Neutrino and Flavour Physics

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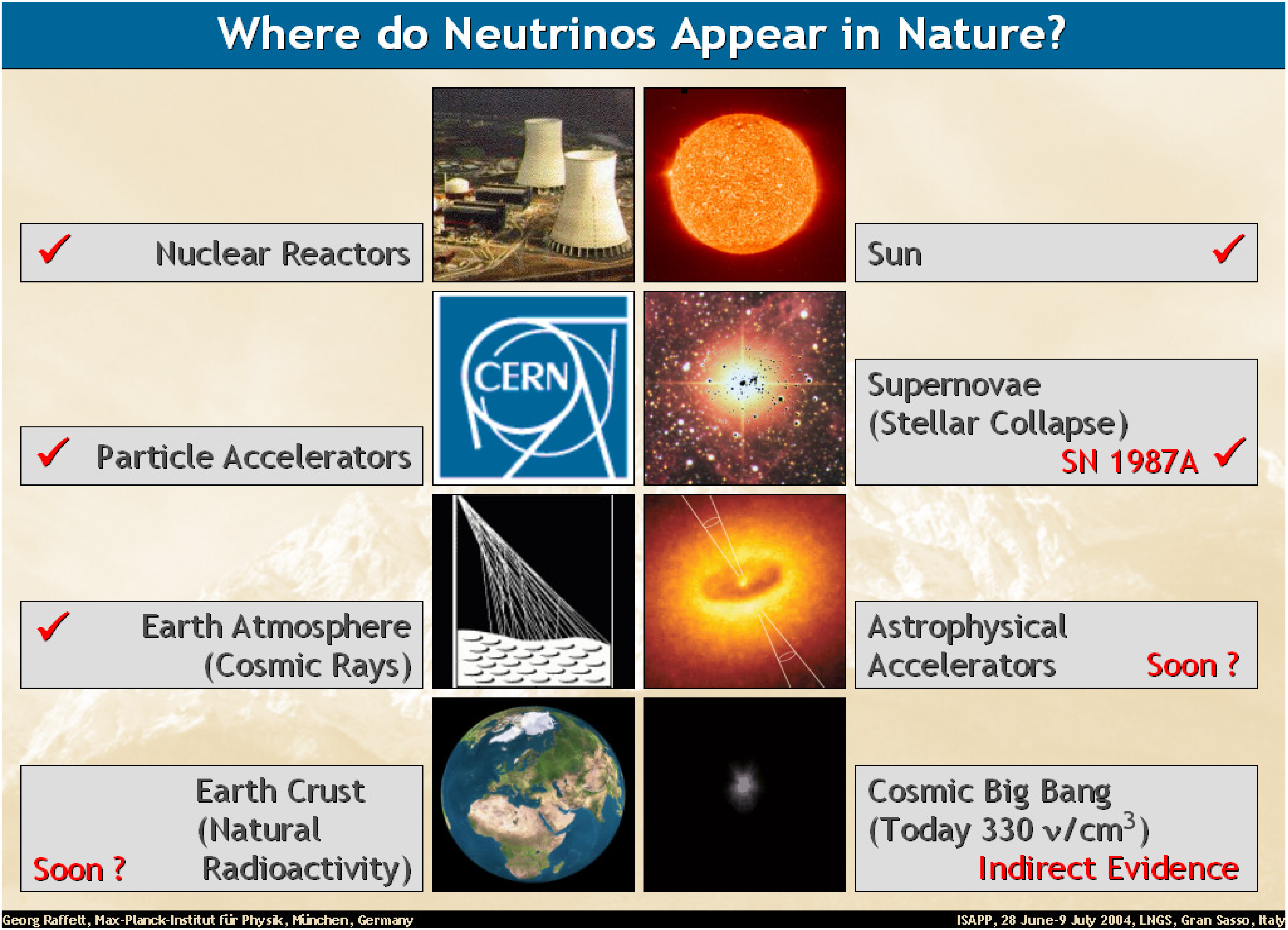
- Neutrinos:
  - solar sector
  - athmospheric sector
  - θ_{13}, the 'reactor' angle
- Supersymmetry in a nutshell
  + lepton flavour violation
- Supersymmetric neutrino mass models and their tests
  - Dirac neutrinos
  - Majorana neutrinos in Seesaw models
  - Neutrino masses via R-parity violation
- Conclusions

Neutrino physics


Where do Neutrinos Appear in Nature?
✓ Nuclear Reactors
Sun ✓
✓ Particle Accelerators
CERN
Supernovae
(Stellar Collapse)
SN 1987A ✓
✓ Earth Atmosphere
(Cosmic Rays)
Astrophysical
Accelerators Soon ?
Earth Crust
(Natural
Radioactivity)
Soon ?
Cosmic Big Bang
(Today 330 ν/cm³)
Indirect Evidence
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
ISAPP, 28 June-9 July 2004, LNGS, Gran Sasso, Italy

If neutrinos are massive . . .

In general: flavour eigenstates $\neq$ mass eigenstates $\nu_{\alpha L} = \sum_i (UV)_{\alpha i} \nu_{iL}$

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

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$V = \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha} & 0 \\ 0 & 0 & e^{i\beta} \end{pmatrix} \qquad c_{ij} = \cos\theta_{ij} \ , \ s_{ij} = \sin\theta_{ij}$$

θ_{23}: atmospheric neutrinos, long baseline experiments
θ_{13}: reactor experiments
θ_{12}: solar neutrinos, KamLAND
α, β: Majorana phases, $0\nu2\beta$-decay (?)

Neutrino oszillations, theory I

QM picture†

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\nu_e(t) = e^{i\hat{H}t}\nu_e = e^{iE_1 t}\cos\theta\nu_1 + e^{iE_2 t}\sin\theta\nu_2$$

Relativistic limit + $t \sim l$ ($v_\nu \simeq 1$) (+ $c = 1$)

$$p \gg m_i \quad , \quad E_i \simeq p + \frac{m_i^2}{2p}$$

$$\nu_e(t) = e^{-ipt}\left(e^{-i\frac{m_1^2}{2p}l}\cos\theta\nu_1 + e^{-i\frac{m_2^2}{2p}l}\sin\theta\nu_2\right)$$

express ν_i via first eq. $\Rightarrow$

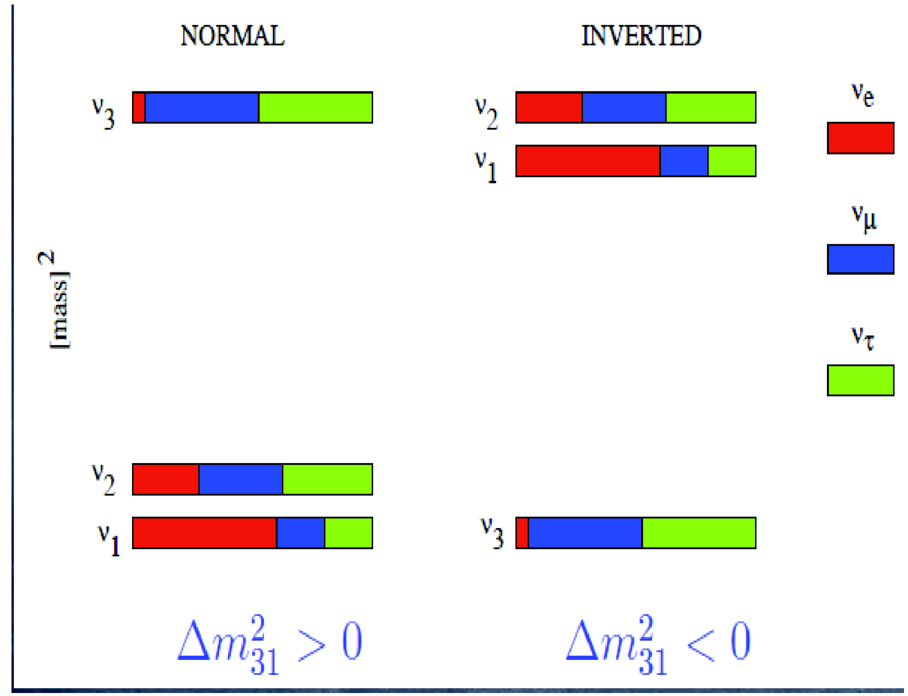
† for comparision of QM and QFT pictures see:
E. K. .Akhmedov, J. Kopp, JHEP **1004**, 008 (2010) [arXiv:1001.4815 [hep-ph]].

$$\nu_e(l) = \nu_e e^{-ipl}\left(e^{-i\frac{m_1^2}{2p}l}\cos^2\theta + e^{-i\frac{m_2^2}{2p}l}\sin^2\theta\right)$$
$$+ \nu_\mu e^{-ipl}\cos\theta\sin\theta\left(-e^{-i\frac{m_1^2}{2p}l} + e^{-i\frac{m_2^2}{2p}l}\right)$$

and the oscillation propability is

$$P(\nu_e \to \nu_\mu) = \sin^2 2\theta \sin^2\left(\frac{l\Delta m_{12}^2}{4p}\right)$$
$$\Delta m_{12}^2 = m_1^2 - m_2^2$$

Mass orderings . . .



- Neutrino oszillations
  - Δm_{31}: atmospheric, lang baseline
  - Δm_{21}: solar, KamLAND
- Absolute ν mass scale (?)

Absolute mass scale

- Tritium β-decay

$$m_\beta = \left(c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2\right)^{1/2}$$

$m_\beta < 2.33$ eV (95% CL) Troitsk, Mainz
KATRIN sensitivty $m_\beta \sim 0.2$ eV

- Neutrinoless double β-decay ($0\nu2\beta$-decay)

$$m_{\beta\beta} = c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\alpha} + s_{13}^2 m_3^2 e^{i\beta}$$

claim in ^{76}Ge $m_{\beta\beta} \in [0.16, 0.52]$ eV (2σ)
2σ upper limit from Cuoricino $m_{\beta\beta} < [0.23, 0.85]$ eV

- Cosmology: 95% CL bounds† on $\sum m_i = m_1 + m_2 + m_3 + \ldots$
  - CMB $<$ 1.19 eV
  - CMB + LSS < 0.71 eV
  - CMB + HST + SN-Ia < 0.75 eV
  - CMB + HST + SN-Ia + BAO < 0.60 eV
  - CMB + HST + SN-Ia + BAO + Ly < 0.19 eV

† Fogli et al., PRD78 (2008) 033010

2 versus 3 ν analysis

- two-neutrino approximation

$$\Delta m^2_{21} \ll \Delta m^2_{31}$$

  - solar + KamLAND: θ_{12}, Δm^2_{21}
  - CHOOZ: θ_{13}, Δm^2_{31}
  - atmospheric + LBL: θ_{23}, Δm^2_{31}

- three-neutrino analysis

2 versus 3 ν analysis

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- three-neutrino analysis
  - solar + KamLAND: θ_{12}, Δm^2_{21}, θ_{13}
  - CHOOZ: θ_{13}, Δm^2_{31}, θ_{12}
  - atmospheric + LBL: θ_{23}, Δm^2_{31}, θ_{13}, Δm^2_{21}

all data samples are connected $\Rightarrow$ global 3ν analysis required

Solar neutrinos

$4p \to {}^4\text{He} + 2e^+ + 2\nu_e + \gamma$

	reaction		flux $(cm^{-2}s^{-1})$
pp cycle	$pp \to de^+\nu$	pp	$5.97(1 \pm 0.006) \cdot 10^{10}$
	$pe^-p \to d\nu$	pep	$1.41(1 \pm 0.011) \cdot 10^8$
	3He $p \to {}^4\text{He}\, e^+\nu$	hep	$7.90(1 \pm 0.15) \cdot 10^3$
	${}^7\text{Be}\, e^- \to {}^7\text{Li}\nu\gamma$	^{7}Be	$5.07(1 \pm 0.06) \cdot 10^9$
	${}^8\text{B} \to {}^8\text{Be}^* e^+\nu$	^{8}B	$5.94(1 \pm 0.11) \cdot 10^6$
CNO	${}^{13}\text{N} \to {}^{13}\text{C}e^+\nu$	^{13}N	$2.88(1 \pm 0.15) \cdot 10^8$
	${}^{15}\text{O} \to {}^{15}\text{N}e^+\nu$	^{15}O	$2.15(1\ {}^{+0.17}_{-0.16}) \cdot 10^8$
	${}^{17}\text{F} \to {}^{17}\text{O}e^+\nu$	^{17}F	$5.82(1\ {}^{+0.19}_{-0.17}) \cdot 10^6$

Peña-Garay, Serenelli, arXix:0811.2424

SSM predictions

Solar neutrinos

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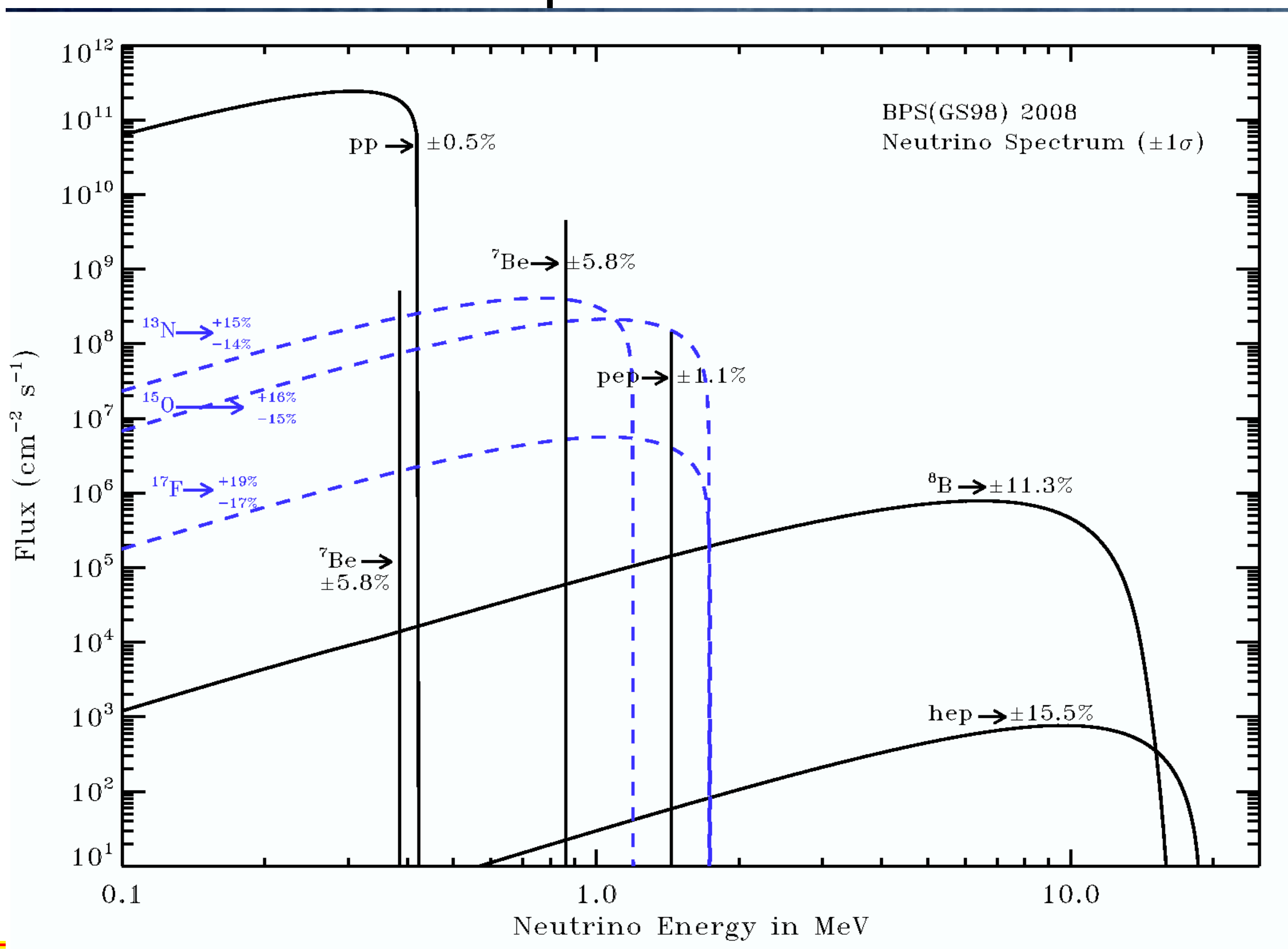


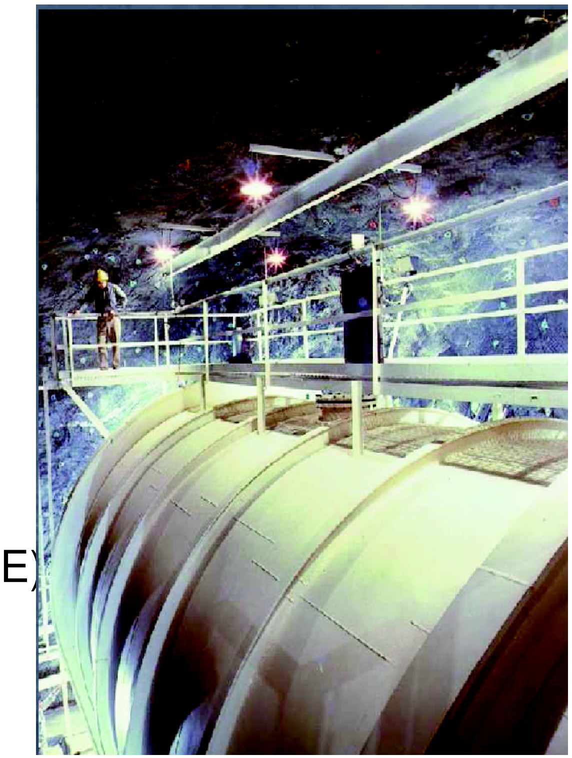
erenelli, arXix:0811.2424

SSM predictions

The first ones: radiochemical experiments

- Chlorine experiment
  - gold mine in Homestake (South Dakota)
  - 615 tons of perchloro-ethylene (C_2CL_4)
  - detection process: $\nu_e + {}^{37}\mathrm{Cl} \to {}^{37}\mathrm{Ar} + e^-$
  - only 1/3 of SSM prediction detected:

$$R_{CL}^{SSM} = 8.12 \pm 1.25 \,\text{SNU}$$
$$R_{CL} = 2.56 \pm 0.16 \pm 0.16 \,\text{SNU}$$



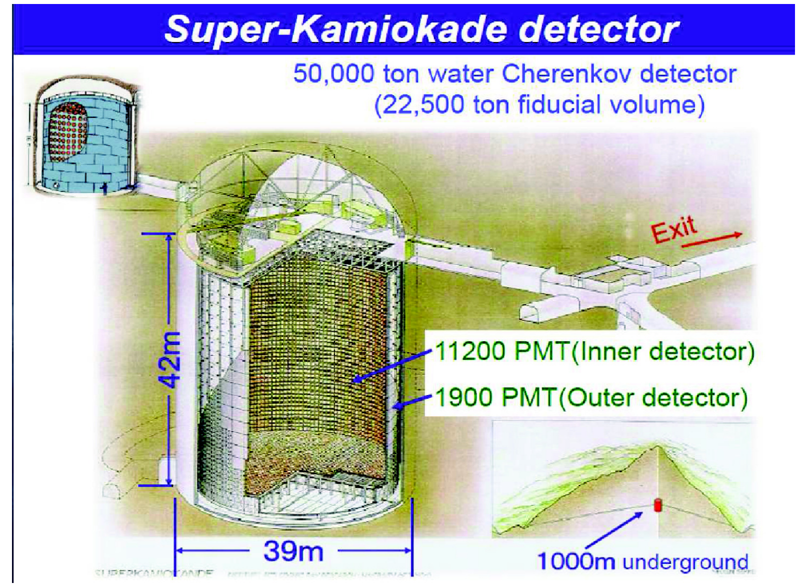
} item Gallium experiments (GALLEX/GNO, SAGE)

$$R_{Ga}^{SSM} = 126.2 \pm 8.5 \,\text{SNU}$$
$$R_{GALLEX/GNO} = 69.3 \pm 4.1 \pm 3.6 \,\text{SNU}$$
$$R_{SAGE} = 66.9 \pm 3.9 \pm 3.6 \,\text{SNU}$$

$\Rightarrow$ 50% deficit

Super-Kamiokande

- water cherenkov detector
- sensitiv to all neutrino flavour: $\nu_x e^- \to \nu_x e^-$
- threshold energy $\sim$ 4-5 MeV
- real-time detector: (E,t)



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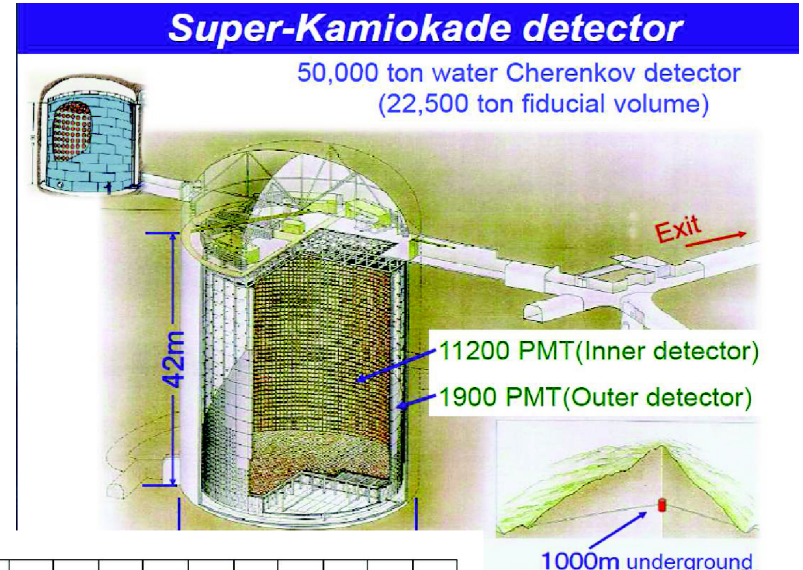
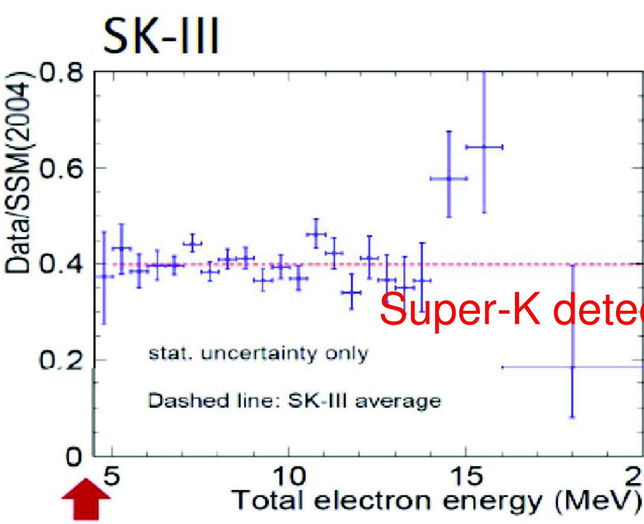
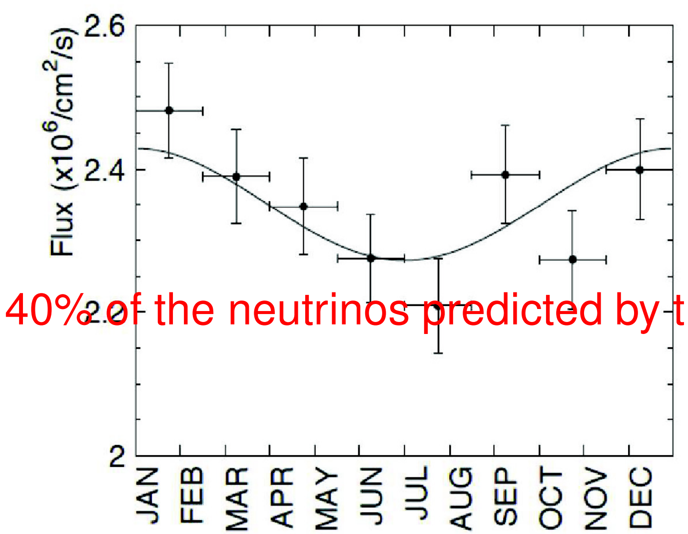




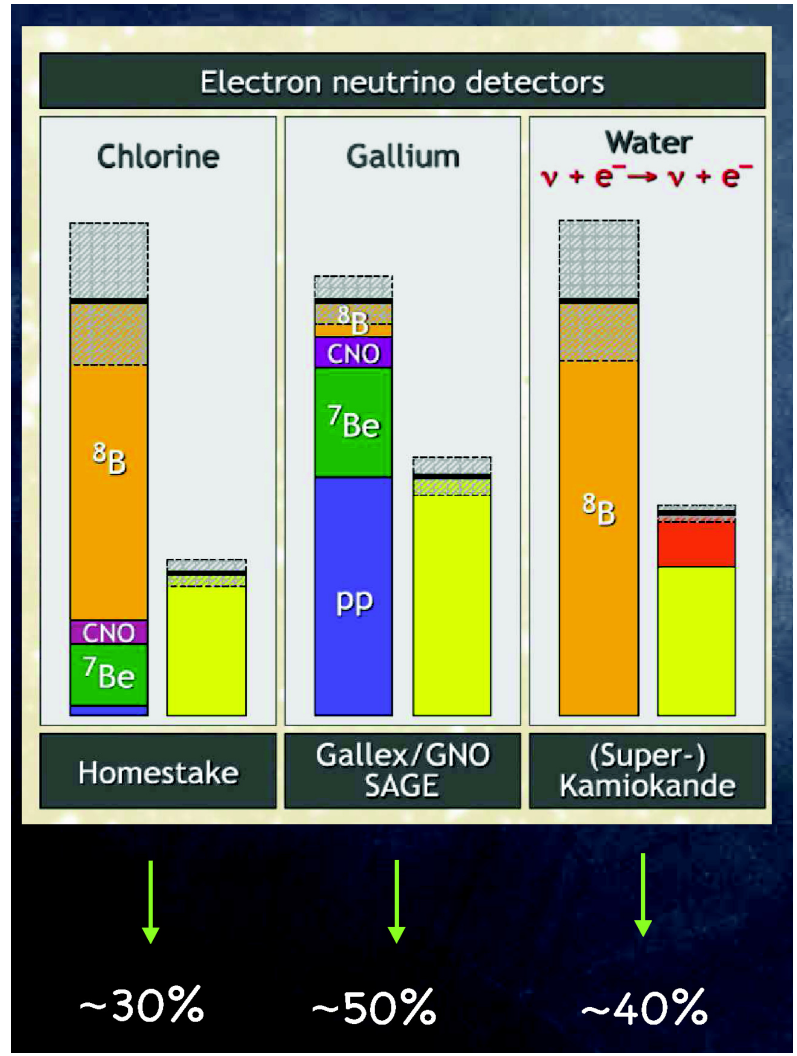


Super-K detects only 40% of the neutrinos predicted by the SSM

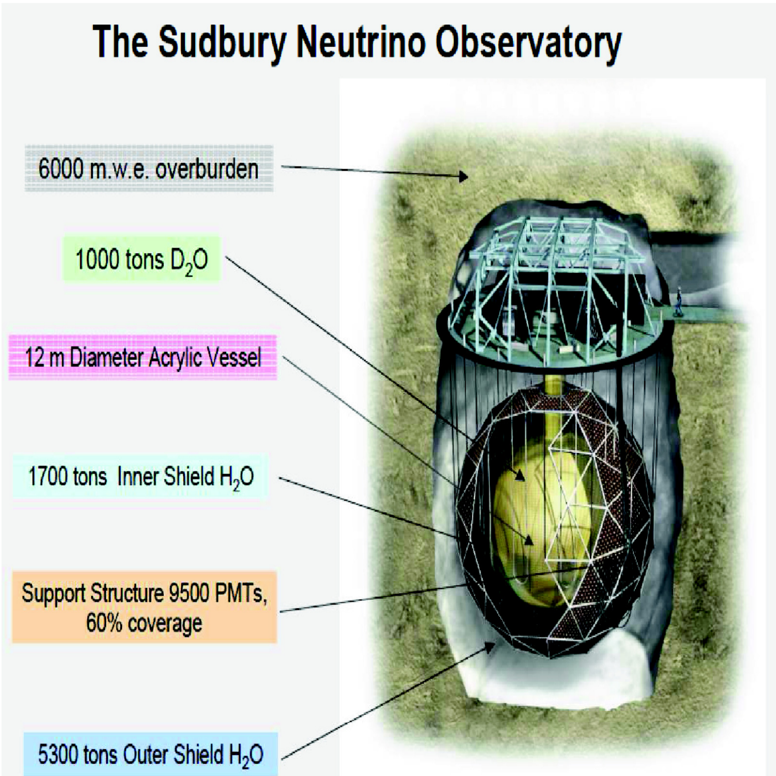
The solar neutrino problem

All experiments detect less neutrinos than expected (30-50%)

- experimental errors?
  $\rightarrow$ different kinds of experiment
- Standard Solar Model incorrect?
- somthing is happening to neutrinos?
- new particles needed?



