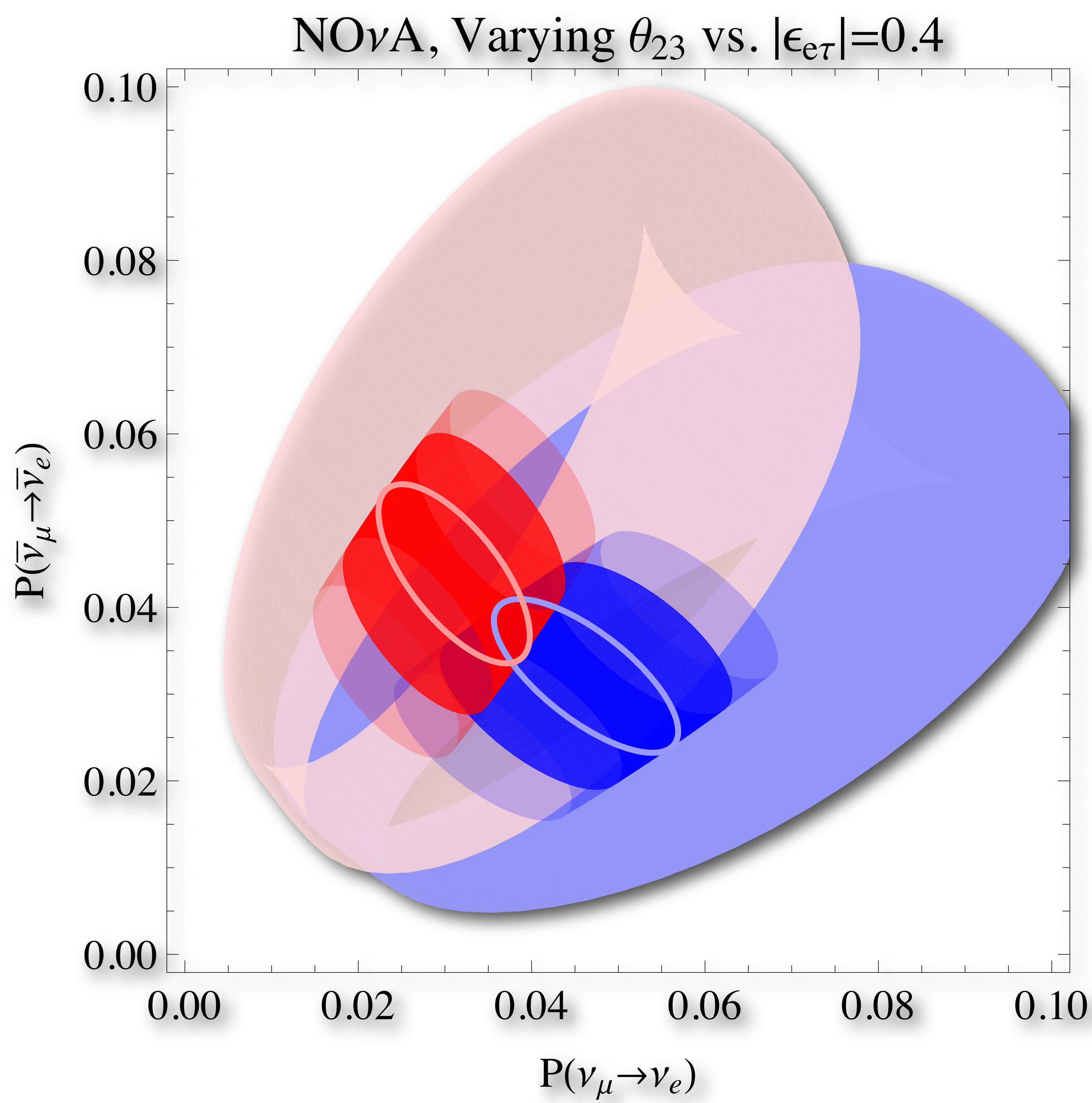


Solution: go to longer baseline!



