CORFU SUMMER INSTITUTE, WORKSHOP ON THE SM AND BEYOND – COSMOLOGY, Aug. 29 – Sept. 5, 2010

LFV, DM and the TeV NEW PHYSICS Challenge

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TEVATRON → LHC → I L C

DM - FLAVOR

for DISCOVERY

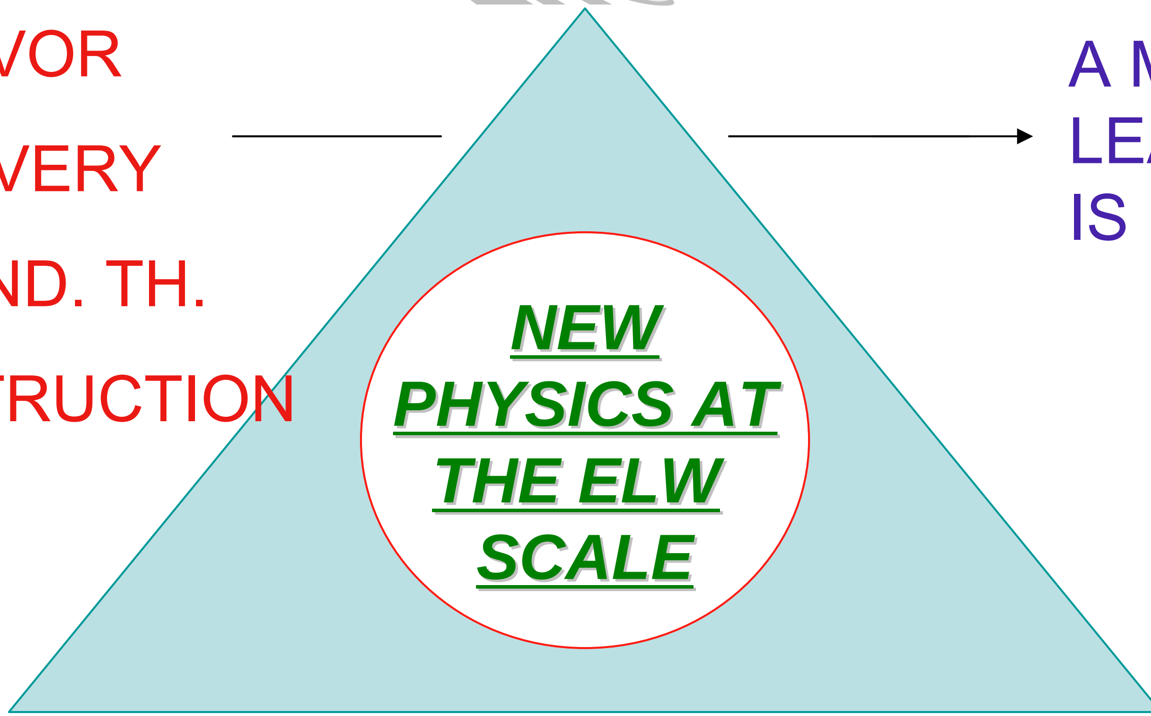
and/or FUND. TH.

RECONSTRUCTION

A MAJOR

LEAP AHEAD

IS NEEDED



DARK MATTER

m_χ n_χ σ_χ…

DARK ENERGY

LINKED TO COSMOLOGICAL EVOLUTION

LEPTOGENESIS

GW

INFLATION

"LOW ENERGY"

PRECISION PHYSICS

FCNC, CP $\neq$, (g-2), $(\beta\beta)_{0\nu\nu}$

LFV, CPV B PHYSICS

NEUTRINO PHYSICS

PROLOGUE

… **no firm experimental indication that some NEW PHYSICS sets in at the electroweak scale (i.e., with new particles and phenomena at the TeV mass scale) and**

… **yet, we are strongly convinced that TeV New Physics is present**

WHY TO GO BEYOND THE SM

"OBSERVATIONAL" REASONS

- HIGH ENERGY PHYSICS

NO (but A_{FB} ……$^{Z \longrightarrow bb}$)

- FCNC, CP≠

NO (but CPV in Bs, sin2β tension)

- HIGH PRECISION LOW-EN.

NO (but $(g-2)_\mu$ …)

- **NEUTRINO PHYSICS**

YES $m_\nu \neq 0$, $\theta_\nu \neq 0$

- **COSMO - PARTICLE PHYSICS**

YES (DM, ΔB_{cosm}, INFLAT., DE)

THEORETICAL REASONS

- INTRINSIC INCONSISTENCY OF SM AS QFT

NO (spont. broken gauge theory without anomalies)

- NO ANSWER TO QUESTIONS THAT "WE" CONSIDER "FUNDAMENTAL" QUESTIONS TO BE ANSWERED BY "FUNDAMENTAL" THEORY

YES **(hierarchy, unification, flavor)**

SOMETHING is needed at the TeV scale to enforce the unitarity of the electroweak theory

Is it possible that there is "only" a light higgs boson and no NP?

- **This is acceptable if one argues that no ultraviolet completion of the SM is needed at the TeV scale** simply because there is **no actual fine-tuning related to the higgs mass stabilization** (**the correct value of the higgs mass is "environmentally" selected**). This explanation is similar to the one adopted for the cosmological constant

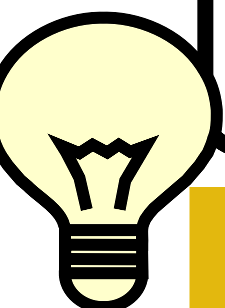
- Barring such wayout, **one is lead to have TeV NP to ensure the unitarity of the elw. theory at the TeV scale**

GENERAL FEATURES OF NEW PHYSICS AT THE ELW. SCALE

- Some amount of **fine-tuning** (typically at the % level) is required to pass unscathed the elw. precision tests, the higgs mass bound and the direct search for new particles at accelerators.
- The **higgs is typically rather light** (<200 GeV) apart from the extreme case of the "Higgsless proposal"
- All models provide **signatures which are (more or less) accessible to LHC physics** (including the higgsless case where new KK states are needed to provide the unitarity of the theory)

COULD (AT LEAST SOME OF) THE "OBSERVATIONAL" NEW PHYSICS BE LINKED TO THE ULTRAVIOLET COMPLETION OF THE SM AT THE ELW. SCALE ?

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)	(x^{μ}, j^{i})	SM part + new part
	Anticomm. Coord.	New bosonic Coord.	to cancel Λ^2 at 1-Loop
2) **SELECTION RULE**	***R-PARITY LSP***	***KK-PARITY LKP***	***T-PARITY LTP***
→ **DISCRETE SYMM.**	Neutralino spin 1/2	spin1	spin0
→ **STABLE NEW PART.**	↓	↓	↓
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

IS THE "*WIMP MIRACLE*" AN ACTUAL MIRACLE?

USUAL STATEMENT

Many possibilities for DM candidates, but WIMPs are really special: peculiar coincidence between particle physics and cosmology parameters to provide a VIABLE DM CANDIDATE AT THE ELW. SCALE

HOWEVER

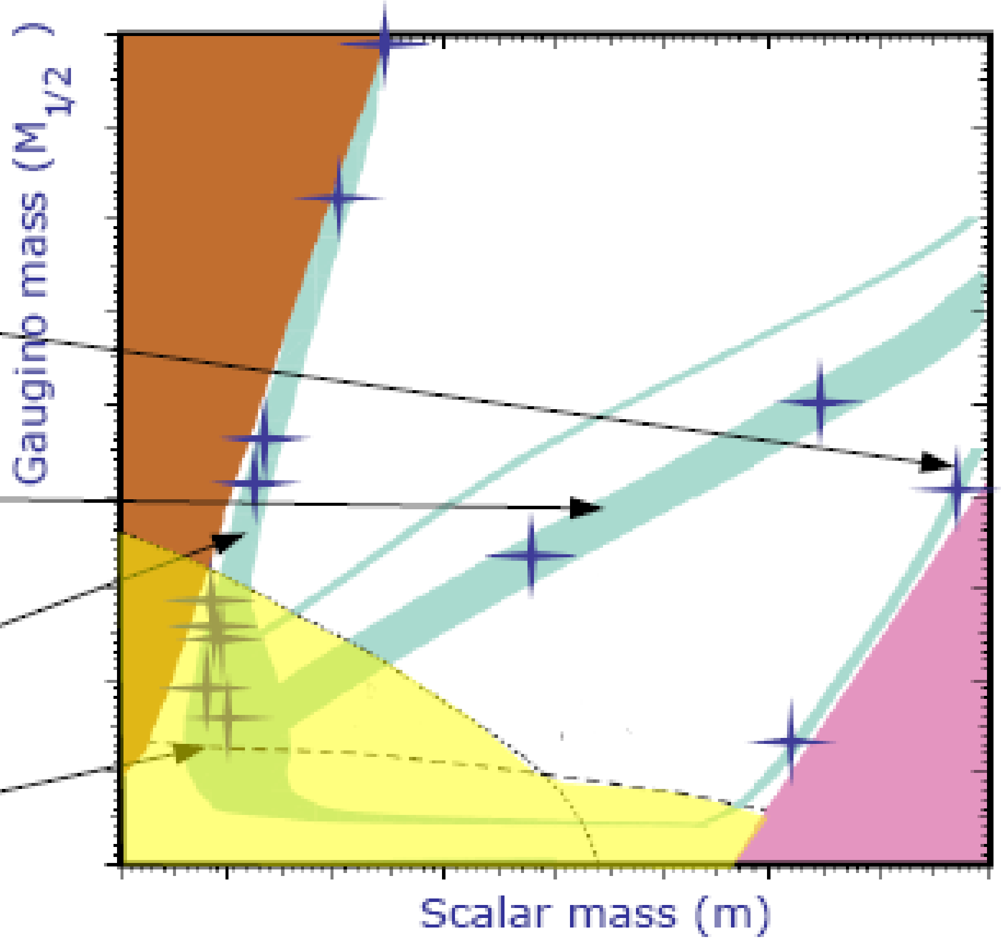
when it comes to quantitatively reproduce the precisely determined DM density → once again the fine-tuning threat…

