Les Rencontres de Physique de la Vallee d'Aoste,
Results and Perspectives in Particle Physics

La Thuile, March 1 – 7, 2009

STATUS OF LFV:
a pre – dinner
THEORY OVERVIEW

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Present “Observational” Evidence for New Physics

- **NEUTRINO MASSES** ★★★
- **DARK MATTER** ★★★
- **MATTER-ANTIMATTER ASYMMETRY** ★★
- **INFLATION** ★

SM FAILS TO GIVE RISE TO A SUITABLE COSMIC MATTER-ANTIMATTER ASYMMETRY

:

- **NOT ENOUGH CP VIOLATION IN THE SM**

  NEED FOR ***NEW SOURCES OF CPV IN ADDITION TO THE PHASE PRESENT IN THE CKM MIXING MATRIX***

- FOR M_{HIGGS} > 80 GeV THE ELW. PHASE TRANSITION OF THE SM IS A SMOOTH CROSSOVER

NEED *NEW PHYSICS BEYOND SM*. IN PARTICULAR, FASCINATING POSSIBILITY: THE ENTIRE MATTER IN THE UNIVERSE ORIGINATES FROM THE SAME MECHANISM RESPONSIBLE FOR THE EXTREME SMALLNESS OF NEUTRINO MASSES

MATTER-ANTIMATTER ASYMMETRY ⟷ NEUTRINO MASSES CONNECTION: BARYOGENESIS THROUGH LEPTOGENESIS

- Key-ingredient of the SEE-SAW mechanism for neutrino masses: **large Majorana mass for RIGHT-HANDED neutrino**
- In the early Universe the heavy RH neutrino decays with Lepton Number violatiion; if these decays are accompanied by a new source of CP violation in the leptonic sector, then

→ it is possible to create a lepton-antilepton asymmetry at the moment RH neutrinos decay. Since SM interactions preserve Baryon and Lepton numbers at all orders in perturbation theory, but violate them at the quantum level, such **LEPTON ASYMMETRY** can be converted by these purely quantum effects into a BARYON-ANTIBARYON ASYMMETRY (**Fukugita-Yanagida mechanism for leptogenesis**)

The Energy Scale from the "Observational" New Physics

- neutrino masses
- dark matter
- baryogenesis
- inflation

→ NO NEED FOR THE NP SCALE TO BE CLOSE TO THE ELW. SCALE

The Energy Scale from the "Theoretical" New Physics

☆ ☆ ☆ Stabilization of the electroweak symmetry breaking at M_W calls for an ULTRAVIOLET COMPLETION of the SM already at the TeV scale +

☆ CORRECT GRAND UNIFICATION "CALLS" FOR NEW PARTICLES AT THE ELW. SCALE

CONNECTION DM – ELW. SCALE

THE WIMP MIRACLE :STABLE ELW. SCALE WIMPs

	SUSY	EXTRA DIM.	LITTLE HIGGS.
1) ENLARGEMENT OF THE SM	(x^μ, θ) Anticomm. Coord.	(x^μ, j^i) New bosonic Coord.	SM part + new part to cancel Λ^2 at 1-Loop
2) SELECTION RULE → DISCRETE SYMM. → STABLE NEW PART.	R-PARITY LSP Neutralino spin 1/2	KK-PARITY LKP spin1	T-PARITY LTP spin0
3) FIND REGION (S) PARAM. SPACE WHERE THE "L" NEW PART. IS NEUTRAL + $\Omega_L h^2$ OK	m_{LSP} ~100 - 200 GeV *	m_{LKP} ~600 - 800 GeV	m_{LTP} ~400 - 800 GeV

* But abandoning gaugino-masss unif. → Possible to have m_{LSP} down to 7 GeV

Bottino, Donato, Fornengo, Scopel

ELW. SYMM. BREAKING STABILIZATION VS. FLAVOR PROTECTION: THE SCALE TENSION

$$M(B_d\text{-}\bar{B}_d) \sim c_{SM} \frac{(y_t V_{tb}^* V_{td})^2}{16\,\pi^2 M_W^2} + c_{new} \frac{1}{\Lambda^2}$$

If $c_{new} \sim c_{SM} \sim 1$

Isidori

$\Lambda > 10^4$ TeV for $O^{(6)} \sim (\bar{s}\, d)^2$ [K^0-$\bar{K}^0$ mixing]

$\Lambda > 10^3$ TeV for $O^{(6)} \sim (\bar{b}\, d)^2$ [B^0-$\bar{B}^0$ mixing]

UV SM COMPLETION TO STABILIZE THE ELW. SYMM. BREAKING: $\Lambda_{UV} \sim O(1\ \text{TeV})$

THE FLAVOUR PROBLEMS

FERMION MASSES

What is the rationale hiding behind the spectrum of fermion masses and mixing angles (our “**Balmer lines**” problem)

→ **LACK OF A FLAVOUR “THEORY”**

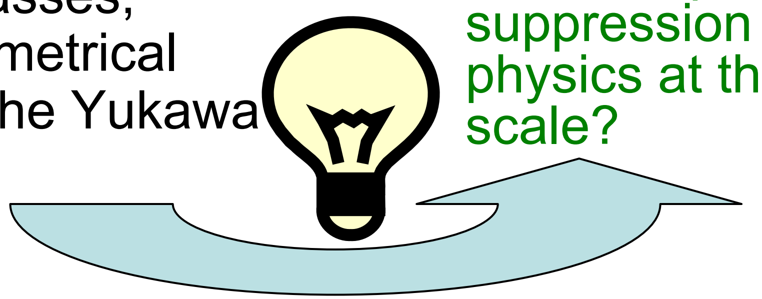
(new flavour – horizontal symmetry, radiatively induced lighter fermion masses, dynamical or geometrical determination of the Yukawa couplings, …?)

FCNC

Flavour changing neutral current (FCNC) processes are suppressed.

In the SM two nice mechanisms are at work: the **GIM mechanism** and the structure of the **CKM mixing matrix.**

How to cope with such delicate suppression if the there is new physics at the electroweak scale?



FLAVOR BLINDNESS OF THE NP AT THE ELW. SCALE?

- **THREE DECADES OF FLAVOR TESTS** (Redundant determination of the UT triangle $\longrightarrow$ verification of the SM, theoretically and experimentally "high precision" FCNC tests, ex. b $\longrightarrow$ s + γ, CP violating flavor conserving and flavor changing tests, lepton flavor violating (LFV) processes, …) clearly state that:
- A) in the **HADRONIC SECTOR** the **CKM flavor pattern of the SM represents the main bulk of the flavor structure and of (flavor violating) CP violation;**
- B) in the **LEPTONIC SECTOR**: although neutrino flavors exhibit large admixtures, LFV, i.e. non – conservation of individual lepton flavor numbers in FCNC transitions among charged leptons, is extremely small: once again the SM is right (to first approximation) predicting negligibly small LFV

What to make of this triumph of the CKM pattern in **hadronic flavor tests**?

New Physics at the Elw. Scale is Flavor Blind
CKM exhausts the flavor changing pattern at the elw. Scale →

MINIMAL FLAVOR VIOLATION

MFV : Flavor originates only from the SM Yukawa coupl.

New Physics introduces

NEW FLAVOR SOURCES in addition to the CKM pattern. They give rise to contributions which are <20% in the "flavor observables" which have already been observed!

Is there a hope to see NP with MFV in HIGH INTENSITY Physics?

