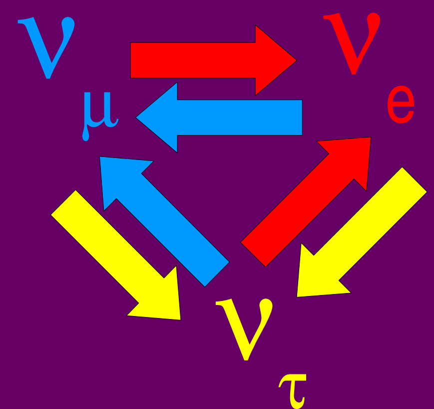
NEUTRINO PHYSICS FROM COLLIDERS



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International School on High Energy Physics
Session C - Wokshop on Collider Physics
Session B - Advanced School on HEP

OUTLINE

- Neutrinos in the Standard Model
- Neutrinos Beyond the Standard Model
- Neutrino Oscillations
- Experimental Evidence
- Connection with Collider Physics

NEUTRINOS IN THE STANDARD MODEL

3 active neutrinos, singlets of $SU(3)_c \otimes U(1)_{em}$

$$L_\ell = \begin{pmatrix} \nu_{L\ell} \\ \ell^-_L \end{pmatrix} \qquad \ell = e, \mu, \tau$$

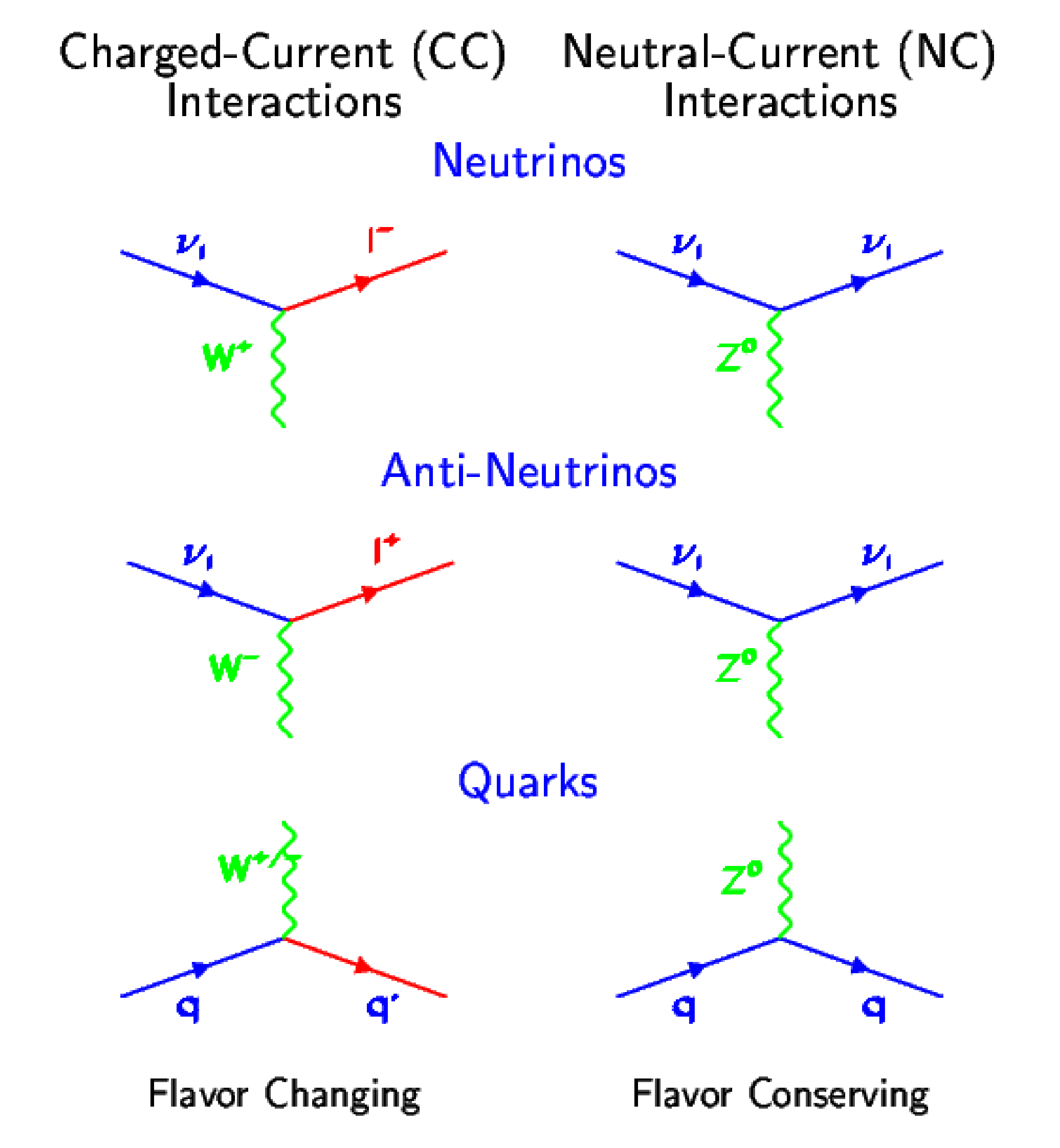
$SU(2)_L$ doublet

$$-\mathcal{L}_{CC} = \frac{g}{\sqrt{2}} \sum_\ell \overline{\nu_{L\ell}} \gamma^\alpha \ell^-_L W^+_\alpha + \mathrm{h.c.}$$

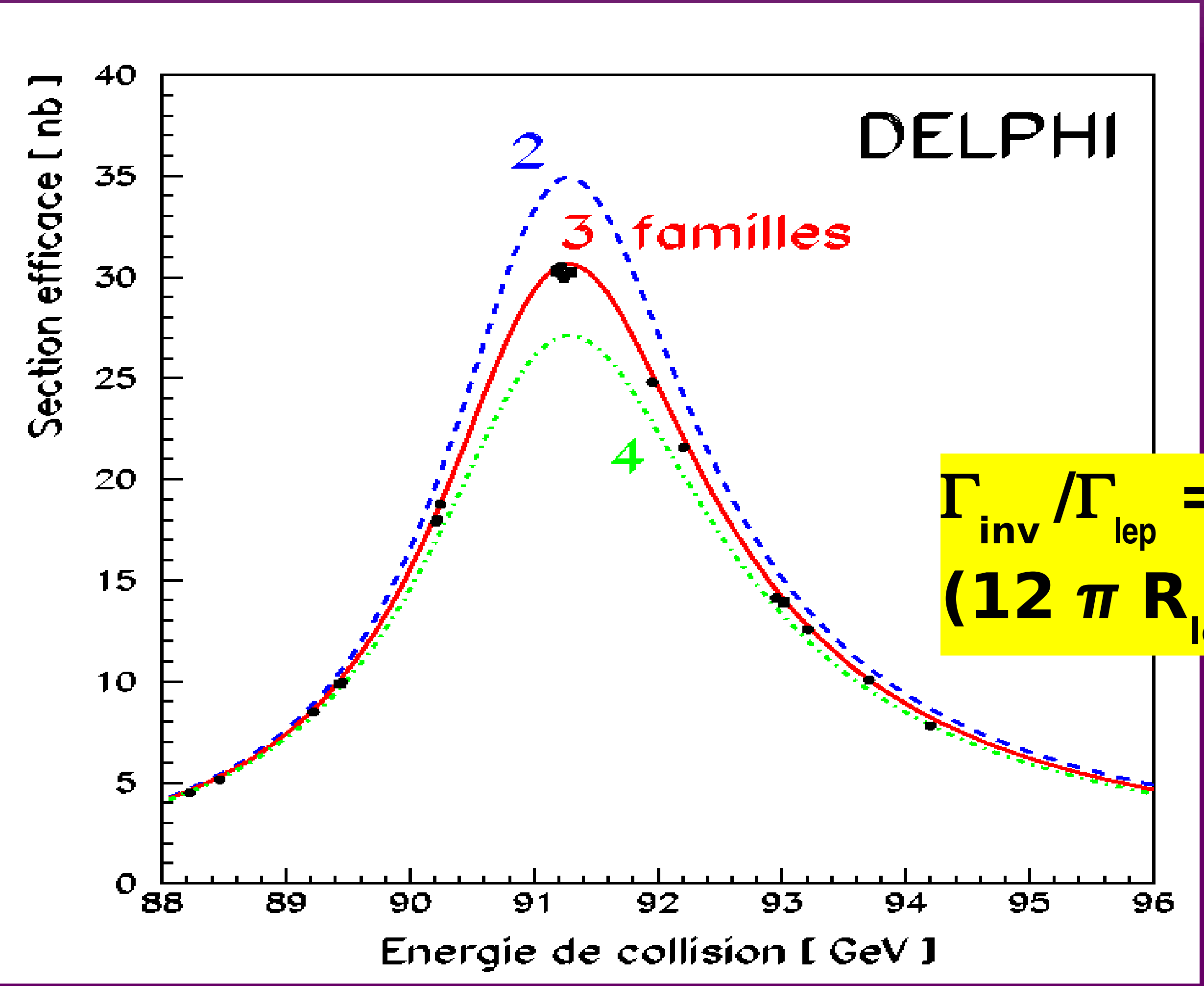
CC interaction

$$-\mathcal{L}_{CN} = \frac{g}{2\cos\theta_W} \sum_\ell \overline{\nu_{L\ell}} \gamma^\alpha \nu_{L\ell} Z^0_\alpha$$

NC interaction


Charged-Current (CC) Interactions
Neutral-Current (NC) Interactions
Neutrinos
ν_l
l^-
W^+
ν_l
ν_l
Z^0
Anti-Neutrinos
ν_l
l^+
W^-
ν_l
ν_l
Z^0
Quarks
$W^{+/-}$
q
q'
Z^0
q
q
Flavor Changing
Flavor Conserving

Number of Neutrinos from LEP



$\Gamma_{inv} = \Gamma_z - \Gamma_{had} - 3\ \Gamma_{lep}$

$\Gamma_{inv}/\Gamma_{lep} =$
$(12\,\pi\, R_{lep}/M_Z^2\, \sigma_{had})^{1/2} - R_{lep} - 3$

$R_{lep} = \Gamma_{had} / \Gamma_{lep}$

Z^0 partial width to invisible final state @LEP (90's) $\rightarrow$ 3 active ν's

$N_\nu = 3.00 \pm 0.07$ (direct meas.) **$N_\nu = 2.994 \pm 0.012$ (SM fit)**

NEUTRINOS IN THE STANDARD MODEL

$$G^{\rm SM} = SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$$

fermion masses arise from

$$-\mathcal{L}_{\rm Yukawa} = Y^{\ell}_{\ell_i \ell_j} \overline{L_{L\ell_i}} \phi E_{R\ell_j} + {\rm h.c.}$$

$$E_R = \ell_R$$

$$\langle \phi \rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix}$$

⟹ $G^{\rm SM} \to SU(3)_c \otimes U(1)_{em}$

loop corrections

~~$$\frac{Y_{ij}}{v} \phi \phi L_{Li} L_{Lj}$$~~

accidental symmetry

$$G^{\rm global} = U_B \otimes U_e \otimes U_\mu \otimes U_\tau$$

Neutrinos are massless in the SM !

NEUTRINOS BEYOND THE STANDARD MODEL

Q = 0

$$\nu \neq \nu^c$$

Dirac Neutrinos

$$\nu = \nu^c = C\bar{\nu}^T$$

Majorana Neutrinos

NEUTRINOS BEYOND THE STANDARD MODEL

$$\nu = \begin{pmatrix} \chi_R \\ \chi_L \end{pmatrix}$$

$$\nu^c = \begin{pmatrix} -i\sigma^2 \chi_L^* \\ i\sigma^2 \chi_R^* \end{pmatrix}$$

Dirac Fermion : needs independent left and right chiral projections

$$\nu^D = \begin{pmatrix} \phi_R \\ \phi_L \end{pmatrix} = \begin{pmatrix} 0 \\ \phi_L \end{pmatrix} + \begin{pmatrix} \phi_R \\ 0 \end{pmatrix} = \nu_L + \nu_R$$

Majorana Fermion : needs only one independent chiral projection

$$\nu^M = \begin{pmatrix} -i\sigma^2 \chi_L^* \\ \chi_L \end{pmatrix} = \begin{pmatrix} 0 \\ \chi_L \end{pmatrix} + \begin{pmatrix} -i\sigma^2 \chi_L^* \\ 0 \end{pmatrix} = \nu_L + \nu_L^c$$

NEUTRINOS BEYOND THE STANDARD MODEL

Most General Neutrino Mass Term

$$\mathcal{L}^{D+M} = \mathcal{L}_L^M + \mathcal{L}_R^M + \mathcal{L}^D$$

$$\mathcal{L}^{D+M} = -\frac{1}{2}\left(\bar{\nu}_L^c \, \bar{\nu}_R\right) \begin{pmatrix} m_L & m_D \\ m_D^T & m_R \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix} + h.c.$$

NEUTRINOS BEYOND THE STANDARD MODEL

1) SM effective low energy theory (have to consider nonrenormalizable terms)

spontaneous symmetry breaking

$(Z_{ij}/M_{BSM})\ \phi\phi\ L_{Li}\ L_{Lj} \Longrightarrow (M)_{ij} = Z_{ij}\ v^2/(2\ M_{BMS})$

the source of this term is some new heavy field (tree level or loop)

