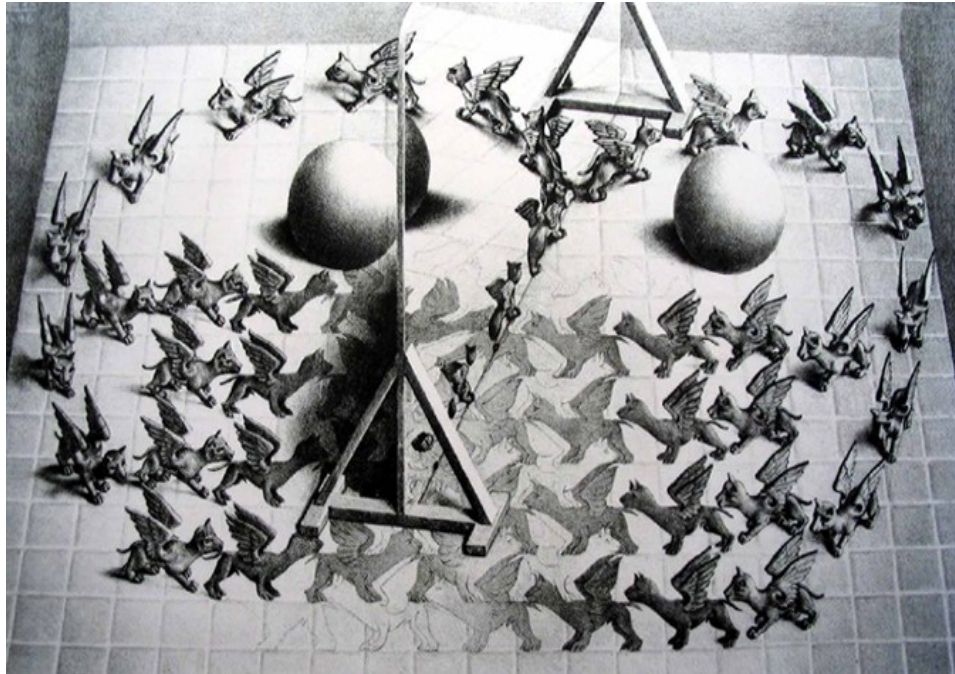# Physics at LHC:
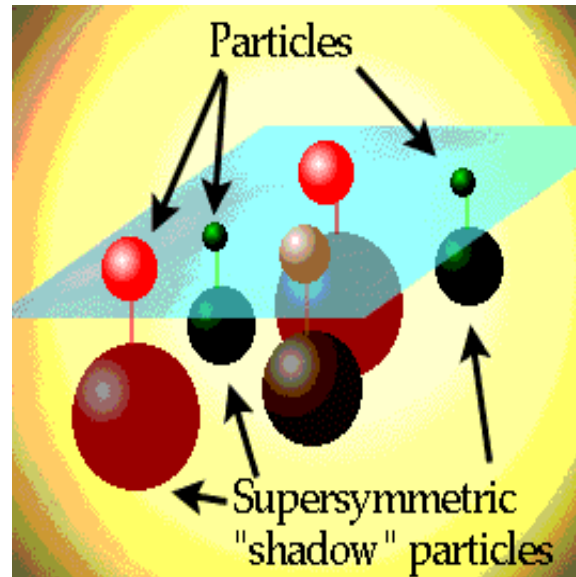## *SUperSYmmetry*

Pedrame Bargassa

26/04/2021

Outline

> *Reminders of last time: Different physical SUSY sectors*

> *Higgs sector*

> *Getting into experimental feedback*

> *Exercises*

<u>Advised readings</u>:

> "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 <u>how</u> SUSY is broken, but can write the **most general broken effective Lagrangian**

> Maximal dimension of soft operators: ≤ 3 → Mass terms, Bilinear & Trilinear terms

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

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:

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

➢ $\widetilde{M}_Q$: Left squark mass

➢ $\widetilde{M}_U$: 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
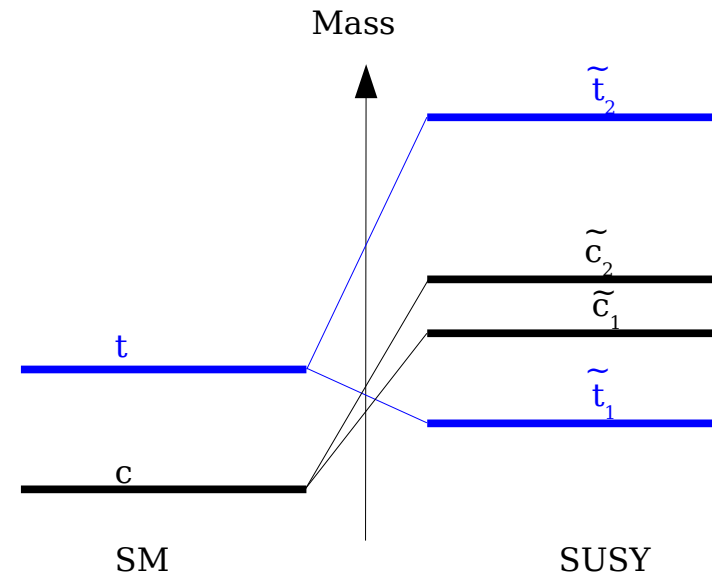
MSSM: Chargino sector

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

Physical states are 4 fermionic mass-eigenstates: Mixtures of neutral winos w^0 , bino b, and 2 neutral higgsinos, which are SUSY eigenstates
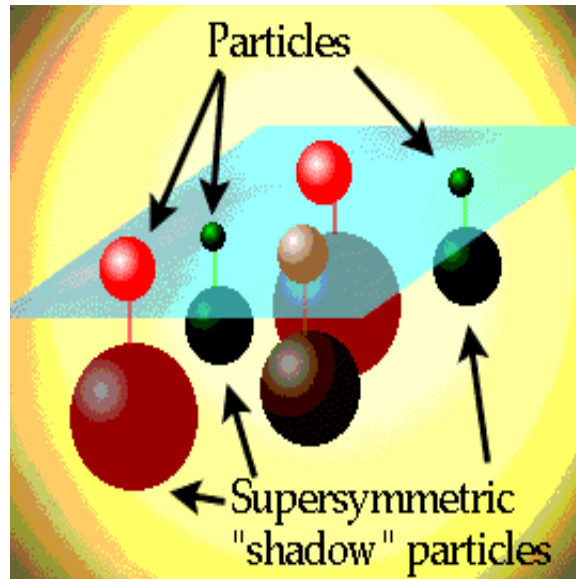
In the neutral [b - w^0 - h^0_1 - h^0_2] basis:

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

➤ 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$^\pm$ / A (CP-odd)

2 VEVs:
$$\langle H_1^0 \rangle \equiv v_1$$
$$\langle H_2^0 \rangle \equiv v_2$$

$\rightarrow$ Key MSSM parameter: $\boxed{\tan\beta \equiv \dfrac{v_2}{v_1}}$

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

3 parameters to describe the MSSM Higgs sector:

Once v$_{1,2}$ are fixed such that: $\boxed{M_W^2 = \dfrac{g^2}{2}(v_1^2 + v_2^2)}$