- In hadronic **FCNC** experiments the best chance is:

Measurement of Br ($B_{s,d} \to \mu^+\mu^-$)

SM:

$$Br\left(B_s \to \mu^+\mu^-\right)_{SM} = (3.37 \pm 0.31) \cdot 10^{-9}$$

$$Br\left(B_d \to \mu^+\mu^-\right)_{SM} = (1.02 \pm 0.09) \cdot 10^{-10}$$

$$< 6 \cdot 10^{-8}$$

$$< 2 \cdot 10^{-8}$$

CDF (95% C.L.)

DØ

- In rare processes where the flavor does **not** change: **magnetic and electric dipole moments** (es. Muon magnetic moment, electric dipole moments of electron and nucleon)

The muon g-2: Standard Model vs. Experiment

- Adding up all the above contribution we get the following SM predictions for a_μ and comparisons with the measured value:

	$a_\mu^{SM} \times 10^{11}$	$\Delta a_\mu \times 10^{11}$	σ
[1]	116 591 793 (60)	287 (87)	3.3
[2]	116 591 778 (61)	302 (88)	3.4
[3]	116 591 807 (72)	273 (96)	2.8
[4]	116 591 828 (63)	252 (89)	2.8
[5]	116 591 991 (70)	89 (95)	0.9

with $a_\mu^{HHO}(lbl) = 110\ (40) \times 10^{-11}$. $\Delta a_\mu = a_\mu^{EXP} - a_\mu^{SM}$.

[1] Eidelman at ICHEP06 & Davier at TAU06 (update of ref. [5]).
[2] Hagiwara, Martin, Nomura, Teubner, PLB649 (2007) 173.
[3] F. Jegerlehner, PhiPsi 08, Frascati, April 2008.
[4] J.F. de Troconiz and F.J. Ynduraín, PRD71 (2005) 073008.
[5] Davier, Eidelman, Hoecker and Zhang, EPJC31 (2003) 503 (τ data).

- The th error is now the same (or even smaller) as the exp. one!
- If BaBar's <u>prelim</u>. results are used <u>instead</u>, Δa_μ drops to ~1.7σ.

Courtesy of M. Passera

What a SuperB can do in testing CMFV

L. Silvestrini at SuperB IV

Minimal Flavour Violation

In **MFV models** with **one Higgs doublet** or **low/moderate tanβ** the NP contribution is a shift of the Inami-Lim function associated to top box diagrams

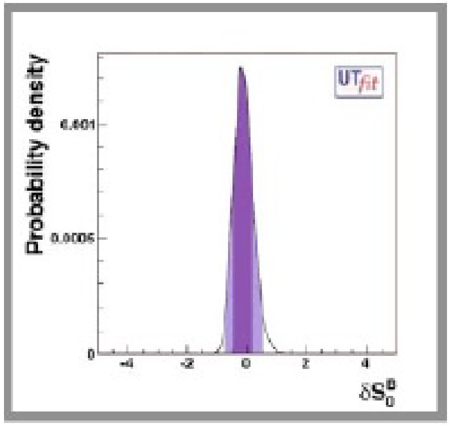
$$S_0(x_t) \to S_0(x_t) + \delta S_0(x_t)$$

$$\delta S_0(x_t) = 4a\left(\frac{\Lambda_0}{\Lambda}\right)^2$$

$$\Lambda_0 = \frac{\lambda_t \sin^2\vartheta_W M_W}{\alpha} \simeq 2.4\ \text{TeV}$$

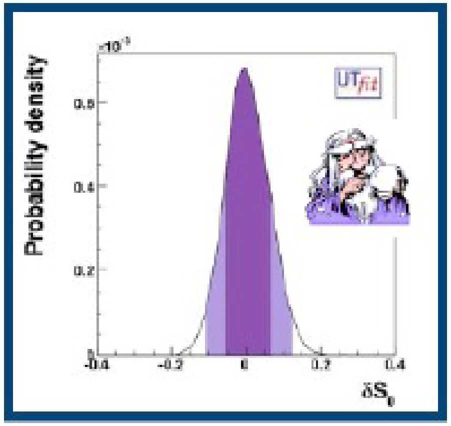
(D'Ambrosio et al., hep-ph/0207036)

$$\delta S_0^B = \delta S_0^K$$



$\delta S_0 = -0.16 \pm 0.32$

$\Lambda > 5.5$ TeV @95%



$\delta S_0 = 0.004 \pm 0.059$

$\Lambda > 28$ TeV @95%

The "worst" case: we still probe virtual particles with masses up to ~12 M_W ~1 TeV

SuperB vs. LHC Sensitivity Reach in testing Λ_{SUSY}

	superB	general MSSM	high-scale MFV
$\lvert (\delta^d_{13})_{LL} \rvert \; (LL \gg RR)$	$1.8 \cdot 10^{-2} \frac{m_{\tilde{q}}}{(350\,\mathrm{GeV})}$	1	$\sim 10^{-3} \frac{(350\,\mathrm{GeV})^2}{m_{\tilde{q}}^2}$
$\lvert (\delta^d_{13})_{LL} \rvert \; (LL \sim RR)$	$1.3 \cdot 10^{-3} \frac{m_{\tilde{q}}}{(350\,\mathrm{GeV})}$	1	$-$
$\lvert (\delta^d_{13})_{LR} \rvert$	$3.3 \cdot 10^{-3} \frac{m_{\tilde{q}}}{(350\,\mathrm{GeV})}$	$\sim 10^{-1} \tan\beta \frac{(350\,\mathrm{GeV})}{m_{\tilde{q}}}$	$\sim 10^{-4} \tan\beta \frac{(350\,\mathrm{GeV})^3}{m_{\tilde{q}}^3}$
$\lvert (\delta^d_{23})_{LR} \rvert$	$1.0 \cdot 10^{-3} \frac{m_{\tilde{q}}}{(350\,\mathrm{GeV})}$	$\sim 10^{-1} \tan\beta \frac{(350\,\mathrm{GeV})}{m_{\tilde{q}}}$	$\sim 10^{-3} \tan\beta \frac{(350\,\mathrm{GeV})^3}{m_{\tilde{q}}^3}$

SuperB can probe MFV (with small-moderate tanβ) for TeV squarks; for a generic non-MFV MSSM → sensitivity to squark masses > 100 TeV !

Ciuchini, Isidori, Silvestrini

SLOW-DECOUPLING OF NP IN FCNC

SUSY SEE-SAW

- **UV COMPLETION OF THE SM TO STABILIZE THE ELW. SCALE:**

LOW-ENERGY SUSY

- **COMPLETION OF THE SM FERMIONIC SPECTRUM TO ALLOW FOR NEUTRINO MASSES:** NATURALLY SMALL PHYSICAL NEUTRINO MASSES WITH RIGHT-HANDED NEUTRINO WITH A LARGE MAJORANA MASS

SEE-SAW

LFV IN CHARGED LEPTONS FCNC

L_i - L_j transitions through W - neutrinos mediation

GIM suppression $(m_\nu / M_W)^2$ ⟶ forever invisible

New mechanism: replace SM GIM suppression with a new GIM suppression where m_ν is replaced by some $\Delta M >> m_\nu$.

Ex.: in SUSY L_i - L_j transitions can be mediated by photino - SLEPTONS exchanges,

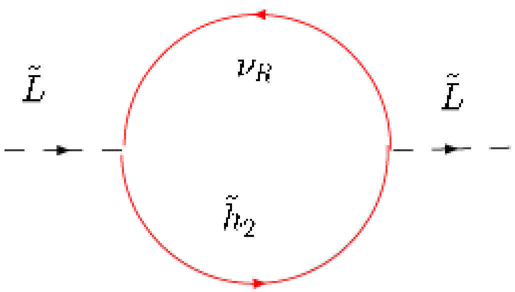
BUT in CMSSM (MSSM with flavor universality in the SUSY breaking sector) $\Delta M_{\text{sleptons}}$ is O(m_{leptons}), hence GIM suppression is still too strong.

