Neutrino Mass Spectrum, Majorana CP-Violation, Neutrinoless Double-Beta Decay and Beyond

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Compelling Evidences for $\nu-$Oscillations

$-\nu_{\text{atm}}$: SK UP-DOWN ASYMMETRY

θ_Z-, $L/E-$ **dependences of $\mu-$like events**

Dominant $\nu_\mu \longrightarrow \nu_\tau$ K2K; MINOS, CNGS (OPERA)

$-\nu_\odot$: **Homestake, Kamiokande, SAGE, GALLEX/GNO**

Super-Kamiokande, SNO; KamLAND

Dominant $\nu_e \longrightarrow \nu_{\mu,\tau}$ **BOREXINO,..., LowNu**

$-$ LSND

Dominant $\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$ **MiniBOONE**

$$\nu_{l\text{L}} = \sum_{j=1} U_{lj}\, \nu_{j\text{L}} \qquad l = e, \mu, \tau. \qquad (1)$$

B. Pontecorvo, 1957; 1958; 1967;

Z. Maki, M. Nakagawa, S. Sakata, 1962;

PMNS Matrix: Standard Parametrization

$$U = V \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\frac{\alpha_{21}}{2}} & 0 \\ 0 & 0 & e^{i\frac{\alpha_{31}}{2}} \end{pmatrix} \quad (2)$$

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13}e^{i\delta} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13}e^{i\delta} \end{pmatrix} \quad (3)$$

- $s_{ij} \equiv \sin\theta_{ij}$, $c_{ij} \equiv \cos\theta_{ij}$, $\theta_{ij} = [0, \frac{\pi}{2}]$,
- δ - Dirac CP-violation phase, $\delta = [0, 2\pi]$,
- α_{21}, α_{31} - the two Majorana CP-violation phases.

S.M. Bilenky, J. Hosek, S.T.P.,1980

- $\Delta m^2_{\odot} \equiv \Delta m^2_{21} \cong 8.0 \times 10^{-5}$ eV$^2 > 0$, $\sin^2\theta_{12} \cong 0.31$, $\cos 2\theta_{12} \gtrsim 0.26$ (2σ),
- $|\Delta m^2_{\rm atm}| \equiv |\Delta m^2_{31}| \cong 2.5 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{23} \cong 1$,
- θ_{13} - the CHOOZ angle: $\sin^2\theta_{13} < 0.027$ (0.044) 2σ (3σ).

A.Bandyopadhyay, S.Choubey, S.Goswami, S.T.P., D.P.Roy, hep-ph/0406328 (updated)

- $\sqrt{\Delta m^2_\odot}\sin^2\theta_{12} \cong 3.0\times 10^{-3}$ eV $(\pm)$ $\sqrt{|\Delta m^2_{\rm atm}|}\sin^2\theta_{13} \lesssim 2.2\times 10^{-3}$ eV;
- $\sqrt{|\Delta m^2_{\rm atm}|} \cong 5\times 10^{-2}$ eV; $\sqrt{|\Delta m^2_{\rm atm}|}\cos 2\theta_{12} \gtrsim 1.3\times 10^{-2}$ eV $(\cos 2\theta_{12} \gtrsim 0.26)$
- m_0: $m_0^2 \gg \Delta m^2_\odot, |\Delta m^2_{\rm atm}|$, $m_0 \gtrsim 0.1$ eV
- ${\rm sgn}(\Delta m^2_{\rm atm}) = {\rm sgn}(\Delta m^2_{31})$ not determined

$$\Delta m^2_{\rm atm} \equiv \Delta m^2_{31} > 0, \quad \text{normal mass ordering}$$

$$\Delta m^2_{\rm atm} \equiv \Delta m^2_{32} < 0, \quad \text{inverted mass ordering}$$

Convention: $m_1 < m_2 < m_3$ - NMO, $m_3 < m_1 < m_2$ - IMO

- Majorana phases α_{21}, α_{31}:
  - $\nu_l \leftrightarrow \nu_{l'}$, $\bar{\nu}_l \leftrightarrow \bar{\nu}_{l'}$ not sensitive;

    S.M. Bilenky, J. Hosek, S.T.P.,1980;
    P. Langacker, S.T.P., G. Steigman, S. Toshev, 1987

  - $|<m>|$ in $(\beta\beta)_{0\nu}$−decay depends on α_{21}, α_{31};
  - $\Gamma(\mu \rightarrow e + \gamma)$ etc. in SUSY theories depend on $\alpha_{21,31}$;
  - BAU, leptogenesis scenario: $\alpha_{21,31}$?

Future Progress

• Determination of the nature - Dirac or Majorana, of ν_j .

• Determination of $\text{sgn}(\Delta m^2_{\text{atm}})$, type of $\nu-$ mass spectrum

$$m_1 \ll m_2 \ll m_3, \qquad \text{NH},$$

$$m_3 \ll m_1 < m_2, \qquad \text{IH},$$

$$m_1 \cong m_2 \cong m_3,\ m^2_{1,2,3} >> \Delta m^2_{\text{atm}},\ \text{QD};\ m_j \gtrsim 0.10\ \text{eV}.$$

• Determining, or obtaining significant constraints on, the absolute scale of ν_j-masses, or $\min(m_j)$.

• Status of the CP-symmetry in the lepton sector: violated due to δ (Dirac), and/or due to α_{21}, α_{31} (Majorana)?

• High precision determination of $\Delta m^2_{\odot}$, $\theta_{\odot}$, Δm^2_{atm}, θ_{atm}.

• Measurement of, or improving by at least a factor of (5 - 10) the existing upper limit on, $\sin^2\theta_{13}$.

• Searching for possible manifestations, other than ν_l-oscillations, of the non-conservation of L_l, $l = e, \mu, \tau$, such as $\mu \rightarrow e + \gamma$, $\tau \rightarrow \mu + \gamma$, etc. decays.

• Understanding at fundamental level the mechanism giving rise to the $\nu-$ masses and mixing and to the L_l-non-conservation. Includes understanding

– the origin of the observed patterns of ν-mixing and ν-masses ;

– the physical origin of CPV phases in $U_{\rm PMNS}$;

– Are the observed patterns of ν-mixing and of $\Delta m^2_{21,31}$ related to the existence of a new symmetry?

– Is there any relations between $q-$mixing and $\nu-$ mixing? Is $\theta_{12}+\theta_c=\pi/4$?

– Is $\theta_{23}=\pi/4$, or $\theta_{23}>\pi/4$ or else $\theta_{23}<\pi/4$?

– Is there any correlation between the values of CPV phases and of mixing angles in $U_{\rm PMNS}$?

• Progress in the theory of ν-mixing might lead to a better understanding of the origin of the BAU.

– Can the Majorana and/or Dirac CPVP in $U_{\rm PMNS}$ be the leptogenesis CPV parameters at the origin of BAU?

$(\beta\beta)_{0\nu}-$Decay Experiments:

- Majorana nature of ν_j
- Type of $\nu-$mass spectrum (NH, IH, QD)
- Absolute neutrino mass scale

^{3}H β-decay , cosmology: m_ν (QD, IH)

- CPV due to Majorana CPV phases

ν_j- Dirac or Majorana particles, **fundamental problem**

ν_j-Dirac: **conserved lepton charge exists,** $L = L_e + L_\mu + L_\tau$**,** $\nu_j \neq \bar{\nu}_j$

ν_j-Majorana: **no lepton charge is exactly conserved,** $\nu_j \equiv \bar{\nu}_j$

The observed patterns of $\nu-$mixing and of $\Delta m^2_{\rm atm}$ and $\Delta m^2_{\odot}$ can be related to Majorana ν_j and an approximate symmetry:

$$L' = L_e - L_\mu - L_\tau$$

S.T.P., 1982

See-saw mechanism: ν_j- Majorana

Establishing that ν_j are Majorana particles would be as important as the discovery of $\nu-$ oscillations.

If ν_j- Majorana particles, U_{PMNS} contains (3-ν mixing)

δ-Dirac, α_{21}, α_{31} - Majorana **physical CPV phases**

ν-oscillations $\nu_l \leftrightarrow \nu_{l'}$, $\bar{\nu}_l \leftrightarrow \bar{\nu}_{l'}$, $l, l' = e, \mu, \tau$,

- **are not sensitive to the nature of ν_j,**

S.M. Bilenky, J. Hosek, S.T.P.,1980;
P. Langacker et al., 1987

- **provide information on $\Delta m^2_{jk} = m^2_j - m^2_k$, but not on the absolute values of ν_j masses.**

The Majorana nature of ν_j can manifest itself in the existence of $\Delta L = \pm 2$ processes:

$$K^+ \rightarrow \pi^- + \mu^+ + \mu^+$$
$$\mu^- + (\text{A}, \text{Z}) \rightarrow \mu^+ + (\text{A}, \text{Z} - 2)$$

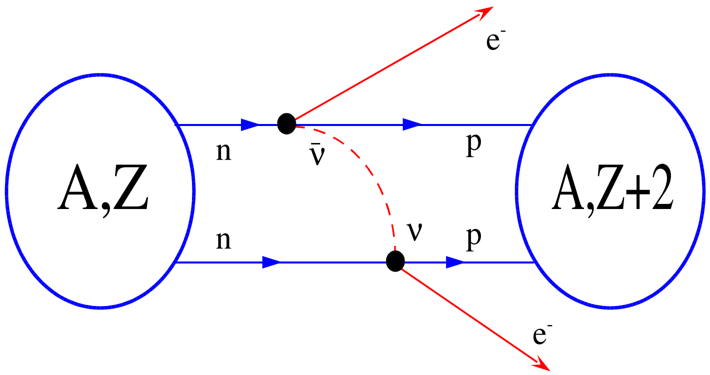
The process most sensitive to the possible Majorana nature of ν_j - $(\beta\beta)_{0\nu}$-decay

$$(\text{A}, \text{Z}) \rightarrow (\text{A}, \text{Z} + 2) + e^- + e^-$$

of certain even-even nuclei, ^{48}Ca, ^{76}Ge, ^{82}Se, ^{100}Mo, ^{116}Cd, ^{130}Te, ^{136}Xe.

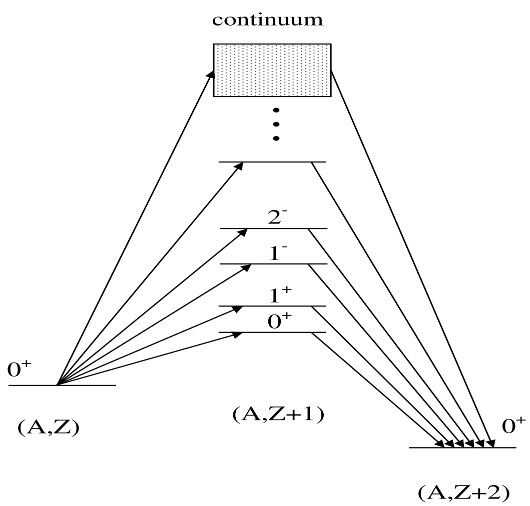
$2n$ from (A,Z) exchange a virtual Majorana ν_j (via the CC weak interaction) and transform into $2p$ of (A,Z+2) and two free e^-.

