PHYSICS BEYOND SM AND LHC

(Corfu 2010)

We all expect physics beyond SM

Fantastic success of SM (LEP!)

But it has its limits reflected by the following questions:

What is the origin of electroweak symmetry breaking and of quantum stability of the Fermi scale?

What explains the hierachy of fermion masses (flavour physics)?

What is the dark matter of the universe?

What explains the matter-antimatter asymmetry ?

Answers to those questions may deal with very different mass scales:

M_w 1 TeV 10^{10}-10^{16} GeV

„naturalness” of the Fermi scale

dark matter

Flavour physics (also neutrino masses)

Baryogenesis (leptogenesis)

GUT physics?

Can we find an one-theory explanation of all that? Would be great but we should not restrict our searches to this requirement.

Still, in perturbative scenarios (like supersymmetry) it is interesting to explore the potential links between the physics at different energy scales

Fermi scale

Spontaneous global symmetry breaking (NAMBU) is crucial for the Brout-Englert-Higgs mechanism:

spontaneous breaking of chiral symmetry (global)

$$SU(2) \times SU(2) \rightarrow SU(2)$$

of some dynamical sector coupled to the weak gauge bosons is the origin of their masses (Nambu-Goldstone bosons are used in the BEH mechanism)

Simple origin of the needed interactions with chiral symmetry (to be spontaneously broken) -
self interacting scalar field (Higgs field)

$$V = m_H^2 H H^+ + \frac{1}{2}\lambda (H H^+)^2$$

$$v^2 = -\frac{2m_H^2}{\lambda}$$

Big virtue - renormalizability; also easy description of fermion masses

Higgs potential: describes but does not explain dynamically the origin of the Fermi scale;

ANALOGY (FOR THE MECHANISM OF SPONTANEOUS SYMMETRY BREAKING)

strong	electroweak
Sigma model	Higgs doublet
Dynamical condensate	?

Moreover , the hierarchy problem

$$m_H^2 = m_H^2|_{tree} + \delta m_H^2$$ (loop correction)

At the scale *M*, embed the SM into some bigger theory and think in terms of the Appelquist-Carazzone decoupling

$$\delta m^2{}_H = \delta m^2_{SM} + \delta m^2_{NEW}$$

$$\delta m_H^2|_{SM} = c_2 M^2 + \ldots$$

$$\delta m_H^2|_{NEW} = c_2 \Lambda^2 + c_4 \ln \Lambda^2 + \ldots$$

M-cut-off to the Standard Model
Λ-cut-off to the extended theory

In the presence of a new scale *M*

$$\delta m^2_{SM} = (2m^2_W + m^2_Z + m^2_H - 4m^2_t)\frac{3M^2}{32\pi^2 v^2}$$

$$|\delta m^2_{SM}| \sim m^2_W \Rightarrow M < 0.6 \text{ TeV}$$

$$|\delta m^2_{SM}| < 10 M^2_W \Rightarrow M < 2\text{TeV}$$

$$|\delta m^2_{SM}| < 100 M^2_W \Rightarrow M < 6\text{TeV}$$

$$(m_H^2|_{tree},\ \delta m_H^2) \sim M_Z^2\,?$$

We expect low scale *M*

We expect it to be built into a structure such that δm_{NEW}^2 is also small

A driving force for looking for extensions of the Standard Model

Indeed….

Hierachical mass scales in particle physics have, so far, „natural" explanations

Proton mass and Planck scale

K_L –K_S mass difference, ΔM = 3×10^{-12} MeV instead of 10^{-6} MeV

π^+ π^- electromagnetic mass difference

No light scalars in nature except
for Nambu-Goldstone bosons (pions)

In summary, three questions about the electroweak symmetry breaking:

1) What is the dynamical origin of the electroweak scale?

2) What stabilises the electroweak scale ?
(where the scale M comes from?)

3) What unitarizes the WW scattering amplitude?

massive W → *A ~ GF E2~ s/v2*

Related but not identical questions: for instance, in the SM WW is unitarized by an elementary scalar (Higgs boson) but we have no idea what is the origin of G_F and what stabilises the Fermi scale.

