Supersymmetry searches at colliders

L. Pape (CERN)

- Broad Outline
  - Some basics, models, sparticle spectra
  - (Low energy experiments)
  - Present and future accelerators

  - Higgs searches
  - Sparticle decays

  - Existing limits on sparticles
  - Future searches

Some basic phenomenology

- Contents:
  - MSSM sparticle contents
  - Gauge interactions
  - Yukawa couplings
  - (Unbroken MSSM Lagrangian)
  - SUSY breaking models
  - Sparticle spectroscopy
- See lectures by H.Haber

MSSM Particle content

- SUSY transforms fermions to bosons and vice versa:

  Q|F> = |B> , Q|B> = |F>

  Symmetry → supermultiplets with same number of fermionic and bosonic degrees of freedom

  SM fermion (2 dof) → complex scalar

  SM gauge boson (2 dof) → SUSY fermion (gaugino)

MSSM = minimal extension of SM:

Supermultiplet components:
-Same gauge quantum numbers
- Differ only by ½ unit of spin

Gauge multiplet		Chiral multiplet	
J = 1	J = 1/2	J = 1/2	J = 0
g	$\tilde{g}$	Q_L, U^C_L, D^C_L	$\tilde{Q}_L, \tilde{U}^C_L, \tilde{D}^C_L$
$W^{\pm}, W^0$	$\tilde{W}^{\pm}, \tilde{W}^0$	L_L, E^C_L	$\tilde{L}_L, \tilde{E}^C_L$
B^0	$\tilde{B}^0$	$\tilde{H}_d, \tilde{H}_u$	H_d, H_u

Quantum Numbers

- Chiral supermultiplet:

  e.g. 1st family

  Charge is SU(3),SU(2),U(1)

  $Q = I_3 + Y/2$

- Gauge supermultiplet:

  After EW symmetry breaking

  Mixing $\tilde{W}^{\pm}, \tilde{H}^{\pm} \Rightarrow c^{\pm}_{1-2}$ charginos

  Mixing $\tilde{W}^{0}, \tilde{B}^{0}, \tilde{H}^{0}_{d}, \tilde{H}^{0}_{u} \Rightarrow c^{0}_{1-4}$ neutralinos

	Charge	Scalar
Q	**(3,2,+1/3)**	$Q = (\tilde{u}_L, \tilde{d}_L)$
U^c	**(3,1,-4/3)**	$U^c = \tilde{u}^c_L$
D^c	**(3,1,+2/3)**	$D^c = \tilde{d}^c_L$
L	**(1,2,-1)**	$L = (\tilde{n}_L, \tilde{e}_L)$
E^c	**(1,1,+2)**	$E^c = \tilde{e}^c_L$
H_d	**(1,2,-1)**	$H_d = (H^0_d, H^-_d)$
H_u	**(1,2,+1)**	$H_u = (H^+_u, H^0_u)$

Fermion	VB	Charge
$\tilde{g}$ **(gluino)**	**g**	**(8,1,0)**
$\tilde{W}$**(Wino)**	**W**	**(1,3,0)**
$\tilde{B}^0$**(Bino)**	**B^0**	**(1,1,0)**

From SM to MSSM interactions

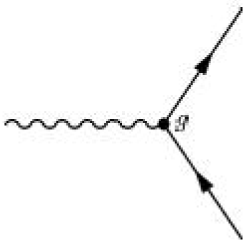
- SM multiplets ? MSSM supermultiplets
  - By including superpartners differing by ½ unit in spin
  - Supermultiplets: Chiral = (ψ,ϕ), Gauge = (A,λ)
- Same supermultiplet → same couplings in interactions
  - But: amplitudes must be scalars in spin space
  - To go from SM to MSSM interaction:

Replace pair of SM particles by their superpartners

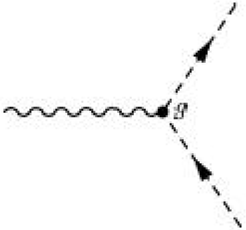
  - Will not produce all MSSM interactions,
    But it provides a useful mnemonic

Gauge interactions (trilinear)

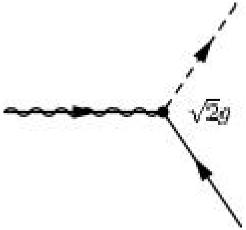
- Trilinear interactions as they control production and decay:



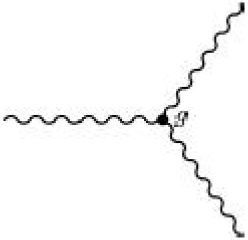
SM: (Aψψ)



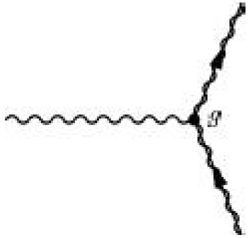
(Aφφ)



(λφψ)



SM: (AAA)



(Aλλ)

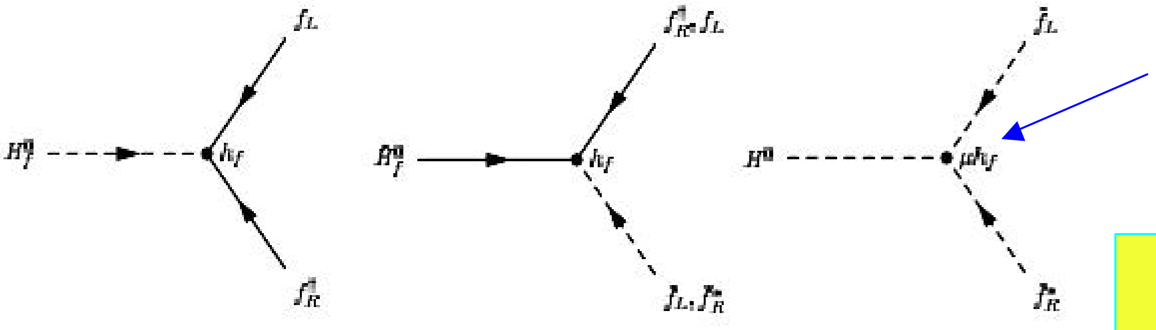
g_1=e/cosq_W , g_2=e/sinq_W, a=e^2/4p

Strength: a_i=g_i^2/4p

a_1~1/100, a_2~1/30, a_3~0.12

More formally: derived from covariant derivatives

Yukawa interactions



μ = dimensionful parameter

$$\tan\beta \equiv v_u / v_d$$

$$v \equiv \sqrt{v_u^2 + v_d^2} = \sqrt{2}\,\frac{M_W}{g_2} \approx 175\,GeV$$

$$h_u = \frac{m_u}{v.\sin\beta}, \quad h_d = \frac{m_d}{v.\cos\beta}$$

Strength: $Y=h^2/4\pi$, (for tanβ=1-35):

Y_t=0.17-0.08, Y_b=1.10^{-4}-6.10^{-2}, Y_τ=2.10^{-5}-1.10^{-2}

Y_μ=6.10^{-8}-5.10^{-5}, Y_e=1.10^{-12}-1.10^{-9}

Top Yukawa can never be neglected
Bottom and Tau Yukawas for large tanβ

More formally: derived from Superpotential

Operator dimensions

- Supermultiplets: Chiral = (ψ,ϕ), Gauge = (A,λ)
  - Lagrangian dimension = (E)

    In field theory: Lagrangian density *L*

    [*L*] = (E/L^3) ➔ [*L*] = (E^4)
  - Fermion fields:

    kinetic term: $\overline{y}\P_m g^m y$ ➔ [ψ] = (E)$^{3/2}$
  - Scalar fields:

    Kinetic term: $\P_m j^* \P^m j$ ➔ [ϕ] = (E)^1
  - Vectro boson fields:

    Kinetic term: $\boldsymbol{F}_{mn}\boldsymbol{F}^{mn}, \boldsymbol{F}_{mn} = \P_m \boldsymbol{A}_n - \P_n \boldsymbol{A}_m + \ldots$ ➔ [A] = (E)^1

Superpotential

- Specifies the Yukawa couplings
- Invariance under SUSY transformations:
  - Polynomial of order 3 in scalar fields, analytic function

$$W = \varepsilon_{ij}\left(-\tilde{L}^i_L h_L \tilde{E}^c_L H^j_d - \tilde{Q}^i_L h_D \tilde{D}^c_L H^j_d + \tilde{Q}^i_L h_U \tilde{U}^c_L H^j_u + \mu H^i_u H^j_d \right)$$

h_i= Yukawa couplings (matrices in generation space)

μ= dimension of mass ➔ mixing of Higgs fields

ε_{ij}= to make SU(2) scalars ($\varepsilon_{12} = -\varepsilon_{21} = +1$)

  - Conserves B and L (R_p=+1 for SM particles, -1 for superpartners)
  - But: additional terms are allowed which violate R_p
  - Note: W is not a potential (dimension 3)
  - Is a function from which to derive pieces of the Lagrangian

Chiral fermions contribution and part of the scalar potential

Chiral fermions contribution

- Chiral fermions contribution:

$$L_{chir} = -\frac{1}{2}\frac{\partial^2 W}{\partial \phi_i \partial \phi_j}\psi_i \psi_j + h.c.$$

- Contains fermion mass terms and Yukawa interactions:
  - $\propto h_d \left(d_L d_L^c\right) H_d^0$ SM-like mass term after EW symm. Breaking

$$m_d = h_d < H_d^0 >= h_d v \cos \beta$$
$$m_u = h_u < H_u^0 >= h_u v \sin \beta$$

  - $\mu\left(\tilde{H}_d^0 \tilde{H}_u^0 - \tilde{H}_d^- \tilde{H}_u^+\right)$ mass mixing terms for higgsinos

Scalar potential

$$V(f_i) = F_i^* F_i + \frac{1}{2} D^a D^a \qquad F_i = \frac{\partial W}{\partial f_i}, \qquad D^a = -g f_i^* T^a_{ij} f_j$$

- F-term, or chiral contribution
  - $|m|^2 \left(|H_d^0|^2 + |H_u^0|^2 \right)$ quadratic Higgs term
  - $\partial W / \partial H_d \Rightarrow m^* h_d \left(\tilde{d}_L \tilde{d}_L^c \right) H_u^{0*}$ mixing L and R sfermions
- D-term, or gauge contribution
  - Forced by supersymmetry and gauge invariance

$$\frac{1}{2} g_2^2 \left(H_d^* \frac{t^a}{2} H_d + H_u^* \frac{t^a}{2} H_u \right)^2 + \frac{1}{8} g_1^2 \left(|H_u|^2 - |H_d|^2 \right)$$

➔Quartic Higgs interaction with gauge coupling strength

as $|\mu|^2 > 0$, no vev is generated, masses are 0

SUPERSYMMETRY BREAKING

- Unbroken MSSM
  - Unbroken SUSY introduces new interactions but no new parameters
  - All particles are massless
  - Superpartners must be heavier than SM particles ➔ SUSY broken
- Soft SUSY breaking (soft = no quadratic divergences)

$$\mathrm{d}V = \Sigma_{\tilde{q},\tilde{l},H_{d,u}} m^2{}_{0,i} \, |\Phi_i|^2 + m_{1/2,a} \, \mathrm{l}_a \, \mathrm{l}_a + h.c.$$

$$+ A_{0,e} \tilde{L}^i_L h_L \tilde{E}^c_L H^j_d + A_{0,d} \tilde{Q}^i_L h_D \tilde{D}^c_L H^j_d + A_{0,u} \tilde{Q}^i_L h_U \tilde{U}^c_L H^j_u + B_0 \mathrm{m} H_d H_u + h.c.$$

  - **$m_{0,i}$** scalar masses (matrix in generation space)
  - **$m_{1/2,a}$** gaugino masses

Parametrization of our ignorance of SUSY breaking mechanism

➔ Effective Lagrangian to derive phenomenology

Gauge coupling unification

- Renormalization Group Equations (RGE):
  - Connect gauge couplings at some scale q_0 to a scale q

$$\alpha_a \equiv \frac{g_a^2}{4\pi} \qquad \boxed{\frac{d}{dt}\alpha_a^{-1}(t) = -\frac{b_a}{4\pi},} \qquad t \equiv \ln(\frac{q_0^2}{q^2})$$

  b_a are constants related to the charges under groups U(1), SU(2), SU(3) summed over all particles entering the loops, e.g.

  SM particles only: $b_a = (41/10, -19/6, -7)$

  Including MSSM particles: $b_a = (33/5, 1, -3)$

  - RGEs allow extrapolation of couplings from weak scale, linear in α^{-1} (at 1 loop)

Gauge coupling unification

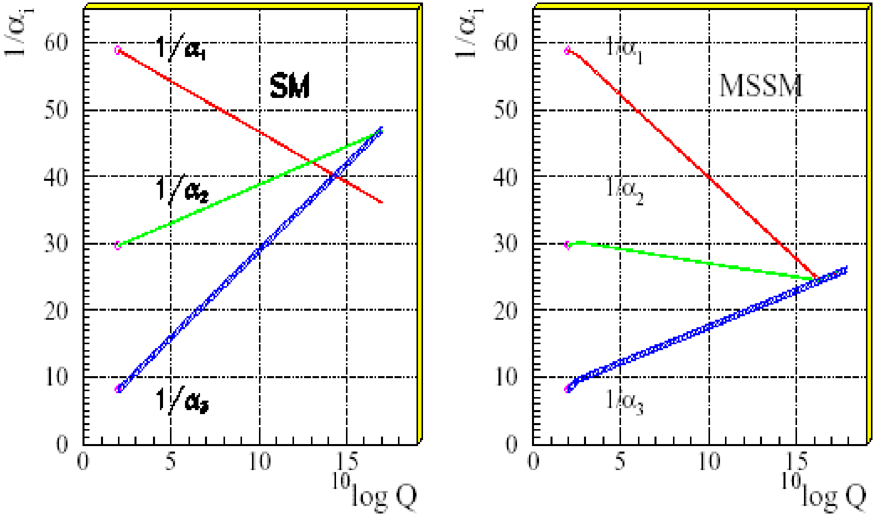
- Do couplings unify at some scale? (GQW1974)
  - Precisely known since measurements at LEP (1991)
  - Evolving with 2-loop RGEs:

    - do not meet if SM only

    - meet if MSSM with

    sparticles around 1-10 TeV

W.de Boer, 1998



Gives support to the GUT idea and to MSSM

With $M_{GUT} = 2\ 10^{16}$ GeV, $\alpha_{GUT} = 1/24$

First experimental hint that there is something beyond SM

Mass Universality, MSUGRA

- In general MSSM
  - Many new parameters → MSSM124
  - Most parameters involve flavour mixing or CP violating phases
- Universal mass parameters
  - Catastrophy is evaded by asuming Universality at GUT scale:
    - → $m_{0,l} = m_0$, common scalar mass
    - → $m_{1/2,a} = m_{1/2}$, common gaugino masses
    - → $A_{0,i} = A_0$,

Remaining parameters:

m_0 , $m_{1/2}$, A_0 , B_0 , m

Called MSUGRA

MSUGRA Spectroscopy(1)

Parameters defined at the GUT scale

Run down to EW scale by Renormalization Group Equations (RGE)

Sfermions: m_0

-Squarks increase fast (α_S)

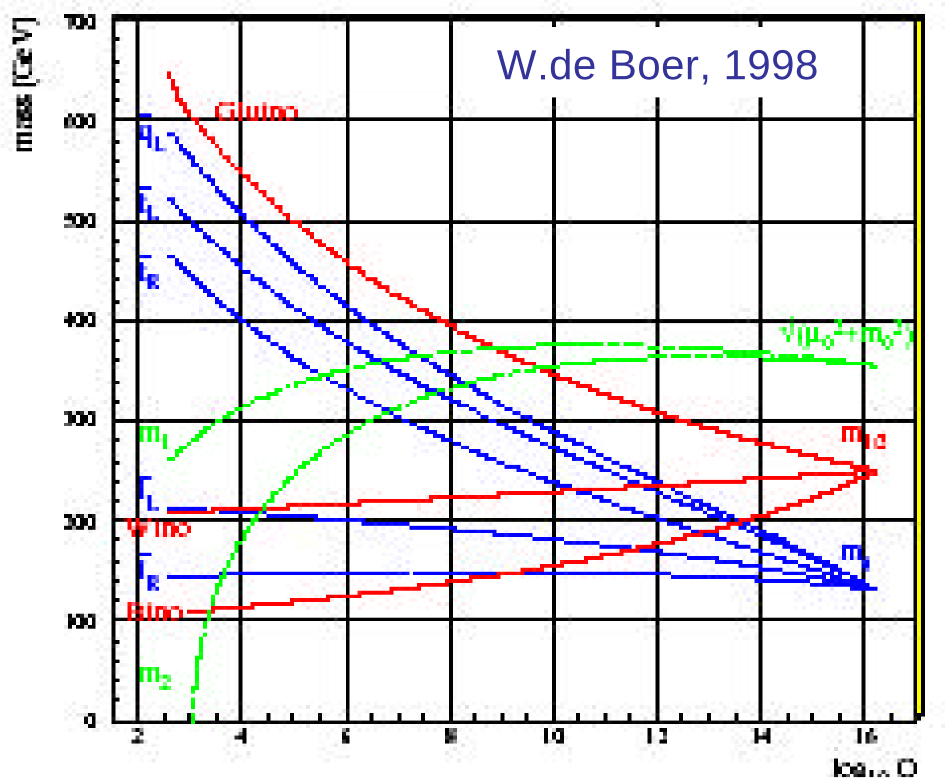
-Sleptons increase slower

Gauginos: $m_{1/2}$

-Gluino increases fast

-Bino/Wino masses decrease (mix with higgsinos)