Nuclear $0\nu\beta\beta$-decay



strong in-medium modification of the basic process

$$dd \rightarrow uue^- e^- (\bar{\nu}_e \bar{\nu}_e)$$



virtual excitation
of states of all multipolarities
in (A,Z+1) nucleus

V. Rodin, talk at Gran Sasso, 2006

$A(\beta\beta)_{0\nu} \sim <m>$ M(A,Z), M(A,Z) - NME,

$$|<m>| = \left| m_1 |U_{e1}|^2 + m_2 |U_{e2}|^2 \; e^{i\alpha_{21}} + m_3 |U_{e3}|^2 \; e^{i\alpha_{31}} \right|$$

$$= \left| m_1 \; c_{12}^2 \; c_{13}^2 + m_2 \; s_{12}^2 \; c_{13}^2 \; e^{i\alpha_{21}} + m_3 \; s_{13}^2 \; e^{i\alpha_{31}} \right|, \quad \theta_{12} \equiv \theta_{\odot}, \; \theta_{13}\text{- CHOOZ}$$

α_{21}, α_{31} - the two Majorana CPVP of the PMNS matrix.

CP-invariance: $\alpha_{21} = 0, \pm\pi, \; \alpha_{31} = 0, \pm\pi;$

$$\eta_{21} \equiv e^{i\alpha_{21}} = \pm 1, \quad \eta_{31} \equiv e^{i\alpha_{31}} = \pm 1$$

relative CP-parities of ν_1 and ν_2, and of ν_1 and ν_3 .

L. Wolfenstein, 1981;

S.M. Bilenky, N. Nedelcheva, S.T.P., 1984;

B. Kayser, 1984.

Best sensitivity: Heidelberg-Moscow ^{76}Ge experiment.

Claim for a positive signal at $> 3\sigma$:

H. Klapdor-Kleingrothaus et al., PL B586 (2004),

$|<m>| = (0.1 - 0.9)$ eV (99.73% C.L.).

IGEX ^{76}Ge: $|<m>| < (0.33 - 1.35)$ eV (90% C.L.).

Taking data - NEMO3 (^{100}Mo), CUORICINO (^{130}Te):

$|<m>| <$(0.7–1.2) eV, $|<m>| <$(0.2–1.1) eV (90% C.L.).

Large number of projects: $|<m>| \sim (0.01 - 0.05)$ eV

CUORE - ^{130}Te,
GERDA - ^{76}Ge,
SuperNEMO - ^{82}Se,
EXO - ^{136}Xe,
MAJORANA - ^{76}Ge,
MOON - ^{100}Mo,
CANDLES - ^{48}Ca,
XMASS - ^{136}Xe.

$|{<}\, m \,{>}|$: m_j, $\theta_\odot \equiv \theta_{12}$, θ_{13}, $\alpha_{21,31}$

$m_{1,2,3}$ - in terms of $\min(m_j)$, $\Delta m^2_{\rm atm}$, $\Delta m^2_\odot$

S.T.P., A.Yu. Smirnov, 1994

Convention: $m_1 < m_2 < m_3$ - NMO, $m_3 < m_1 < m_2$ - IMO

$$\Delta m^2_\odot \equiv \Delta m^2_{21}, \quad m_2 = \sqrt{m_1^2 + \Delta m^2_\odot},$$

while either

$$\Delta m^2_{\rm atm} \equiv \Delta m^2_{31} > 0, \quad m_3 = \sqrt{m_1^2 + \Delta m^2_{\rm atm}}, \quad \text{normal mass ordering}, \quad \text{or}$$

$$\Delta m^2_{\rm atm} \equiv \Delta m^2_{32} < 0, \quad m_1 = \sqrt{m_3^2 + |\Delta m^2_{\rm atm}| - \Delta m^2_\odot}, \quad \text{inverted mass ordering}$$

The neutrino mass spectrum –

Normal hierarchical (NH) if $m_1 << m_2 << m_3$,

Inverted hierarchical (IH) if $m_3 << m_1 \cong m_2$,

Quasi-degenerate (QD) if $m_1 \cong m_2 \cong m_3 = m$, $m_j^2 >> |\Delta m^2_{\rm atm}|$; $m_j \gtrsim 0.1$ eV

Given $|\Delta m^2_{\rm atm}|$, $\Delta m^2_\odot$, $\theta_\odot$, θ_{13},

$$|{<}\, m \,{>}| = |{<}\, m \,{>}| \; (\mathrm{m_{min}}, \alpha_{21}, \alpha_{31}; \mathrm{S}), \; \mathrm{S} = \mathrm{NH, IH}.$$

$A(\beta\beta)_{0\nu} \sim <m>$ M(A,Z), M(A,Z) - NME,

$$|<m>| \cong \left|\sqrt{\Delta m^2_\odot}\sin^2\theta_{12}e^{i\alpha} + \sqrt{\Delta m^2_{31}}\sin^2\theta_{13}e^{i\beta_M}\right|\ , \ m_1 \ll m_2 \ll m_3 \ \text{(NH)},$$

$$|<m>| \cong \sqrt{m_3^2 + \Delta m^2_{13}}\left|\cos^2\theta_{12} + e^{i\alpha}\ \sin^2\theta_{12}\right|\ , \ m_3 < (\ll) m_1 < m_2 \ \text{(IH)},$$

$$|<m>| \cong m\left|\cos^2\theta_{12} + e^{i\alpha}\ \sin^2\theta_{12}\right|\ , \ m_{1,2,3} \cong m \gtrsim 0.10 \text{ eV} \ \text{(QD)},$$

$\theta_{12} \equiv \theta_\odot$, θ_{13}-CHOOZ; $\alpha \equiv \alpha_{21}$, $\beta_M \equiv \alpha_{31}$.

CP-invariance: $\alpha = 0, \pm\pi$, $\beta_M = 0, \pm\pi$;

$$|<m>| \lesssim 5 \times 10^{-3} \text{ eV, NH;}$$

$$\sqrt{\Delta m^2_{13}}\cos 2\theta_{12} \cong 0.013 \text{ eV} \lesssim |<m>| \lesssim \sqrt{\Delta m^2_{13}} \cong 0.05 \text{ eV}, \quad \text{IH;}$$

$$m\cos 2\theta_{12} \lesssim |<m>| \lesssim m,\ m \gtrsim 0.10 \text{ eV}, \quad \text{QD}\ .$$

Absolute Neutrino Mass Measurements

The Troitzk and Mainz ^{3}H β-decay experiments

$$m_{\nu_e} < 2.3 \text{ eV} \qquad (95\% \text{ C.L.})$$

There are prospects to reach sensitivity

$$\text{KATRIN}: \qquad m_{\nu_e} \sim 0.2 \text{ eV}$$

Cosmological and astrophysical data: the WMAP result combined with data from large scale structure surveys (2dFGRS, SDSS)

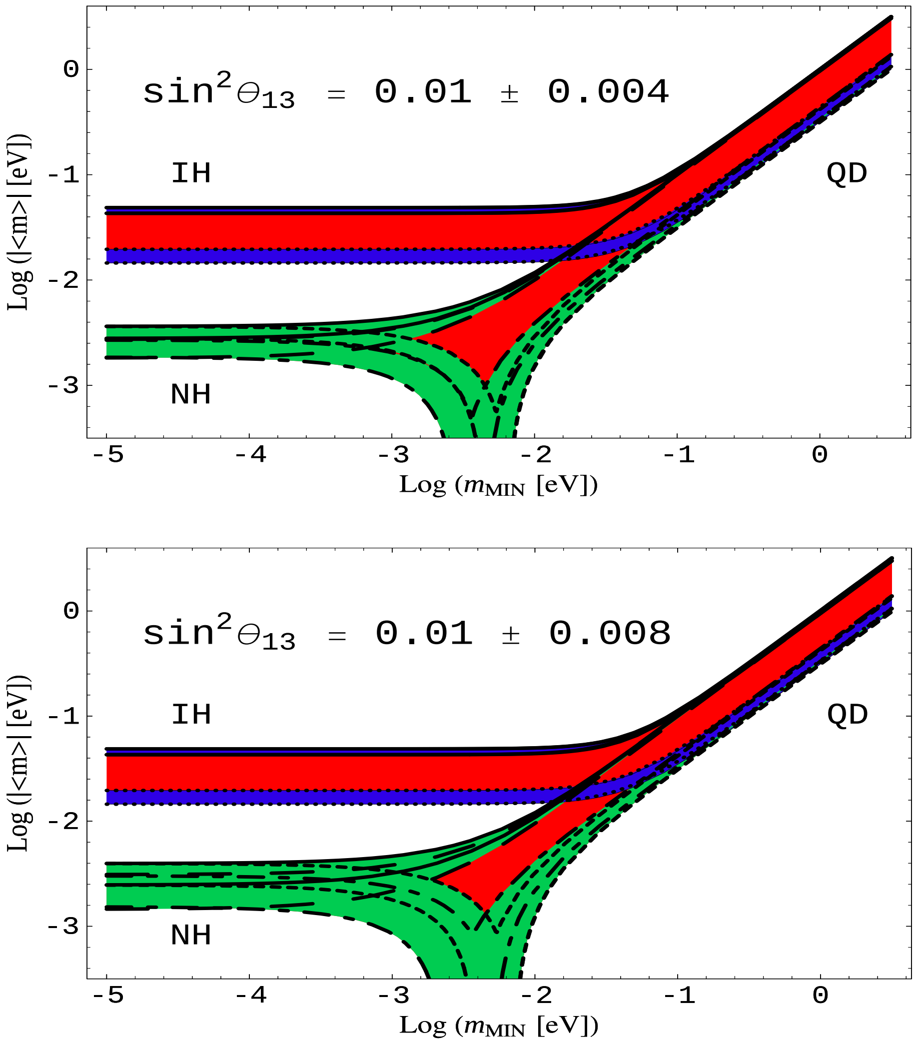
$$\sum_j m_j \equiv \Sigma < (0.4 - 1.7) \text{ eV}$$

The WMAP and future PLANCK experiments can be sensitive to

$$\sum_j m_j \cong 0.4 \text{ eV}$$

Data on weak lensing of galaxies by large scale structure, combined with data from the WMAP and PLANCK experiments may allow to determine

$$\sum_j m_j : \qquad \delta \cong 0.04 \text{ eV}.$$



S. Pascoli, S.T.P., T. Schwetz, hep-ph/0505226

$3\sigma(\Delta m^2_\odot) = 6\%$, $3\sigma(\sin^2\theta_\odot) = 12\%$, $3\sigma(|\Delta m^2_{\rm atm}|) = 18\%$.

