What is left to measure in neutrino physics?

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SWAPS 2014
Cartigny

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Outline

- **Present status of neutrino physics (briefly)**

- **Questions for the future**

What is the nature of neutrinos? Dirac vs Majorana?

What are the values of the masses? Absolute scale (KATRIN, ...?) and the ordering.

Is there CP-violation? Its discovery in the next generation of LBL depends on the value of delta.

What are the precise values of mixing angles? Do they suggest an underlying pattern?

Is the standard picture correct? Are there NSI? Sterile neutrinos? Other effects?

Present status of neutrino physics

Neutrino oscillations have been observed in solar, atmospheric, reactor and accelerator neutrino experiments. The **probability** at a distance L is:

$$P(\nu_\mu \to \nu_e) = \sin^2(2\theta)\sin^2\frac{(m_2^2 - m_1^2)L}{4E}$$

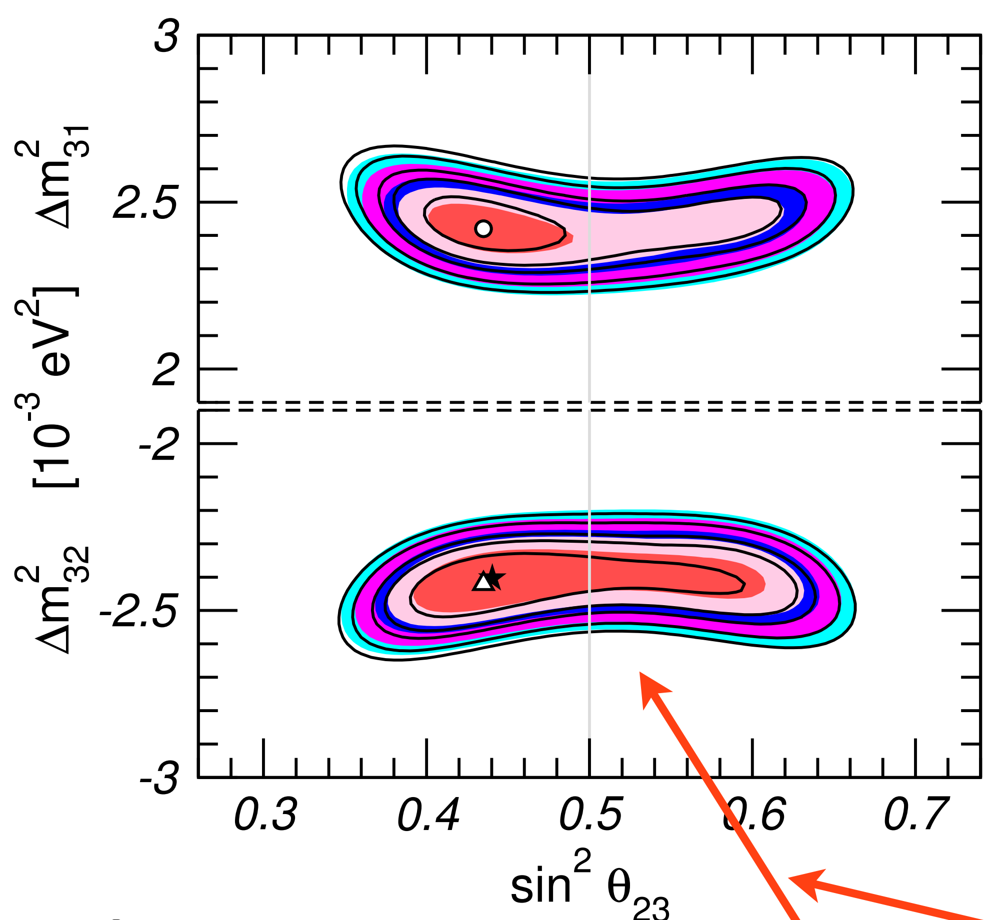
The oscillation probability implies that

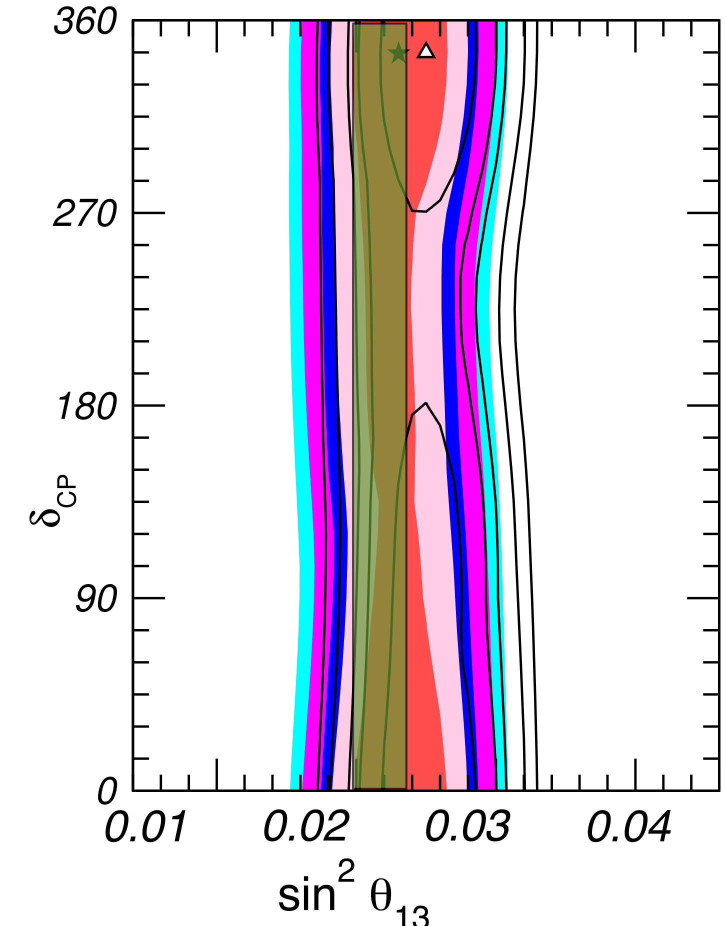
- **neutrinos have mass** (as the different massive components of initial state propagate with different phases)
- **neutrinos mix** (Misaligned flavour and massive states)

First evidence of physics beyond the Standard Model.

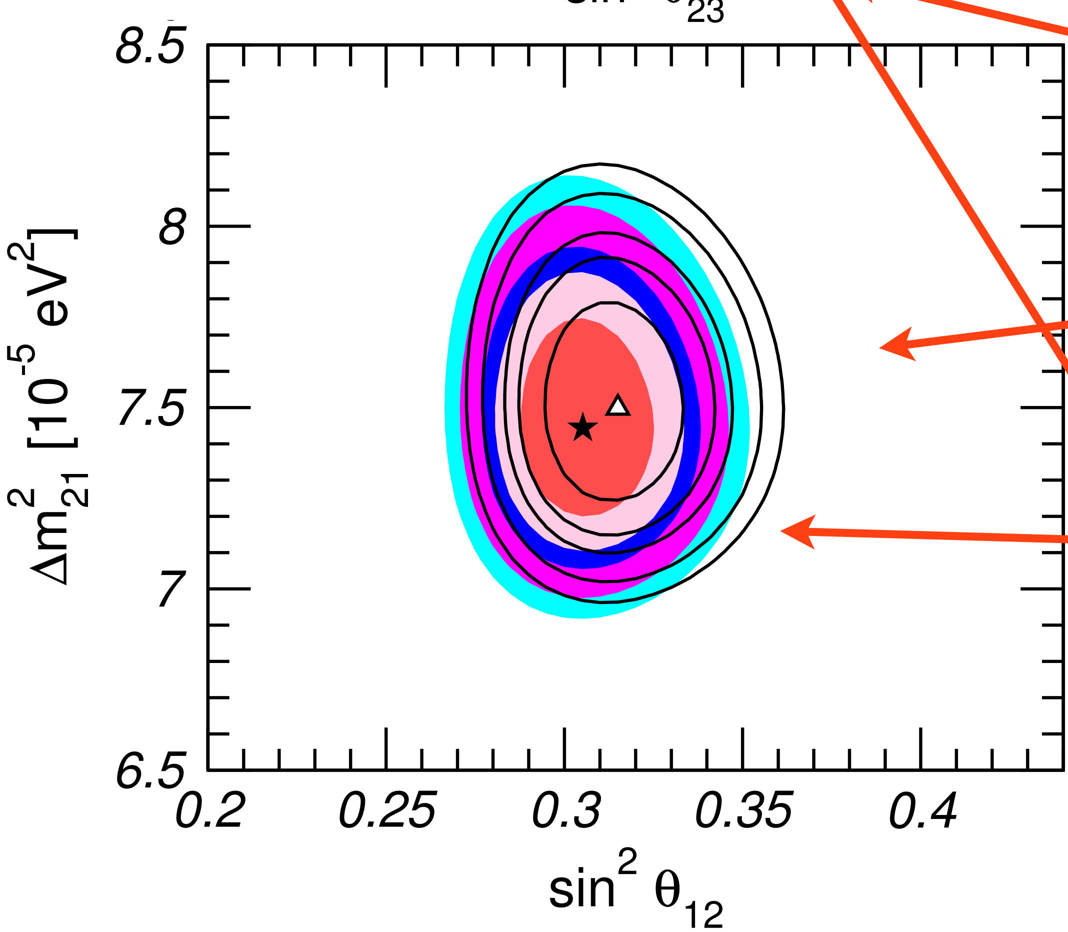
Current neutrino parameters

Global fit to neutrino oscillation data





NuFit: M. C. Gonzalez-Garcia et al., 1209.3023



3 sizable mixing angles

2 mass squared differences

See K. Scholberg's talk for updated results of individual experiments

In the SM, neutrinos are expected to be massless (no Dirac masses because no r.h. nu and no Majorana masses because of gauge invariance).

- **Masses are non-zero and are much smaller than the other fermions.**

There are two possible orderings:
normal (m1<m2<m3) and inverted (m3<m1<m2).

- Mixing is described by the Pontecorvo-Maki-Nakagawa-Sakata matrix, which enters in the CC interactions.

Mixing angles are much larger than in the quark sector.

This points towards a different origin of neutrino masses and mixing from the ones for quarks: a different window on the physics BSM.

Phenomenology questions for the future

- **What is the nature of neutrinos? Dirac vs Majorana?**
- **What are the values of the masses?** Absolute scale (KATRIN, ...?) and the ordering.
- **Is there CP-violation?** Its discovery in the next generation of LBL depends on the value of delta.
- **What are the precise values of mixing angles?** Do they suggest an underlying pattern?
- **Is the standard picture correct?** Are there NSI? Sterile neutrinos? Other effects?

Nature of Neutrinos: Majorana vs Dirac

Neutrinos can be **Majorana** or **Dirac** particles. In the SM only neutrinos can be Majorana because they are neutral.

Majorana condition $\nu = C\bar{\nu}^T$

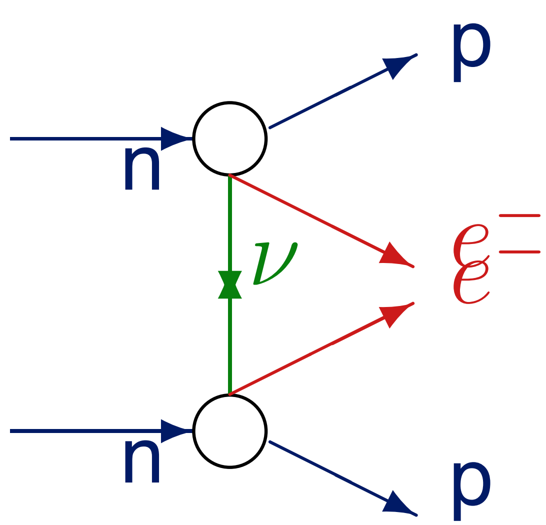
The **nature** of neutrinos is linked to the conservation of the **Lepton number (L).**

- This is crucial information to understand the **Physics BSM: with or without L-conservation**?
 Lepton number violation is a necessary condition for **Leptogenesis**.

- Tests of LNV:
 - At low energy, neutrinoless double beta decay,
 - LNV tau and meson decays,
 - collider searches.

Neutrinoless double beta decay

Neutrinoless double beta decay, (A, Z) → (A, Z+2) + 2e, will test the nature of neutrinos.



The half-life time depends on neutrino properties

$$\left[T_{0\nu}^{1/2}(0^+ \to 0^+)\right]^{-1} \propto |M_F - g_A^2 M_{GT}|^2 \, |<m>|^2$$

- The effective Majorana mass parameter:

$$|<m>| \equiv |\, m_1|U_{e1}|^2 + m_2|U_{e2}|^2 e^{i\alpha_{21}} + m_3|U_{e3}|^2 e^{i\alpha_{31}} \,| \,,$$

Mixing angles (known)

CPV phases (unknown)

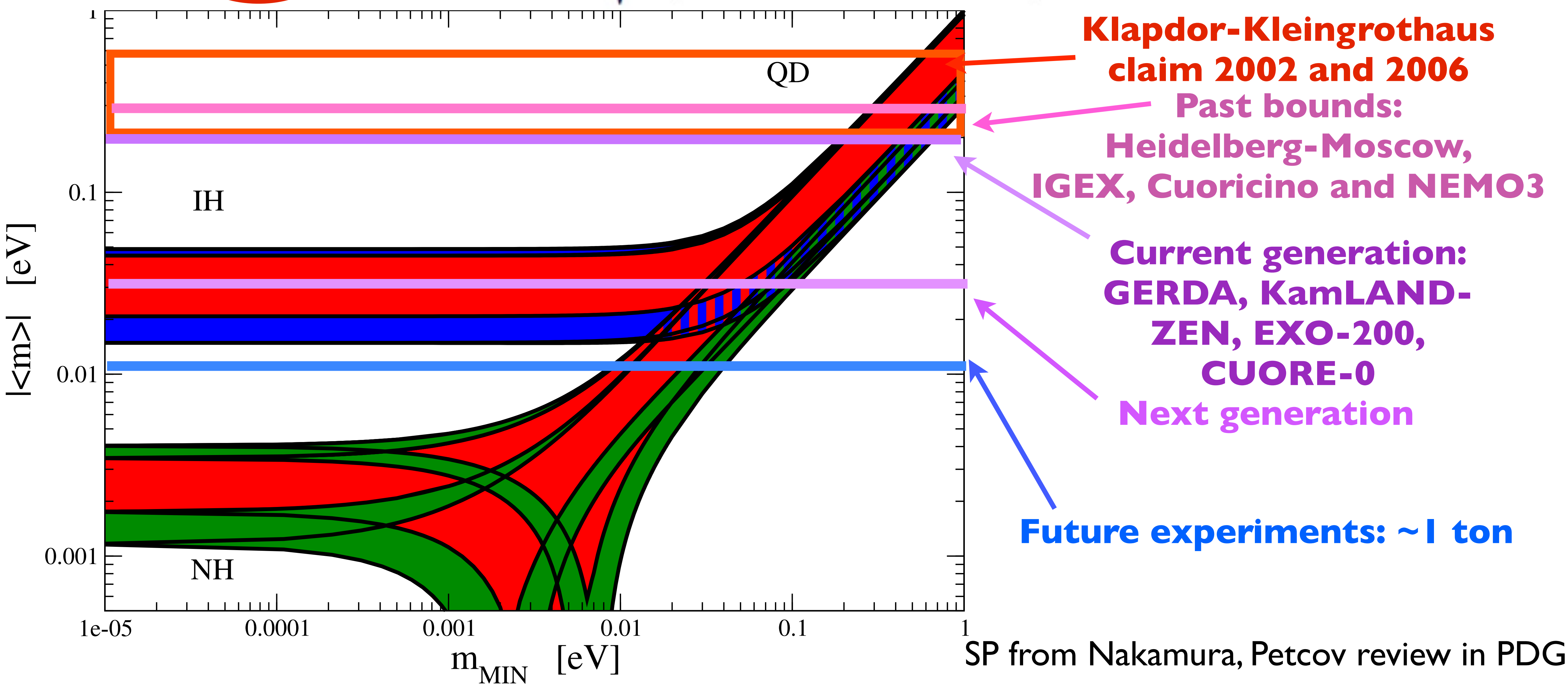
- $|M_F - g_A^2 M_{GT}|^2$ the nuclear matrix elements

See Giuliani's talk

Predictions for betabeta decay

- Example: IH (m3<<m1~m2): 10 meV < |<m>| < 50 meV

$$\sqrt{\Delta m^2_{\rm atm}}\cos 2\theta_\odot \leq |<m>| \simeq \sqrt{\left(1-\sin^2 2\theta_\odot \sin^2\frac{\alpha_{21}}{2}\right)\Delta m^2_{\rm atm}} \leq \sqrt{\Delta m^2_{\rm atm}}$$



SP from Nakamura, Petcov review in PDG

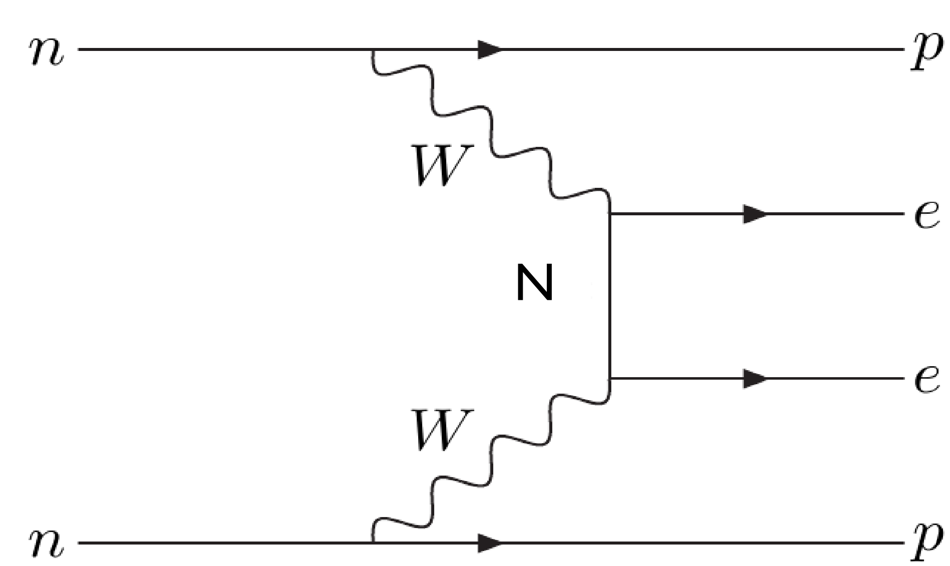
Wide experimental program for the future: **a positive signal would indicate that L is violated!**

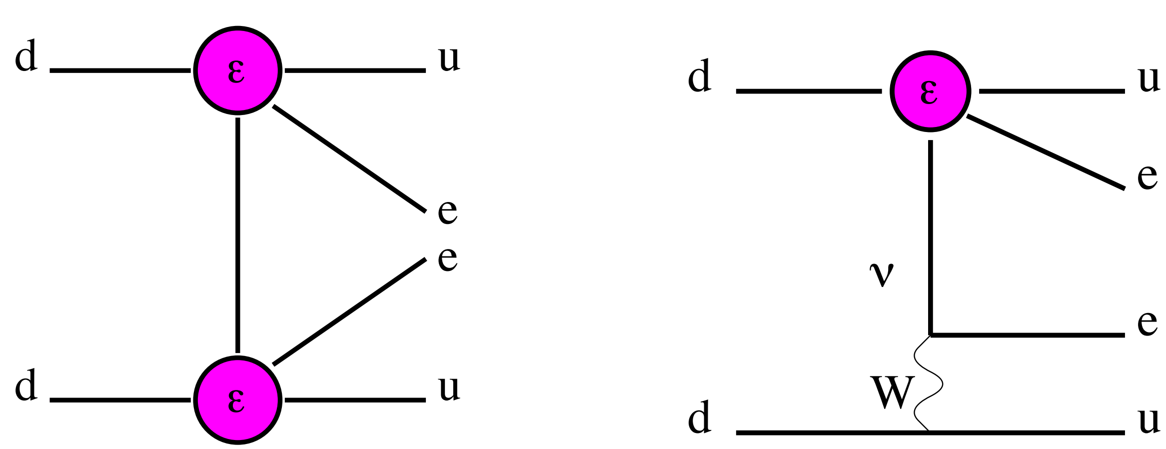
See Cremonesi's, Bongrand's, Schönert's, Shimizu's, Marino's, Winslow's talks at Neutrino 2014

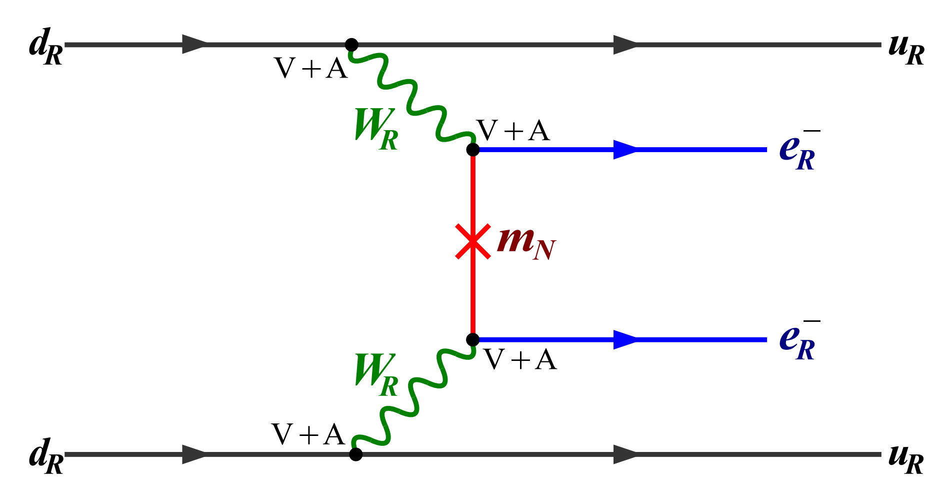
Other mechanisms

Neutrinoless double beta decay can also be mediated by other LNV mechanisms.

