Physics beyond the Standard Model

Basics and Phenomenology of Supersymmetry

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- **Problems of the SM: GUTs, SUSY, alternatives**
- **SUSY and the MSSM**
- **The Higgs and SUSY particle spectrum in the MSSM**
- **Higgs and sparticles at colliders**

1. Spectrum and constraints

Determination of spectrum:

– RGEs (two loops, numerics)

– EWSB and $V_{\rm soft}$ (iterations)

– Masses, couplings, RC

Sophisticated RGE programs:

– example of SuSpect

(Kneur, Moultaka, AD)

– other programs also exist:

(Isajet, SoftSUSY, Spheno, ...)

Viable parameter space:

– choose inputs, param. scan

– impose known constraints

(Th, Experimental, DM, ...)

Low energy input: $\alpha(M_Z), \alpha_S(M_Z)$, $M_t^{\rm pole}$, $M_\tau^{\rm pole}$, $m_b^{\overline{\rm MS}}(m_b)$; $\tan\beta(M_Z)$
Radiative corrections $\Rightarrow$ $g_{1,2,3}^{\overline{\rm DR}}(M_Z)$, $Y_\tau^{\overline{\rm DR}}(M_Z), Y_b^{\overline{\rm DR}}(M_Z), Y_t^{\overline{\rm DR}}(M_Z)$
First iteration: no SUSY radiative corrections.

↓

One– or two–loop RGE with choice: $g_1 = g_2 \cdot \sqrt{3/5}$, $M_{\rm GUT} \sim 2 \cdot 10^{16}$ GeV

↓

Choice of SUSY-breaking model (mSUGRA, GMSB, AMSB, or pMSSM).
Fix your high–energy input (mSUGRA: $m_0, m_{1/2}, A_0$, sign(μ), etc...).

↓

Run down all parameters with RGE to m_Z and $M_{\rm EWSB}$ scales
First iteration: guess for $M_{\rm EWSB}$.

↓

EWSB: $\mu^2, \mu B = F_{\rm non-linear}(m_{H_u}, m_{H_d}, \tan\beta, V_{\rm loop})$
$V_{\rm loop} \equiv$ Effective potential at 1–loop with all masses.
First iteration: V_{loop} not included

↓

Check of consistent EWSB (μ convergence, no tachyons, simple CCB/UFB, etc...)

↓

Diagonalization of mass matrices and calculation of masses / couplings
Radiative corrections to the physical Higgs, sfermions, gaugino masses.
First iteration: no radiative corrections.

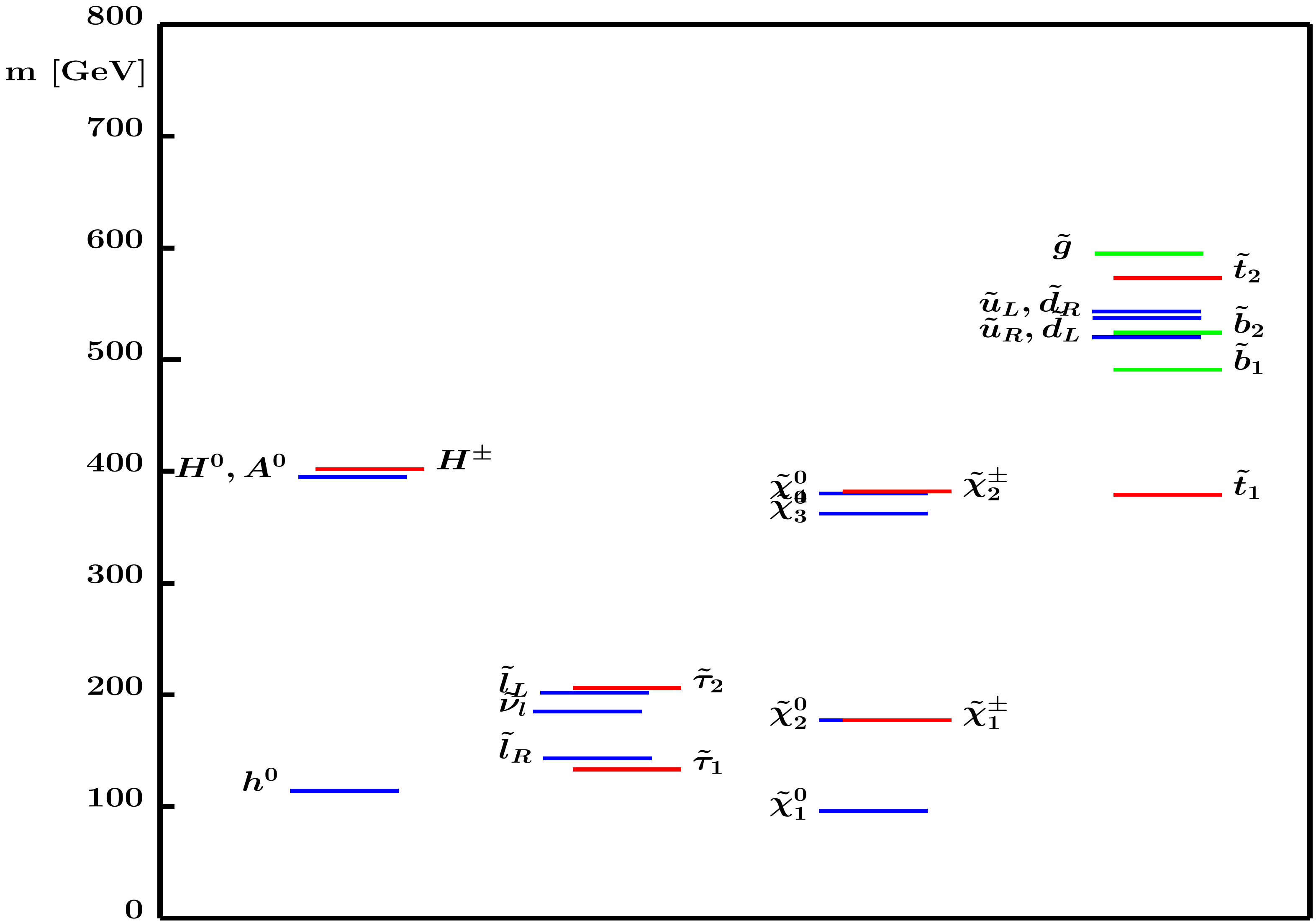
↓

Check of a reasonable spectrum:
– no tachyonic masses (from RGE, EWSB or mix),
–information provided on fine-tuning, CCB/UFB conditions,
–calculation of MSSM contributions to: $\Delta\rho$, $(g-2)$, $b \to s\gamma$.

1. Spectrum and constraints: Theoretical constraints

- **No RGE problems:**
  - **Perturbative couplings/No Landau poles**
  - **Non tachyonic sfermions (in particular for 3d generation)**
  - **Consistent unification of gauge couplings**
- **Proper implementation of EWSB:**
  - **Non tachyonic A boson or μ parameter**
  - **Convergent/stable value of μ after several iterations**
  - **Vacuum non CCB nor UFB**
- **Reasonnable SUSY spectrum:**
  - **Non tachyonic sfermions from mixing**
  - **Higgs masses not NaN**
  - **The LSP is the lightest neutralino χ_1^0**

3. Spectrum and constraints: example of spectrum



1. Spectrum/constraints: direct exper. constraints

Bounds from $\tilde{P}$ searches:

- **Bounds from LEPI/LEPII:**
  $m_{\tilde{\chi}_1^\pm} \gtrsim 104$ GeV
  $m_{\tilde{f}} \gtrsim 100$ GeV
  with $\tilde{f} = \tilde{t}_1, \tilde{b}_1, \tilde{l}^\pm, \tilde{\nu}$

- **Bounds from the Tevatron:**
  $m_{\tilde{g}} \gtrsim 300$ GeV
  $m_{\tilde{q}_{1,2}} \gtrsim 260$ GeV
  with $\tilde{q} = \tilde{u}, \tilde{d}, \tilde{s}, \tilde{c}, \tilde{b}$

- **Possible refinements:**
  – (almost) stable χ_1^+ at LEPII
  – degenerate $\tilde{t}_1, \tilde{\tau}_1$ with LSP
  – $\tilde{t}_1$ with large Δm at Tevatron

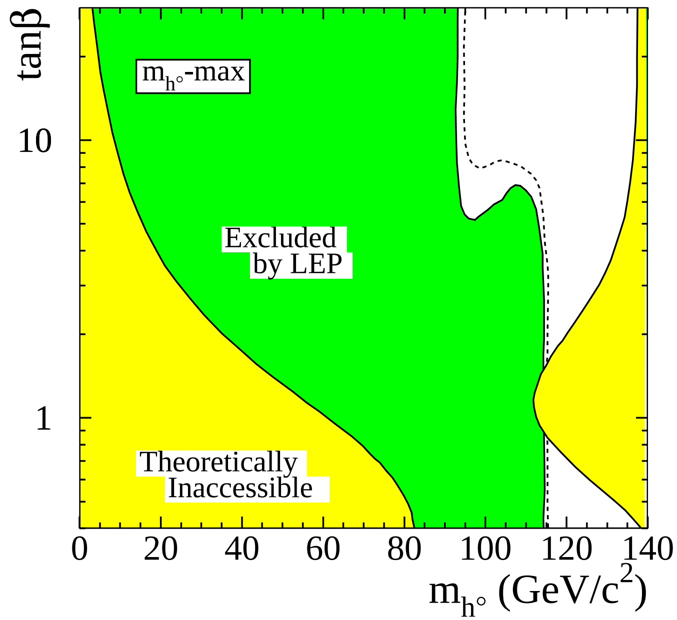
Bounds from Higgs searches at LEPII:

$M_A \gg M_Z \Rightarrow M_h > 114$ GeV

$M_A \sim M_Z \Rightarrow M_h, M_A \gtrsim 92$ GeV

– Slightly depend on m_t, H mixing, ...

