Neutrinos as a window to New Physics

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March 22nd, 2016

Outline

- Why neutrinos?
- Long-baseline neutrino oscillations
  - Standard searches
  - Non-Standard searches
- Neutrinos beyond oscillations
- Outlook

Why neutrinos?

Why neutrinos?

Physics Beyond the Standard Model!

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Physics Beyond the Standard Model!

1) Dirac mass: as for the rest of fermions in the SM

$$Y_\nu \overline{L}_L \widetilde{\phi} \nu_R \to m_\nu \bar{\nu}_L \nu_R$$

$$Y_\nu \lesssim 10^{-12}$$

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$$Y_\nu \overline{L}_L \widetilde{\phi} \nu_R \to m_\nu \bar{\nu}_L \nu_R$$

$$\boxed{Y_\nu \lesssim 10^{-12}}$$

2) A Majorana mass. For example:

$$Y_\nu \bar{L}_L \widetilde{\phi} \nu_R + \frac{1}{2} M \overline{\nu}^c_R \nu_R$$

$$\boxed{(\not{L})}$$

Why neutrinos?

Physics Beyond the Standard Model!

Many open questions!

- Neutrino mass absolute scale? Why so small neutrino masses?
- Dirac/Majorana?
- Flavor puzzle
- CP-violation?
- Spectrum of neutrino masses?

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- Neutrino mass absolute scale? Why so small neutrino masses? Beta-decay/cosmology
- Dirac/Majorana? Neutrinoless/colliders
- Flavor puzzle Oscillations
- CP-violation? Oscillations
- Spectrum of neutrino masses?

Oscillations/neutrinoless/cosmology

Why neutrinos?

...so many open questions...

- Are there more than three neutrinos? Oscillations/ neutrinoless/cosmology/...
- Do neutrinos decay? Oscillations/supernovae/astrophysical
- Do they have electromagnetic properties? Reactor neutrinos/solar neutrinos/...
- Do they have new interactions? Oscillations/astrophysical
- ...

To-Do-list in neutrino oscillations:

CP-violation

Blennow, PC, Fernandez-Martinez, 1511.02859,
Blennow, PC, Fernandez-Martinez, 1407.3274
Christensen, PC, Huber, 1301.7727
...

Mass ordering (spectrum)

Blennow, PC, Huber, Schwetz, 1311.1822
Blennow, PC, Donini, Fernandez-Martinez, 1303.0003

Improved precision

PC, Minakata, Parke, 1406.2551
PC, Donini, Fernandez-Martinez, Hernandez, 1203.5651

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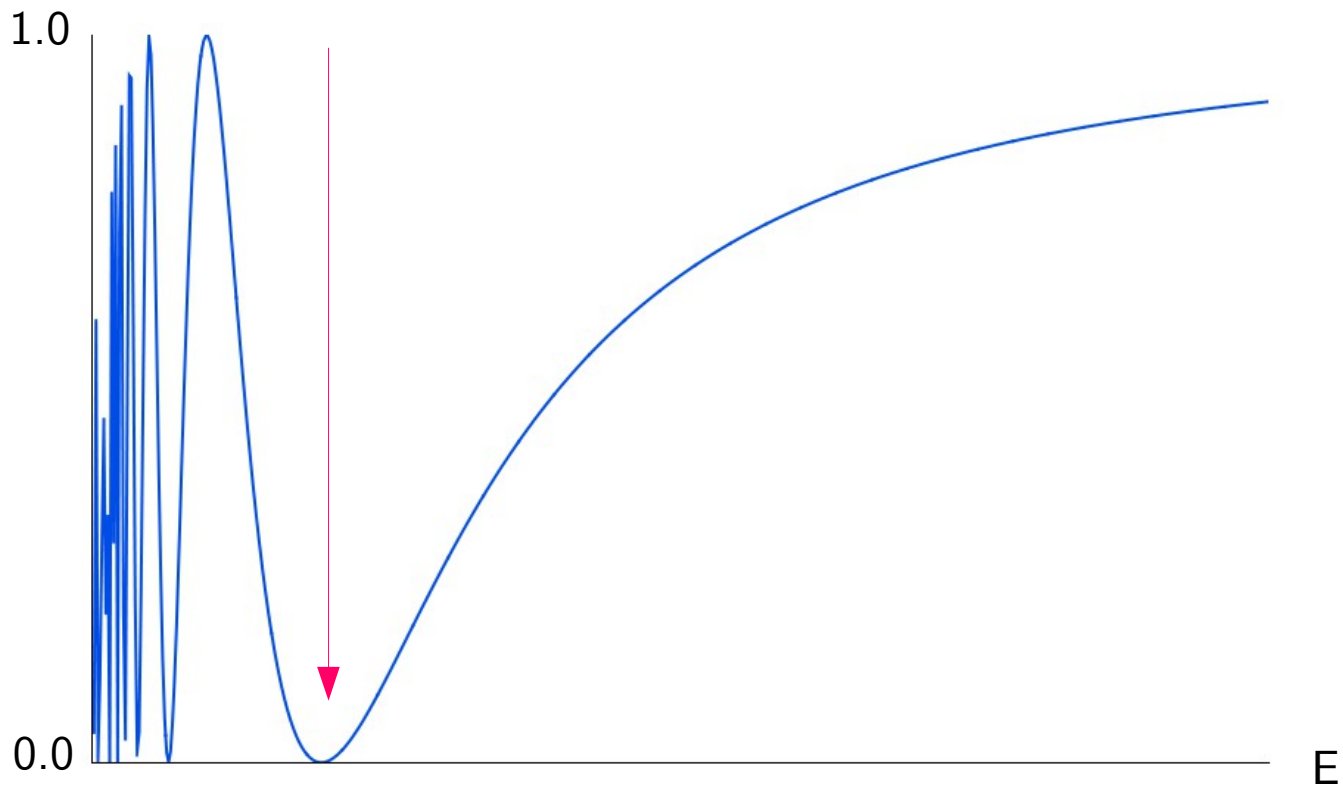
Systematic uncertainties

Ankowski et al, 1507.085610
Ankowski et al, 1507.08561
PC, Huber, Jen, Mariani, 1311.4506
PC, Huber, 1307.1243
PC, Huber, Kopp, Winter, 1209.5973

The two-family approximation

$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2 L}{4E_\nu} \right)$$



$$E_{peak} = \Delta m^2 L/(2\pi)$$

CP violation searches $\rightarrow$ 3 families

Three-family ν_e appearance oscillation probability (vacuum):

$$
\begin{aligned}
P_{\mu e} &= (\sin\theta_{23}\sin 2\theta_{13})^2 \sin^2(\Delta_{31}) \\
&+ \sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}\cos\theta_{13}\Delta_{21}\sin(\Delta_{31})\cos(\pm\delta + \Delta_{31}) \\
&+ (\cos\theta_{23}\sin 2\theta_{12})^2 \sin^2(\Delta_{21})
\end{aligned}
$$

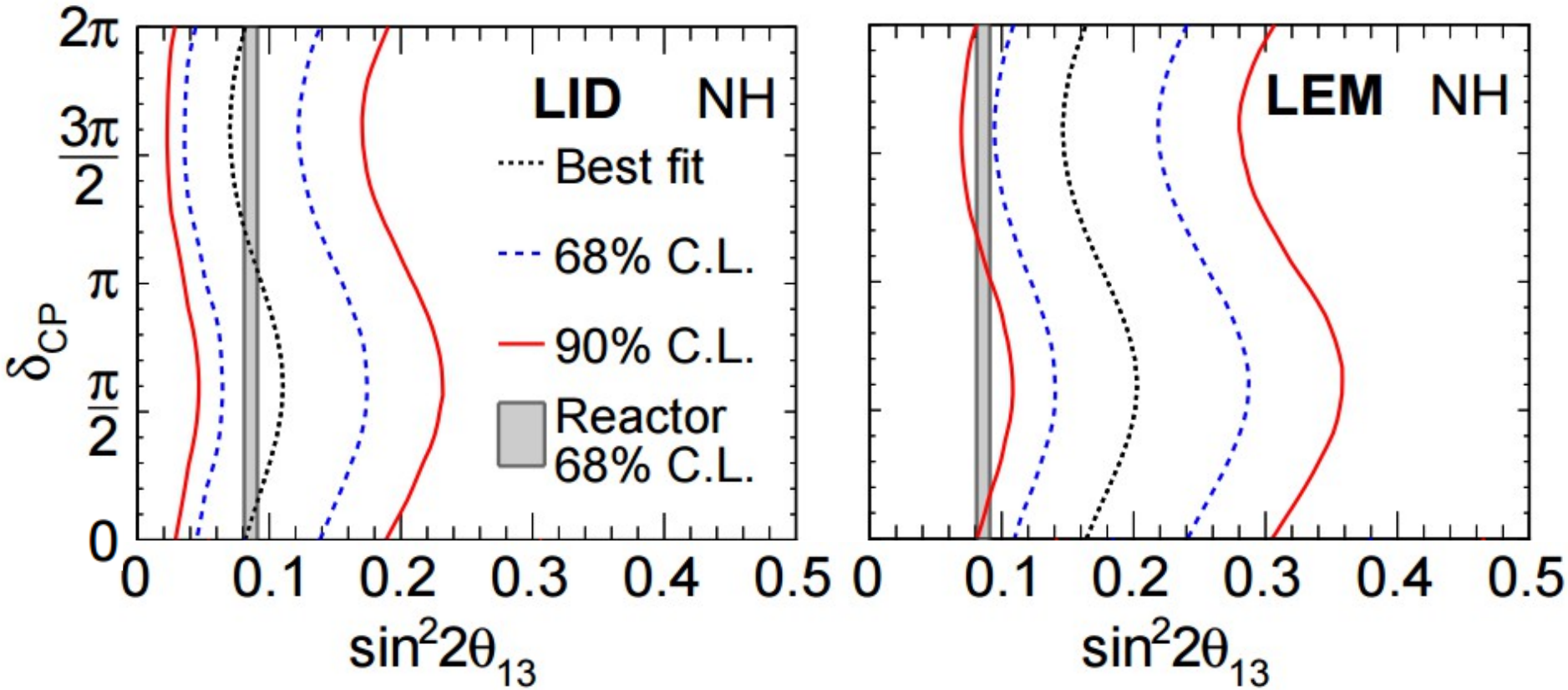
Neutrino/Antineutrino

$$\Delta_{ij} \equiv \frac{\Delta m^2_{ij} L}{4E}$$

Cervera et al, hep-ph/0002108
(see also Akhmedov et al, hep-ph/0402175, and
Asano and Minakata, 1103.4387)