LHC reach in the SUSY parameter space (example CMSSM – A, M, m, tanβ, μ)

Regions compatible with Neutralino DM (having correct relic density)

- Focus-Point region (Higgsino-Bino neutralino)
- Resonant annihilation (with pesudoscalar Higgs
- Coannihilation region (small LSP-NLSP mass difference)
- Bulk (small SUSY masses)

  Mostly excluded by LEP constraints (still available in non-minimal models)



(see e.g., Ellis, Ferstl, Olive)

Cerdeno ‘09

DM and NON-STANDARD COSMOLOGIES BEFORE NUCLEOSYNTHESIS

- **NEUTRALINO RELIC DENSITY MAY DIFFER FROM ITS STANDARD VALUE**, i.e. the value it gets when the expansion rate of the Universe is what is expected in Standard Cosmology (EX.: **SCALAR-TENSOR THEORIES OF GRAVITY**, **KINATION**, **EXTRA-DIM. RANDALL-SUNDRUM TYPE II MODEL**, ETC.)

- **WIMPS MAY BE "COLDER",** i.e. they may have smaller typical velocities and, hence, they may lead to smaller masses for the first structures which form **GELMINI, GONDOLO**

WHY H ≠ H$_{GR}$

$$H_{\mathrm{GR}}^2 = \frac{1}{3M_p^2}\rho_{\mathrm{tot}} \simeq 2.76\, g_* \frac{T^4}{M_p^2}$$

1. Change the number of relativistic d.o.f.'s, g_* ;

R. Catena

2. Consider a ρ_{tot} not dominated by relativistic d.o.f.'s;
   - Kination
     P. Salati, Phys. Lett. B 571 (2003) 121

3. Consider theories where the effective Planck mass is different from the constant M_p:
   - Scalar-Tensor theories
     R. C., N. Fornengo, A. Masiero, M. Pietroni and F. Rosati, Phys. Rev. D 70 (2004) 063519
   - Extradimensions
     L. Randall and R. Sundrum, Phys. Rev. Lett. 83 (1999) 4690

LARGER WIMP ANNIHILATION CROSS-SECTION IN NON-STANDARD COSMOLOGIES

- **Having a Universe expansion rate at the WIMP freeze-out larger than in Standard Cosmology→ possible to provide a DM adequate WIMP population even in the presence of a larger annihilation cross-section** (**Catena, Fornengo, A.M., Pietroni**)

- **Possible application to increase the present DM annihilation rate to account for the PAMELA results in the DM interpretation** (instead of other mechanisms like the Sommerfeld effect or a nearby resonance)

El Zant, Khalil, Okada

EXP. BOUNDS on the DEVIATION from H in GR

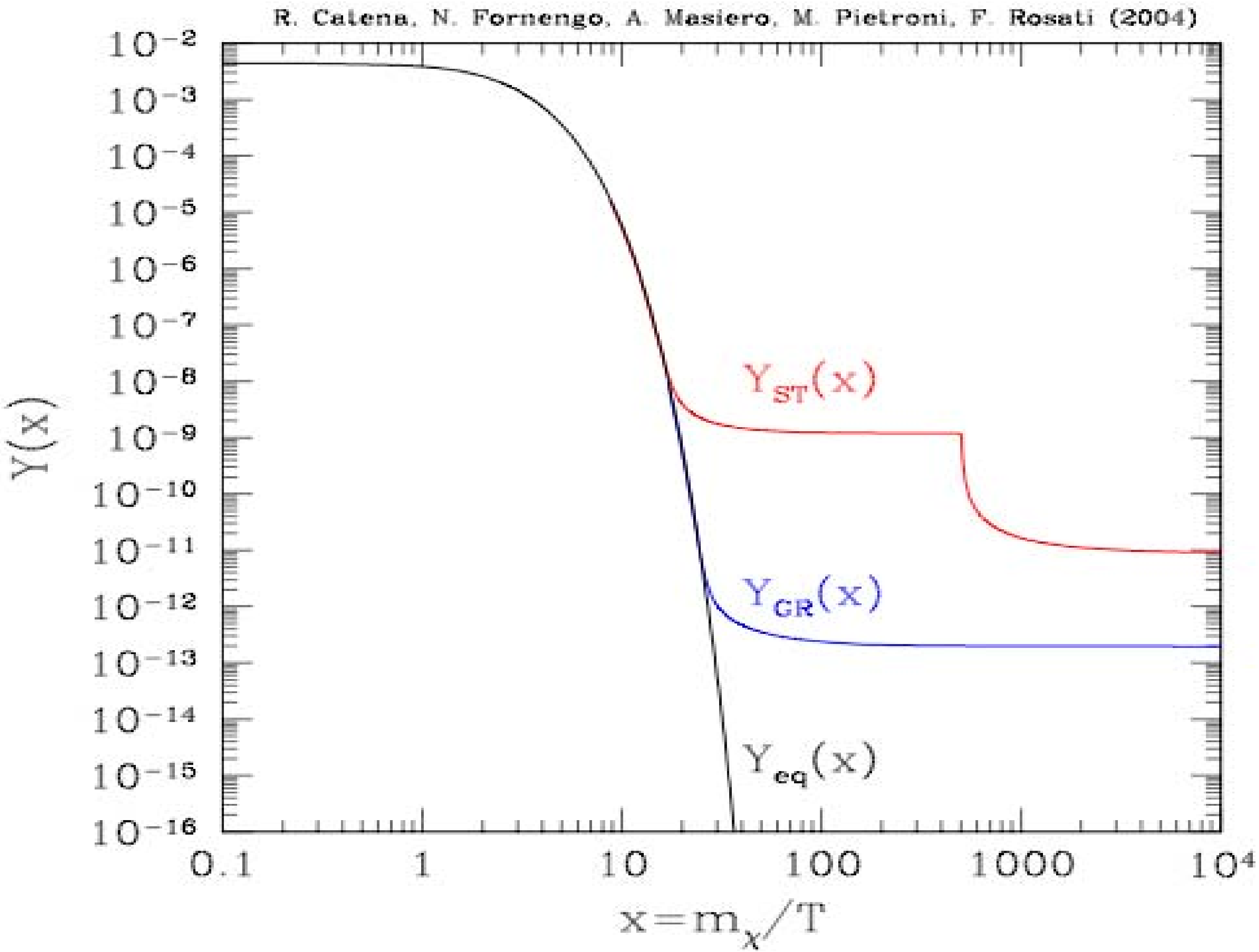
$$H^2_{\mathrm{ST}} \simeq A^2(\varphi) \times H^2_{\mathrm{GR}}$$

$$\begin{cases} 0.1 \gtrsim \frac{\Delta H^2}{H^2} \equiv \frac{H^2_{\mathrm{ST}} - H^2_{\mathrm{GR}}}{H^2_{\mathrm{GR}}} = A^2(\varphi_{\mathrm{BBN}}) - 1 & \text{at BBN}^1 \\ \gamma_{\mathrm{PN}} - 1 = -\frac{2\alpha^2}{1+\alpha^2} = (2.1 \pm 2.3) \times 10^{-5} & \text{Today}^2 \end{cases}$$

CATENA, FORNENGO, A.M., PIETRONI, ROSATI

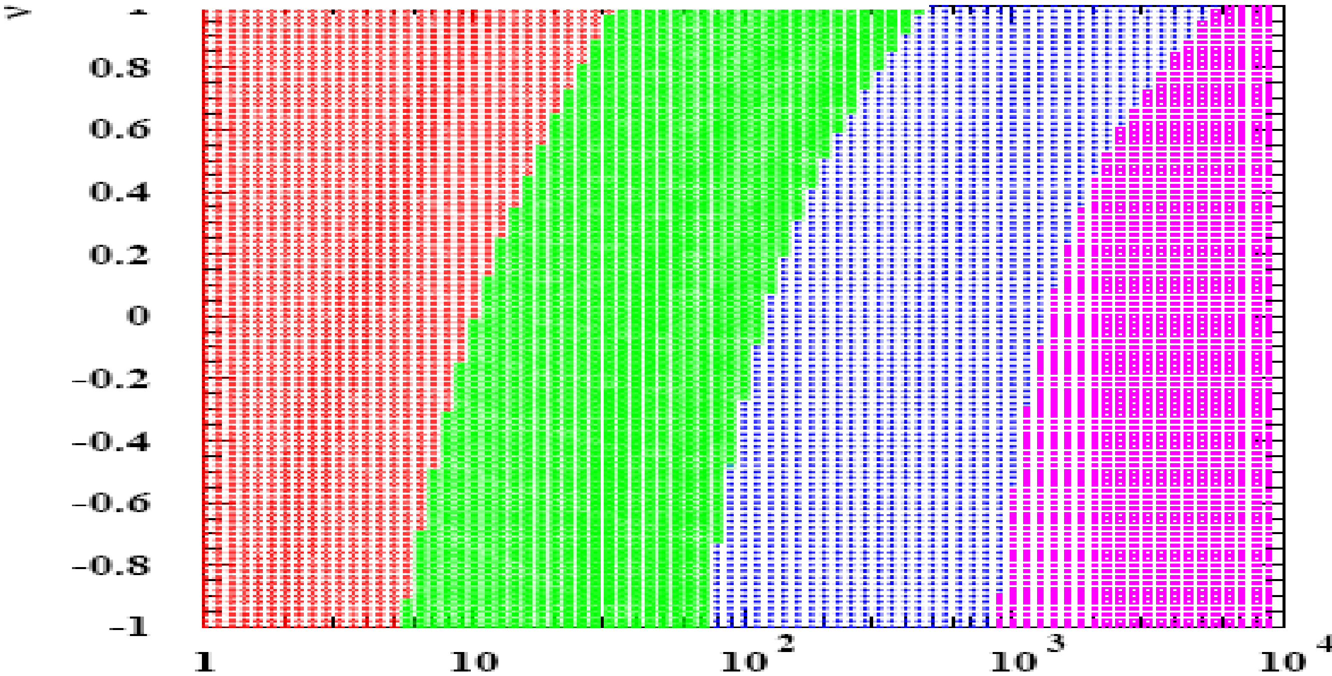
BERTOTTI, IESS, TORTORA

NEUTRALINO RELIC ABUNDANCE IN GR AND S-T THEORIES OF GRAVITY



$$H = A(T) H_{\rm std} \quad \text{at early times}$$
$$H = H_{\rm std} \quad \text{at later times}$$