The LHC should give us some answer to (2) and (3) but not necessarily to (1)

Basic concepts:

- **Supersymmetry**

- **New strong interactions to cut-off the SM; can be linked to extra dimensions**

(LEP DATA is a strong constraint on the physics beyond the SM)

The rest of these lectures:

- Some comments on supersymmetry, with the emphasize on the link between different scales

- A summary on strong interactions as a cutoff to the SM

Supersymmetry

- cut-off to SM is M_{soft}
- no quadratic dependence on cut-off Λ to MSSM in quantum corrections to the Higgs potential
- dynamical generation of the Higgs potential in terms of the soft supersymmetry breaking parameters (to be explained by a still deeper theory) and of quantum corrections to the scalar potential

IT „ANSWERS" ALL THREE QUESTIONS

The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles:

$$[u, d, c, s, t, b]_{L,R} \quad [e, \mu, \tau]_{L,R} \quad [\nu_{e,\mu,\tau}]_L \qquad \text{Spin } \tfrac{1}{2}$$

$$[\tilde{u}, \tilde{d}, \tilde{c}, \tilde{s}, \tilde{t}, \tilde{b}]_{L,R} \quad [\tilde{e}, \tilde{\mu}, \tilde{\tau}]_{L,R} \quad [\tilde{\nu}_{e,\mu,\tau}]_L \qquad \text{Spin } 0$$

$$g \quad \underbrace{W^{\pm}, H^{\pm}} \quad \underbrace{\gamma, Z, H_1^0, H_2^0} \qquad \text{Spin } 1 \text{ / Spin } 0$$

$$\tilde{g} \quad \tilde{\chi}^{\pm}_{1,2} \quad \tilde{\chi}^{0}_{1,2,3,4} \qquad \text{Spin } \frac{1}{2}$$

Two Higgs doublets, physical states: $h^0, H^0, A^0, H^{\pm}$

General parametrisation of possible SUSY-breaking terms
$\Rightarrow$ free parameters, no prediction for SUSY mass scale

SUSY breaking

Simplest ansatz: the Constrained MSSM (CMSSM)

Assume universality at high energy scale ($M_{\rm GUT}$, $M_{\rm Pl}$, ...)
renormalisation group running down to weak scale
require correct value of $M_{\rm Z}$

$\Rightarrow$ CMSSM characterised by

$$m_0^2,\ m_{1/2},\ A_0,\ \tan\beta,\ \mathrm{sign}\,\mu$$

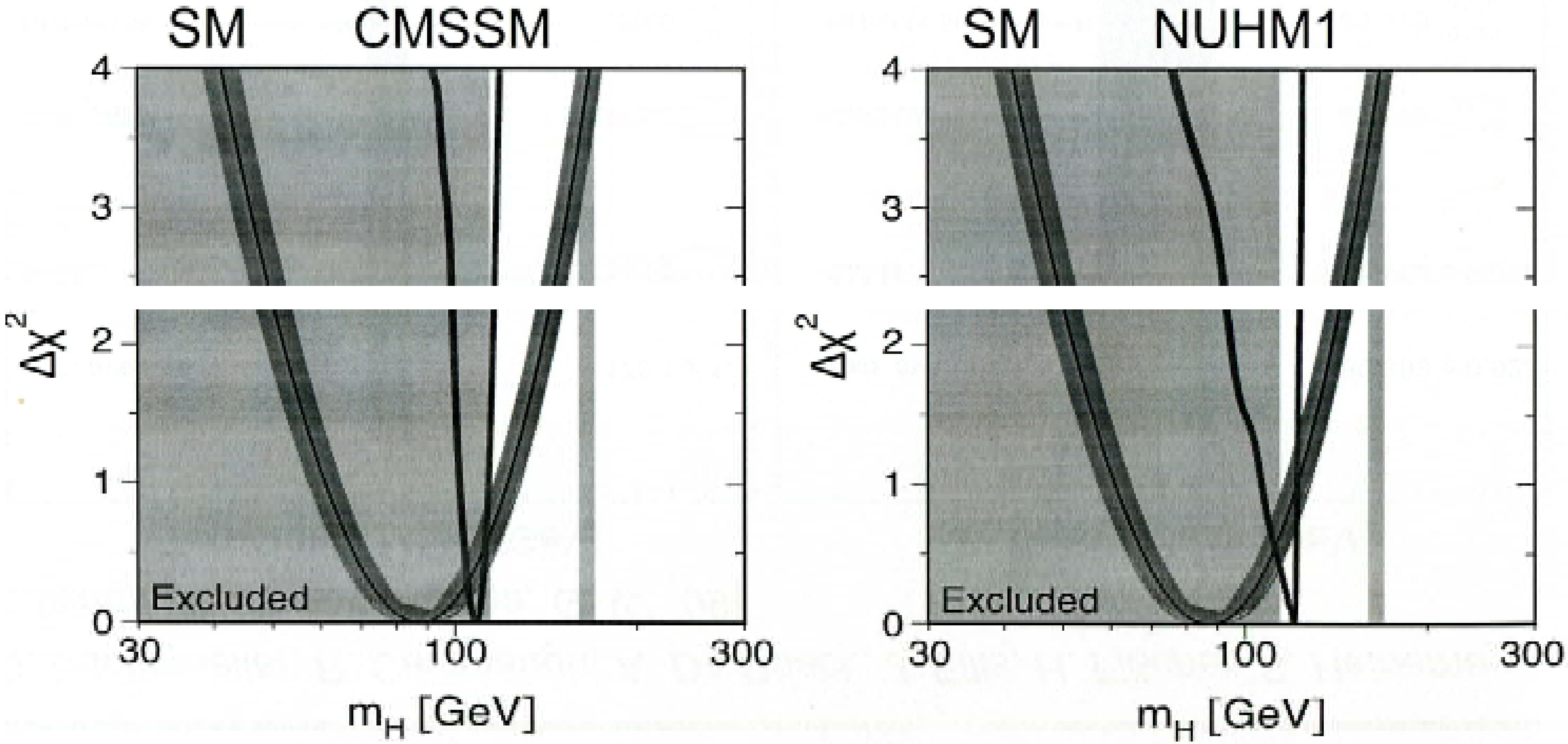
CMSSM is in agreement with all experimental constraints:
Electroweak precision observables (EWPO) + flavour physics
+ cold dark matter density + ...

