Effective description of squark interactions

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J.G., Siannah Peñaranda, Raül Sánchez-Florit, JHEP 0904:016,2009, arXiv:0812.1114

Outline

Introduction

The Standard Model

- Present paradigm of elementary particles composition and interactions
- Gauge theory
  - $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$
  - Spontaneous Symmetry Breaking $SU(2)_L \otimes U(1)_Y \Rightarrow U(1)_Q$

    $\Rightarrow$ Massive gauge bosons: M_Z, M_W
- Probed at the 10^{-3} level at LEP, SLD, Tevatron, ...
- Theoretical problems: hierarchy problem
- Prepared for whatever new physics might appear at Experiments!

  $\Rightarrow$ Study possible extensions of the SM

Missing: Higgs boson

- Experimental determination SSB
- Last (and necessary) building block of the Standard Model
  - or any electroweak gauge theory with massive gauge bosons

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Experiments

Tevatron II: $p\bar{p}$ @ $\sqrt{S} = 2TeV$

- Well, and running, and providing interesting results! (single top, Higgs exclusions, B-physics, . . .)
- Marginal role in (direct) SUSY search.

The Large Hadron Collider:pp @ $\sqrt{S} = 14TeV$

- Start: autum 2009
- $M \leq 2.5$ TeV ($\tilde{q}$, $\tilde{g}$). Measurement of properties.

Higgs boson

Standard Model: Discovery guaranteed in the range $114 - 1000\,\mathrm{GeV}$

International Linear Collider: e^+e^- @ $\sqrt{S} = 0.5 - 1.5TeV$

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- High precision measurements, $M \leq \sqrt{S}/2$

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Supersymmetry

Supersymmetry (SUSY) . . .

- . . . is the extension of the Poincaré symmetry of space-time
- . . . leads to a symmetry between fermions & bosons

Gauge theory with minimal SUSY:

- same number of fermionic & bosonic degrees of freedom
  $\Rightarrow$ a superpartner of different spin exists for each particle
- couplings are correlated
  $\Rightarrow$ e.g. scalar 4-point int. $\Leftrightarrow$ gauge couplings
- superpartners have the same mass
  $\Rightarrow$ SUSY must be broken at the electroweak scale

Gauge theory with broken SUSY

- superpartner masses enter as additional free parameters (essentially)

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Low Energy Supersymmetry

- Existence of a light Higgs boson, $M_{h^0} \lesssim 130\,\mathrm{GeV}$.
  M. Carena *et al.*, *Nucl. Phys.* **B 580** (2000) 29 [hep-ph/0001002].

  J.R. Espinosa, R. Zhang, *JHEP* **0003** (2000) 026, [hep-ph/9912236].
- SUSY models predictions are not in contradiction with high precision EW data.

MSSM: Minimal Supersymmetric Standard Model

gauge group: $SU(3)_c \times SU(2)_I \times U(1)_Y$

Regular particles	Spin	Superfields	Spin	superpartners
fermions quarks $u\ d\ s\ c\ b\ t$ leptons $e\ \nu_e\ \mu\ \nu_\mu\ \tau\ \nu_\tau$	$\frac{1}{2}$	$\hat{Q} = \begin{pmatrix} \hat{u}_L \\ \hat{d}_L \end{pmatrix}, \hat{D} = \hat{d}_R^c, \hat{U} = \hat{u}_R^c$ $\hat{L} = \begin{pmatrix} \hat{\nu}_L \\ \hat{e}_L \end{pmatrix}, \hat{E} = \hat{e}_R^c$	0	sfermions squarks $\tilde{u}\ \tilde{d}\ \tilde{s}\ \tilde{c}\ \tilde{b}\ \tilde{t}$ sleptons $\tilde{e}\ \tilde{\nu_e}\ \tilde{\mu}\ \tilde{\nu_\mu}\ \tilde{\tau}\ \tilde{\nu_\tau}$
Gauge Bosons $G, W^\pm, Z, \gamma$	1	$\hat{G}, \hat{W}^\pm, \hat{Z}, \hat{\gamma}$	$\frac{1}{2}$	gauginos $\tilde{G}, \tilde{W}^\pm, \tilde{Z}, \tilde{\gamma}$
Higgs bosons H_u, H_d	0	$\hat{H}_d = \begin{pmatrix} \hat{H}_d^0 \\ \hat{H}_d^- \end{pmatrix}, \hat{H}_u = \begin{pmatrix} \hat{H}_u^+ \\ \hat{H}_u^0 \end{pmatrix}$	$\frac{1}{2}$	Higgsinos $\tilde{H}_u, \tilde{H}_d$

