# Neutrino phenomenology

Pilar Coloma

Fermilab

Heavy Quarks and Leptons Conference
Virginia Tech
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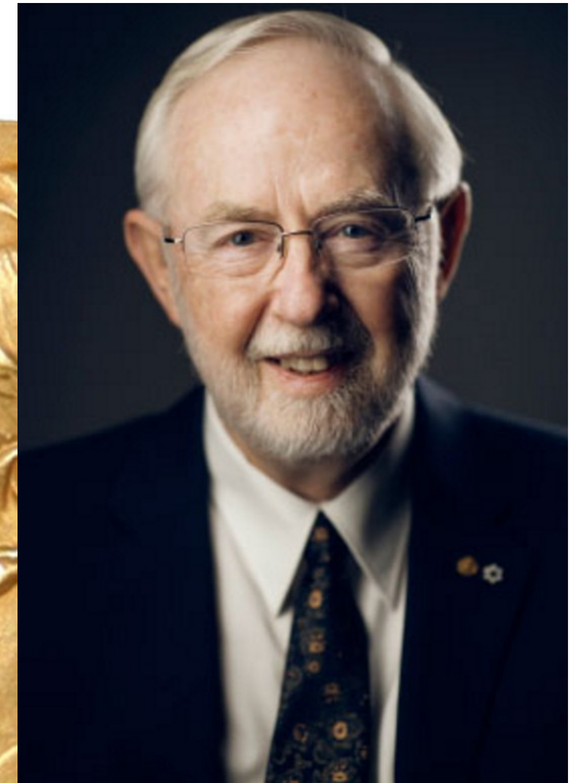


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# The leptonic mixing matrix

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

Atmospheric — Reactor/Interference — Solar

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

Pontecorvo, 1957
Maki, Nakagawa, Sakata, 1962

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

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

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

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

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

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

# 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?
- 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?

# What next?

- Is there CP violation in the neutrino sector? What is the ordering of neutrino masses?
  Long-baseline experiments, medium baseline reactor exps, atmospheric neutrino exps
- Flavor puzzle?
- Are neutrinos Majorana or Dirac?
  Neutrinoless double beta decay/colliders/meson decays
- Are there more than three neutrinos?
  SBND, SOX, SHiP, ...
- Where do neutrino masses come from? Is there new phenomenology out there waiting for us?
  Mu → e gamma, Mu → e in nuclei
  Meson decays
- What is the absolute scale of neutrino masses?
- Is the lightest neutrino massless?
  KATRIN, Project8, cosmology

# Majorana or Dirac?

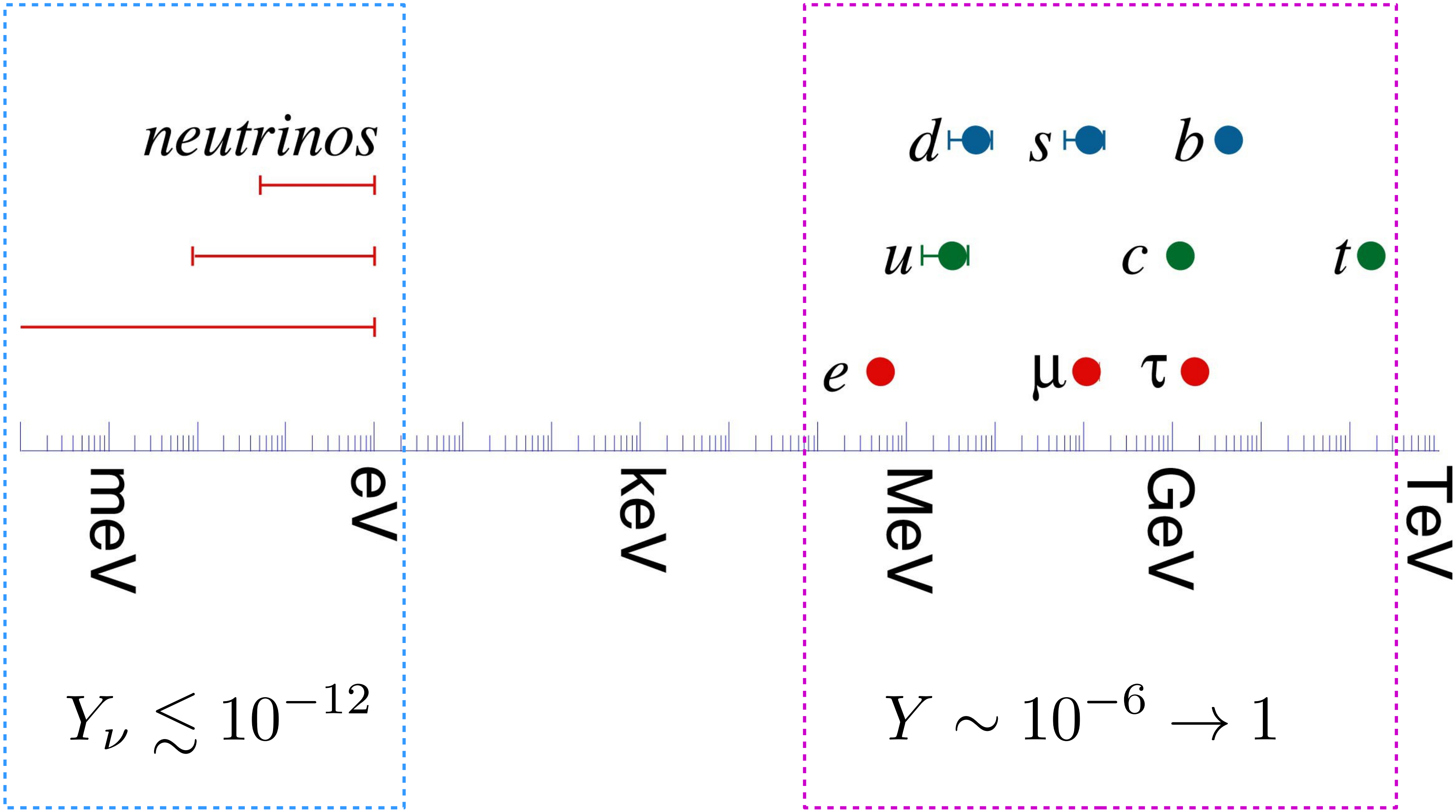
New fields are required to give neutrinos a mass. Two main ways:

