Neutrino Oscillation Phenomenology

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Neutrino oscillations

- consistent picture of three flavor oscillations from many experiments:

  solar neutrinos

  atmospheric neutrinos

  reactor neutrinos

  accelerator neutrinos

- with some “anomalies”

Three-flavor neutrino oscillations

- Three-flavor mixing matrix

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

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

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

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

	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.346$
$\theta_{12}/^\circ$	$33.57^{+0.77}_{-0.75}$	$31.37 \to 36.01$
$\sin^2\theta_{23}$	$0.446^{+0.008}_{-0.008} \oplus 0.593^{+0.027}_{-0.043}$	$0.366 \to 0.663$
$\theta_{23}/^\circ$	$41.9^{+0.5}_{-0.4} \oplus 50.3^{+1.6}_{-2.5}$	$37.2 \to 54.5$
$\sin^2\theta_{13}$	$0.0231^{+0.0019}_{-0.0019}$	$0.0173 \to 0.0288$
$\theta_{13}/^\circ$	$8.73^{+0.35}_{-0.36}$	$7.56 \to 9.77$
$\delta_{CP}/^\circ$	266^{+55}_{-63}	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.45^{+0.19}_{-0.16}$	$6.98 \to 8.05$
$\frac{\Delta m^2_{31}}{10^{-3}\ \mathrm{eV}^2}$ (N)	$+2.417^{+0.014}_{-0.014}$	$+2.247 \to +2.623$
$\frac{\Delta m^2_{32}}{10^{-3}\ \mathrm{eV}^2}$ (I)	$-2.411^{+0.062}_{-0.062}$	$-2.602 \to -2.226$

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

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

Learning about neutrinos

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Neutrino oscillations

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Other (neutrino) observations

- absolute mass scale

A lot more!

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.

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!

Neutrino mass

Simplest scenario:

right-handed neutrino

Majorana mass $M > v$ ⟶ 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: $m \sim \frac{Y'^2 v'^2}{M'}$

v' and M' can both be much smaller

Different scenarios

keV, MeV, GeV discussed in different contexts

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 (get more from the data you have/can get)

Non-Standard neutrino Interactions (NSI)

Neutrino oscillations in matter
Phys. Rev. D **17**, 2369 – Published 1 May 1978
L. Wolfenstein

ABSTRACT

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.

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

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 $\epsilon_{\alpha\beta}$
- 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 $\epsilon_{\alpha\beta}$

NSI constraints

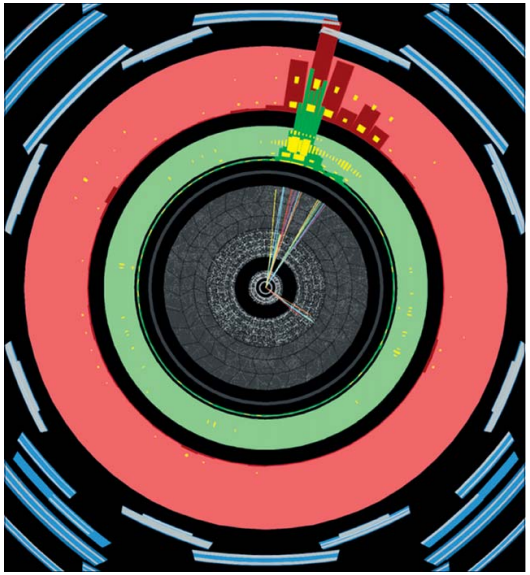
- Can get strong constraints on higher dim. operators coming from high energy theory through SU(2) invariance and charged lepton data
- G_F measurements from μ decay (affected by NSI) and M_W, M_Z
- CKM unitarity (through G_F)
- Lepton universality
- Collider data (monojet + missing energy, single photon +MET, multi-lepton processes)

- Changes in neutrino cross-section vs. data in neutrino scattering experiments
- Neutrino oscillations: contact and propagation in matter
  solar, atmospheric, accelerator, supernova, reactors

μ sector very well constrained, τ sector least constrained

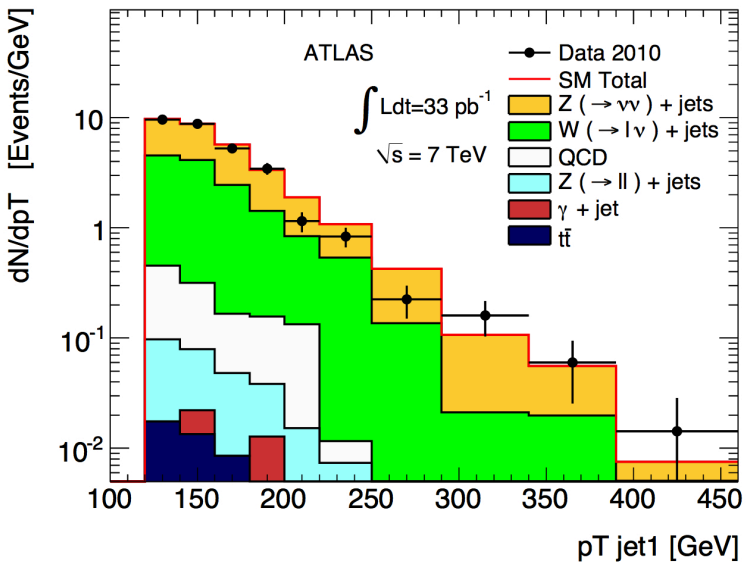
NSI effects: colliders

LHC monojet events



One jet
Large missing E_T

Recoil against ?
- dark matter
- extra dimensional KK gravitons
- …



SM background involves neutrinos!

jet+Z-> jet + nu nubar
jet_+W - > jet + l nu

NSI modify SM rate!