Sudbury Neutrino Observatory, SNO

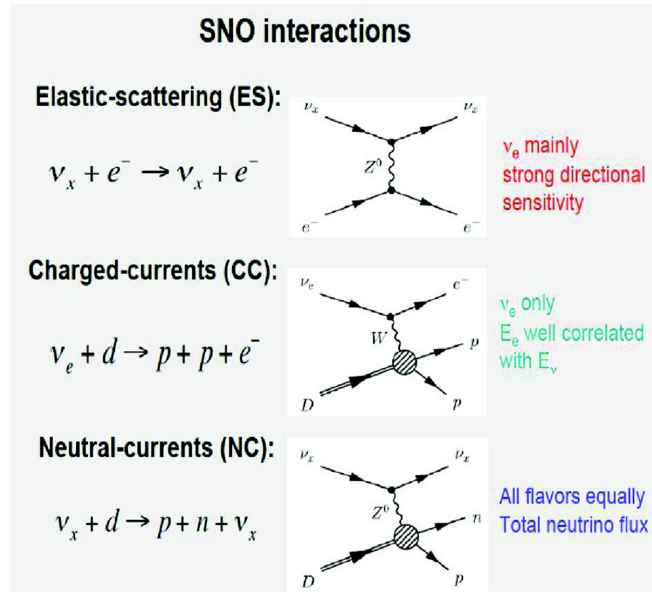


ν_e-flux (CC)): $\frac{\phi_{CC}^{SNO}}{\phi_{NC}^{SNO}} = 0.301 \pm 0.033$ 30%

total ν-flux (NC): $\phi_{NC}^{SNO} = 5.54^{+0.33+0.36}_{-0.31-0.34}$

$\Rightarrow$ 100%

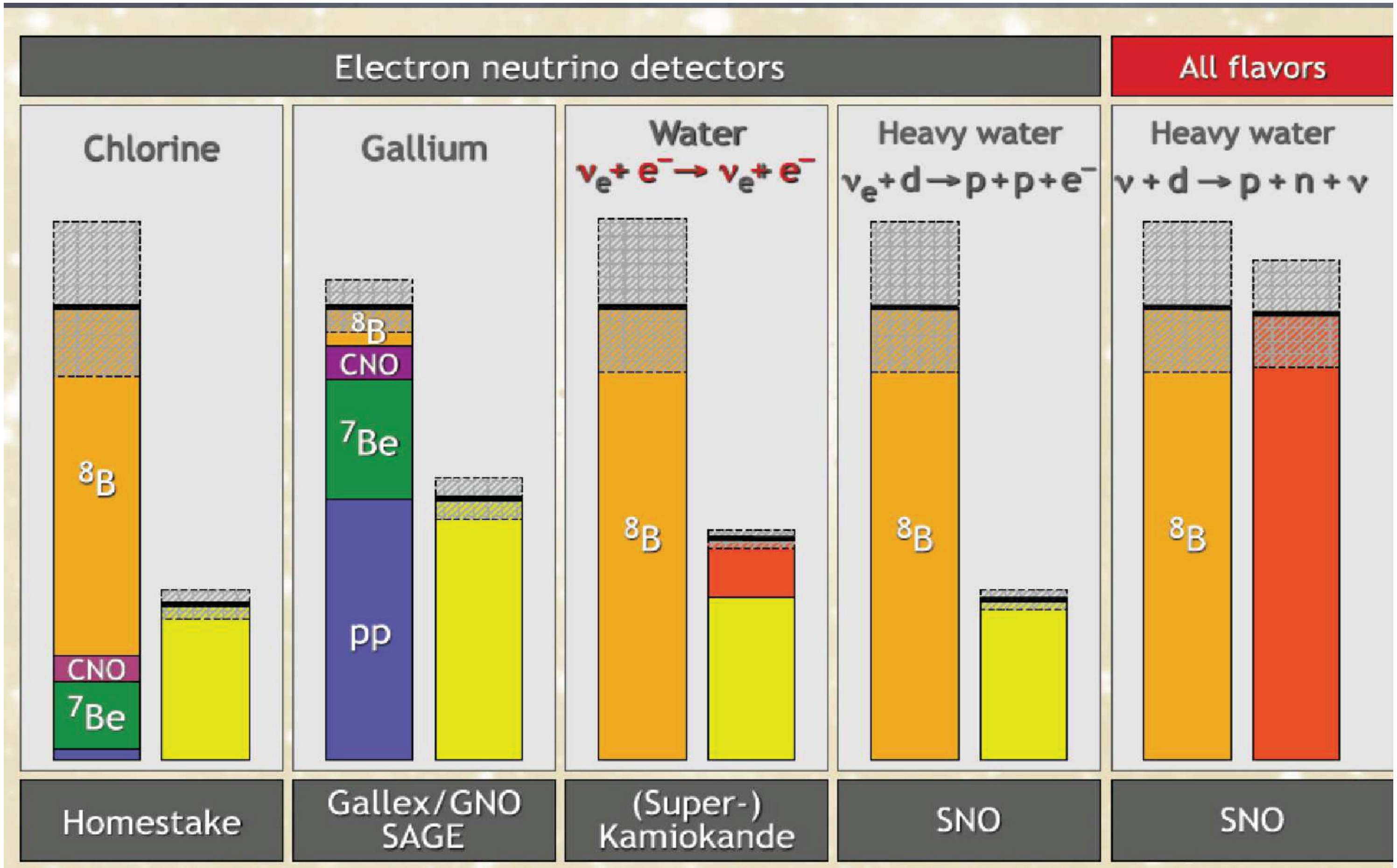
SNO is sensitive to all ν flavours



NC, 3 phases

- D_2O phase
  $n + d \to t + \gamma +$ 6.25 MeV
- Salt phase (D_2O + 2 tons NaCl)
  $n + {}^{35}\text{Cl} \to {}^{35}\text{Cl} + \gamma' s +$ 8.6 MeV
- NCD phase (^{3}He proportional counters)
  $n + {}^3\text{He} \to p + t +$ 0.76 MeV

Solar puzzle solved

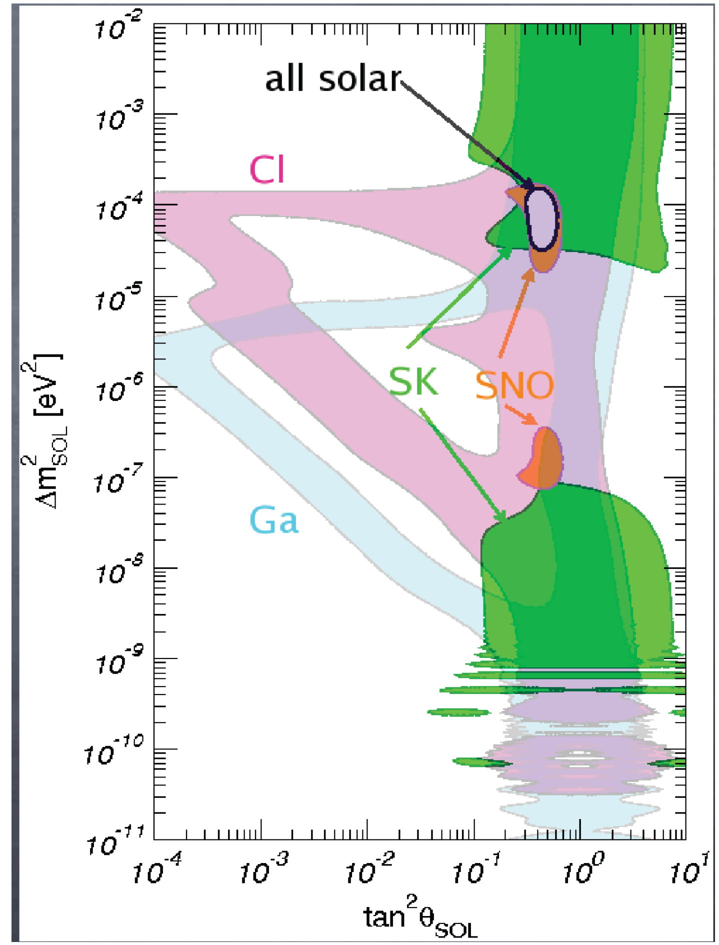


Sun produces ν_e that arrive as 1/3 ν_e +1/3 ν_μ +1/3 ν_τ

$\Rightarrow$ neutrino oscillations

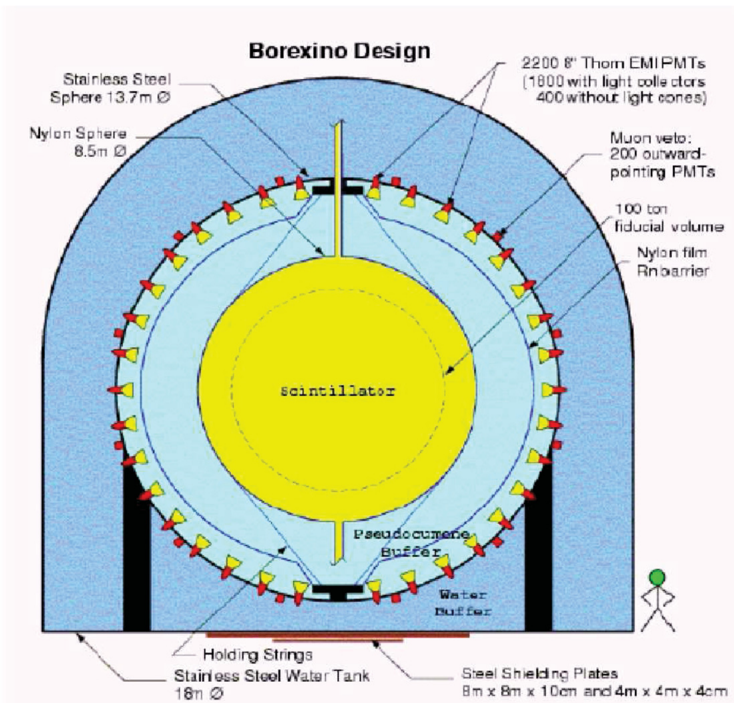
Solar ν oscillations parameters

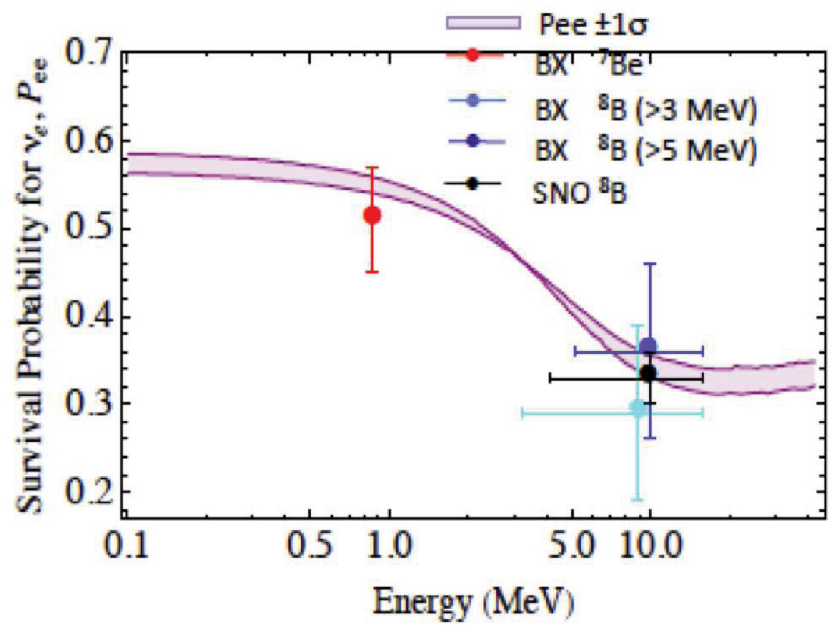
- Homestake ($E_\nu > 0.814$ MeV)
  $\nu_e + {}^{37}\text{Cl} \to {}^{37}\text{Ar} + e^-$
- SAGE/GALLEX-GNO ($E_\nu > 0.233$ MeV)
  $\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-$
- Super-Kamiokande ($E_e \geq 5$ MeV)
  $\nu_x + e^- \to \nu_x + e^-$
- SNO ($E_e \geq 5$ MeV)
  [CC] $\nu_e + d \to p + p + e^-$
  [NC] $\nu_x + d \to \nu_x + p + n$
  [ES] $\nu_x + e^- \to \nu_x + e^-$



Borexino: low energy solar neutrinos

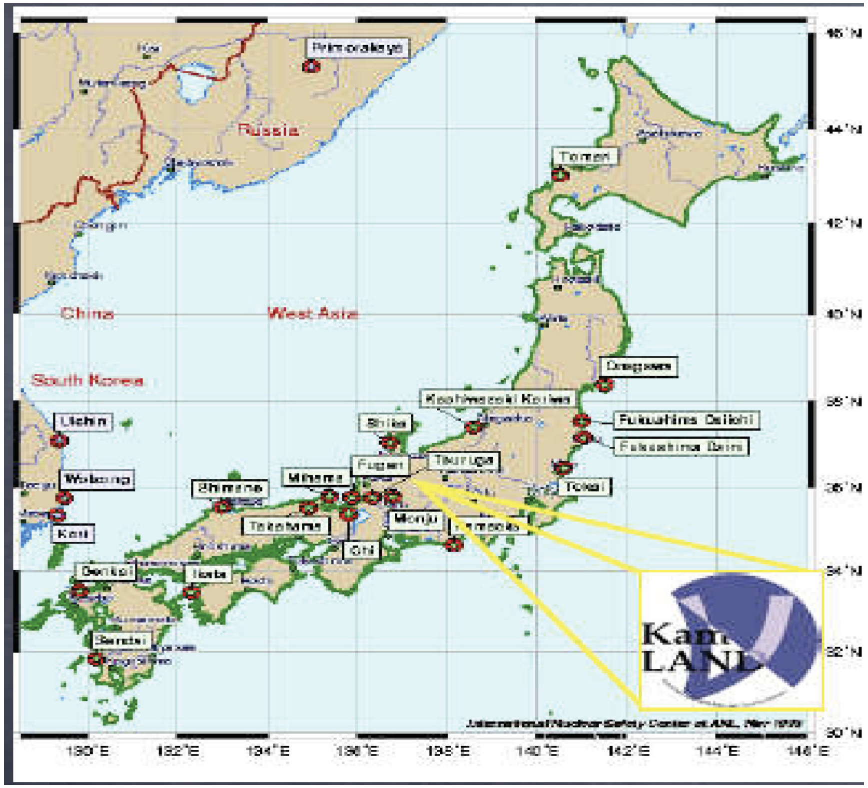
- 300 ton liquid scintillator
- first real-time measurement of ^{7}Be neutrinos ($< 5\%$ error)
- first real-time measurement of ^{8}B flux below 4 MeV

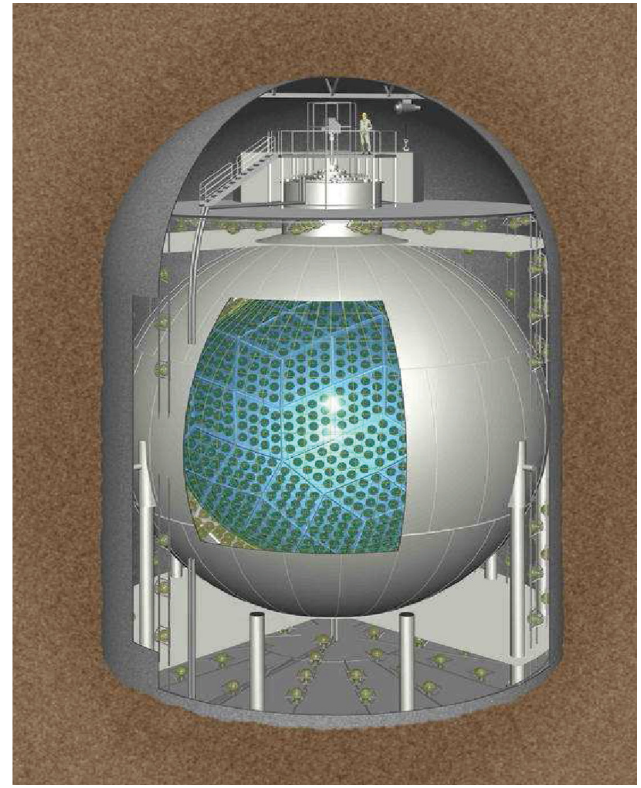




consistent with LMA parameters

The KamLAND reactor experiment

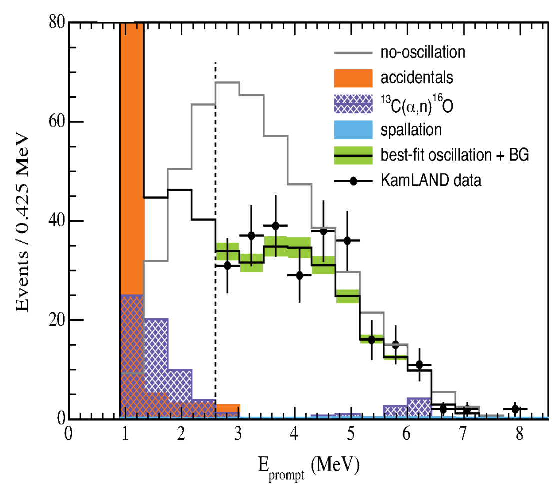


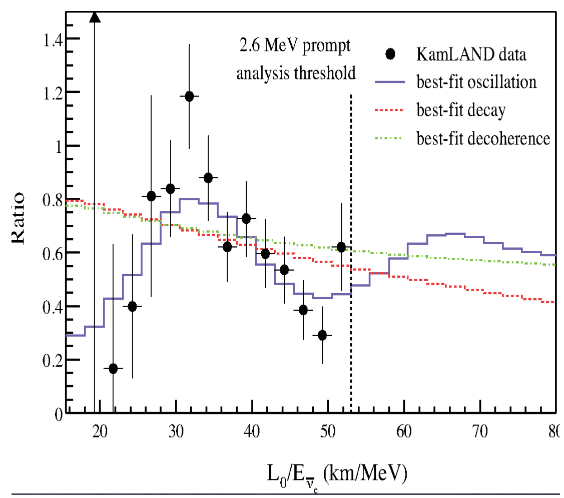


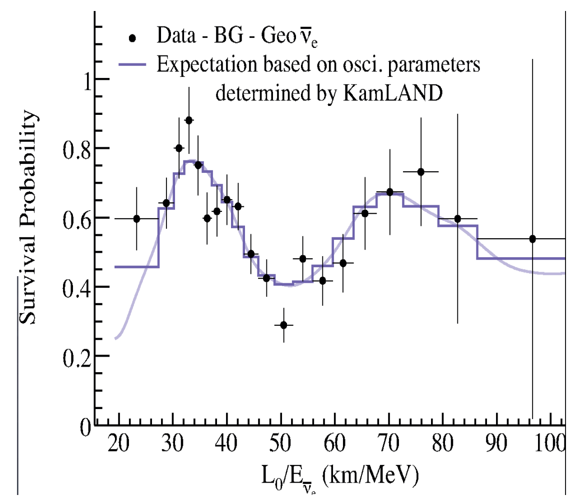
- $\bar{\nu}_e + p \to e^+ + n$
- average distance $\sim$ 180 km
- sensitive to $\Delta m^2_{21} \sim$ few 10^{-5} ev^2 (Δm^2 LMA)

KamLAND results

- 2002: firste evidence $\bar{\nu}_e$ disappearance $\to$ confirmation of solar LMA ν oszillation
  KamLAND coll., PRL 90 (2003) 021802
- 2004: specral distortions (L/E)
  KamLAND coll., PRL 94 (2005) 081801
- 2008: 1-period oscillations observed $\to$ high precision determination of Δm^2_{21}
  KamLAND coll., PRL 100 (2008) 221803

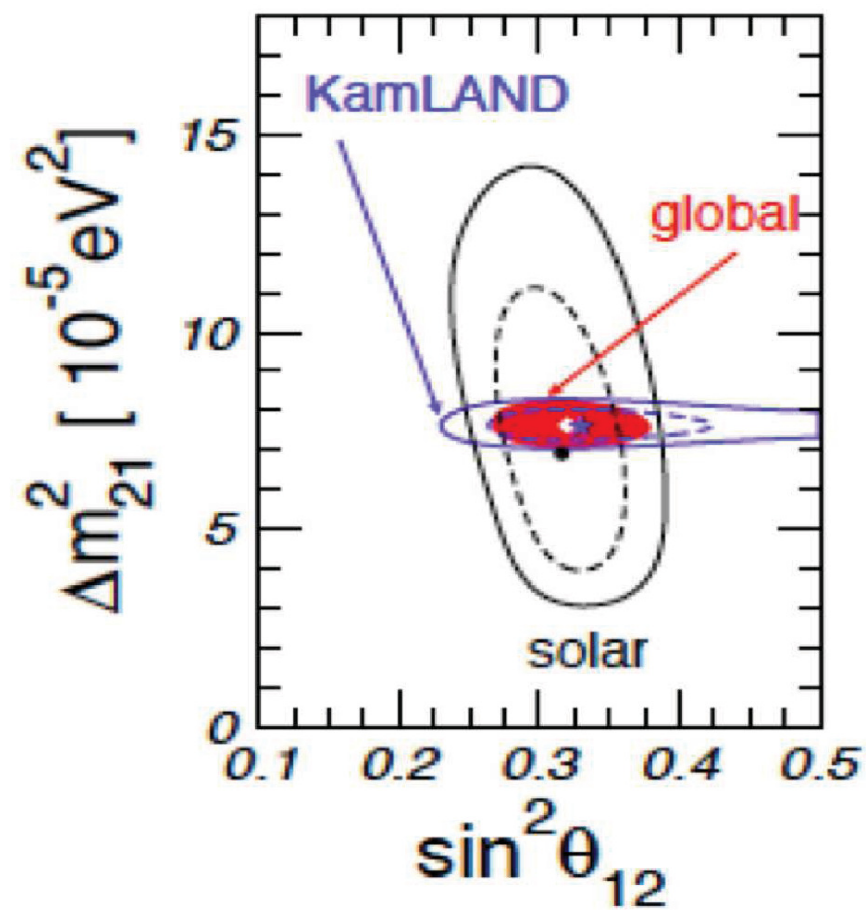






Kombination solar + KamLand

- KamLAND confirms LMA
- best fit point:
  $\Delta m^2_{21} = 7.59^{+0.20}_{-0.18} \cdot 10^{-5}$ eV^2
  $\sin^2\theta_{12} = 0.312^{+0.017}_{-0.015}$
- max. mixing excluded at 7σ
- bound on θ_{12} dominated by solar data
- bound on Δm^2_{21} dominated by KamLAND

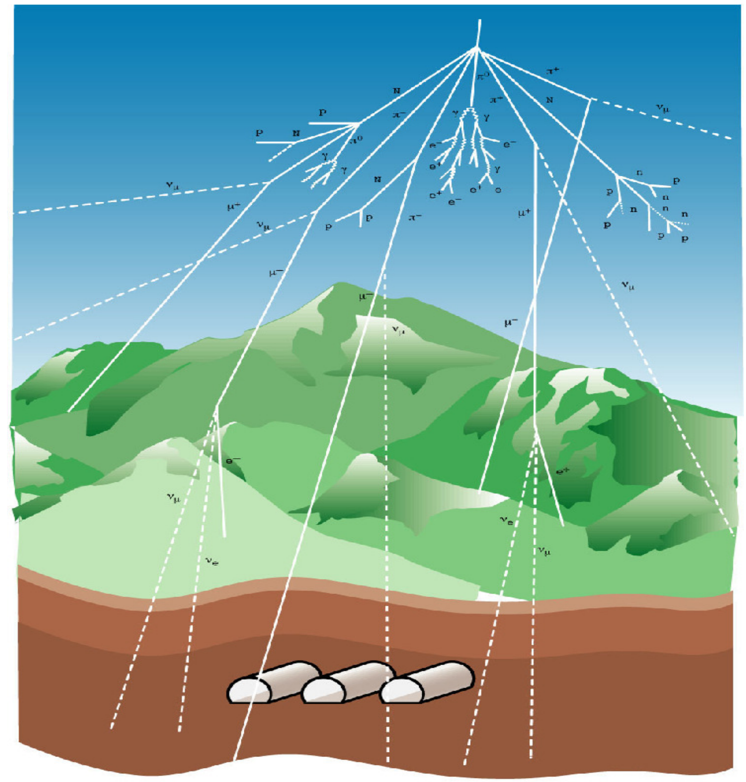


T. Schwetz, M. Tortola, J. W. F. Valle, arXiv:1103.0734 [hep-ph]

Atmospheric neutrino anomaly I

- Cosmic rays interacting with the atmosphere
-

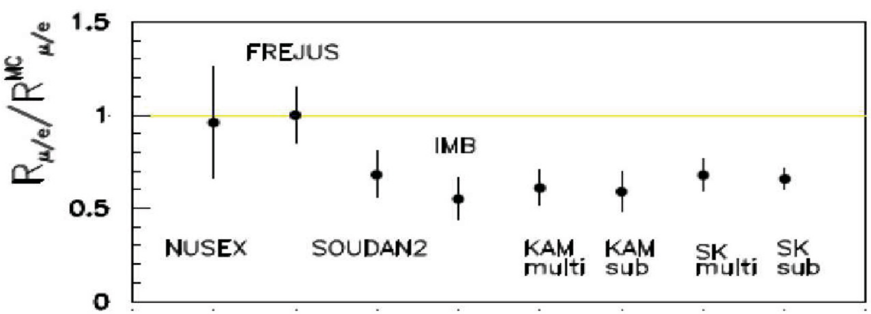
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$
$$\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$$



- Expectation

$$R_{\mu/e} = \frac{N_{\nu_\mu} + N_{\bar{\nu}_\mu}}{N_{\nu_e} + N_{\bar{\nu}_e}} \simeq 2$$