This whole sector is described by (only) 2 other parameters:
$\rightarrow \tan\beta$
$\rightarrow$ M$_A$ $\boxed{M_A^2 = \dfrac{2\,|\,\mu B\,|}{\sin 2\beta}}$
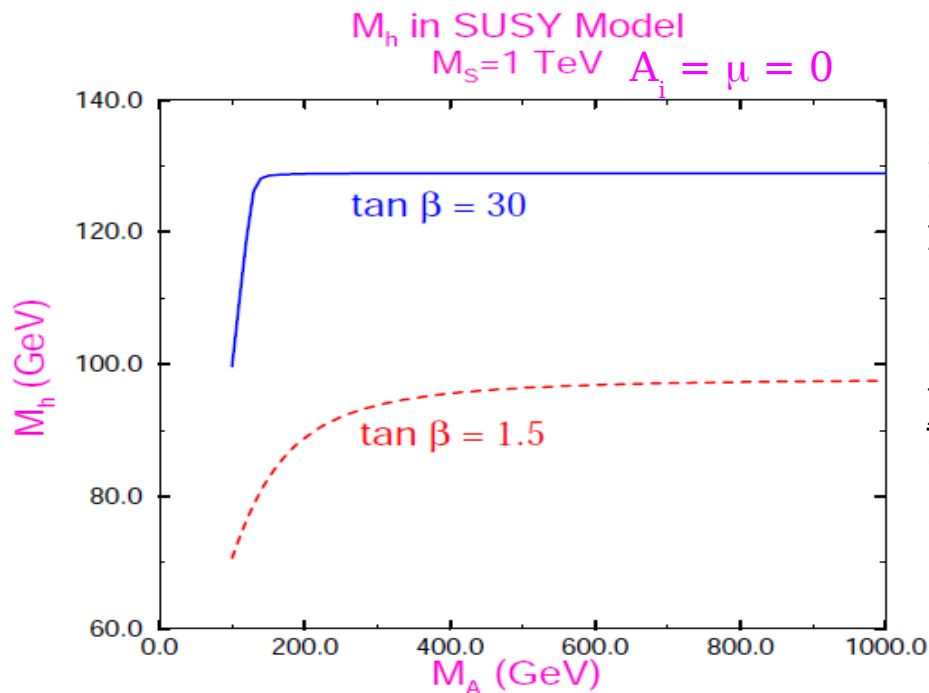
Equation governing lightest Higgs mass:

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

with: $\epsilon_h \equiv \dfrac{3G_F}{\sqrt{2}\pi^2} M_T^4 \log\left(\dfrac{\tilde{m}^2}{M_T^2}\right)$

Contribution of 1-loop correction only !
Squark masses: Higgs mass
particularly sensitive to $\sim t_{1,2}$ system

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

M_h in SUSY Model
$M_S = 1$ TeV $A_i = \mu = 0$

$\tan\beta = 30$

$\tan\beta = 1.5$

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

$\rightarrow$ The "well-known" $M_h < 135$ GeV/c^2
limit for any-SUSY lightest Higgs
$\rightarrow$ …is dependent on
$\qquad \rightarrow$ 2-loop calculations
$\qquad \rightarrow$ Renormalization calculations
$\qquad\quad$ which can evolve…

MSSM: Higgs mass & squarks / Limit

Equation governing lightest Higgs mass:

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

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

Upper bound: When $M_A \to \infty$
$M_h^2 = M_A^2 - f(M_A^4)$
$M_H^2 = M_A^2 + f(M_A^4)$

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: $M_h^{max} \sim 150$ 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:

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

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

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

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$^\pm$, 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:

L$_{yukawa}$ = -G$_d$ (ū,d̄)$_L$ (φ$^+$,φ1^0) d$_R$ - G$_u$ (ū,d̄)$_L$ (φ2^0,φ$^-$) u$_R$ + hc

Then break EW with φ = (1/√2)(0,v$_{1,2}$+Higgs) ← "Rapid" notation

Then re-rewrite things in
terms of coupling:

$$\mathcal{L} = -\frac{gm_i}{2M_W}\left[C_{ffh}\bar{f}_i f_i h + C_{ffH}\bar{f}_i f_i H + C_{ffA}\bar{f}_i \gamma_5 f_i A\right]$$
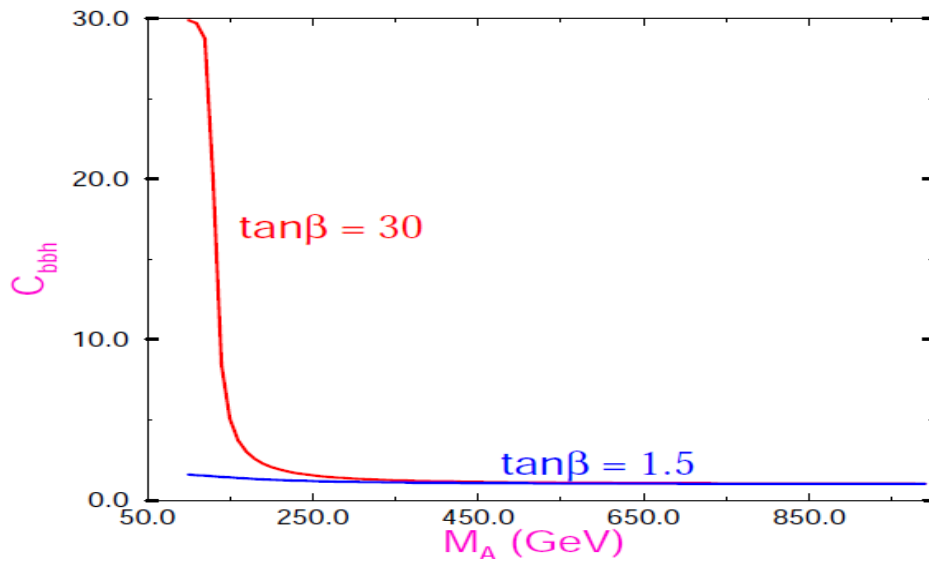
- ➤ Coupling to same fermions:
  "Opposite" behaviors of 2 lightest
  neutral higgs h and H

- ➤ Coupling to the same Higgs:
  "Opposite" behaviors of u/d quarks

- ➤ *Let's see what the 2nd case
  graphically means...*

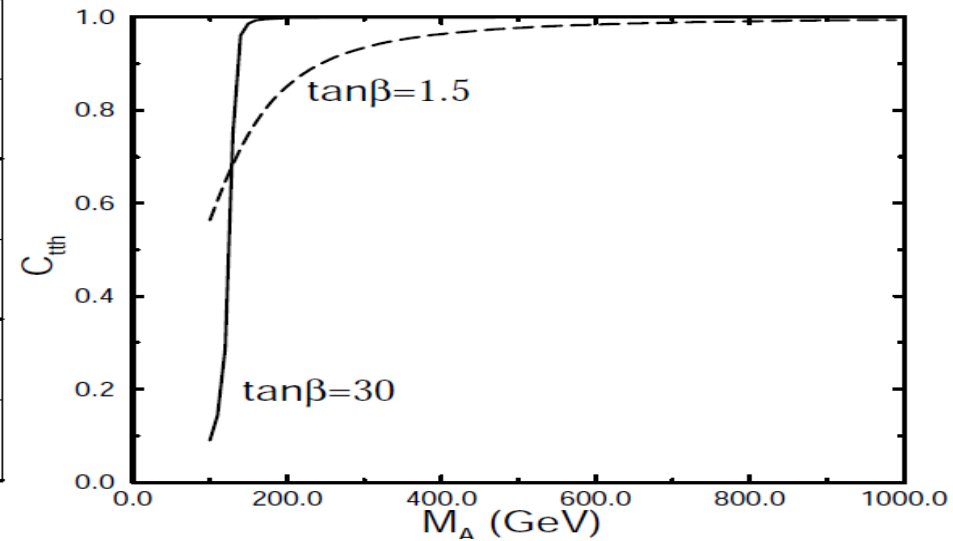| f	C_{ffh}	C_{ffH}	C_{ffA}
u	$\dfrac{\cos\alpha}{\sin\beta}$	$\dfrac{\sin\alpha}{\sin\beta}$	$\cot\beta$
d	$-\dfrac{\sin\alpha}{\cos\beta}$	$\dfrac{\cos\alpha}{\cos\beta}$	$\tan\beta$