- Light sterile neutrinos
- Heavy sterile neutrinos
- R-parity violating SUSY
- Extra dimensional models
- Left-Right models



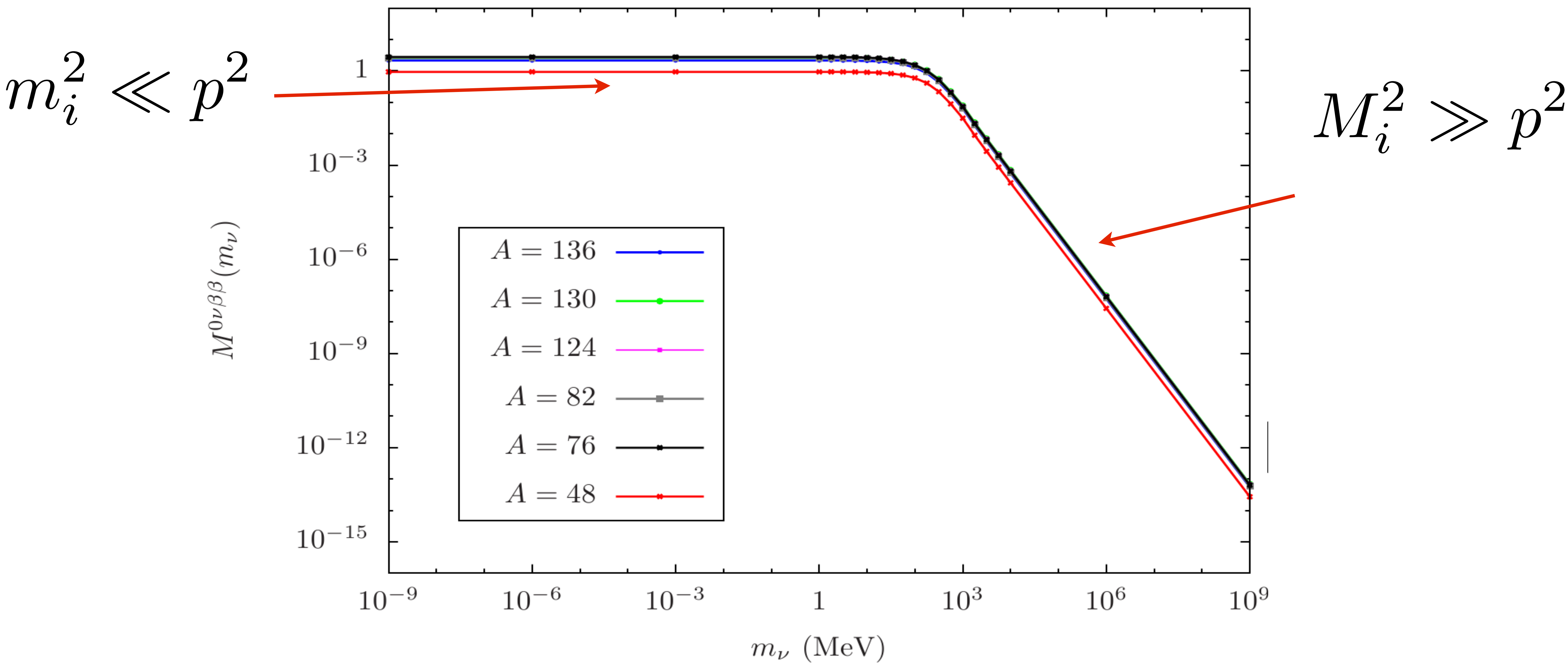




Deppisch, Hirsch, Pas, 1208.0727

In most cases the new mechanisms (with heavy particles) are subdominant as the NME for heavy particles suppress their contribution.

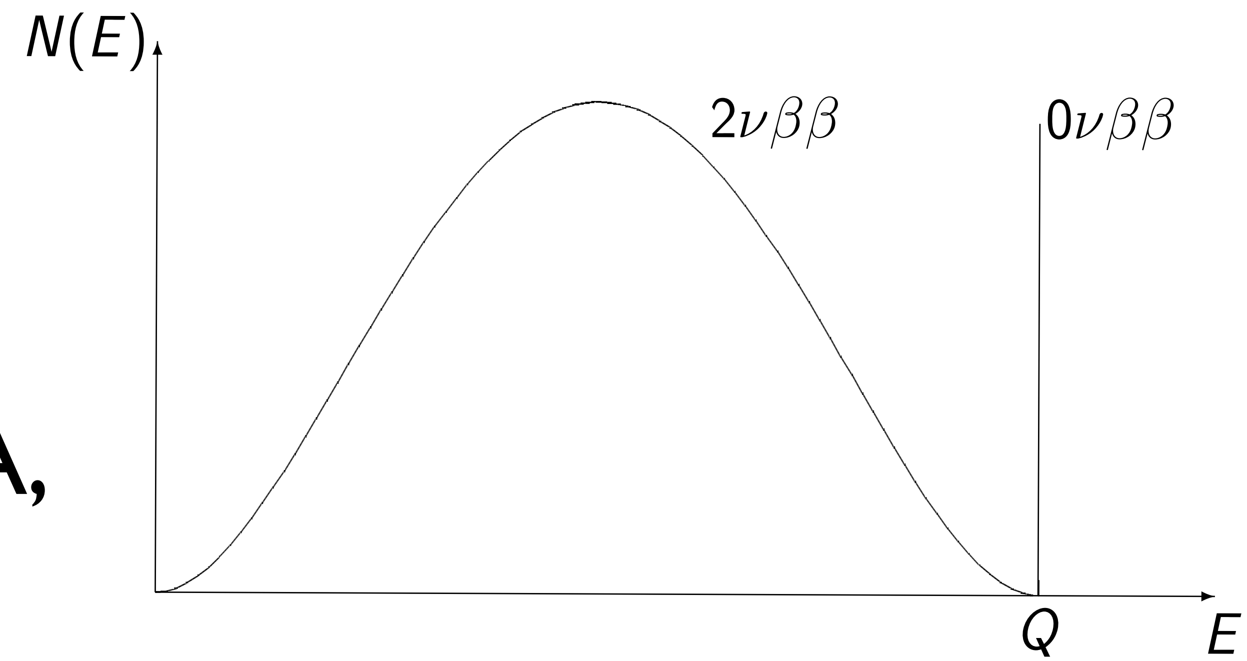
http://www.th.mppmu.mpg.de/members/blennow/nme_mnu.dat



The NME behaviour changes at p~100 MeV, the scale of the process.

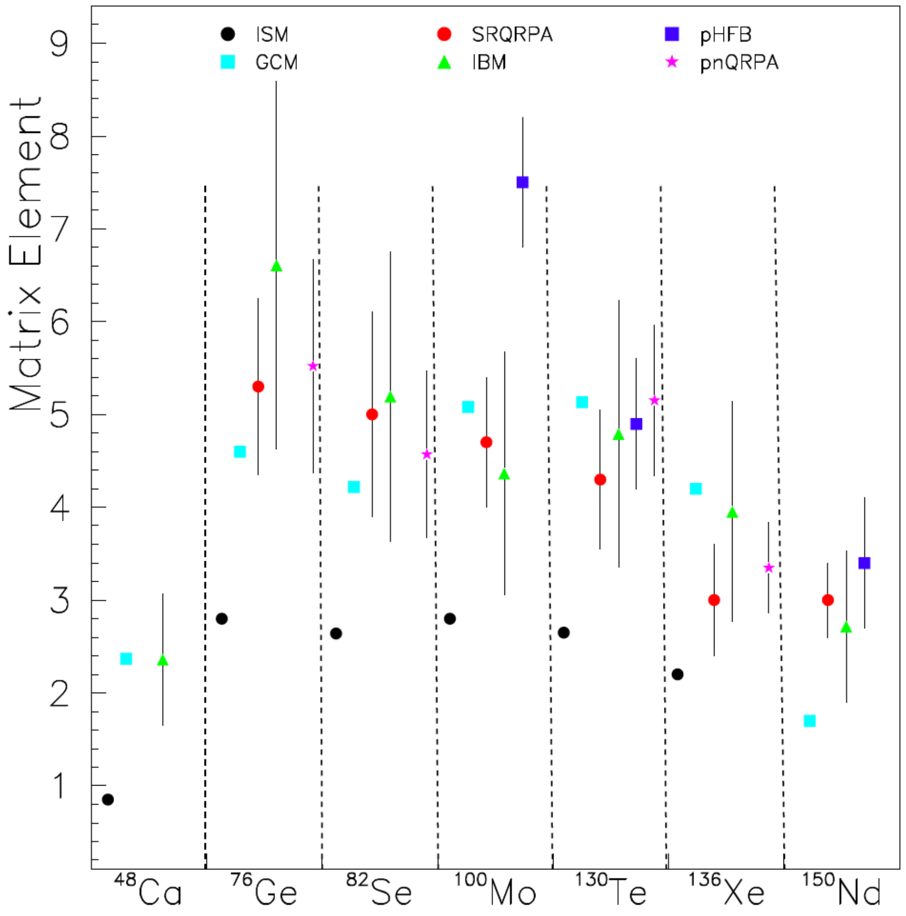
Experimental searches of betabeta decay

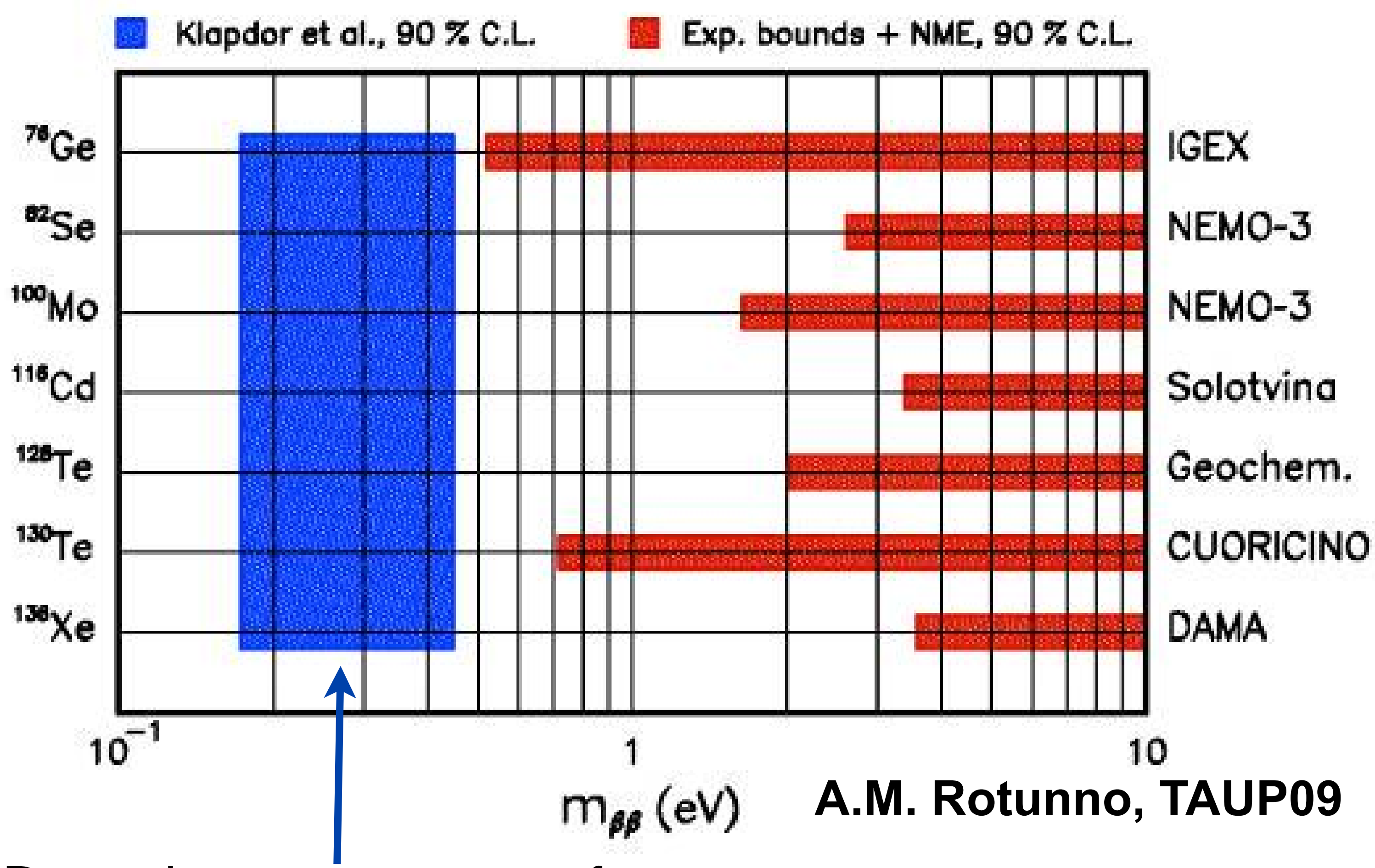
Neutrinoless double beta decay proceeds in nuclei in which single beta decay is kinematically forbidden but double beta decay (A, Z) → (A, Z+2) + 2 e + 2 v is allowed.



NMEs

B. Schwingenheuer, Annalen der Physik, 2012

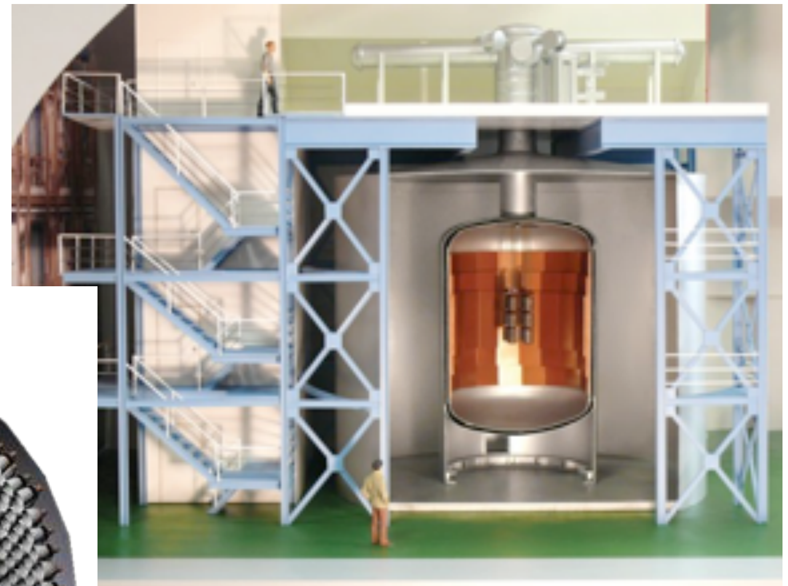


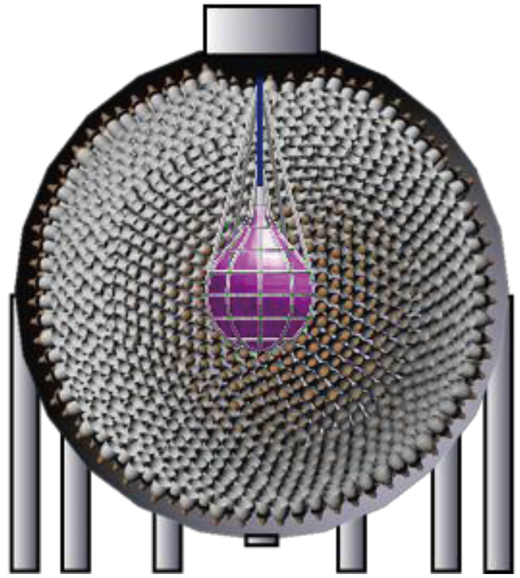


A.M. Rotunno, TAUP09

Depending on treatment of background, from 4.2 to 1.3 sigma

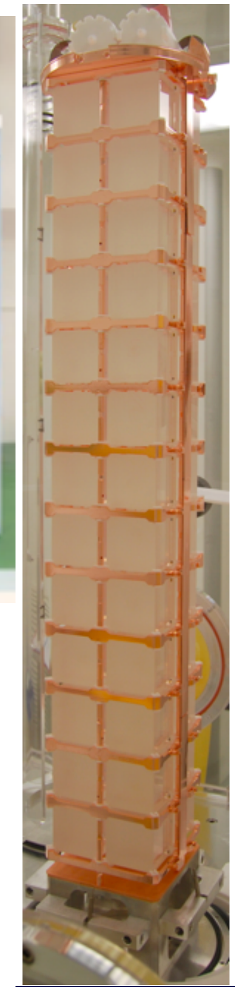
GERDA



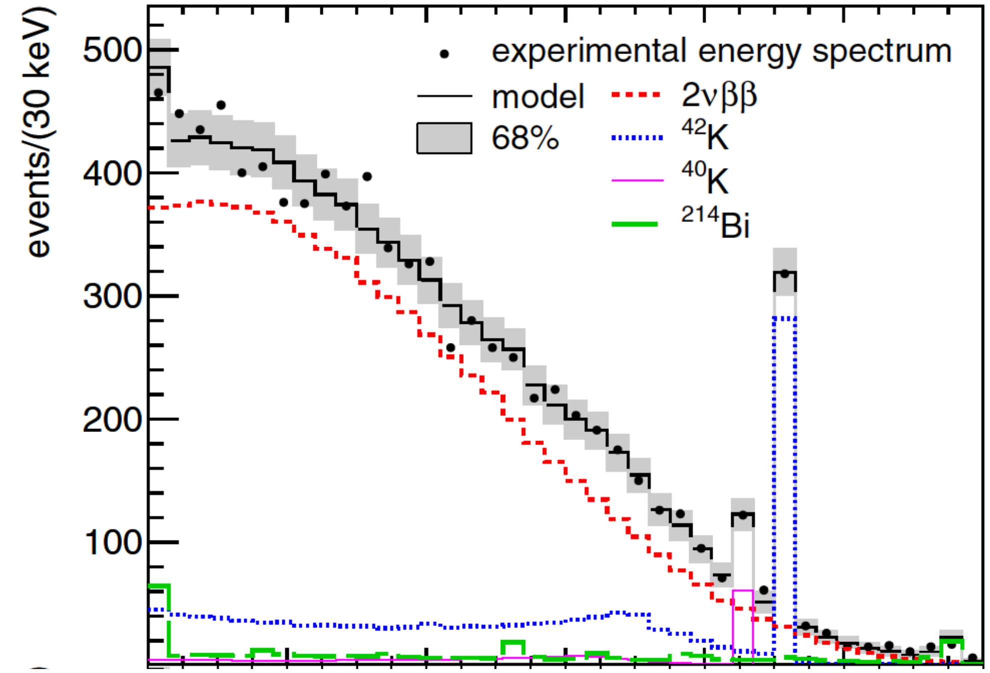


KamLAND-Zen

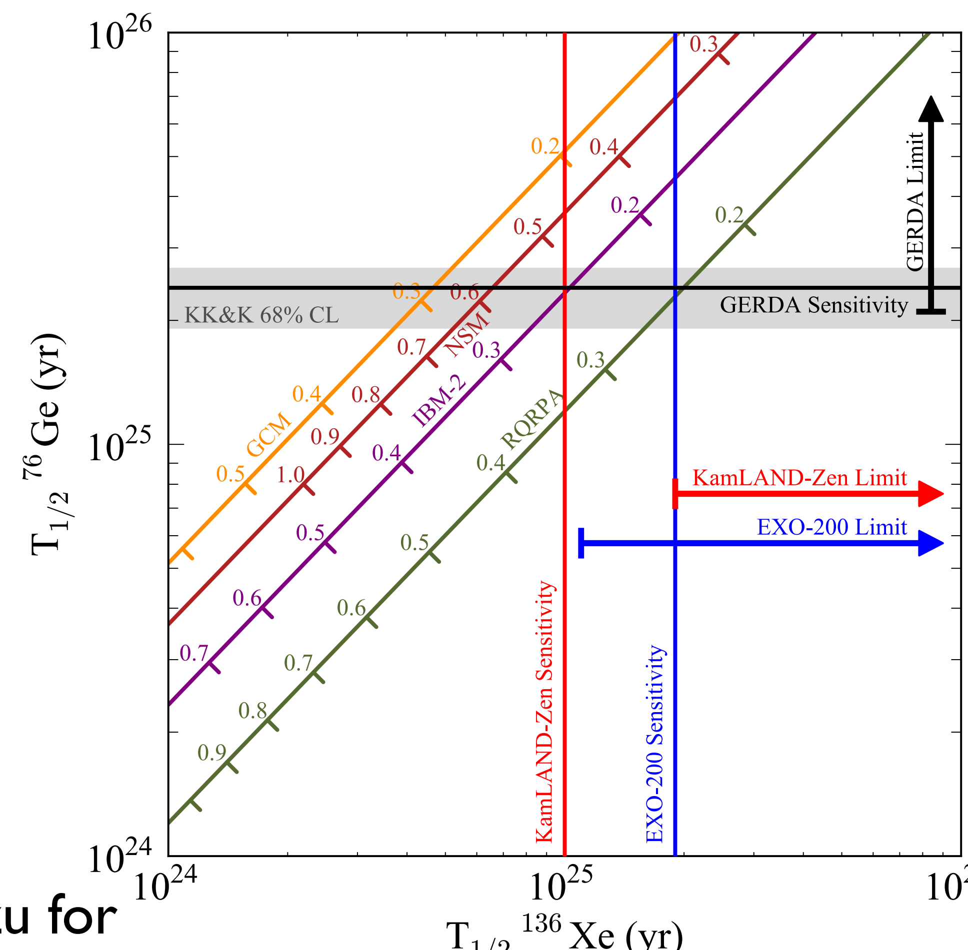
EXO-200 location, at the WIPP Site, USA



CUORE-0



S. Schoenert, for GERDA at Neutrino 2014



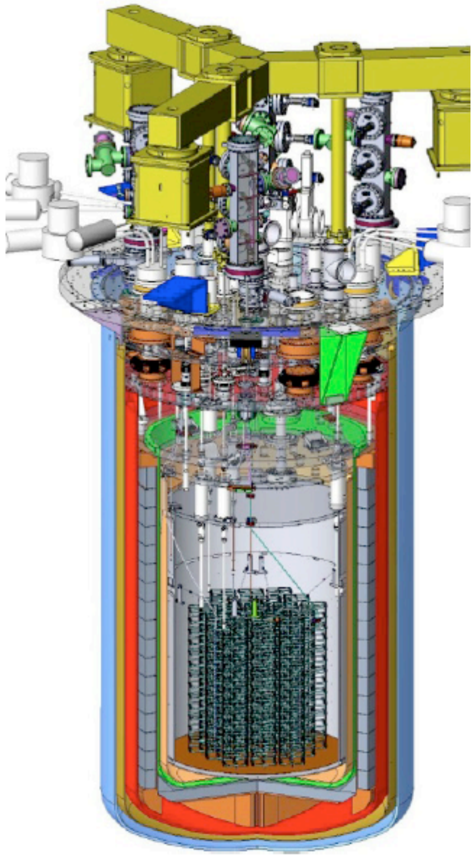
See Gornea's and Benato's talks

The new generation of experiments is already taking data (e.g., EXO, KamLAND-ZEN, CUORE-0, GERDA,...).

