Corfu3 2011: Higgs and flavour

Lecture 4

Higgs sector

Generic characteristics of the scalar sector in (perturbative or non-perturbative) extensions of the SM with elementary (2HDM, supersymmetry) or composite scalars

- **often more than one scalar and/or vectors coupled to *WW***
- **none of the scalars couple to *WW* and to fermions exactly like the SM Higgs boson (because of the mixing between them)**

Looks like good news but… how big effects can we expect?

Implications (with perturbative or non-perturbative BSM physics)

- *WW* scattering amplitude is not fully unitarized by a single scalar; other scalars (elementary or composite) or vectors must be active in unitarization

- production cross sections for h and its decay rates are modified (usually more difficult to discover)

Unfortunately, the departures from the SM Higgs are likely to be tiny-v/M; take e.g. M=1 TeV (but not necessarily!),
particularly with the limits on BSM particles coming from the LHC

Partial unitarization of the WW scattering by the lightest scalar

$$A_{WW} \sim \frac{s}{v^2} - \left(1 - \frac{v^2}{M^2}\right)\frac{s}{v^2}\frac{t}{t-m_h^2} + \sum_n$$

$$\approx \frac{s}{f^2} + \sum_n$$

$$m_A^2 = \frac{2B\mu}{\sin 2\beta}$$

$\boxed{\text{MSSM}}$

$$\begin{pmatrix} h \\ H \end{pmatrix} \equiv \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h_u \\ h_d \end{pmatrix}$$

where

$$\frac{\sin 2\alpha}{\sin 2\beta} = \frac{m_A^2 + m_Z^2}{m_H^2 - m_h^2}$$

$$\frac{\cos 2\alpha}{\cos 2\beta} = \frac{m_A^2 - m_Z^2}{m_H^2 - m_h^2}$$

$M_h < M_Z$: ~~first test of SUSY~~ ?

1) What are experimental signatures of h ?

2) suppose a Higgs scalar is discovered; can we distinguish between SM and SUSY Higgs boson ?

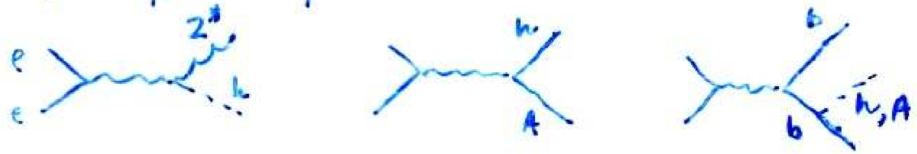
$$\operatorname{tg} 2\alpha = \operatorname{tg} 2\beta \, \frac{M_A^2 + M_Z^2}{M_A^2 - M_Z^2}$$

3) Search for H^0 & A^0; $H^{\pm}$

	ZZ	ZA	$u\bar{u}$	$D\bar{D}$
h	$\sin(\beta-\alpha)$	$\cos(\alpha-\beta)$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{-\sin\alpha}{\cos\beta}$
H	$\cos(\beta-\alpha)$	$\sin(\alpha-\beta)$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\cos\beta}$
A	—	—	$\operatorname{ctg}\beta$	$\operatorname{tg}\beta$

$M_A \to \infty \Rightarrow \sin(\beta-\alpha) \cong 1$, $\cos(\alpha-\beta) \cong 0$, SM couplings of h!

For different regions of $(\operatorname{tg}\beta, M_A)$ dominance of different production mechanisms



ORIGIN OF LARGE CORRECTIONS

On dimensional grounds and from no-renormalization theorem for unbroken SUSY theories

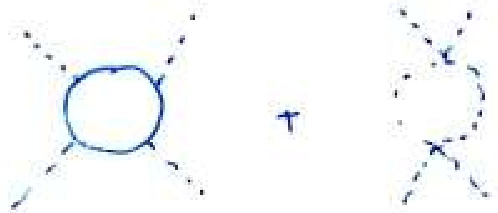
$$\delta m_i^2 = \hat{m}_i^2 - m_i^2 \sim O(M_{SUSY}^2)$$

and log div

$$\delta \lambda_i = \lambda_i - \frac{g_1^2 + g_2^2}{4}, \quad \text{etc}$$

finite and $O(\log M)$
(no new counterterms)

