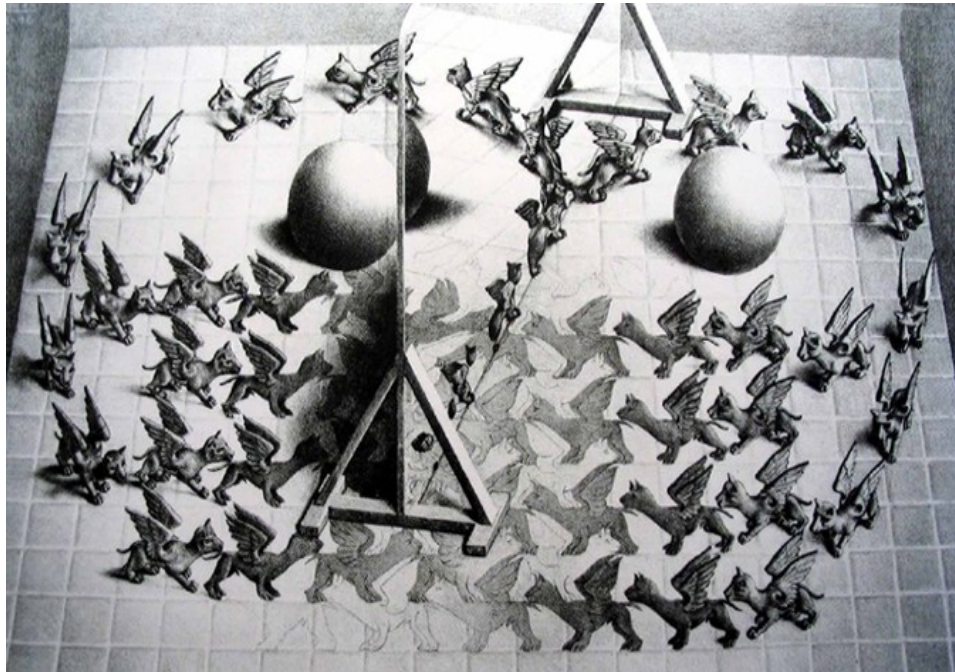


Physics at LHC: *SUperSYmmetry*

Pedrame Bargassa



LIP 14/06/2016

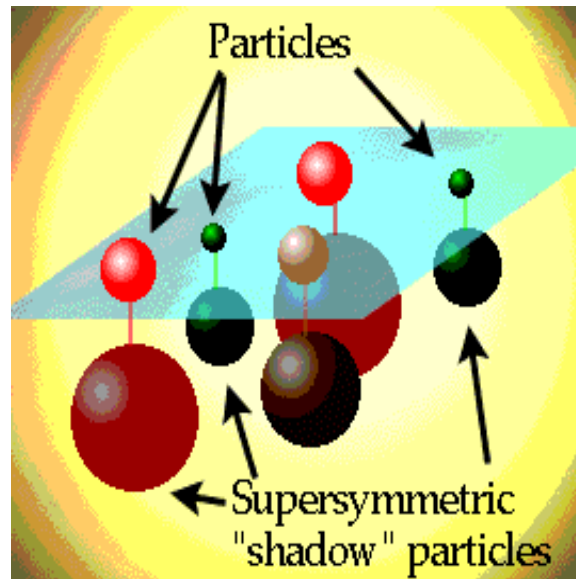
Outline

- *Reminders of last time: Different physical SUSY sectors*
- *Deeper look in Higgs sector*
- *Getting into experimental feedback*
- *Exercises*

Advised readings:

- “SUSY & Such” S. Dawson, [arxiv:hep-ph/9612229v2](https://arxiv.org/abs/hep-ph/9612229v2)
- “A supersymmetry primer” S. P. Martin, [arxiv:hep-ph/9709356](https://arxiv.org/abs/hep-ph/9709356)

Quick reminders of last time



MSSM: Effective Lagrangian

- We don't know how SUSY is broken, but can write the **most general broken effective Lagrangian**
- Maximal dimension of soft operators: $\leq 3 \rightarrow$ Mass terms, Bilinear & Trilinear terms

$$\begin{aligned} -\mathcal{L}_{soft} = & m_1^2 |H_1|^2 + m_2^2 |H_2|^2 - B\mu\epsilon_{ij}(H_1^i H_2^j + \text{h.c.}) + \tilde{M}_Q^2(\tilde{u}_L^* \tilde{u}_L + \tilde{d}_L^* \tilde{d}_L) \\ & + \tilde{M}_u^2 \tilde{u}_R^* \tilde{u}_R + \tilde{M}_d^2 \tilde{d}_R^* \tilde{d}_R + \tilde{M}_L^2(\tilde{e}_L^* \tilde{e}_L + \tilde{\nu}_L^* \tilde{\nu}_L) + \tilde{M}_e^2 \tilde{e}_R^* \tilde{e}_R \\ & + \frac{1}{2} \left[M_3 \bar{g}\tilde{g} + M_2 \bar{\omega}_i \tilde{\omega}_i + M_1 \bar{b}\tilde{b} \right] + \frac{g}{\sqrt{2}M_W} \epsilon_{ij} \left[\frac{M_d}{\cos\beta} A_d H_1^i \tilde{Q}^j \tilde{d}_R^* \right. \\ & \left. + \frac{M_u}{\sin\beta} A_u H_2^j \tilde{Q}^i \tilde{u}_R^* + \frac{M_e}{\cos\beta} A_e H_1^i \tilde{L}^j \tilde{e}_R^* + \text{h.c.} \right] . \end{aligned}$$

Specificity of SUSY: Writing the most general Lagrangian, generalizing the spins of fields, SUCH that quadratic divergences are always shut down

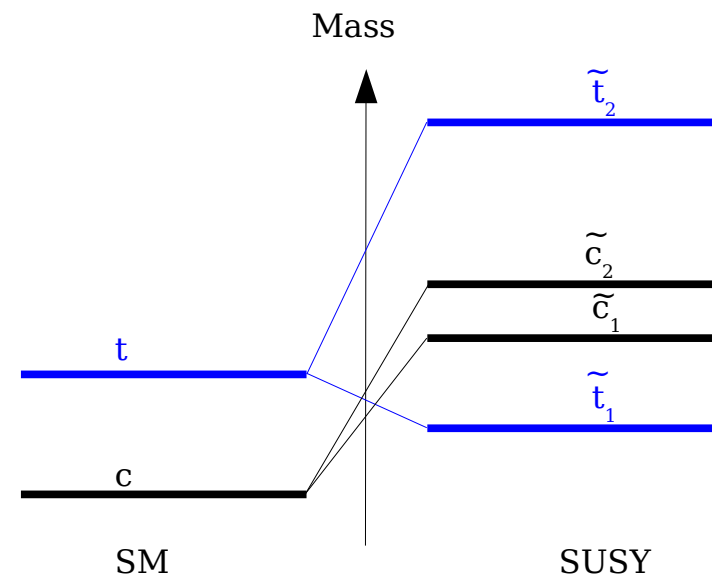
MSSM: Squark & Slepton sector

Physical states are 2 scalar mass-eigenstates: Mixtures of left- & -right chiral superpartners (scalars) of SM quark and leptons

Let's pick-up example of the top sector: If $[f_L - f_R]$ chiral basis:

$$M_{\tilde{t}}^2 = \begin{pmatrix} \tilde{M}_Q^2 + M_T^2 + M_Z^2 \left(\frac{1}{2} - \frac{2}{3} \sin^2 \theta_W \right) \cos 2\beta & M_T (A_T + \mu \cot \beta) \\ M_T (A_T + \mu \cot \beta) & \tilde{M}_U^2 + M_T^2 + \frac{2}{3} M_Z^2 \sin^2 \theta_W \cos 2\beta \end{pmatrix}$$

- \tilde{M}_Q : Left squark mass
- \tilde{M}_U : Right squark mass
- A_T : Trilinear coupling specific to the top sector
- $M_Q = M_T$: Mass of the SM particle
- μ : Higgs (bilinear) mixing parameter
- β : Higgs vev-specific parameter (see in a couple of slides): **Plays a role in the mixing**