➔ 2 charginos, 4 neutralinos



$\log_{10}Q$

Usually: lightest χ^0_1 is Lightest SUSY Particle (LSP) ➔ stable ➔ E_{miss}

MSUGRA Spectroscopy(2)

Higgs mass parameters H_u and H_d at the GUT scale: $\sqrt{m_0^2 + m^2}$

Large Yukawa coupling of H_u to t-quark

Drives mass^2 parameter of $H_u < 0$

➔Triggers EW symmetry breaking

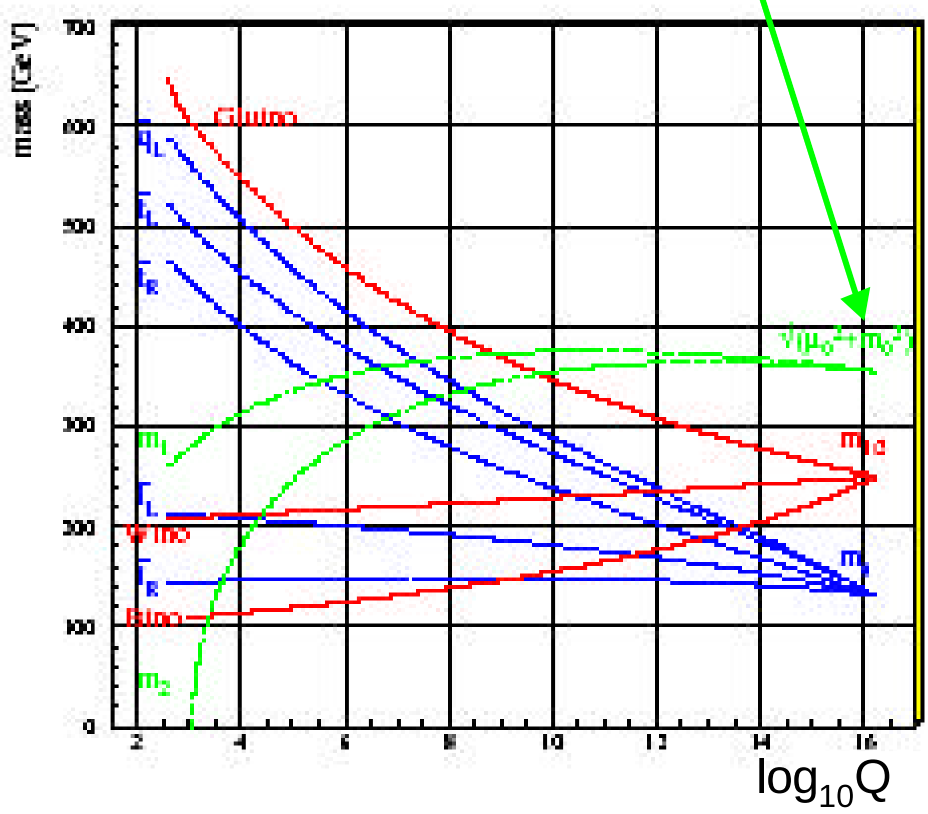
Radiative EWSB occurs naturally in MSSM

Minimization of Higgs potential

➔reduces number of parameters

m_0 , $m_{1/2}$, A_0 , $\tan\beta$, sgn(μ)

$\tan\beta = v_u / v_d$

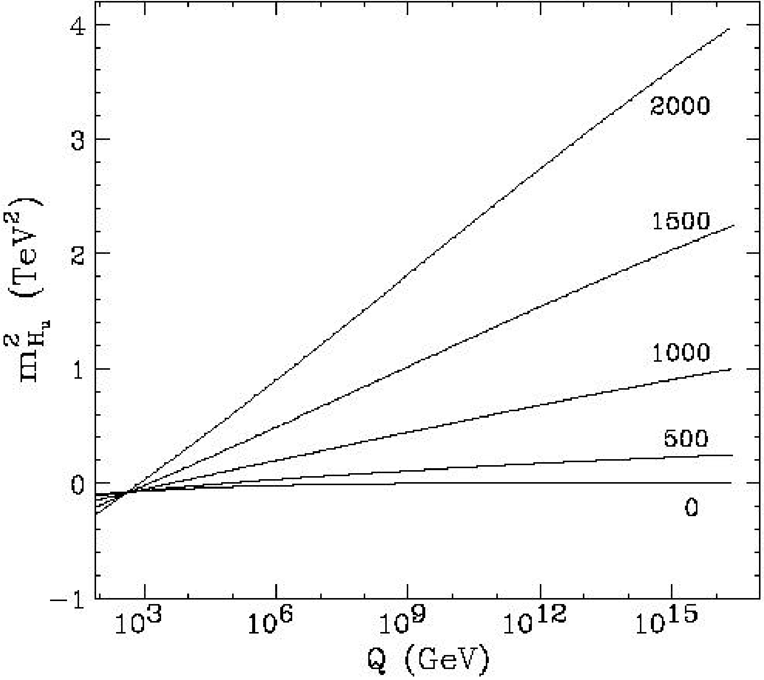


Focus Point scenario

- Focus Point
  - If $m_0 >> M_i$, A_i then RGE of M_{Hu} determined by M_i, A_i
    - ➔ value of M_{Hu} at EW scale is independent of m_0
    - ➔ Large values of m_0 do not imply fine tuning
  - Needs tanβ>5 and m_t~175 GeV
  - May have heavy sfermions

    But light gauginos

Feng, Matchev, Moroi, hep-ph/990933



Gaugino mass RGEs

- Universal gaugino masses: $m_{1/2}$ at GUT scale
- Renormalization Group Equations (RGE):

$$\frac{\boldsymbol{M}_1}{a_1} = \frac{\boldsymbol{M}_2}{a_2} = \frac{\boldsymbol{M}_3}{a_3}$$

- Weak scale values:

$$\boldsymbol{M}_3 = \boldsymbol{M}_{\tilde{g}} @ 2.7\boldsymbol{m}_{1/2}$$

$$\boldsymbol{M}_2 @ 0.8\boldsymbol{m}_{1/2}$$

$$\boldsymbol{M}_1 @ 0.4\boldsymbol{m}_{1/2} @ 0.5\boldsymbol{M}_2$$

- SU(3) unbroken: M_3=physical gluino mass, up to QCD corrections
- After SU(2)xU(1) breaking, Wino and Bino masses are mixed
- Note: same relations apply to GMSB

Chargino/neutralino masses

- Gauginos mix with higgsinos
  - Off diagonal coupling (l, j, y) Þ $(\tilde{W}^{+} H_d^0 \tilde{H}_d^{-})$
- Mass matrices:
  - Charginos (2x2) matrix: M_2, μ, tanβ
  - Neutralinos (4x4) matrix: M_1, M_2, μ, tanβ
  - In limit where neglect terms in tanβ, simplify to

$$M(c_1^{\pm}) » M_2, M(c_2^{\pm}) » m$$

$$M(c_1^{0}) » M_1, M(c_2^{0}) » M_2, M(c_3^{0}) » M(c_4^{0}) » m$$

  - ➔ two extreme cases:

$m >> M_2$ ⟶ Lightest χ are “gaugino-like”

$M_2 >> m$ ⟶ Lightest χ are “higgsino-like”

  - In MSUGRA (+GMSB): usually gaugino-like, χ_1^0=Bino, χ_2^0,$\chi_1^{\pm}$=Winos

Squark and slepton masses(1)

- First two families: start from m_0 at GUT scale
  - Yukawas are negligible
  - Running dominated by $m_{1/2}$ and α_is
  - Splitting by D-term (sfermion)^2(higgs)^2 after SU(2)xU(1) breaking
  - At weak scale (approx. formulae)

$$
\begin{aligned}
m^2(\tilde{u}_L) &= m_0^2 + 5.9 m_{1/2}^2 + 0.35 \cos 2\beta M_Z^2 \\
m^2(\tilde{d}_L) &= m_0^2 + 5.9 m_{1/2}^2 - 0.42 \cos 2\beta M_Z^2 \\
m^2(\tilde{u}_R) &= m_0^2 + 5.5 m_{1/2}^2 + 0.15 \cos 2\beta M_Z^2 \\
m^2(\tilde{d}_R) &= m_0^2 + 5.4 m_{1/2}^2 - 0.07 \cos 2\beta M_Z^2 \\
m^2(\tilde{e}_L) &= m_0^2 + .49 m_{1/2}^2 - 0.27 \cos 2\beta M_Z^2 \\
m^2(\tilde{\nu}_L) &= m_0^2 + .49 m_{1/2}^2 + 0.50 \cos 2\beta M_Z^2 \\
m^2(\tilde{e}_R) &= m_0^2 + .15 m_{1/2}^2 - 0.23 \cos 2\beta M_Z^2
\end{aligned}
$$

D-term sum rule: $m_{\tilde{e}_L}^2 - m_{\tilde{\nu}_L}^2 = m_{\tilde{d}_L}^2 - m_{\tilde{u}_L}^2 = -M_W^2 \cos 2\beta$

note that m_{gluino} is at most ~1.2 m_{squark} (for m_0=0)

Squark and slepton masses(2)

CERN

- **Third family:** Yukawa couplings cannot be neglected
  - At weak scale (tanβ = 10)

$$m^2(\tilde{t}_L) = m_t^2 + .69m_0^2 + 5.0m_{1/2}^2 + 0.35\cos 2\beta M_Z^2$$
$$m^2(\tilde{b}_L) = m_b^2 + .69m_0^2 + 5.0m_{1/2}^2 - 0.42\cos 2\beta M_Z^2$$
$$m^2(\tilde{t}_R) = m_t^2 + .33m_0^2 + 3.7m_{1/2}^2 + 0.15\cos 2\beta M_Z^2$$
$$m^2(\tilde{b}_R) = m_b^2 + m^2(\tilde{d}_R)$$

  - ➔ Yukawa couplings decrease mass
  - Also L-R mixing: SUSY breaking and F-term

$$\begin{pmatrix} m^2(\tilde{t}_L) & m_t(A_t - \mu\cot\beta) \\ m_t(A_t - \mu\cot\beta) & m^2(\tilde{t}_R) \end{pmatrix}$$

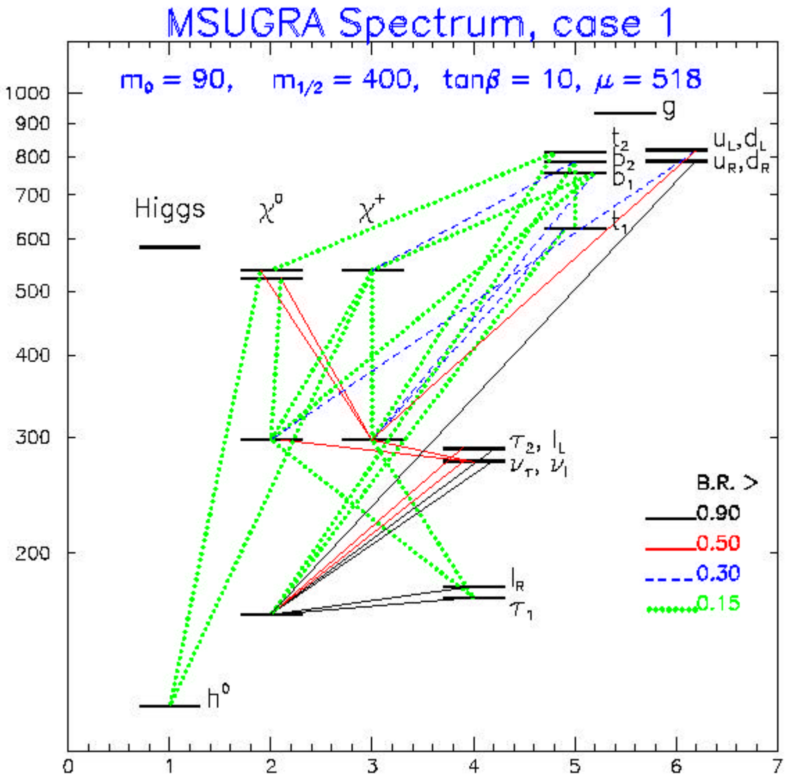
  - ➔ $m^2_{\tilde{t}_{1,2}} = \dfrac{1}{2}\left[m^2_{\tilde{t}_L} + m^2_{\tilde{t}_R} \mp \sqrt{(m^2_{\tilde{t}_L} - m^2_{\tilde{t}_R})^2 + 4m_t^2(A_t - \mu\cot\beta)^2}\right]$
  - Similar for sbottom/stau replacing cotβ by tanβ

Lightest squark: $\tilde{t}_1(\textit{low}\tan\beta), \tilde{b}_1(\textit{high}\tan\beta)$

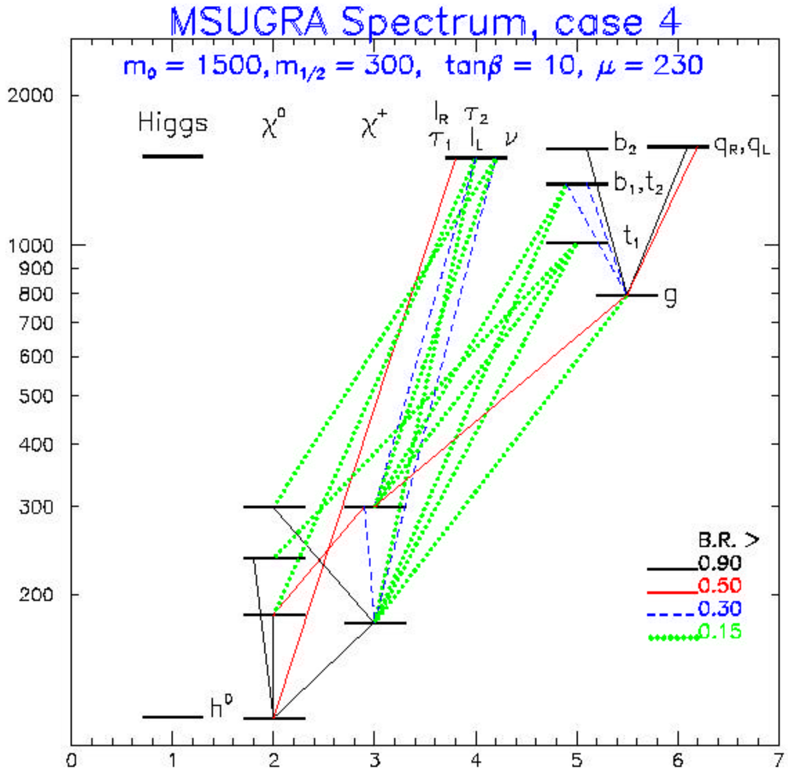
Example MSUGRA spectrum

- Stable neutralino LSP

Low m_0

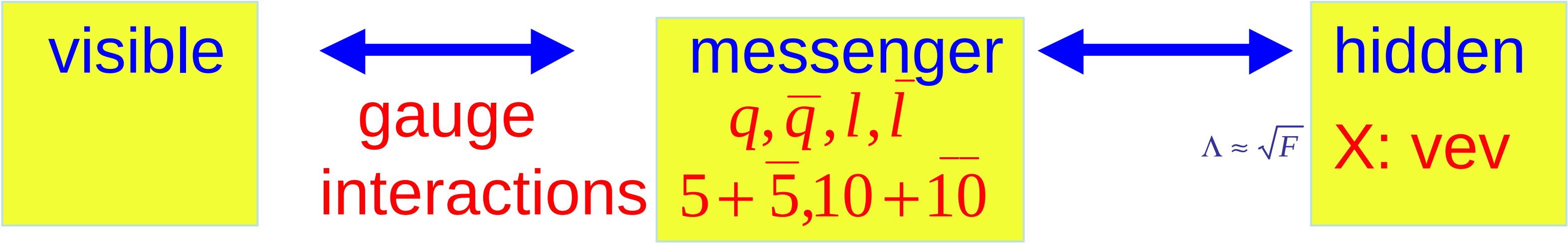


High m_0 (Focus Point)



Gauge Mediated SUSY Breaking

- Gauge mediation (GMSB): 3 sectors



visible

gauge interactions

messenger

$q, \bar{q}, l, \bar{l}$

$5 + \bar{5}, 10 + \overline{10}$

$\Lambda \approx \sqrt{F}$

hidden

X: vev

- Loops: $m_{soft} = \frac{a}{4p}\sqrt{F}$, for m_{soft} at EW scale $\sqrt{F} \approx 10^4 - 10^5 GeV$
- Gravitino is the LSP (m ~ eV)
- Parameters
  - M= messenger scale (amount of RGE evolution)
  - $\Lambda \approx \sqrt{F}$ mass splitting of scalar messengers (F= vev of X)
  - N= messenger index, where a 5 contributes with 1 and a 10 with 3
  - μ and B obtained from gauge boson mass and tanβ

Λ, M, N, tanβ, sign(μ)

- Gauginos:

$$M_a = \frac{a_a(t)}{4p} N\Lambda \qquad t = \ln\left(M^2 / Q^2\right)$$

- Scalars (at messenger scale):

$$\tilde{m}^2 = 2N\Lambda^2 \sum C_a \left(\frac{a_a}{4p}\right)^2$$

  - With C_3=4/3 (=0 if singlet), C_2=3/4 (=0 if singlet), C_1=3/5.(Y/2)^2
- Note the different dependence on N

GMSB spectroscopy

- LSP=gravitino

  Who is NLSP?

