NEUTRINO PHENOMENOLOGY WITH SOFT BILINEAR R_p VIOLATION

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OUTLINE

- MSSM Superpotential with $\not{R}_p$
- BASIS INVARIANTS
- NEUTRINO MASSES : ESTIMATES
- MODEL
- PHENOMENOLOGY*

R-violating Superpotential

- The superpotential of the MSSM with lepton number violation is

$$W = \mu^I H_u L_I + \lambda^{IJk} L_I L_J E_k^c + \lambda'^{Ipq} L_I Q_p D_q^c + h_u^{pq} H_u Q_p U_q^c \qquad (1)$$

where $L_I = (H_d, L_i)$

$\mu_I = (\mu_0, \mu_i)$, $\frac{1}{2}h_e^{jk} = \lambda^{0jk}$, $\lambda^{ijk} = \lambda^{ijk}$, $\lambda'^{0pq} = h_d^{pq}$, $\lambda'^{ipq} = \lambda^{ipq}$.
$\frac{1}{2}h_\tau = \lambda_\tau^{01}$, $\lambda_b^0 = h_b$,

- In a generic basis, we write the superpotential for one generation as

$$W = \mu^I H_u L_I + \lambda^{IJ} L_I L_J E^c + \lambda^I L_I Q D^c + h_t H_u Q U^c \qquad (2)$$

and the soft SUSY breaking terms as

$$\begin{aligned} V_{soft} &= m_u^2 H_u^\dagger H_u + L^{I\dagger}[\tilde{m}_L^2]_{IJ} L^J + B^I H_u L_I \\ &+ A_t H_u Q U^c + A_I^b L^I Q D^c + A_\tau^{IJ} L_I L_J E^c + h.c. \quad . \end{aligned}$$

$$B_I \neq B\mu_I \qquad (3)$$

Basis Invariants

$$\delta_\mu^i = \frac{\vec{\mu} \cdot \lambda^i \cdot \vec{v}}{|\vec{\mu}| m_i^e} \to \frac{\mu_i}{\mu_4} \tag{2}$$

$$\delta_{\lambda'}^{ipq} = \frac{\vec{\lambda}'^{pq} \cdot \lambda^i \cdot \vec{v}}{m_i^e} \to \lambda'^{ipq} \tag{3}$$

$$\delta_B^i = \frac{\vec{B} \cdot \lambda^i \cdot \vec{v}}{|\vec{B}| m_i^e} \to \frac{B_i}{B_4} \tag{4}$$

$$\delta_\lambda^{ijk} = \frac{\vec{v} \cdot \lambda^i \lambda^k \lambda^j \cdot \vec{v}}{m_i^e m_j^e} \to \lambda^{ijk} \tag{5}$$

We calculate the neutrino mass matrix elements by:

- basis-independent calculation of one-loop diagrams propagating MSSM mass eigenstates
- bilinear R-parity violating masses are included in the mass insertion approximation (ν masses are small, can be done perturbatively)

$\hookrightarrow$ direct constraint on RPV from ν data.

δ_μ is equivalent to

$$\sin\zeta = \frac{\mu_I \times v_I}{|\mu||v|}$$

ν's $\left\{ \begin{array}{l} \text{Hall, Suzuki} \\ \text{Nowakowski, Pilaftsis} \\ \text{Banks et al,} \\ \text{Nardi} \\ \text{de Carlos, White} \\ \text{Valle et al} \\ \vdots \end{array} \right.$

Tree level neutrino mass is non-zero if $\delta_\mu \neq 0$:

$$m_\nu^{tree} = -(\vec{\mu} \cdot \hat{L}_i) \sum_\alpha \frac{Z^*_{\alpha 3} Z^*_{\alpha 3}}{m_{\chi_\alpha}} (\vec{\mu} \cdot \hat{L}_j), \tag{6}$$

which gives a mass

$$m_3^{tree} = \sum_{i,\alpha} (\delta^i_\mu)^2 Z^{*2}_{\alpha 3} |\mu|^2 / m_{\chi_\alpha} \tag{7}$$

$$\hat{\nu}_3^{tree} = \frac{\delta^i_\mu}{\delta_\mu} \hat{L}_i, \tag{8}$$

where $\delta_\mu = \sqrt{\Sigma_i (\delta^i_\mu)^2}$, $\hat{L}_i = \frac{\lambda^i \cdot \vec{v}}{|\lambda^i \cdot \vec{v}|}$

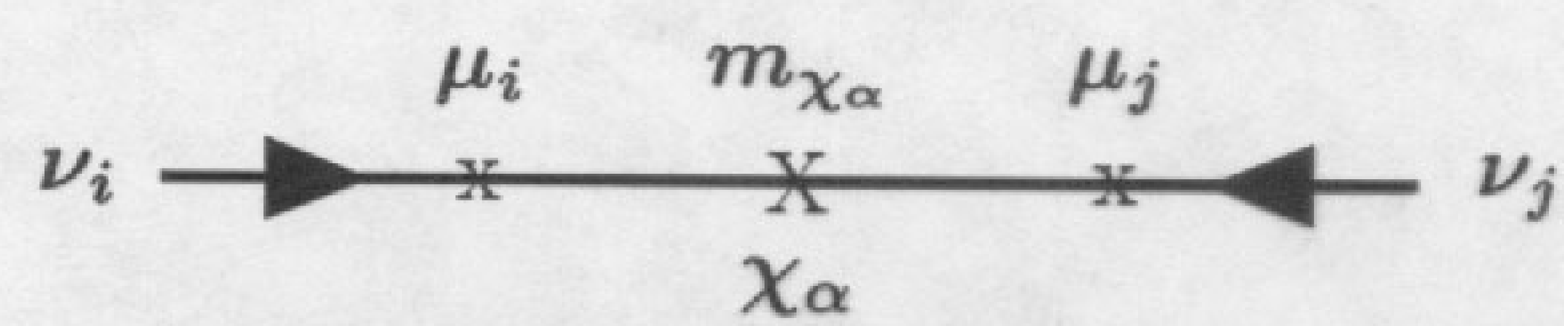


Figure 1: Tree-level neutrino mass in the mass insertion approximation

Diagrams

- two scalar-fermion-fermion couplings at the vertices of the loop
- two $\Delta L = 1$ interactions
- loop can contain coloured or colour-singlet charged or neutral particles
- either two gauge couplings, one gauge and one Yukawa/trilinear, or two Yukawa/trilinear couplings at the vertices
- neutral loop can only have two gauge couplings
- charged loop cannot have two gauge couplings as $\Delta L = 2$ is forbidden on a charged line.
- charged loop can have one gauge and one Yukawa at the vertices. Need gaugino-lepton mixing on fermion line.

