Some results on the squark interactions with charginos/neutralinos

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Jaume Guasch, S.P., Raül Sánchez-Florit, JHEP 0904:016,2009, arXiv:0812.1114

Outline

Sfermion Decays to charginos/neutralinos

- In this work we concentrate on fermionic decays of sfermions

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

- 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. Guasch, Ph.D. Thesis, UAB 1999.
  J. Guasch, 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

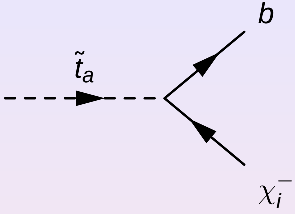
Jaume Guasch, S.P., Raül Sánchez-Florit, JHEP 0904:016,2009, arXiv:0812.1114

- Recompute the QCD corrections to squark decays
  - QCD corrections include contributions from gluon loops, gluino loops, and gluon bremsstrahlung
  - The full one-loop corrections have been performed using the *FeynArts/FormCalc/LoopTools* packages
- Find the leading terms of the corrections
- Propose and analyze an effective description of squark interactions with charginos/neutralinos
- 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

Tree-level interactions

[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

M. Carena *et al.*, Nucl. Phys. **B577**, 88–120 (2000),`arXiv:hep-ph/9912516`

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

$$\Delta m_b^{SQCD} = \frac{2\alpha_s}{3\pi} m_{\tilde{g}}\, \mu \tan\beta\, I(m_{\tilde{b}_1}, m_{\tilde{b}_2}, m_{\tilde{g}}) \;,$$

$$\Delta m_t^{SQCD} = \frac{2\alpha_s}{3\pi} m_{\tilde{g}} \frac{\mu}{\tan\beta} I(m_{\tilde{t}_1}, m_{\tilde{t}_2}, m_{\tilde{g}}) \;,$$

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

The effective description of squark decays consists in replacing the tree-level quark masses in the couplings by the effective Yukawa couplings, and use the corresponding lagrangian to compute the partial decay width

$$\Gamma^{Yuk.-eff.} = \Gamma^{tree}(m_q^{eff.})$$

Analytical and 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

  $\Rightarrow$ allow us to quantify the degree of accuracy obtained by the effective description
- δ-remainder: One loop effects NOT described by the effective couplings

Parameters

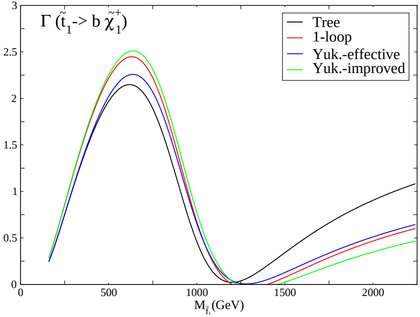
An example of numerical inputs for illustrative purposes:

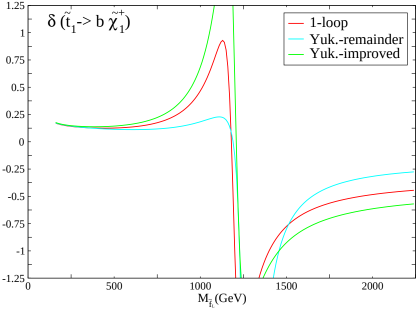
$$\tan\beta = 5\ ,\ \mu = 300\,\mathrm{GeV}\ ,\ M = 200\,\mathrm{GeV}\ ,\ M_{\tilde{f}\mathrm{L}} = 800\,\mathrm{GeV}\ ,$$
$$m_{\tilde{g}} = 3000\,\mathrm{GeV}\ , M_{SUSY} \equiv M_{\tilde{f}\mathrm{R}} = 1000\,\mathrm{GeV}\ ,$$
$$A_t = A_b = 2M_{\tilde{f}\mathrm{L}} + \mu/\tan\beta = 1660\,\mathrm{GeV}\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

The central values for the physical SUSY particle masses are:

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

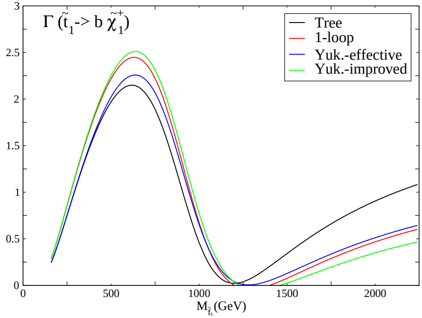
We have checked that our conclusions hold for a wide range of the parameter space

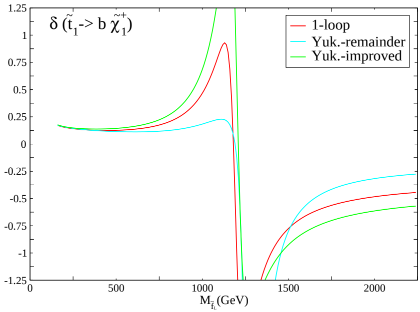




At $M_{\tilde{f}L} \sim 1250\,\mathrm{GeV}$: A big dip in the corrections, with negative corrections surpassing -100% – which would mean a *negative* decay width, and obviously does not make sense.

