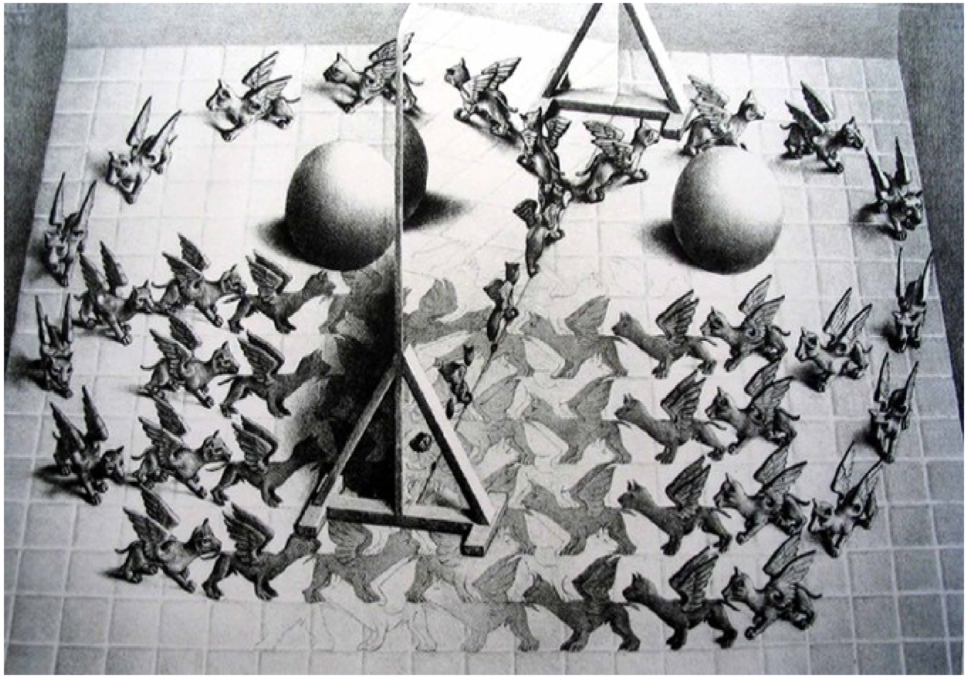
Physics at LHC:
SUperSYmmetry

Pedrame Bargassa



22/04/2020

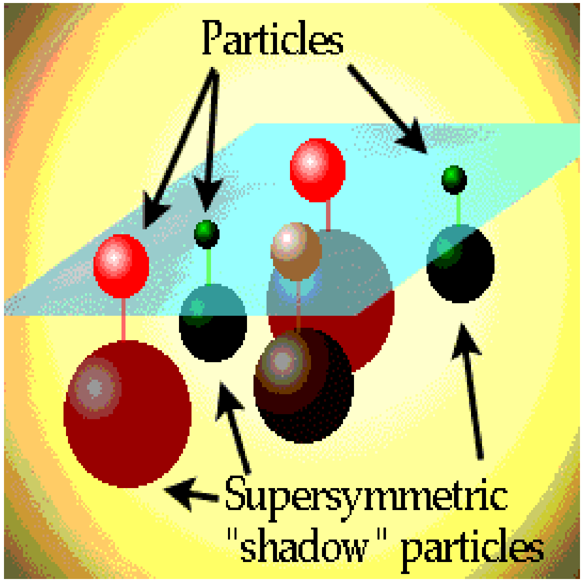
Outline

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

Advised readings:

- “SUSY & Such” S. Dawson, arxiv:hep-ph/9612229v2
- “A supersymmetry primer” S. P. Martin, arxiv: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: ≤ 3 → Mass terms, Bilinear & Trilinear terms