EXO-200: T0nu > 1.1 10^25 yrs
KamLAND-Zen: T0nu > 2.6 10^25 yrs
GERDA: T0nu > 2.1 10^25 yrs

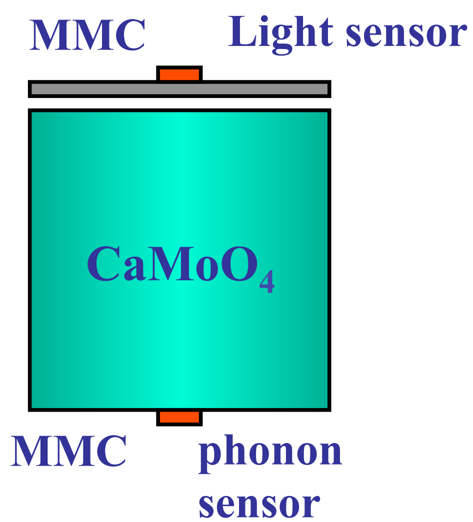
I. Shimizu for KamLAND-Zen at Neutrino 2014

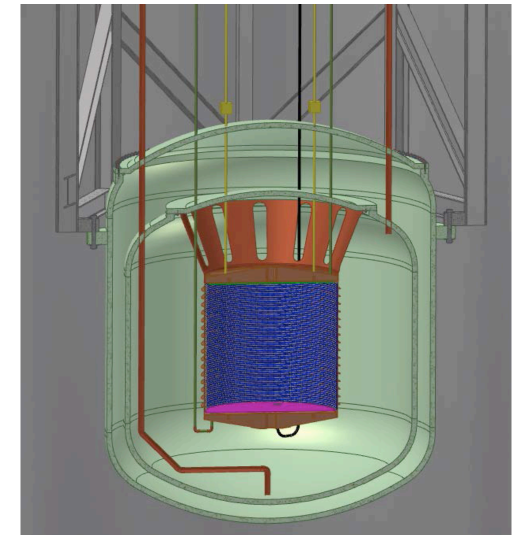
Marino for EXO-200 at Neutrino 2014



CUORE
bolometer
with cc

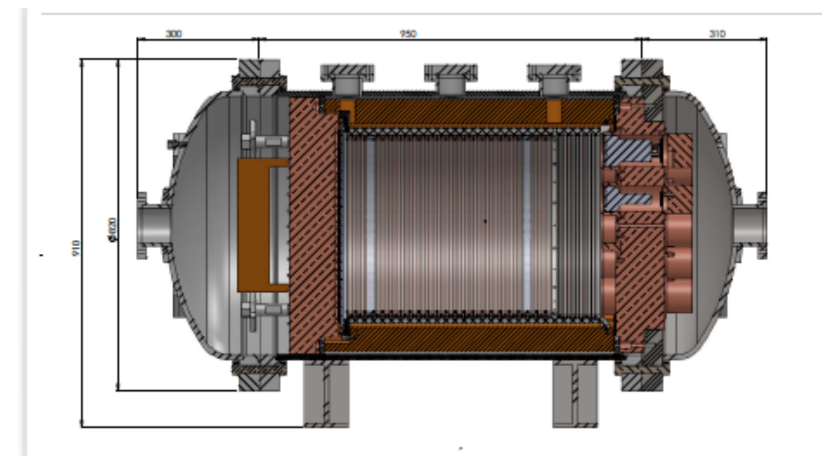
AMoRE





nEXO
5ton of Xe

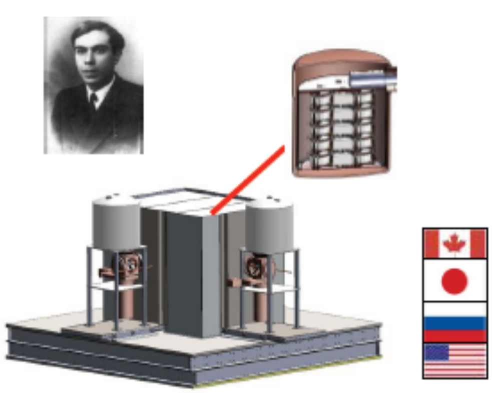
NEXT
5ton of Xe

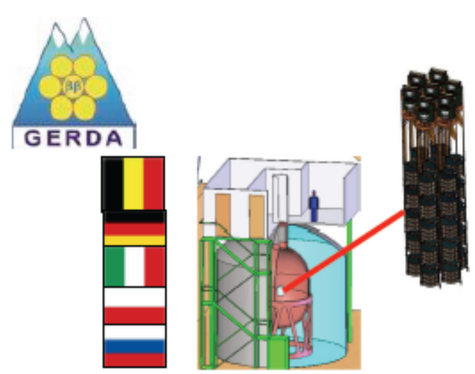


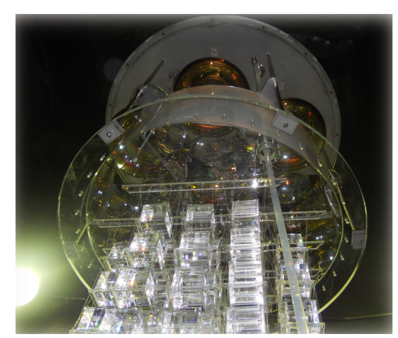
MAGIX
5ton of Xe

Majorana
uses Ge

GERDA
uses Ge

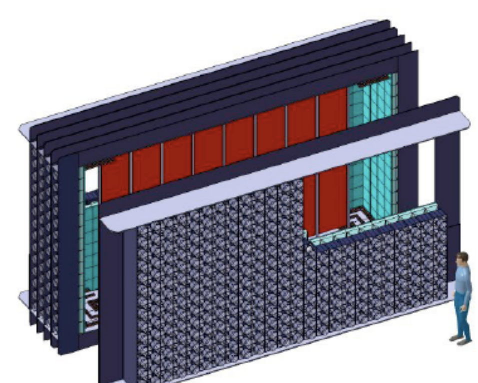






CANDLES
uses Ca

SNO+



SuperNEMO
and **DCBA**

L. Winslow at Neutrino 2014

Phenomenology questions for the future

- What is the nature of neutrinos? Dirac vs Majorana?
- **What are the values of the masses?** Absolute scale (KATRIN, ...?) and the ordering.
- **Is there CP-violation?** Its discovery in the next generation of LBL depends on the value of theta13 and of delta.
- **What are the precise values of mixing angles? Do they suggest an underlying pattern?**
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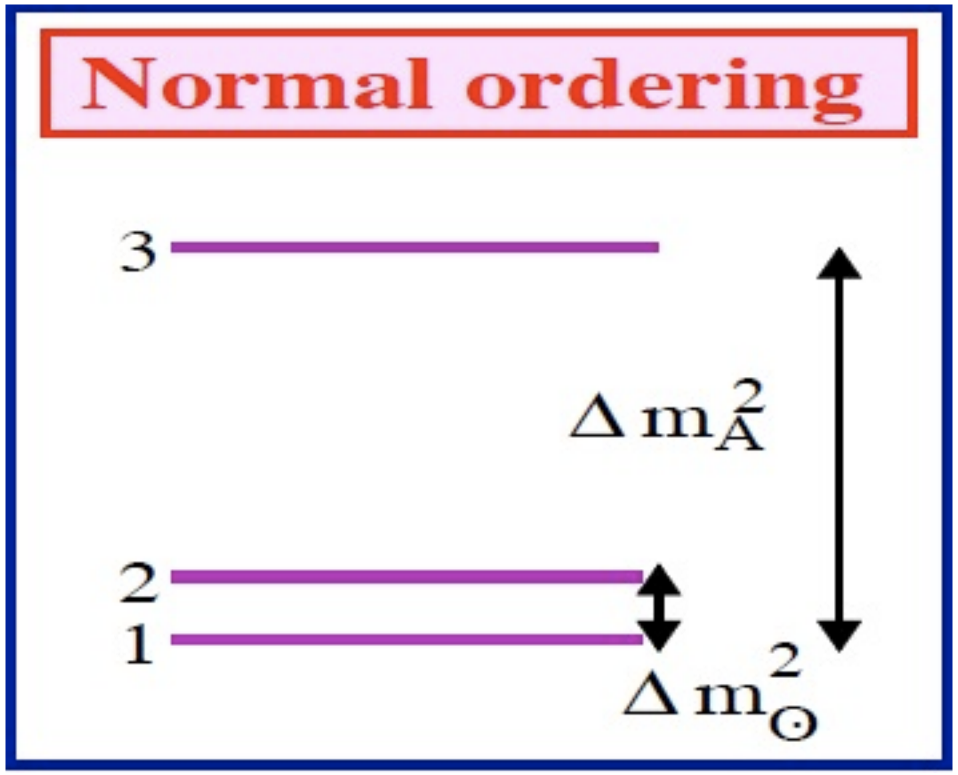
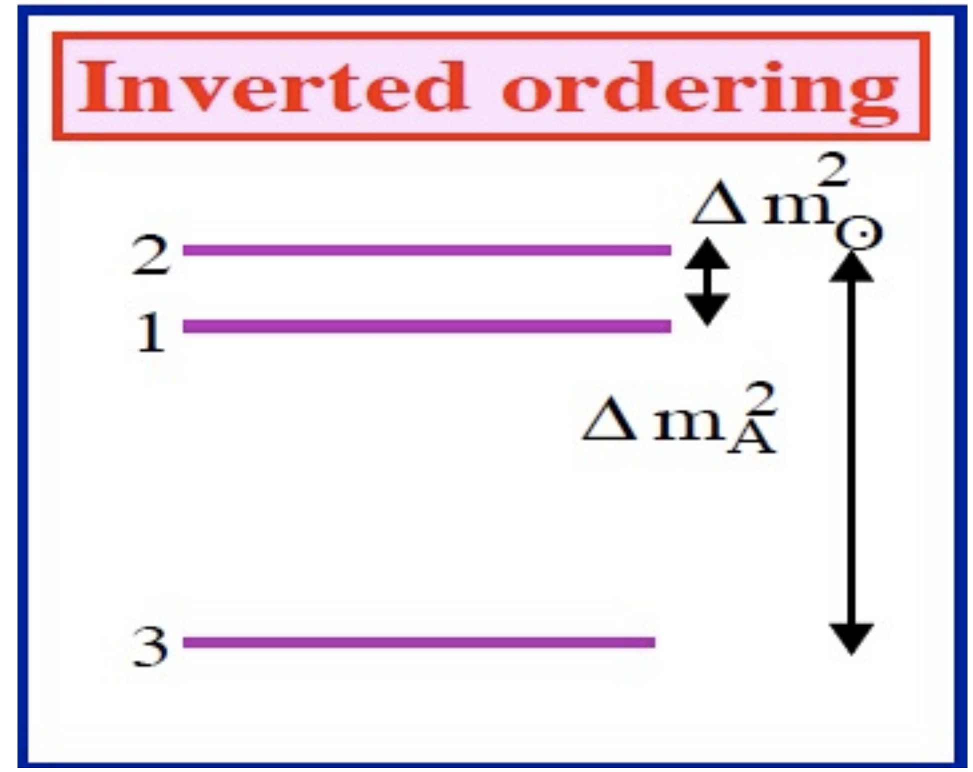
Neutrino masses

$\Delta m_s^2 \ll \Delta m_A^2$ implies at least 3 massive neutrinos.





$$m_1 = m_{\rm min}$$
$$m_2 = \sqrt{m_{\rm min}^2 + \Delta m_{\rm sol}^2}$$
$$m_3 = \sqrt{m_{\rm min}^2 + \Delta m_{\rm A}^2}$$

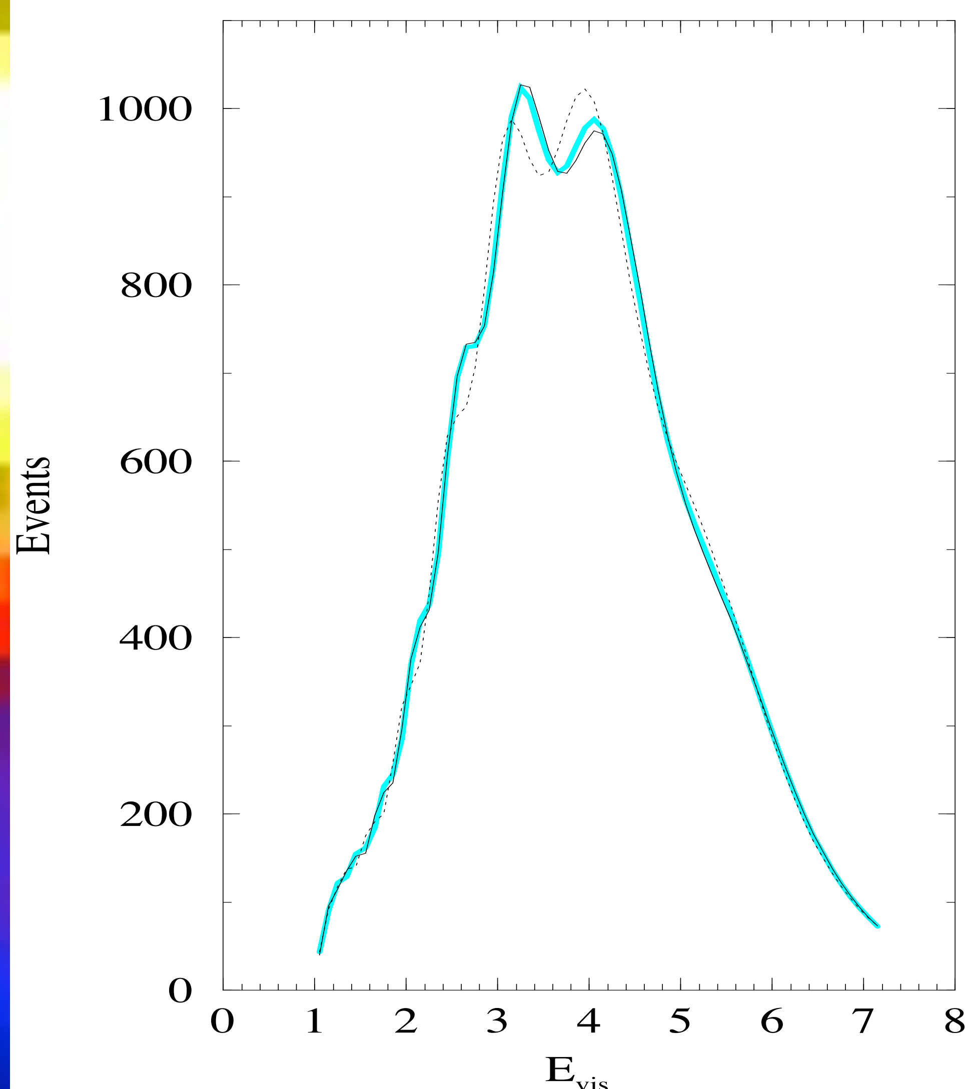
$$m_3 = m_{\rm min}$$
$$m_1 = \sqrt{m_{\rm min}^2 + \Delta m_{\rm A}^2 - \Delta m_{\rm sol}^2}$$
$$m_2 = \sqrt{m_{\rm min}^2 + \Delta m_{\rm A}^2}$$

Measuring the masses requires:

- the mass scale: $m_{\rm min}$
- the mass ordering.

Reactor neutrinos and the ordering

Thanks to the "unexpectedly large" value of theta13, it might be possible to establish the neutrino mass hierarchy from neutrino oscillations within this decade at some confidence level.



Choubey, Petcov, Piai, hep-ph/0306017

$$
\begin{aligned}
P_{\nu_e \to \nu_e} &= 1 - \cos^4\theta_{13}\,\sin^2 2\theta_{12}\,\sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right) \\
&- \sin^2 2\theta_{13}\left[\cos^2\theta_{12}\,\sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + \sin^2\theta_{12}\,\sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)\right]
\end{aligned}
$$

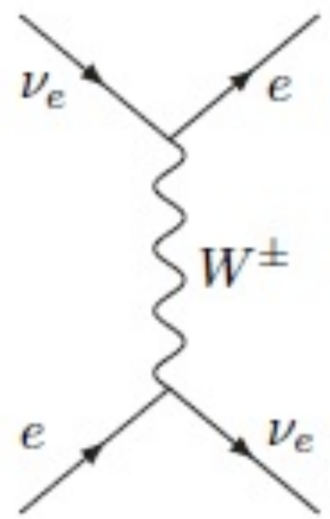
$(\chi^2)^{min}_{stat}$	$\sin^2 2\theta_{13}^{\rm true} = 0.1$			$\sin^2 2\theta_{13}^{\rm true} = 0.12$		
Detector exposure, kT GW yr	Energy resolution					
	2%	3%	4%	2%	3%	4%
100	6.50	5.20	3.98	9.45	7.57	5.75
150	9.70	7.80	5.95	14.15	11.35	8.60

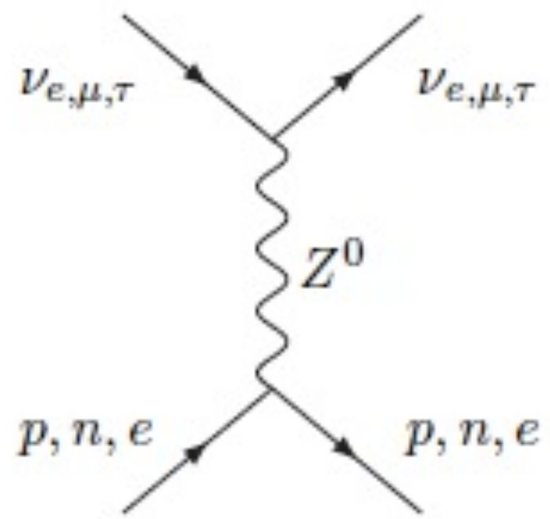
Petcov, Piai, hep-ph/0112074, Choubey, Petcov, Piai, hep-ph/0306017, Goshal, Petcov, 1208.6473; see also Ciuffoli et al.; Qian et al.

The JUNO reactor experiment is considering detectors at ~60 km to perform this measurement. Excellent energy resolution is needed.

Neutrino oscillations in matter and the ordering

- When neutrinos travel through a medium, they interact with the background of electron, proton and neutrons and acquire an effective mass.





- Typically the background is CP and CPT violating, e.g. the Earth and the Sun contain only electrons, protons and neutrons, and the resulting oscillations are CP and CPT violating.