How to further decrease the SUSY GIM suppression power in LFV through slepton exchange?

SUSY SEESAW: ***Flavor universal SUSY breaking and yet large lepton flavor violation***

Borzumati, A. M. 1986 (after discussions with W. Marciano and A. Sanda)

$$L = f_l\, \bar{e}_R L h_1 + f_\nu\, \bar{\nu}_R L h_2 + M\, \nu_R \nu_R$$



$$\left(m^2_{\tilde{L}}\right)_{ij} \sim \frac{1}{8\pi^2}(3m_0^2 + A_0^2)\left(f_\nu^\dagger f_\nu\right)_{ij} \log\frac{M}{M_G}$$

Non-diagonality of the slepton mass matrix in the basis of diagonal lepton mass matrix depends on the unitary matrix U which diagonalizes $(f_\nu^+ f_\nu)$

How Large LFV in SUSY SEESAW?

- 1) Size of the **Dirac neutrino couplings f_ν**

- 2) Size of the **diagonalizing matrix U**

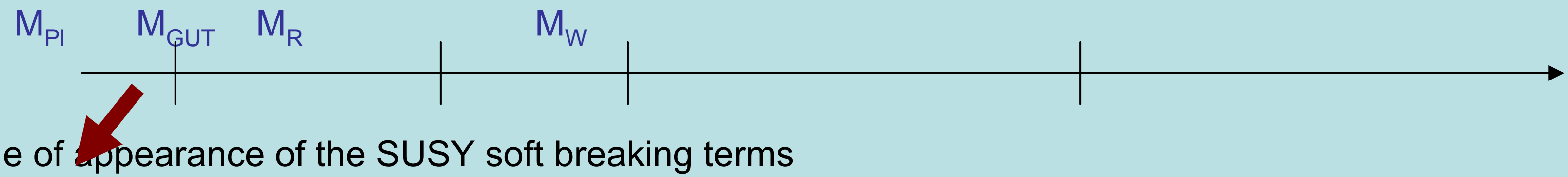
In **MSSM seesaw** or in **SUSY SU(5)** (Moroi): not possible to correlate the neutrino Yukawa couplings to know Yukawas;

In **SUSY SO(10)** (A.M., Vempati, Vives) at least one neutrino Dirac Yukawa coupling has to be of the **order of the top Yukawa coupling** → one large of O(1) f_ν

U → two "extreme" cases:

a) **U with "small" entries** → **U = CKM**;
b) **U with "large" entries** with the exception of the 13 entry → **U = PMNS** matrix responsible for the diagonalization of the neutrino mass matrix

LFV in SUSYGUTs with SEESAW



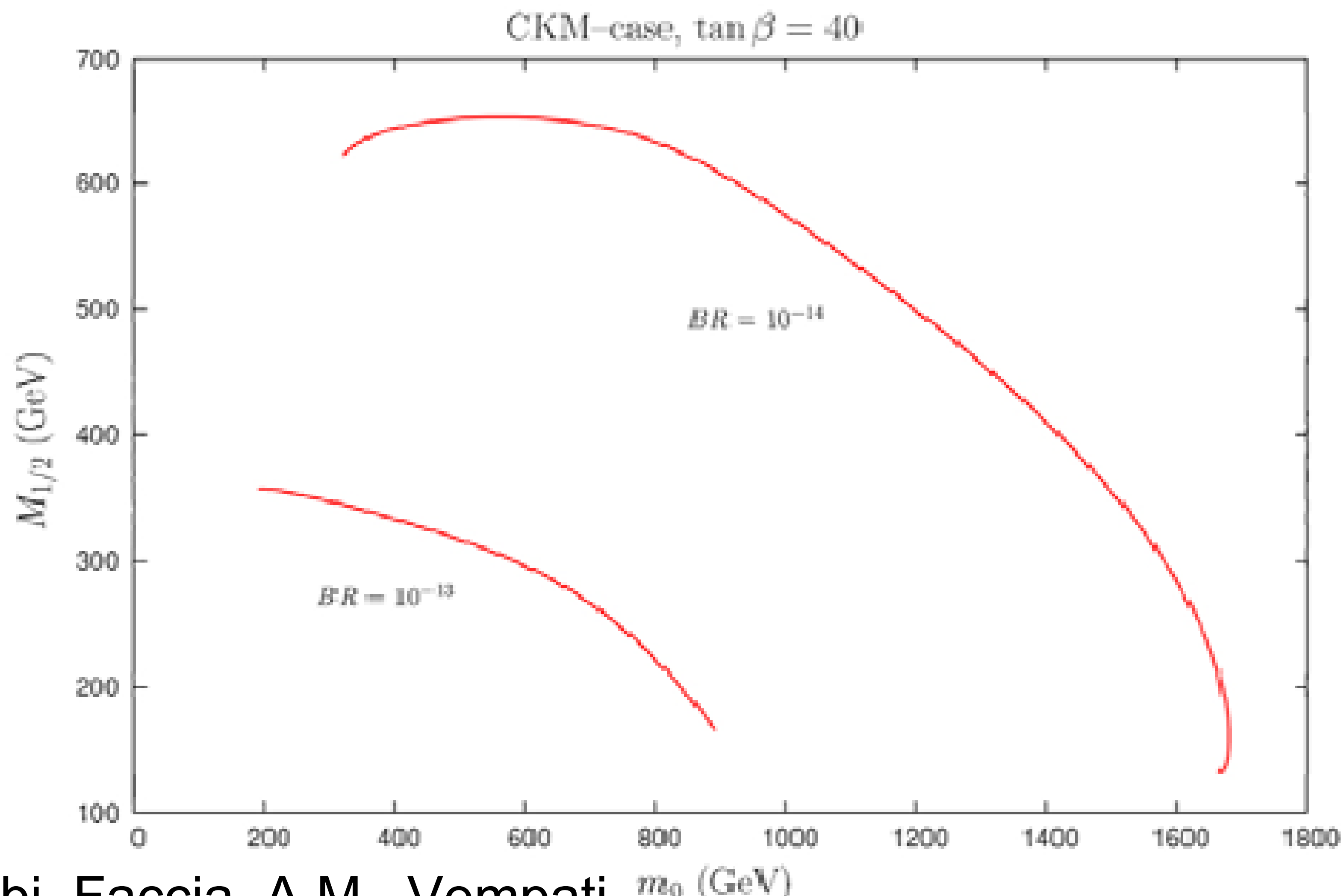
Scale of appearance of the SUSY soft breaking terms
resulting from the spontaneous breaking of supergravity

Low-energy SUSY has "memory" of all the multi-step RG occurring from such superlarge scale down to M_W

potentially large LFV

Barbieri, Hall; Barbieri, Hall, Strumia; Hisano, Nomura,
Yanagida; Hisano, Moroi, Tobe Yamaguchi; Moroi;A.M.,, Vempati, Vives;
Carvalho, Ellis, Gomez, Lola; Calibbi, Faccia, A.M, Vempati
LFV in MSSMseesaw: μ $e\gamma$ Borzumati, A.M.
τ $\mu\gamma$ Blazek, King;
General analysis: Casas Ibarra; Lavignac, Masina,Savoy; Hisano, Moroi, Tobe, Yamaguchi; Ellis, Hisano, Raidal, Shimizu; Fukuyama, Kikuchi, Okada; Petcov, Rodejohann, Shindou, Takanishi; Arganda, Herrero; Deppish, Pas, Redelbach, Rueckl; Petcov, Shindou

