Report on the Madrid workshop: theoretical issues and experiment

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The SM as an effective theory

$$\mathcal{L}_{SM}^{eff} = \mathcal{L}_{SM}^{ren} + \frac{h_{ij}}{\Lambda}(H L_i)(H L_j) + \ldots$$

$$m_\nu = h v \cdot \frac{v}{\Lambda}$$

$$\Lambda \sim 0.5 \cdot 10^{15} GeV\ h \left(\frac{0.05\,\text{eV}}{m_\nu} \right)$$

- Measure the physical parameters; what do we learn?
- Probe the set up
- Non-oscillation (new physics) effects?

Physical observables in the lepton sector

$$m_e, m_\mu, m_\tau, m_1, m_2, m_3, \theta_{23}, \theta_{12}, \theta_{13}, \delta, \alpha, \beta$$

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

$$(0 \leq \theta_{12}, \theta_{23}, \theta_{13} \leq \pi/2, \quad 0 \leq \delta \leq 2\pi)$$

$$L \supset -m_{e_i} e_i^c e_i - \frac{g}{\sqrt{2}} U_{ij} \bar{e}_i \hat{W} P_L \nu_j - \frac{1}{2} m_i \nu_i \nu_i$$

$$\Delta m^2_{21}$$

$$|\Delta m^2_{32}|$$

$$\mathrm{sign}(\Delta m^2_{32})$$

$$\theta_{12}, \theta_{23}, \theta_{13}, \delta$$

$m_{e,\mu,\tau}$

m_{lightest}

α

β

$m_{e,\mu,\tau}$

Δm^2_{21}

$|\Delta m^2_{32}|$

$\mathrm{sign}(\Delta m^2_{32})$

$\theta_{12}, \theta_{23}, \theta_{13}, \delta$

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$\theta_{12}, \theta_{23}, \theta_{13}, \delta$

m_{lightest}

α

β

Hernandez

$\nu_\mu \to \nu_e$

T2K upgrade of K2K with a more intense beam and OA

NOνA upgrade of MINOS with a better detector and OA

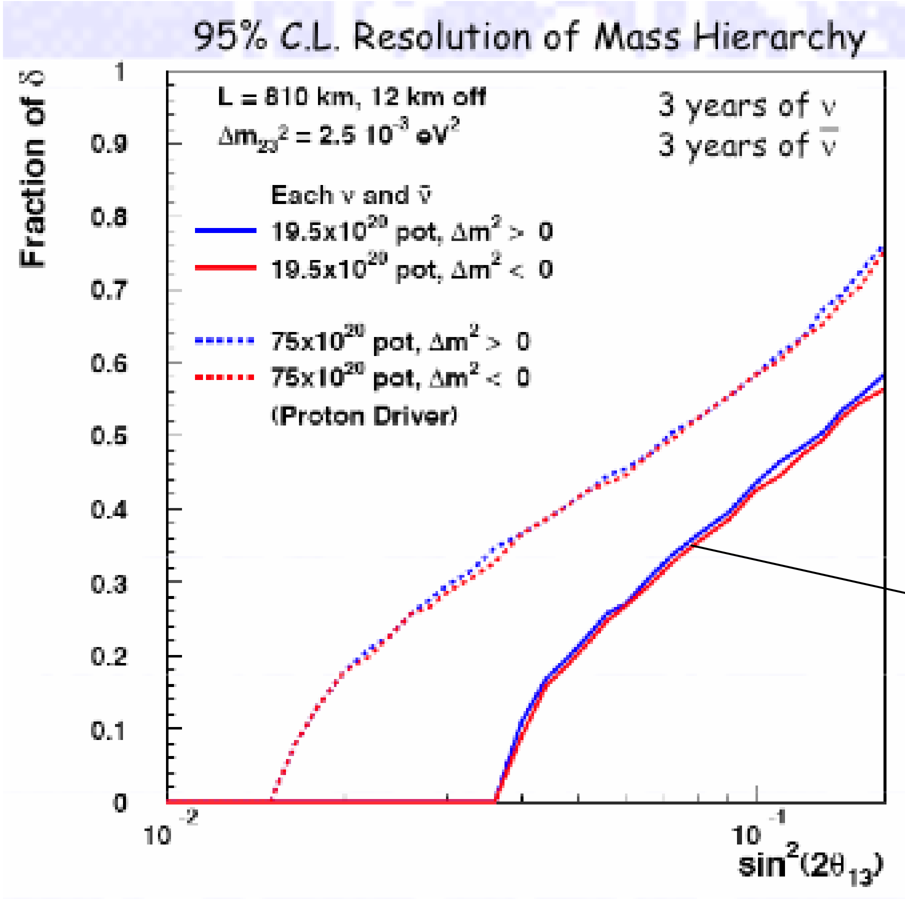
3σ CL

	L(km)	$\sin^2 2\theta_{13}$	δ	$\text{sign}(\Delta_{23})$	$\text{sign}(\cos 2\theta_{23})$
T2K-I (2008)	295	~0.01 0.02	-	-	-
NOνAI (2011)	810	0.003 0.02	-	some	-

Sensitivity to θ_{13} strongly depends on δ in both cases and also on $\text{sign}(\Delta_{23})$ in NOνA

Hernandez

Hierarchy at NOνA–I

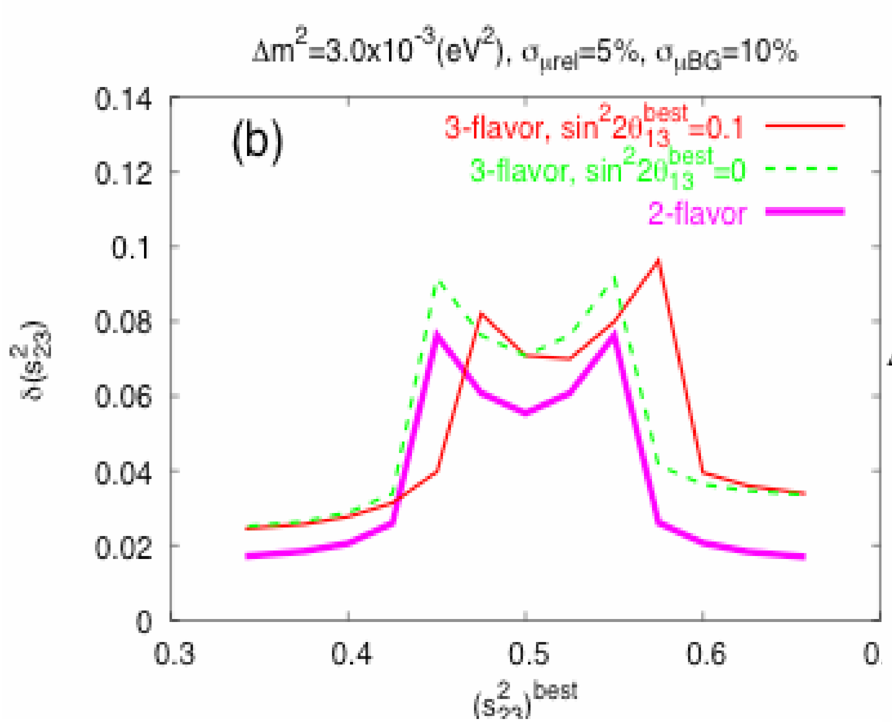


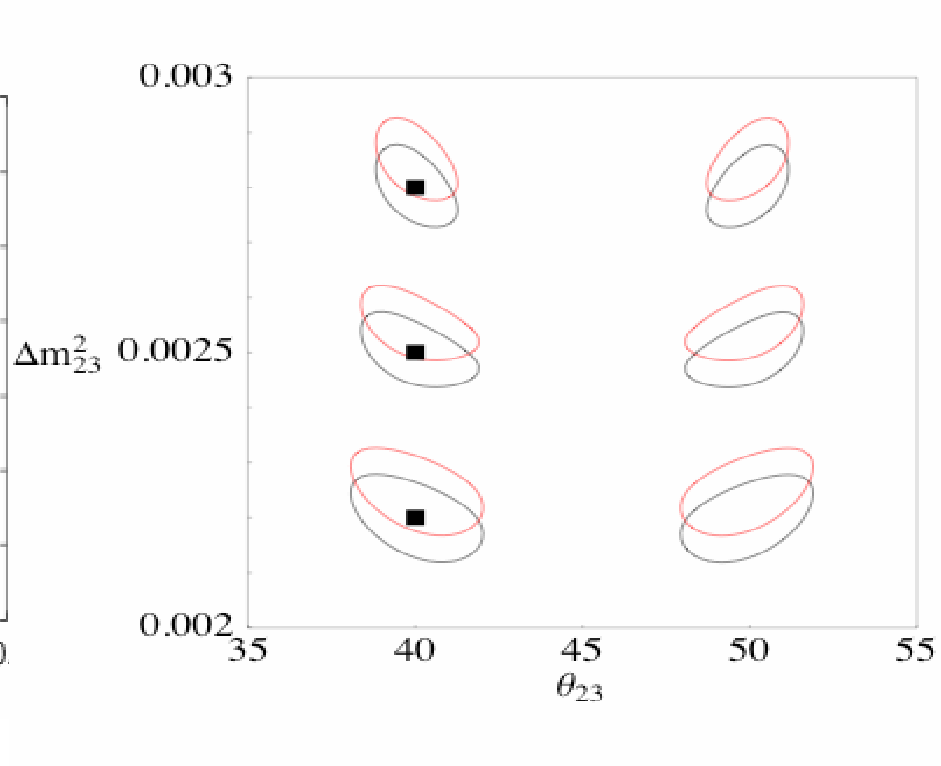
NOνA–I

Only for $\sin^2 2\theta_{13} > 0.04$ and some values of δ

Hernandez

Sensitivity to $\sin^2\theta_{23}$





Minakata,Sonoyama

Fernandez-Martinez et al

For $42^o < \theta_{23} < 50^o$ the error on s^2_{23} remains O(10-20%) which is not much better than the present error!