MSSM: Chargino sector

Physical states are 2 fermionic mass-eigenstates: Mixtures of charged winos and charged higgsinos, which are SUSY eigenstates

In the charged [wino - higgsino] basis:

$$M_{\tilde{\chi}^{\pm}} = \begin{pmatrix} M_2 & \sqrt{2}M_W \sin \beta \\ \sqrt{2}M_W \cos \beta & -\mu \end{pmatrix}$$

- M_2 : Mass of the wino
- μ : Higgs (bilinear) mixing parameter
 - The more $M_2 \gg 1$: The more the charginos are wino-like
 - The more $\mu \gg 1$: The more the charginos are higgsino-like
 - β : Not playing a role in mixing

Comments:

MSSM: Neutralino sector

Physical states are 4 fermionic mass-eigenstates: Mixtures of neutral winos w^0 , bino b , and 2 neutral higgsinos, which are SUSY eigenstates

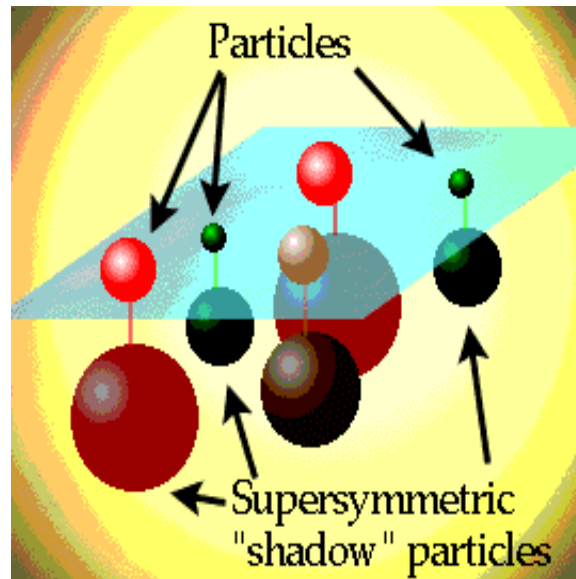
In the neutral $[b - w^0 - h^0_1 - h^0_2]$ basis:

$$M_{\tilde{\chi}_i^0} = \begin{pmatrix} M_1 & 0 & -M_Z \cos \beta \sin \theta_W & M_Z \sin \beta \sin \theta_W \\ 0 & M_2 & M_Z \cos \beta \cos \theta_W & -M_Z \sin \beta \cos \theta_W \\ -M_Z \cos \beta \sin \theta_W & M_Z \cos \beta \sin \theta_W & 0 & \mu \\ M_Z \sin \beta \sin \theta_W & -M_Z \sin \beta \cos \theta_W & \mu & 0 \end{pmatrix}$$

- M_1 : Mass of the bino
- M_2 : Mass of the wino
- μ : Higgs (bilinear) mixing parameter

Exercise: Qualitatively gauge the influence of each parameters in the mass-matrix above on the “type” of neutralinos

***Higgs sector:
"Richer" than others...***



MSSM: Higgs sector

2 Higgs complex doublets:

$$V_H = \left(|\mu|^2 + m_1^2 \right) |H_1|^2 + \left(|\mu|^2 + m_2^2 \right) |H_2|^2 - \mu B \epsilon_{ij} \left(H_1^i H_2^j + \text{h.c.} \right) \\ + \frac{g^2 + g'^2}{8} \left(|H_1|^2 - |H_2|^2 \right)^2 + \frac{1}{2} g^2 |H_1^* H_2|^2 \quad .$$

8 degrees of freedom - 3 (massive gauge bosons) = 5 physical Higgs fields:
h / H / H[±] / A (CP-odd)

2 VEVs: $\langle H_1^0 \rangle \equiv v_1$ $\langle H_2^0 \rangle \equiv v_2$ → Key MSSM parameter: $\tan \beta \equiv \frac{v_2}{v_1}$

$$\tan 2\alpha = \frac{(M_A^2 + M_Z^2) \sin 2\beta}{(M_A^2 - M_Z^2) \cos 2\beta + \epsilon_h / \sin^2 \beta}$$

3 parameters to describe the MSSM Higgs sector:

Once $v_{1,2}$ are fixed such that:

$$M_W^2 = \frac{g^2}{2} (v_1^2 + v_2^2)$$

This whole sector is described by (only) 2 other parameters:

→ $\tan \beta$

→ M_A :

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

MSSM: Higgs mass & squarks / Limit

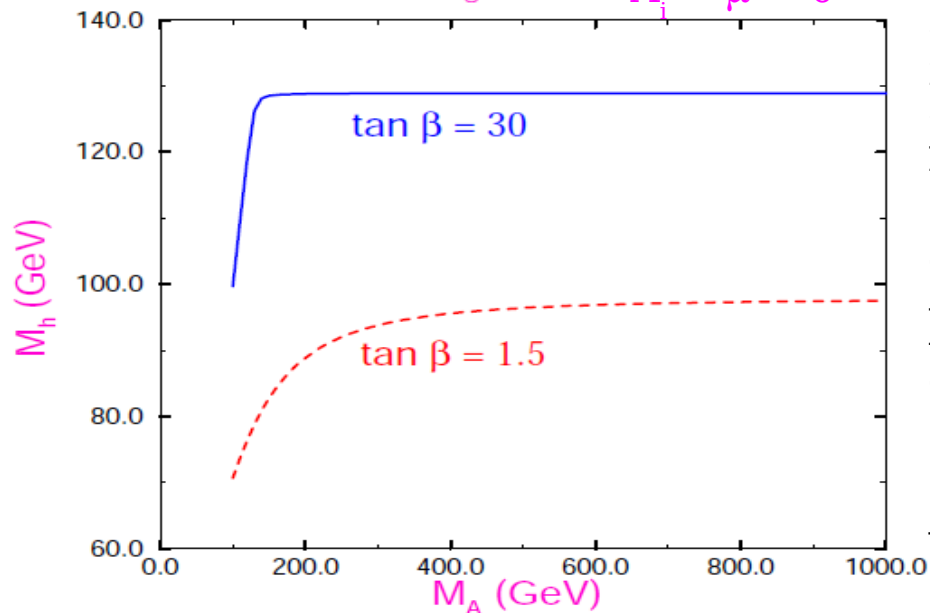
Equation governing lightest Higgs mass:

$$M_{h,H}^2 = \frac{1}{2} \left\{ M_A^2 + M_Z^2 + \frac{\epsilon_h}{\sin^2 \beta} \pm \left[\left(M_A^2 - M_Z^2 \right) \cos 2\beta + \frac{\epsilon_h}{\sin^2 \beta} \right]^2 + \left(M_A^2 + M_Z^2 \right)^2 \sin^2 2\beta \right\}^{1/2}$$

with: $\epsilon_h \equiv \frac{3G_F}{\sqrt{2}\pi^2} M_T^4 \log\left(\frac{\tilde{m}^2}{M_T^2}\right)$ Contribution of 1-loop correction only !
 Squark masses: Higgs mass particularly sensitive to $\sim t_{1,2}$ system

Upper bound: $M_h^2 < M_Z^2 \cos^2 2\beta + \epsilon_h$

M_h in SUSY Model
 $M_s = 1 \text{ TeV}$ $A_t = \mu = 0$



Here: No mixing.
 M(h) can go higher if stop-sector mixing larger

→ The “well-known” $M_h < 135 \text{ GeV}/c^2$ limit for any-SUSY lightest Higgs
 → ...is dependent on
 → 2-loop calculations
 → Renormalization calculations which can evolve...