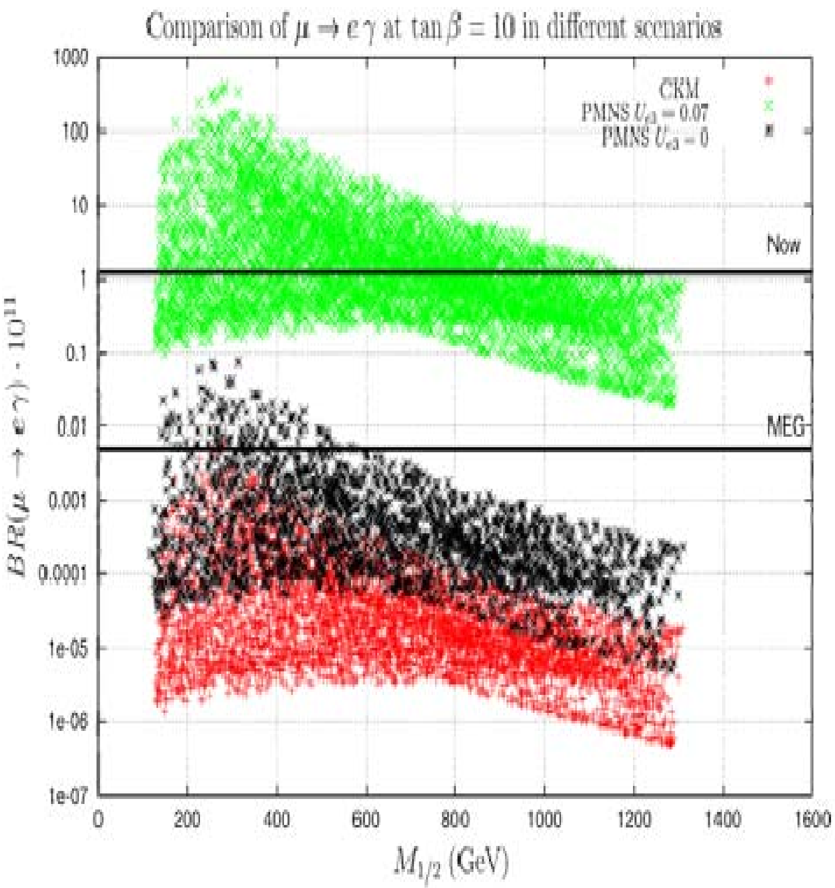
MEG POTENTIALITIES TO EXPLORE THE SUSY SEESAW PARAM. SPACE

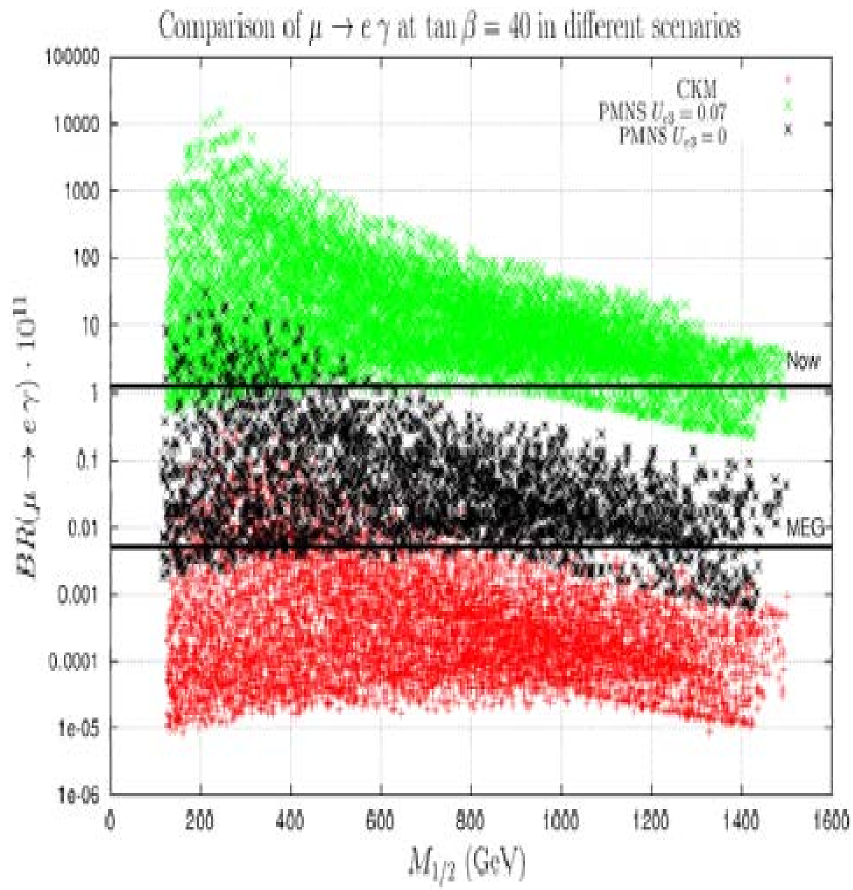


Calibbi, Faccia, A.M., Vempati

$\mu \rightarrow e+\gamma$ in SUSYGUT: past and future

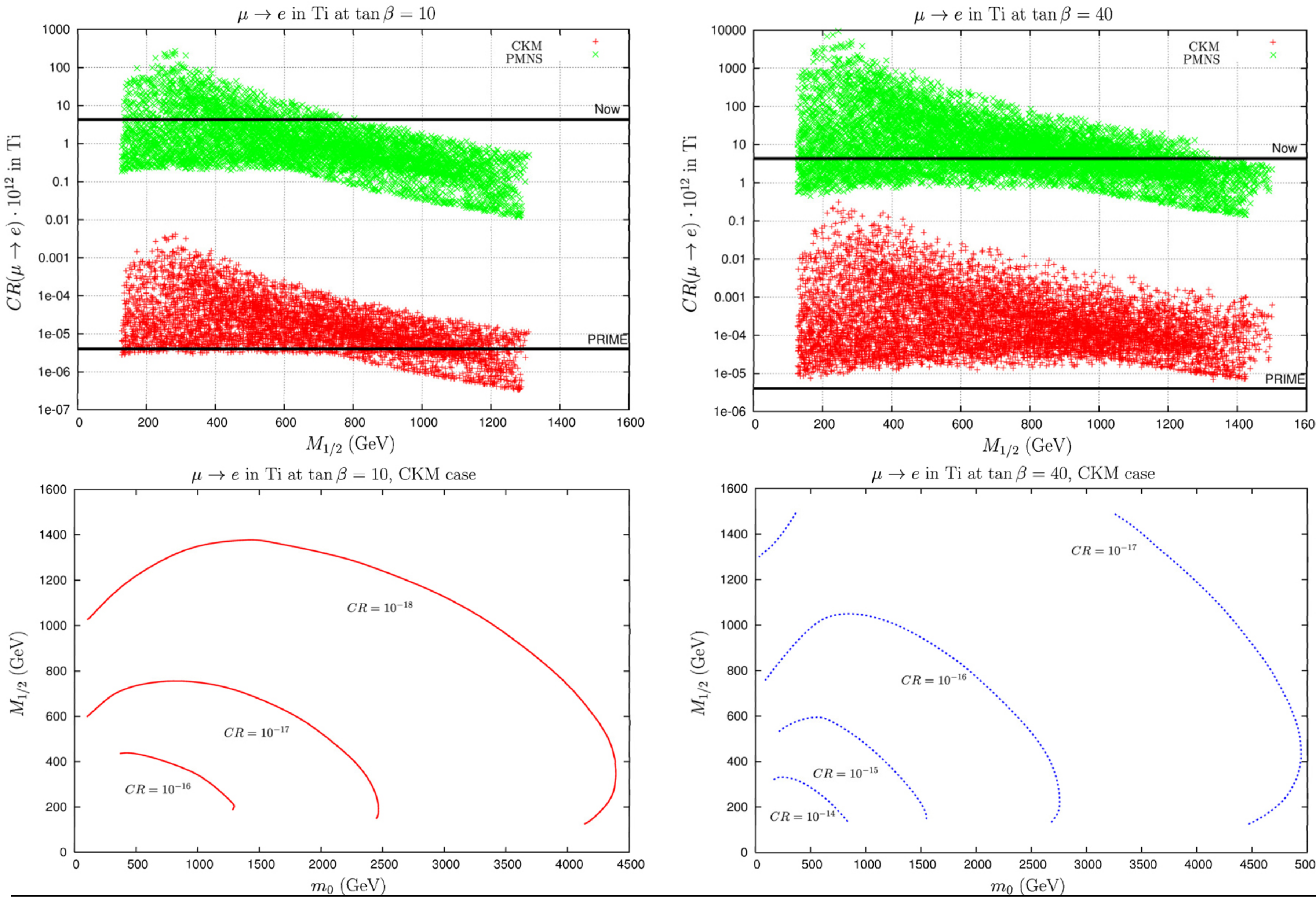
$\mu \rightarrow e\gamma$ in the $U_{e3} = 0$ PMNS case