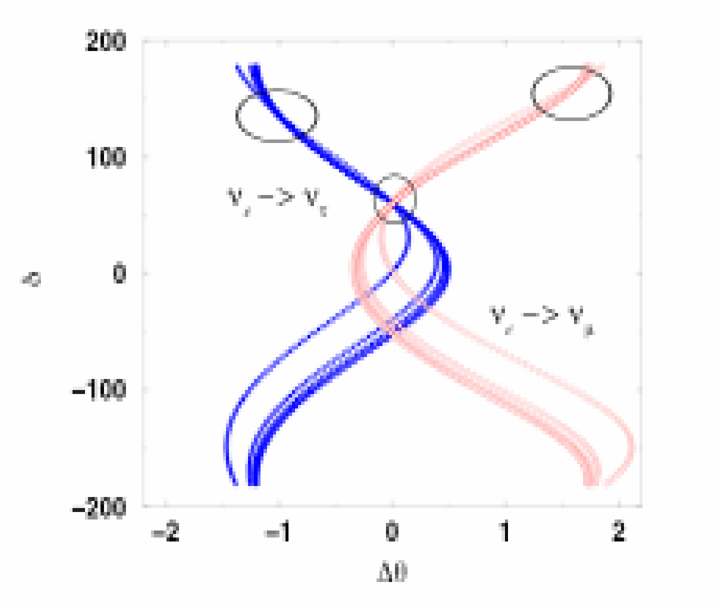
Hernandez

Ultimate anti-degeneracy machine

νFACT &40KTon iron calorimeter 2800km (Golden) $\nu_e \rightarrow \nu_\mu$

νFACT & 4Ton Emulsion 730km(Silver) $\nu_e \rightarrow \nu_\tau$

SPL&Megaton Cerenkov (Bronce) 130km $\nu_\mu \rightarrow \nu_e$

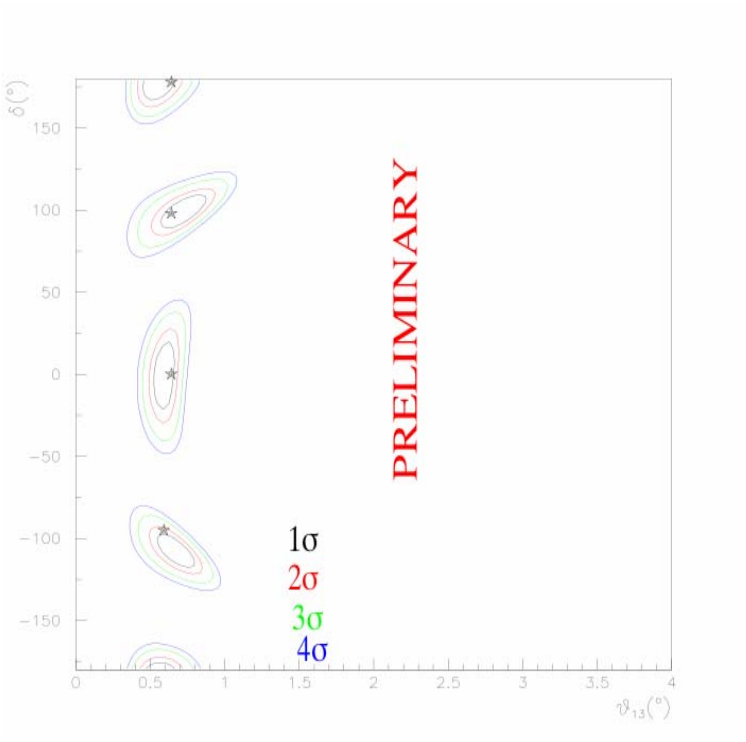


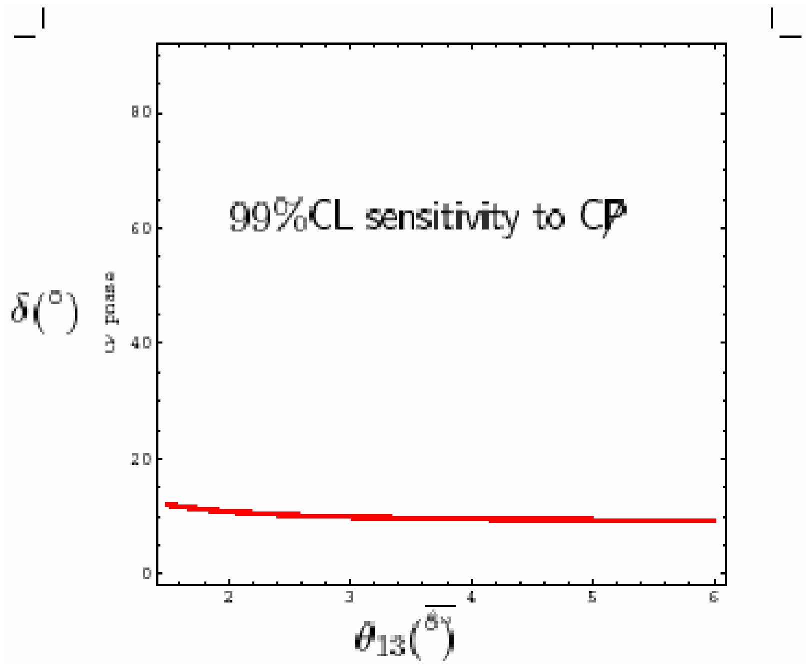
Donini, Meloni, Migliozzi

The intrinsic and the θ_{23} octant ambiguities are resolved (up to uncertainties) if the eμ and eτ are combined

Hernandez

θ_{13} sensitivity down to 0.3° !





Mena

Hierarchy and octant solved for $\theta_{13} > 1° – 2°$

Overconstraining: eμ,ee,eτ,μτ,μe,μμ for ν and $\bar{\nu}$!

Hernandez

The new era (discovery)

(roughly…depends on the actual value of the parameters)

	θ_{13}	δ	sign(Δ_{23})	θ_{23}
~2013	> 4º	marginal	θ_{13} > 6º (0%) θ_{13} >13º(50%)	40º-50º deg.
~202?	>0.3-0.6º	|δ|> 10º large θ_{13}	θ_{13} > 1º- 2º(100%)	

While T2K-I seems to be a rather optimal setup for the next generation superbeam, the "optimal" next-to-new generation experiment is still under investigation

- θ_{13}
- θ_{23}
- θ_{12}
- Normal vs Inverse hierarchy

as handles on the origin of masses and mixings

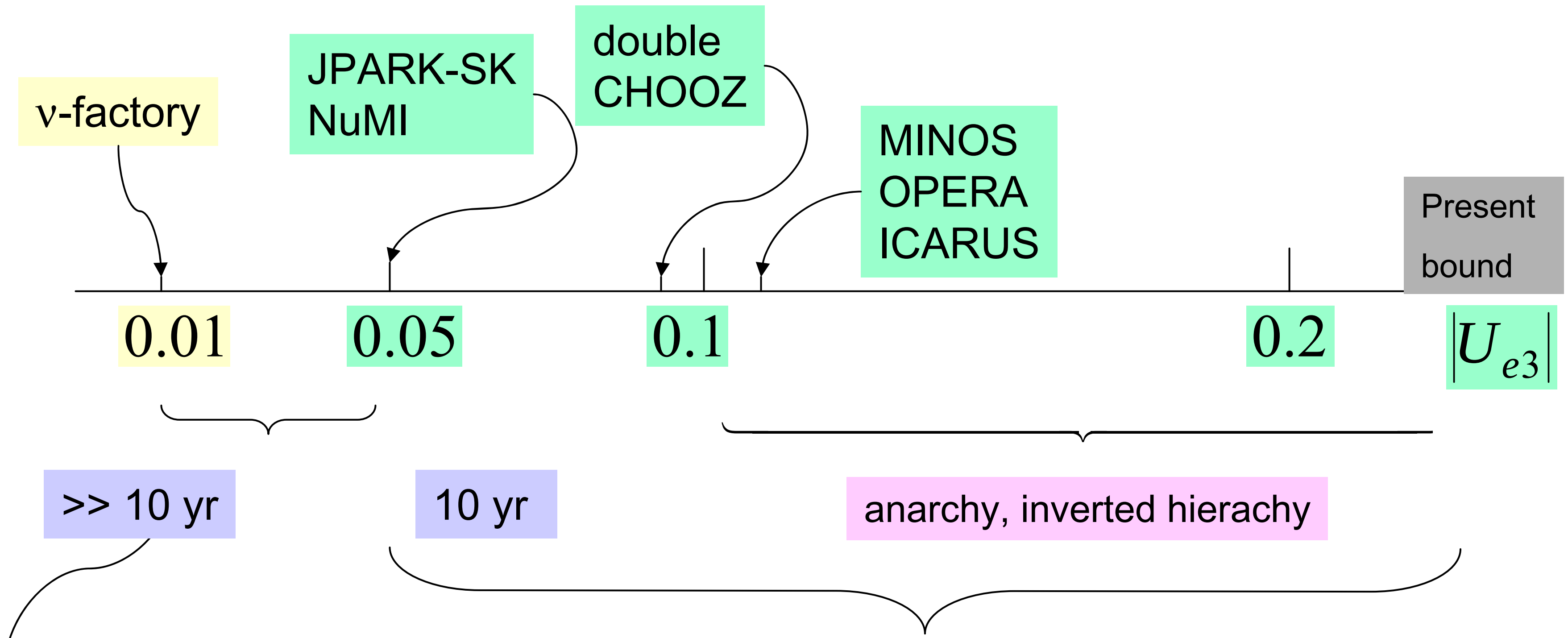
θ_{13}

- Phenomenology
  - Access leptonic CP-violation
  - Supernova signals
  - Subleading effects
- Origin of masses and mixing
  - (Discriminate models - too many)
  - **Size** of θ_{13}: "normal" models vs "special" models
  - Test models with **precise** predictions (if not too many)

in particular:

- Probe the origin of the solar and atmospheric angles
- The Neutrino mass pattern

- Most of plausible range for Ue3 explored in 10 yr from now



|Ue3|<0.05 would select a very narrow (not empty) subset of existing models

``normal models'': $\theta_{13} \gtrsim \sqrt{\frac{\Delta m^2_{SUN}}{\Delta m^2_{ATM}}}, \sqrt{\frac{m_e}{m_\mu}}$

similar conclusion by:

Barbieri, Hambye, Romanino 0302118
Ibarra, Ross 0307051
Chen, Mahanthappa 0305088
Lebed, Martin 0312219
Joshipura @ NOON 2004

Example of "normal" models (θ_{23} from nu's)

Normal hierarchy: $m_\nu \propto \begin{pmatrix} & \varepsilon & \varepsilon' \\ \varepsilon & B & A \\ \varepsilon' & A & 1 \end{pmatrix}$ θ_{23}^{ν} large : $A \sim B \sim 1$
$m_2 \ll m_3 : A^2 - B \ll 1$

We expect: $\theta_{13} \sim \frac{\tan\theta_{23}}{2} \sin 2\theta_{12} \left(\frac{\Delta m^2_{21}}{\Delta m^2_{32}} \right)^{1/2} > 0.07$

Inverse hierarchy: $m_\nu = \begin{pmatrix} & A & B \\ A & & \\ B & & \end{pmatrix} + \text{corrections}$ $\tan\theta_{23} = \frac{B}{A}$

We expect: $s_{13} \supset s^e_{12} s_{23} \sim \frac{45^\circ - \theta_{12}}{2} \sim \text{exp limit}$

A small θ_{13} presumably indicates that the atmospheric angle comes from the charged sector

Yet another contribution to θ_{13}

$$m_D = \ldots \begin{pmatrix} 0 & \varepsilon' & \\ \varepsilon' & \varepsilon & \\ & & 1 \end{pmatrix}$$ is successful: $\theta_c \approx \sqrt{\frac{m_d}{m_s}}$ (precise) [Gatto Sartori]

Implementing the same pattern in m_E (e.g. SU(5))

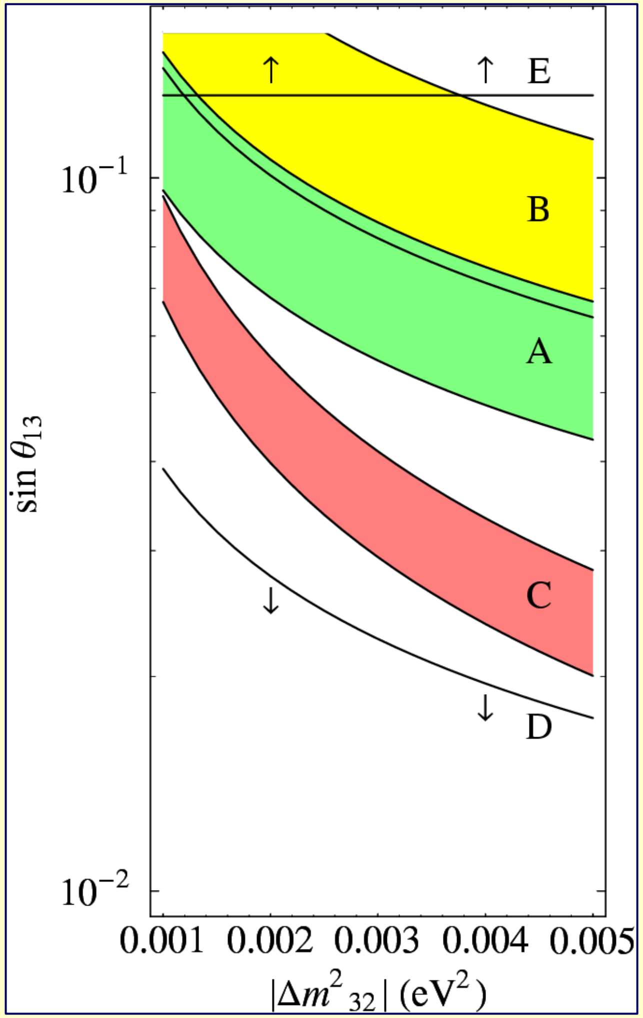
$$\theta_{12}^e \approx \sqrt{\frac{m_e}{m_\mu}} = \frac{1}{3}\sqrt{\frac{m_d}{m_s}} \approx \frac{\theta_c}{3}$$

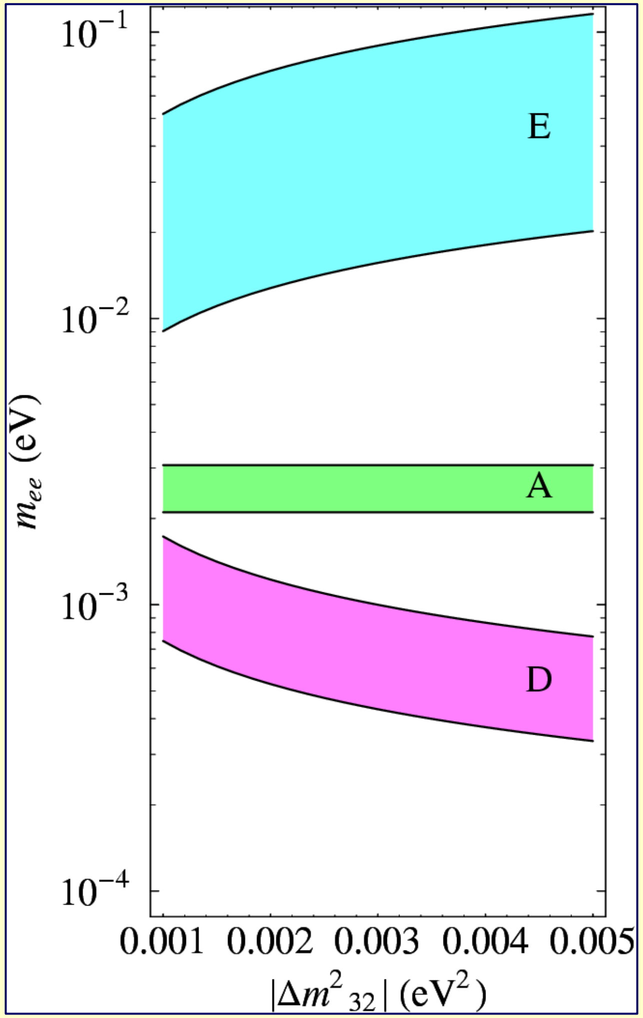
$$\theta_{13} \supset s_{23}\sqrt{\frac{m_e}{m_\mu}} \sim \frac{1}{3} \times \text{exp limit} \sim 3^o$$

Central value observable with suberbeams (but > O(1) uncertainty)

Predictive models

Barbieri, Hambye, AR





Is the atmospheric angle large or maximal?

- Large = O(π/4); maximal = π/4 ± correction << 1
- SK : $\sin^2 2\theta_{23} > 0.9$ not enough

$$\tan\theta_{23} = a/b \quad a \sim b \leftrightarrow \text{large } \theta_{23};\ a = b \leftrightarrow \text{maximal } \theta_{23}$$

$$1 - \varepsilon < a/b < 1 + \varepsilon \quad \sin^2 2\theta_{23} > 1 - \varepsilon^2$$

$$0.7 < a/b < 1.4 \quad \sin^2 2\theta_{23} > 0.9$$

$$0.9 < a/b < 1.1 \quad \sin^2 2\theta_{23} > 0.99$$

- Obtaining a maximal atm angle in a 3 neutrino context is non-trivial. A maximal angle would set a powerful constraint on the origin of lepton mixing (non-abelian horizontal symmetries?)