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

MSSM: Higgs couplings to fermions
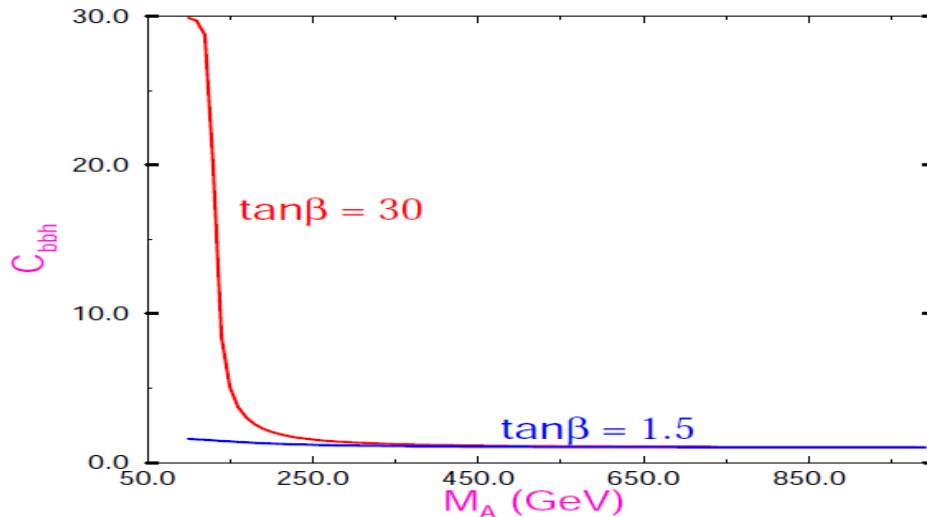
Higgs Couplings to b in SUSY

$tan\beta = 30$

$tan\beta = 1.5$

Higgs Couplings to u,c,t in SUSY

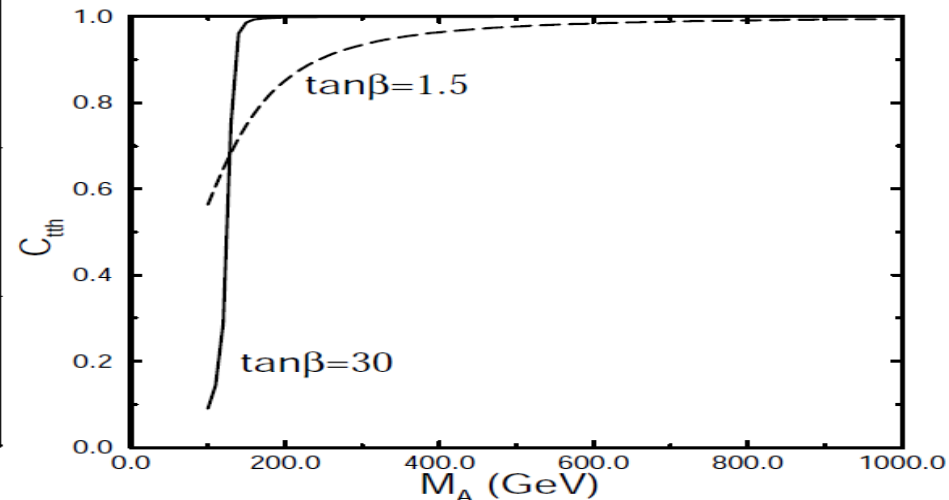$tan\beta=1.5$

$tan\beta=30$

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} 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 !