Sparticles decay to NLSP

- Low N:

  χ_0^1 is NLSP

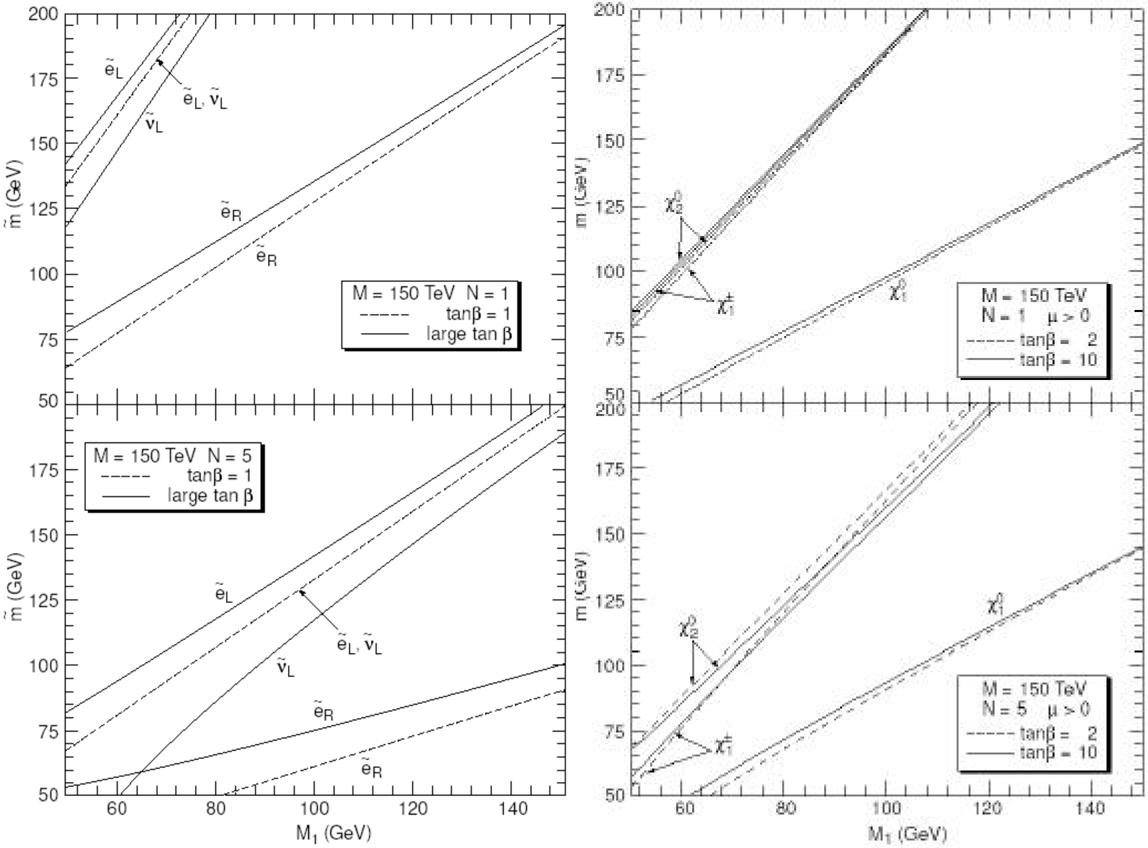
  $c_1^0 \rightarrow g + \tilde{G}$

- High N:

  Stau is NLSP

  $\tilde{t}_1 \rightarrow t + \tilde{G}$

Guidice,Rattazi, hep-ph/9801271



- Typical signature of GMSB:

  E_{miss} + γ or τ or long-lived particles

Anomaly Mediated SUSY Breaking

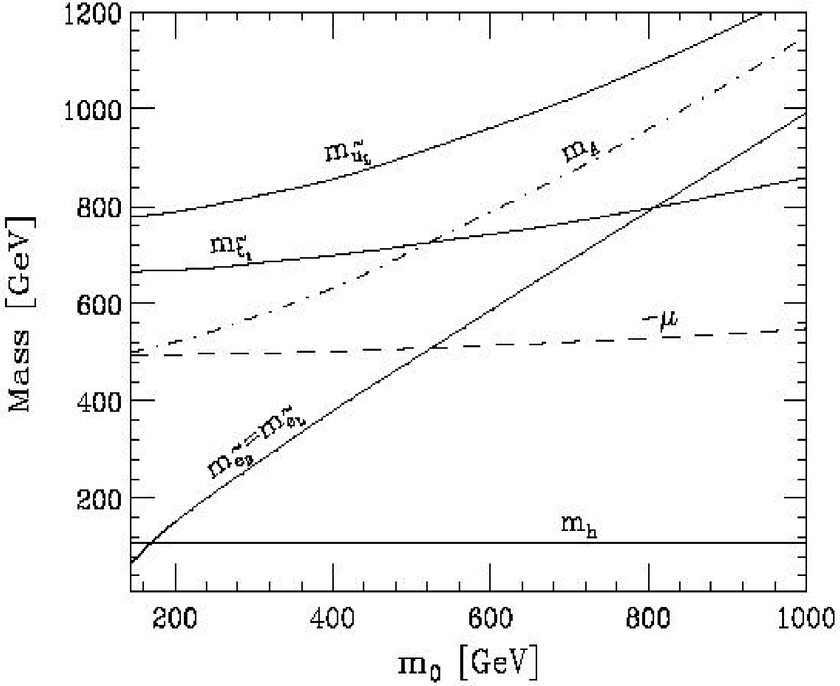
- Principle
  - SUGRA Lagrangian has conformal (=scale) invariance
  - But broken at quantum level due to cut-off scale (regularization)
  - Leads to residual couplings (anomaly) to observable fields
- Parameters
  - In pure AMSB, only 1 parameter $m_{3/2}$=gravitino mass
  - But leads to tachyonic sleptons → introduce m_0 (universal scalar mass)
  - Also tanβ and μ
  - After imposing correct EWSB

$m_{3/2}$, m_0, tanβ, sign(μ)

AMSB Spectroscopy

- Charginos/neutralinos:
  - $(M_1, M_2, M_3) = (2.8:1:-7.1)$
  - Wino lighter than Bino
  - $\chi_1^\pm$ nearly degenerate with χ_1^0
  - μ (from EWSB) larger than in MSUGRA
- Scalars:
  - Sleptons L and R of 1st 2 families nearly degenerate (accidental) with mass m_0
- Signature:
  - E_{miss}, like MSUGRA
  - $\chi_1^\pm \rightarrow \pi^\pm \chi_1^0$ (soft pion) may be long lived

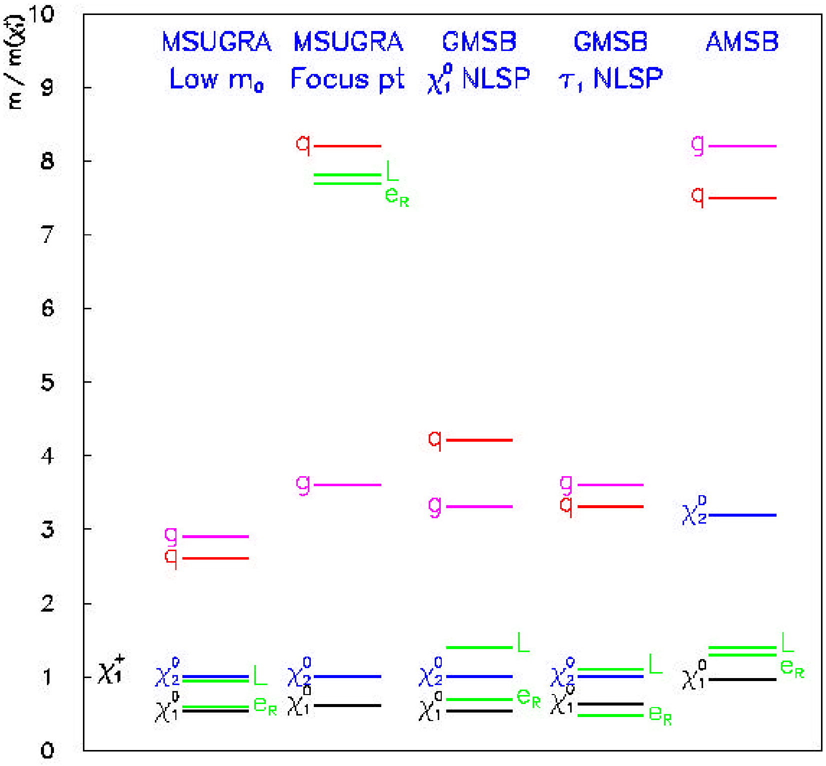
Gheghetta, Giudice, Wells, hep-ph/990437



$(m_{3/2} = 36 \text{ TeV}, \tan\beta = 5, \mu < 0)$

Comparison of Spectra

- Mass relative to $\chi_1^\pm$



R-parity violation

- SUSY permits to add terms to Superpotential

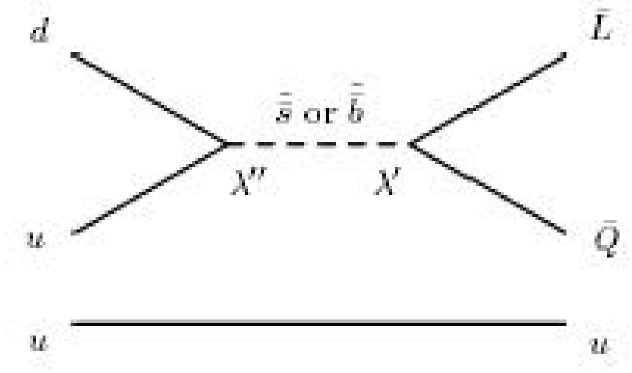
$$W_{RPV} = \lambda_{ijk}\tilde{L}_i\tilde{L}_j\tilde{E}_k^c + \lambda'_{ijk}\tilde{L}_i\tilde{Q}_j\tilde{D}_k^c + \lambda''_{ijk}\tilde{U}_i^c\tilde{D}_j^c\tilde{D}_k^c$$

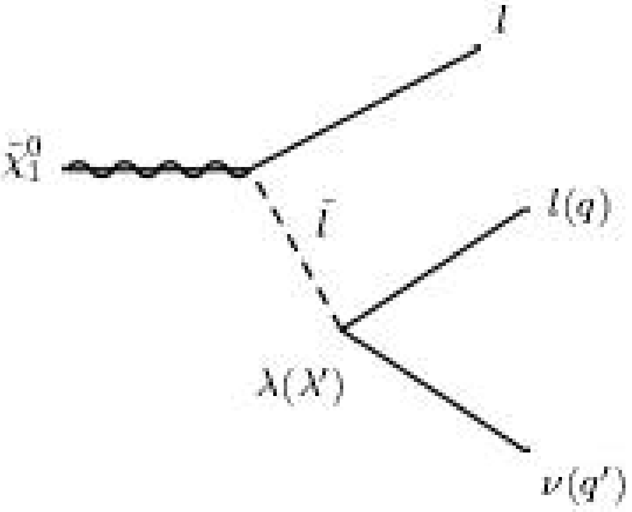
  - Yukawa couplings with i,j,k=generation indices
  - Violate conservation of R-parity $R_p=(-1)^{3B+L+2S}$
  - 1st 2 terms $\Delta L=1$, last term $\Delta B=1$
- New parameters:
  - λ: antisymmetric by SU(2) invariance: i<j, 9terms
  - λ’: 27 terms
  - λ’’:antisymmetric by $SU(3)_C$ invariance: j<k, 9 terms

    ➔ 45 new free parameters

R-parity violation

- Constrained by proton lifetime
  - λ' and λ'' non zero
- Several other low energy constraints
  - Review by H.Dreiner hep-ph/9707435
- LSP Neutralino decays
  - Via fermion-sfermion pair, followed by RPV decay
  - Missing energy signature is lost
  - New signatures appear (additional leptons and/or jets)
- LSP could be sfermion, decaying via RPV
- Single production of sfermions
  - E.g. sneutrino at LEP or squark at HERA





SUSY Signatures

Supersymmetry, MSUGRA

- E_T^{miss}, Inclusive searches
- Dileptons, Taus, Z0, h0
- Bottoms
- mass reconstruction

Gauge Mediated

- Photon events + E_T^{miss}
- Multi-tau events + E_T^{miss}
- Long-lived sparticles

R-parity violation

- Multi-leptons
- Multi-jets

Low Energy Measurements

- Contents
  - $b \to s\,\gamma$ decay
  - Other FCNC decays of b and s
  - $g_\mu - 2$ saga
  - Many others
    - Proton decay, K0-K0bar oscillations, lepton violating decays, CP violation, electric dipole moments, atomic parity violation, LEP/SLC precision measurements …
- May bring first evidence for physics beyond the SM

  ➔ Keep eyes wide open!
- See lectures of D.Wyler and W.Hollik

Accelerators

- Contents
  - Present accelerators
  - Future funded accelerators
  - Future proposed accelerators

Present accelerators

			$\sqrt{s}$, GeV	pb^{-1}/exp
LEP	e^+e^-	ADLO		
	LEP 1	1989-95	91	150
	LEP 2	95-2000	130-208	700
Tevatron	$\bar{p}$-p	CDF,D0		
	Run 1		1800	110
	Run 2	01-~08	2000	? (3-20.10^3)
HERA	$e^{\pm}p$	H1,Zeus		
		1993-97	300	50
		98-~07	318	?(1.10^3)

Future accelerators

- LHC (funded, at CERN)
  - Expected to start in ~Summer 2007, true data taking 2008
  - E_{cm} = 14 TeV, p+p
  - Run ~3 years at luminosity=10^{33}cm^{-2}s^{-1} (~10 fb^{-1}/year)
  - Continue at 10^{34}cm^{-2}s^{-1} (~100 fb^{-1}/year)
- e+e- Collider
  - 3 techniques proposed: TESLA, NLC, JLC
    Start at 0.5, upgrade to ~1 TeV
    Decision on technique this year
    Detailed TDR for 2007, site selection 2008(?)
  - CLIC up to 3-5 TeV
    Feasibility to be demonstrated for 2010
    Construction could start in 2013 (last 7 years)
- Others: μ collider, VLHC

Sparticle production

- Two basically different approaches
  - e^+e^- collider

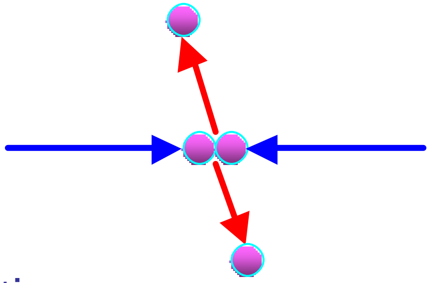
    Pure partonic interactions

    fixed E_{cm}= partonic energy (kinematical constraints)

    allows E scans (e.g. thresholds) to be made/polarization

    ➔ **precision measurements**

    but limited E_{cms}



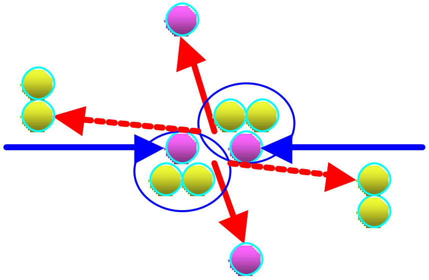
  - Hadron collider (p-p or $\bar{p}$-p)

    Variable partonic energy, e.g.

$$\sigma_{qg} = \int dx_q dx_g . F_q(x_q) . F_g(x_g) . \hat{\sigma}_{qg}(s' = x_q x_g s)$$

    but machine reaches higher energy

    ➔ **exploratory machine**

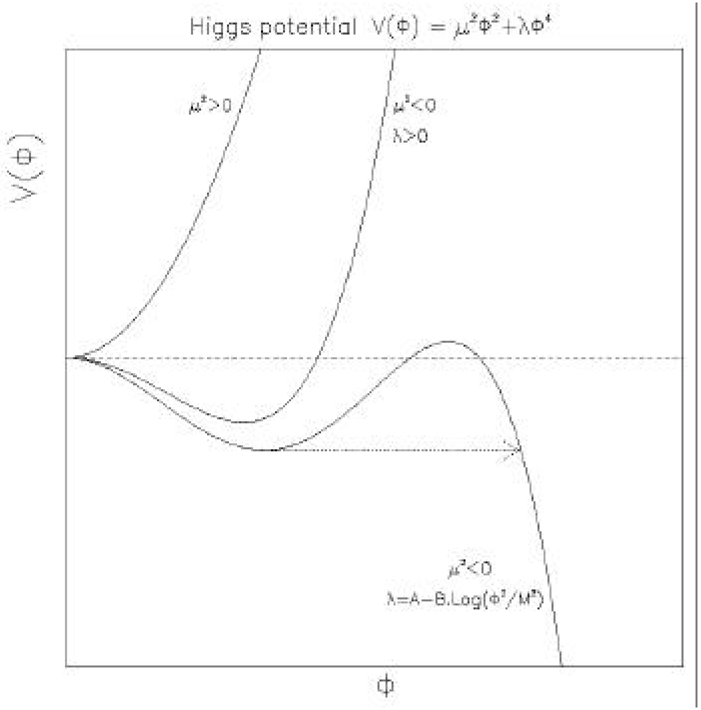


SUSY Higgses

- Contents
  - Higgs mass in SM
  - Higgs mass in MSSM
  - Higgs mass radiative corrections
  - Production in e+e- colliders
  - Limits from LEP and Tevatron
  - Future searches: Tevatron, LHC and LC