- Example: **inverse hierarchy**

$$m_\nu = \begin{pmatrix} & a & b \\ a & & \\ b & & \end{pmatrix} + \text{corrections} \quad \tan\theta_{23} = \frac{b}{a}$$

Is there a relation between θ_{12} and θ_C?

at present: large uncertainty for θ_{12}

Lepton mixings

Parameter	Best-fit value	3σ range
θ_{12}	33.2°	28.7° .. 38.1°
θ_{23}	45.0°	35.7° .. 55.6°
θ_{13}	2.6°	0° .. 12.5°

Quark mixings

Parameter	Best-fit value	2σ range
θ^q_{12}	12.88°	12.75° .. 13.01°
θ^q_{23}	0.21°	0.17° .. 0.25°
θ^q_{13}	2.36°	2.25° .. 2.48°

Is there a relation $\theta_{12} + \theta_C = 45^\circ$ hidden behind the large uncertainties?

'Quark-lepton complementarity'

Recent papers: Raidal ('04), Smirnov, Minakata ('04), Mohapatra, Frampton ('04), Ferrandis, Pakvasa ('04), ...

- Future: few % accuracy for $\sin^2\theta_{12}$ possible, e.g. from reactor experiments; could test of 'quark-lepton complementarity' to high precision

  see e.g.: Minakata *et al*, hep-ph/0407326

- If 'confirmed' (not accidental):
  - Relation between quark and lepton mixing angles would point towards unification
  - Challenging for model building. However, we could learn a great deal ... (predictions at M_U modified by RG running!)

Challenges for Quark-Lepton Complementarity

- Approach: $\theta^{\nu}_{12} = \pi/4$ from the neutrino sector, deviation induced by θ^{e}_{12} related to θ_C
- Using a Georgi Jarlskog (Clebsch) factor of -3 for $(Y_e)_{22}$: no QLC predicted

$\theta^d_{12} = \lambda = \theta_C$

Note: same operators lead to entries in Y_e and Y_d!

Assume: $\theta^{\nu}_{12} = \pi/4$ (and large θ^{ν}_{23}), e.g. with inverted neutrino mass hierarchy:

$$Y_\mathrm{d} \sim \begin{pmatrix} 0 & 1\lambda^4 & \lambda^4 \\ * & 1\lambda^3 & \lambda^2 \\ * & * & 1 \end{pmatrix}, \quad Y_\mathrm{e} \sim \begin{pmatrix} 0 & \lambda^4 & \lambda^4 \\ * & -3\,\lambda^3 & \lambda^2 \\ * & * & 1 \end{pmatrix}, \quad m_\mathrm{LL} \sim \begin{pmatrix} 0 & m & m' \\ m & 0 & 0 \\ m' & 0 & 0 \end{pmatrix}$$

$\theta^e_{12} = 1/3\,\lambda = 1/3\,\theta_C$

- In addition: one has to 'shift' R^e_{12} to the right $\Delta\theta_{12} \Rightarrow$ additional factor $1/\sqrt{2}$

$$U_\mathrm{MNS} \approx R^{e\dagger}_{12} R^{\nu}_{23} U^{\nu}_{13} R^{\nu}_{12} P^{\nu}_0 \quad \Rightarrow \quad s_{12} \approx \frac{1}{\sqrt{2}} - \frac{1}{2}\theta^e_{12} \quad \rightarrow \quad \theta_{12} \approx \frac{\pi}{4} - \frac{1}{\sqrt{2}}\theta^e_{12}$$

$$\theta_{12} \approx \frac{\pi}{4} - \frac{1}{\sqrt{2}}\frac{1}{3}\theta_\mathrm{C} \Rightarrow \Delta\theta_{12} = \frac{1}{\sqrt{2}}\frac{1}{3}\theta_\mathrm{C} \approx 3^\circ$$

Too small for explaining observed deviation from $\theta_{12} = \pi/4$

- in particular: no QLC!

$$U_{PMNS} = \begin{pmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix} + O(\frac{\text{VEV}}{\Lambda})^2$$

[Harrison, Perkins, Scott 2002]

$$\vartheta_{13} \approx O\left(\frac{\text{VEV}}{\Lambda}\right)^2$$

$$\vartheta_{23} \approx \frac{\pi}{4} + O\left(\frac{\text{VEV}}{\Lambda}\right)^2$$

$$\tan^2 \vartheta_{12} = 0.5 + O\left(\frac{\text{VEV}}{\Lambda}\right)^2$$

$$\tan^2 \vartheta_{12} = 0.45 \pm 0.05 \text{ [exp]}$$

$\frac{\text{VEV}}{\Lambda} \approx \lambda$ expected

Another example of precise prediction for θ_{12}

ν spectrum is between normal and degenerate

$m_1 \approx a + d$ $m_2 \approx a$ $m_3 \approx -a + d$ [units $\frac{v_u^2}{\Lambda}$]

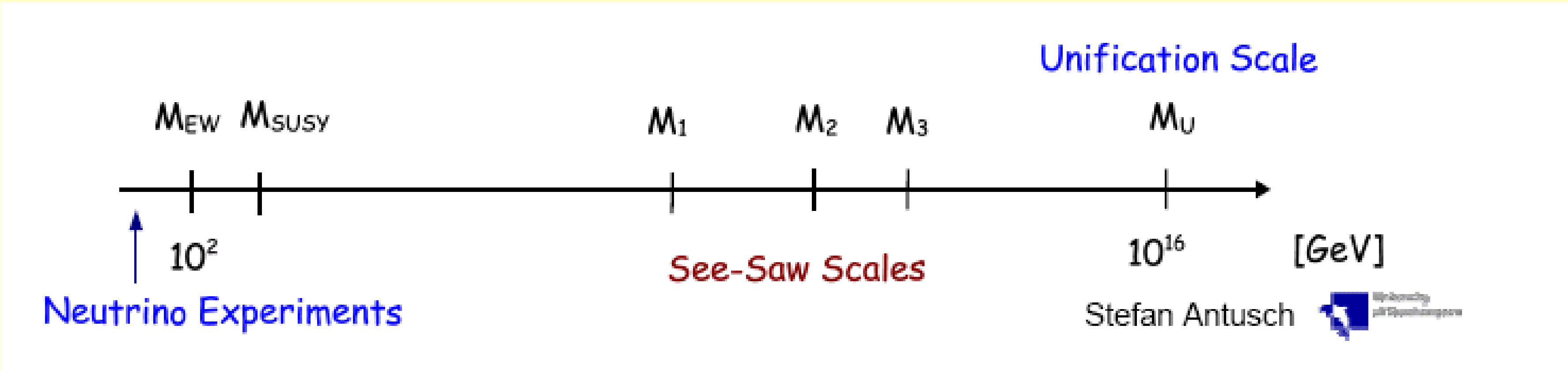
$d \approx -2a$ to reproduce $\frac{\Delta m^2_{sol}}{\Delta m^2_{atm}} \approx \frac{1}{35}$

prediction:

$$|m_3|^2 = |m_{ee}|^2 + \frac{10}{9} \Delta m^2_{atm} \left(1 - \frac{\Delta m^2_{sol}}{\Delta m^2_{atm}}\right)$$

Caveat: RGE running corrections

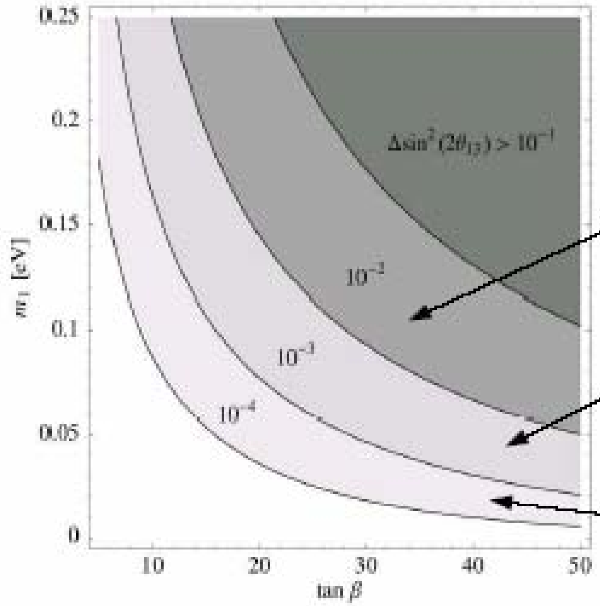
Intrinsic limitation on the use of precise data as an handle on the origin of masses and mixings: the theoretical uncertainty on the connection with high energy



RG Corrections to θ_{13} = 0 @ High Energy

Graphical illustration of RG corrections ($\Delta\sin^2(2\theta_{13})$)

(running of dim. 5 operator between $\Lambda = 10^{12}$ GeV and M_{EW} in the MSSM)



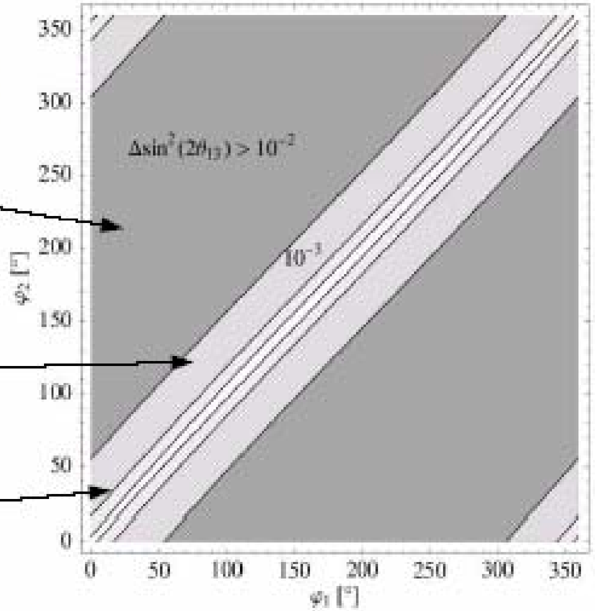
($\varphi_1 - \varphi_2$ = 180°, δ = 0, normal scheme)

Expected sensitivities:

Reactor and superbeam exp.