MSSM: Higgs mass & squarks / Limit

Equation governing lightest Higgs mass:

$$M_{h,H}^2 = \frac{1}{2} \left\{ M_A^2 + M_Z^2 + \frac{\epsilon_h}{\sin^2 \beta} \pm \left[\left(M_A^2 - M_Z^2 \right) \cos 2\beta + \frac{\epsilon_h}{\sin^2 \beta} \right]^2 + \left(M_A^2 + M_Z^2 \right)^2 \sin^2 2\beta \right\}^{1/2}$$

with: $\epsilon_h \equiv \frac{3G_F}{\sqrt{2}\pi^2} M_T^4 \log \left(\frac{\tilde{m}^2}{M_T^2} \right)$ Contribution of 1-loop correction only !
Squark masses: Higgs mass particularly sensitive to $\sim t_{1,2}$ system

Upper bound: When $M_A \rightarrow \infty$

$$M_h^2 = M_A^2 - f(M_A^4)$$

$$M_H^2 = M_A^2 + f(M_A^4)$$

Just to know:

→ With richer Higgs structure: Can also have $M_h^{\max} > 130 \text{ GeV}/c^2$

→ μB perturbative up to Planck-scale:

For any SUSY: $M_h^{\max} \sim 150 \text{ GeV}/c^2$

MSSM: Higgs couplings to bosons

Let's look at couplings:

$$Z^\mu Z^\nu h : \frac{igM_Z}{\cos\theta_W} \sin(\beta - \alpha) g^{\mu\nu} \quad \begin{array}{l} \sin(\beta - \alpha) \rightarrow 1 \text{ for } M_A \rightarrow \infty \\ \cos(\beta - \alpha) \rightarrow 0 \end{array}$$

$$Z^\mu Z^\nu H : \frac{igM_Z}{\cos\theta_W} \cos(\beta - \alpha) g^{\mu\nu}$$

$$W^\mu W^\nu h : igM_W \sin(\beta - \alpha) g^{\mu\nu}$$

SM couplings

Similar for coupling to γ & fermions

Exercise: Demonstrate the 2 relations above

It is possible that:

1/ Light h “SM like”:

- Mass: Rather low
- $\text{Br}(h \rightarrow \gamma\gamma) \sim$ Like in SM

2/ $\{H, H^\pm, A\}$ much heavier & degenerate

- Couplings of lightest Higgs to fermions/ γ /W/Z \sim Like in SM
- Couplings of “additional” Higgs to fermions/ γ /W/Z ~ 0

This is called the **decoupled regime**:

- 1/ The lightest Higgs field is a) rather light b) behaves *a la* SM
- 2/ The “new” physical Higgs fields are (much ?) higher in mass

MSSM: Higgs couplings to fermions

Let's plug in L_{yukawa} the full MSSM Higgs fields & the SM fermions:

$$L_{\text{yukawa}} = -\mathbf{G}_d (\bar{\mathbf{u}}, \bar{\mathbf{d}})_L (\phi^+, \phi^0) \mathbf{d}_R - \mathbf{G}_u (\bar{\mathbf{u}}, \bar{\mathbf{d}})_L (\phi^0, \phi^-) \mathbf{u}_R + \text{hc}$$

Then break EW with $\phi = (1/\sqrt{2})(0, v_{1,2} + \text{Higgs}) \leftarrow$ "Rapid" notation

Then re-rewrite things in terms of coupling:

$$\mathcal{L} = -\frac{gm_i}{2M_W} \left[C_{ffh} \bar{f}_i f_i h + C_{ffH} \bar{f}_i f_i H + C_{ffA} \bar{f}_i \gamma_5 f_i A \right]$$

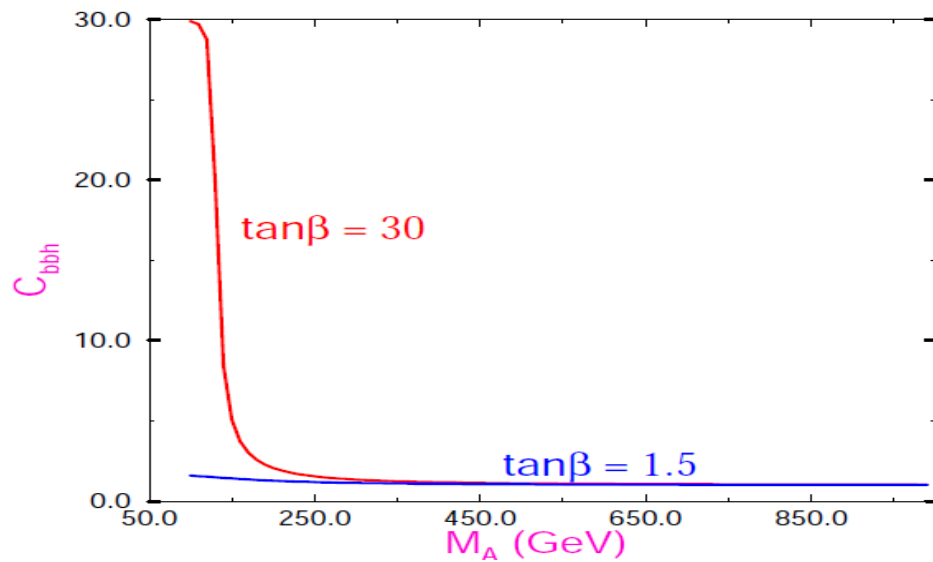
| f | C_{ffh} | C_{ffH} | C_{ffA} |
|-----|-----------------------------------|----------------------------------|--------------|
| u | $\frac{\cos \alpha}{\sin \beta}$ | $\frac{\sin \alpha}{\sin \beta}$ | $\cot \beta$ |
| d | $-\frac{\sin \alpha}{\cos \beta}$ | $\frac{\cos \alpha}{\cos \beta}$ | $\tan \beta$ |

- **Coupling to same fermions:**
"Opposite" behaviors of 2 lightest neutral higgs h and H
- **Coupling to the same Higgs:**
"Opposite" behaviors of u/d quarks
- Let's see what *the 2nd case graphically means...*

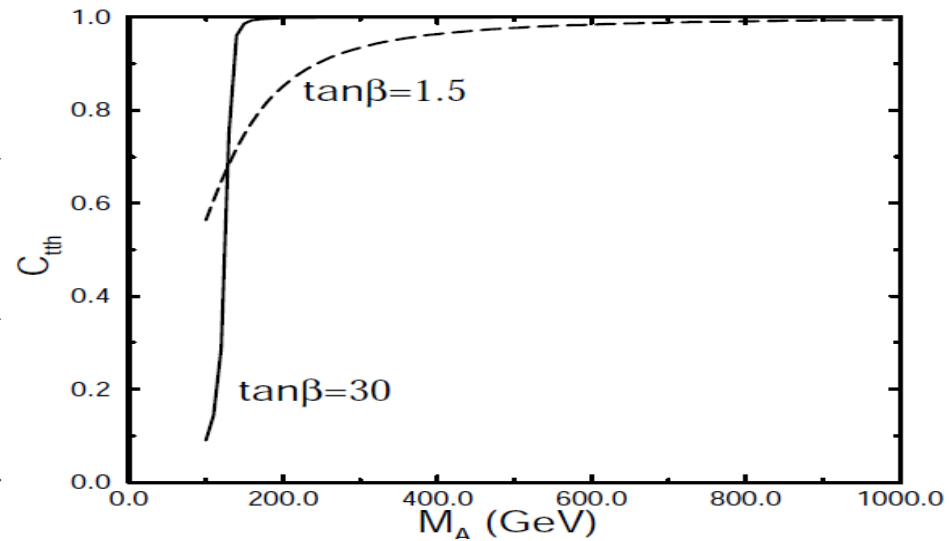
$$\tan 2\alpha = \frac{(M_A^2 + M_Z^2) \sin 2\beta}{(M_A^2 - M_Z^2) \cos 2\beta + \epsilon_h / \sin^2 \beta}$$