$$A(T) = 1 + \eta \left(\frac{T}{T_{\rm f}}\right)^{\nu} \tanh\left(\frac{T - T_{\rm re}}{T_{\rm re}}\right)$$



v = -1 ST cosmologies

v = +1 kination

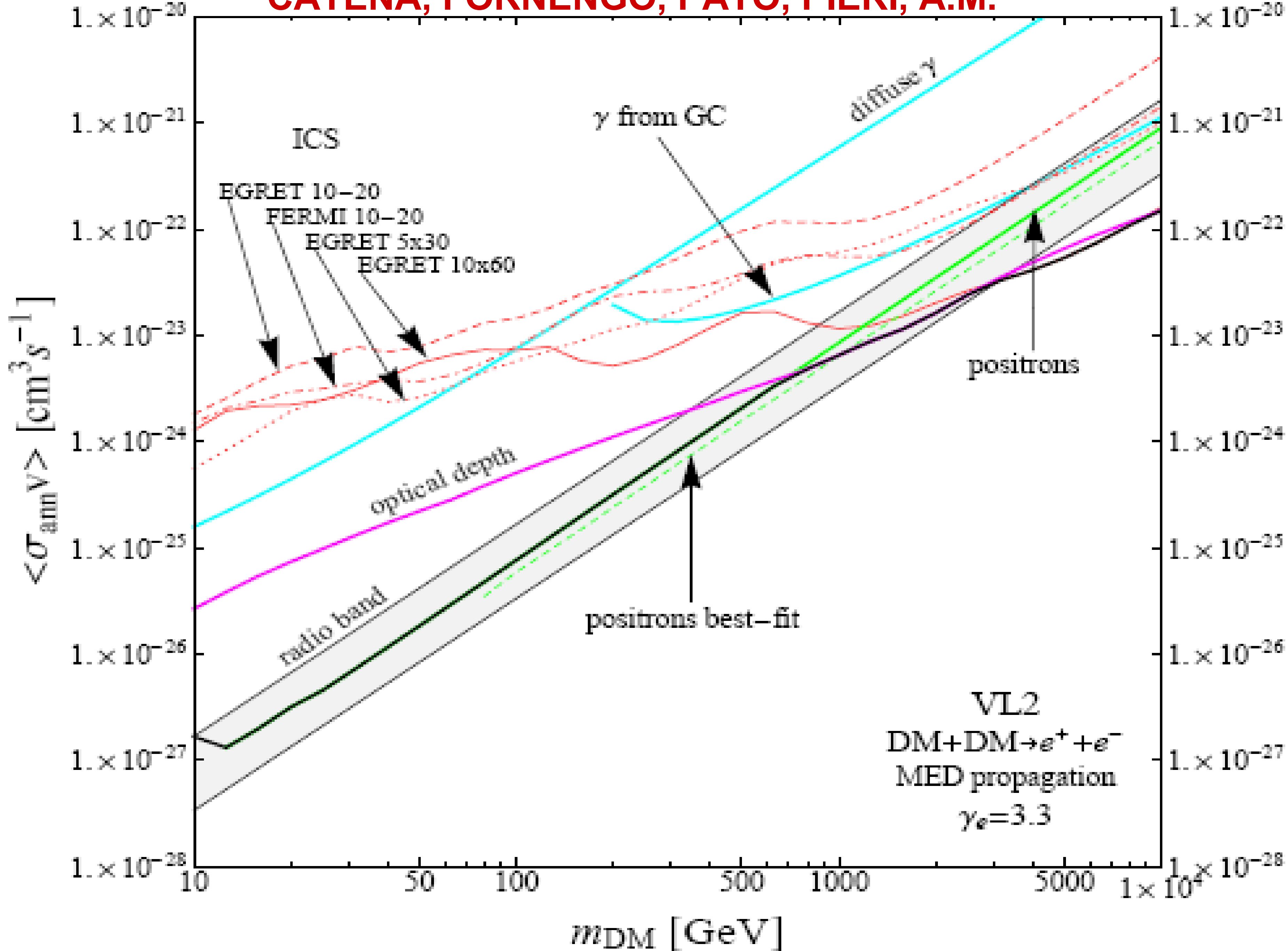
v = +2 RS type II brane csomology

v = 0 overall boost of H

FIG. 12: Contour plot of the enhancement $R = (\Omega h^2)/(\Omega h^2)_{\rm GR}$ of the WIMP relic abundance in a scenario with enhanced Hubble rate compared to the standard GR cosmology. The different bands refer to (from left to right): $1 \le R \le 10$, $10 < R \le 100$, $100 < R \le 1000$, $1000 < R$. The highest value of R is around $7.5 \cdot 10^3$. We have fixed $m_\chi = 500$ GeV and $T_{\rm re} = 10^{-3}$ GeV. For all points, the WIMP relic–density, as calculated in the modified cosmology, satisfies the dark matter density constraint.

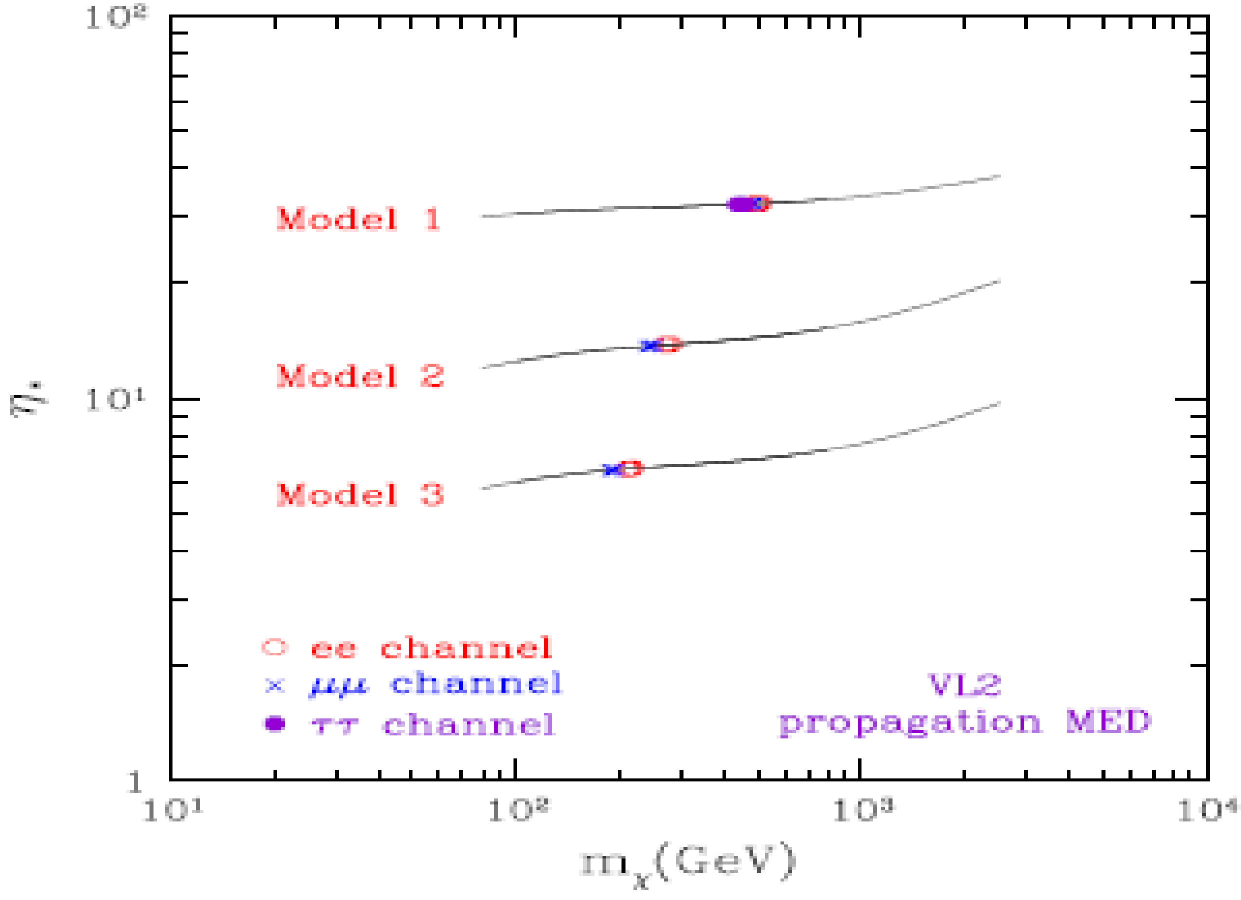
SCHELKE, CATENA, FORNENGO, A.M., PIETRONI

CATENA, FORNENGO, PATO, PIERI, A.M.