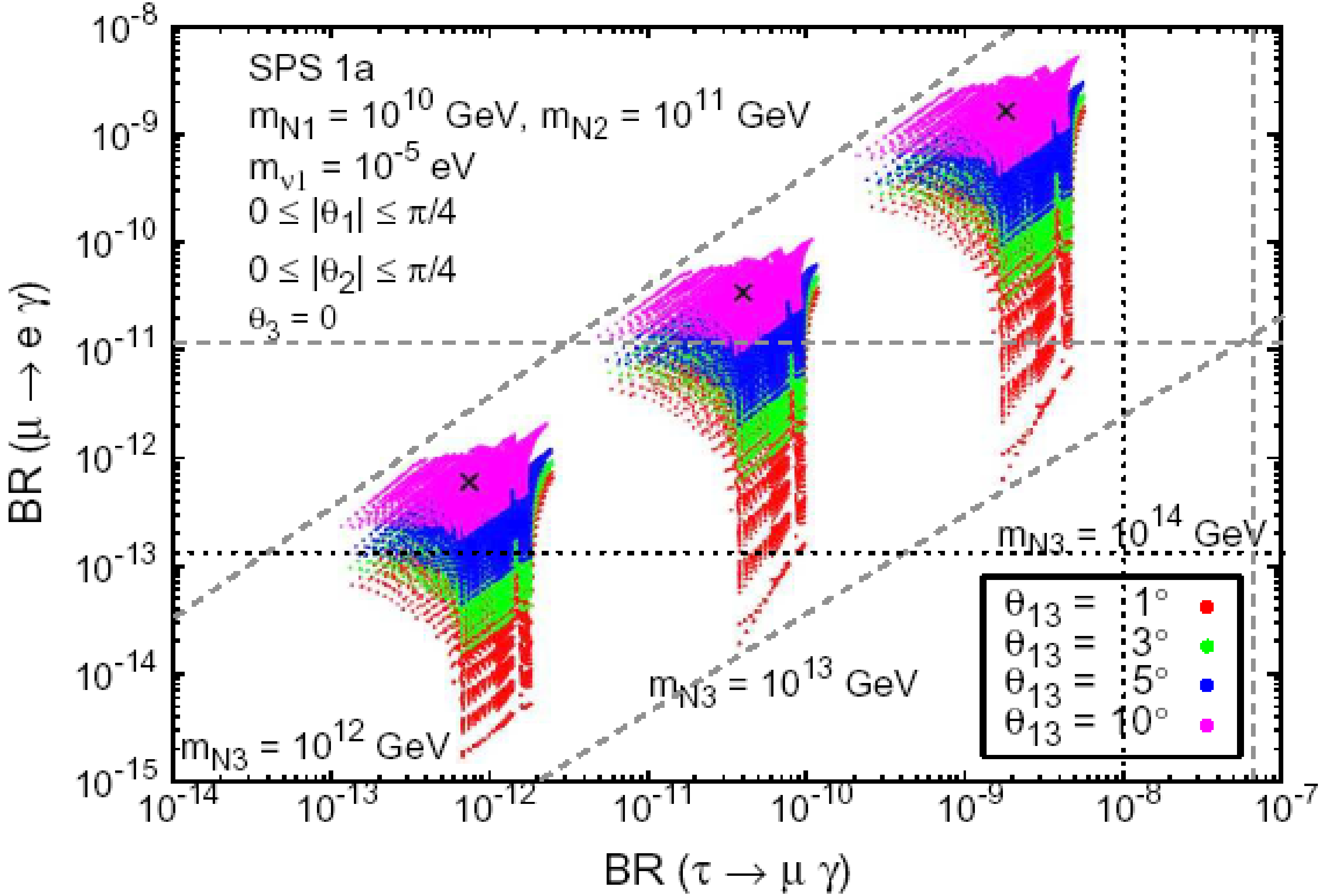


CFMV

$\mu \to e$ in Ti and **PRISM/PRIME** conversion experiment



Antusch, Arganda, Herrero, Teixeira



LFV ⟷ LHC SENSITIVITIES IN PROBING THE SUSY PARAM. SPACE

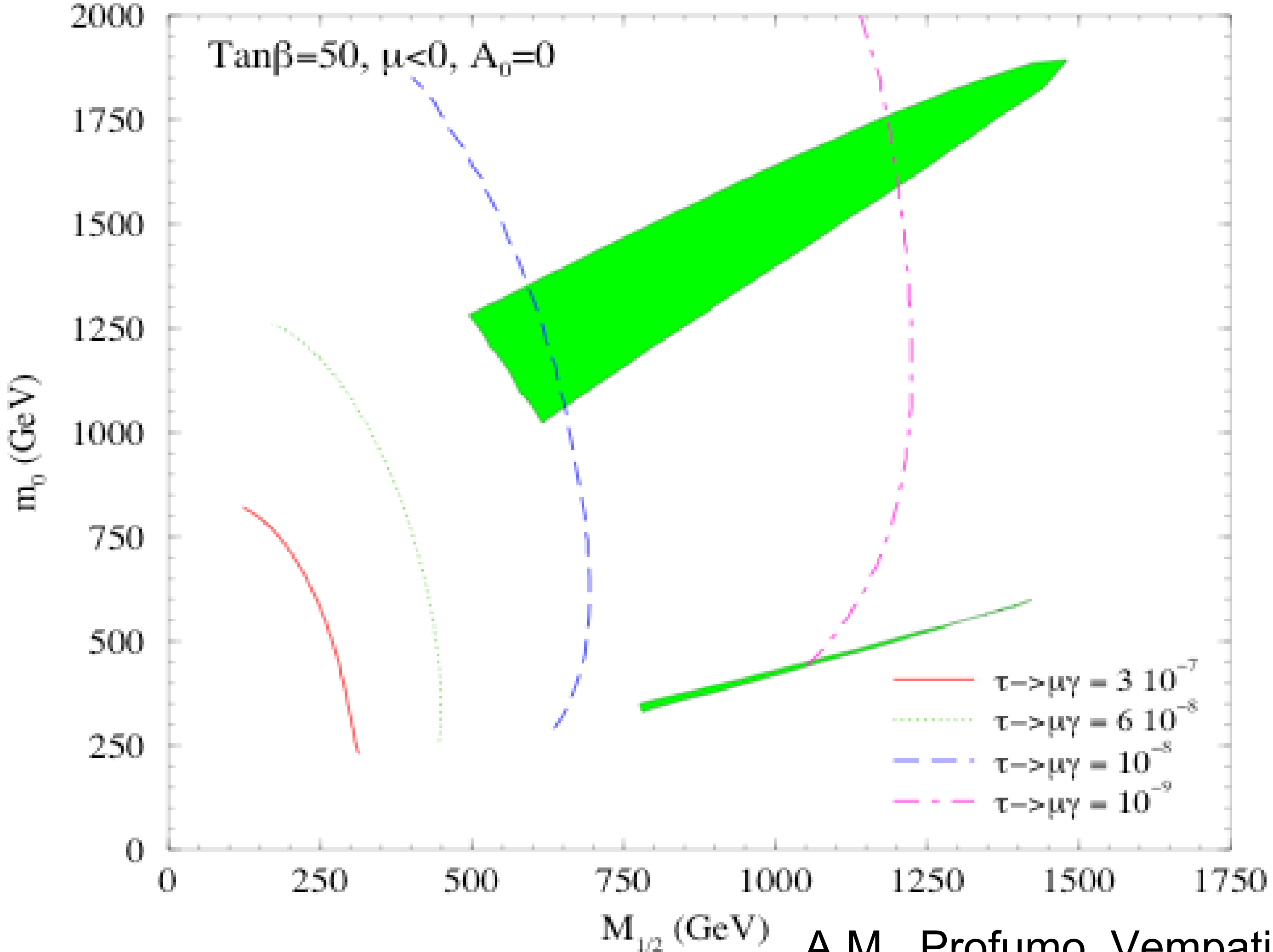
TABLE IX: Reach in $(m_0, m_{\tilde{g}})$ of the present and planned experiment from their $\tau \to \mu\gamma$ sensitivity.