Friedland, Graesser, Shoemaker, Vecchi (2012)

Bounds on NSI per quark:

	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

$\epsilon_{\alpha\beta}$: simple, general parametrization of new, more complex physics

In some parameter space: contact NSI no longer a good approximation

model dependence important

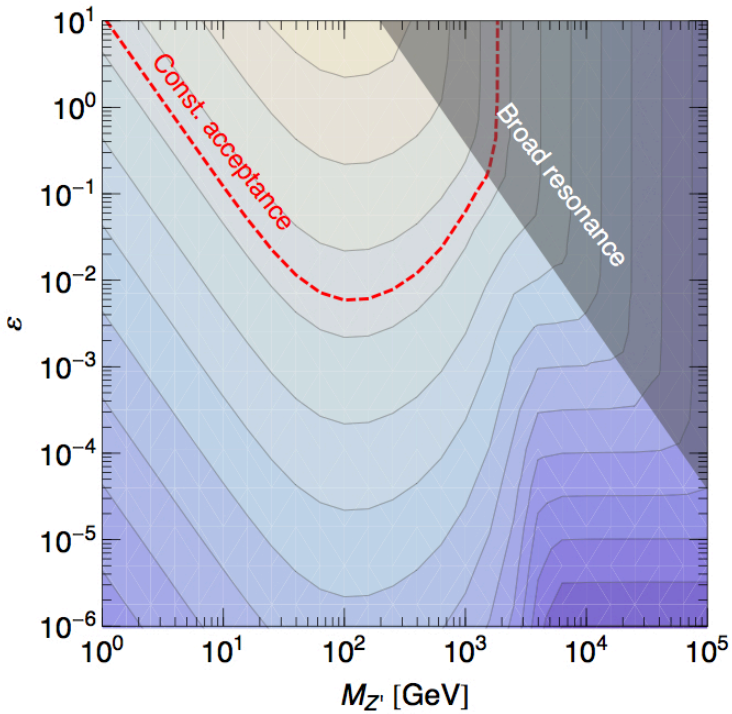
Neutrino oscillation example:

can treat eV sterile neutrino as constant NSI in atmospheric data at large L/E, where eV scale gets averaged out

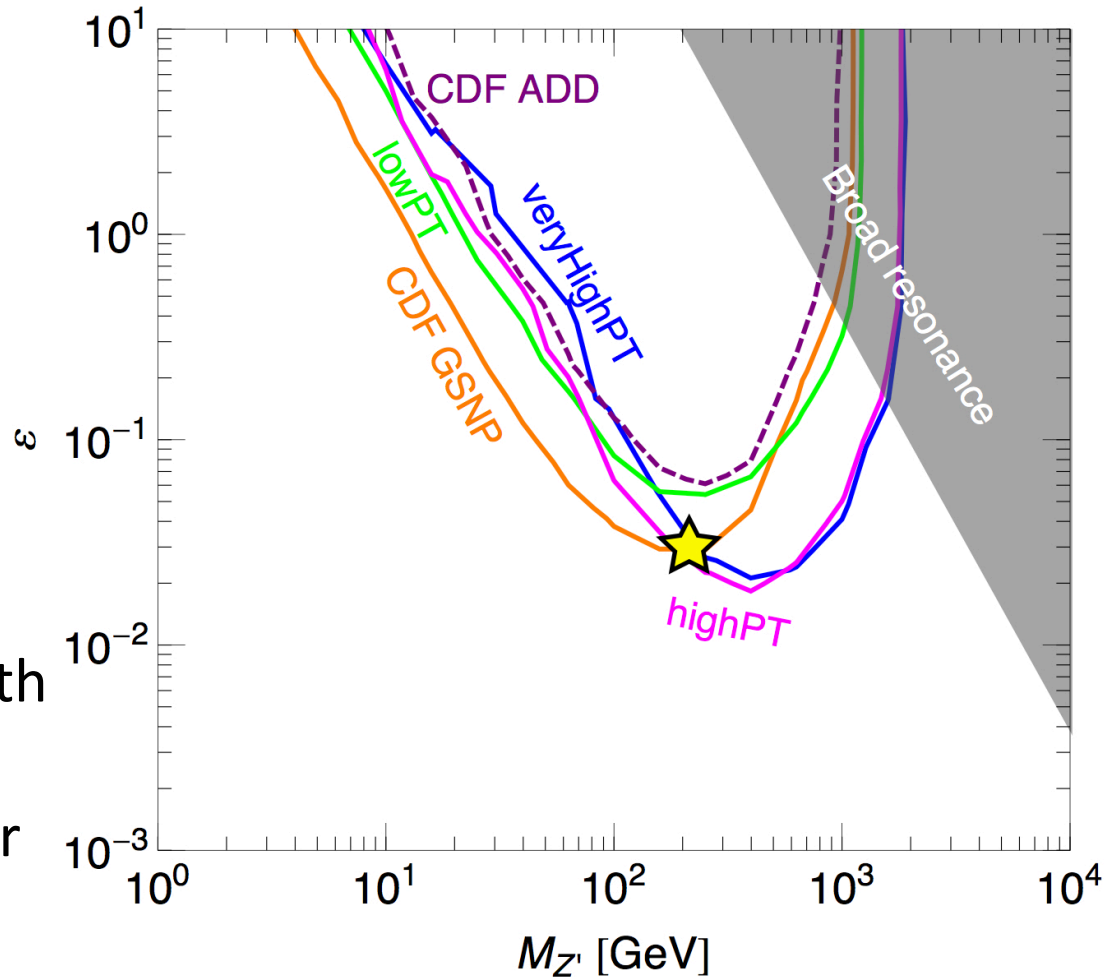
when looking at lower L/E: can probe the eV mass scale oscillation directly: energy dependence, model dependence

Friedland, Graesser, Shoemaker, Vecchi (2012)

Z' model



Constraints apply to dark matter, NSI, …
How to tell them apart?



Overconstrain!