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

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

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

# Smallness of neutrino masses




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

$Y \sim 10^{-6} \to 1$

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

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

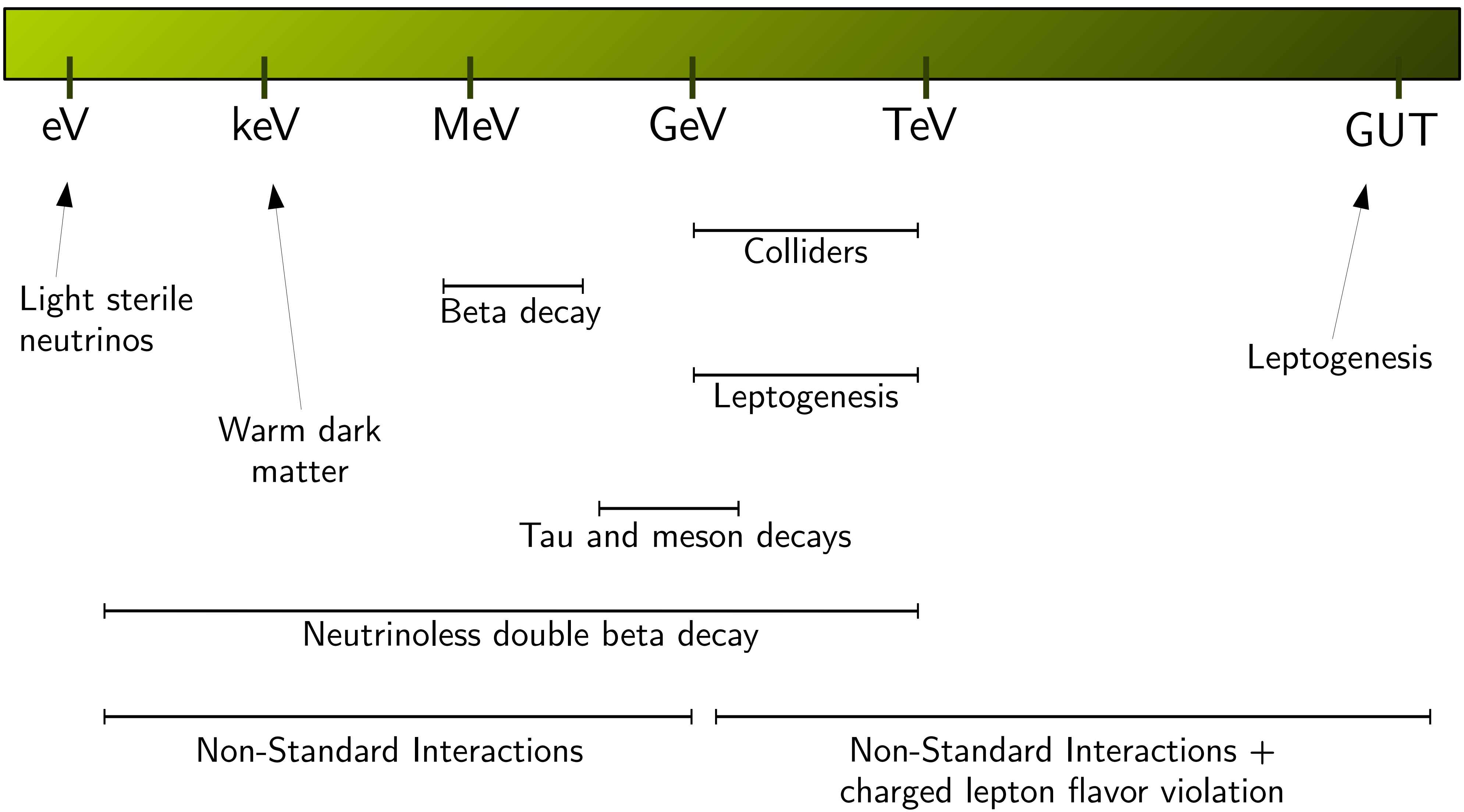
$$\boxed{Y_\nu \lesssim 10^{-12}}$$

2) A Majorana mass. For example:

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

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

# Scale of new physics



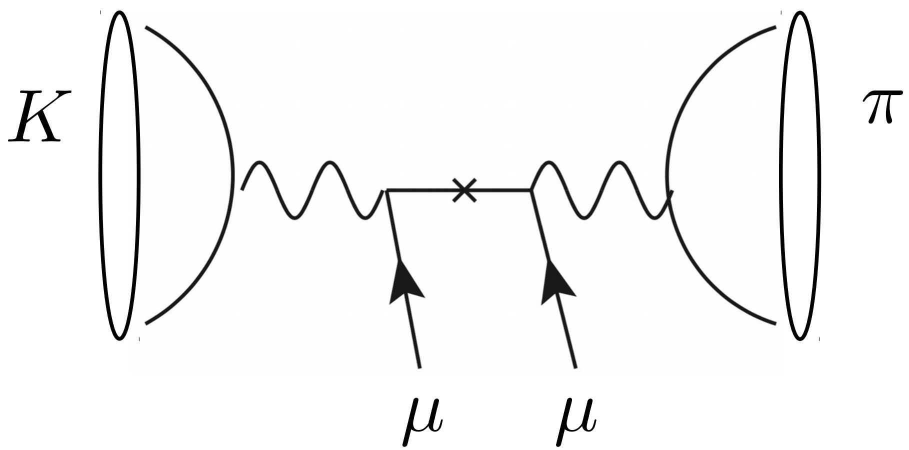
# Meson decays and heavy neutrinos

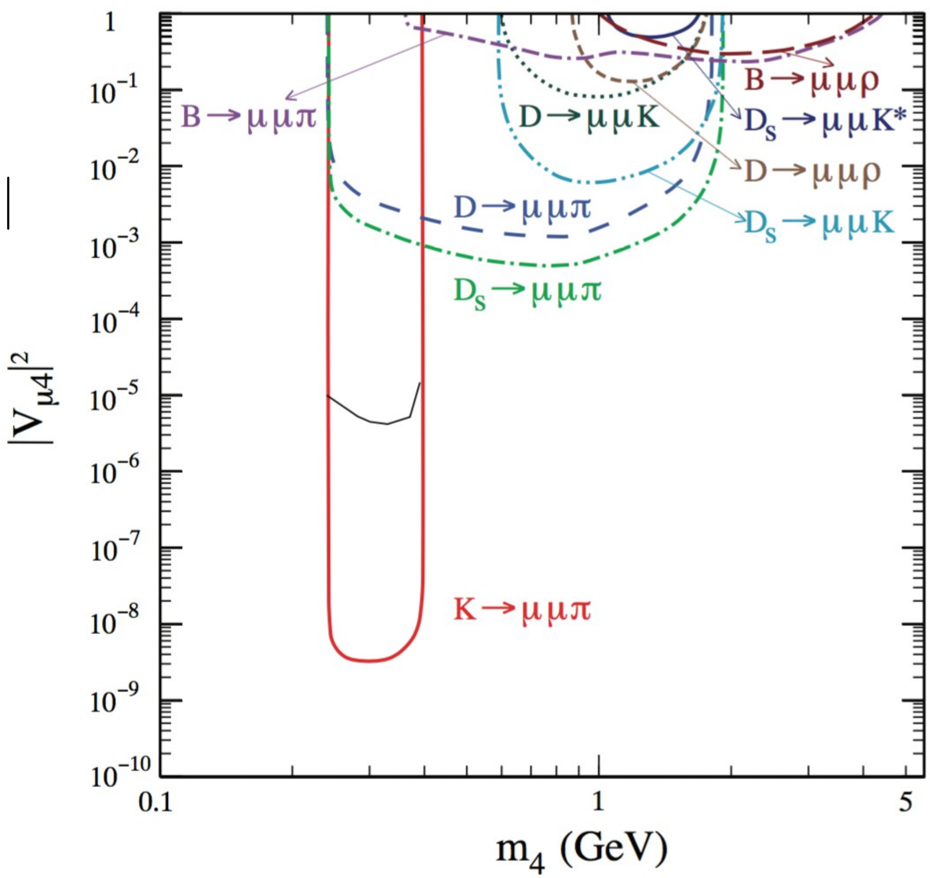
$$M_1^+ \to M_2^- \ell_1^+ \ell_2^+$$

$$\mathcal{B} \sim 10^{-16}\,\mathrm{GeV}\,\tau_{\mathrm{M}_1} |\mathrm{V}^{\mathrm{CKM}}_{\mathrm{M}_1} \mathrm{V}^{\mathrm{CKM}}_{\mathrm{M}_2}|^2 |\mathrm{V}_{\ell_1 4} \mathrm{V}_{\ell_2 4}|$$