Dominant contribution



$$\delta \lambda_i \sim Y_t^4 \ln \frac{M_{SUSY}}{m_t} \Rightarrow$$

1) $\Rightarrow \Delta M_h \sim \boxed{\frac{3 g^2 m_t^2}{8\pi^2 M_W^2 \sin^2\beta}} m_t^2 \ln \frac{M^2}{m_t^2}$

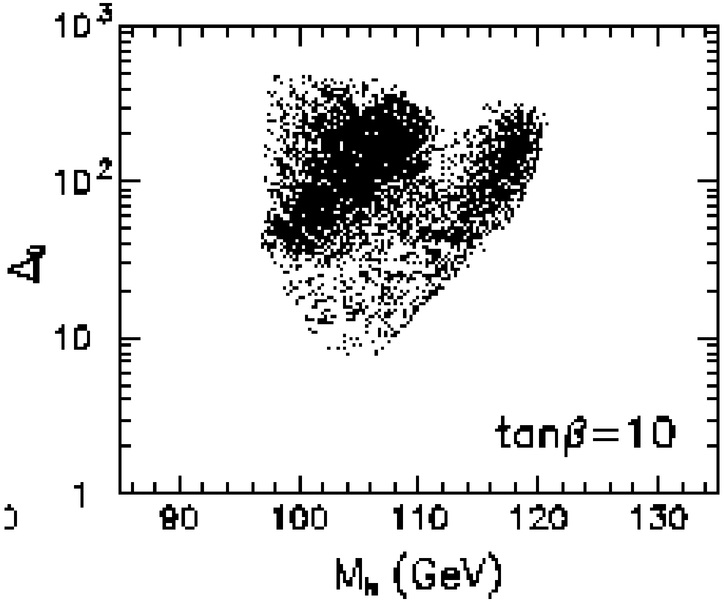
2) $\delta m_i^2 \sim O(M^2) \overset{?}{\Rightarrow} \boxed{M_A \sim O(M_{SUSY})}$

Upper bound on m_h

The Higgs boson mass in supersymmetric models
(of the lightest one/closest to the SM Higgs):

MSSM (Haber,Hempling '91, Barbieri et al. '91…)

$$m_H^2 = M_Z^2 \cos^2 2\beta + \frac{3\alpha}{4\pi s_W^2}\frac{m_t^4}{M_W^2}[\ln \frac{M_{\tilde{t}_1}^2 M_{\tilde{t}_2}^2}{m_t^4} + \ldots]$$



New exclusion limits: SM Higgs boson is excluded at 95% CL in the range 145-460 GeV.

Very interesting but not surprising in view of the precision fits

Open windows for the SM Higgs : 114-145 GeV
> 460 GeV

Exclusion limits as a function of the scalar couplings?
Upper bounds on various scalar couplings as a function of its mass?

Invisible Higgs?

Several options for larger m_h with no excesive fine-tuning

e.g. additional singlet(s)