Neutrino NSI can interfere with SM processes

Multi –lepton events can offer orthogonal constraint

NSI effects

- Neutrino oscillations

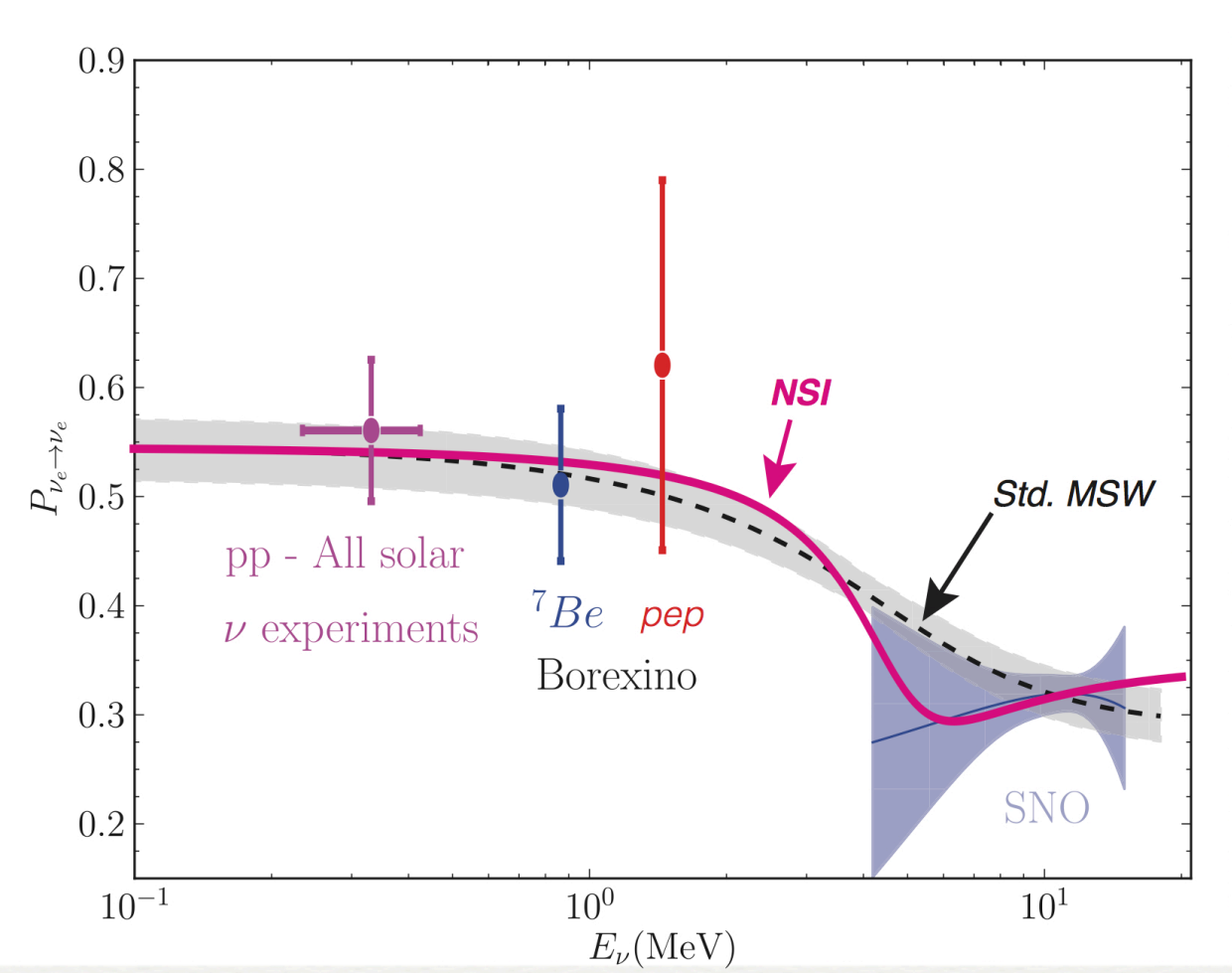
$$H^{NSI}_{matter} = \sqrt{2} G_F n_e \begin{pmatrix} 1+\epsilon_{ee} & |\epsilon_{e\mu}| e^{i\delta_{e\mu}} & |\epsilon_{e\tau}| e^{i\delta_{e\tau}} \\ |\epsilon_{e\mu}| e^{-i\delta_{e\mu}} & \epsilon_{\mu\mu} & |\epsilon_{\mu\tau}| e^{i\delta_{\mu\tau}} \\ |\epsilon_{e\tau}| e^{-i\delta_{e\tau}} & |\epsilon_{\mu\tau}| e^{-i\delta_{\mu\tau}} & \epsilon_{\tau\tau} \end{pmatrix}$$

$$\epsilon_{\alpha\beta} = \sum_{f,P} \epsilon^{ffP}_{\alpha\beta} \frac{n_f}{n_e}$$

- General scenario: many parameters (6 magnitudes + 3 phases)
- In a given setup some are more relevant than others
  (like 2 flavor analysis worked well as first approximation to 3 flavors)
- Typical: add one or two NSI parameters at a time