- ★ extensions of SM generally imply neutrino mass
- ★ understand origin and smallness of neutrino mass
- ★ term violates L (total and flavor) → lepton mixing

NEUTRINOS BEYOND THE STANDARD MODEL

2) adding new fields

$\nu_{s1}, \nu_{s2}, \nu_{s3}, \nu_{s4}, \nu_{s5}, \ldots, \nu_{sm}$ **m sterile neutrinos**

two types of mass term arise from renormalizable terms

$$-\mathcal{L}_{M_\nu} = M_{D_{ij}} \overline{\nu_{Li}} \nu_{sj} + \frac{1}{2} M_{M_{ij}} \overline{\nu^c_{si}} \nu_{sj} + \text{h.c}$$

$$-\mathcal{L}_{M_\nu} = \frac{1}{2} \overline{\vec{\nu}^c} M_\nu \vec{\nu} + \text{h.c}$$

$$\vec{\nu} = (\nu_{Li}\ \nu_{sj})^T$$

$$M_\nu = \begin{pmatrix} 0 & M_D \\ M_D^T & M_N \end{pmatrix}$$

complex & symmetric
diagonilized
by U matrix (3+m)

NEUTRINOS BEYOND THE STANDARD MODEL

2) adding new fields

$$-\mathcal{L}_{\mathrm{M}_\nu} = M_{D_{ij}} \overline{\nu_{Li}} \nu_{sj} + \frac{1}{2} M_{M_{ij}} \overline{\nu^c_{si}} \nu_{sj} + \mathrm{h.c}$$

Dirac Mass Term

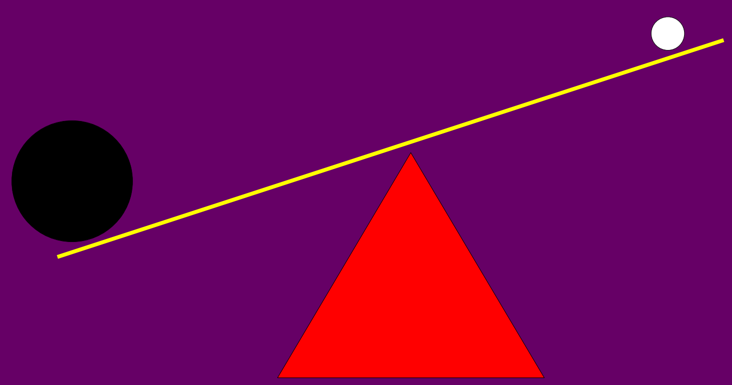
- Transform as $SU(2)_L$ doublet: generated after spontaneous symmetry breaking from a Yukawa term
- Conserves total L (but not flavor L)

Majorana Mass Term

- Singlet of G^{SM} : can appear as a bare mass term
- Breaks L (by 2 units)

NEUTRINOS BEYOND THE STANDARD MODEL

$M_N >> \langle\phi\rangle$: see-saw mechanism *[Ramond (79); Gell-Mann et al. (79); Yanagida (79)]*



$m_1 \approx M_N$

$m_2 \approx m_D^2 / M_N$

$$M_\nu = \begin{pmatrix} 0 & M_D \\ M_D^T & M_N \end{pmatrix}$$

NEUTRINOS BEYOND THE STANDARD MODEL

mass eigenstates

$(\nu_1, \nu_2, \nu_3, \ldots \nu_n) \quad n = 3 + m$

(e, μ, τ)

interaction eigenstates

$(\nu_{Le}, \nu_{L\mu}, \nu_{L\tau}, \nu_{s1}, \ldots, \nu_{sm})$

(e^I, μ^I, τ^I)

$$-\mathcal{L}_M = (\overline{e_L^I \mu_L^I \tau_L^I})\, M_\ell \begin{pmatrix} e_R^I \\ \mu_R^I \\ \tau_R^I \end{pmatrix} + \frac{1}{2}\overline{\vec{\nu}^c}\, M_\nu\, \vec{\nu} + \text{h.c.}$$

V^ℓ (3x3) unitary

$$V^{\ell\dagger} M_\ell M_\ell^\dagger V^\ell = \text{diag}(m_e^2, m_\mu^2, m_\tau^2)$$

V^ν (nxn) unitary

$$V^{\nu\dagger} M_\nu M_\nu^\dagger V^\nu = \text{diag}(m_1^2, m_2^2, m_3^2, \ldots, m_n^2)$$

NEUTRINOS BEYOND THE STANDARD MODEL

mass eigenstates

$$(\nu_1, \nu_2, \nu_3, \ldots \nu_n) \quad n = 3 + m$$

$$(e, \mu, \tau)$$

interaction eigenstates

$$(\nu_{Le}, \nu_{L\mu}, \nu_{L\tau}, \nu_{s1}, \ldots, \nu_{sm})$$

$$(e^I, \mu^I, \tau^I)$$

$$-\mathcal{L}_{\rm CC} = \frac{g}{\sqrt{2}} (\overline{e_{\rm L} \mu_{\rm L} \tau_{\rm L}}) \gamma^\alpha U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ . \\ . \\ \nu_n \end{pmatrix} W_\alpha^- + \mathrm{h.c.}$$

$$U_{ij} = P_{\ell,ii} V^{\ell\dagger}_{ik} V^{\nu}_{kj} (P_{\nu,jj})$$

U mixing matrix

NEUTRINO OSCILLATIONS

[Pontecorvo (57), Maki, Nakagawa, Sakata (62)]

observed eigenstate: $|\nu_\alpha\rangle = \sum_{i=1}^{n} U^*_{\alpha i} |\nu_i\rangle \quad \alpha = e, \mu, \tau$

after travel distance L (L≈ t): $|\nu_\alpha(t)\rangle = \sum_{i=1}^{n} U^*_{\alpha i} |\nu_i(t)\rangle$

$$P_{\alpha\beta} = |\langle \nu_\beta | \nu_\alpha(t)\rangle|^2$$

$$= |\sum_{i=1}^{n} \sum_{j=1}^{n} U^*_{\alpha i} U_{\beta j} \langle \nu_j(0) | \nu_i(t)\rangle|^2$$

neutrinos with mass m_j, energy E_j can be described as

$$|\nu_j(t)\rangle = e^{-\imath E_j t} |\nu_j(0)\rangle$$

NEUTRINO OSCILLATIONS

[Pontecorvo (57), Maki, Nakagawa, Sakata (62)]

$$E_j = \sqrt{p_j^2 + m_j^2} \approx p_j + \frac{m_j^2}{2E_j}$$

$p_i \approx p_j \equiv p \approx E$

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4 \sum_{i-1}^{n-1} \sum_{j-i+1}^{n} \mathrm{Re}\left[U_{\alpha i} U_{\beta i}^{\star} U_{\alpha j}^{\star} U_{\beta j}\right] \sin^2 \Delta_{ij}$$

$$\mp 2 \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \mathrm{Im}\left[U_{\alpha i} U_{\beta i}^{\star} U_{\alpha j}^{\star} U_{\beta j}\right] \sin 2\Delta_{ij}$$

CP-violating term : neutrino (-), antineutrino(+)

NEUTRINO OSCILLATIONS

[Pontecorvo (57), Maki, Nakagawa, Sakata (62)]

$$E_j = \sqrt{p_j^2 + m_j^2} \approx p_j + \frac{m_j^2}{2E_j}$$

$p_i \approx p_j \equiv p \approx E$

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4 \sum_{i-1}^{n-1} \sum_{j-i+1}^{n} \mathrm{Re}\left[\mathrm{U}_{\alpha \mathrm{i}} \mathrm{U}^{\star}_{\beta \mathrm{i}} \mathrm{U}^{\star}_{\alpha \mathrm{j}} \mathrm{U}_{\beta \mathrm{j}}\right] \sin^2 \Delta_{\mathrm{ij}}$$

$$\Delta_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E} \qquad \Delta m_{ij}^2 \equiv m_i^2 - m_j^2$$

$$\Delta_{ij} = 1{,}27 \, \frac{\Delta m_{ij}^2}{\mathrm{eV}^2} \, \frac{L/E}{\mathrm{m/MeV}}$$

$$L_{ij}^{\mathrm{osc}} = \frac{4\pi E}{\Delta m_{ij}^2}$$

NEUTRINO OSCILLATIONS

$$U_{MNS} = \begin{array}{c} \\ \end{array}\begin{array}{ccc} \nu_1 & \nu_2 & \nu_3 \end{array}$$

$$U_{MNS} = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \begin{matrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{matrix}$$

mixing matrix

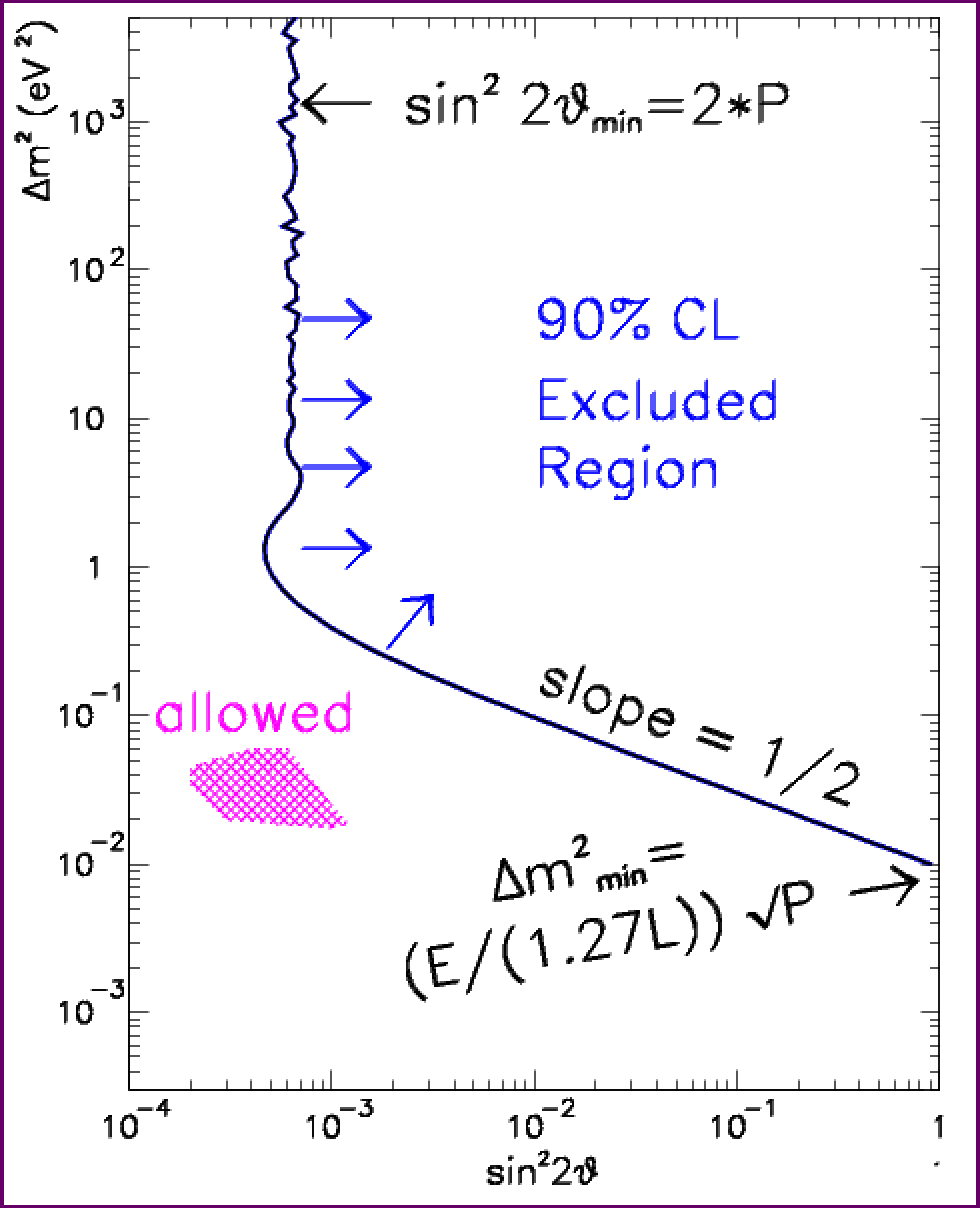
$\theta_{12} = \theta_{sol}$ $\theta_{23} = \theta_{atm} \sim \pi/4$ $\theta_{13} \sim 0$