MSSM: Higgs couplings to fermions

Higgs Couplings to b in SUSY



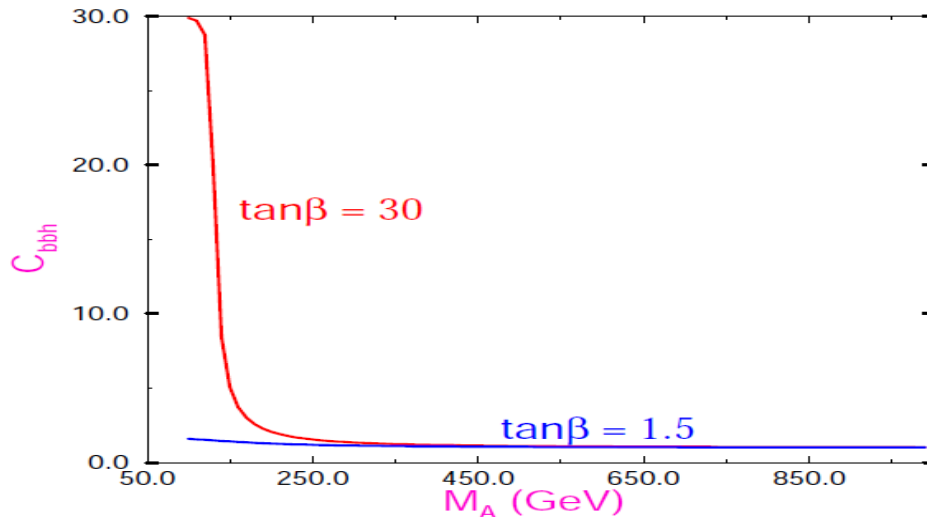
Higgs Couplings to u,c,t in SUSY



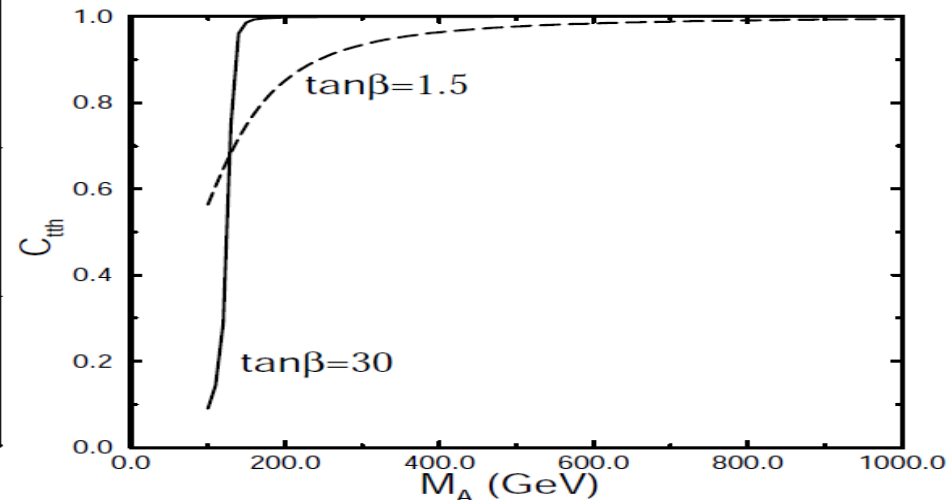
Let's find the different effects

MSSM: Higgs couplings to fermions

Higgs Couplings to b in SUSY



Higgs Couplings to u,c,t in SUSY



➤ Opposite behaviours versus M_A : See couplings: $C_{ddh} \propto 1/\cos\beta \propto \tan\beta$

➤ Different behaviours versus $\tan\beta$: See couplings

➤ Down/Up quark couplings: Always bigger/smaller than 1

➤ MSSM Higgs hunters are interested in final states with b, τ !

➤ Only interesting @ high $\tan\beta$ AND low M_A

➤ High M_A : All h-fermion coupling $\rightarrow 1$!

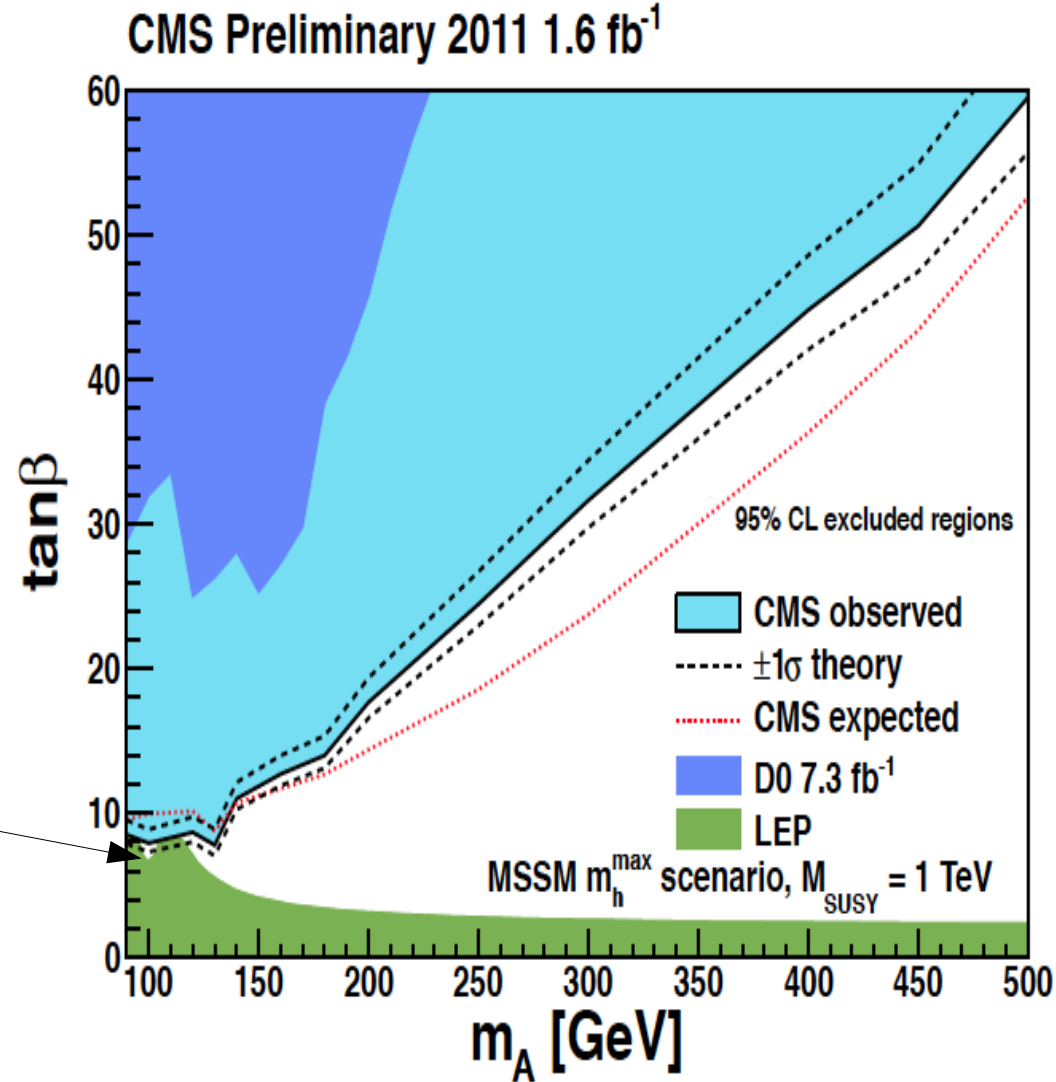
➤ **In decoupled regime:** No enhancement effect for down quarks. Things are pretty “democratic” across quark generations

➤ *Guess what's the present experimental picture...*

Do present Higgs search limits "exclude MSSM" ?