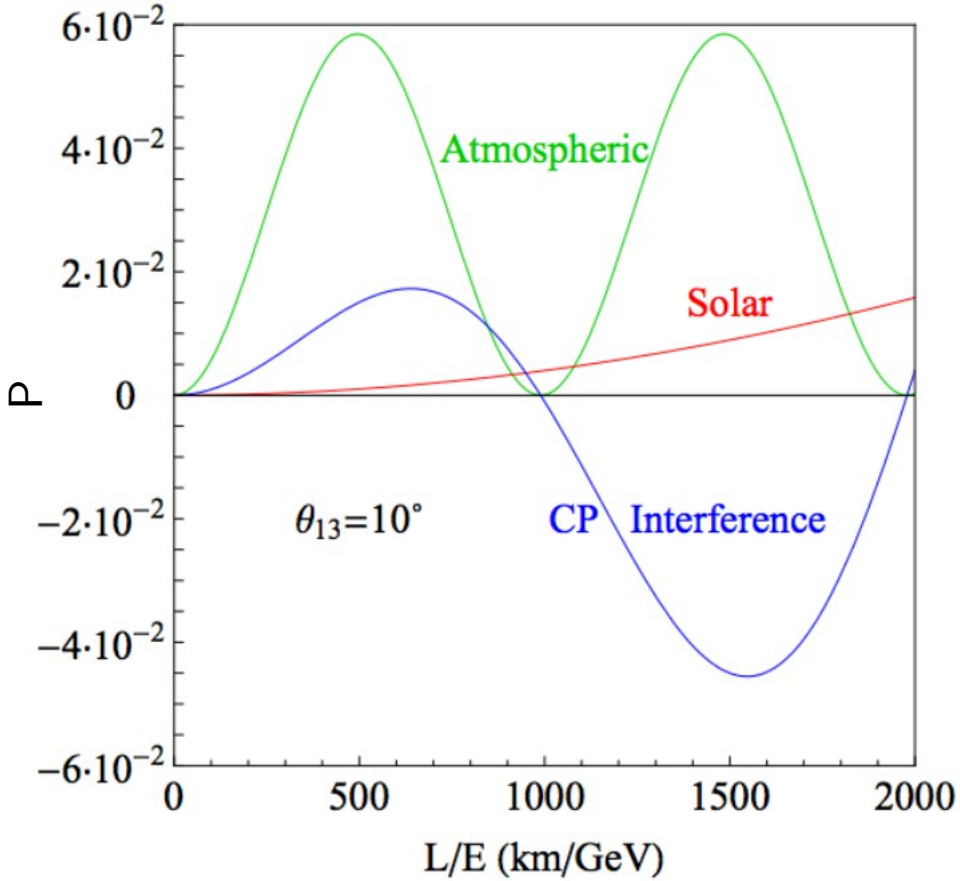
Hints for CP violation?

The combination of current long-baseline and reactor data currently provides a hint for CP violation:



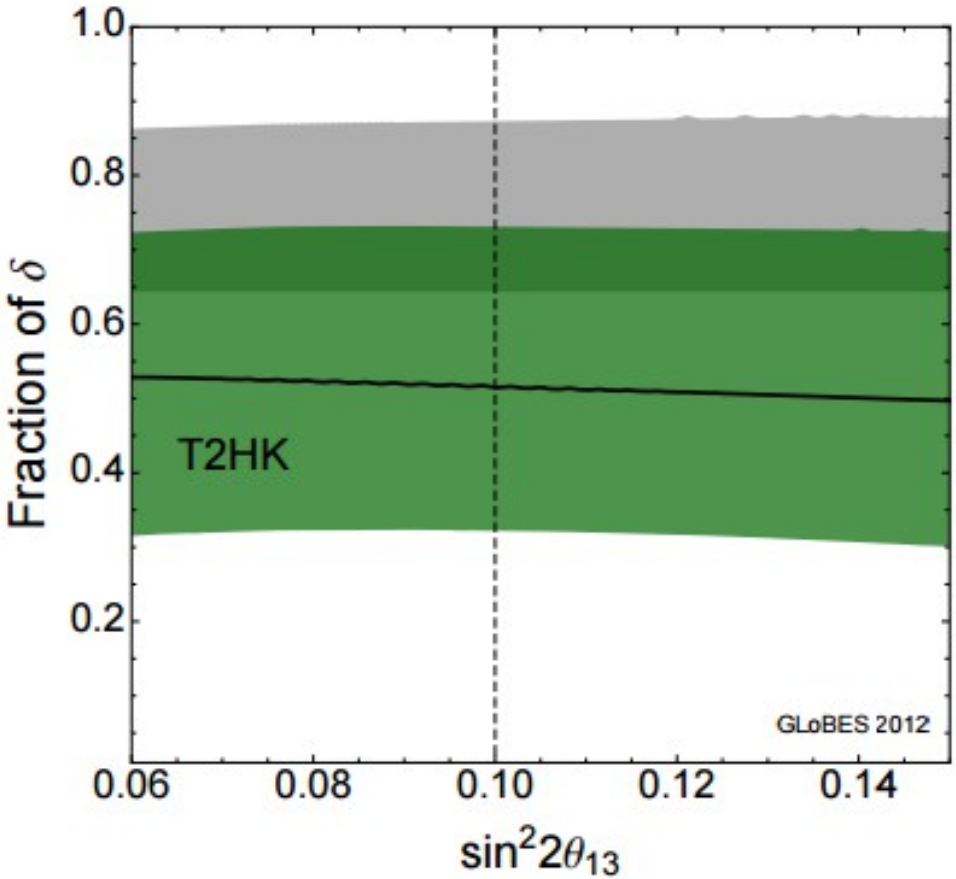
First NOvA results, 1601.05022
(For T2K results see 1311.4750 and 1502.01550)

CP violation and systematics



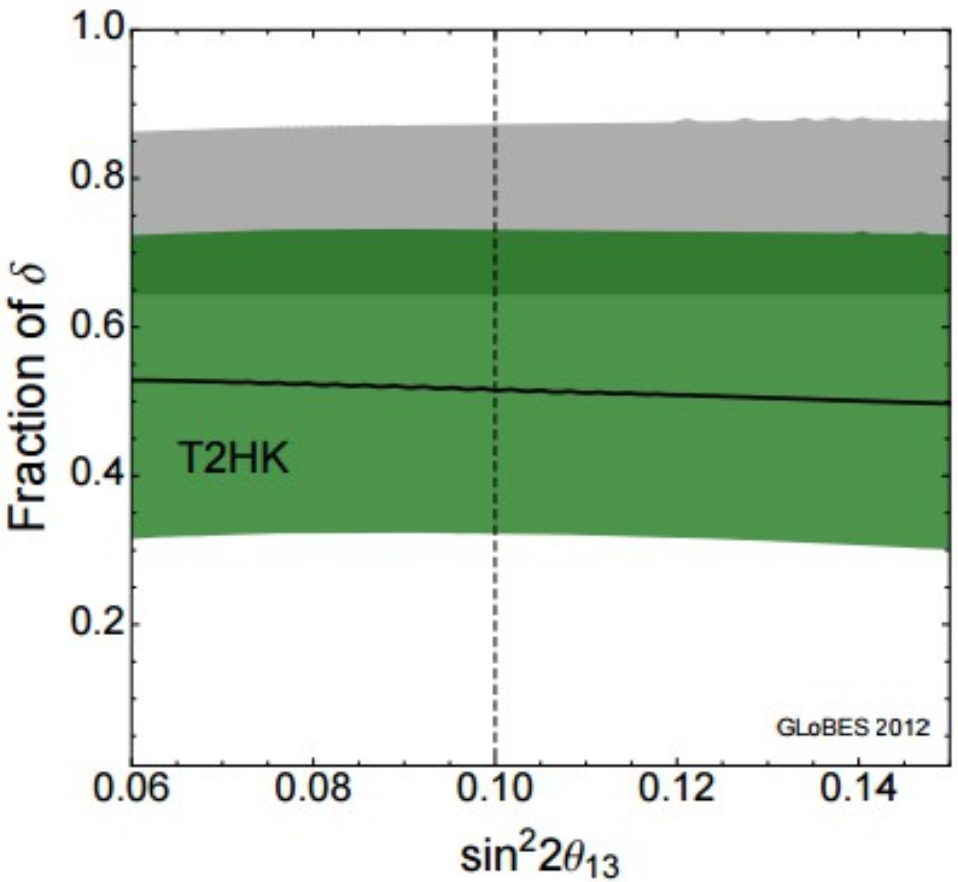
PC and Fernandez-Martinez, 1110.4583 [hep-ph].
(See also Marciano, hep-ph/0108181, Ishitsuka et al, hep-ph/0504026, Meregaglia and Rubbia, 0801.4035)