Lifetime of $M_1$

For instance,

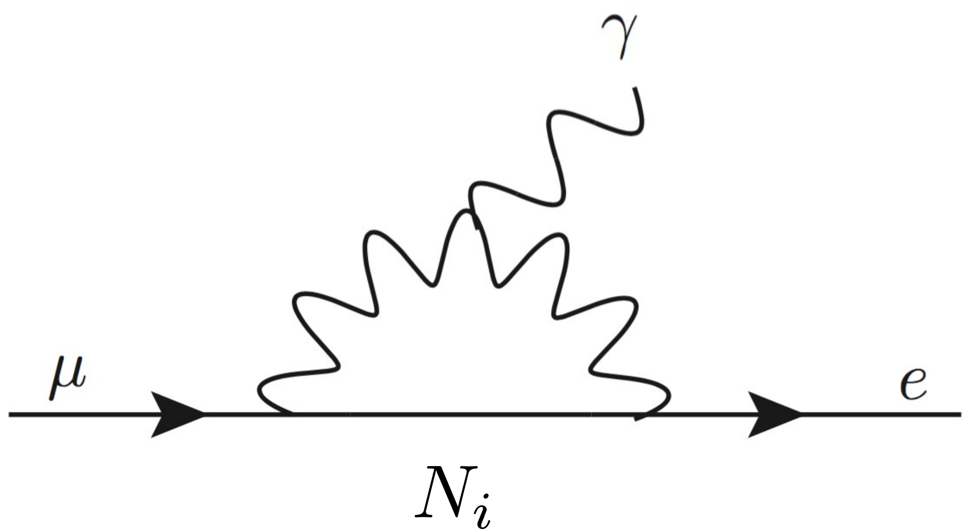



Atre, Han, Pascoli, Zhang, 0901.3589

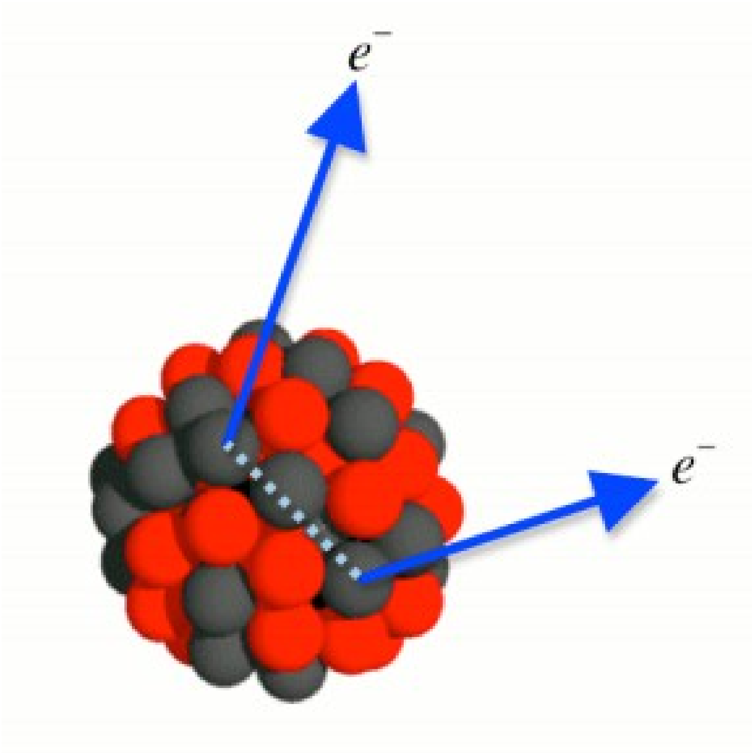
# Lepton flavor violation

Heavy neutrino exchange can enhance the rate for lepton flavor violating processes:

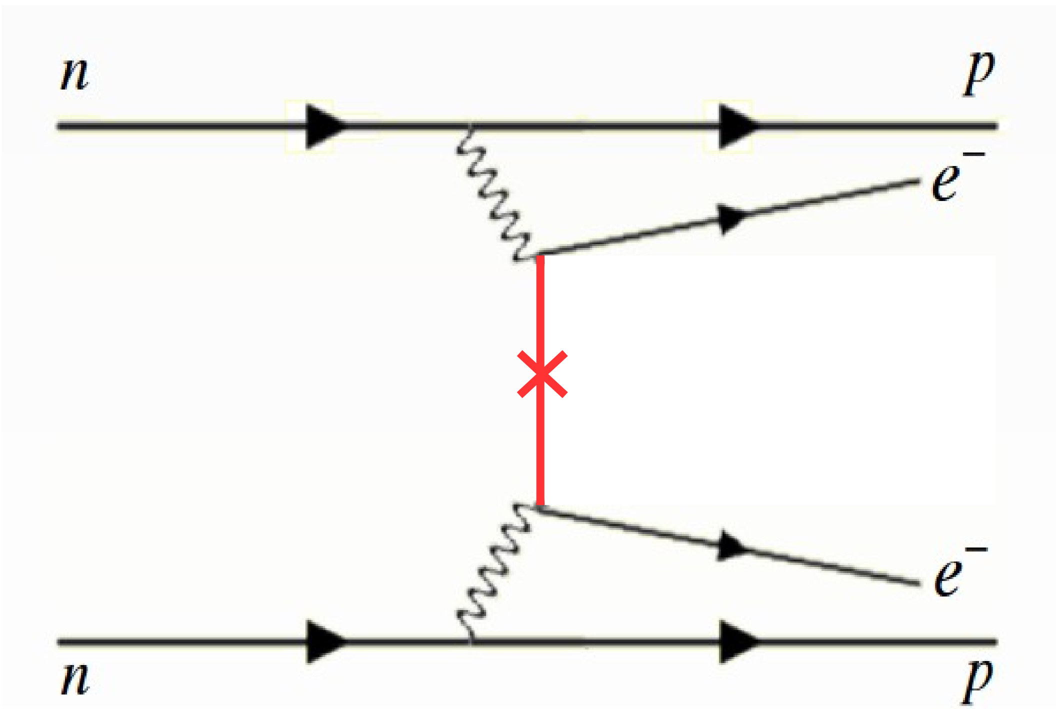



$$\mathcal{B}(\mu \to e\gamma) = \frac{3\alpha}{8\pi}\left|\sum_i V_{ei}V^*_{\mu i} f\left(\frac{m_i^2}{m_W^2}\right)\right|^2$$