Not really:

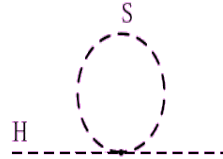
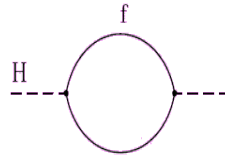
- M_A has no (dynamic) reason to be $< 500, 700 \text{ GeV}/c^2$
 - High M_A region still quite open
- Be careful: Do not interpret this plot as a "probability density plot for something to exist": **IF** SUSY exists, it will be in 1 given spot
 - Could be here
- **Now one thing is sure: IF SUSY exists, M_A pretty high: Decoupled regime seems preferred**



The 1st M in MSSM means Minimal: We are dealing with 124 parameters here... "Not constrained at all" framework

Motivation for the \tilde{t}_1 : Special relations with the Higgs

Stop/Higgs yukawa coupling



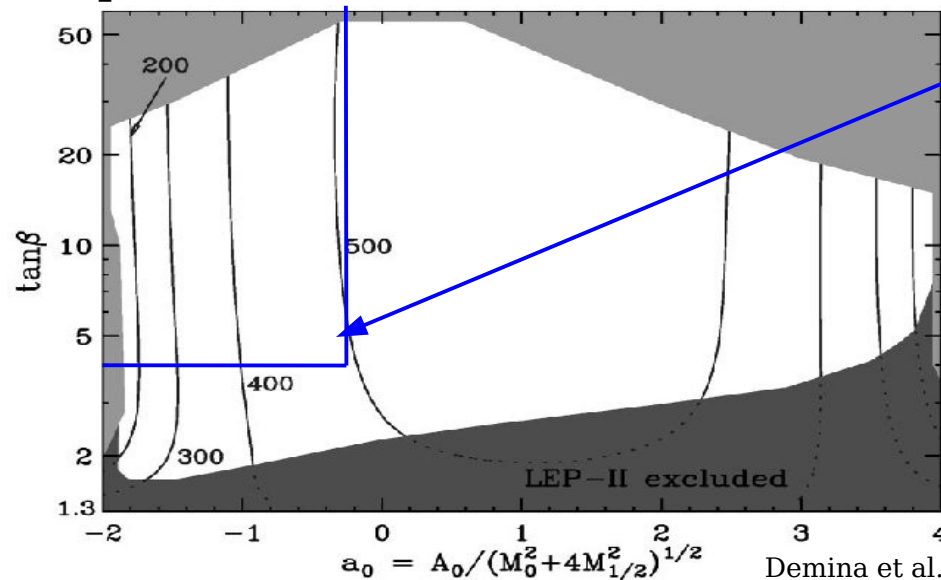
$$\longrightarrow M(h) = f [M(\tilde{q}, \tilde{t}_{1,2})]$$

$$M_{h,H}^2 = \frac{1}{2} \left\{ M_A^2 + M_Z^2 + \frac{\epsilon_h}{\sin^2 \beta} \pm \left[\left(M_A^2 - M_Z^2 \right) \cos 2\beta + \frac{\epsilon_h}{\sin^2 \beta} \right]^2 + \left(M_A^2 + M_Z^2 \right)^2 \sin^2 2\beta \right\}^{1/2}$$

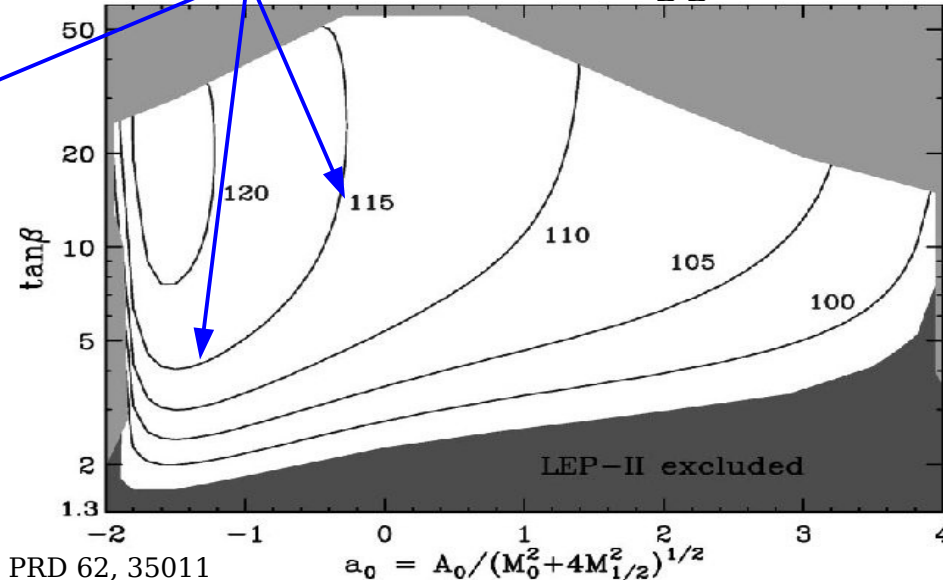
with: $\epsilon_h \equiv \frac{3G_F}{\sqrt{2}\pi^2} M_T^4 \log\left(\frac{\tilde{m}^2}{M_T^2}\right)$ ← Squark masses: Higgs mass particularly sensitive to $\sim \tilde{t}_{1,2}$ system

LHC: Higgs & stop searches can constraint each other

Stop masses



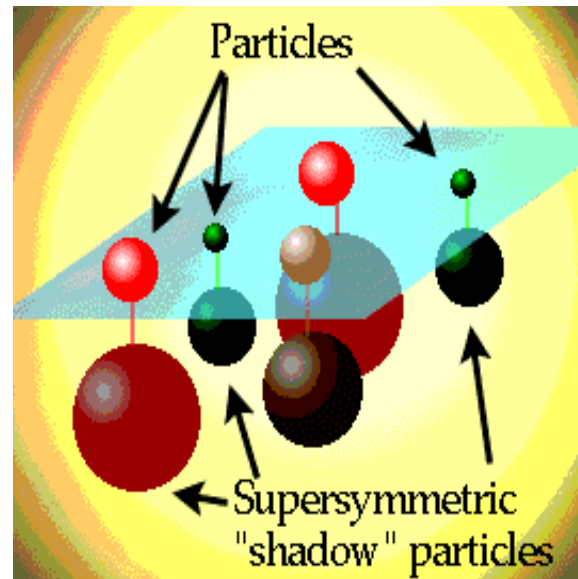
Higgs masses



Demina et al., PRD 62, 35011

$a_0 = A_0 / (M_0^2 + 4M_{1/2}^2)^{1/2}$

Experimental feedbacks, Hints (?)...



Looking for SUSY in EW data

Why did-we not get any hint of SUSY in EW Data ?

→ When looking at sector other than Higgs: Such SUSY contributions are suppressed $\propto [M_W/M_{\text{SUSY}}]^2$ where M_{SUSY} is the scale SUSY particles

What about performing a global fit to the EW data and try to fix SUSY spectrum ?

→ **No stringent limit on physical masses**

→ Not really astonishing: Try to fit with 124 degrees of freedom...

→ There “seems” to be information about $\tan\beta$: Two “preferred” values:

→ $\tan\beta \sim 2$: Well, this is more & more suppressed by Higgs searches

→ $\tan\beta \sim 30$: ...

→ What to think about this ? Probably better to look more directly for SUSY particles

Looking “a bit more” directly: $\text{Br}(b \rightarrow s X)$

Famous “on the edge of SM” measurement:

$$BR(B \rightarrow X_s \gamma) = (2.32 \pm .67) \times 10^{-4}$$

Out of SM... ?

- Either statistical fluctuation
- Or new physics around corner

Let's plug-in SUSY: **Let's draw a SUSY diagram allowing such a process**

Looking “a bit more” directly: $\text{Br}(b \rightarrow s X)$

Famous “on the edge of SM” measurement:

$$BR(B \rightarrow X_s \gamma) = (2.32 \pm .67) \times 10^{-4}$$

Out of SM... ?