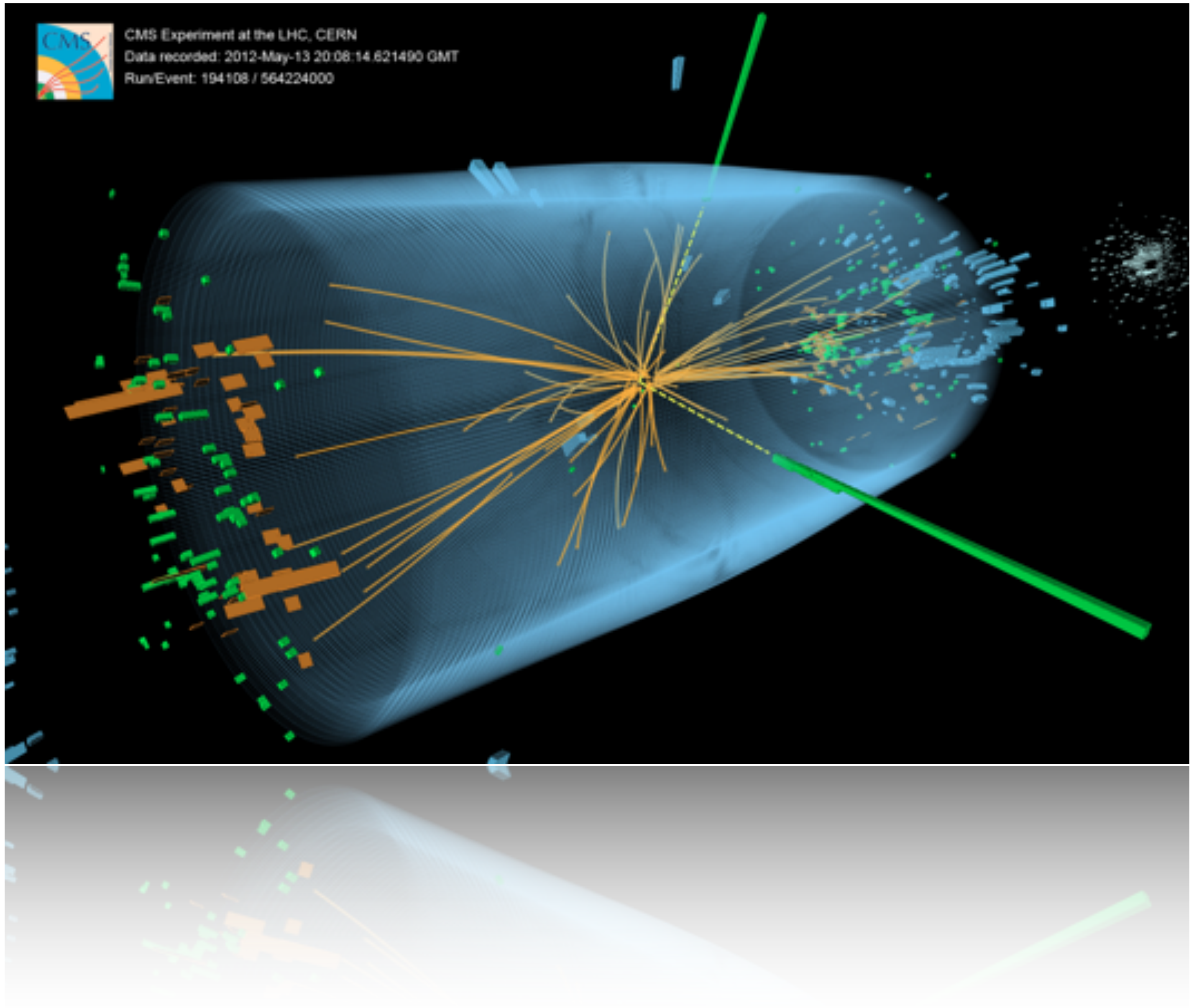


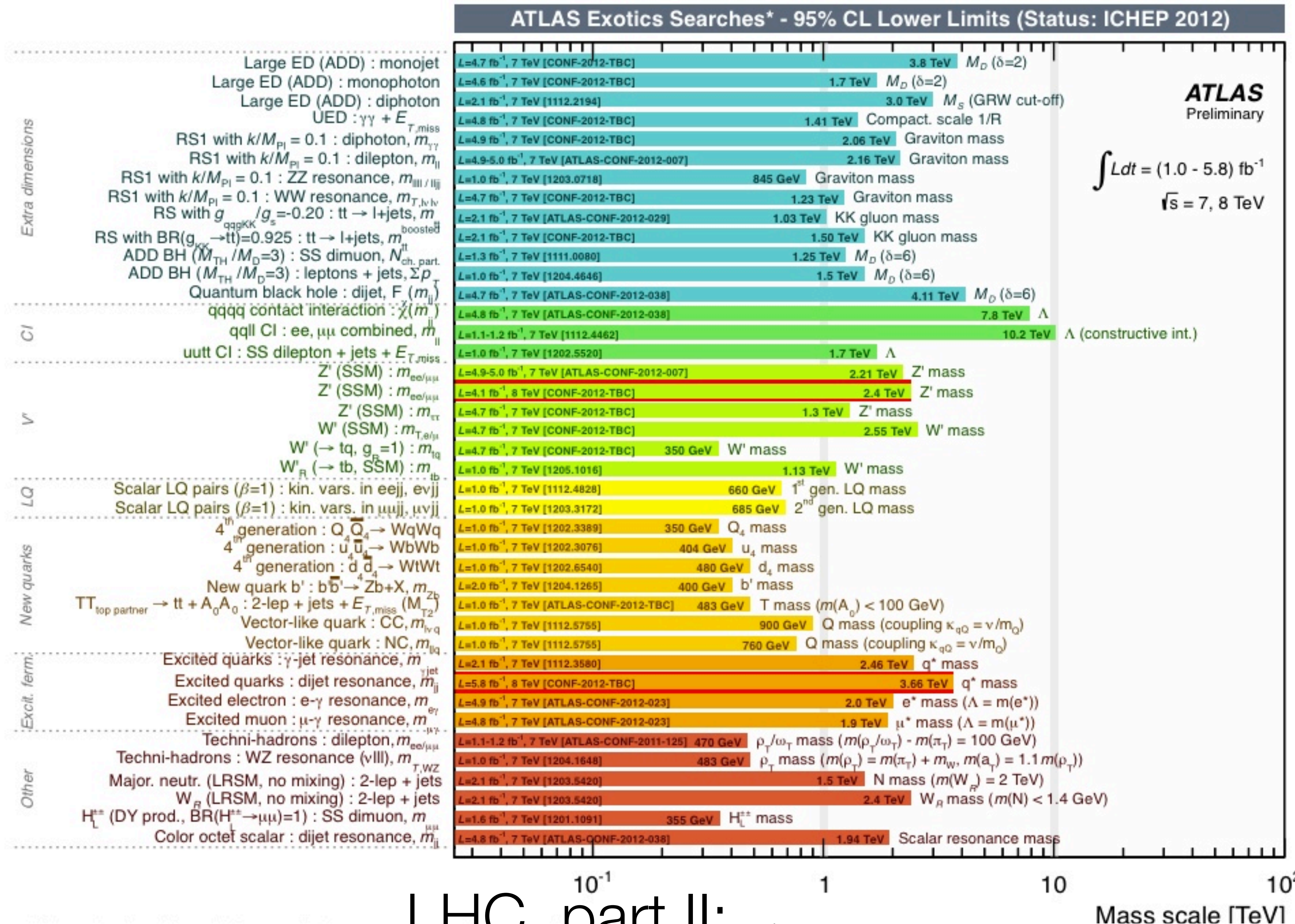
What about $|\epsilon_{e\tau}| \sim 0.4$?



Digression: LHC

- Was designed to find the Higgs
    - Specifically, detectors were optimized for $H \to \gamma\gamma$
- The discovery made front page of almost every newspaper in the world!