	PMNS		CKM	
Exp.	$t_\beta = 40$	$t_\beta = 10$	$t_\beta = 40$	$t_\beta = 10$
BaBar, Belle	1.2 TeV	no	no	no
SuperKEKB	2 TeV	0.9 TeV	no	no
Super Flavour [a]	2.8 TeV	1.5 TeV	0.9 TeV	no

[a]Post–LHC era proposed/discussed experiment

Calibbi, Faccia, A.M., Vempati

LFV - DM CONSTRAINTS IN MINIMAL SUPERGRAVITY



A.M., Profumo, Vempati, Yaguna

LFV vs. MUON (g – 2) in MSSM

Isidori, Mescia, Paradisi, Temes

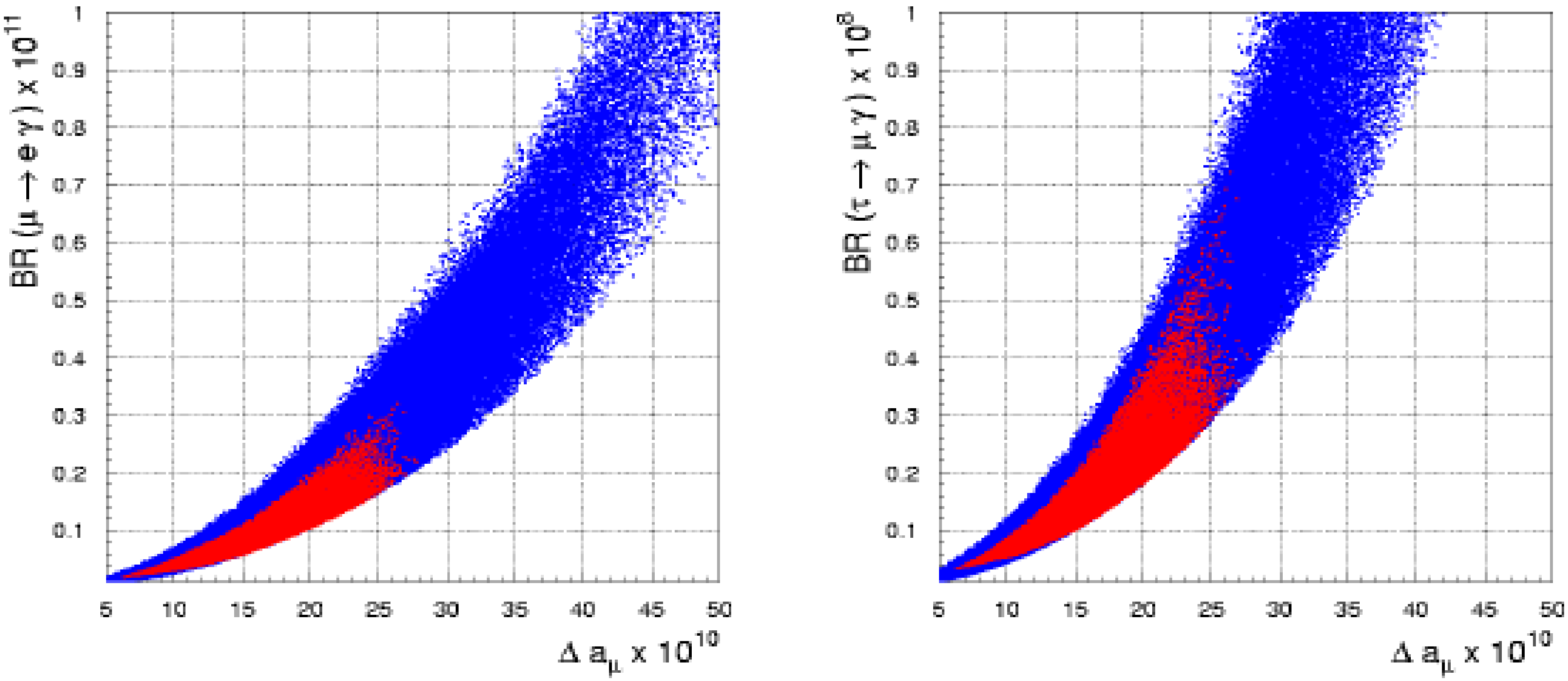


Figure 6: Expectations for $\mathcal{B}(\mu \to e\gamma)$ and $\mathcal{B}(\tau \to \mu\gamma)$ vs. $\Delta a_\mu = (g_\mu - g_\mu^{\rm SM})/2$, assuming $|\delta_{LL}^{12}| = 10^{-4}$ and $|\delta_{LL}^{23}| = 10^{-2}$. The plots have been obtained employing the following ranges: 300 GeV $\leq M_{\tilde{\ell}} \leq$ 600 GeV, 200 GeV $\leq M_2 \leq$ 1000 GeV, 500 GeV $\leq \mu \leq$ 1000 GeV, $10 \leq \tan\beta \leq 50$, and setting $A_U = -1$ TeV, $M_{\tilde{q}} = 1.5$ TeV. Moreover, the GUT relations $M_2 \approx 2M_1$ and $M_3 \approx 6M_1$ are assumed. The red areas correspond to points within the funnel region which satisfy the B-physics constraints listed in Section 3.2 [$\mathcal{B}(B_s \to \mu^+\mu^-) < 8 \times 10^{-8}$, $1.01 < R_{Bs\gamma} < 1.24$, $0.8 < R_{B\tau\nu} < 0.9$,