Superbeam exp. (upgrade)

Neutrino factory



($\tan\beta$ = 50, m_1= 0.08eV, δ = 0)

Even for θ_{13} = 0 @ high energy, RG running $\Rightarrow$ in general non-zero θ_{13} @ low energy

S.A., J. Kersten, M. Lindner, M. Ratz (hep-ph/0305273)

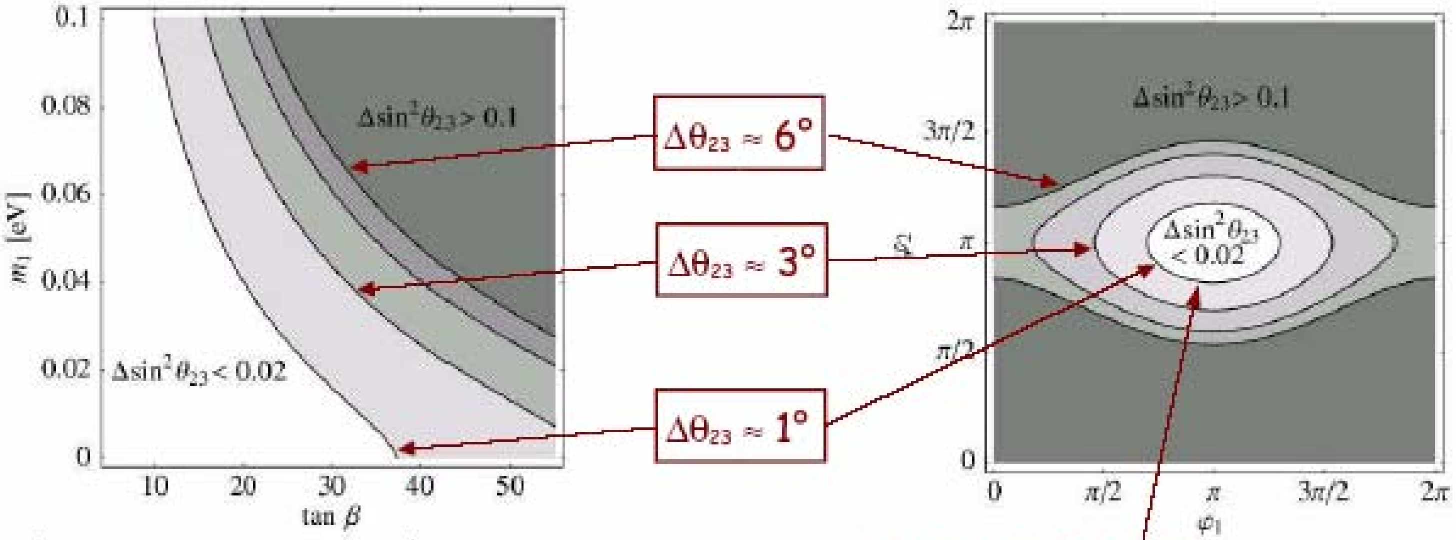
RG Corrections to Maximal Mixing $\theta_{23} = 45°$

Analytical Approximation (below see-saw scales): $\Delta\theta_{23} = \dot{\theta}_{23} \ln(\Lambda/M_{EW})$

$$\dot{\theta}_{23} \approx -\frac{y_\tau^2}{32\pi^2} \sin 2\theta_{23} \frac{1}{\Delta m^2_{\rm atm}} \left[c_{12}^2 \left| m_2 e^{i\varphi_2} + m_3 \right|^2 + s_{12}^2 \left| m_1 e^{i\varphi_1} + m_3 \right|^2 \right] + \mathcal{O}(\theta_{13})$$

Note: $\Delta\theta_{23} > (<) \; 0$ for $\Delta m^2_{atm} < (>) \; 0$

Example: Conservative estimate (ignore Y_ν contributions) of RG corrections (MSSM)



(MSSM, $\varphi_1 = \varphi_2 = 0$, $\theta_{13} = 0$)

Majorana CP phases ($m_1 = 0.075$ eV)
(can damp RG effects, but $\Delta\theta_{23}$ always $\neq 0$!)

S.A., J. Kersten, M. Lindner, M. Ratz (hep-ph/0305273)
S.A., M. Huber, J. Kersten, T. Schwetz, W. Winter (hep-ph/0404268)

The uncertainties on the running can significantly affect t12 only if it originates from an unstable pattern

$$\begin{pmatrix} 1+\varepsilon & \varepsilon \\ \varepsilon & 1+\varepsilon \end{pmatrix}$$

Unstable (angles depend on the epsilons)

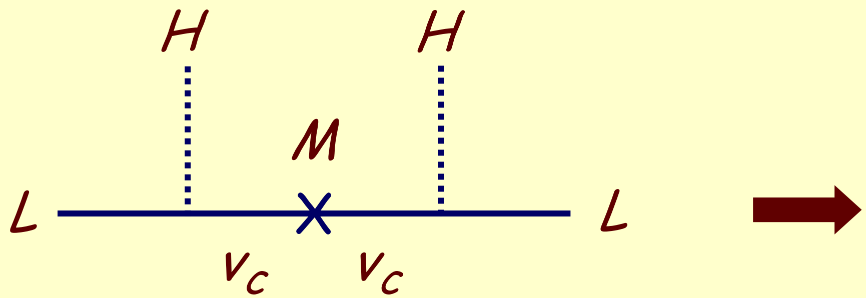
$$\begin{pmatrix} \varepsilon & 1+\varepsilon \\ 1+\varepsilon & \varepsilon \end{pmatrix}$$

Stable (angles do not depend on the epsilons)

Probing the origin of neutrino masses

$$\mathcal{L}_{SM}^{eff} = \mathcal{L}_{SM}^{ren} + \frac{h_{ij}}{\Lambda}(H L_i)(H L_j) + \ldots$$

Does $\frac{h_{ij}}{\Lambda}(H L_i)(H L_j)$ originate from the see-saw mechanism?



$$\frac{h}{\Lambda} \to -\lambda^T \frac{1}{M} \lambda$$

$$m_\nu = -m_D^T \frac{1}{M} m_D$$

To believe seesaw

(Sufficient conditions but not necessary)

- LHC finds SUSY, LC establishes SUSY
- no more particles beyond the MSSM at TeV scale
- Gaugino masses unify (two more coincidences)
- Scalar masses unify for 1st, 2nd generations (two for 10, one for 5*, times two)
- Scalar masses unify for the 3rd generation 10 (two more coincidences)

⇒ strong hint that there are no additional particles beyond the MSSM below M_{GUT} except for gauge singlets.

To believe seesaw (cont.)

(Sufficient conditions but not necessary)

- $0\nu\beta\beta$ seen, neutrinos are Majorana
- LBL oscillation finds θ_{13} soon just below the CHOOZ limit
- determines the normal hierarchy and finds CP violation
- Scalar masses unify for the 3rd generation 5* up to the neutrino Yukawa coupling y_3~1 above $M_3=y_3^2v^2/m_3$

⇒ neutrino parameters consistent with leptogenesis

...

Probing the origin of neutrino masses

$$\mathcal{L}_{SM}^{eff} = \mathcal{L}_{SM}^{ren} + \frac{h_{ij}}{\Lambda}(H L_i)(H L_j) + \ldots$$

Is $\frac{h_{ij}}{\Lambda}(H L_i)(H L_j)$ really the origin of neutrino masses?

$$\Lambda \gg \langle H \rangle ?$$

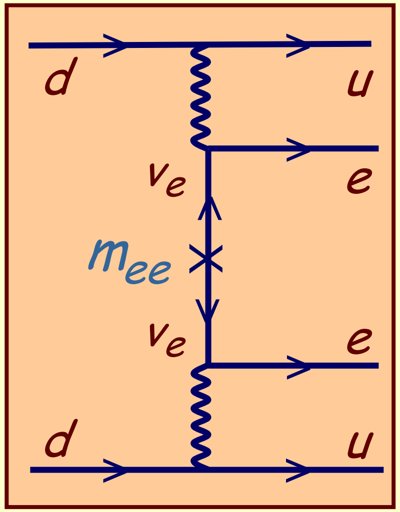
Probe the Majorana nature of neutrinos

$0\nu 2\beta$ decay

$$(A,Z) \to (A,Z+2) + 2e^-; \quad \text{e.g.}: {}^{76}G \to {}^{76}Se + 2e^-$$

$$\Gamma \propto |m_{ee}|^2 \langle Q \rangle^2$$

$$m_{ee} = U_{eh}^2 m_h = c_{13}^2 (m_1 c_{12}^2 + m_2 s_{12}^2 e^{2i\alpha}) + m_3 s_{13}^2 e^{2i\beta}$$



Present Limits :