Most sensitive precision observables

- W-boson mass: M_W
- Effective weak mixing angle: $\sin^2 \theta_{\text{eff}}$
- Anomalous magnetic moment of the muon: $(g-2)_\mu$
- FCNC b decay: $\text{BR}(b \to s\gamma)$
- Cold dark matter (CDM) density: Ω_{CDM}
- ...

Indirect prediction for the Higgs mass in the SM and the CMSSM / NUHM1 from precision data

χ^2 fit for M_h, without imposing direct search limit



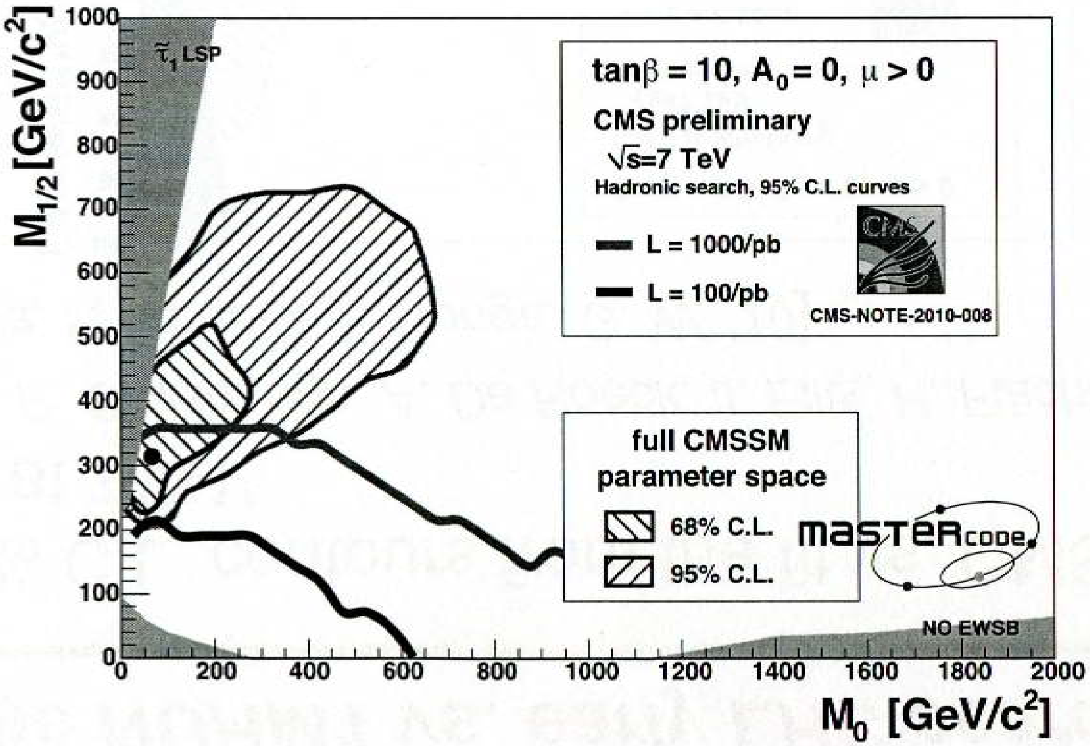
$M_h^{CMSSM} = 108 \pm 6$ GeV $\quad$ $M_h^{NUHM1} = 121^{+2}_{-14}$ GeV

⇒ Accurate indirect prediction: Higgs "just around the corner"?