DEVIATION from μ - e UNIVERSALITY

A.M., Paradisi, Petronzio

- Denoting by $\Delta r_{NP}^{e-\mu}$ the deviation from $\mu - e$ universality in $R_{K,\pi}$ due to new physics, i.e.:

$$R_{K,\pi} = R_{K,\pi}^{SM} \left(1 + \Delta r_{K,\pi\, NP}^{e-\mu}\right),$$

- we get at the 2σ level:

$$-0.063 \leq \Delta r_{K\, NP}^{e-\mu} \leq 0.017 \quad \mathrm{NA48/2}$$

$$-0.0107 \leq \Delta r_{\pi\, NP}^{e-\mu} \leq 0.0022 \quad \mathrm{PDG}$$

Presently: error on R_K down to the **1% level** (KLOE (09), talk by Antonelli and NA48 (07 data);using 40% of the data collected in 08, NA62 is now decreasing the uncertainty at the **0.7% level**, talk by Bucci. **Prospects**: Summer conf. we'll have the result concerning the 40% data analysis by NA62 and when the analysis of the whole sample of data is accomplished **the stat. uncertainty will be <0.3%** (talk by Bucci)

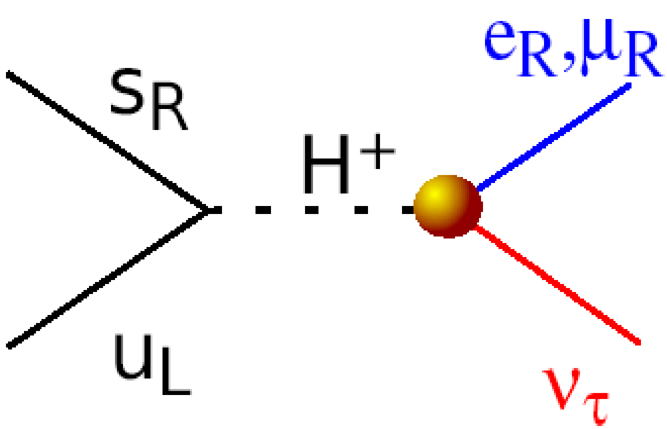
HIGGS-MEDIATED LFV COUPLINGS

- When non-holomorphic terms are generated by loop effects (HRS corrections)
- And a source of LFV among the sleptons is present
- $\longrightarrow$ Higgs-mediated (radiatively induced) H-lepton-lepton LFV couplings arise

Babu, Kolda; Sher; Kitano,Koike,Komine, Okada; Dedes, Ellis, Raidal; Brignole,Rossi; Arganda,Curiel,Herrero,Temes; Paradisi; Brignole,Rossi

H mediated LFV SUSY contributions to R_K

$$R_K^{LFV} = \frac{\sum_i K \to e\nu_i}{\sum_i K \to \mu\nu_i} \simeq \frac{\Gamma_{SM}(K \to e\nu_e) + \Gamma(K \to e\nu_\tau)}{\Gamma_{SM}(K \to \mu\nu_\mu)} \;, \quad i = e, \mu, \tau$$



$$eH^\pm \nu_\tau \to \frac{g_2}{\sqrt{2}} \frac{m_\tau}{M_W} \Delta_R^{31} \tan^2\beta$$

$$\Delta_R^{31} \sim \frac{\alpha_2}{4\pi} \delta_{RR}^{31}$$

$$\Delta_R^{31} \sim 5 \cdot 10^{-4} \quad t_\beta = 40 \quad M_{H^\pm} = 500\text{GeV}$$

$$\Downarrow$$

$$\Delta r_{K\,SUSY}^{e-\mu} \simeq \left(\frac{m_K^4}{M_{H^\pm}^4}\right)\left(\frac{m_\tau^2}{m_e^2}\right) |\Delta_R^{31}|^2 \tan^6\beta \approx 10^{-2}$$

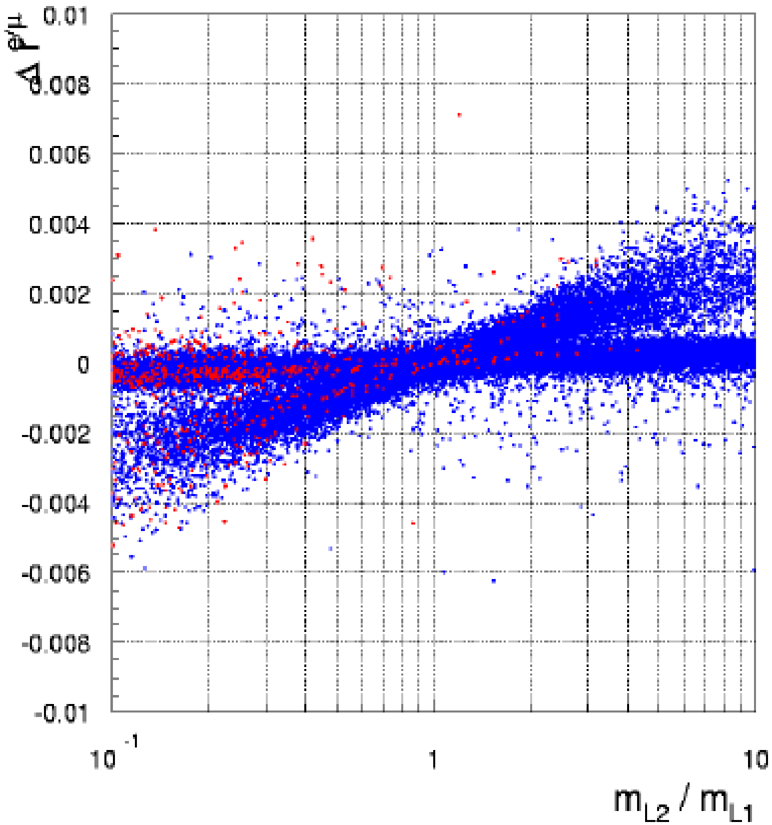
Extension to B $\longrightarrow$ lν deviation from universality

Isidori, Paradisi

A.M., PARADISI. PETRONZIO

LFU breaking occurs in a **LF conserving** case because of the splitting in slepton masses

LFU breaking occurs with LFV



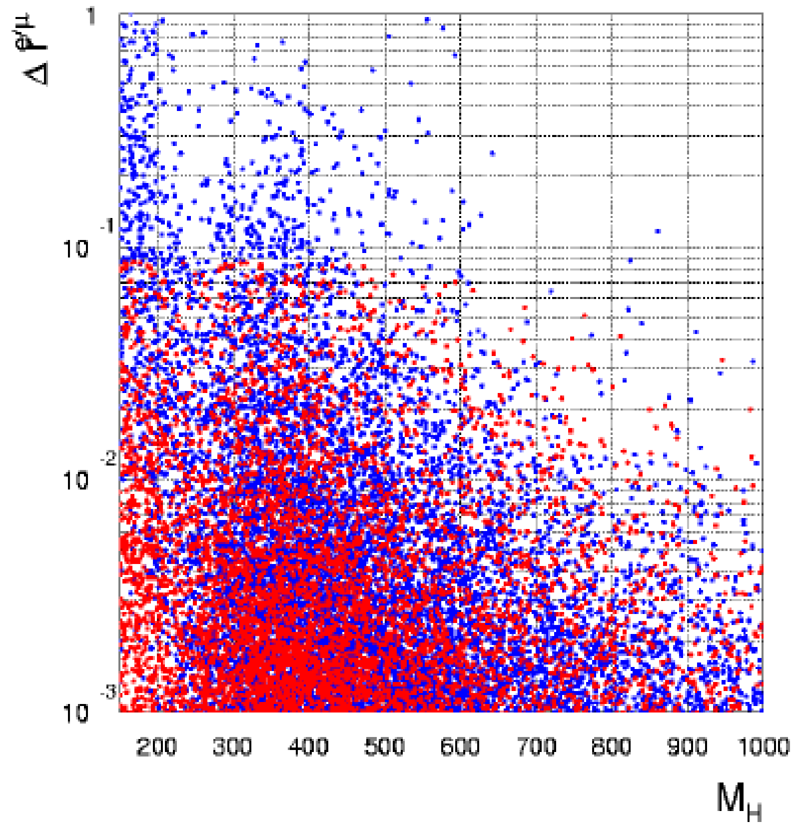


Figure 2: Left:$\Delta r_K^{e/\mu}$ as a function of the mass splitting between the second and the first (left-handed) slepton generations. Red dots can saturate the $(g-2)_\mu$ discrepancy at the 95% C.L., i.e. $1 \times 10^{-9} < (g-2)_\mu < 5 \times 10^{-9}$. Right: $\Delta r_K^{e/\mu}$ as a function of M_{H+}.

