Neutrino phenomenology

Pilar Coloma
Fermilab

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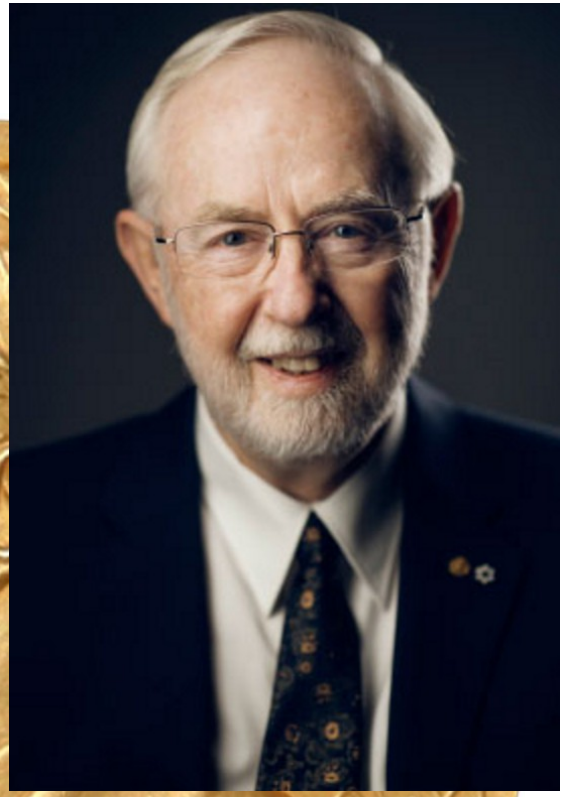

Takaaki Kajita

Super-Kamiokande Collaboration

University of Tokyo, Kashiwa, Japan

Arthur B. McDonald

Sudbury Neutrino Observatory Collaboration

Queen's University, Kingston, Canada

The leptonic mixing matrix

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric Reactor/Interference Solar

$$\times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1} & 0 \\ 0 & 0 & e^{i\alpha_2} \end{pmatrix}$$

$$\theta_{13} \sim 9^\circ$$

$$\theta_{23} \sim 45^\circ$$

$$\theta_{12} \sim 33^\circ$$

$$\Delta m^2_{21} \sim 7.5 \times 10^{-5}\,\mathrm{eV}^2$$

$$|\,\Delta m^2_{31}\,| \sim 2.5 \times 10^{-3}\,\mathrm{eV}^2$$

For up-to-date results and/or precise values, see e.g. www.nu-fit.org or Capozzi et al, 1601.07777

NEUTRINOS HAVE MASS

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Now, which type of mass?

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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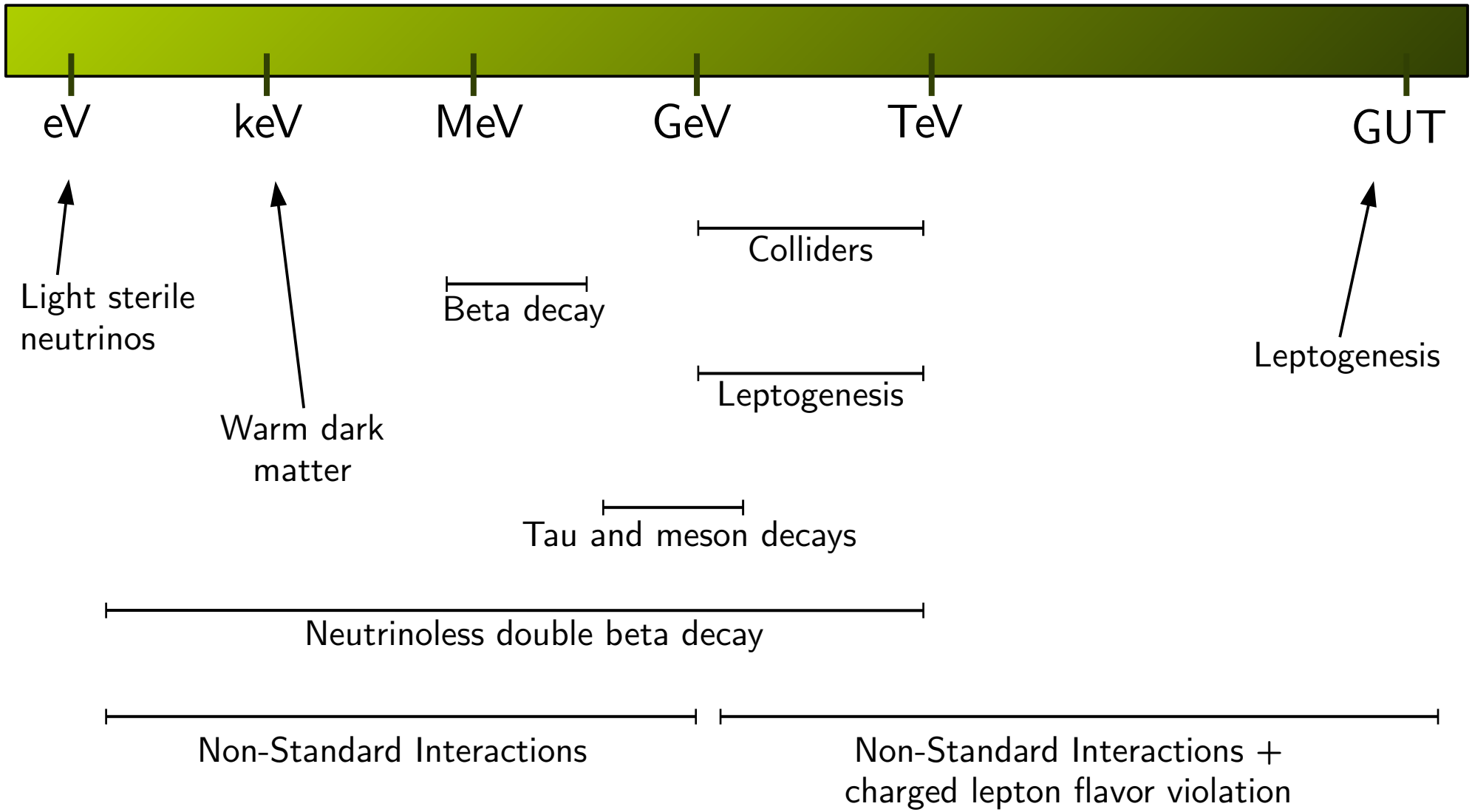
2) A Majorana mass. For example:

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

$$(\not{L})$$

Scale of new physics



What next?

- Is there CP violation in the neutrino sector? What is the ordering of neutrino masses?
- Flavor puzzle?
- Are neutrinos Majorana or Dirac?
- Are there more than three neutrinos?
- Do neutrinos have new interactions?
- Where do neutrino masses come from? Is there new phenomenology out there waiting for us?
- What is the absolute scale of neutrino masses?
- Is the lightest neutrino massless?
- ...

Part I: Standard searches

CP violation searches

Three-family ν_e appearance oscillation probability (vacuum):

Atmospheric

CP interference

$$P_{\mu e} \simeq (\sin\theta_{23}\sin 2\theta_{13})^2 \sin^2(\Delta_{31})$$
$$+ \sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}\cos\theta_{13}\Delta_{21}\sin(\Delta_{31})\cos(\pm\delta + \Delta_{31})$$
$$+ (\cos\theta_{23}\sin 2\theta_{12})^2 \sin^2(\Delta_{21})$$

Solar

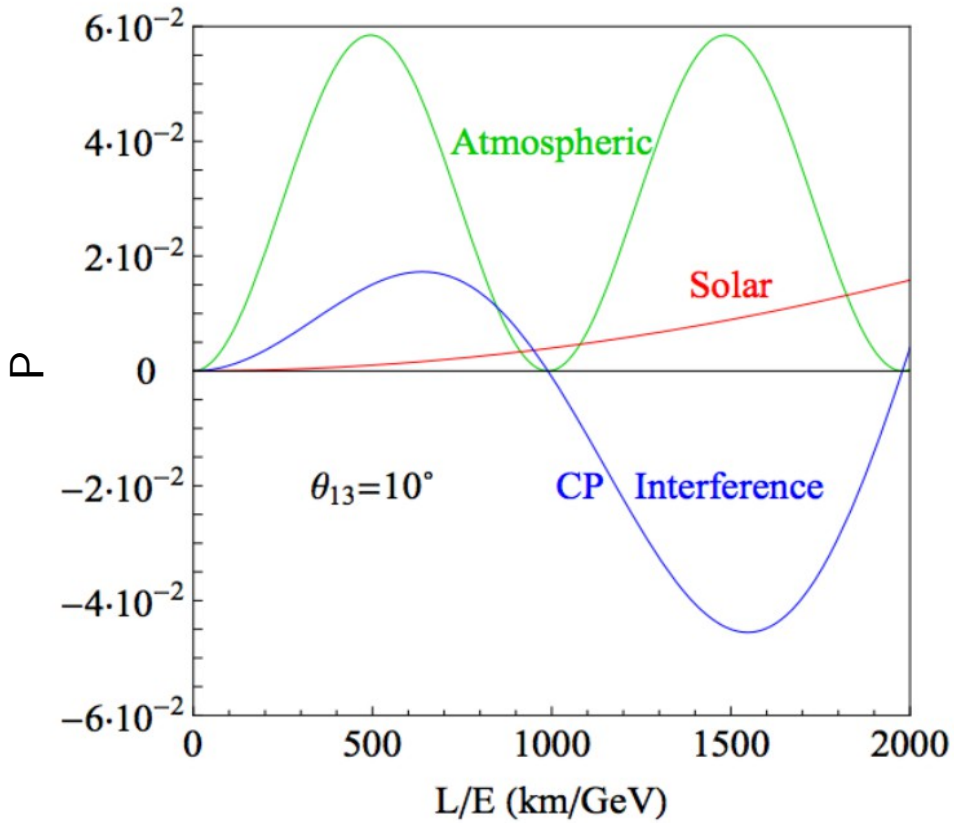
Neutrino/Antineutrino

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

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

CP violation searches

The combination of long-baseline and reactor experiments is already giving a hint for the value of δ (see NOvA talk by Adam Aurisano)
More powerful facilities will be needed to reach a higher significance (See DUNE talk by Dan Cherdack)