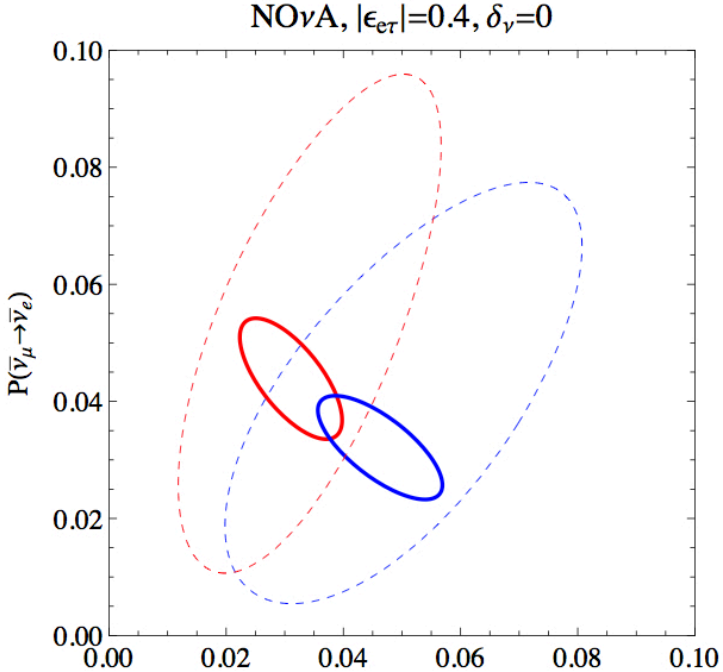
NSI effects

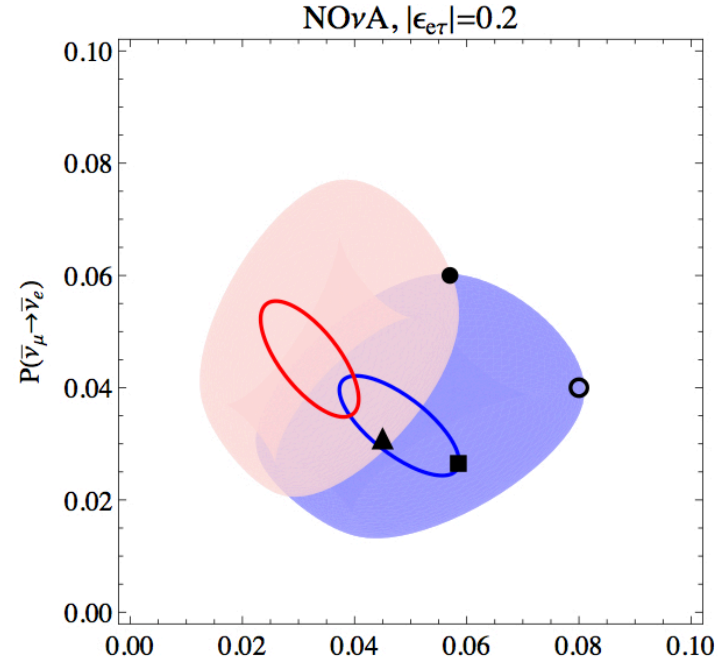
$\epsilon_{e\tau}$ effects in the Sun: can improve fit of low energy spectrum

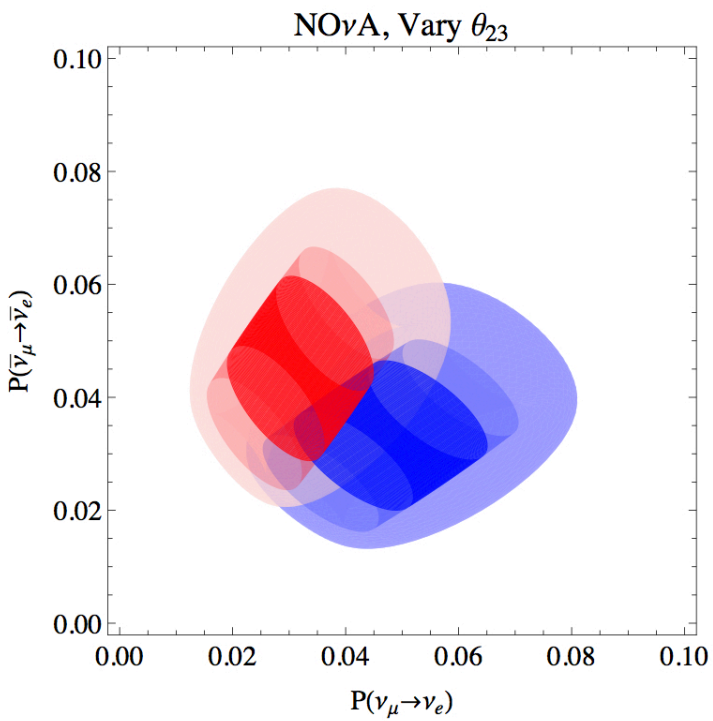


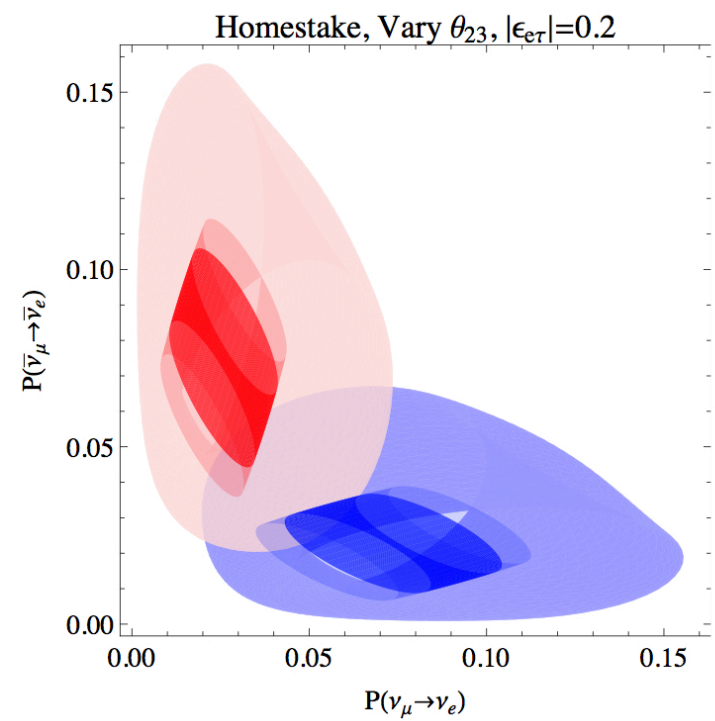
→ can also affect long baseline and atmopsheric data

Friedland, Shoemaker (2012)