- $\Gamma^{tree} \sim 0 \Rightarrow \Gamma^{1-loop} < 0 \Rightarrow$ One-loop perturbation theory does not hold (Non-perturbative behaviour can not be described by effective theory)
- $\Gamma^{eff} > 0$ (by definition) $\Rightarrow$ the effective description can not reproduce the one-loop result at all



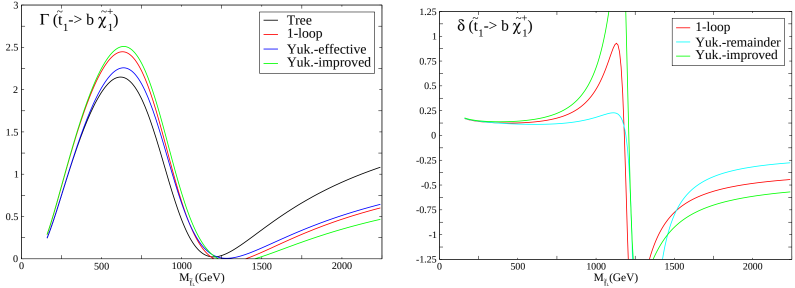


However,

- they appear in tiny regions of the parameter space
- this effect occurs precisely on decay channels that have a negligibly small branching ratio (the dip coincides with the minimum of the partial decay width)

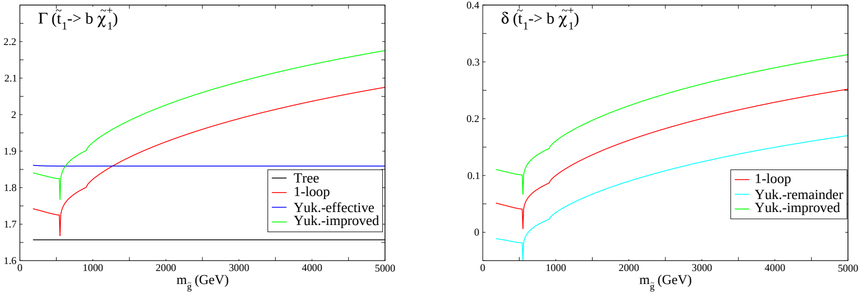
$\Rightarrow$ Region not interesting phenomenologically!

Partial decay widths Γ and relative corrections δ



- For squark masses larger than $1250\,\mathrm{GeV}$:
  - one-loop correction is around -45% whereas the *remainder* correction is around $-28\% \Rightarrow$ roughly, one third of the one-loop corrections can be described as coming from the effective couplings
- For squark masses below $1250\,\mathrm{GeV}$:
  - one-loop corrections are relatively small (15%), whereas the effective description gives a slightly smaller result $\Rightarrow$ the effective description can not describe properly the radiative corrections

Gluino Mass



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

Not reproduced by Yukawa-effective

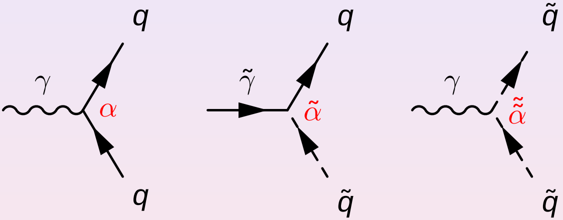
- Large remainder corrections, with non-flat behaviour

See also talk by Heidi Rzehak

Logarithmic terms: where do they come from?

Fundamental

- SUSY: SUSY particle couplings are the same as SM



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

Logarithmic terms: where do they come from?

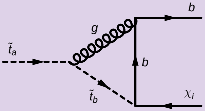
Fundamental

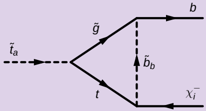
- SUSY: $\alpha = \tilde{\alpha}$
- SUSY is broken (by $m_{\tilde{g}}$)

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

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

One-loop

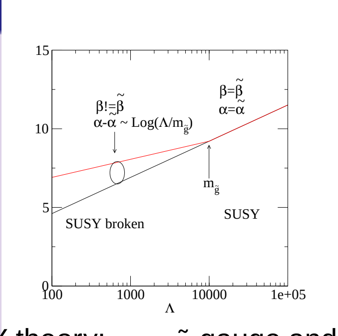




$\Delta_\varepsilon + \log \mu_D/M_1 \qquad \Delta_\varepsilon + \log \mu_D/M_2 \qquad = \log M_1/M_2$

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

Effective Theory



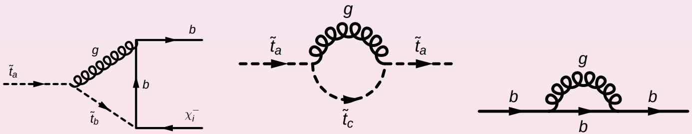
- At $Q > m_{\tilde{g}}$: SUSY theory: $\alpha = \tilde{\alpha}$ gauge and gaugino couplings run equal $\beta = \tilde{\beta}$
- At $Q < m_{\tilde{g}}$ SUSY broken: the β functions are different: $\beta \neq \tilde{\beta}$