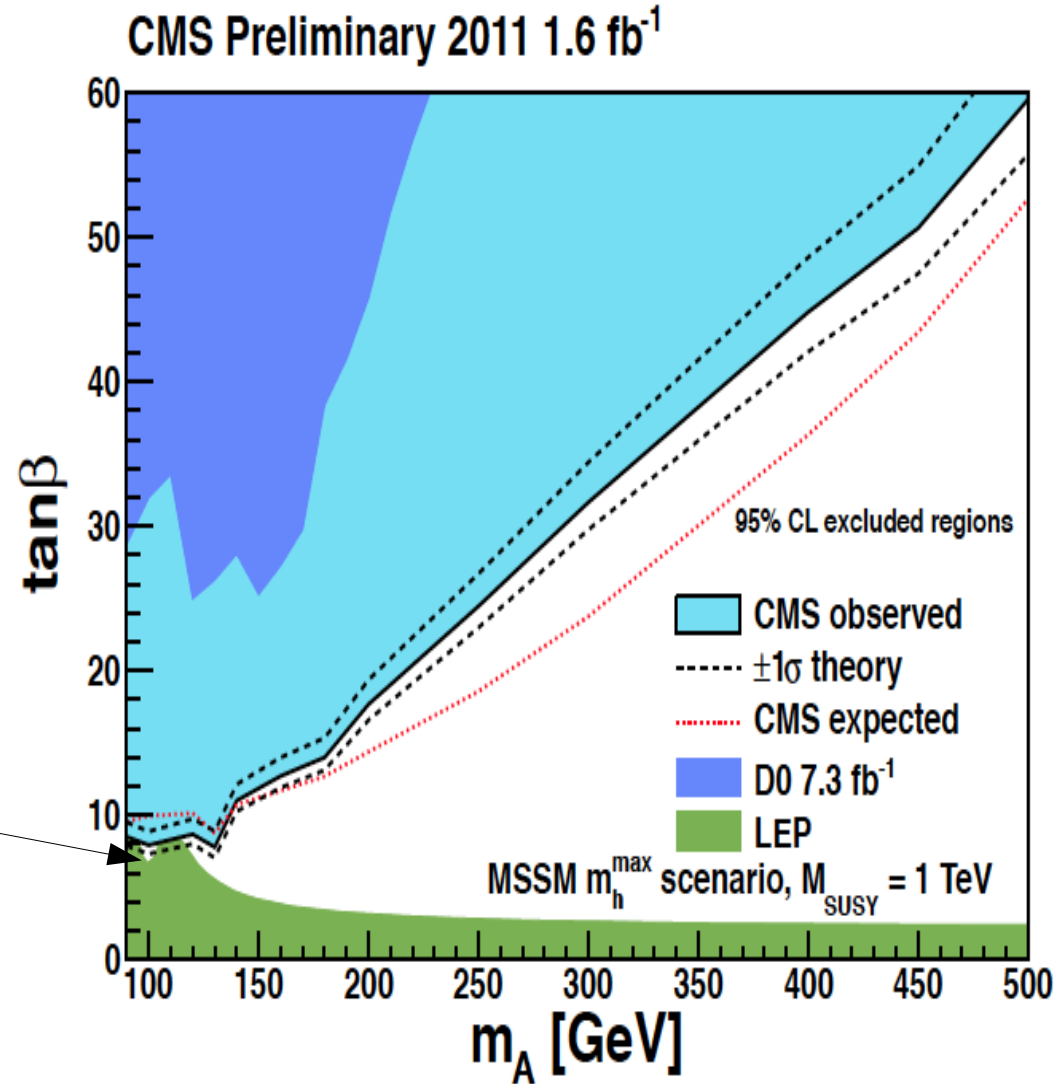   - ➢ Only interesting @ high $\tan\beta$ AND low M_A

- ➢ High M_A: All h-fermion coupling → 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
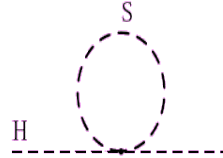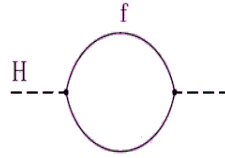- **Now one thing is sure: IF SUSY exists, M_A pretty high: Decoupled regime seems preferred**

CMS Preliminary 2011 1.6 fb^{-1}

95% CL excluded regions

- CMS observed
- $\pm 1\sigma$ theory
- CMS expected
- D0 7.3 fb^{-1}
- LEP

MSSM m_h^{max} scenario, M_{SUSY} = 1 TeV

tanβ vs m_A [GeV]