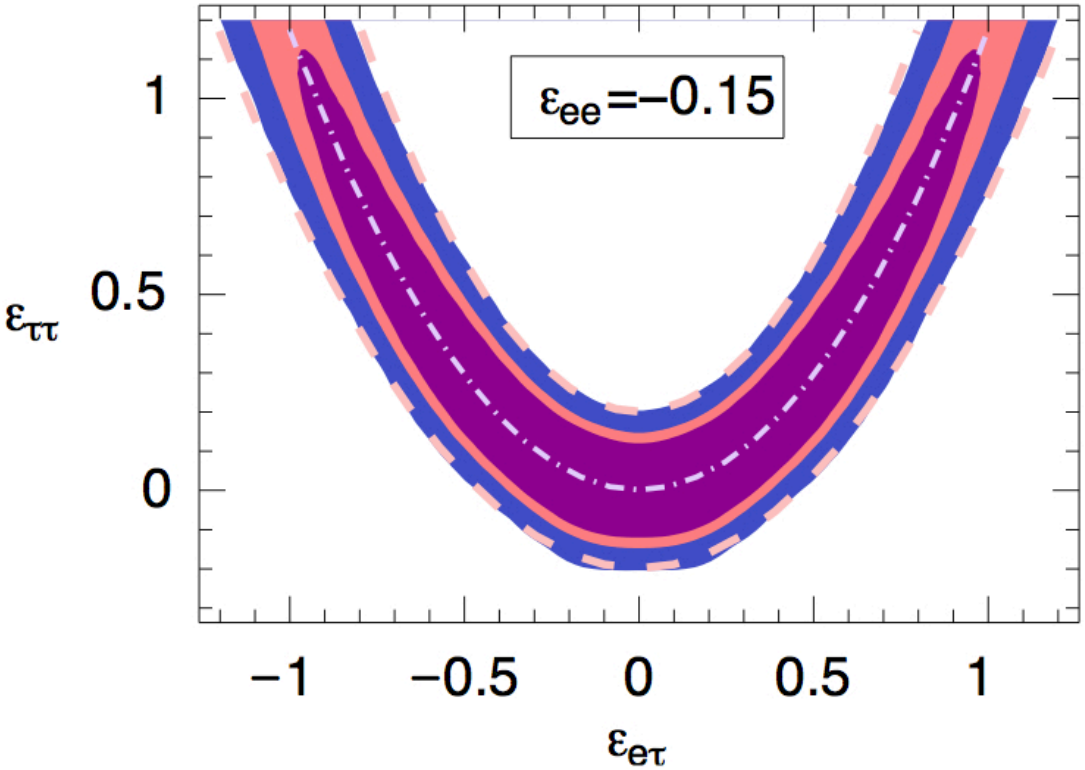




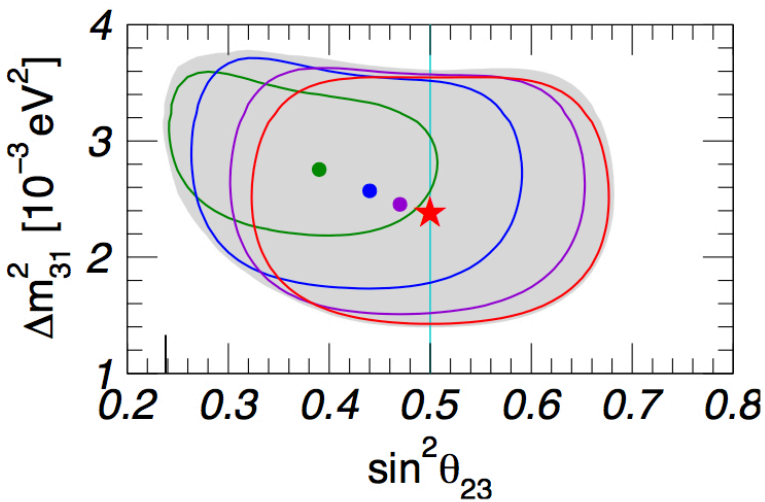


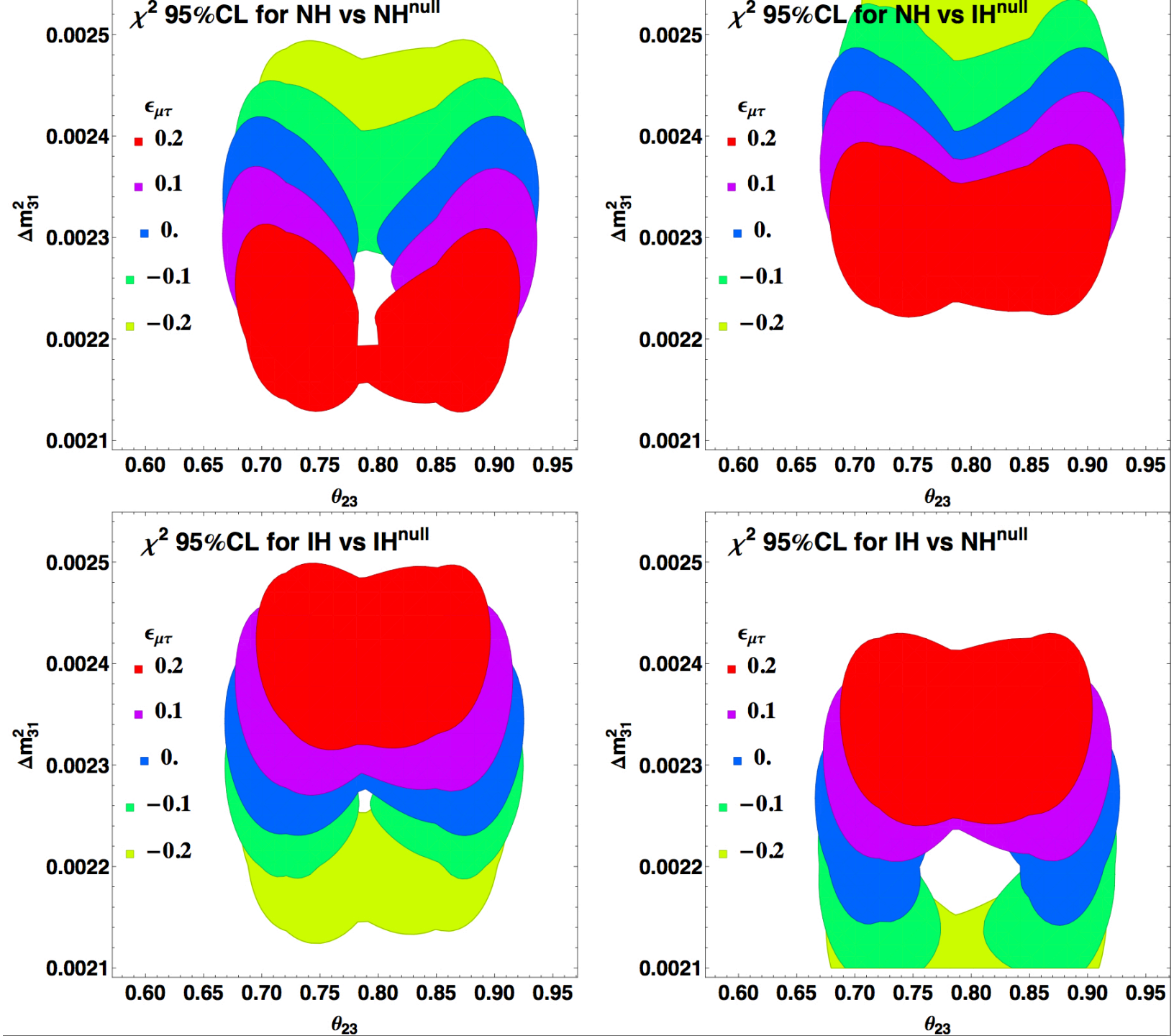
Friedland, Shoemaker (2012)