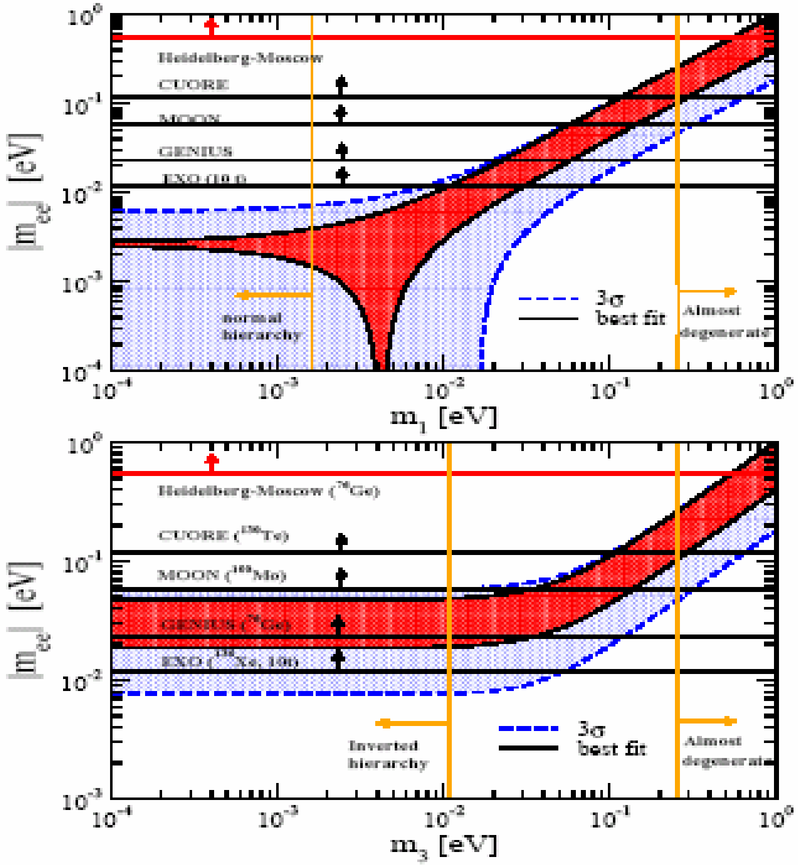
Candidate nucleus	Detector type	(kg yr)	Present $T_{1/2}^{0\nu\beta\beta}$ (yr)	<m> (eV)
^{48}Ca			$>9.5*10^{21}$ (76%CL)	
^{76}Ge	Ge diode	~30	$>1.9*10^{25}$ (90%CL)	$<0.39^{+0.17}_{-0.28}$
^{82}Se			$>9.5*10^{21}$ (90%CL)	
^{100}Mo			$>5.5*10^{22}$ (90%CL)	
^{116}Cd			$>7.0*10^{22}$ (90%CL)	
^{128}Te	TeO_2 cryo	~3	$>1.1*10^{23}$ (90%CL)	
^{130}Te	TeO_2 cryo	~3	$>2.1*10^{23}$ (90%CL)	<1.1 - 2.6
^{136}Xe	Xe scint	~10	$>1.2*10^{24}$ (90%CL)	<2.9
^{150}Nd			$>1.2*10^{21}$ (90%CL)	
^{160}Gd			$>1.3*10^{21}$ (90%CL)	

Peña-Garay

Projected/proposed

Experiment	Nucleus	Detector	$T^{0\nu}$ (y)	$\langle m_\nu \rangle$ eV
CUORE	^{130}Te	.77 t of TeO_2 bolometers (nat)	7×10^{26}	.014-.091
EXO	^{136}Xe	10 t Xe TPC + Ba tagging	1×10^{28}	.013-.037
Gertha	^{76}Ge	1 t Ge diodes in LN	1×10^{28}	.013-.050
Majorana	^{76}Ge	1 t Ge diodes	4×10^{27}	.021-.070
MOON	^{100}Mo	34 t nat.Mo sheets/plastic sc.	1×10^{27}	.014-.057
DCBA	^{150}Nd	20 kg Nd-tracking	2×10^{25}	.035-.055
CAMEO	^{116}Cd	1 t $CdWO_4$ in liquid scintillator	$> 10^{26}$	.053-.24
COBRA	^{116}Cd, ^{130}Te	10 kg of CdTe semiconductors	1×10^{24}	.5-2.
Candles	^{48}Ca	Tons of CaF_2 in liq. scint.	1×10^{26}	.15-.26
GSO	^{116}Cd	2 t Gd_2SiO_5:Ce scint in liq scint	2×10^{26}	.038-.172
Xmass	^{136}Xe	1 t of liquid Xe	3×10^{26}	.086-.252

$\beta\beta_{0\nu}$ decay sensitivities cf tritium & cosmo



Klapdor, Paes, Smirnov, ... Bilenky, Faessler, Simkovic hep-ph/0402250

can not yet reconstruct majorana phases Barger, Glashow, Langacker, Marfatia, PLB540 (2002) 247

Alternative origin of small neutrino masses

- If $\Lambda \gg \langle H \rangle$ is not the reason of the smallness of neutrino masses $\Rightarrow$ small couplings
- Example: Dirac neutrinos

$$\lambda\, \nu_c L H \to m_\nu = \lambda v \qquad \text{(as for the other fermions)}$$

need $\lambda < 10^{-11}$ **and** $M_R \ll \langle H \rangle$

- Why? *L* conserved +
  - $\lambda\, \nu_c L H$ forbidden by a symmetry (e.g. because it has charge *n* under some U(1) symmetry)

$$\lambda\, \nu_c L H \to \lambda \left(\frac{\phi}{\Lambda}\right)^n \nu_c L H \quad Q_\phi = -1 \quad \longrightarrow \quad \lambda_{eff} = \lambda \left(\frac{\langle \phi \rangle}{\Lambda}\right)^n$$

Late neutrino mass

- Seesaw formula: $m_\nu = v^2/\Lambda << v$ because $v << \Lambda$
- Another way to get small mass with O(1) coupling:

  $m_\nu = v(<\phi>/\Lambda)^n$ (Dirac)

  $m_\nu = v^2(<\phi>^n/\Lambda^{n+1})$ (Majorana)

  Even if Λ ~TeV, $<\phi> << v$ works.
- "Late" neutrino mass because $<\phi> << v$ implies a late time phase transition
- *e.g.*, $n=2$, Λ ~TeV $\Rightarrow$ $<\phi>$~MeV

Viable

- Remarkably, phenomenological constraint weak despite the low scale
- For m_ϕ>1MeV, $\phi \to \nu\nu$ above BBN, OK
- SN1987A limit OK because ϕ couples with strength $\propto m_\nu$
- If gauged, the domain walls are becoming important only now, possible imprint on CMB anisotropy

(Checko, Hall, Okui, Oliver)

(Davoudiasl, Kitano, Kribs, HM)

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(Alternative origin of small neutrino masses, continues)

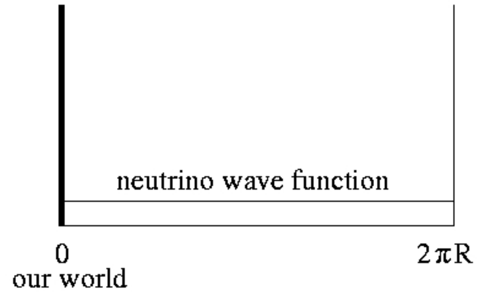
ξ_i are small due to geometry

$\Lambda_F \equiv$ scale of flavour physics [unknown at present]

$E \approx \Lambda_F$ a four-dimensional description of particle interactions might break down

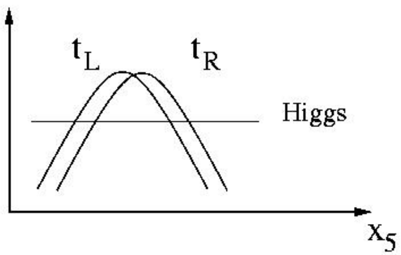
- Large Extra Dimensions $\quad \dfrac{y_{\nu_e}}{y_e} \approx \dfrac{1}{\sqrt{2\pi R\Lambda}} << 1 \quad \text{if} \;\; R >> \dfrac{1}{\Lambda}$

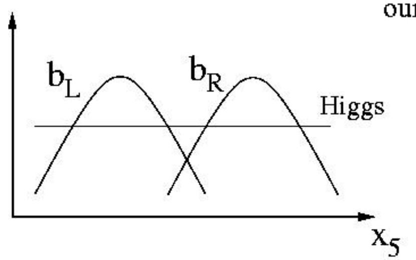
flat zero mode for ν^c



extra dimension could be tiny

- localized fermion zero modes





- Yukawa coupling in string theory

matter as twisted states in orbifold compactification of heterotic string

matter from intersecting D branes in type IIA strings

$$y_{ij} = e^{-A_{ij}}$$

Ibanez; Hamidi, Vafa; Dixon, Friedan, Martinec, Shenker; Casas, Munoz; Cremades, Ibanez, Marchesano; Abel, Owen