# Neutrinoless double beta decay




Figures from R. Saakyan's talk at NuPhys2014




$$(T_{1/2})^{-1} \propto \langle m_{0\nu\beta\beta} \rangle^2 \mid \mathcal{M}^{0\nu\beta\beta} \mid^2$$

Depends on the New Physics model

Depends on the nucleus

# Synergy between experiments

Neutrinoless effective mass:

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

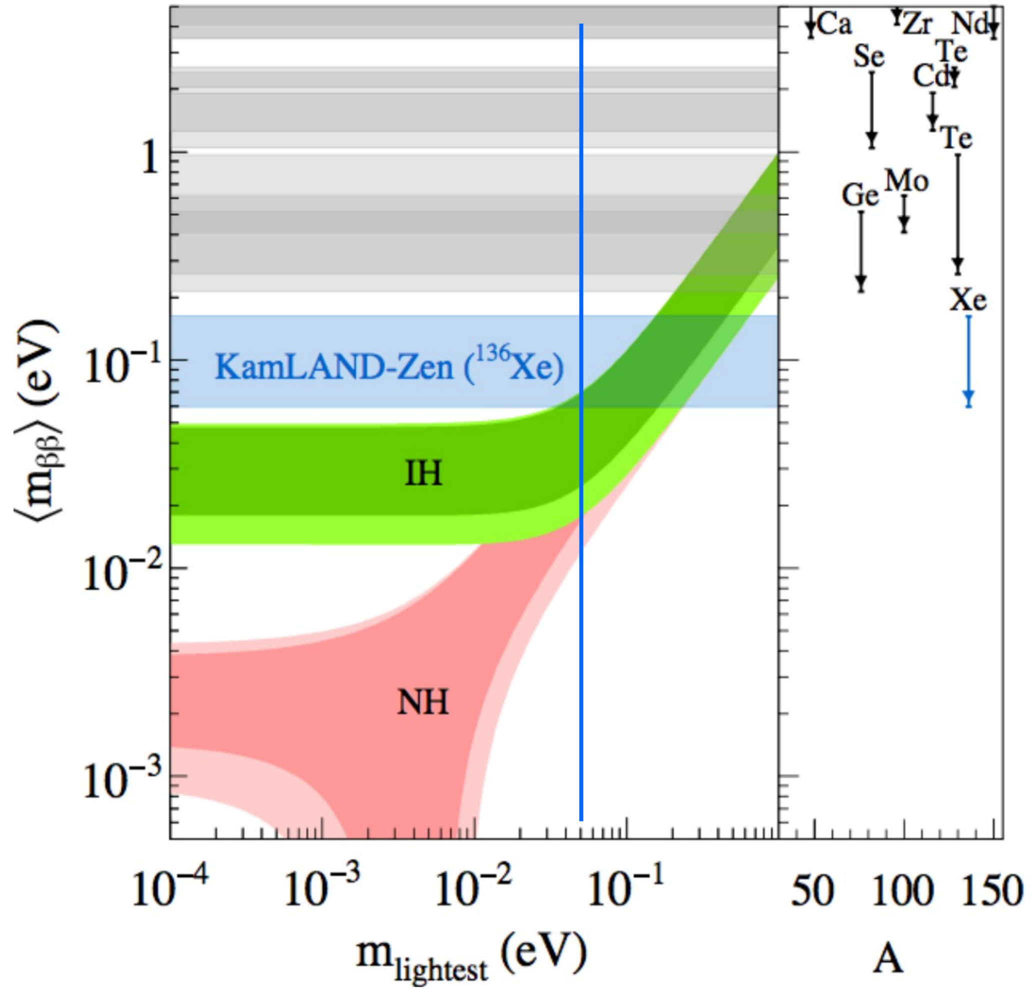
Planck TT + lowP + BAO:

$$\boxed{\sum m_\nu < 0.21\text{eV}}$$

Planck coll., 1502.01589

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

Kamland-Zen coll., 1605.02889



# Synergy between experiments

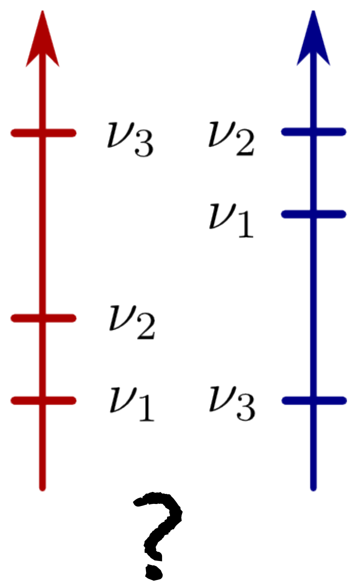
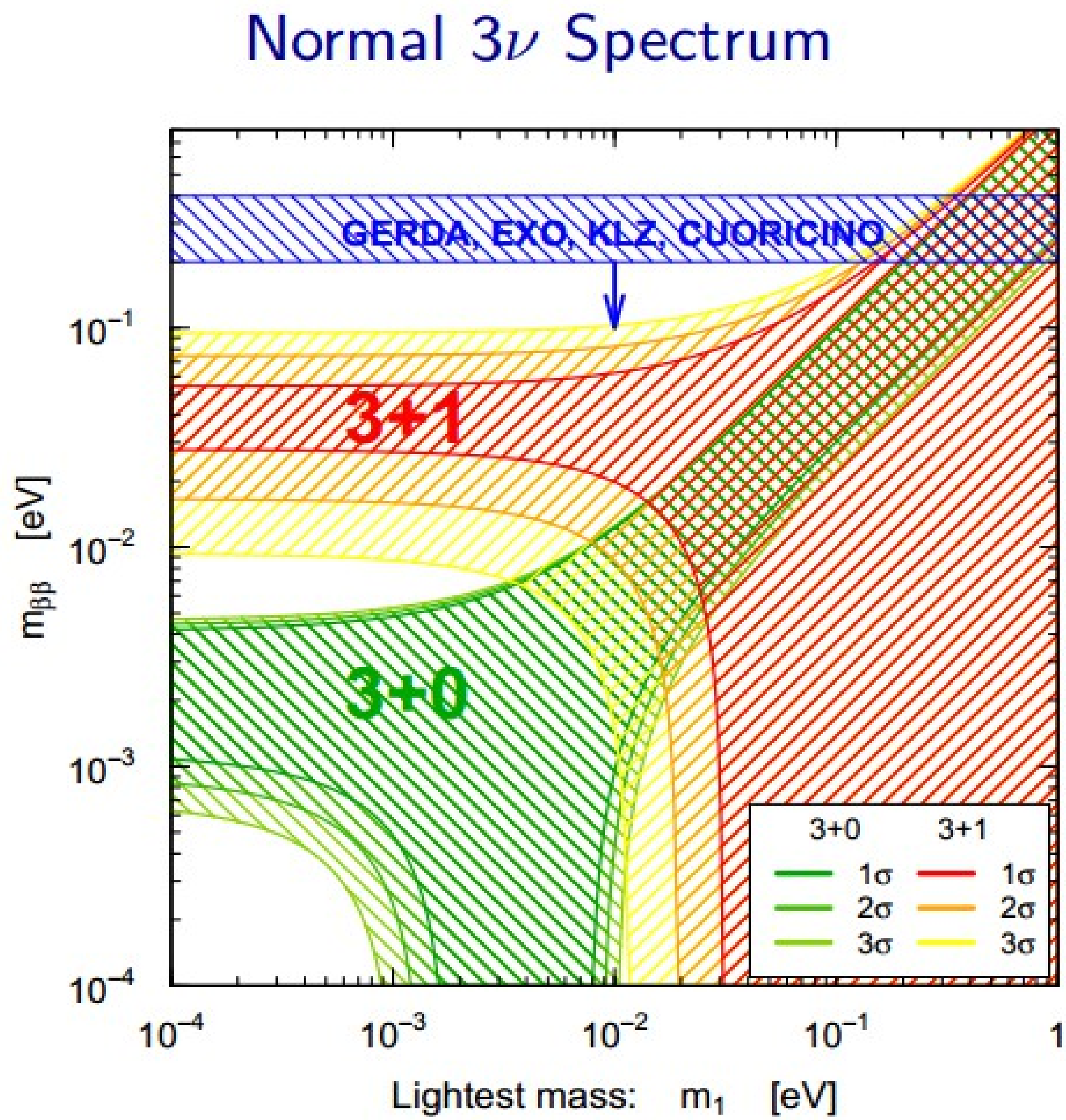
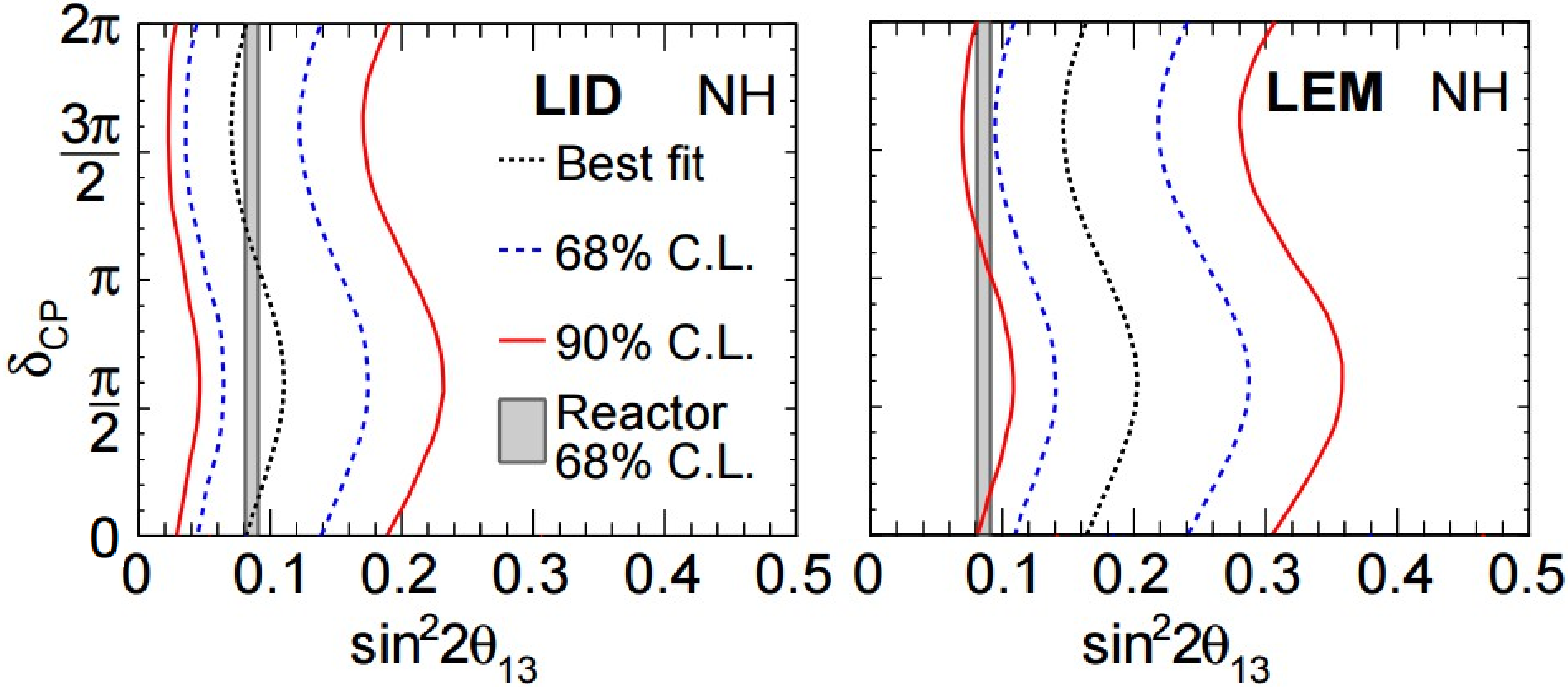