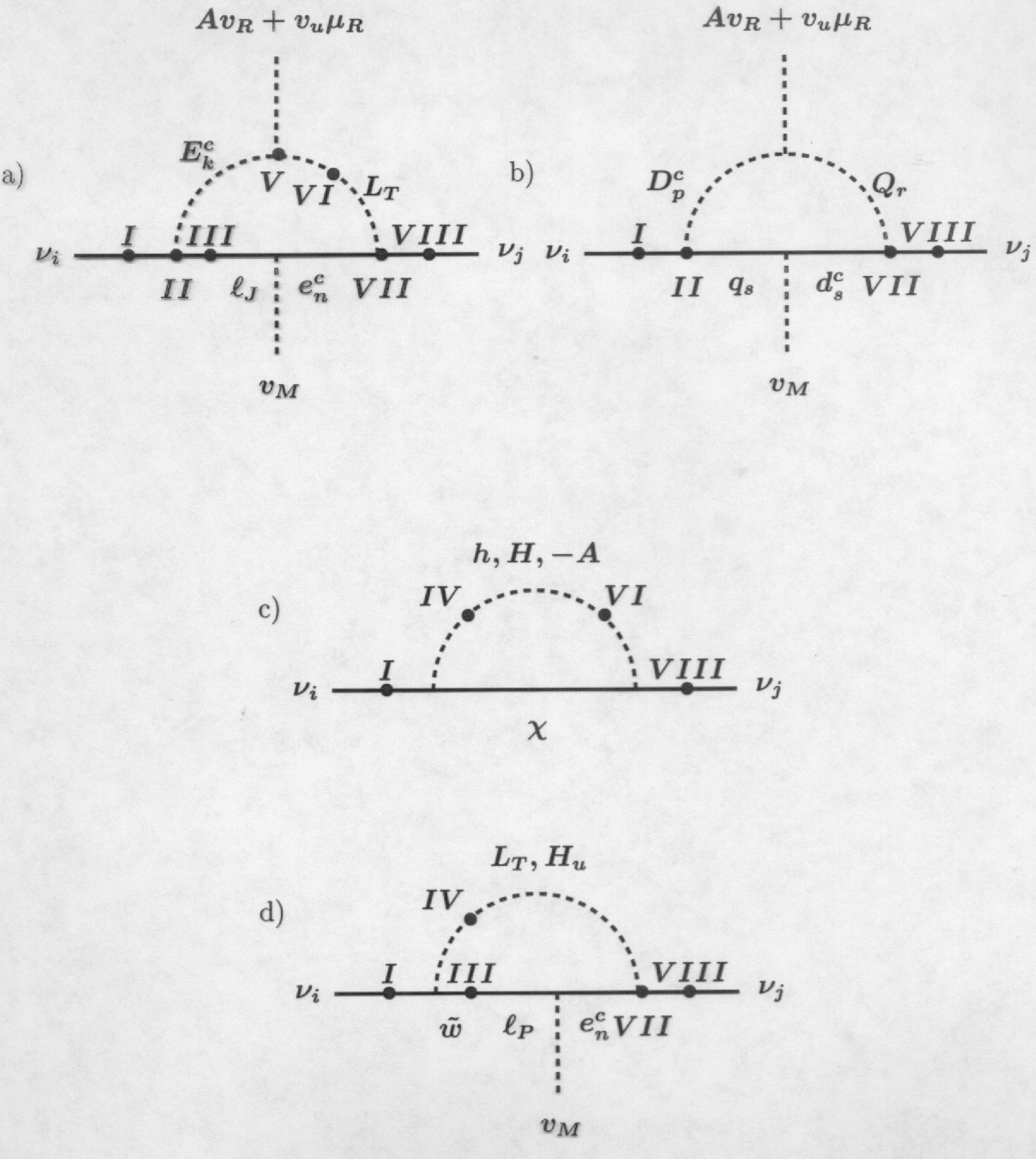
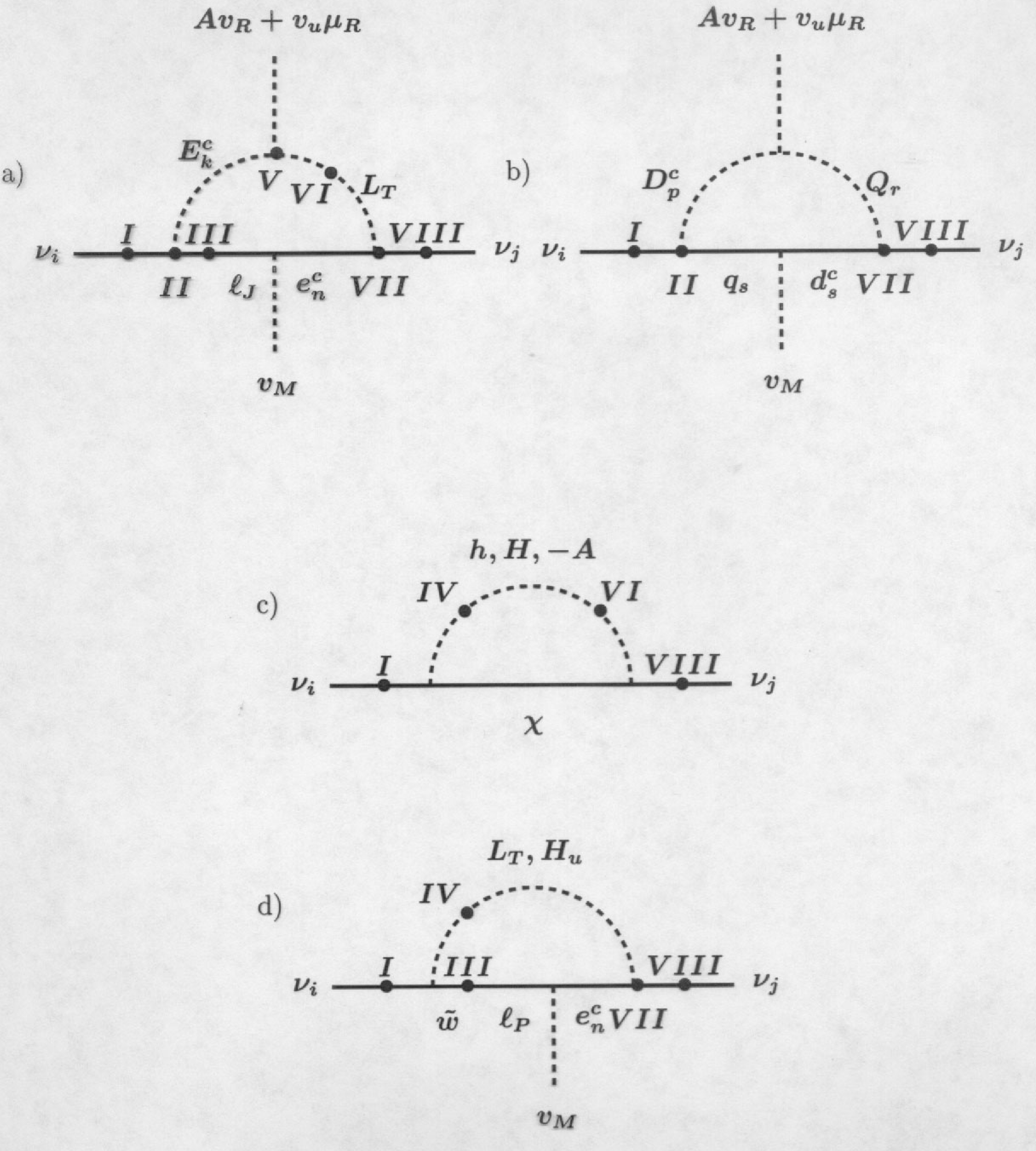


Figure 2: Schematic representation of one-loop diagrams contributing to neutrino masses. The blobs indicate possible positions for $\not{R}_p$ interactions, which can be trilinears (at positions II and VII) or mass insertions. The misalignment between $\vec{\mu}$ and $\vec{v}$ allows a mass insertion on the lepton/higgsino lines (at points I, III, or VIII) and at the A-term on the scalar line (position V). The soft $\not{R}_p$ masses appear as mass insertions at positions VI and IV on the scalar line. Figure a) corresponds to the charged loop with trilinear couplings λ (or h_e) at the vertices. Figure b) is the coloured loops with trilinear λ' or yukawa h_b couplings. Figure c) is the neutral loops with two gauge couplings, and figure d) corresponds to the charged loop with one gauge and a Yukawa coupling. This diagram occurs if gauginos mix with charged leptons—that is if $\delta_{..} \neq 0$. See also figure 3.