The oscillation probability becomes (for constant density)

$$P_{\nu_\mu\rightarrow\nu_e} = \sin^2\theta_{23}\sin^2 2\theta^m_{13}\sin^2\frac{\Delta^m_{13}L}{2}$$

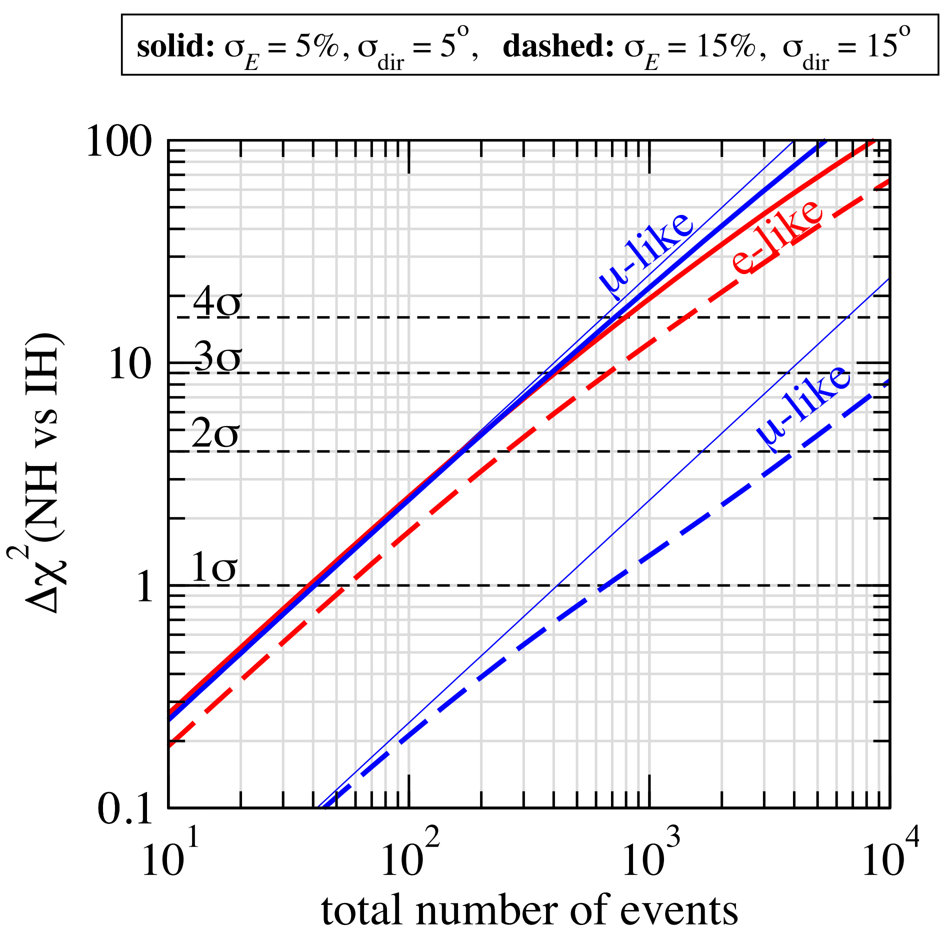
The mixing angle in matter is

$$\sin^2(2\theta_m) = \frac{\left(\frac{\Delta m^2}{2E}\sin(2\theta)\right)^2}{\left(\frac{\Delta m^2}{2E}\cos(2\theta)-\sqrt{2}G_F N_e\right)^2+\left(\frac{\Delta m^2}{2E}\sin(2\theta)\right)^2}$$

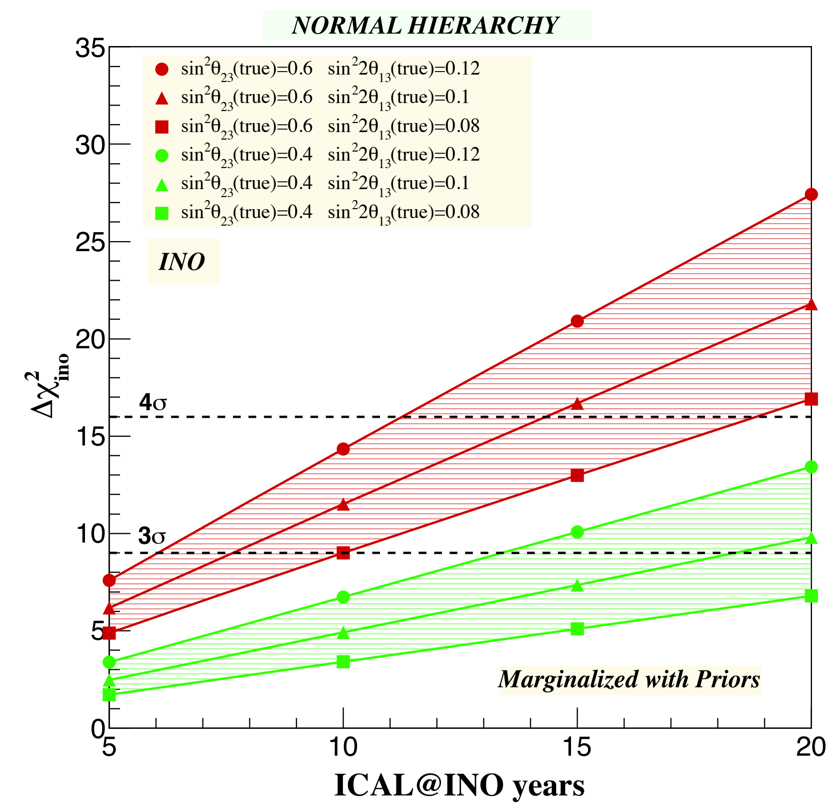
- If $\sqrt{2}G_F N_e = \frac{\Delta m^2}{2E}\cos 2\theta$: resonance $\theta_m = \pi/4$
- The resonance condition can be satisfied for
  - neutrinos if $\Delta m^2 > 0$
  - antineutrinos if $\Delta m^2 < 0$

Atmospheric neutrinos and the ordering

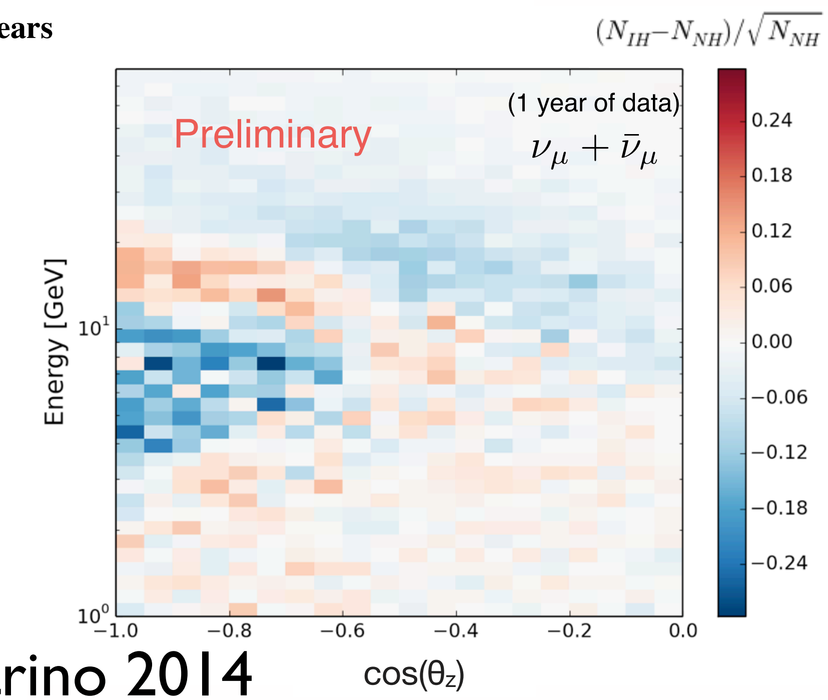
Atmospheric neutrino oscillations are sensitive to the mass hierarchy. This requires large number of events, good energy and angular resolution and, possibly, charge discrimination.
Petcov et al.; Akhmedov, Smirnov et al.; Gandhi et al.; Mena et al.; Schwetz et al.; Koskinen; Gonzalez-Garcia et al.; Barger et al.; ....



Petcov, Schwetz, hep-ph/0511277



D. Indumathi at Neutrino 2014



PINGU in IceCube, ORCA in KM3Net

D. Grant at Neutrino 2014

See Halzen's talk

Long baseline neutrino oscillations and the ordering

Long baseline neutrino oscillation experiments (T2K, LBNE, EU superbeams, neutrino factories and beta beams) will aim at studying the subdominant channels

$$\nu_{\mu,e} \to \nu_{e,\mu} \quad \bar{\nu}_{\mu,e} \to \bar{\nu}_{e,\mu}$$

$$P(\nu_\mu \to \nu_e) \sim \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E}$$

for negligible matter and CPV effects.

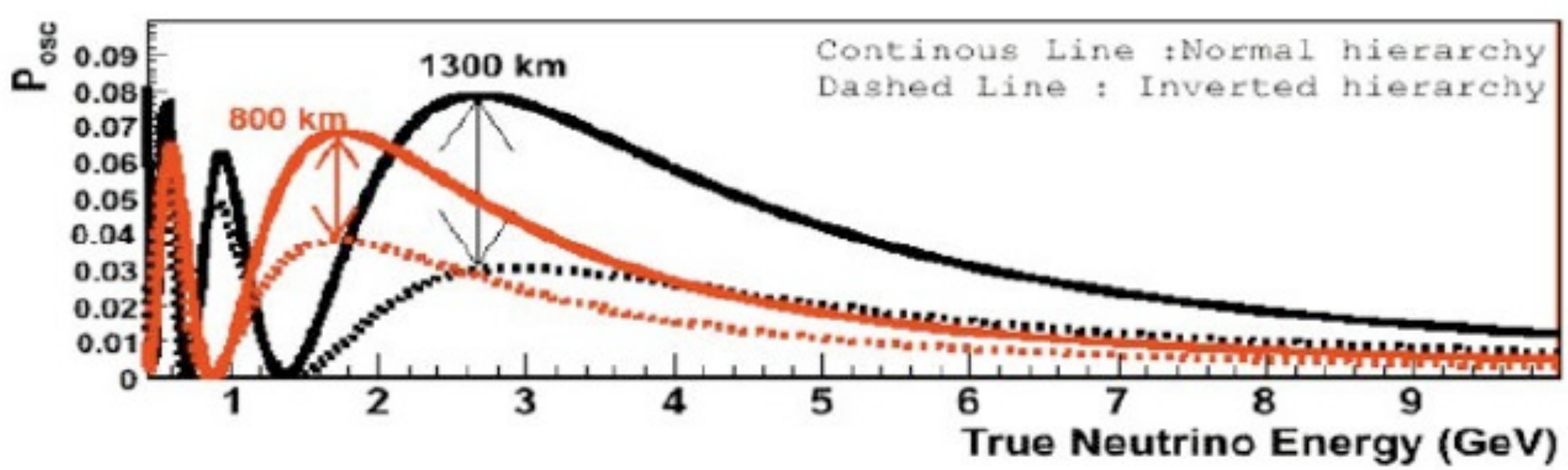
in order to establish

1. **the mixing angles (θ_{23}, θ_{13}) with precision**
2. **the mass hierarchy**
3. **Leptonic CPV**
4. **Non-standard effects.**

Matter effects modify the oscillation probability as discussed and are stronger the longer the baseline.

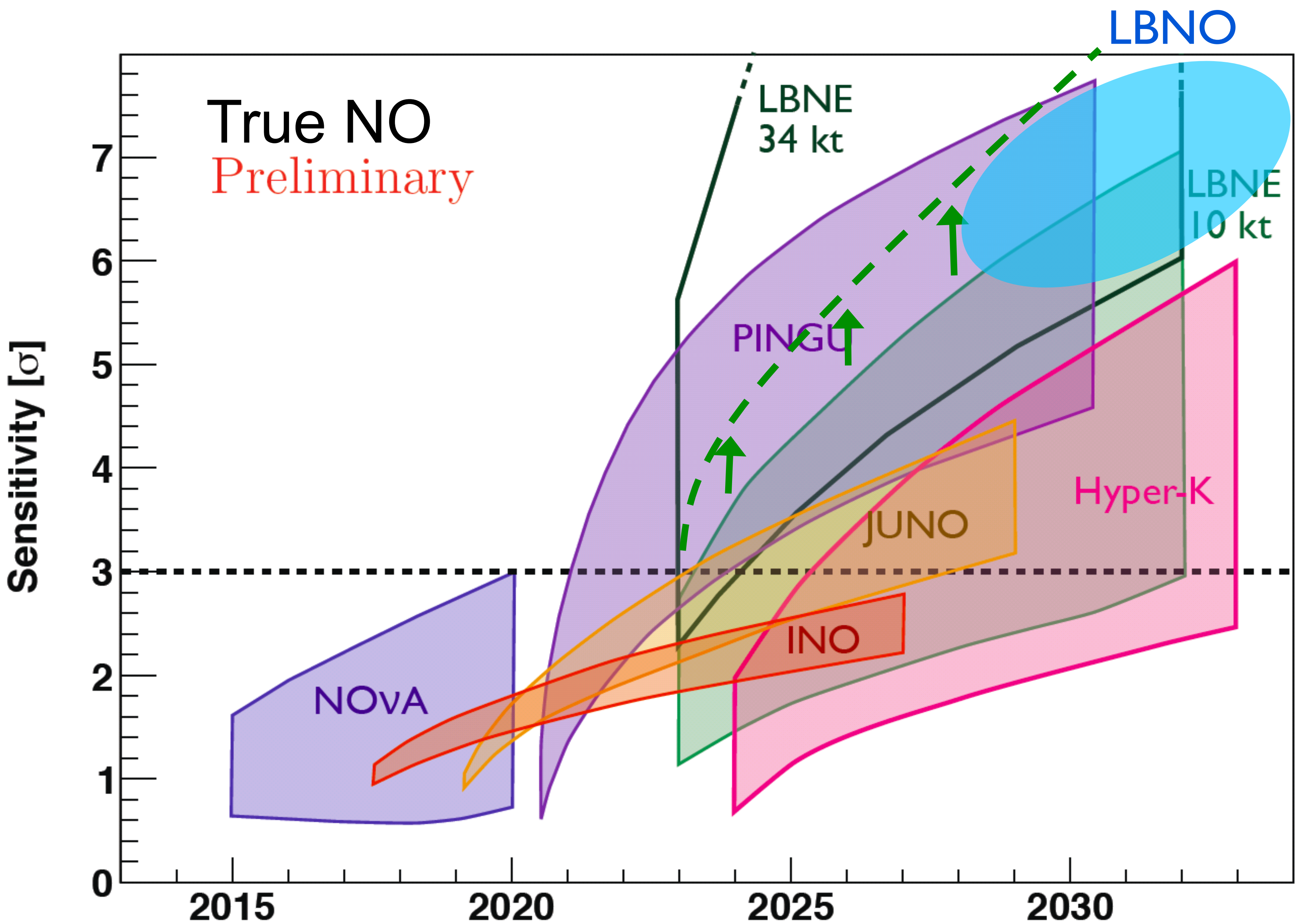
$$P_{\mu e} \simeq 4 c_{23}^2 s_{13}^2 \frac{1}{(1-r_A)^2} \sin^2 \frac{(1-r_A)\Delta_{31} L}{4E}$$
$$+ \sin 2\theta_{12} \sin 2\theta_{23} s_{13} \frac{\Delta_{21} L}{2E} \sin \frac{(1-r_A)\Delta_{31} L}{4E} \cos\left(\delta - \frac{\Delta_{31} L}{4E}\right)$$
$$+ s_{23}^2 \sin^2 2\theta_{12} \frac{\Delta_{21}^2 L^2}{16 E^2} - 4 c_{23}^2 s_{13}^4 \sin^2 \frac{(1-r_A)\Delta_{31} L}{4E}$$

A. Cervera et al., hep-ph/0002108; K. Asano, H. Minakata, 1103.4387; S. K. Agarwalla et al., 1302.6773...



See also W. Winter's talk at Neutrino 2014

- The determination of CPV and of the mass ordering are entangled (problem of degeneracies).
- Matter effects are stronger at high energies.



Bands:

- Beam experiments: δ_{CP}
- PINGU, INO: θ_{23}
- JUNO: Energy resolution (3%-3.5%) $(E/MeV)^{0.5}$

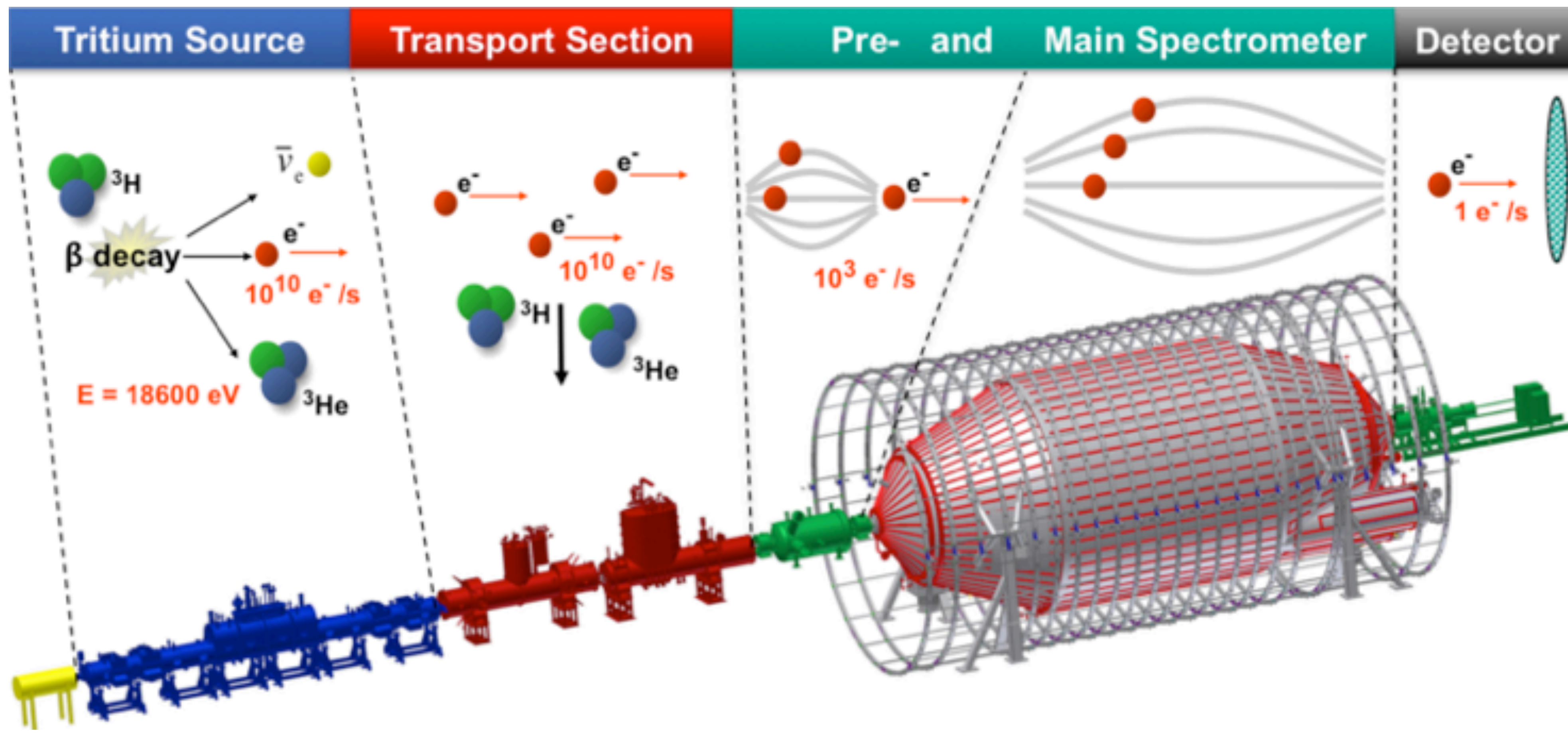
Caveats:

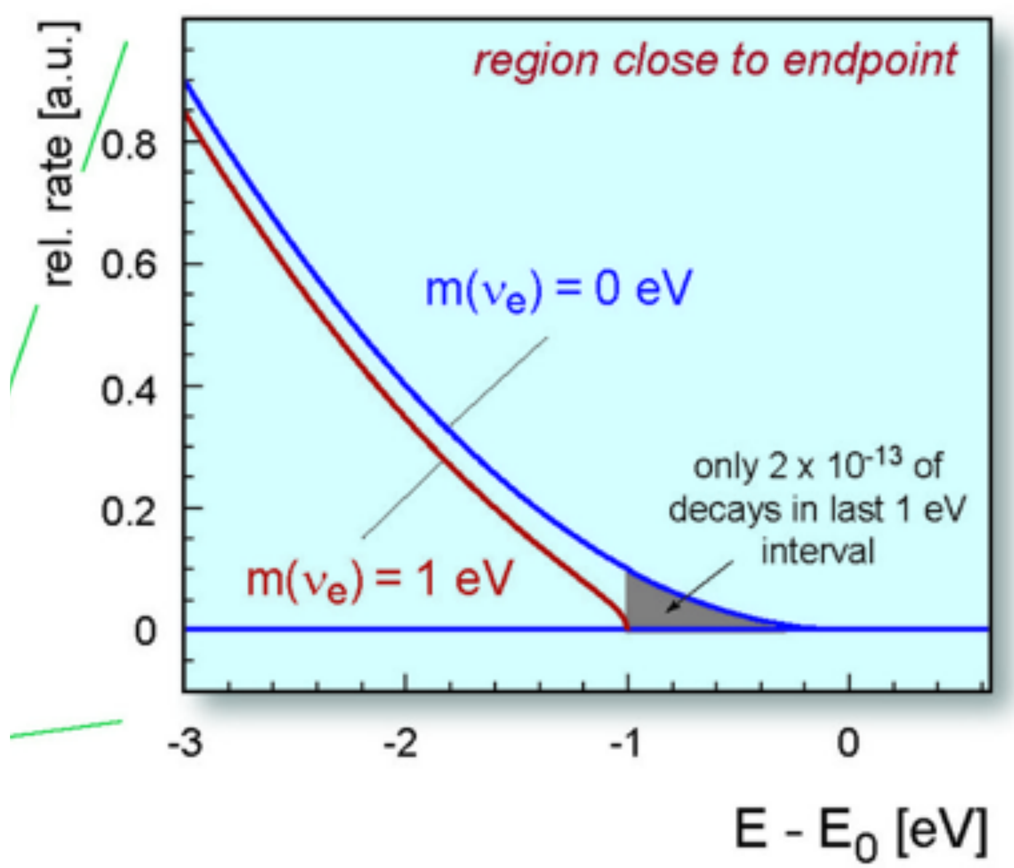
- LBNE sensitivity scales with (true) θ_{23} as well (dashed curve)

From W. Winter's talk at Neutrino 2014

	Long baseline beam (e. g. LBNE)	Atmospheric (e. g. PINGU)	Reactor long baseline
Benefit	Robust, clean signal	Predictable timescale/cost	Independent technology
Risk (osc. params.)	δ_{CP}, θ_{23}	θ_{23}	-
Challenges	Timescale	Energy res., directional res., particle ID	Energy resolution!!!