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

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

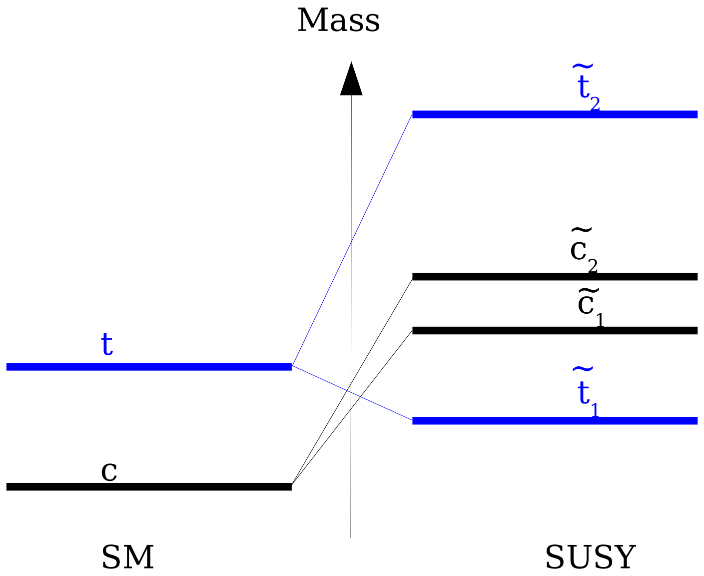
MSSM: Squark & Slepton sector

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

Comments:

- 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

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

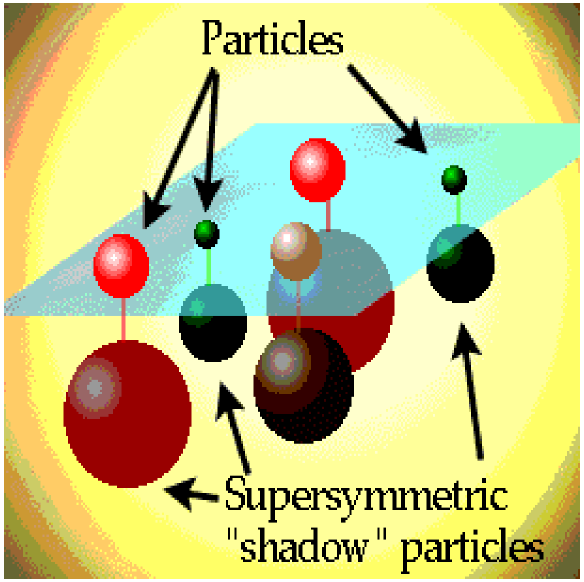
In the neutral [b - w^0 - h^0_1 - h^0_2] basis:

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

- 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

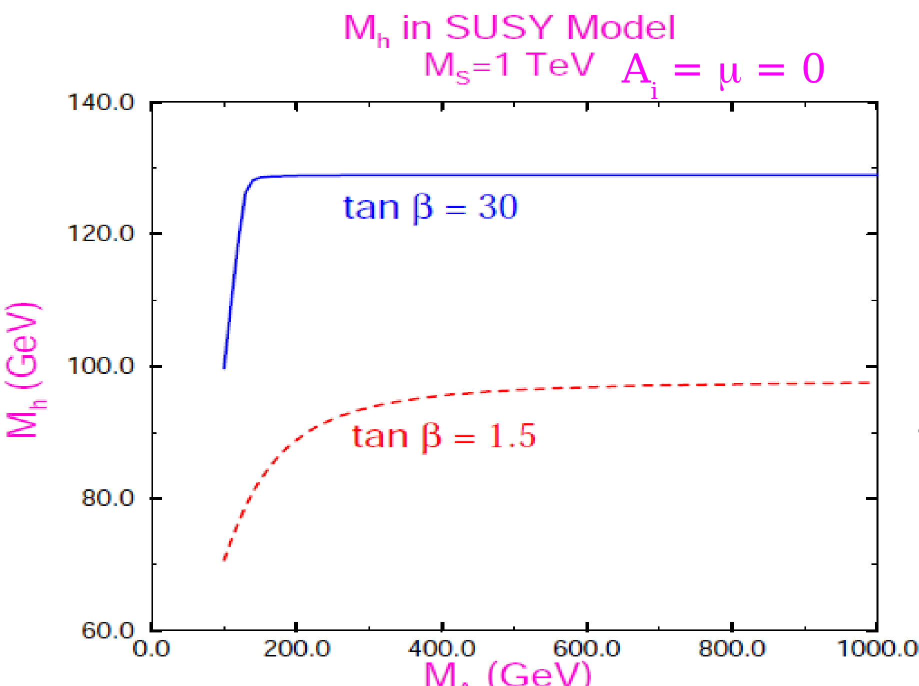
Equation governing lightest Higgs mass:

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

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



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

→ The "well-known" $M_h < 135$ GeV/c^2 <u>limit for any-SUSY lightest Higgs</u>
→ ...is dependent on
- → 2-loop calculations
- → Renormalization calculations which can evolve...