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No.	diagram	position of $\not{R}_p$	$16\pi^2 m_{SUSY}[m_v]^{ij}$
1	a	$II \quad VII$	$\delta_\lambda^{ink}\delta_\lambda^{jkn} m_{e_n} m_{e_k}$
2	b	$II \quad VII$	$3\delta_{\lambda'}^{iqq}\delta_{\lambda'}^{jqq}(m_{d_q})^2$
3	c	$IV \quad VI$	$g^2\delta_B^i\delta_B^j m_\chi m_{SUSY}/4$
4	b	$I \ VII + II \ VIII$	$3(\delta_\mu^i\delta_{\lambda'}^{jqq} + \delta_\mu^j\delta_{\lambda'}^{iqq})(m_{d_q})^2 h_d^q$
5	a	$II \quad VI$	$\delta_\lambda^{ijk} m_{e_k}\delta_B^k(m_{e_j}h_e^j - m_{e_i}h_e^i)$
6	a	$I \ VII + II \ VIII$	$(\delta_\mu^i\delta_\lambda^{jkk} + \delta_\mu^j\delta_\lambda^{ikk})(m_{e_k})^2 h_e^k$
7	a	$I \quad V$	$\delta_\mu^i\delta_\mu^j((m_{e_j}h_e^j)^2 + (m_{e_i}h_e^i)^2)$
8	a	$II \quad V$	$\delta_\lambda^{ijk}\delta_\mu^k m_{e_k}(h_e^i m_{e_i} - h_e^j m_{e_j})$
9	a	$III \quad V$	$\delta_\mu^i\delta_\mu^j m_{e_j} m_{e_i} h_e^i h_e^j$
10	a	$III \quad VIII$	$\delta_\mu^i\delta_\mu^j((m_{e_i}h_e^i)^2 + (m_{e_j}h_e^j)^2)$
11	a	$I \quad VI$	$\delta_\mu^i\delta_B^j(m_{e_j}h_e^j)^2 + \delta_\mu^j\delta_B^i(m_{e_i}h_e^i)^2$
12	a	$III \quad VII$	$\delta_\lambda^{jin}\delta_\mu^n m_{e_n}(m_{e_j}h_e^j - m_{e_i}h_e^i)$
13	a	$III \quad VI$	$(\delta_B^i\delta_\mu^j h_e^j h_e^i m_{e_i} m_{e_j} + \delta_B^j\delta_\mu^i h_e^i h_e^j m_{e_j} m_{e_i})$
14	d	$III \quad IV$	$g(\delta_B^i\delta_\mu^j(m_{e_j})^2 + \delta_B^j\delta_\mu^i(m_{e_i})^2)$
15	d	$III \quad VIII$	$g\delta_\mu^i\delta_\mu^j((m_{e_i})^2 + (m_{e_j})^2)$
16	d	$I \quad III$	$g\delta_\mu^i\delta_\mu^j((m_{e_i})^2 + (m_{e_j})^2)$
17	d	$I \quad VII$	$g m_{e_k} m_{SUSY}(\delta_\mu^i\delta_\lambda^{jkk} + \delta_\mu^j\delta_\lambda^{ikk})$ $3g m_{d_k} m_{SUSY}(\delta_\mu^i\delta_{\lambda'}^{jkk} + \delta_\mu^j\delta_{\lambda'}^{ikk})$
18	d	$III \quad VII$	zero for degenerate sleptons
19	c	$I \ VI + IV \ VIII$	$g^2 m_{SUSY}^2(\delta_B^i\delta_\mu^j + \delta_\mu^i\delta_B^j)/4$
20	d	$I \quad V$	$g\delta_\mu^i\delta_\mu^j((m_{e_i})^2 + (m_{e_j})^2)$
21	d	$I \quad IV$	$g(\delta_\mu^i\delta_B^j(m_{e_j})^2 + \delta_\mu^j\delta_B^i(m_{e_i})^2)$

Table 2: Estimated contributions to $[m_\nu]^{ij}$ from all the diagrams. In the second two columns is the label of the diagram of figure 2, and the position on the diagram of the two $\Delta L = 1$ interactions. Column four is the "basis independent" estimated contribution to the neutrino mass matrix in the flavour basis. All indices other than i and j are summed.

Phenomenology

Neutrinos

Experiment	Δm^2 (eV^2)	$\sin^2 2\theta$	$\tan^2\theta$
Atmospheric	$(2-5)\times 10^{-3}$	$0.88-1$	–
MSW-LMA	$(2-70)\times 10^{-5}$	$0.6 - 1$	$(2-40)\times 10^{-1}$
MSW-SMA	$(0.4-1)\times 10^{-5}$	$10^{-3} - 10^{-2}$	$(1-30)\times 10^{-4}$
MSW-LOW	$4\times 10^{-10}-2\times 10^{-7}$	$0.7 - 1$	$(1-80)\times 10^{-1}$
Vacuum	$(1-6)\times 10^{-10}$	$0.5 - 1$	$(1-90)\times 10^{-1}$
Just-so	$(4-10)\times 10^{-12}$	$0.5 - 1$	$(3-30)\times 10^{-1}$
CHOOZ	$>3\times 10^{-3}$	<0.22	

Table 1: Allowed mass squared differences and mixing angles for MSW-LMA, MSW-SMA, MSW-LOW, Vacuum and Just-so oscillation solutions. Chooz bound also shown. SNO data included.

The 3×3 rotation matrix from neutrino flavour (f) to mass (m) eigenstates can be parametrised by three rotations: $V_{fm} = R_{23}(\theta_{23})R_{13}(\theta_{13})R_{12}(\theta_{12})$. Neglecting Majorana and Dirac phases,

$$V_{fm} \equiv \begin{bmatrix} c_{12}c_{13} & c_{13}s_{12} & s_{13} \\ -c_{23}s_{12} - c_{12}s_{13}s_{23} & c_{12}c_{23} - s_{12}s_{13}s_{23} & c_{13}s_{23} \\ s_{23}s_{12} - c_{12}c_{23}s_{13} & -c_{12}s_{23} - c_{23}s_{12}s_{13} & c_{13}c_{23} \end{bmatrix}. \tag{9}$$

Soft $\not{R}$

Model B

$$m_\nu = m_\mu^{(0)}\hat{\delta}^i_\mu\hat{\delta}^j_\mu + m_{\mu B}^{(0)}(\hat{\delta}^i_\mu\hat{\delta}^j_B + \hat{\delta}^i_B\hat{\delta}^j_\mu) + m_B^{(0)}\hat{\delta}^i_B\hat{\delta}^j_B \tag{14}$$

where

$$\begin{aligned} m_\mu^{(0)} &= |\vec{\delta}_\mu|^2 m_{SUSY} \\ m_{\mu B}^{(0)} &= \frac{\alpha}{16\pi}|\vec{\delta}_\mu||\vec{\delta}_B| m_{SUSY} = \sqrt{\frac{\alpha}{16\pi} m_\mu^{(0)} m_B^{(0)}} \\ m_B^{(0)} &= \frac{\alpha}{16\pi}|\vec{\delta}_B|^2 m_{SUSY} \end{aligned}$$

$\alpha = \frac{g^2}{4\pi}$, $\hat{\delta}_\mu$ and $\hat{\delta}_B$ are unit vectors in $\{L^i\}$ space.

$\vec{\delta}_\mu$ and $\vec{\delta}_B$, are not required to be orthogonal. An orthonormal basis would be $\hat{\delta}_\mu$ and $\hat{\delta}_{B_\perp}$ where

$$\delta^i_{B_\perp} = \delta^i_B - (\delta_B \cdot \hat{\delta}_\mu)\hat{\delta}^i_\mu \quad . \tag{15}$$

So m_ν can be written

$$m_\nu \equiv m_\mu \hat{\delta}^i_\mu \hat{\delta}^j_\mu + m_{\mu B}(\hat{\delta}^i_\mu \hat{\delta}^j_{B_\perp} + \hat{\delta}^i_{B_\perp}\hat{\delta}^j_\mu) + m_B \hat{\delta}^i_{B_\perp}\hat{\delta}^j_{B_\perp}$$

$\cos\rho = \hat{\delta}_\mu \cdot \hat{\delta}_B$.

m_ν has two non-zero eigenvalues:

- Hierarchical: $\Delta m^2_{atm} = m_3^2$ and $\Delta m^2_{sol} = m_2^2$
- Pseudo-Dirac: $\Delta m^2_{atm} = m_3^2, m_2^2$ and $\Delta m^2_{sol} = m_3^2 - m_2^2$.

Suppose $(\delta^1_\mu, \delta^2_\mu, \delta^3_\mu)$ is rotated by an angle γ with respect to (V_{13}, V_{23}, V_{33})

$$\frac{\alpha}{16\pi}|\delta_B|^2 m_{SUSY}\sin^2\rho = (\cos^2\gamma m_2 + \sin^2\gamma m_3) \tag{16}$$

$$|\delta_\mu|^2 m_{SUSY}\left(1 - \frac{\alpha}{16\pi}\right) = \frac{m_2 m_3}{\cos^2\gamma m_2 + \sin^2\gamma m_3} \tag{17}$$

$$\cot\rho = \frac{\cos\gamma\sin\gamma(m_2 - m_3)}{\cos^2\gamma m_2 + \sin^2\gamma m_3} - \sqrt{\frac{\alpha}{16\pi}\frac{m_2 m_3}{(\cos^2\gamma m_2 + \sin^2\gamma m_3)^2}} \tag{18}$$