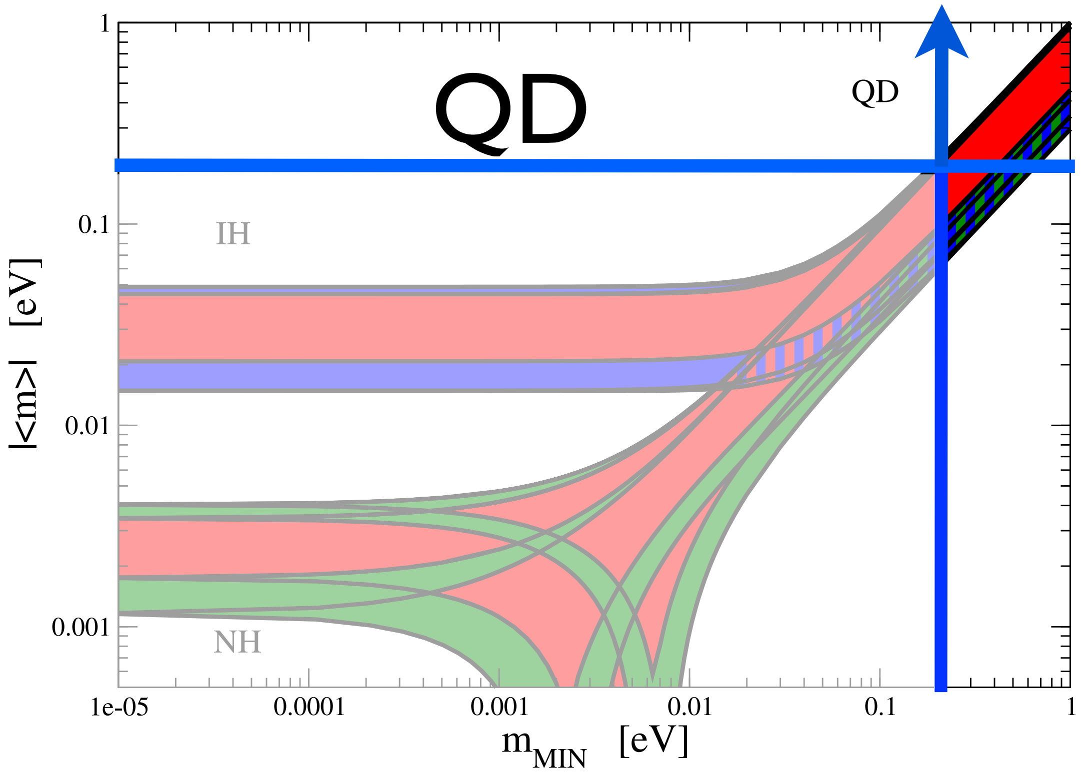
Katrin and the absolute neutrino mass

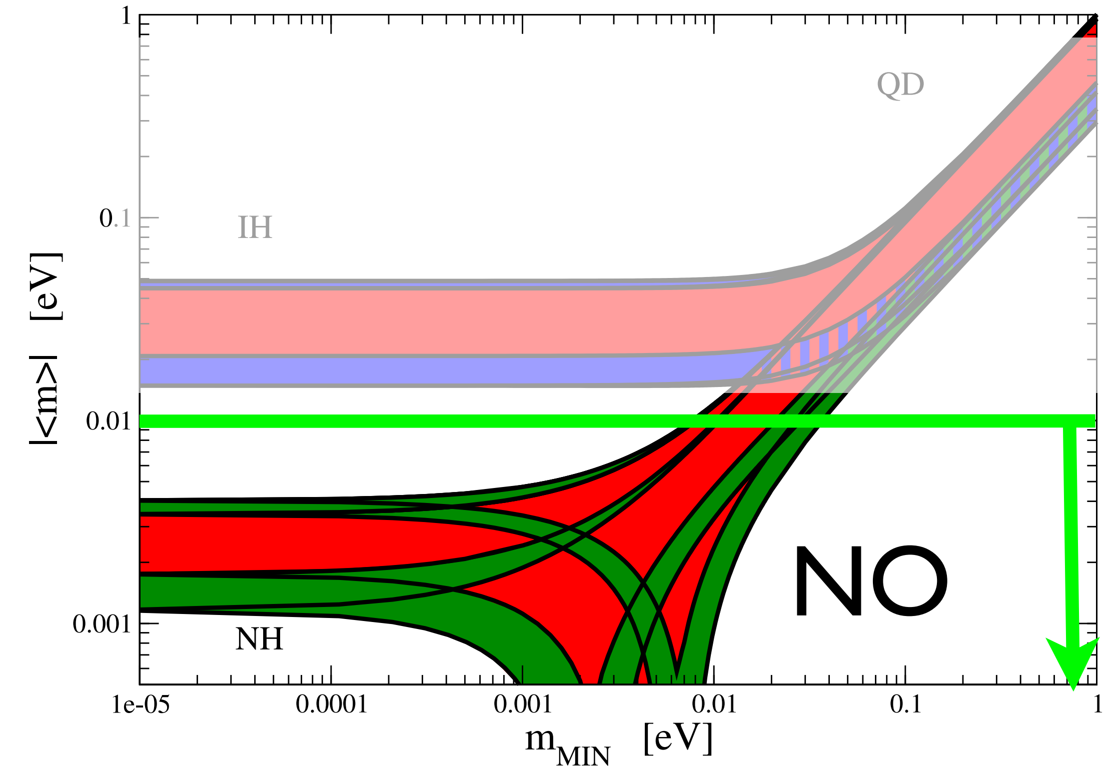




KATRIN is in the commissioning phase. It should reach a sensitivity down to m<0.2 eV and a 5-sigma discovery of m=0.35 eV.

Nuless dbeta decay and the mass spectrum





- If |<m>| > 0.2 eV, then the neutrino spectrum is QD. The measurement of m1 is entangled with the value of the Majorana phase.

- If no signal for |<m>|~10 meV, then only NO is allowed for Majorana neutrinos (and no extra ones).

Crucial interplay with cosmology and LBL.
Ex: If LBL experiments find IO, neutrinos are Dirac particles (without cancellations).

Neutrino masses from cosmology

Two main techniques to probe the matter density:

- observing the distribution of biased tracers
- gravitational lensing

Probe	Current $\sum m_\nu$ (eV)	Forecast $\sum m_\nu$ (eV)	Key Systematics	Current Surveys	Future Surveys
CMB Primordial	1.3	0.6	Recombination	WMAP, Planck	None
CMB Primordial + Distance	0.58	0.35	Distance measurements	WMAP, Planck	None
Lensing of CMB	∞	$0.2-0.05$	NG of Secondary anisotropies	Planck, ACT [39], SPT [96]	EBEX [57], ACTPol, SPTPol, POLARBEAR [5], CMBPol [6]
Galaxy Distribution	0.6	0.1	Nonlinearities, Bias	SDSS [58, 59], BOSS [82]	DES [84], BigBOSS [81], DESpec [85], LSST [92], Subaru PFS [97], HETDEX [35]
Lensing of Galaxies	0.6	0.07	Baryons, NL, Photometric redshifts	CFHT-LS [23], COSMOS [50]	DES [84], Hyper SuprimeCam, LSST [92], Euclid [88], WFIRST[100]
Lyman α	0.2	0.1	Bias, Metals, QSO continuum	SDSS, BOSS, Keck	BigBOSS[81], TMT[99], GMT[89]
21 cm	∞	$0.1-0.006$	Foregrounds, Astrophysical modeling	GBT [11], LOFAR [91], PAPER [53], GMRT [86]	MWA [93], SKA [95], FFTT [49]
Galaxy Clusters	0.3	0.1	Mass Function, Mass Calibration	SDSS, SPT, ACT, XMM [101] Chandra [83]	DES, eRosita [87], LSST

K.N. Abazajian et al., 1103.5083

$$\sum_i m_i < 0.66 \text{ eV}$$

Planck Coll., 1303.5076

See Refregier's and Lesgourgues' talks

Most precise determination of masses in future. Problem of underlying cosmological model and systematic errors.

Phenomenology questions for the future

- What is the nature of neutrinos? Dirac vs Majorana?
- **What are the values of the masses?** Absolute scale (KATRIN, ...?) and the ordering.
- **Is there CP-violation?** Its discovery in the next generation of LBL depends on the value of theta13 and of delta.
- **Wh**... **gles?** **Do**...
- **Is** ... NSI? Ster...

CP-violation has been observed in the quark sector. Does it occur also in the leptonic sector? and if so, what is its origin?

CP-violation

Mixing is described by the Pontecorvo-Maki-Nakagawa-Sakata matrix, which enters in the CC interactions

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i}|\nu_i\rangle$$

$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}}\sum_{k\alpha}\left(U^*_{\alpha k}\bar{\nu}_{kL}\gamma^\rho l_{\alpha L}W_\rho + \text{h.c.}\right)$$

$$U = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$$

Solar, reactor $\theta_\odot \sim 30^o$ Atm, Acc. $\theta_A \sim 45^o$

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta} \end{pmatrix}\begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix}\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha_{21}/2} & 0 \\ 0 & 0 & e^{-i\alpha_{31}/2+i\delta} \end{pmatrix}$$

CPV phase Reactor, Acc. $\theta_{13} \sim 9^o$ CPV Majorana phases

CPV?

CPV is a fundamental question to answer, possibly related to the origin of the baryon asymmetry.

1. Different flavour models can lead to specific predictions for the value of the delta phase:

- Sum rules: $\sin\theta_{23} - \frac{1}{\sqrt{2}} = a_0 + \lambda \sin\theta_{13} \cos\delta + \text{higher orders}$
- discrete symmetries models
- charged lepton corrections to U_ν: $U_{\rm PMNS} = U_e^\dagger U_\nu$

e.g. M.-C. Chen and Mahanthappa; Girardi et al.; Petcov; Alonso, Gavela, Isidori, Maiani; Ding et al.; Ma; Hernandez, Smirnov; Feruglio et al.; Mohapatra, Nishi; Holthausen, Lindner, Schmidt; and others

2. In order to generate dynamically a baryon asymmetry, the Sakharov's conditions need to be satisfied:

Neutrinoless double beta decay

- B (or L) violation;

LBL

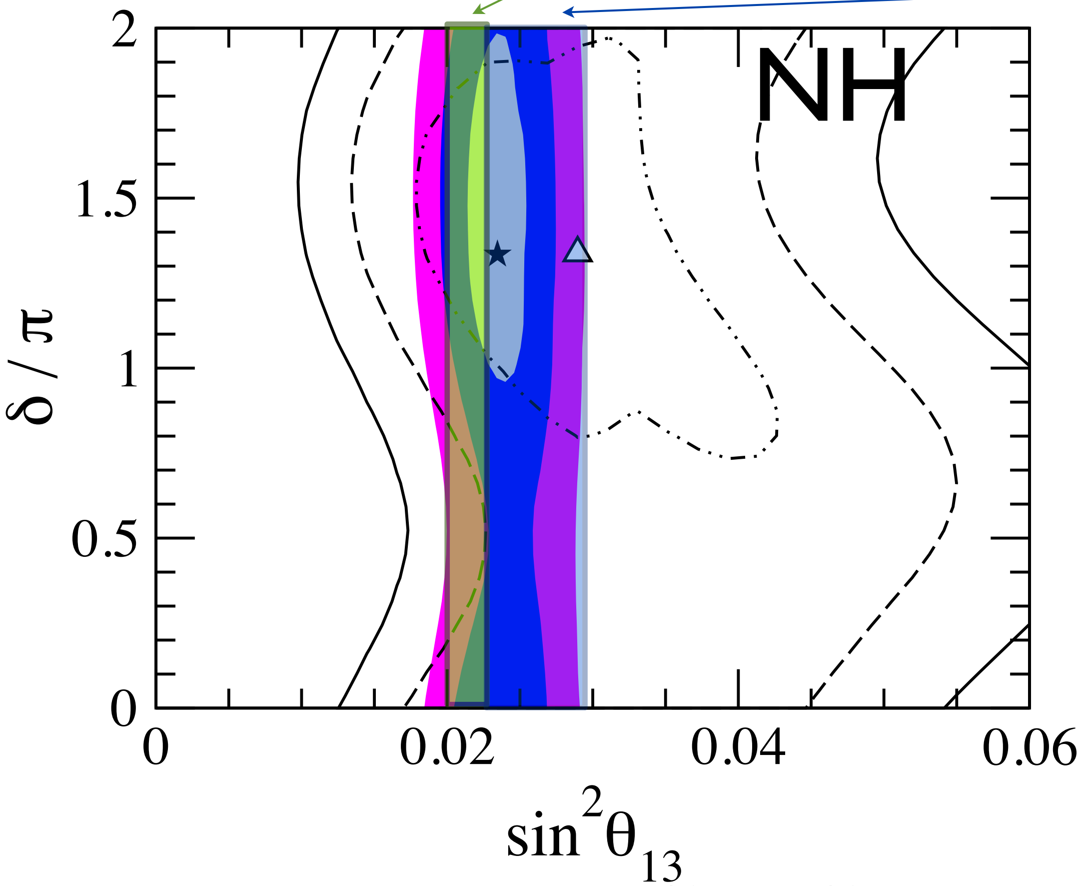
- C, CP violation;

Expansion of the Universe

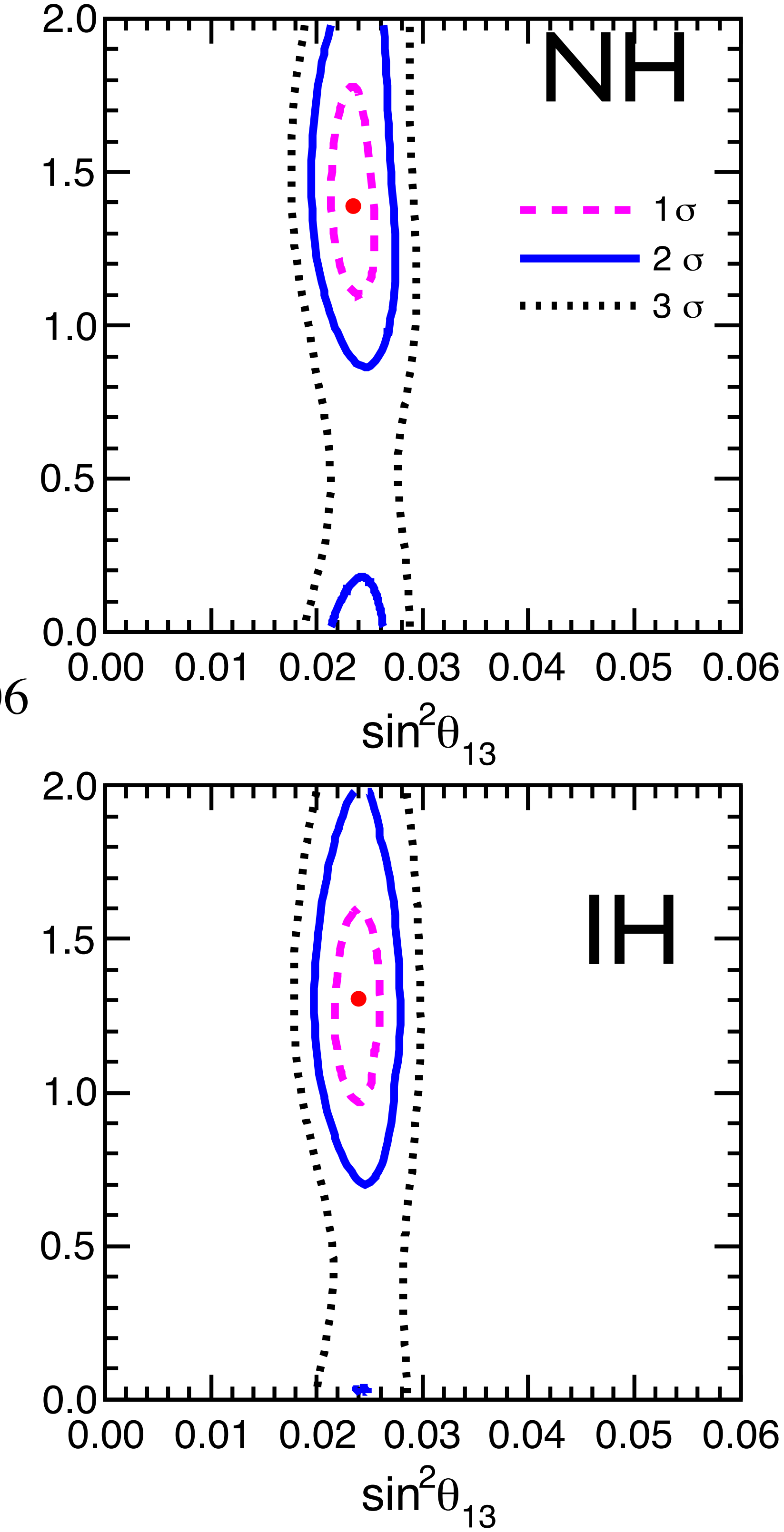
- departure from thermal equilibrium.

Leptogenesis in models of neutrino masses

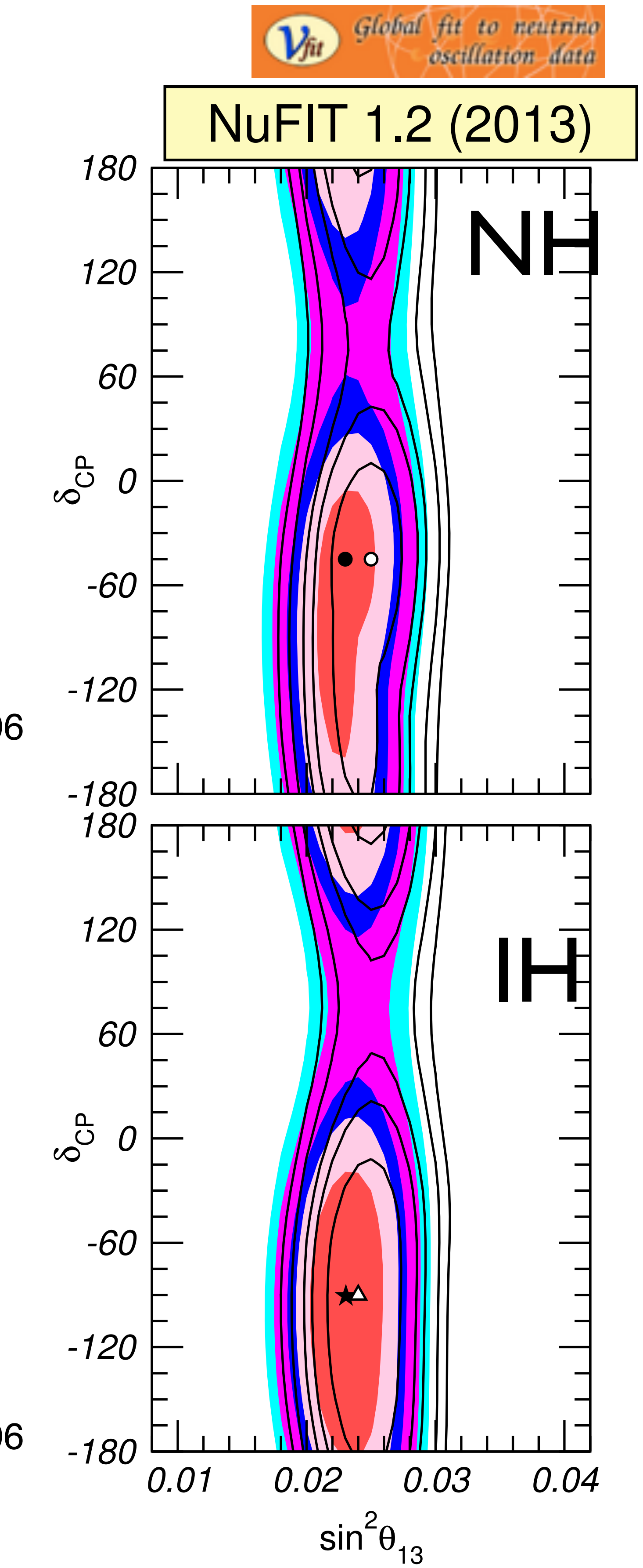
Hints of CP-violation



D.V. Forero et al., 1405.7540



F. Capozzi et al., 1312.2878



NuFit: M. C. Gonzalez-Garcia et al., 1209.3023

There is a slight preference for CP-violation, which is mainly due to the combination of T2K and reactor neutrino data.

CP-violation in LBL experiments

CP-violation will manifest itself in neutrino oscillations, due to the delta phase. The CP-asymmetry:

$$P(\nu_\mu \to \nu_e; t) - P(\bar{\nu}_\mu \to \bar{\nu}_e; t) =$$

$$= 4 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin\delta \left[\sin\left(\frac{\Delta m_{21}^2 L}{2E}\right) + \sin\left(\frac{\Delta m_{23}^2 L}{2E}\right) + \sin\left(\frac{\Delta m_{31}^2 L}{2E}\right) \right]$$

- CP-violation requires all angles to be nonzero.
- It is proportional to the sine of the delta phase.
- If one can neglects Δm_{21}^2, the asymmetry goes to zero: effective 2-neutrino probabilities are CP-symmetric.

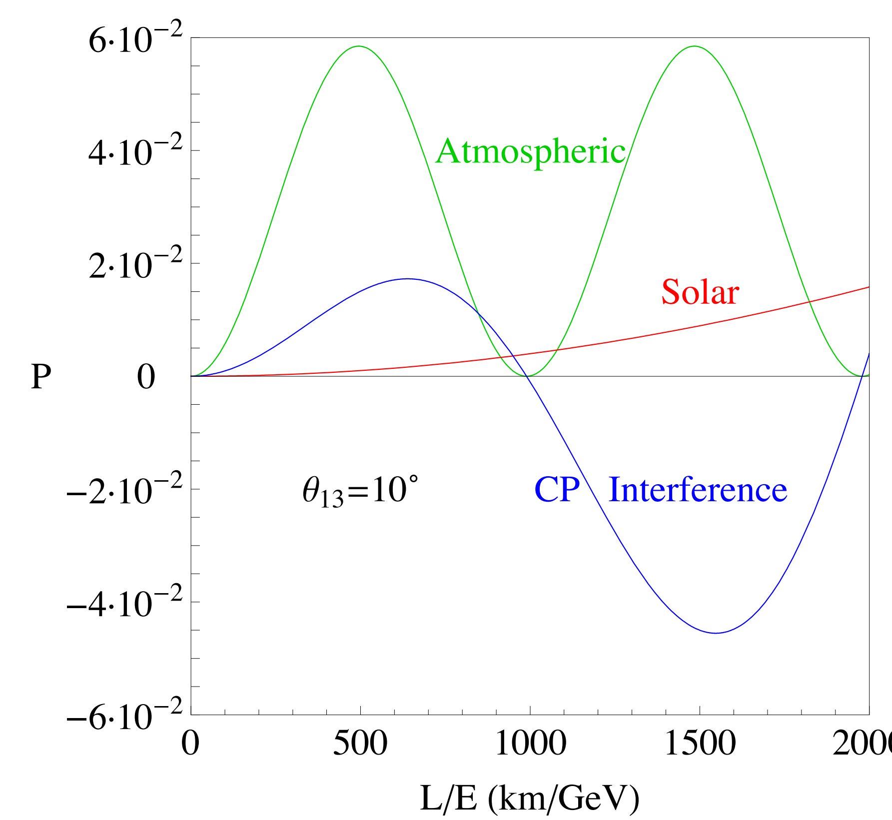
CPV needs to be searched for in long baseline neutrino experiments which have access to 3-neutrino oscillations.

$$P_{\mu e} \simeq 4 c_{23}^2 s_{13}^2 \frac{1}{(1-r_A)^2} \sin^2 \frac{(1-r_A)\Delta_{31} L}{4E}$$
$$+ \sin 2\theta_{12} \sin 2\theta_{23} s_{13} \frac{\Delta_{21} L}{2E} \sin \frac{(1-r_A)\Delta_{31} L}{4E} \cos\left(\delta - \frac{\Delta_{31} L}{4E}\right)$$
$$+ s_{23}^2 \sin^2 2\theta_{12} \frac{\Delta_{21}^2 L^2}{16 E^2} - 4 c_{23}^2 s_{13}^4 \sin^2 \frac{(1-r_A)\Delta_{31} L}{4E}$$

A. Cervera et al., hep-ph/0002108;
K. Asano, H. Minakata, 1103.4387;
S. K. Agarwalla et al., 1302.6773...

See also W. Winter's talk

- The CP asymmetry peaks for sin^2 2 theta13 ~0.001. Large theta13 makes its searches possible but not ideal.
- Crucial to know mass ordering.
- CPV effects more pronounced at low energy.