- Either statistical fluctuation
- Or new physics around corner

Let's plug-in SUSY: $b \rightarrow \text{Loop } \{\chi_1^-, t_1\} \rightarrow s$

$$\frac{BR(b \rightarrow s \gamma)}{BR(b \rightarrow ce\bar{\nu})} \sim \frac{|V_{ts} V_{tb}|^2}{|V_{cb}|^2} \frac{6\alpha}{\pi} \left\{ C + \frac{M_T^2 A_T \mu}{\tilde{m}_T^4} \tan \beta \right\}^2$$

SM prediction: Slightly above measurement → Indication of $A_T \mu < 0$

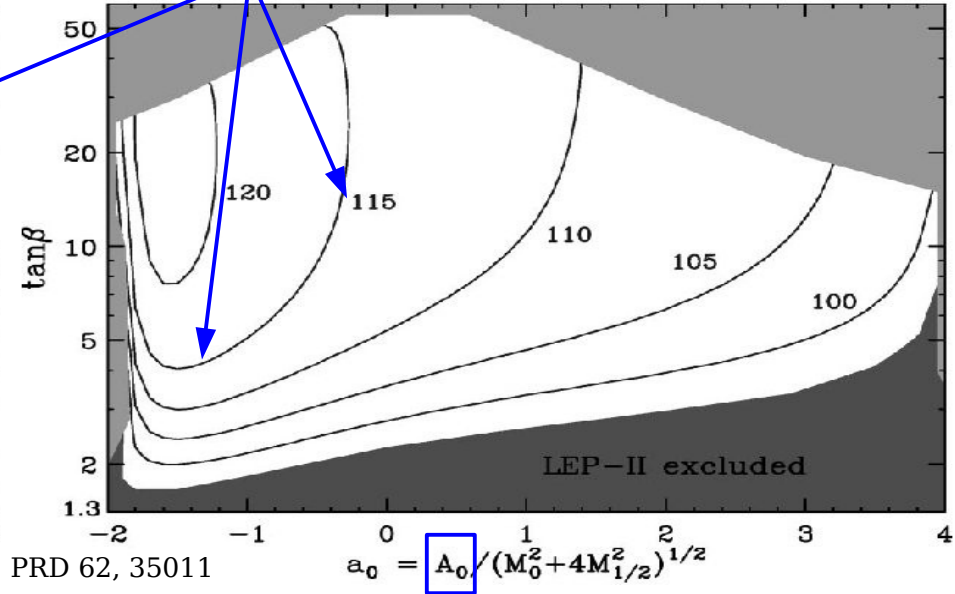
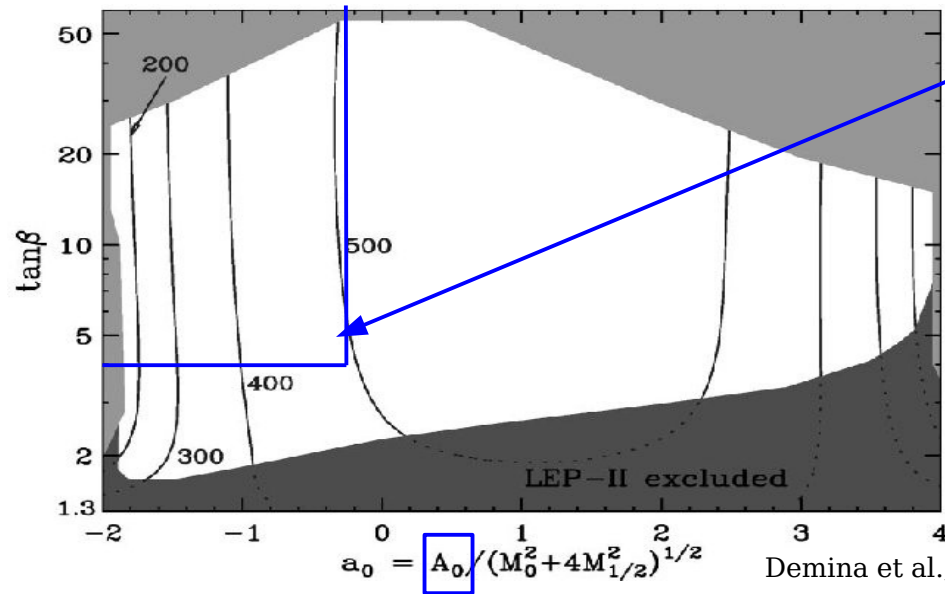
Depending on $\tan \beta$: This probes t_1 masses in $[100, 300]$ GeV/ c^2 region

Let's look at the of $A_T \mu < 0$ issue...

Looking “a bit more” directly: Indications ?

Stop masses

Higgs masses

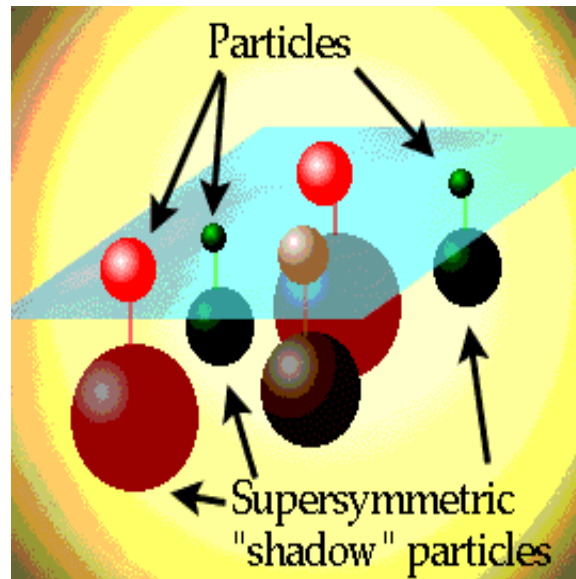


$A_\mu < 0$: Compatible with:

- 1/ $M(h) > 115, 120 \text{ GeV}/c^2$
- 2/ $M(t_1) < 500 \text{ GeV}/c^2$

Other thoughts ?

Exercises



SUSY diagrams

Let's start from the bottom of the SUSY scale...

$$\chi_2^0 \rightarrow ll \chi_1^0$$

$$\chi_1^\pm \rightarrow l^\pm \nu \chi_1^0$$

@LHC: Give a production process for lightest chargino production
Then give the full diagram

$$t_1 \rightarrow b \chi_1^\pm$$

$$t_1 \rightarrow t \chi_1^0$$

$$t_1 \rightarrow c \chi_1^0$$

SUSY diagrams

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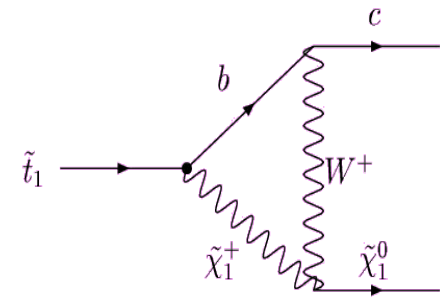
$$t_1 \rightarrow t \chi_1^0$$