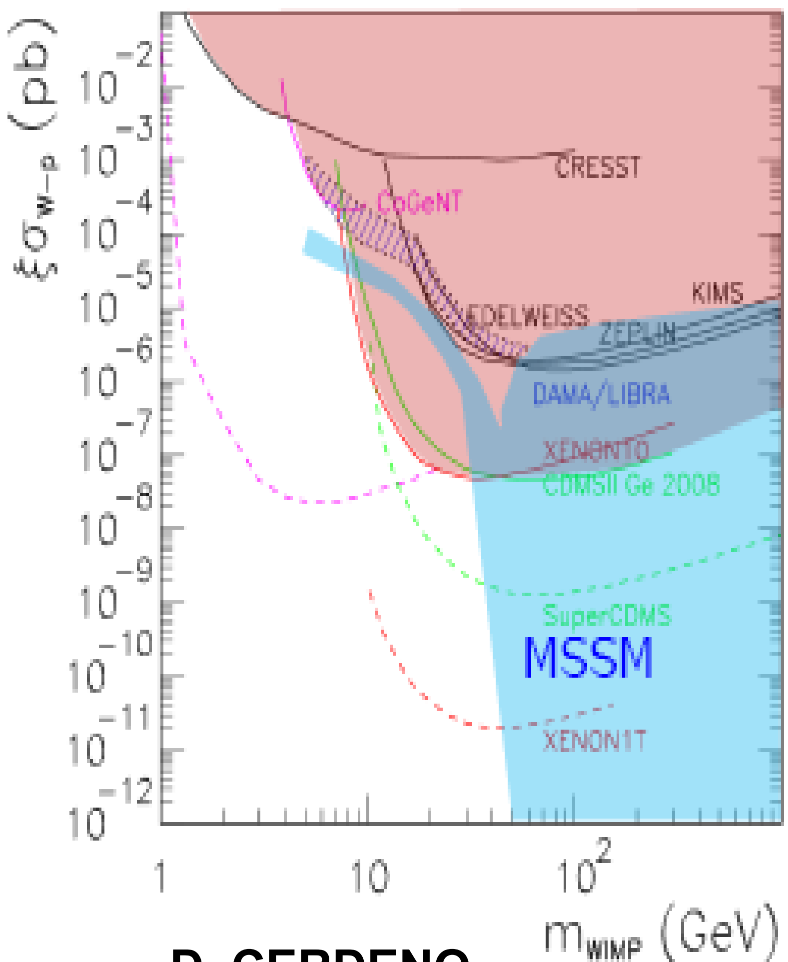


For a ~100 GeV WIMP, large departures from GR ($H/H_{GR} > 100$) are unlikely

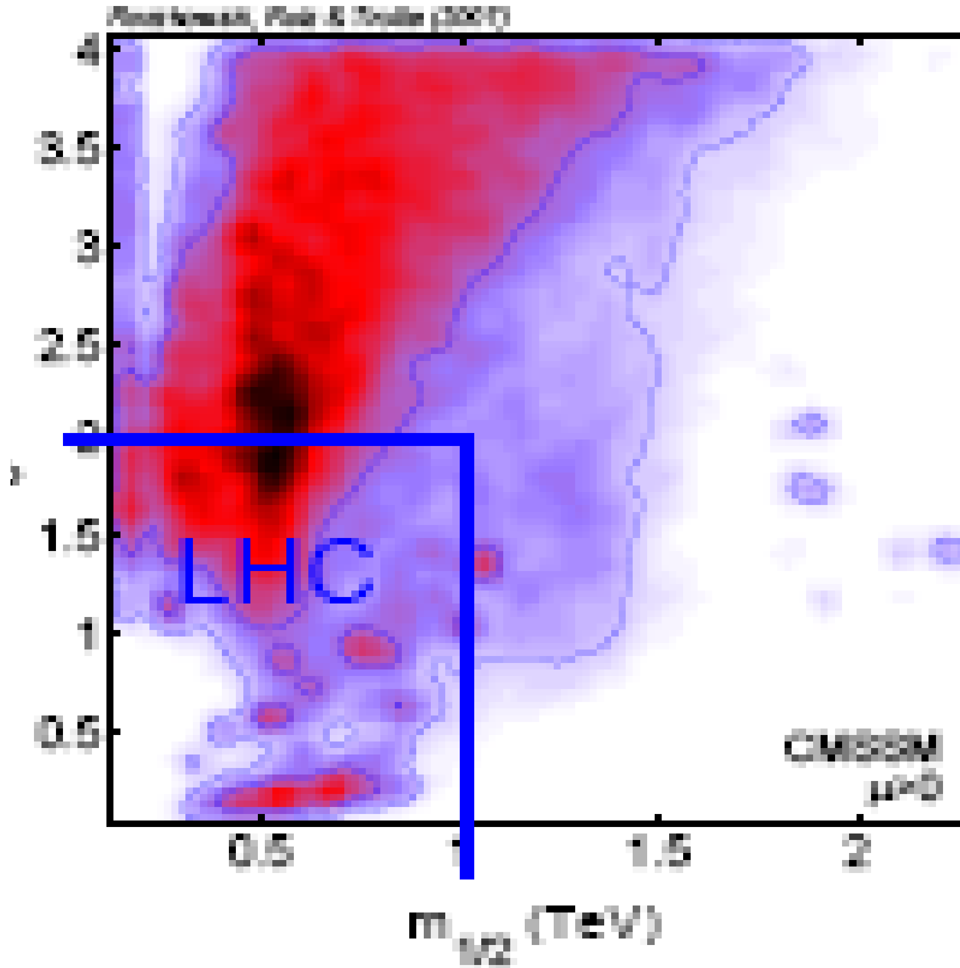
CFPPM '10



On the LHC – Direct DM searches coverage of the MSSM parameter space

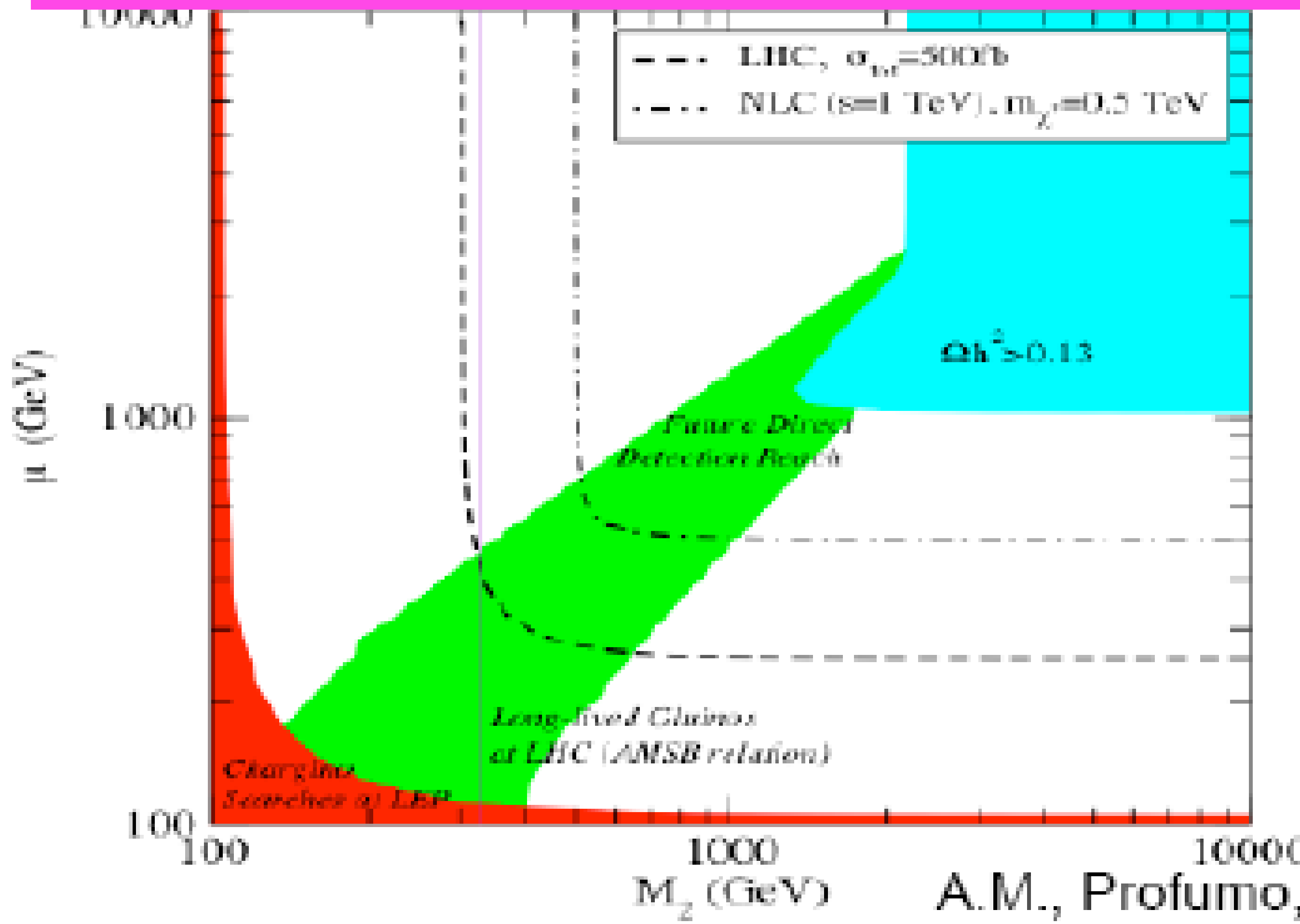


D. CERDENO
WONDER10



L. Roszkowsk et al.

LHC, ILC, DM SEARCHES SENSITIVITIES



A.M., Profumo, Ullio

DIRECT AND INDIRECT SEARCHES FOR WIMPs

- PROBING NEW PHYSICS AT THE ELW. SCALE

- INFORMATION ON THE EVOLUTION OF THE EARLY UNIVERSE BEFORE THE NUCLEOSYNTHESIS TIME, i.e. at times < 1 sec.

