UCD, Davis, August 15, 2011

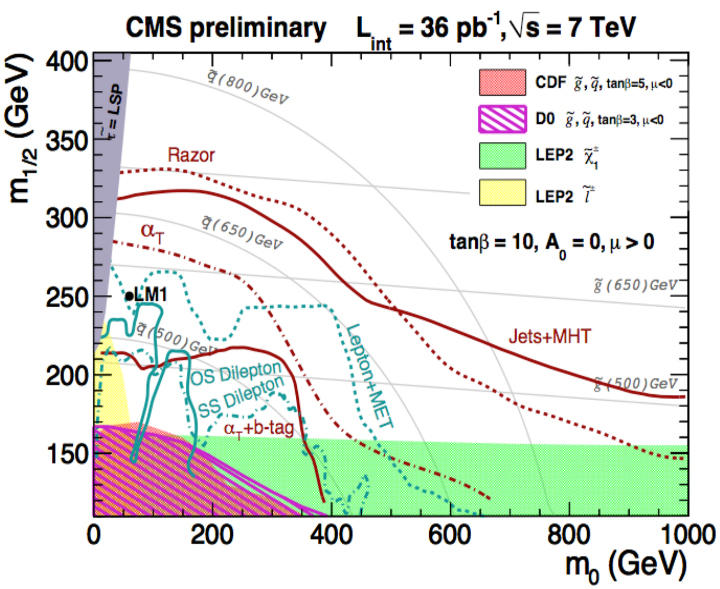
LFV, DM and LHC: how's SUSY health these days?

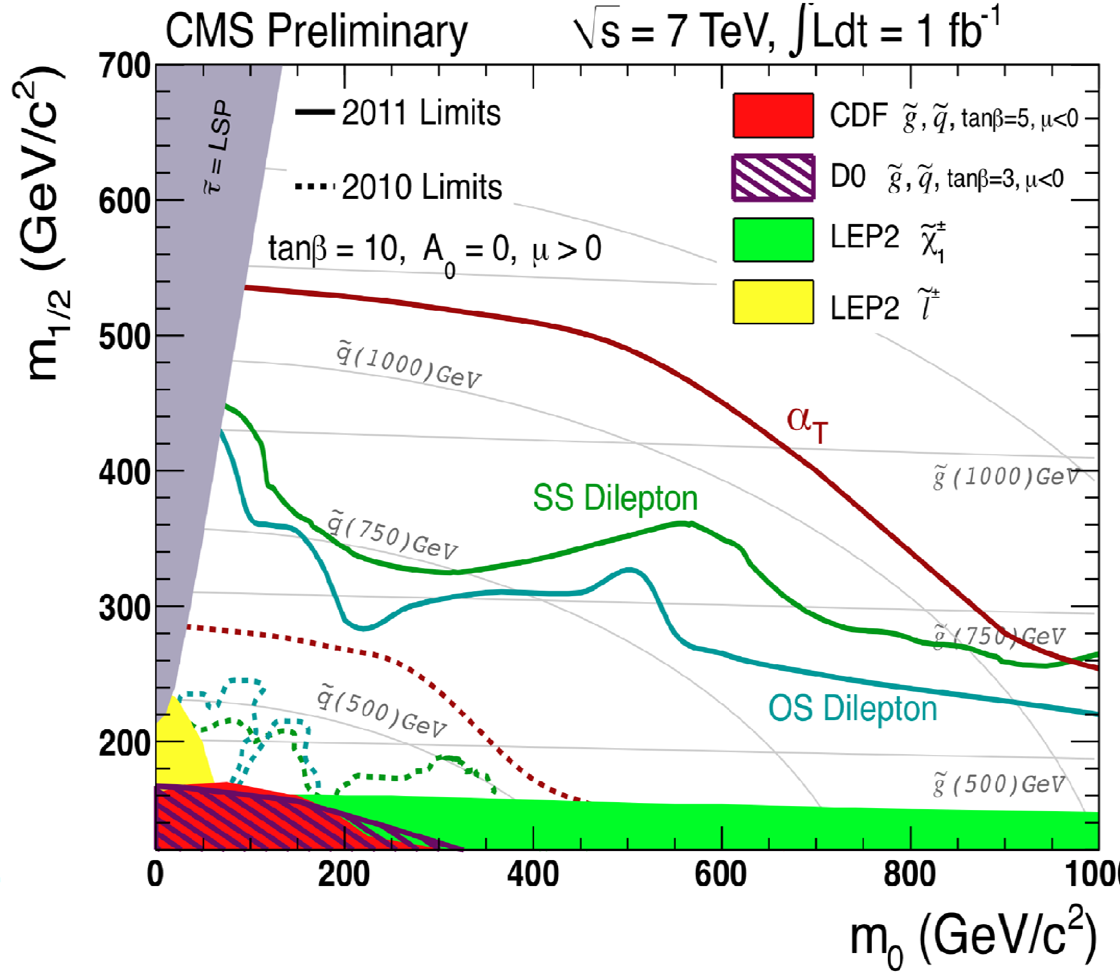
Antonio Masiero
Univ. of Padova and INFN, Padova

Progress on SUSY

G. Tonelli EPS-HEP 2011

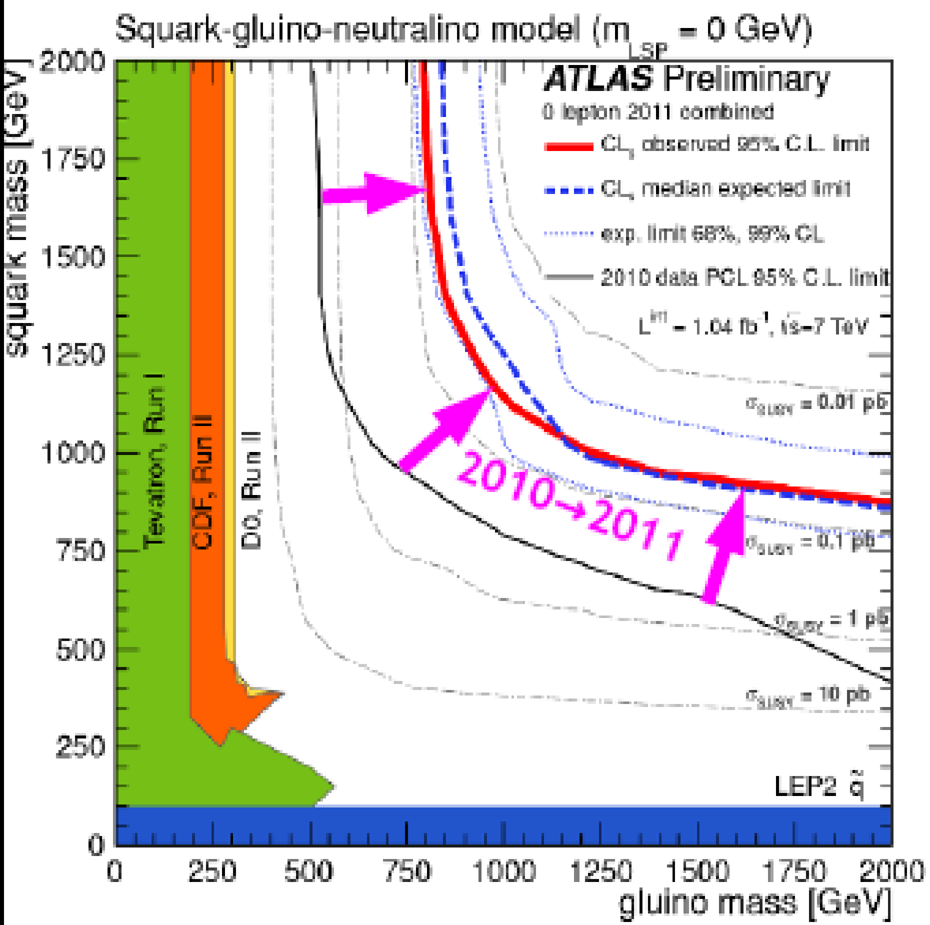
Results of the first three SUSY analyses completed on 2011 data (α_T , Same Sign and Opposite Sign dileptons).

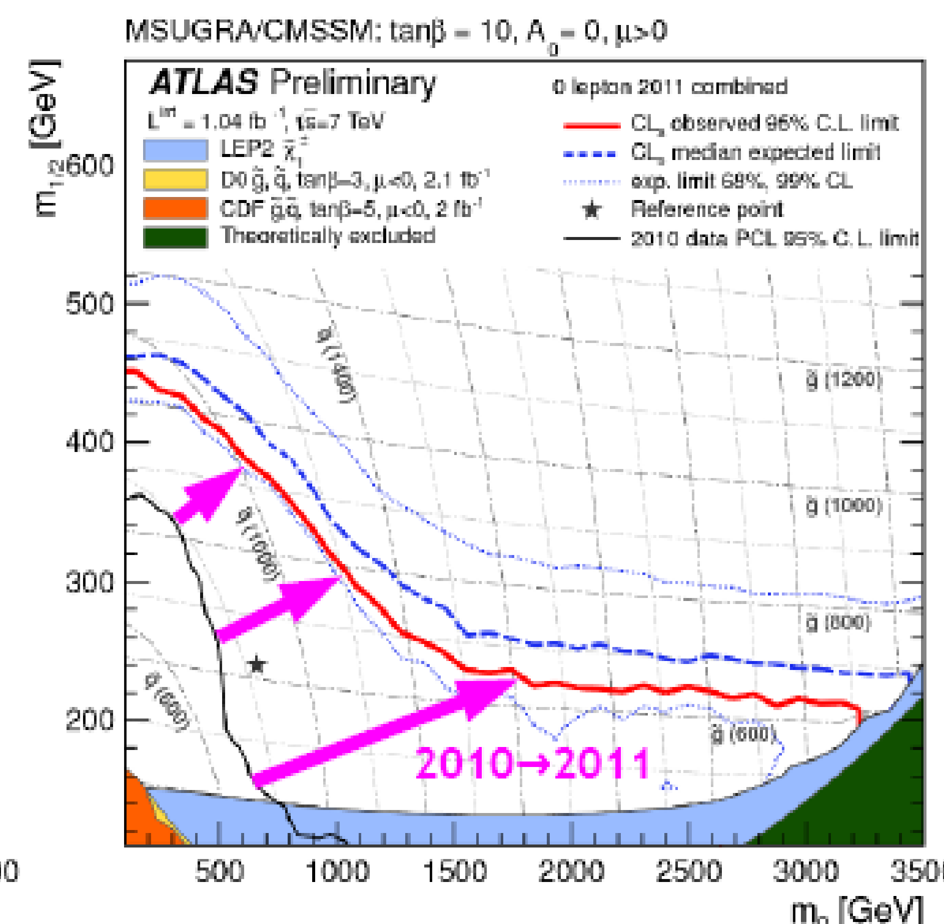




Within the constrained SSM models we are crossing the border of excluding gluinos and squarks up to 1TeV and beyond. The air is getting thin for constrained SUSY. More conclusive results after summer.

SUSY in 0-lepton channel





Simplified model with two $\tilde{q}$ generations, $m(\tilde{\chi}_1^0)\sim 0$

$m_{\tilde{g}} > 800$ GeV $\quad m_{\tilde{q}} > 850$ GeV

Equal mass case: $m_{\tilde{g}} = m_{\tilde{q}} > 1.075$ TeV

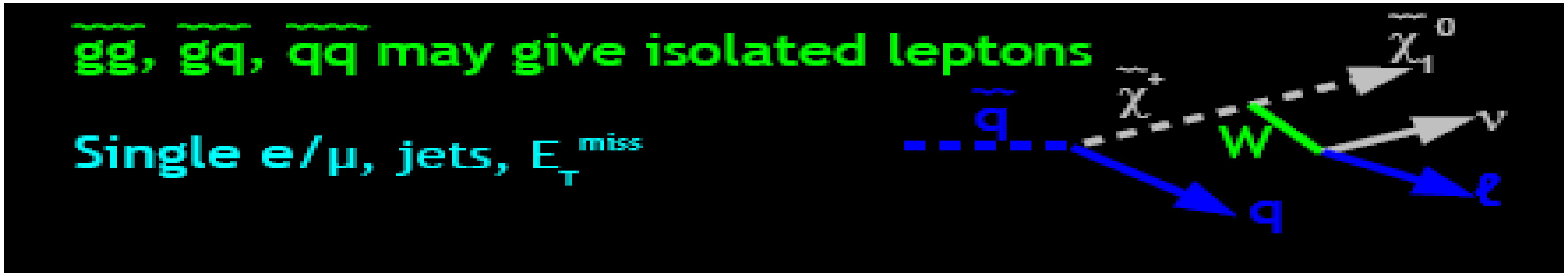
MSUGRA/CMSSM: $\tan\beta=10$, $A_0=0$, $\mu>0$

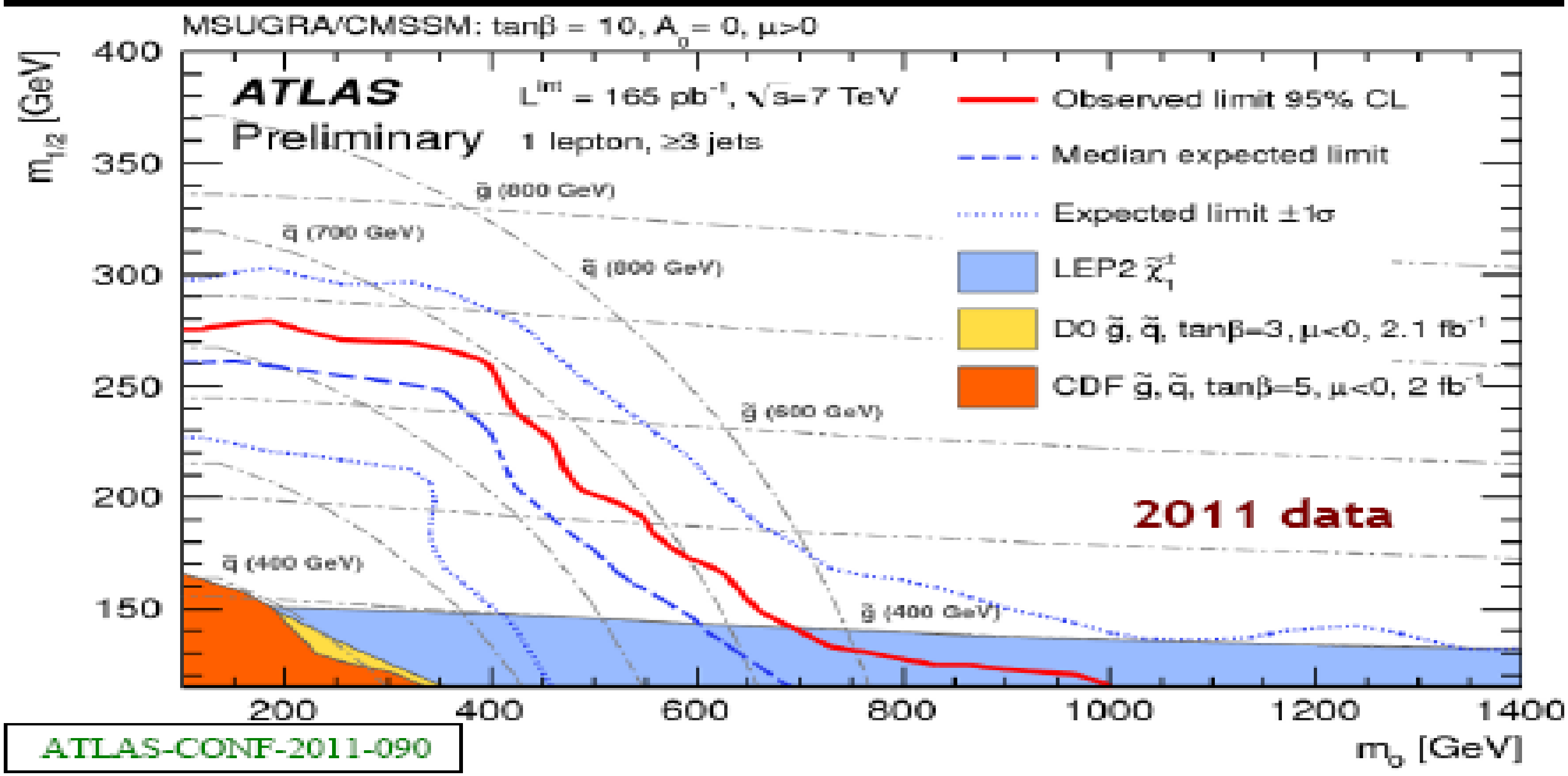
Equal mass case: $m_{\tilde{q}} = m_{\tilde{g}} > 980$ GeV