Nuclear Matrix Element Uncertainty

$$|<m>| \; = \zeta \; ((|<m>|_{\,\rm exp})_{\rm MIN} \pm \Delta) \;, \quad \zeta \geq 1,$$

$(|<m>|_{\,\rm exp})_{\rm MIN}$ – obtained with the **maximal physically allowed value of NME**.

A measurement of the $(\beta\beta)_{0\nu}$-decay half-life time

$$(|<m>|_{\,\rm exp})_{\rm MIN} - \Delta \leq |<m>| \; \leq \zeta((|<m>|_{\,\rm exp})_{\rm MIN} + \Delta) \; .$$

The estimated range of ζ^2:

^{48}Ca, $\zeta^2 \simeq 3.5$

^{76}Ge, $\zeta^2 \simeq 10$

^{82}Se, $\zeta^2 \simeq 10$

^{130}Te, $\zeta^2 \simeq 38.7$

S. Elliot, P. Vogel, 2002

NH vs IH (QD):

$$\zeta \; |<m>|^{\rm NH}_{\rm max} < |<m>|^{\rm IH(QD)}_{\rm min} \;, \; \zeta \geq 1 \; .$$

IH vs QD:

$$\zeta \; |<m>|^{\rm IH}_{\rm max} < |<m>|^{\rm QD}_{\rm min} \;, \; \zeta \geq 1 \; .$$

S. Pascoli, S.T.P., W. Rodejohann, 2003

Method of Analysis

$$\Gamma_{\text{th}} = G\,|\mathcal{M}|^2\,\left(|\!<\!m\!>\!|\;(\mathbf{x})\right)^2\,,\;\; \mathbf{x} = (\mathbf{x}_{\text{osc}}, \mathbf{x}^{\mathbf{0}\nu}_{\beta\beta})$$

$$\mathbf{x}_{\text{osc}} = (\theta_{\mathbf{12}}, \theta_{\mathbf{13}}, |\boldsymbol{\Delta}\mathbf{m}^{\mathbf{2}}_{\mathbf{31}}|, \boldsymbol{\Delta}\mathbf{m}^{\mathbf{2}}_{\mathbf{21}})\,,$$

$$\mathbf{x}^{\mathbf{0}\nu}_{\beta\beta} = (m_0, \text{sgn}(\boldsymbol{\Delta}\mathbf{m}^{\mathbf{2}}_{\mathbf{31}}), \alpha_{\mathbf{21}}, \alpha_{\mathbf{31}})\,.$$

$$|\!<\!m\!>\!|^{\;\text{obs}} \equiv \sqrt{\frac{\Gamma_{\text{obs}}}{G}}\,\frac{1}{|\mathcal{M}_0|}\,, \qquad \sigma_{\beta\beta} = \frac{1}{2}\,\frac{1}{\sqrt{\Gamma_{\text{obs}} G}}\,\frac{1}{|\mathcal{M}_0|}\,\sigma(\Gamma_{\text{obs}})\,,$$

$|\mathcal{M}_0|$ is some nominal value of the NME.

$$\chi^2(\mathbf{x}^{\mathbf{0}\nu}_{\beta\beta}, \mathbf{F}) = \min_{\xi\in[1/\sqrt{F},\sqrt{F}]} \frac{\left[\xi\,|\!<\!m\!>\!|\;(\mathbf{x}) - |\!<\!m\!>\!|^{\;\text{obs}}\right]^2}{\sigma^2_{\beta\beta} + \xi^2\sigma^2_{\text{th}}}\,.$$

$$\xi \equiv \frac{|\mathcal{M}|}{|\mathcal{M}_0|}\,, \quad \xi = [1/\sqrt{F}, \sqrt{F}], \quad F \geq 1,$$

$|\mathcal{M}|$ is the *true* value of the NME.

S. Pascoli, S.T.P., T. Schwetz, hep-ph/0505226

Majorana CPV Phases and $|<m>|$

IH spectrum: $m_{\rm min} < 0.01$ eV, $\sin^2\theta -$ negligible

$$\sqrt{\Delta m^2_{\rm atm}}|\cos 2\theta_\odot| \leq |<m>| \ \leq \sqrt{\Delta m^2_{\rm atm}}.$$

"Just CP-violating" region:

$$(|<m>|_{\rm exp})_{\rm MAX} < \sqrt{(\Delta m^2_{\rm atm})_{\rm MIN}}\ ,$$

$$(|<m>|_{\rm exp})_{\rm MIN} > \sqrt{(\Delta m^2_{\rm atm})_{\rm MAX}}\,(\cos 2\theta_\odot)_{\rm MAX}\ ,$$

$$|<m>|\ = \zeta\ ((|<m>|_{\rm exp})_{\rm MIN} \pm \Delta)\ ,\quad \zeta \geq 1$$

Necessary condition for establishing CP-violation:

$$1 \leq \zeta < \frac{\sqrt{(\Delta m^2_{\rm atm})_{\rm MIN}}}{\sqrt{(\Delta m^2_{\rm atm})_{\rm MAX}}\,(\cos 2\theta_\odot)_{\rm MAX} + 2\Delta} \simeq \frac{1}{(\cos 2\theta_\odot)_{\rm MAX}}$$

QD spectrum, $m_{1,2,3} \simeq m_0 \gtrsim 0.20$ eV - similar condition: $\Delta m^2_{\rm atm} \rightarrow m_0^2$.

CPV can be established provided

– $|{<}m{>}|$ measured with $\Delta \lesssim 15\%$;

– Δm^2_{atm} (IH) or m_0 (QD) measured with $\delta \lesssim 10\%$;

– $\xi \lesssim 1.5$;

– α_{21} (QD): in the interval $\sim [\frac{\pi}{4} - \frac{3\pi}{4}]$, or $\sim [\frac{5\pi}{4} - \frac{3\pi}{2}]$;

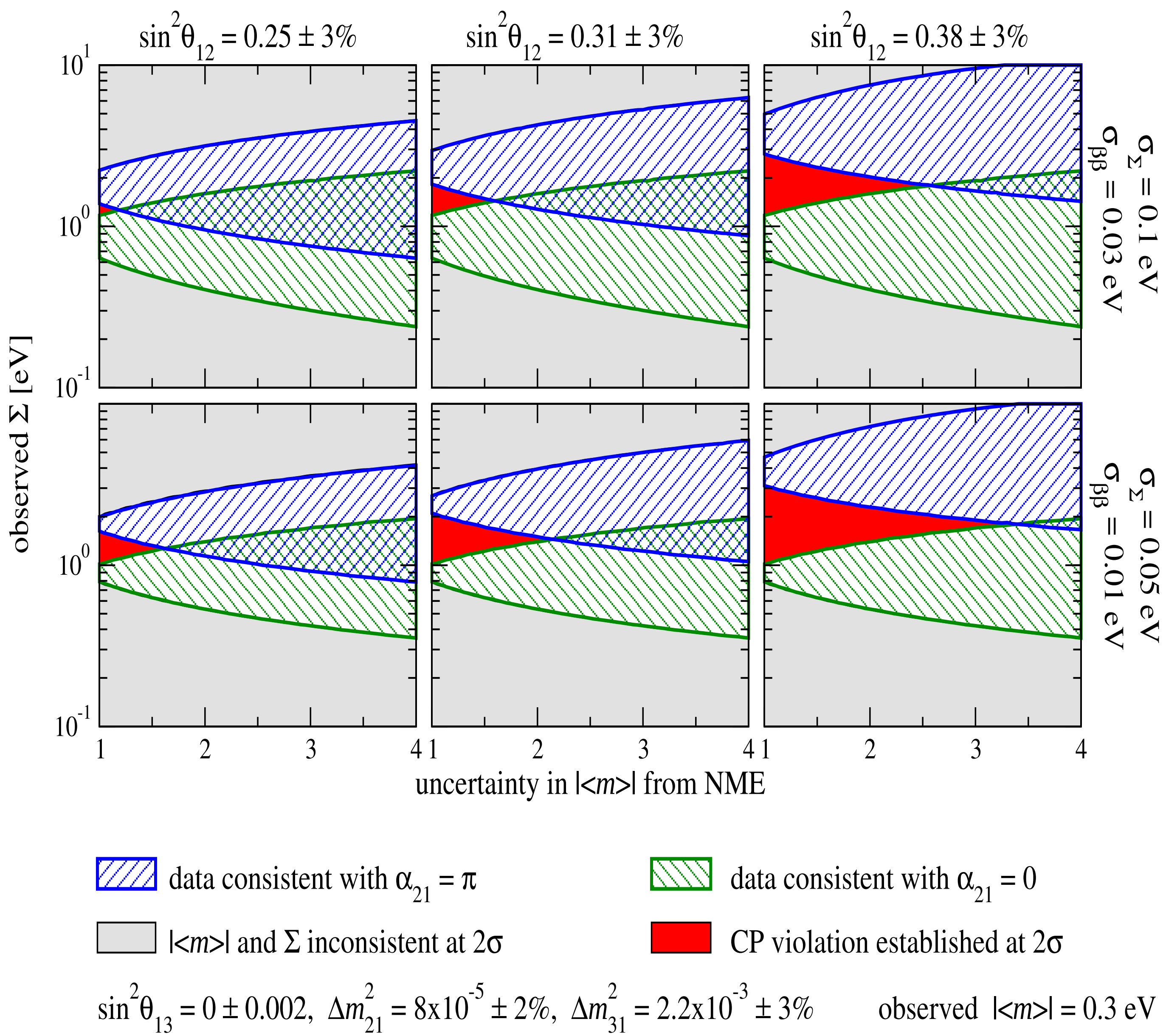
– $\tan^2\theta_\odot \gtrsim 0.40$.