-- it could provide an explanation to $N_g = 3$

-- relation to flavour symmetries possible but not straightforward

-- connection with data unclear, worth to explore

Alternative origin of small neutrino masses

- If $\Lambda \gg \langle H \rangle$ is not the reason of the smallness of neutrino masses $\Rightarrow$ small couplings
- Example: Dirac neutrinos

$$\lambda \, \nu_c L H \to m_\nu = \lambda v$$ (as for the other fermions)

need $\lambda < 10^{-11}$ and $M_R \ll \langle H \rangle$

- Example: additional light sterile neutrinos
  - Also not protected by the electroweak symmetry
  - LSND?
  - A small mixing (independent of LSND) can be probed at a nufact

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- 3 active neutrinos $N = 2.984 \pm 0.009$ $(m_t, m_H) = (174.3, 115)$ GeV
  (invisible Z width)

- all experiments but LSND explained by 3 ν_a
  LSND $\rightarrow$ 3 ν_a + [at least] 1 ν_s

- inclusion of ν_s worsens the fits
  - solar: $\nu_e \rightarrow \sin\vartheta_s \, \nu_s + \dots$ $\sin^2\vartheta_s < 0.1 \quad (1\sigma)$ [Bahcall&Pena-Garay 2003]
  - atm: $\nu_\mu \rightarrow \nu_\tau$ favoured over $\nu_\mu \rightarrow \nu_s$
    - zenith angle dependence of high-energy ν_μ [SK,MACRO] 3σ
      (no matter effects for ν_s)
    - no NC interactions for ν_s [SK]
    - τ-like CC events [SK] 2σ
  - 2+2 and 3+1 fits have a poor quality [Cirelli,Marandella,Strumia,Vissani 2004]

- WMAP + LSS $\sum m_\nu < 1.4\,\text{eV}\ (95\%\,\text{CL}) \quad \text{for}\ 3\nu_a + 1\nu_s$

  [Hannestad&Raffelt 2004
  Crotty, Lesgourgues, Pastor 2004]

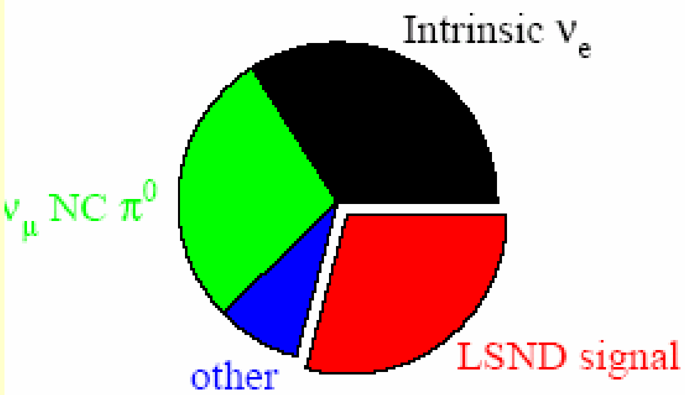
- LSND soon checked by MiniBooNE (1st event September 2002)
  no room for LSND with 3 ν_a (CPT violation disfavoured by now)
  [Pakvasa&Valle 0301061, Barenboim, Borissov, Lykken 0212116]

MiniBooNE $\nu_\mu \to \nu_e$ Search

- **Goal:** Confirm or refute in a **definitive** and **independent** way the LSND evidence for $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations

- **Challenge:** $\langle P(\bar{\nu}_\mu \to \bar{\nu}_e)\rangle_{\text{LSND}} = (0.264 \pm 0.067 \pm 0.045)\%$, a small number!!

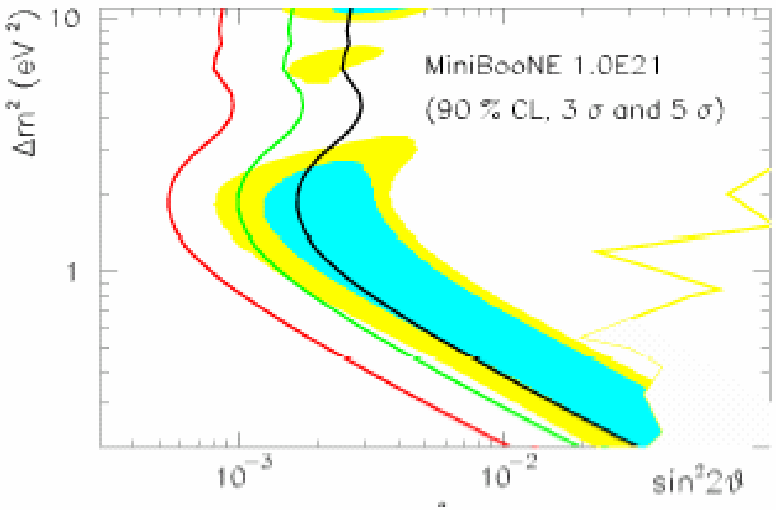
- **Signal and backgrounds:**
  Expectations for 10^{21} protons on target (currently: $N_{\text{pot}} = 5.5 \cdot 10^{20}$, $dN_{\text{pot}}/dt = 0.08 \cdot 10^{20}$/week)

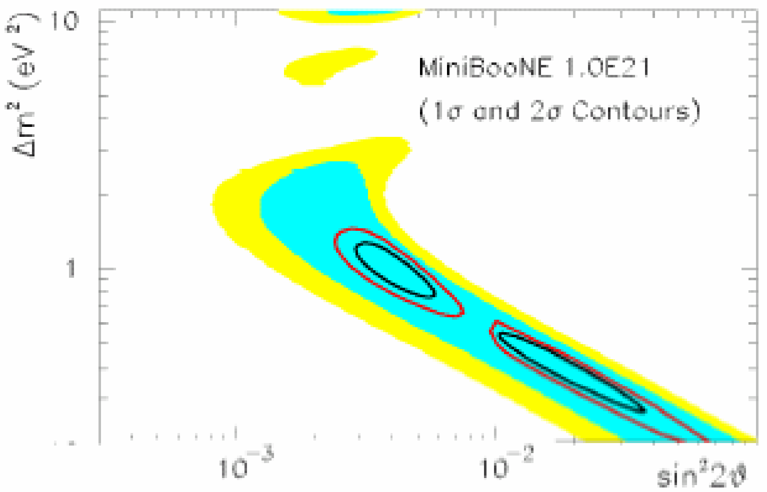


- $\simeq$300 signal events (if LSND is correct)
- $\simeq$700 background events
- Intrinsic ν_e component in the beam and ν_μ NC π^0 production are main backgrounds
- Signal and backgrounds have different energy distributions

Oscillation Sensitivity: Null and Positive Scenarios

- Fit energy distribution to extract signal. Estimates based on 10^{21} pot





Null MiniBooNE result:

- 4σ sensitivity to entire LSND 90% CL allowed region
- Combined analysis of MiniBooNE + LSND would show incompatibility at 99% CL, in CP and CPT-conserving scenarios

MiniBooNE confirms LSND:

- Should see $> 5\sigma$ excess at LSND central value
- Distinguish $1\,\mathrm{eV}^2$ from $0.4\,\mathrm{eV}^2$ at 2σ

New physics effects?

$$\mathcal{L}_{SM}^{eff} = \mathcal{L}_{SM}^{ren} + \frac{h_{ij}}{\Lambda}(H L_i)(H L_j) + \ldots$$

Can we see additional effects independent of oscillations and neutrino masses?

New physics in neutrino oscillations

- Solar

  Wolfenstein, Valle, Fukugita Yanagida, Roulet, Guzzo Masiero Petcov, Barger Phillips Whisnant, Degl'Innocenti Ricci, Fogli Lisi, Krastev Bahcall, Bergmann, Bergmann, Berezhiani, Raghavan, Rossi

- Atmospheric

  Ma Roy, Brooijmans, Gonzalez-Garcia et al, Lipari Lusignoli, Fornengo et al, Bergmann Grossman Pierce

- LSND

  Bergmann Grossman

- Supernovae

  Mansour Kuo, Bergmann Kagan, Fogli et al

- Accelerators
  - production, detection

    Bueno et al, Bigi et al, Formaggio et al, Datta et al, Gonzalez-Garcia et al, Ota Sato Yamashita
  - propagation in matter

    Ota Sato Yamashita, Gago, Huber Valle, Huber Schwetz Valle

  gives rise to an unmistakable signal at high energy

  Campanelli AR

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Enhancement of NP effects at high energy

$$\nu_\alpha f \to \nu_\beta f \Rightarrow V_{\alpha\beta} = \varepsilon_{\alpha\beta} V_{\rm MSW} \quad (f = u, d, e)$$

$$M^2_{\rm eff} = \Delta m^2_{32} \begin{pmatrix} s^2_{13} + (E/E_{\rm res})(1+\varepsilon_{ee}) & s_{13}/\sqrt{2} + (E/E_{\rm res})\,\varepsilon_{e\mu} & s_{13}/\sqrt{2} + (E/E_{\rm res})\,\varepsilon_{e\tau} \\ s_{13}/\sqrt{2} + (E/E_{\rm res})\,\varepsilon_{\mu e} & 1/2 + (E/E_{\rm res})\,\varepsilon_{\mu\mu} & 1/2 + (E/E_{\rm res})\,\varepsilon_{\mu\tau} \\ s_{13}/\sqrt{2} + (E/E_{\rm res})\,\varepsilon_{\tau e} & 1/2 + (E/E_{\rm res})\,\varepsilon_{\tau\mu} & 1/2 + (E/E_{\rm res})\,\varepsilon_{\tau\tau} \end{pmatrix}$$

$$E_{\rm res} \approx 8\,{\rm GeV} \left(\frac{\Delta m^2_{31}}{2\times 10^{-3}\,{\rm eV}^2}\right)\left(\frac{1.65\,{\rm g/cm^3}}{\rho Y_e}\right), \quad \Delta m^2_{21} = 0, \quad \theta_{23} = \frac{\pi}{4}$$