MSSM: Higgs mass & squarks / Limit

Equation governing lightest Higgs mass:

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

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 $\tilde{t}_{1,2}$ 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 $M_h^{max} > 130$ GeV/c^2

→ μB perturbative up to Planck-scale:

For any SUSY: M_h^{max}~150 GeV/c^2

And m(lightest Higgs) = 125 GeV/c^2

Does this mean that it is a Susy Higgs ? ;-)

MSSM: Higgs couplings to bosons

Let's look at couplings:

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

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

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

SM couplings

$$\sin(\beta-\alpha) \quad \to 1 \text{ for } M_A \to \infty$$
$$\cos(\beta-\alpha) \quad \to 0 \quad .$$

Similar for coupling to γ & fermions

Exercise: Demonstrate the 2 relations above

It is possible that:

1/ Light h "SM like":

→ Mass: Rather low

→ ~All branching ratios: Like in SM

2/ {H, H±, A} much heavier & degenerate

→ Couplings of lightest Higgs to fermions/γ/W/Z ~ 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:

$$\mathbf{L_{yukawa} = -G_d\,(\bar{u},\bar{d})_L\,(\phi^+,\phi 1^0)\,d_R - G_u\,(\bar{u},\bar{d})_L\,(\phi 2^0,\phi^-)\,u_R + hc}$$

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:

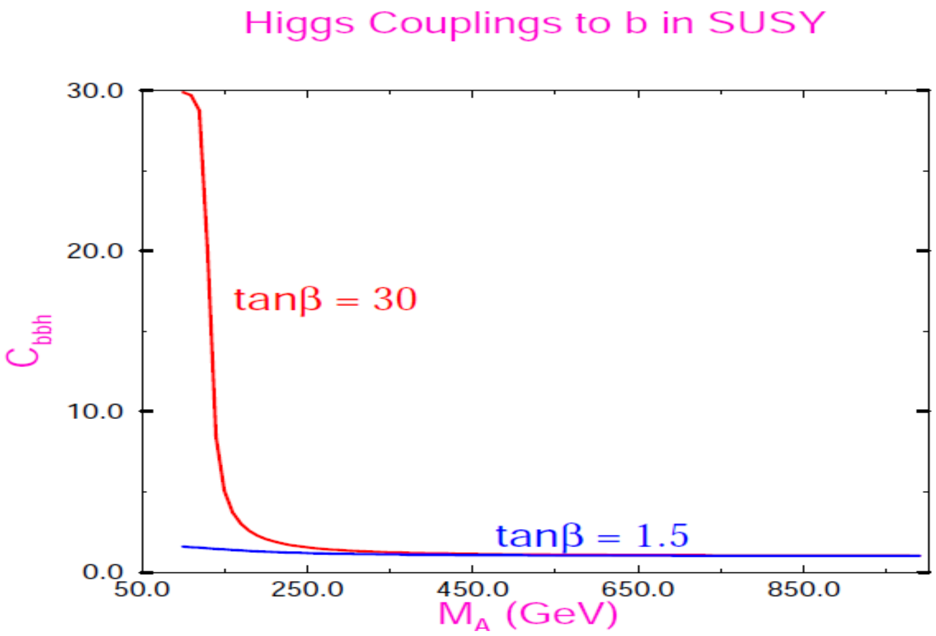
$$\mathcal{L} = -\frac{g m_i}{2M_W}\left[C_{ffh}\bar{f}_i f_i h + C_{ffH}\bar{f}_i f_i H + C_{ffA}\bar{f}_i \gamma_5 f_i A\right]$$