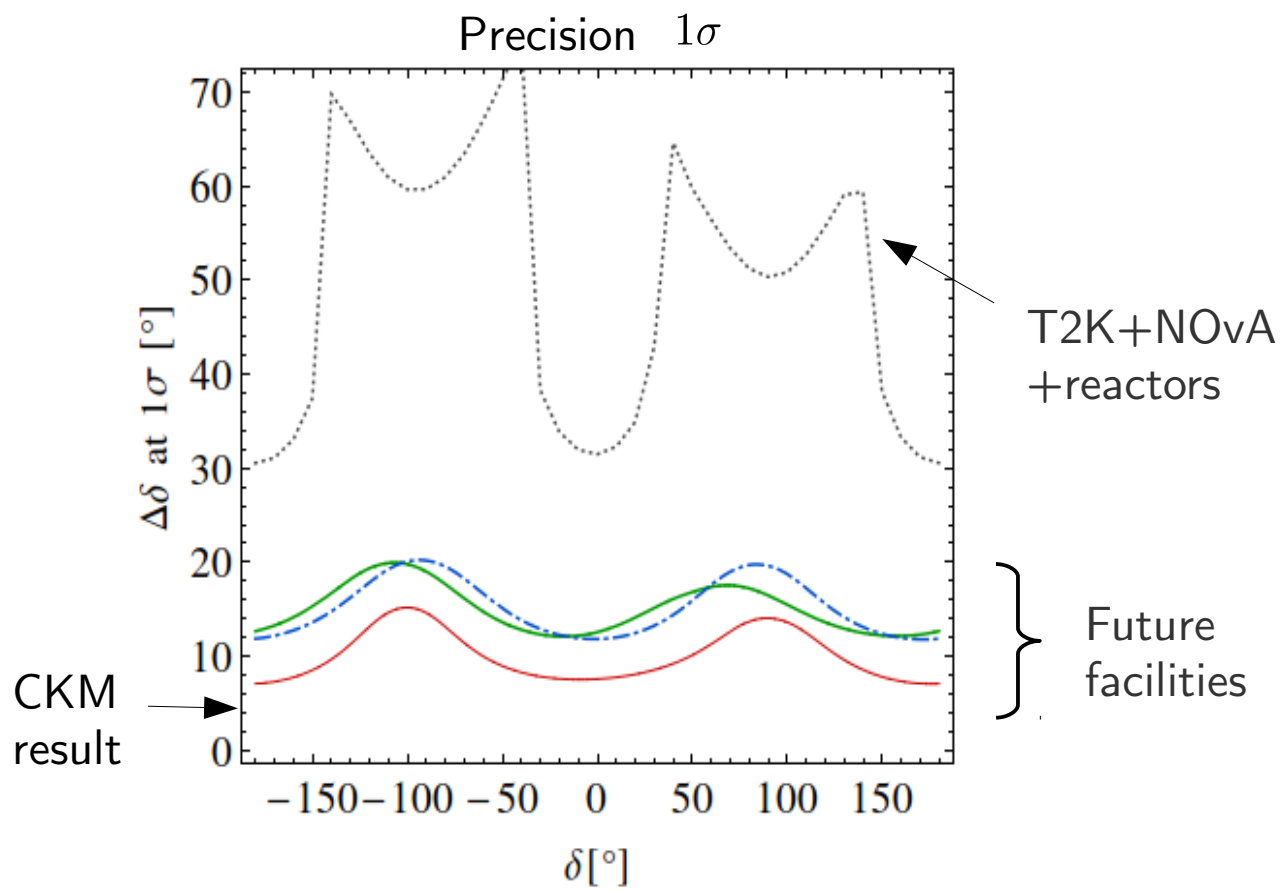


CP violation versus precision

In vacuum,

$$(\Delta\delta)_\pm \propto \left| \frac{1}{\sin(\Delta \mp \delta)} \right|$$

$$\Delta \equiv \frac{\Delta m^2_{31} L}{4E}$$



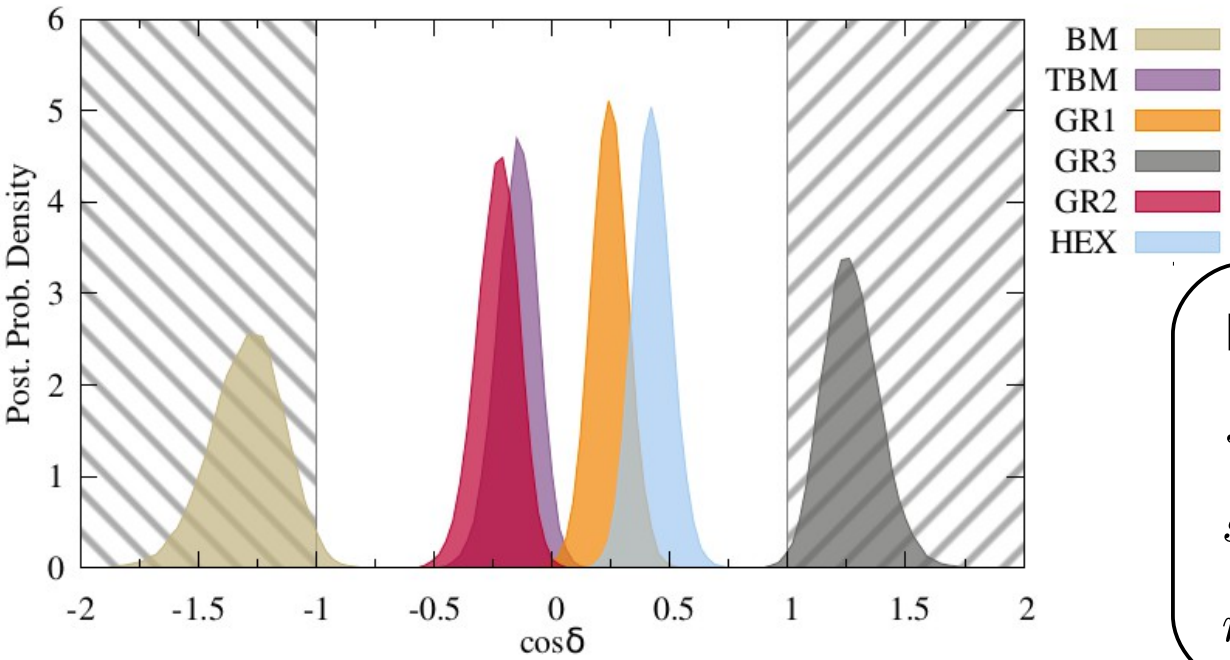
PC, Donini, Fernandez-Martinez,
Hernandez, 1203.5651

Why precision?

To test the flavor pattern in the nuSM!

$$U = U_e^\dagger U_\nu$$

(Small corrections)



For example, for TBM:

$$s = r\cos\delta + \mathcal{O}(\epsilon^2)$$

$$s = \sqrt{3}\sin\theta_{12} - 1$$

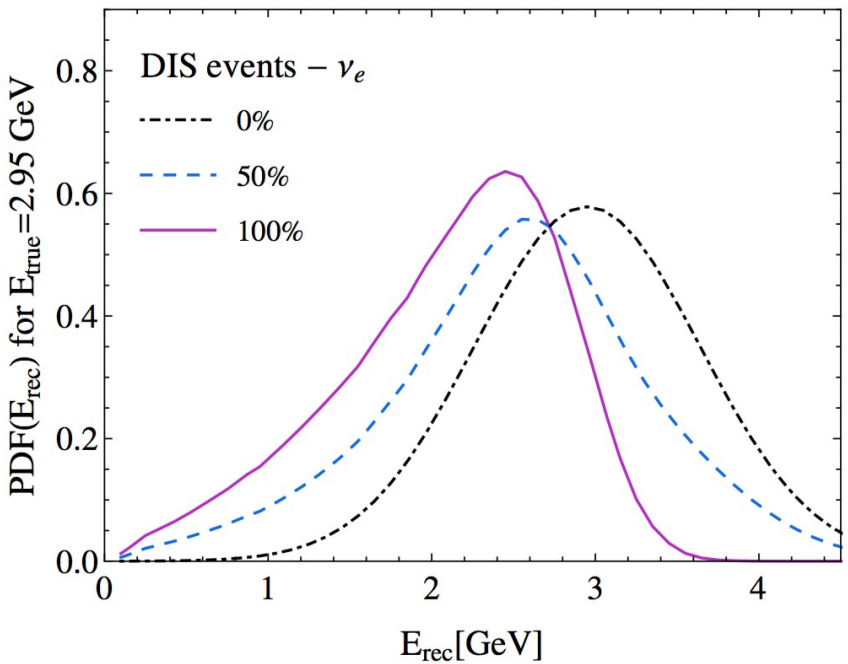
$$r \equiv \sqrt{2}\sin\theta_{13}$$

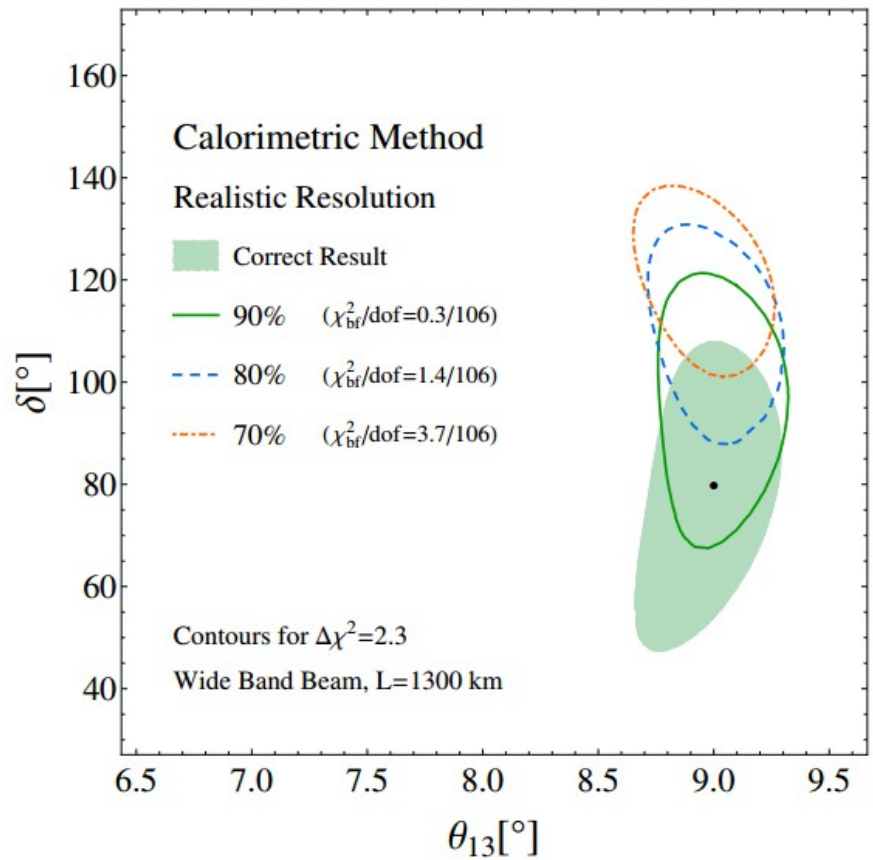
$$(\theta_{23}^e = \theta_{13}^e = \theta_{13}^\nu = 0)$$

Ballett, King, Luhn, Pascoli, Schmidt, 1410.7573 [hep-ph]