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: $\Lambda_{UV} \sim O(1\text{ TeV})$

How large Λ NP and/or how small the "angles" of the Λ = 1 TeV NP couplings have to be to cope with the FCNC ?

Mixing	$\Lambda_{\rm NP}^{\rm CPC} \gtrsim$	$\Lambda_{\rm NP}^{\rm CPV} \gtrsim$
$K-\overline{K}$	1000 TeV	20000 TeV
$D-\overline{D}$	1000 TeV	3000 TeV
$B-\overline{B}$	400 TeV	800 TeV
$B_s-\overline{B}_s$	70 TeV	70 TeV

$K-\overline{K}$	8×10^{-7}	6×10^{-9}
$D-\overline{D}$	5×10^{-7}	1×10^{-7}
$B-\overline{B}$	5×10^{-6}	1×10^{-6}
$B_s-\overline{B}_s$	2×10^{-4}	2×10^{-4}

Y. NIR et al.

$K-\overline{K}$	8×10^{-7}	6×10^{-9}
$D-\overline{D}$	5×10^{-7}	1×10^{-7}
$B-\overline{B}$	5×10^{-6}	1×10^{-6}
$B_s-\overline{B_s}$	2×10^{-4}	2×10^{-4}

→ **SMALLNESS OF THE NP COUPLINGS IF THE NP SCALE IS 1 TEV**

$$Y_t\sim1,\quad Y_c\sim10^{-2},\quad Y_u\sim10^{-5}$$
$$Y_b\sim10^{-2},\quad Y_s\sim10^{-3},\quad Y_d\sim10^{-4}$$
$$Y_\tau\sim10^{-2},\quad Y_\mu\sim10^{-3},\quad Y_e\sim10^{-6}$$
$$|V_{us}|\sim0.2,\quad |V_{cb}|\sim0.04,\quad |V_{ub}|\sim0.004,\quad \delta_{\rm KM}\sim1$$

→ **SMALLNESS OF THE SM COUPLINGS**

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 $\rightarrow$ 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 $\rightarrow$

MINIMAL FLAVOR VIOLATION

MFV : Flavor originates only from the SM Yukawa coupl.

New Physics introduces

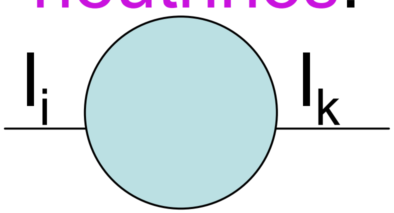
NEW FLAVOR SOURCES in addition to the CKM pattern. They give rise to contributions which are <10% in the "flavor observables" which have already been observed!

ON THE FLAVOR BLINDNESS OF THE NP: IS IT THEN HOPELESS TO LOOK FOR DEPARTURES FROM THE SM IN FLAVOR PHYSICS?

- ***NO***: a relevant example → **SUPERGRAVITY with "FLAVOR BLIND SUSY BREAKING" and NEUTRINO MASSES VIA A SEE-SAW MECHANISM**

LFV and NEW PHYSICS

- Flavor in the HADRONIC SECTOR:
  CKM paradigm
- Flavor in the LEPTONIC SECTOR:
  - Neutrino masses and (large) mixings
  - Extreme smallness of LFV in the charged lepton sector of the SM with massive neutrinos:



suppressed by $(m_{\nu_i}^2 - m_{\nu_k}^2) / M_W^2$

LFV IN CHARGED LEPTONS FCNC

L_i - L_j transitions through W - neutrinos mediation

GIM suppression $(m_\nu / M_W)^2 \longrightarrow$ 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,

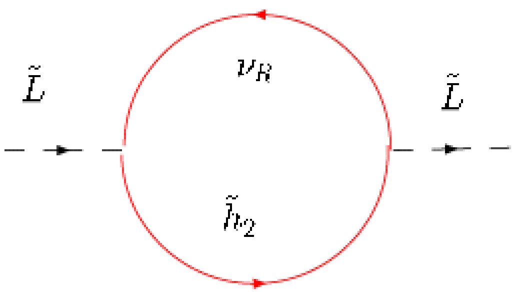
BUT in CMSSM (MSSM with flavor universality in the SUSY breaking sector) $\Delta M_{\text{sleptons}}$ is O(m_{leptons}), hence GIM suppression is still too strong.

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)

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



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

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;

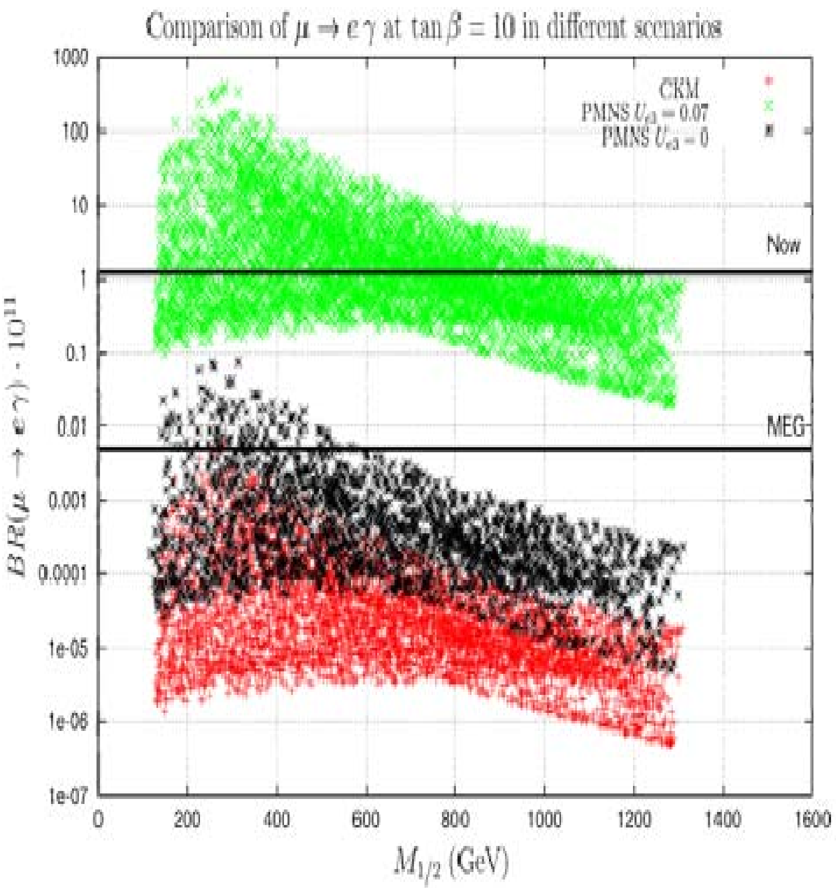
In **SUSY SO(10)** (A.M., Vempati, Vives) at least one neutrino Dirac Yukawa coupling has to be of the **order of the top Yukawa coupling** → one large of O(1) f_ν

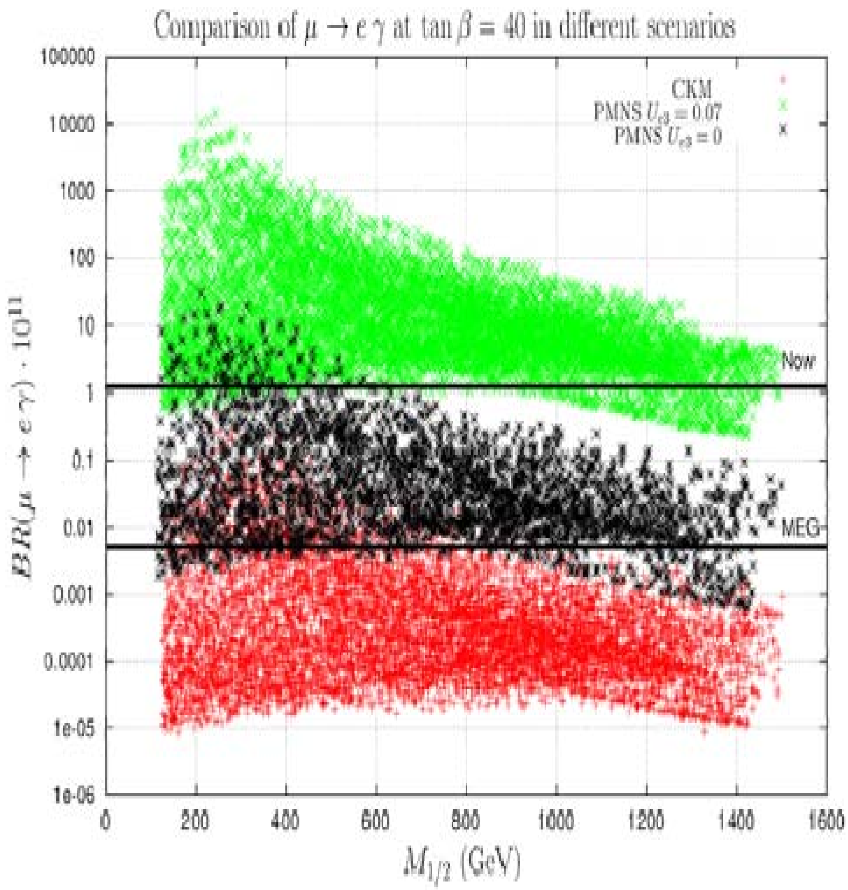
U → two "extreme" cases:

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

μ → e+γ in SUSYGUT: past and future

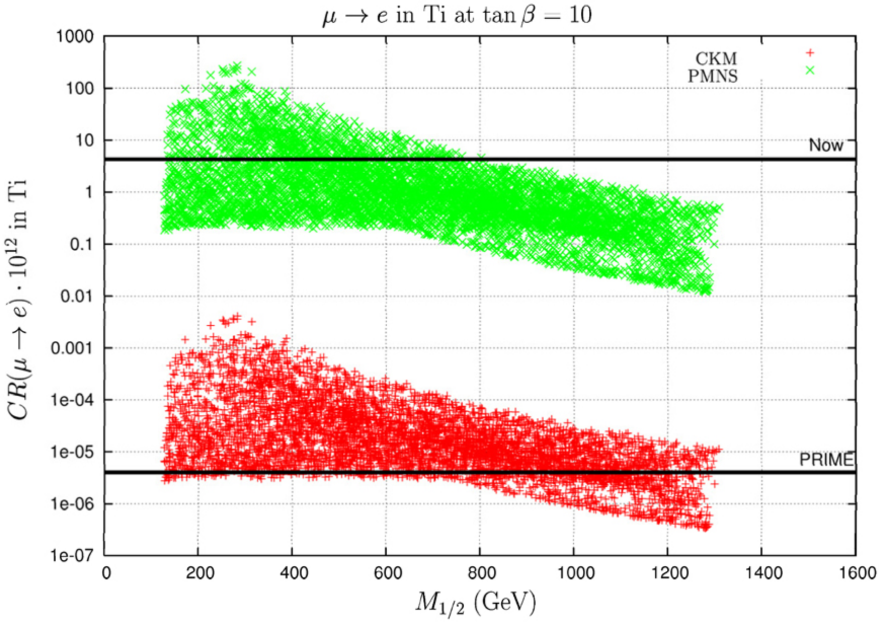
$\mu \to e\,\gamma$ in the $U_{e3} = 0$ PMNS case