CP violation and systematics

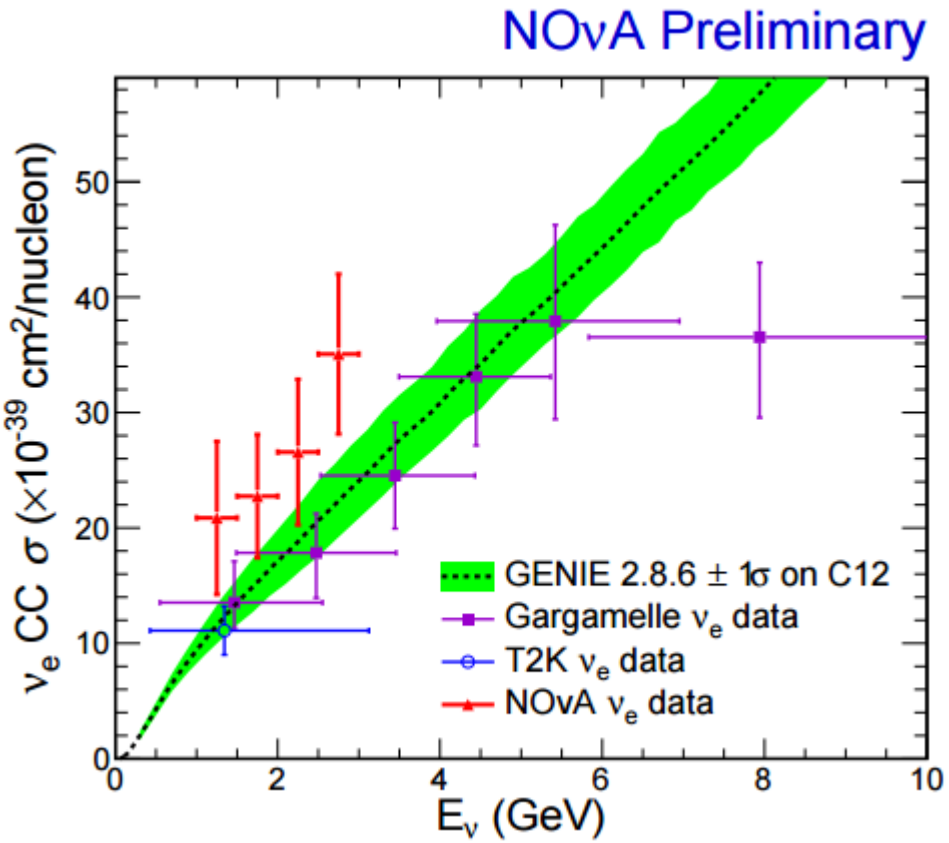


PC, Huber, Kopp,
Winter, 1209.5973

CP violation and systematics

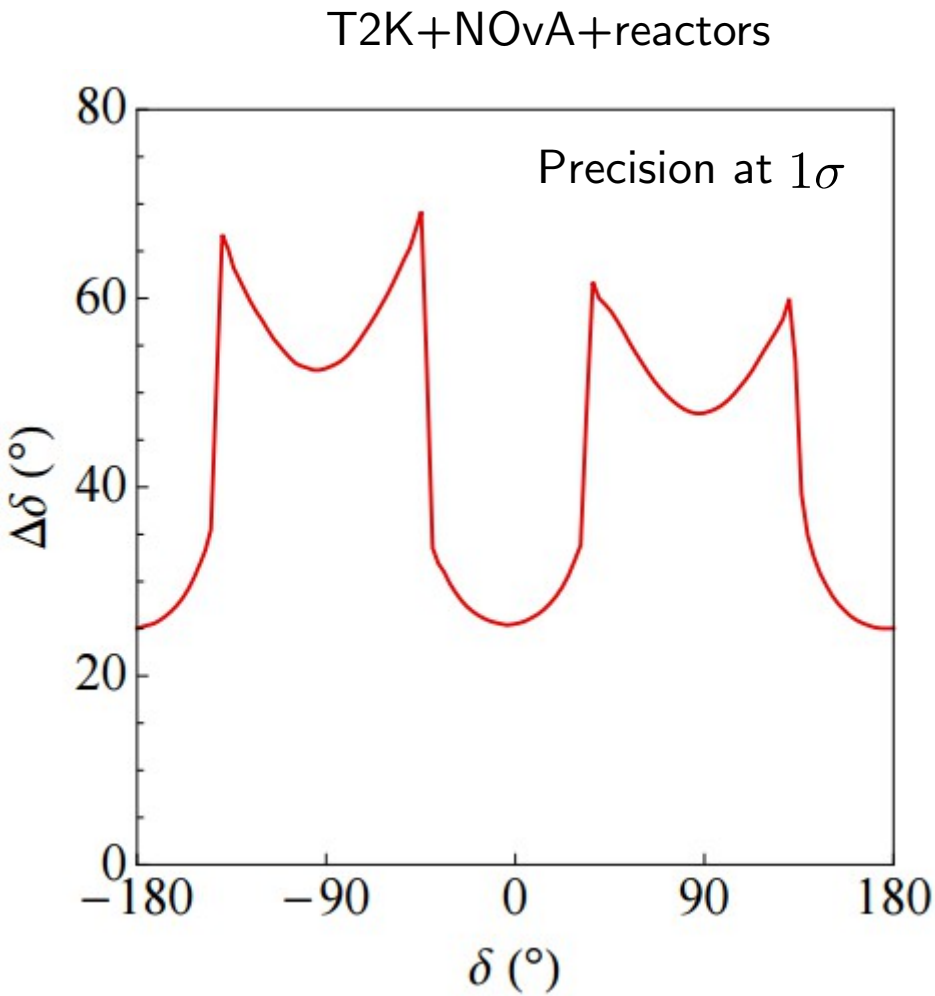


PC, Huber, Kopp, Winter, 1209.5973



Xuebing Bu (for the NovA collaboration), 1601.01213 (see also W&C seminar at Fermilab on Feb 26, 2016)

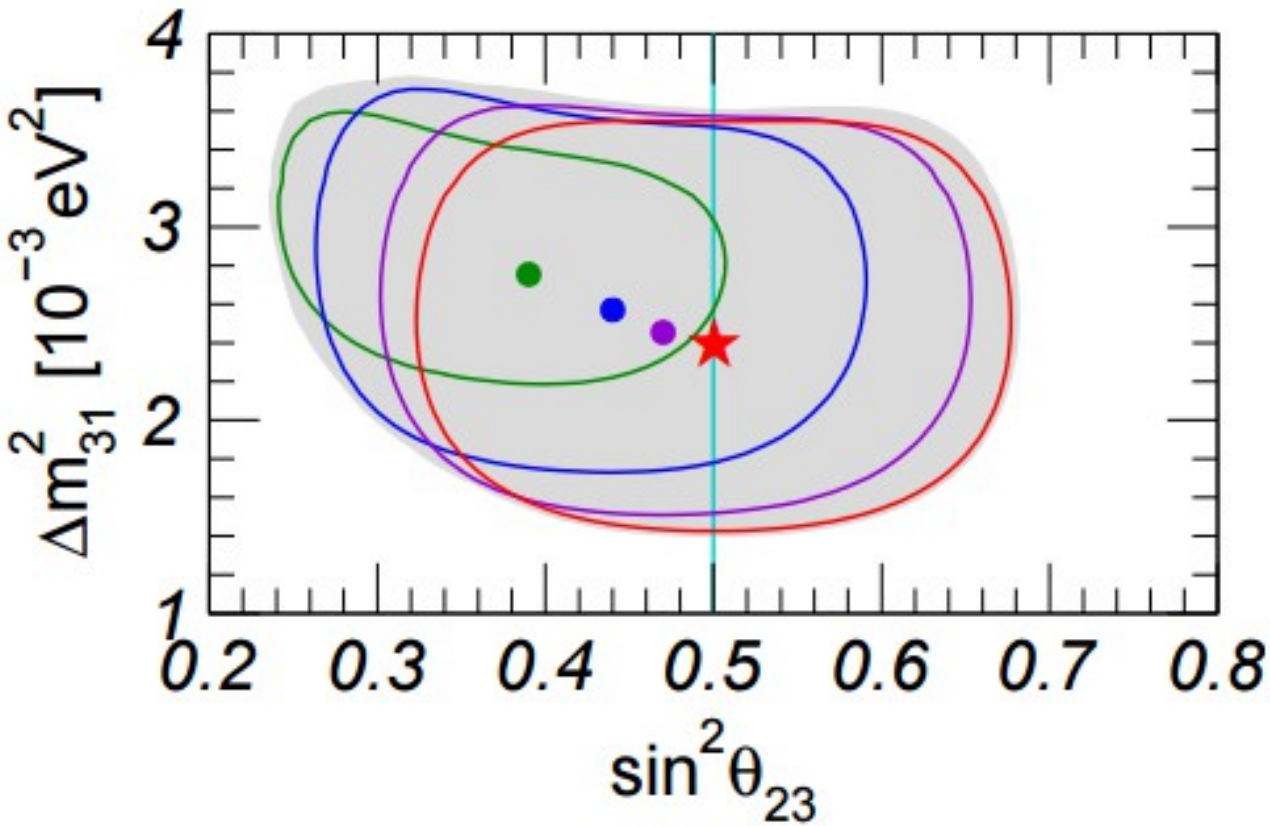
CP violation versus precision



PC, Donini, Fernandez-Martinez, Hernandez, 1203.5651
(See also PC, Huber, Kopp, Winter, 1209.5973)

Why precision?

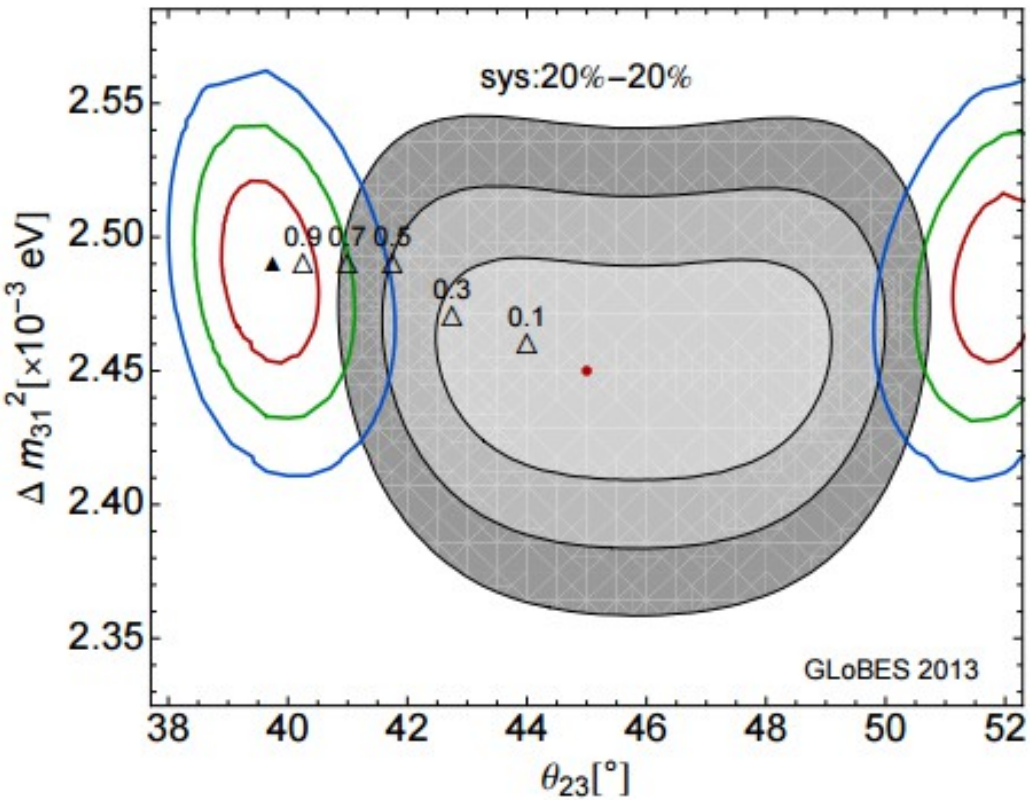
Effect of NSI on a fit to atmospheric neutrino data:



Friedland, Lunardini, Maltoni, hep-ph/0408264
(see also Friedland, Lunardini, hep-ph/0506143, hep-ph/0606101)