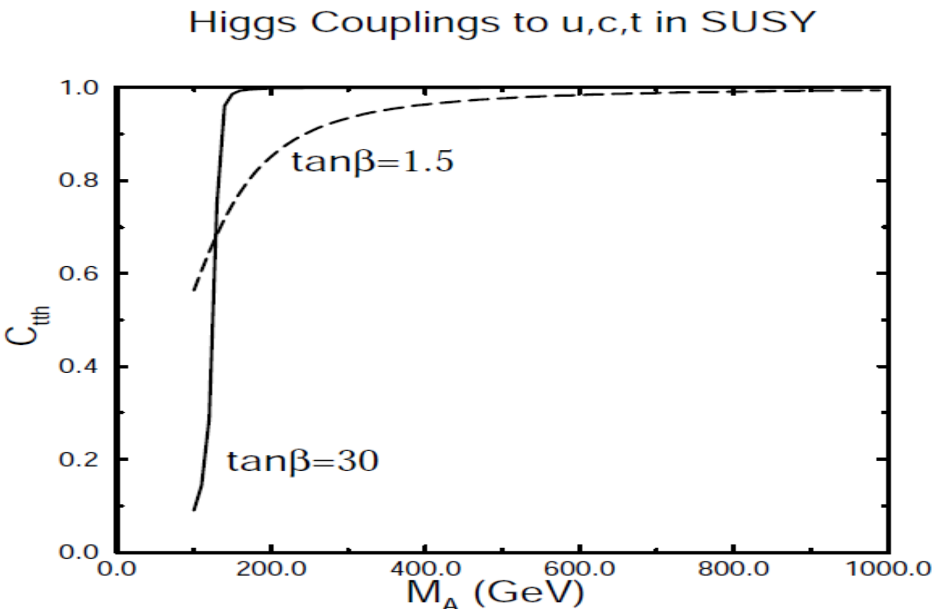
f	C_{ffh}	C_{ffH}	C_{ffA}
u	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\cot\beta$
d	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$\tan\beta$