– Include a $\Delta^{\rm th} M_h \sim 3$ GeV error.



(Excluded boundary to be fitted)

Note: include 1.7σ Higgs signal??

1. Spectrum/constraints: indirect exper. constraints

- **High precision electroweak measurements:** agree with SM

  Large $(\tilde{t}, \tilde{b})$ mass splitting might generate large contributions:

  $\Delta^{\rm SUSY}\rho = \Pi_{ZZ}(0)/M_Z^2 - \Pi_{WW}(0)/M_W^2 \lesssim 2.2 \cdot 10^{-3}$

  (loose constraints from direct SUSY contributions to $Zb\bar{b}$ vertex)

- **The $(g-2)_\mu$ constraint:** 2.5σ away from SM (only e^+e^- data)

  Might be accounted for by $\tilde{\mu}$–χ^0 and $\tilde{\nu}_\mu$–$\chi^\pm$ loop contributions

  $1.06 \cdot 10^{-9} \leq \frac{1}{2} g_\mu^{\rm SUSY} \leq 4.36 \cdot 10^{-9}$

  (OK with SM if+ τ data: $-5.7 \cdot 10^{-10} \leq \frac{1}{2} g_\mu^{\rm SUSY} \leq 4.7 \cdot 10^{-9}$)

- **The $b \to s\gamma$ constraint:** experimental value agrees with SM

  Strong constraints on the t–$H^\pm$ and $\tilde{t}$–$\chi^\pm$ loop contributions

  $2.65 \cdot 10^{-4} \leq B(b \to s\gamma) \leq 4.45 \cdot 10^{-4}$

  (might be aleviated with a small amount of flavor violation)

- **The $b \to s\ell^+\ell^-$ constraint:** not very stringent in mSUGRA yet

1. Spectrum and constraints: the dark matter constraint

- **WMAP measurement of temperature anisotropies in CMB, ...**

  $\Omega_{\rm DM}\, h^2 \simeq 0.113 \pm 0.009 \Rightarrow 0.09 \leq \Omega_{\rm DM}\, h^2 \leq 0.14$ **at 99% CL**

- **In the MSSM, LSP neutralino χ_1^0 is best candidate for CDM**

  – electrically neutral and (often maybe too) weakly interacting

  – stable if R–parity is conserved

  – massive: $m_{\chi_1^0} \gtrsim 50$ GeV in constrained models (mSUGRA)

- **Calculation of $\Omega_{\chi_1^0}\, h^2 \propto \langle v\sigma(\chi\chi \to {\rm SM\, part.})\rangle^{-1}$ complicated:**
  - **Many final states ($\Phi = h, H, A, H^\pm$; $f = \ell, q$; $V = W, Z, \gamma$)**

    $$\chi_1^0\chi_1^0 \to f\bar{f}, VV, \Phi_i\Phi_j, \Phi_i V \ \ {\rm etc....}$$

  - **Several channels are present; for example in $\chi_1^0\chi_1^0 \to f\bar{f}$:**
    t–channel $\tilde{f}$, s–channel Z and s–channel A, h, H exchanges

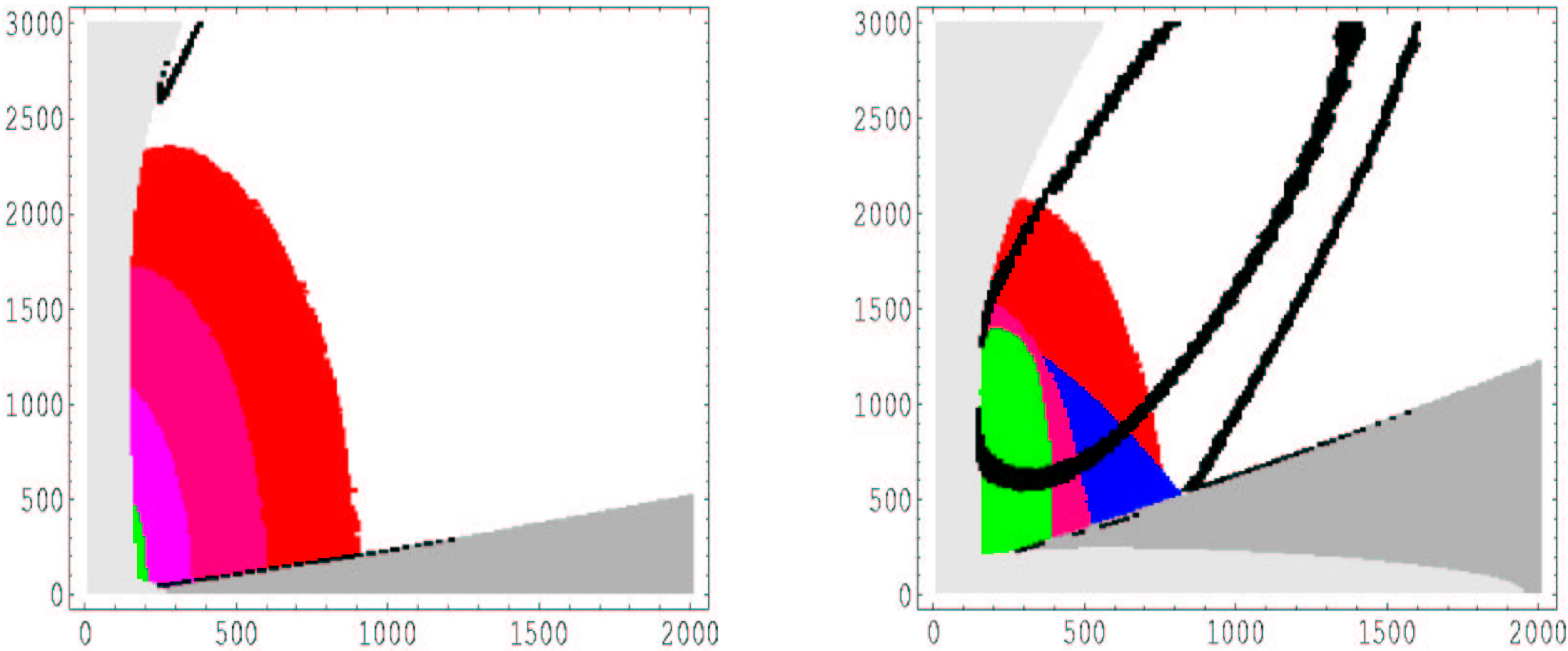
  - **Co-annihilation processes with NLSP taken into account:**

$$\chi_1^0 + \tilde{P} \to X + Y \ \ {\rm and} \ \ \tilde{P} + \tilde{P}^{(*)} \to X + Y \ \ {\rm if}\ m_{\tilde{P}} \sim m_\chi$$

1. Spectrum and constraints: an example of a scan

An $(m_{1/2}, m_0)$ scan with $A = 0, \mu > 0, m_t = 172.5$ GeV:

$\mathbf{m_0}$ $\tan\beta = 10$ $\tan\beta = 50$



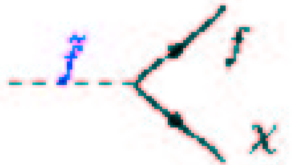
$\mathbf{m_{1/}}$

Generically, four (known) regions with the required ammount of DM:

bulk region (excluded), focus point, co-annihilation, A/h pole regions

2. Decays of the Higgs and SUSY particles

Squarks and Sleptons



$f \equiv \ell, q = u, d, s, c$ and $Q = t, b$

$\chi \equiv \chi_i^0, \chi_i^{\pm}, \tilde{g}$

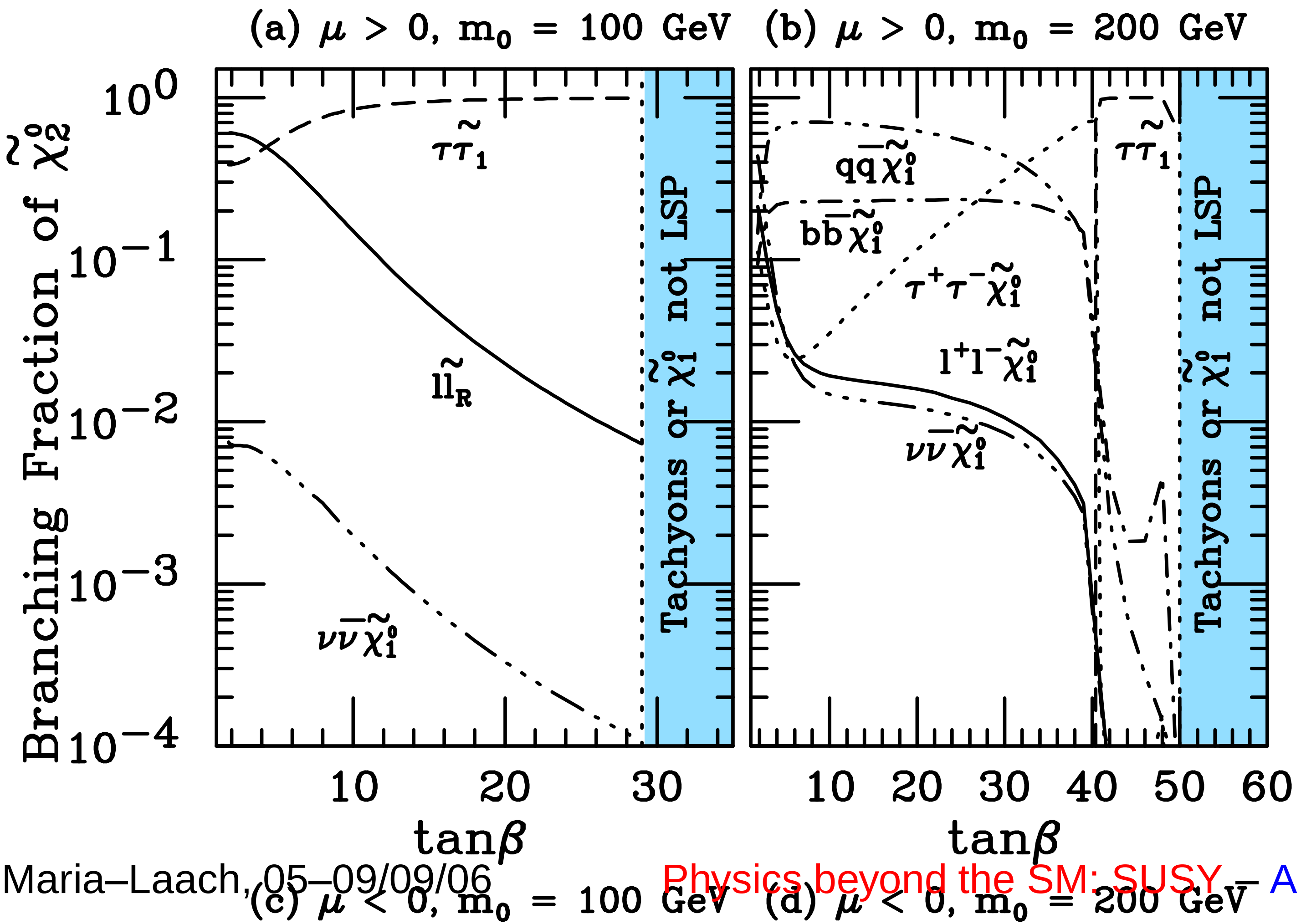
Charginos and neutralinos

Gluinos

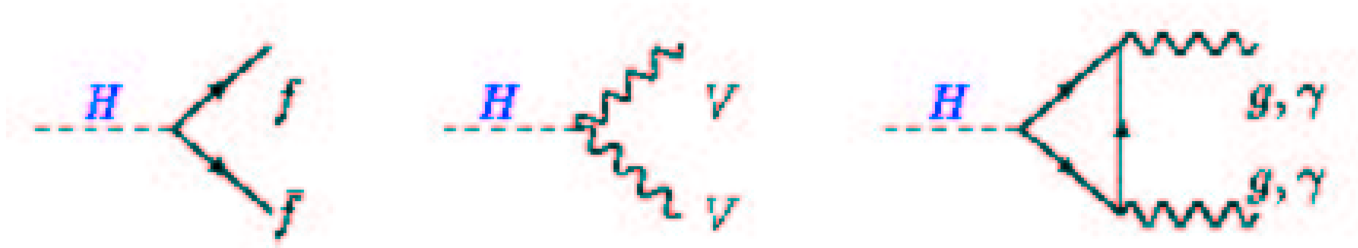
2. Decays: possible decays of sparticles

- **Possibility of cascade decays:** $\tilde{q} \to q + \chi_2^0 \to q + \chi_1^0 f\bar{f}$.
- **Signature in usual MSSM:** $\not{E}_T$ **from escaping** χ_1^0 **LSPs.**
- **In GMSB, signature is due to NLSP** $(\chi_1^0, \tilde{\tau}_1) \to \tilde{G} + (\gamma, \tau)$.

Example of final state decay in mSUGRA: χ_2^0



2. Decays: SM Higgs particle



- "Low mass" range, $M_H \lesssim 130$ GeV:

– $H \to b\bar{b}$ dominant, BR = 60–90%

– $H \to \tau^+\tau^-, c\bar{c}, gg$ BR= a few %

– $H \to \gamma\gamma, \gamma Z$, BR = a few permille.

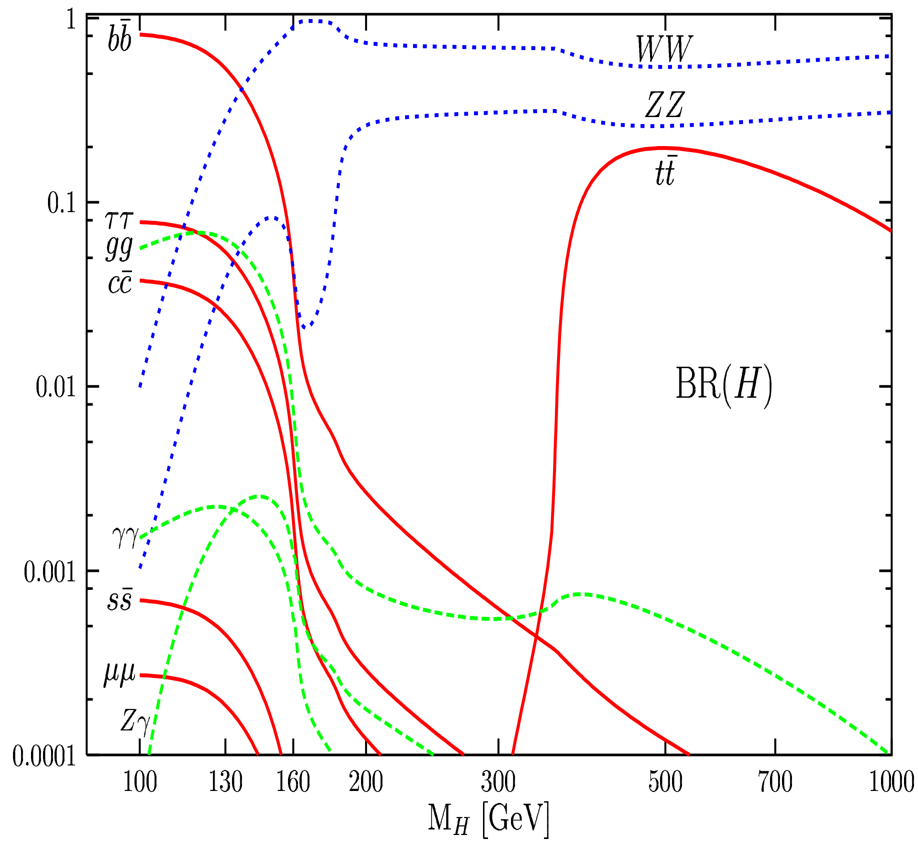
- "High mass" range, $M_H \gtrsim 130$ GeV:

– $\mathbf{H \to WW^*, ZZ^*}$ (BR $\to \frac{2}{3}$ or $\frac{1}{3}$),

– $H \to t\bar{t}$ for high M_H; BR $\lesssim 20\%$.

- Total width: a few MeV to 100 GeV

  for M_H =100 to 700 GeV.



2. Decays: SUSY Higgs couplings

Higgs decays (and cross sections) strongly depend on couplings

Couplings in terms of H_{SM} and their values in decoupling limit:

Φ	$g_{\Phi\bar{u}u}$	$g_{\Phi\bar{d}d}$	$g_{\Phi VV}$
h	$\frac{\cos\alpha}{\sin\beta} \to 1$	$\frac{\sin\alpha}{\cos\beta} \to 1$	$\sin(\beta-\alpha) \to 1$
H	$\frac{\sin\alpha}{\sin\beta} \to 1/\tan\beta$	$\frac{\cos\alpha}{\cos\beta} \to \tan\beta$	$\cos(\beta-\alpha) \to 0$
A	$1/\tan\beta$	$\tan\beta$	0

– **The couplings of $H^{\pm}$ have the same intensity as those of A.**

– **Couplings of h, H to VV are suppressed; no AVV couplings (CP)**

– **For $\tan\beta > 1$: cplgs to d enhanced, cplgs to u suppressed.**

– **For $\tan\beta \gg 1$: couplings to b quarks b ($m_b \tan\beta$) very strong.**

– **For $M_A \gg M_Z$: h couples like the SM Higgs boson and H like A.**

2. Decays: MSSM Higgs particles

General features in Higgs decays

- h: same as $H_{\rm SM}$ in general (in particular in decoupling limit)

  $h \to b\bar{b}$ and $\tau^+\tau^-$ potentially enhanced ($\tan\beta \gtrsim 3$).
- A: only $b\bar{b}, \tau^+\tau^-$ and $t\bar{t}$ decays (no VV, hZ suppressed).
- H: same as A in general $(WW, ZZ, hh$ decays suppressed).
- $H^\pm$: $\tau\nu$ and tb decays (depending if $M_{H^\pm} <$ or $> m_t$).