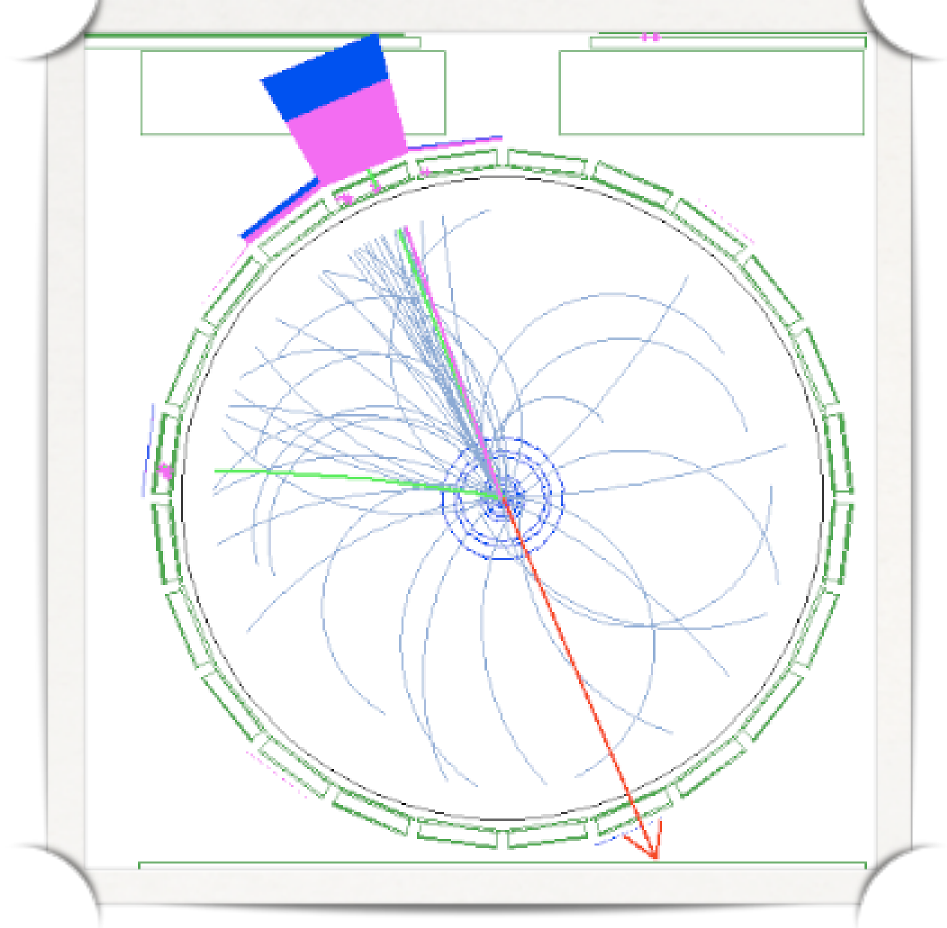


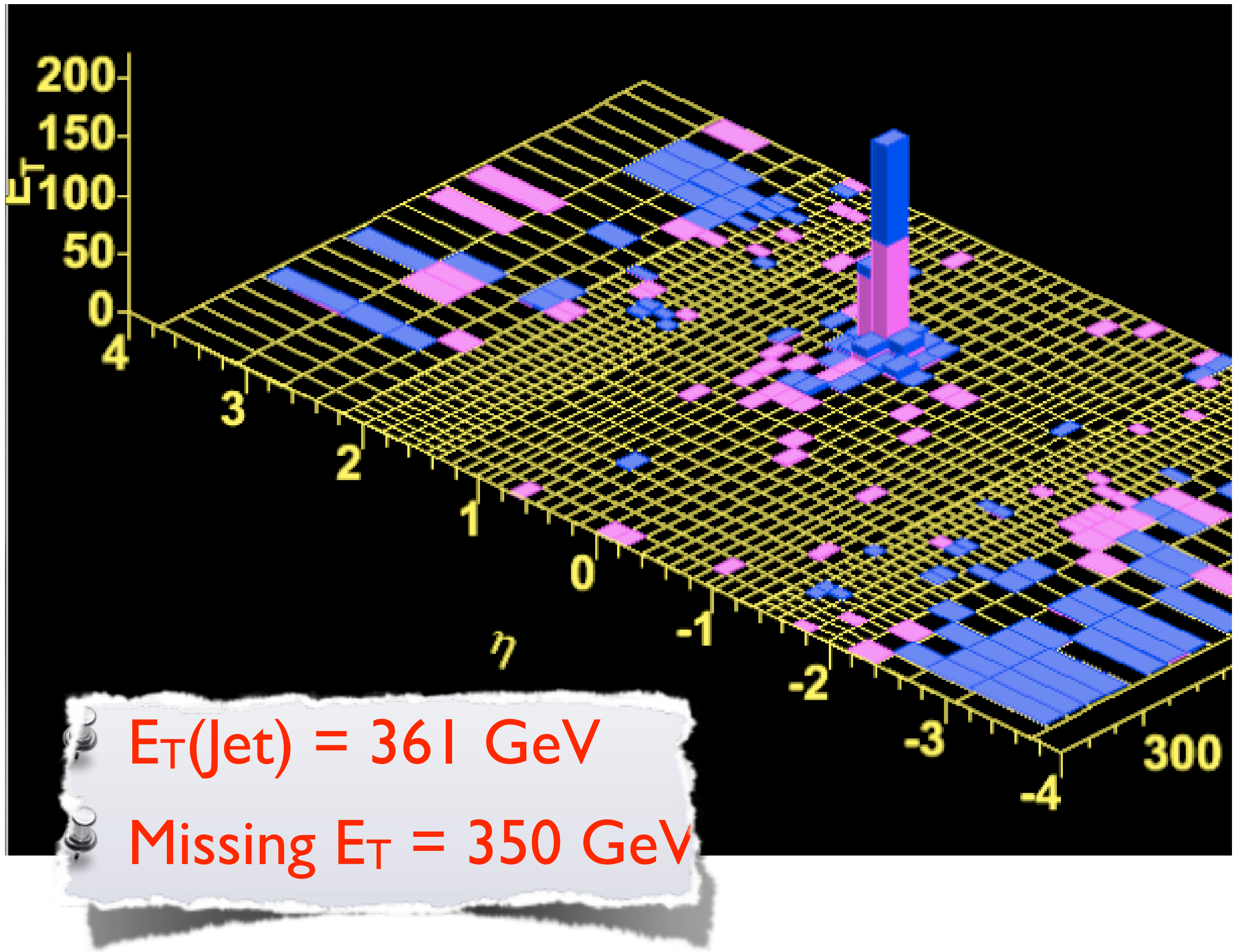
LHC, part II: new physics searches

SUSY, Extra dim, techni-stuff, ...