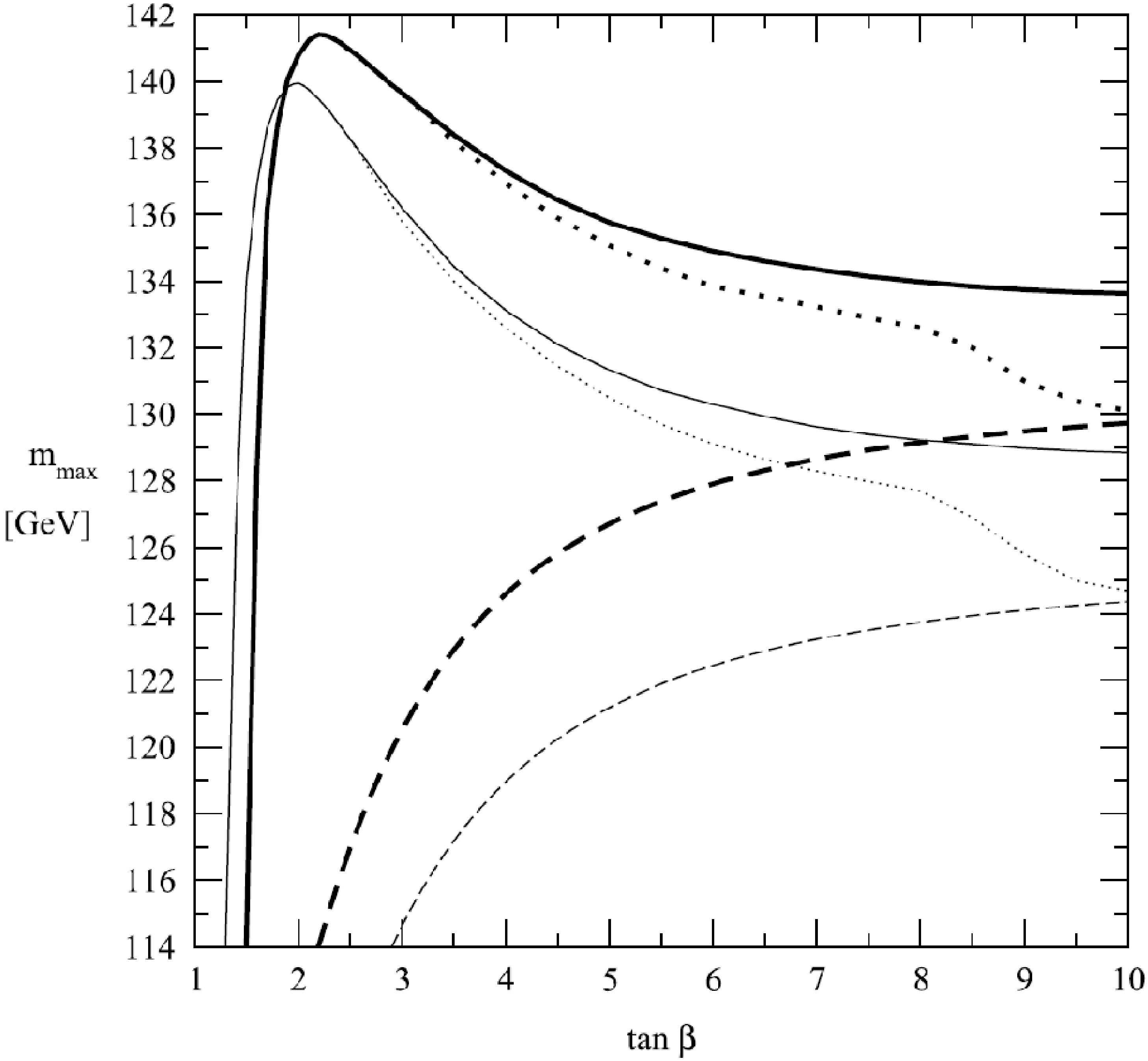
(Espinosa, Quiros 92, Gunion, Ellwanger, …Kolda) various versions

$$W = \lambda S H_u H_d + \ldots$$

$$M_h^2 = M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \Delta_{mix} + rad.corr.$$

Even for λ small enough to remain perturbative up to M_{GUT}, $m_h \sim 140$ GeV is accessible either for low $\tan\beta$ or for large $\tan\beta$ with large Δ_{mix}

Larger λ (Barbieri et al..) $\Rightarrow$ **m_h up to 300 GeV**
(for perturbative theory up to 10 TeV)



142
140
138
136
134
132
130
128
126
124
122
120
118
116
114
m_max
[GeV]
1
2
3
4
5
6
7
8
9
10
tan β