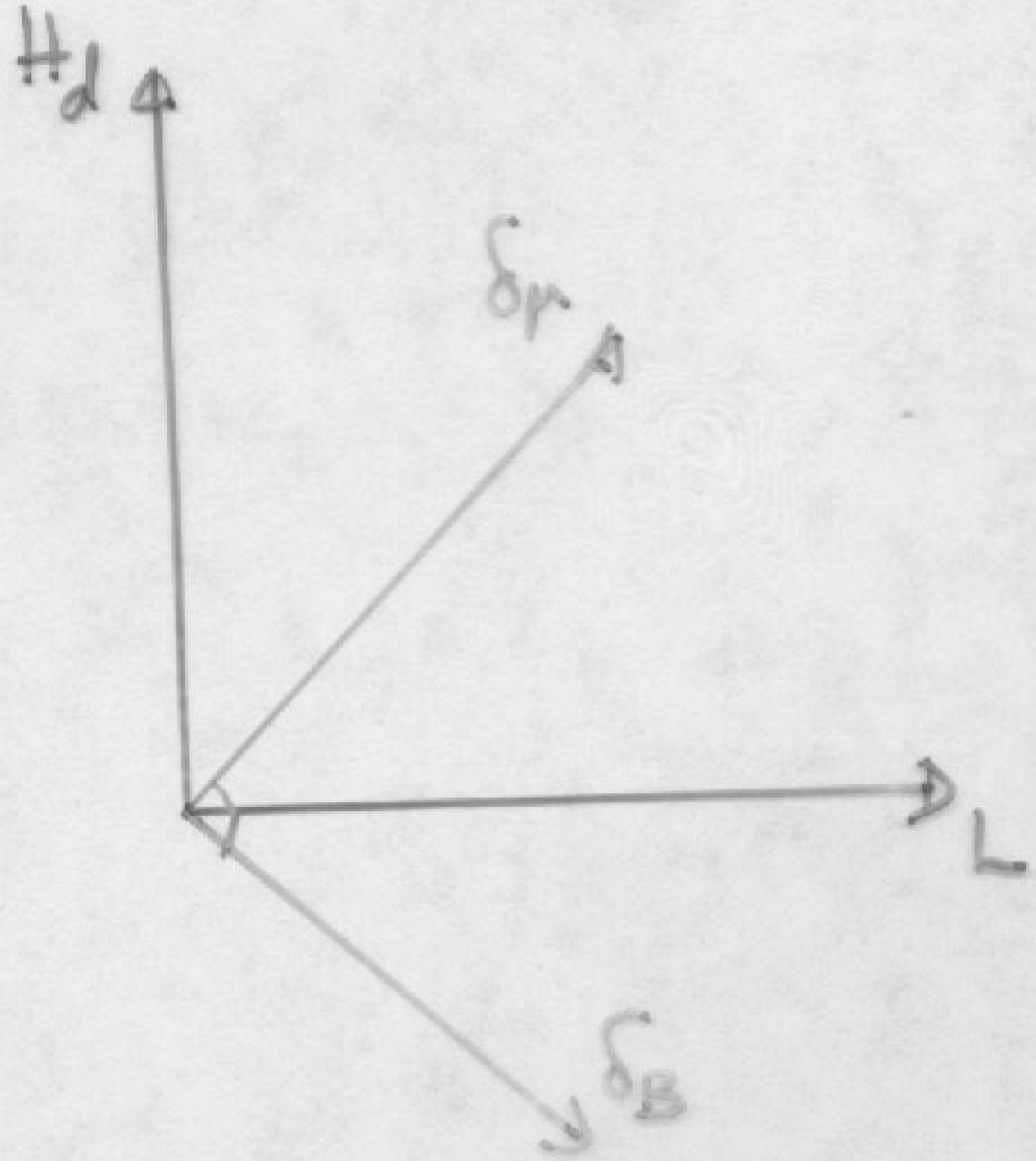
$$\frac{1}{|\delta_\mu|}\delta^f_\mu = \cos\gamma V_{f3} + \sin\gamma V_{f2} \tag{19}$$

$$\frac{1}{|\delta_{B_\perp}|}\delta^f_{B_\perp} = -\sin\gamma V_{f3} + \cos\gamma V_{f2} \tag{20}$$

Degenerate spectrum

$$m_2 \sim m_3 \sim \sqrt{\Delta m^2_{atm}}$$

$$\Rightarrow \rho \sim \pm \pi/2$$



$$\rightsquigarrow \quad \frac{\alpha}{16\pi} |\delta_B|^2 \simeq |\delta_\mu|^2 \simeq \frac{\sqrt{\Delta m^2_{atm}}}{m_{susy}}$$

Hierarchical spectrum

CHOOZ requires

$V_{e3} = \cos\gamma\hat{\delta}^e_\mu - \sin\gamma\hat{\delta}^e_{B_\perp} \lesssim .1$.

- LMA: $V_{e2} \sim 1/\sqrt{2}$
  so $\delta^e_\mu \simeq \frac{1}{\sqrt{2}}\sin\gamma$, and $\delta^e_{B_\perp} \simeq \frac{1}{\sqrt{2}}\cos\gamma$
  V_{e3} is small due to a cancellation between δ^e_μ and $\delta^e_{B_\perp}$.
- SMA: both δ^e_μ and $\delta^e_{B_\perp}$ may be small.

  Cosmological attractive: would allow a BAU produced before the electroweak phase transition to survive.

  Primordial asymmetry stored in a conserved quantum number to survive.

  For $B/3 - L_e$ to be effectively conserved before the phase transition,

$$B_4\mu^e - \mu_4 B^e \lesssim 2\times 10^{-7}|\mu||B| \qquad (21)$$

For $\delta_\mu \sim 10^{-6}$, $\delta_B \sim 10^{-4}$, to generate the atmospheric and SMA solar masses, this is satisfied for $\hat{\delta}^e_\mu \lesssim .1$ or $\hat{\delta}^e_B \lesssim 2\times 10^{-3}$.

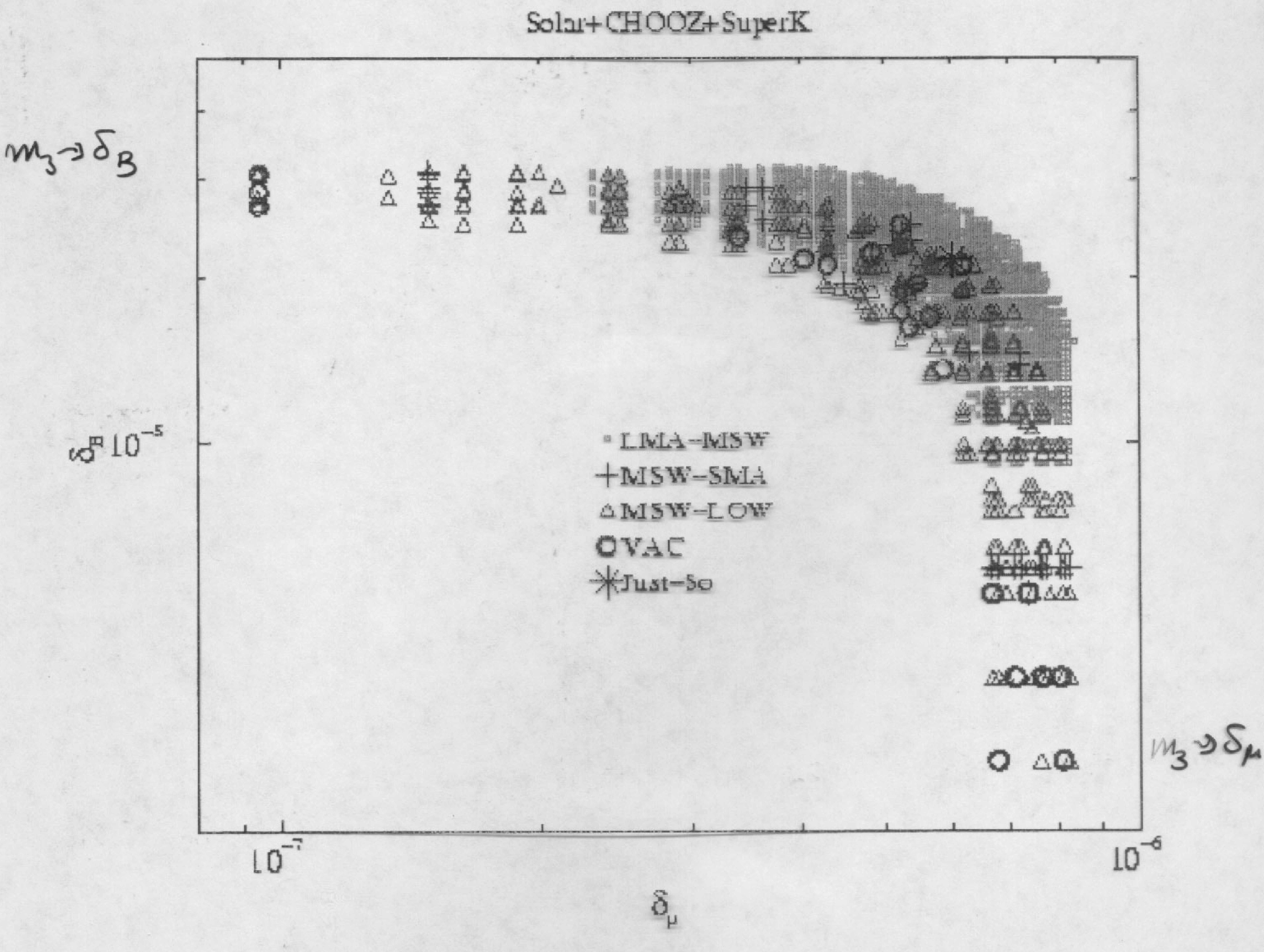
- For a hierarchical spectrum, for small values of angle γ