(see also, e.g., Girardi et al, 1410.8056 and 1504.00658, Meloni, 1308.4578)

Systematics

Impact of missing energy in calorimetric reconstruction:



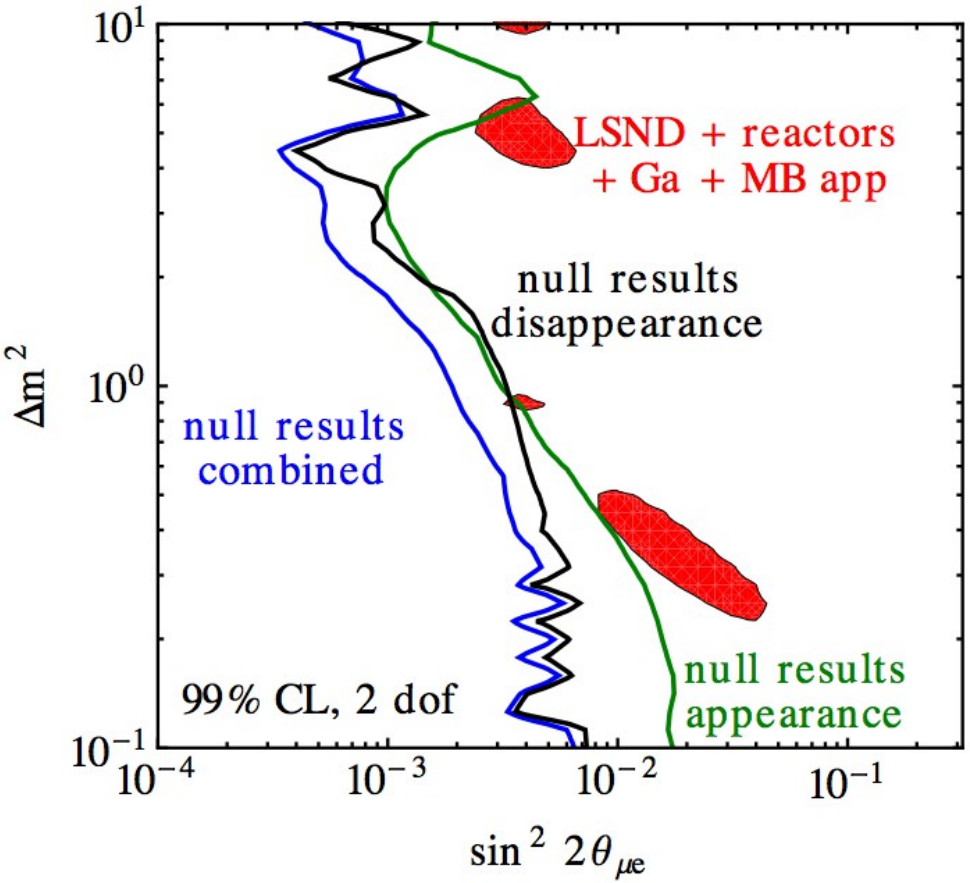


MINERvA, LARIAT, CAPTAIN and MicroBooNE (among others) will be very helpful in reducing systematic uncertainties in LAr!!