S. Pascoli, S.T.P., W. Rodejohann, 2002

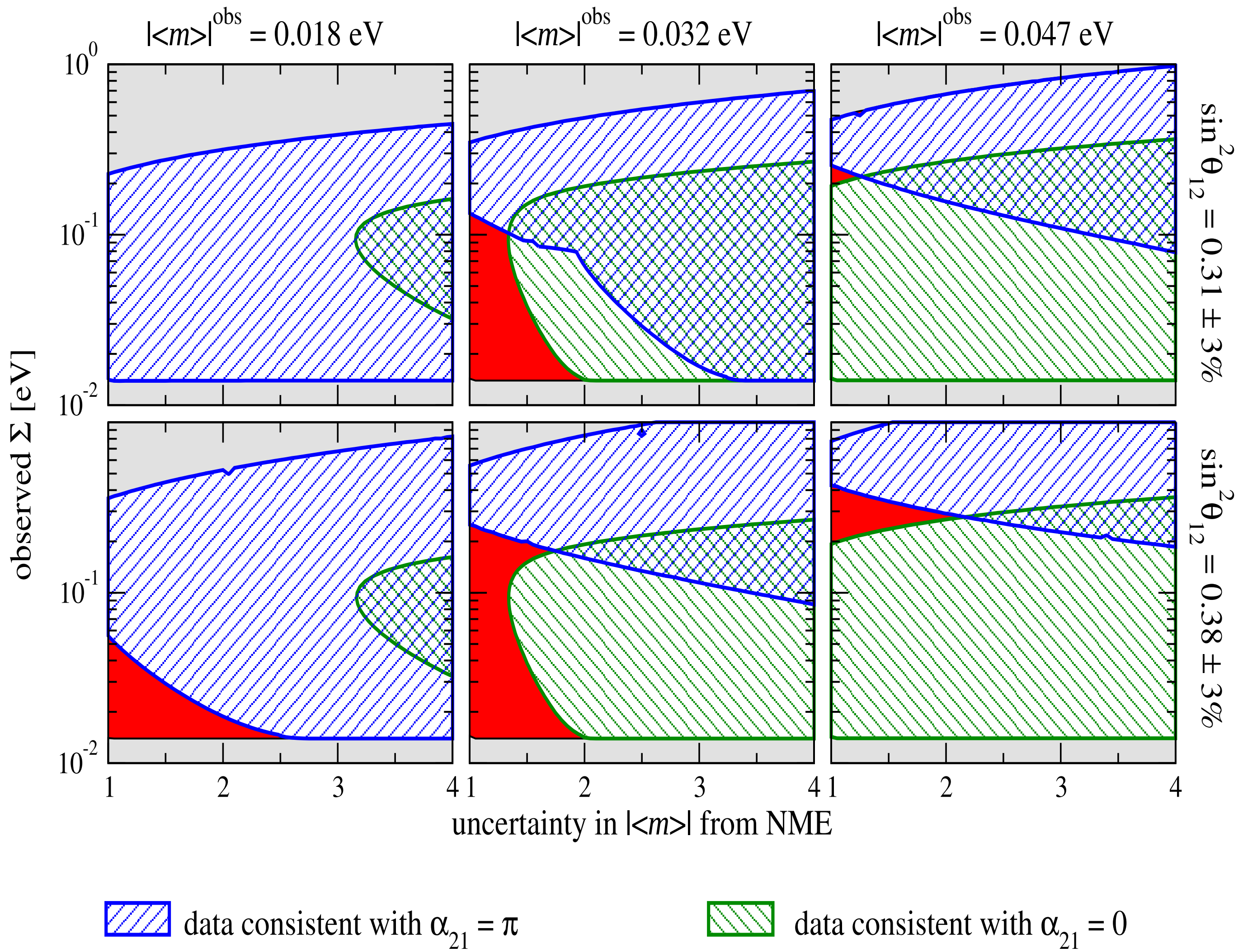
S. Pascoli, S.T.P., L. Wolfenstein, 2002

No "No-go for detecting CP-Violation via $(\beta\beta)_{0\nu}$-decay"

V. Barger *et al.*, 2002



S. Pascoli, S.T.P., T. Schwetz, hep-ph/0505226



$\sin^2\theta_{13} = 0 \pm 0.002$, $\Delta m^2_{21} = 8\text{x}10^{-5} \pm 2\%$, $\Delta m^2_{31} = -2.2\text{x}10^{-3} \pm 3\%$, $\sigma_{\beta\beta} = 0.004$ eV, $\sigma_\Sigma = 0.04$ eV

S. Pascoli, S.T.P., T. Schwetz, hep-ph/0505226

On the NME Uncertainties

The $(\beta\beta)_{0\nu}$-decay half-life

$$(T^{0\nu}_{1/2}(A,Z))^{-1} = |{<}m{>}|^{\,2}\,|M^{0\nu}(A,Z)|^2\,G^{0\nu}(E_0,Z),$$

$G^{0\nu}(E_0,Z)$, E_0 - known phase-space factor and energy release.

If we use a model M of the calculation of NME,

$$|{<}m{>}|^{\,2}_{M}(A,Z) = \frac{1}{T^{0\nu}_{1/2}(A,Z)\,|M^{0\nu}_{M}(A,Z)|^2\,G^{0\nu}(E_0,Z)}.$$

Suppose $(\beta\beta)_{0\nu}-$decay of several nuclei is observed.

$|{<}m{>}|$ cannot depend on parent nucleus (A_j, Z_j).

If the light Majorana ν-exchange - dominant mechanism of $(\beta\beta)_{0\nu}$-decay, **model M for NME can be correct only if**

$$|{<}m{>}|^{\,2}_{M}(A_1,Z_1) \simeq |{<}m{>}|^{\,2}_{M}(A_2,Z_2) = ...$$

For different models

$$|{<}m{>}|^{\,2}_{M_2}(A,Z) = \eta^{M_2;M_1}(A,Z)\,|{<}m{>}|^{\,2}_{M_1}(A,Z)\ ,$$

$$\eta^{M_2;M_1}(A,Z) = \frac{|M^{0\nu}_{M_1}(A,Z)|^2}{|M^{0\nu}_{M_2}(A,Z)|^2}\ .$$

Nucleus	$\eta^{M_2;M_1}$	$\eta^{M_3;M_1}$	$\eta^{M_2;M_3}$
^{76}Ge	0.37	0.19	1.93
^{82}Se	—	0.38	—
^{100}Mo	—	—	6.56
^{130}Te	0.74	0.10	7.32
^{136}Xe	0.53	0.02	22.42

M_1 (SM): E. Caurier et al., 1999; M_2 (QRPA): V. Rodin et al., 2003;
M_3 (QRPA): O. Civatarese and J. Suhonen, 2003.

The observation of $(\beta\beta)_{0\nu}$-decay of at least 3 nuclei would be important for the solution of the problem of NME.

Table 2 suggests: ^{76}Ge, ^{130}Te, ^{136}Xe .

If for some model M

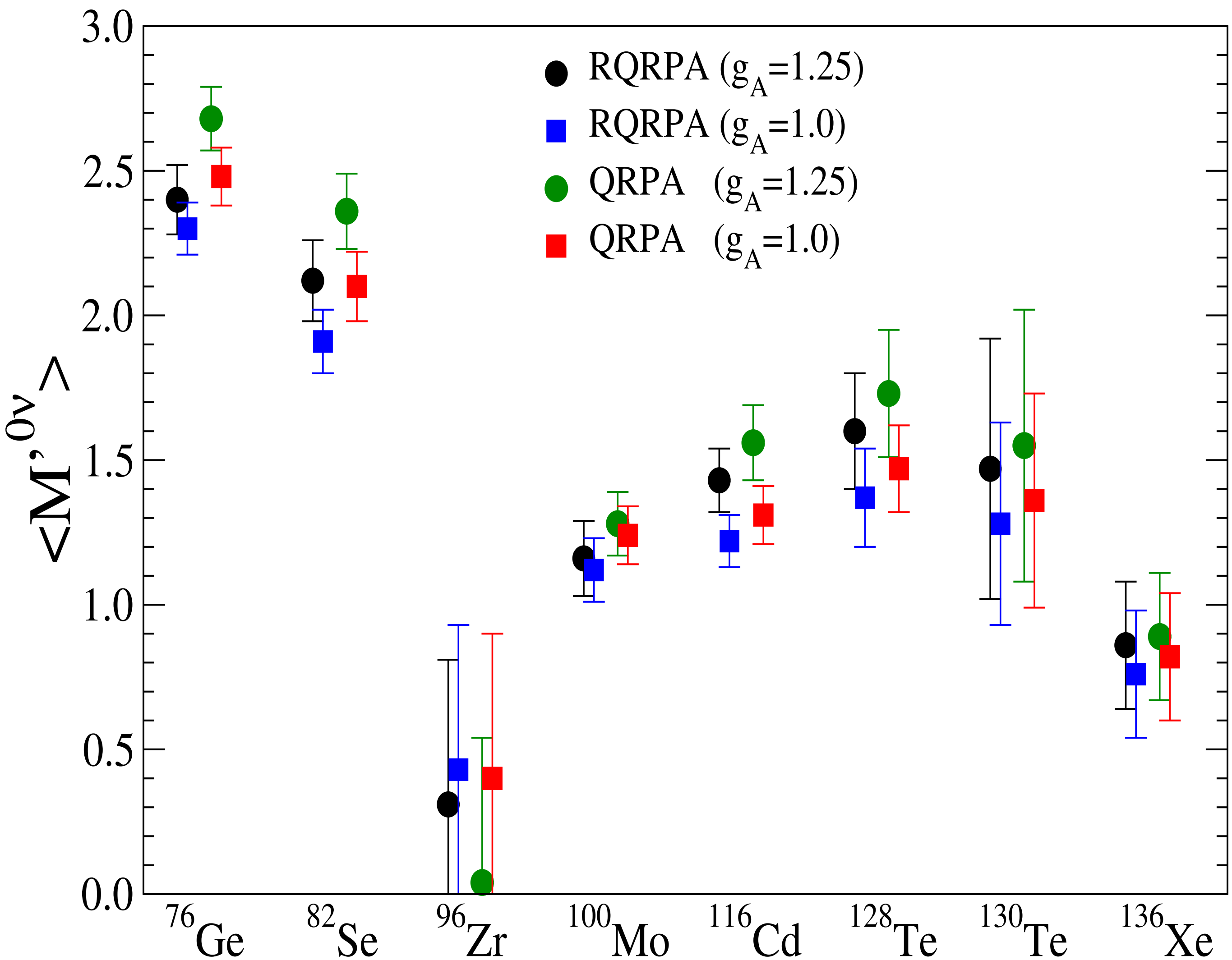
$$|<m>|\ ^2_M(A_1, Z_1) \simeq |<m>|\ ^2_M(A_2, Z_2) = ... \equiv |<m>|\ ^2_0\ ,$$

$|<m>|\ _0$ - the true value (most likely).
Strong dependence of NME on (A, Z) - crucial for the test.

S. M. Bilenky, S.T.P., 2004

Encouraging results on the problem of calculating the NME $(\xi \lesssim 1.5)$ have been obtained recently in

V. A. Rodin, A. Faessler, F. Simkovic, P. Vogel, nucl-th/0503063



V. A. Rodin *et al.*, nucl-th/0503063

The errors have no statistical origin, just illustrate the degree of the variation of the results by changing the basis size. The systematic error of the QRPA (due to neglecting many-particle configurations): $(3 \div 5) \times 10\%$, can vary from one nucleus to another.

The Majorana CPV Phases, $\mu \to e + \gamma$ Decay, Leptogenesis and $(\beta\beta)_{0\nu}$-Decay

M_ν from the See-Saw Mechanism

P. Minkowski, 1977.

M. Gell-Mann, P. Ramond, R. Slansky, 1979;

T. Yanagida, 1979;

R. Mohapatra, G. Senjanovic, 1980.

- Explains the smallness of $\nu-$masses.

- Through **leptogenesis theory** links the $\nu-$mass generation to the generation of baryon asymmetry of the Universe Y_B.

S. Fukugita, T. Yanagida, 1986.

- In SUSY GUT's with see-saw mechanism of $\nu-$mass generation, the LFV decays

$$\mu \to e + \gamma, \quad \tau \to \mu + \gamma, \quad \tau \to e + \gamma \text{ , etc.}$$

are predicted to take place with rates within the reach of present and future experiments.