- 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...*

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

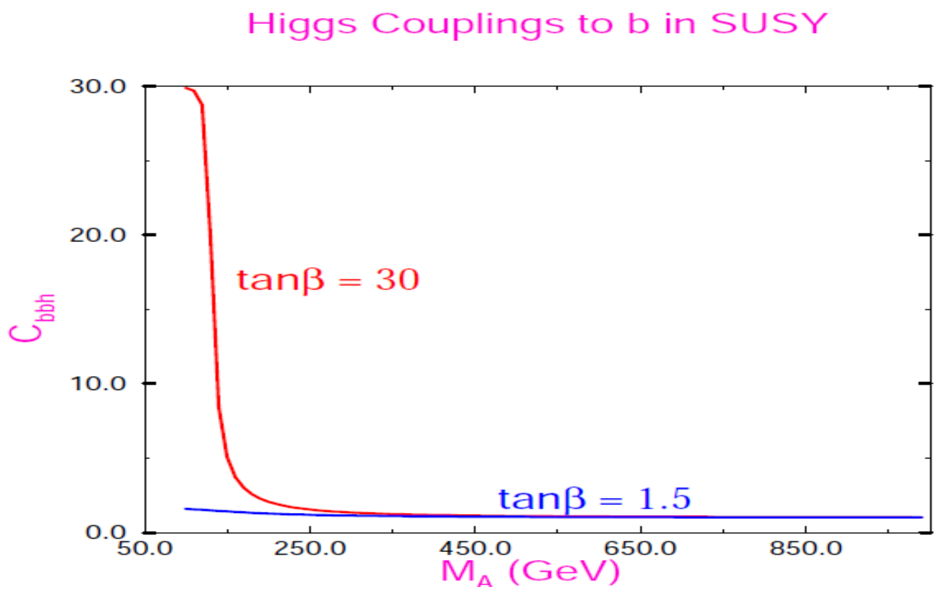
MSSM: Higgs couplings to fermions

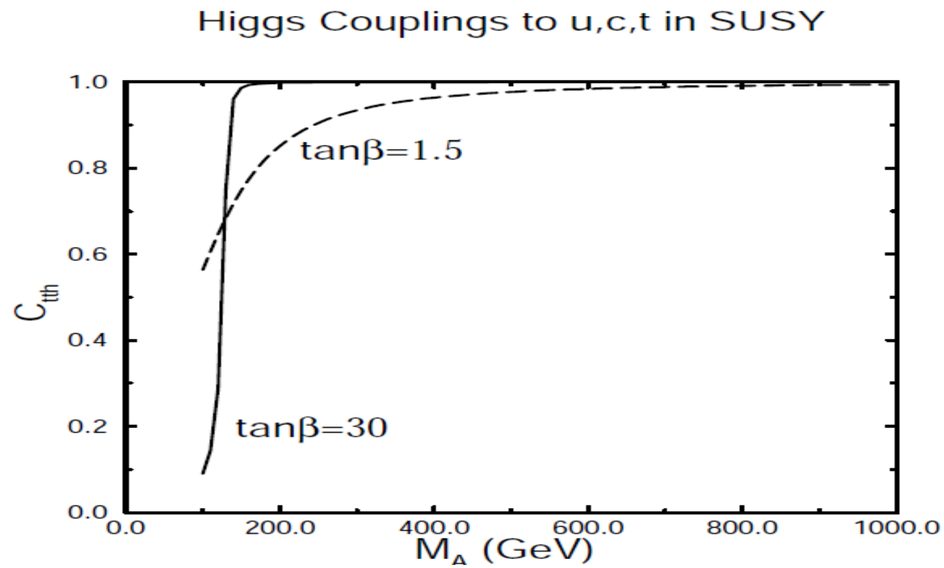




Let's find the different effects

MSSM: Higgs couplings to fermions

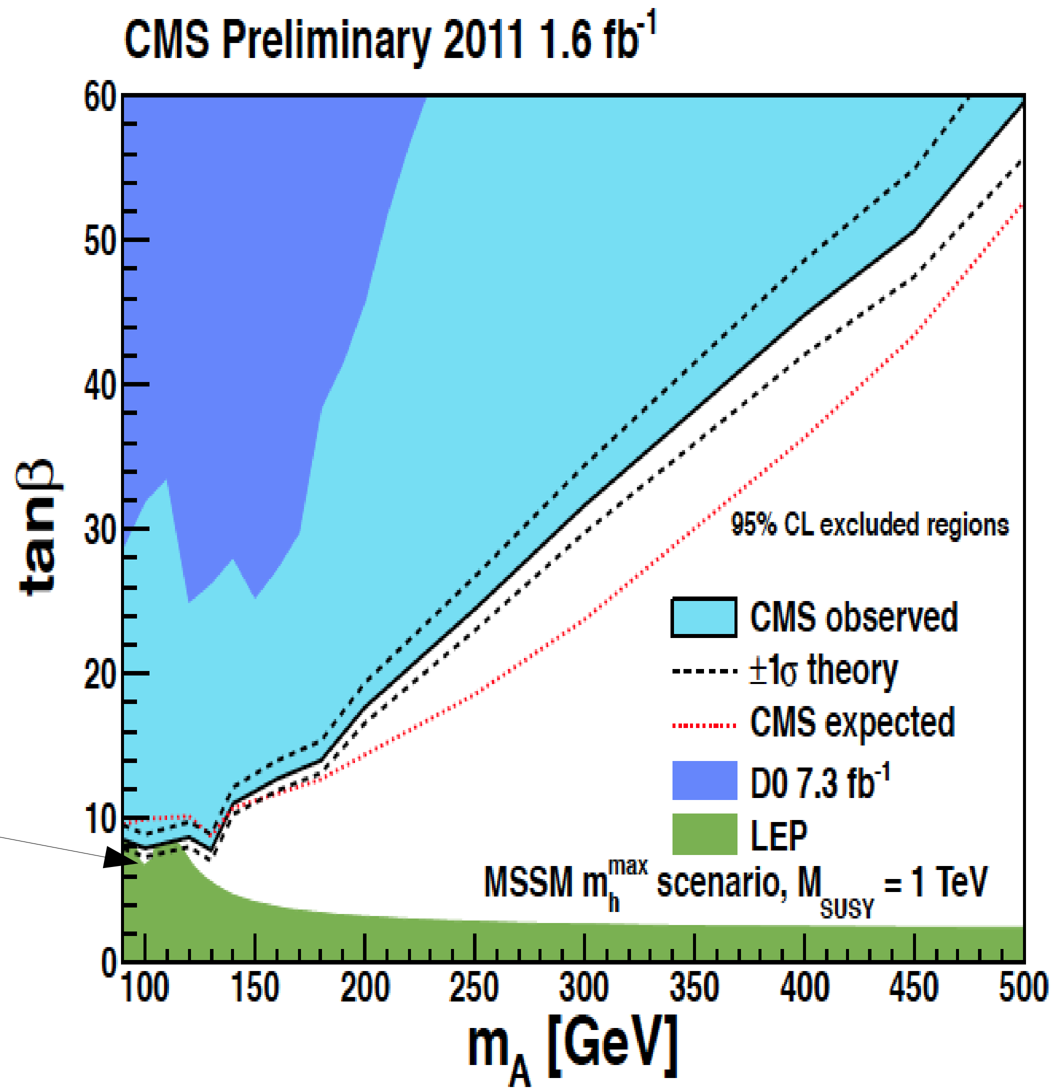




- Opposite behaviours versus M_A: See couplings: C_{ddh} α $1/\cos\beta$ α $\tan\beta$
- Different behaviours versus $\tan\beta$: See couplings
- Down/Up quark couplings: Always bigger/smaller than 1
  - MSSM Higgs hunters are interested in final states with b, τ !
    - Only interesting @ high $\tan\beta$ 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" ?