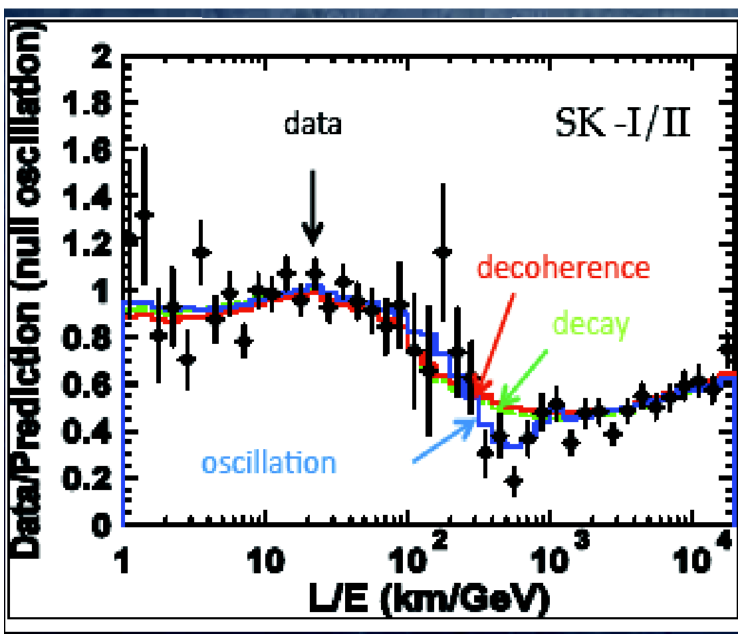
- However

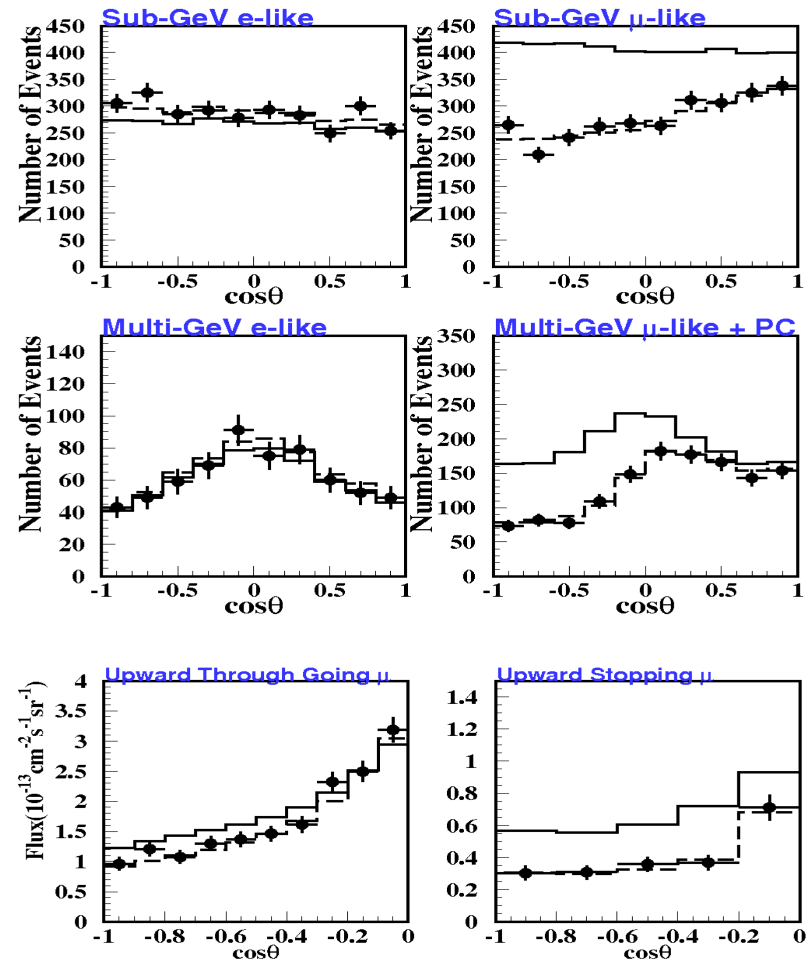


Atmosperhic neutrino anomaly II

- 1998: Evidence for ν_μ oscillations at Super-K
  Super-K. coll., PRL 81 (1998) 1563
- 2004: oscillatory L/E pattern
  Super-K. coll., PRL 93 (2004) 101801

$$P_{\mu\mu} = 1 - \sin^2 2\theta_{23} \sin^2 \left(\frac{\Delta m^2_{31}}{4} \frac{L}{E_\nu} \right)$$



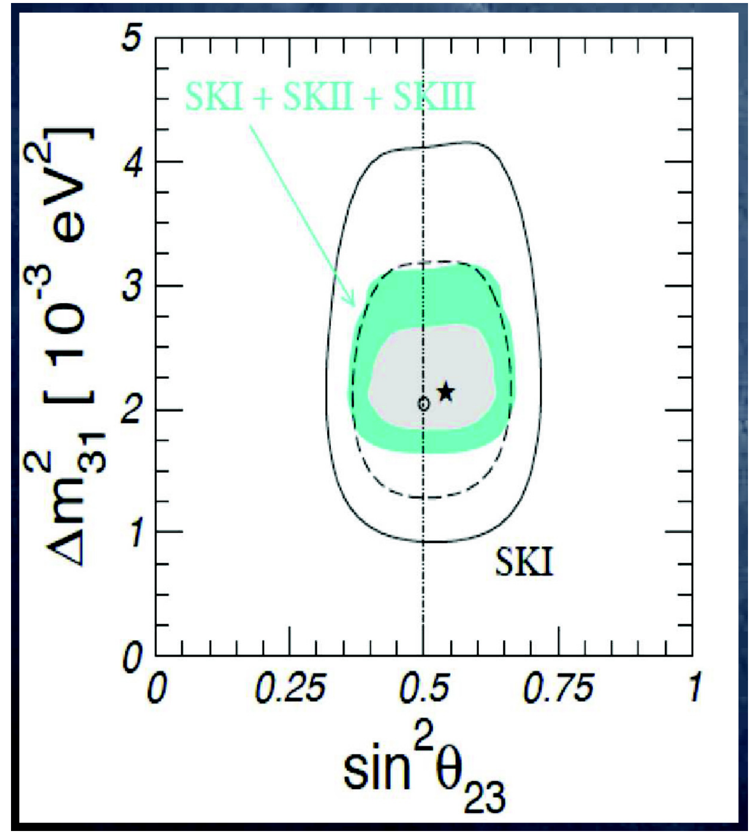


Atmospheric parameters

- Three-neutrino analysis including latest Super-K data
- 90% CL and 3σ regions
- Best fit point (IH)

$$\sin^2\theta_{23} = 0.54$$

$$\Delta m^2_{31} = 2.14 \cdot 10^{-3}\,\text{eV}^2$$



T. Schwetz, M. Tortola, J. W. F. Valle, arXiv:1103.0734 [hep-ph]

Long-baseline accelerator experiments I

Use fixed target experiments to generate pions

$$p + X \quad \to \quad \pi^{\pm} + Y$$

$$\pi^{+} \quad \to \quad \mu^{+} + \nu_{\mu}$$
$$\mu^{+} \to e^{+} + \nu_e + \bar{\nu}_{\mu}$$

$$\pi^{-} \quad \to \quad \mu^{-} + \bar{\nu}_{\mu}$$
$$\mu^{-} \to e^{-} + \bar{\nu}_e + \nu_{\mu}$$

$\Rightarrow$ beam can be focalized to select only neutrinos or anti-neutrinos

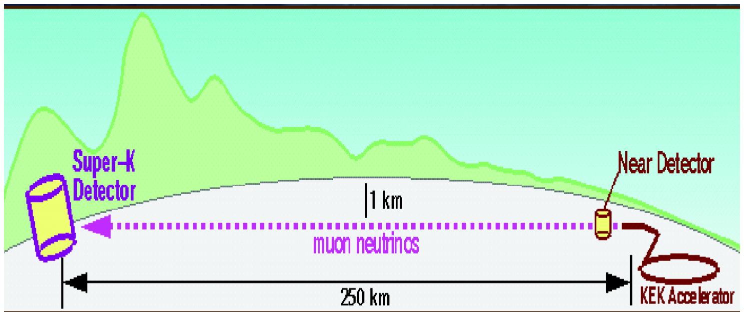
Goal: test atmospheric oscillations and improve parameter determination

$\Rightarrow$ need to adjust parameters to be sensitive to $\Delta m^2 \sim 10^{-3}$ eV^2

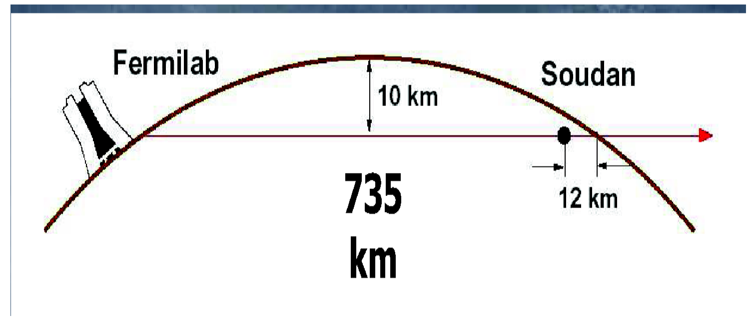
- K2K: L $\simeq$ 250 km, $E_n u \simeq 1.3$ GeV
- MINOS: L $\simeq$ 735 km, $E_n u \simeq 3$ GeV

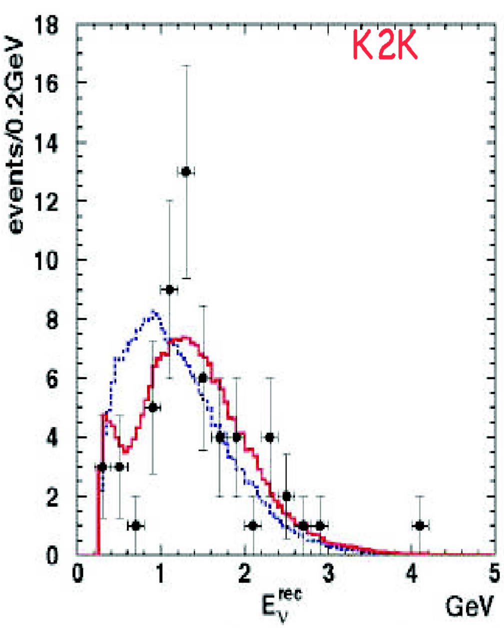
Long-baseline accelerator experiments II

K2K: KEK $\rightarrow$ Kamioka

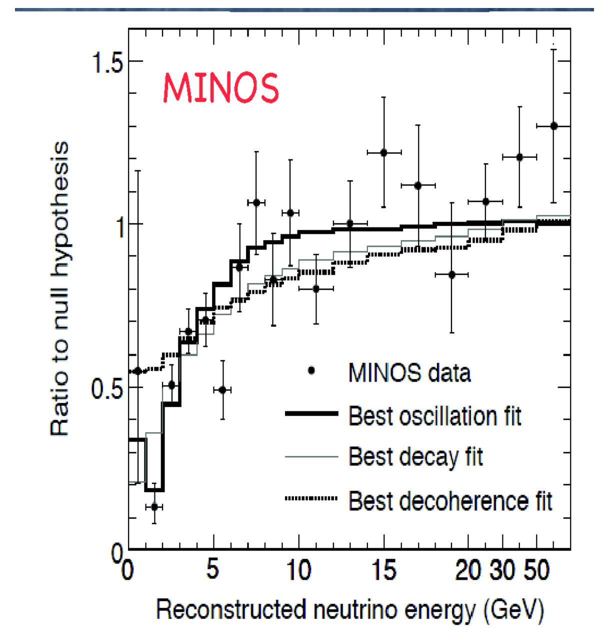


MINOS: Fermilab $\rightarrow$ Soudan





- ν_μ disappearance
- spectral distortions



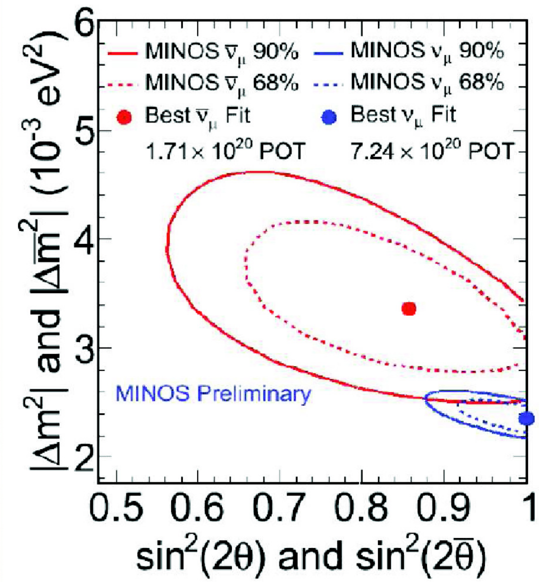
atm ν oscillations confirmed by laboratory experiments

MINOS results

- $\nu_\mu + \bar{\nu}_\mu$ disappearance data

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - \sin^2(2\theta_{23}) \times \sin^2\left(\frac{1.27(\Delta m^2_{32}/\text{eV}^2)(L/\text{km})}{E/\text{GeV}}\right)$$

$|\Delta m^2| = 2.35^{+0.11}_{-0.08}$ eV^2 $\sin^2(2\theta) > 0.91$ (90% CL)
$|\overline{\Delta m^2}| = 3.36^{+0.45}_{-0.40}$ eV^2 $\sin^2(2\bar{\theta}) = 0.86 \pm 0.11$
consistent at 2σ



- ν_e appearance data

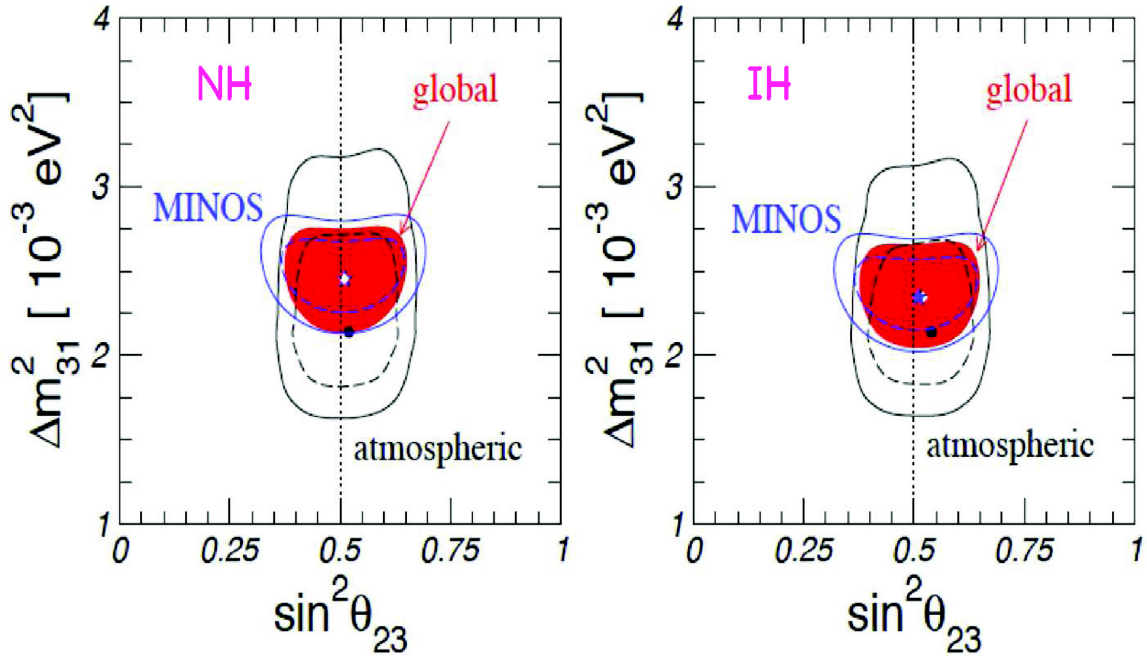
$$P(\nu_\mu \to \nu_e) \simeq \sin^2(\theta_{23})\sin^2(2\theta_{13})\sin^2\left(\frac{1.27(\Delta m^2_{32}/\text{eV}^2)(L/\text{km})}{E/\text{GeV}}\right)$$

54 e^- observed, $49.1 \pm 7.0 \pm 2.7$ expected

$\Rightarrow$ NH: $\sin^2(2\theta_{13}) < 0.12$ (90% CL)

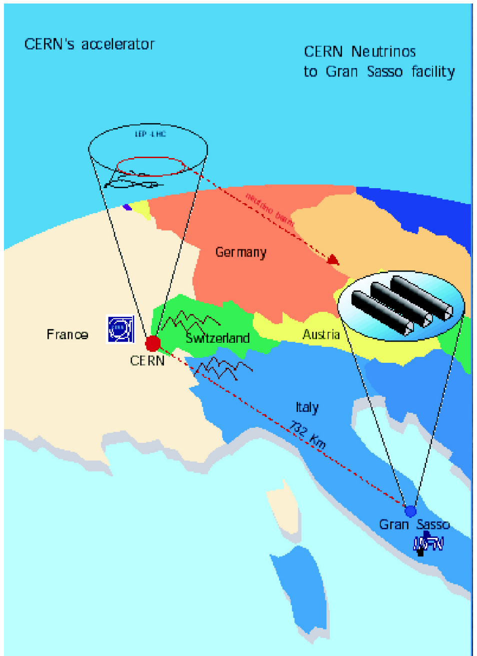
IH: $\sin^2(2\theta_{13}) < 0.20$ (90% CL)

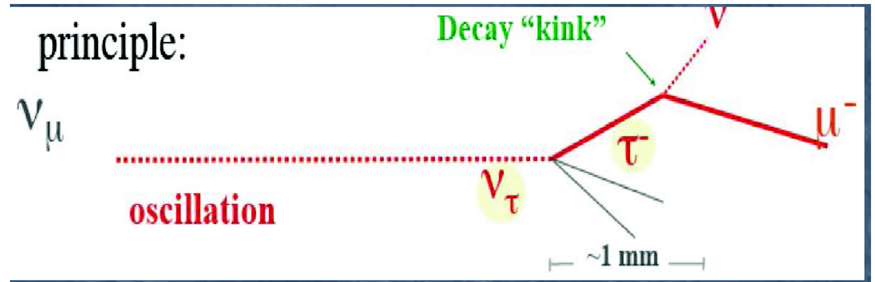
Combining atm + LBL data



- atm data $\Rightarrow$ precision on θ_{23}
- LBL data$\Rightarrow$ precision on Δm^2_{31}
- Best fit: NH $\sin^2(2\theta_{23}) = 0.51 \pm 0.06$, $\Delta m^2_{31} = (2.45 \pm 0.09) 10^{-3}$ eV^2
  IH $\sin^2(2\theta_{23}) = 0.52 \pm 0.06$, $\Delta m^2_{31} = -(2.34 \pm 0.10) 10^{-3}$ eV^2

T. Schwetz, M. Tortola, J. W. F. Valle, Vortrag.tex-arXiv:1103.0734 [hep-ph]





L = 732 km

$\langle E \rangle \sim 17$ GeV

2010: first obs. of ν_τ in ν_μ beam

OPERA: latest results

arXiv:1109.4897: some ν travel with $v > c$ and

$$\frac{v-c}{c} = (2.48 \pm 0.28(stat.) \pm 0.30(sys.)) \times 10^{-5}$$

afterwards: about 65 papers until yesterday
various ideas, suggestions, critics . . .

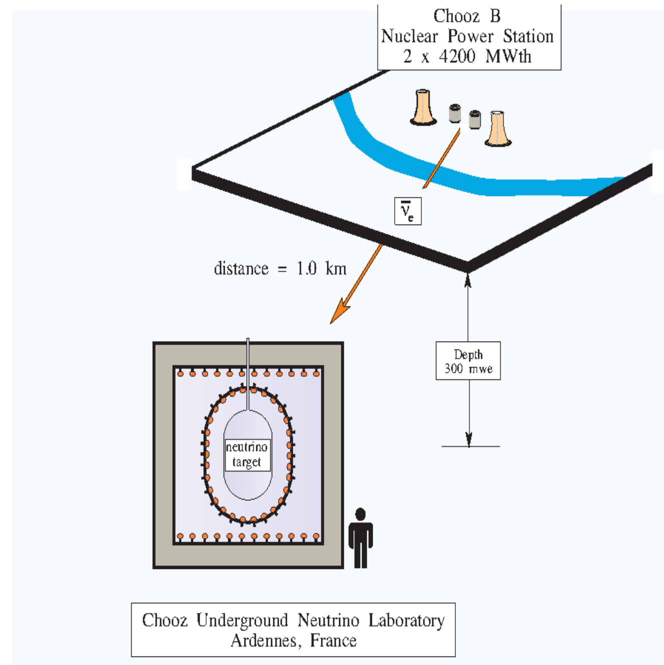
- very difficult to combine with oszillation data and SN 1987a
- Lorentz violation? ⇒ equivalent to Cherenkov radiation?
- Deformed Lorentz transformations?
- Extra dimensions?
- Domain walls?
- Additional (dark) neutrinos?
- Dark Gravity Theories?

⋮

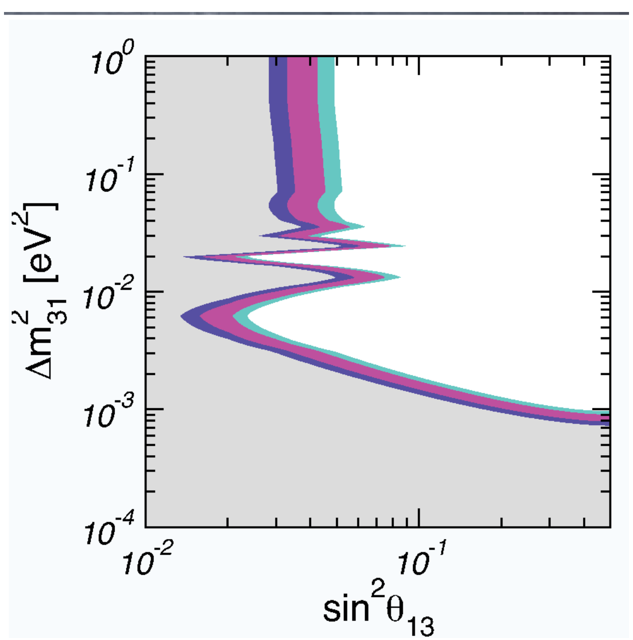
The CHOOZ reactor experiment

- disappearance of reactor ν_es
- 2 ν approximation

$$P(\nu_e \to \nu_e) \quad \simeq \quad 1 - \sin^2(2\theta_{13}) \sin^2\left(\frac{\Delta m^2_{31} L}{E}\right)$$

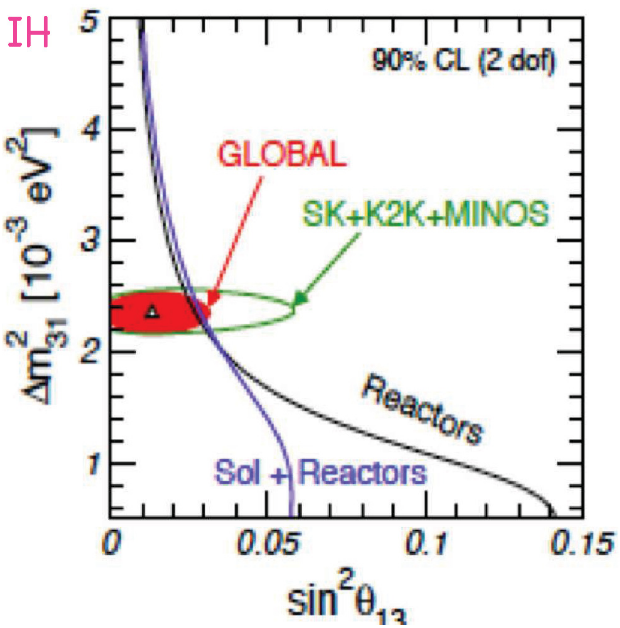


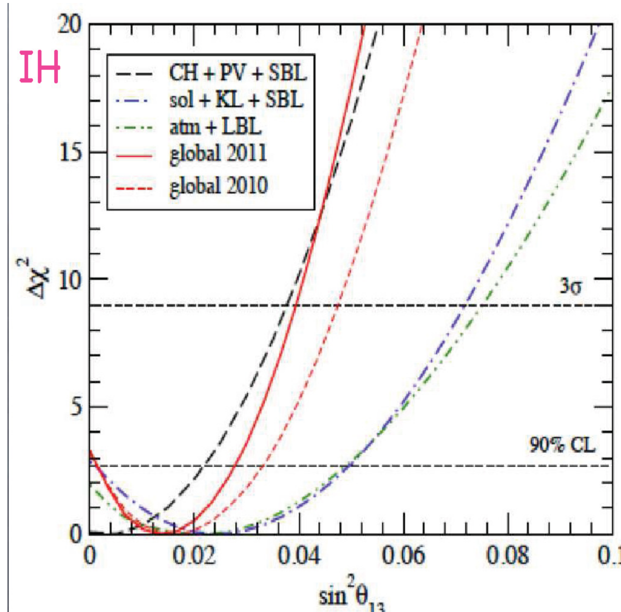
- non-observation of ν_e disappearance



Global bound on θ_{13}

- solar + KamLAND + SBL: $\sin^2\theta_{13} < 0.072$ (3 σ)
- athmospheric + LBL: $\sin^2\theta_{13} < 0.057$ (0.075) for NH (IH) (3 σ)
- CHOOZ + SBL: $\sin^2\theta_{13} < 0.038$ (3 σ)
- Global bound: $\sin^2\theta_{13} < 0.035$ (0.039) for NH (IH) (3 σ)
- weak 1.8 σ indication of $\theta_{13} \neq 0$: $\sin^2\theta_{13} = 0.010^{+0.009}_{-0.006}$ $(0.013^{+0.009}_{-0.007})$ for NH (IH)

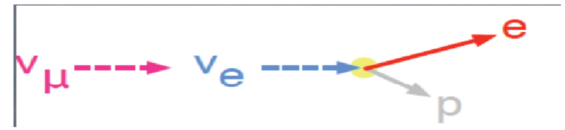




T. Schwetz, M. Tortola, J. W. F. Valle, arXiv:1103.0734 [hep-ph]

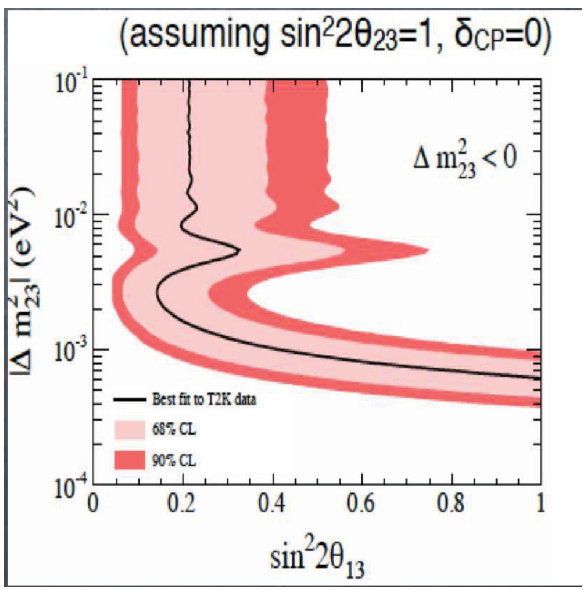
New results from T2K

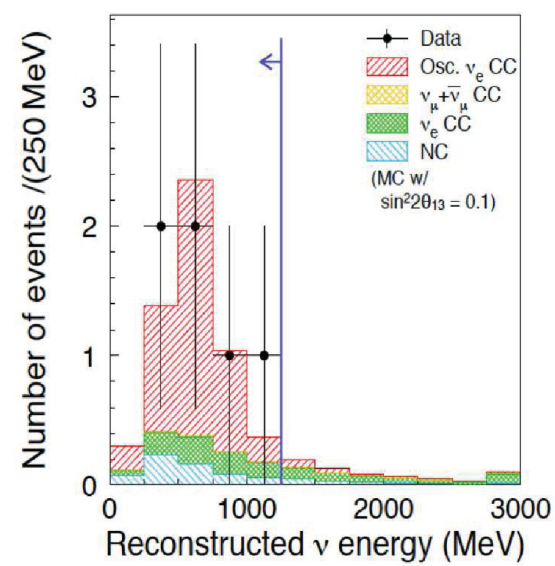
- search for ν_e appearance



$$P(\nu_\mu \to \nu_e) \simeq \sin^2(\theta_{23}) \sin^2(2\theta_{13}) \sin^2\left(\frac{1.27(\Delta m^2_{32}/\text{eV}^2)(L/\text{km})}{E/\text{GeV}}\right)$$

- Expected number of events for $\sin^2\theta_{13} = 0$: 1.5 events
- after all selection cuts: 6 candidates remain (2.5 σ significance)





T2K coll. arXiv:1106.2822

Supersymmetry in a nut-shell
+ flavour violation

Why supersymmetry

- What is the nature of dark matter ?
- What is the origin of the observed baryon asymmetry?
- Why three generations ?