Mixing (h, s) with H decoupled

$$\begin{bmatrix} M_{hh}^2 & M_{hs}^2 \\ M_{hs}^2 & M_{ss}^2 \end{bmatrix}$$

M_h^2 – mass with mixing

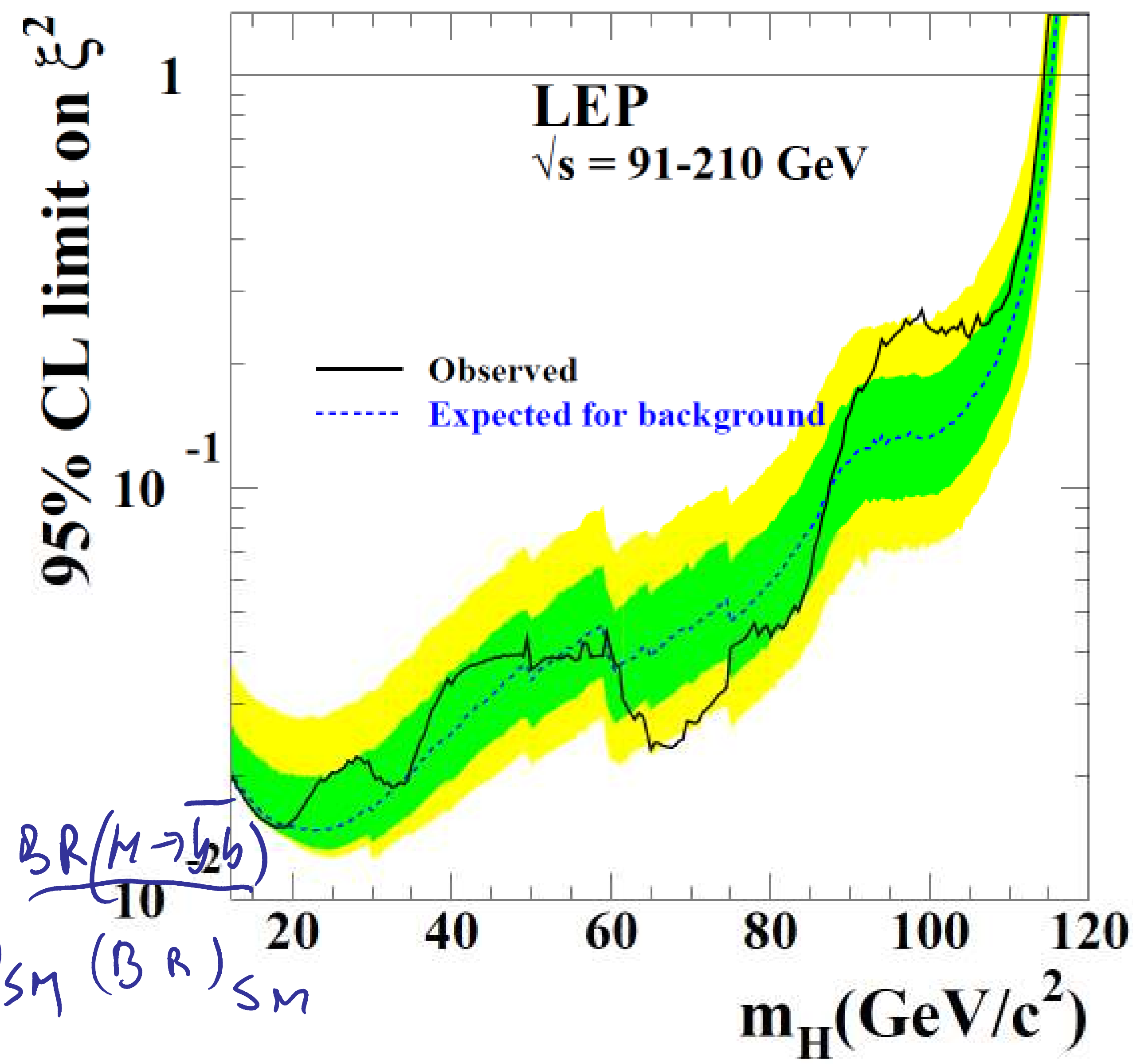
$M_{h_0}^2$ – mass without mixing

M_s^2 – singlet mass with mixing

For $\sin 2\beta \simeq 0$:

$$M_h^2 = \frac{M_{h_0}^2 - \sin^2\gamma\, M_s^2}{\cos^2\gamma} = M_{h_0}^2 + \tan^2\gamma \underbrace{\left(M_{h_0}^2 - M_s^2\right)}_{\text{take } > 0}$$

$\sin^2\gamma \equiv \xi$



$$\xi^2 = \frac{g_{ZZ}^2}{(g_{ZZ}^2)_{SM}} \frac{BR(H \to b\bar{b})}{(BR)_{SM}}$$

Examples

M_{h_0}	M_S	$\sin^2\gamma = \xi$	M_H
110	90	1/3	119
120	90	1/3	132
130	90	1/3	145

NMSSM can be useful in two ways:

Can explain supersymmetric Higgs boson above 120-125 Gev

For the Higgs around 115 -125 GeV can make supersymmetry consistent with stops lighter than the MSSM stops for the same higgs mass

(SUPERSYMMETRIC) FLAVOUR PROBLEM AND SUPERSYMMETRIC SPECTRUM

Flavour problem:

- understand the pattern of fermion masses and mixing (fermion mass problem)

- understand the suppression of FCNC (compared to the generic electroweak strength) and CP violation (flavour changing problem)

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

E.g. K-K mixing

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

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

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

suppression scale

loop factor

U - CKM matrix

Go beyond SM

to explain the pattern of quark, lepton masses, mixing

<u>**Another reason to go beyond SM is to easy the hierachy problem; what is their interplay?**</u>

This physics BSM has new sources of FCNC and CP violation; they will be controlled by the proposed theory of fermion masses

but IS IT ENOUGH?

(particularly for physics at TeV)

SOFT TERMS CREATE A PROBLEM

Uncontrolled flavour structure of the soft terms would be a disaster

Often taken attitude in supersymmetric models, e.g. MSSM:

Worry only about the hierachy problem and control new sources of FCNC, leaving aside the question about the pattern of the fermion masses;
The fermion mass problem as in SM.

„Solutions" to the flavour changing problem: CMSSM (Minimal Flavour Violation) , Gauge mediation….

Supersymmetry and gravity mediation of its breaking

Assumption: no other constraints on the soft terms except imposing the "theory" of fermion masses

Theories of fermion masses

(in supersymmetric and non-supersymmetric models) are based on

- horizontal (family) symmetries (spontaneously broken gauge symmetries)

- fermion wave function renormalisation effects, or equivalently overlap of localised fermion wave functions in extra dimension

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 $\geq$ 0):

left-handed doublets $\quad q_L^i : \quad q_i$

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

Higgs field $\quad q_H = 0$

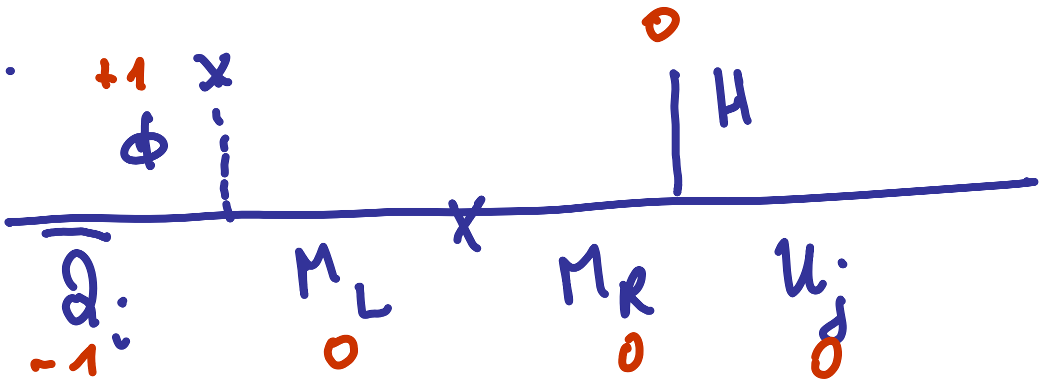
ALSO, A SET OF VECTOR-LIKE FERMIONS WITH SOME HORIZONTAL CHARGES (MODEL DEPENDENT), DOUBLTS ANS SINGLETS OF SU(2)

(Messengers)

Begin with $O(1)$ dimensionless couplings and explain the hierarchy of Yukawas

Messengers: heavy vector-like fermions M_L, M_R, charged under SM groups and horizontal charges

E.g.:



$$\left(\frac{\langle\phi\rangle}{M}\right)^{q_i+u_j} H \bar{Q}_i u_j$$

Yukawa matrix

$$\bar{Q}_L Y_U U_R H_c = \bar{Q}_L^i [a_i^j (\frac{\theta}{M})^{q_i + u_j}] U_R^j H_c$$