D. CHARLTON EPS-HEP 2011

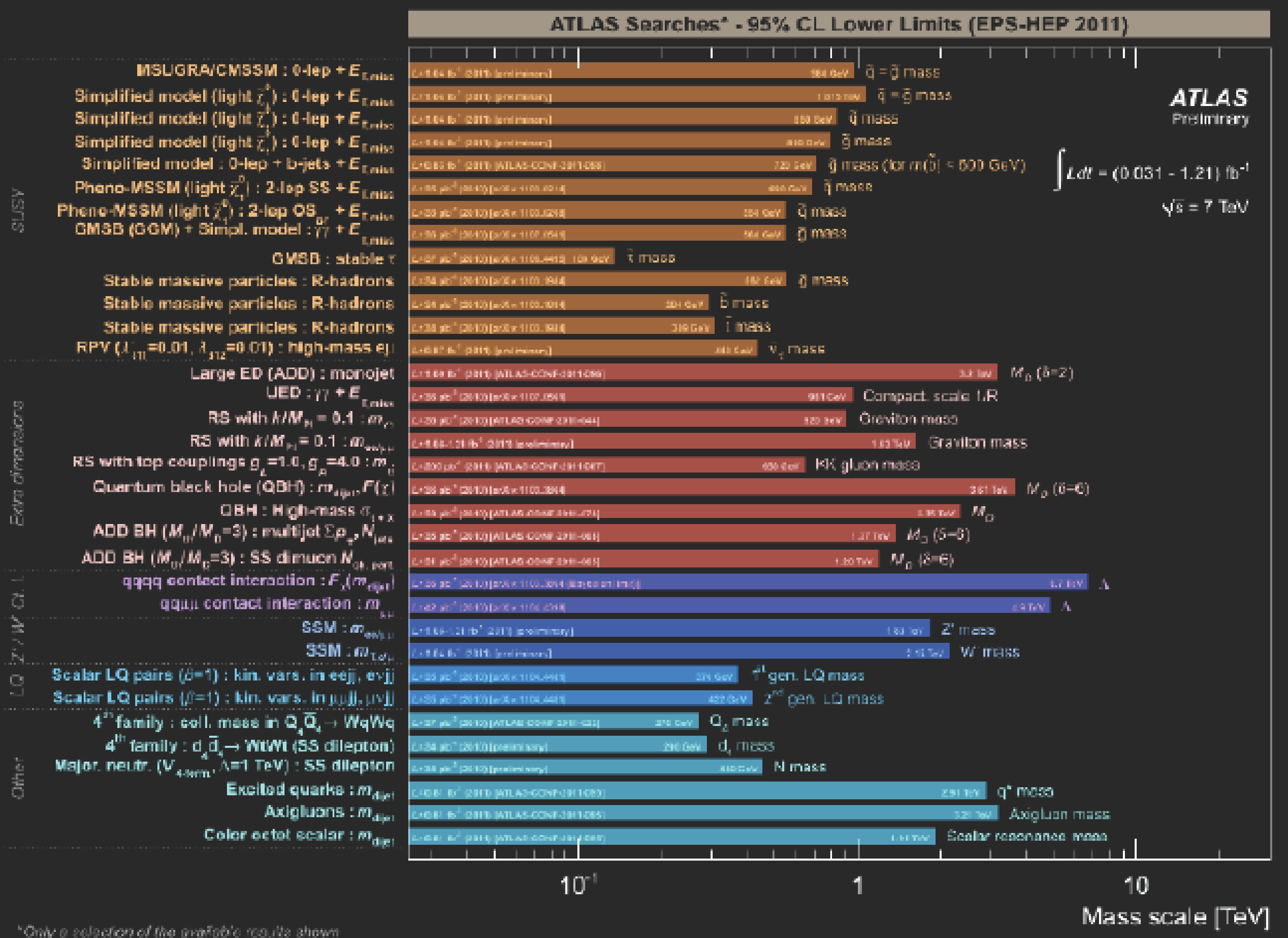
SUSY in 1-lepton channel

D. CHARLTON EPS-HEP 2011





ATLAS-CONF-2011-090



ATLAS Searches* - 95% CL Lower Limits (EPS-HEP 2011)
ATLAS
Preliminary
$\int L dt = (0.031 - 1.21)$ fb^{-1}
$\sqrt{s} = 7$ TeV
SUSY
MSUGRA/CMSSM : 0-lep + $E_{T,miss}$
Simplified model (light $\tilde{\chi}_1^0$) : 0-lep + $E_{T,miss}$
Simplified model (light $\tilde{\chi}_1^0$) : 0-lep + $E_{T,miss}$
Simplified model (light $\tilde{\chi}_1^0$) : 0-lep + $E_{T,miss}$
Simplified model : 0-lep + b-jets + $E_{T,miss}$
Pheno-MSSM (light $\tilde{\chi}_1^0$) : 2-lep SS + $E_{T,miss}$
Pheno-MSSM (light $\tilde{\chi}_1^0$) : 2-lep OS$_{SF}$ + $E_{T,miss}$
GMSB (GGM) + Simpl. model : $\gamma\gamma$ + $E_{T,miss}$
GMSB : stable $\tilde{\tau}$
Stable massive particles : R-hadrons
Stable massive particles : R-hadrons
Stable massive particles : R-hadrons
RPV (λ'_{311}=0.01, λ_{312}=0.01) : high-mass eμ
$\tilde{q} = \tilde{g}$ mass
$\tilde{q} = \tilde{g}$ mass
$\tilde{q}$ mass
$\tilde{g}$ mass
$\tilde{g}$ mass (for $m(\tilde{b}) < 600$ GeV)
$\tilde{q}$ mass
$\tilde{q}$ mass
$\tilde{g}$ mass
$\tilde{\tau}$ mass
$\tilde{g}$ mass
$\tilde{b}$ mass
$\tilde{t}$ mass
$\tilde{\nu}_\tau$ mass
Extra dimensions
Large ED (ADD) : monojet
UED : $\gamma\gamma$ + $E_{T,miss}$
RS with k/M_{Pl} = 0.1 : $m_{\gamma\gamma}$
RS with k/M_{Pl} = 0.1 : $m_{ee/\mu\mu}$
RS with top couplings g_L=1.0, g_R=4.0 : $m_{t\bar{t}}$
Quantum black hole (QBH) : m_{dijet}, $F(\chi)$
QBH : High-mass σ_{t+X}
ADD BH (M_{th}/M_D=3) : multijet Σp_T, N_{jets}
ADD BH (M_{th}/M_D=3) : SS dimuon $N_{ch. part.}$
M_D (δ=2)
Compact. scale 1/R
Graviton mass
Graviton mass
KK gluon mass
M_D (δ=6)
M_D
M_D (δ=6)
M_D (δ=6)
CI
qqqq contact interaction : $F_\chi(m_{dijet})$
qqμμ contact interaction : $m_{\mu\mu}$
Λ
Λ
Z' / W'
SSM : $m_{ee/\mu\mu}$
SSM : $m_{T,e/\mu}$
Z' mass
W' mass
LQ
Scalar LQ pairs (β=1) : kin. vars. in eejj, eνjj
Scalar LQ pairs (β=1) : kin. vars. in μμjj, μνjj
1st gen. LQ mass
2nd gen. LQ mass
Other
4th family : coll. mass in $Q_4\bar{Q}_4 \rightarrow WqWq$
4th family : $d_4\bar{d}_4 \rightarrow WtWt$ (SS dilepton)
Major. neutr. ($V_{4\text{-ferm.}}$, Λ=1 TeV) : SS dilepton
Excited quarks : m_{dijet}
Axigluons : m_{dijet}
Color octet scalar : m_{dijet}
Q_4 mass
d_4 mass
N mass
q* mass
Axigluon mass
Scalar resonance mass
10^{-1}
1
10
Mass scale [TeV]
*Only a selection of the available results shown

Impressive bounds on squarks and gluinos, into TeV range...

What do we learn? → **Papucci talk**

1. Plain vanilla SUSY models (like MSSM with flavor-universal soft masses) are being pushed into a corner

but

Rychkov EPS-HEP 2011

2. Several other, theoretically motivated, scenarios remain very poorly constrained by existing searches

"Flavor-Split" spectra (heavy 1st-2nd gen squarks, gluino below 1-1.5 TeV, light 3rd gen)	"Squashed" spectra (everything below ~500GeV but splittings are small, O(10GeV))	Low MET scenarios (not necessarily RPV)

WHY TO GO BEYOND THE SM

"OBSERVATIONAL" REASONS

- HIGH ENERGY PHYSICS

NO (but A_{FB} …… $Z \to bb$)

- FCNC, CP≠

NO (but CPV in Bs, sin2β tension…)

- HIGH PRECISION LOW-EN.

NO (but $(g\text{-}2)_\mu$ …)

- **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)

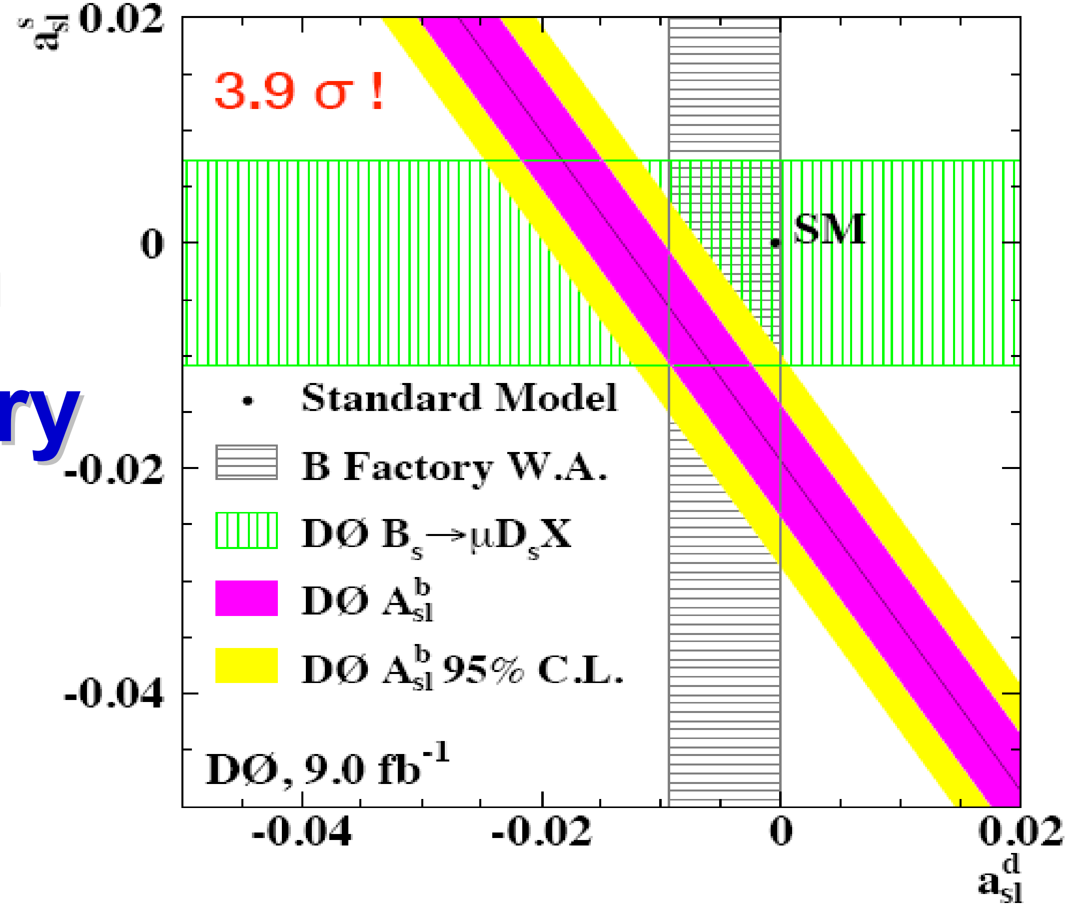
- NO ANSWER TO QUESTIONS THAT "WE" CONSIDER "FUNDAMENTAL" QUESTIONS TO BE ANSWERED BY "FUNDAMENTAL" THEORY

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

EVIDENCE OF NP ALONG THE HIGH INTENSITY ROAD?

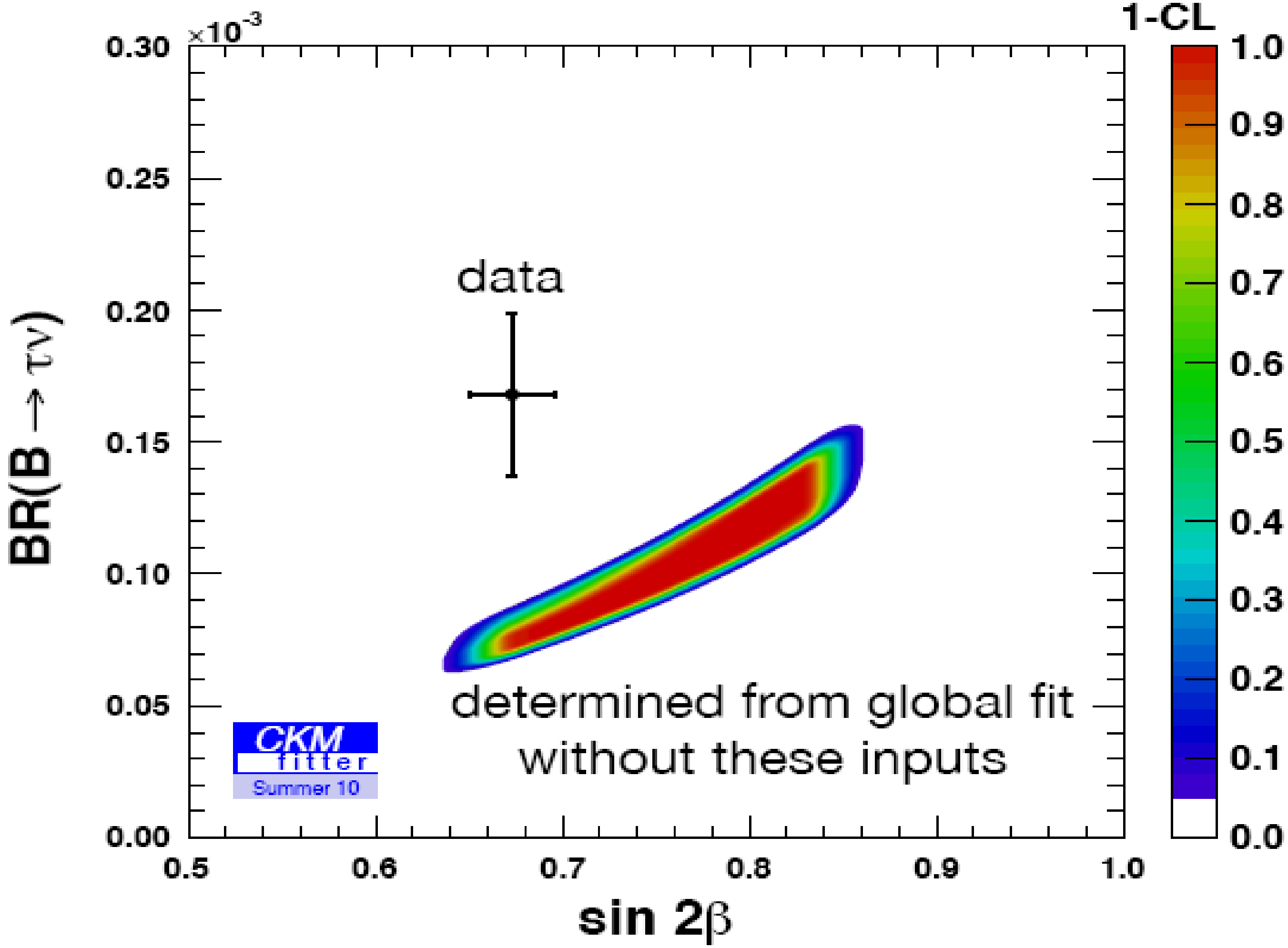
- “FLAVOR COLDS for the SM:

Like-sign dimuon charge asymmetry



But *tension* in the UT fit even neglecting CPV in the B_s mixing

Lenz, Nierste + CKMfitter (2010)



V_{ub} CRISIS

- discrepancies in the determinations of V_{ub} from inclusive semileptonic decays $B \to X_u l\nu$, exclusive semileptonic decays $B \to \pi l\nu$, and leptonic decay $B \to \tau\nu$ ("V_{ub} crisis")
- large difference of (14.4±2.9)% in the direct CP asymmetries measured in $B^0 \to K^+\pi^-$ vs. $B^+ \to K^+\pi^0$ decays, which is in conflict with the prediction of (2.2±2.4)% from QCD factorization ("$B \to K\pi$ puzzle")
- enhanced $B_s \to \mu^+\mu^-$ branching ratio observed by CDF (but not by LHCb and CMS ☹)

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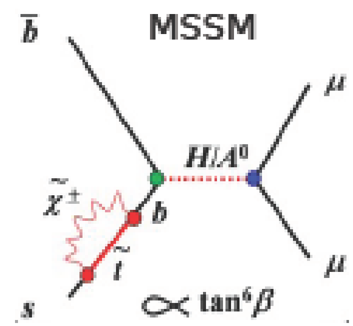
Rare decays $B_{d,s} \to \mu^+\mu^-$

- interesting rare decays, which can be much enhanced in models with a warped extra dimension or SUSY models with large tanβ



Excess in B_s mode reported by CDF:

$$\mathcal{B}(B_s \to \mu^+\mu^-) = (1.8^{+1.1}_{-0.9}) \cdot 10^{-8} \qquad \text{SM:} \quad (3.2 \pm 0.2) \cdot 10^{-9}$$

$$\mathcal{B}(B_d \to \mu^+\mu^-) < 6.0 \cdot 10^{-9} \qquad \text{SM:} \quad (1.0 \pm 0.1) \cdot 10^{-10}$$

Unfortunately no excess seen at LHCb (CMS):

$$\mathcal{B}(B_s \to \mu^+\mu^-) < 1.5\ (1.9) \cdot 10^{-8}$$

$$\mathcal{B}(B_d \to \mu^+\mu^-) < 5.2\ (4.6) \cdot 10^{-9}$$

(at 95% CL)

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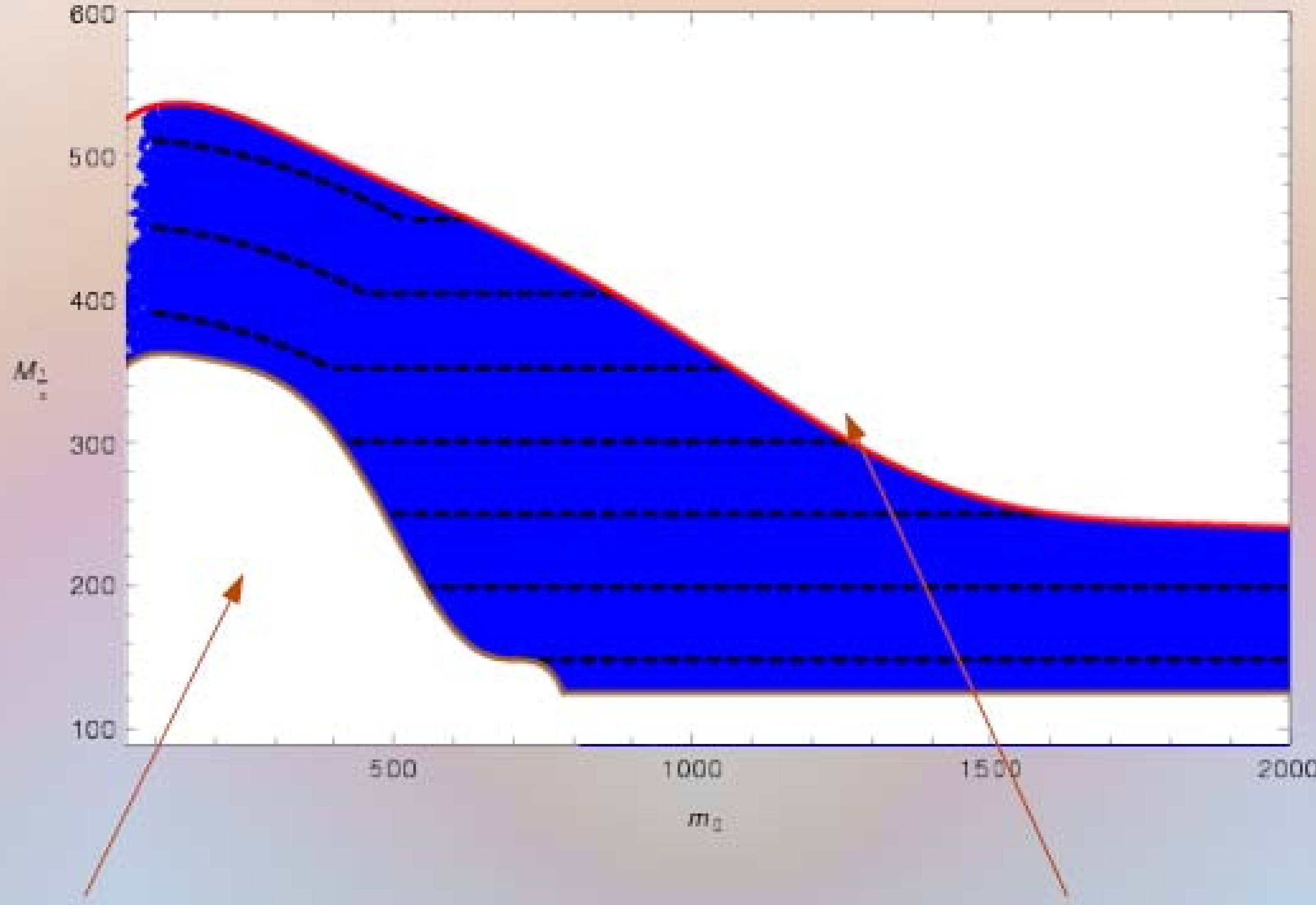
These bounds to not rule out the CDF result, but without refined LHC measurements the situation is inconclusive!

Relevant Parameter Space for 2 fb^{-1}

Jones at the EPS-HEP 2011 on the work in progress by Calibbi, Hodgkinson, Jones, A.M. and Vives

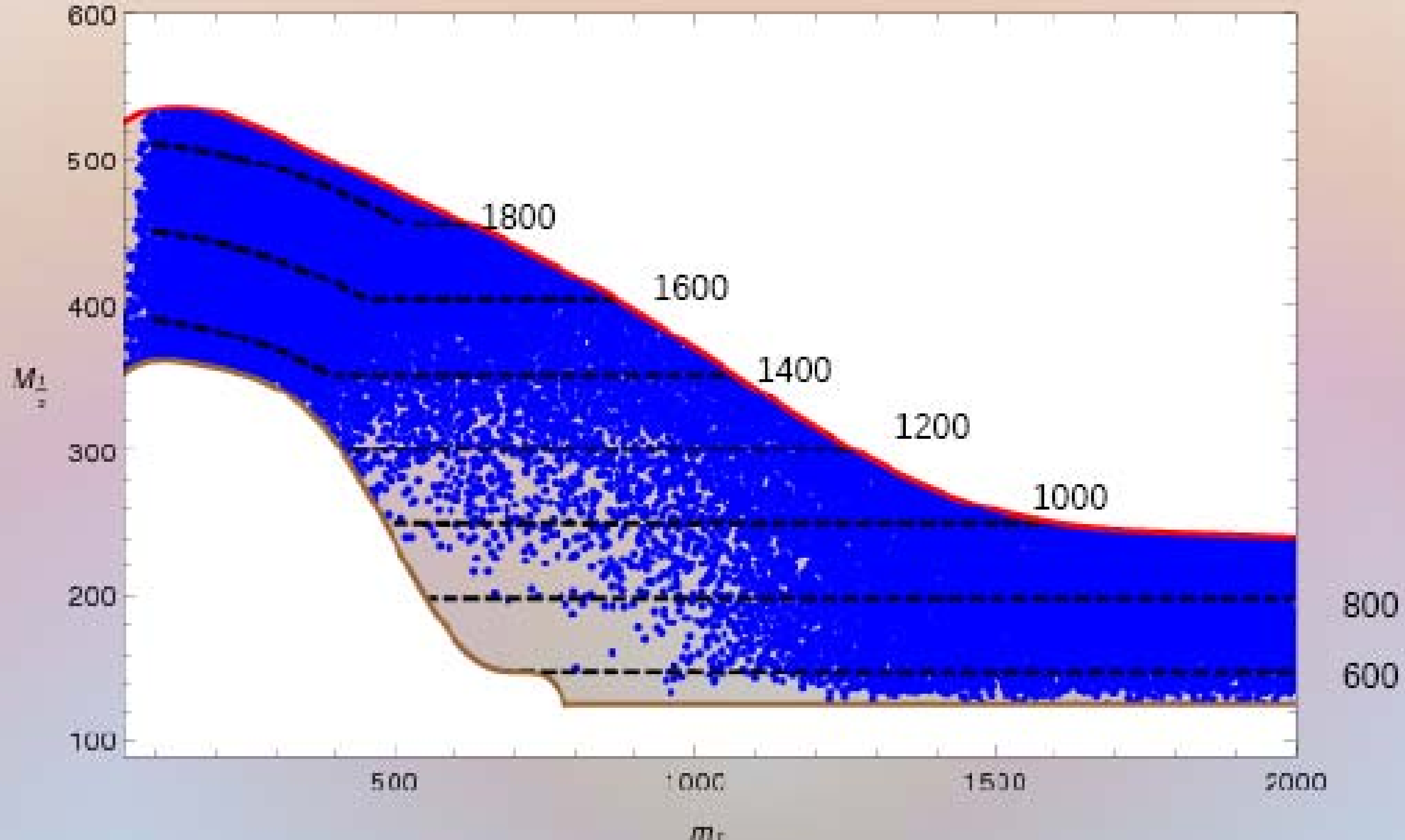


ATLAS Collaboration (1102.5290 [hep-ex])

Baer, Barger, Lessa, Tata (1004.3594 [hep-ph])

Flavour 3σ Constraints

$b \to s\gamma$ $(g-2)_\mu$



CHJMV work in progress

The Role of $B_s \to \mu\mu$

IMPACT ON THE SUSY PARAMETER SPACE

- LHCb with 2 fb^{-1}
  - Exclusion of $BR(B_s \to \mu\mu)$ down to 4×10^{-9}, 95% C.L.
  - 3σ evidence of $BR(B_s \to \mu\mu)$ down to 5×10^{-9}.
  - 5σ discovery of $BR(B_s \to \mu\mu)$ down to 9×10^{-9}.

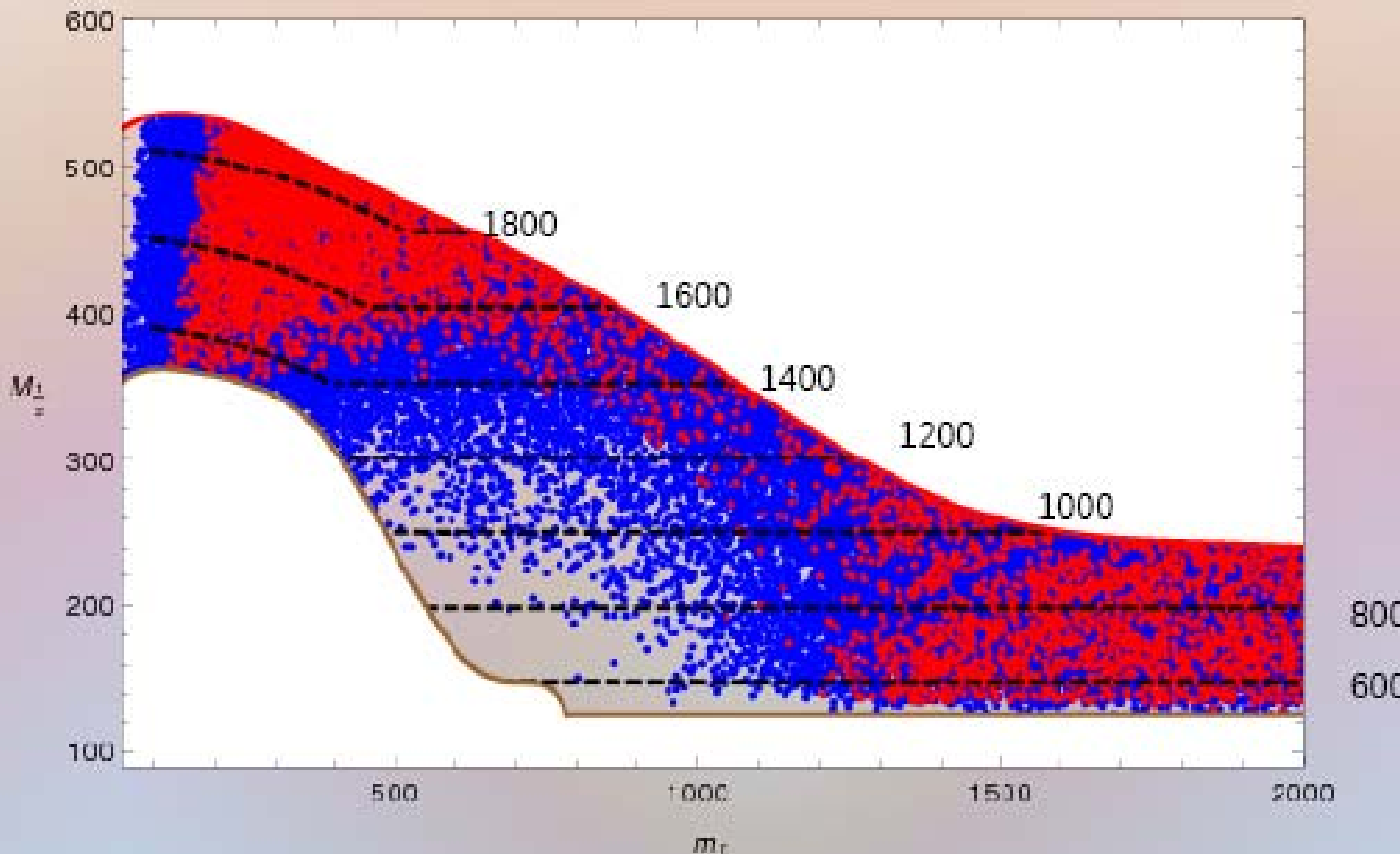
R. Lambert @ Moriond

- CDF with 7 fb^{-1}
  - $BR(B_s \to \mu\mu) = (1.8 \pm 1) \times 10^{-8}$

CDF Collaboration (1107.2304 [hep-ex])