$$\cos^2 \gamma m_2 \sim \sin^2 \gamma m_3$$

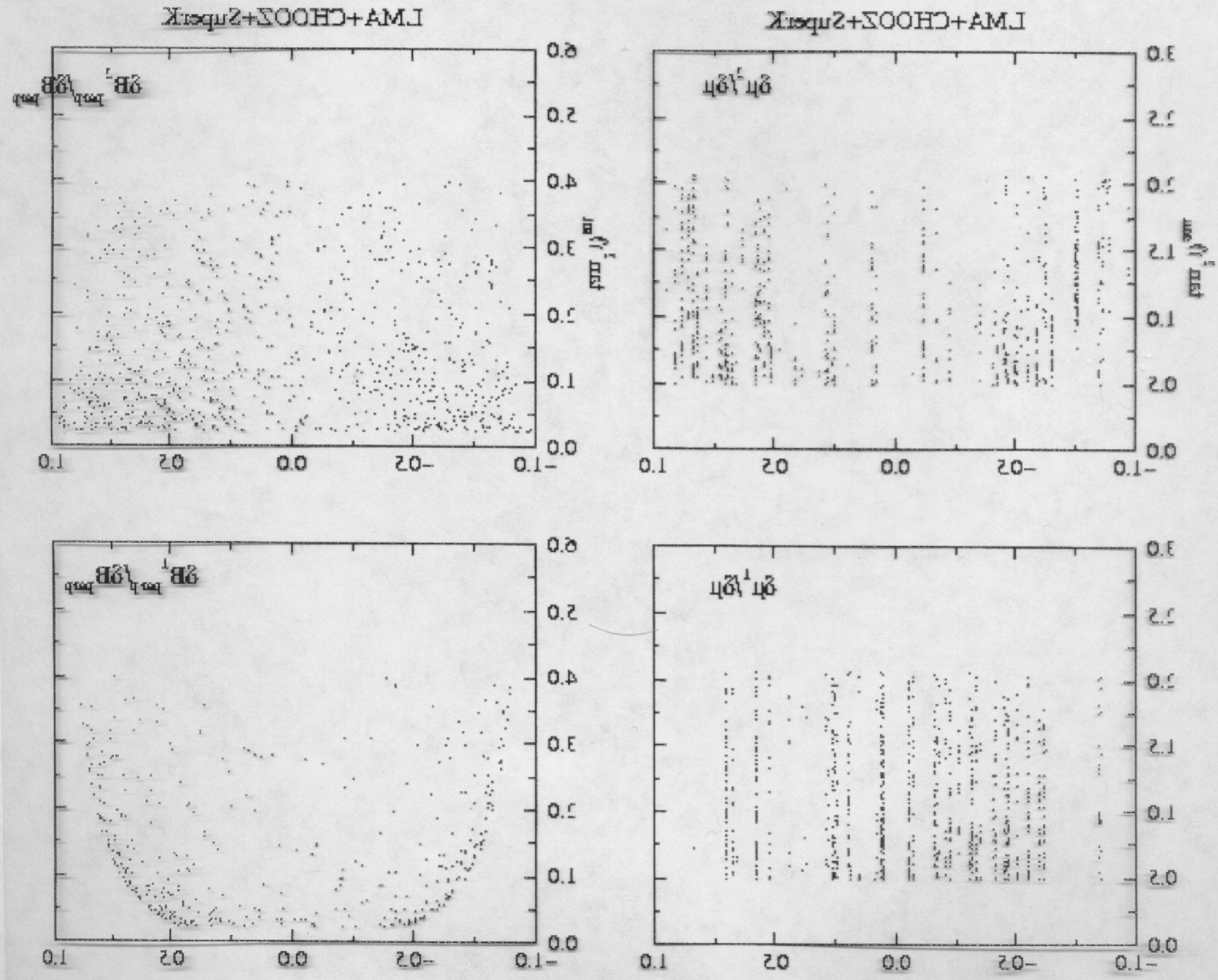
- $|\delta_\mu| \sim m_3 \to (\Delta m^2_{atm})^{1/2}$ θ_{atm} def. $(\delta^\mu_\mu, \delta^\tau_\mu)$
- $|\delta_B| \sim m_2 \to (\Delta m^2_{solar})^{1/2}$.