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

E.g. q = 3,2,0

Horizontal symmetries again

They control also the soft sfermion masses

Chiral superfields $\quad f_i$

vector-like pairs $\quad F_i + \bar{F}_i$

Flavon θ

Superpotential (U(1) symmetry imposed)

$$W = \theta \bar{f}_i F_j + \theta \bar{F}_i F_j + M \bar{F}_i F_i$$

$$+ \ldots$$

Kähler (leading terms)

$$K = f_i^\dagger f_i + F_i^\dagger F_i$$

$$+ \frac{X^\dagger X}{M_{Pl}^2} \left(a_i f_i^\dagger f_i + b_j f_i^\dagger F_j \Big|_{q(f_i) = q(F_j)} \right.$$

$$\left. + c_j F_i^\dagger f_j + d_i F_i^\dagger F_i \right)$$

NO assumption about universality of soft terms

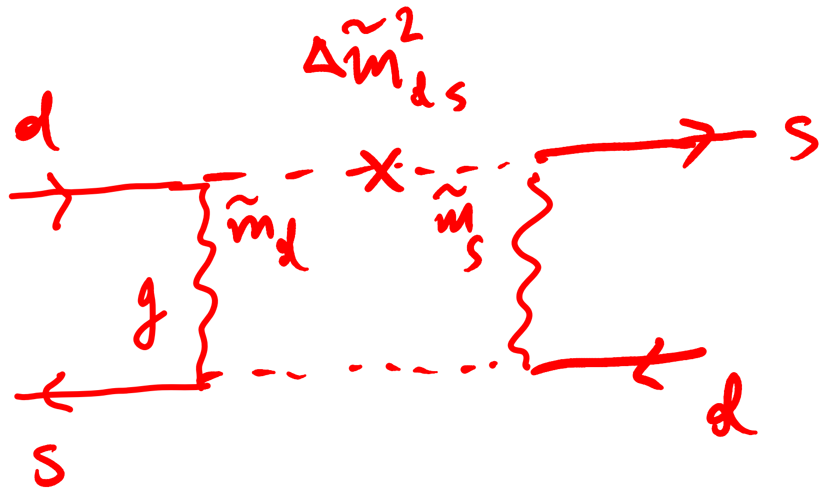
After integrating out the heavy fields, we get the standard result for the "SM" soft terms

$$(\tilde{m}_f^2)_{ij} \sim \tilde{m}^2 \left(a_i \delta_{ij} + d_{ij} \epsilon^{q_i - q_j} \right)$$

where $\tilde{m}^2 = F_X F_X / M_{PL}^2$

$$\epsilon = \frac{\langle \theta \rangle}{M_F}$$

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



In the SCKM basis

with the mass diagonal quarks

one defines mass insertions

(Gabbiani, Gabrielli, Masiero, Silvestrini, 1996):

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

In family symmetry models, δ's are predicted as $O(\varepsilon^p)$, e.g.

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

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

and can be compared with experimental bounds on them

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

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 for squark mass 500 GeV

Some details:

Leading flavour changing sfermion mass operators (generically present in gravity mediation models)

- $$M^2_{\mathsf{SUSY}} \tilde{Q}^\dagger_{Li} \tilde{Q}_{Lj} \left(\frac{\theta}{M}\right)^{q_i - q_j}$$

  and similarly for RR up and down squarks

- for U(1): D-term contribution to

  the diagonal mass splitting

  $$\tilde{m}_i^2 - \tilde{m}_j^2 = g(q_i - q_j) < D >$$

$$\cancel{< D > \sim M^2_{SUSY}}$$

$\langle D \rangle$ **correlated with** $\tilde{m}_F^2$ **in a model dependent way**

e.g.

D term induced only by soft terms generated by F term breaking

$$\langle D \rangle \cong \tilde{m}_F^2$$

F term and D term breaking

$$m_F^2 = \varepsilon^2 D$$

$F_2 \sim m\sqrt{\xi}$

$\varphi_1 \sim \sqrt{\xi}$

F - I $\quad \phi_1(\varphi_1, F_1, \psi_1) \quad \phi_2(\varphi_2, F_2, \psi_2)$

$$m_F^2 = \frac{F_2^2}{M_{PL}^2} = \frac{m^2\xi}{M_{PL}^2} = D\frac{\xi}{M_{PL}^2} = D\underbrace{\left(\frac{\xi}{M_{mess}^2}\right)}_{\epsilon^2}\frac{M^2_{mess}}{M_{PL}}$$