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

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:

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

$G(m_{\tilde{g}})$: 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

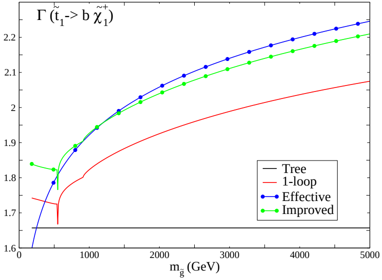
$$g^{eff.}(Q) = g \left(\frac{\alpha_s(Q)}{\alpha_s(m_{\tilde{g}})}\right)^{\frac{2}{\beta_0}} \simeq g \left(1 - \frac{\alpha_s(Q)}{\pi} \log \frac{Q}{m_{\tilde{g}}}\right) ,$$

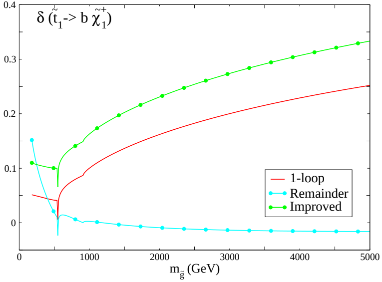
$$\tilde{\lambda}^{eff.}_{b,t}(Q) = \lambda^{eff.}_{b,t}(Q) \left(\frac{\alpha_s(Q)}{\alpha_s(m_{\tilde{g}})}\right)^{\frac{-2}{\beta_0}} \simeq \lambda^{eff.}_{b,t}(Q) \left(1 + \frac{\alpha_s(Q)}{\pi} \log \frac{Q}{m_{\tilde{g}}}\right) ,$$

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

- 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

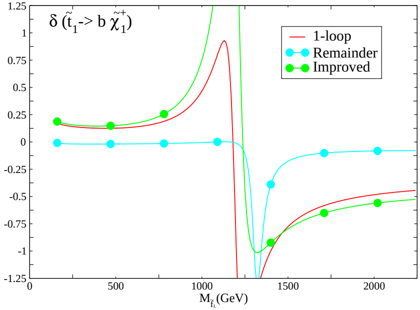
⇒ The effective description gives a good approximation to the one-loop behaviour

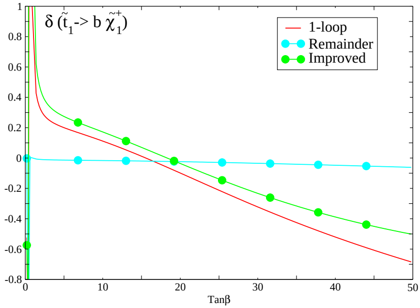
Behaviour checked for:

- 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





$$\delta^{1-loop} = \frac{\delta\Gamma^{1-loop}}{\Gamma^{tree}}$$

$$\delta^{Yuk.-rem.} = \frac{\Gamma^{1-loop} - \Gamma^{1-loop\ Yuk.-eff.}}{\Gamma^{tree}(m_q^{eff.})}$$

$$\delta^{Yuk.-imp.} = \frac{\Gamma^{Yuk.-imp.} - \Gamma^{tree}(m_q)}{\Gamma^{tree}(m_q)}$$

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: See also talk by Heidi Rzehak
  - Due to breaking of SUSY

$\Rightarrow$ Deviation of SUSY prediction: $\alpha = \tilde{\alpha}$!

- Future
  - Generalize this description to every SUSY process

MSSM: Minimal Supersymmetric Standard Model

$\tan\beta$					
	$\tan\alpha, m_{H^0}$ $\Uparrow$ $M_{H^\pm}$				
$\begin{pmatrix}\nu_e \\ e^-\end{pmatrix} \cdots \begin{pmatrix}t' \\ b'\end{pmatrix}$	$H_1,\ H_2$	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					
$\tan\beta$					

MSSM: Minimal Supersymmetric Standard Model

$\tan\beta$					
	$\tan\alpha, m_{H^0}$ $\Uparrow$ $M_{H^\pm}$				
$\begin{pmatrix}\tilde e_L^-, \tilde e_R^-\end{pmatrix} \cdots \begin{pmatrix}\tilde b_L, \tilde b_R\end{pmatrix}$	H_1, H_2	B	W	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					
$\tan\beta$					

- 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.

Threshold Corrections

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

- $\beta_0 \equiv$ QCD β-function
- Has contributions from each strong interacting particle (quark, squark) with mass $M < Q$
- We integrate in steps:
  - At each value of a particle mass M_i, we change the β_0 function:

$$Q \underset{\beta_0^0}{\longrightarrow} M_1 \underset{\beta_0^1}{\longrightarrow} M_2 \underset{\beta_0^2}{\longrightarrow} M_3 \underset{\beta_0^3}{\longrightarrow}$$

$\Rightarrow$ In this way we include the threshold corrections to the effective couplings

e.g. A. Box, X. Tata, *Phys.Rev.***D77** (2008) 055007 arXiv:0712.2858 [hep-ph]