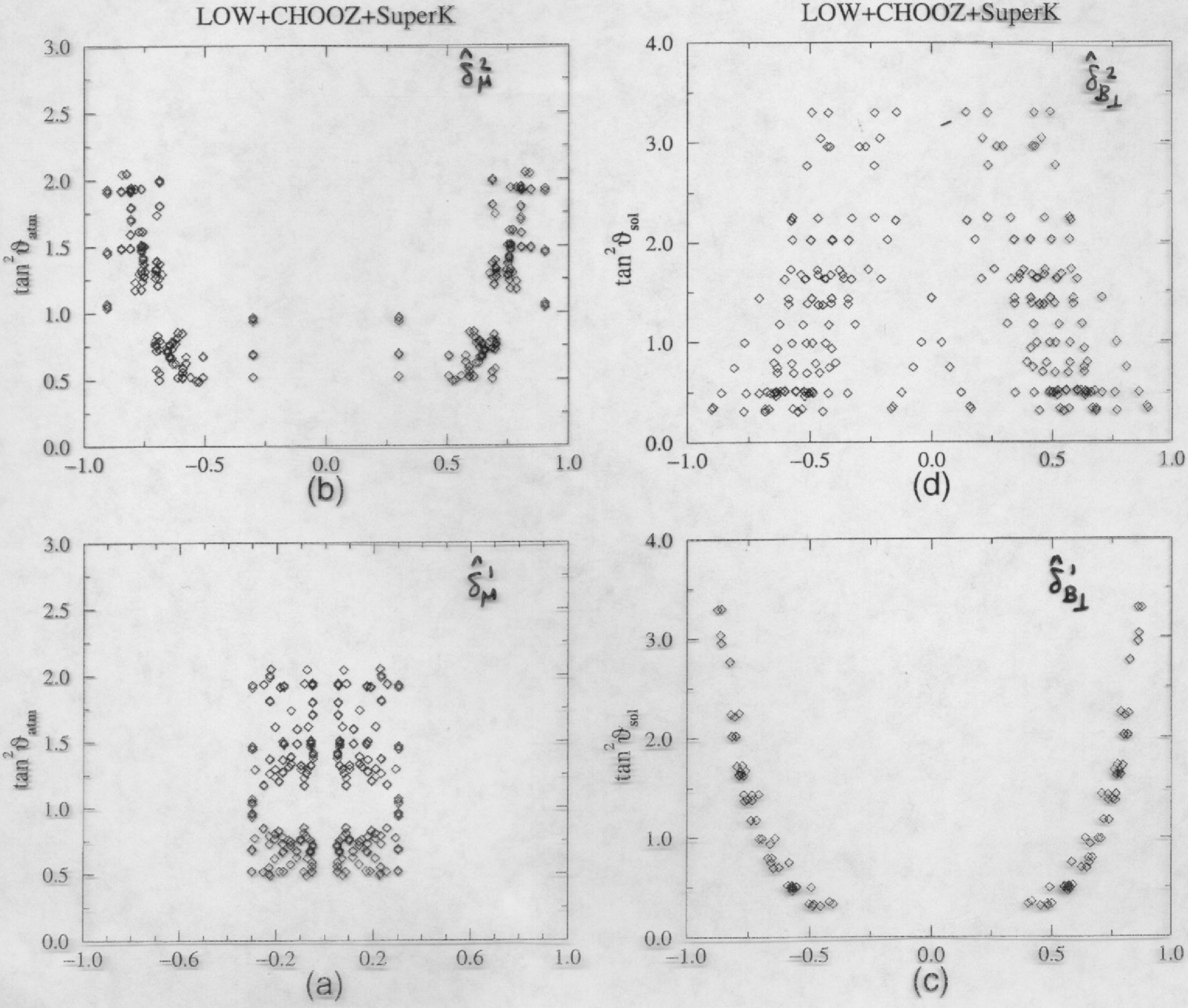
For all other values of γ

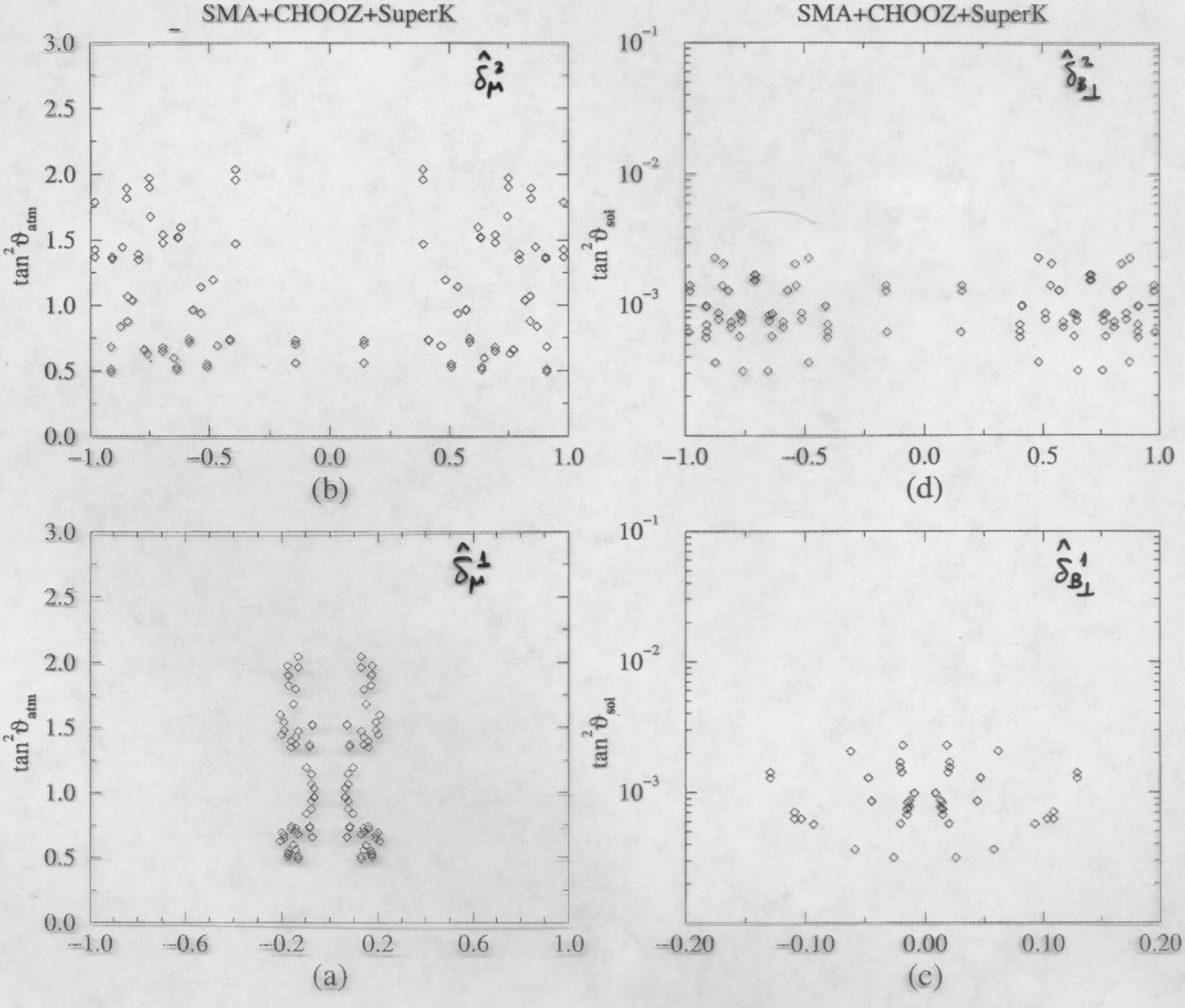
- $|\delta_B| \to (\Delta m^2_{atm})^{1/2}$ θ_{atm} def $(\delta^\mu_{B_\perp}, \delta^\tau_{B_\perp})$
- $|\delta_\mu| \to (\Delta m^2_{solar})^{1/2}$.



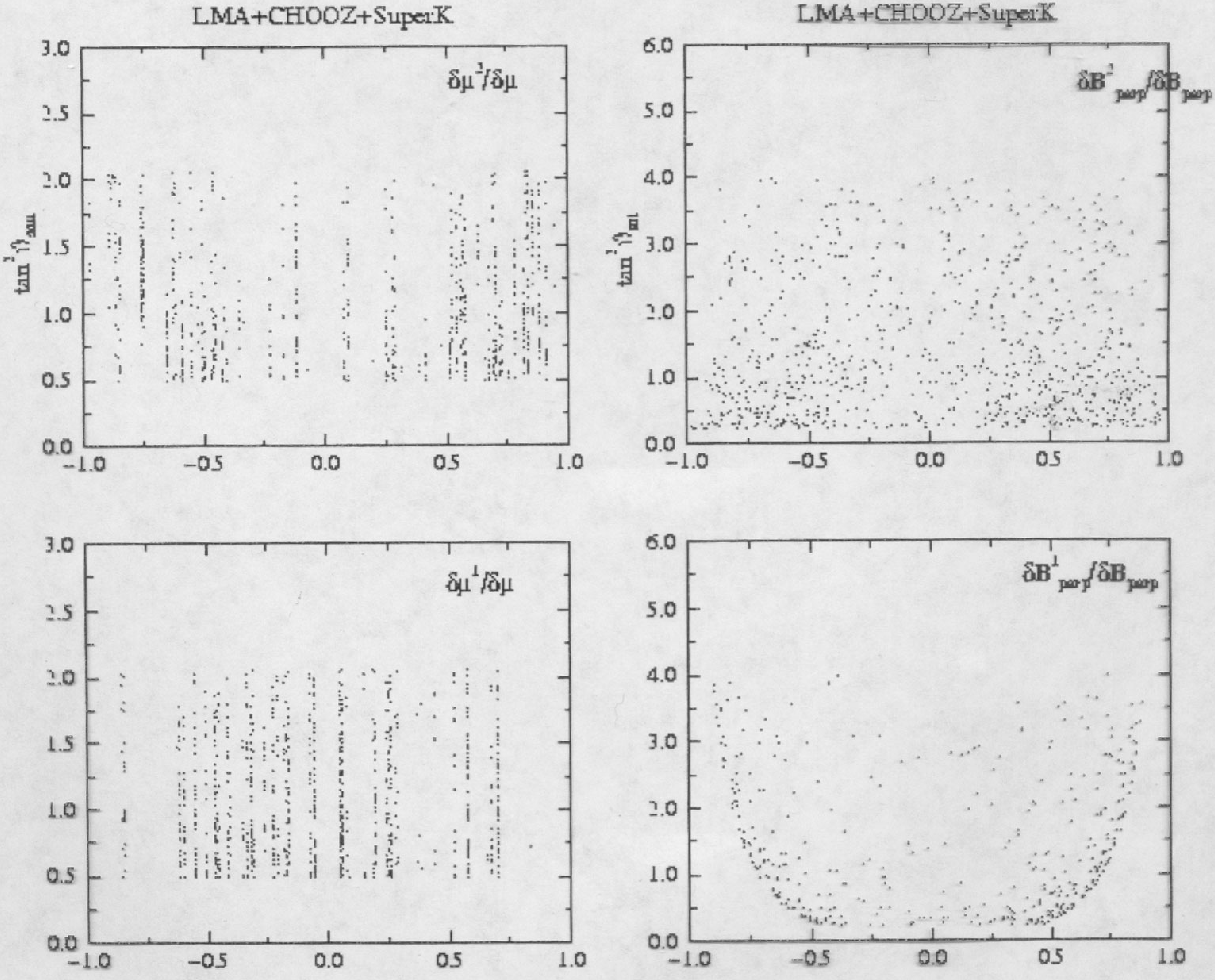
Solar+CHOOZ+SuperK
$m_3 \to \delta_B$
10^{-5}
LMA-MSW
MSW-SMA
MSW-LOW
VAC
Just-So
$m_3 \to \delta_\mu$
10^{-7}
10^{-6}
δ_μ


LMA+CHOOZ+SuperK
LMA+CHOOZ+SuperK


LOW+CHOOZ+SuperK
LOW+CHOOZ+SuperK
$\hat{\delta}^2_\mu$
$\tan^2\vartheta_{atm}$
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−1.0
−0.5
0.0
0.5
1.0
(b)
$\hat{\delta}^2_{B\perp}$
$\tan^2\vartheta_{sol}$
4.0
3.0
2.0
1.0
0.0
−1.0
−0.5
0.0
0.5
1.0
(d)
$\hat{\delta}^1_\mu$
$\tan^2\vartheta_{atm}$
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−1.0
−0.6
−0.2
0.2
0.6
1.0
(a)
$\hat{\delta}^1_{B\perp}$
$\tan^2\vartheta_{sol}$
4.0
3.0
2.0
1.0
0.0
−1.0
−0.5
0.0
0.5
1.0
(c)