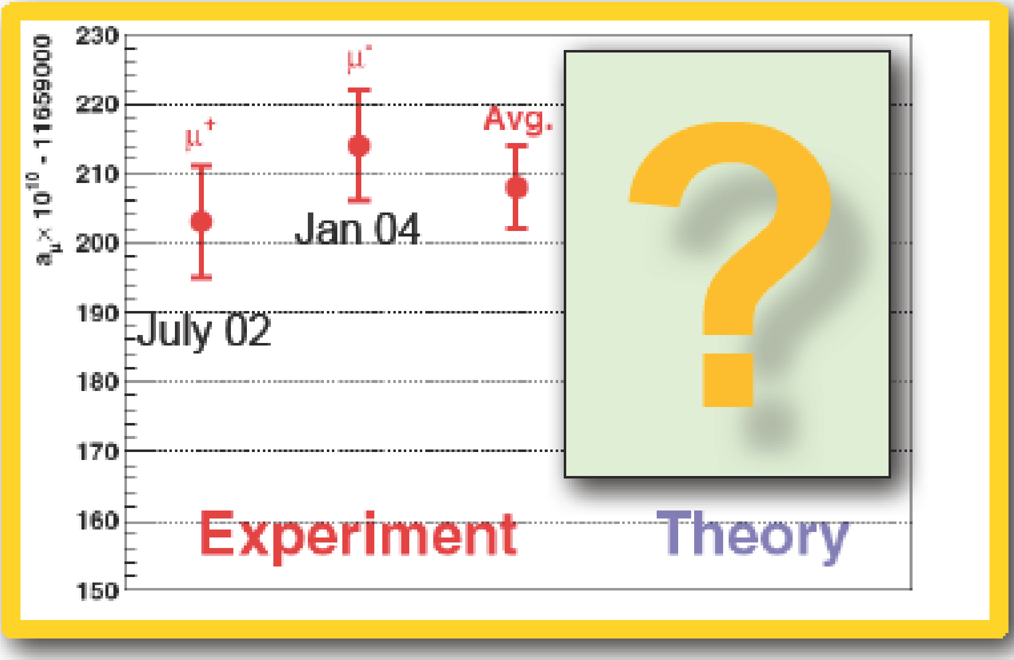
Exclusion due to B_s -> μ μ

$$\mathrm{BR}\left(B_s \rightarrow \mu\mu\right) < 4 \times 10^{-9}$$



CHJMV work in progress

The muon g-2: the experimental result



- **Today:** $a_\mu^{EXP} = (116592089 \pm 54_{stat} \pm 33_{sys}) \times 10^{-11}$ [0.5ppm].
- **Future:** new muon g-2 experiments proposed at:
  - Fermilab (P989), aiming at 0.14ppm **STAGE-1 APPROVAL!!**
  - J-PARC aiming at 0.1 ppm

  [D. Hetzog & N. Saito, U.Paris, Feb 2010; B. Lee Roberts & T. Mibe, Tau2010]
- **Are theorists ready for this (amazing) precision?** [not yet]

The muon g-2: Standard Model vs. Experiment

Adding up all contributions, we get the following SM predictions and comparisons with the measured value:

$a_\mu^{EXP} = 116592089\ (63) \times 10^{-11}$

E821 – Final Report: PRD73 (2006) 072
with latest value of $\lambda=\mu_\mu/\mu_p$ (CODATA'06)

	$a_\mu^{SM} \times 10^{11}$	$(\Delta a_\mu = a_\mu^{EXP} - a_\mu^{SM}) \times 10^{11}$	σ
[1]	116 591 782 (59)	307 (86)	3.6
[2]	116 591 802 (49)	287 (80)	3.6
[3]	116 591 830 (52)	259 (82)	3.2
[4]	116 591 894 (54)	195 (83)	2.4

with a_μ^{HHO}(lbl) = 105 (26) x 10^{-11}

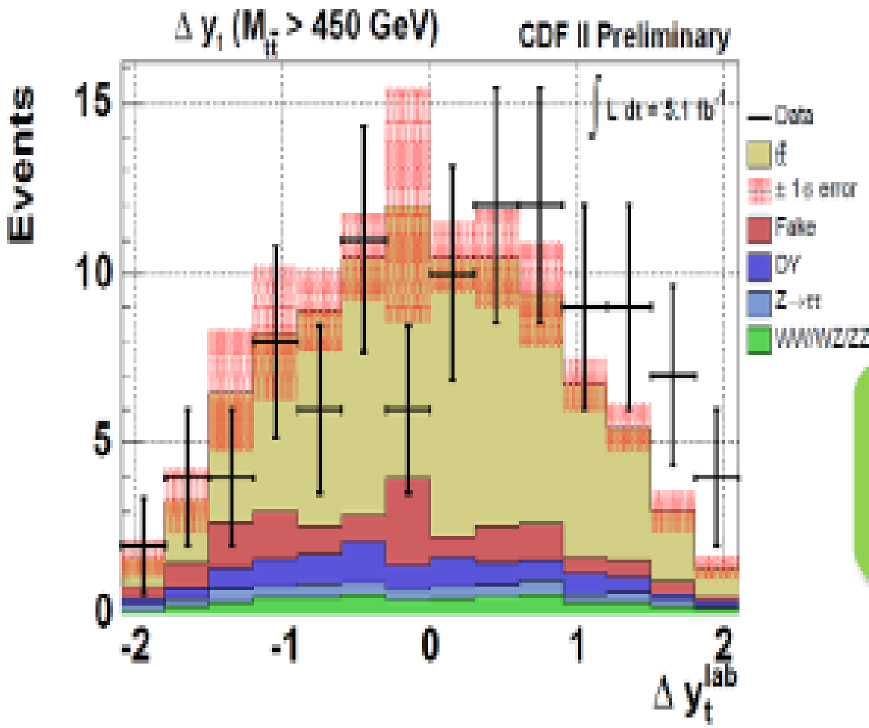
[1] F. Jegerlehner, A. Nyffeler, Phys. Rept. 477 (2009) 1
[2] Davier et al, arXiv:1010.4180, Oct 2010 (includes BaBar and KLOE10 2π)
[3] HLMNT10: Hagiwara et al, Tau 2010, Sep. 2010 (incl BaBar and KLOE10 2π)
[4] Davier et al, arXiv:1010.4180, Oct 2010, τ data.

Note that the th. error is now about the same as the exp. one

Top anti-Top asymmetry

CDF

5.1 fb^{-1}



CDF public note 10436

$$A_{fb} = 0.42 \pm (0.15)^{stat} \pm (0.05)^{syst}$$

(dilepton final state)

- ✓ 2.3σ from the SM prediction.
- ✓ 3.4σ in the l+jets topology.

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- ✓ axigluons, diquarks, new weak bosons, EDs etc..

- ✓ Or gluon radiations modeling at NLO?

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**

% FINE-TUNING FOR THE NEW PHYSICS AT THE ELW. SCALE

- **Elementary Higgs** →In the **MSSM** % fine-tuning among the SUSY param. to avoid light SUSY particles which would have been already seen at LEP and Tevatron ***and now also at LHC***

- **Elementary Higgs** → **PSEUDO-GOLDSTONE boson in the LITTLE HIGGS model** → Λ^2 div. cancelled by new colored fermions, new W,Z, γ, 2Higgs doublets… → % fine-tuning to avoid too large elw. Corrections

- **COMPOSITE HIGGS** in **a 5-dim**. holographic theory (Higgs is a PSEUDO-GOLDSTONE boson and the elw. symmetry breaking is triggered by bulk effects (in 5 dim. the theory is **WEAKLY** coupled, but in 4 dim. the bulk looks like a **STRONGLY** coupled sector) → also here % fine-tuning needed to survive the elw. precision tests

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**

***THE DM ROAD TO NEW PHYSICS BEYOND THE SM*:**

IS **DM** A PARTICLE OF THE ***NEW PHYSICS AT THE ELECTROWEAK ENERGY 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.** → **STABLE NEW PART.**	Neutralino spin 1/2	spin1	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

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

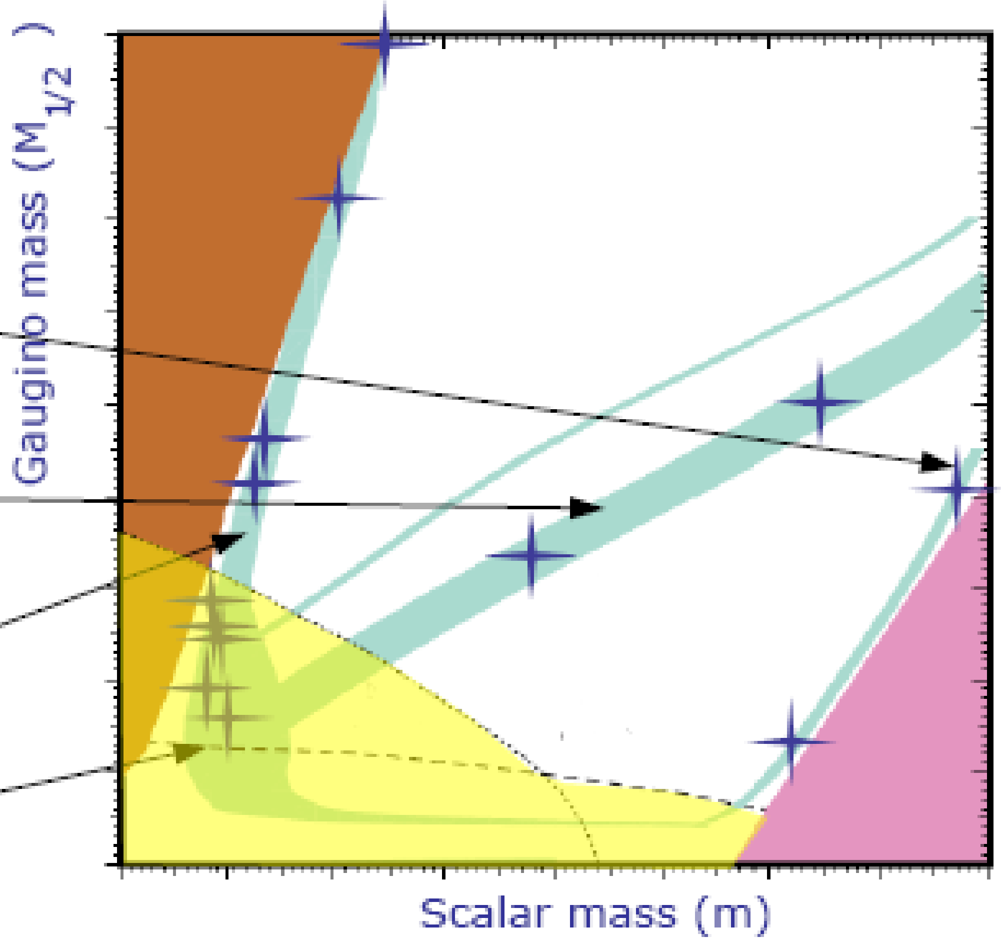
when it comes to quantitatively reproduce the precisely determined DM density → once again the fine-tuning threat…

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)

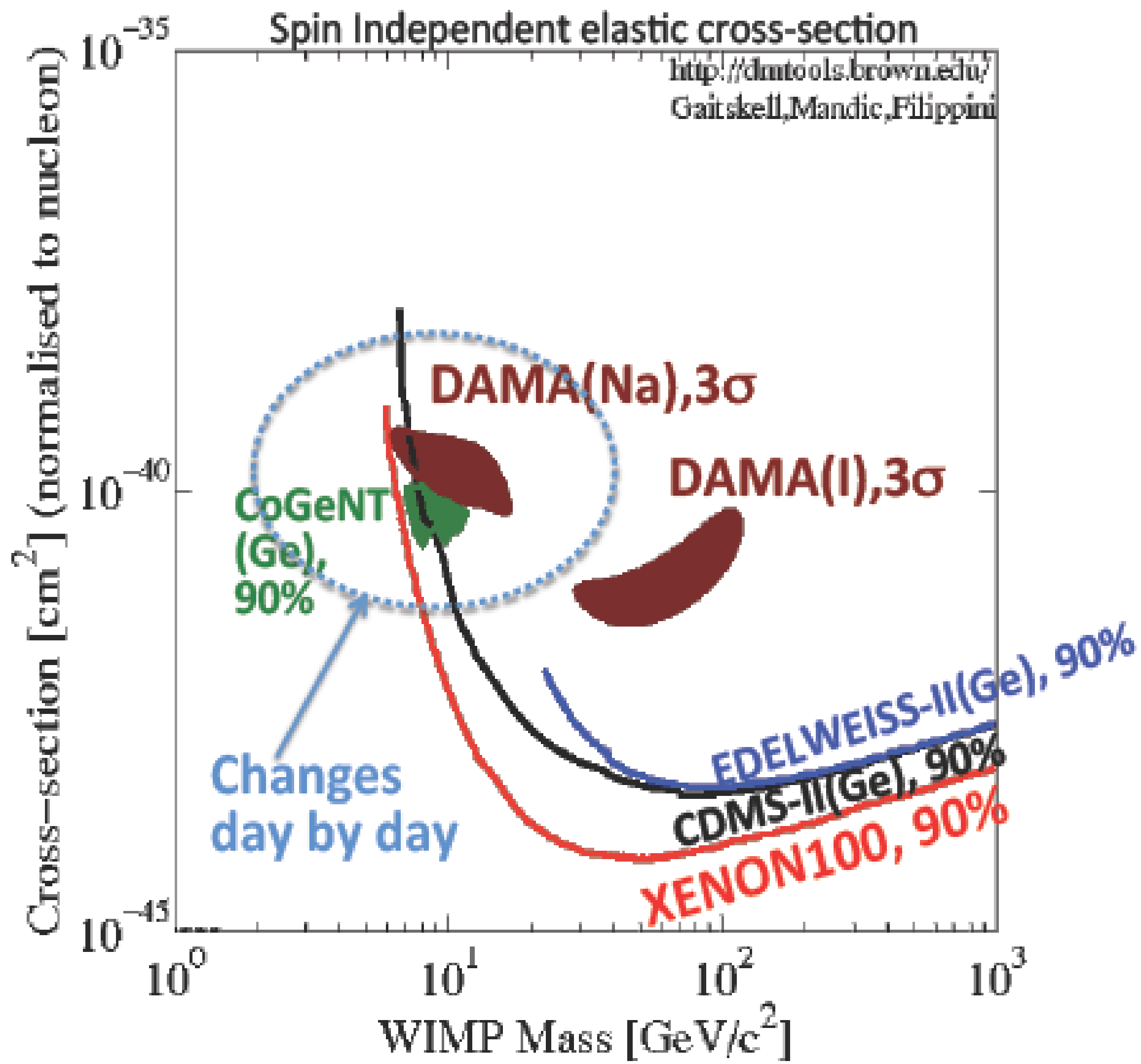
Cerdeno ‘09

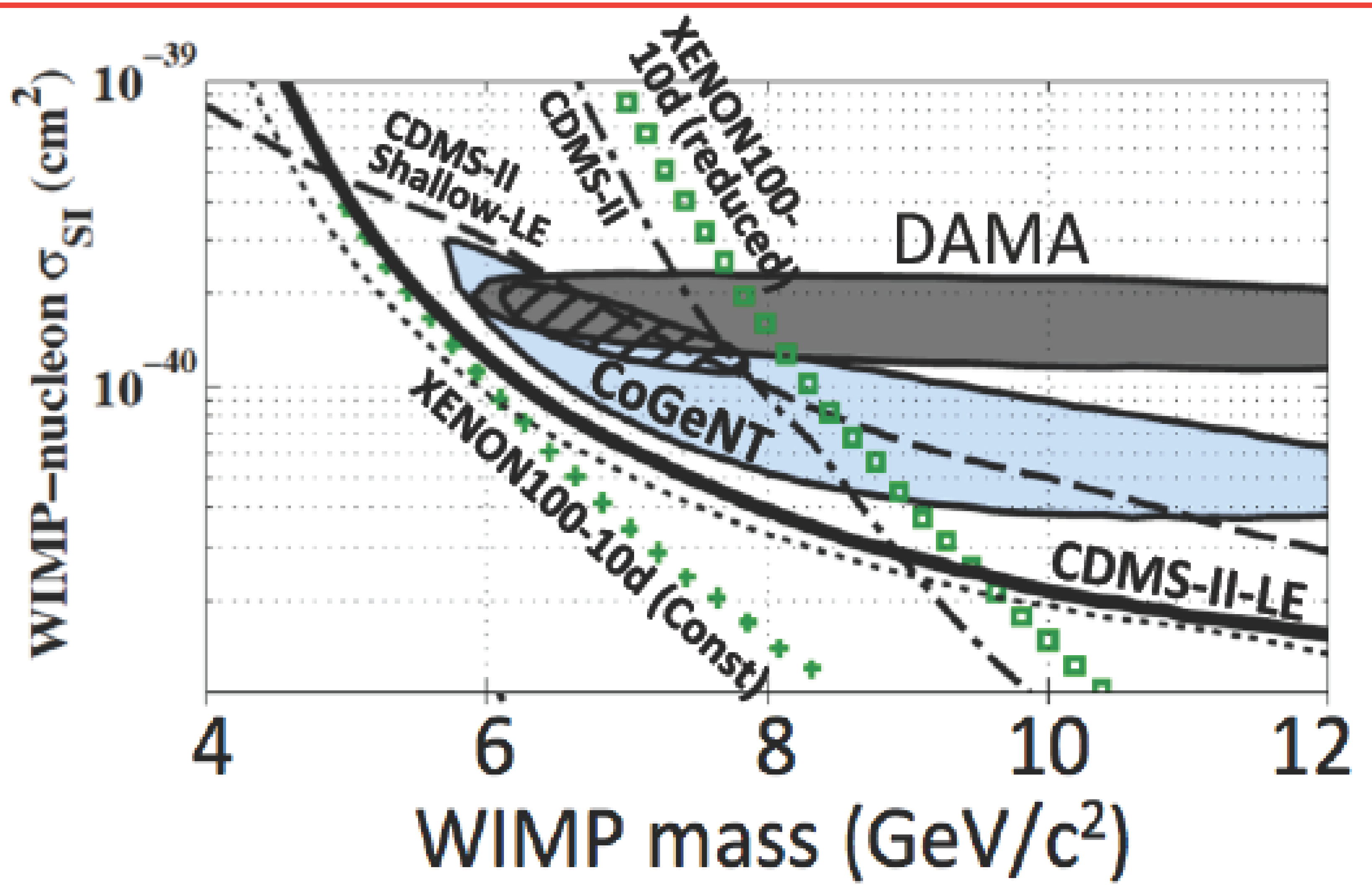
Recent Status

Sorry,
We did not plot all the results

CRESST-II:
Wait until their FINAL results

Low threshold Analysis by CDMS-II (LE) and XENON-10 (LE)