NSI effects: atmospheric neutrinos



Friedland,
Lunardini, Maltoni (2005)





LBNE
10kton
5+5yr

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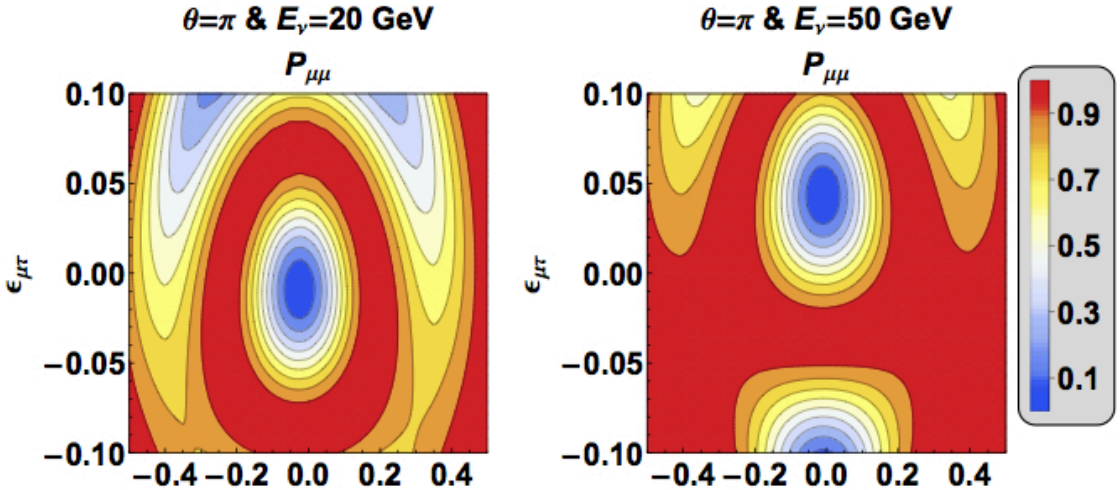