φ_1 plays role of fermion

In models based on horizontal U(1) symmetry
to explain the fermion mass hierarchy, (with D term breaking)

$$(\tilde{m}_X^2)^{AB} = q_X^A \delta^{AB} \tilde{m}_D^2 + \varepsilon^{|q_X^A - q_X^B|} \tilde{m}_F^2$$

X = *Q*, *U*, *D*

q_X^A – the respective horizontal charges

ε - Cabibbo angle

$$\tilde{m}_D^2 = g\langle D\rangle$$

$\tilde{m}_F^2$ - gravity mediation contribution
inverted hierarchy for $q^3 = 0$, $q^{1,2} > 0$

Flavour-motivated „inverted hierarchy” spectrum

3rd generation light, 1st and 2nd heavy

Dudas et al. 95, Barbieri et al. 95
Cohen et al.. 96
Nelson and Wright 97
Arkani-Hamed and Murayama 97
Lavignac et al.. 05
Barbieri et al.. 07

is much weaker constrained

Then, with $q_3 = 0$ we get the desired pattern of sfermion masses (1^{st} & 2^{nd} heavy, 3^{rd} light)

inverted hierarchy

No conflict with F.T.

FCNC sufficiently suppressed for $m_D \gtrsim 3$ TeV

3. SUSY: b-Jets + lepton + Missing E_T

- What if gluinos decay preferentially to 3rd generation?
- Consider several pheno. scenarii, such as:

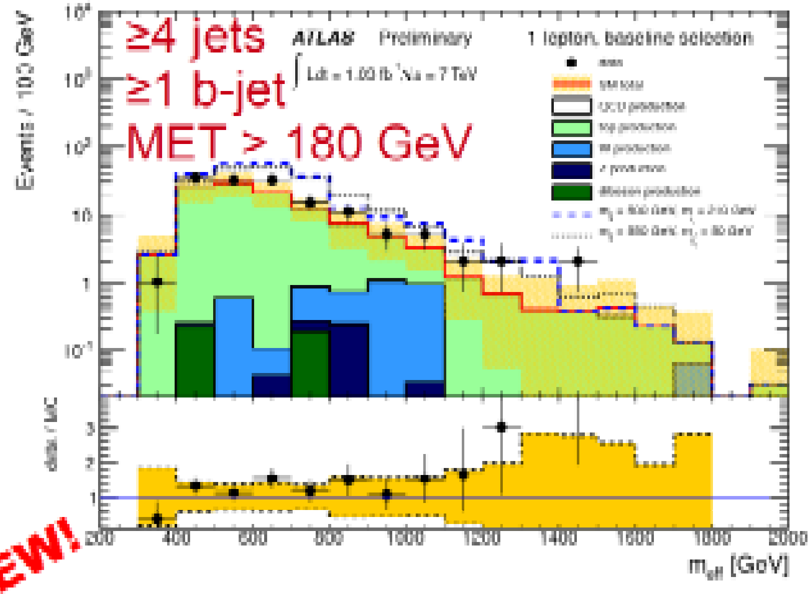
  Assume $m(\tilde{g}) > m(\tilde{t}_1) > m(\tilde{\chi}_1^{\pm}) > m(\tilde{\chi}_1^0)$
  (and everything else heavier)

  Consider only the following decays:

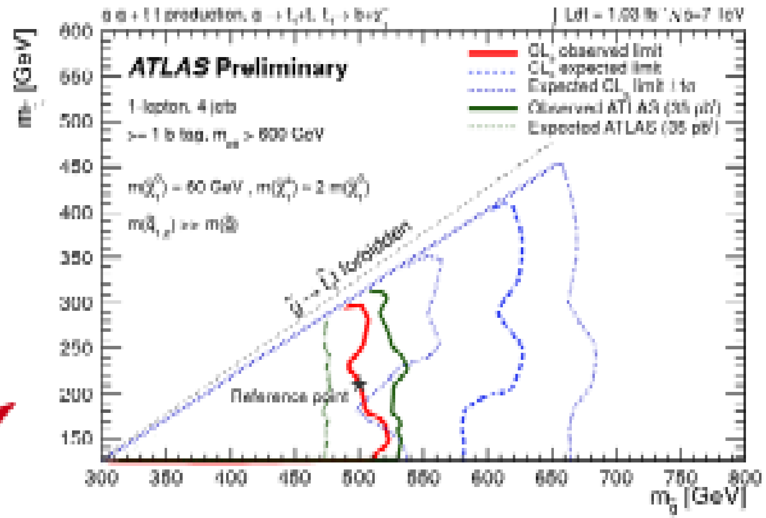
  $\tilde{g} \rightarrow \tilde{t}_1 t$; $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^{\pm}$