WIMP–nucleon σSI (cm2)
10−39
10−40
CDMS-II Shallow-LE
CDMS-II
XENON100-10d (reduced)
DAMA
CoGeNT
XENON100-10d (Const)
CDMS-II-LE
4
6
8
10
12
WIMP mass (GeV/c2)

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}

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

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

R. Catena

2. Consider a $\rho_{\rm tot}$ 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

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.

4. 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 TeV)

Flavor Structure in the SM and Beyond

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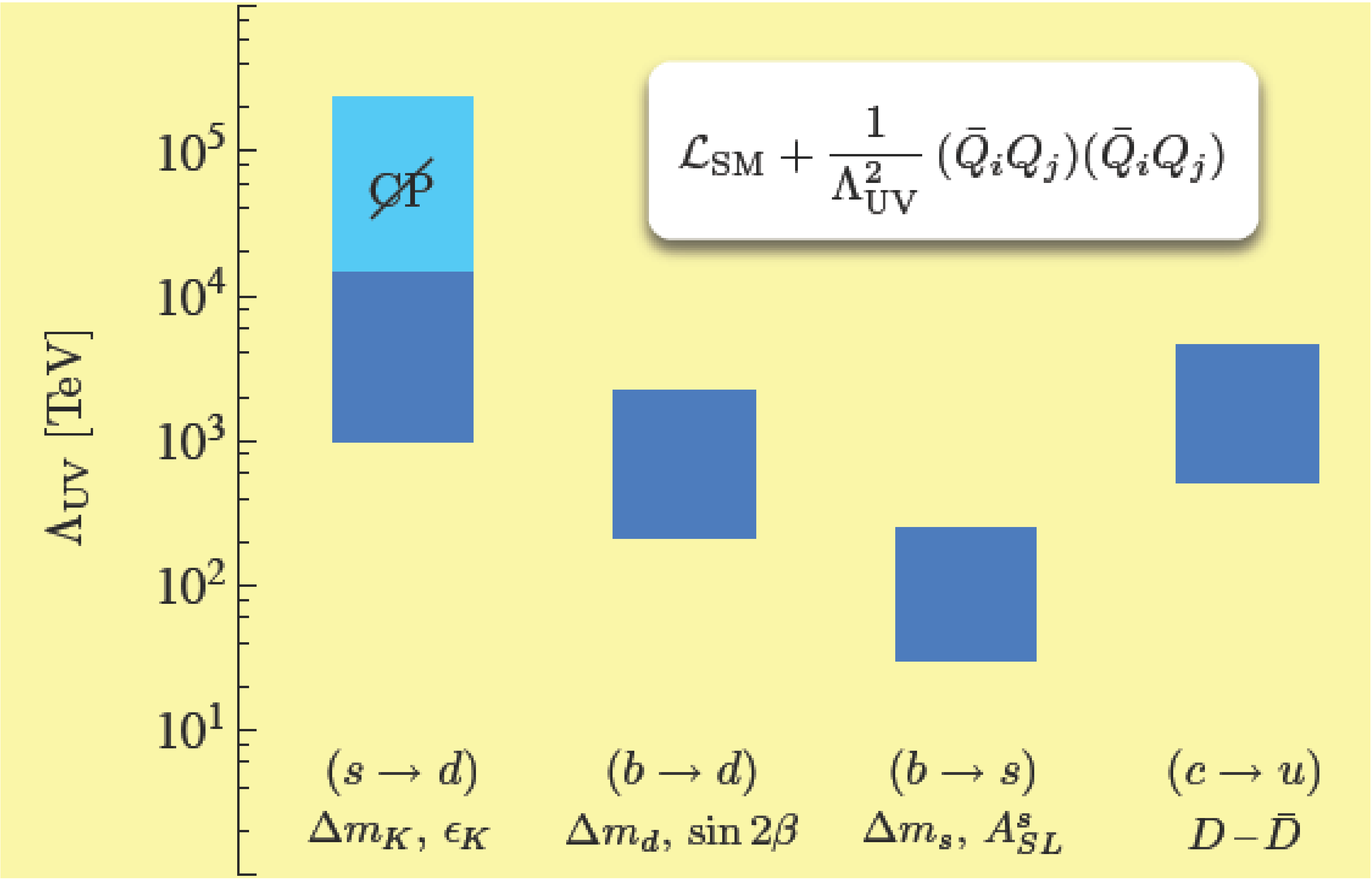


Generic bounds without a flavor symmetry

$K-\overline{K}$	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**

NIR

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"**

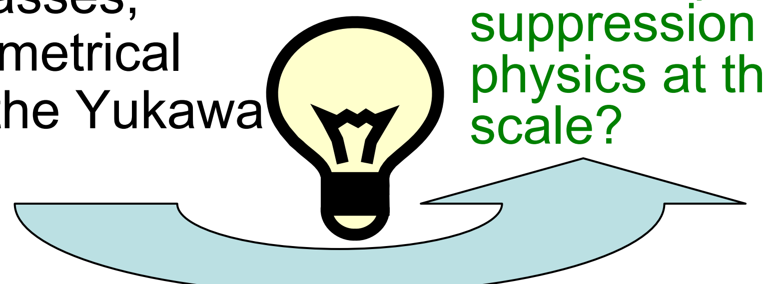
(new flavour – horizontal symmetry, radiatively induced lighter fermion masses, dynamical or geometrical determination of the Yukawa couplings, …?)

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?

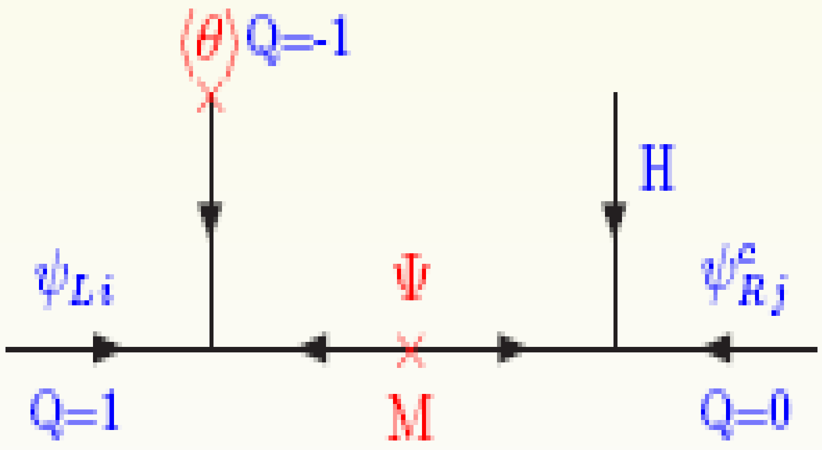


MSSM ⊗ FAMILY SYMM.

- **AMBITION**: **simultaneously** accounting for the "correct" SM fermion masses and mixings (***SM Flavor Puzzle***) **and** a structure of the SUSY soft breaking masses allowing for adequate FCNC suppression + possible "explanation" of the alleged SM FCNC difficulties (***SUSY Flavor Puzzle***)

- Mechanism a la Frogatt – Nielsen with **abelian or non-abelian family symmetry**

- Froggatt-Nielsen mechanism and flavour symmetry to understand small Yukawa elements. Example: $U(1)_{fl}$



$$\Rightarrow Y_{ij} = \left(\frac{\langle\theta\rangle}{M}\right) \ll 1$$

Yukawa Textures

What we want:

$$Y_u \propto \begin{pmatrix} 0 & \varepsilon^3 & \varepsilon^3 \\ \varepsilon^3 & \varepsilon^2 & \varepsilon^2 \\ \varepsilon^3 & \varepsilon^2 & 1 \end{pmatrix} \qquad Y_d \propto \begin{pmatrix} 0 & \bar{\varepsilon}^3 & \bar{\varepsilon}^3 \\ \bar{\varepsilon}^3 & \bar{\varepsilon}^2 & \bar{\varepsilon}^2 \\ \bar{\varepsilon}^3 & \bar{\varepsilon}^2 & 1 \end{pmatrix}$$

$$\varepsilon = 0.05 \qquad \bar{\varepsilon} = 0.15$$

R. G. Roberts, A. Romanino, G. G. Ross, L. Velasco-Sevilla (hep-ph/0104088)

$SU(3)$ Flavour model

ROBERTS, ROMANINO, ROSS, VELASCO-SEVILLA;
ROSS, VELASCO-SEVILLA, VIVES

- $Q, L \sim \mathbf{3}$ and $d^c, u^c, e^c \sim \mathbf{3}$; flavon fields: $\theta_3, \theta_{23} \sim \overline{\mathbf{3}}$, $\overline{\theta}_3, \overline{\theta}_{23} \sim \mathbf{3}$
- Family Symmetry breaking: $SU(3) \xrightarrow{\langle\theta_3\rangle} SU(2) \xrightarrow{\langle\theta_{23}\rangle} \emptyset$

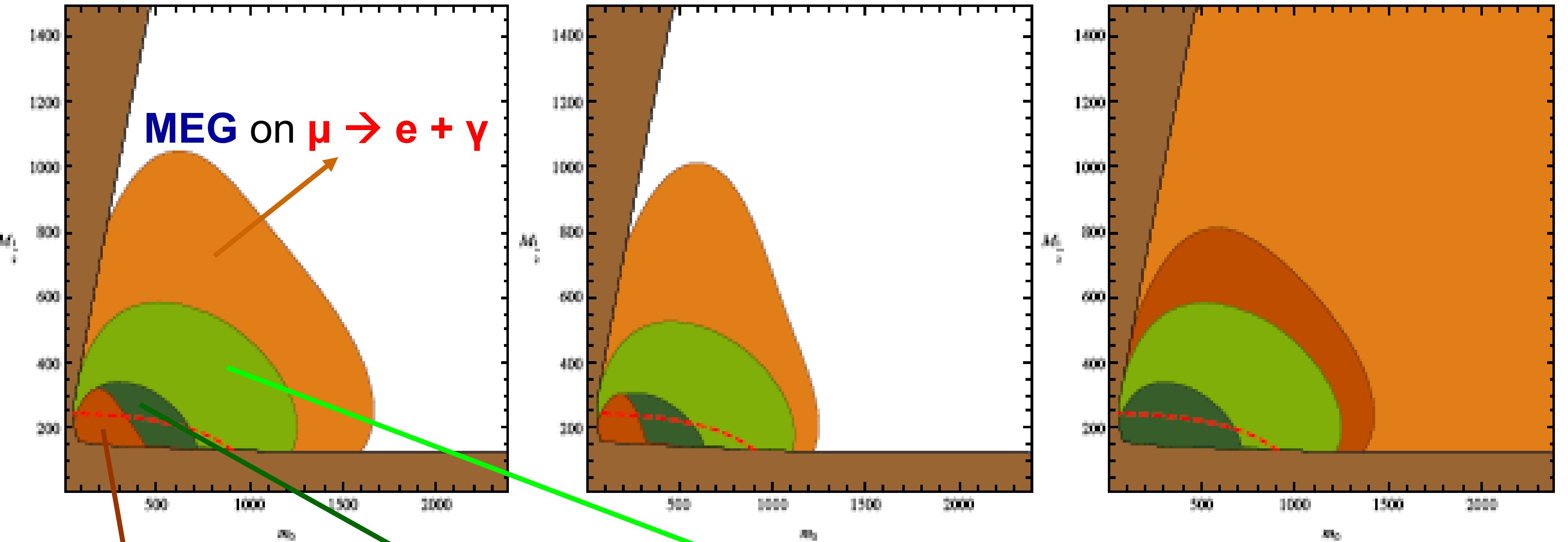
$$\theta_3, \overline{\theta}_3 = \begin{pmatrix} 0 \\ 0 \\ a_3 \end{pmatrix}, \quad \theta_{23}, \overline{\theta}_{23} = \begin{pmatrix} 0 \\ b \\ b \end{pmatrix} \text{ with } \left(\frac{a_3}{M}\right) \sim \mathcal{O}(1), \ \left(\frac{b}{M_u}\right) \simeq \left(\frac{b}{M_d}\right)^2 = \varepsilon \sim 0.05.$$

- Yukawa superpotential: $W_Y = H \psi_i \psi_j^c \left[\theta_3^i \theta_3^j + \theta_{23}^i \theta_{23}^j \left(\theta_3 \overline{\theta_3}\right) + \epsilon^{ikl} \overline{\theta}_{23,k} \overline{\theta}_{3,l} \theta_{23}^j \left(\theta_{23} \overline{\theta_3}\right)\right]$

$$Y^f = \begin{pmatrix} 0 & a\,\varepsilon^3 & b\,\varepsilon^3 \\ a\,\varepsilon^3 & \varepsilon^2 & c\,\varepsilon^2 \\ b\,\varepsilon^3 & c\,\varepsilon^2 & 1 \end{pmatrix} \frac{|a_3|^2}{M^2},$$

O. VIVES

LFV CONSTRAINTS IN THE $M_0 - M_{1/2}$ SUSY PLANE



PRESENT BOUND ON
τ → μ + γ

FUTURE BOUND ON τ → μ + γ
at SUPER B

PRESENT BOUND ON
μ → e + γ

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

FLAVOR BLINDNESS OF THE NP AT THE ELW. SCALE?

- **THREE DECADES OF FLAVOR TESTS** (Redundant determination of the UT triangle → verification of the SM, theoretically and experimentally "high precision" FCNC tests, ex. b → 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 <10% in the "flavor observables" which have already been observed!