Collider NSI bounds: LHC Monojet searches

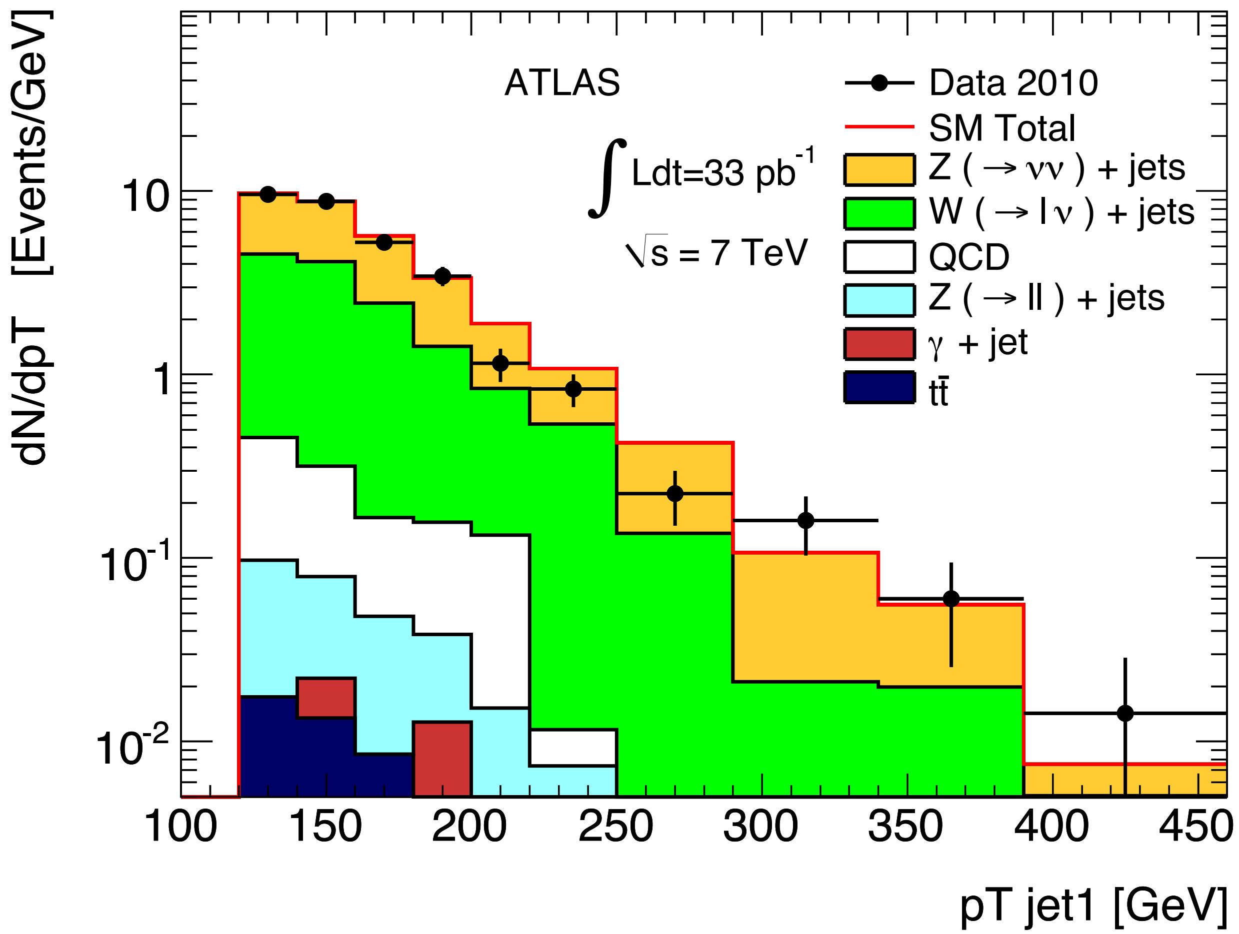
- "monojet" events contain a single prominent jet recoiling against "nothing"
- "nothing" could be, e.g., dark matter particles, extra-dim KK gravitons, etc





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

Do NSI remain contact at the LHC energies?