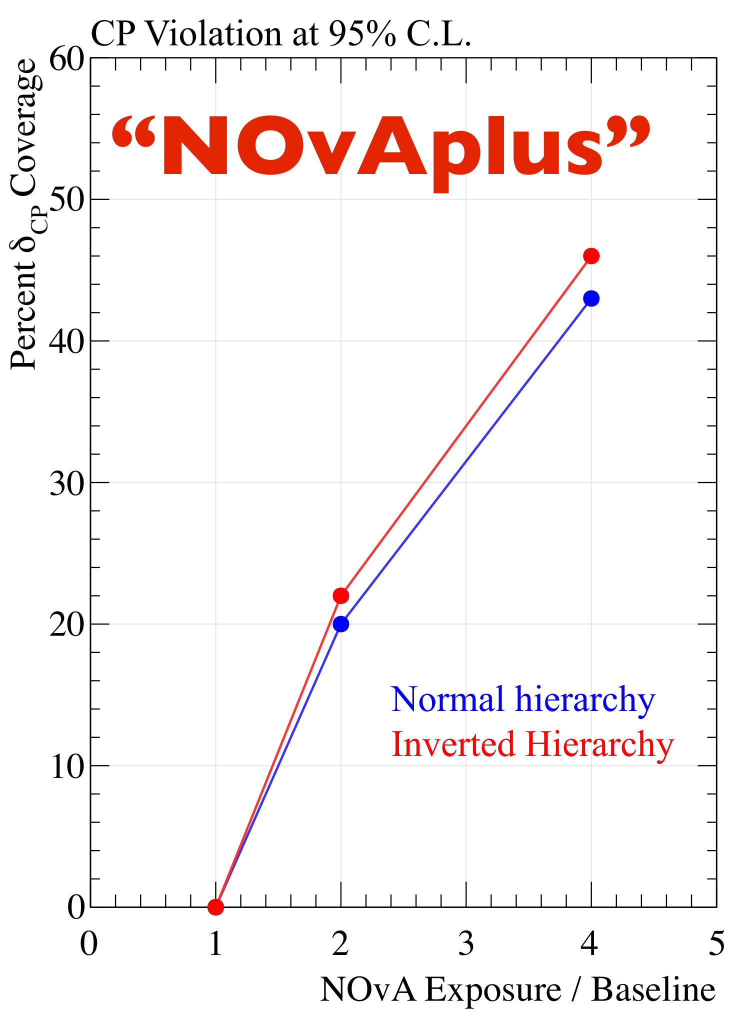
P. Coloma, E. Fernandez-Martinez, JHEP1204

CPV Searches

Category	Experiment	Status	Oscillation parameters
Accelerator	MINOS+ [74]	Data-taking	MH/CP/octant
Accelerator	T2K [21]	Data-taking	MH/CP/octant
Accelerator	NOvA [108]	Commissioning	MH/CP/octant
Accelerator	RADAR [76]	Design/ R&D	MH/CP/octant
Accelerator	CHIPS [75]	Design/ R&D	MH/CP/octant
Accelerator	LBNE [87]	Design/ R&D	MH/CP/octant
Accelerator	Hyper-K [97]	Design/ R&D	MH/CP/octant
Accelerator	LBNO [109]	Design/ R&D	MH/CP/octant
Accelerator	ESSνSB [110]	Design/ R&D	MH/CP/octant
Accelerator	DAEδALUS [111]	Design/ R&D	CP

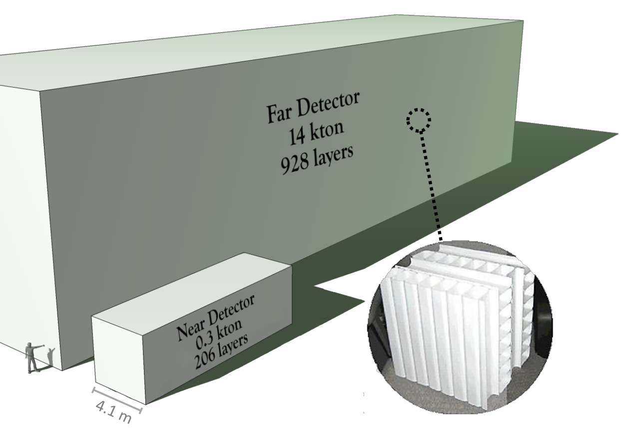
WG Report: Neutrinos, de Gouvea (Convener) et al., 1310.4340

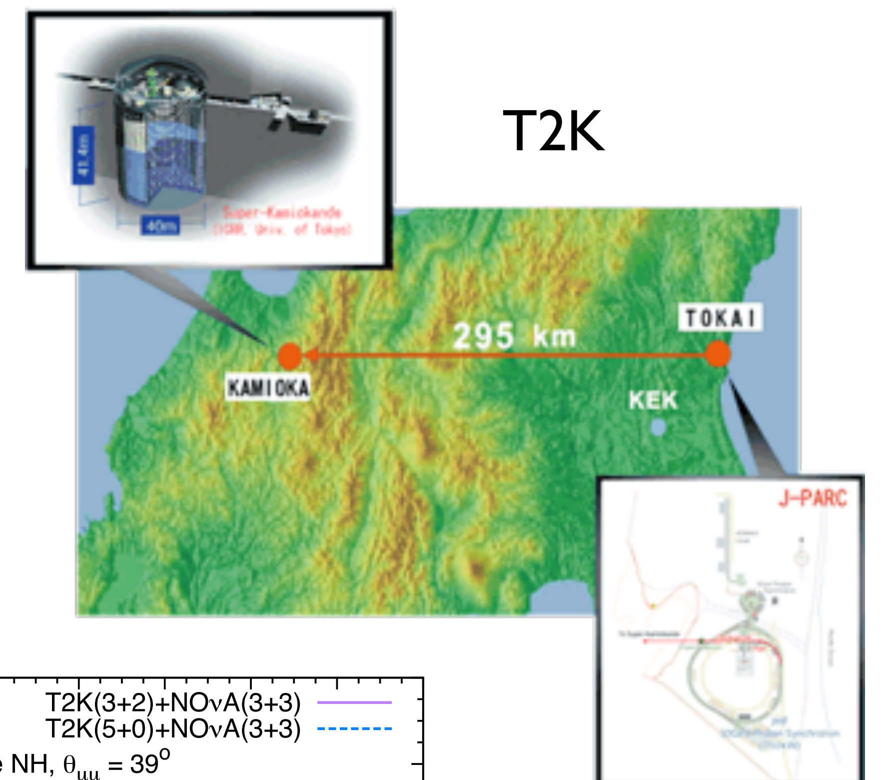
Near future: T2K and NOvA. Marginal sensitivity to CPV