Higgs mass in SM (1)

- One Higgs field SU(2) doublet
  - Masses generated by Higgs v.e.v.
    $V(\phi) = \mu^2|\phi|^2 + \lambda\,|\phi|^4$,
    with $\mu^2<0$ and $\lambda>0$



  - Higgs mass: $M_H^2 = 2\,v^2\,\lambda(v)$ for v = 175 GeV
  - Parameters μ and λ are free in SM
    ➔ Higss mass is undetermined in SM

Higgs mass in SM (2)

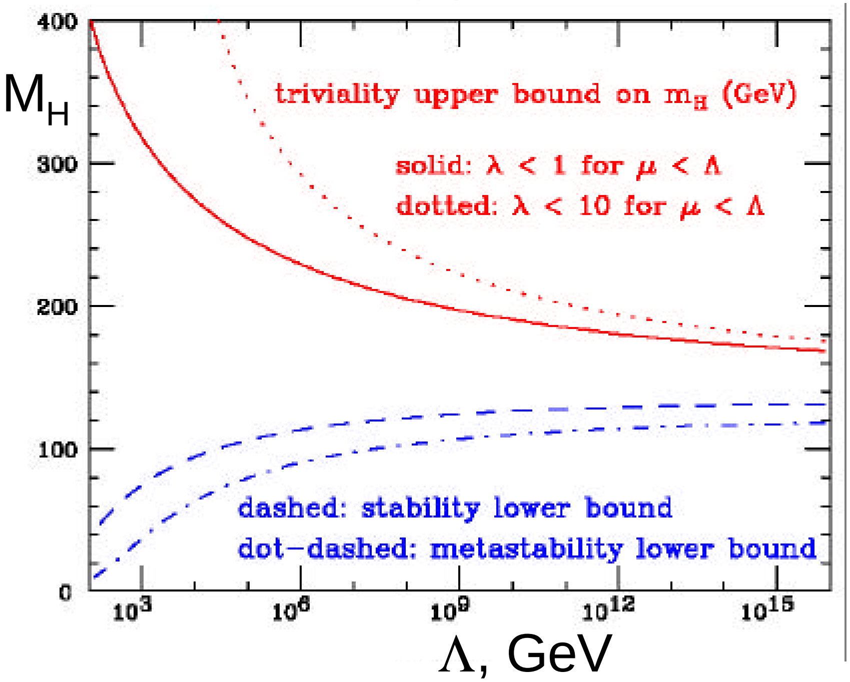
- Limits on Higgs mass can be derived from rad.corr.
  - RGE evolution of λ due to Higgs and top (h_t=Yukawa) loops:

$$\frac{dl(t)}{dt} = \frac{3}{4p^2}\left(l^2 + l h_t^2 - h_t^4\right), t = \ln(\Lambda / v)$$

- Perturbativity: h_t << λ
  - λ^2 dominates → strong coupling
  - Upper limit on M_H
- Vaccum stability: h_t >> λ
  - $-h_t^4$ dominates → λ(t) negative
  - Potential unbounded from below
  - Lower bound on M_H
- SM valid up to Planck scale:

130 < M_H < 180 GeV

Ridolfi, hep-ph/0106300



Higgs in MSSM

- In MSSM: 2 Higgs fields → 8 degrees of freedom

  3 are used to make $W^{\pm}$ and Z^0 massive

  MSSM contains 5 physical Higgs states

$$H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix} \qquad H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}$$

- **2 charged scalars $H^{\pm}$**

  Mixture of H_d^- and H_u^+, fixed by $\tan\beta$

- **1 neutral CP-odd A^0**

  Mixture of $\mathrm{Im}(H_d^0)$ and $\mathrm{Im}(H_u^0)$, fixed by $\tan\beta$

- **2 neutral CP-even h^0 and H^0**

  Mixture of $\mathrm{Re}(H_d^0)$ and $\mathrm{Re}(H_u^0)$, with mixing angle α

Higgs mass at tree level

- From scalar potential, tree level masses are:

$$m^2_{H^\pm} = M_W^2 + m_A^2$$

$$m^2_{H,h} = \frac{1}{2}(m_A^2 + M_Z^2) \pm \frac{1}{2}\sqrt{(m_A^2 + M_Z^2)^2 - 4m_A^2 M_Z^2 \cos^2 2b}$$

- Higgs masses depend on only 2 parameters: m_A and tanβ
  - tanβ→1: $m_h=0$, $m_H^2=M_Z^2+m_A^2$
  - tanβ→8 :m_h, $m_H^0=\min,\max(M_Z,m_A)$
- Mass hierarchy at tree level:
  - 0 $= m_h = M_Z|\cos 2\beta|$
  - $m_h = m_A = m_H^0$
  - $m_H^0 = M_Z$
  - $m_H^\pm = M_W$
- Expect light h^0 (coupling of $|\phi|^4$ term of gauge strength)

  → observable at LEP2

  But radiative corrections are large, especially on m_h

Higgs mass radiative corrections

- Top loop corrections: 1-loop leading log approximation

$$\Delta(m_h^2) = \frac{3m_t^4}{4\pi^2 v^2}\ln\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right)$$

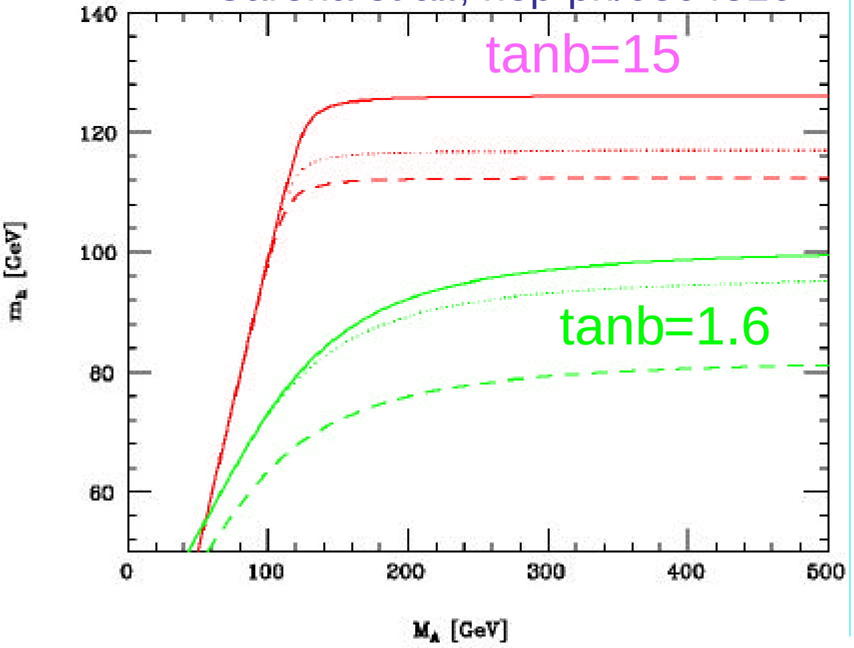
  - Introduces a dependence on top and stop masses
  - More accurate calculation:also on stop mixing $X_t = A_t - \mu\cot\beta$
- In MSSM, **m_h^0 has upper bound**
  - Increases with tanβ
  - Increases from min $X_t/M_{SUSY}=0$ To max $(X_t/M_{SUSY})^2=6$

m_h =130 GeV

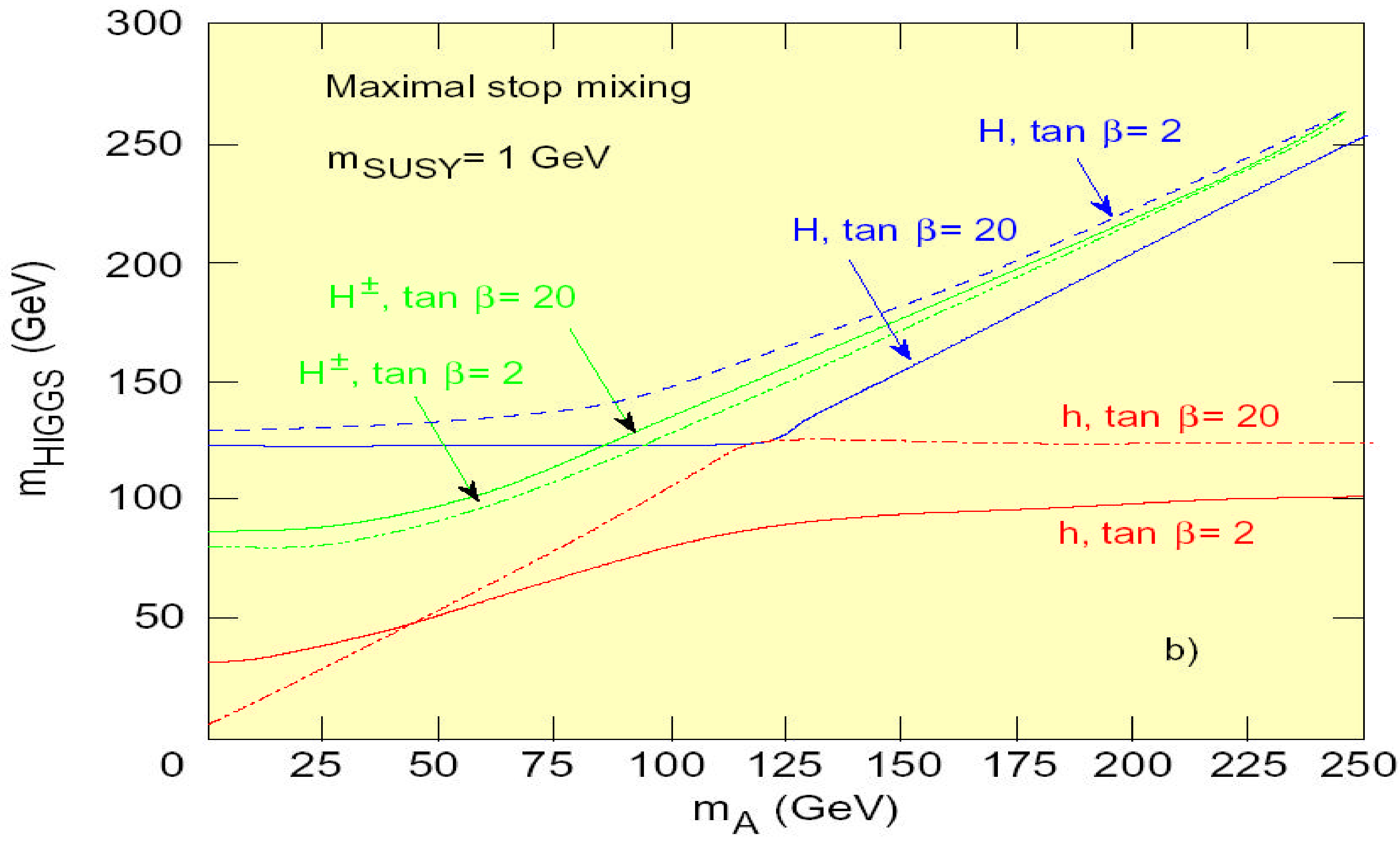
(for M_{SUSY} = 1 TeV, m_t=175 GeV)

➔ Lower than preferred SM range

Carena et al., hep-ph/9504316



Higgs masses, summary



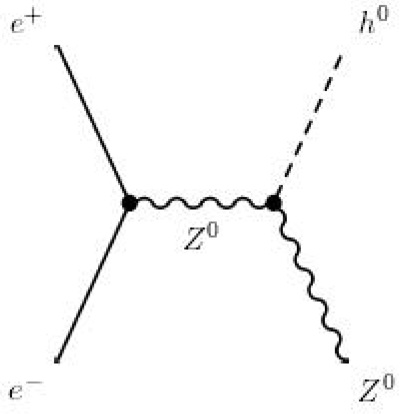
Higgs decays

- Light Higgs h^0 <130 GeV:
  - $B(bb)$~80-85%, $B(\tau\tau)$ ~8%, $B(\mu\mu)$ ~2.10^{-4}, $B(\gamma\gamma)$ ~$1.5.10^{-3}$
  - For m_h>120 GeV $B(WW^*)$ and $B(ZZ^*)$ increase
- H^0/A^0 (>130 GeV):
  - Large $\tan\beta$>10: $B(bb)$ dominates, $B(\tau\tau)$ ~10%,
  - Small $\tan\beta$: $H^0 \rightarrow WW^*$, ZZ^*, hh dominate

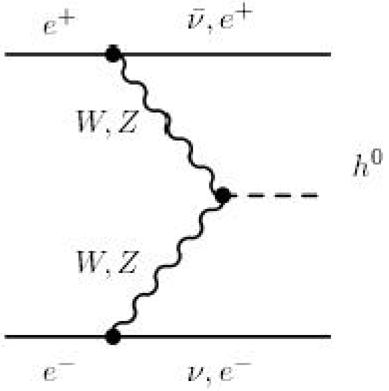
    and $A^0 \rightarrow Zh$ dominates

    but for m(H,A)>350 GeV $B(tt)$~90%
- $H^\pm$:
  - $m(H^\pm)<m_t$: $B(\tau\nu)$~100%
  - For $m(H^\pm)$>200 GeV: $B(tb)$ dominates, $B(\tau\nu)$~10%
- All can decay to gauginos (depends on parameters)

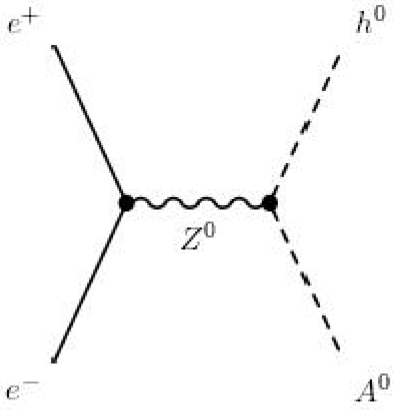
Production in e^+e^- machines(1)



Higgsstrahlung



Fusion (small)



Associated production

$$e^+e^- \rightarrow h^0 Z, \quad s \propto \sin^2(b-a)$$
$$e^+e^- \rightarrow h^0 A, \quad s \propto \cos^2(b-a)r$$

α is mixing angle of h^0 and H^0

The processes are complementary

Production in e^+e^- machines(2)

Large m_A :

β-$\alpha = \pi/2$

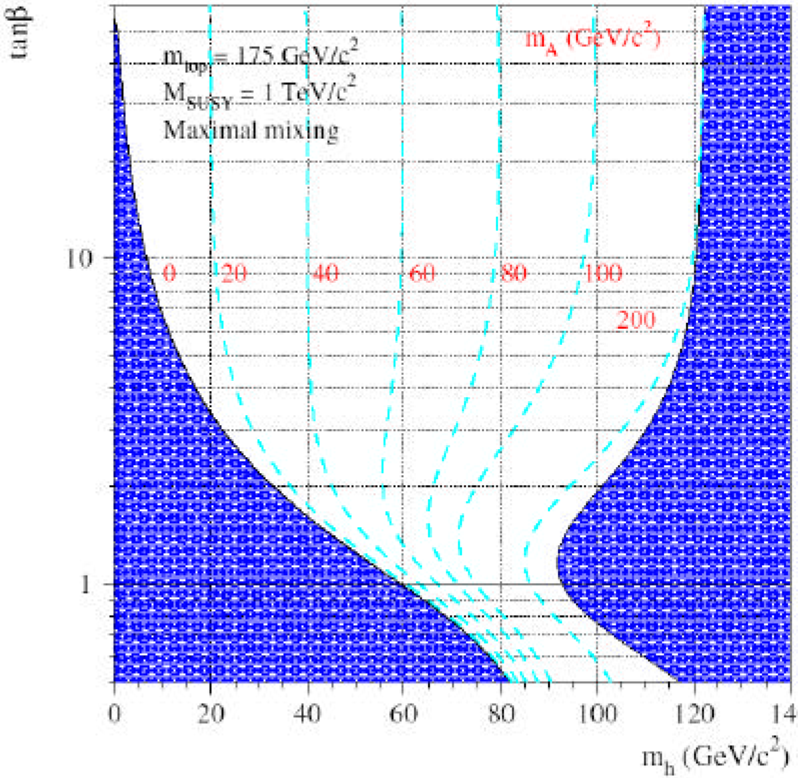
h^0Z^0 dominates, h^0 is SM-like

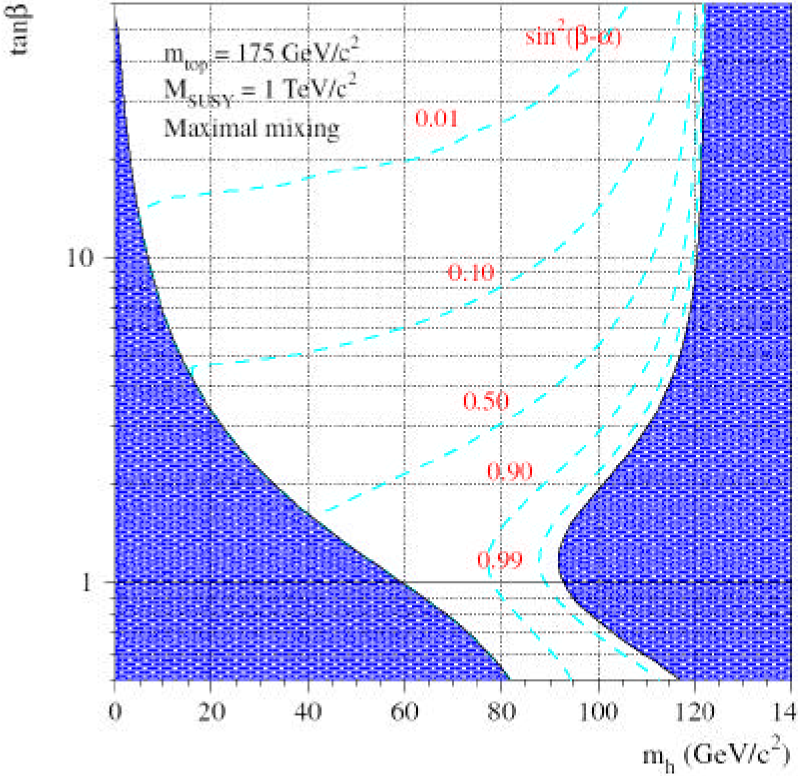
$$\cos 2a = -\cos 2b \, \frac{m_A^2 - M_Z^2}{m_H^2 - m_h^2}$$