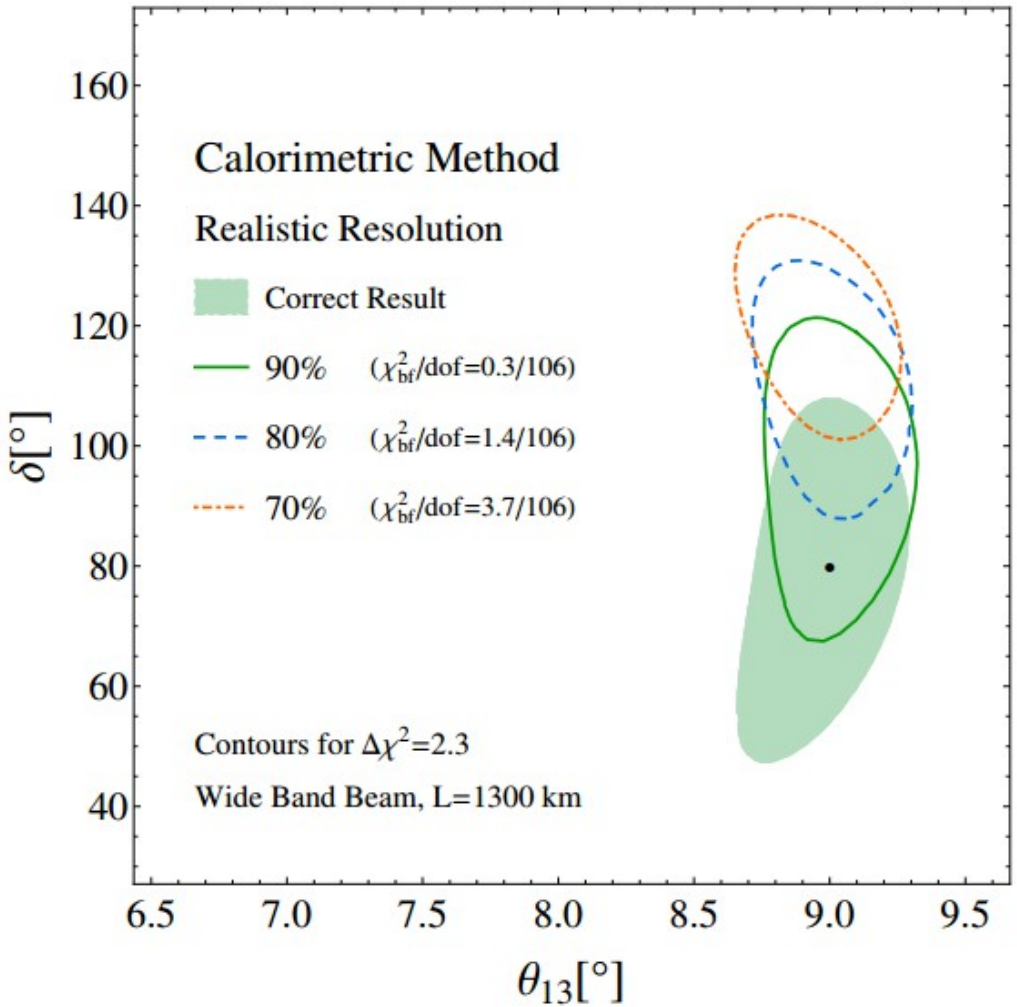
Precision and systematics

Effect of non-QE events and Final State Interactions on a fit to long-baseline neutrino data:



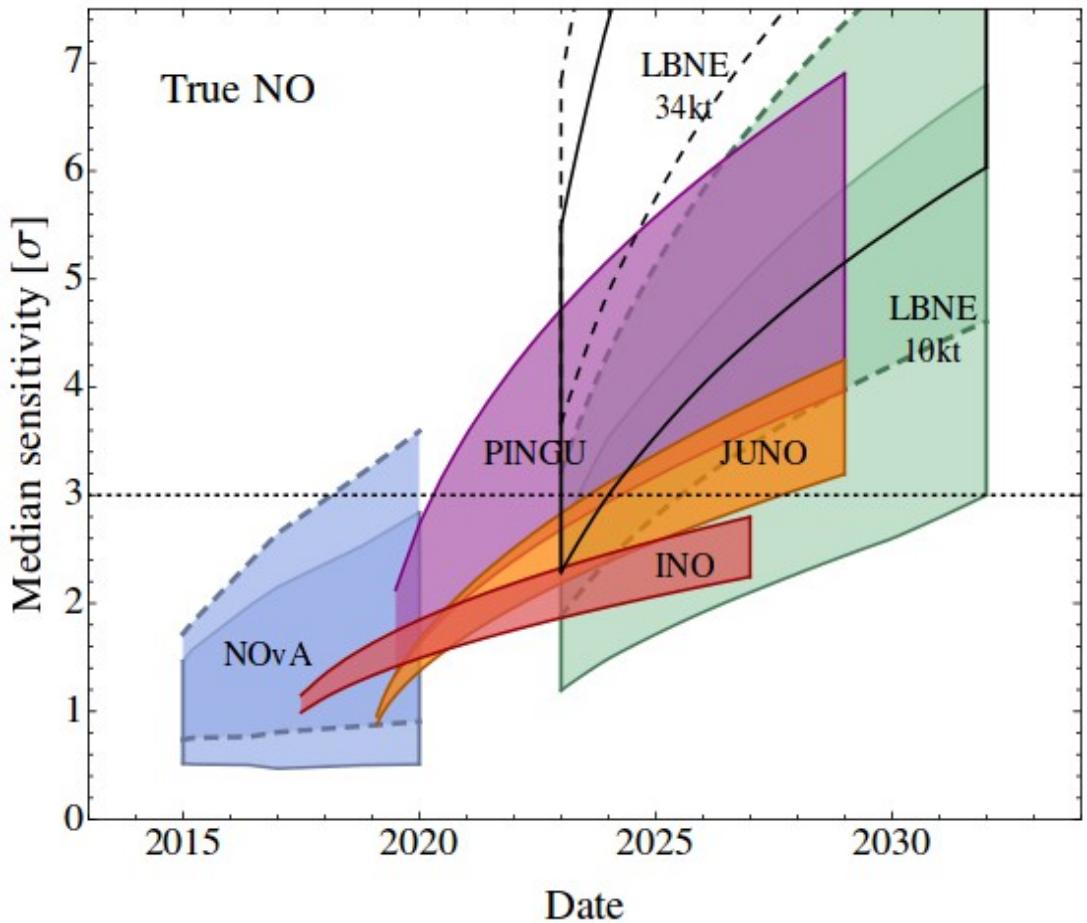
PC, Huber, 1307.1243
(See also PC, Huber, Jen and Mariani, 1311.4506)

Precision and systematics



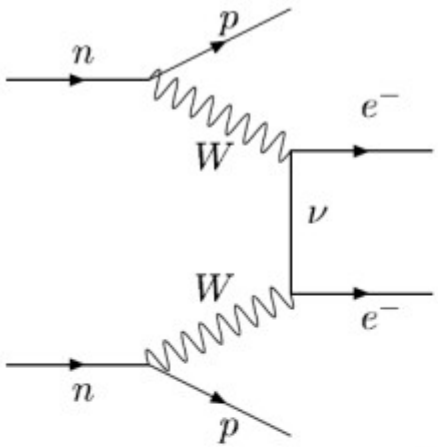
Ankowski, PC, Huber, Mariani, Vagnoni, 1507.08561