$\Delta m^2_{ij} = m^2_i - m^2_j$

CP violating fase $\delta = ?$

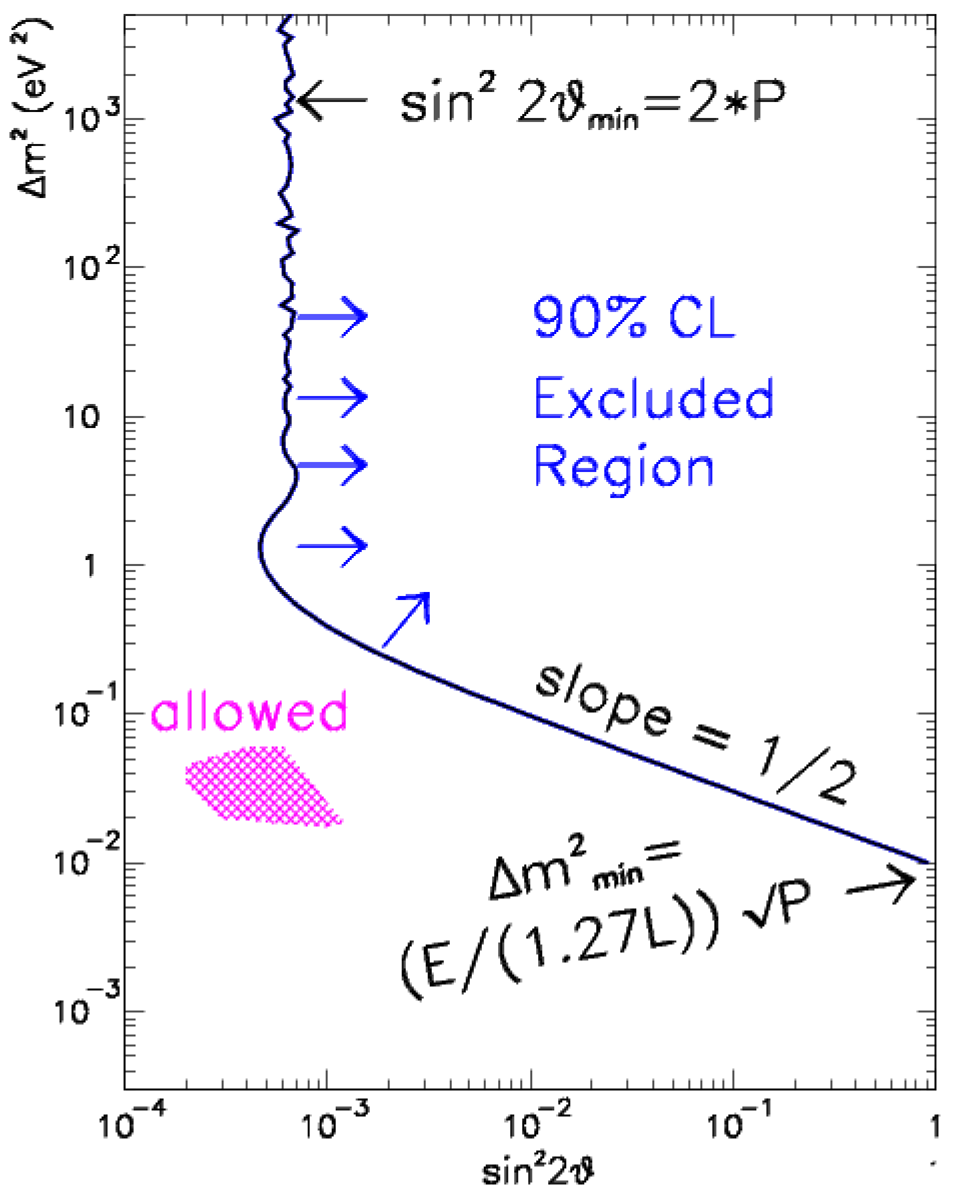
$\Delta m^2_{31} = \Delta m^2_{32} + \Delta m^2_{21}$

NEUTRINO OSCILLATIONS



$$\langle P_{\alpha\beta} \rangle = \frac{\int dE_\nu\, \phi(E_\nu)\, \sigma(E_\nu)\varepsilon(E_\nu) P_{\alpha\beta}(E_\nu)}{\int dE_\nu\, \phi(E_\nu)\, \sigma(E_\nu)\, \varepsilon(E_\nu)}$$

NEUTRINO OSCILLATIONS



- If you see an oscillation signal with

  $P_{osc} = P \pm \delta P$

  then carve out an allowed region in (Δm^2,$\sin^2 2\theta$) plane.

$$P = \sin^2 2\theta \, \sin^2(1.27\, \Delta m^2\, L/E)$$

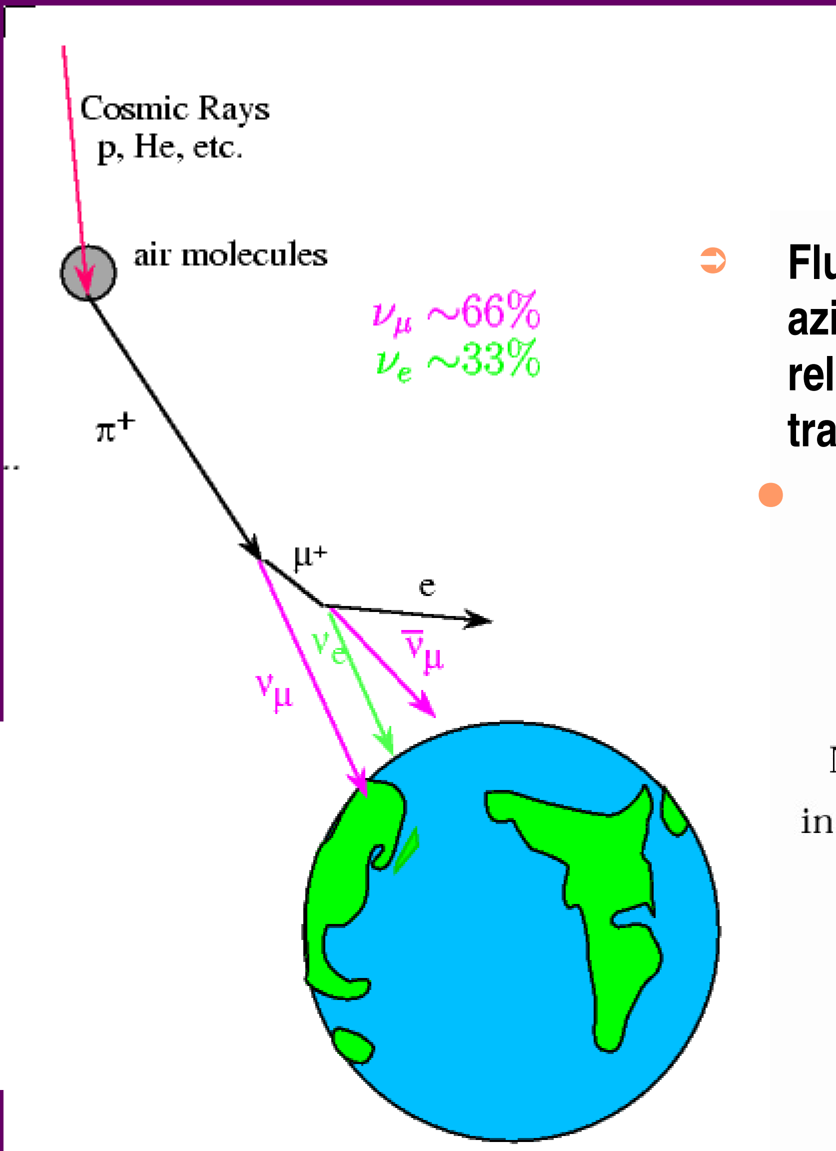
- If you see no signal and limit oscillation with

  $P_{osc} < P$ @ 90% CL

  then carve out an excluded region in the (Δm^2,$\sin^2 2\theta$) plane.

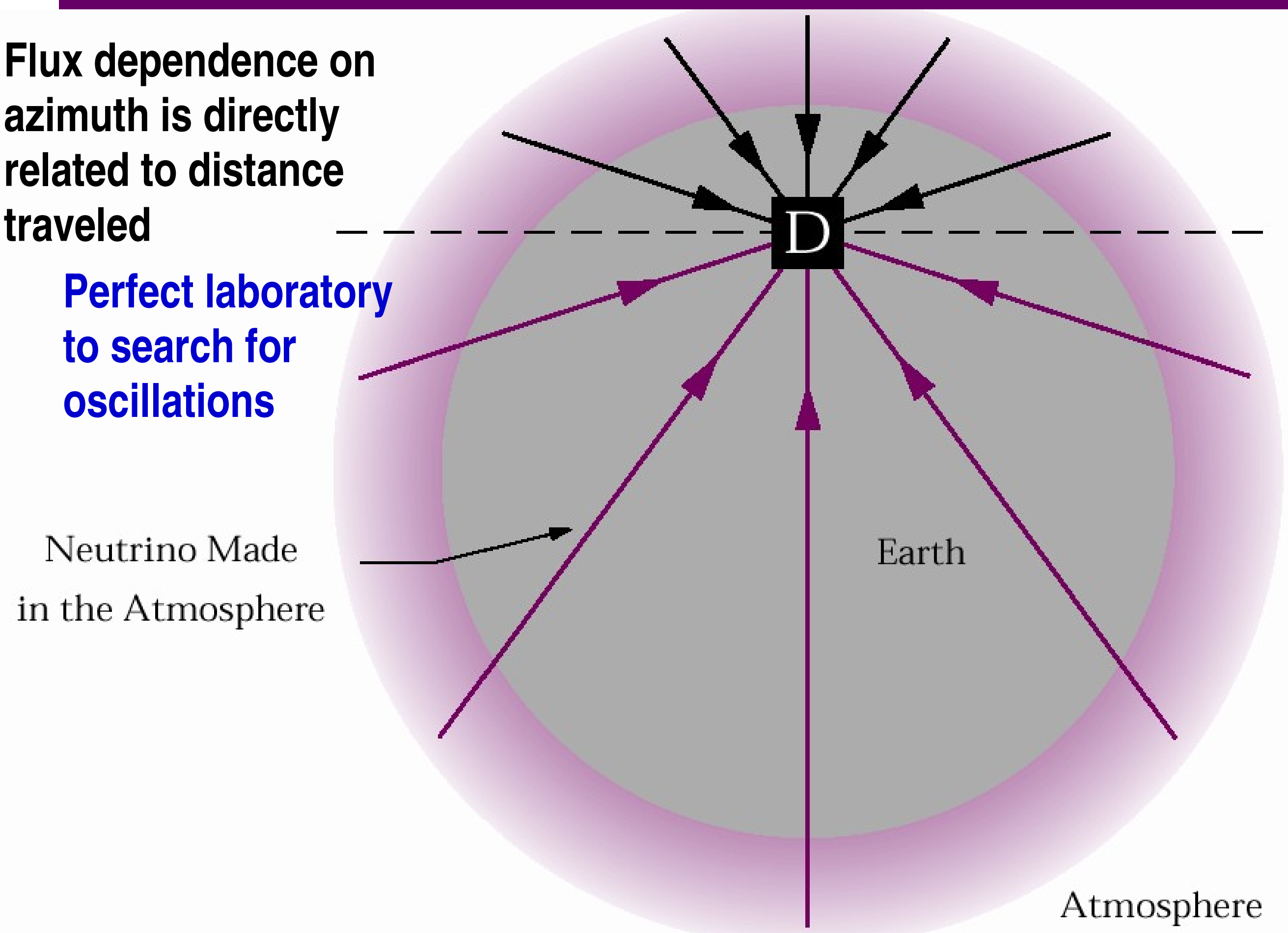
EXPERIMENTAL EVIDENCE

ATMOSPHERIC NEUTRINOS

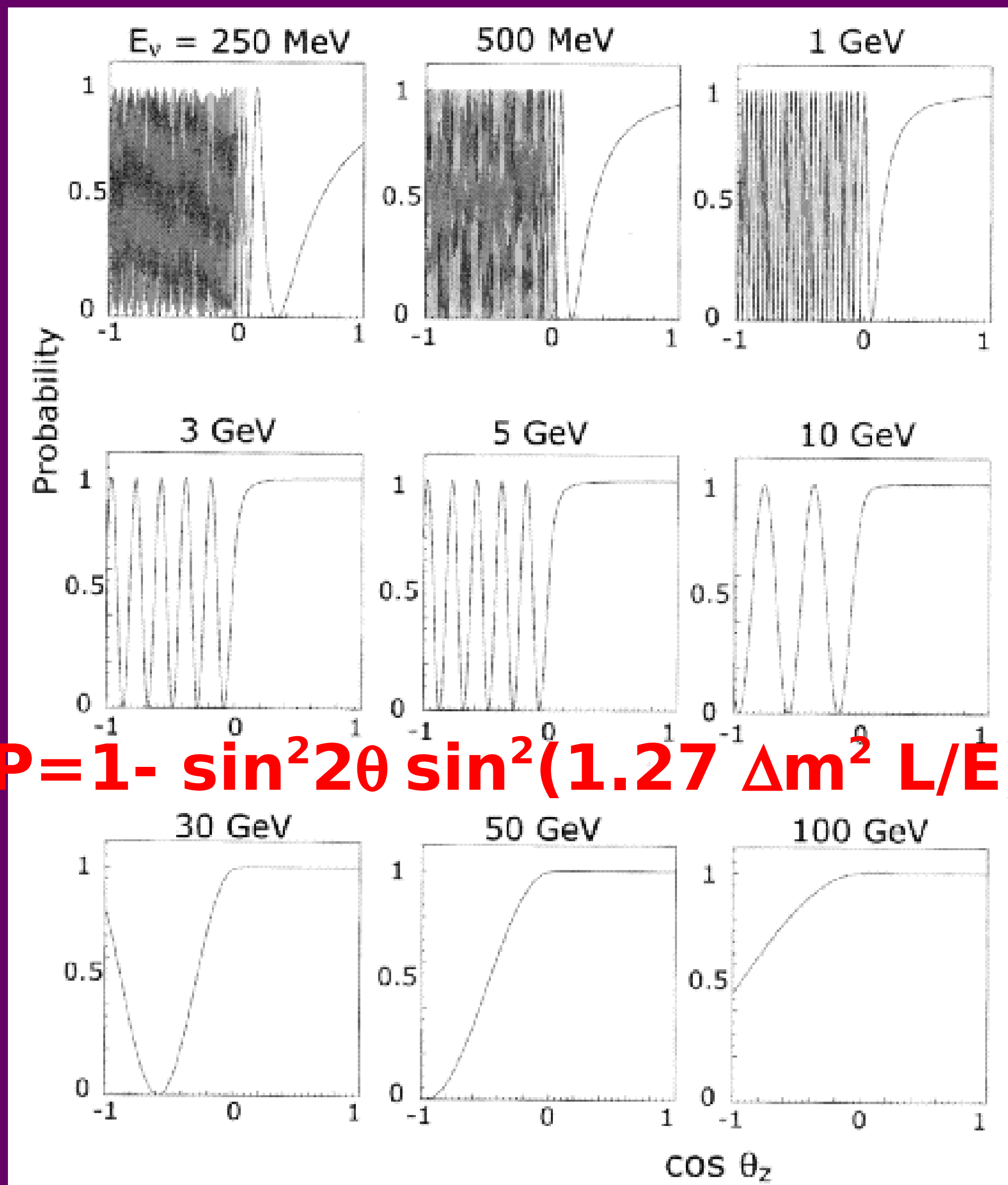


ν_μ disappearance observed !