Large tanβ, m_h~m_A

β-$\alpha = \pi$

h^0A^0 dominates, m_h=100 GeV



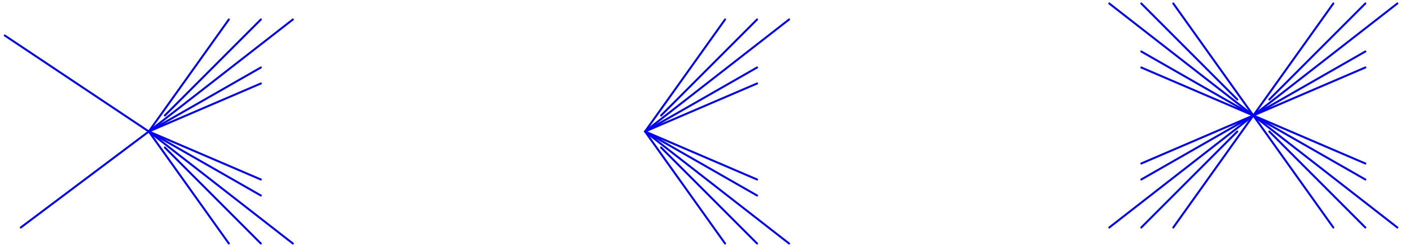


Higgs search topologies

- **h^0 Z topologies**:
  - B(h^0? b-bbar)=86%, B(h^0? τ–τbar)=8%

$$Z^0 \to l^+l^- \qquad Z^0 \to n\bar{n} \qquad Z^0 \to q\bar{q}$$
$$h^0 \to b\bar{b} \qquad h^0 \to b\bar{b} \qquad h^0 \to b\bar{b}$$

B.R.=9.3% B.R.=18% B.R.=64%

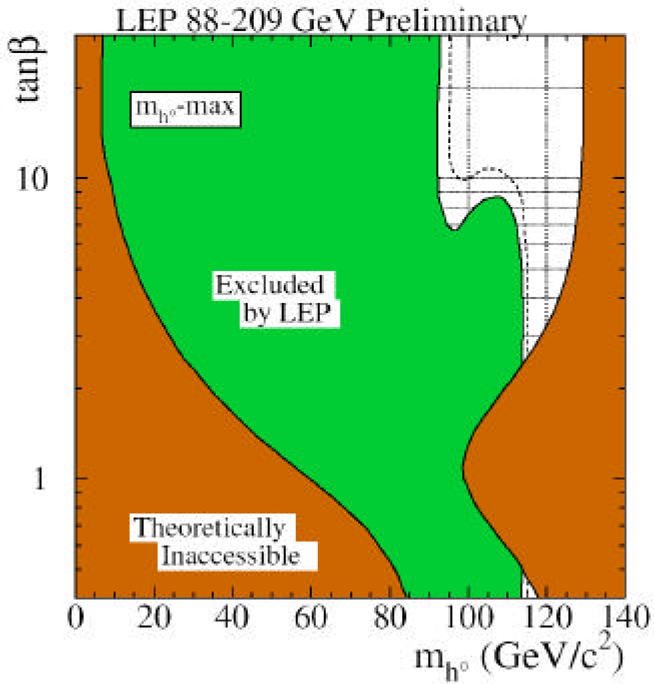


  - Also $h^0 \to t\bar{t}, \; Z^0 \to q\bar{q}$ (B.R.=5.4%) included in search
  - For m_h > 130 GeV WW* and ZZ* become important
- **h^0 A topologies**
  - For m_A<350 GeV: $b\bar{b}\,b\bar{b}, b\bar{b}\,t\bar{t}, 4t$
  - For m_A>350 GeV: $A \to t\bar{t}$ may be important

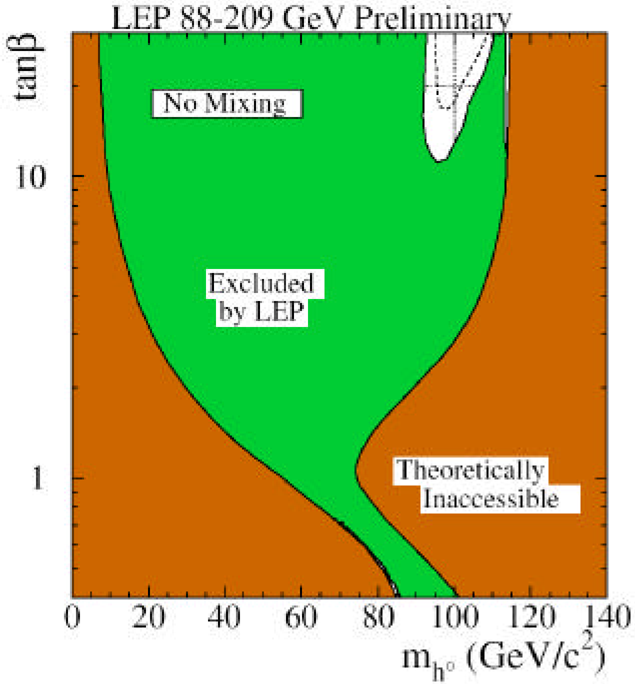
Higgs mass limits from LEP

LEP 95% C.L. exclusion from ADLO:

Maximal stop mixing (m_h^{max})



No stop mixing



Large m_A: m_h=114.1 GeV

For m_h^{max}: m_h=91.0, m_A=91.9 GeV tanβ =2.4

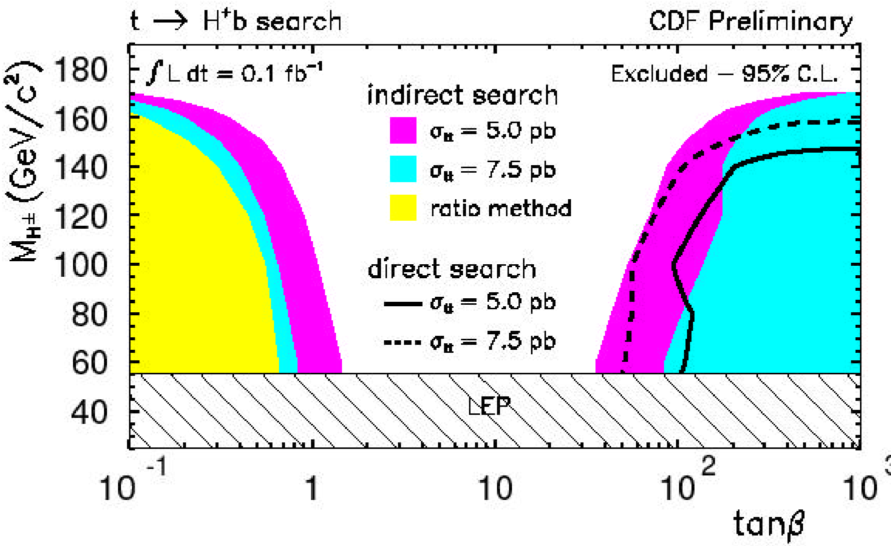
Non-conventional Higgses

- H? γγ
  - Crucial channel for LHC, but small BR (2.10^{-3})
  - So far, insufficient sensitivity at LEP and Tevatron
- H invisible decays
  - E.g. decay to neutralinos
  - “Easy” at LEP, ADLO limit 114.4 GeV
- Flavour-blind H search
  - Usually search H? bb, but BR may be suppressed
  - Look for decays into 2 jets or ττ in HZ channel
  - LEP (preliminary) limit is 112.5 GeV
- Charged H
  - Decays to cs or τν
  - LEP (preliminary) limit about 80 GeV

Charged Higgs at Tevatron

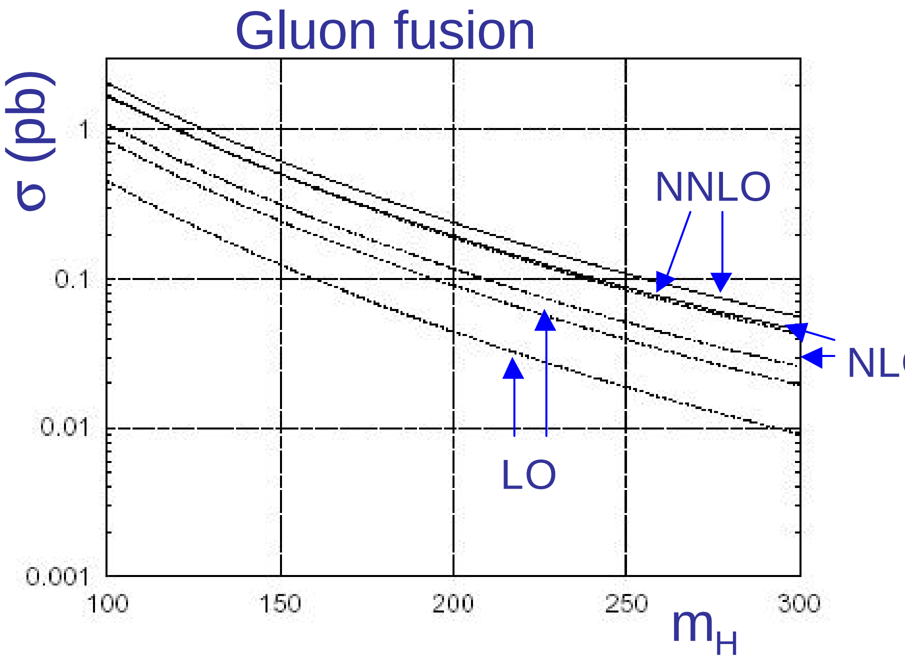
- Searched in t-tbar, t→H⁺b
  - BR large if tanβ large or very low
- Indirect search:
  - Measure σ(ttbar), t→Wb
  - Theory → limit on BR(t→H⁺b)
- At tanβ>1: $H^+ \rightarrow t^+ n$
  - → direct search
- At very low tanβ: $H^+ \rightarrow c\bar{s}$
  - Ratio method
  - Evts 1l+jets from WbWb or HbWb
  - Evts 2l+jets only from WbWb
  - → ratio gives limit BR(t→H⁺b)
- Caveat: neglects other decays: $H^{\pm}$ ® $h^0 W^{\pm}, c^{\pm} c^0, \tilde{t}\tilde{n}$

CDF



Future searches: Tevatron(1)

- **Dominant cross-section:**
  - Gluon fusion (top/bottom loop)
  - Decay $h^0 \to b\bar{b}$ hopeless
  - But $h^0 \to VV^*$ with leptonic decays for large m_h
- **Also** $q\bar{q} \to V^* \to Vh^0$
  - with $h^0 \to b\bar{b}$, triggered by leptonic decay of W or Z
  - for m_h < 140 GeV



Anastasiou, Melnikov, hep-ph/0207004

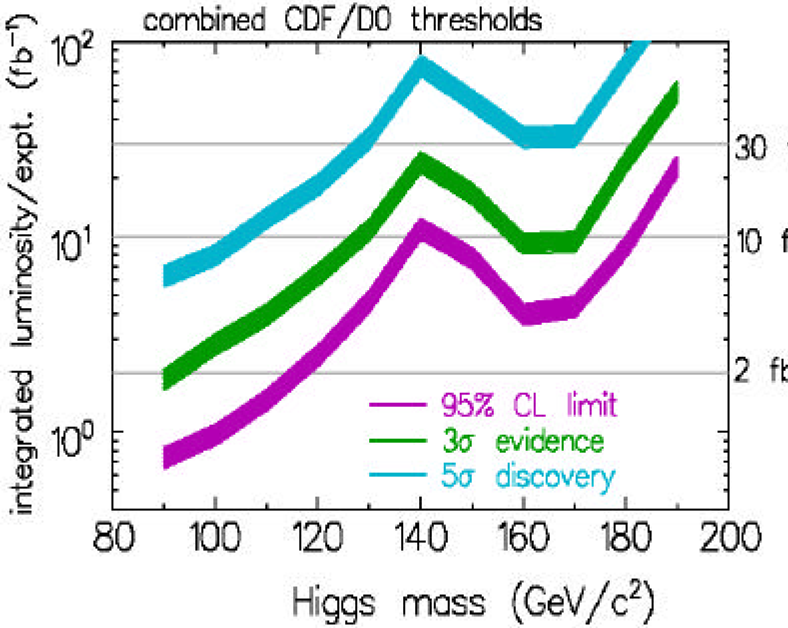
2 curves: $\mu=m_H/2, 2m_H$

Future searches: Tevatron(2)

- Tevatron Run II
  - After 2 fb^{-1}:
    Excl 120 GeV (95% CL)
  - After 11 fb^{-1} for 2008
    Excl 180 GeV (95% CL)
    3 σ < 130, 155-175 GeV
    5 σ < 110 GeV
  - Discovery up to 130 GeV
    would require 30 fb^{-1}

$$q\bar{q} \to W + h/H$$
$$W \to l\nu$$
$$h/H \to b\bar{b}$$

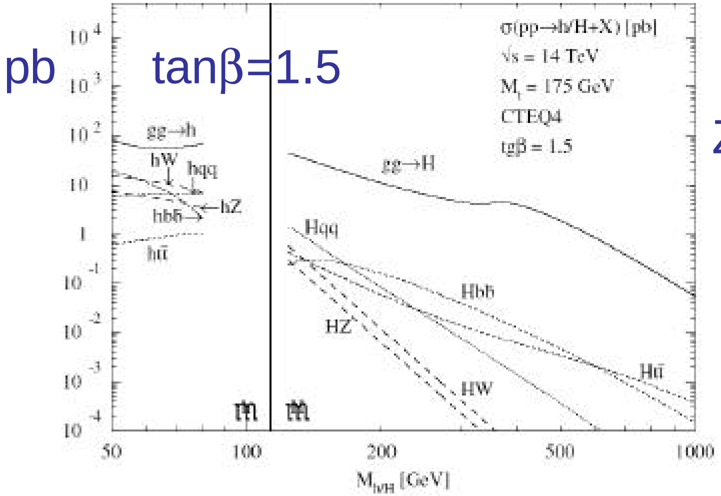
$$gg \to H$$
$$h/H \to WW^*$$
$$W \to l\nu$$



Carena et al., hep-ph/0010338

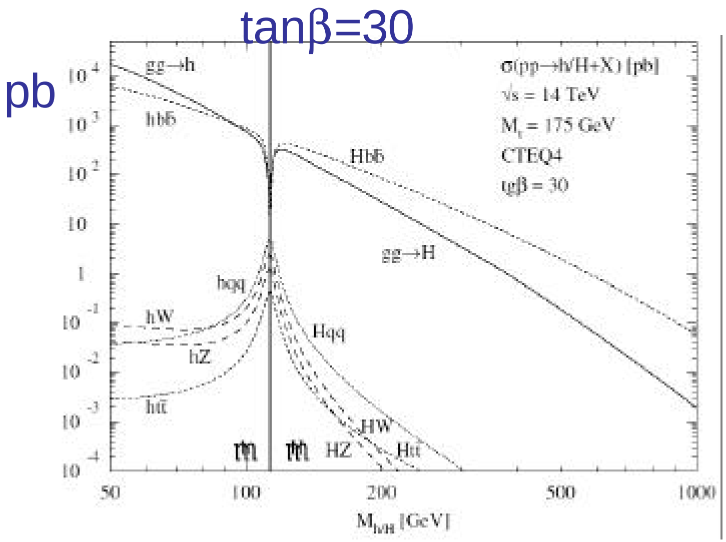
Future searches: LHC(1)

- Dominant cross sections:
  - Gluon fusion
  - Higgsstrahlung, e.g. Hb-bbar at high tanβ
  - Gauge boson fusion (Hqq) low, especially at high tanβ)
  - Associated production with VB (strongly suppressed)