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

Stop/Higgs yukawa coupling

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

$$M^2_{h,H} = \frac{1}{2}\left\{ M^2_A + M^2_Z + \frac{\epsilon_h}{\sin^2\beta} \pm \left[\left(M^2_A - M^2_Z)\cos 2\beta + \frac{\epsilon_h}{\sin^2\beta}\right)^2 + \left(M^2_A + M^2_Z\right)^2 \sin^2 2\beta\right]^{1/2}\right\}$$
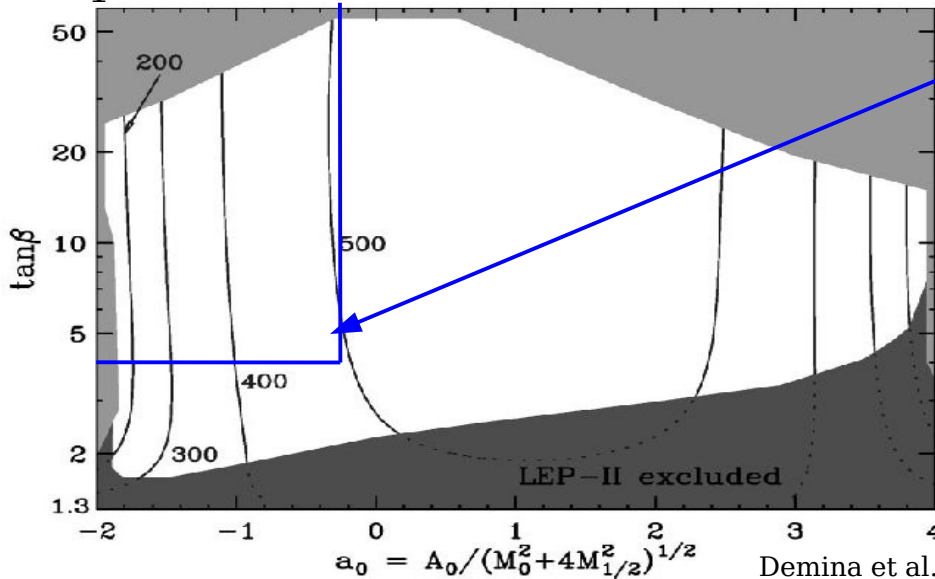
with: $\epsilon_h \equiv \dfrac{3G_F}{\sqrt{2}\pi^2} M^4_T \log\left(\dfrac{\tilde{m}^2}{M^2_T}\right)$
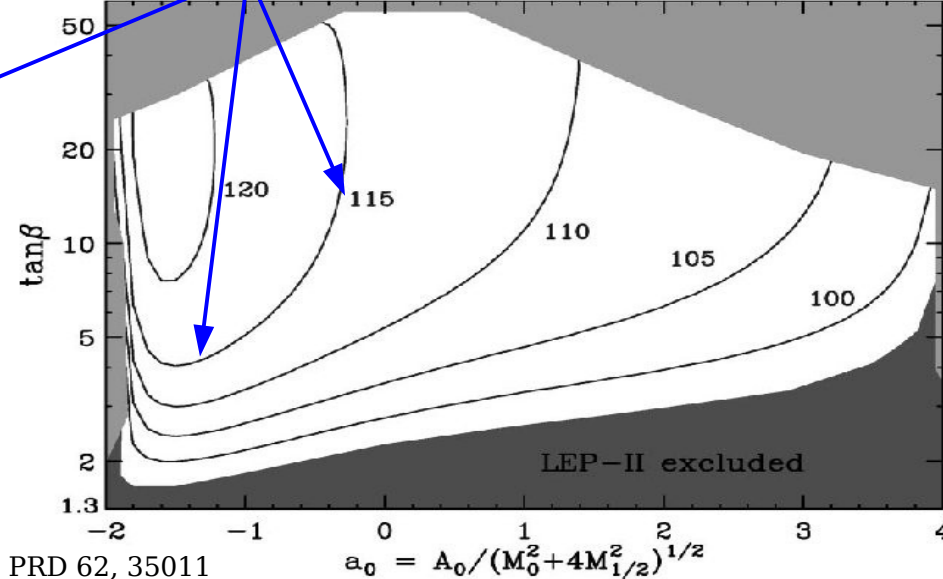
Squark masses: Higgs mass <u>particularly</u> sensitive to $\sim t_{1,2}$ system