- Flux dependence on azimuth is directly related to distance traveled
- **Perfect laboratory to search for oscillations**



Oscillation Survival Probability for $\nu_\mu \rightarrow \nu_\tau$



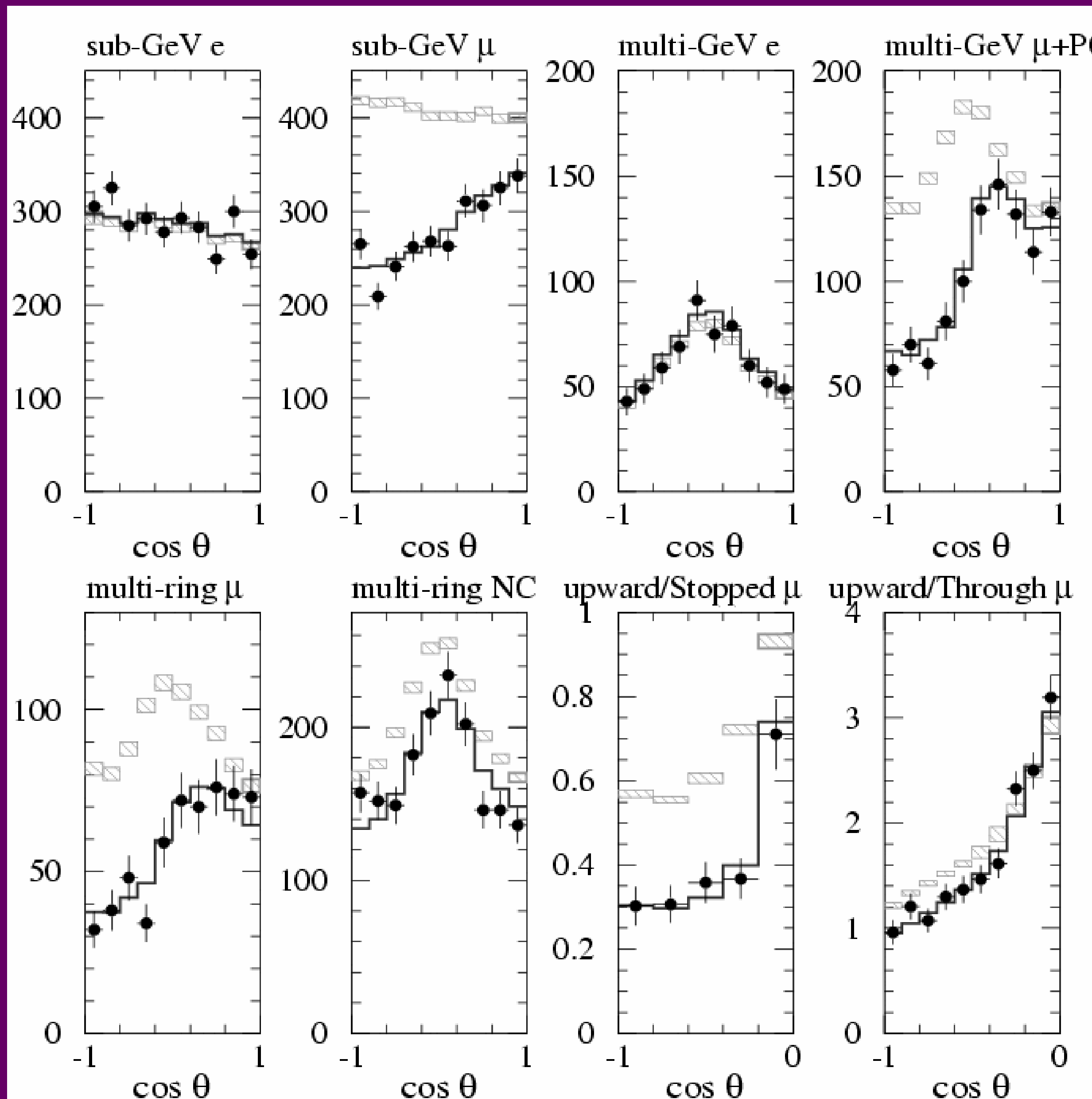
$P=1- \sin^2 2\theta \sin^2(1.27\, \Delta m^2\, L/E)$

$\Delta m^2 = 5\times10^{-3}\ eV^2$

$\sin^2 2\theta = 1.0$

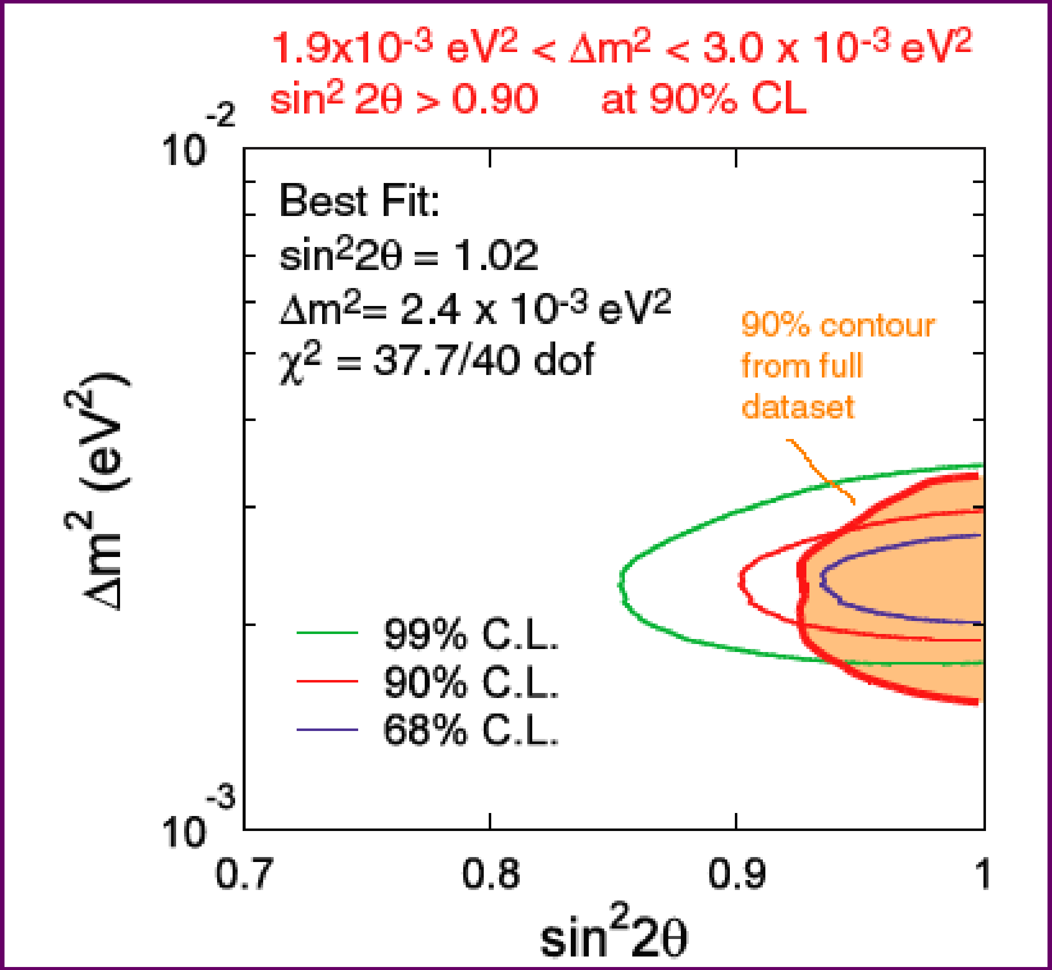
ATMOSPHERIC NEUTRINOS

$\nu_\mu \to \nu_\tau$



Super-Kamiokande (1998)

ATMOSPHERIC NEUTRINOS



$$L_{ij}^{osc} = \frac{4\pi E}{\Delta m_{ij}^2}$$

$\nu_\mu \rightarrow \nu_\tau$

Super-Kamiokande 2004

$\Delta m^2_{32} = 2.5 \times 10^{-3}\,\mathrm{eV}^2$

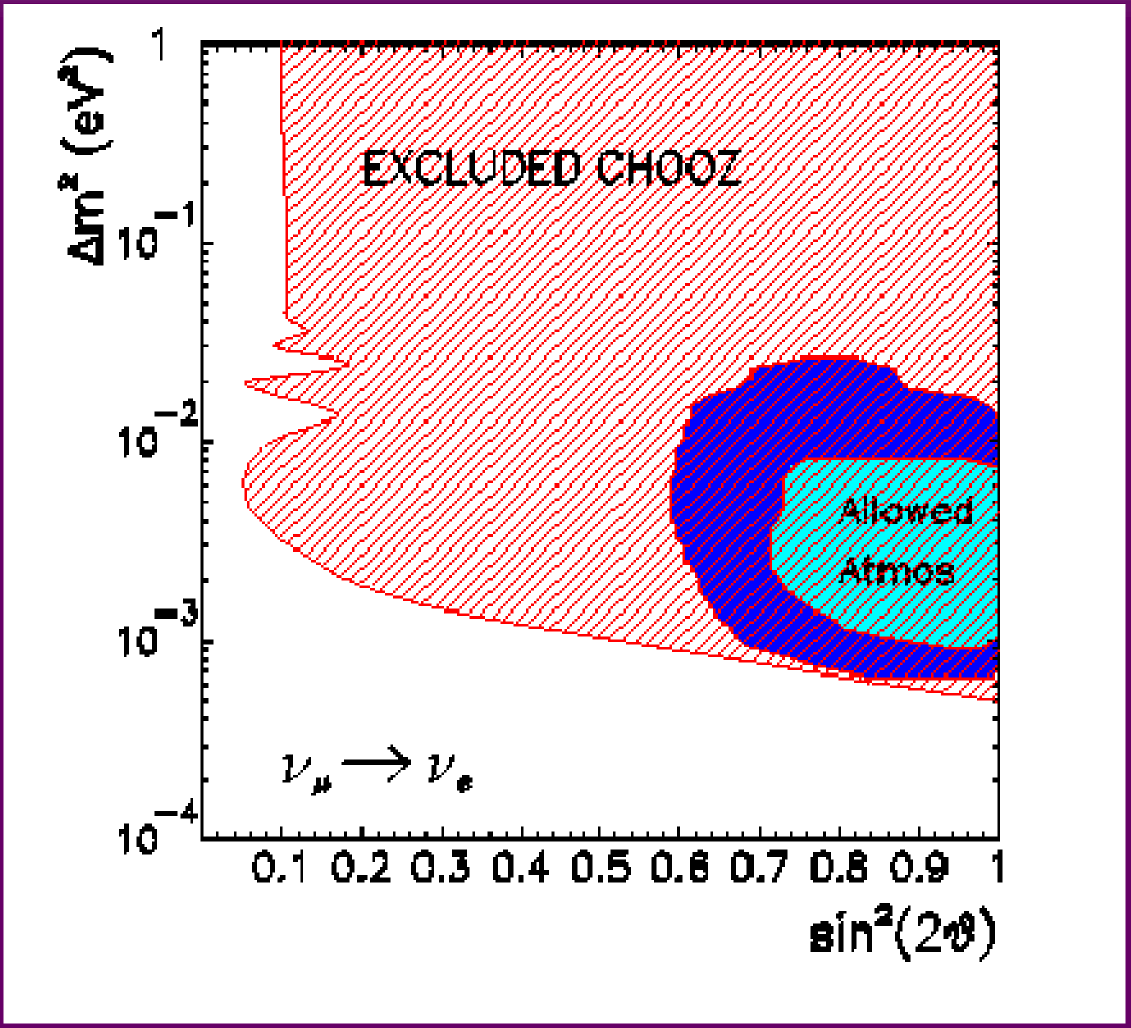
$\sin^2 2\theta_{23} = 1.$

$$P_{\mu\mu}^{atm} \approx 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\pi L}{L_{32}^{osc}}\right)$$

K2K confirms !