Predictions for the SUSY scale from precision data: CMSSM

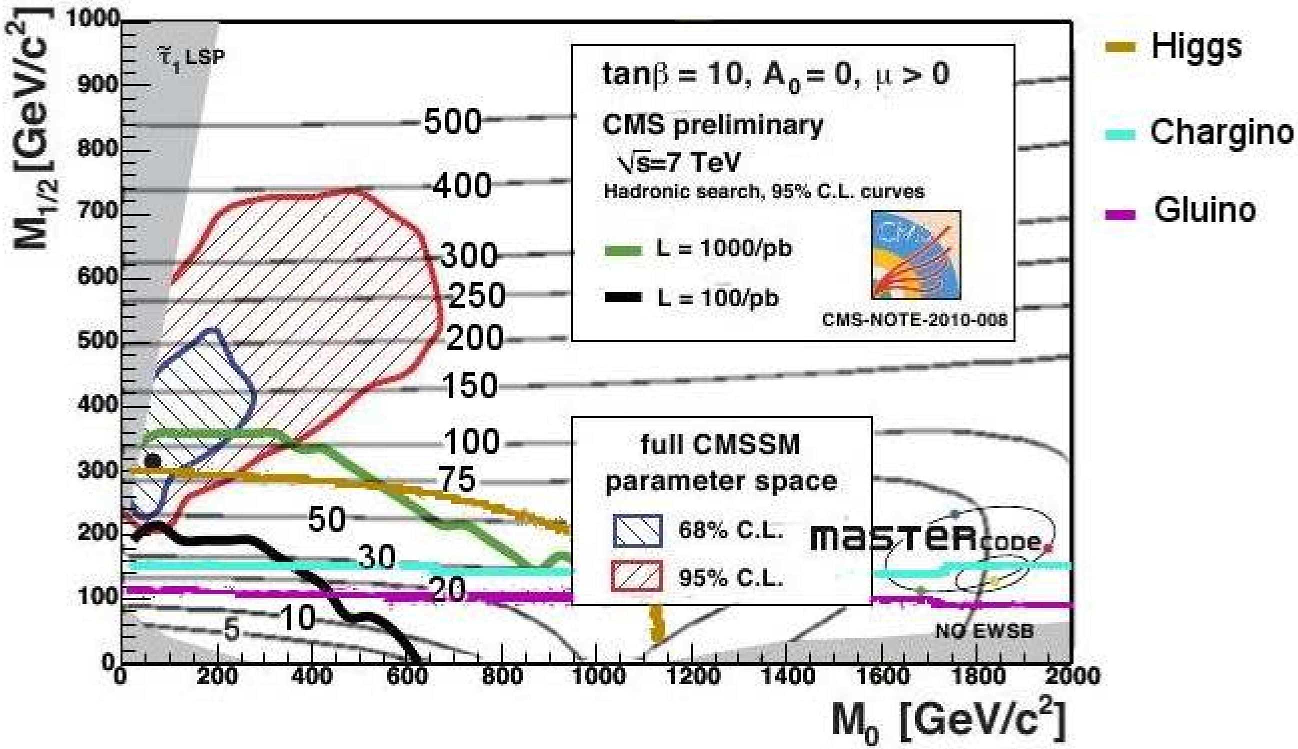
Comparison: preferred region in the m_0–$m_{1/2}$ plane vs. CMS 95% C.L. reach (→ *F. Ronga's talk, Thu.*) for $0.1, 1\ \mathrm{fb}^{-1}$ at $7\ \mathrm{TeV}$

[*O. Buchmueller, R. Cavanaugh, A. De Roeck, J. Ellis, H. Flächer, S. Heinemeyer, G. Isidori, K. Olive, P. Paradisi, F. Ronga, G. W. '10*]



⇒ Good prospects for early discovery! Get hint in first run?