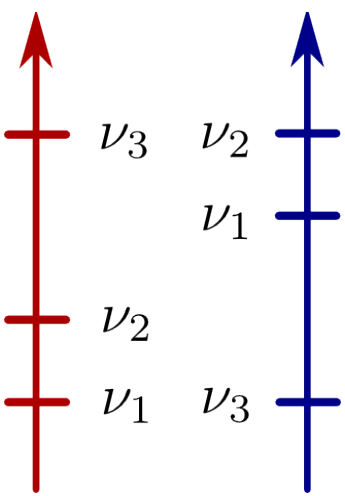
Prospects for mass ordering

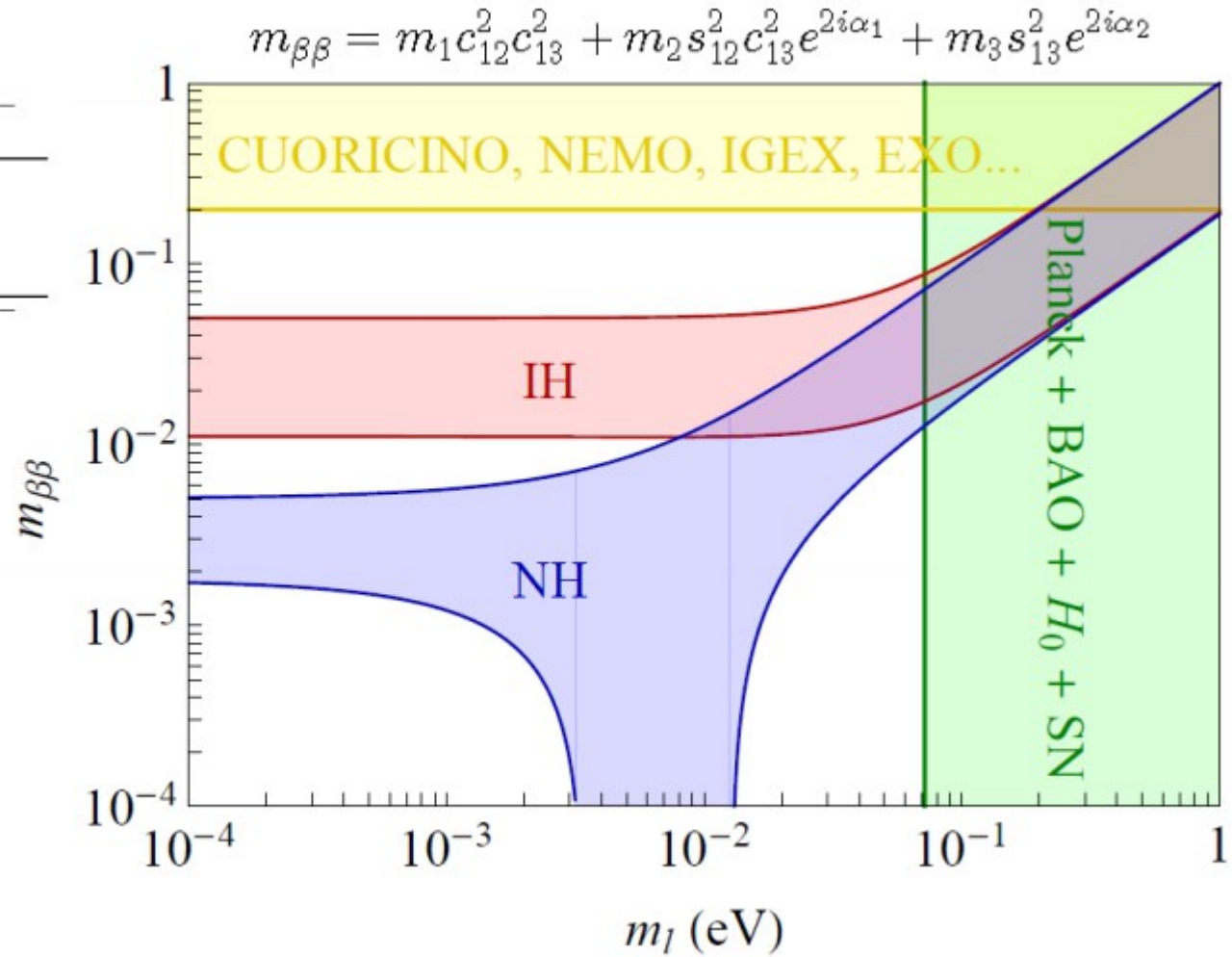


Blennow, PC, Huber and Schwetz, 1311.1822

Mass ordering and new physics



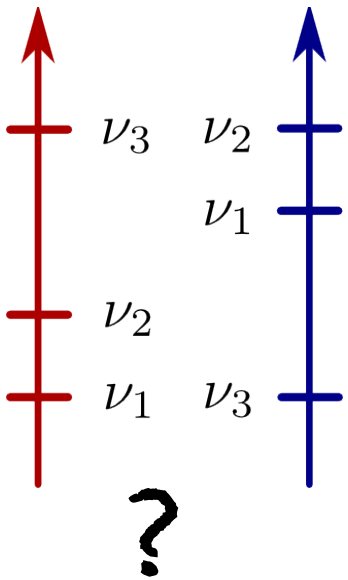


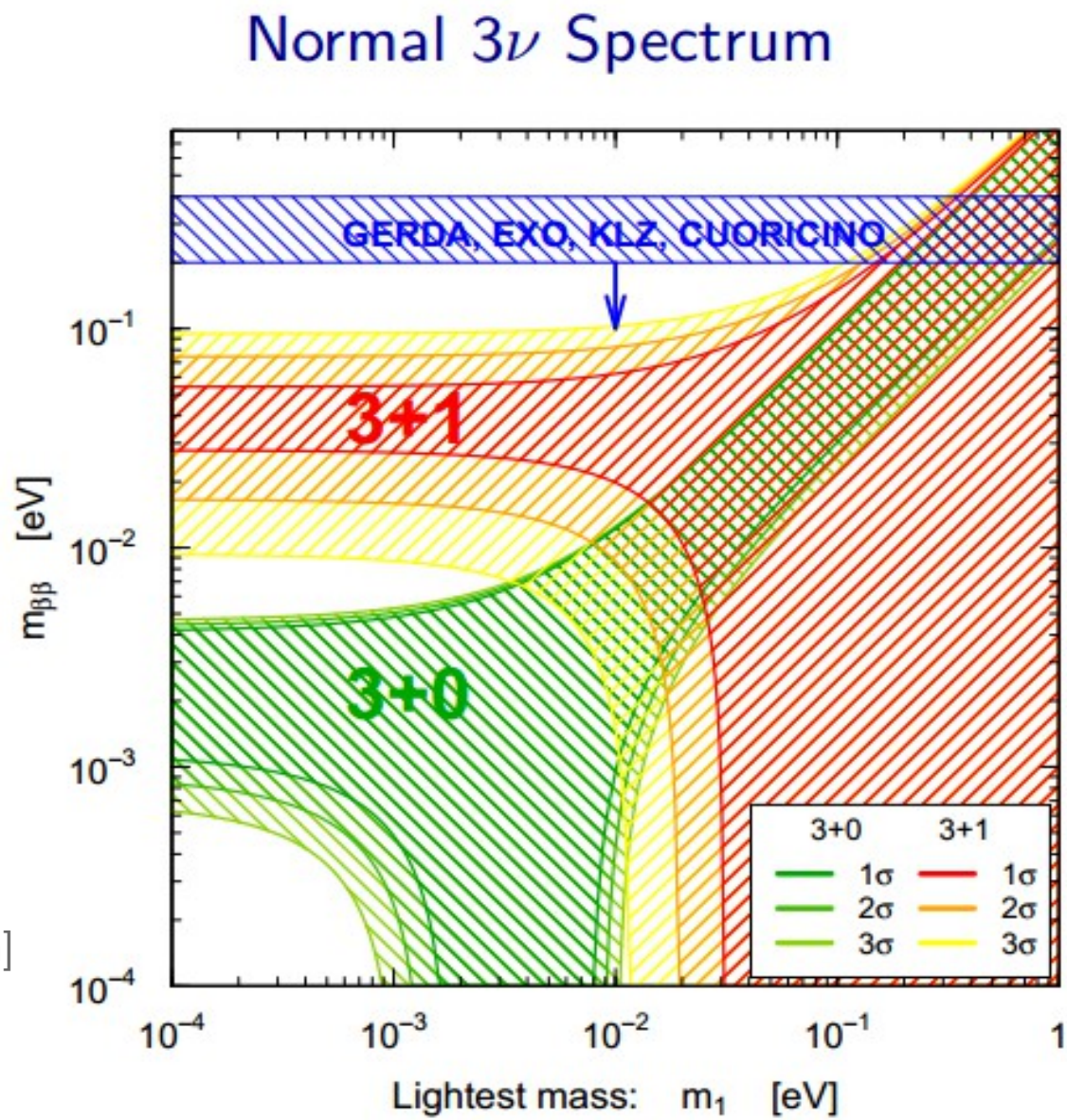


Plot updated from Blennow et al, 1005.3240

(See also e.g. Minakata, Nunokawa, Quiroga, 1402.6014, and Dodelson, Lykken, 1403.5173)

Mass ordering and new physics





Giunti and Zavanin, 1505.00978 [hep-ph] (see also e.g., Bilenky et al, hep-ph/0104218)

New Physics Searches at long-baseline experiments

Non-Standard Interactions — PC, 1511.06357

Sterile neutrinos — Blennow, PC, Fernandez-Martinez, 1407.1317
PC, Huber, Link, 1406.4914

Neutrino decay — PC and Peres, in preparation

...

Going beyond ν masses

$$\mathcal{L}^{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\,\delta\mathcal{L}^{d=5} + \frac{1}{\Lambda^2}\,\delta\mathcal{L}^{d=6} + \ldots$$

The only d=5 operator which can be built within the SM particle content is

$$\mathcal{L}^{(5)} = \frac{c_5}{\Lambda_{NP}}(\overline{L}_L\widetilde{\phi})(\widetilde{\phi}^t L_L^c) \longrightarrow m_\nu \propto c_5\frac{v^2}{\Lambda}$$

Weinberg, 1979

If neutrino masses are generated through this operator, we should expect additional effects coming from higher dimension operators too!

Non-Standard Interactions

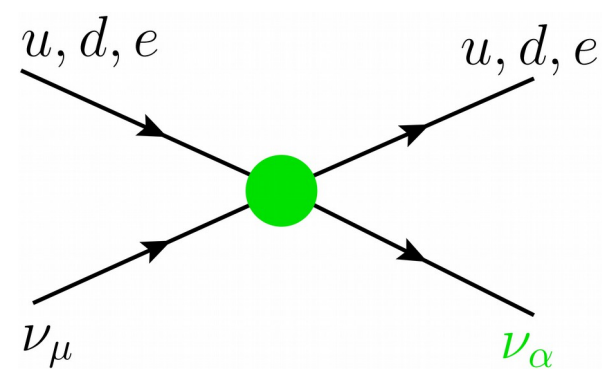
$$\mathcal{L}^{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\,\delta\mathcal{L}^{d=5} + \frac{1}{\Lambda^2}\,\delta\mathcal{L}^{d=6} + \ldots$$

NSI can affect neutrinos in propagation through matter. After EWSB, we get:

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

Neutrino oscillations will only be sensitive to vectorial NSI through the combination:

$$\varepsilon_{\alpha\beta} \equiv (1/n_e)\sum_{f,P} n_f \epsilon^{fP}_{\alpha\beta}$$



$$\varepsilon^f_{\mu\alpha}\left(\overline{f}\gamma^\rho f\right)\left(\overline{\nu}_\mu\gamma_{\rho,L}\nu_\alpha\right)$$