Ankowski et al, 1507.08561
(see also Ankowski et al, 1507.08560)

Part II: Non-Standard searches

Sterile neutrinos



Will be addressed by the SBN program, and MINOS+

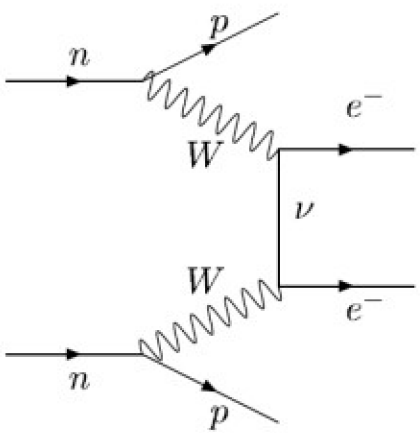
(see talks by Angela Fava, Paul Sail and Michael Mooney)

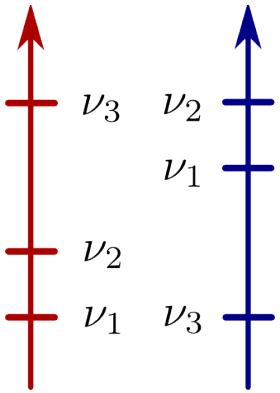
$$P_{ee} = 1 - 2|U_{e4}|^2(1 - |U_{e4}|^2)$$