F. Borzumati, A. Masiero, 1986.

- The ν_j are **Majorana particles**; $(\beta\beta)_{0\nu}-$decay is allowed.

See-Saw: Dirac ν-mass m_D + Majorana mass M_R for N_R

The Role of the CPV Phases

$$-\mathcal{L} = \overline{N_{Ri}}\,(m_D)_{ij}\,\nu_{Lj} + \frac{1}{2}\,\overline{(N_{Ri})^c}\,(M_R)_{ij}\,N_{Rj}$$

m_D generated by the Yukawa interaction:

$$-\mathcal{L}_{\mathrm{Y}} = \overline{N_{Ri}}\,(Y_\nu)_{ij}\,L_j\,H_u,\ \ v_u = 174\ \mathrm{GeV}\sin\beta,\ \ v_u Y_\nu = m_D - \text{complex}$$

For M_R - sufficiently large,

$$m_\nu \simeq m_D^T\,M_R^{-1}\,m_D = v_u^2\ Y_\nu^T\,M_R^{-1}\,Y_\nu = U^*_{\mathrm{PMNS}}\ m_\nu^{\mathrm{diag}}\ U^\dagger_{\mathrm{PMNS}}\ .$$

Basis: $M_R = (M_1, M_2, M_3)$; $D_N \equiv \mathrm{diag}(M_1, M_2, M_3)$, $D_\nu \equiv \mathrm{diag}(m_1, m_2, m_3)$.

$Y_\nu = \sqrt{D_N}\ R\ \sqrt{D_\nu}\ (U_{\mathrm{PMNS}})^\dagger / v_u$, all at M_R ; R-complex, $R^T R = \mathbf{1}$.

J.A. Casas and A. Ibarra, 2001

In GUTs, $M_R < M_X$, $M_X \sim 10^{16}$ GeV;

in GUTs, e.g., $M_R = (10^9, 10^{12}, 10^{15})$ GeV, $m_D \sim 1$ GeV.

Leptogenesis

$$Y_B = \frac{n_B - n_{\bar{B}}}{S} \sim 6 \times 10^{-10}$$

$$Y_B \cong -10^{-2} \quad \kappa\, \varepsilon$$

W. Buchmüller, M. Plümacher, 1998;
W. Buchmüller, P. Di Bari, M. Plümacher, 2004

$\kappa-$ efficiency factor; $\kappa \sim 10^{-1} - 10^{-3}$: $\varepsilon \gtrsim 10^{-7}$.

ε: $CP-$, $L-$ violating asymmetry generated in out of equilibrium $N_{Rj}-$decays in the early Universe,

$$\varepsilon_1 = \frac{\Gamma(N_1 \to \Phi^- \ell^+) - \Gamma(N_1 \to \Phi^+ \ell^-)}{\Gamma(N_1 \to \Phi^- \ell^+) + \Gamma(N_1 \to \Phi^+ \ell^-)}$$

$$\simeq \frac{1}{8\,\pi} \frac{1}{(Y_\nu Y_\nu^\dagger)_{11}} \sum_{j=2,3} \mathrm{Im}(Y_\nu Y_\nu^\dagger)^2_{1j} \, \left(f(M_j^2/M_1^2) + g(M_j^2/M_1^2) \right) \ .$$

$$f(x) = \sqrt{x} \left(1 - (1 + x)\, \ln \left(\frac{1+x}{x} \right) \right) \ , \quad g(x) = \frac{\sqrt{x}}{1-x}$$

M.A. Luty, 1992;
L. Covi, E. Roulet, and F. Vissani, 1996

$$\frac{1}{\kappa} \simeq \frac{3.3 \times 10^{-3}\ \mathrm{eV}}{\widetilde{m}_1} + \left(\frac{\widetilde{m}_1}{0.55 \times 10^{-3}\ \mathrm{eV}} \right)^{1.16} , \quad \widetilde{m}_1 \equiv \frac{v_u^2}{M_1} \left(Y_\nu Y_\nu^\dagger \right)_{11}$$

G. F. Giudice *et al.*, 2004

LFV Charged Lepton Decays

$m_\nu \neq 0$, $U_{\rm PMNS} \neq \mathbf{1}$: L_e, L_μ, L_τ not conserved

$\mu \to e + \gamma$, $\mu \to 3e$, $\tau \to \mu + \gamma$, $\tau \to e + \gamma$, etc., allowed.

$BR(\mu \to e + \gamma) < 1.2 \times 10^{-11}$ (MEGA)

$BR(\tau \to \mu + \gamma) < 6.8 \times 10^{-8}$ (BABAR)

PSI: $BR(\mu \to e + \gamma) < 10^{-13} - 10^{-14}$ (MEG)

Plans: $BR(\tau \to \mu + \gamma) < 10^{-8} - 10^{-9}$ (LHC)

Standard Theory with $m_\nu \neq 0$, $U_{\rm PMNS} \neq \mathbf{1}$:

$$BR(\mu \to e + \gamma) \sim 2.5 \times 10^{-4}\ (\tfrac{m_j}{M_W})^4 \lesssim 10^{-46}$$

S.T.P, 1977;

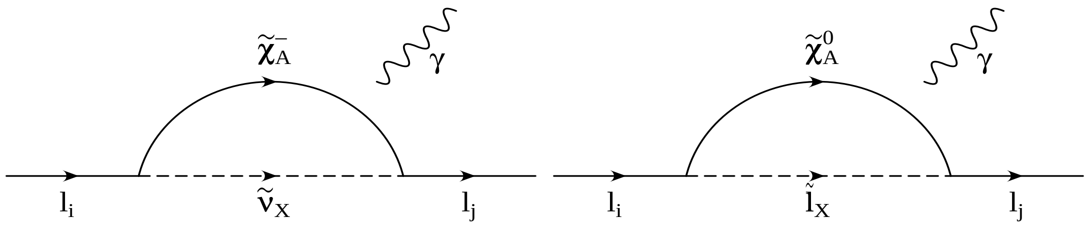
SUSY GUTs with see-saw mechanism:

• Flavour universality of SUSY breaking at $M_X \sim 10^{16}$ GeV (scalar masses m_0, trilinear couplings $A_0 \equiv a_0 m_0$, gaugino masses $m_{1/2}$)

• RG running: "large" LFV corrections to the slepton masses $\delta m^2 \sim Y_\nu^\dagger Y_\nu$

F. Borzumati, A. Masiero, 1986.

$$\left(m^2_{sL}\right)_{ji} \approx -\frac{1}{8\pi^2}(3m_0^2 + A_0^2)\left(Y_\nu^\dagger Y_\nu\right)_{ji} \log\frac{M_{\rm X}}{M_{\rm R}}\,, \qquad m_0, A_0 - \text{ at } M_X\ .$$



$$BR(\ell_i \to \ell_j + \gamma) \simeq \alpha^3 \left(\frac{(3 + A_0^2)\, m_0^2}{8\pi^2 m_S^4 G_F} \right)^2 \left| (Y_\nu^\dagger L Y_\nu)_{ij} \right|^2 \tan^2\beta \;\sim \frac{\left| (Y_\nu^\dagger L Y_\nu)_{ij} \right|^2}{G_F^2\, m_{\mathsf{SUSY}}^4}\; \tan^2\beta \,,$$

m_S- sparticle mass (at M_X); $L_k = \ln M_X / M_k,\ k = 1, 2, 3$.

$$m_S^8 \simeq 0.5\ m_0^2\ m_{1/2}^2\ (m_0^2 + 0.6 m_{1/2}^2)^2\ .$$

S.T.P., S. Profumo, Y. Takanishi, C. Yaguna, 2003

For, e.g., $A_0 \sim m_S \sim m_0 \sim 10^2$ GeV, $M_X \sim 10^{16}$ GeV, $M_R \sim 10^{11}$ GeV, $\tan\beta = 10$,

$$BR(\ell_i \to \ell_j + \gamma) \sim 10^{-11} \left| (m_D^\dagger m_D)_{ij}\ \text{GeV}^{-2} \right|^2$$

"Benchmark SUSY scenario":

$m_0 = m_{1/2} = 250$ GeV, $A_0 = a_0 m_0 = -100$ GeV, $\tan\beta \sim 5 - 10$.

χ_1^0: $m_1 \sim 100$ GeV; χ_2^0, χ^+: $m_2 \sim 250$ GeV; $m_{sq} \sim (400 - 600)$ GeV (LHC).

$$BR(\ell_i \to \ell_j + \gamma) \simeq 9.1 \times 10^{-10} \left| \left(\mathbf{Y}_\nu^\dagger L \mathbf{Y}_\nu \right)_{ij} \right|^2\ \tan^2\beta \,, \qquad \tan^2\beta \gtrsim 10\ .$$

- Leptogenesis: $\text{Im}(Y_\nu Y_\nu^\dagger)^2$, $(Y_\nu Y_\nu^\dagger)_{11}$
- $\mu \to e + \gamma$, etc.: $Y_\nu^\dagger L Y_\nu$
- See-saw: $Y_\nu = \sqrt{D_N}\ R\ \sqrt{D_\nu}\ (U_{\text{PMNS}})^\dagger$, all at M_R ; $R^T R = \mathbf{1}$.

J.A. Casas and A. Ibarra, 2001

Leptogenesis: $Y_\nu Y_\nu^\dagger = \sqrt{D_N}\ R\ D_\nu\ R^\dagger\ \sqrt{D_N}$, R should be complex.

$R = R_{12}(\omega_{12}) R_{13}(\omega_{13}) R_{23}(\omega_{23}) = R_{12}(\omega_{12}) R_{23}(\omega_{23}) R_{12}(\omega'_{12})$, ω_{ij}-complex.

$\mu \to e + \gamma$: $(Y_\nu^\dagger L Y_\nu)_{21} = (Y_\nu^\dagger)_{21} L_1 (Y_\nu)_{11} + (Y_\nu^\dagger)_{22} L_2 (Y_\nu)_{21} + (Y_\nu^\dagger)_{23} L_3 (Y_\nu)_{31}$

$(Y_\nu^\dagger)_{21} L_1 (Y_\nu)_{11} \propto \sqrt{m_j m_k}\ M_1/v_u^2$, $j, k \neq 1$ (3), NH (IH);

$(Y_\nu^\dagger)_{22} L_2 (Y_\nu)_{21} \propto \sqrt{m_j m_k}\ M_2/v_u^2$;

$(Y_\nu^\dagger)_{23} L_3 (Y_\nu)_{31} \propto \sqrt{m_j m_k}\ M_3/v_u^2$.

Hierarchical spectrum: $M_1 \ll M_2 \ll M_3$

The Role of LFV Decays: $\mu \to e + \gamma$

Assume:

$M_1 \ll M_2 \ll M_3$, $M_3 \gtrsim 5 \times 10^{13}$ GeV (GUTs)
($m_\nu \cong m_D^2/M_R$; $m_D \sim 175$ GeV, $m_\nu \sim 5 \times 10^{-2}$ eV, then $M_R \sim 6 \times 10^{14}$ GeV.)