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

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

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

V. Lubicz, SuperB_Padova 2008

Estimates of error for 2015

Hadronic matrix element	Current lattice error	6 TFlop Year	60 TFlop Year [2011 LHCb]	1-10 PFlop Year [2015 SuperB
$f_+^{K\pi}(0)$	0.9% (22% on 1-f_+)	0.7% (17% on 1-f_+)	0.4% (10% on 1-f_+)	**< 0.1% (2.4% on 1-f_+)**
$\hat{B}_K$	11%	5%	3%	**1%**
f_B	14%	3.5 - 4.5%	2.5 - 4.0%	**1 – 1.5%**
$f_{Bs}B_{Bs}^{1/2}$	13%	4 - 5%	3 - 4%	**1 – 1.5%**
ξ	5% (26% on ξ-1)	3% (18% on ξ-1)	1.5 - 2 % (9-12% on ξ-1)	**0.5 – 0.8 % (3-4% on ξ-1)**
$\mathcal{F}_{B\to D/D^*l\nu}$	4% (40% on 1-$\mathcal{F}$)	2% (21% on 1-$\mathcal{F}$)	1.2% (13% on 1-$\mathcal{F}$)	**0.5% (5% on 1-$\mathcal{F}$)**
$f_+^{B\pi}, \ldots$	11%	5.5 - 6.5%	4 - 5%	**2 – 3%**
$T_1^{B\to K^*/\rho}$	13%	----	----	**3 – 4%**

SUSY SEE-SAW

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

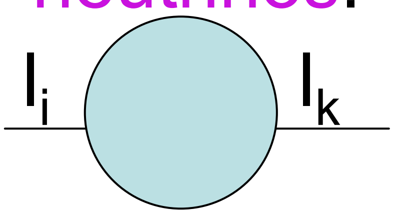
LOW-ENERGY SUSY

- **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

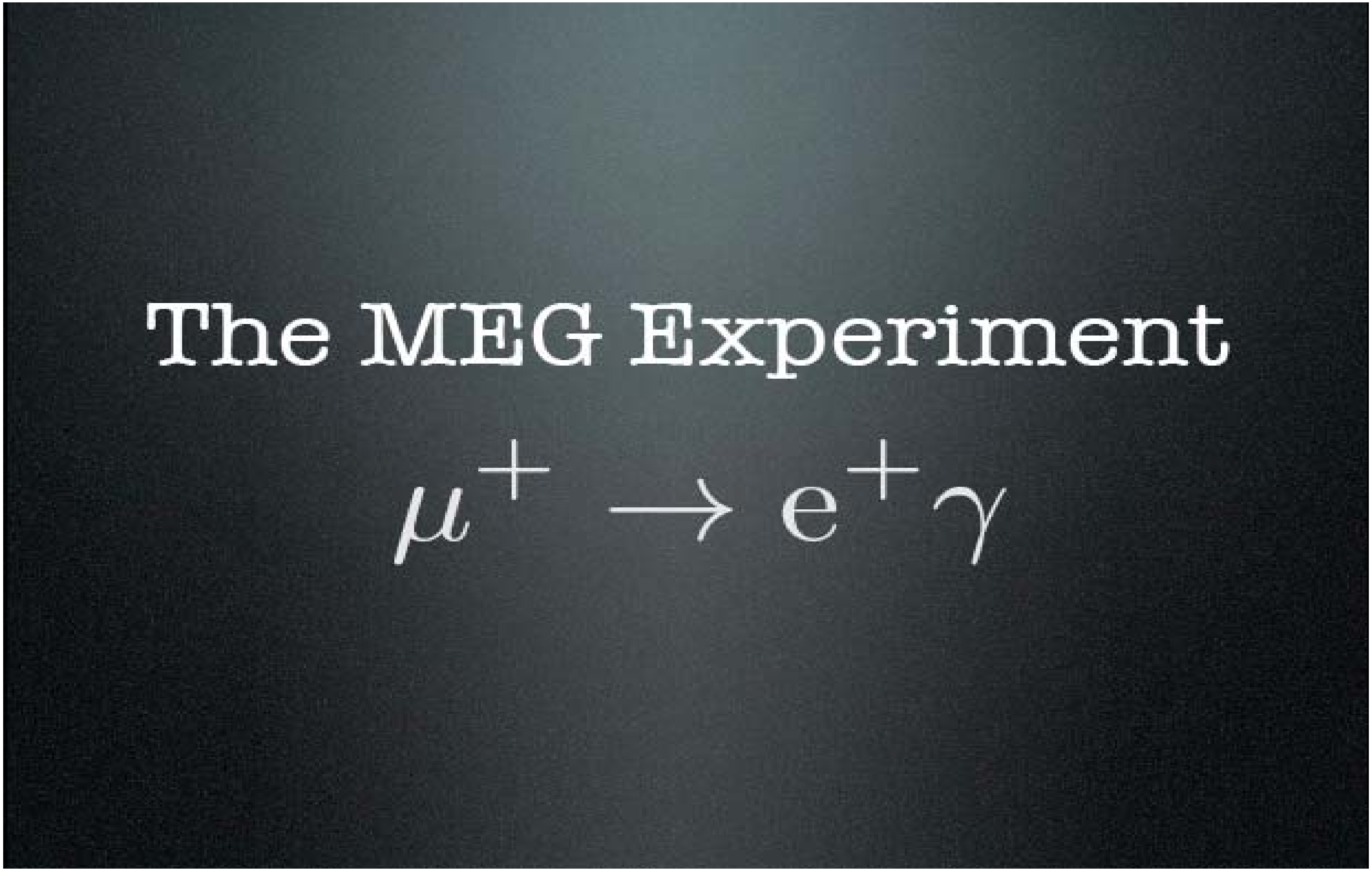
LFV and NEW PHYSICS

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

NEW BOUND OF MEG AT THE EPS 2011



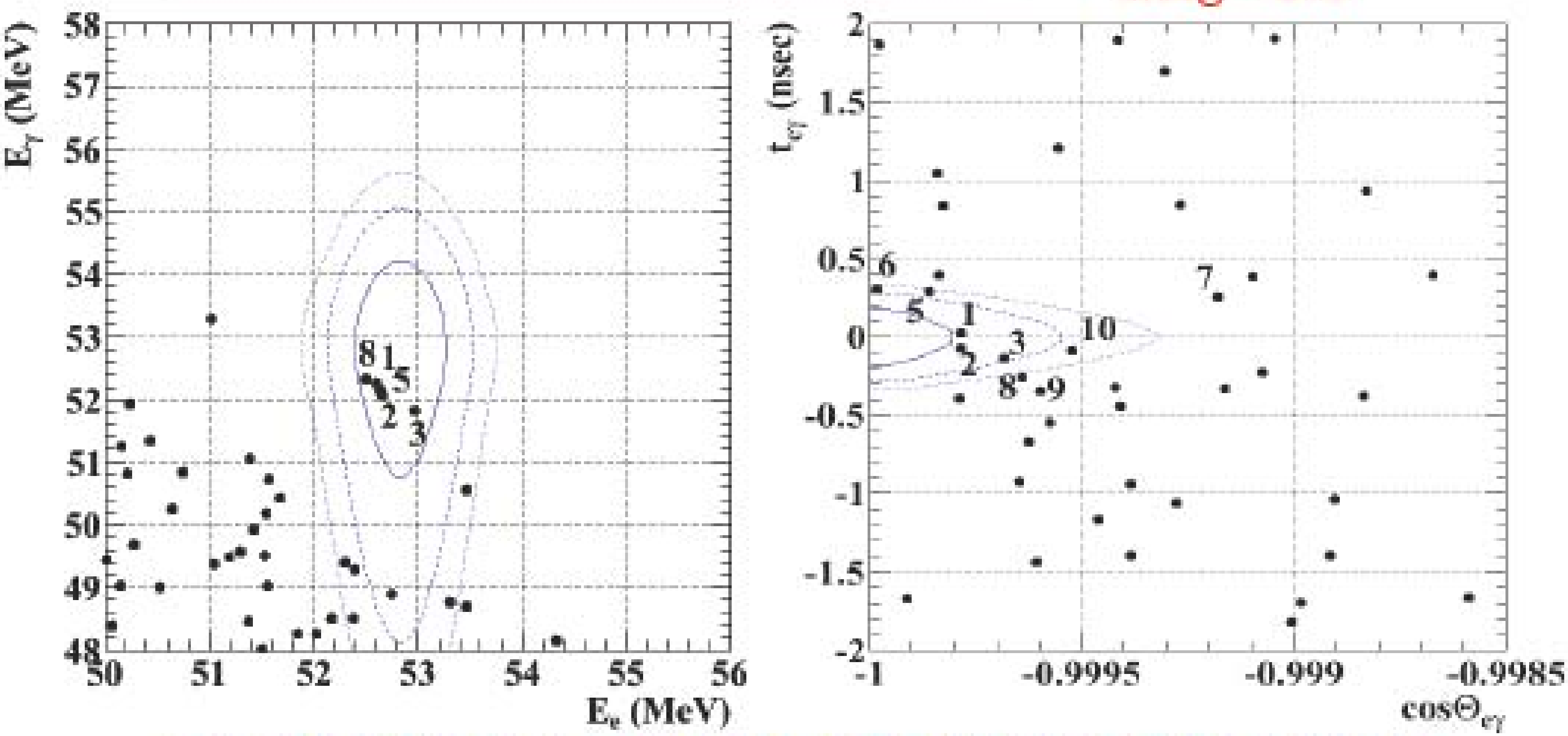
SHOWN AT ICHEP 2010

Event distribution after unblinding

BR < 1.5×10^{-11} @90%CL

6.1×10^{-12} expected

Nsig = 3.0

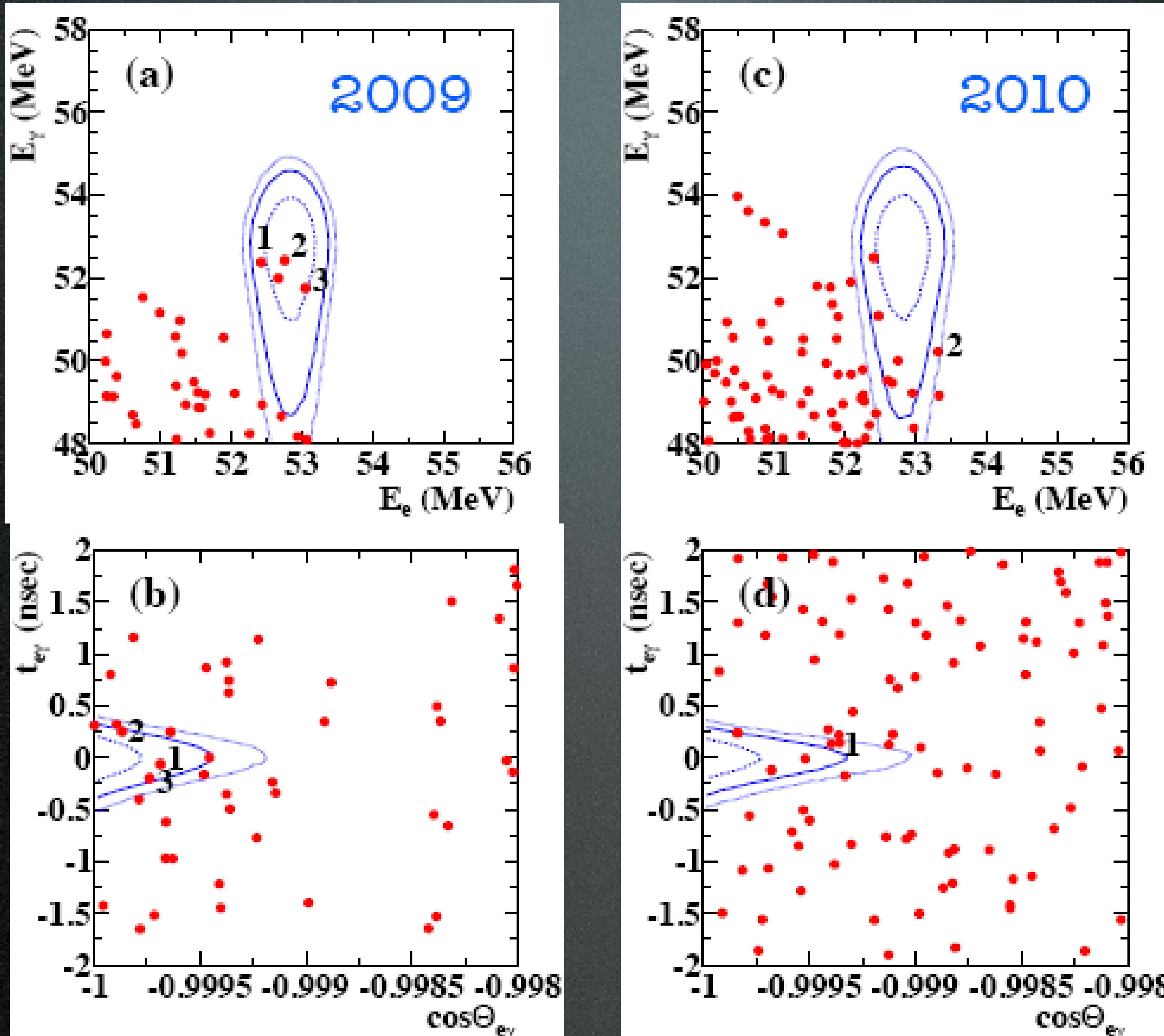


preliminary result of MEG 2009 data

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.

Numbers in figures are ranking by $L_{sig}/(L_{RMD}+L_{BG})$. Same numbered dots in the right and the left figure are an identical event.



(a)
2009
(c)
2010
E_γ (MeV)
E_e (MeV)
(b)
(d)
t_eγ (nsec)
cosΘ_eγ

MEG summary

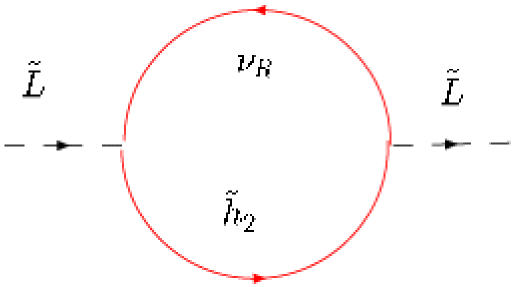
- 2009+2010 data consistent w/ no signal
- New physics is now constrained by 5× tighter upper limit: BR < 2.4×10^{-12} @90% C.L. (Preprint will be posted at arXiv today)
- MEG is accumulating more data this and next year to reach $O(10^{-13})$ sensitivity; So stay tuned!
- Detector improvements/upgrades