  Why do have neutrinos so tiny masses?
- ”Why does electroweak symmetry break?” or

  ”Why is $\mu^2 < 0$ in the SM?”
- Hierarchy problem

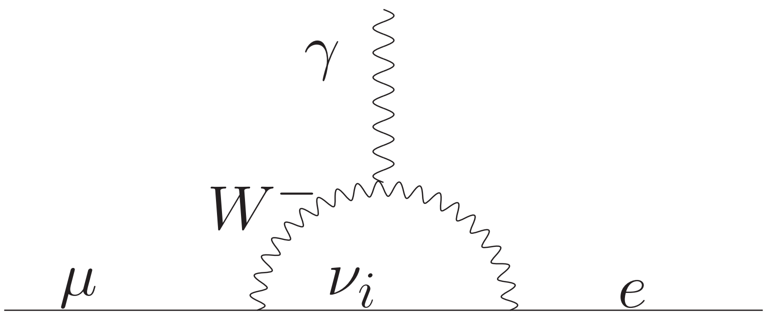
	Standard Model		MSSM
matter:	e d d d	$\Leftrightarrow$	$\tilde{e}$ $\tilde{d}$ $\tilde{d}$ $\tilde{d}$
	ν_e u u u		$\tilde{\nu}_e$ $\tilde{u}$ $\tilde{u}$ $\tilde{u}$
gauge sector:	γ Z^0 $W^\pm$ g	$\Leftrightarrow$	$\tilde{\gamma}$ $\tilde{z}^0$ $\tilde{w}^\pm$ $\tilde{g}$
Higgs sector:	H^0	$\Leftrightarrow$	$\tilde{h}^0$

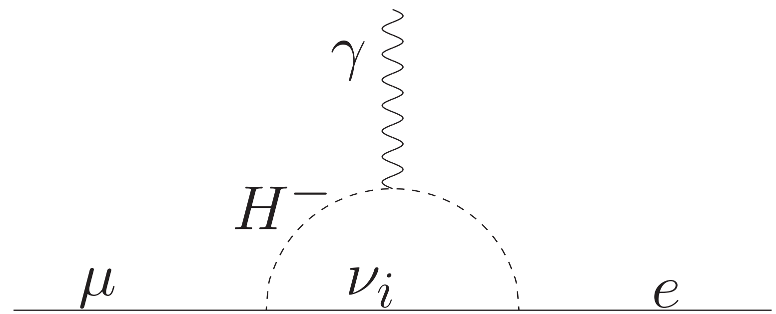
	Standard Model					MSSM				
matter:	e	d	d	d	$\Leftrightarrow$	$\tilde{e}$	$\tilde{d}$	$\tilde{d}$	$\tilde{d}$	
	ν_e	u	u	u		$\tilde{\nu}_e$	$\tilde{u}$	$\tilde{u}$	$\tilde{u}$	
gauge sector:	γ	Z^0	$W^\pm$	g	$\Leftrightarrow$	$\tilde{\gamma}$	$\tilde{z}^0$	$\tilde{w}^\pm$	$\tilde{g}$	
Higgs sector:	h^0	H^0	A^0	$H^\pm$	$\Leftrightarrow$	$\tilde{h}^0_d$	$\tilde{h}^0_u$	$\tilde{h}^\pm$		

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

$(\tilde{\gamma}, \tilde{z}^0, \tilde{h}^0_d, \tilde{h}^0_u) \to \tilde{\chi}^0_i$, $(\tilde{w}^\pm, \tilde{h}^\pm) \to \tilde{\chi}^\pm_j$

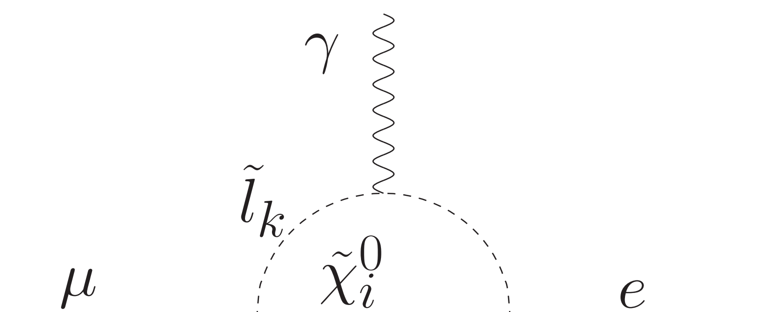
SUSY phenomenology: low energy observables

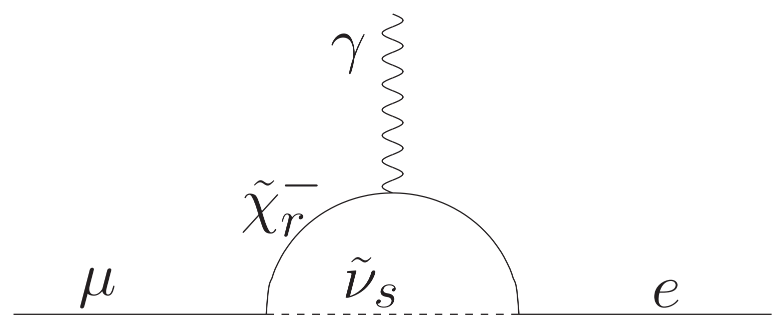


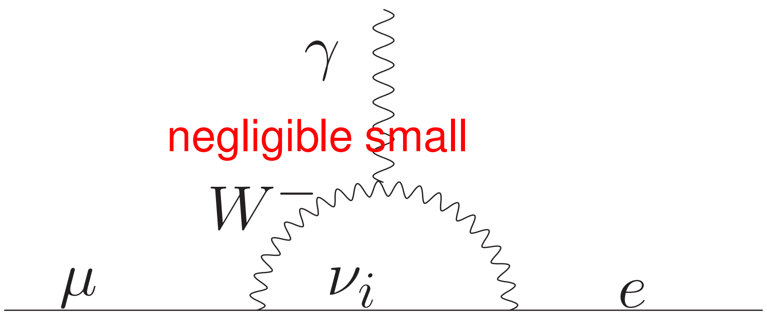


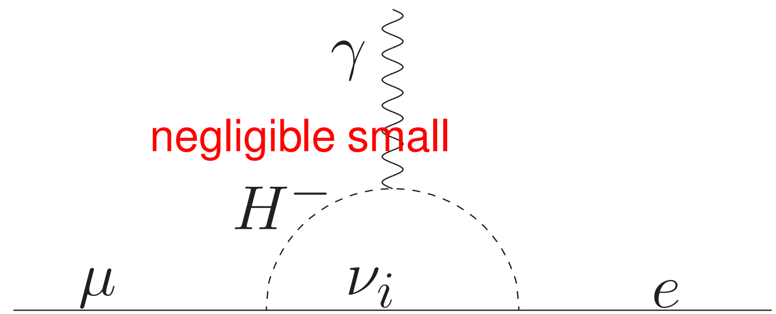
$$\tilde{\chi}^0_i = (\tilde{\gamma}, \tilde{z}^0, \tilde{h}^0_d, \tilde{h}^0_d)$$

$$\tilde{\chi}^-_i = (\tilde{w}^-, \tilde{h}^-)$$

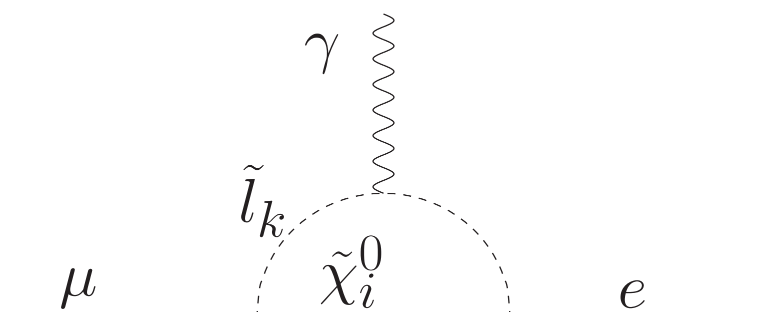




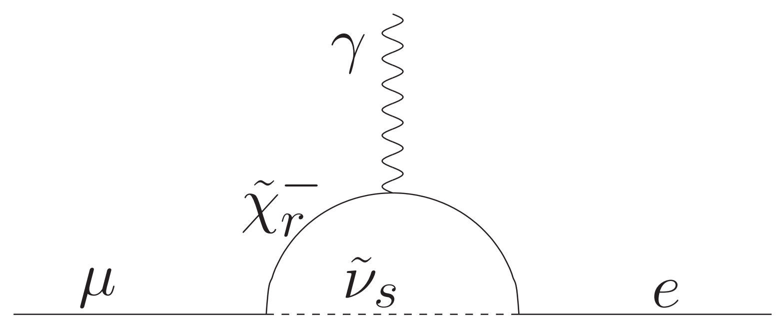




$$\tilde{\chi}^0_i = (\tilde{\gamma}, \tilde{z}^0, \tilde{h}^0_d, \tilde{h}^0_d)$$



$$\tilde{\chi}^-_i = (\tilde{w}^-, \tilde{h}^-)$$



$\Rightarrow$ anomalous magnetic moment, electric dipole moment,

rare lepton decays, e.g. BR($\mu \to e\gamma$) $\lesssim 2.4 \cdot 10^{-12}$

Lepton flavour violation, experimental data

Neutrinos: tiny masses

$\Delta m^2_{atm} \simeq 2.5 \cdot 10^{-3}$ eV^2

$\Delta m^2_{sol} \simeq 7.6 \cdot 10^{-5}$ eV^2

^{3}H decay: $m_\nu \lesssim 2$ eV

Neutrinos: large mixings

$|\tan\theta_{23}|^2 \simeq 1$

$|\tan\theta_{12}|^2 \simeq 0.4$

$\sin\theta^2_{13} \lesssim 0.05$

strong bounds for charged leptons

$BR(\mu \to e\gamma) \lesssim 2.4 \cdot 10^{-12}$

$BR(\mu^- \to e^- e^+ e^-) \lesssim 10^{-12}$

$BR(\tau \to e\gamma) \lesssim 1.1 \cdot 10^{-7}$

$BR(\tau \to \mu\gamma) \lesssim 4.5 \cdot 10^{-8}$

$BR(\tau \to l l l') \lesssim O(10^{-8})$ $(l, l' = e, \mu)$

$$|d_e| \lesssim 10^{-27}\ e\ cm,\ |d_\mu| \lesssim 1.5 \cdot 10^{-18}\ e\ cm,\ |d_\tau| \lesssim 1.5 \cdot 10^{-16}\ e\ cm$$

SUSY contributions to anomalous magnetic moments

$$|\Delta a_e| \leq 10^{-12},\ \ 0 \leq \Delta a_\mu \leq 43 \cdot 10^{-10},\ \ |\Delta a_\tau| \leq 0.058$$

SUSY neutrino mass models and their tests

Dirac neutrinos

analog to leptons or quarks

$$Y_\nu \, H \, \bar{\nu}_L \, \nu_R \to Y_\nu \, v \, \bar{\nu}_L \, \nu_R = m_\nu \, \bar{\nu}_L \, \nu_R$$

requires $Y_\nu \ll Y_e$

$\Rightarrow$ no impact for future collider experiments

Exception: $\tilde{\nu}_R$ is LSP and thus a candidate for dark matter
$\Rightarrow$ long lived NLSP, e.g. $\tilde{t}_1 \to l^+ b \tilde{\nu}_R$

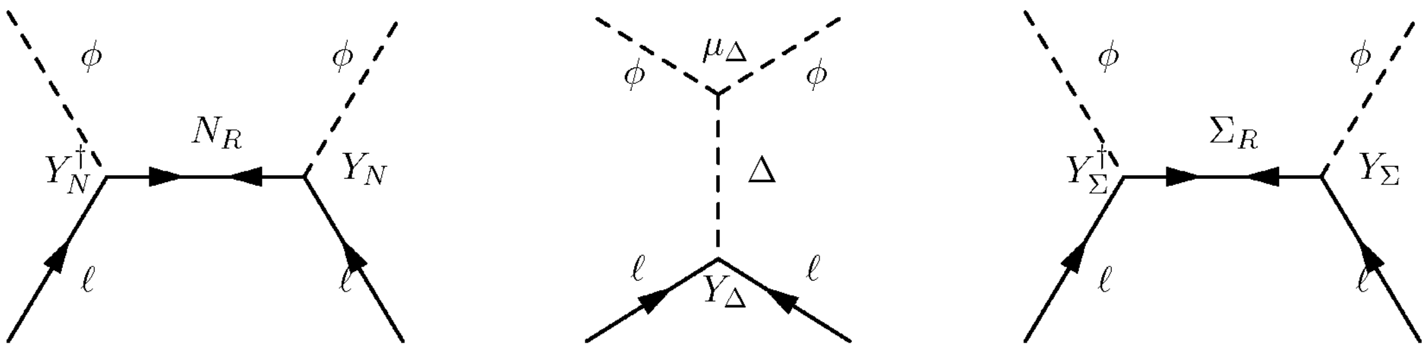
Remark: $m_{\tilde{\nu}_R}$ hardly runs $\Rightarrow$ e.g. $m_{\tilde{\nu}_R} \simeq m_0$ in mSUGRA
$m_{\tilde{\nu}_R} \simeq 0$ in GMSB

S. Gopalakrishna, A. de Gouvea and W. P., JHEP **0611** (2006) 050
S. K. Gupta, B. Mukhopadhyaya, S. K. Rai, PRD **75** (2007) 075007
D. Choudhury, S. K. Gupta, B. Mukhopadhyaya, PRD **78** (2008) 015023

Majorana neutrinos: Seesaw mechanism*

Neutrino masses due to

$$\frac{f}{\Lambda}(HL)(HL)$$



* P. Minkowski, Phys. Lett. B **67** (1977) 421; T. Yanagida, KEK-report 79-18 (1979); M. Gell-Mann, P. Ramond, R. Slansky, in *Supergravity*, North Holland (1979), p. 315; R.N. Mohapatra and G. Senjanovic, *Phys. Rev. Lett.* **44** 912 (1980); M. Magg and C.Wetterich, Phys. Lett. B 94 (1980) 61; G. Lazarides, Q. Shafi and C. Wetterich, Nucl. Phys. B 181 (1981) 287; J. Schechter and J. W. F. Valle, Phys. Rev. **D25**, 774 (1982); R. Foot, H. Lew, X. G. He and G. C. Joshi, Z. Phys. C 44 (1989) 441.

The Setup: GUT scale

Relevant SU(5) invariant parts of the superpotentials at M_{GUT}

- Type-I

$$W_{\rm RHN} = \mathbf{Y}_N^{\rm I}\, N^c\, \overline{5}_M \cdot 5_H + \frac{1}{2}\, M_R\, N^c N^c$$

- Type-II

$$W_{\rm 15H} = \frac{1}{\sqrt{2}}\mathbf{Y}_N^{\rm II}\, \overline{5}_M \cdot 15 \cdot \overline{5}_M + \frac{1}{\sqrt{2}}\lambda_1 \overline{5}_H \cdot 15 \cdot \overline{5}_H + \frac{1}{\sqrt{2}}\lambda_2 5_H \cdot \overline{15} \cdot 5_H$$
$$+ M_{15} 15 \cdot \overline{15}$$

- Type-III

$$W_{\rm 24H} = 5_H 24_M Y_N^{III} \overline{5}_M + \frac{1}{2} 24_M M_{24} 24_M$$

The $SU(5)$-broken phase

Under $SU(3) \times SU_L(2) \times U(1)_Y$

- The **5**, **10** and $\mathbf{5}_H$ contain

$$\overline{5}_M = (d^c, L),\ 10 = (u^c, e^c, Q),\ 5_H = (H^c, H_u),\ \overline{5}_H = (\overline{H}^c, H_d)$$

- The $\mathbf{15}$ decomposes as

$$\mathbf{15} = S(6, 1, -\frac{2}{3}) + T(1, 3, 1) + Z(3, 2, \frac{1}{6})$$

- The $\mathbf{24}$ decomposes as

$$\mathbf{24}_M = W_M(1, 3, 0) + B_M(1, 1, 0) + \overline{X}_M(3, 2, -\frac{5}{6}) + X_M(\overline{3}, 2, \frac{5}{6}) + G_M(8, 1, 0)$$

Seesaw I

Postulate very heavy right-handed neutrinos yielding the following superpotential below M_{GUT}:

$$W_I = W_{MSSM} + W_\nu \ ,$$
$$W_\nu = \widehat{N}^c Y_\nu \widehat{L} \cdot \widehat{H}_u + \frac{1}{2}\widehat{N}^c M_R \widehat{N}^c \ ,$$

Neutrino mass matrix

$$m_\nu = -\frac{v_u^2}{2} Y_\nu^T M_R^{-1} Y_\nu$$

Inverting the seesaw equation gives Y_ν a la Casas & Ibarra

$$Y_\nu = \sqrt{2}\frac{i}{v_u}\sqrt{\hat{M}_R} \cdot R \cdot \sqrt{\hat{m}_\nu} \cdot U^\dagger$$

$\hat{m}_\nu$, $\hat{M}_R$ . . . diagonal matrices containing the corresponding eigenvalues
U . . . . neutrino mixing matrix
R . . . . complex orthogonal matrix.

Below M_{GUT} the superpotential reads

$$
\begin{aligned}
W_{II} \quad &= \quad W_{MSSM} + \frac{1}{\sqrt{2}}(Y_T \widehat{L}\widehat{T}_1 \widehat{L} + Y_S \widehat{D}^c \widehat{S}_1 \widehat{D}^c) + Y_Z \widehat{D}^c \widehat{Z}_1 \widehat{L} \\
&+ \quad \frac{1}{\sqrt{2}}(\lambda_1 \widehat{H}_d \widehat{T}_1 \widehat{H}_d + \lambda_2 \widehat{H}_u \widehat{T}_2 \widehat{H}_u) + M_T \widehat{T}_1 \widehat{T}_2 + M_Z \widehat{Z}_1 \widehat{Z}_2 + M_S \widehat{S}_1 \widehat{S}_2
\end{aligned}
$$

fields with index 1 (2) originate from the 15-plet ($\overline{15}$-plet).

The effective mass matrix is

$$m_\nu = -\frac{v_u^2}{2} \frac{\lambda_2}{M_T} Y_T .$$

Note that

$$\hat{Y}_T = U^T \cdot Y_T \cdot U \ ,$$

In the $SU(5)$ broken phase the superpotential becomes

$$W_{III} = W_{MSSM} + \widehat{H}_u(\widehat{W}_M Y_N - \sqrt{\frac{3}{10}}\widehat{B}_M Y_B)\widehat{L} + \widehat{H}_u \widehat{\overline{X}}_M Y_X \widehat{D}^c$$
$$+\frac{1}{2}\widehat{B}_M M_B \widehat{B}_M + \frac{1}{2}\widehat{G}_M M_G \widehat{G}_M + \frac{1}{2}\widehat{W}_M M_W \widehat{W}_M + \widehat{X}_M M_X \widehat{\overline{X}}_M$$

giving

$$m_\nu = -\frac{v_u^2}{2}\left(\frac{3}{10} Y_B^T M_B^{-1} Y_B + \frac{1}{2} Y_W^T M_W^{-1} Y_W\right) \simeq -v_u^2 \frac{4}{10} Y_W^T M_W^{-1} Y_W$$

last step: valid if $M_B \simeq M_W$ and $Y_B \simeq Y_W$
$\Rightarrow$ Casas-Ibarra decomposition for Y_W as in type-I up to factor $4/5$

Effect of heavy particles on MSSM parameters

MSSM: $(b_1, b_2, b_3) = (33/5, 1, -3)$

per 15-plet $\Delta b_i = 7/2$ $\Rightarrow$ type II model $\Delta b_i = 7$

per 24-plet $\Delta b_i = 5$ $\Rightarrow$ type III model $\Delta b_i = 15$

Effect of heavy particles on MSSM parameters

MSSM: $(b_1, b_2, b_3) = (33/5, 1, -3)$

per 15-plet $\Delta b_i = 7/2$ $\Rightarrow$ type II model $\Delta b_i = 7$

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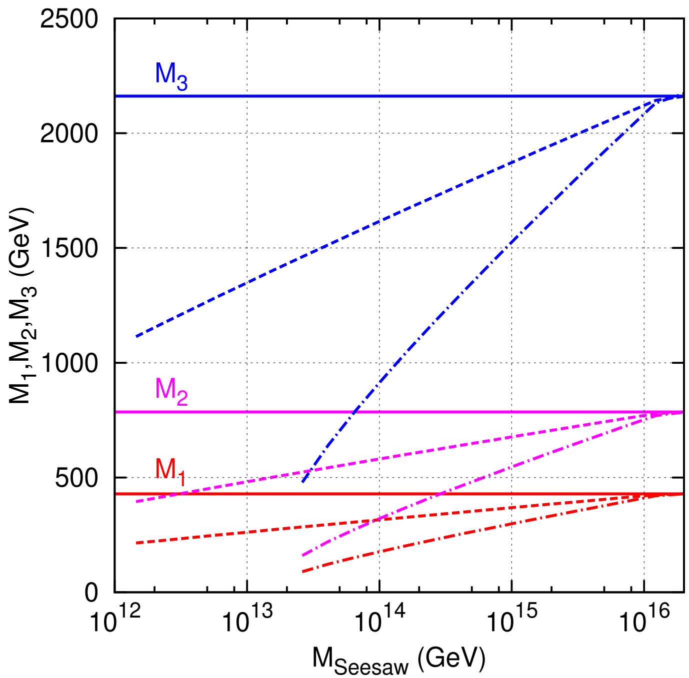
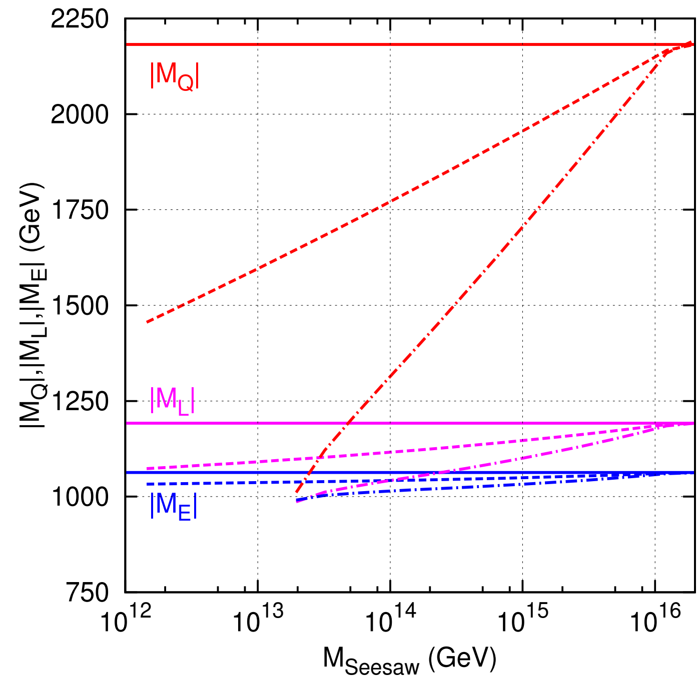


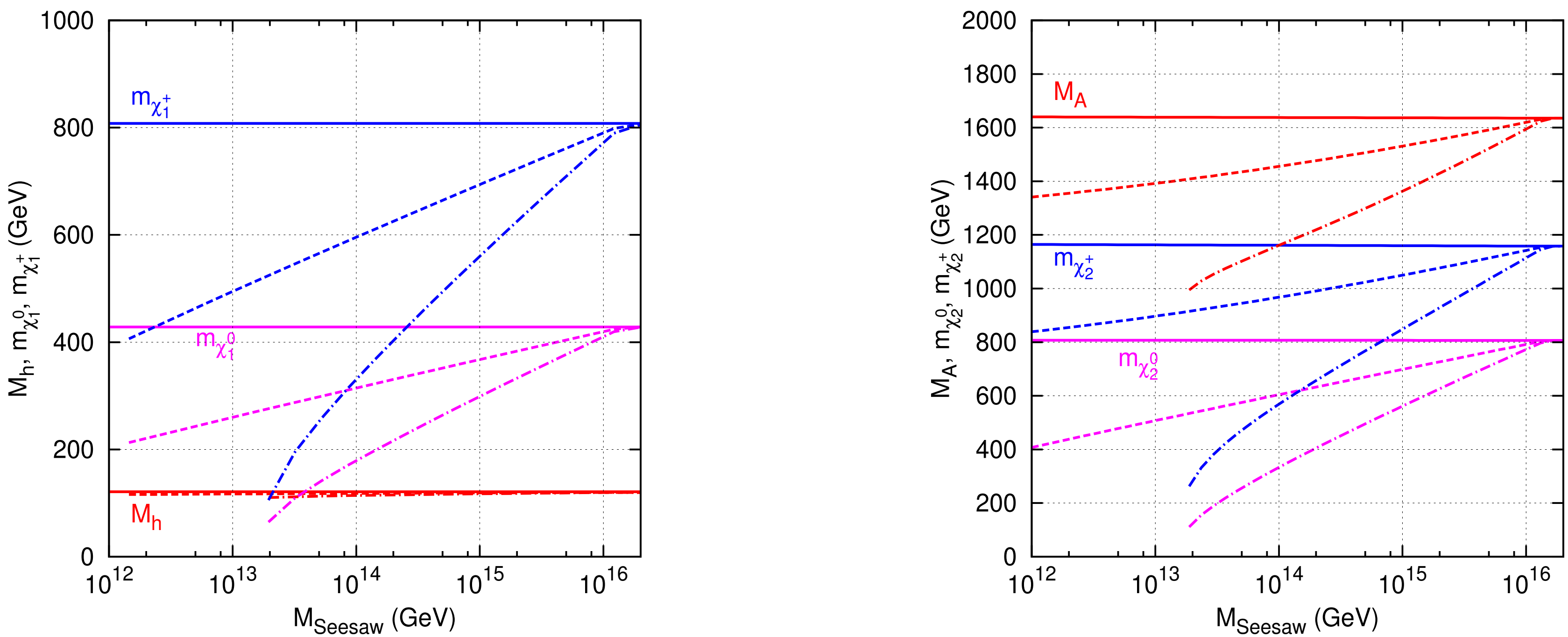


$Q = 1$ TeV, $m_0 = M_{1/2} = 1$ TeV, $A_0 = 0$, $\tan\beta = 10$ and $\mu > 0$

Full lines . . . seesaw type I, dashed lines . . . type II, dash-dotted lines . . . type III
degenerate spectrum of the seesaw particles

J. N. Esteves, M. Hirsch, W.P., J. C. Romao, F. Staub, arXiv:1010.6000

Effect on heavy particles on MSSM spectrum, I

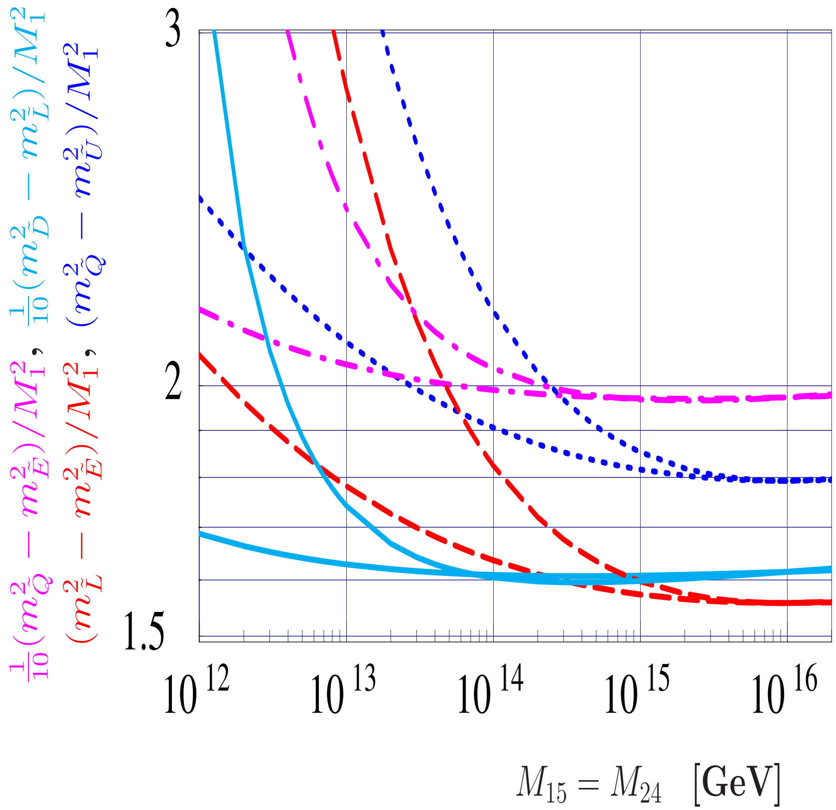


$m_0 = M_{1/2} = 1$ TeV, $A_0 = 0$, $\tan\beta = 10$ and $\mu > 0$

Full lines . . . seesaw type I, dashed lines . . . type II, dash-dotted lines . . . type III degenerate spectrum of the seesaw particles

J. N. Esteves, M. Hirsch, W.P., J. C. Romao, F. Staub, arXiv:1010.6000

"Invariants"



Seesaw I ($\simeq$ MSSM)