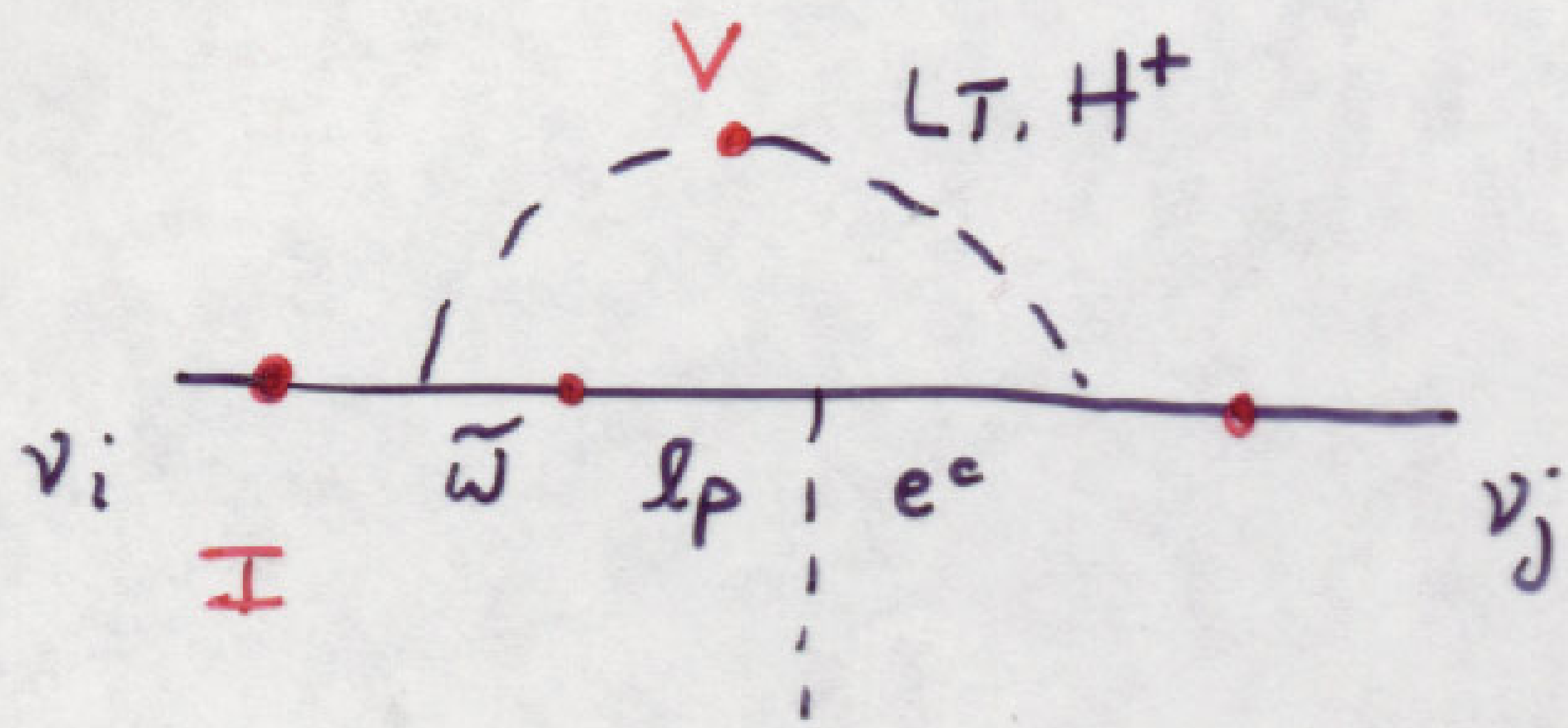


SMA+CHOOZ+SuperK
SMA+CHOOZ+SuperK
$\hat{\delta}^2_\mu$
$\hat{\delta}^2_{B_\perp}$
$\hat{\delta}^1_\mu$
$\hat{\delta}^1_{B_\perp}$
$\tan^2\vartheta_{atm}$
$\tan^2\vartheta_{sol}$
(b)
(d)
(a)
(c)


LMA+CHOOZ+SuperK
LMA+CHOOZ+SuperK
$\delta\mu^2/\delta\mu$
$\delta B^2_{perp}/\delta B_{perp}$
$\tan^2\theta_{atm}$
$\tan^2\theta_{sol}$
$\delta\mu^1/\delta\mu$
$\delta B^1_{perp}/\delta B_{perp}$
0.0
0.5
1.0
1.5
2.0
2.5
3.0
4.0
5.0
6.0
-1.0
-0.5
0.0
0.5
1.0

Model C

Only $\delta_\mu \neq 0$.



To fit atmospheric ν data

m_3 : $|\vec{\delta_\mu}| \sim \dfrac{[\Delta m^2_{atm}]^{1/2}}{m_{susy}}$

$\delta_\mu^\mu \sim \delta_\mu^\tau \gg \delta_\mu^e$
(SK + Chooz)

m_2 : $(I, V) \sim g\, \delta_\mu^i \delta_\mu^j \tan\beta \dfrac{m_{e_j}^2}{16\pi^2 m_{susy}}$

$\Rightarrow \quad m_2 \lesssim m_\nu^{tree} \left(\dfrac{\tan\beta\, h_\tau^2}{8\pi^2} \right)^2$

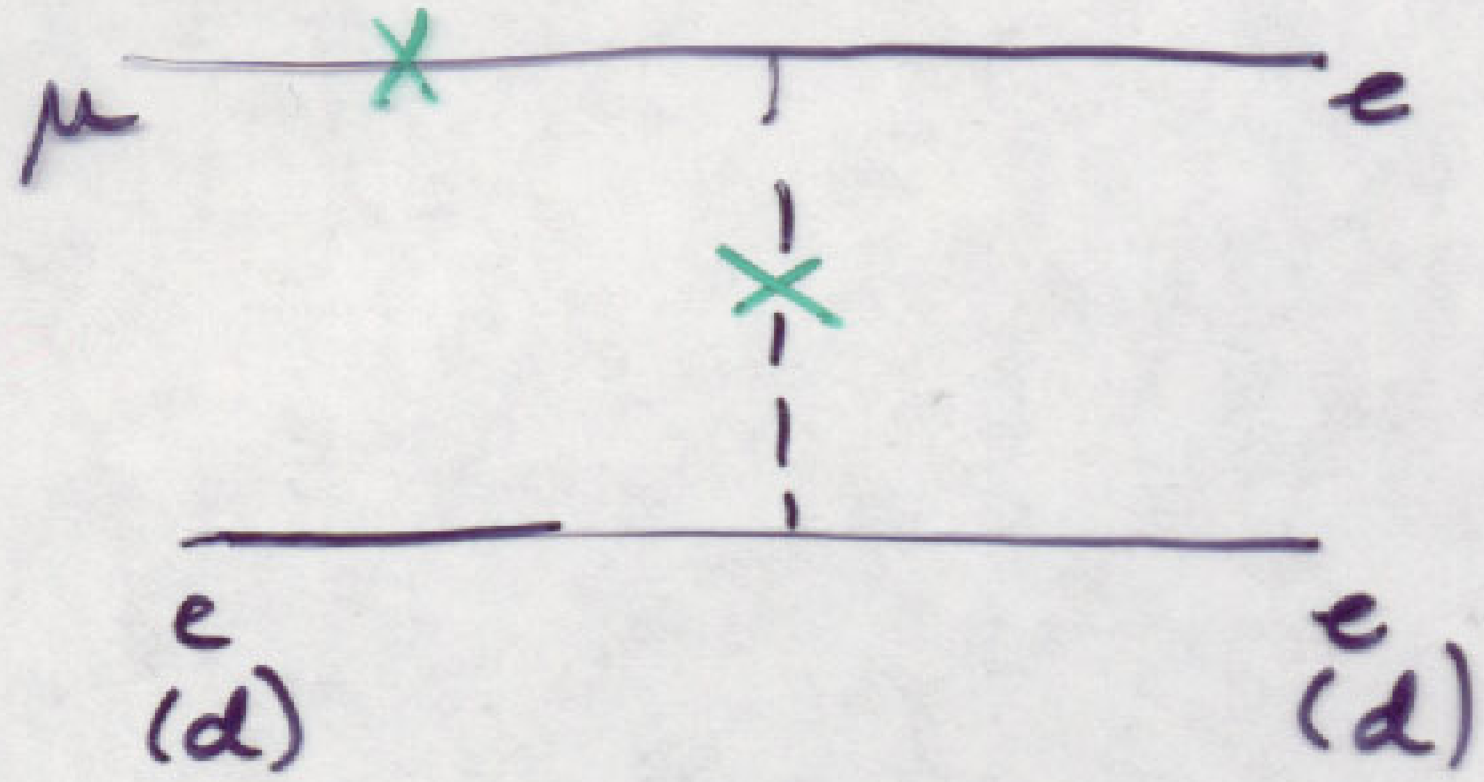
$\hookrightarrow$ for $\tan\beta \sim 50$
$m_2 \sim 10^{-5} m_\nu^{tree}$