NC process

Previous constraints on NSI

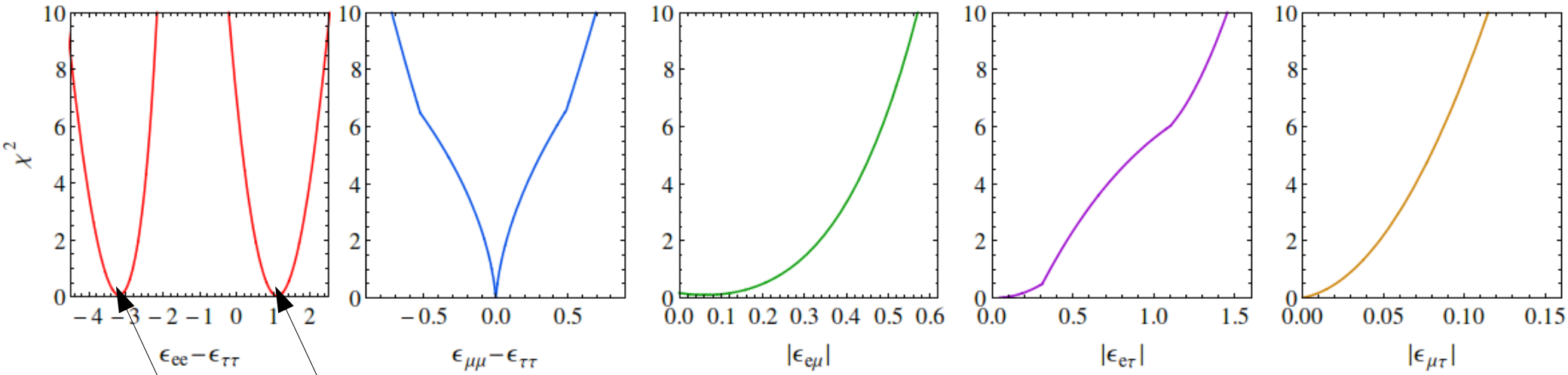


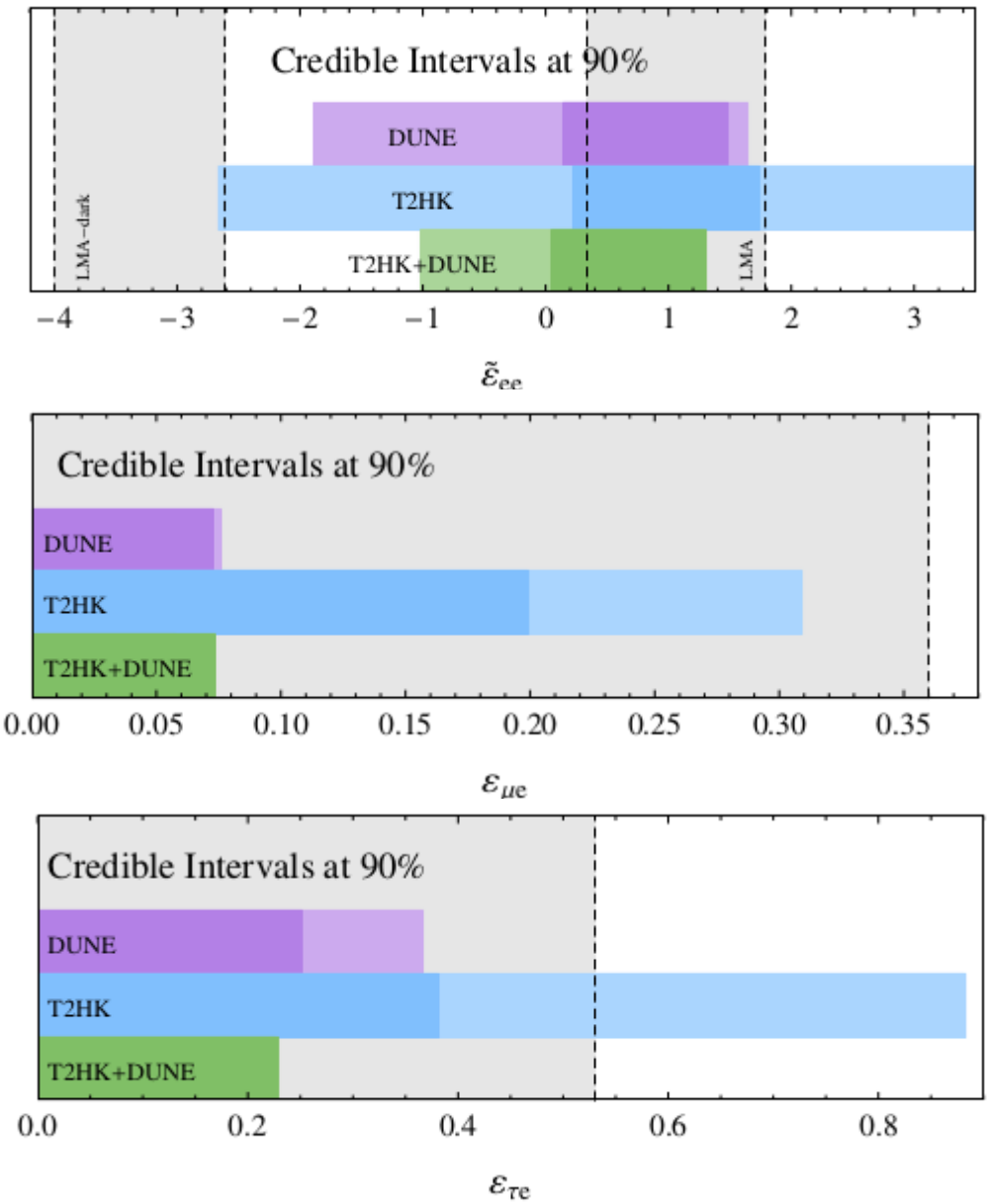
Figure adapted from Gonzalez-Garcia and Maltoni, 1307.3092

LMA solution (standard oscillation parameters)

LMA-Dark solution (solar angle in the higher octant)