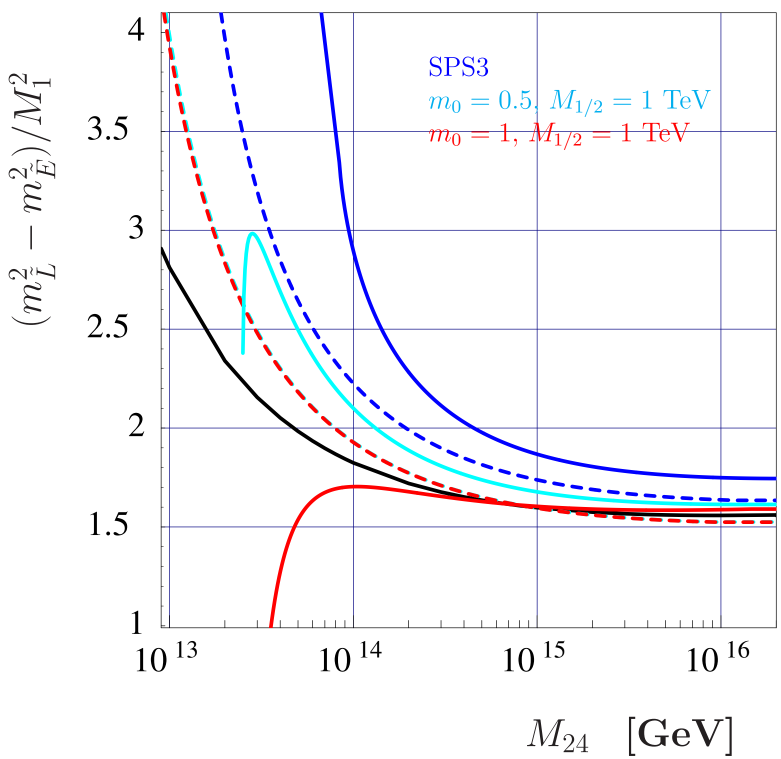
$\frac{m_Q^2 - m_E^2}{M_1^2} \simeq 20$, $\frac{m_D^2 - m_L^2}{M_1^2} \simeq 18$

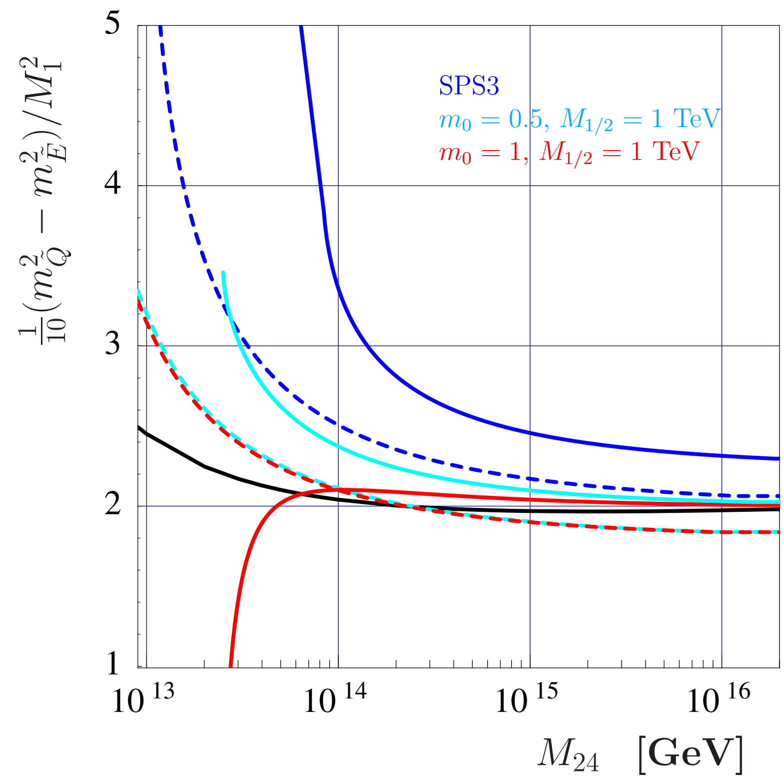
$\frac{m_L^2 - m_E^2}{M_1^2} \simeq 1.6$, $\frac{m_Q^2 - m_U^2}{M_1^2} \simeq 1.55$

(solution of 1-loop RGEs)

M. Hirsch, S. Kaneko, W. P., Phys. Rev. D **78** (2008) 093004
J. Esteves, M.Hirsch, J. Romão, W. P., F. Staub, arXiv:1010.6000

"Invariants", limits for seesaw type-III models





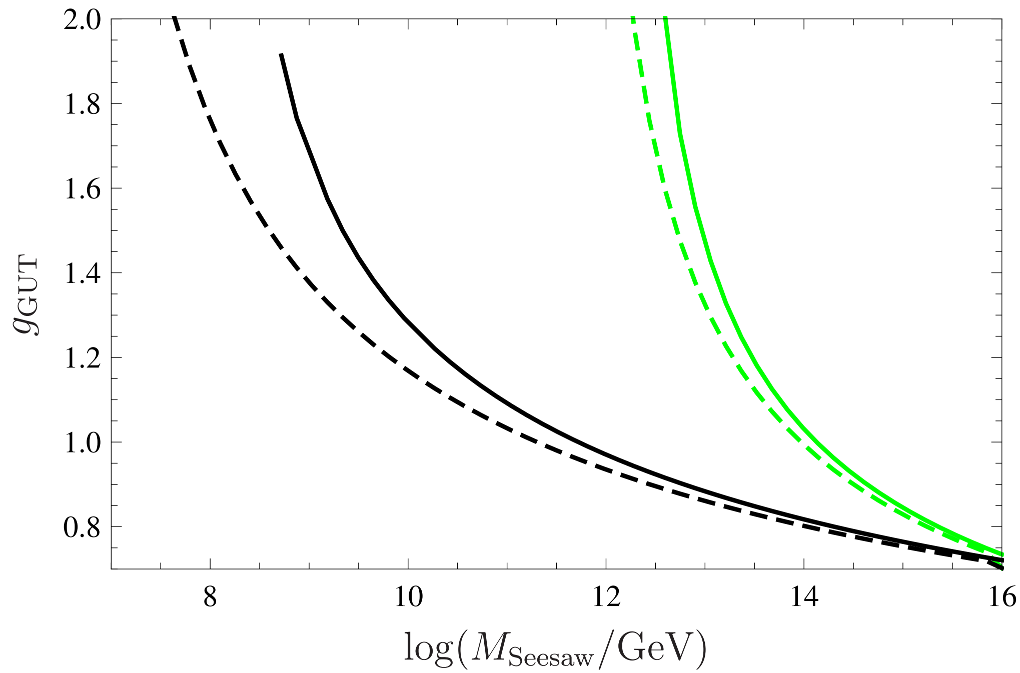
blue lines . . . SPS3

light blue lines . . . $m_0 = 500$ GeV and $M_{1/2} = 1$ TeV

red lines . . . $m_0 = M_{1/2} = 1$ TeV

black line . . . analytical approximation

full (dashed) lines . . . 2-loop (1-loop) results



$m_0 = M_{1/2} = 1$ TeV, $A_0 = 0$, $\tan\beta = 10$ and $\mu > 0$
$M_{GUT} = 2 \times 10^{16}$ GeV
black lines . . . seesaw type-II
green lines . . . seesaw type-III with three **24**-plets with degenerate mass spectrum
full (dashed) lines . . . 2-loop (1-loop) results

LFV in the slepton sector: approximate formulas, I

one-step integration of the RGEs assuming mSUGRA boundary

$$\Delta M^2_{L,ij} \simeq -\frac{a_k}{8\pi^2}\left(3m_0^2 + A_0^2\right)\left(Y_N^{k,\dagger} L Y_N^k\right)_{ij}$$

$$\Delta A_{l,ij} \simeq -a_k \frac{3}{16\pi^2} A_0 \left(Y_e Y_N^{k,\dagger} L Y_N^k\right)_{ij}$$

$$\Delta M^2_{E,ij} \simeq 0$$

$$L_{ij} = \ln(M_{GUT}/M_i)\delta_{ij}$$

for $i \neq j$ with Y_e diagonal

$$a_I = 1 \;,\; a_{II} = 6 \text{ and } a_{III} = \frac{9}{5}$$

LFV in the slepton sector: approximate formulas, II

$(\Delta M^2_{\tilde{L}})_{ij}$ and $(\Delta A_l)_{ij}$ induce

$$\begin{aligned} l_j &\to l_i\gamma \ , \ l_i l_k^+ l_r^- \\ \tilde{l}_j &\to l_i\tilde{\chi}^0_s \\ \tilde{\chi}^0_s &\to l_i\tilde{l}_k \end{aligned}$$

Neglecting L-R mixing:

$$\begin{aligned} Br(l_i \to l_j\gamma) &\propto \alpha^3 m^5_{l_i} \frac{|(\delta m^2_L)_{ij}|^2}{\widetilde{m}^8} \tan^2\beta \\ \frac{Br(\tilde{\tau}_2 \to e + \chi^0_1)}{Br(\tilde{\tau}_2 \to \mu + \chi^0_1)} &\simeq \Big(\frac{(\Delta M^2_L)_{13}}{(\Delta M^2_L)_{23}}\Big)^2 \end{aligned}$$

Moreover, in most of the parameter space

$$\frac{\mathrm{Br}(l_i \to 3l_j)}{\mathrm{Br}(l_i \to l_j + \gamma)} \simeq \frac{\alpha}{3\pi}\Big(\log(\frac{m^2_{l_i}}{m^2_{l_j}}) - \frac{11}{4}\Big)$$

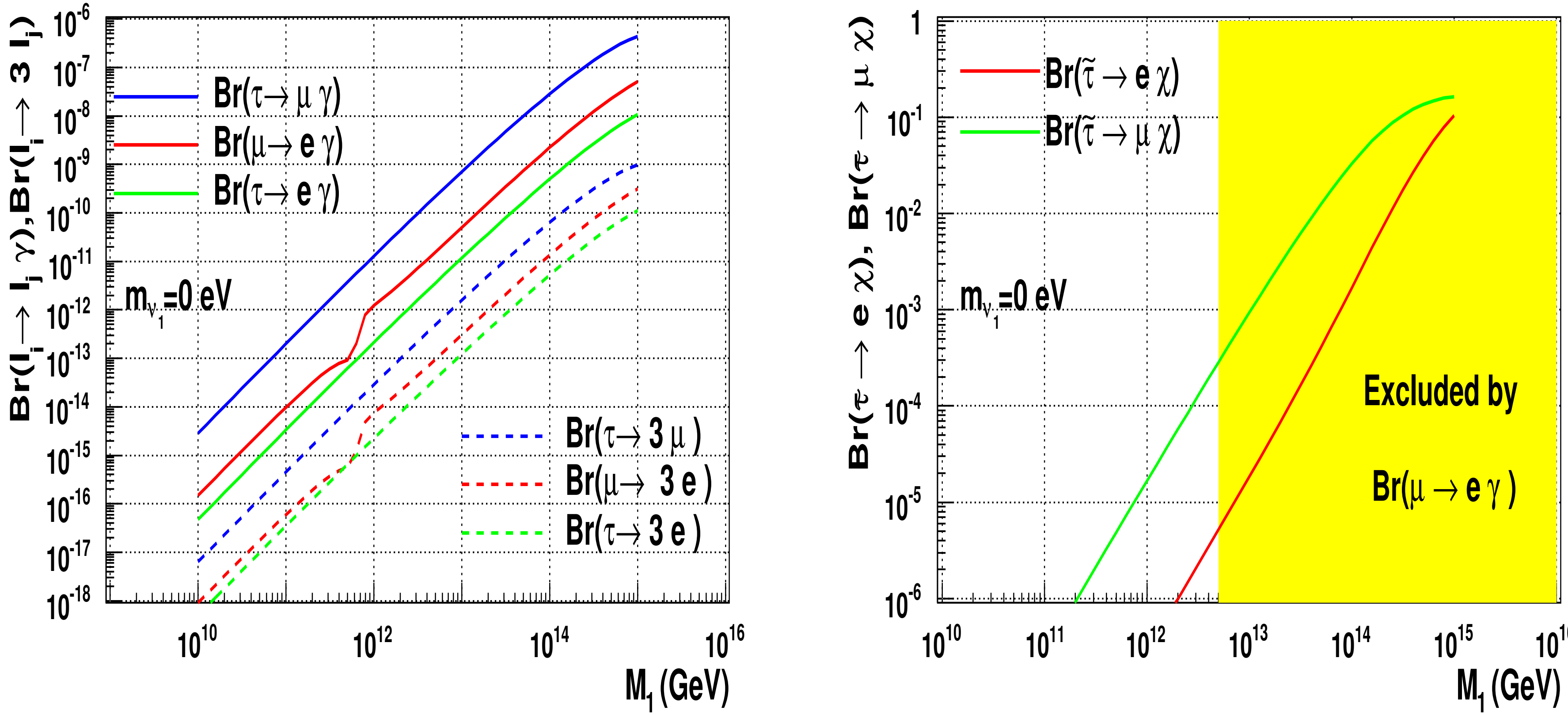
take all parameters real

$$U = U_{\text{TBM}} = \begin{pmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & -\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

$$R = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Use 2-loop RGEs and 1-loop corrections including flavour effects

Seesaw I

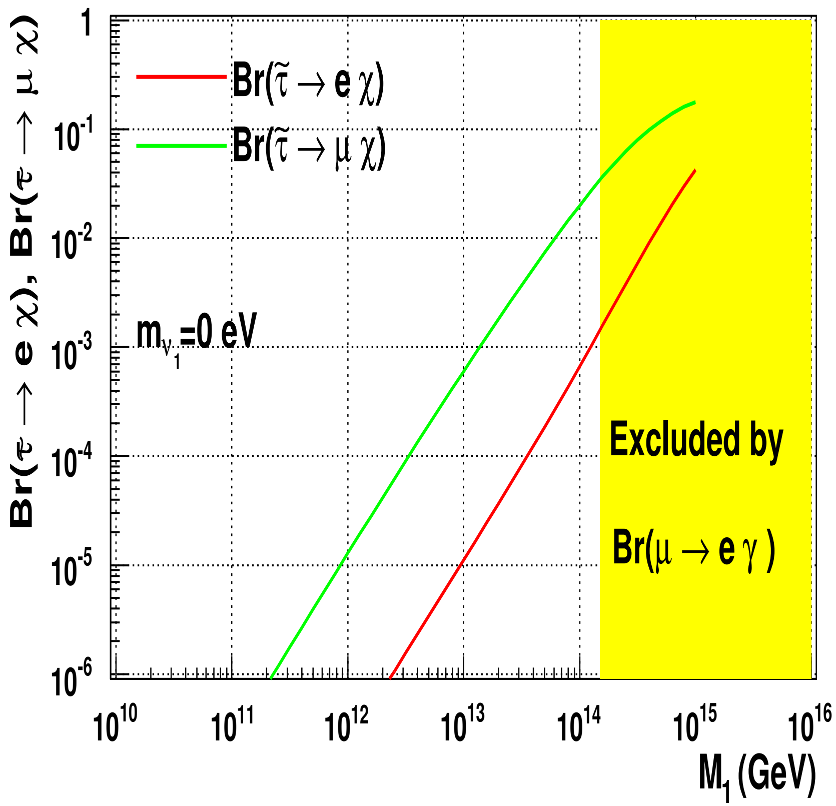


degenerate ν_R

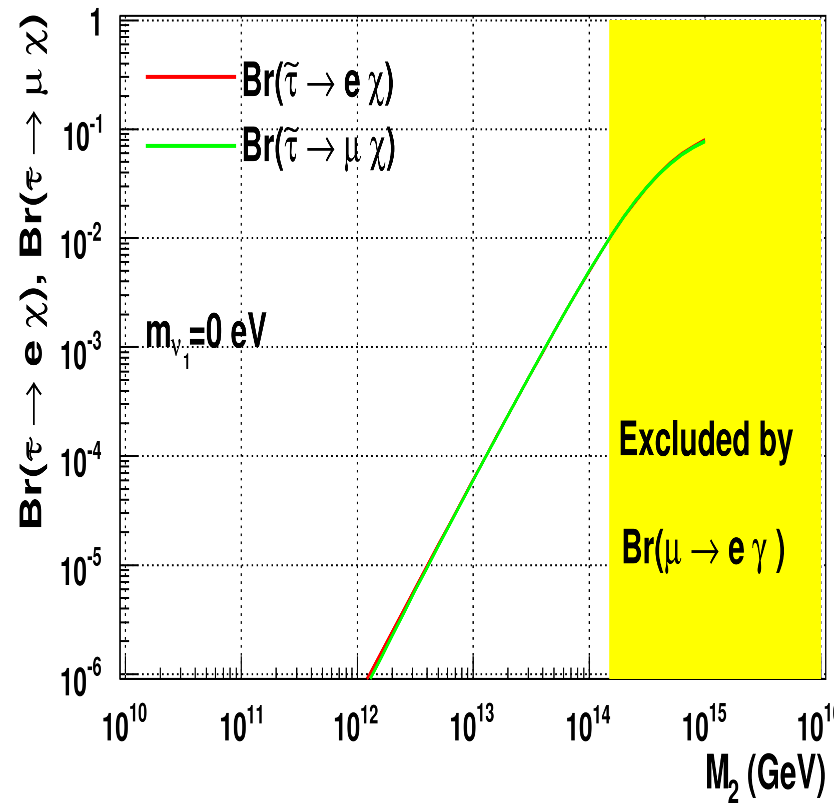
SPS1a' ($M_0 = 70$ GeV, $M_{1/2} = 250$ GeV, $A_0 = -300$ GeV, $\tan\beta = 10$, $\mu > 0$)

M. Hirsch et al. Phys. Rev. D **78** (2008) 013006

Seesaw I



degenerate ν_R



hierarchical ν_R

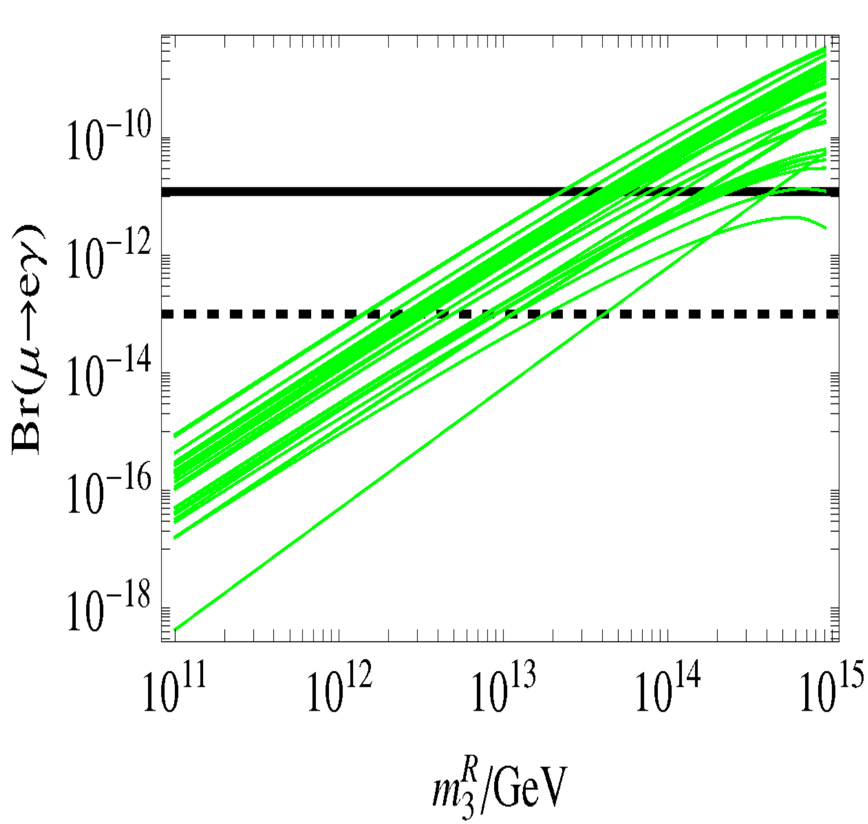
$(M_1 = M_3 = 10^{10}$ GeV)

SPS3 ($M_0 = 90$ GeV, $M_{1/2} = 400$ GeV, $A_0 = 0$ GeV, $\tan\beta = 10$, $\mu > 0$)

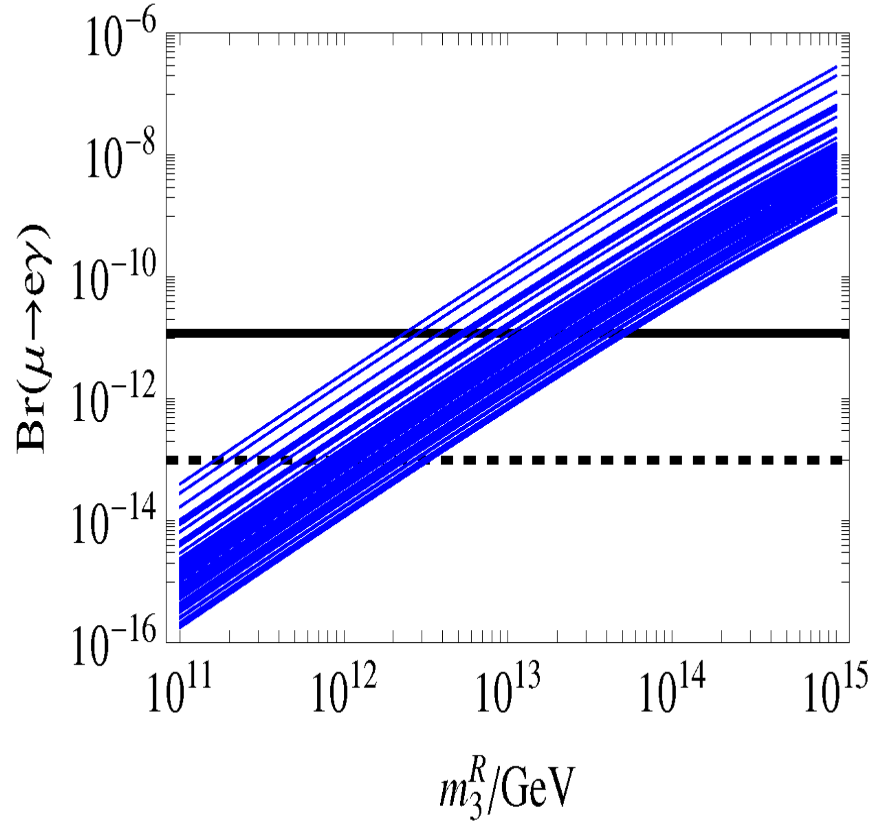
M. Hirsch et al. Phys. Rev. D **78** (2008) 013006

Texture models, hierarchical ν_R

real textures



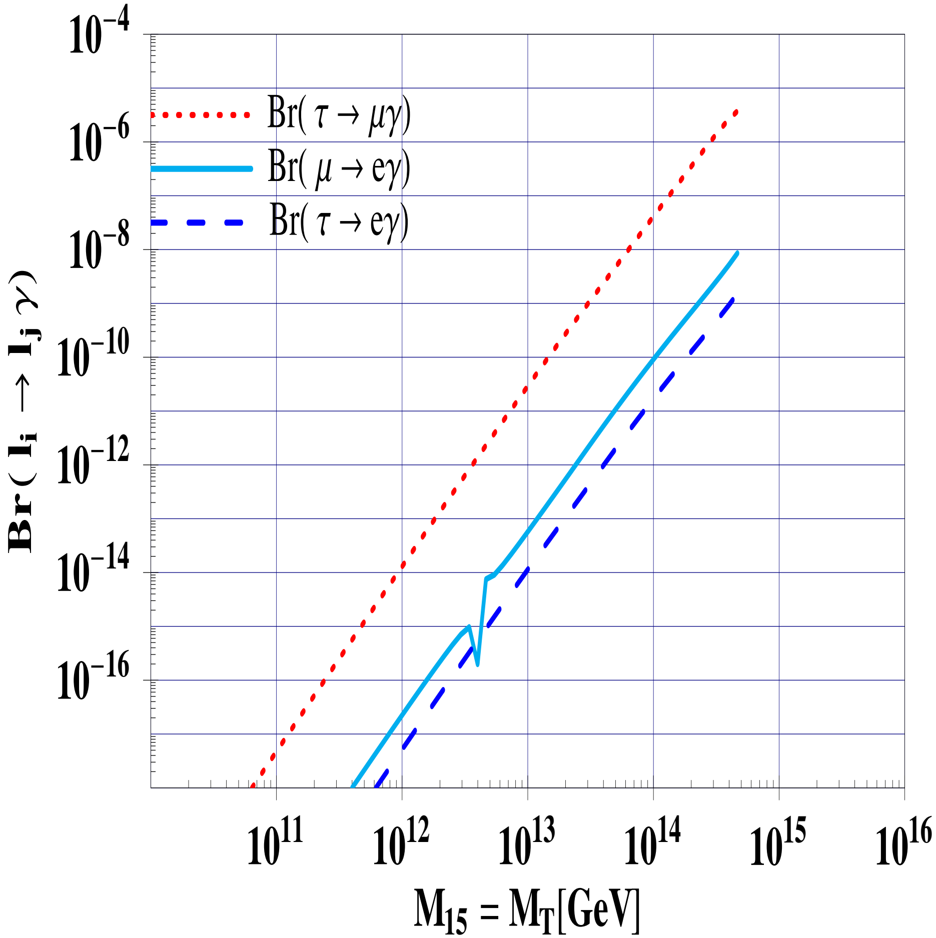
"complexification" of one texture

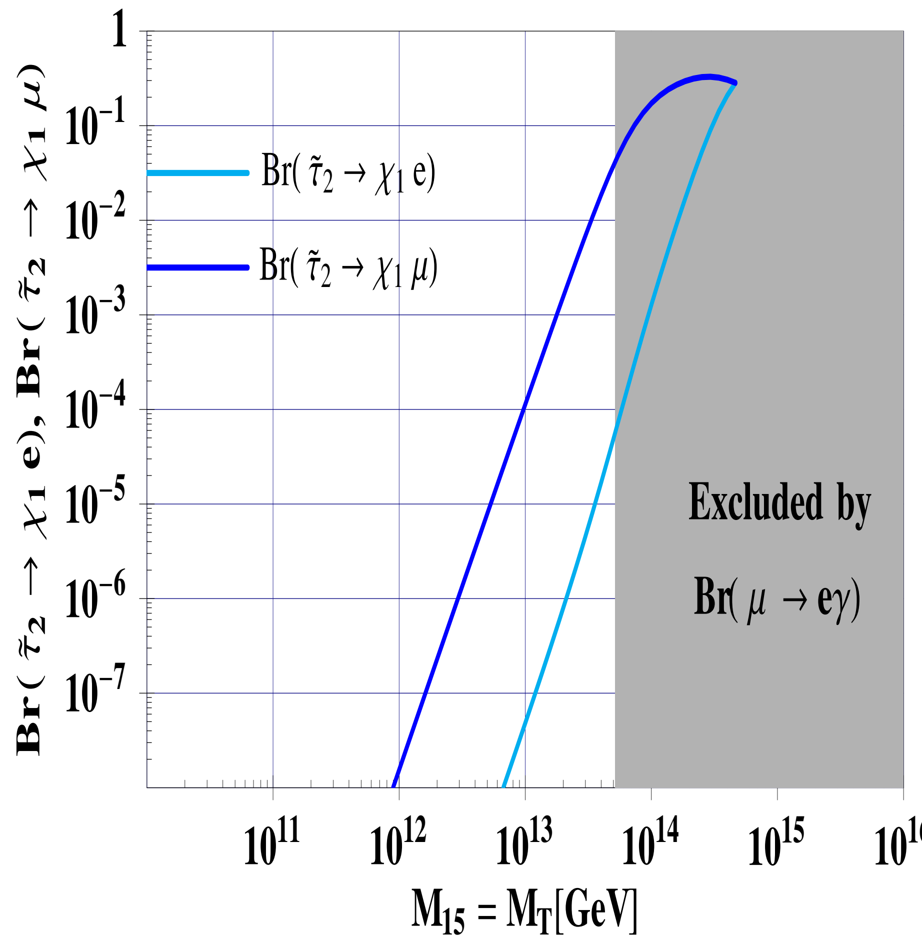


SPS1a' ($M_0 = 70$ GeV, $M_{1/2} = 250$ GeV, $A_0 = -300$ GeV, $\tan\beta = 10$, $\mu > 0$)