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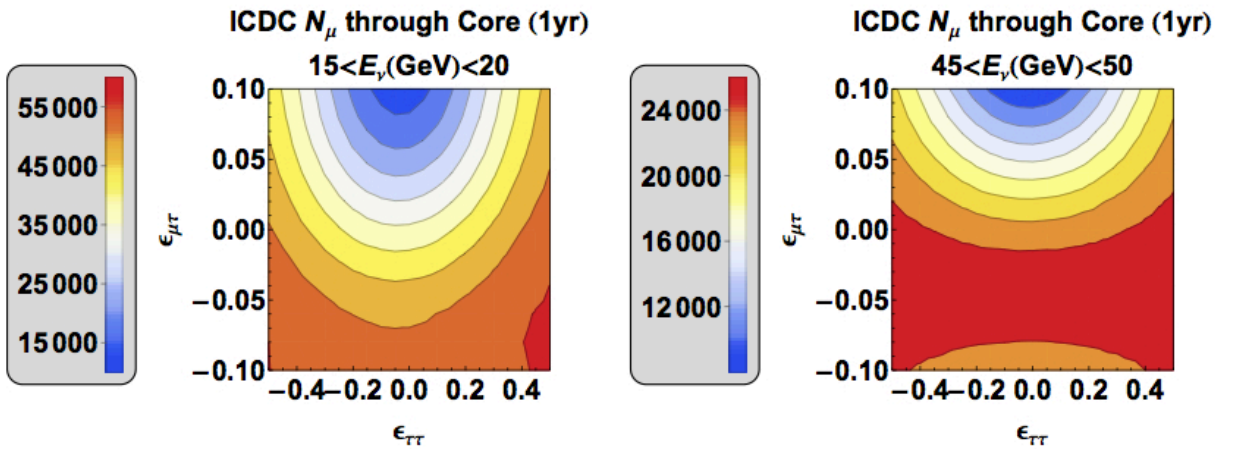
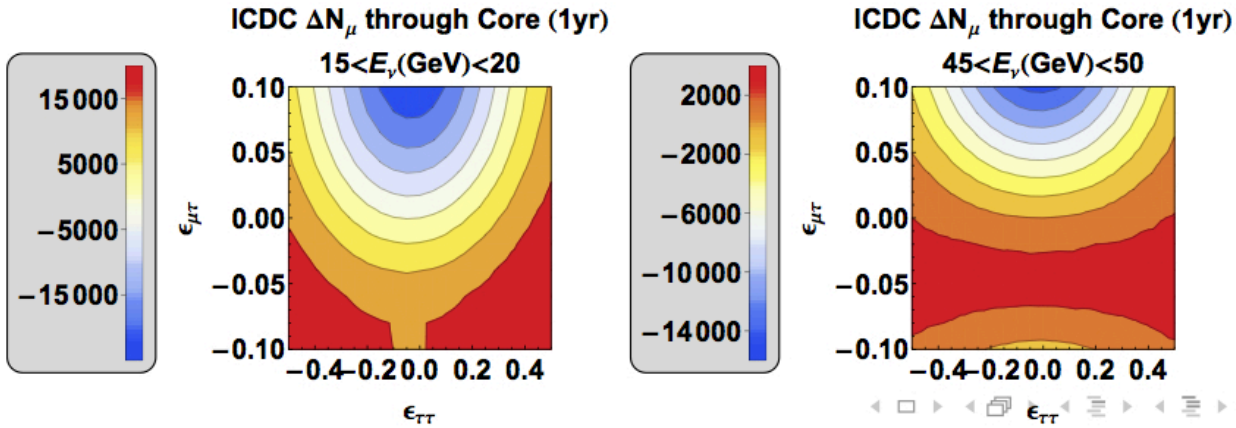
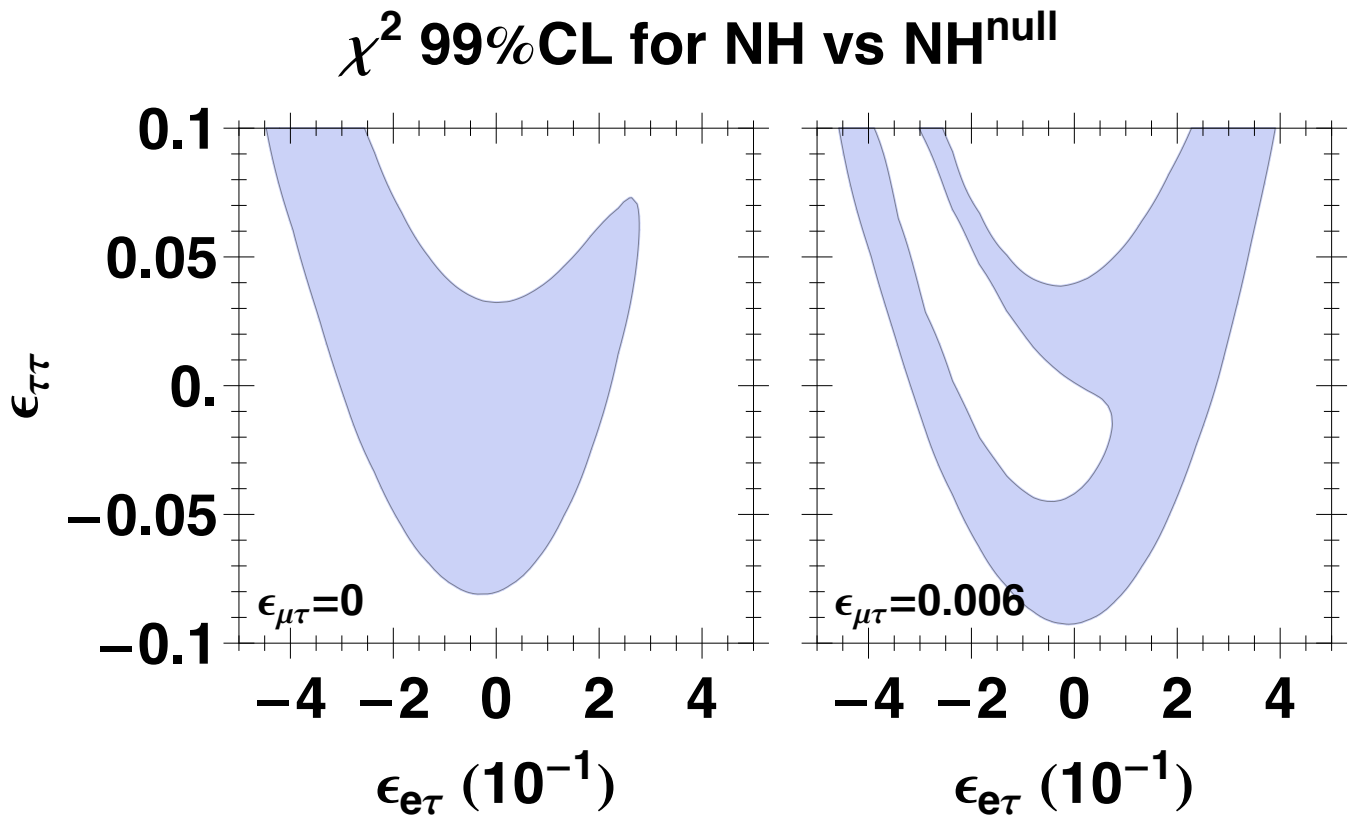


ICDC/PINGU
1year



NSI effects: atmospheric neutrinos



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Neutrinos

- Fist experimental evidence of physics beyond standard model
- Different: small mass, large mixing, possibly Majorana
- Want to understand:
  - What is the origin of neutrino mass?
  - How does it relate to origin of other fermion masses?
  - Are small masses, large mixings and Majorana nature connecterd?
  - How do we understand all flavour structure (neutrinos, charged leptons and quarks)?
  - How do we understand the baryon asymmetry?
  - How do neutrino properties affect astrophysics?
  - How do neutrino properties affect cosmology?
  - Are neutrinos connected to the dark sector?
  - … … …

Outlook

- Need to first measure all properties: guaranteed useful information
- Expect surprises (lots of past examples)
- Anticipate surprises and prepare:
  - Explore different frameworks/scenarios beyond minimal
  - Test framework
    - Sometimes precision parameter measurement in minimal scenario can lead to framework test
    - Often more efficient to seek different ways to over-constrain system in order to get framework test
  - "Model-independent" parametrizations valuable:
    - very general, easier to constrain from global analysis
  - Models and examples valuable:
    - can identify special features missed in general analysis (these can either enhance or relax constraints/sensitivity)

Outlook

Data absolutely required!