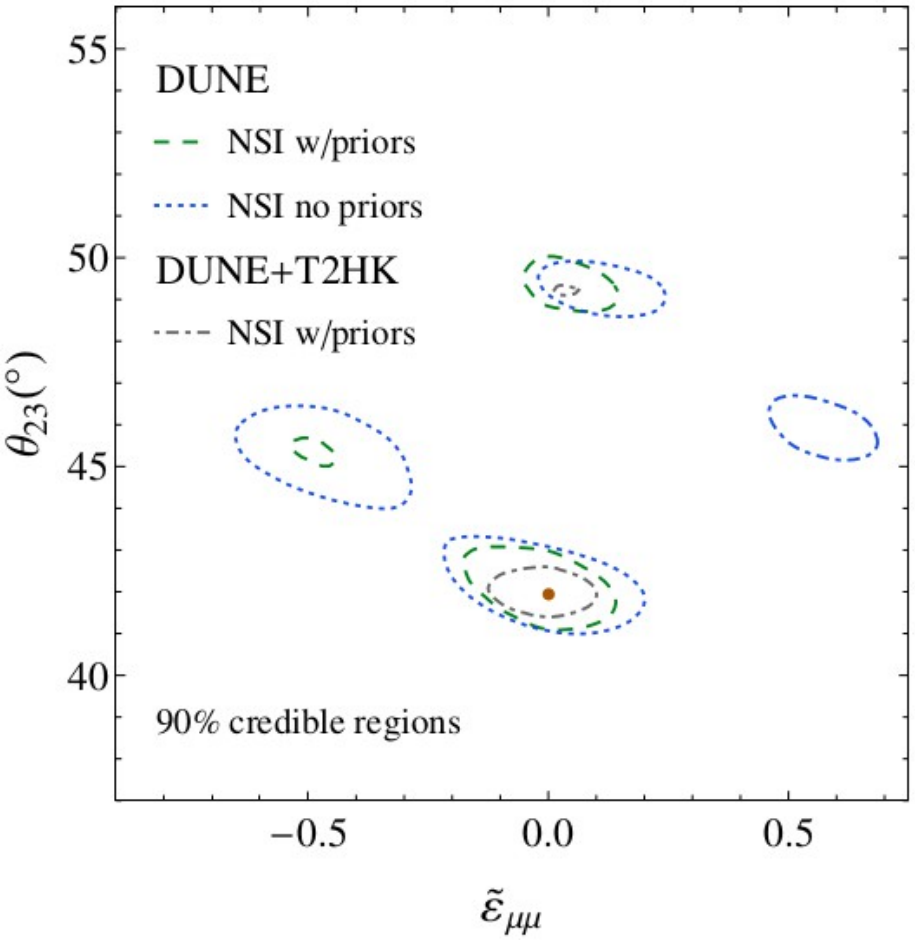
Miranda, Tortola, Valle, hep-ph/0406280

DUNE sensitivities to NSI



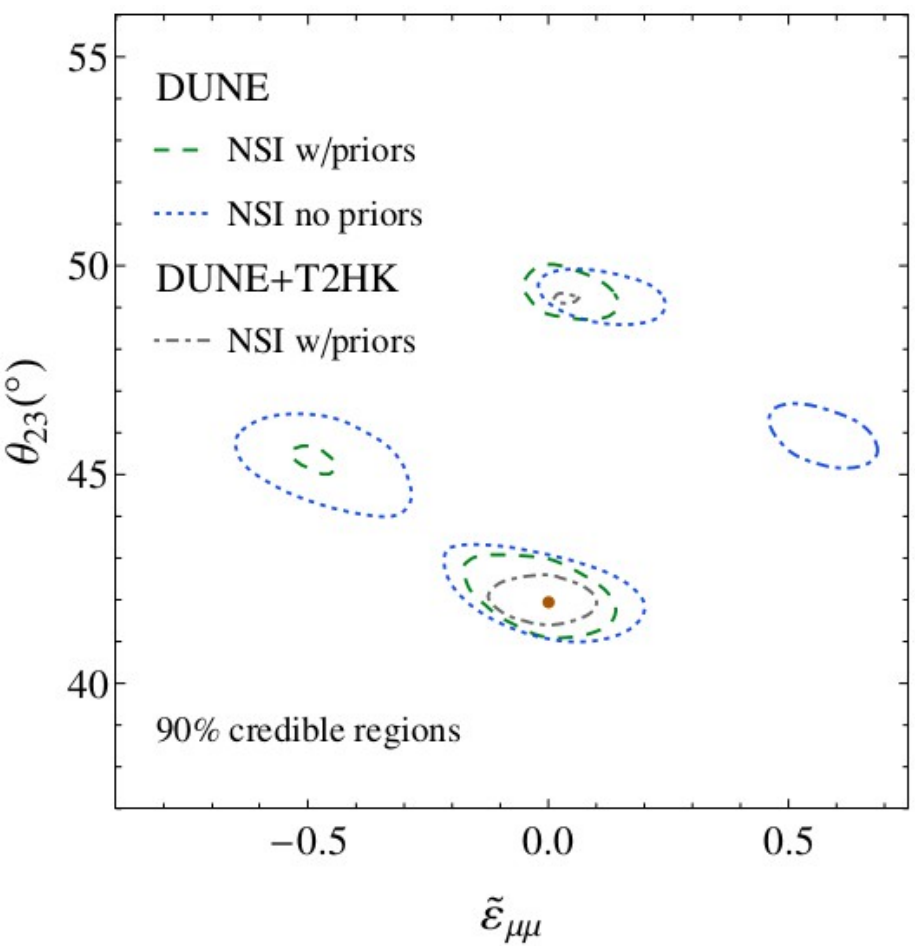
PC, 1511.06357

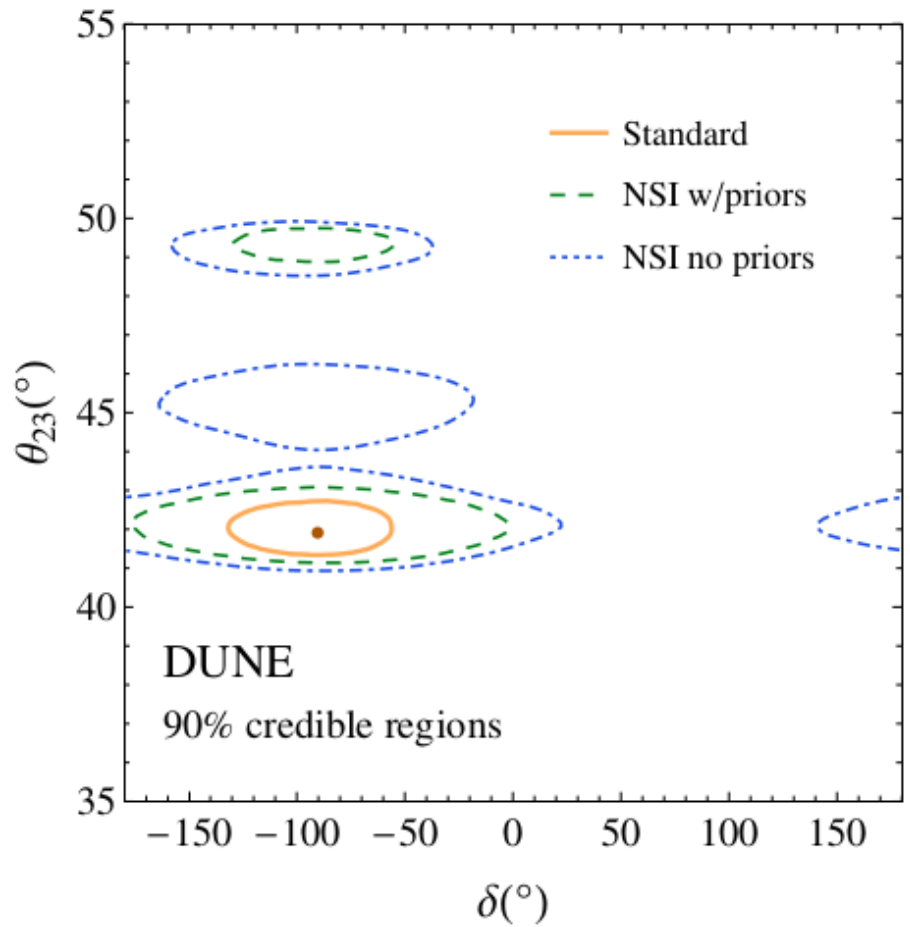
Potential issues: degeneracies



PC, 1511.06357

Potential issues: degeneracies





PC, 1511.06357

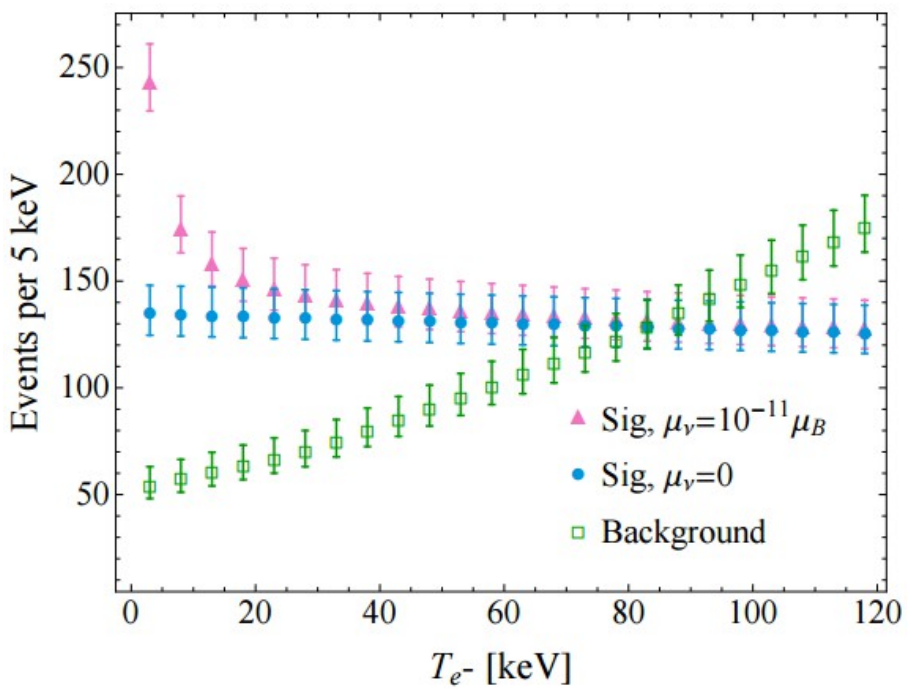
Neutrinos beyond oscillations

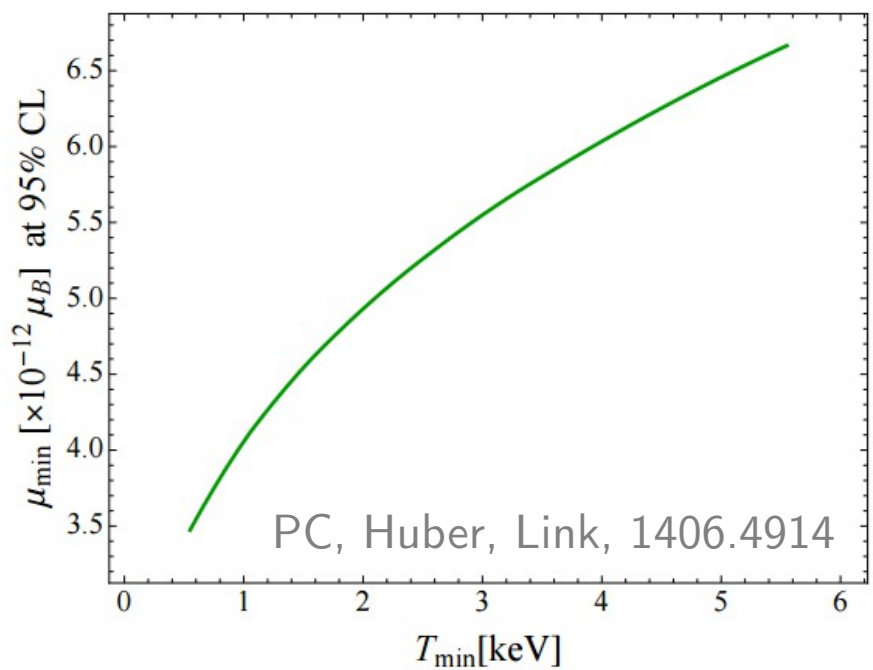
PC, Dobrescu, Frugiuele, Harnik, 1512.03852
PC, Dobrescu, Lopez-Pavon, 1508.04129
PC, Huber, Link, 1406.4914

Neutrinos at dark matter experiments

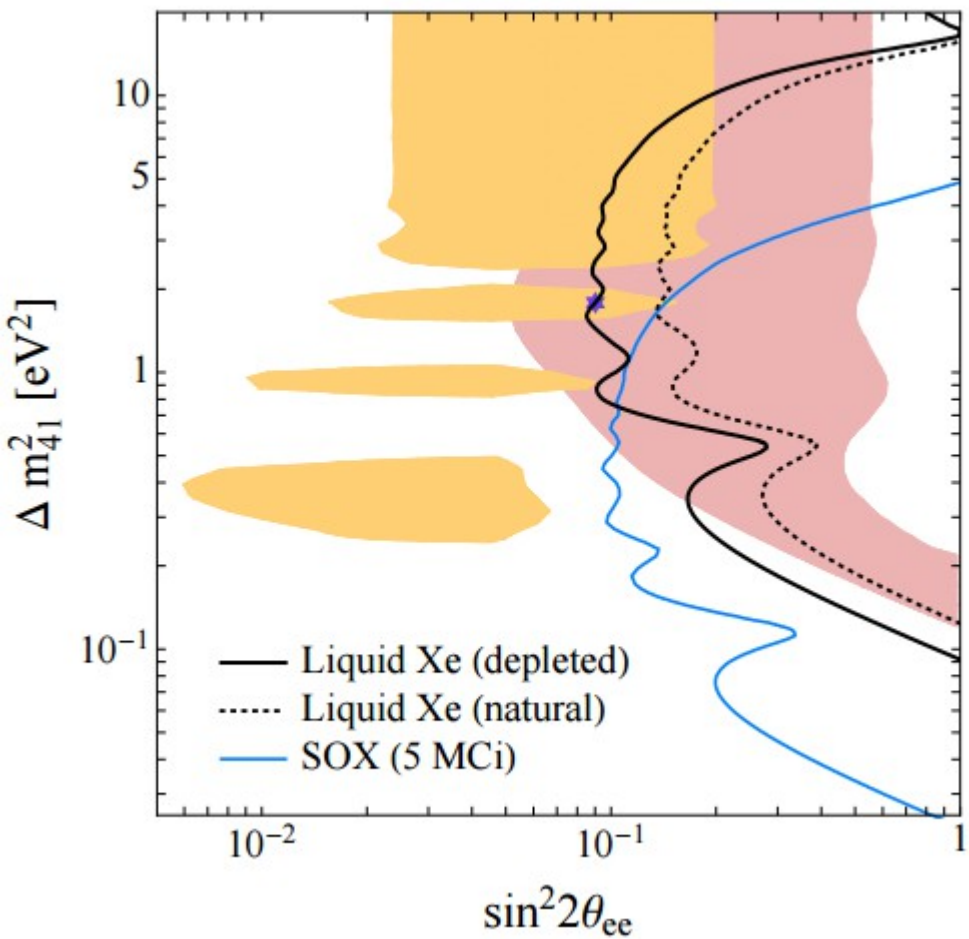
Bounds on neutrino magnetic moment from a radioactive source combined with the LZ detector:

$$\left(\frac{d\sigma}{dT}\right)_{tot} = \left(\frac{d\sigma}{dT}\right)_{SM} + \frac{\pi\alpha^2}{m_e^2}\left(\frac{1}{T} - \frac{1}{E_\nu}\right)\left(\frac{\mu_\nu}{\mu_B}\right)^2$$





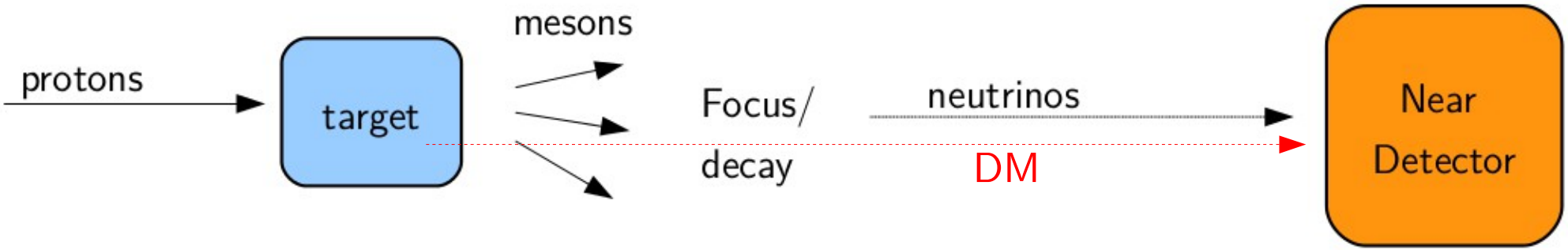
Neutrinos at dark matter experiments

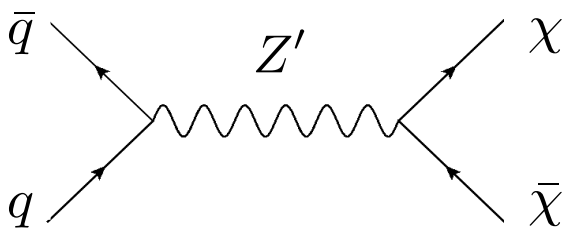


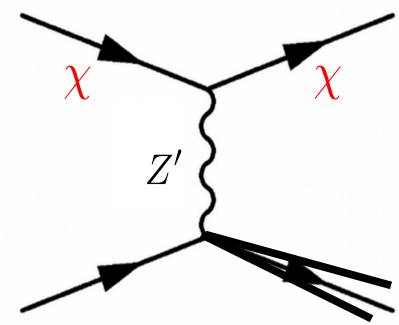
This setup would also be able to probe some of the sterile neutrino anomalies, by observing oscillations inside the detector