Figure taken from
Giunti's talk at NuPhys 2014
(see also Giunti and Zavanin,
1505.00978)



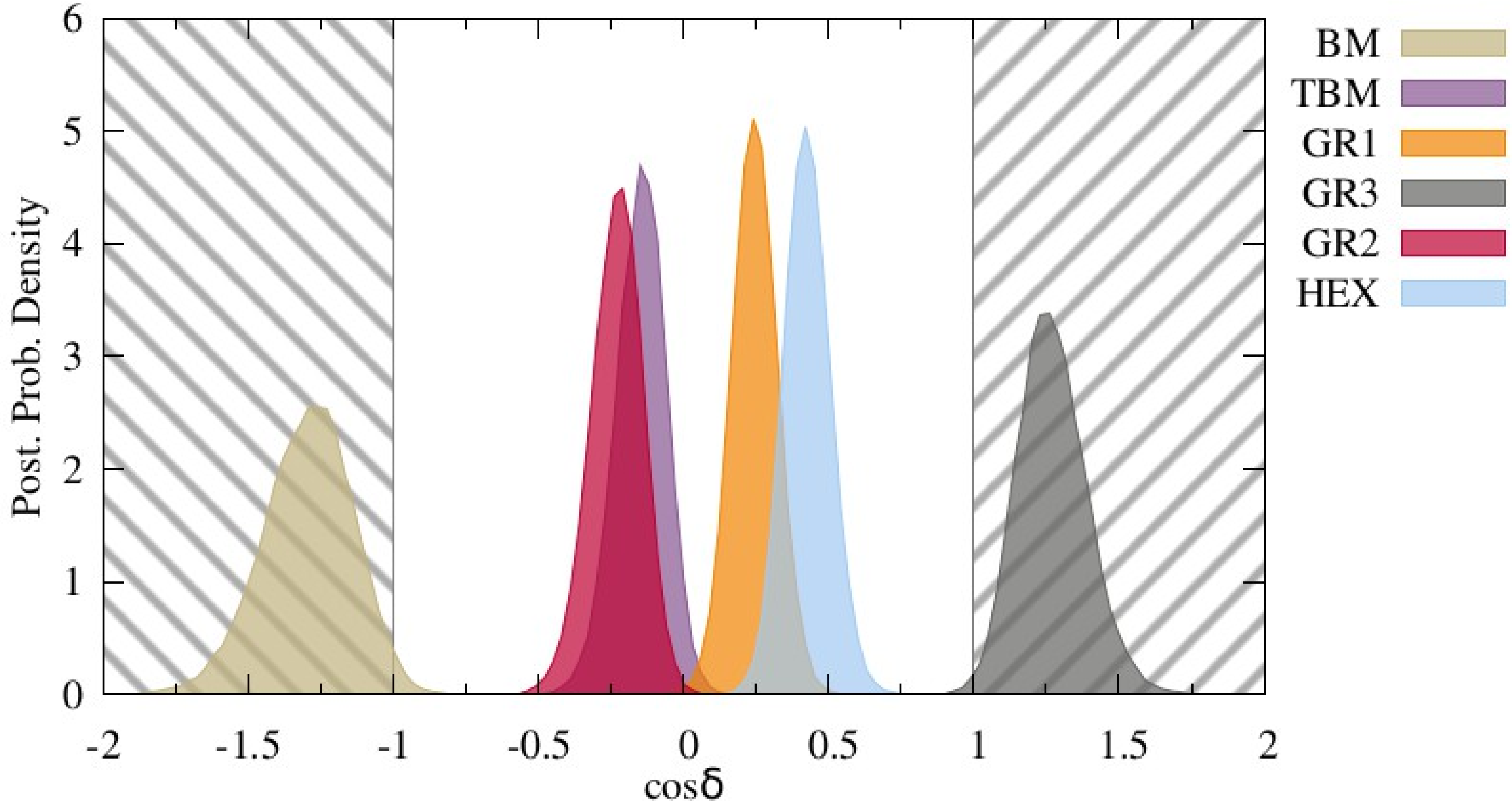
# Hints for CP violation?