F. Deppisch, F. Plentinger, G. Seidl, JHEP **1101** (2011) 004

Seesaw II with a pair of 15-plets



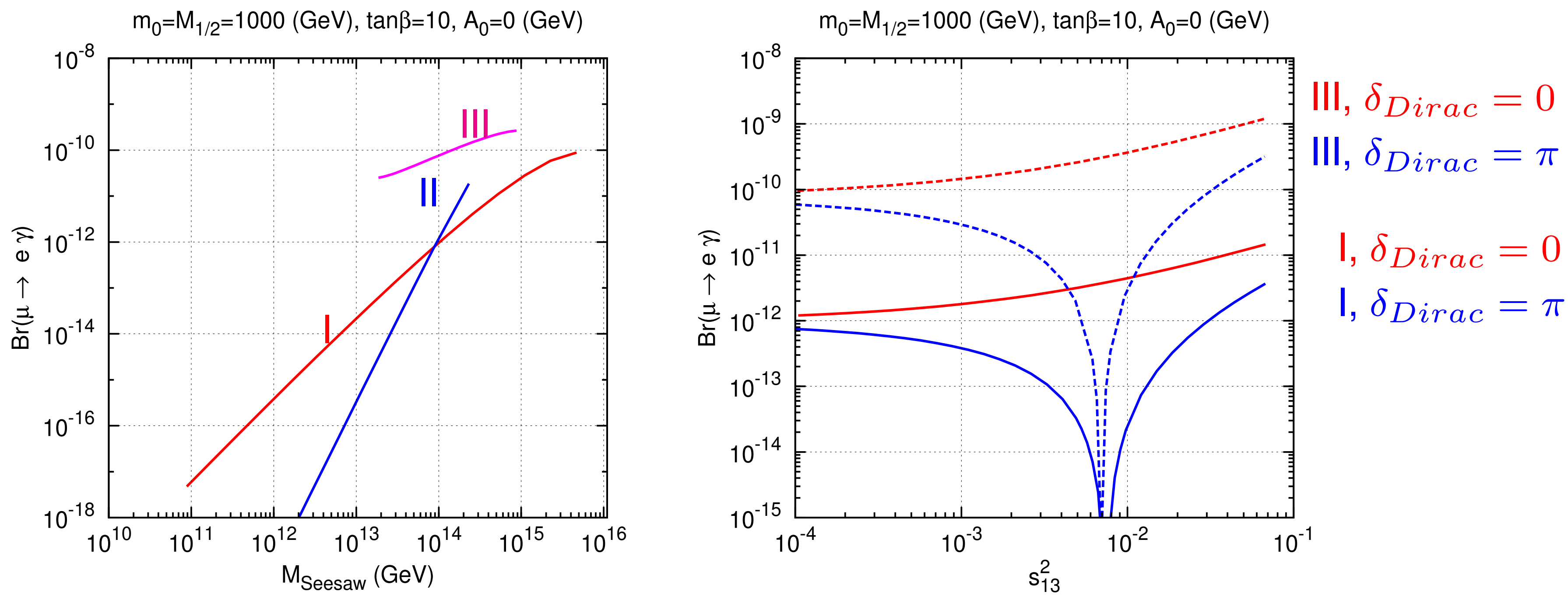


$\lambda_1 = \lambda_2 = 0.5$

SPS3 ($M_0 = 90$ GeV, $M_{1/2} = 400$ GeV, $A_0 = 0$ GeV, $\tan\beta = 10$, $\mu > 0$)

M. Hirsch, S. Kaneko, W. P., Phys. Rev. D **78** (2008) 093004.

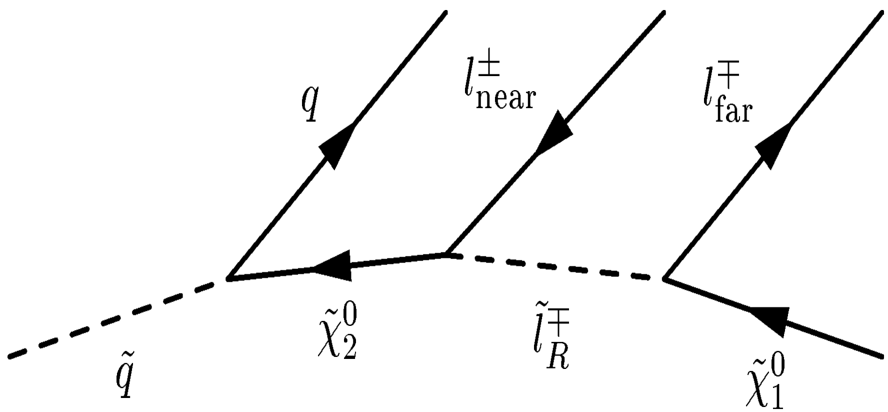
Seesaw III in comparison



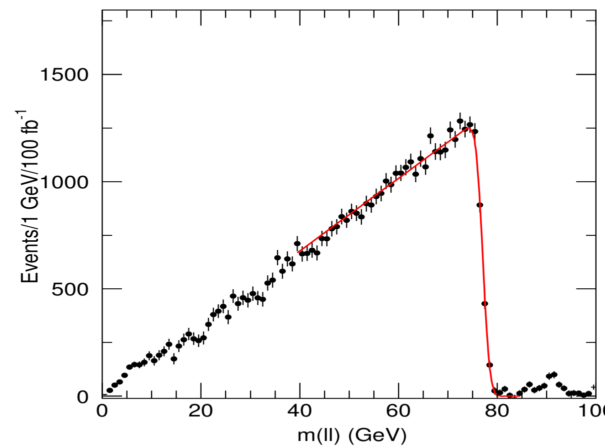
degenerate spectrum of the seesaw particles, $M_{seesaw} = 10^{14}$ GeV

J. Esteves, M.Hirsch, J. Romão, W.P., F. Staub, arXiv:1010.6000

Masses at LHC



G. Polesello



5 kinematical observables depending on 4 SUSY masses

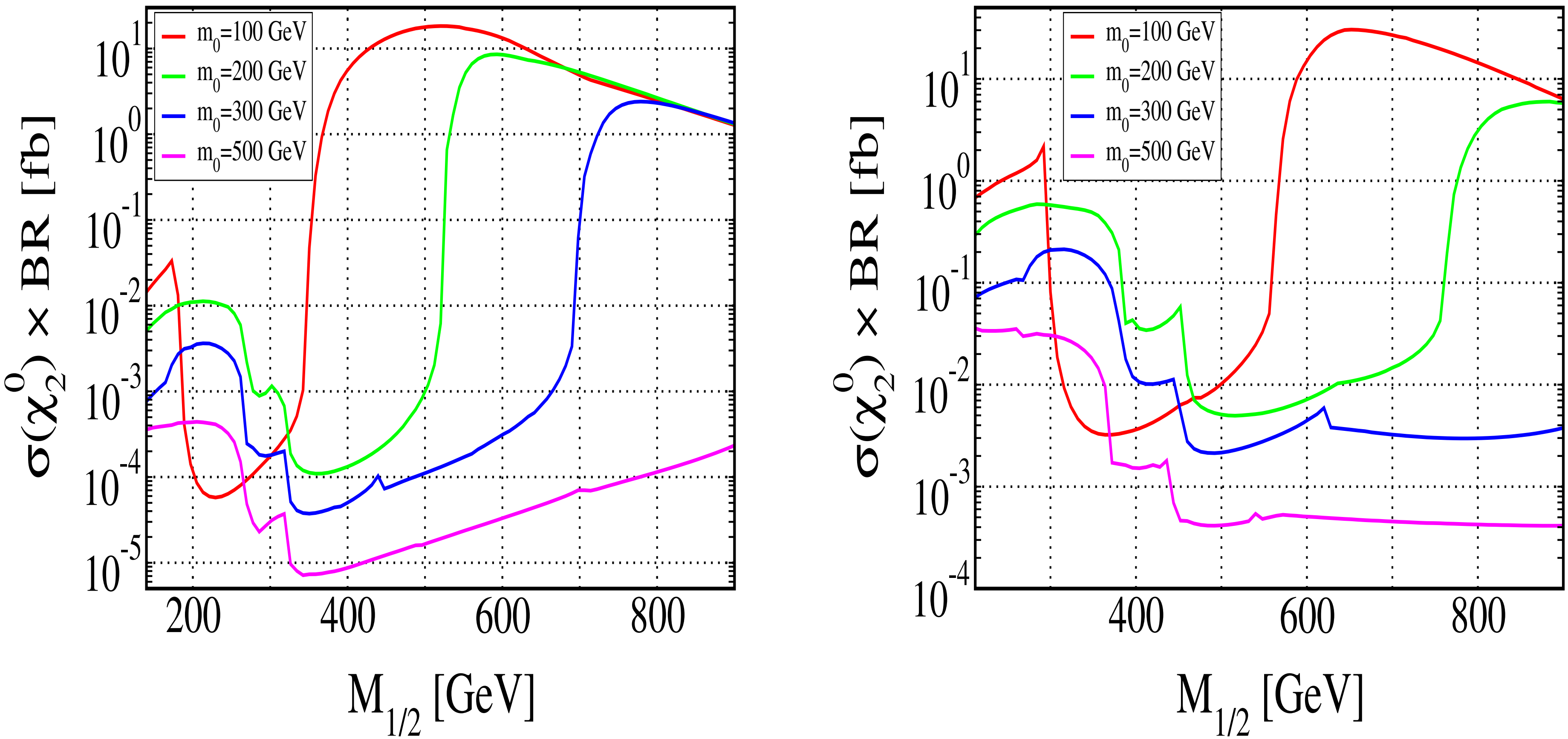
e.g.: $m(ll) = 77.02 \pm 0.05 \pm 0.08$

$\Rightarrow$ mass determination within 2-5%

For background suppression

$$N(e^+e^-) + N(\mu^+\mu^-) - N(e^+\mu^-) - N(\mu^+e^-)$$

Seesaw I + II, signal at LHC



$\sigma(pp \to \tilde{\chi}_2^0) \times BR(\chi_2^0 \to \sum_{i,j} \tilde{l}_i l_j \to \mu^\pm \tau^\mp \tilde{\chi}_1^0)$

$A_0 = 0$, $\tan\beta = 10$, $\mu > 0$ (Seesaw II: $\lambda_1 = 0.02$, $\lambda_2 = 0.5$)

J.N. Esteves et al., arXiv:0903.1408

general problem up to now: $m_\nu \simeq 0.1$ eV $\Rightarrow Y^2/M$ fixed

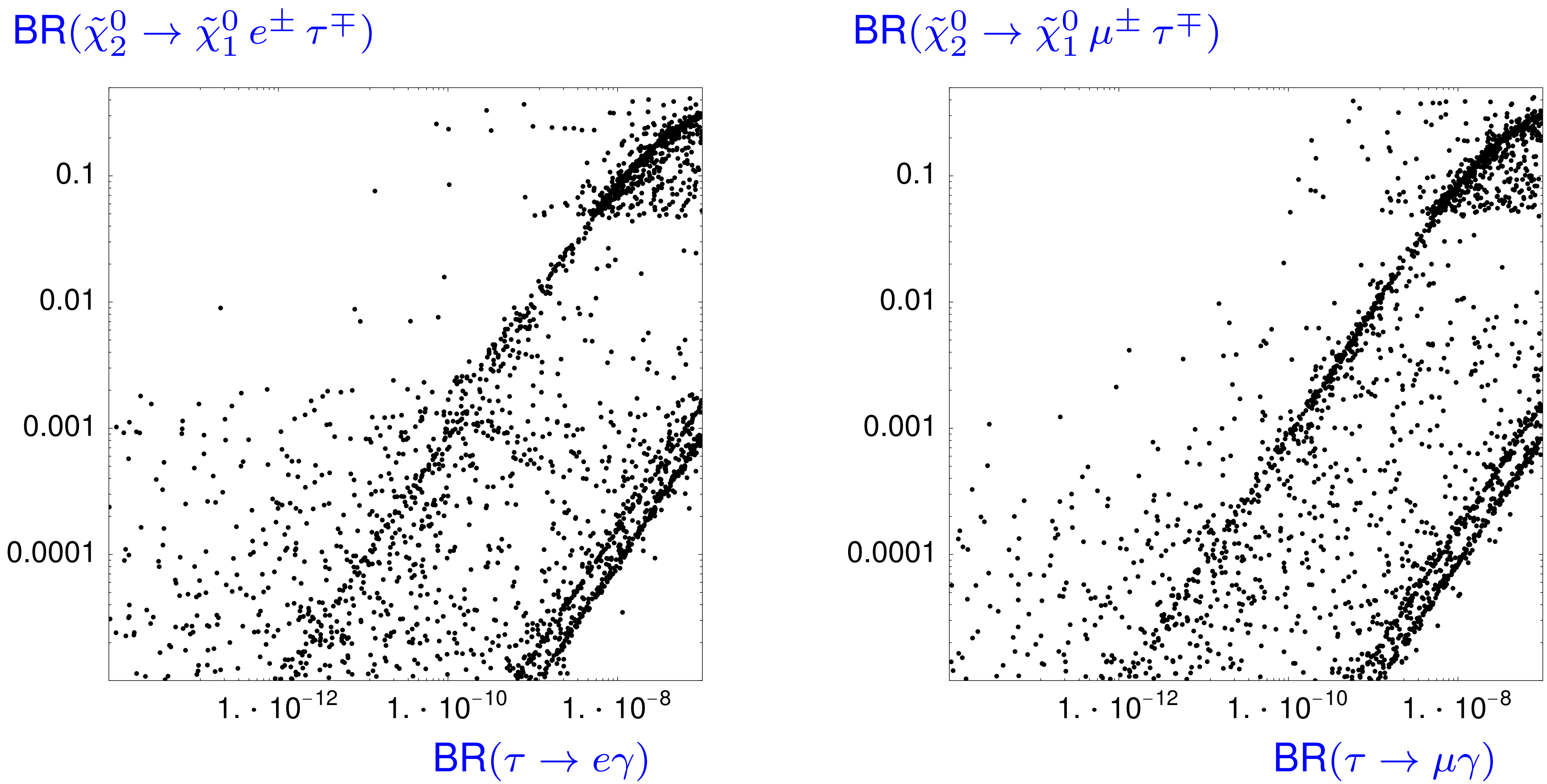
forbid dim-5 operator, e.g. Z_3 + NMSSM[†]

$$\frac{(LH_u)^2 S}{M_6^2} \quad , \quad \frac{(LH_u)^2 S^2}{M_7^3}$$

solves at the same time the μ-problem

† I. Gogoladze, N. Okada, Q. Shafi, Phys. Lett. B **672** (2009) 235

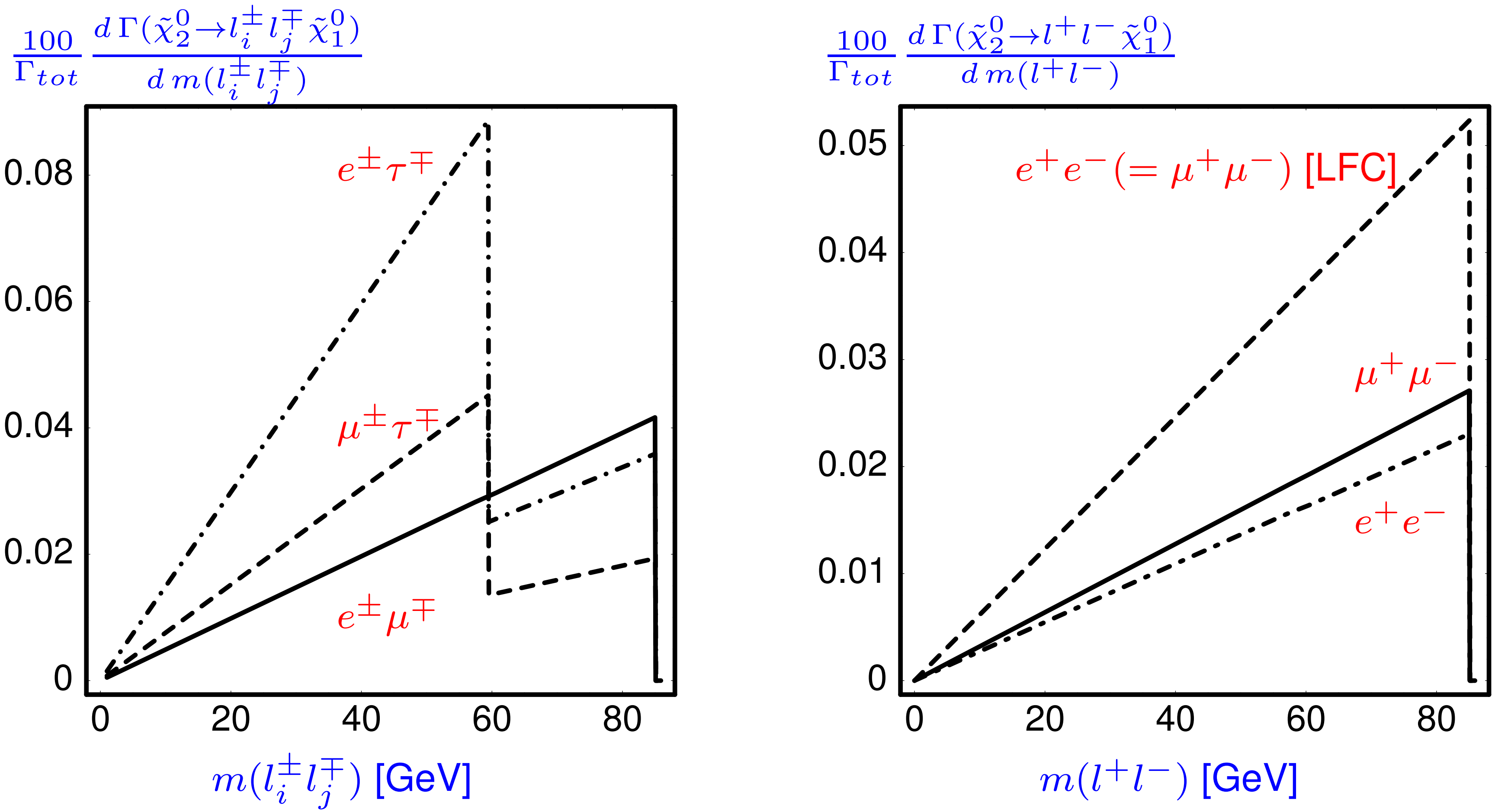
arbitrary $M^2_{E,ij}$, $M^2_{L,ij}$, $A_{l,ij}$: $\tilde{\chi}^0_2 \to \tilde{l}_i l_j \to l_k l_j \tilde{\chi}^0_1$



Variations around SPS1a

($M_0 = 100$ GeV, $M_{1/2} = 250$ GeV, $A_0 = -100$ GeV, $\tan\beta = 10$)

Flavour mixing and edge variables



A. Bartl et al., Eur. Phys. J. C **46** (2006) 783

Bilinear R-parity breaking and GMSB

Basis idea: transfer of SUSY breaking from hidden sector via messenger fields using gauge interactions

Messenger scale: $M_i(M_M) \sim g(x)\alpha_i\Lambda_G$

$M_j^2(M_M) \sim f(x)\sum C_i\alpha_i^2\Lambda_G^2$

$x = \Lambda_G/M_M,\, f(x), g(x) = (n_5 + 3n_{10})O(1)$

Generic prediction: light gravitino being the LSP

NLSP: $\tilde{\chi}_1^0$ or $\tilde{l}_R$ ($l = e, \mu, \tau$)

add bilinear R-parity violating terms:

$$W = W_{MSSM} + \epsilon_i \widehat{L}_i \widehat{H}_u$$

$$V_{\rm soft} = V_{\rm soft}^{MSSM} + B_i\epsilon_i\tilde{L}_i H_u.$$

$\Rightarrow$ sneutrino vevs v_i

in the following: take v_i as free parameters instead B_i

basis $\psi^{0T} = (-i\lambda', -i\lambda^3, \widetilde{H}_d^0, \widetilde{H}_u^0, \nu_e, \nu_\mu, \nu_\tau)$ we get:

$$M_N = \begin{bmatrix} \mathcal{M}_{\chi^0} & m^T \\ m & 0 \end{bmatrix}$$

$$\mathcal{M}_{\chi^0} = \begin{bmatrix} M_1 & 0 & -\frac{1}{2}g'v_d & \frac{1}{2}g'v_u \\ 0 & M_2 & \frac{1}{2}gv_d & -\frac{1}{2}gv_u \\ -\frac{1}{2}g'v_d & \frac{1}{2}gv_d & 0 & -\mu \\ \frac{1}{2}g'v_u & -\frac{1}{2}gv_u & -\mu & 0 \end{bmatrix}, \quad m = \begin{bmatrix} -\frac{1}{2}g'v_1 & \frac{1}{2}gv_1 & 0 & \epsilon_1 \\ -\frac{1}{2}g'v_2 & \frac{1}{2}gv_2 & 0 & \epsilon_2 \\ -\frac{1}{2}g'v_3 & \frac{1}{2}gv_3 & 0 & \epsilon_3 \end{bmatrix}$$

Approximate diagonalization as in usual seesaw mechanism gives

$$m_{\nu,eff} = \frac{M_1 g^2 + M_2 g'^2}{4\, det(\mathcal{M}_{\chi^0})} \begin{pmatrix} \Lambda_1^2 & \Lambda_1\Lambda_2 & \Lambda_1\Lambda_3 \\ \Lambda_1\Lambda_2 & \Lambda_2^2 & \Lambda_2\Lambda_3 \\ \Lambda_1\Lambda_3 & \Lambda_2\Lambda_3 & \Lambda_3^2 \end{pmatrix}, \qquad \Lambda_i = \mu v_i + v_d \epsilon_i$$

second ν mass via loops

$$\begin{aligned} m_\nu^{1\mathrm{lp}} &\simeq \frac{1}{16\pi^2}\left(3h_b^2 \sin(2\theta_{\tilde b}) m_b \log\frac{m^2_{\tilde b_2}}{m^2_{\tilde b_1}} + h_\tau^2 \sin(2\theta_{\tilde\tau}) m_\tau \log\frac{m^2_{\tilde\tau_2}}{m^2_{\tilde\tau_1}}\right)\frac{(\tilde\epsilon_1^2+\tilde\epsilon_2^2)}{\mu^2} \\ \tilde\epsilon_i &= V^\nu_{ji}\epsilon_j \end{aligned}$$

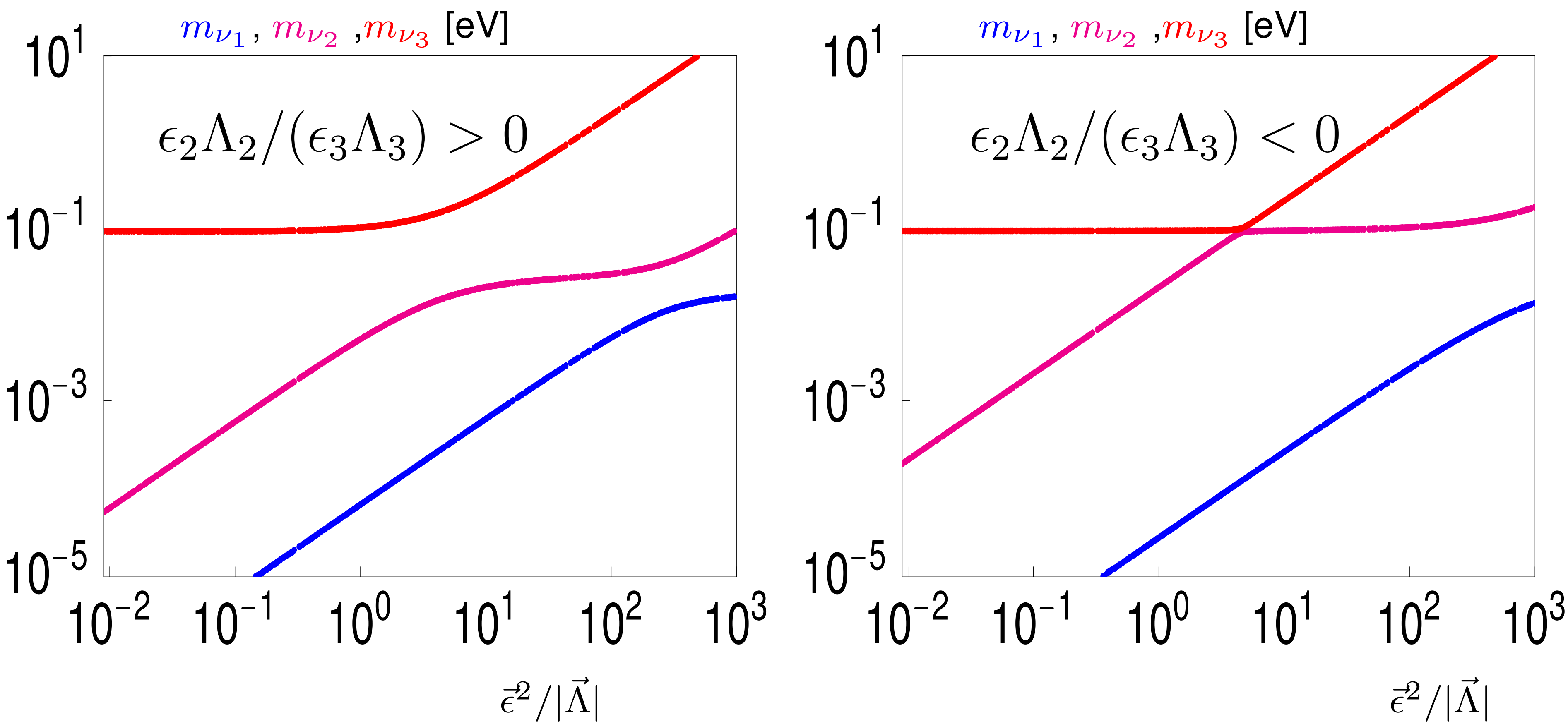
mixing angles

$$\tan^2\theta_{atm} \simeq \left(\frac{\Lambda_2}{\Lambda_3}\right)^2, \; U^2_{e3} \simeq \frac{|\Lambda_1|}{\sqrt{\Lambda_2^2+\Lambda_3^2}}, \; \tan^2\theta_{sol} \simeq \left(\frac{\tilde\epsilon_1}{\tilde\epsilon_2}\right)^2$$

experimental data require:

$$\frac{|\vec\Lambda|}{\sqrt{\det\mathcal{M}_{\tilde\chi^0}}} \sim O(10^{-6}), \qquad \frac{|\vec\epsilon|}{\mu} \sim O(10^{-4})$$

Two examples of neutrino masses as function of $\vec{\epsilon}^2/|\vec{\Lambda}|$
(other parameters fixed):



Neutralino decays

dominant modes R-parity violating modes

$$\Gamma(\tilde{\chi}_1^0 \to W^\pm l_i^\mp) \quad \propto \quad \frac{\Lambda_i^2}{\det \mathcal{M}_{\tilde{\chi}^0}}$$

$$\Gamma(\tilde{\chi}_1^0 \to \sum_i Z\nu_i) \quad \simeq \quad \frac{1}{2}\sum_i \Gamma(\tilde{\chi}_1^0 \to W^\pm l_i^\mp)$$

$$\Gamma(\tilde{\chi}_1^0 \to \nu\tau^+ l_i^-) \quad \propto \quad \frac{\epsilon_i^2}{\mu^2}$$