$$P_{\mu\mu} = 1 - 2|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2)$$
$$P_{\mu e} = 2|U_{e4}|^2|U_{\mu 4}|^2$$

Kopp, Machado, Maltoni, Schwetz, 1303.3011

Mass ordering and new physics

$$m_{0\nu\beta\beta} = \left| \sum_i m_i U_{ei}^2 \right|$$





3-neutrino case:

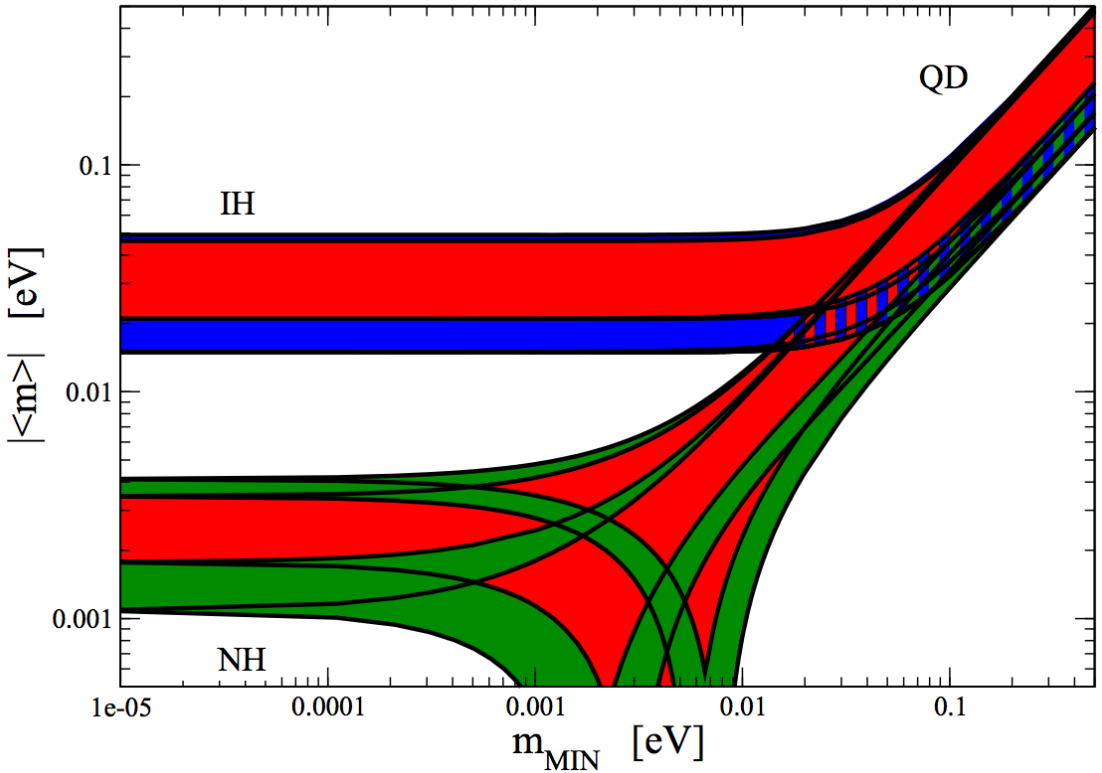
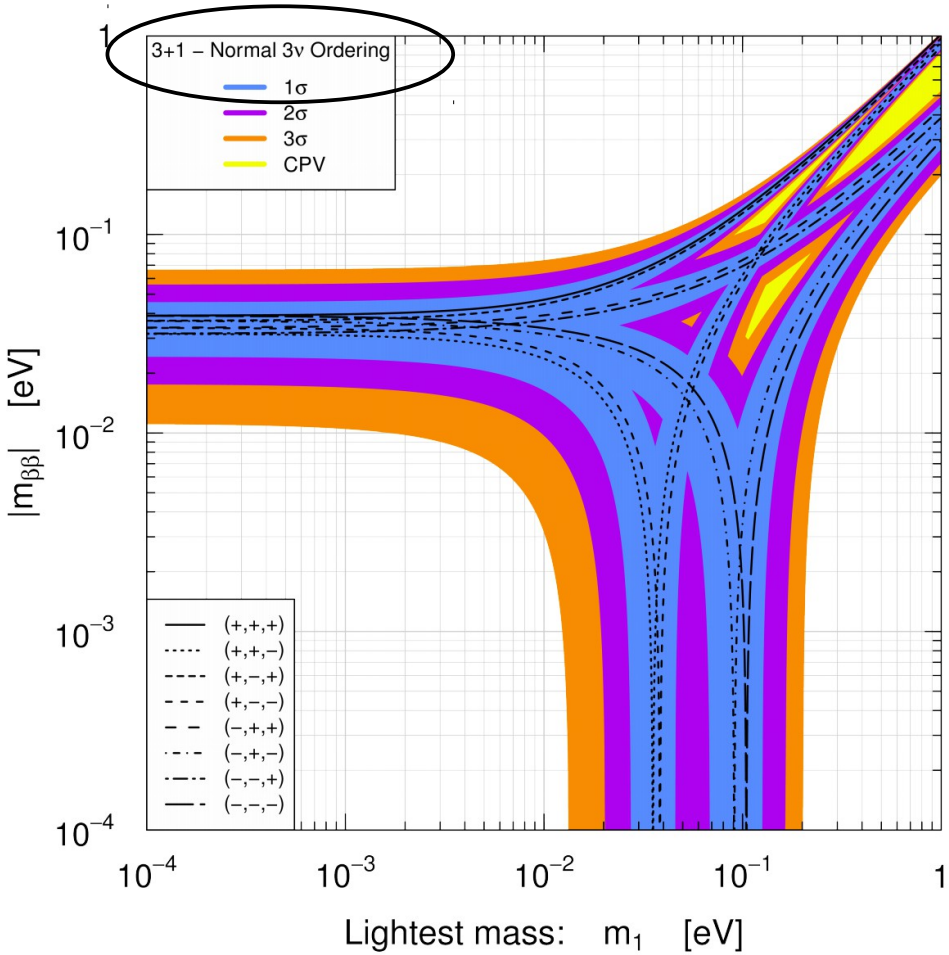