$M_{SUSY} \sim (100 - 600)$ GeV (LHC), e.g.,

$$m_0 = m_{1/2} = 250 \text{ GeV}, \quad A_0 = a_0 m_0 = -100 \text{ GeV},$$

$BR(\mu \to e + \gamma) < 1.2 \times 10^{-11}$ implies:

terms $\sim M_3$ in $|(\mathbf{Y}_\nu^\dagger L \mathbf{Y}_\nu)_{21}|$ – **suppressed**, i.e., $Y_{\nu 32} \cong 0$, or $Y_{\nu 31} \cong 0$.

One possible solution - the form of $\mathbf{R}$:

$R = R_{12}(\omega_{12}) R_{13}(\pi/2) R_{23}(\omega_{23}) = R(\omega_{12} - \omega_{23}) \equiv R(\omega)$, NH,

$R = R_{12}(\omega_{12}) R_{23}(0) R_{12}(\omega'_{12}) = R_{12}(\omega_{12} + \omega'_{12}) \equiv R_{12}(\omega)$, IH.

NH spectrum:

$$\mathbf{R} \simeq \begin{pmatrix} 0 & \sin\omega & \cos\omega \\ 0 & \cos\omega & -\sin\omega \\ -1 & 0 & 0 \end{pmatrix}, \qquad \omega = \rho + i\sigma \,. \tag{4}$$

S.T.P., W. Rodejohann, T. Shindou, Y. Takanishi, 2005

also: J. Ellis et al., 2004; A. Ibarra, G.G. Ross, 2004

The terms $\sim M_2$ in $|(\mathbf{Y}_\nu^\dagger L \mathbf{Y}_\nu)_{21}|$ – **dominant**.

Leptogenesis, NH spectrum: $M_1 \gtrsim 10^{10}$ GeV, $\omega-$complex.

$M_2 \gtrsim 10^{11}$ (10^{12}) GeV: predicted $BR(\mu \to e + \gamma) \gtrsim 10^{-13}$ (10^{-11}) for $\tan^2\beta = 30$.

$$\epsilon_1 \simeq -\frac{3}{8\pi}\left(\frac{m_3 M_1}{v_u^2}\right)\frac{\mathrm{Im}\left[c_\omega^2 + \frac{\Delta m_\odot^2}{\Delta m_{31}^2}\; s_\omega^2\right]}{|c_\omega|^2 + \sqrt{\frac{\Delta m_\odot^2}{\Delta m_{31}^2}}\; |s_\omega|^2}$$

$$|\epsilon_1| \lesssim \frac{3}{8\pi}\left(\frac{m_3 M_1}{v_u^2}\right) \simeq 1.97 \times 10^{-7}\left(\frac{m_3}{0.05\ \mathrm{eV}}\right)\left(\frac{M_1}{10^9\ \mathrm{GeV}}\right)\left(\frac{174\ \mathrm{GeV}}{v_u}\right)^2 .$$

$$\widetilde{m}_1 \simeq m_3|c_\omega|^2 + m_2|s_\omega|^2 = \frac{1}{2}(m_3 + m_2)\cosh 2\sigma + \frac{1}{2}(m_3 - m_2)\cos 2\rho \geq m_2 \,.$$

$$9 \times 10^{-3}\ \mathrm{eV} < \widetilde{m}_1 \lesssim 0.12 eV : \quad 1.9 \times 10^{-3} \lesssim \kappa < 3.9 \times 10^{-2}$$

.

IH (QD) spectrum:

$$\mathbf{R} \simeq \begin{pmatrix} \cos\omega & \sin\omega & 0 \\ -\sin\omega & \cos\omega & 0 \\ 0 & 0 & 1 \end{pmatrix} . \quad (5)$$

The terms $\sim M_2$ in $|(\mathbf{Y}_\nu^\dagger L \mathbf{Y}_\nu)_{21}|$ – **dominant**.

Leptogenesis, IH spectrum: $M_1 \gtrsim 7 \times 10^{12}$ GeV, $\omega-$complex.

$M_2 \gtrsim 5 \times 10^{13}$ GeV: predicted $BR(\mu \to e + \gamma) \gg 10^{-11}$

$$\epsilon_1 \simeq -\frac{3}{8\pi}\left(\frac{m_2\ M_1}{v_u^2}\right)\frac{\Delta m_\odot^2}{|\Delta m_{31}^2|}\frac{\text{Im}\left[\sin^2\omega_{12}\right]}{\left(1+\frac{\Delta m_\odot^2}{2|\Delta m_{31}^2|}\right)|\sin\omega_{12}|^2+|\cos\omega_{12}|^2}$$

$$|\epsilon_1| \lesssim \frac{3}{16\pi}\left(\frac{m_2\, M_1}{v_u^2}\right)\frac{\Delta m_\odot^2}{|\Delta m_{31}^2|} \simeq 3.2\times 10^{-9}\left(\frac{m_2}{0.05\ \text{eV}}\right)\left(\frac{M_1}{10^9\ \text{GeV}}\right)\left(\frac{174\ \text{GeV}}{v_u}\right)^2 ,$$

$$\widetilde{m}_1 \simeq m_{1,2}(|\cos\omega_{12}|^2 + |\sin\omega_{12}|^2) = m_{1,2}\cosh 2\sigma \geq m_{1,2} .$$

5×10^{-2} eV $< \widetilde{m}_1 \lesssim 0.1 eV$: $2.4\times 10^{-3} \lesssim \kappa < 5.4\times 10^{-3}$

.

S.T.P., W. Rodejohann, T. Shindou, Y. Takanishi, 2005

Two possibilities:

- $M_{SUSY} \sim (600 - 2000)$ GeV, ($m_{1/2} \gg m_0$, e.g, $m_0 = 300$ GeV, $m_{1/2} = 1400$ GeV, $a_0 m_0 = 0$)

- $M_{SUSY} \sim (100 - 600)$ GeV, but $\mathbf{Y}_{\nu 21} = 0$, or $\mathbf{Y}_{\nu 22} = 0$

A. $\mathbf{Y}_{\nu 21} = 0$:

$$\tan\omega = e^{-i\alpha/2}\ \tan\theta_{12}.$$

B. $\mathbf{Y}_{\nu 22} \cong 0$, neglecting s_{13}:

$$\tan\omega = -e^{-i\alpha/2}\ \cot\theta_{12}.$$

Leptogenesis: $\omega-$complex; thus $\alpha \neq 0, \pi$, CP-violating values

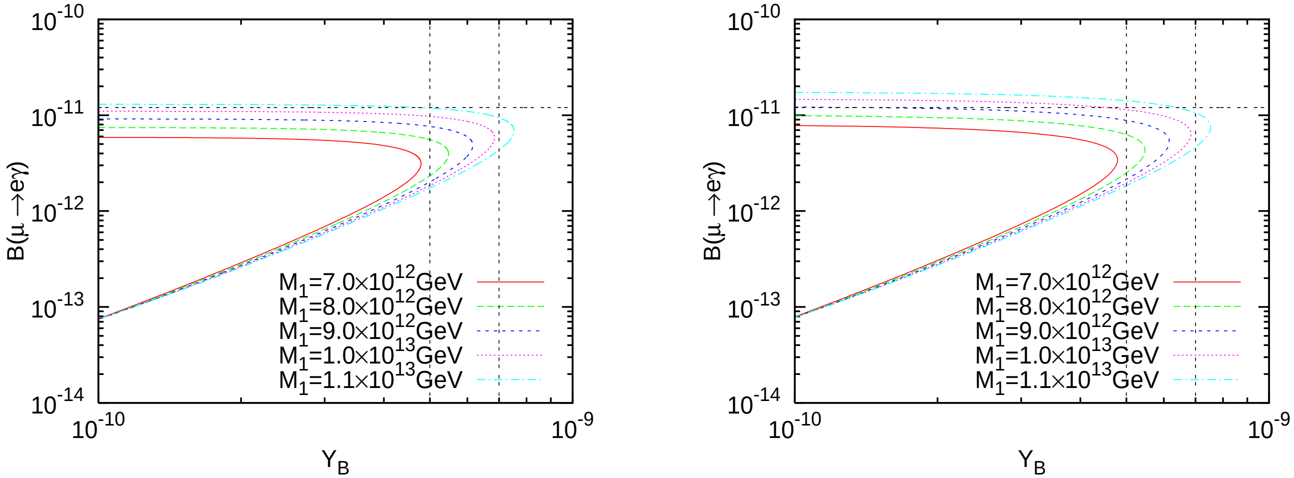
B. $\mathbf{Y}_{\nu 22} = 0$, including s_{13}:

$$\tan\omega = -\frac{c_{12} - s_{12}s_{13}e^{-i\delta}}{s_{12} + c_{12}s_{13}e^{-i\delta}}\ e^{-i\alpha/2}$$

Correlations between $BR(\mu \rightarrow e + \gamma)$, $Y_{\rm B}$ and $|{<}m{>}|$:

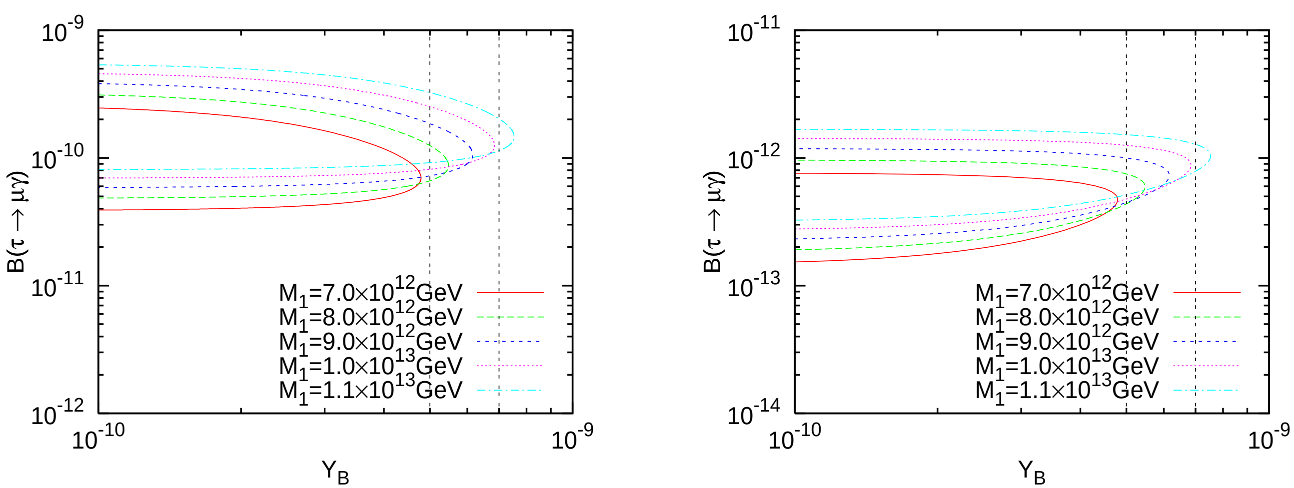
$$|{<}m{>}|\ \cong \sqrt{\Delta m^2_{13}}\left|\cos^2\theta_{12} + e^{i\alpha}\ \sin^2\theta_{12}\right|$$