The previous plot with superimposed fine tuning contours and Higgs mass limit (Badziak, Olechowski)



Focus point region disfavoured by the fit mainly due to *g*-2 (light sleptons are favoured)

$\Delta\chi^2$ for CMSSM and NUHM1 with (solid) and without (dashed) $(g_\mu - 2)$ constraint

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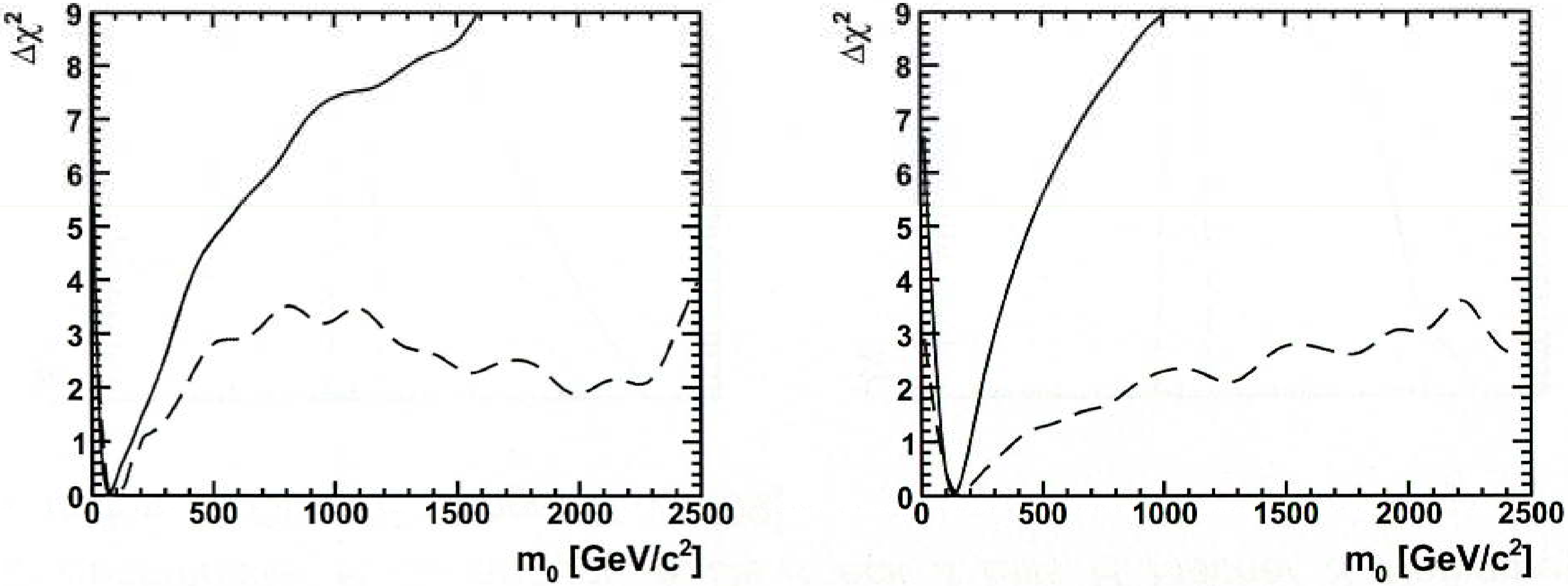
G. Isidori, K. Olive, F. Ronga, G. W. '09]



⇒ Slight Preference for light SUSY scale even if $(g_\mu - 2)$ is excluded from the fit