Figure from PDG, courtesy of Silvia Pascoli

Mass ordering and new physics



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

3-neutrino case:

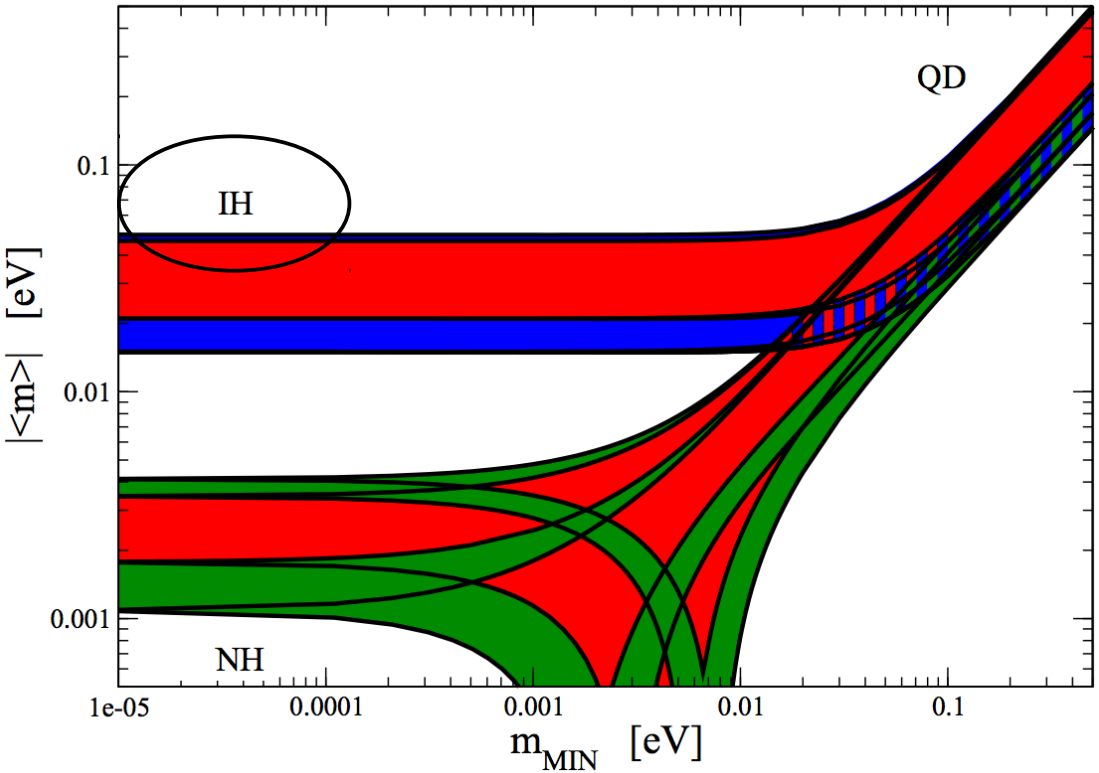


Figure from PDG, courtesy of Silvia Pascoli

Non-Standard Interactions

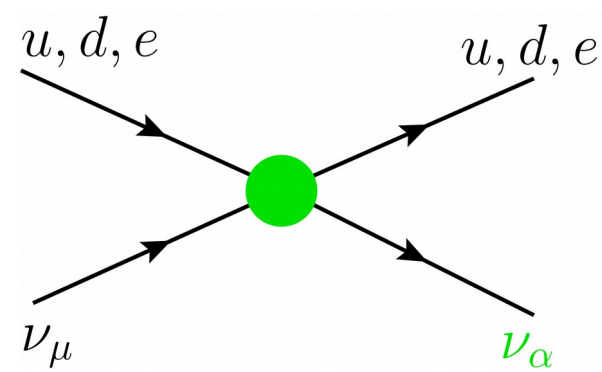
$$\mathcal{L}^{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\,\delta\mathcal{L}^{d=5} + \frac{1}{\Lambda^2}\,\delta\mathcal{L}^{d=6} + \ldots$$

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

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

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

$$\varepsilon_{\alpha\beta} \equiv \sum_{f,P} \frac{n_f}{n_e} \epsilon^{fP}_{\alpha\beta}$$

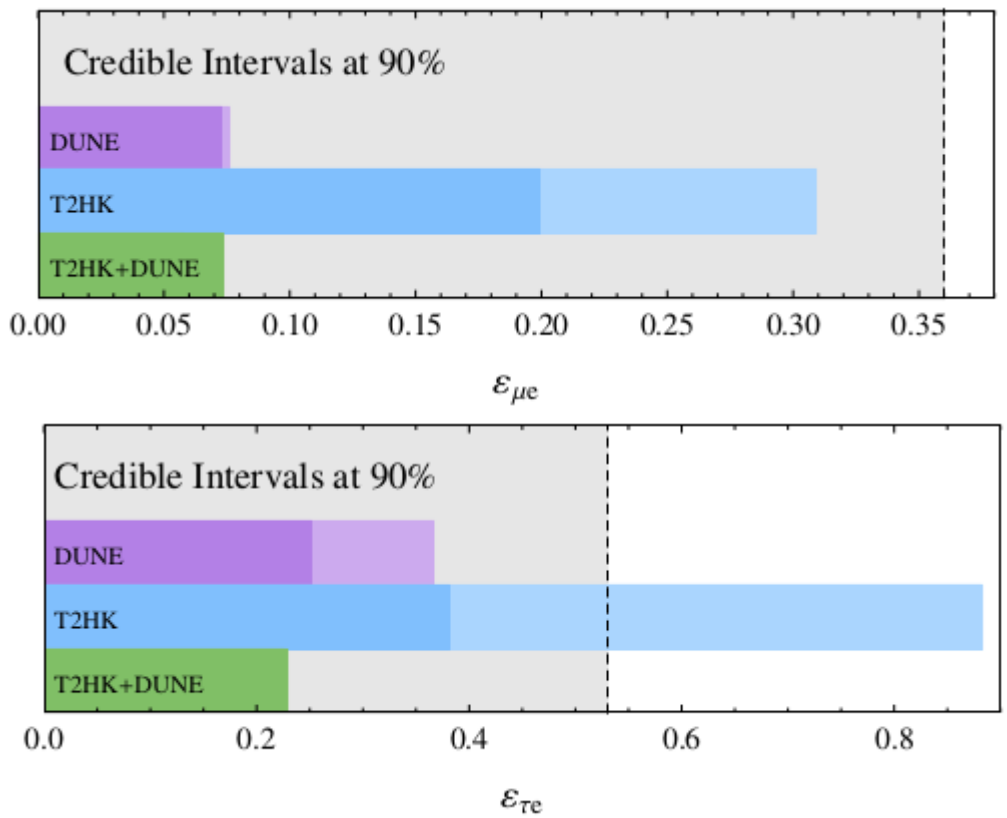


$$\varepsilon^f_{\mu\alpha} \left(\overline{f}\gamma^\rho f\right) \left(\overline{\nu}_\mu \gamma_{\rho,L} \nu_\alpha\right)$$

NC process

DUNE sensitivities to NSI

$$H_{\rm mat} = \sqrt{2} G_F N_e(x) \begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix}$$



PC, 1511.06357

(Previous bounds taken from Gonzalez-Garcia and Maltoni, 1307.3092)

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!

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

- Systematic errors need to be kept under control
- Complementarity between different data sets is crucial

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

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