LHC: Higgs & stop searches can <u>constraint</u> each other

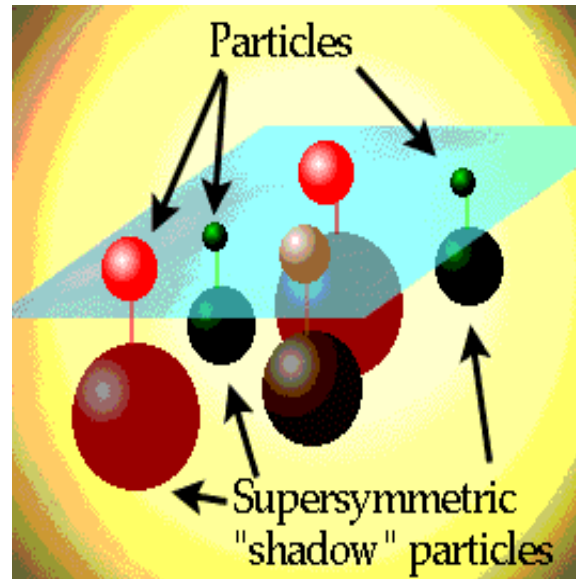Stop masses   Higgs masses

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 $\tan\beta$: Two "preferred" values:
    → $\tan\beta\sim2$: Well, this is more & more suppressed by Higgs searches
    → $\tan\beta\sim30$: ...
        → What to think about this ? Probably better to look more directly for SUSY particles

Famous "on the edge of SM" measurement:

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

Out of SM... ?

$\rightarrow$ Either statistical fluctuation

$\rightarrow$ 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:

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

Out of SM... ?

→ Either statistical fluctuation

→ Or new physics around corner

Let's plug-in SUSY: b → Loop $\{\chi^-_1, t_1\}$ → s
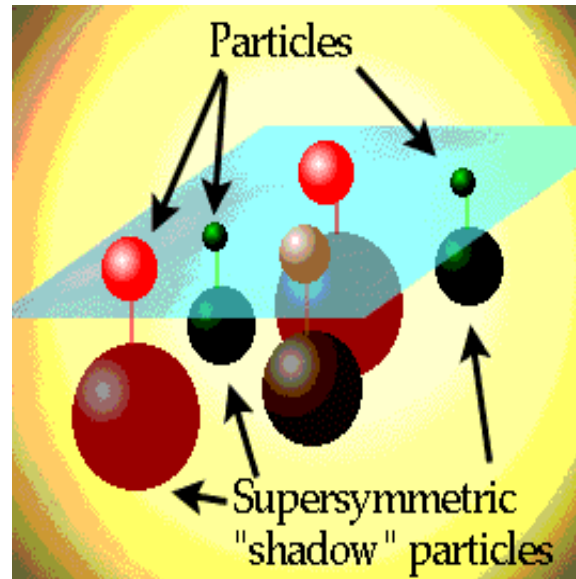
$$\frac{BR(b \to s\gamma)}{BR(b \to ce\overline{\nu})} \sim \frac{|V_{ts}V_{tb}|^2}{|V_{cb}|^2}\frac{6\alpha}{\pi}\left\{C + \frac{M_T^2 A_T \mu}{\tilde{m}_T^4}\tan\beta\right\}^2$$

<u>SM prediction</u>:
Whether above/below measurement → Indication of sign of μ

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

Exercises

SUSY diagrams

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

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

$\chi^\pm_1 \rightarrow l^\pm \nu\; \chi^0_1$
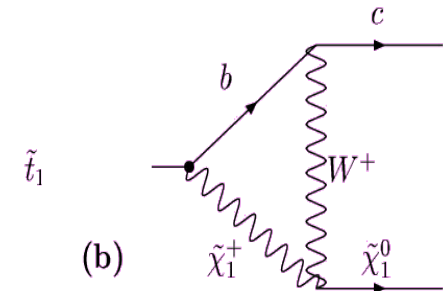
@LHC: Give a production process for lightest chargino production
         Then give the full diagram

$t_1 \rightarrow b\; \chi^\pm_1$

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

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

SUSY diagrams

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

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

$\chi^\pm_1 \to l^\pm \nu\, \chi^0_1$

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

$t_1 \to b\, \chi^\pm_1$

$t_1 \to t\, \chi^0_1$

$t_1 \to c\, \chi^0_1$

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

(b)

@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