H_u, H_d lead to 5 physical Higgs bosons: h^0, H^0, A^0, H^+, H^-
$\tilde{W}^\pm, \tilde{Z}, \tilde{\gamma}$ and $\tilde{H}_u, \tilde{H}_d \rightarrow$ 2 charginos χ_1^+, χ_2^+; 4 neutralinos $\chi_1^0, \cdots, \chi_4^0$

MSSM: Minimal Supersymmetric Standard Model

tan β

- Two neutral Higggs $\rightarrow$ two vaccum expectation values: v_u, v_d
- $M_W^2 \sim v_u^2 + v_d^2$
- $\tan\beta = \frac{v_u}{v_d}$
- β is a mixing angle in the Higgs sector (together with α)
- potential large Yukawa couplings of bottom quarks

Gauge Bosons $G, W^{\pm}, Z, \gamma$	1	$\hat{G}, \hat{W}^{\pm}, \hat{Z}, \hat{\gamma}$	$\frac{1}{2}$	gauginos $\tilde{G}, \tilde{W}^{\pm}, \tilde{Z}, \tilde{\gamma}$
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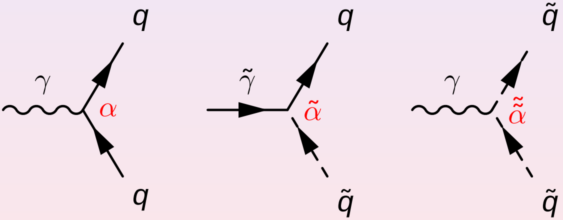
Determination of particle properties

- If new particles are found: what are they? (which model do they belong?)
  - $\Rightarrow$ Check model predictions: obey their properties SUSY relations?
  - $\Rightarrow$ Check precision predictions at the same level as SM
- SUSY: SUSY particle couplings are the same as SM



- $\alpha = \tilde{\tilde{\alpha}}$: charge of particle $\tilde{q}$
- $\alpha = \tilde{\alpha}$: genuine SUSY prediction

Sfermion Decays to charginos/neutralinos

- Check of SUSY: equality of particles and sparticles couplings
  - Can not be checked on *S*-channel pair-production
- In this work we concentrate on fermionic decays of sfermions

$$\boxed{\tilde{f} \longrightarrow f^{(\prime)} \chi^{(0,+,-)}}$$

- Some of these decays channels are *always* available: $\tilde{b} \to b\chi_1^0$. χ_1^0 is usually the Lightest SUSY Particle (LSP).
- Whenever open, some of these channels have a non-negligible Branching Ratio.
- Previous computations: Full one-loop QCD and Electroweak corrections are available

  S. Kraml *et al.*, *Phys. Lett.* **B386** (1996) 175, hep-ph/9605412.
  A. Djouadi, W. Hollik, C. Jünger, *Phys. Rev.* **D55** (1997) 6975, hep-ph/9609419.
  J. G., Ph.D. Thesis, UAB 1999.