Spira,

Zerwas



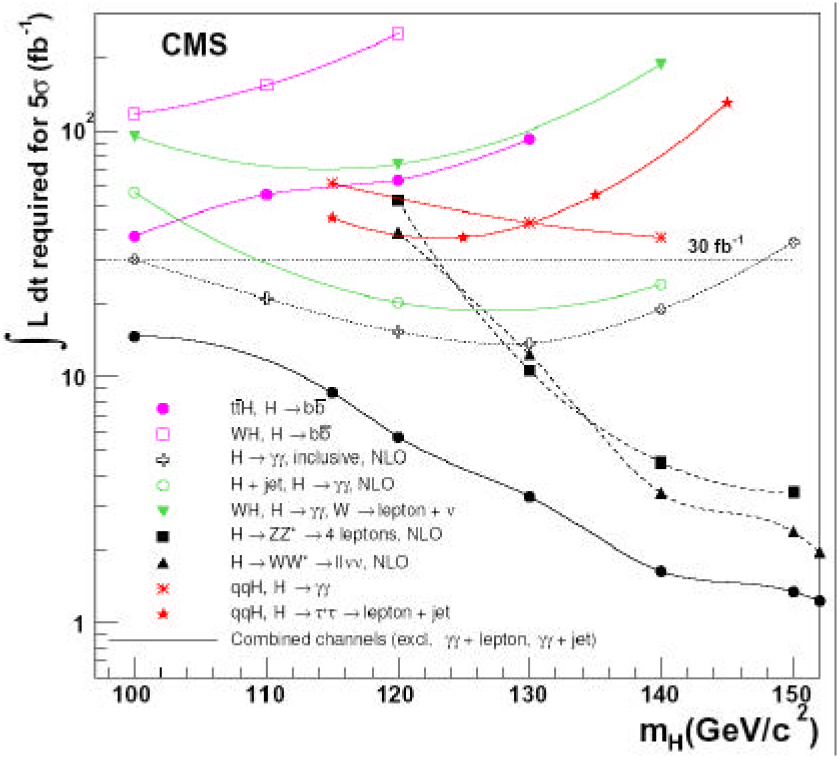
Future searches: LHC(2)

- Low Higgs mass region:
  - H→γγ most powerful

    Already with 30 fb^{-1} get 5σ up to 150 GeV
  - ~60 fb^{-1}: $qqH, H \to t\,t$
  - >60-100 fb^{-1}: $t\bar{t}H, H \to b\bar{b}$
  - → several modes observable
- Higher masses > 130 GeV
  - H→WW*,ZZ*

    Already with 10 fb^{-1}

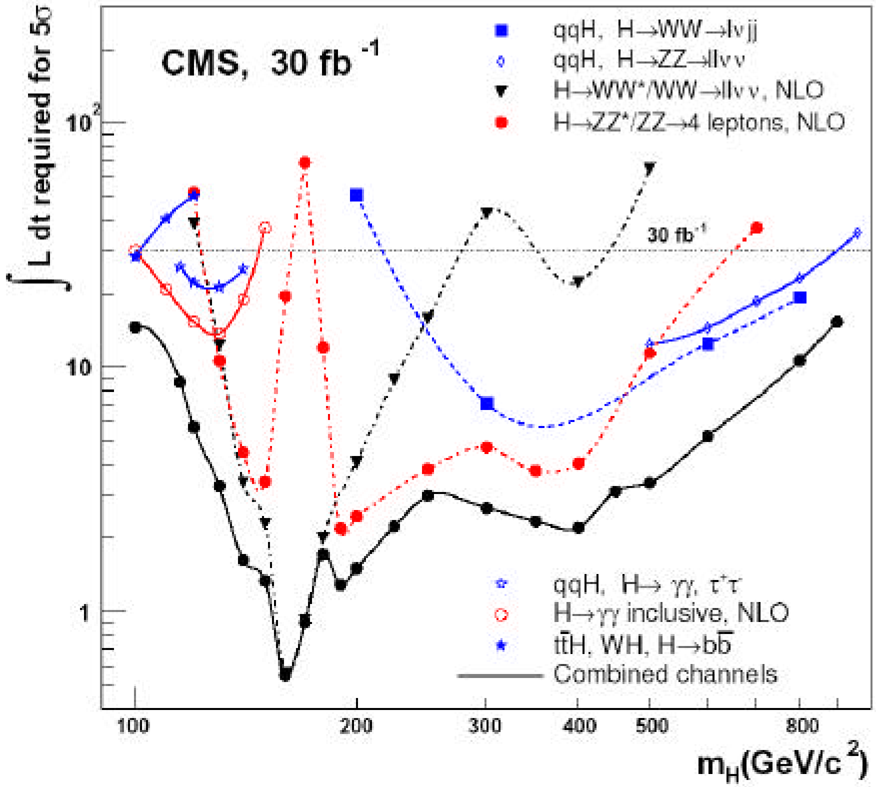
SM(-like) Higgs



Future searches: LHC(3)

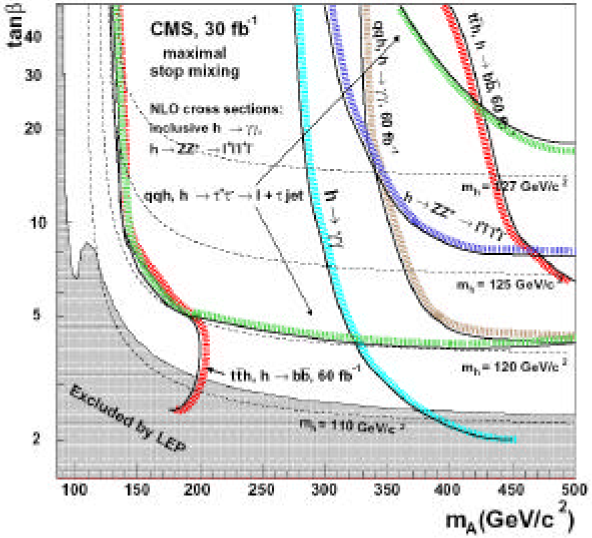
- Up to highest masses, with < 30 fb-1
  - Using H→WW,ZZ

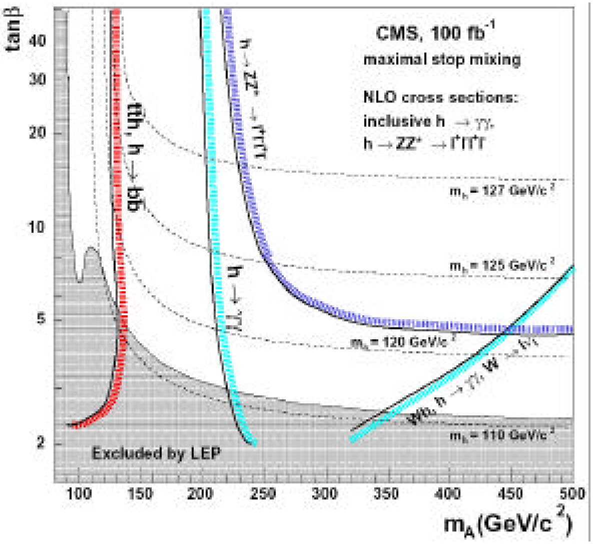
SM(-like) Higgs



Future searches: LHC(4)

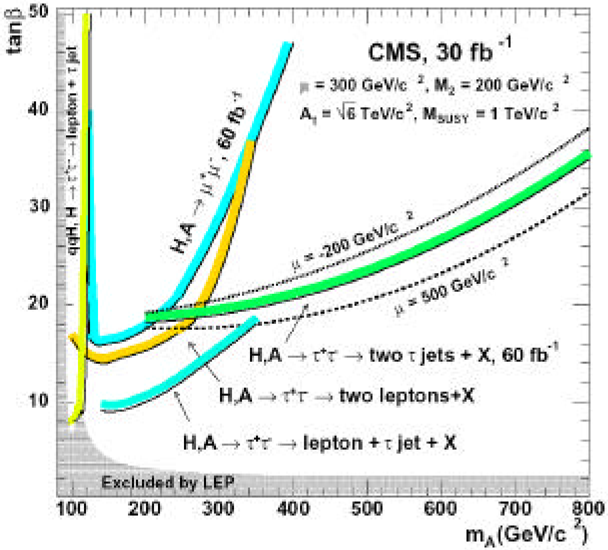
- $h^0 \rightarrow \gamma\gamma$ only for $m_A > 200$ GeV
  - Importance of tth, $h \rightarrow bb$ and qqh, $h \rightarrow \tau\tau$
- Still $m_A < 130$ GeV not covered ($m_h < 120$ GeV, not SM-like)
  - Hope to cover with $gg \rightarrow bbh$, $h \rightarrow \mu\mu, \tau\tau$ (or sparticle decays)
- Caveat:
  - $gg \rightarrow h^0$ from loops with t or b
  - In SUSY also stop+sbottom Stop-top negative interference
  - May preclude discovery by $h^0 \rightarrow \gamma\gamma$ if $m(\tilde{t}_1) < 200 GeV$

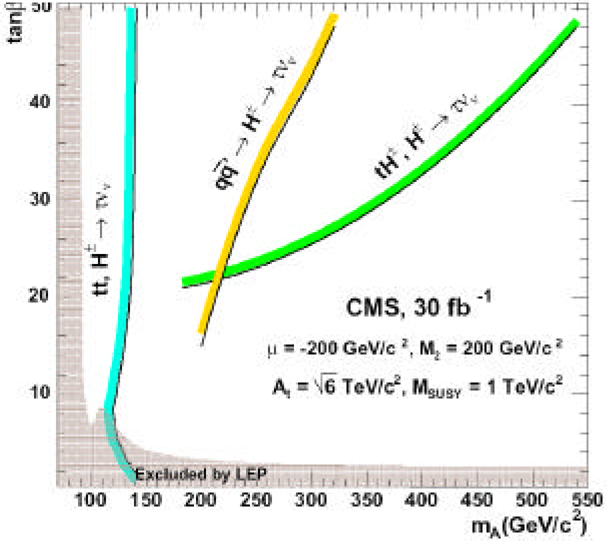




Future searches: LHC(5)

- Heavy neutral Higgses
  - Based on H,A→ττ, μμ
  - No sensitivity for large m_A and low/intermediate tanβ
- Charged Higgs
  - Based on H±→τν, tb
  - No sensitivity for large m_A and low/intermediate tanβ
- Overall conclusion for LHC
  - Should discover Higgs, but
  - Still holes for $m(h^0)<120$ GeV
  - May miss H^0/A^0 if large m_A and low tanβ



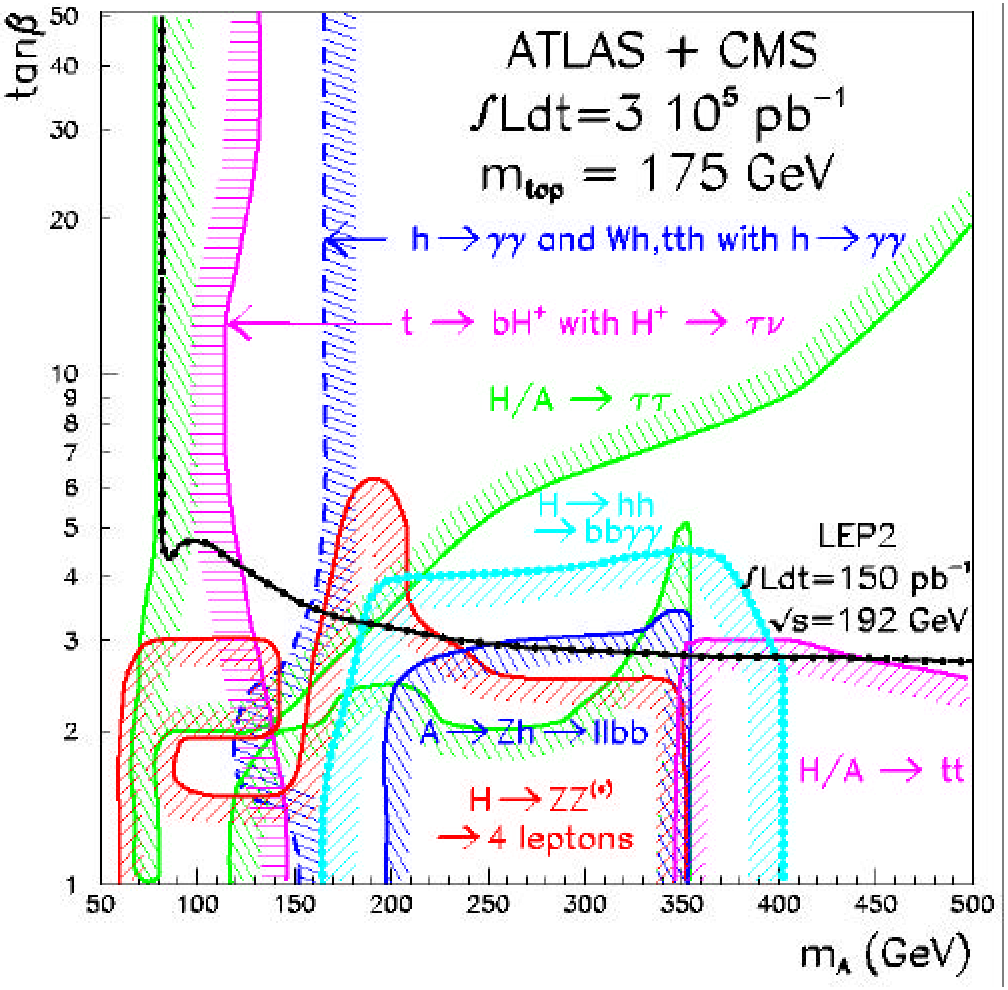


Future searches: LHC(6)

- Higgs from sparticle decays
  - → see later

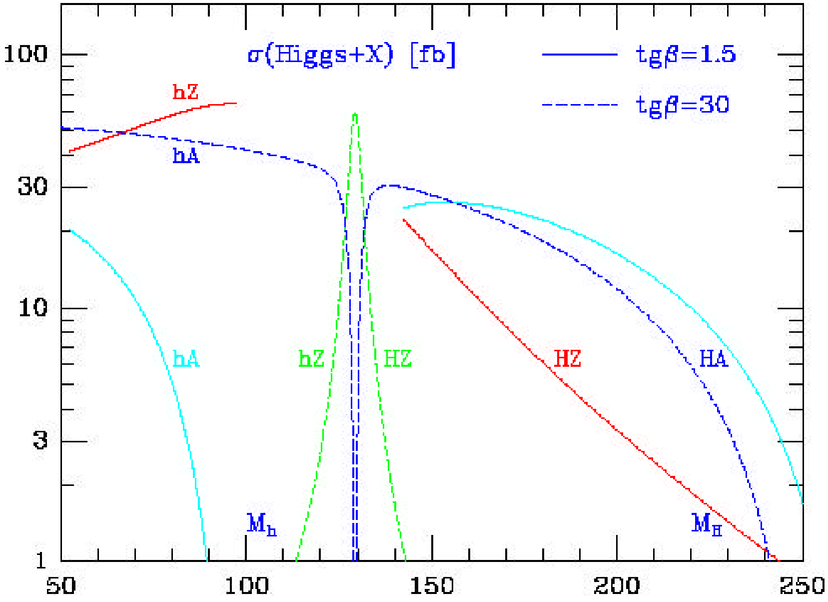
Future searches: LHC

Old figure:



Future searches: LC

- Cross-section
  - Familiar from LEP200
  - Increase of fusion

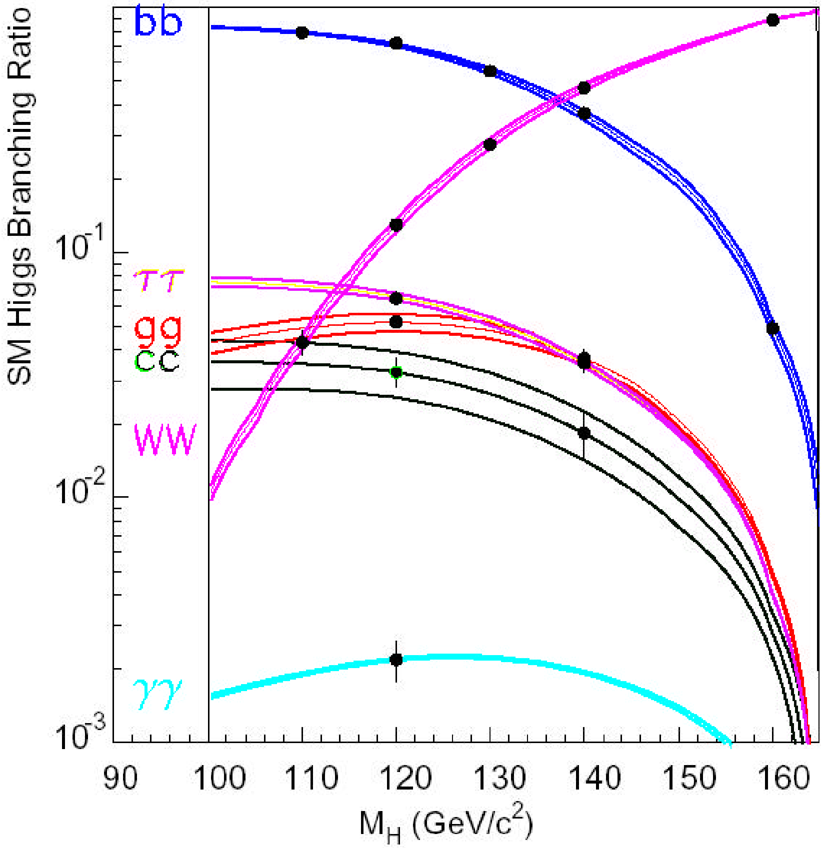


CERN

Future searches: LC

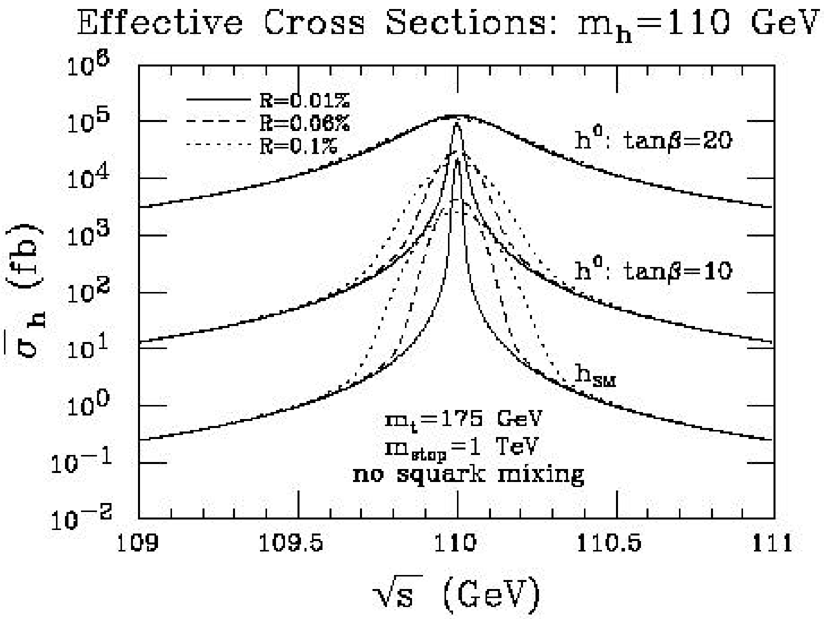
- Light Higgs likely discovered before LC start
  - LC for precision measurements
- 500 GeV LC measurements:
  - mass to 0.05%
  - determine spin/parity
- Branching ratio measurement
  - for 500 fb^{-1} (~2 years)
- May need multi-TeV machine for heavy Higgses