  and $\tilde{\chi}_1^{\pm} \rightarrow W^* \tilde{\chi}_1^0$
- Complex final states with lepton(s) and b-jets
- Limit on gluino mass:

  m(gluino) > 500 GeV at 95% C.L.



NEW!



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Inverted hirerarchy and LHC searches

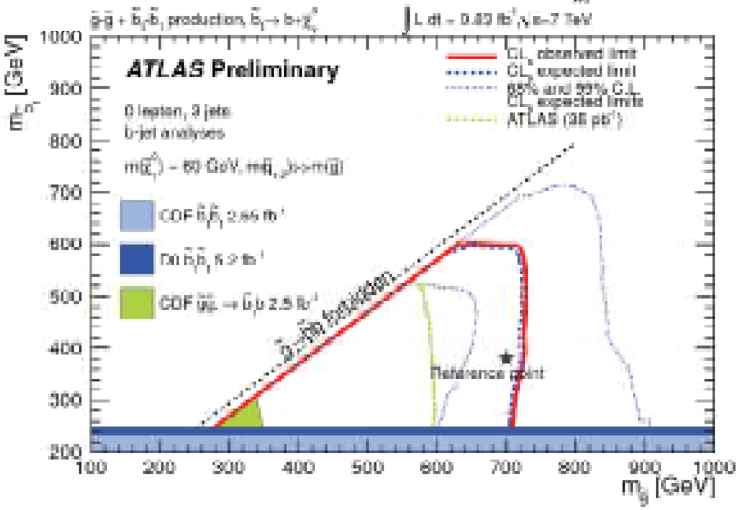
$$pp \to \tilde{g}\tilde{g}, \qquad \tilde{g} \to b\bar{b}\chi^0,\ t\bar{t}\chi^0,$$

$$\tilde{g} \to t\bar{b}\chi^-,\ \bar{t}b\chi^+$$

$$\searrow W^-\chi^0$$

Phenomenological MSSM

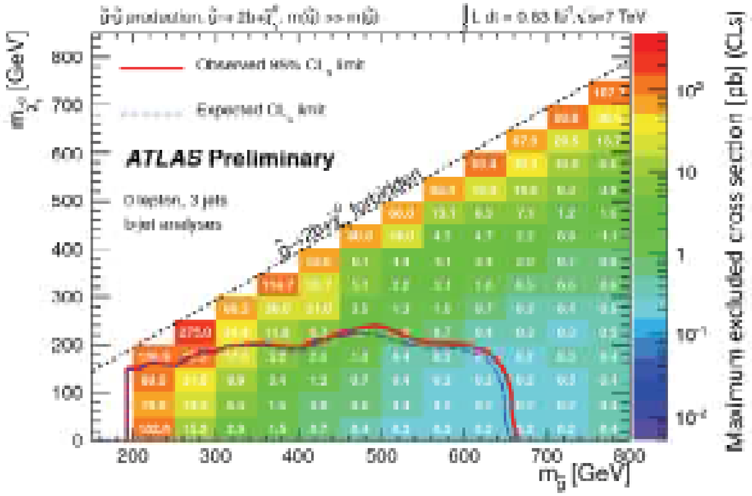
$BR(\tilde{g} \to \tilde{b}_1 b) = 100\%$ $BR(\tilde{b}_1 \to b + \tilde{\chi}_1^0) = 100\%$ $m_{\tilde{\chi}_1^0} = 60$ GeV



Gluino masses below 720 GeV excluded for sbottom masses below 600 GeV

General simplified model

Gluino-gluino production with 3-body decay to $b\bar{b}\tilde{\chi}_1^0$



Gluino masses between 200-660 GeV excluded up to LSP mass of 160 GeV

End