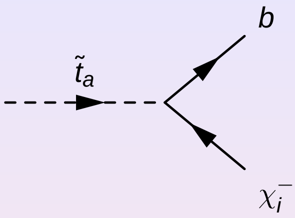
  J. G., W. Hollik, J. Solà, *Phys. Lett.* **B437** (1998) 88, hep-ph/9802329. *JHEP* **0210** (2002) 040, hep-ph/0207364

  $\Rightarrow$ large corrections and non-decoupling effects
- To compare with experiment we need:
  - Precision predictions AND good approximations

Present work

- Recompute the QCD corrections to squark decays
- Find the leading terms of the corrections
- Perform a renormalization group analysis, and compare with the one-loop result
  - $\Rightarrow$ asses the precision of the running coupling approximation
- Combine the one-loop and renormalization-group computations

[Example: top-squark → bottom chargino]



$$\mathcal{L}_{\chi_r \tilde{f}_a f'} = -g\, \tilde{f}_a^* \bar{\chi}_r \left(A^{(f)}_{+ar} P_L + A^{(f)}_{-ar} P_R \right) f' \,.$$

$$\begin{aligned} A^{(t)}_{+ai} &= R^{(t)}_{1a} V^*_{i1} - \lambda_t R^{(t)}_{2a} V^*_{i2} \,, \\ A^{(t)}_{-ai} &= -\lambda_b R^{(t)}_{1a} U_{i2} \,, \end{aligned}$$

- gauge couplings: g
- Yukawa couplings: $\lambda_{t,b} = \frac{m_{t,b}}{v_{2,1}} = \frac{m_{t,b}}{\sqrt{2} M_W \{\sin,\cos\}\beta}$
- Squark mixing matrices: R
- Chargino mixing matrices: U, V
- Chirality projectors: $P_{L,R}$
- 2 squarks: $a = 1, 2$ and 2 charginos $i = 1, 2$

Yukawa-effective couplings

- QCD $\bigoplus$ SUSY Higgs physics
  $\Rightarrow$ Running mass $\bigoplus$ SUSY threshold corrections

$$\lambda_b^{eff.} \equiv \frac{m_b^{eff.}}{v_1} \equiv \frac{m_b(Q)}{v_1(1+\Delta m_b)} \quad , \quad \lambda_t^{eff.} \equiv \frac{m_t^{eff.}}{v_2} \equiv \frac{m_t(Q)}{v_2(1+\Delta m_t)} \quad ,$$

$$\begin{aligned} \Delta m_b^{SQCD} &= \frac{2\alpha_s}{3\pi} m_{\tilde{g}} \mu \tan\beta \, I(m_{\tilde{b}_1}, m_{\tilde{b}_2}, m_{\tilde{g}}) \quad , \\ \Delta m_t^{SQCD} &= \frac{2\alpha_s}{3\pi} m_{\tilde{g}} \frac{\mu}{\tan\beta} I(m_{\tilde{t}_1}, m_{\tilde{t}_2}, m_{\tilde{g}}) \quad , \end{aligned} \tag{1}$$

$$I(a,b,c) = \frac{a^2b^2\ln(a^2/b^2) + b^2c^2\ln(b^2/c^2) + c^2a^2\ln(c^2/a^2)}{(a^2-b^2)(b^2-c^2)(a^2-c^2)} \quad .$$

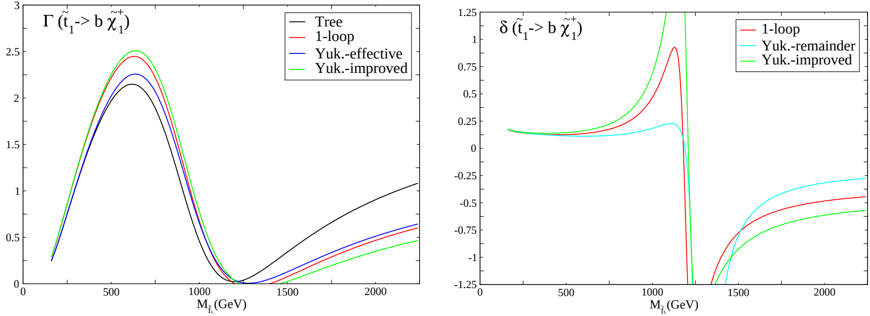
Numerical analysis

- Total decay widths Γ and relative corrections δ
- One-loop
- Yukawa-effective
- Yukawa-Improved:
  - Combination of: Effective couplings $\bigoplus$ one-loop
  - Contains: Higher order effects $\bigoplus$ kinematic effects
- δ-remainder: One loop effects NOT described by the effective couplings