Battaglia et al., hep-ex/0201018



Future searches: MuCOL

- MuCOL may produce Higgs in s-channel
- Expects ~1 fb^{-1} per year
- can have very small beam energy spread
  - Ideal for line shape measurement
- could measure
  - Mass to ±0.1 MeV (at 110 GeV)
  - Width to ±0.5 MeV
  - Cross-section to ±5%



Sparticle decays

- Contents
  - Chargino/neutralino
  - Sleptons
  - Squarks and gluinos

Chargino/neutralino decays

Chargino		Neutralino	
$c_i^{\pm} \text{ ® } \tilde{n} + \boldsymbol{l}, \tilde{\boldsymbol{l}} + n$	$(l\, j\, y)$	$c_i^{0} \text{ ® } \tilde{\boldsymbol{l}} + \boldsymbol{l}, \tilde{n} + n$	$(l\, j\, y)$
$c_i^{\pm} \text{ ® } c_j^{0} + \boldsymbol{W}^{\pm}$	$(\boldsymbol{A}\, l\, l), (\boldsymbol{A}\, y\, y)$	$c_i^{0} \text{ ® } c_j^{0} + \boldsymbol{Z}^{0}$	$(\boldsymbol{A}\, y\, y)$
$c_2^{\pm} \text{ ® } c_1^{\pm} + \boldsymbol{Z}^{0}$	$(\boldsymbol{A}\, l\, l), (\boldsymbol{A}\, y\, y)$	$c_i^{0} \text{ ® } c_1^{\pm} + \boldsymbol{W}^{\mp}$	$(\boldsymbol{A}\, l\, l), (\boldsymbol{A}\, y\, y)$
$c_i^{\pm} \text{ ® } c_j^{0} + \boldsymbol{H}^{\pm}$	$(l\, j\, y)$	$c_i^{0} \text{ ® } c_j^{0} + \boldsymbol{H}^{0}$	$(l\, j\, y)$
$c_2^{\pm} \text{ ® } c_1^{\pm} + \boldsymbol{H}^{0}$	$(l\, j\, y)$	$c_i^{0} \text{ ® } c_1^{\pm} + \boldsymbol{H}^{\mp}$	$(l\, j\, y)$
		$c_2^{0} \text{ ® } c_1^{0} + g$	Loop decay

Are couplings with gauge strength

Dominant one depends on spectrum and $\chi^{\pm}/\chi^{0}$ composition

Slepton decays

- Slepton decay: $\tilde{l}^\pm \to \chi_i^0 + l^\pm, \chi_i^\pm + \nu \quad (\lambda\ \varphi\ \psi)$
  - slepton$_L$ prefers a Wino ($\chi^\pm_1$ or χ^0_2 in MSUGRA → cascade)
  - slepton$_R$ only decays to a Bino (χ^0_1 in MSUGRA)
- Stau decays may be more complicated:
  - At large tanβ, Yukawa couplings contribute
    ➔ can decay to higgsino
  - e.g. $\tilde{\tau}_R \to \tilde{h}^0 + \tau^\pm, \tilde{h}^\pm + \nu_\tau$
  - But only $\tilde{\tau}_L \to \tilde{h}^0 + \tau^\pm$ is possible
    and $\tilde{\tau}_L \to \tilde{h}^\pm + \nu_\tau$ is forbidden, as higgsino requires helicity flip

Squark/gluino decays

- Squark strong decay: $\tilde{q} \circledR \tilde{g} + q$ for $m(\tilde{q}) > m(\tilde{g})$
  - Preferred if kinematically allowed
- Electroweak decay: $\tilde{q} \circledR \mathrm{c}_i^0 + q, \mathrm{c}_i^\pm + q'$ $(\mathrm{l\ j\ y})$
  - squark$_L$ prefers a Wino ($\chi^\pm_1$ or χ^0_2 in MSUGRA → cascade)
  - squark$_R$ only decays to a Bino (χ^0_1 in MSUGRA)
- Stop EW decay:
  - For light stop (m < m($\chi^\pm_1$)) above decays forbidden
    - ➔ Loop decay $\tilde{t}_1 \circledR \mathrm{c}_1^0 + c$ may dominate
- Gluino decay: $\tilde{g} \circledR \tilde{q} + \bar{q}$ for $m(\tilde{q}) < m(\tilde{g})$
- If lighter than squarks:

$$\tilde{g} \circledR \mathrm{c}^\pm + q + \bar{q}', \mathrm{c}^0 + q + \bar{q}, \mathrm{c}^0 + g$$

- Caveat: only main decay modes
  - Others in special regions of parameter space, e.g. $\tilde{b} \rightarrow \tilde{t}_1 + W$
  - For stop/sbottom Yukawa couplings may be relevant

Existing Limits, stable χ^0_1

- Contents
  - From Tevatron and LEP direct searches
  - LEP limits on LSP mass
  - Constraints on MSUGRA parameter space
  - Including CDM constraints
- (Limits also exist for):
  - GMSB, AMSB scenarios
  - R-p violating couplings

(See http://lepsusy.web.cern.ch/lepsusy/Welcome.html)

Slepton limits from LEP

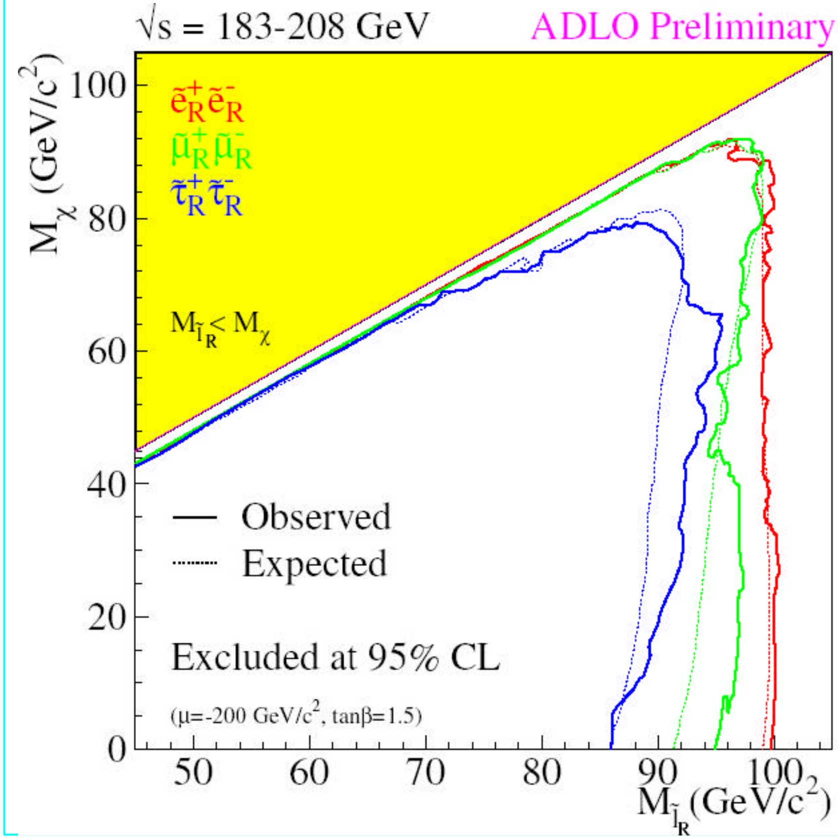
- Sneutrino, LEP1
  - Expect: $\tilde{n} \circledR n c_1^0$
    - ➔ “invisible” in Z^0 decays
  - LEP1 limit: $\Delta\Gamma_{inv} < 2$ MeV
  - Sneutrino width:

$$\frac{\Gamma(Z^0 \circledR \tilde{n}\tilde{n})}{\Gamma(Z^0 \circledR nn)} = \frac{1}{2}\left(1 - \frac{4m_{\tilde{n}}^2}{m_Z^2}\right)^{3/2}$$

  - Limit on sneutrino mass (assuming 1 family):

$$m(\tilde{n}) > 43.7 GeV$$

- Charged sleptons, LEP2
  - Based on $\tilde{l}^{\pm} \to c_1^0 + l^{\pm}$

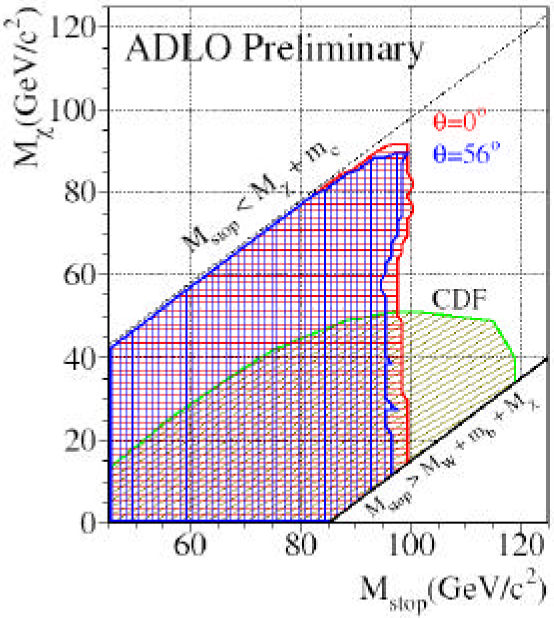


Squark/gluino limits

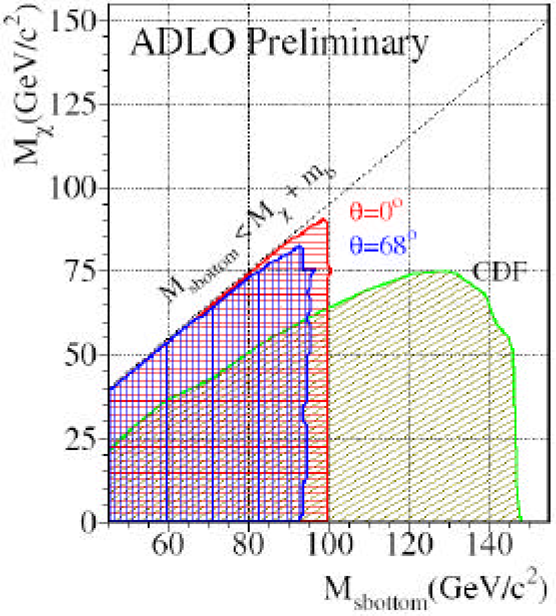
CERN

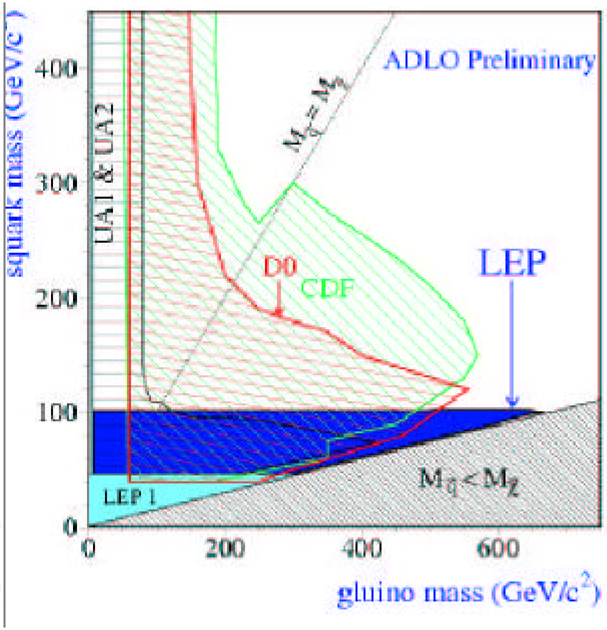
- Limits from LEP and Tevatron, examples:

$\tilde{t} \rightarrow c\chi_1^0$



$\tilde{b} \rightarrow b\chi_1^0$

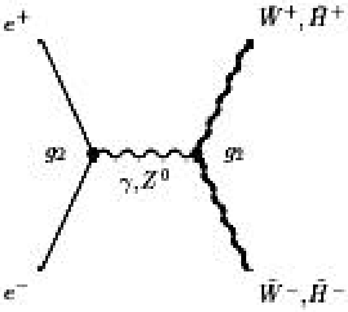


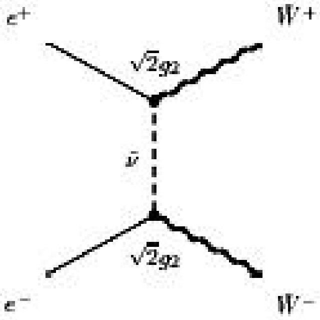


Complementarity between LEP and Tevatron

Chargino/neutralino production

- Charginos:





– σ typically ~ pb

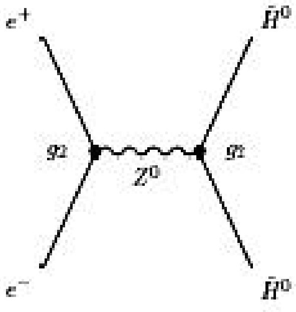
negative interference s- and t-channel

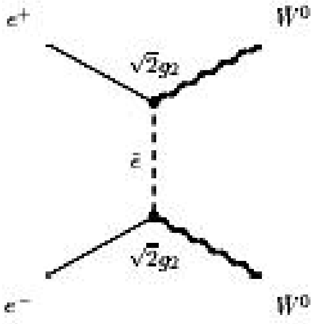
For gaugino-like charginos

σ negligible for small sneutrino mass

➔ loss of sensitivity

- Neutralinos:





– σ typically ~ pb

t-channel only gaugino-like

increases for light selectron

➔some compensation for x-sect loss

in gaugino-like charginos

Chargino/neutralino topologies

- Chargino main decay mode for LEP: $c_1^{\pm} \rightarrow W^{\pm *} c_1^{0}$

$W \rightarrow ln$
$W \rightarrow ln$

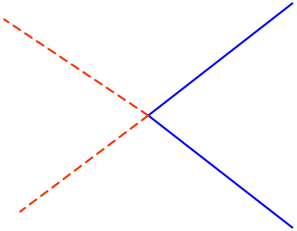
B.R.=1/9

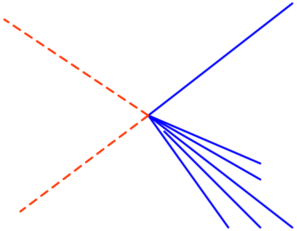
$W \rightarrow ln$
$W \rightarrow q\bar{q}$

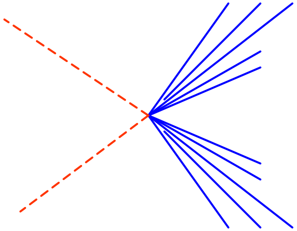
B.R.=4/9

$W \rightarrow q\bar{q}$
$W \rightarrow q\bar{q}$

B.R.=4/9





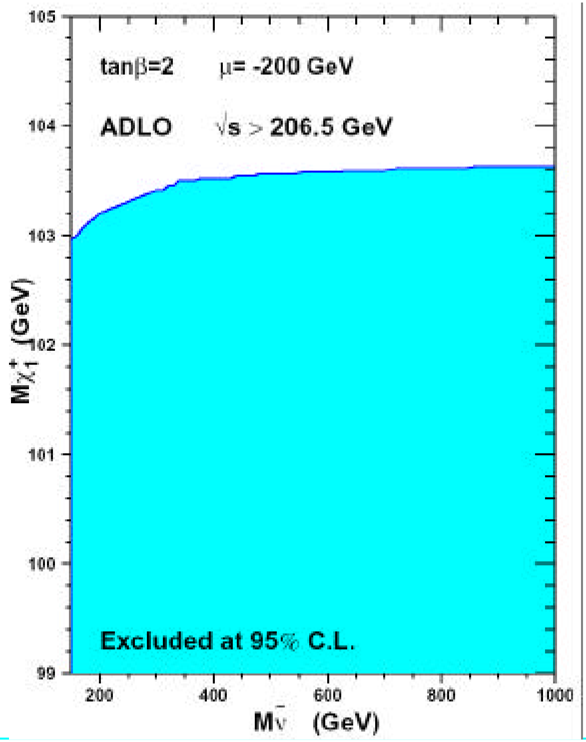


small background

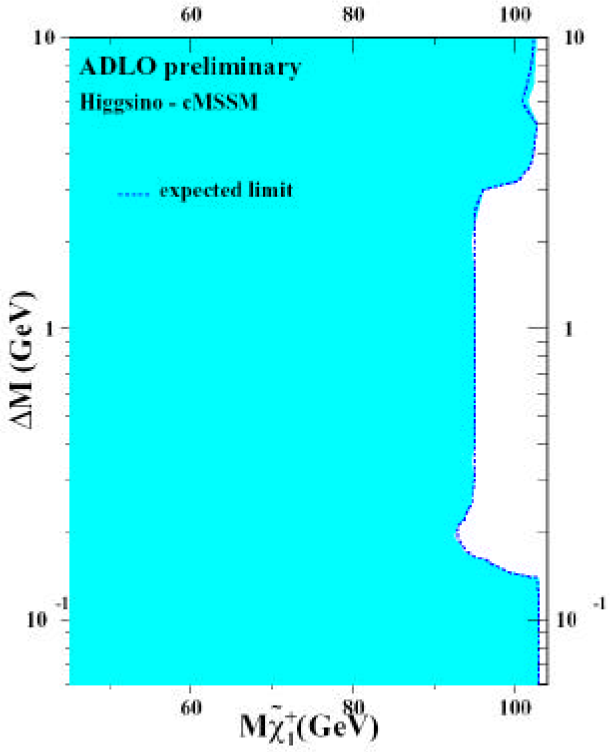
  - Use acoplanarity
- Neutralino: mainly $e^{+}e^{-} \rightarrow c_2^{0} c_1^{0},\ c_2^{0} \rightarrow Z^{0*} c_1^{0}$
  - ➔ acoplanar $l^{+}l^{-}$ or 2-jets
  - Other production modes also considered ($\chi^0_2\ \chi^0_2$, $\chi^0_2\ \chi^0_3$, …)

Chargino limits

- Charginos: large m_0
  - Gaugino-like
  - Depends on sneutrino mass



- Small $\Delta M = M(\chi_1^{\pm}) - M(\chi_1^0)$
  - Higgsino-like
  - Stable, IP, 2nd Vx, ISR
  - Is also a limit on LSP!