CHOOZ (1999)

Experiment with reactor neutrinos in France



$P^{osc} < 0.05$

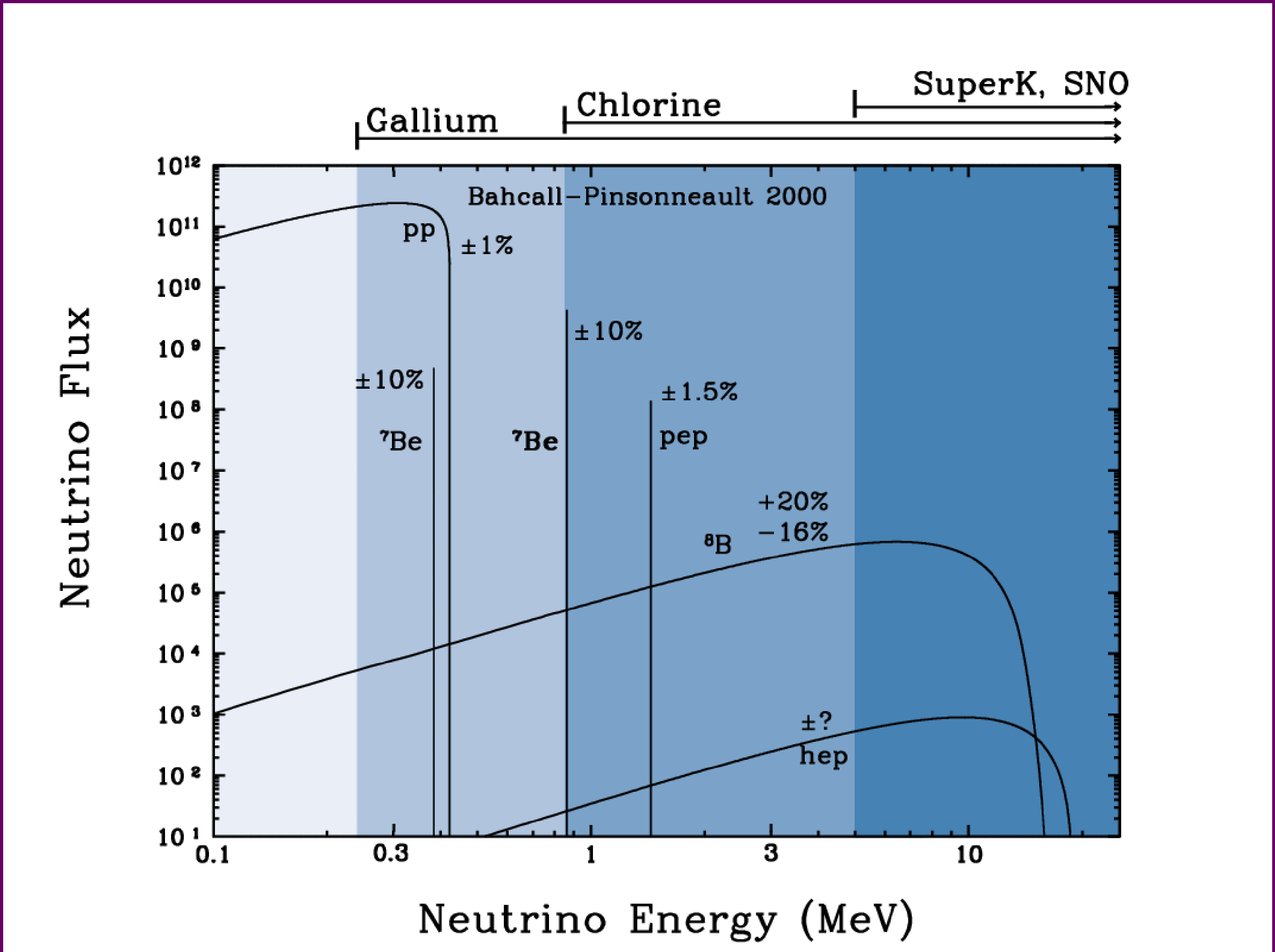
$\sin^2 2\theta_{13} < 0.15$

$\sin^2\theta_{13} < 0.04$

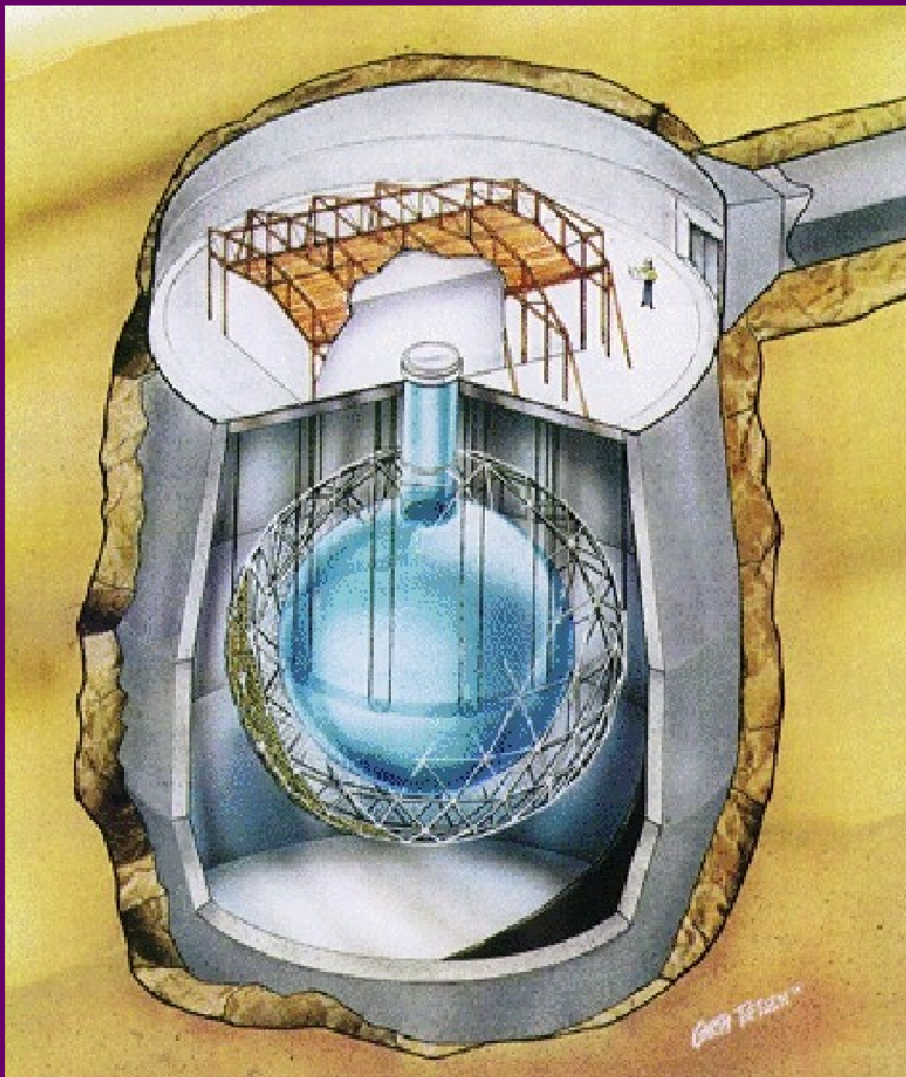
$$L_{ij}^{osc} = \frac{4\pi E}{\Delta m_{ij}^2}$$

$$P_{ee}^{CHOOZ} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\pi L}{L_{32}^{osc}}\right)$$

SOLAR NEUTRINOS



Sudbury Neutrino Observatory (SNO)



Reações no Detector SNO

Corrente Carregada (CC)

$$d + \nu_e \longrightarrow p + p + e^-$$

Corrente Neutra (CN)

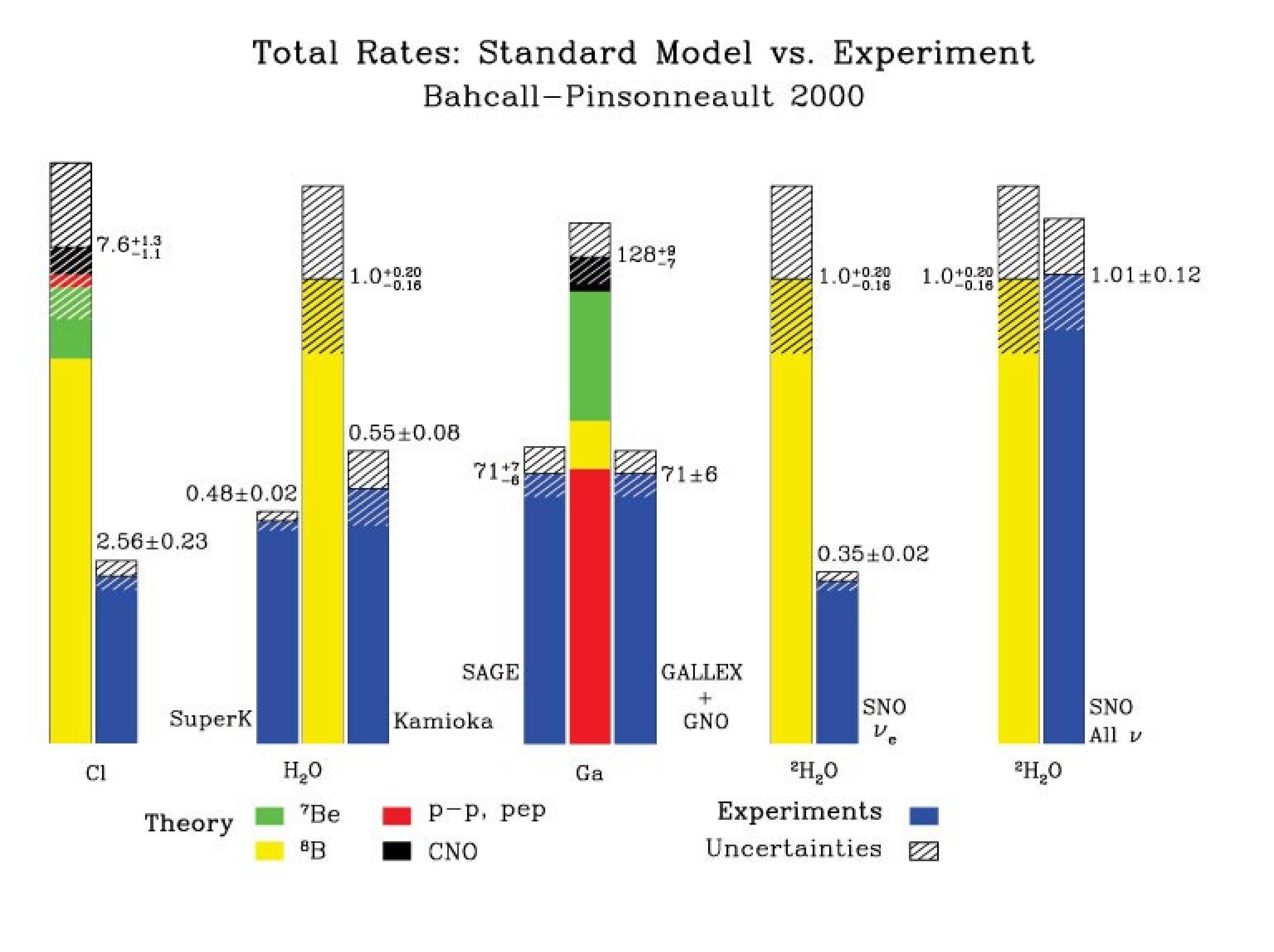
$$d + \nu_{e,\mu,\tau} \longrightarrow p + n + \nu_{e,\mu,\tau}$$

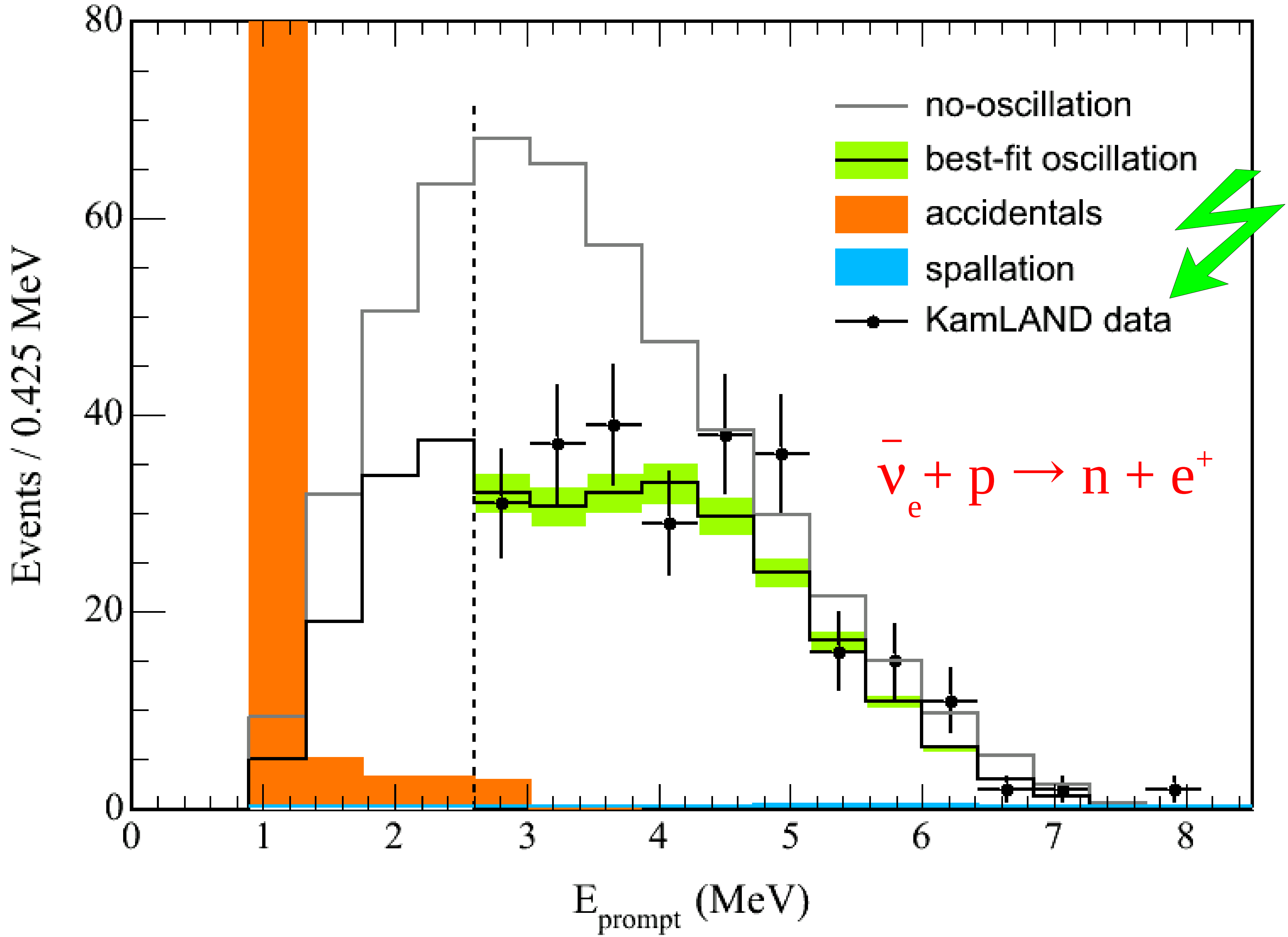
Espalhamento Elástico (CC+CN)