Parameters

$$\tan\beta = 5\ ,\ \mu = 300\,\mathrm{GeV}\ ,\ M = 200\,\mathrm{GeV}\ ,\ M_{\tilde{f}\mathrm{L}} = 800\,\mathrm{GeV}\ ,$$
$$m_{\tilde{g}} = 3000\,\mathrm{GeV}\ , M_{SUSY} \equiv M_{\tilde{f}\mathrm{R}} = 1000\,\mathrm{GeV}\ ,$$
$$A_t = A_b = 2M_{\tilde{f}\mathrm{L}} + \mu/\tan\beta = 1660\,\mathrm{GeV}\ ,$$

$$\begin{aligned} M_{\chi^+} &= (170.40, 337.50)\,\mathrm{GeV}\ , \\ M_{\chi^0} &= (89.52, 172.28, 305.46, 338.58)\,\mathrm{GeV}\ , \\ m_{\tilde{b}} &= (802.05, 1000.30)\,\mathrm{GeV}\ , \\ m_{\tilde{t}} &= (720.55, 1084.25)\,\mathrm{GeV}\ . \end{aligned}$$

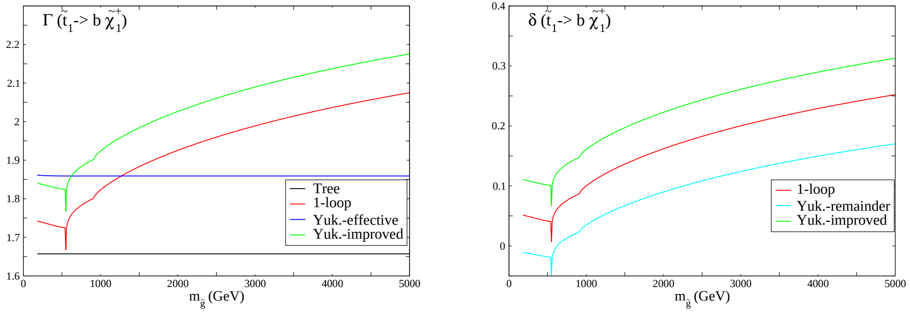


At $M_{\tilde{f}L} \sim 1250\,\mathrm{GeV}$:

- $\Gamma^{tree} \sim 0 \Rightarrow \Gamma^{1-loop} < 0$
- $\Gamma^{eff} > 0$ (by definition)
- Non-perturbative behaviour can not be described by effective theory

  $\Rightarrow$ Region not interesting phenomenologically!

Gluino Mass



- One-loop $\sim \log m_{\tilde{g}}$

Not reproduced by Yukawa-effective

- Large remainder corrections, with non-flat behaviour

Logarithmic terms: where do they come from?

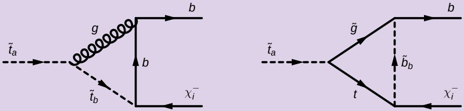
Fundamental

- SUSY: $\alpha = \tilde{\alpha}$
- SUSY is broken (by $m_{\tilde{g}}$)

$\Rightarrow \quad \alpha \neq \tilde{\alpha}$

$\Rightarrow \quad \alpha - \tilde{\alpha} \simeq \log(\Lambda_{\rm SUSY-breaking}) \simeq \log m_{\tilde{g}}$