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



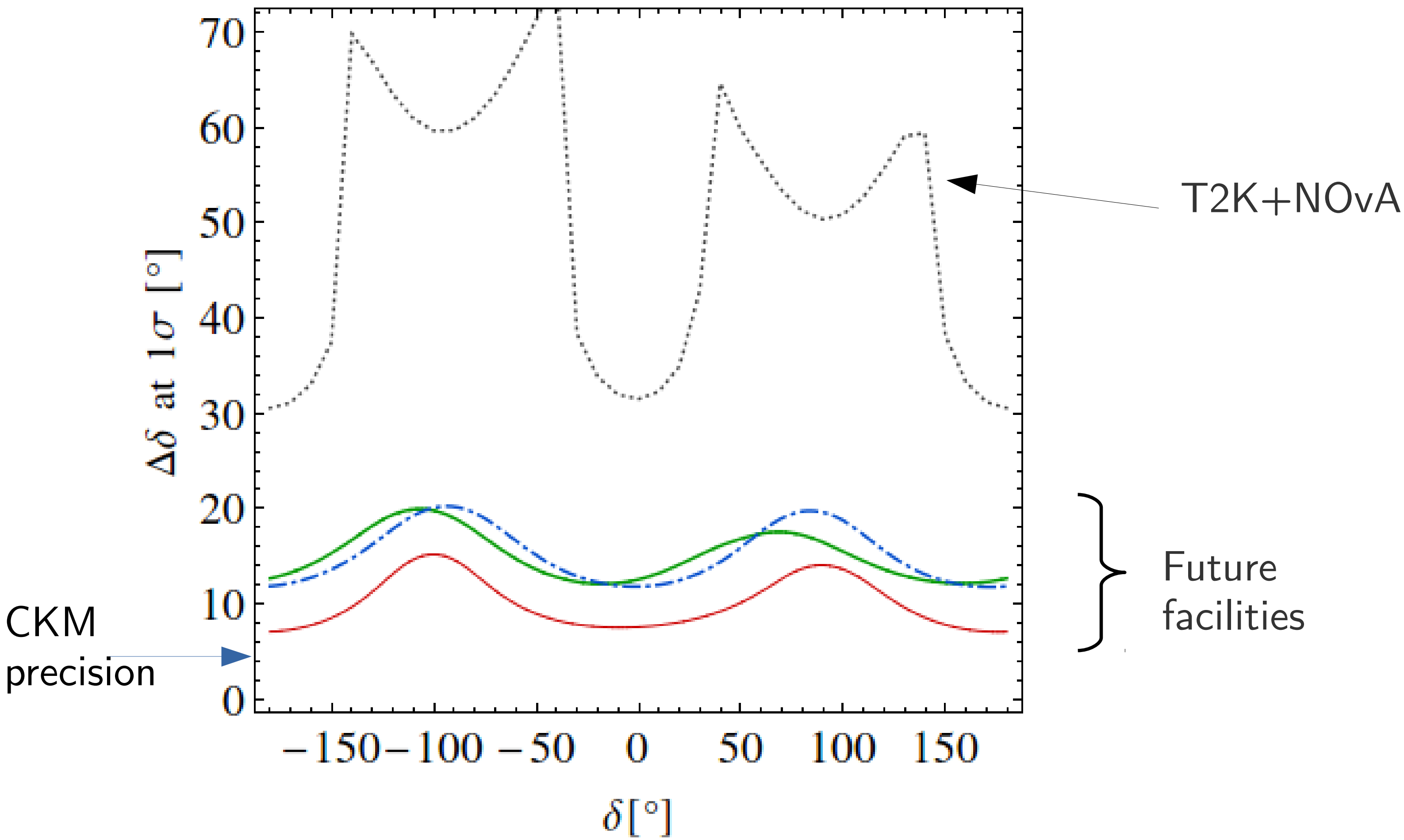

First NOvA results, 1601.05022
(For T2K results see 1311.4750 and 1502.01550)

# Flavor puzzle: why precision?




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

# Flavor puzzle: why precision?




See e.g. Coloma, Donini, Fernandez-Martinez, Hernandez, 1203.5651; Coloma, Huber, Kopp, Winter, 1209.5973

# Some thoughts to wrap up...

- The neutrino picture is still far from being complete
- Neutrino physics is entering the precision Era
- Neutrinos provide an excellent opportunity to test the flavor pattern in the Standard Model
- Cross checks between different data sets may be crucial to disentangle neutrino properties and New Physics

Thank you!