The MSW term and the new effects are enhanced at large $E/E_{\rm res}$

if $\varepsilon_{\alpha\beta} = 0$: $\theta_{\alpha\beta} \to 1/E$ $\quad P_{\alpha\beta} \to 1/E^2$ $\quad$ at $E \gg E_{\rm res}$

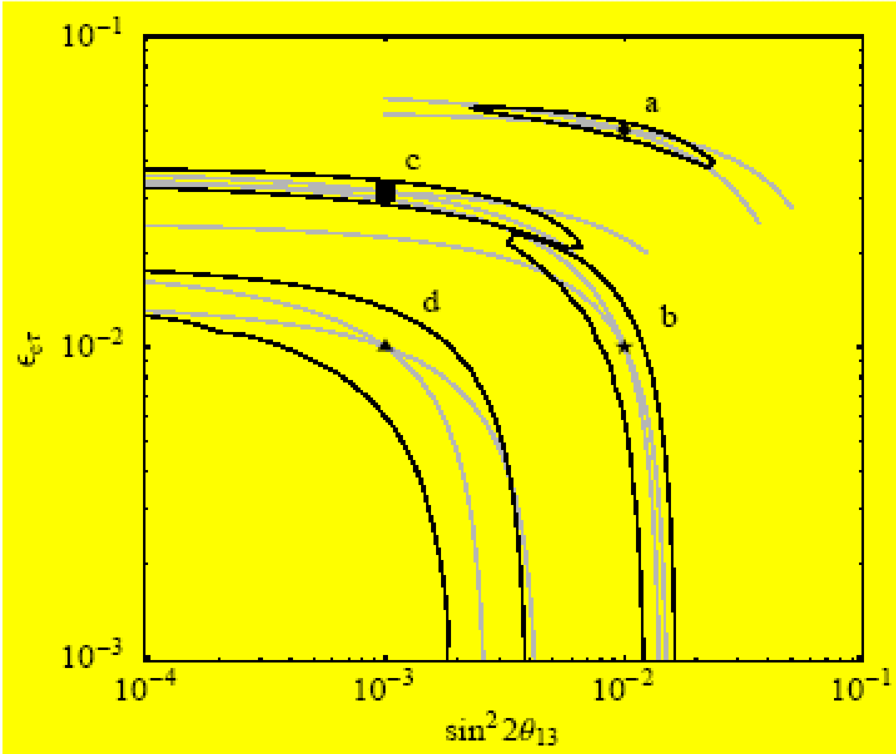
if $\varepsilon_{\alpha\beta} \neq 0$: $\theta_{\alpha\beta} \to {\rm const}$ $\quad P_{\alpha\beta} \to 4\varepsilon^2_{\alpha\beta}\sin^2(LV/2)$ $\quad$ at $E \gg E_{\rm res}$

FCI-oscillation confusion theorem

•

a neutrino factory is less sensitive to θ_{13} because non-standard neutrino interactions are confused with oscillations

Huber et al, PRL88 (2002) 101804



near-site programme essential

2×10^{20} mu/yr/polarity $\times$ 5 yr, 40 kt magn iron calorim, 10% muon E-resoln above 4 GeV

However: enhancement of NP effects at high energy

$$\nu_\alpha f \to \nu_\beta f \Rightarrow V_{\alpha\beta} = \varepsilon_{\alpha\beta} V_{\mathrm{MSW}} \quad (f = u, d, e)$$

$$M^2_{\mathrm{eff}} = \Delta m^2_{32} \begin{pmatrix} s^2_{13} + (E/E_{\mathrm{res}})(1+\varepsilon_{ee}) & s_{13}/\sqrt{2} + (E/E_{\mathrm{res}})\,\varepsilon_{e\mu} & s_{13}/\sqrt{2} + (E/E_{\mathrm{res}})\,\varepsilon_{e\tau} \\ s_{13}/\sqrt{2} + (E/E_{\mathrm{res}})\,\varepsilon_{\mu e} & 1/2 + (E/E_{\mathrm{res}})\,\varepsilon_{\mu\mu} & 1/2 + (E/E_{\mathrm{res}})\,\varepsilon_{\mu\tau} \\ s_{13}/\sqrt{2} + (E/E_{\mathrm{res}})\,\varepsilon_{\tau e} & 1/2 + (E/E_{\mathrm{res}})\,\varepsilon_{\tau\mu} & 1/2 + (E/E_{\mathrm{res}})\,\varepsilon_{\tau\tau} \end{pmatrix}$$

$$E_{\mathrm{res}} \approx 8\,\mathrm{GeV}\left(\frac{\Delta m^2_{31}}{2\times 10^{-3}\,\mathrm{eV}^2}\right)\left(\frac{1.65\,\mathrm{g/cm}^3}{\rho Y_e}\right), \quad \Delta m^2_{21} = 0, \quad \theta_{23} = \frac{\pi}{4}$$

$$\varepsilon_{e\tau} < 0.1; \text{ dominates for } E > E_{\mathrm{NP}} \equiv \frac{s_{13}}{\sqrt{2}\varepsilon_{e\tau}} E_{\mathrm{res}}$$

The MSW term and the new effects are enhanced at large E/E_{res}

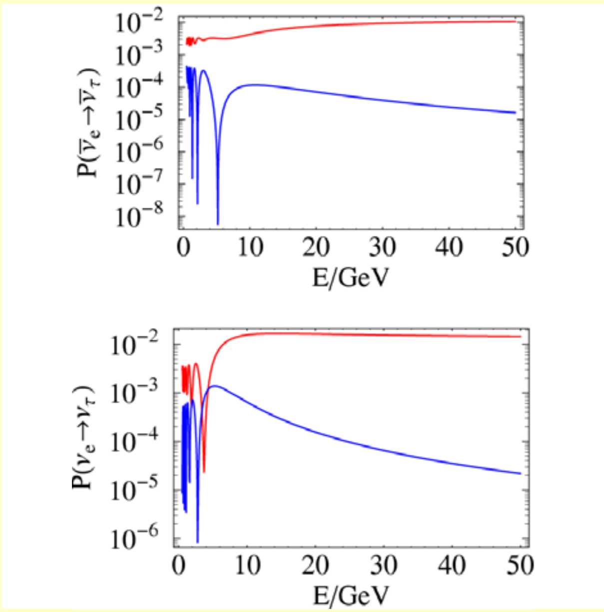
$$\text{if } \varepsilon_{\alpha\beta} = 0: \quad \theta_{\alpha\beta} \to 1/E \quad P_{\alpha\beta} \to 1/E^2 \quad \text{at } E \gg E_{\mathrm{res}}$$

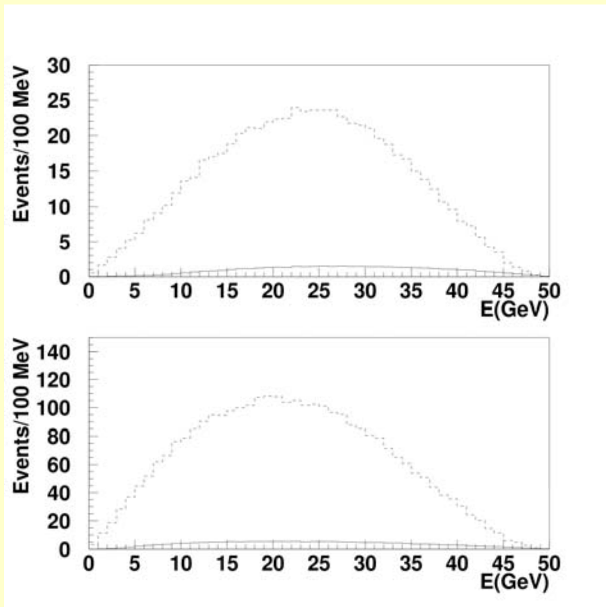
$$\text{if } \varepsilon_{\alpha\beta} \neq 0: \quad \theta_{\alpha\beta} \to \text{const} \quad P_{\alpha\beta} \to 4\varepsilon^2_{\alpha\beta} \sin^2(LV/2) \quad \text{at } E \gg E_{\mathrm{res}}$$

Sensitivity at a neutrino factory

- High energy + beam purity = neutrino factory
- The high E enhancement of the ν_τ spectrum can be observed through $\tau \to \mu$ decays (BR ~ 17%)
- With $E_\mu = 40\,\text{GeV}, L = 3000\,\text{km}, 40\,\text{kt}$, the experiment would be sensitive to $\varepsilon_{e\tau} \sim 0.008$
  - e.g. for $\varepsilon_{e\tau} = 0.07, \sin^2(2\theta_{13}) = 10^{-3}$:

Campanelli, AR





Summary

- Neutrino precision physics goes well beyond measuring a few parameters
- It allows to address fundamental issues either directly (CP-violation, hierarchy, lepton number violation) or through "circumstantial evidence" (see-saw, origin of neutrino masses, origin of mass and mixing patter)
- It represents one of the very few handles to address the origin of flavour.