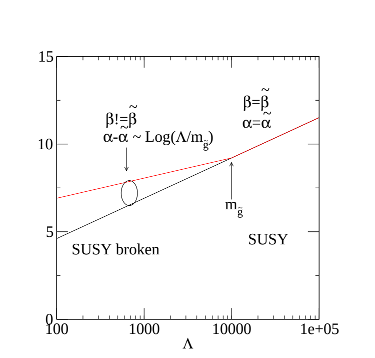
One-loop



$\Delta_\varepsilon + \log \mu_D/M_1 \qquad \Delta_\varepsilon + \log \mu_D/M_2 \qquad = \log M_1/M_2$

- If we remove gluinos ($m_{\tilde{g}} \to \infty$) $\Rightarrow$ Divergent result$\Rightarrow$$\log m_{\tilde{g}}$

Effective Theory



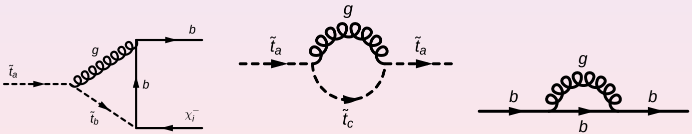
- At $Q > m_{\tilde{g}}$: SUSY theory: $\alpha = \tilde{\alpha}$ gauge and gaugino couplings run equal $\beta = \tilde{\beta}$
- At $Q < m_{\tilde{g}}$ SUSY broken: the β functions are different: $\beta \neq \tilde{\beta}$

  $\Rightarrow\ \tilde{\alpha} - \alpha \sim (\tilde{\beta} - \beta) \log m_{\tilde{g}}$

Effective Theory

Construct an effective theory:

- $Q > m_{\tilde{g}}$: SUSY theory $(q, \tilde{q}, \chi^-, g, \tilde{g})$:
  - Chargino couplings are given by the SUSY relations
- $Q < m_{\tilde{g}}$: broken SUSY $(q, \tilde{q}, \chi^-, g)$ – no gluinos
  - Compute the QCD running of the chargino couplings from the matching scale ($m_{\tilde{g}}$) down to the process scale (Q)
    - Only contributions from gluons!



$$A(Q) = A(m_{\tilde g}) \left(\frac{\alpha_s(Q)}{\alpha_s(m_{\tilde g})}\right)^{2/\beta_0}$$

β_0: QCD β-function

- Now we have to compute $A(m_{\tilde g})$: $A(m_{\tilde g}) = H(m_{\tilde g}) + G(m_{\tilde g})$

$H(m_{\tilde g})$: Higgs coupling ($\lambda_{b,t}$): runs as the mass:

$$\begin{aligned}
\lambda(m_{\tilde g}) &= \lambda(Q) \left(\frac{\alpha_s(m_{\tilde g})}{\alpha_s(Q)}\right)^{4/\beta_0} \\
H(Q) &= H(m_{\tilde g}) \left(\frac{\alpha_s(Q)}{\alpha_s(m_{\tilde g})}\right)^{2/\beta_0} \\
&= \lambda(Q) \left(\frac{\alpha_s(Q)}{\alpha_s(m_{\tilde g})}\right)^{-2/\beta_0} \\
&\simeq \lambda(Q) \left(1 + \frac{\alpha_s(Q)}{\pi} \log \frac{Q}{m_{\tilde g}}\right)
\end{aligned}$$

$G(m_{\tilde g})$: gauge coupling (g): It does not run due to QCD

$$\begin{aligned}
G(m_{\tilde g}) &= g(0) \\
G(Q) &= G(m_{\tilde g}) \left(\frac{\alpha_s(Q)}{\alpha_s(m_{\tilde g})}\right)^{2/\beta_0} \\
&= g \left(\frac{\alpha_s(Q)}{\alpha_s(m_{\tilde g})}\right)^{2/\beta_0} \\
&\simeq g \left(1 - \frac{\alpha_s(Q)}{\pi} \log \frac{Q}{m_{\tilde g}}\right)
\end{aligned}$$