χ^2 functions for the relic density in the CMSSM and NUHM

without (solid) and with (dashed) the $\Omega_{\rm CDM}$ constraint

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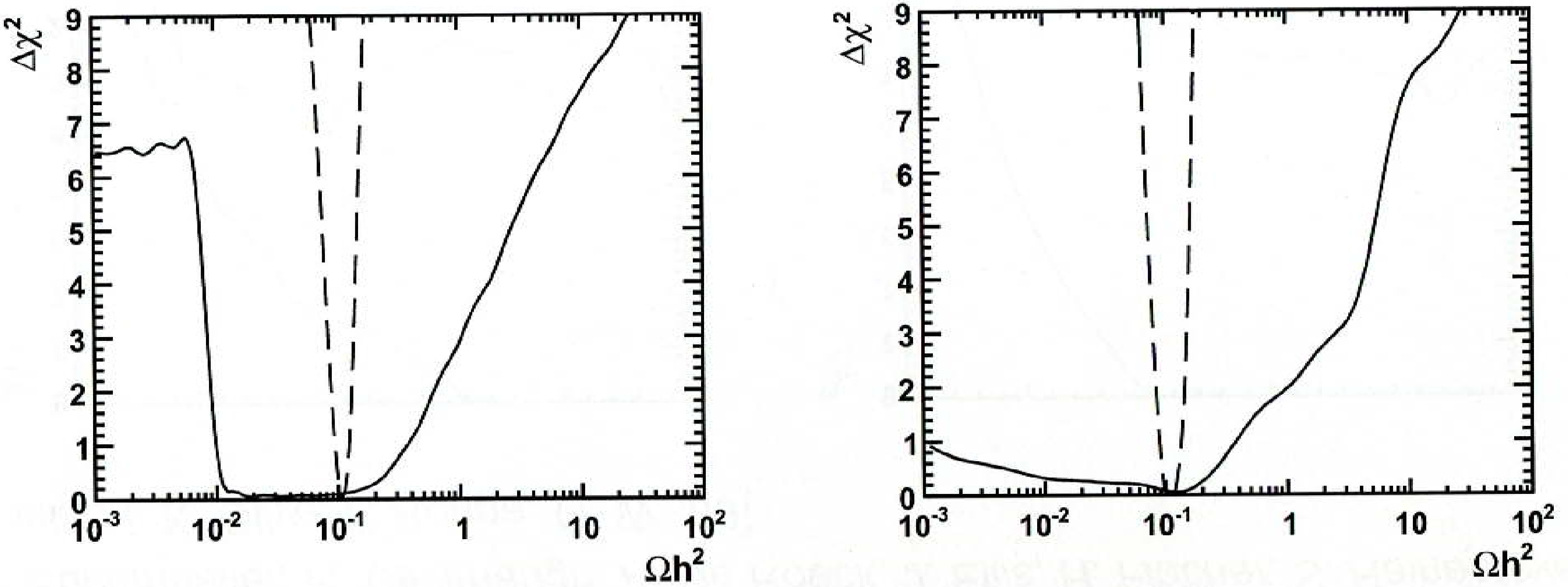


$\Rightarrow$ Indirect CDM prediction is in agreement with the measure value of the CDM relic density

Supersymmetric spectrum and:

1) The flavour problem

2) Baryogenesis via leptogenesis

as an illustration of

1) The potential link between the physics at different energy scales

2) Departures from the CMSSM in a „motivated" way

Flavour problem:

- understand the fermion masses and mixing;
- understand the suppression of FCNC (compared to the generic electroweak strength) and CP violation

The Standard Model does not have a problem with the second point

- **absence of tree-level effects**
- **GIM mechanism (unitarity of the quark mixing matrix**

but does not address the first one

Standard Model

$$\mathcal{L}_{eff}^{\Delta S=2} \sim \frac{1}{M_W^2}\frac{g^4}{(4\pi)^2}\{(U_{ts}^* U_{td})^2 +$$

$$+ (U_{cs}^* U_{cd})^2 \frac{m_c^2}{M_W^2} + \ldots\}(\bar{s}_L \gamma_\mu d_l)(\bar{s}\gamma^\mu d_L)$$

$$\sim \frac{1}{M_W^2}\frac{g^4}{(4\pi)^2} 10^{-5} (\bar{s}_L \gamma_\mu d_L)(\bar{s}_L \gamma^\mu d_L)$$

suppression scale

loop factor

The first two factors are the generic loop factors, the third one is the additional suppresion factor

Go beyond SM:

- to ease the hierachy problem
  –physics with the scale Mh around 1 TeV

- **to explain the pattern of quark masses, mixing**

Physics BSM may have new sources of FCNC and CP violation; they will be controlled by the proposed theory of fermion masses

but IS IT ENOUGH?

Precision of the FCNC and CP violation data
leaves little room for new effects from physics BSM.

With generic (anarchical) flavour structure, for

$$\frac{C}{\Lambda^2}\bar{Q}_i Q_j \bar{Q}_k Q_l \sim \mathcal{L}_{SM}^{\text{eff}}$$

one gets

$$\Lambda \sim 10^{\frac{5}{2}}\frac{\alpha_s}{\alpha_W}M_W \sim 100\text{TeV}, \quad C \sim \alpha_s^2$$ (SUSY)

If the scale of new physics is around 1 TeV, to solve the hierarchy problem, its flavour structure must indeed be strongly constrained.

Theories of fermion masses in supersymmetric models are based on

- horizontal (family) symmetries (spontaneously broken gauge symmetries) (many papers; most recent: Lalak, SP, Ross)

- fermion wave function renormalisation effects (Nelson-Strassler)…(Dudas, von Gersdorff, Parmantier, SP)

What about FCNC and CP violation in such models, once the parameters are chosen so that the fermion masses and mixing are reproduced? Any special predictions for the superpartner spectrum, to suppress those effects?