$$e^- + \nu_{e,\mu,\tau} \longrightarrow e^- + \nu_{e,\mu,\tau}$$

1 kton D_2O - Sudbury, Canadá

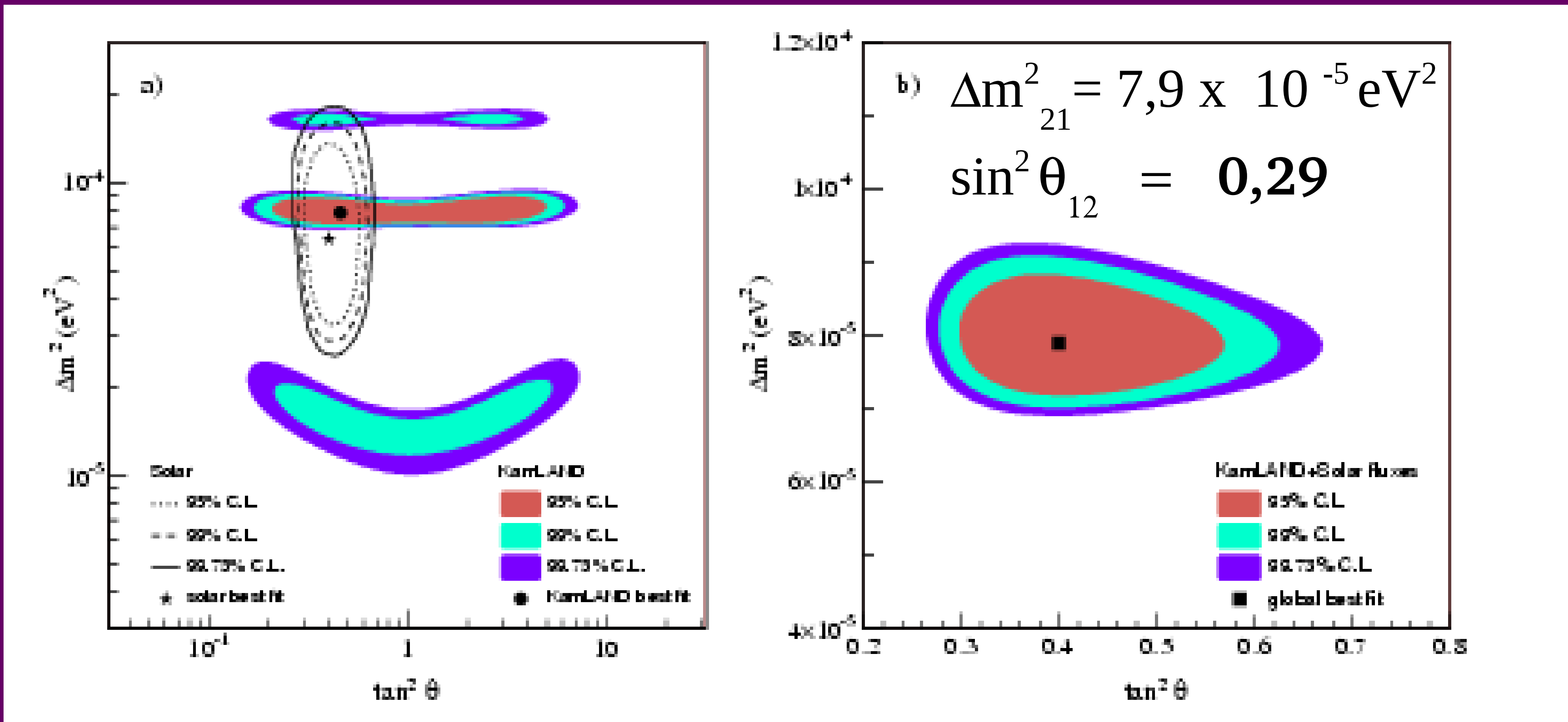
Neutrinos arrive as different flavors





80
60
40
20
0
Events / 0.425 MeV
0
1
2
3
4
5
6
7
8
E_prompt (MeV)
no-oscillation
best-fit oscillation
accidentals
spallation
KamLAND data
$\bar{\nu}_e + p \rightarrow n + e^+$

SOLAR + KamLAND



$$P_{ee}^{\mathrm{KL}} \approx s_{13}^4 + c_{13}^4 \sin^2 2\theta_{12} \sin^2\left(\frac{\pi L}{L_{21}^{\mathrm{osc}}}\right)$$

CURRENT STATUS

$7.3 \times 10^{-5}\ eV^2 \leq \Delta m^2_{21} \leq 9 \times 10^{-5}\ eV^2$

Dominated by KamLAND

$1.5 \times 10^{-3}\ eV^2 \leq |\Delta m^2_{32}| \leq 3.4 \times 10^{-3}\ eV^2$

Dominated by Atmospheric SK

$0.50 < \sin \theta_{12} < 0.61$ (SNO)

$\sin \theta_{13} < 0.20$ (CHOOZ)

$0.6 < \sin \theta_{23} < 0.8$ (ATM)

@ 90 % CL

CONNECTION WITH COLLIDER PHYSICS

- **production of heavy Neutrinos (N)**

  $pp \Rightarrow l^{+}\, l'^{+}\, N$ $\quad$ $l, l' = e, \mu, \tau$ $\quad$ @LHC

  [A. Ali, A.V.Borisov, N.B. Zamorin (2001)]

  $e^+e^- \Rightarrow N\,\nu \Rightarrow l\,W\,\nu$ $\quad$ @CLIC

  [F. del Aguila, J.A. Aguilar-Saavedra (2005)]

- **Bilinear R-parity violating scenarios (AMSB,SUGRA) @Tevatron and LHC**

  [Valle et al., de Campos et al.]

Production of Heavy N

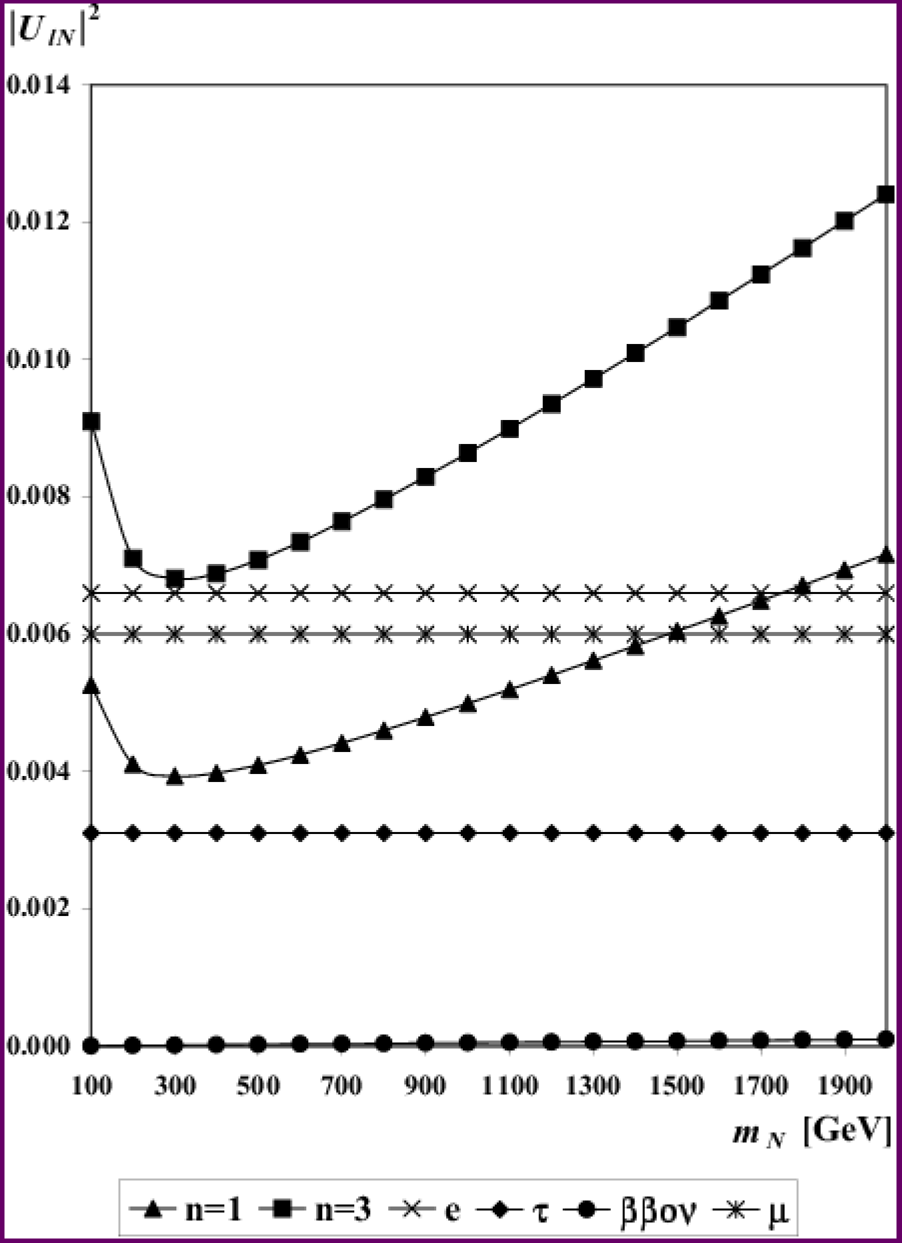
$pp \Rightarrow l^+ \, l'^+ \, N \qquad l = e, \mu, \tau \qquad$ @LHC

[A. Ali, A.V.Borisov, N.B. Zamorin (2001)]

$$\sigma(pp \Rightarrow l^+ \, l'^+ \, N) = 0.8 \, (1 - \tfrac{1}{2}\delta_{ll'}) \, |U_{lN} \, U_{l'N}|^2 \, F(\sqrt{s}, m_N) \text{ fb}$$

$\sqrt{s} = 14$ TeV

Production of Heavy N



Production of Heavy N

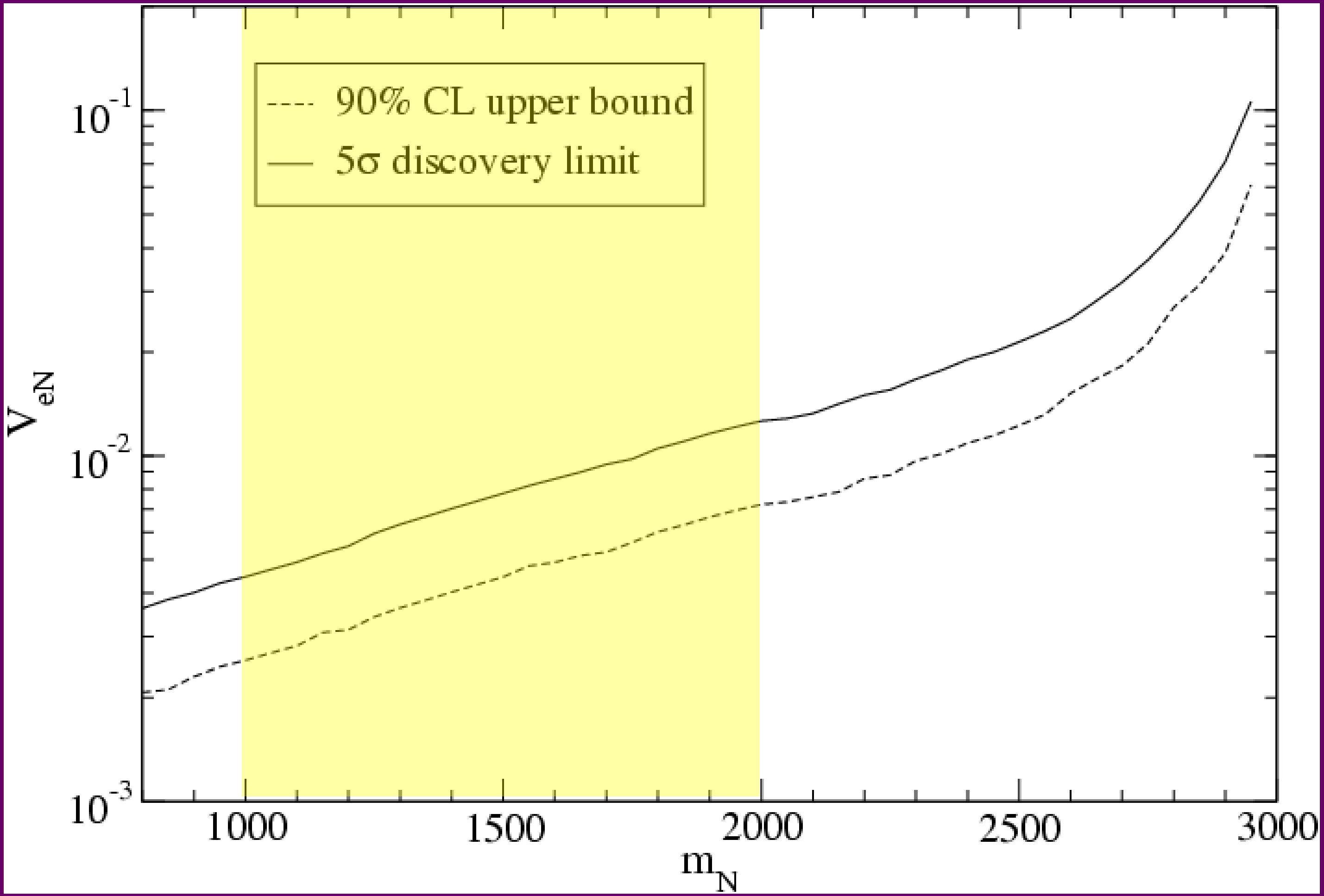
$e^+e^- \Rightarrow N\,\nu \Rightarrow l\,W\,\nu$ @CLIC