Effective chargino/neutralino couplings

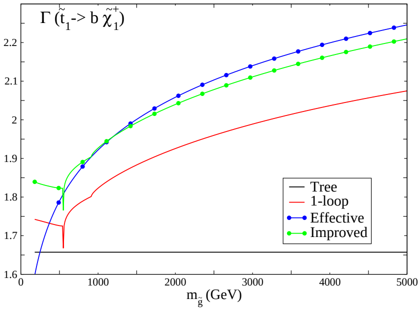
$$g^{eff.}(Q) = g\left(\frac{\alpha_s(Q)}{\alpha_s(m_{\tilde{g}})}\right)^{\frac{2}{\beta_0}} \simeq g\left(1 - \frac{\alpha_s(Q)}{\pi}\log\frac{Q}{m_{\tilde{g}}}\right) ,$$

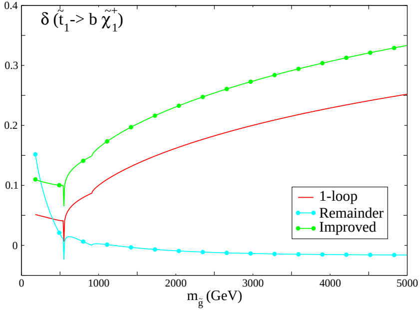
$$\tilde{\lambda}^{eff.}_{b,t}(Q) = \lambda^{eff.}_{b,t}(Q)\left(\frac{\alpha_s(Q)}{\alpha_s(m_{\tilde{g}})}\right)^{\frac{-2}{\beta_0}} \simeq \lambda^{eff.}_{b,t}(Q)\left(1 + \frac{\alpha_s(Q)}{\pi}\log\frac{Q}{m_{\tilde{g}}}\right) ,$$

$$\lambda^{eff.}_b \equiv \frac{m^{eff.}_b}{v_1} \equiv \frac{m_b(Q)}{v_1(1+\Delta m_b)} , \quad \lambda^{eff.}_t \equiv \frac{m^{eff.}_t}{v_2} \equiv \frac{m_t(Q)}{v_2(1+\Delta m_t)} ,$$

- Define again: effective, remainder, . . .

Gluino Mass





- The Effective description follows the logarithmic behaviour of the one-loop
- The Remainder contributions tend to zero at large gluino mass

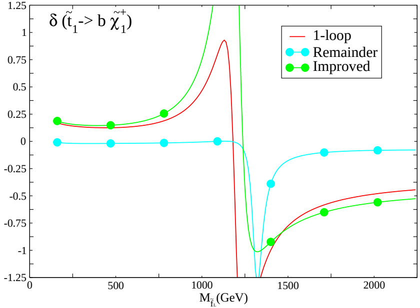
⇒ The effective description gives a good approximation to the one-loop behaviour

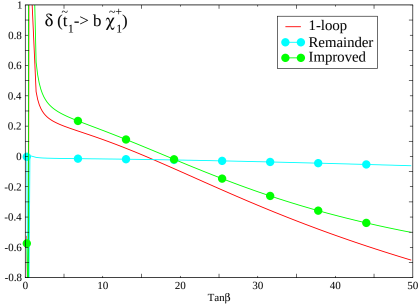
Behaviour checked for:

- All squark decay channels into charginos/neutralinos
- Change in any input parameter ($m_{\tilde{g}}, \tan\beta, \ldots$)

In all cases:

- Remainder corrections decrease after including the $\log m_{\tilde{g}}$ terms
  $\Rightarrow$ better approximation than only Yukawa-effective
- Remainder corrections stay flat under variations of parameters
  $\Rightarrow$ are a good approximation to the one-loop behaviour
- Except:
  - Corners of the parameter space where: $\Gamma^{tree} \to 0$
    $\Rightarrow$ Phenomenologically uninteresting