Simple example

Gauged U(1) family symmetry, spontaneously broken by a vev of a single familon field Θ with U(1) charge +1

Fermion charges (all ≥ 0):

left-handed doublets $Q_L^i :$ q_i

left-handed singlets $U_i^C,\, D_i^C :$ $u_i,\, d_i$

Higgs field $q_H = 0$

Yukawa matrix

$$\bar{Q}_L Y_U U_R H_c = \bar{Q}^i_L [a^j_i (\frac{\theta}{M})^{q_i + u_j}] U^j_R H_c$$

a_i^j ≡ 3 x 3 matrix of O(1) coefficients

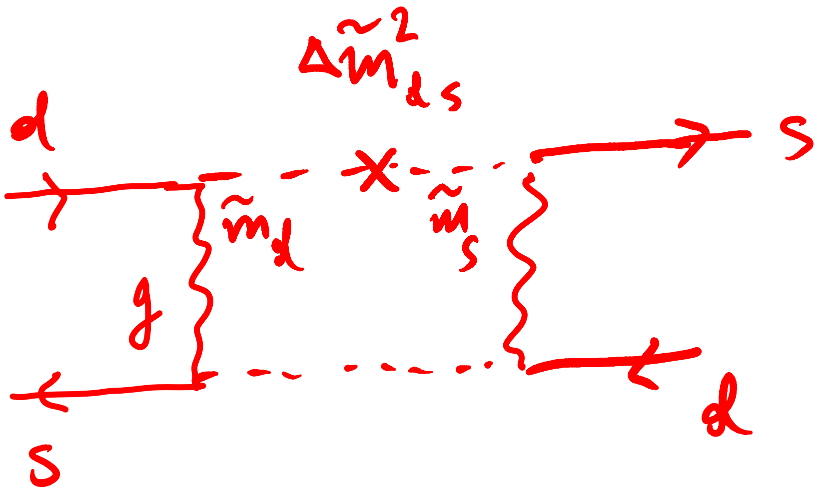
$$\epsilon \equiv \frac{\theta}{M} \sim \text{Cabibbo angle}$$

M-mass of the flavour messengers (heavy vector-like fermions)

Finite number of charge assignments that correctly describe fermion masses and mixing

But horizontal symmetries control also the soft sfermion masses and sfermion exchange contributes to FCNC and CP violation transitions

New sources of FCNC and CP violation, e.g.



$$\delta_{ijMN} = \frac{\Delta\tilde{m}^2_{ijMN}}{\tilde{m}^2_{av}}, \quad M, N = L, R$$

$$\begin{aligned} L_{eff} &= \frac{\alpha_s^2}{216\tilde{m}^2_{qij}}((\delta^d_{12\,LL})^2(\bar{d}_L\gamma_\mu s_L\bar{d}_L\gamma_\mu s_L) \times f(x) \\ &+ (\delta^d_{12\,RR})^2(\bar{d}_R\gamma_\mu s_R\bar{d}_R\gamma_\mu s_R) \times f'(x) \\ &+ (\delta^d_{12\,LL})(\delta^d_{12\,RR})(\bar{d}_R s_L\bar{d}_L s_R) \times f''(x) + \ldots + \text{h.c.}) \end{aligned}$$

In family symmetry models, δ's are predicted as **O(ε^p)**, e.g.

$$m^2_{\tilde{q}ij}\tilde{q}_i^\dagger \tilde{q}_j \epsilon^{|q_i - q_j|}$$

$$\rightarrow \;\; (\delta^{\tilde{q}}_{ij})_{LL} = \epsilon^{|q_i - q_j|}$$

and can be compared with experimental bounds on them

$$
\begin{aligned}
L_{eff} &= \frac{\alpha_s^2}{216\tilde{m}_{qij}^2}((\delta^d_{12\,LL})^2(\bar{d}_L\gamma_\mu s_L\bar{d}_L\gamma_\mu s_L)\times f(x) \\
&+ (\delta^d_{12\,RR})^2(\bar{d}_R\gamma_\mu s_R\bar{d}_R\gamma_\mu s_R)\times f'(x) \\
&+ (\delta^d_{12\,LL})(\delta^d_{12\,RR})(\bar{d}_R s_L\bar{d}_L s_R)\times f''(x) + \ldots + \text{h.c.})
\end{aligned}
$$

q	ij	$(\delta^q_{ij})_{MM}$	$\langle\delta^q_{ij}\rangle$
d	12	$0.01 \sim \epsilon^2$	$0.0007 \sim \epsilon^4$
d	13	$0.07 \sim \epsilon$	$0.025 \sim \epsilon^2$
d	23	$0.21 \sim \epsilon$	$0.07 \sim \epsilon$
u	12	$0.035 \sim \epsilon^2$	$0.003 \sim \epsilon^3$