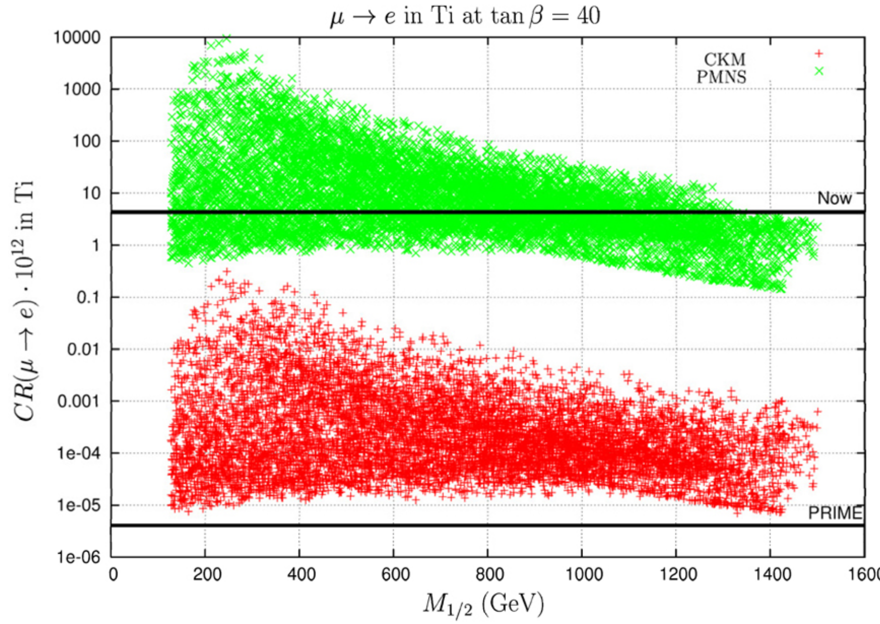


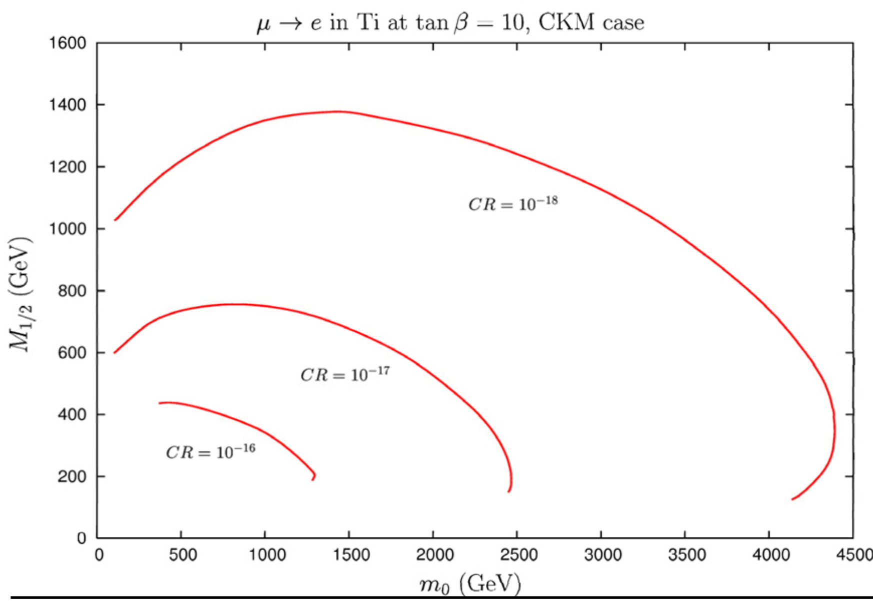


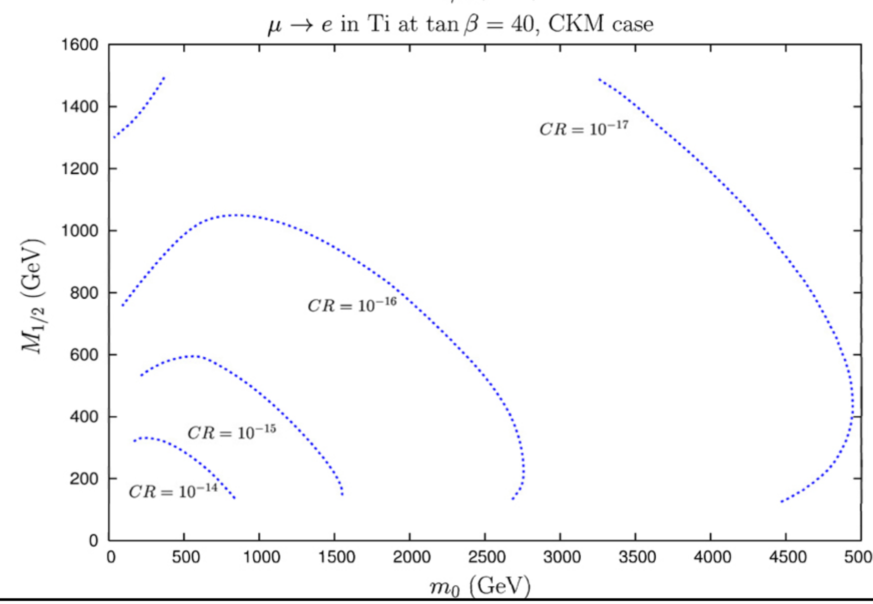
CATENA, FACCIA, A.M., VEMPATI

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

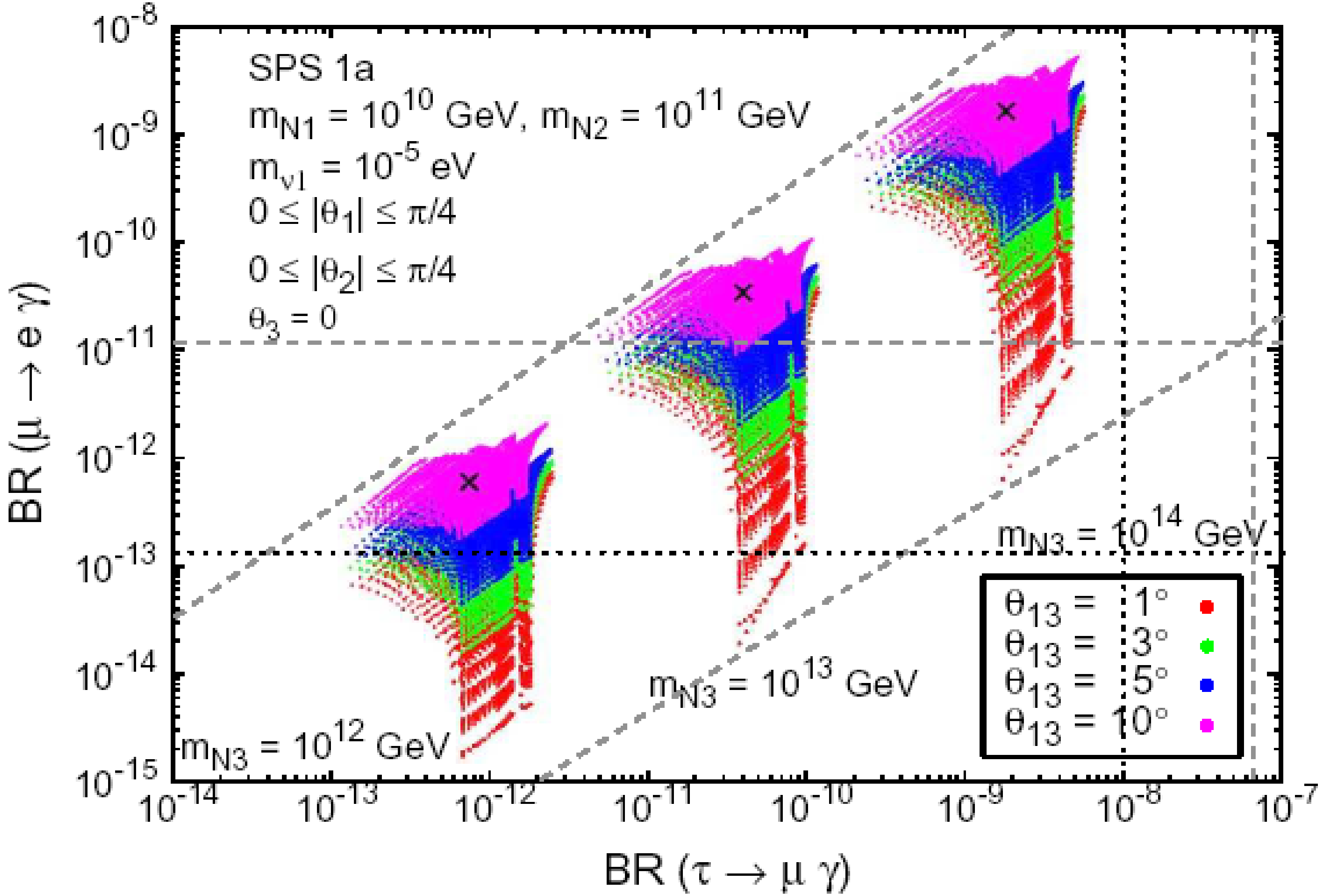




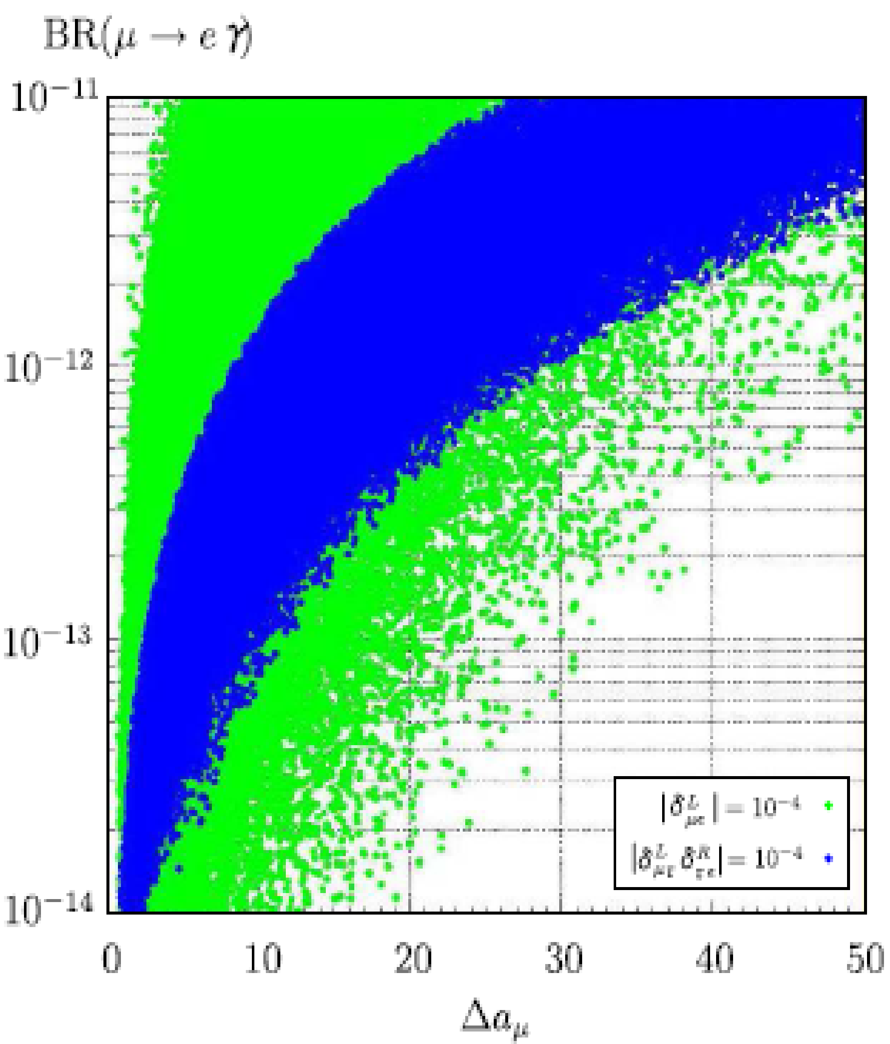




Antusch, Arganda, Herrero, Teixeira



LFV, g – 2, EDM: a promising correlation in SUSY SEESAW



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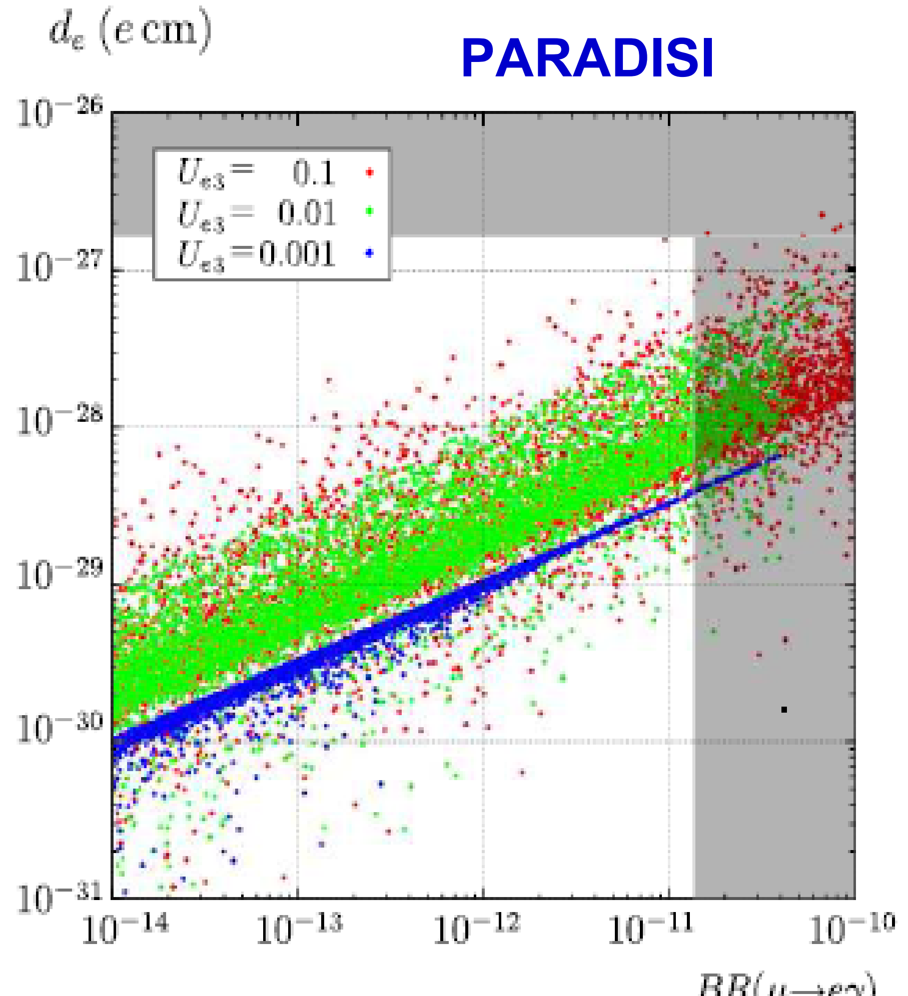
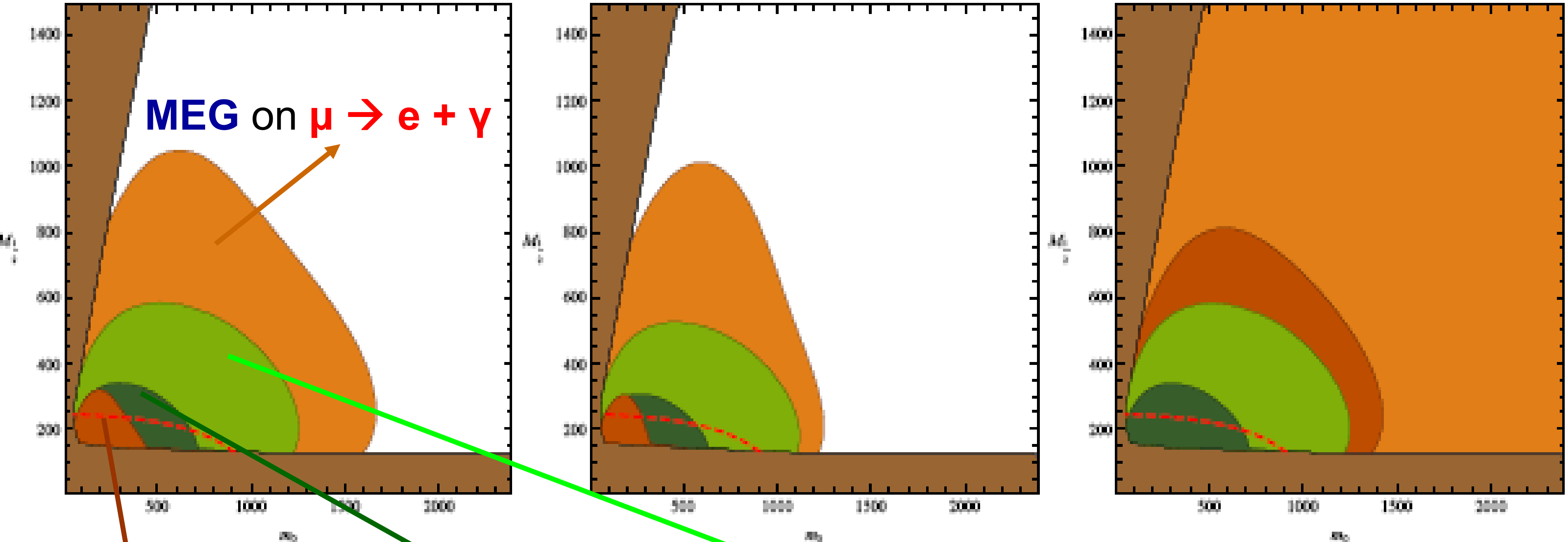