S.T. Petcov, T. Shindou, 2006



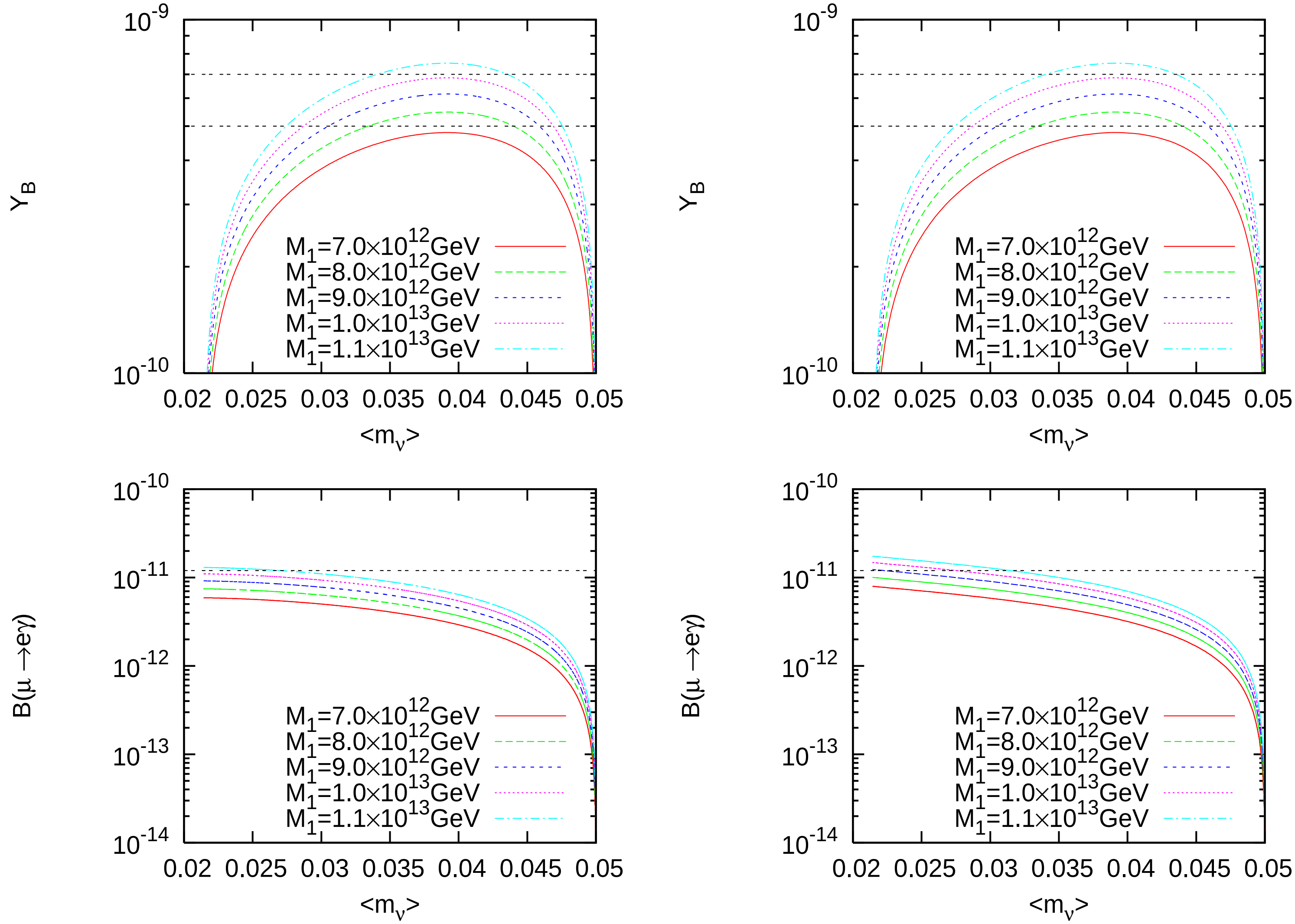
$(Y_\nu)_{21} = 0$ $(Y_\nu)_{22} \approx 0$

Figure 1: B($\mu \to e\gamma$) for $s_{13} = 0$ as a function of Y_B. The SUSY parameters are fixed as $m_0 = m_{1/2} = 450$, $A_0 = 0$, and $\tan\beta = 5$.



$(Y_\nu)_{21} = 0$ $(Y_\nu)_{22} \approx 0$

Figure 2: B($\tau \to \mu\gamma$) for $s_{13} = 0$ as a function of Y_B. The mass of next lightest heavy neutrino is taken as $M_2/M_1 = 10$, and the SUSY parameters are fixed as $m_0 = m_{1/2} = 450$, $A_0 = 0$, and $\tan\beta = 5$.



$(Y_\nu)_{21} = 0$ $\qquad$ $(Y_\nu)_{22} \approx 0$

Figure 6: Predicted values of Y_B and $\mathrm{B}(\mu \to e\gamma)$ for $s_{13} = 0$. The SUSY parameters are fixed as $m_0 = m_{1/2} = 450$, $A_0 = 0$, and $\tan\beta = 5$.

Conclusions

Determining the nature - Dirac or Majorana, of massive neutrinos is of fundamental importance for understanding the origin of neutrino masses.

$(\beta\beta)_{0\nu}$-decay experiments have remarkable physics potential:

– **Can establish the Majorana nature of ν_j**

– **Can provide unique information on the ν mass spectrum**

– **Can provide unique information on the absolute scale of ν masses**

– **Can provide information on the Majorana CPV phases**

The knowledge of the values of the relevant $(\beta\beta)_{0\nu}-$decay NME with a sufficiently small uncertainty is crucial for obtaining quantitative information on the neutrino mass and mixing parameters from a measurement of $\Gamma(\beta\beta)_{0\nu}$.

The precision in the measurement of $\Gamma(\beta\beta)_{0\nu}$ will also be very important for the quantitative interpretation of the data.

Conclusions (contd.)

The see-saw mechanism provides a link between ν-mass generation and BAU.

SUSY see-saw: LFV processes $\mu \to e + \gamma$, etc.

LHC: constraints on (discovery of?) SUSY.

$\mu \to e + \gamma$, leptogenesis - significant constraints on the theory.

Majorana CPV phases in $U_{\rm PMNS}$: $(\beta\beta)_{0\nu}$-decay, $Y_{\rm B}$, $\mu \to e + \gamma$.

Supporting Slides

Oscillation Parameters

$$\Delta m^2_\odot = 8.0 \times 10^{-5}~\text{eV}^2~, \quad 3\sigma(\Delta m^2_\odot) = 12\%~,$$

$$\sin^2\theta_\odot = 0.31~, \quad 3\sigma(\sin^2\theta_\odot) = 24\%~,$$

$$|\Delta m^2_{\text{atm}}| = 2.2 \times 10^{-3}~\text{eV}~, \quad 3\sigma(|\Delta m^2_{\text{atm}}|) = 50\%.$$

Future:

3 kTy KamLAND: $3\sigma(\Delta m^2_\odot) = 7\%$, $3\sigma(\sin^2\theta_\odot) = 18\%$;

A. Bandyopadhyay et al., hep-ph/0410283

SK-Gd (0.1% Gd: 43×(KL $\bar{\nu}_e$ rate)), 3y: $3\sigma(\Delta m^2_\odot) \cong 4\%$

S. Choubey, S.T.P., hep-ph/0404103;
J. Beacom and M. Vagins, hep-ph/0309300

KL type reactor $\bar{\nu}_e$ detector, $L \sim 60$ km, ~ 60 GW kTy: $3\sigma(\sin^2\theta_\odot) \cong 12\%$

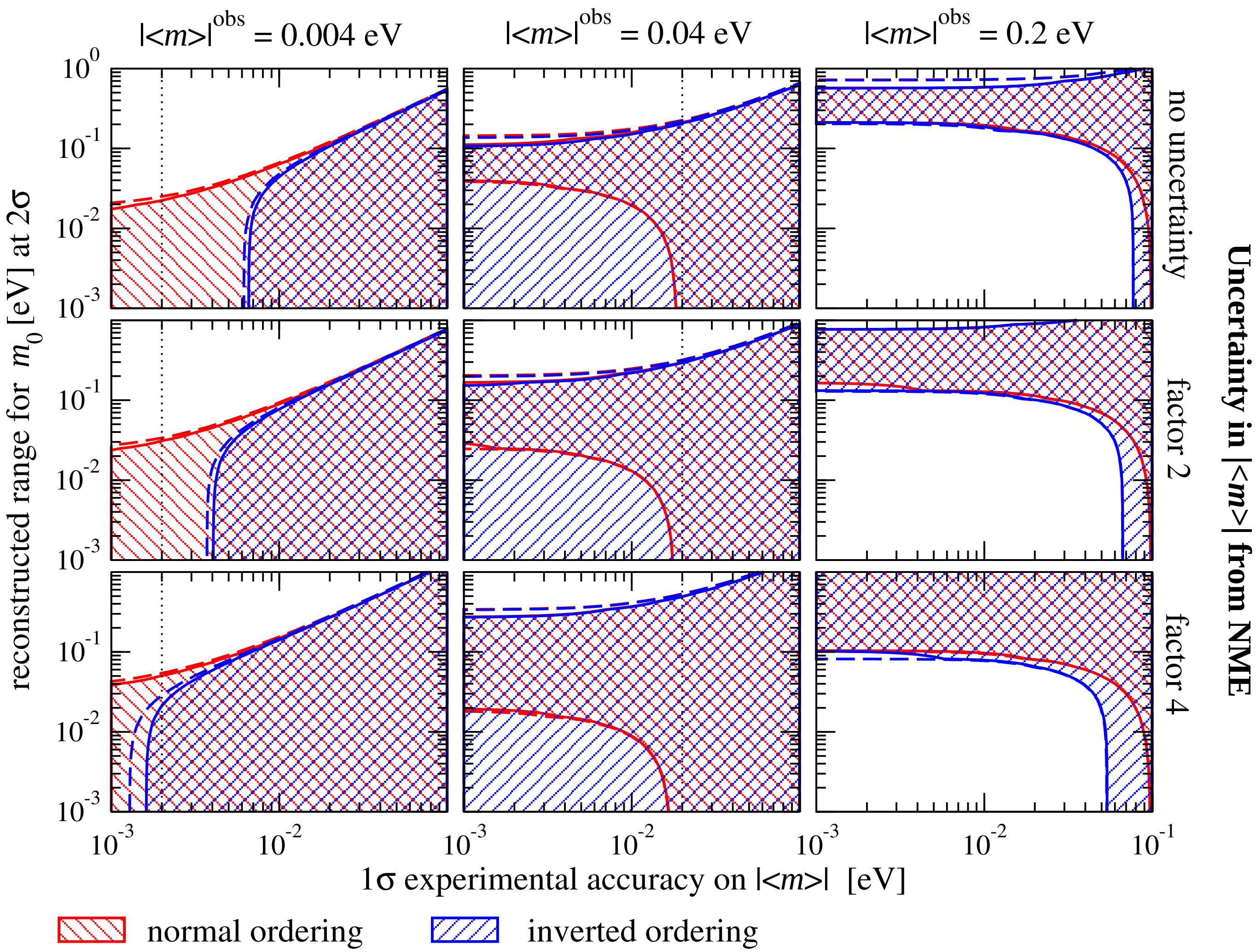
A. Bandyopadhyay et al., hep-ph/0410283 and hep-ph/0302243;
H. Minakata et al., hep-ph/0407326

T2K (SK): $3\sigma(|\Delta m^2_{\text{atm}}|) \cong 6\%$

sgn(Δm^2_{atm}): ν_{atm} experiments, studying the subdominant $\nu_{\mu(e)} \rightarrow \nu_{e(\mu)}$ and $\bar{\nu}_{\mu(e)} \rightarrow \bar{\nu}_{e(\mu)}$ oscillations; LBL $\nu-$oscillation experiments (T2K, NOνA); $\nu-$factory.