- M_A has no (dynamic) reason to be < 500, 700 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

Stop/Higgs yukawa coupling

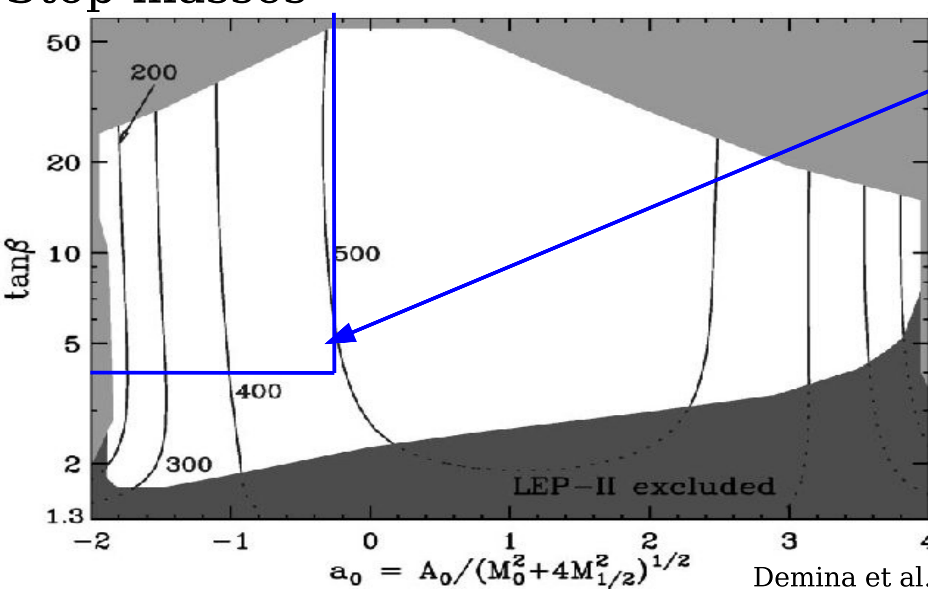
→ M(h) = f [M($\tilde{q}$,$\tilde{t}_{1,2}$)]

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

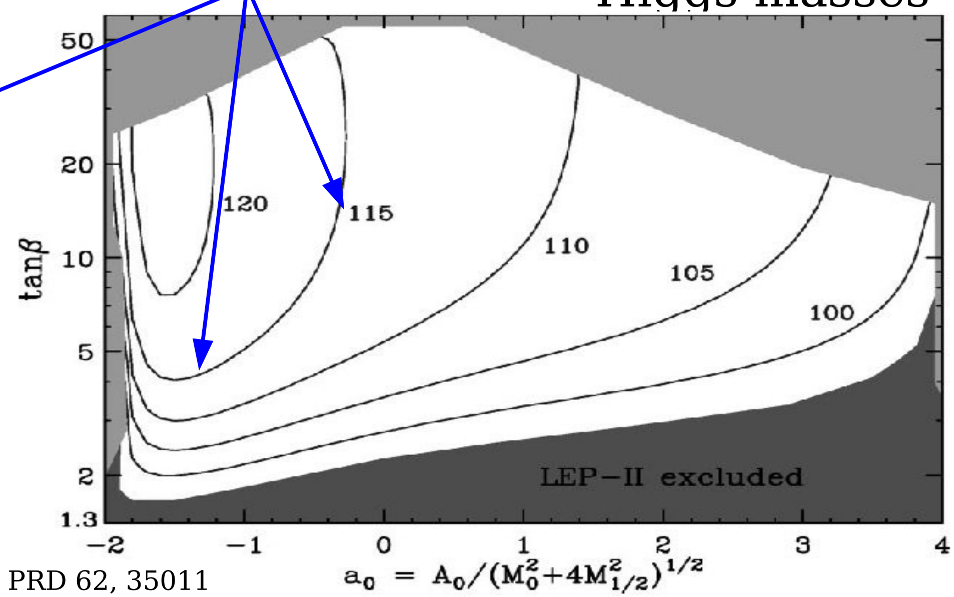
with: $\epsilon_h \equiv \frac{3G_F}{\sqrt{2}\pi^2}M_T^4\log\left(\frac{\tilde{m}^2}{M_T^2}\right)$ ◄ Squark masses: Higgs mass particularly sensitive to ~$t_{1,2}$ system