PC, Huber, Link, 1406.4914

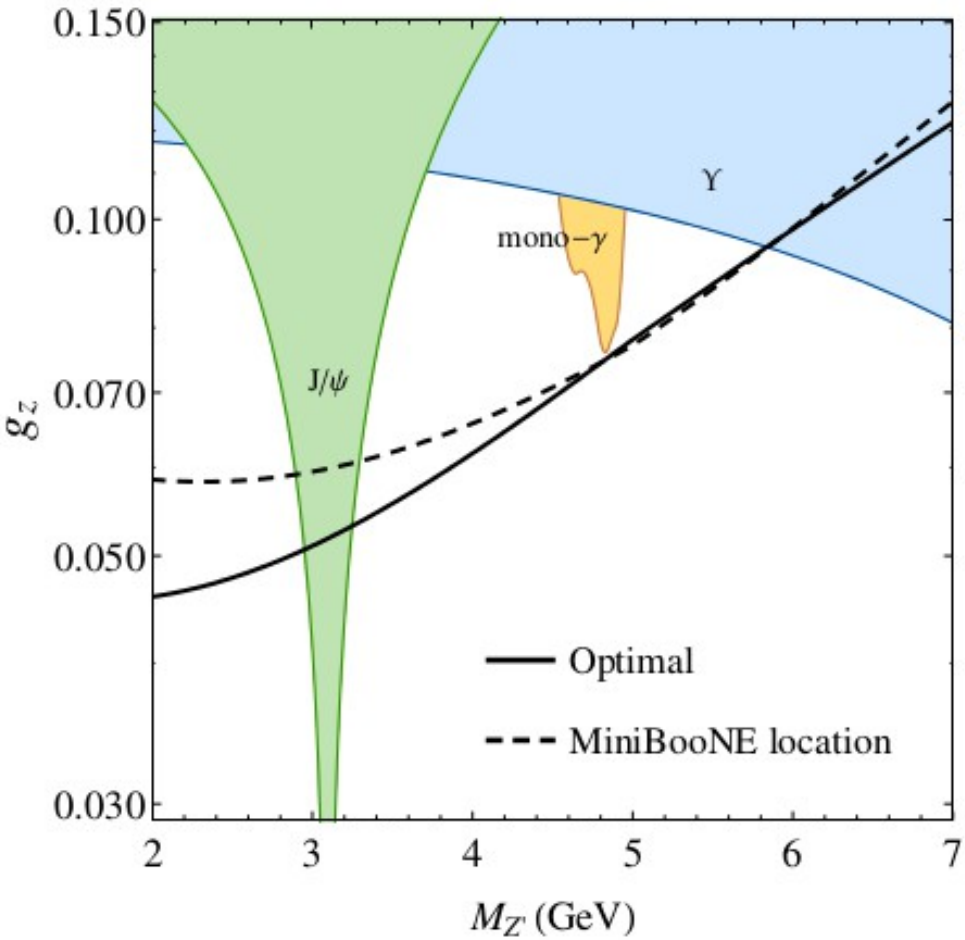
Dark matter at neutrino experiments



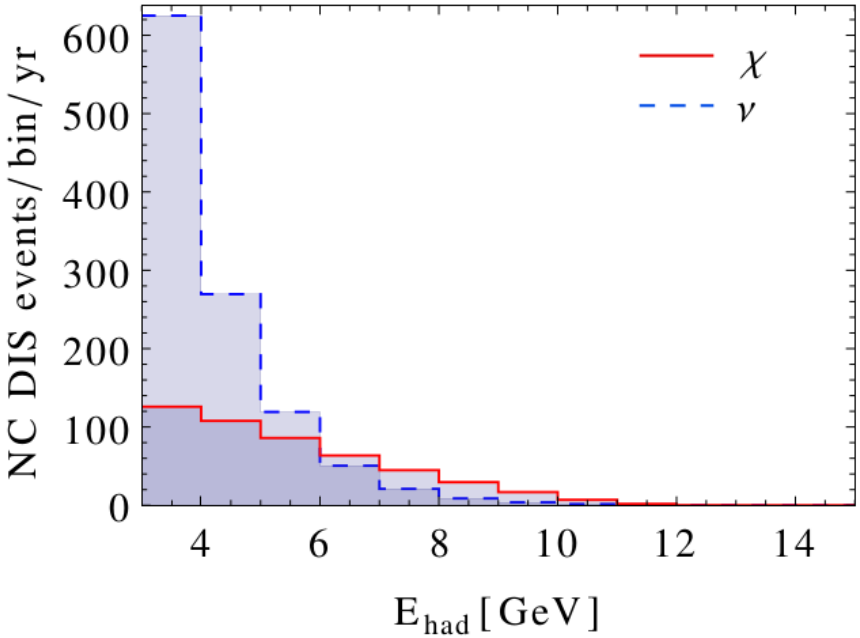




Dark matter at neutrino experiments



An excess of neutral current neutrino-like events could be a signal from a portal to a dark sector:



PC, Dobrescu, Frugiuele, Harnik, 1512.03852

Neutrino signals at colliders

- In 2014, CMS reported an excess in eejj events in a search for heavy neutrinos and W' bosons: CMS collaboration, 1407.3683
  - No dimuon-dijet excess observed
  - Only opposite-sign events recorded
- Left-right models $SU(3)_c x SU(2)_L x SU(2)_R x U(1)_{B-L}$ include both W' and heavy right handed neutrinos and could account for this excess. Requirements:
  - The mass of the heavy muon right-handed neutrino is heavier than the W'
  - The heavy electron neutrino cannot be "completely" Majorana

Neutrino signals at colliders

- A very natural way to achieve this is through a U(1) (or Z_3) flavor symmetry:

$$-\frac{y_{\mu\mu}}{2}(\bar{L}_R^\mu)^c i\sigma_2 T L_R^\mu - y_{e\tau}(\bar{L}_R^e)^c i\sigma_2 T L_R^\tau + \text{H.c.}$$

$$\begin{aligned} L_R^e &= (N_R^e, e_R)^\top && \text{Charge +1} \\ L_R^\mu &= (N_R^\mu, \mu_R)^\top && \text{Charge 0} \\ L_R^\tau &= (N_R^\tau, \tau_R)^\top && \text{Charge -1} \end{aligned}$$

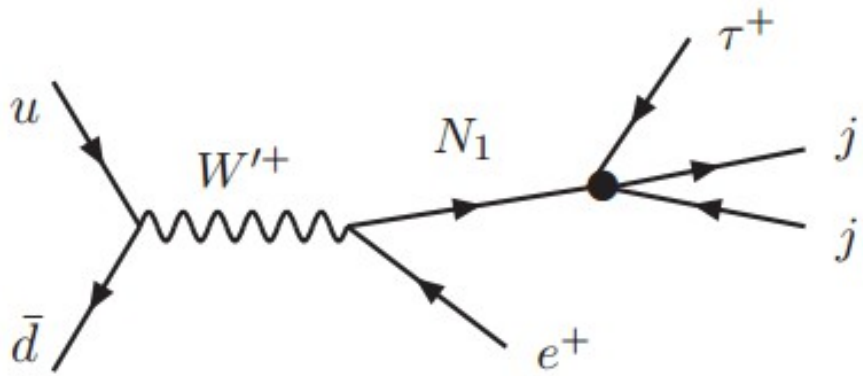
Triplet: neutral under flavor symmetry

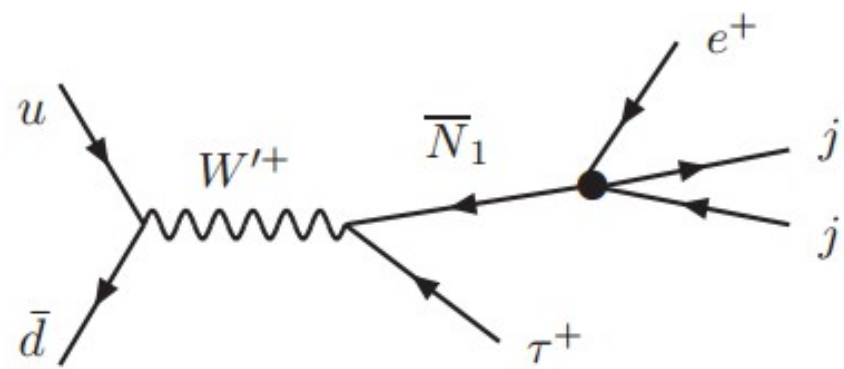
$$\begin{aligned} N_R^\tau &\equiv N_{1_L}^c \\ N_R^e &\equiv N_{1_R} \end{aligned} \longrightarrow \frac{g_R}{\sqrt{2}} W'_\nu (\bar{N}_{1_R}\gamma^\nu e_R + \bar{N}_{1_L}^c \gamma^\nu \tau_R) + \text{H.c.}$$

PC, Dobrescu, Lopez-Pavon, 1508.04129

Neutrino signals at colliders

- The flavor structure forbids same-sign dilepton signatures





- It also strongly suppresses neutrinoless double beta decay and charged-lepton flavor-violating processes
- Light neutrino masses and mixing at low energies are generated via a seesaw mechanism

Summary and conclusions

We are entering the precision Era in Neutrino Physics:

- The field is changing very rapidly. Perfect time to work on neutrino oscillations, new measurements coming soon!

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Neutrino experiments can (should!) be used to search for New Physics:

- It is relatively easy to confuse New Physics with systematic errors
- Complementarity between different data sets is crucial

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Neutrino masses were a surprise. What else can we expect?

- Neutrino magnetic moments? Sterile neutrinos? Non-Standard Interactions? Non-Unitarity effects? Charged lepton flavor violation? Neutrino decay? Collider signatures? ...

Thank you!!