Possible new effects

– Although suppressed, decays into $V\Phi$ and/or VV possible.

– 3–body decays important ($h \to WW^*, H/A \to tt^*, H^+ \to tb^* ...)$

– SUSY particle loops might be important ($h/A/H \to b\bar{b}, h \to gg)$.

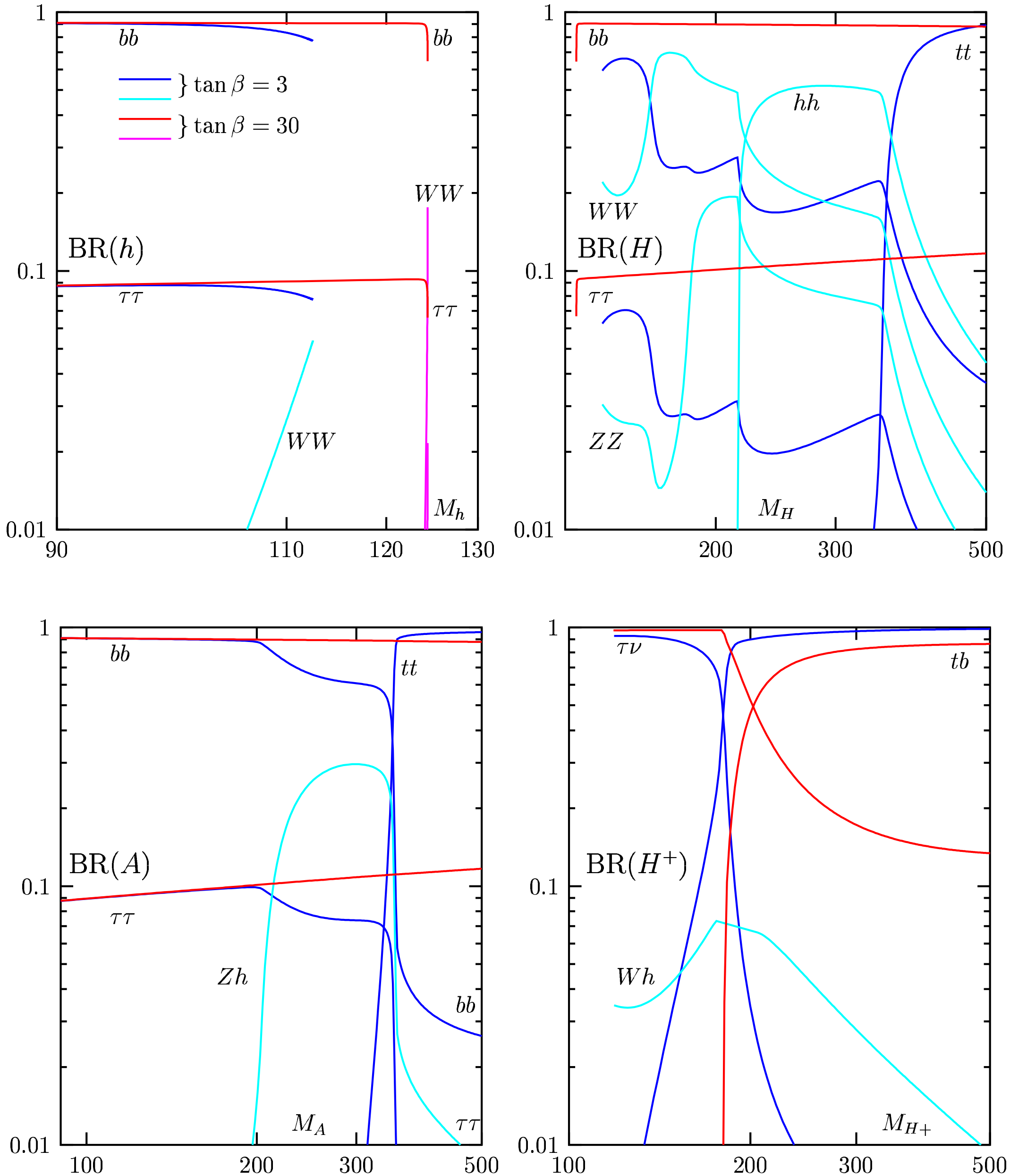
– Decays into sparticles if kinematically allowed significant:

$h \to \chi_1^0 \chi_1^0$ still possible in non universal MSSMs.

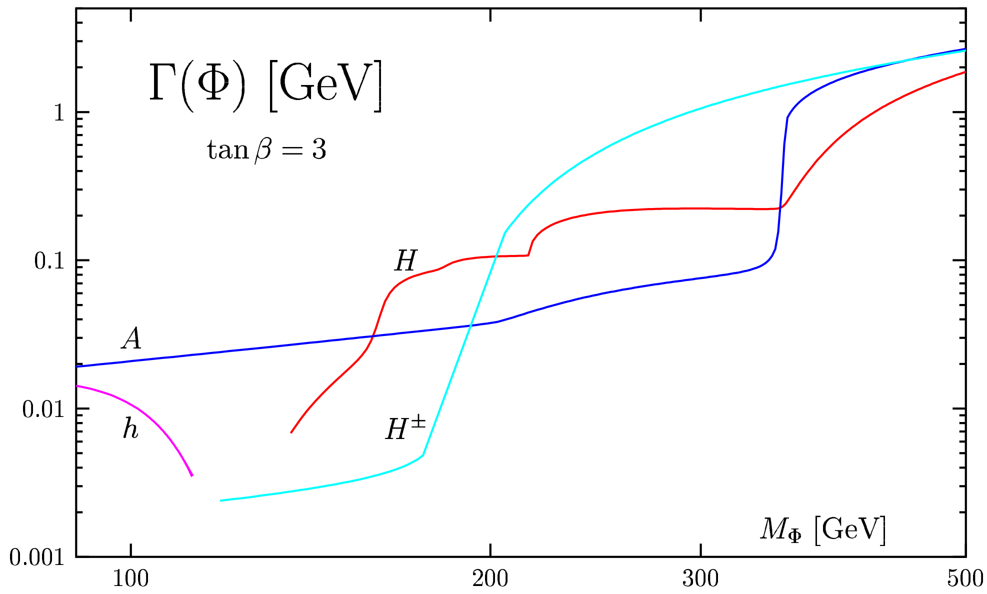
$H, A \to \chi_i^+ \chi_j^-, \chi_i^0 \chi_j^0$ and $H^\pm \to \chi_i^0 \chi_j^\pm$ important for low $\tan\beta$.

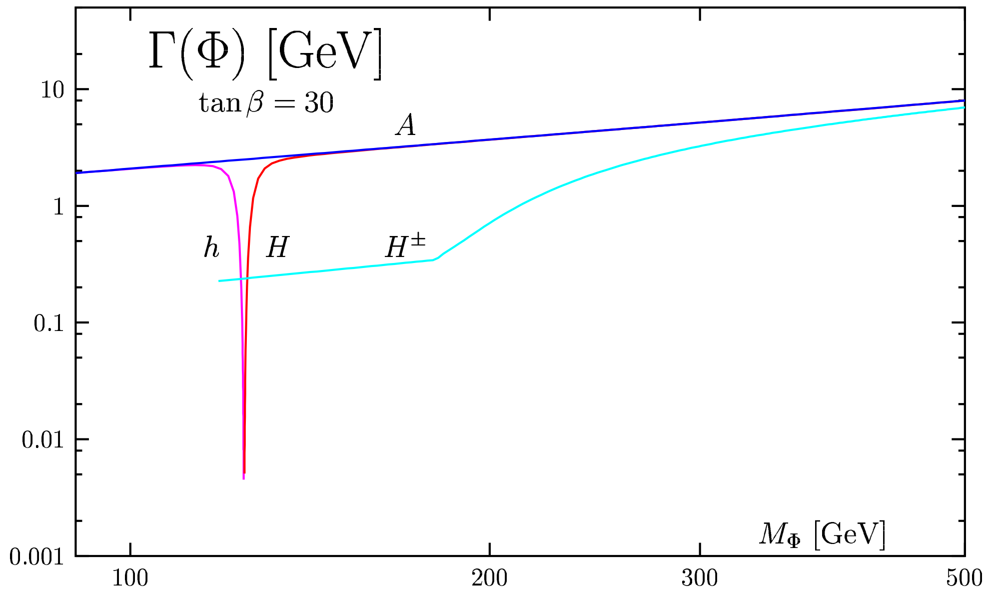
Total decay widths: Small compared to SM.