T. MORI AT THE EPS-HEP 2011

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

THE STRONG ENHANCEMENT OF LFV IN SUSY SEESAW MODELS CAN OCCUR

EVEN IF THE MECHANISM RESPONSIBLE FOR SUSY BREAKING IS ABSOLUTELY FLAVOR BLIND

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

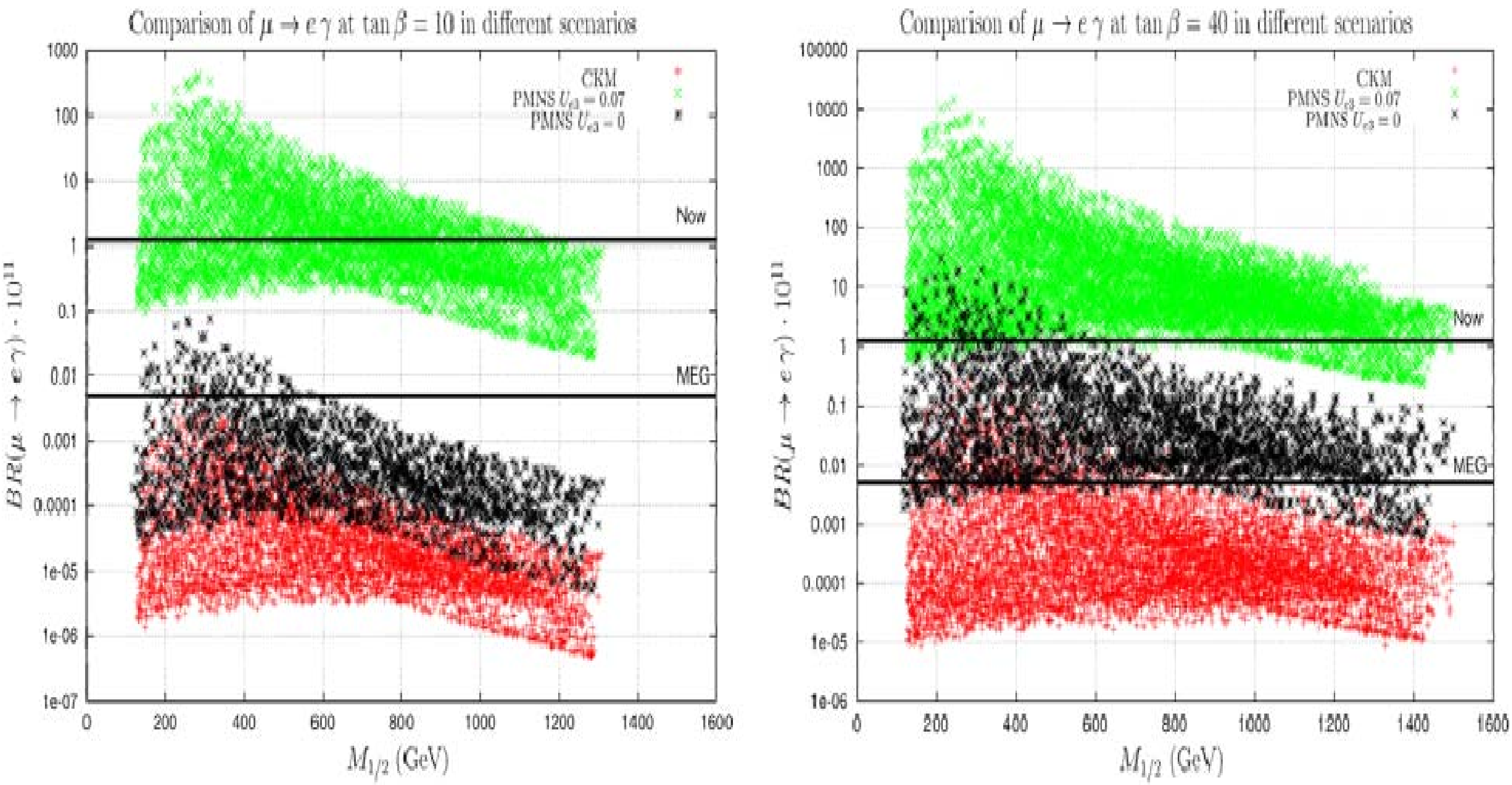
LFV in MSSMseesaw: μ $e\gamma$ Borzumati, A.M.

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

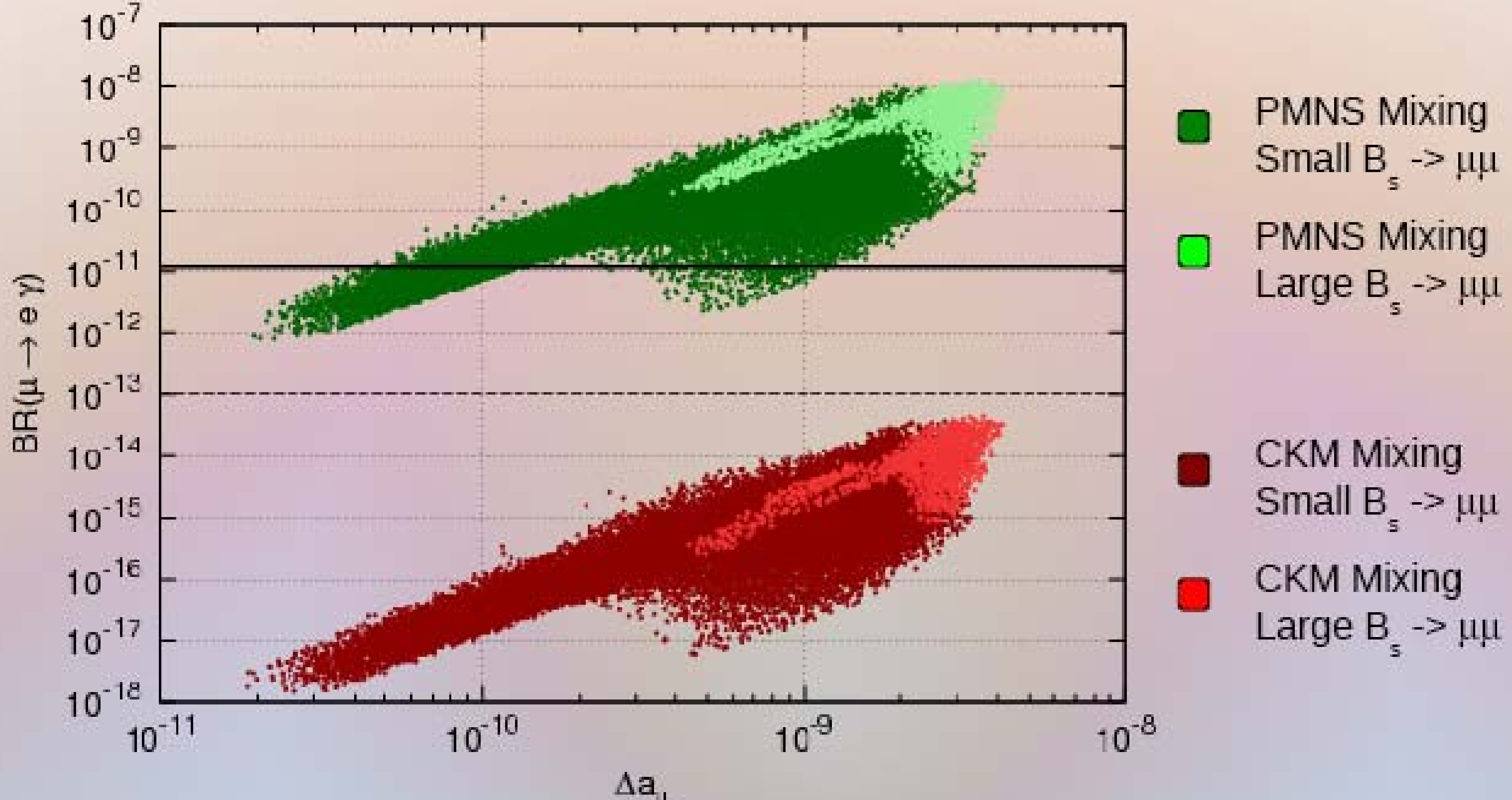
$\mu \rightarrow e+\gamma$ in SUSYGUT: past and future

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



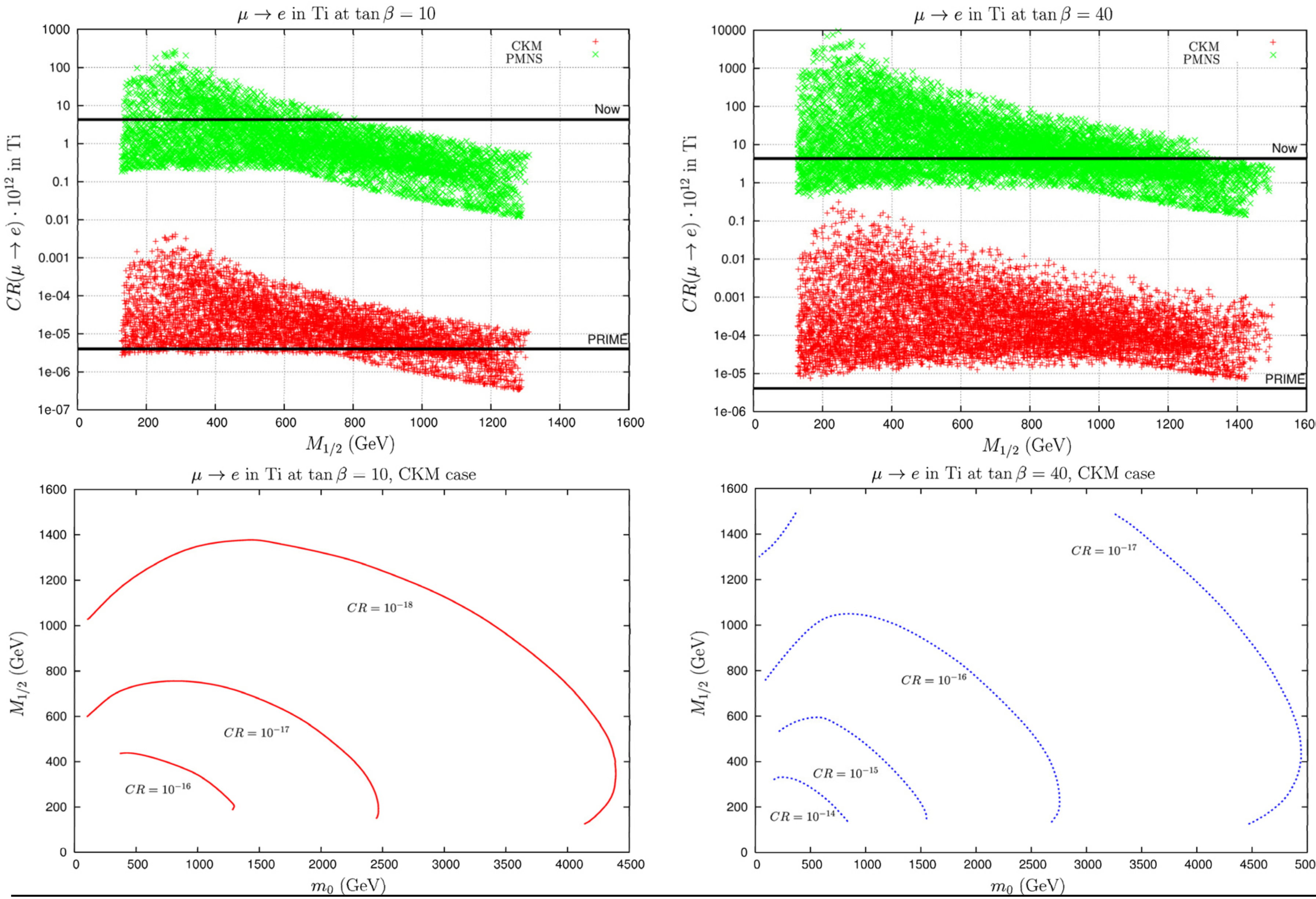
CFMV

Comparing CKM and PMNS

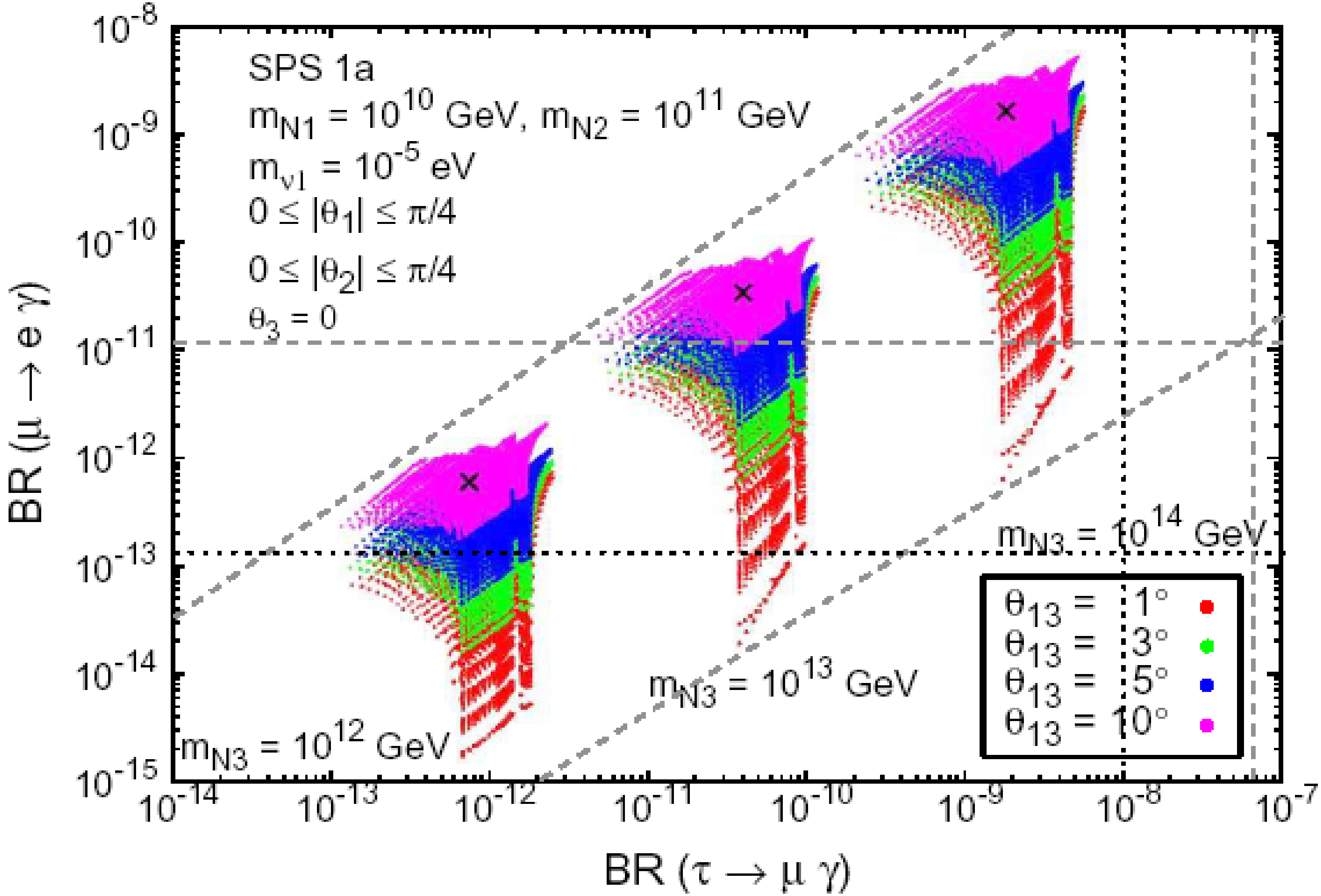


$m_{\nu_1} = 0.001$ eV $\qquad \sin^2 2\theta_{13} = 0.04$

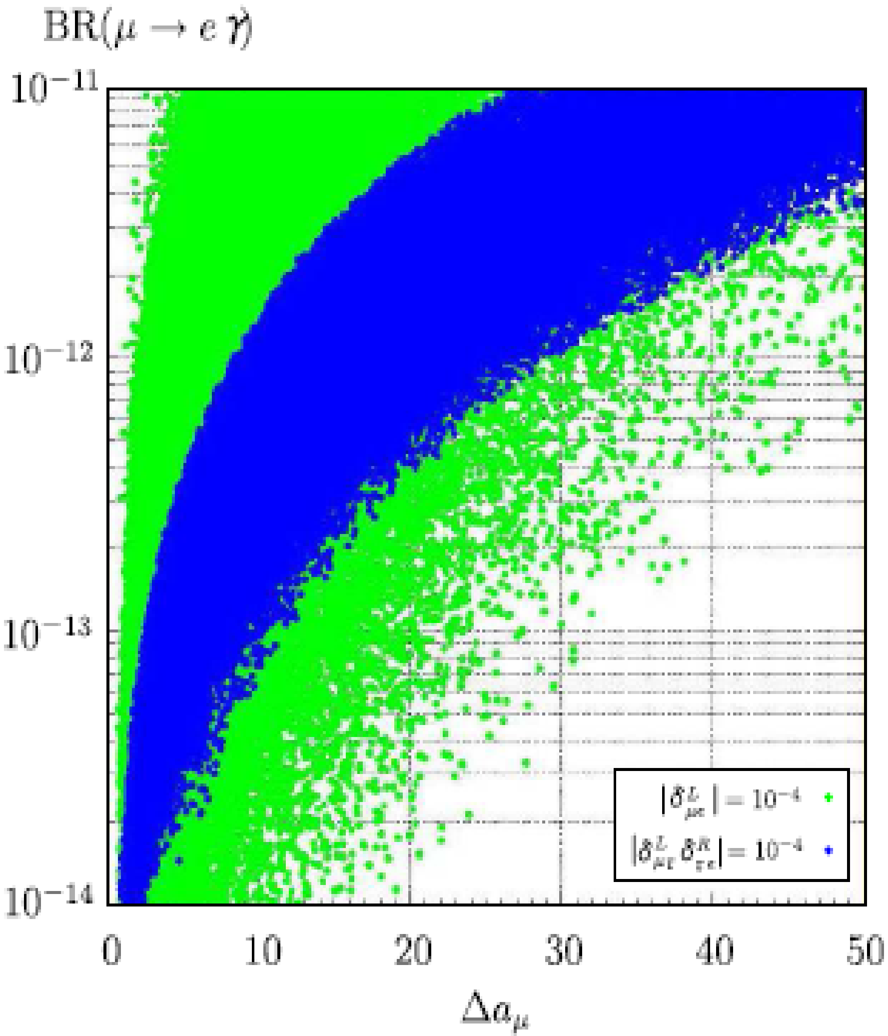
$\mu \to e$ in Ti and **PRISM/PRIME** conversion experiment