LHC: Higgs & stop searches can constraint each other

Stop masses

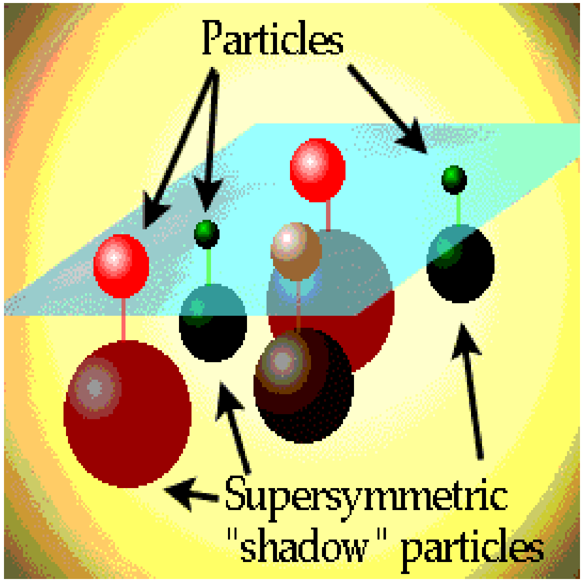


Higgs masses



Demina et al., PRD 62, 35011

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 α $[M_W/M_{SUSY}]^2$ 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 tanβ: Two “preferred” values:
  → tanβ~2 : Well, this is more & more suppressed by Higgs searches
  → tanβ~30: …
    → What to think about this ? Probably better to look more directly for SUSY particles

Looking “a bit more” directly: Br(b -> s X)

Famous “on the edge of SM” measurement:

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

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: Br(b -> s X)

Famous "on the edge of SM" measurement:

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Out of SM... ?

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Let's plug-in SUSY: b → Loop $\{\chi^-_1, t_1\}$ → s

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

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

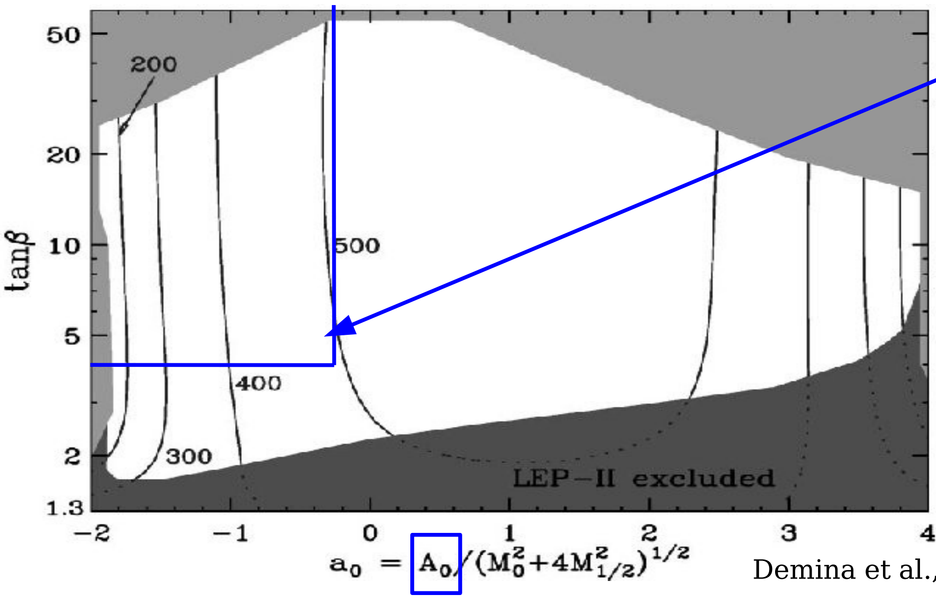
Depending on tanβ: This probes t_1 masses in [100,300] GeV/c^2 region

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

Looking "a bit more" directly: Indications ?