2. Decays: BR MSSM Higgs particles



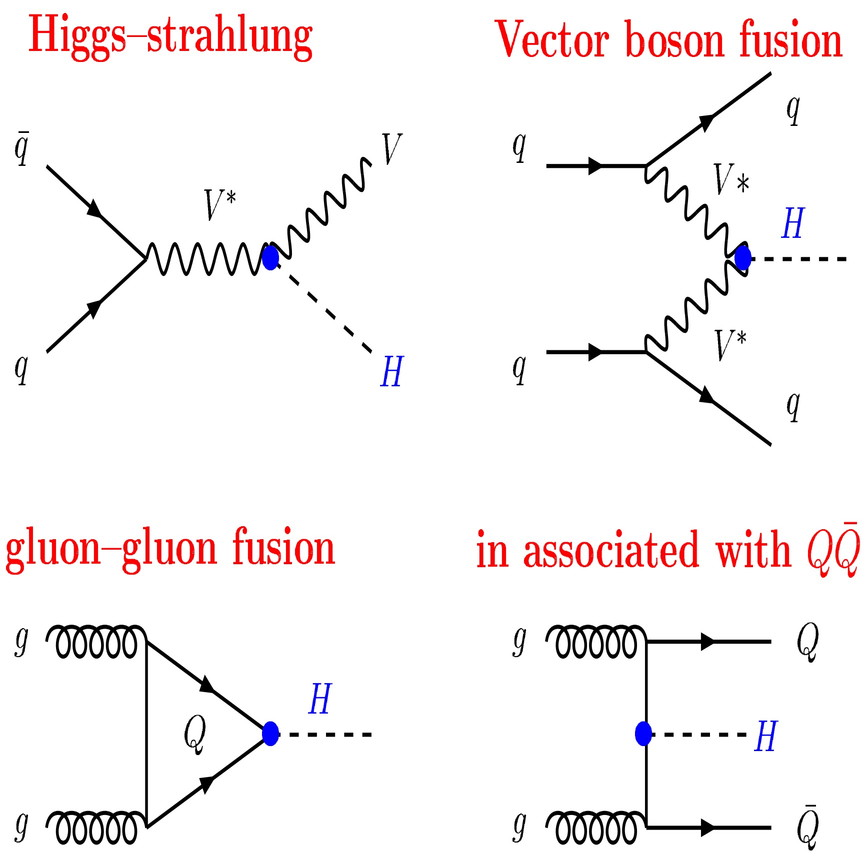
2. Decays: MSSM Higgs particle widths



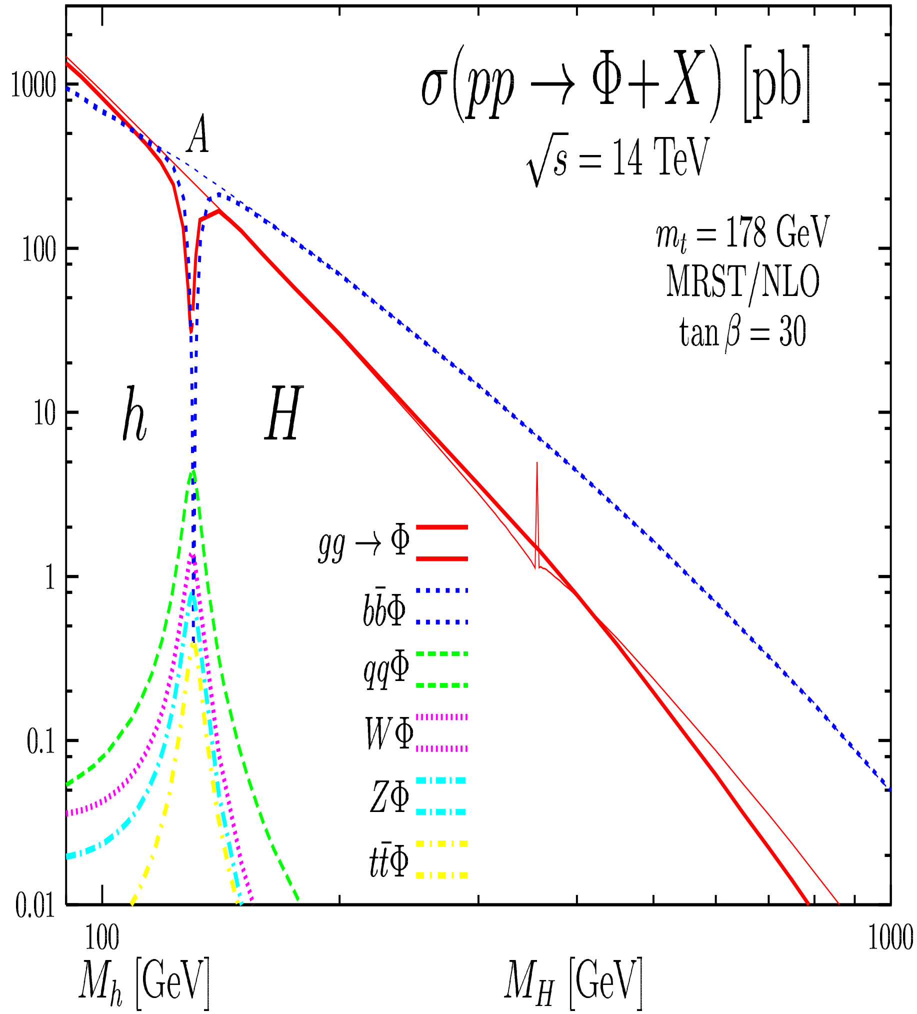


3. Production in $pp/p\bar{p}$: Higgs particles

Production mechanisms

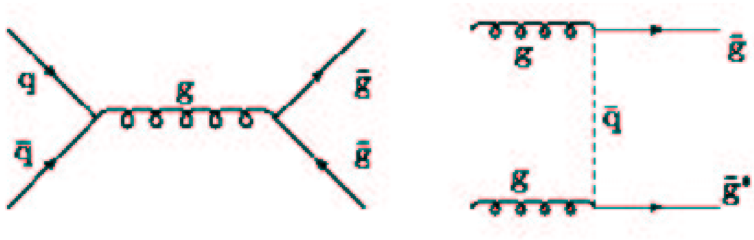


Cross sections at LHC

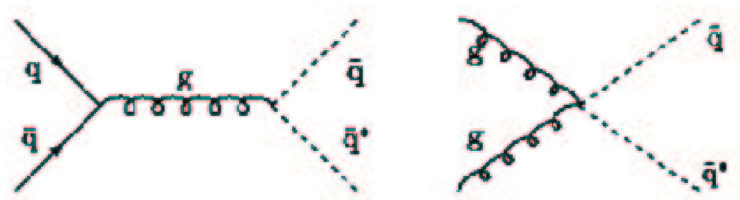


3. Production in $pp/p\bar{p}$: SUSY particles

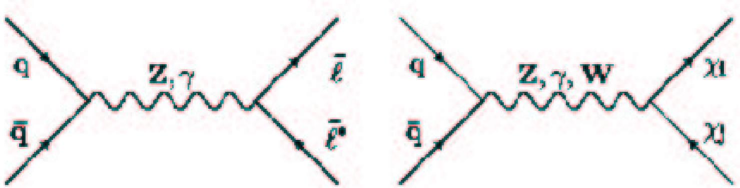
- **Gluino production**