Experimental bounds

Conclusions for supersymmetric family symmetry models (Lalak,SP, Ross):

they can remain consistent with the bounds on FCNC and CP violation for superpartner physical masses $\leq$O(1 TeV) but generically require strong flavour blind renormalisation effects on the squark masses. This requires $m_{1/2}/m_0 \gtrsim 7$

e.g. $m_{1/2} = 300\mathrm{GeV},\ m_0 \sim 50\mathrm{GeV}$

$$m_{\tilde{g}} = 900\mathrm{GeV},\ m_{\tilde{q}} = 800\mathrm{GeV}$$

(similar to the fits)

Comparison with models based on wave function renormalisation effects

Superpotential and kaehler potential for family symmetry models (at the scale M of spontaneous breaking of horizontal symmetry):

$$W = \epsilon^{q_i+u_j+h_u}(Y_{ij}^U + A_{ij}^U X)Q_i U_j H_u +$$

$$+\epsilon^{q_i+d_j+h_d}(Y_{ij}^D + A_{ij}^D X)Q_i D_j H_d +$$

$$+\epsilon^{l_i+e_j+h_d}(Y_{ij}^E + A_{ij}^E X)L_i E_j H_d$$

$$K = \epsilon^{|q_i-q_j|}(1 + C_i j X^\dagger X)Q_I^\dagger Q_j + \ldots$$

X- a supersymmetry breaking spurion: X=\theta^2 F
Y, A of order unity

Wave function renormalisation models (mass hierachy generated by wave function renormalisation) at some high scale M

$$W = (Y_{ij}^U + A_{ij}^U X) Q_i U_j H_u + (Y_{ij}^D + A_{ij}^D X) Q_i D_j H_d +$$

$$+ (Y_{ij}^E + A_{ij}^E X) L_i E_j H_d$$

$$K = \epsilon^{-2q_i} Q_i^\dagger Q_i + C_{ij} X^\dagger X Q_i^\dagger Q_j + \ldots$$

Y,A,C are anarchical of order 1

Origin of wave function renormalisation: RG running from M0 to M determined by a superconformal sector (Nelson,Strassler) or wave function localisation in extra dimension of the radius 1/M

In the canonical basis:

$$W = \epsilon^{q_i+u_j+h_u}(Y^U_{ij} + A^U_{ij}X)Q_iU_jH_u +$$

$$+\epsilon^{q_i+d_j+h_d}(Y^D_{ij} + A^D_{ij}X)Q_iD_jH_d +$$

$$+\epsilon^{l_i+e_j+h_d}(Y^E_{ij} + A^E_{ij}X)L_iE_jH_d$$

$$K = Q^\dagger_i Q_i + C_{ij}\epsilon^{q_i+q_j}X^\dagger X Q^\dagger_i Q_j + ...$$

We get the same predictions for the fermion masses if we identify q_i with the Values of the horizontal charges.

Big difference in the sfermion soft mass prediction

Comparison with the wave function renormalisation models:

Fixing the parameters so that both approaches predict the same fermion masses and mixing, we get

$$\tilde{m}^2_{d,LL,ij} \sim r_q m^2_{1/2} \delta_{ij} + \widehat{m}^2_q \epsilon^{|q_i \pm q_j|}$$

$$\tilde{m}^2_{e,LL,ij} \sim r_l m^2_{1/2} \delta_{ij} + \widehat{m}^2_l \epsilon^{|l_i \pm l_j|}$$

Conclusion for the wave function renormalisation models (Dudas, von Gersdorff, Parmentier, SP):

- New FCNC and CP violation are very strongly suppressed (some new effects can only be seen in the (bs) and lepton sectors)

- The ratio of the 1st and 2nd generation squark to slepton masses is given by the ratio of the gauge couplings. All are predicted in terms of the gaugino mass.
  The 1st and 2nd generation squarks are degenerate with gluinos.

Stop mass can be driven by m0 (focus point with light gluino)