SUSY GUTs

- UV COMPLETION OF THE SM TO STABILIZE THE ELW. SCALE:

LOW-ENERGY SUSY

TREND OF UNIFICATION OF THE SM GAUGE COUPLINGS AT HIGH SCALE:

GUTs

Large ν mixing ⟷ large b-s transitions in SUSY GUTs

In SU(5) d_R ⟷ l_L connection in the 5-plet
Large $(\Delta^l_{23})_{LL}$ induced by large f_ν of $O(f_{top})$
is accompanied by large $(\Delta^d_{23})_{RR}$

In SU(5) assume large f_ν (Moroi)
In SO(10) f_ν large because of an underlying Pati-Salam symmetry
(**Darwin Chang**, A.M., Murayama)

See also: Akama, Kiyo, Komine, Moroi; Hisano, Moroi, Tobe, Yamaguchi, Yanagida; Hisano, Nomura; Kitano,Koike, Komine, Okada

FCNC HADRON-LEPTON CONNECTION IN SUSYGUT

If

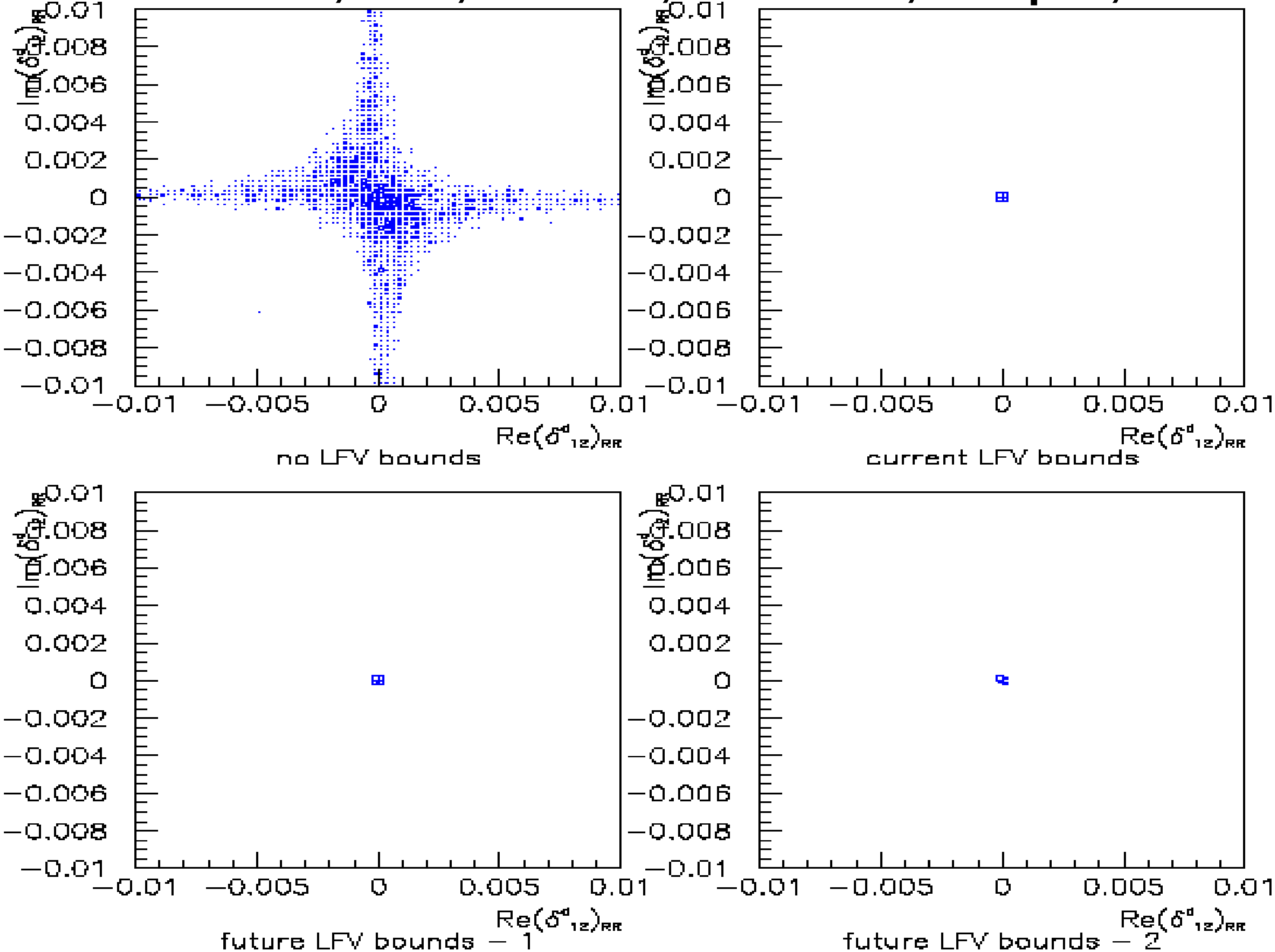
soft **SUSY breaking terms** arise
at a scale > M_{GUT}, they have to **respect**
the underlying quark-lepton GU symmetry

constraints on δ^{quark} **from LFV** and
constraints on δ^{lepton} **from hadronic FCNC**

Ciuchini, A.M., Silvestrini, Vempati, Vives PRL 2004
general analysis **Ciuchini, A.M., Paradisi, Silvestrini, Vempati, Vives** NPB 2007
For previous works: Baek, Goto, Okada, Okumura PRD 2001;
Hisano, Shimizu, PLB 2003;
Cheung, Kang, Kim, Lee PLB 2007
Borzumati, Mishima, Yamashita hep-ph 0705:2664
For recent works: Goto, Okada, Shindou, Tanaka PRD 2008;
Ko, J-h. Park, Yamaguchi arXiv:0809:2784

Bounds on the hadronic $(\delta_{12})_{RR}$ as modified by the inclusion of the LFV correlated bound

Ciuchini, A.M., Paradisi, Silvestrini, Vempati, Vives



FINAL PRE – DINNER THOUGHTS

- The traditional **competition** between direct and indirect (FCNC, CPV) searches to establish who is going **to see the new physics first** is no longer the priority, rather

- **COMPLEMENTARITY** between direct and indirect searches for New Physics is the key-word

- Twofold meaning of such complementarity:

i) **synergy in "reconstructing" the "fundamental theory"** staying behind the signatures of NP;

ii) **coverage of complementary areas of the NP parameter space** (ex.: multi-TeV SUSY physics)

- So far the high-intensity, high – precision road has not produced significant hints for NP (“**physiological**” **departures from the SM expectation** – possible exception the (g – 2) of the muon), however ***Super Flavor machines can change the picture*** (remember, CPV discovered because the % accuracy was not enough …)

- To the virtues of the FCNC road to NP, LFV adds the fact that it can be the crucial link between the NP responsible for neutrino masses and the NP at the ELW. scale: ***if ELW. scale NP includes in its spectrum some new particles carrying Lepton Flavor Number, then the LFV in neutrino physics can be transferred to the LFV in the charged lepton sector***
- ***IN THE HIGH INTENSITY ROAD TO NEW PHYSICS, LFV IS A (VERY) GOOD INVESTMENT!***