Many different types of observations/experiments needed

- neutrino oscillations
- beta decay
- neutrinoless double beta decay
- electromagnetic properties
- rare decays
- other flavor physics
- collider physics
- astrophysics
- cosmology

Outlook

Data absolutely required!

Many different types of observations/experiments needed

- neutrino oscillations: appearance, disappearance, different flavour channels, different baselines, different energies, different sources, etc.
- beta decay
- neutrinoless double beta decay: different nuclei
- electromagnetic properties (magnetic moments, EDMs, etc.)
- rare decays
- other flavor physics
- collider physics
- astrophysics: many energies, many environments, etc.
- cosmology

→ Reconstruct a consistent picture that leads to understanding fundamental questions

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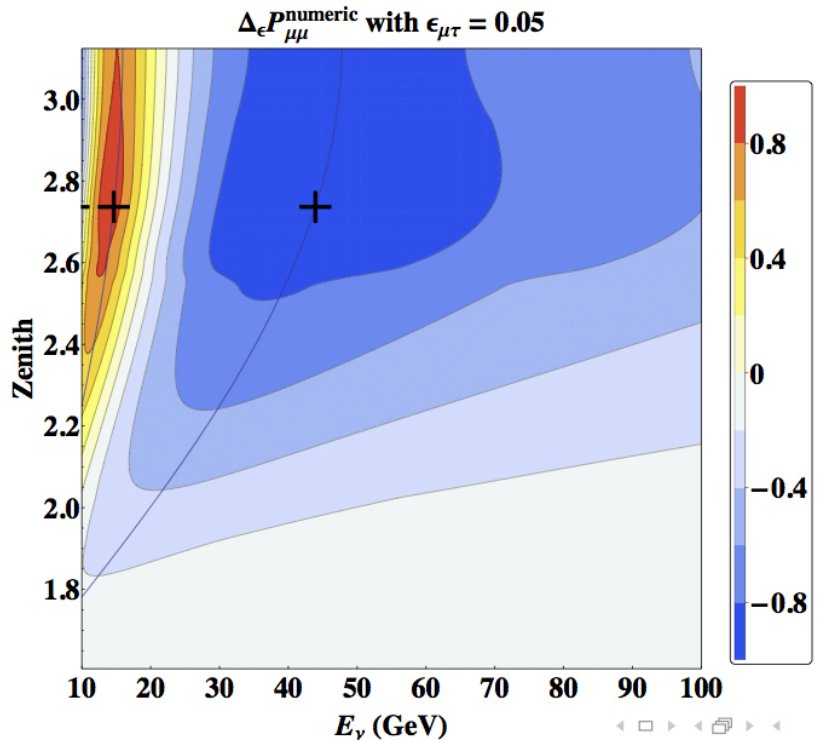

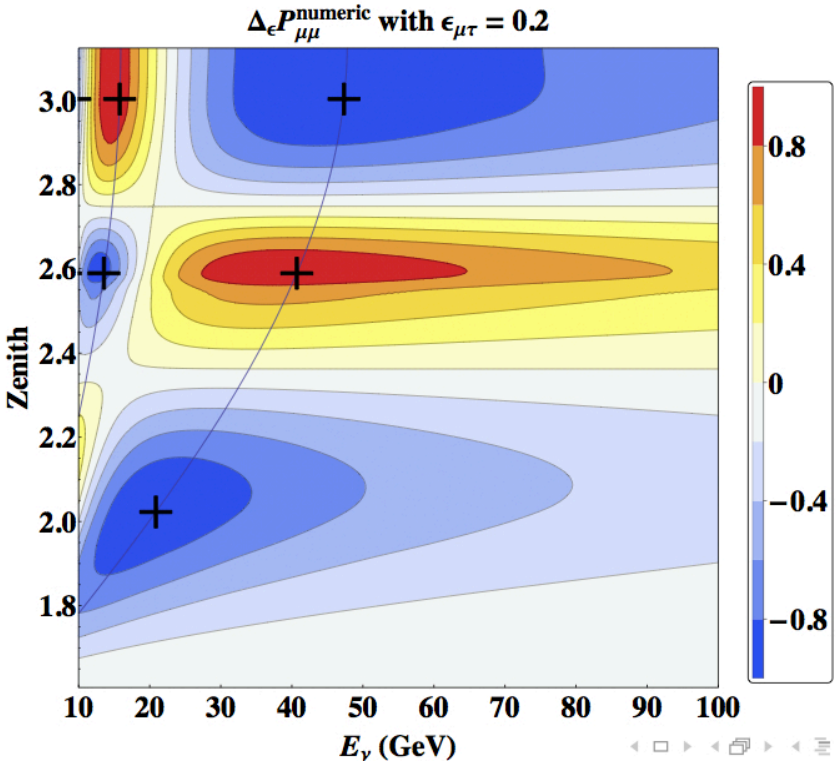

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Degeneracy between sign of NSI and mass hierarchy

NSIs make a big difference in matter

Independent measurements of hierarchy through different methods can resolve that:

- matter effect in long baseline, atmospheric
  vs.
- interference of atmospheric and solar scales in reactor measurements