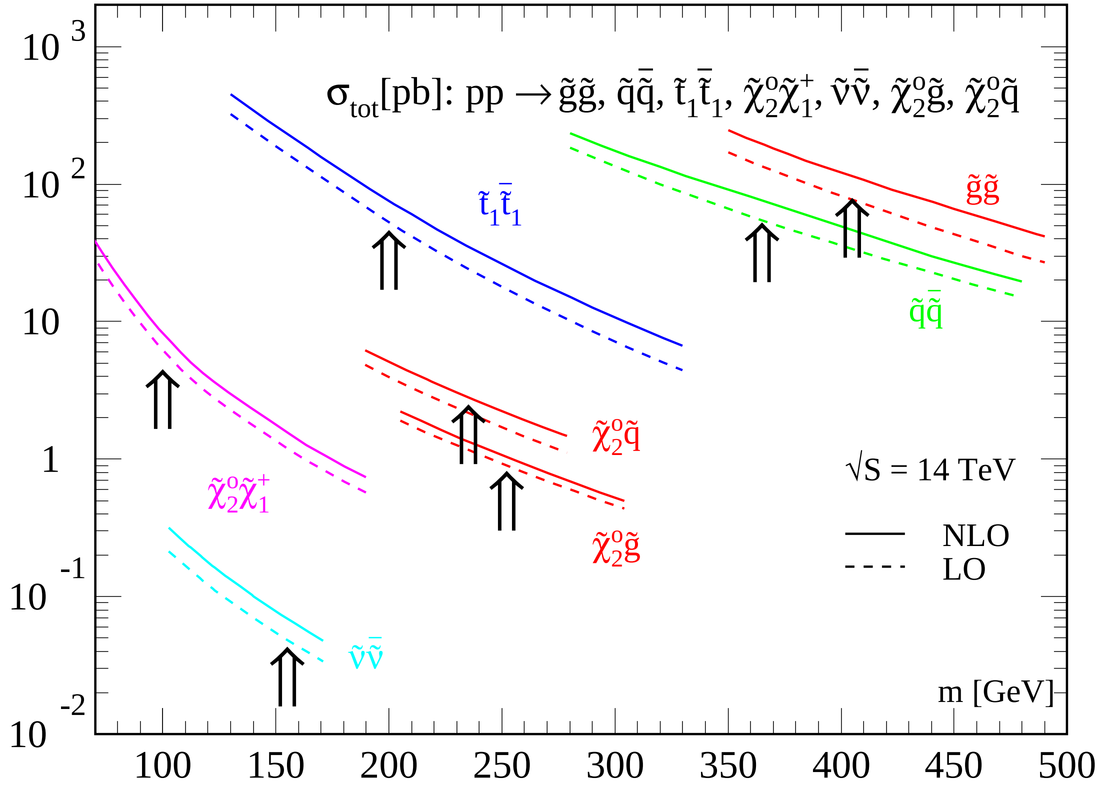
- **Squark production**



- **$\chi/\tilde{\ell}$ production**

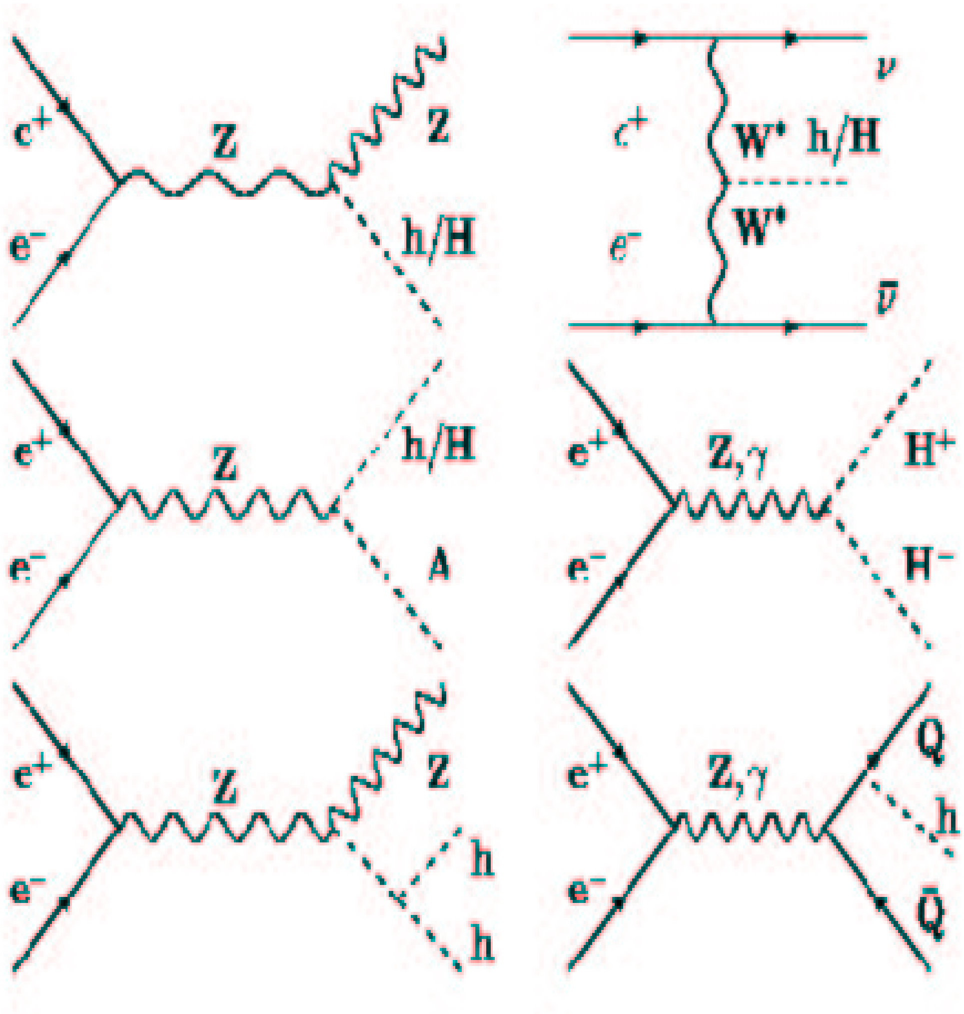


Cross sections at the LHC

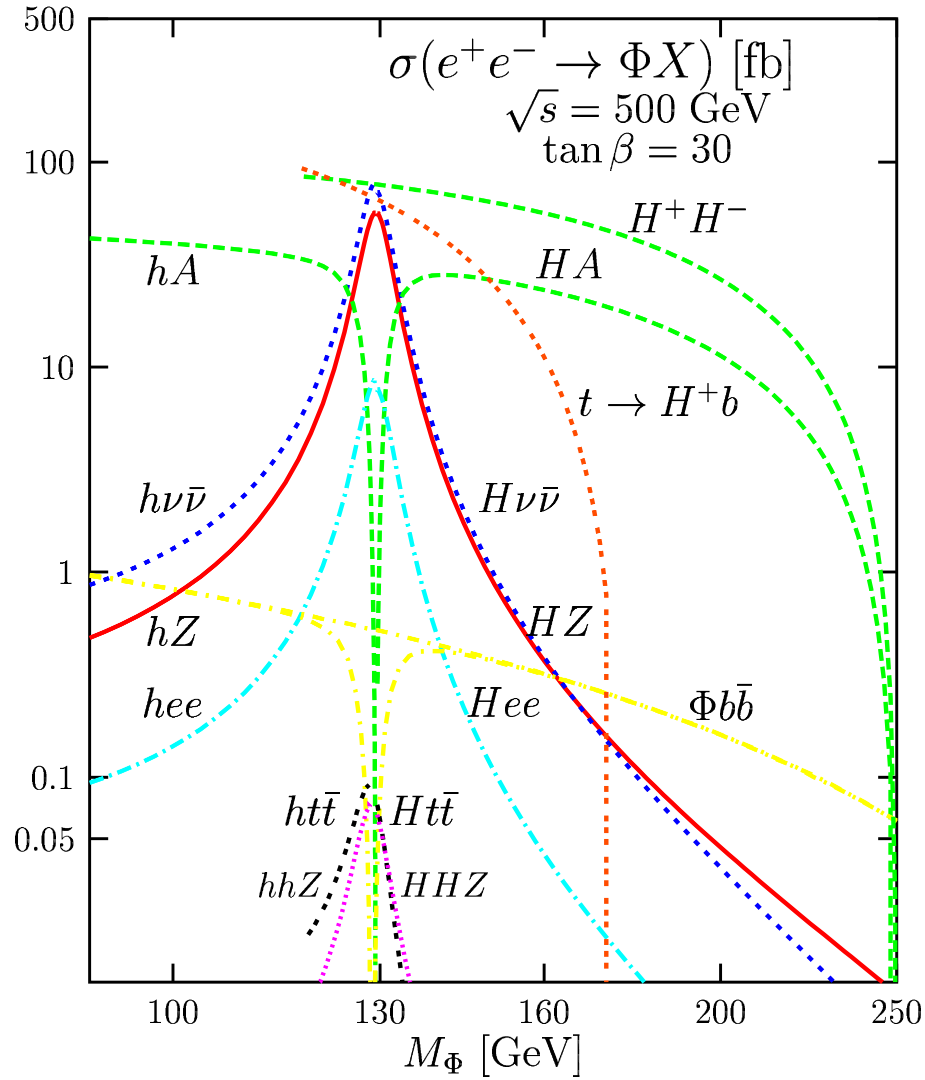


3. Production in e^+e^-: Higgs particles

Production mechanisms

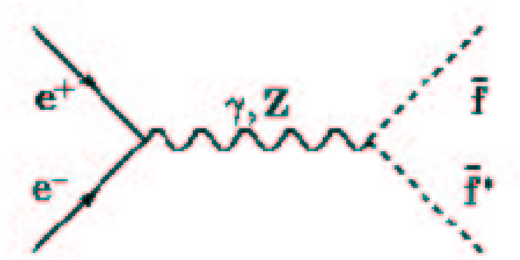


Cross sections at the ILC

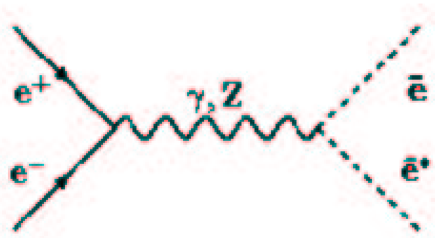


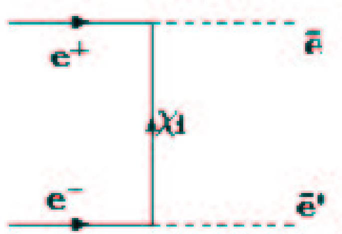