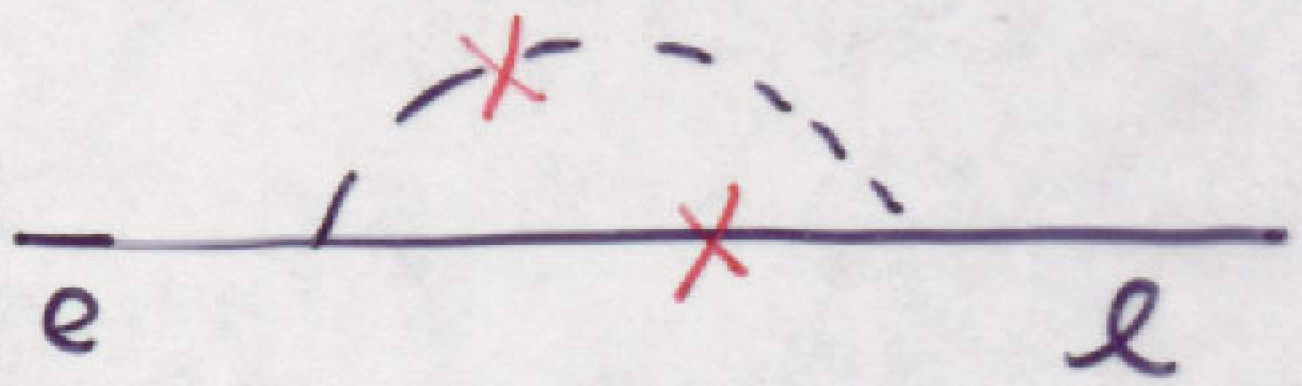
but only small solar angles can be obtained.

LFV Low Energy Processes

$(\mu \to e\gamma)$ $(\mu \to eee)$ ($\mu - e$ conversion)

Tree level



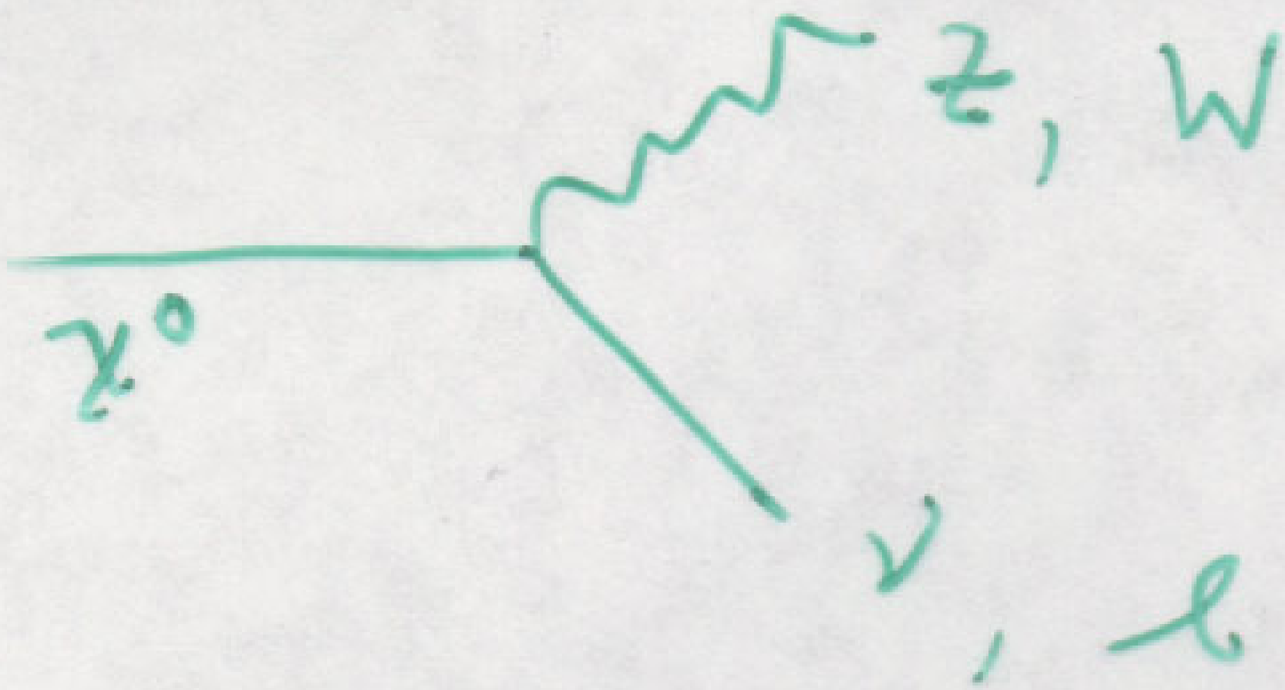


$$A \sim \begin{pmatrix} \delta_\mu^i \delta_B^j \\ \delta_\mu^i \delta_\mu^j \\ \delta_B^i \delta_B^j \end{pmatrix}$$

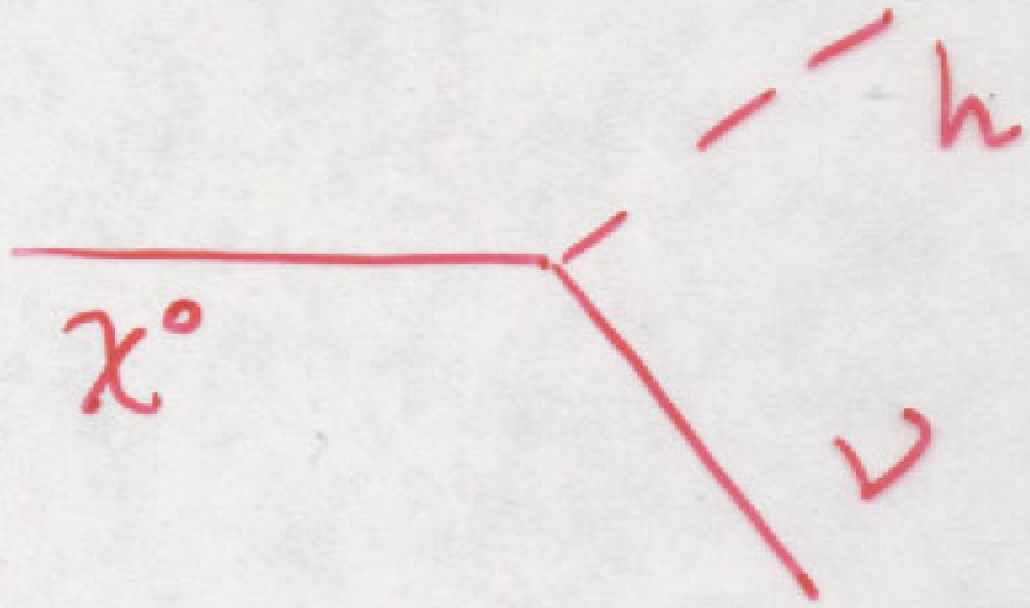
$$\to BR \simeq \frac{1}{G_F^2} \left(\frac{\delta\delta}{m_{susy}^2} \right)^2 \sim 10^{-18}$$

Ratios of BR will be defined according to each combined constraint of Super K + Chooz + ☉.

LSP decays



Mukhopadhyaya, Vissani, Roy



Hempfling

In GMSB

$\tilde{\gamma} \to \gamma\, G$

Carena, Pokorski, Wagner

Higgs decays

Top, stop decays

Conclusions

* We can accomodate the ν oscillation scenario in a model with only soft $\not{R}$ given atmospheric, solar or CHOOZ constraints.

* Low energy LFV processes have BR below current and expected experimental limits.

* Can have signatures at colliders from LSP, Higgs, top, stop decays.