[F. del Aguila, J.A. Aguilar-Saavedra (2005)]

$\sqrt{s} = 3$ TeV

can detect heavy Majorana/Dirac N with m_N = 1-2 TeV

Production of Heavy N



Bilinear R-parity Violating SUSY Models

- Unlike the SM, SUSY extensions allow renormalizable lepton and baryon number violation.

$$\frac{1}{2}\lambda_{ijk}\ell_i\ell_j\bar{e}_k + \lambda'_{ijk}\ell_i q_j\bar{d}_k + \frac{1}{2}\lambda''_{ijk}\bar{u}_i\bar{d}_j\bar{d}_k + \epsilon_i H_u \ell_i$$

- These terms can be forbidden imposing a discrete symmetry, R parity:

$$R = (-1)^{3B+L+2s}$$

SM states are even while SUSY states are odd under R.

- If ν's have majorana masses there is no reason to exclude lepton number violating interactions.

- It would be nice to understand the pattern of masses and mixings using a weak scale SUSY extension of the SM.

- Nice fact: SUSY with R–parity (lepton number) violation can generate neutrino masses at the electroweak scale in agreement with experimental data. Schechter, Valle, Ross, Hall, ...

Bilinear R-parity Violating SUSY Models

SUSY with bilinear R-parity violation

➾ In the minimal SUSY extension of the SM the new states are

particle name	symbol	spin
gluino	$\tilde{g}$	1/2
charginos	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^{\pm}$	1/2
neutralinos	$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$	1/2
sleptons	$\tilde{e}_L, \tilde{\nu}_{e_L}, \tilde{e}_R$	0
	$\tilde{\mu}_L, \tilde{\nu}_{\mu_L}, \tilde{\mu}_R$	0
	$\tilde{\tau}_1, \tilde{\tau}_2, \tilde{\nu}_{\tau_L}$	0
squarks	$\tilde{u}_L, \tilde{d}_L, \tilde{u}_R, \tilde{d}_R$	0
	$\tilde{c}_L, \tilde{s}_L, \tilde{c}_R, \tilde{s}_R$	0
	$\tilde{t}_1, \tilde{t}_2, \tilde{b}_1, \tilde{b}_2$	0
higgs	h, H, A, $H^{\pm}$	0

➾ We must include the soft breaking terms (source of lots of free parameters!). We will concentrate on two scenarios: SUGRA and AMSB. Valle et al; de Campos et al

Bilinear R-parity Violating SUSY Models

Electroweak symmetry breaking: **the two Higgs doublets H_d and H_u and the sneutrino acquire a vev.**

The symmetry is radiatively broken in AMSB and SUGRA

Neutral fermion mass matrix:

- sneutrino vev's contributes to the mixing between neutrinos and neutralinos (charged leptons and charginos). In the basis $\psi^{0T} = (-i\lambda', -i\lambda^3, \widetilde{H}_d^1, \widetilde{H}_u^2, \nu_e, \nu_\mu, \nu_\tau)$ the neutral fermion mass matrix is

$$M_N = \begin{bmatrix} \mathcal{M}_{\chi^0} & m^T \\ m & 0 \end{bmatrix} \quad \text{where} \quad m = \begin{bmatrix} -\frac{1}{2}g'v_1 & \frac{1}{2}gv_1 & 0 & \epsilon_1 \\ -\frac{1}{2}g'v_2 & \frac{1}{2}gv_2 & 0 & \epsilon_2 \\ -\frac{1}{2}g'v_3 & \frac{1}{2}gv_3 & 0 & \epsilon_3 \end{bmatrix}$$

- For $|\epsilon_i| \ll \mu$ we define $\xi \equiv m \cdot \mathcal{M}_{\chi^0}^{-1}$. M_N is approximately diagonalized by

$$\mathcal{N}^* \simeq \begin{pmatrix} N^* & 0 \\ 0 & V_\nu^T \end{pmatrix} \otimes \begin{pmatrix} 1 & \xi^\dagger \\ -\xi & 1 \end{pmatrix}, \qquad (1)$$

where N^* diagonalizes the 4×4 neutralino mass matrix $\mathcal{M}_{\chi^0}$ and V_ν diagonalizes the

Bilinear R-parity Violating SUSY Models

effective tree level neutrino mass matrix

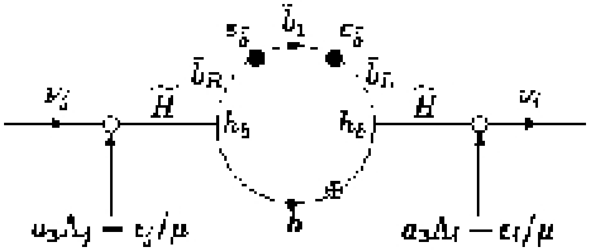
$$\mathbf{M}^{\text{eff}} = -m\,\mathcal{M}_{\chi^0}^{-1}\,m^T \;=\; \frac{M_1 g^2 + M_2 g'^2}{4\,\det(M_{\chi^0})} \begin{pmatrix} \Lambda_1^2 & \Lambda_1\Lambda_2 & \Lambda_1\Lambda_3 \\ \Lambda_1\Lambda_2 & \Lambda_2^2 & \Lambda_2\Lambda_3 \\ \Lambda_1\Lambda_3 & \Lambda_2\Lambda_3 & \Lambda_3^2 \end{pmatrix}$$

with $\Lambda_i = \mu v_i + v_d \epsilon_i$. This is a low scale see-saw!

- M_N exhibits just one massive neutrino at tree level:

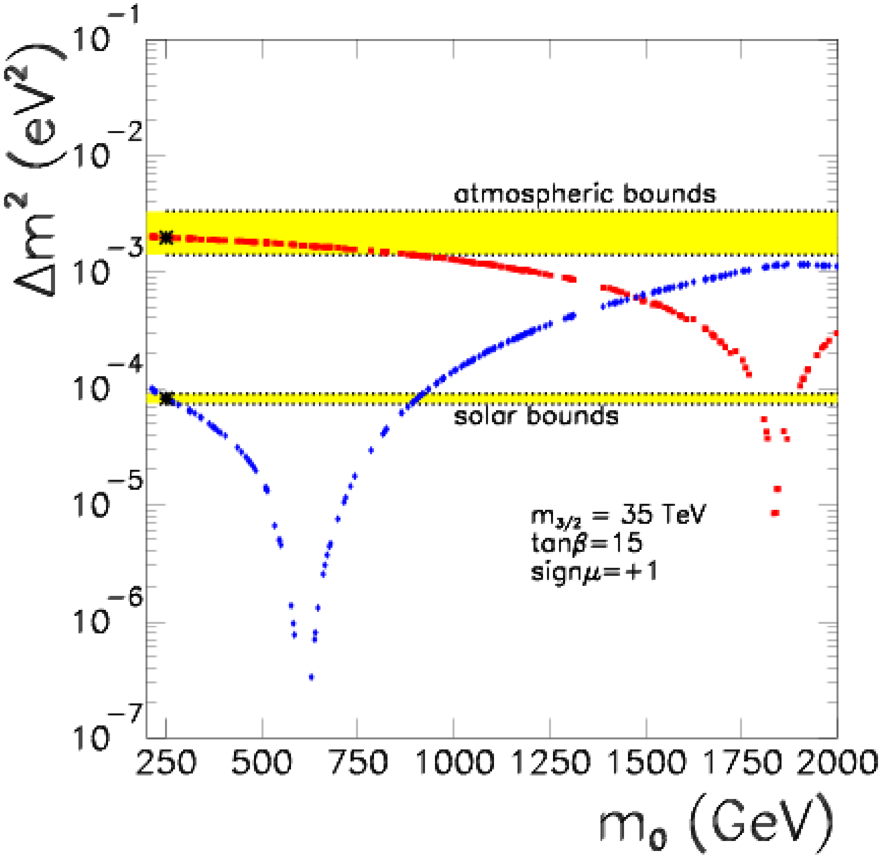
$$m_{\nu_3}^{\text{tree}} = \frac{M_1 g^2 + M_2 g'^2}{4\,\det(M_{\chi^0})}|\vec{\Lambda}|^2 \;,\quad \tan\theta_{13} = -\frac{\Lambda_1}{\sqrt{\Lambda_2^2+\Lambda_3^2}} \quad \text{and} \quad \tan\theta_{23} = -\frac{\Lambda_2}{\Lambda_3}\,.$$

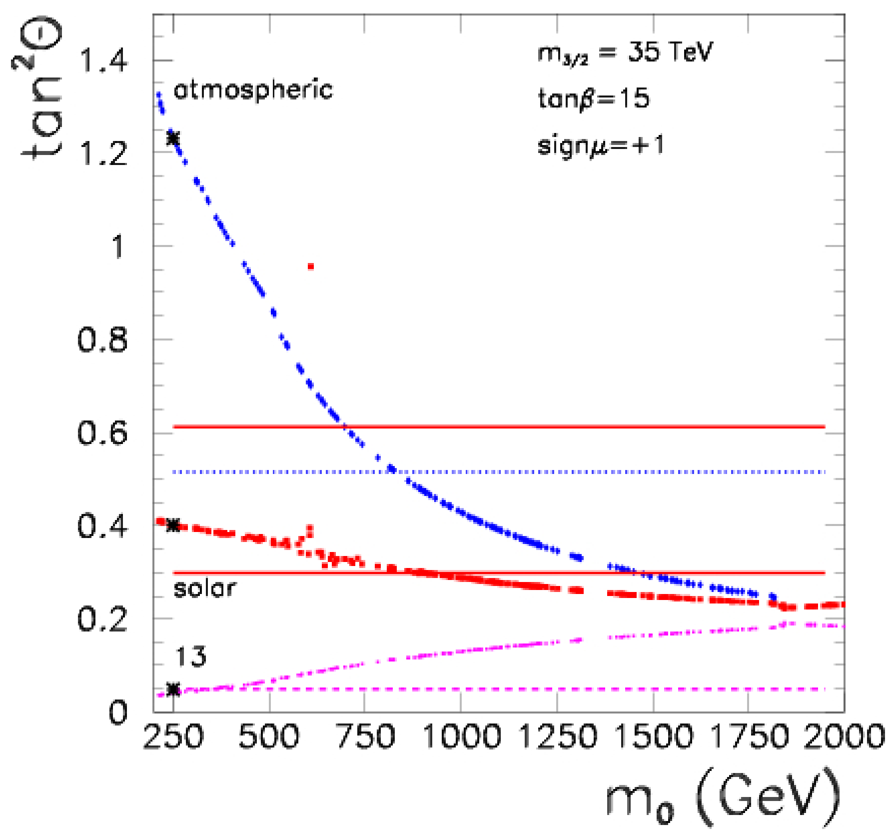
- The inclusion of radiative correction for the neutral fermion mass matrix gives rise to masses to the three neutrinos.