LFV CONSTRAINTS IN THE $M_0 - M_{1/2}$ SUSY PLANE with an SU(3) FLAVOR SYMMETRY



PRESENT BOUND ON $\tau \rightarrow \mu + \gamma$

FUTURE BOUND ON $\tau \rightarrow \mu + \gamma$ at SUPER B

PRESENT BOUND ON $\mu \rightarrow e + \gamma$

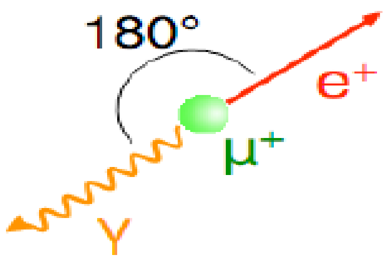
CALIBBI, JONES, A.M., J-H. PARK, POROD and VIVES

IS THE FIRST EVIDENCE OF LFV AROUND THE CORNER ?

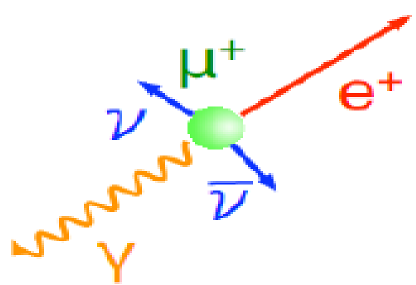
$\mu \rightarrow e\,\gamma$

Signal and Background

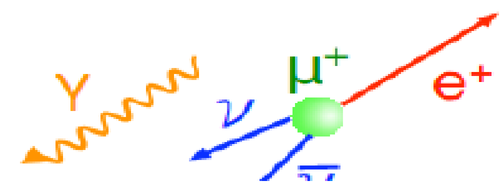
Signal



Prompt Background



Accidental Background



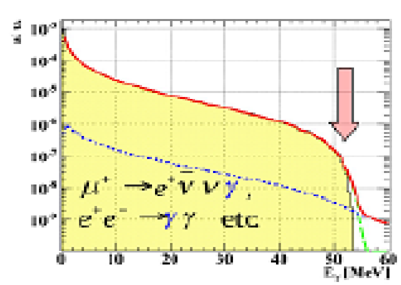
$$B_{acc} \propto \delta E_e \cdot (\delta E_\gamma)^2 \cdot (\delta \vartheta_{e\gamma})^2 \cdot \delta t_{e\gamma}$$

			Radiative muon decay	Accidental pileup
e γ	Angle	Back-to-Back	Any angle	Any angle
	Energy	52.8 MeV/c	< 52.8 MeV/c	< 52.8 MeV/c
	Time	Same time	Same time	Flat

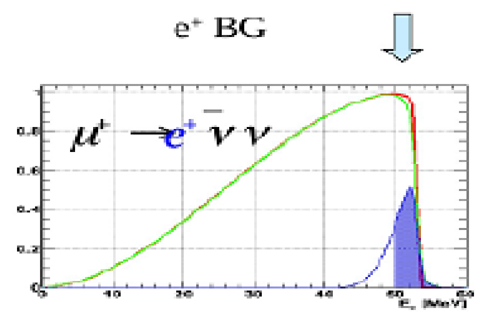
Dominant background is accidental.

Detector resolution is crucial.

γ BG



e+ BG



Sensitivity

Average 90% C.L. upper limit of toy MC with null signal.

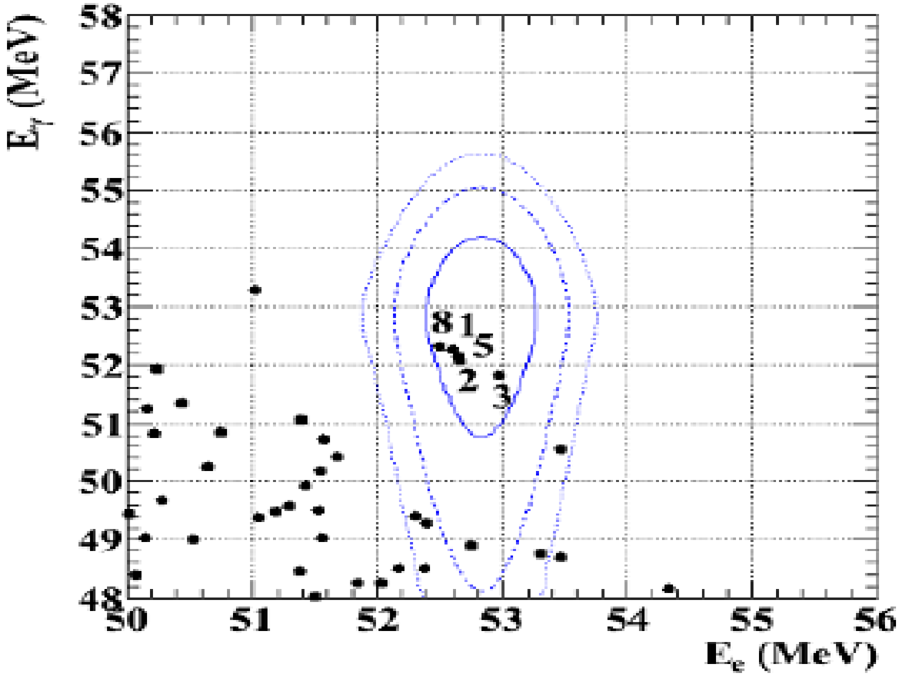
Sensitivity : 6.1×10^{-12}

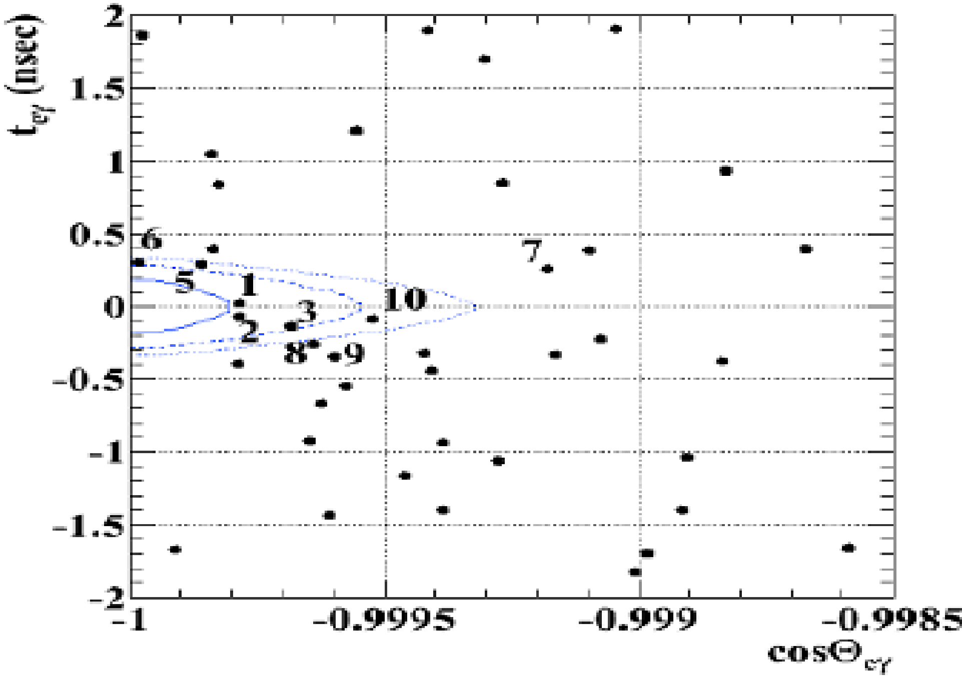
Preliminary

Sideband fit result is consistent. Br < $4 \sim 6\times10^{-12}$

Event distribution after unblinding

BALDINI, ICHEP10





Blue lines are 1(39.3 % included inside the region w.r.t. analysis window), 1.64(74.2%) and 2(86.5%) sigma regions.

For each plot, cut on other variables for roughly 90% window is applied.

A FUTURE FOR FLAVOR PHYSICS AND DM SEARCHES TO GO BEYOND THE SM?

- 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:

synergy in “reconstructing” the “fundamental theory” staying behind the signatures of NP;

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

NEW PHYSICS EFFECTS IN THE FLAVOR ROAD AND DM ROAD DECOUPLE LESS FAST THAN IN THE HIGH ENERGY ROAD