δ ($\tilde{t}_1$-> b $\tilde{\chi}_1^+$)
1-loop
Remainder
Improved
1.25
1
0.75
0.5
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
0
500
1000
1500
2000
$M_{\tilde{f}_L}$(GeV)


δ ($\tilde{t}_1$-> b $\tilde{\chi}_1^+$)
1-loop
Remainder
Improved
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
0
10
20
30
40
50
Tanβ

Conclusions

- Effective description of squark interactions
  - Running mass $\bigoplus$ threshold corrections
  - Additional $\log m_{\tilde{g}}$ term
- Describes correctly squark decays
- Easy/cheap to include in Monte-Carlo simulations
- Non-decoupling behaviour:
  - Due to breaking of SUSY

  $\Rightarrow$ Deviation of SUSY prediction: $\alpha = \tilde{\alpha}$!
- Future
  - Generalize this description to every SUSY process

Index

$\tan\beta$					
	$\tan\alpha, m_{H^0}$ $\Uparrow$ $M_{H^\pm}$				
$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \cdots \begin{pmatrix} t' \\ b' \end{pmatrix}$	H_1, H_2	B	W	g	$R = 0$
$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \cdots \begin{pmatrix} t \\ b \end{pmatrix}$	$H^\pm, A^0, H^0, h^0$	$\gamma, Z, W^\pm$		g	
$\begin{pmatrix} \tilde{\nu}_e \\ \tilde{e}_L^-, \tilde{e}_R^- \end{pmatrix} \cdots \begin{pmatrix} \tilde{t}_L, \tilde{t}_R \\ \tilde{b}_L, \tilde{b}_R \end{pmatrix}$	$\tilde{h}_1, \tilde{h}_2$	$\tilde{B}$	$\tilde{w}$	$\tilde{g}$	$R = 1$
$\begin{pmatrix} \tilde{\nu}_e \\ \tilde{e}_1^-, \tilde{e}_2^- \end{pmatrix} \cdots \begin{pmatrix} \tilde{t}_1, \tilde{t}_2 \\ \tilde{b}_1, \tilde{b}_2 \end{pmatrix}$	$\chi^-_{\{1,2\}},\ \chi^0_{\{1,\ldots,4\}}$			$\tilde{g}$	
$m_{\tilde{b}_1}, m_{\tilde{b}_2}, m_{\tilde{t}_1}$ A_b, A_t (θ_b, θ_t)		M'	M	$m_{\tilde{g}}$	
μ					
$\tan\beta$					

$\tan\beta$					
	$\tan\alpha, m_{H^0}$ $\Uparrow$ $M_{H^\pm}$				
$\begin{pmatrix}\nu_e\\ e^-\end{pmatrix} \cdots \begin{pmatrix}t'\\ b'\end{pmatrix}$	H_1, H_2	B	W	g	$R = 0$
$\begin{pmatrix}\tilde{\nu}_e\\ \tilde{e}_1^-, \tilde{e}_2^-\end{pmatrix} \cdots \begin{pmatrix}\tilde{t}_1, \tilde{t}_2\\ \tilde{b}_1, \tilde{b}_2\end{pmatrix}$	$\chi^-_{\{1,2\}}, \chi^0_{\{1,\ldots,4\}}$			$\tilde{g}$	
$m_{\tilde{b}_1}, m_{\tilde{b}_2}, m_{\tilde{t}_1}$ A_b, A_t (θ_b, θ_t)		M'	M	$m_{\tilde{g}}$	
μ					
$\tan\beta$					

- Main parameter: $\tan\beta = \frac{v_2}{v_1}$
  $\Rightarrow$ Potential large Yukawa couplings of bottom quarks
- Squark mixing $\propto m_q$
  $\Rightarrow$ only $\tilde{t}$ (and $\tilde{b}$ at large $\tan\beta$) can have large mass splitting.