3. Production in e^+e^-: SUSY particles

- **Sfermion production**

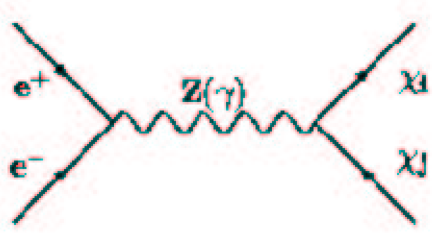


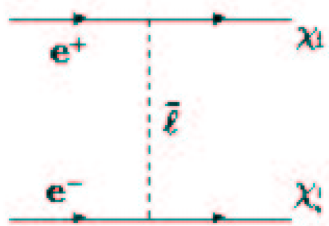
- **Selectron/sneutrino production**



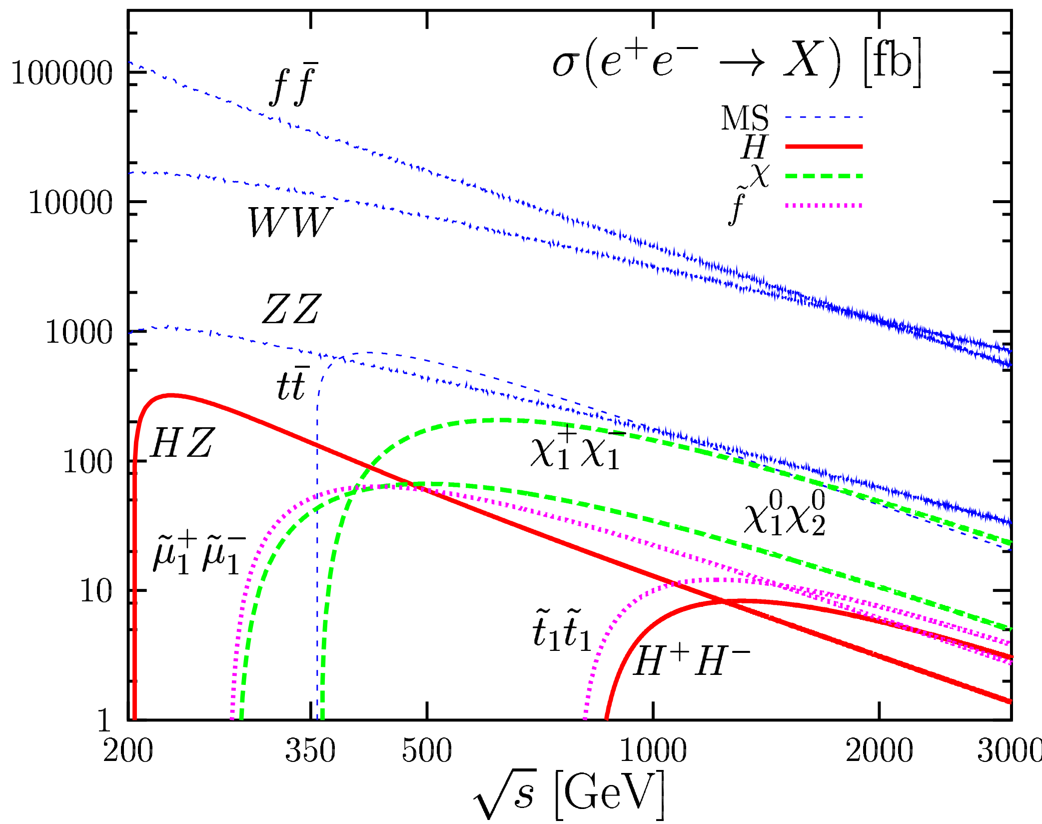


- **Chargino/neutralino production**



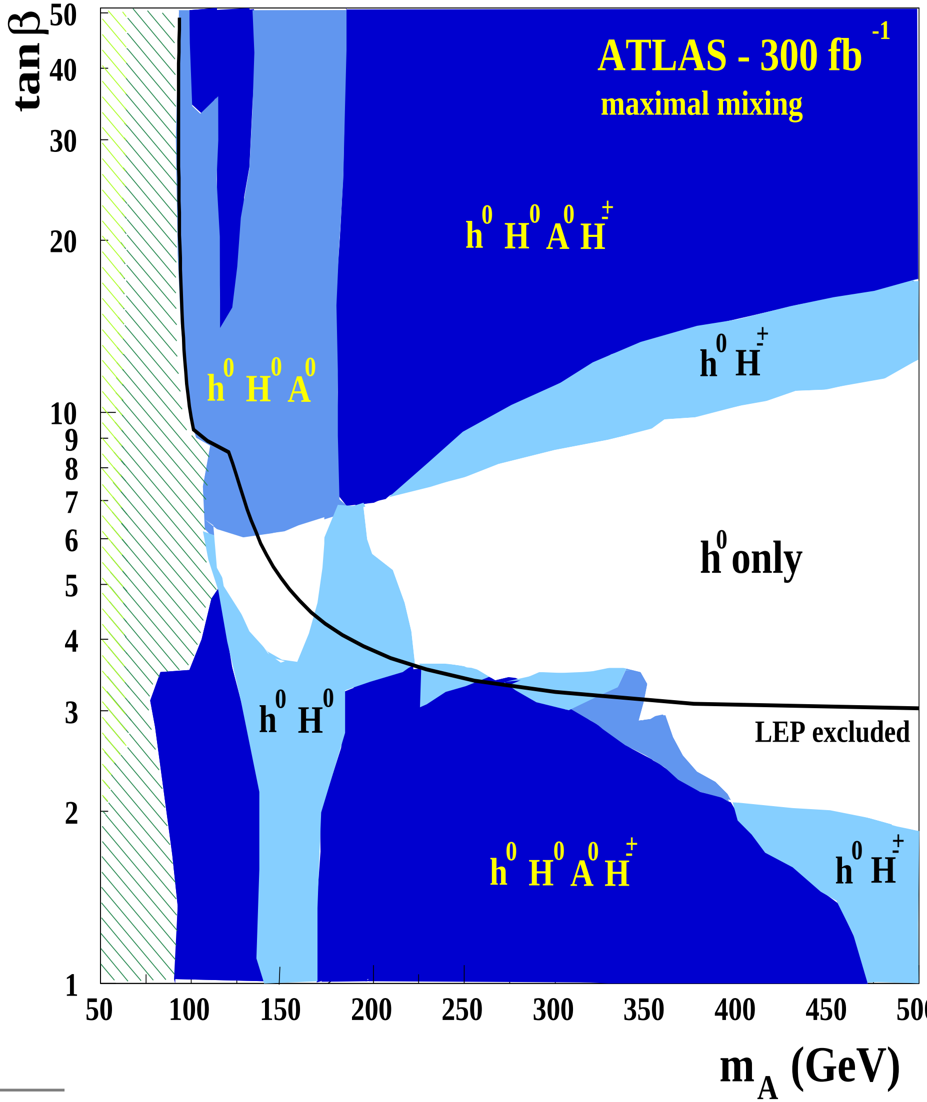


Cross sections at the ILC

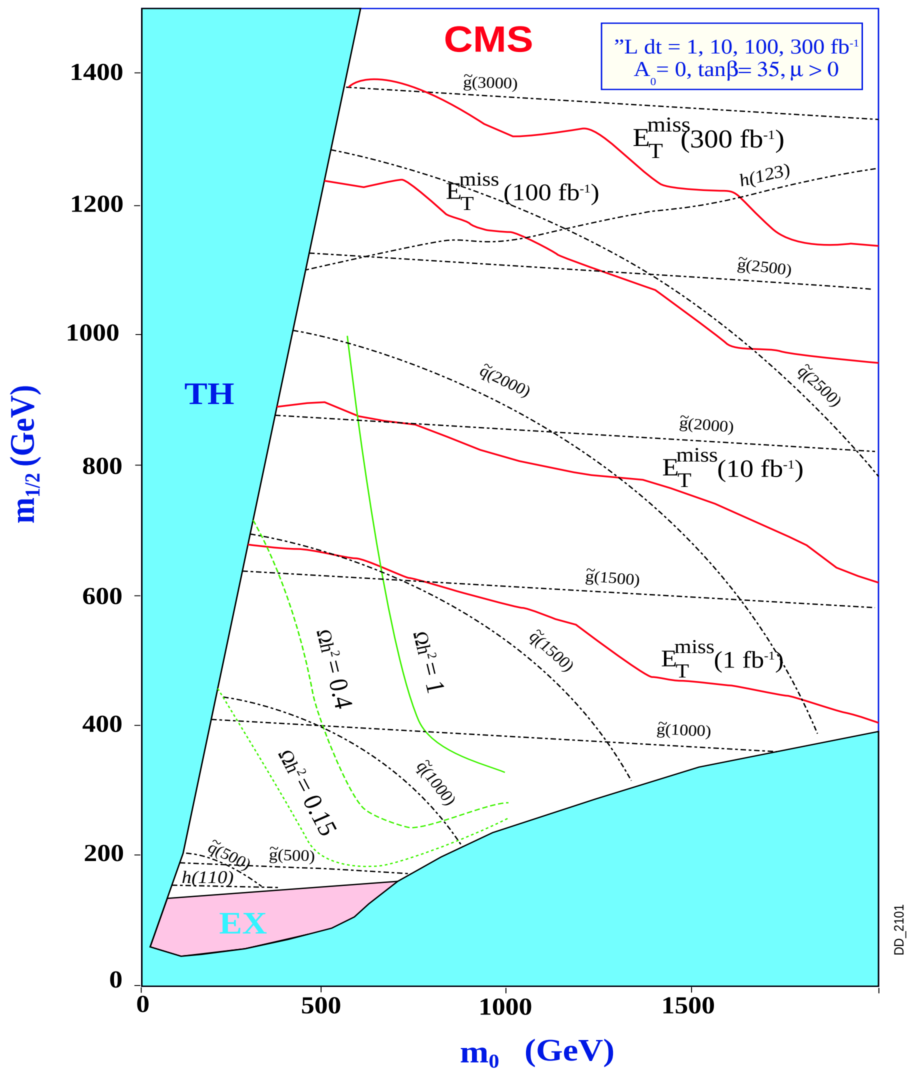


3. Discovery reach at the LHC:

Great discoveries are expected soon!