Stop masses

Higgs masses



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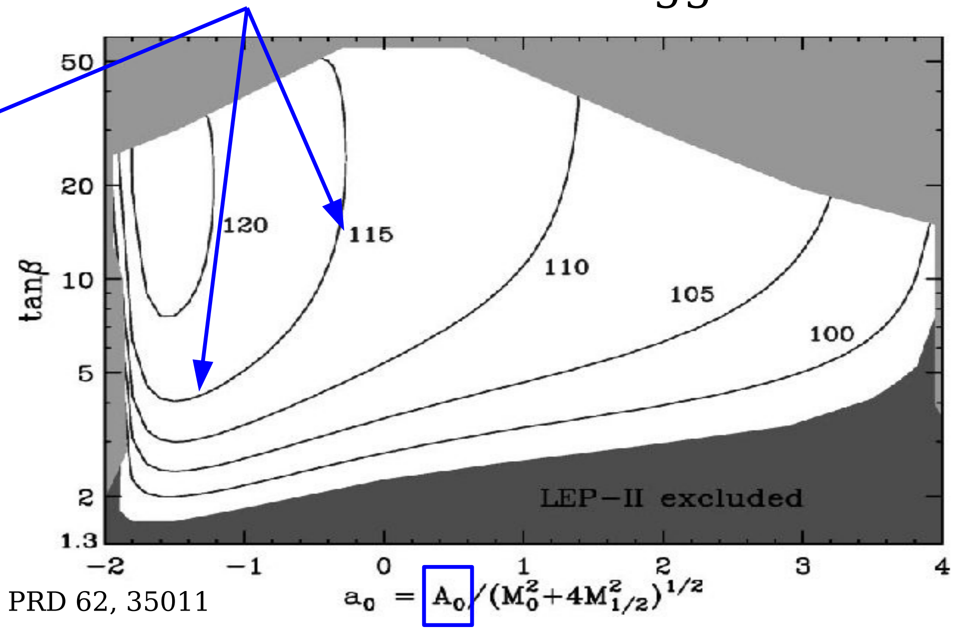


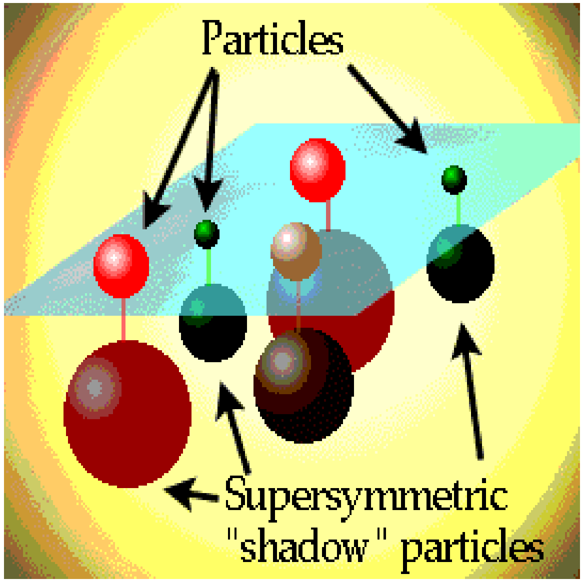
$A_t\mu < 0$: Compatible with:

1/ $M(h) > 115, 120\ \mathrm{GeV}/c^2$

2/ $M(t_1) < 500\ \mathrm{GeV}/c^2$

Other thoughts ?

Exercises



SUSY diagrams

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

$\chi^0_2 \rightarrow l\, l\, \chi^0_1$

$\chi^{\pm}_1 \rightarrow l^{\pm}\nu\ \chi^0_1$

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

$t_1 \rightarrow b\ \chi^{\pm}_1$

$t_1 \rightarrow t\ \chi^0_1$

$t_1 \rightarrow c\ \chi^0_1$

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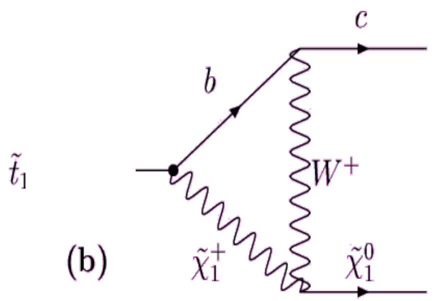
$t_1 \rightarrow c\ \ \chi^0_1$

$t_1 \rightarrow b\, W\ \ \chi^0_1$



@LHC: Give an example of simplest production mode for t_1
Now push it to the semi-leptonic final state via b $\chi^\pm_1$ scenario

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

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