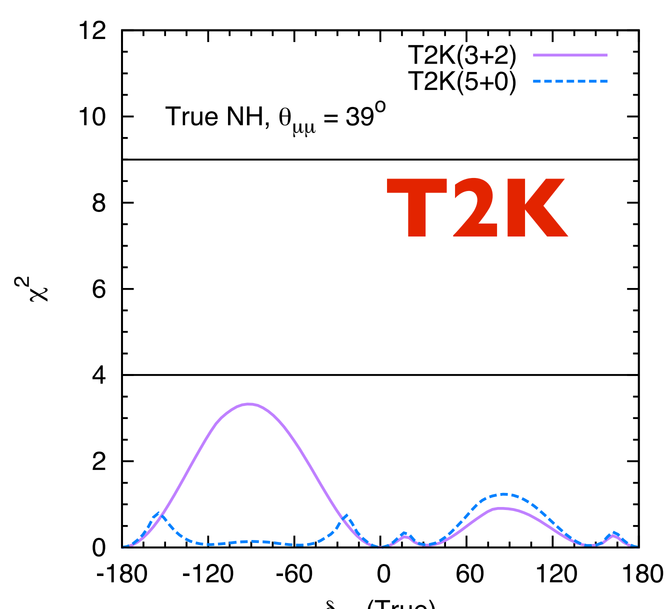


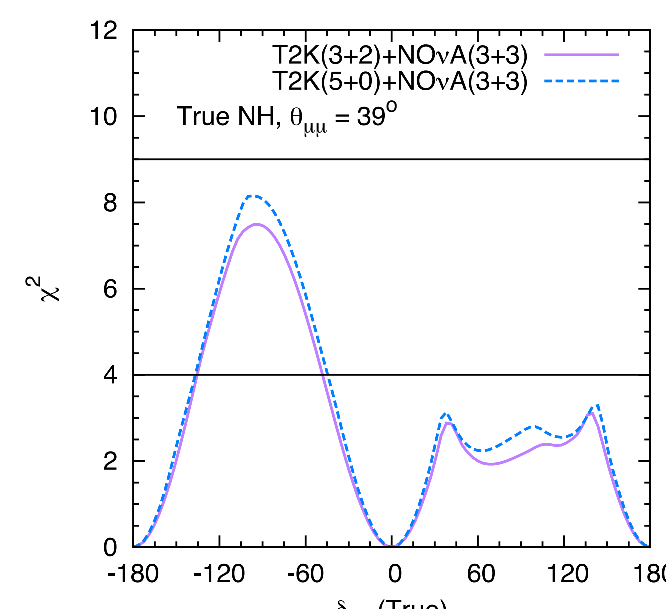
NOvA Coll., 1308.0106

NOvA



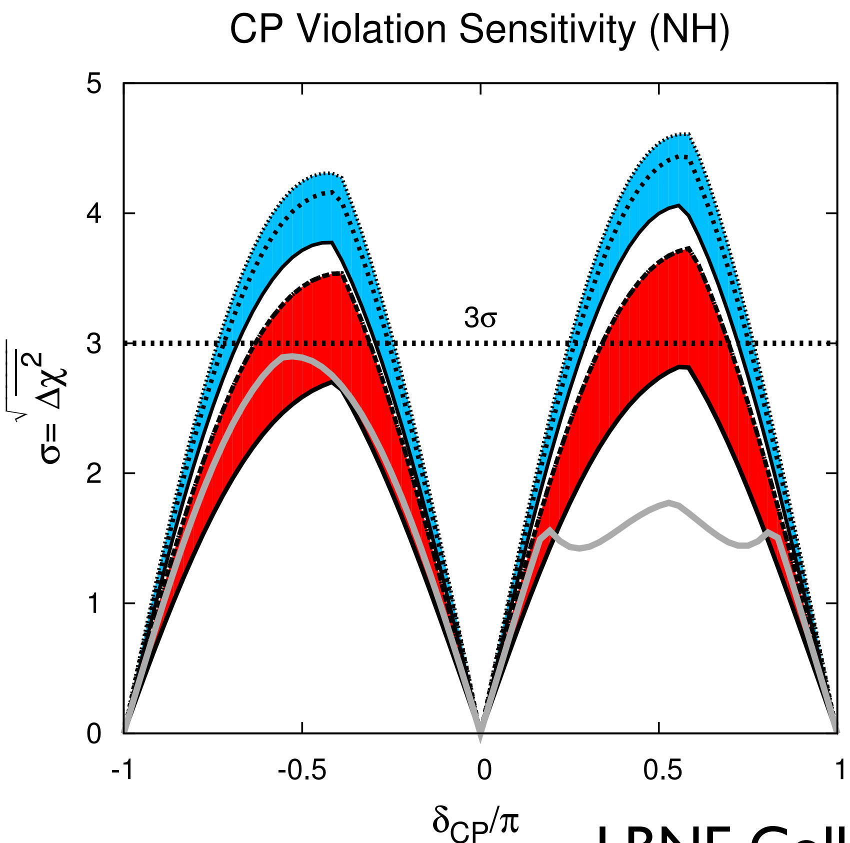




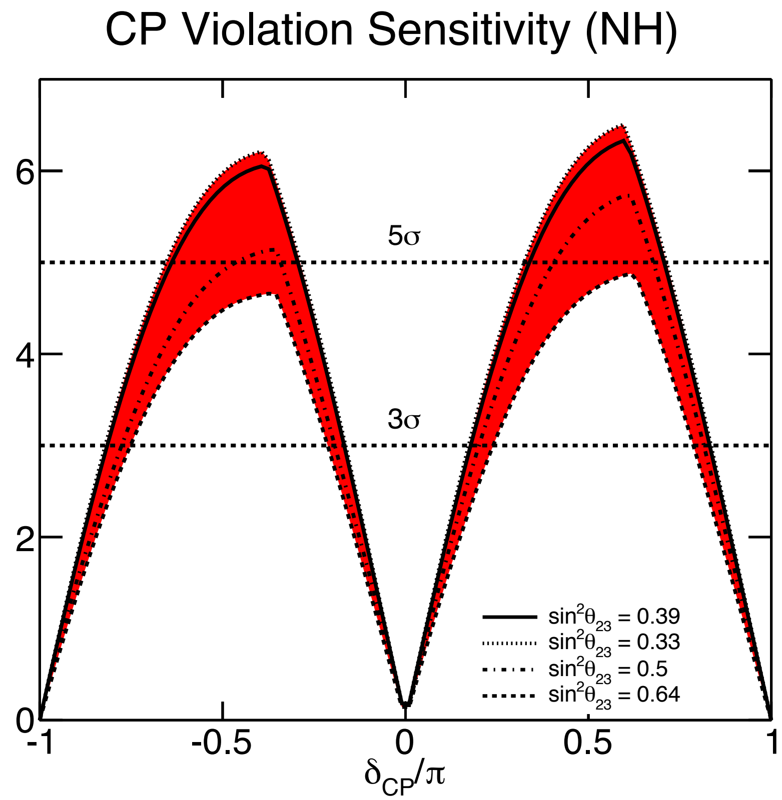


M. Gosh et al., 1401.7243; see also Machado et al.; Huber et al.

LBNE-10Kton

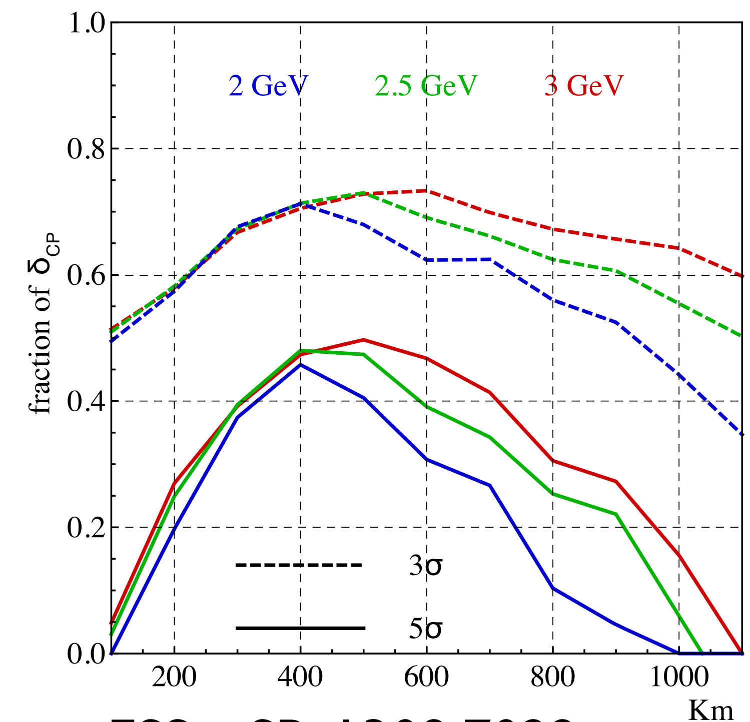


LBNE-34kton



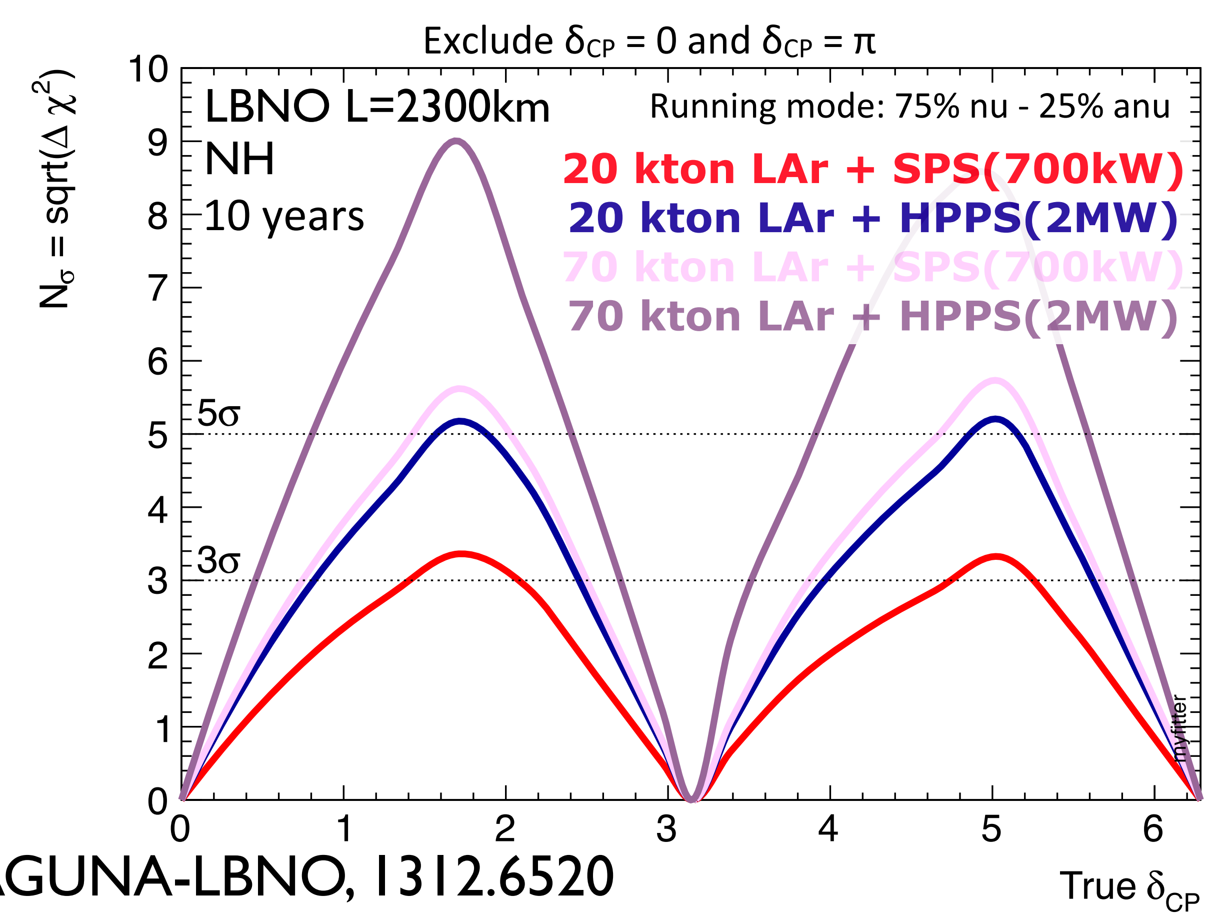
LBNE Coll., 1307.7335

ESSnuSB



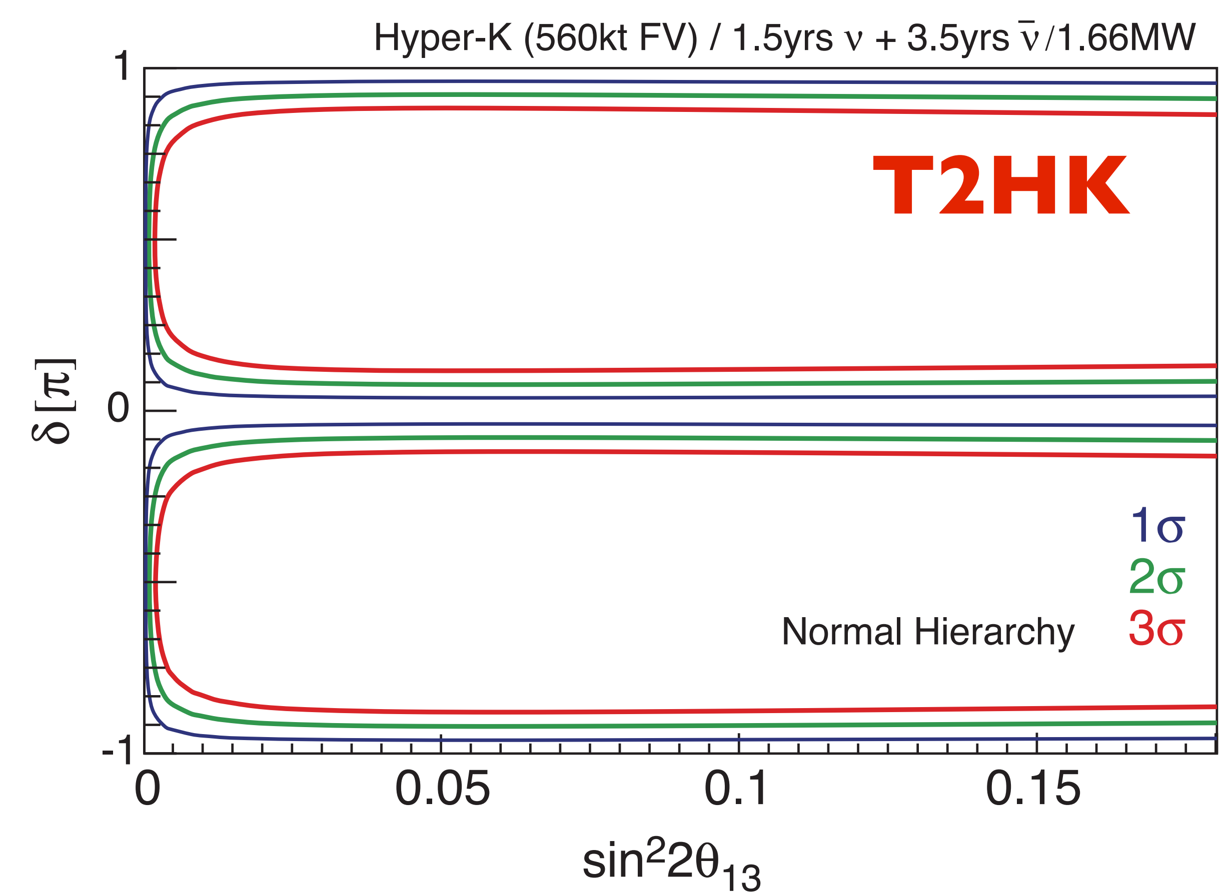
ESSnuSB, 1309.7022

LBNO

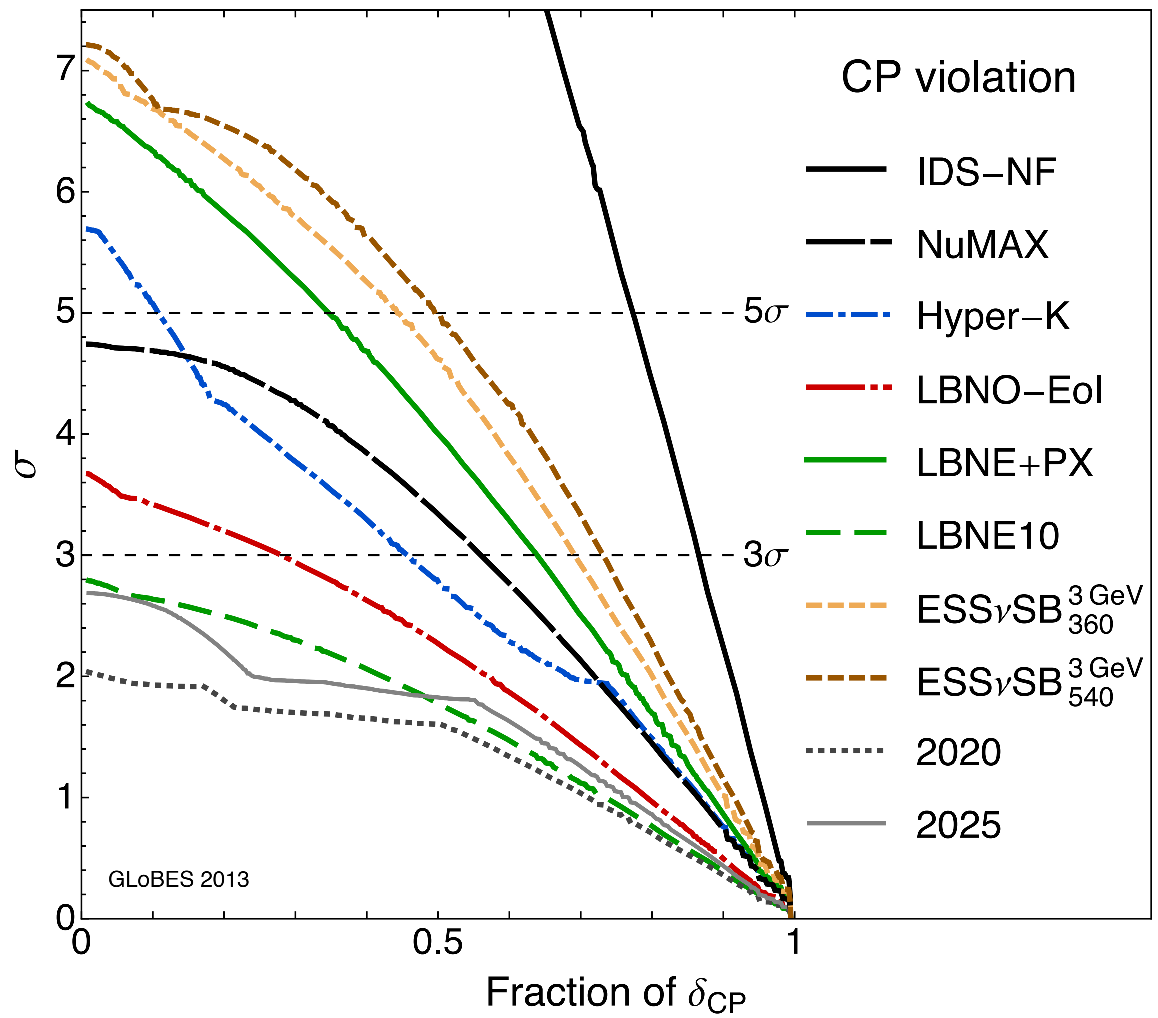


LAGUNA-LBNO, 1312.6520

T2HK



T2HK LoI, Abe et al., 1109.3262



ESSnuSB, 1309.7022

Neutrino factory: Has the best sensitivity to CPV. Due to large theta13, low energy muons and not-too-long baselines are needed.

Comparisons should be made with great care as they critically depend on:

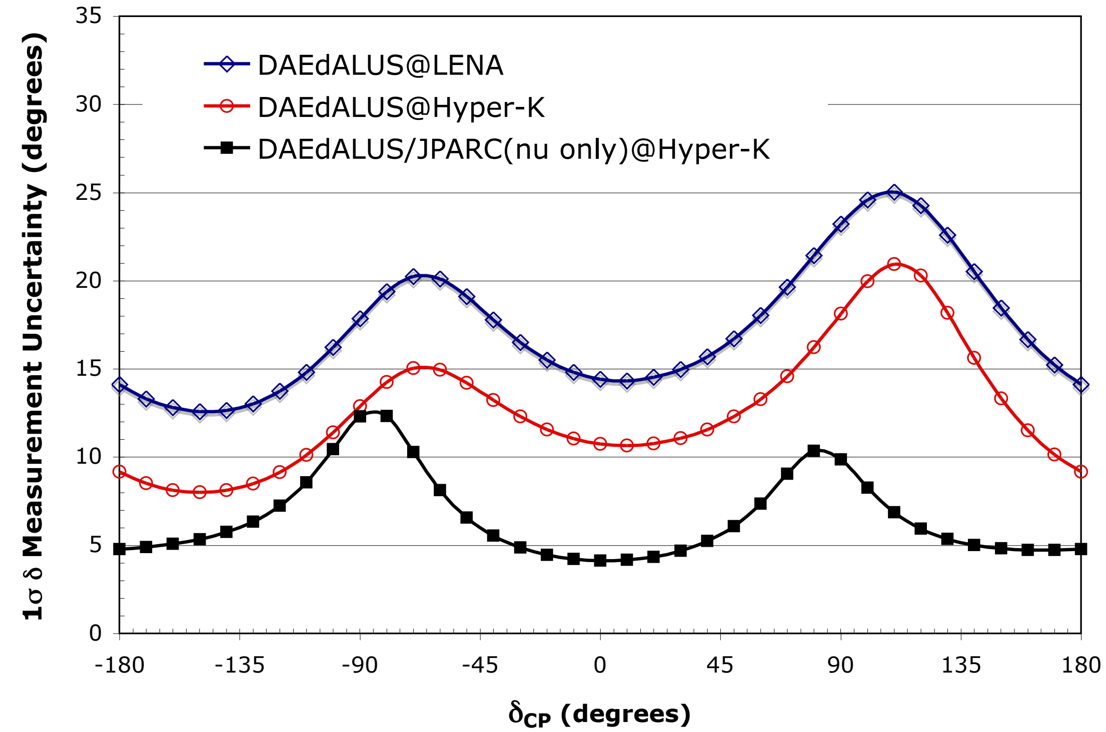
- setup assumed: detector and its performance, beam...
- values of oscillation parameters and their errors
- treatment of backgrounds and systematic errors.

See Scholberg's, Fleming's, Rubbia's, Yokohama's talks

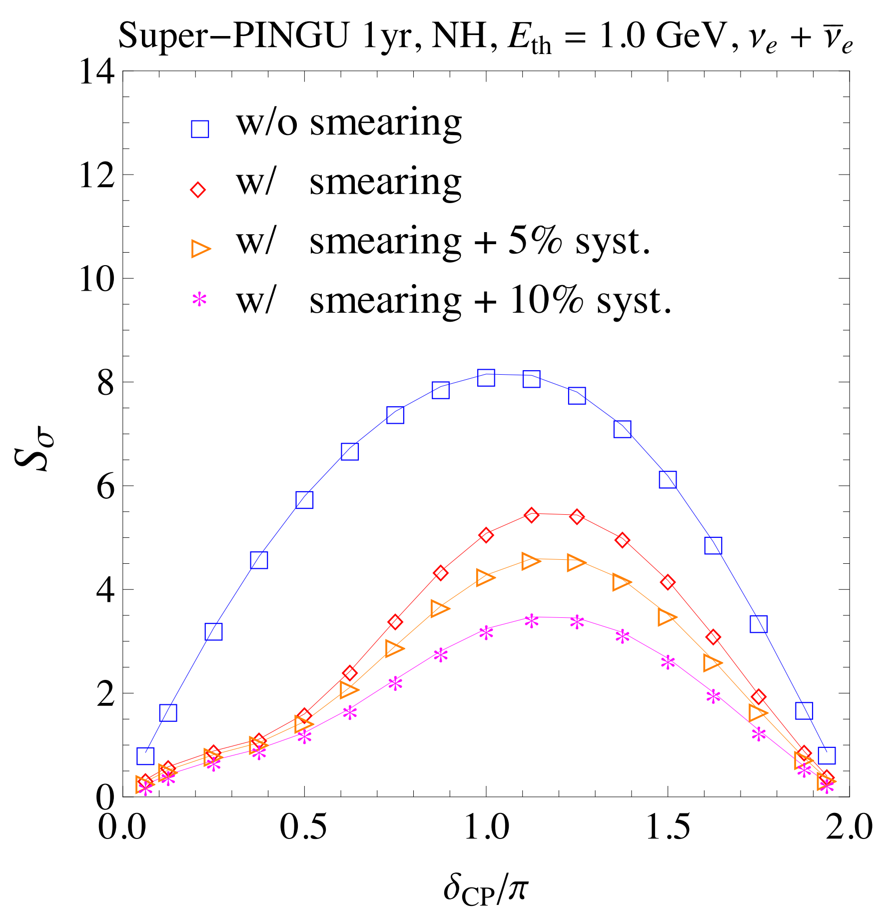
Information on CPV could also come from...

DAEdALUS

Uses the probability of oscillation of low energy muon antineutrino into electron antineutrinos at short baselines (1.5-20 Km).



DAEdALUS Coll., 1307.2949



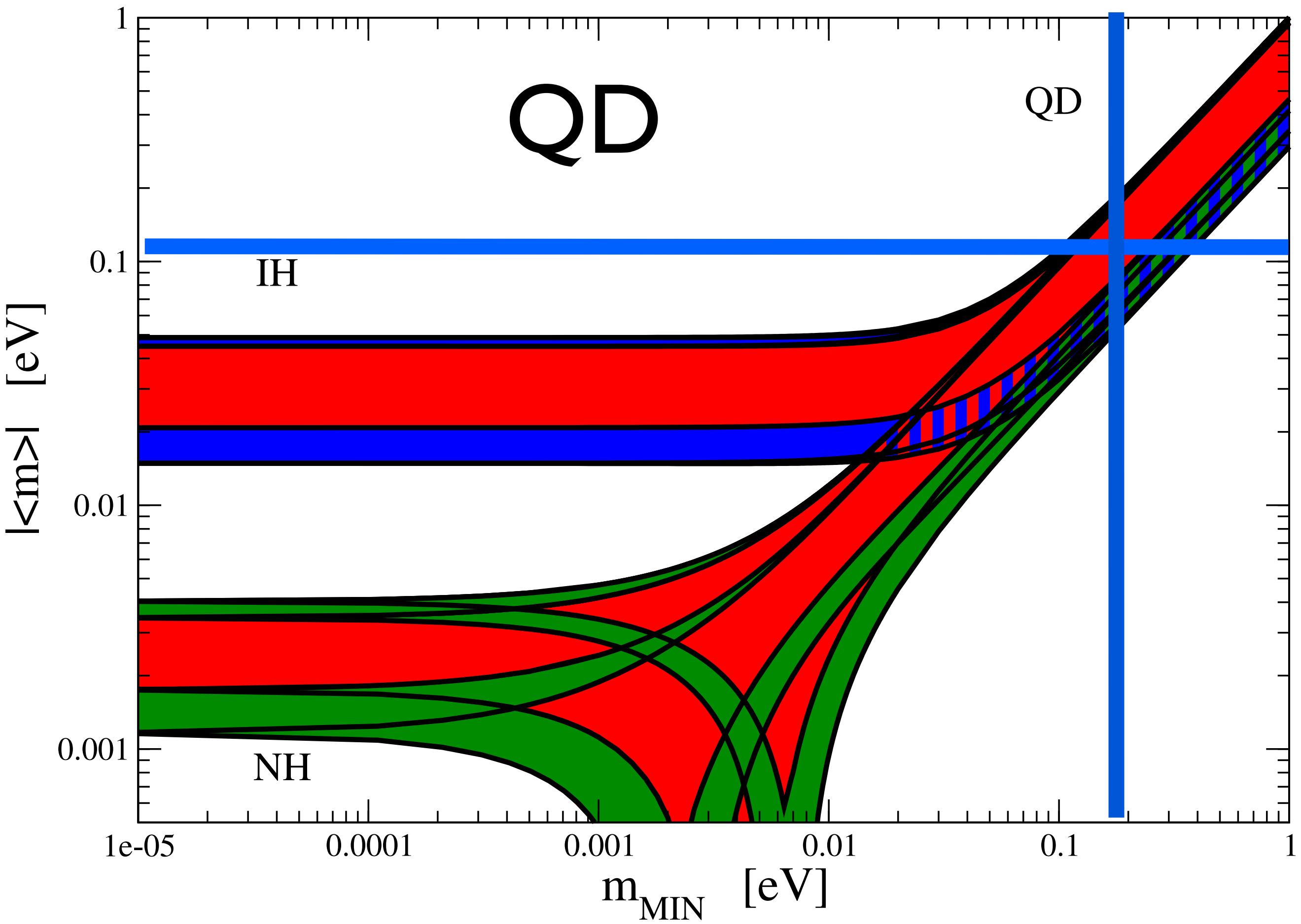
Razzaque, Smirnov, 1406.1407

Atmospheric neutrinos

These experiments have access to a broad range of baselines and energies. Limited energy and angular resolution and nu-anti nu discrimination affect their reach.

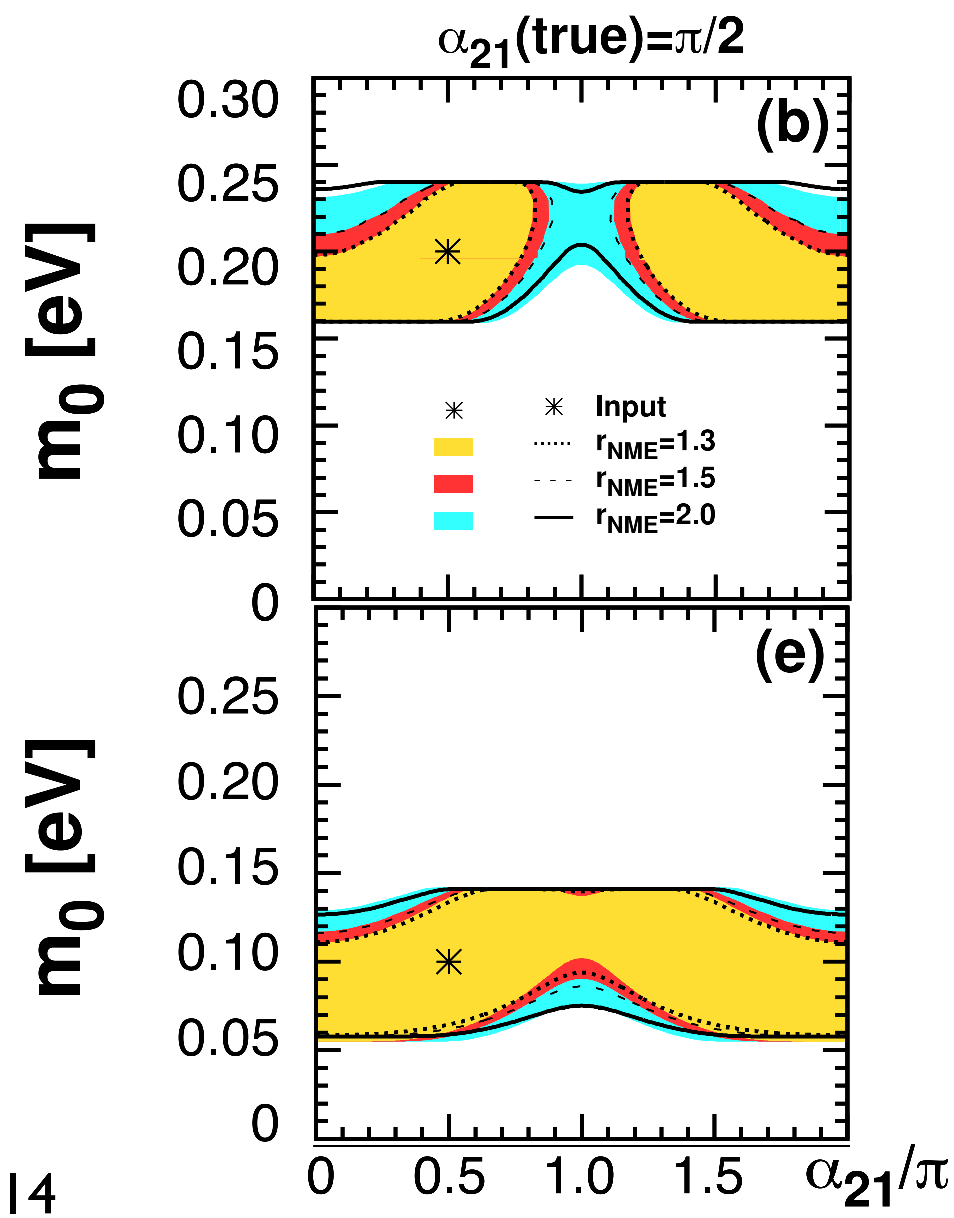
Peres, Smirnov; Kimura et al., Gonzalez-Garcia, Maltoni; Akhmedov et al.; Mena et al.; Hay, Latimer; Agarwalla et al.; Ohlsson et al.; Ge et al.; Abe et al.; Kearns et al.; Adams et al; ...

Determining CP-violation with neutrinoless 2beta decay



If |<m>| and the masses are measured with sufficient precision, then it may be possible to establish CPV due to Majorana phases.

See also M. Hirsch's talk



However, this requires also a very precise determination of NME.

See also, SP, Petcov and Wolfenstein, PLB524.; SP, S. Petcov, T. Schwetz, NPB734; F. Simkovic, et al., PRD 87; Joniec, Zralek, PRD73; Deppisch et al, PRD72; Bahcall et al., PRD70; de Gouvea et al, PRD67; SP, et al., PLB579; Nunokawa et al., PRD66; Barger et al., PLB540.

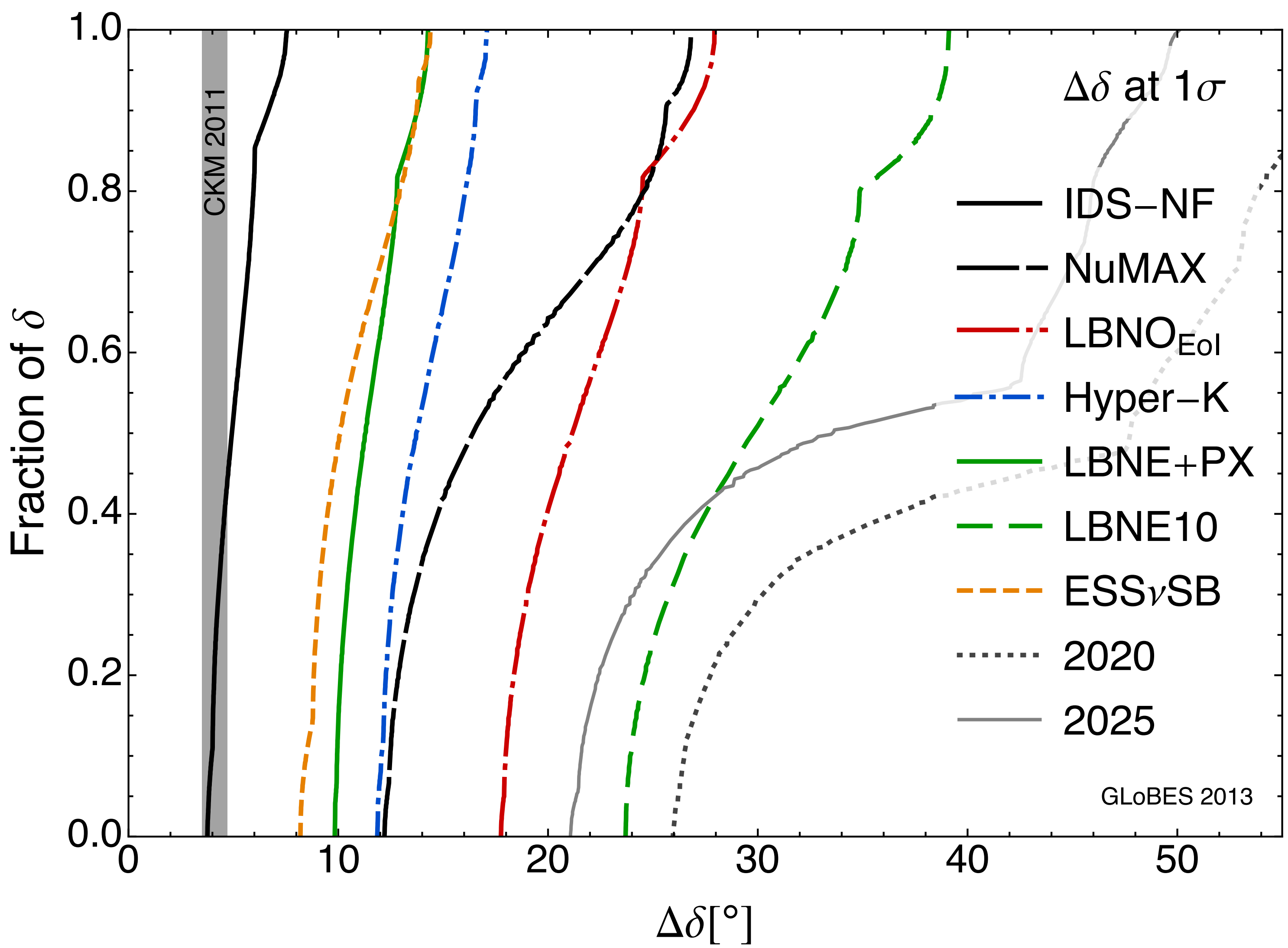
H. Minakata et al., 1402.6014

Phenomenology questions for the future

- **What is the nature of neutrinos? Dirac vs Majorana?**
- **What are the values of the masses?** Absolute scale (KATRIN, ...?) and the ordering.
- **Is there CP-violation?** Its discovery in the next generation of LBL depends on the value of delta.
- **What are the precise values of mixing angles?** Do they suggest an underlying pattern?
- **Is the standard picture correct?** Are there NSI? Sterile neutrinos? Other effects?