- If yes, bounds in the Table

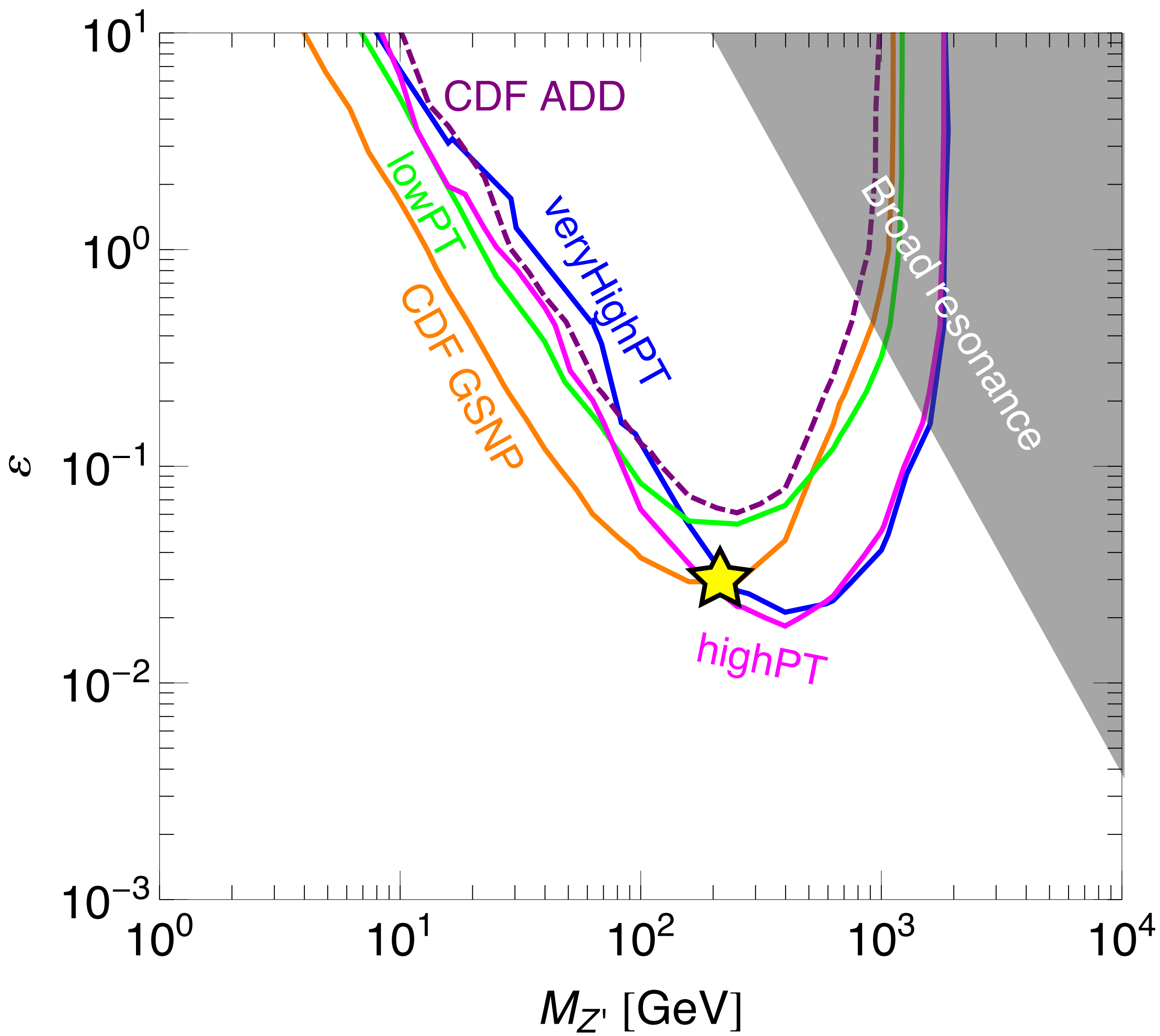
	CDF		ATLAS [31]		
	GSNP [32]	ADD [4, 5]	LowPt	HighPt	veryHighPt
$\varepsilon^{uP}_{\alpha\beta=\alpha}$	0.45	0.51	0.40	0.19	0.17
$\varepsilon^{dP}_{\alpha\beta=\alpha}$	1.12	1.43	0.54	0.28	0.26
$\varepsilon^{uP}_{\alpha\beta\neq\alpha}$	0.32	0.36	0.28	0.13	0.12
$\varepsilon^{dP}_{\alpha\beta\neq\alpha}$	0.79	1.00	0.38	0.20	0.18

- Notice that these NSI are *per quark*! Keep in mind when comparing to NSIs in oscillation experiments

- But what if the NSI are not contact?

- No longer “model-independent”

LHC and Tevatron monojet constraints



Also directly translates into a DM bound

-Tevatron data is more constraining for

$$m_{Z'} \lesssim 200 \text{ GeV}$$

Contact:

$$\sigma_{monojet} \sim \alpha_s g_q^2 g_X^2 \frac{p_T^2}{M^4}$$

Light mediator:

$$\sigma_{monojet} \sim \alpha_s g_q^2 g_X^2 \frac{1}{p_T^2}$$

-Would a yet softer cut yield better bounds?

Conclusions NSI

- Neutrino NSI may represent a “portal” to new physics
- Solar neutrinos may be providing a hint. Not excluded by other experiments.
- Sensitivity of long-baseline experiments benefits from large $\theta 13$ (interference!)
- Additional source of CP-violation! What have you measured?
- *Multiple baselines*, *spectral information* desired to correctly interpret data and understand degeneracies.
- Connections to collider experiments, dark matter searches, stellar cooling, etc
    - Very interesting physics!