$\sin^2\theta_{13}$: reactor $\bar{\nu}_e$ experiments, $L \sim (1-2)$ km: Double CHOOZ, Braidwood, Daya-Bay, KASKA - factor (5 - 10).

Absolute Neutrino Mass Scale

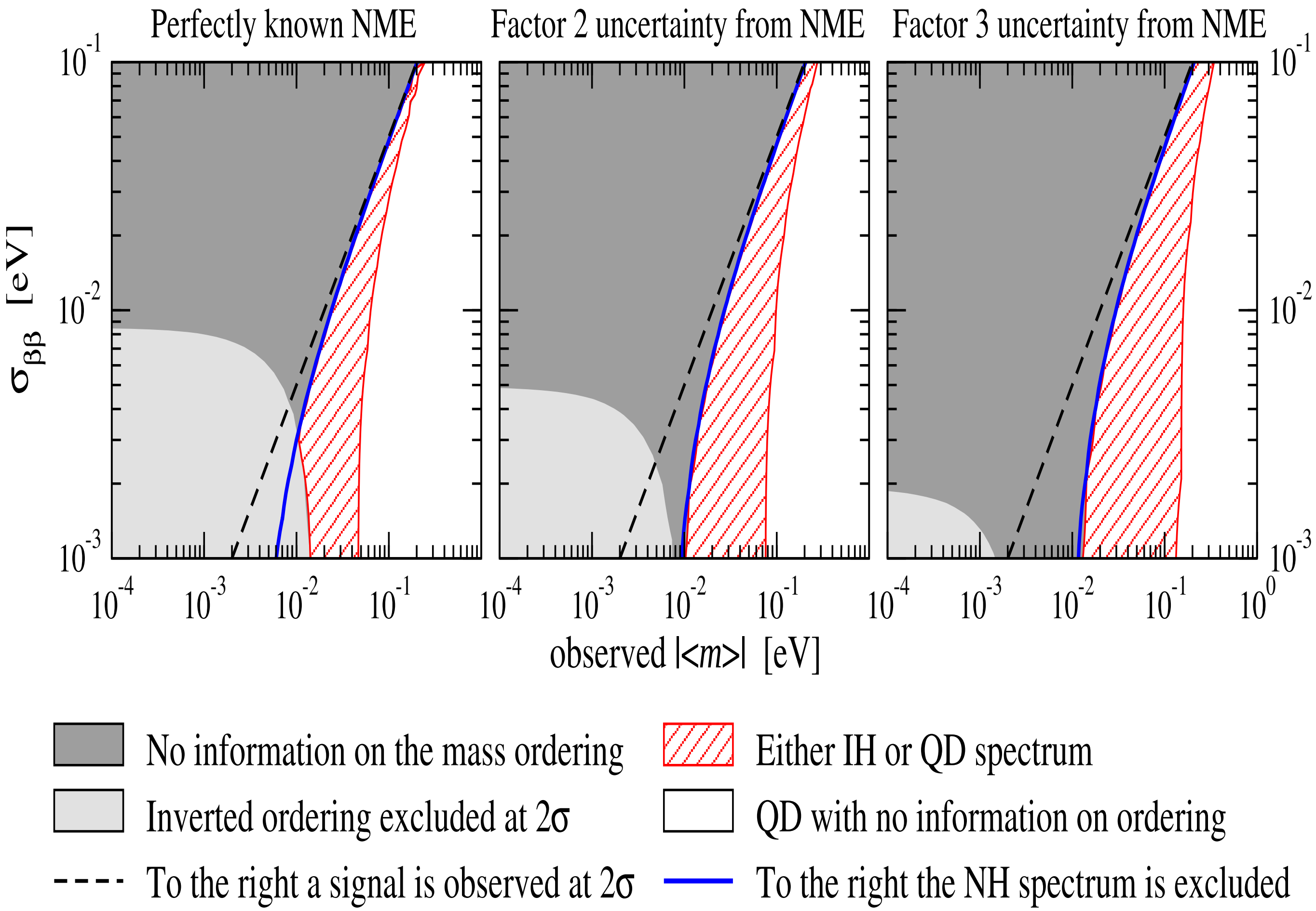


dashed: $\sigma(\sin^2\theta_{13}) = 0.016$, $\sigma(\sin^2\theta_{12}) = 7.5\%$, $\sigma(\Delta m^2_{21}) = 4\%$, $\sigma(\Delta m^2_{31}) = 13\%$ $\sin^2\theta_{13} = 0$

solid: $\sigma(\sin^2\theta_{13}) = 0.002$, $\sigma(\sin^2\theta_{12}) = 3.0\%$, $\sigma(\Delta m^2_{21}) = 2\%$, $\sigma(\Delta m^2_{31}) = 5\%$ $\sin^2\theta_{12} = 0.31$

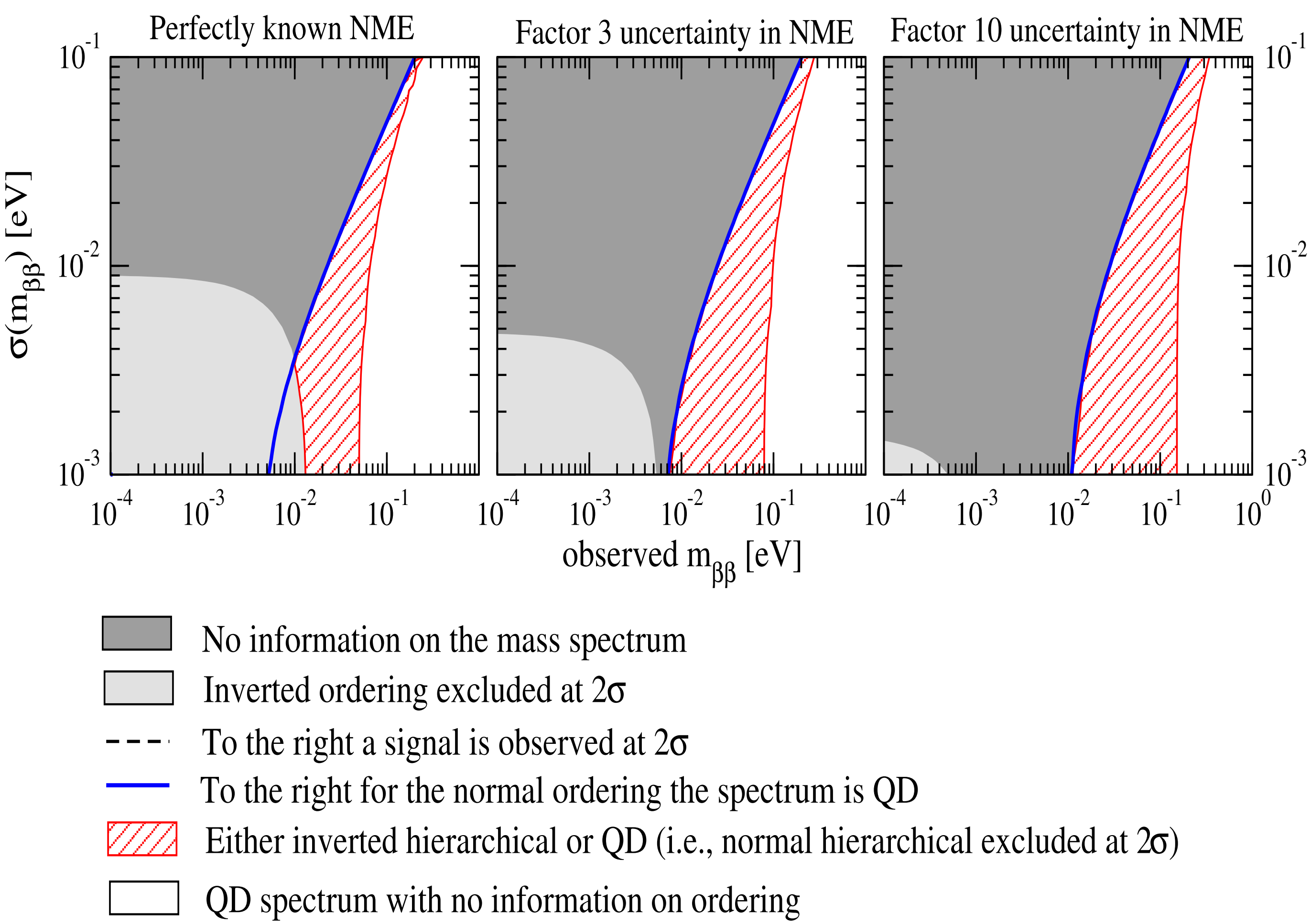
S. Pascoli, S.T.P., T. Schwetz, hep-ph/0505226

Distinguishing Between Different Spectra



$\sin^2\theta_{13} = 0.03 \pm 0.006$, $\sin^2\theta_{12} = 0.31 \pm 3\%$, $\Delta m^2_{21} = 8\text{x}10^{-5} \pm 2\%$, $|\Delta m^2_{31}| = 2.2\text{x}10^{-3} \pm 3\%$

S. Pascoli, S.T.P., T. Schwetz, hep-ph/0505226



$\sin^2\theta_{13} = 0$ +/- 0.016, $\sin^2\theta_{12} = 0.3$ +/- 7.5%, $\Delta m^2_{21} = 8\text{x}10^{-5}$ +/- 4%, $\Delta m^2_{31} = 2.2\text{x}10^{-3}$ +/- 13%

S. Pascoli, S.T.P., T. Schwetz, 2005