$$t_1 \rightarrow c \chi_1^0$$

$$t_1 \rightarrow b W \chi_1^0$$

@LHC: Give an example of simplest production mode for t_1

Now push it to the semi-leptonic final state via $b \chi_1^\pm$ scenario



SUSY diagrams

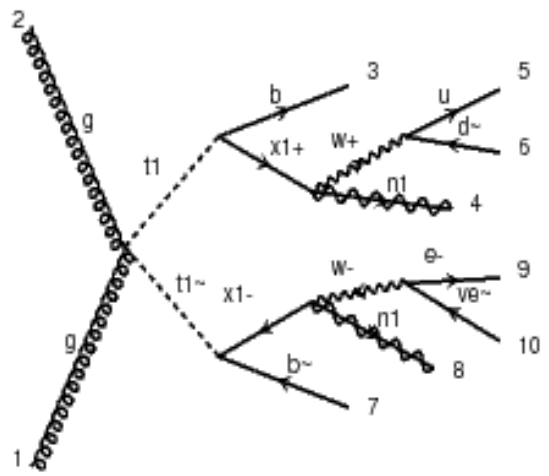


diagram 1 QED=6, QCD=2

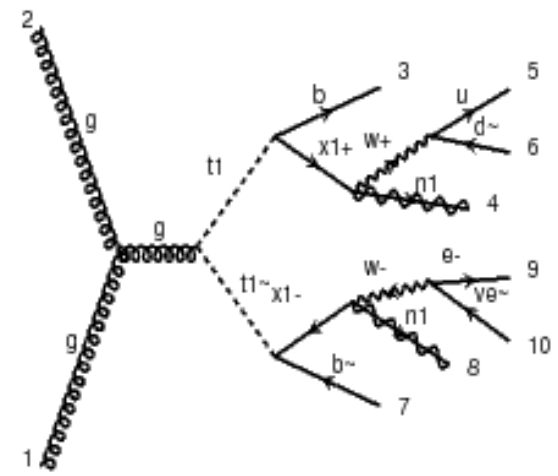


diagram 2 QED=6, QCD=2

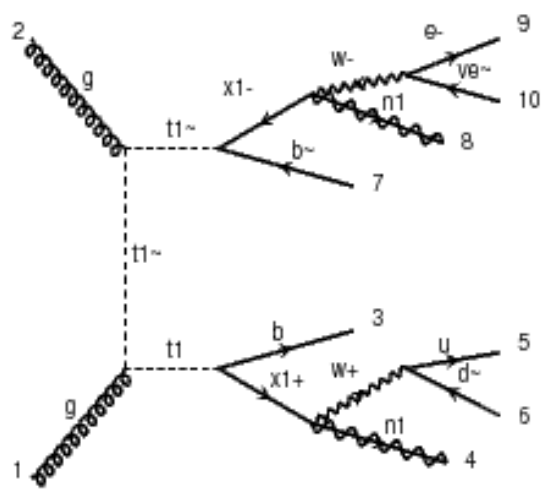


diagram 3 QED=6, QCD=2

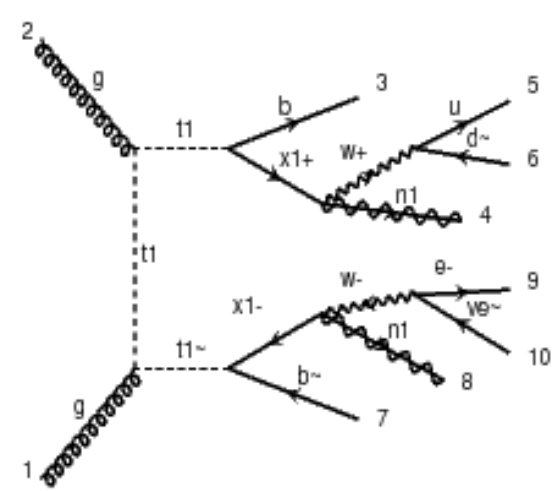
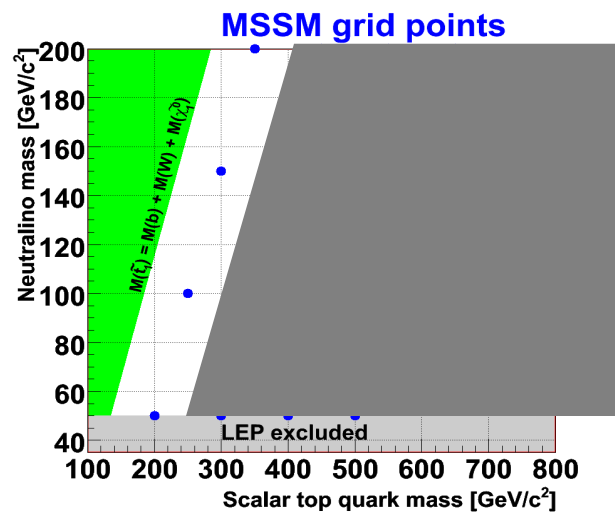


diagram 4 QED=6, QCD=2

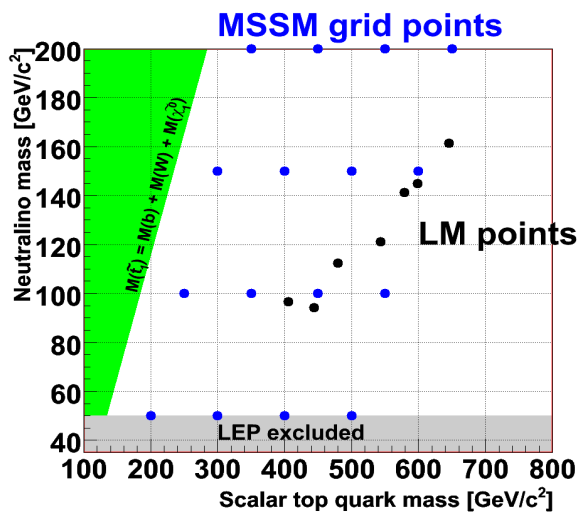
Welcome to exercise & verify with MadGraph

Stop decays: Different diagrams for different domains

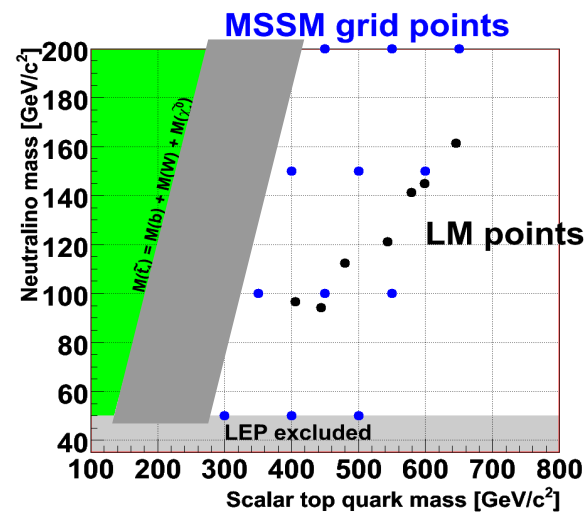
$$\tilde{t}_1 \rightarrow b W^+ \tilde{\chi}_1^0$$



$$\tilde{t}_1 \rightarrow b \tilde{\chi}_1^+$$



$$\tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$$



Conditions:

$$b + W + \tilde{\chi}_1^0 < \tilde{t}_1$$

$$\tilde{t}_1 < t + \tilde{\chi}_1^0 :$$

$$\text{Close } \tilde{t}_1 \rightarrow t + \tilde{\chi}_1^0$$

$$b + W + \tilde{\chi}_1^0 < \tilde{t}_1$$

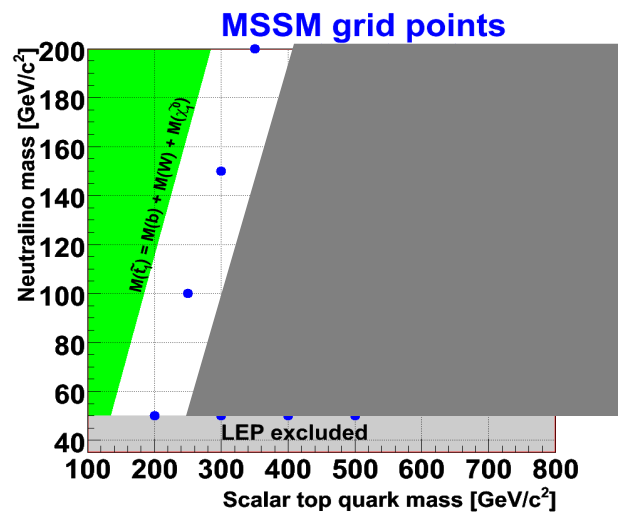
$$W + \tilde{\chi}_1^0 < \tilde{\chi}_1^+ < \tilde{t}_1 - b$$