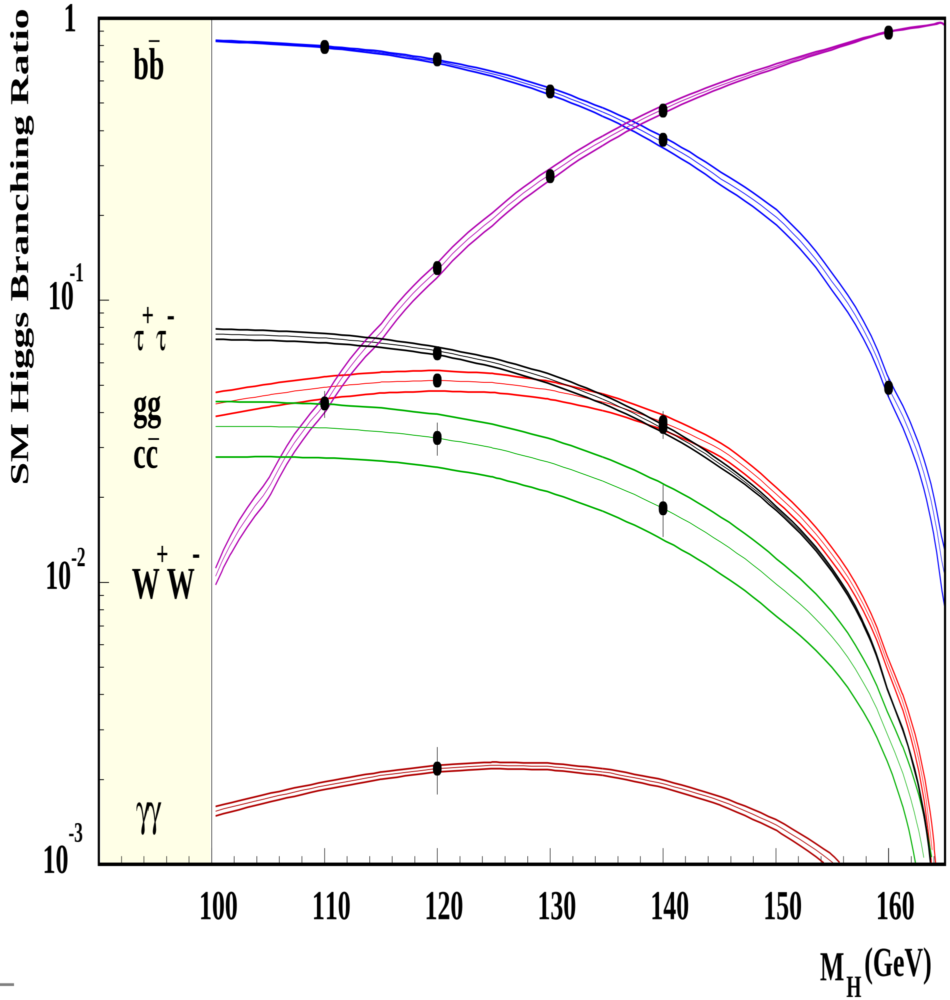
The CMS $\tilde{q},\tilde{g}$ mass reach in E_T^{miss}+ jets inclusive chann for various integrated luminosities

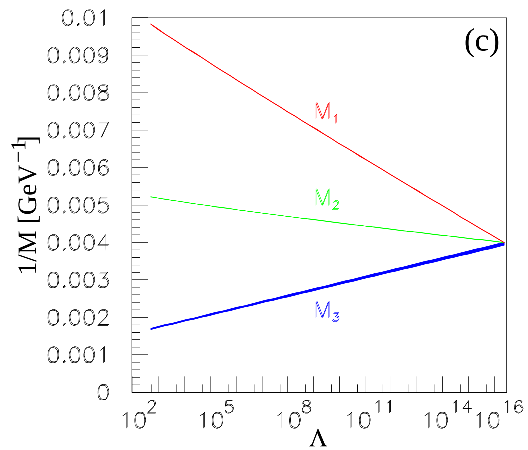


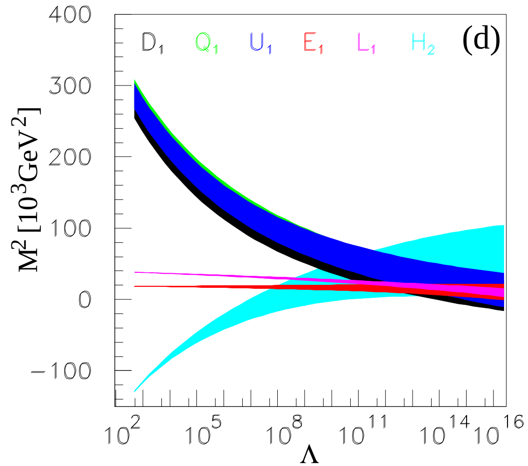
3. Precision measurements at ILC?

But we will need another decade of precision mesurements!?

to probe the fundamental theory that is behind these discoveries....

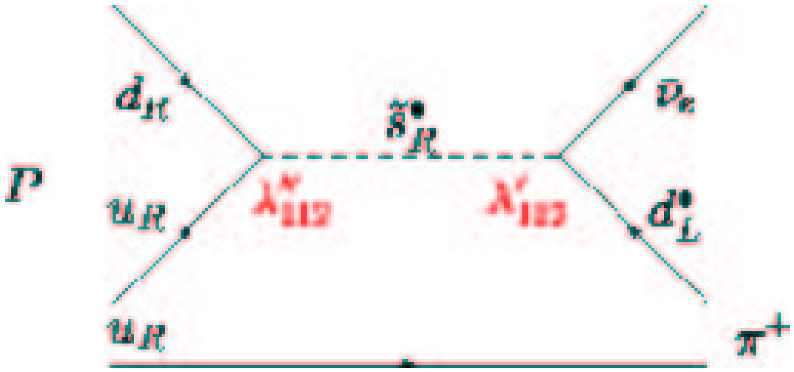






4. Extensions of MSSM: Rp violation

To avoid fast P decay, we do not need both L and B conservation



In most general W, include ΔL=1 or ΔB=1 interactions:

$$\mathbf{W_{\Delta L=1} = \frac{1}{2}\lambda_{ijk} L_i L_j \bar{e}_k + \lambda'_{ijk} L_i Q_j \bar{d}_k + \mu'_i L_i H_u}$$

$$\mathbf{W_{\Delta B=1} = \frac{1}{2}\lambda''_{ijk} \bar{u}_i \bar{d}_j \bar{d}_k}$$

P decay modes and experimental limits on $\not{B}$ and $\not{L}$ imply $\lambda^{', ''}_{ijk} \ll 1$.

- **However, at least 45 new parameters in the general case.**
- **no stable LSP and thus no SUSY DM candidate...**
- **But, rich phenomenology (e.g. s channel sfermion production)**
- **enters in neutrino phenomenology and adresses small ν masses**

4. Extensions of the MSSM: CP violation

One can allow for some CP–violating parameters, in particular:

- Complex $\mathrm{M_1}, \mathrm{M_2}, \mathrm{M_3}$ (some phases rotated away) and μ
- Complex trilinear $\mathrm{A_f}$ couplings, in particular $\mathrm{A_f}$.

The MSSM Higgs sector stays CP–conserving at the tree–level but complex parameters enter at the one–loop level through μ and $\mathrm{A_t}$.

- CP violation is needed for (direct) baryogenesis in MSSM
- However, many new parameters will enter in the general case
- Complicates the determination of spectrum but less fine-tunning!
- Strongly constrained by data ($n_{\rm edm}..$) and needs cancelations
- No sign yet of any additionnaly from $\not{C}$P in B–factories etc...

One can also allow for flavor non–diagonal interactions, howver:

- Parameters strongly constrained from FCNC, K, B physics...
- Only adds complications/parameters (no theory motivation)...

4. Extensions of the MSSM: NMSSM

The μ problem: μ enters EWSB and the determination of M_Z.

It must be of order SUSY–breaking parameters such as M_{H_1}, M_{H_2}.

But μ is a SUSY preserving parameter, comes from $W \propto \mu \hat{H}_1 \hat{H}_2$,

and, a priori, no reason for having $\mu \propto M_Z, M_{\rm SUSY} \ll M_{\rm GUT}$....

Solution: μ is related to a vev of an additional field S with $\langle S \rangle = s$

NMSSM: introduce a gauge singlet superfield $\hat{S}$ into superpotential

$$W = W_{\rm MSSM} + \lambda \hat{H}_1 \hat{H}_2 \hat{S} + \frac{1}{3} \kappa \hat{S}$$

Extended spectrum in NMSSM compared to MSSM:

- **one additional neutralino state: $\Rightarrow \chi^0_{1,...,5}$**
- **two additional Higgs particles $\Rightarrow H_1, H_2, H_3, \; A_1, A_2, \; H^+, H^-$**

$\Rightarrow$ less constrained and fine tuned model, richer phenomenology...

Ex: upper bound on h mass is $M_h^{\rm NMSSM} = M_h^{\rm MSSM} + 20$–40 GeV.

LEP searches bounds are not valid and h lighter than 100 GeV.

4. Extensions of the MSSM:

LHC will tell!