Bilinear R-parity Violating SUSY Models

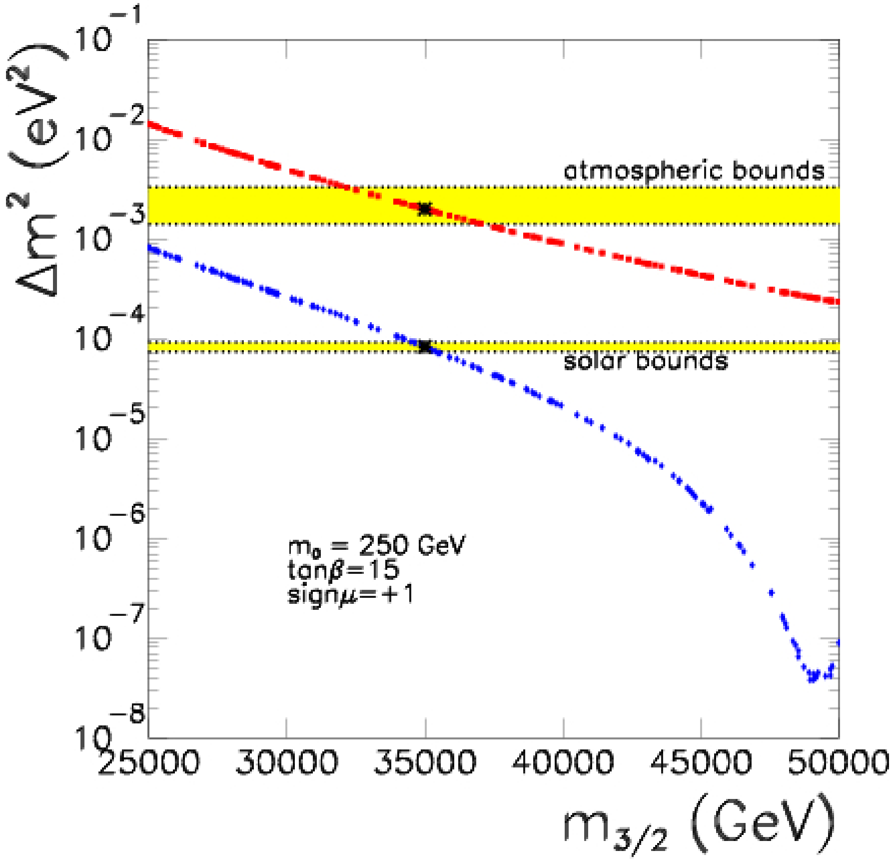
Dependence on AMSB parameters

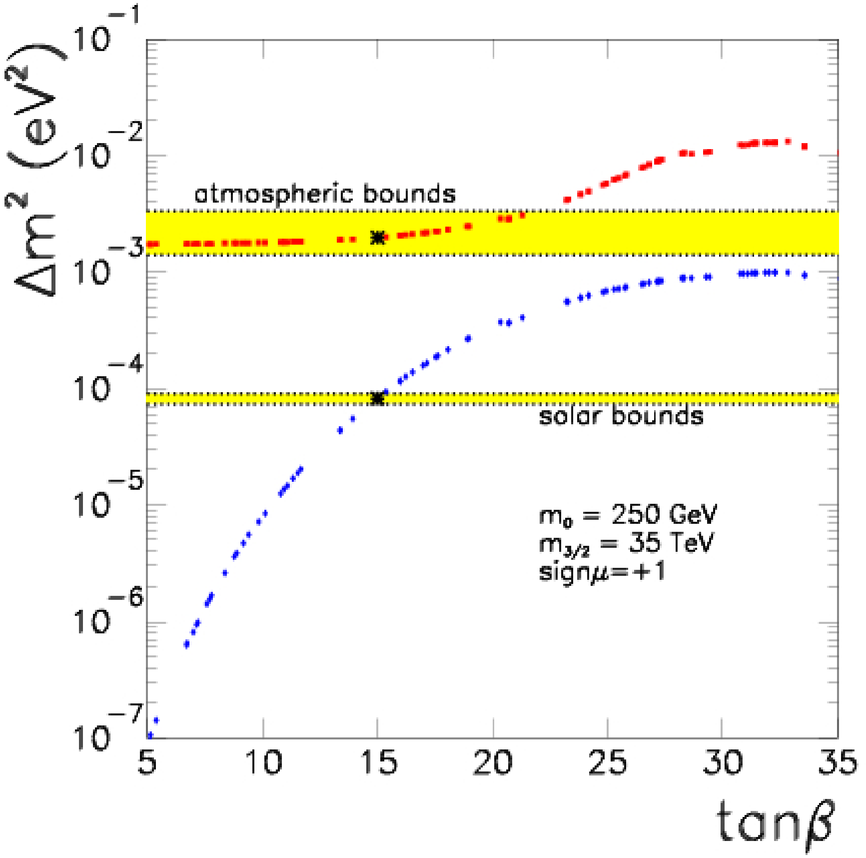




Bilinear R-parity Violating SUSY Models

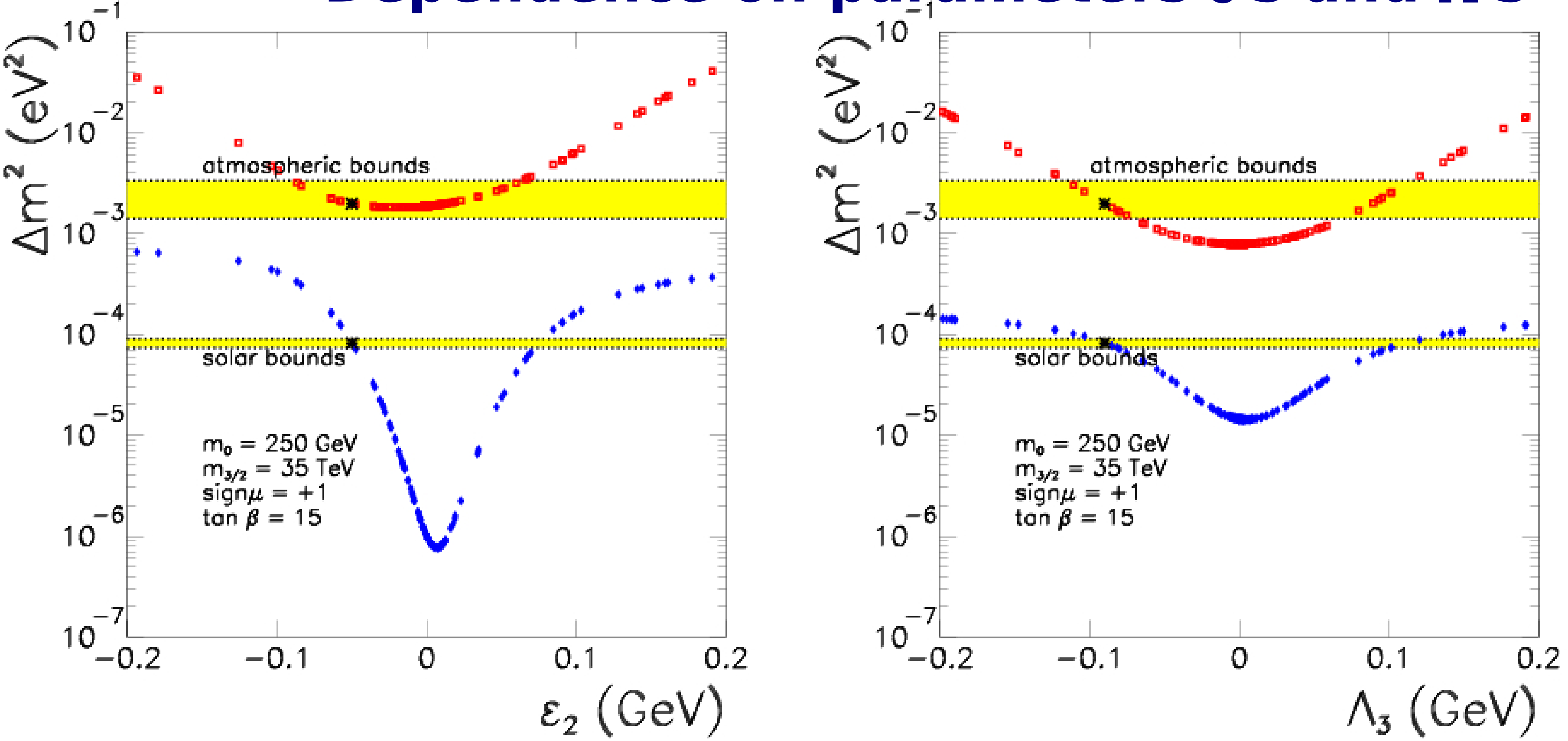
Dependence on AMSB parameters



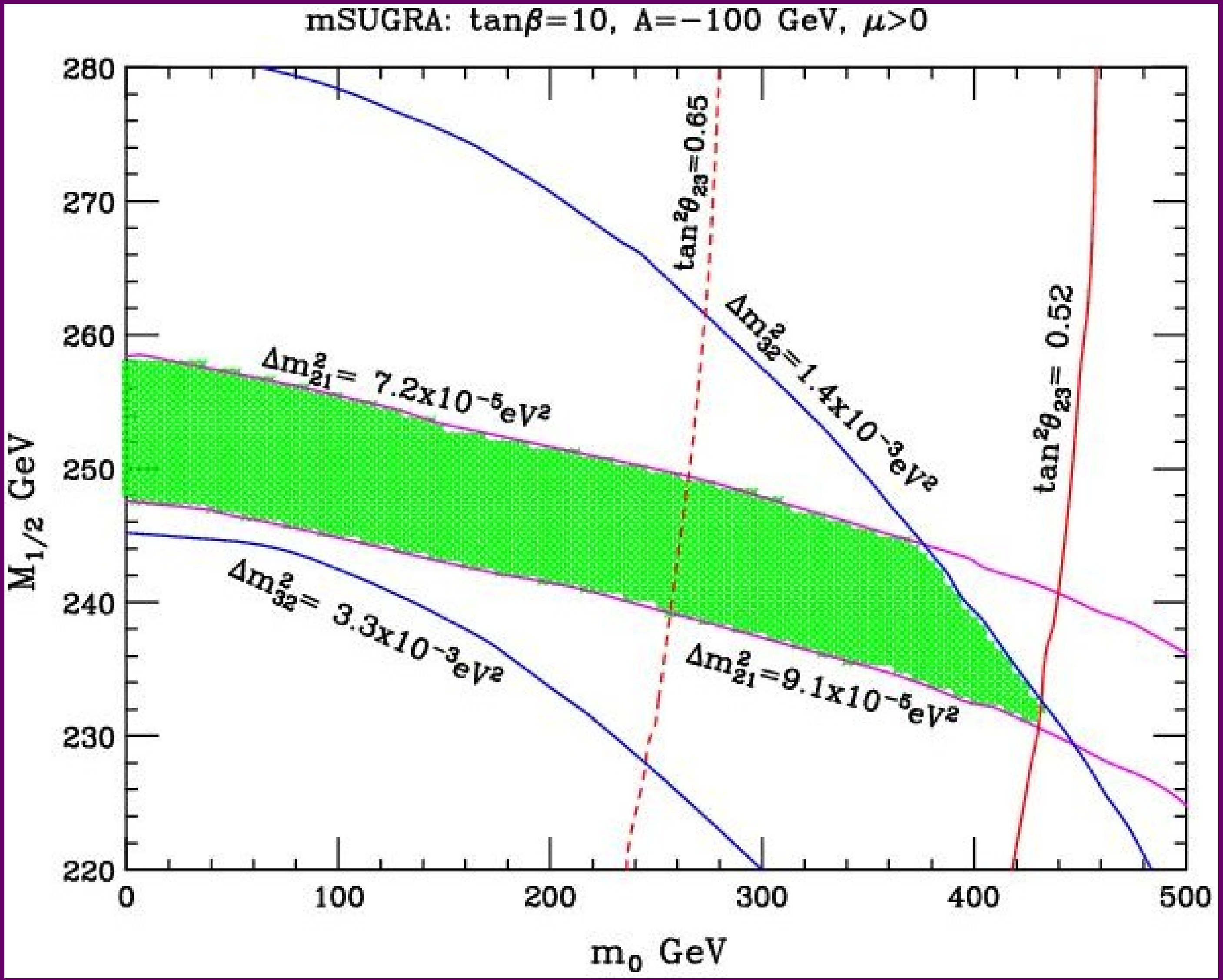


Bilinear R-parity Violating SUSY Models

Dependence on parameters ε's and Λ's



Bilinear R-parity Violating SUSY Models



Allow region in m_0 x $m_{1/2}$ for fixed BrpV parameters

Bilinear R-parity Violating SUSY Models

SUSY particle decays

- In BRpV models the LSP is no longer stable.
- This allow to test these models at colliders! Hirsch (PRD); Romão (PRD); Bartl (NPB); Porod (PRD)
- Rotating to the mass eigenstates leads to effective couplings like

$\tilde{\chi}_1^0 - W^{\pm} - \ell$	$\tilde{\chi}_1^0 - Z - \nu$	$\tilde{d}_L - d - \nu$	$\tilde{u}_L - d - \ell$	$\tilde{\ell} - \ell - \nu$

- Possible lightest neutralino decays

$$\tilde{\chi}_1^0 \to \nu \ell^+ \ell'^-$$
$$\tilde{\chi}_1^0 \to \nu \nu \nu$$
$$\tilde{\chi}_1^0 \to \nu q \bar{q} \quad \text{or} \quad \ell q \bar{q}$$

- New $\tilde{\chi}_1^{\pm}$ decays induced by BRpV are

$$\tilde{\chi}_1^{\pm} \to \bar{q} q' \nu_i \,,$$
$$\tilde{\chi}_1^{\pm} \to \ell^{\pm} q \bar{q} \,,$$
$$\tilde{\chi}_1^{\pm} \to \ell_i^{+} \ell_j^{-} \ell_k^{\pm} \,,$$
$$\tilde{\chi}_1^{\pm} \to \ell_i^{\pm} \nu_j \nu_k \,,$$