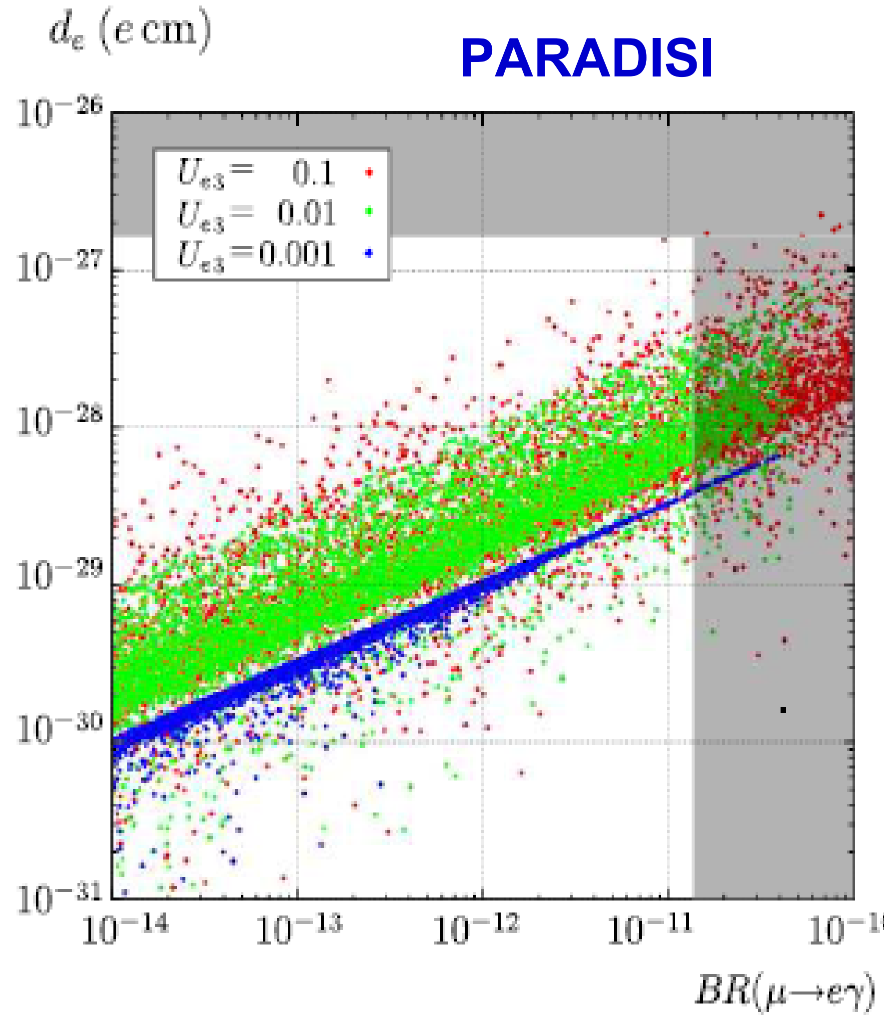
Antusch, Arganda, Herrero, Teixeira



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



PARADISI



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:

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

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

Presently: error on R_K down to the **1% level** (KLOE (09) and NA48 (07 data);using 40% of the data collected in 08, NA62 is now decreasing the uncertainty at the **0.7% level**
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%**

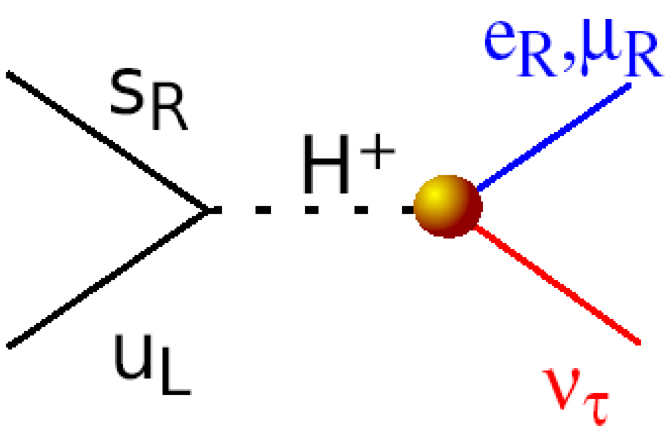
HIGGS-MEDIATED LFV COUPLINGS

- When non-holomorphic terms are generated by loop effects (HRS corrections)
- And a source of LFV among the sleptons is present
- → 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 → $l\nu$ deviation from universality

Isidori, Paradisi

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

A.M., PARADISI. PETRONZIO

LFU breaking occurs with LFV

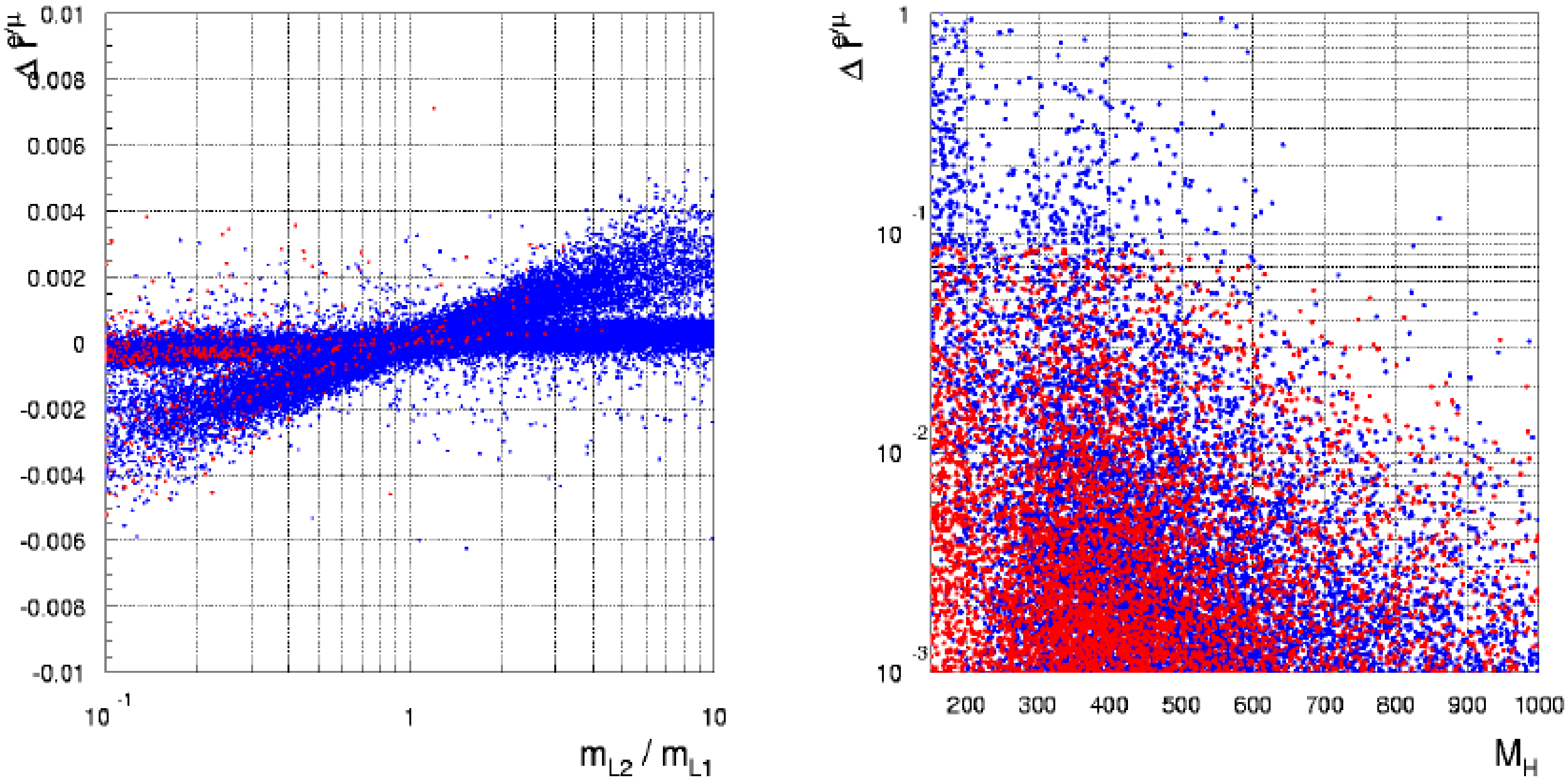


Figure 2: Left: $\Delta r_K^{e/\mu}$ as a function of the mass splitting between the second and the first (left-handed) slepton generations. Red dots can saturate the $(g-2)_\mu$ discrepancy at the 95% C.L., i.e. $1 \times 10^{-9} < (g-2)_\mu < 5 \times 10^{-9}$. Right: $\Delta r_K^{e/\mu}$ as a function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

lf

M_{Pl} M_{GUT} M_W

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

GUT -RELATED SUSY SOFT BREAKING TERMS

$$m^2_Q = m^2_{\tilde{e}^c} = m^2_{\tilde{u}^c} = m^2_{\mathbf{10}}$$

$$m^2_{\tilde{d}^c} = m^2_L = m^2_{\bar{\mathbf{5}}}$$

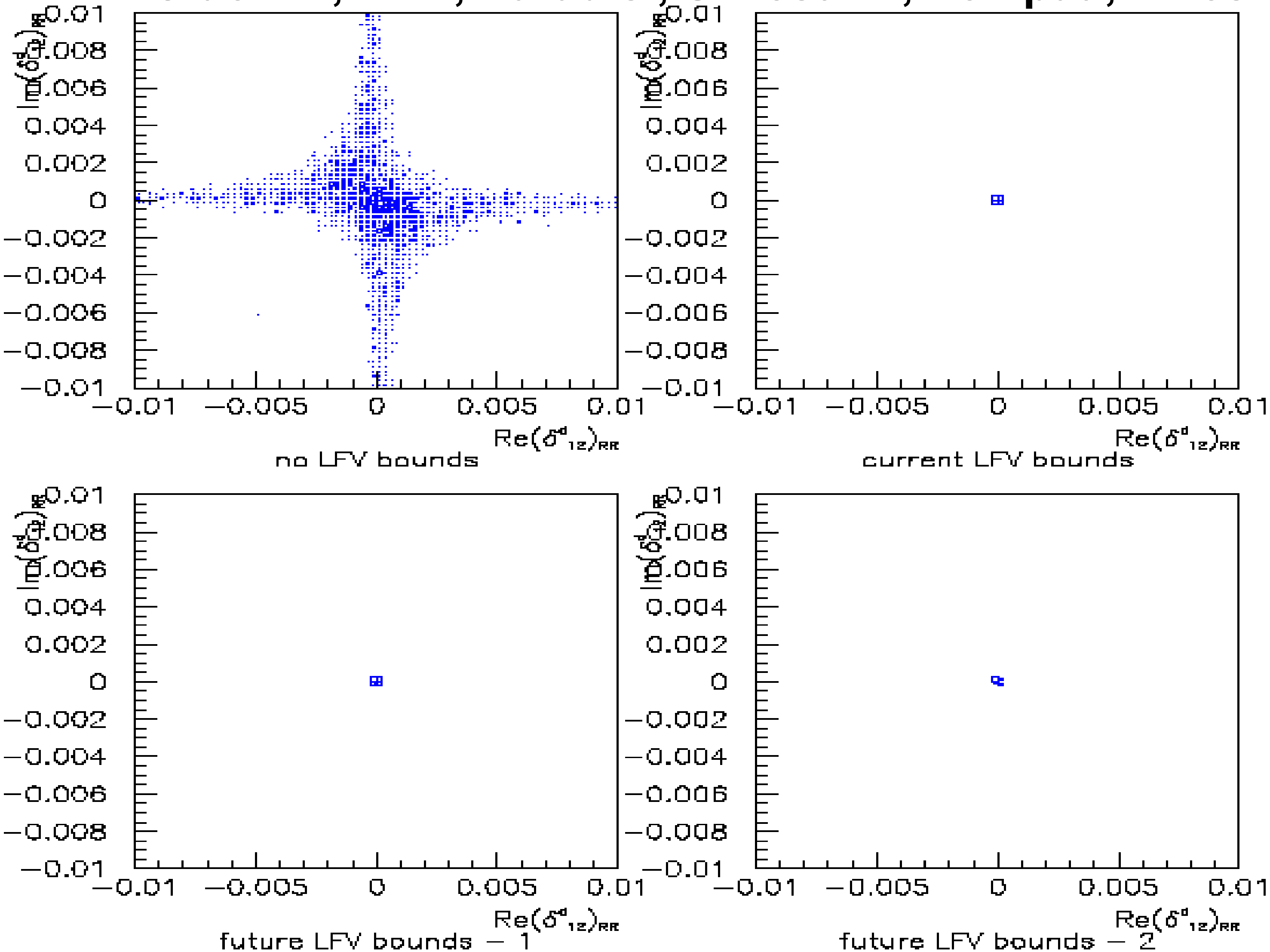
$$A^e_{ij} = A^d_{ji} \, .$$

SU(5) RELATIONS

	Relations at weak-scale	Relationss at M_{GUT}
(1)	$(\delta^u_{ij})_{\mathrm{RR}} \approx (m^2_{e^c}/m^2_{u^c})\ (\delta^l_{ij})_{\mathrm{RR}}$	$m^2_{u^c{}_0} = m^2_{e^c{}_0}$
(2)	$(\delta^q_{ij})_{\mathrm{LL}} \approx (m^2_{e^c}/m^2_{Q})\ (\delta^l_{ij})_{\mathrm{RR}}$	$m^2_{Q_0} = m^2_{e^c{}_0}$
(3)	$(\delta^d_{ij})_{\mathrm{RR}} \approx (m^2_{L}/m^2_{d^c})\ (\delta^l_{ij})_{\mathrm{LL}}$	$m^2_{d^c{}_0} = m^2_{L_0}$
(4)	$(\delta^d_{ij})_{\mathrm{LR}} \approx (m^2_{L_{avg}}/m^2_{Q_{avg}})\ (m_b/m_\tau)\ (\delta^l_{ij})^\star_{\mathrm{LR}}$	$A^e_{ij_0} = A^d_{ji_0}$

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

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



3 QUESTIONS

- Are we sure that there is new physics (NP) at the TeV scale? YES (barring an antropic approach)
- If yes, are we sure that LHC will see something “new”, i.e. beyond the SM with its “standard higgs boson”? YES
- If there is new physics at the TeV scale, what can flavor and DM physics tell to LHC and viceversa? (or, putting it in a less politically correct fashion: if LHC starts seeing some new physics signals, are flavor and DM physics still a valuable road to NP, or are they definitely missing that train? NO, actually to catch the “right train” it is highly desirable, though maybe strictly not necessary, to make use of all the three roads at the same time

A FUTURE FOR FLAVOR PHYSICS IN OUR SEARCH 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:

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)