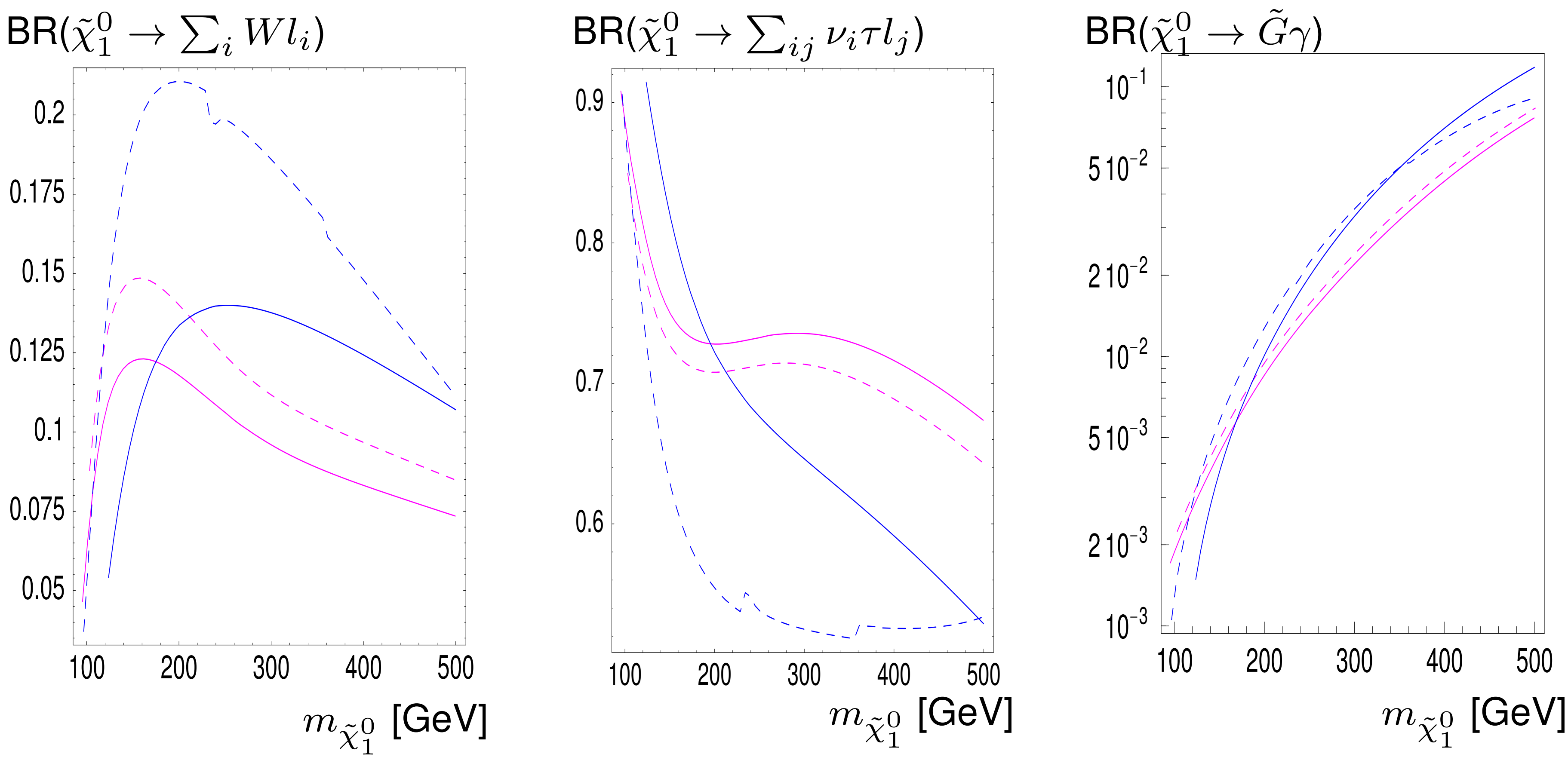
R-parity conserving mode

$$\Gamma(\tilde{\chi}_1^0 \to \tilde{G}\gamma) \quad \simeq \quad 1.2 \times 10^{-6} \kappa_\gamma^2 \left(\frac{m_{\tilde{\chi}_1^0}}{100 \;\; \mathrm{GeV}}\right)^5 \left(\frac{100 \;\; \mathrm{eV}}{m_{3/2}}\right)^2 \mathrm{eV}$$

total width

$$\Gamma \simeq (10^{-4} - 10^{-2})\,\mathrm{eV}$$

Neutralino decays



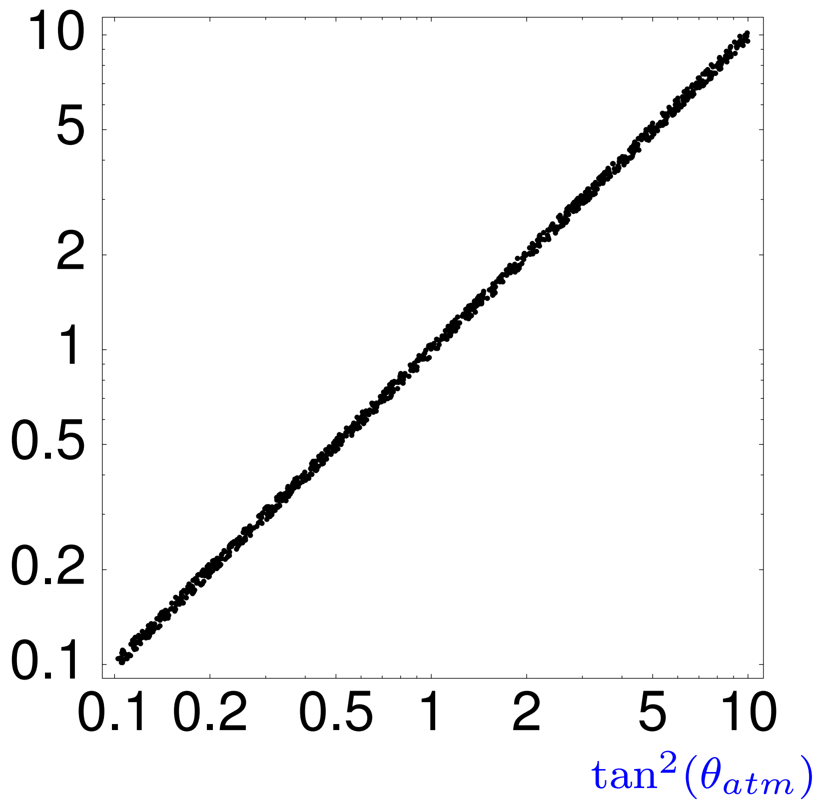
— $\tan\beta = 10$, $\mu > 0$, - - $\tan\beta = 10$, $\mu < 0$, — $\tan\beta = 35$, $\mu > 0$, - - $\tan\beta = 35$, $\mu < 0$

$m_{3/2} = 100$ eV, $n_5 = 1$

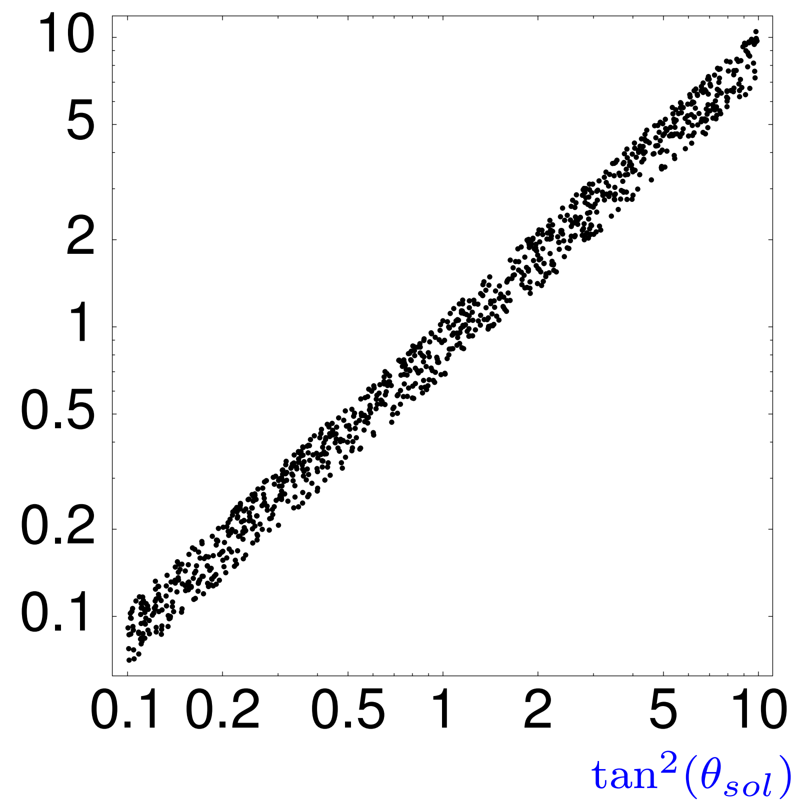
M. Hirsch, W. P. und D. Restrepo, JHEP **0503**, 062 (2005)

Correlations

BR($\tilde{\chi}^0_1 \to W\mu$) / BR($\tilde{\chi}^0_1 \to W\tau$)



BR($\tilde{\chi}^0_1 \to \nu e\tau$) /BR($\tilde{\chi}^0_1 \to \nu\mu\tau$)



Comments

- $$\frac{m_{\tilde{\tau}_1}}{m_{\tilde{\chi}_1^0}} \propto \frac{1}{\sqrt{n_5}}$$

  $\Rightarrow$ for $n_5 \geq 3$ hardly points with $\tilde{\chi}_1^0$ LSP
- $\tilde{l}_R$ NLSPs: BR($l\nu$) $\gg$ BR($l\tilde{G}$)
- $n_5 = 2$: BR($\tilde{G}\gamma$) reduced by a factor 2-3
- $\tilde{G}$ decays via R-parity violating couplings, however:

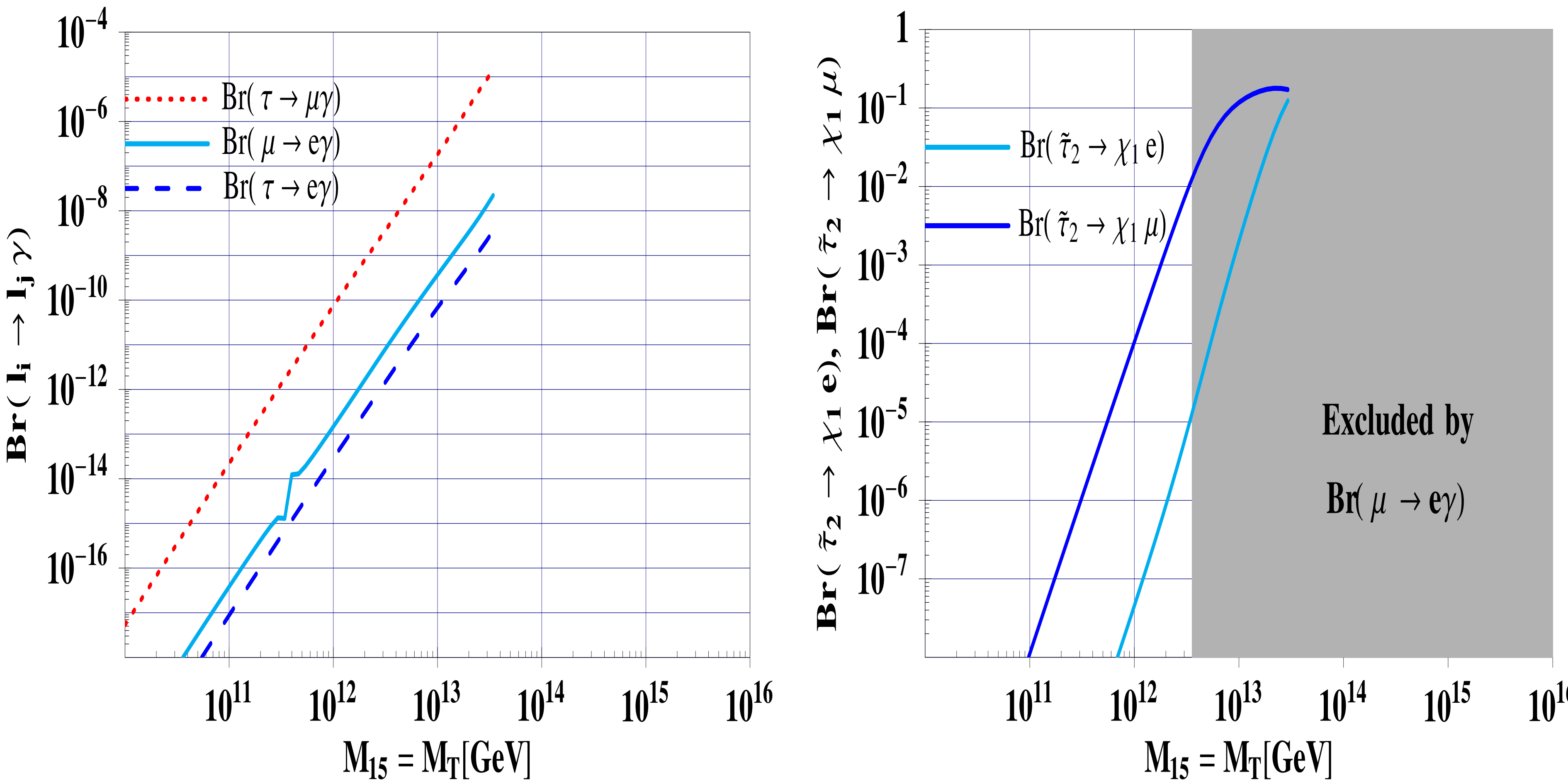
$$\Gamma(\tilde{G}) \simeq 3.5 \cdot 10^{-16} \frac{m_\nu [\mathrm{eV}]}{0.05\mathrm{eV}} \frac{m_{3/2}^3}{M_{Pl}^2} \quad \Rightarrow \tau(\tilde{G}) \sim O(10^{31}) \mathrm{Hubbletimes}$$

- Neutrino physics
  - Oscillations are established
  - good knowledge of $m_{21}^2 \sin^2\theta_{12}$, $|m_{31}^2| \sin^2\theta_{23}$
  - Open questions
    - absolute mass scale
    - normal or inverse hierarchy
    - values of θ_{13} and the phases
    - are there steril neutrinos
    - OPERA ?

Summary, II

- Tests of SUSY neutrino mass models
  - Dirac neutrinos: displaced vertices if $\tilde{\nu}_R$ LSP, e.g. $\tilde{t}_1 \to lb\tilde{\nu}_R$ (but NMSSM: $\tilde{t}_1 \to lb\nu\tilde{\chi}^0_1$)
  - Seesaw models:
    - in case of Seesaw II, III: different mass ratios
    - promosing: $\tilde{\tau}_2$ decays
    - very difficult to test at LHC, signals of O(10 fb) or below
  - R-parity violation
    - interesting correlations between ν-physics and LSP decays, testable at LHC
    - displaced vertices
    - Can the model be pinned down?

Seesaw II with 15-plets

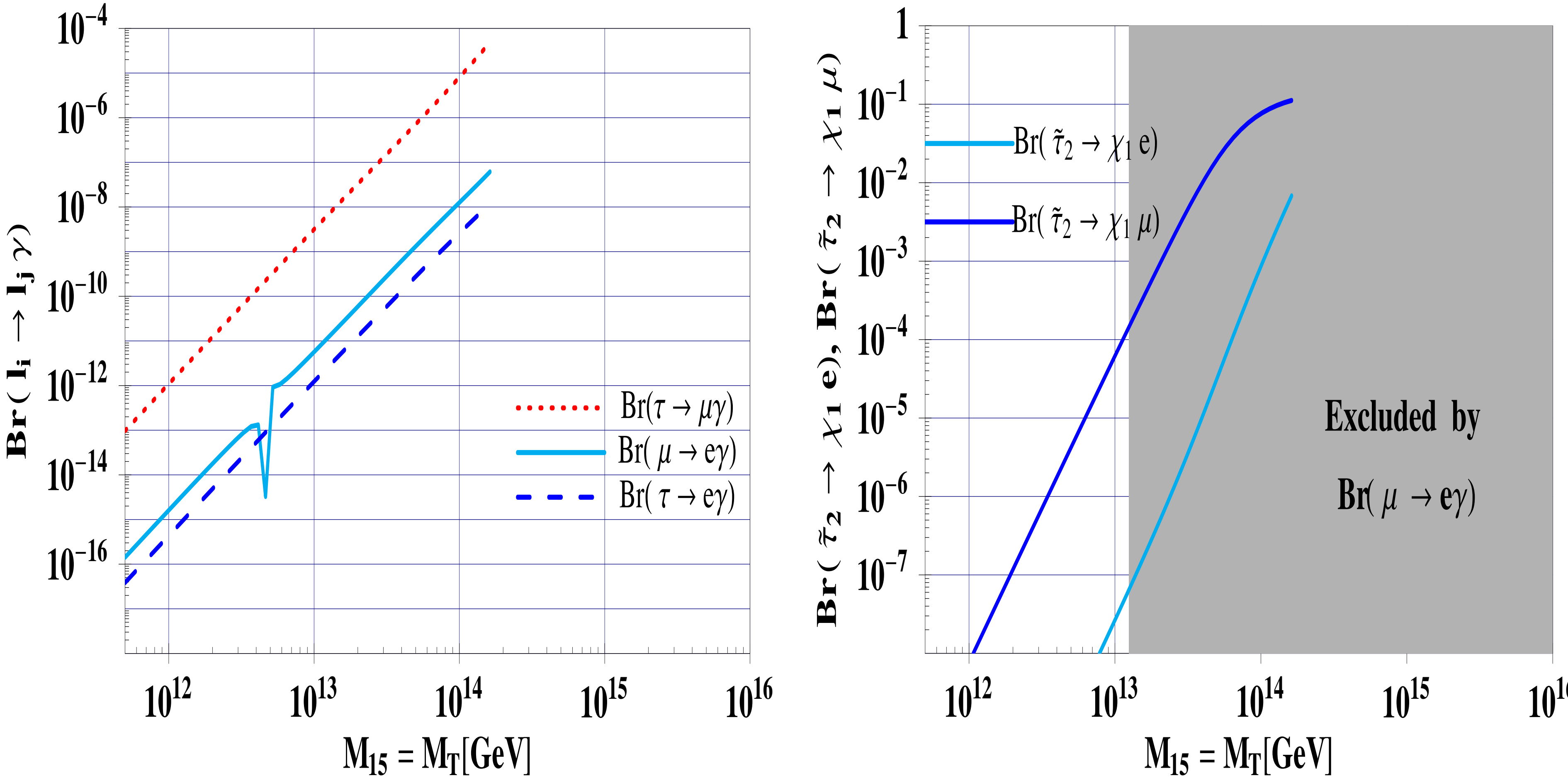


$\lambda_1 = \lambda_2 = 0.05$

SPS3 ($M_0 = 90$ GeV, $M_{1/2} = 400$ GeV, $A_0 = 0$ GeV, $\tan\beta = 10$), $\mu > 0$

M. Hirsch, S. Kaneko, W. P., Phys. Rev. D **78** (2008) 093004.

Seesaw II with 15-plets

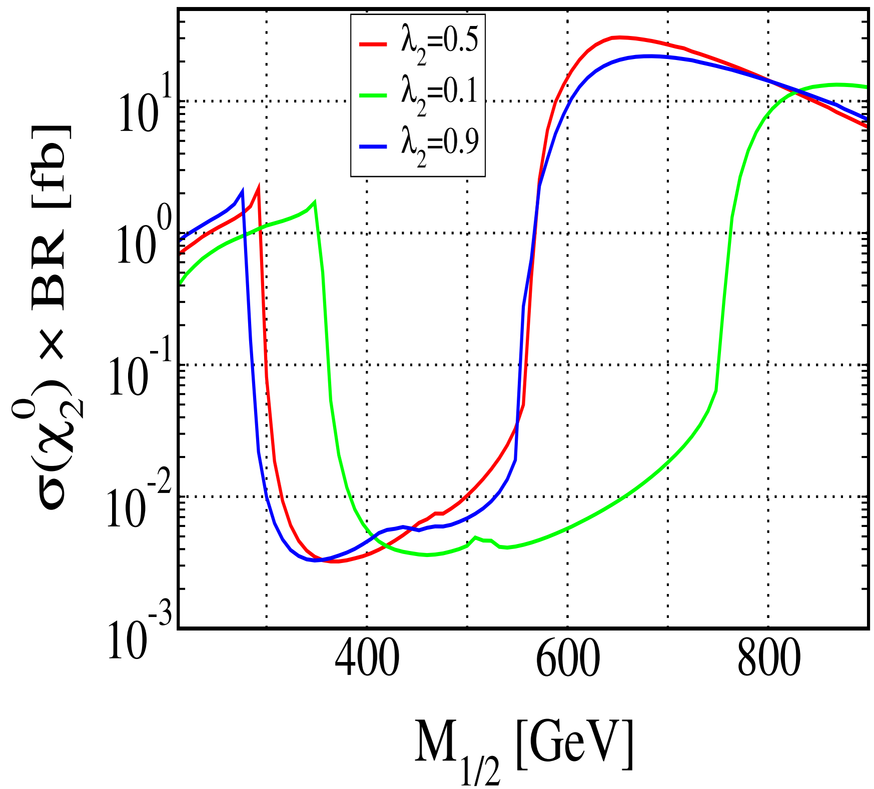


$\lambda_1 = \lambda_2 = 0.5$

SPS1a' ($M_0 = 70$ GeV, $M_{1/2} = 250$ GeV, $A_0 = -300$ GeV, $\tan\beta = 10$), $\mu > 0$

M. Hirsch, S. Kaneko, W. P., Phys. Rev. D **78** (2008) 093004.

Seesaw II, signal at LHC



$\sigma(pp \to \tilde{\chi}_2^0) \times BR(\chi_2^0 \to \sum_{i,j} \tilde{l}_i l_j \to \mu^\pm \tau^\mp \tilde{\chi}_1^0)$

$m_0 = 100$ GeV $A_0 = 0$, $\tan\beta = 10$, $\mu > 0$, $\lambda_1 = 0.02$

J.N. Esteves et al., arXiv:0903.1408

Connection to trilinear R-parity violation: rotate $(\widehat{H}_d, \widehat{L}_i)$ such, that $\epsilon'_i = 0$; gives in leading order of ϵ_i/μ:

$$\lambda'_{ijk} = \frac{\epsilon_i}{\mu} \delta_{jk} h_{d_k}$$

and

$$\lambda_{121} = h_e \tfrac{\epsilon_2}{\mu}, \quad \lambda_{122} = h_\mu \tfrac{\epsilon_1}{\mu}, \quad \lambda_{123} = 0$$

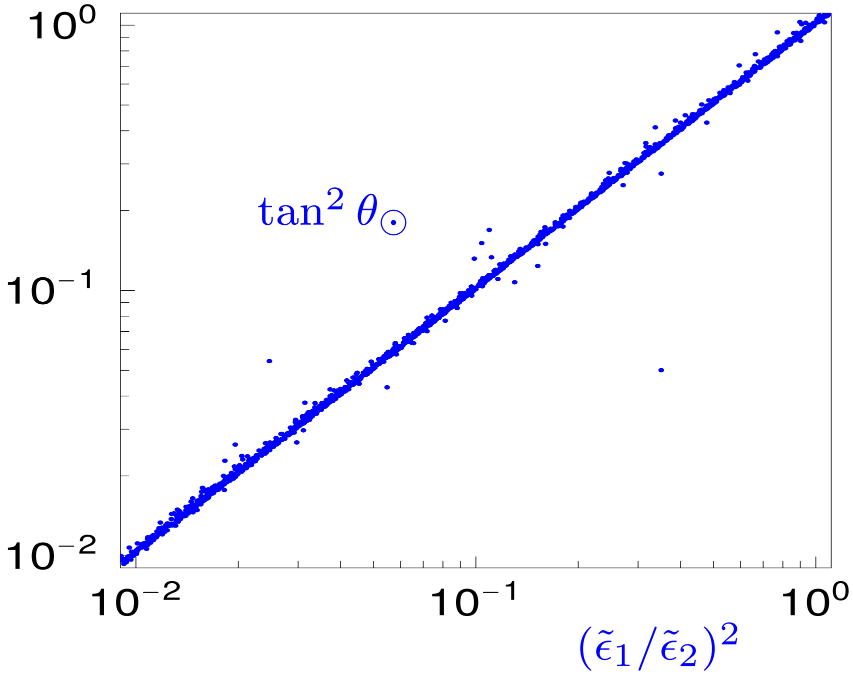
$$\lambda_{131} = h_e \tfrac{\epsilon_3}{\mu}, \quad \lambda_{132} = 0, \quad \lambda_{133} = h_\tau \tfrac{\epsilon_1}{\mu}$$

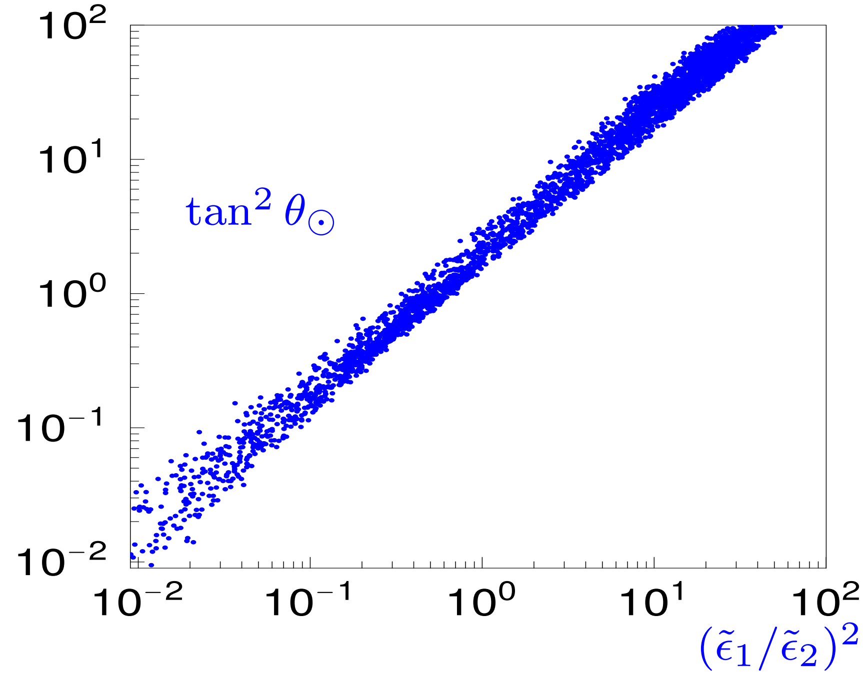
$$\lambda_{231} = 0, \quad \lambda_{232} = h_\mu \tfrac{\epsilon_3}{\mu}, \quad \lambda_{233} = h_\tau \tfrac{\epsilon_2}{\mu}$$

$$\lambda_{ijk} = -\lambda_{jik}$$

Solar angle

$$\text{Approximation formula gives}: \tan^2\theta_\odot \simeq \left(\frac{\tilde{\epsilon}_1}{\tilde{\epsilon}_2}\right)^2$$





⇒ Left figure: Neutralino LSP, b–$\tilde{b}_i$ loop usually dominant

⇒ Right figure: Stau LSP, both, b–$\tilde{b}_i$ and $S^\pm_j$–$\tilde{\chi}^\mp_k$ ($j = 1, .., 7$, $k = 1, .., 5$), equally important

Standard thermal history of the universe:

$$\Omega_{3/2} h^2 \simeq 0.11 \left(\frac{m_{3/2}}{100\,\mathrm{eV}}\right)\left(\frac{100}{g_*}\right) \qquad (g_* \simeq 90 - 140)$$

Current data:

$$\Omega_{CDM} h^2 \simeq 0.105 \pm 0.008$$

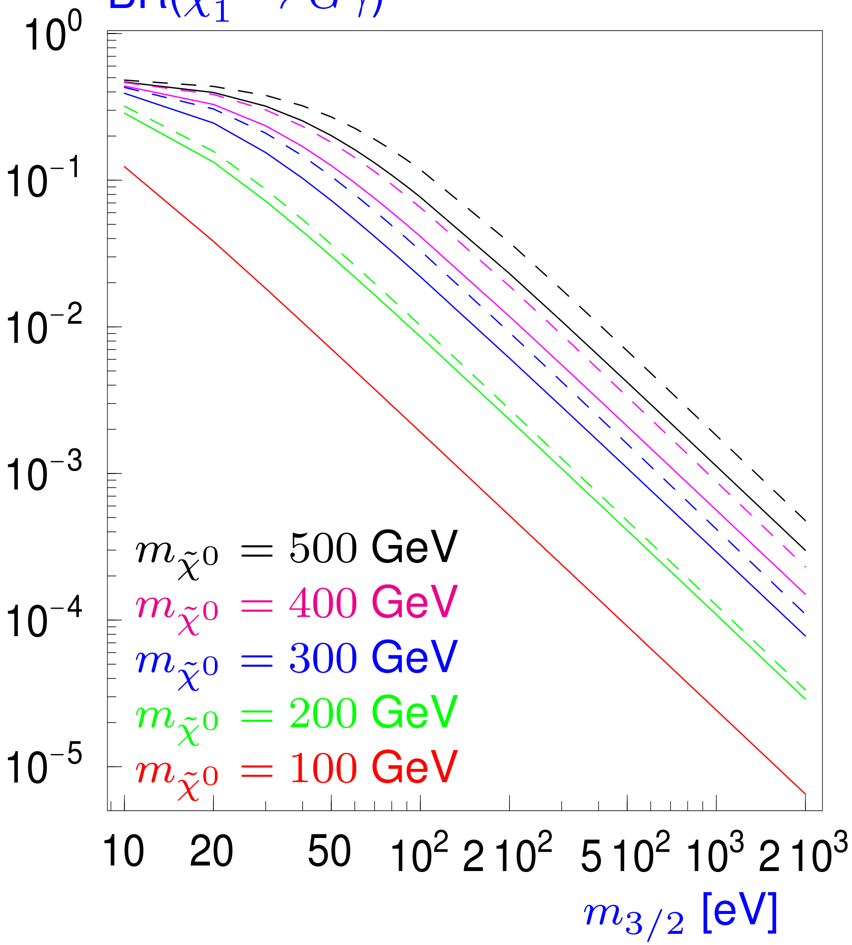
$\Rightarrow m_{3/2} \simeq 100\ \mathrm{eV}$ if DM candidate, warm dark matter

constraints from Lyman-α forest: $m_{WDM} \gtrsim 550\ \mathrm{eV}$
(M. Viel et al., arXiv:astro-ph/0501562)
$\Rightarrow$ assume additional entropy production, e.g. non-standard decays of messenger particles