← Not exclusive: Will co-exist →

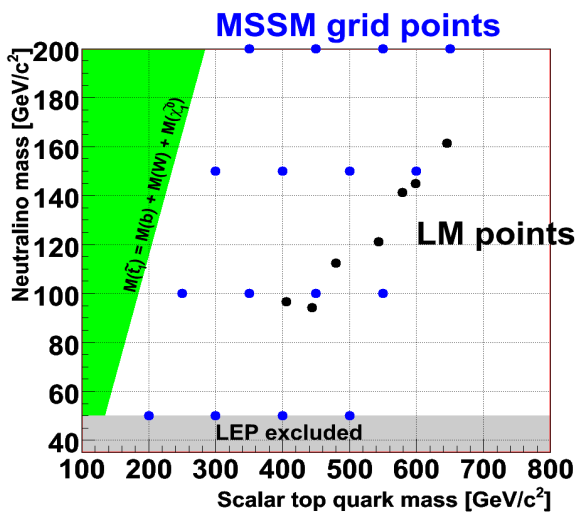
$$t + \tilde{\chi}_1^0 < \tilde{t}_1$$

Stop decays: Different diagrams for different domains

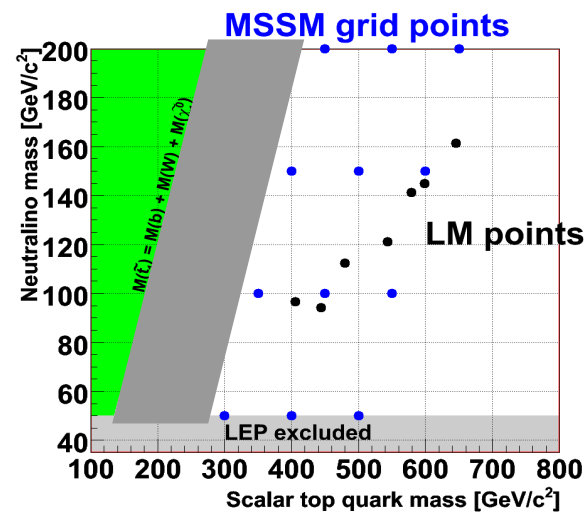
$$\tilde{t}_1 \rightarrow b W^+ \tilde{\chi}_1^0$$



$$\tilde{t}_1 \rightarrow b \tilde{\chi}_1^+$$



$$\tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$$



Conditions:

$$b + W + \tilde{\chi}_1^0 < \tilde{t}_1$$

$$\tilde{t}_1 < t + \tilde{\chi}_1^0 :$$

$$\text{Close } \tilde{t}_1 \rightarrow t + \tilde{\chi}_1^0$$

“Dominance” conditions:

$$\tilde{t}_1 < \tilde{\chi}_1^+ + b :$$

Make $\tilde{\chi}_1^+$ virtual

$$b + W + \tilde{\chi}_1^0 < \tilde{t}_1$$

$$W + \tilde{\chi}_1^0 < \tilde{\chi}_1^+ < \tilde{t}_1 - b$$

← Not exclusive: Will co-exist →

$$t + \tilde{\chi}_1^0 < \tilde{t}_1$$

$$t + \tilde{\chi}_1^0 < \tilde{\chi}_1^+ + b :$$

Privilege vs $b \tilde{\chi}_1^+$

SUSY diagrams

@LHC: Give an example of simplest production mode for:

- squarks
- gluino
- squark+gluino production

Simplest diagram for t_1 production via gluino pair-production

SUSY diagrams

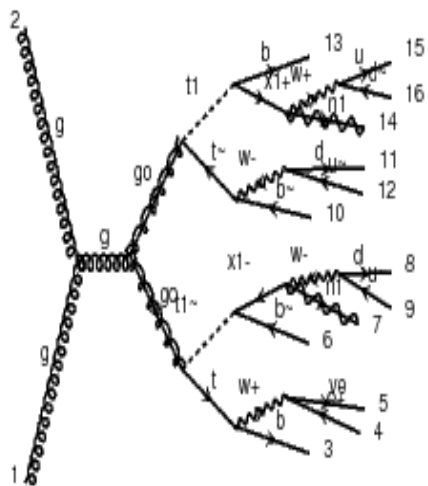


diagram 1 QCD=4, QED=10

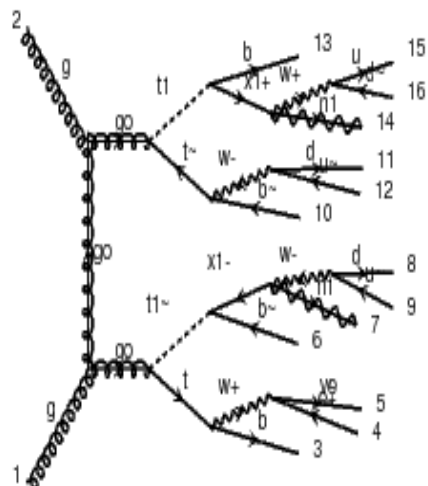


diagram 2 QCD=4, QED=10

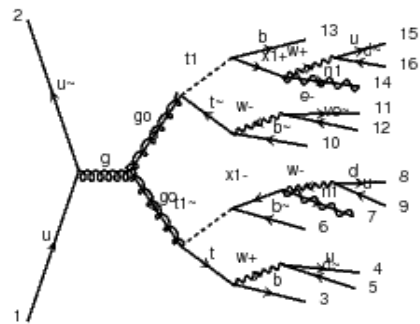


diagram 1 QCD=4, QED=10

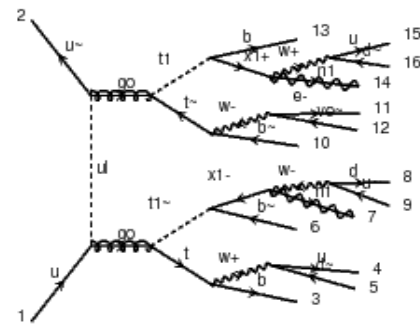


diagram 2 QCD=4, QED=10

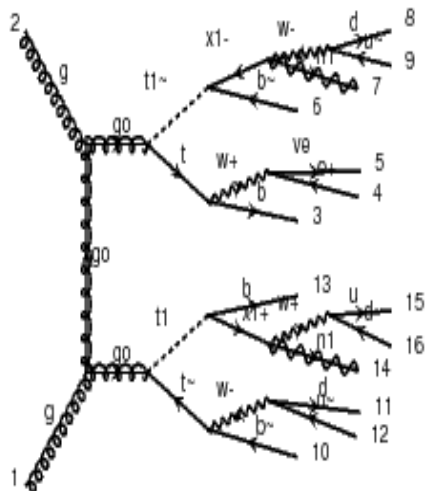


diagram 3 QCD=4, QED=10

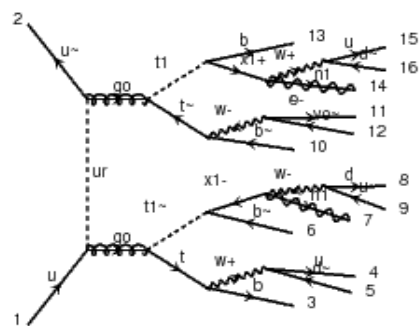


diagram 3 QCD=4, QED=10

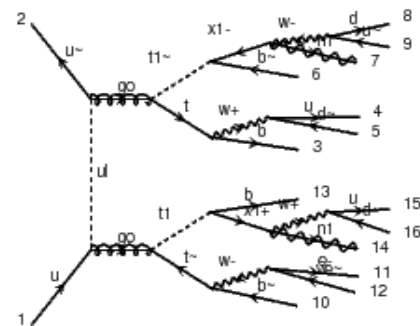


diagram 4 QCD=4, QED=10

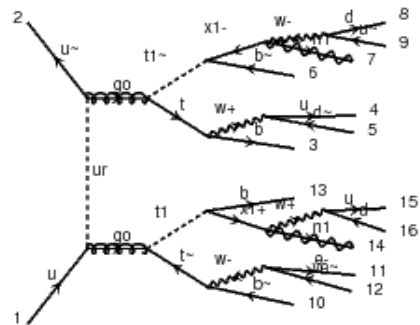


diagram 5 QCD=4, QED=10

SUSY diagrams

t_1 production via – give each time the mass condition(s):

- Simplest squark production
- Simplest sbottom production
- Squark production with intermediate slepton
- t_2 production