The precision measurement of the oscillation parameters will become very important in the future.

- The values of the mixing angles seem to indicate an underlying symmetry: $\theta_{23} \sim 45^o, \quad \theta_{13}$ not too far from 0.
- Predictions for the CPV phase delta and relations among parameters in flavour models



Crucial information in order to discriminate between different flavour models.

WG Report: Neutrinos, de Gouvea (Convener) et al., 1310.4340; see also, Coloma et al., JHEP 1206; Minakata, Parke, PRD87; D. Meloni, PLB728

Phenomenology questions for the future

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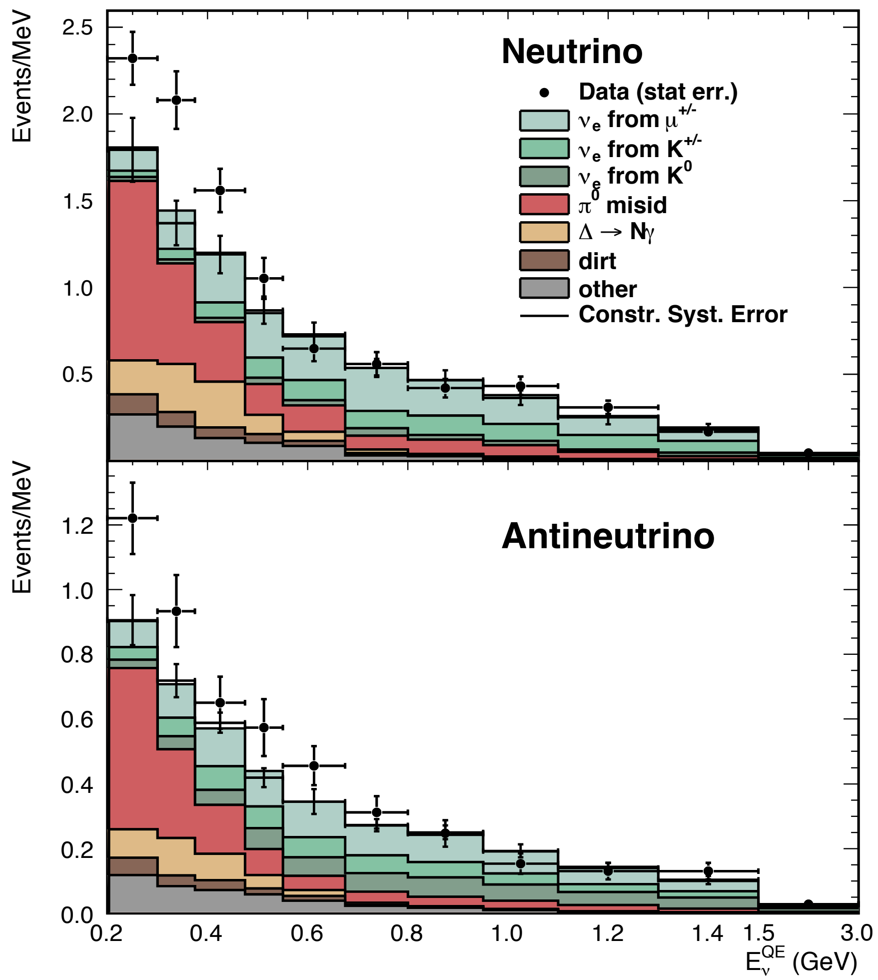
Non-standard effects: sterile neutrinos

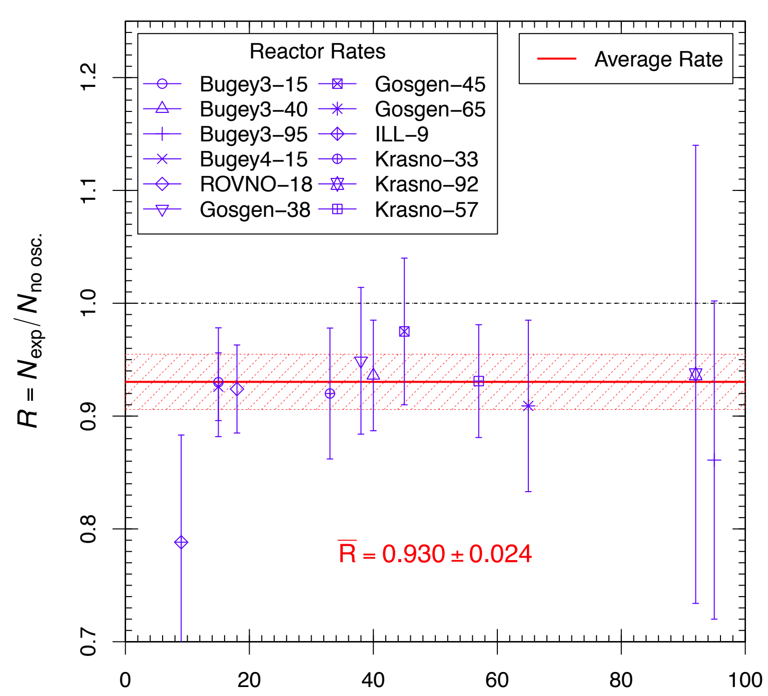
MiniBooNE, PRL 110



There are hints beyond the standard 3 neutrino mixing.

MiniBooNE was designed to test the LSND excess. It found an excess of events at low energy. MicroBooNE is going to probe these hints.

See Weber's talk



Mention et al., 2011. See also Muller et al., PRC 832011; Huber et al, PRC84 2011. And Sinev, 1103.2452; Ciuffoli et al., JHEP 12 2012; Zhang et al., PRD87 2013; Ivanov et al., 1306.1995.

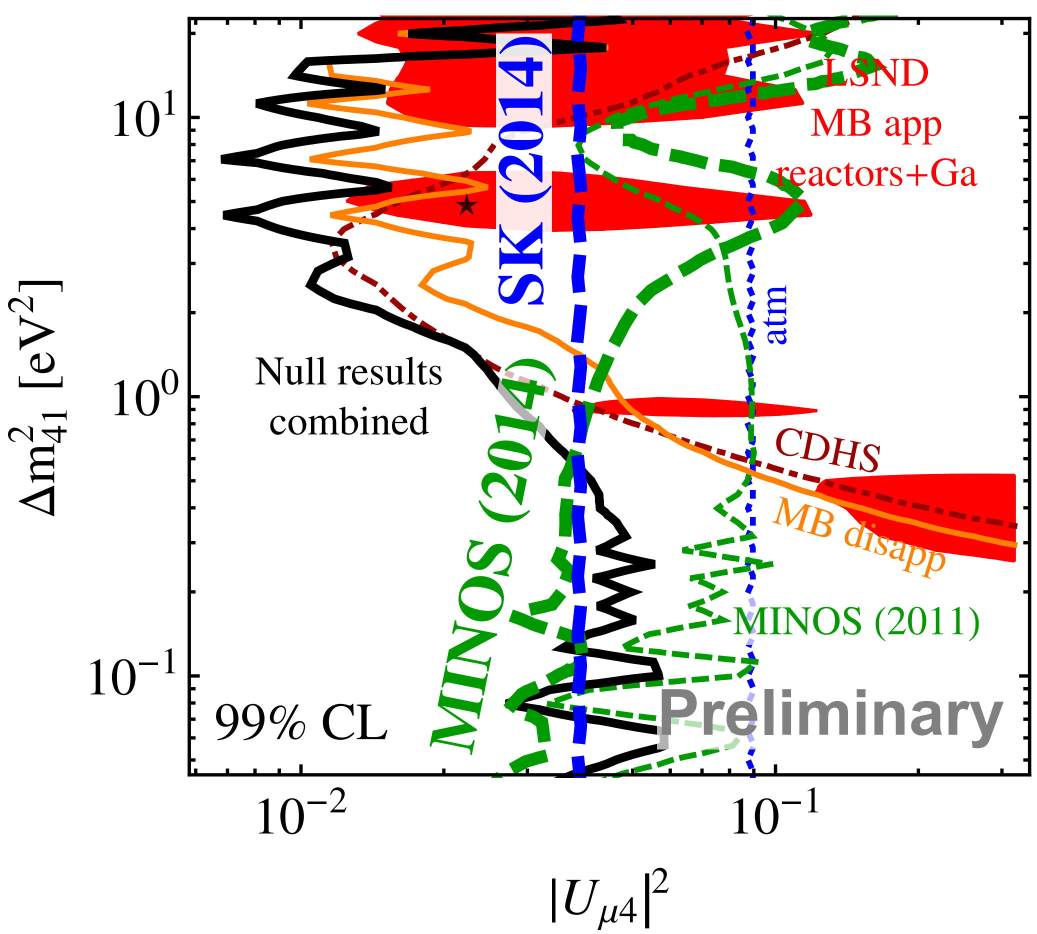
Reactor anomaly: A recomputation of the reactor fluxes seems to indicate neutrino disappearance (2.8 sigma), compatible with oscillations into sterile neutrinos with large masses.

Disappearance experiments:

$$P_{\alpha\alpha} = 1 - 2|U_{\alpha 4}|^2(1 - |U_{\alpha 4}|^2)\sin^2\frac{\Delta m_{41}^2 L}{4E}$$

Appearance experiments require mixing both with electron neutrinos and muon neutrinos:

$$P(\nu_\alpha \to \nu_\beta) = 4|U_{\alpha 4}|^2|U_{\beta 4}|^2\sin^2\frac{\Delta m_{41}^2 L}{4E}$$



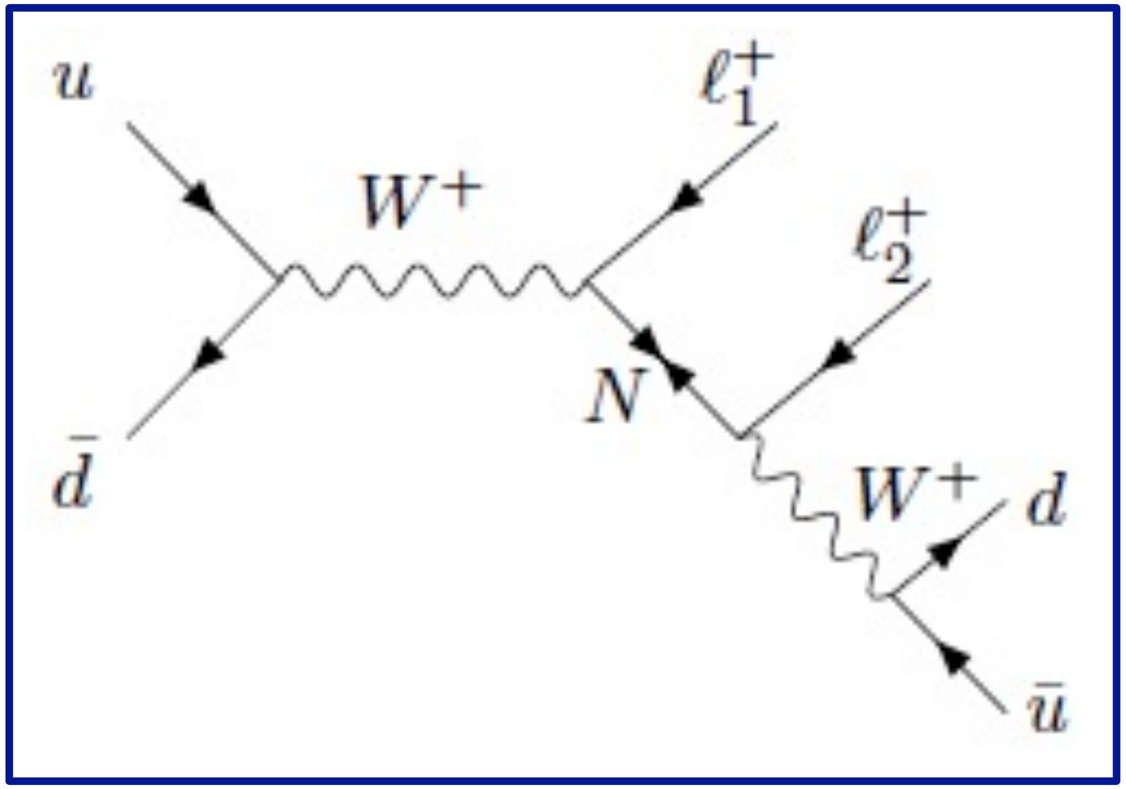
Kopp et al., JHEP 1305 2013 + preliminary at Neutrino 2014
See also Giunti et al., 1308.5288, Conrad et al., 1207.4765

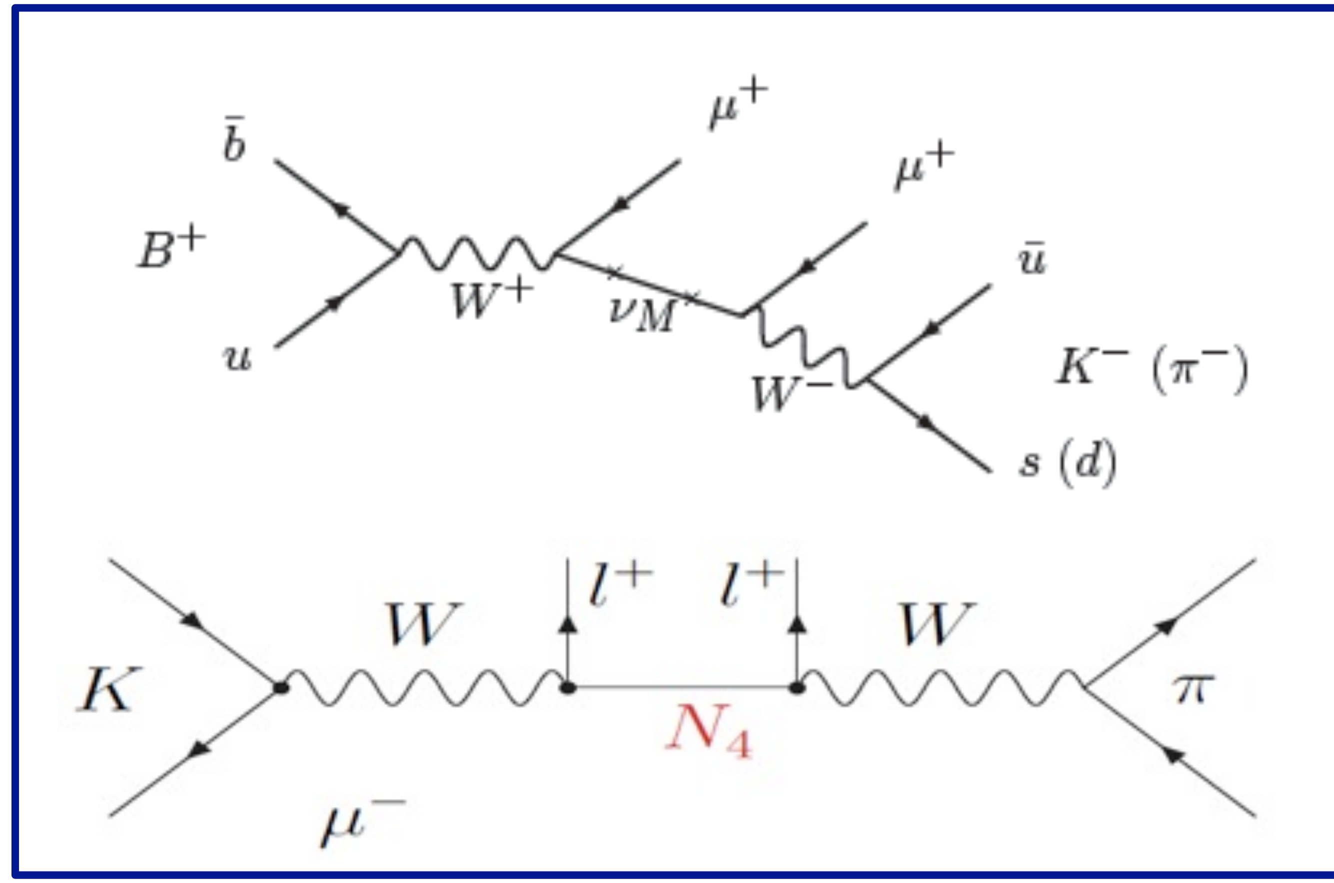
There is a significant tension between appearance and disappearance data.

It is possible to introduce 2 extra sterile neutrinos but the tension remains.

Many plans to test these anomalies: nuclear decays, reactors and accelerators.

Leptonic physics at colliders and in rare meson/tau decays





LNV signals at colliders

Signature: same-sign leptons and no missing E_T. CMS and ATLAS searches have reported no signal.

Tau and Meson LNV decays.

They get resonantly enhanced for M~ 100 MeV - few GeV.

Channel	Observed 95% CL
$K^+\mu^-\mu^-$	5.4×10^{-8}
$D^+\mu^-\mu^-$	6.9×10^{-7}
$D^{*+}\mu^-\mu^-$	2.4×10^{-6}
$\pi^+\mu^-\mu^-$	1.3×10^{-8}
$D_s^+\mu^-\mu^-$	5.8×10^{-7}
$D^0\pi^+\mu^-\mu^-$	1.5×10^{-6}

LHC-b

PRL 108 and PRD 85.

@Silvia Pascoli

Invisibles decay of the Z

If sterile neutrinos are heavier than the Z mass, then they cannot be produced in its decay -> violation of unitarity.

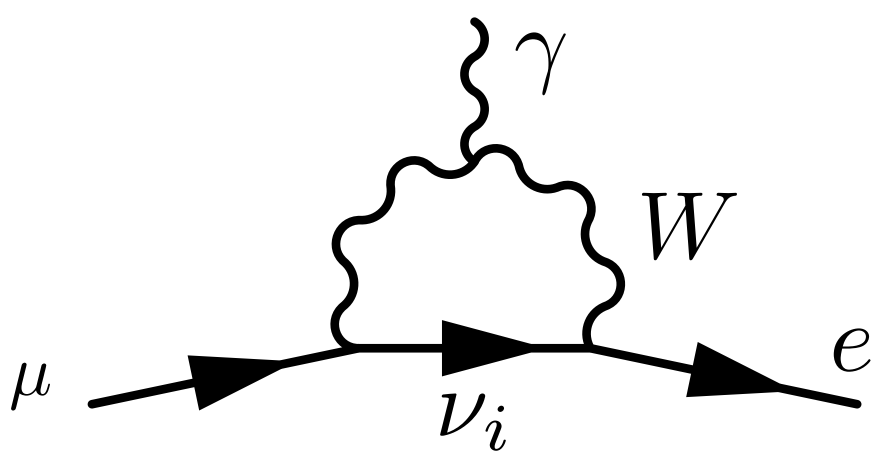
C. Jarlskog, 1990

$$N_\nu = 2.984 \pm 0.008$$ Phys. Rept. 427, 2006

A future collider such as FCC-ee could improve this bound very significantly. See A. Blondel's talk at TLEP IOP meeting

Lepton flavour violation in charged leptons decays

Lepton flavour violations have been observed in the neutral sector (nu oscillations). How about the charged lepton sector?



$$Br(\mu \to e\gamma) \sim 10^{-53}$$

Neutrino masses induce LFV processes but they are very suppressed.

Any observation of LFV would indicate new physics BSM and provide clues about the origin of neutrino masses.

Conclusions

A very rich experimental programme of current experiments, R&D and future plans.

- **Neutrinoless double beta decay: nature of neutrinos**, neutrino masses and CPV (?).
- **Long baselines neutrino: mass hierarchy and CPV** and provide precision measurements of the parameters. Comparisons should be done with great care.
- **Atmospheric neutrinos: mass hierarchy**, CPV (?).
- **Reactor neutrinos:** mass hierarchy, precise measurement of theta12.
- **KATRIN and beta decay exp**: **neutrino masses**
- **Short baseline exp:** sterile neutrinos and other effects

Is there a priority list?

- **What is the nature of neutrinos? Dirac vs Majorana?**
- **Is there CP-violation?** Its discovery in the next generation of LBL depends on the value of delta.
- **What are the values of the masses?** Absolute scale (KATRIN, ...?) and the ordering.
- **What are the precise values of mixing angles?** Do they suggest an underlying pattern?
- **Is the standard picture correct?** Are there NSI? Sterile neutrinos? Other effects?

Theoretical guidance is useful but...

Other considerations are also important (timeliness, technological development, feasibility, ...)

Unexpected results (see e.g. neutrino oscillations) could change the priority completely and open new questions.

What is left to measure in neutrino physics?

LOTS!!!