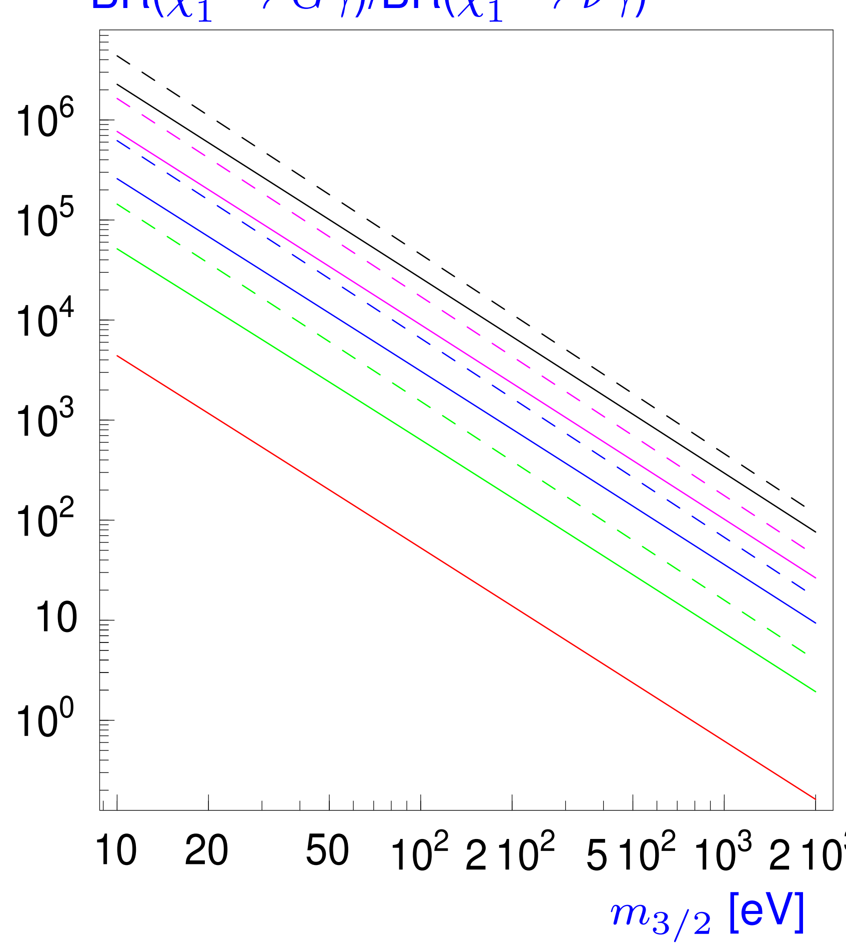
(E. Baltz, H. Murayama, astro-ph/0108172; M. Fujii and T. Yanagida hep-ph/0208191)
does not work in practice: F. Staub, W. P., J. Niemeyer, arXiv:0907.0530

GMSB signals

$\text{BR}(\tilde{\chi}_1^0 \to \tilde{G}\gamma)$

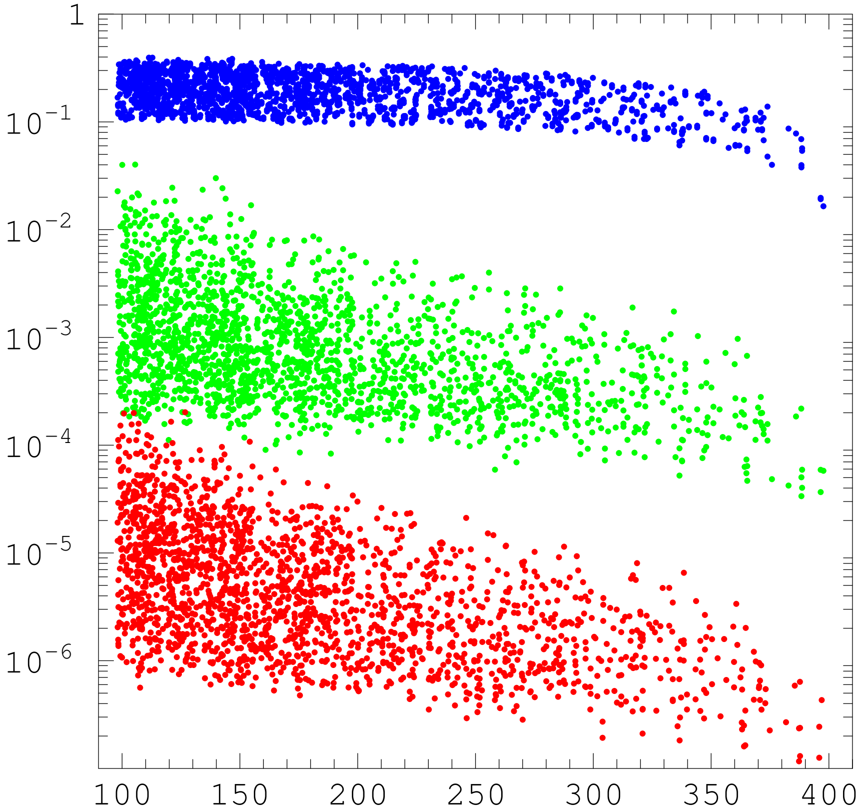


$\text{BR}(\tilde{\chi}_1^0 \to \tilde{G}\gamma)/\text{BR}(\tilde{\chi}_1^0 \to \nu\gamma)$



$$n_5 = 1, \tan\beta = 10$$

Decay length ($\tilde{e}$, $\tilde{\mu}$, $\tilde{\tau}$) [cm]



$m_{\tilde{l}}$ [GeV]

$\Rightarrow$ $\tilde{e}$, $\tilde{\mu}$, $\tilde{\tau}$ can be separated

in this model.

Moreover

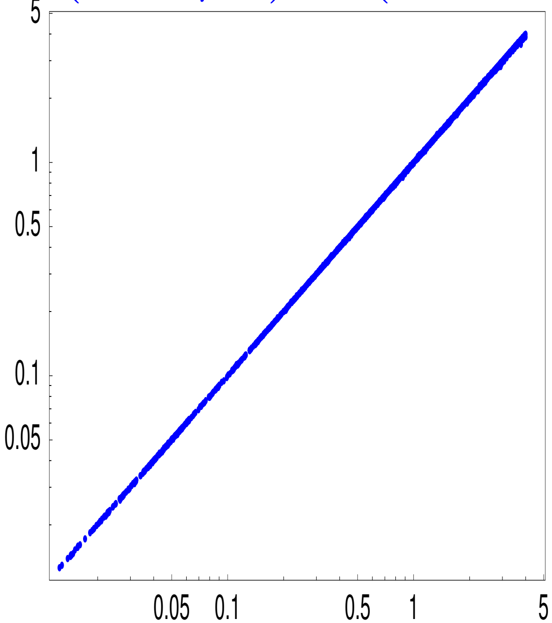
$$\frac{\Gamma(\tilde{\tau})}{\Gamma(\tilde{\mu})} \simeq \left(\frac{Y_\tau}{Y_\mu}\right)^2 \frac{m_{\tilde{\tau}}}{m_{\tilde{\mu}}}$$

$$\tilde{l}_j \to l_i \sum_k \nu_k \ , \ qq'$$

M. Hirsch, W. Porod, J. C. Romão and J. W. F. Valle, Phys. Rev. **D66** (2002) 095006.

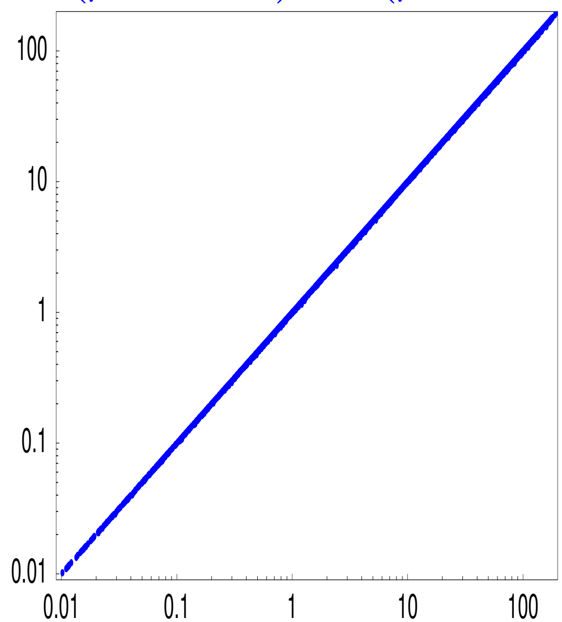
Charged Scalar LSP

BR($\tilde{e}_1 \to \mu\nu_i$)/ BR($\tilde{e}_1 \to \tau\nu_i$)



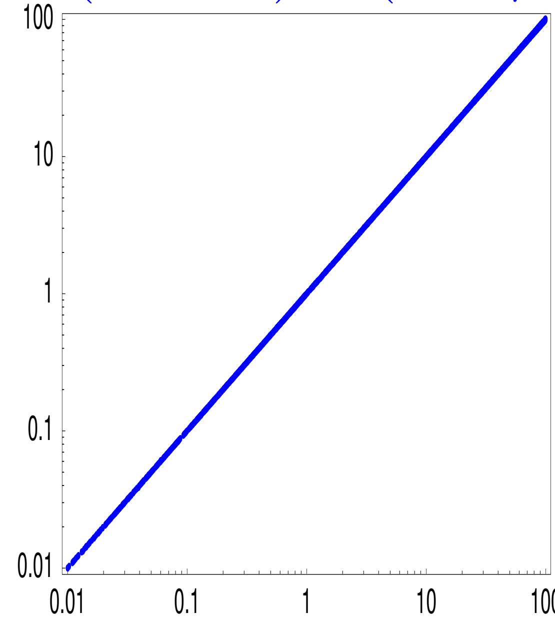
$(\epsilon_2/\epsilon_3)^2$

BR($\tilde{\mu}_1 \to e\nu_i$)/ BR($\tilde{\mu}_1 \to \tau\nu_i$)



$(\epsilon_1/\epsilon_3)^2$

BR($\tilde{\tau}_1 \to e\nu_i$)/ BR($\tilde{\tau}_1 \to \mu\nu_i$)



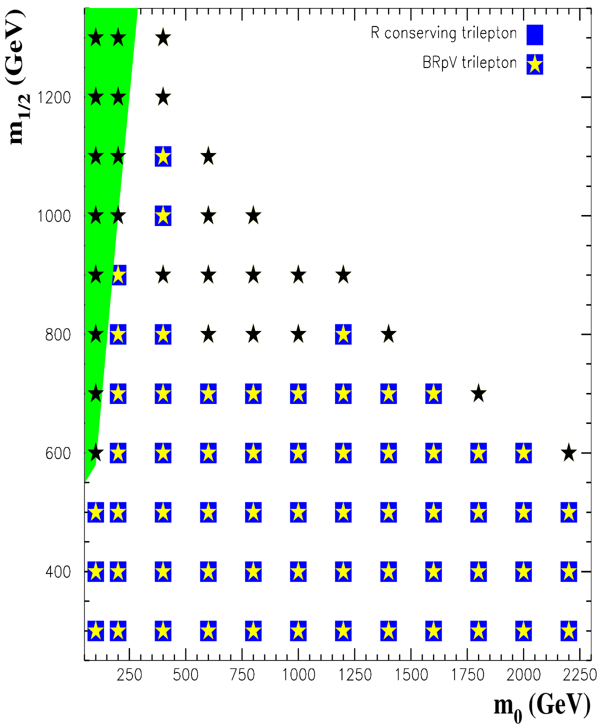
$(\epsilon_1/\epsilon_2)^2$

Cross check possible: $(\epsilon_1/\epsilon_3)^2/(\epsilon_1/\epsilon_2)^2 \equiv (\epsilon_2/\epsilon_3)^2$

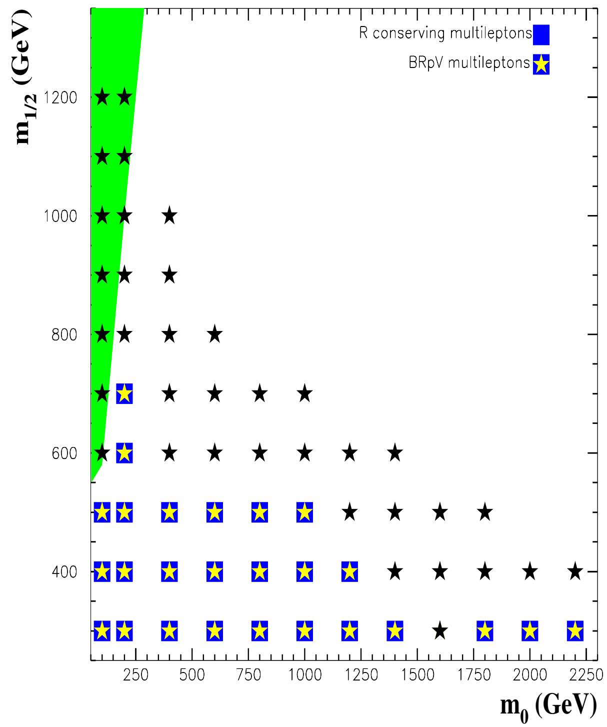
$\Rightarrow$ Measure 2 ratios, 3rd is fixed.

bilinear R-parity violation, reach in mSUGRA

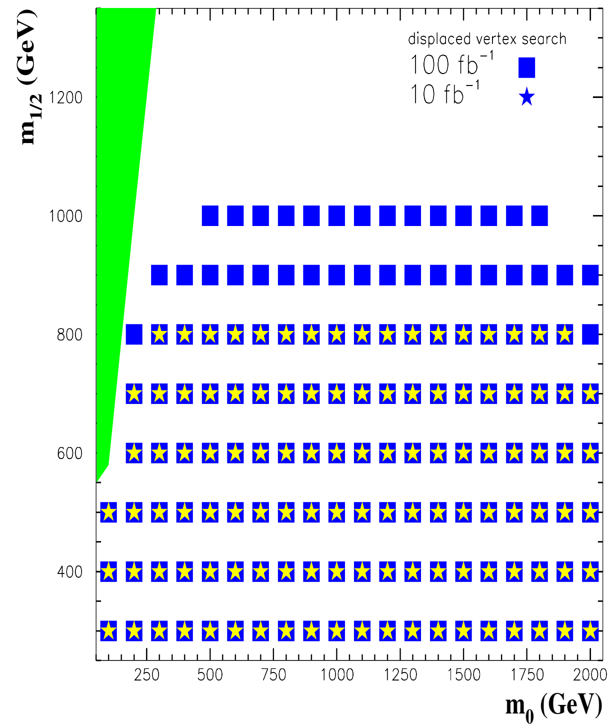
3-lepton channel



multi-lepton channel



displaced vertex



$L = 100$ fb^{-1}, $A_0 = -100$ GeV, $\tan\beta = 10$, $\mu > 0$

F. de Campos et al., JHEP **0805**, 048 (2008)

SUSY masses at LHC

talk by I. Borjanovic at 'Flavour in the era of LHC', Nov.'05, CERN

$L=100\ fb^{-1}$

Fit results

Edge	Nominal Value	Fit Value	Syst. Error Energy Scale	Statistical Error
$m(ll)^{edge}$	77.077	77.024	0.08	0.05
$m(qll)^{edge}$	431.1	431.3	4.3	2.4
$m(ql)^{edge}_{min}$	302.1	300.8	3.0	1.5
$m(ql)^{edge}_{max}$	380.3	379.4	3.8	1.8
$m(qll)^{thres}$	203.0	204.6	2.0	2.8

Mass reconstruction

5 endpoints measurements, 4 unknown masses

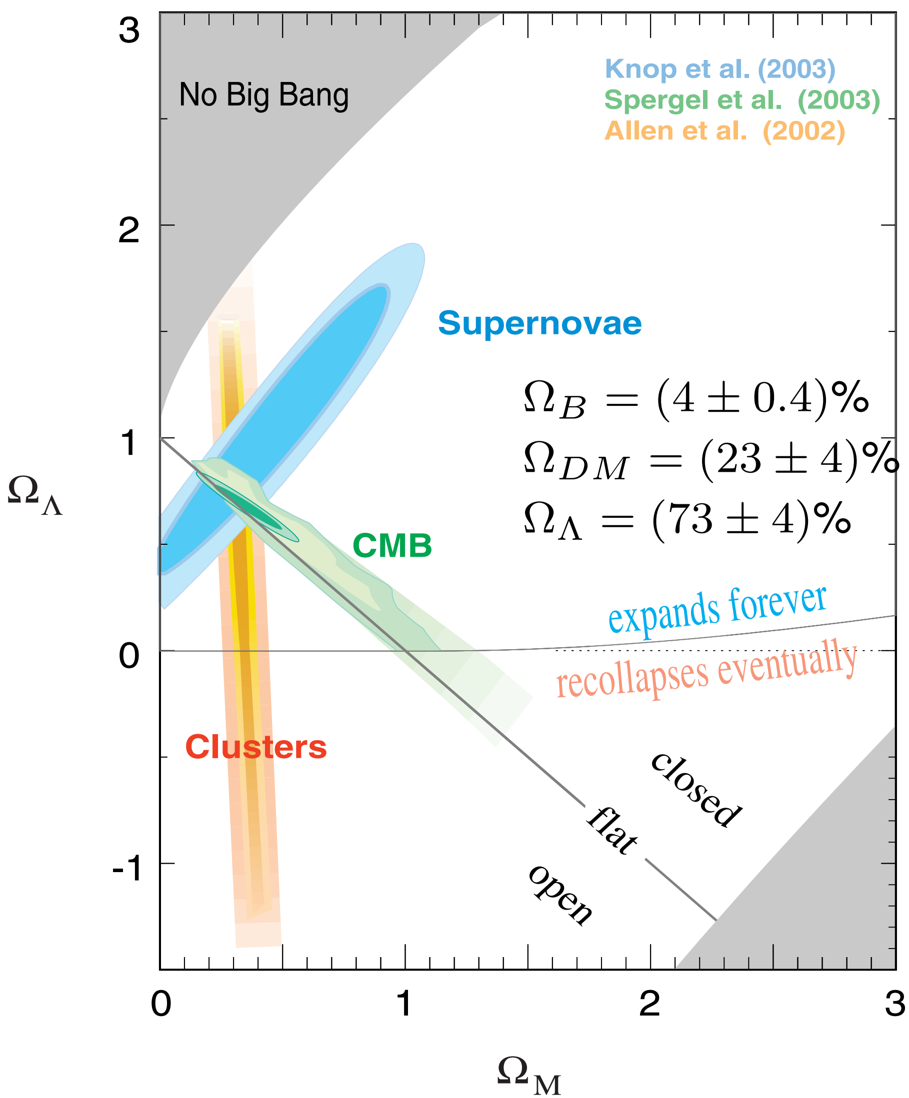
$$\chi^2 = \sum \chi_j^2 = \sum \left[\frac{E_j^{theory}(\vec{m}) - E_j^{exp}}{\sigma_j^{exp}} \right]^2$$

$$E_j^i = E_j^{nom} + a_j^i \sigma_j^{fit} + b^i \sigma_j^{Escale}$$

$m(\chi_1^0) = 96$ GeV
$m(l_R) = 143$ GeV
$m(\chi_2^0) = 177$ GeV
$m(q_L) = 540$ GeV

$\Delta m(\chi_1^0) = 4.8$ GeV, $\Delta m(\chi_2^0) = 4.7$ GeV,
$\Delta m(l_R) = 4.8$ GeV, $\Delta m(q_L) = 8.7$ GeV

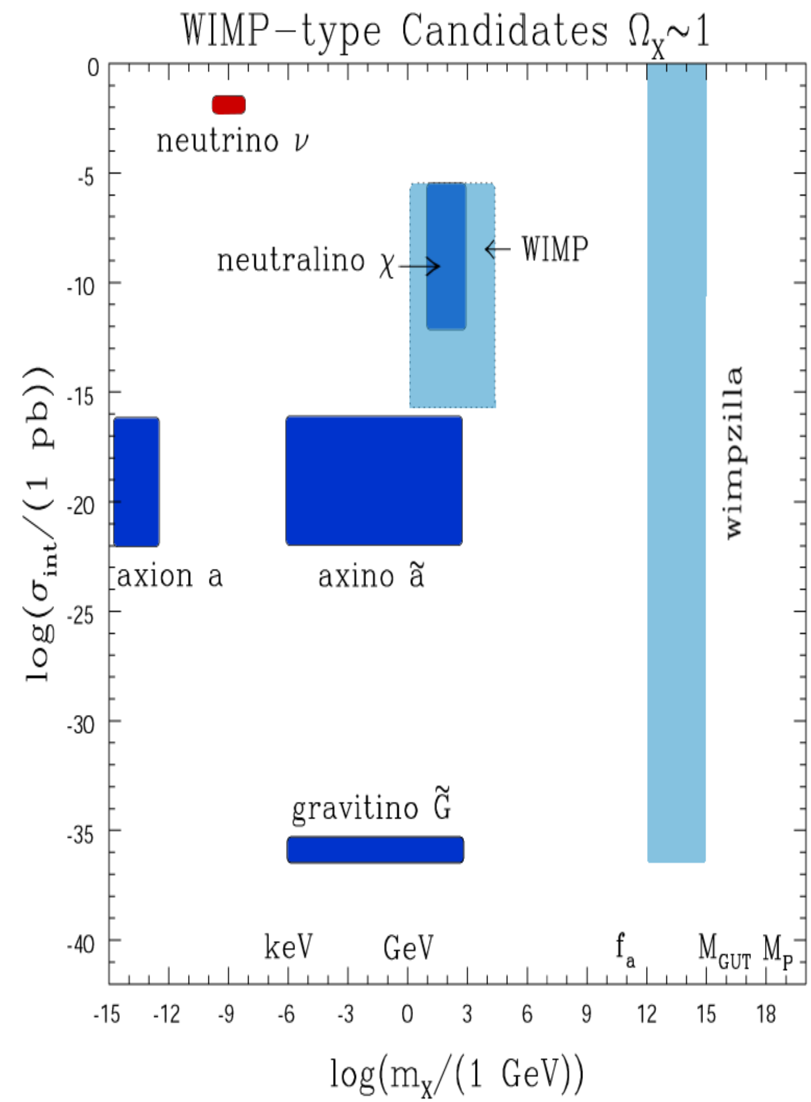
Gjelsten, Lytken, Miller, Osland, Polesello, ATL-PHYS-2004-007



$\Omega_B = (4 \pm 0.4)\%$

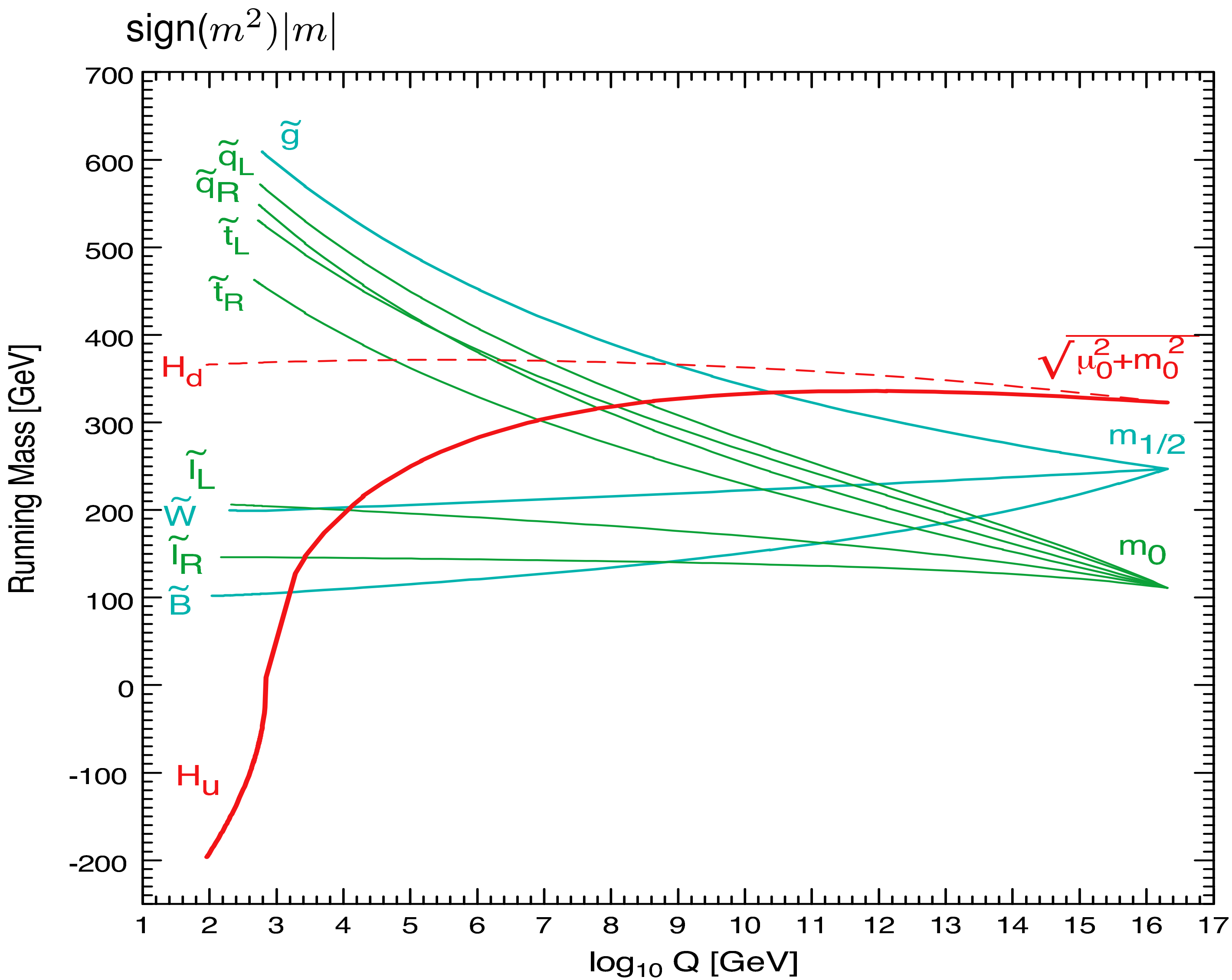
$\Omega_{DM} = (23 \pm 4)\%$

$\Omega_\Lambda = (73 \pm 4)\%$



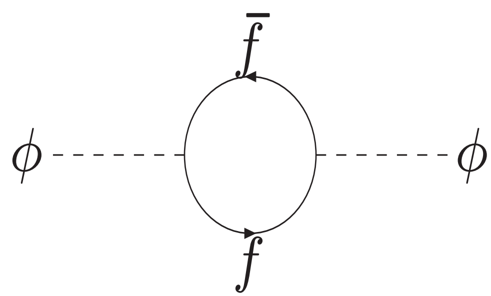
R.A. Knopp et al., Astrophys. J. **598** (2003) 102   L. Roszkowski, astro-ph/0404052

Running SUSY masses

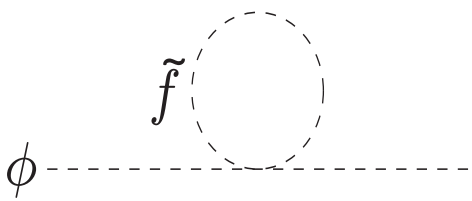


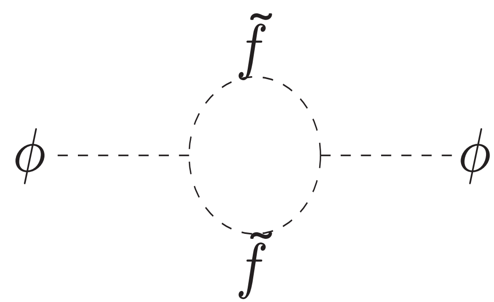
G. Kane, C. Kolda, L. Roszkowski, J. Wells, PRD 1994

Hierarchy problem



$$\delta m^2 = -N(f)\frac{\lambda_f^2}{8\pi^2}\Lambda^2 + \dots$$





$$\delta m^2 = N(f)\frac{\lambda_f^2}{8\pi^2}\Lambda^2 - \dots$$

exacte SUSY: $\delta m^2 = 0$

softly broken SUSY: $\delta m^2 \propto m_f^2 \log(m_{\tilde{f}}^2/m_f^2)$