Direct search limits

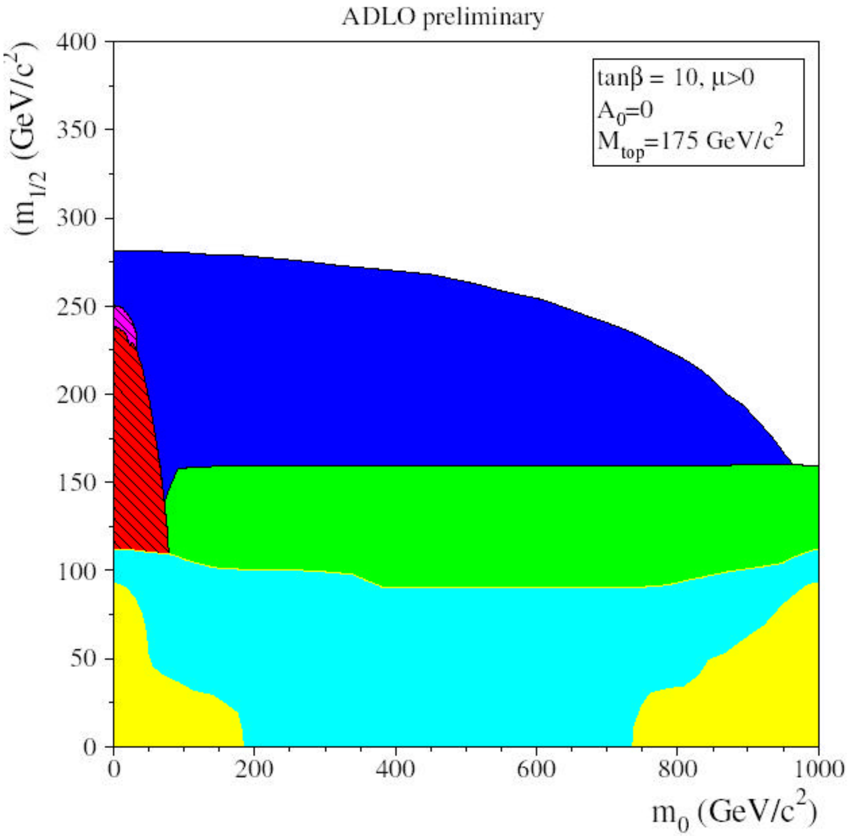
Channel	M > (GeV)	ΔM	
$\tilde{\mathrm{n}}$	43.7	EW measts	ADLO
$\tilde{e}$ ® $e\mathrm{c}_1^0$	99	10 GeV	ADLO
$\tilde{\mathrm{m}}$ ® $\mathrm{m}\mathrm{c}_1^0$	95	10 GeV	ADLO
$\tilde{\mathrm{t}}$ ® $\mathrm{t}\,\mathrm{c}_1^0$	85	10 GeV	ADLO
$\tilde{t}$ ® $c\mathrm{c}_1^0$	95	20 GeV	ADLO
$\tilde{t}$ ® $bl\tilde{\mathrm{n}}$	96	20 GeV	ALO
$\tilde{b}$ ® $b\mathrm{c}_1^0$	94	20 GeV	ADLO
$\tilde{g}$ ® $j + E_T^m$	195	-	CDF
$\mathrm{c}_1^{\pm}$ ® $W\mathrm{c}_1^0$	103.5	Large m_0	ADLO
$\mathrm{c}_1^{\pm}$ ® $W\mathrm{c}_1^0$	92.4	Small ΔM	ADLO

Indirect limits on LSP(1)

- No full coverage from neutralinos only
  - ➔ no direct limits on χ_1^0 mass
- Requires to combine results from:
  - Chargino searches: weak if gaugino and low $\boldsymbol{m}(\tilde{n})$
  - Neutralino searches: weak if not higgsino, but improves if gaugino for low $\boldsymbol{m}(\tilde{\boldsymbol{e}})$
  - Slepton searches
    -LEP2 limit on $\boldsymbol{m}(\tilde{\boldsymbol{e}})$ using sum rule: $\boldsymbol{m}^2_{\tilde{n}_L} = \boldsymbol{m}^2_{\tilde{\boldsymbol{e}}_L} + \boldsymbol{M}^2_W \cos 2b$
    -LEP1 limit on $\boldsymbol{m}(\tilde{n})\ ^3\ 43\boldsymbol{GeV}$
  - Scalar mass universality: $\boldsymbol{m}^2_{\tilde{\boldsymbol{e}}} = \boldsymbol{m}^2_0 + .81\boldsymbol{M}^2_2 - .27\boldsymbol{M}^2_Z \cos 2b$
    ➔ Allows exclusion of low regions of M_2 for fixed m_0
  - Higgs searches: excludes low tanβ

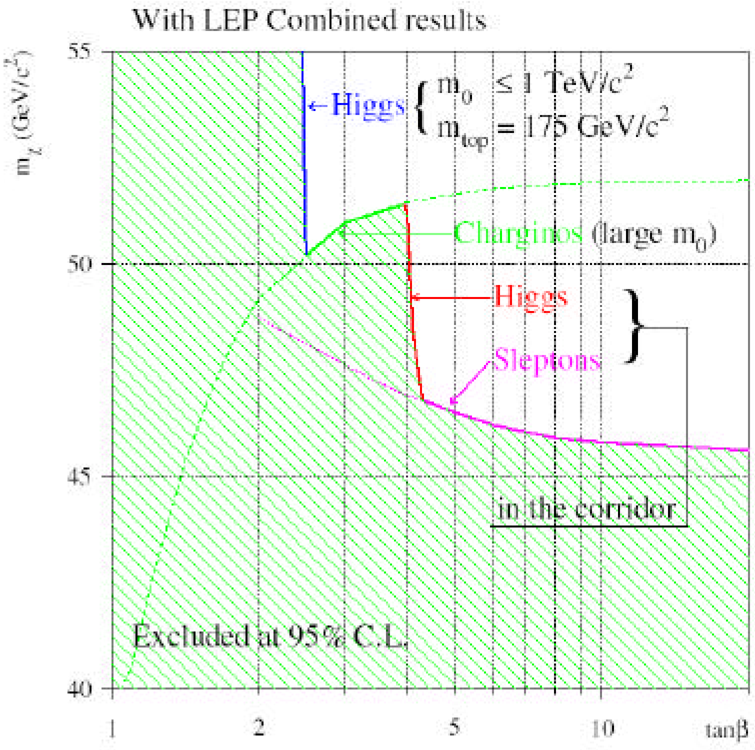
Indirect limits on LSP(2)

- Example of interplay of these constraints (MSUGRA):
  - Yellow: no REWSB
  - Light blue: inconsistent with LEP1 measurements
  - Green: excluded by chargino
  - Red: excluded by slepton
  - Blue: excluded by hZ
- Regions depend on tanβ

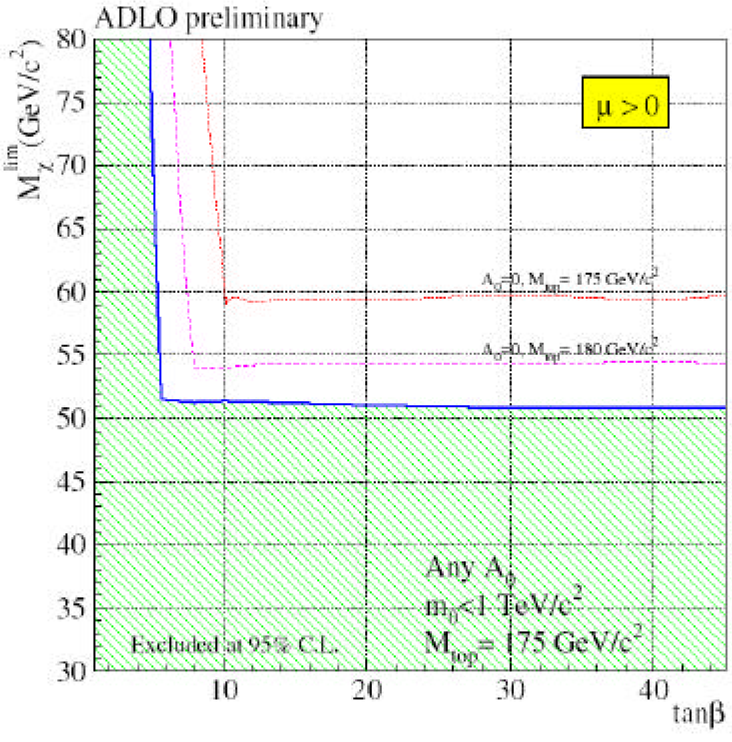


Indirect limits on LSP(3)

- In MSSM



- In MSUGRA



$M(\chi^0_1 = LSP) > 45\text{-}50$ GeV

Constrained MSUGRA

- **GUT universality of gaugino+scalar masses + REWSB**

m_0 , $m_{1/2}$, A_0 , $\tan\beta$, sgn(μ)

$m(\tilde{t}_1) < m(\chi_1^0)$

$m(h^0) > 114 GeV$

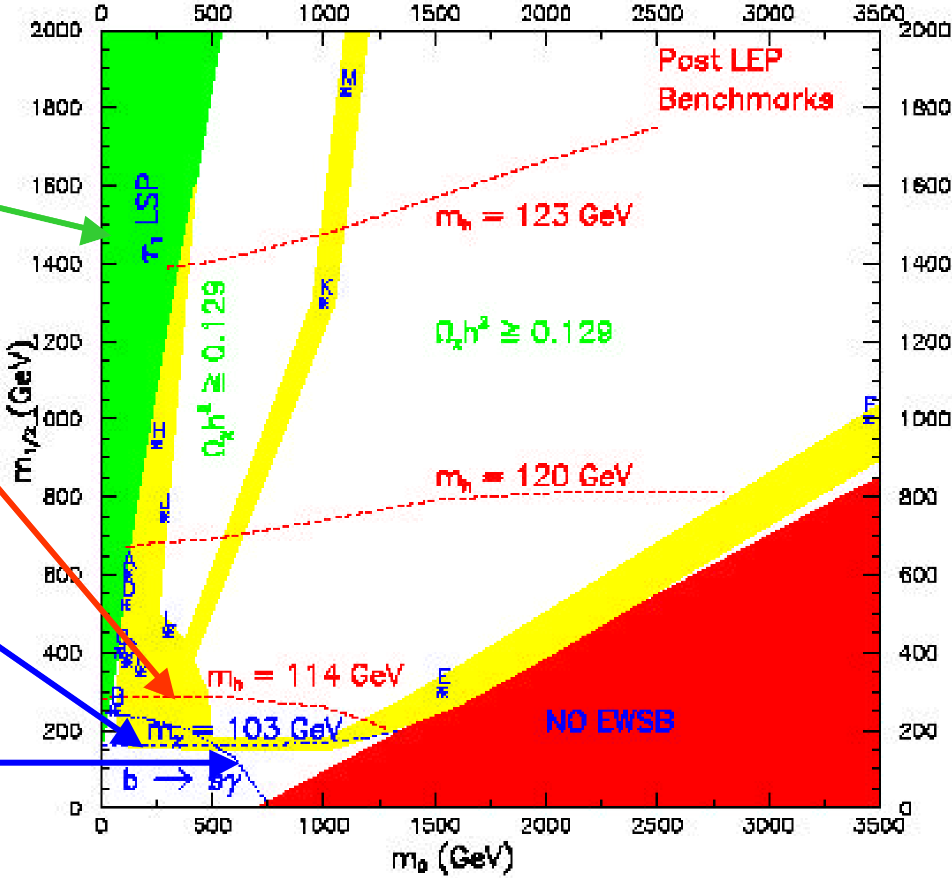
Weakens at large tanβ

$m(\chi_1^\pm) > 103 GeV$

Depends weakly on tanβ

$b \rightarrow s + \gamma$

Stronger at large tanβ

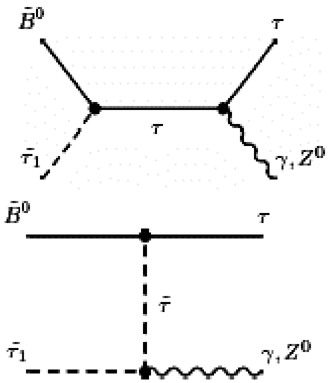


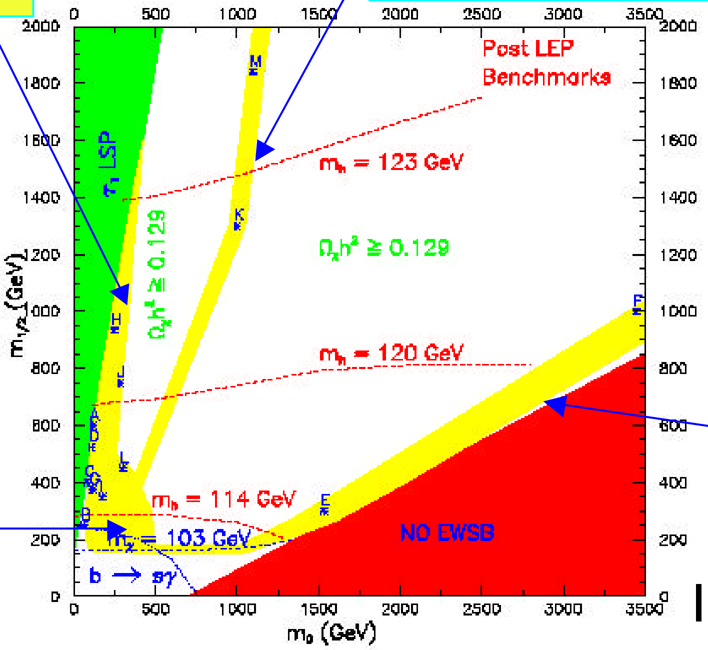
Constrained MSUGRA

- **CDM constraints after WMAP :** $0.094 \le \Omega h^2 \le 0.129$

coannihilation

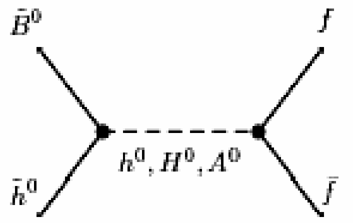
$m(\tilde{\tau}_1) \cong m(c_1^0)$





Rapid annihilation funnels

For large tanβ



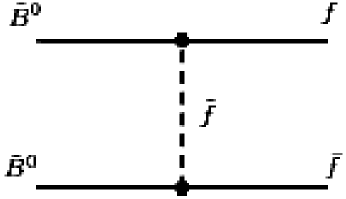
Focus point

Large m0, small m1/2

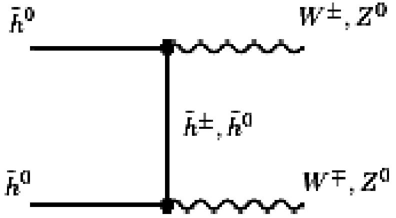
Intermediate/large tanβ

annihilation

$LSP = \tilde{B}^0$



χ^0_1 mixed



CMSUGRA allowed regions

- **More quantitavely:**

-**red**: stau LSP

-**green**: excluded by $b \to sg$

-**cyan**: CDM constraint:

$$0.1 \le \Omega h^2 \le 0.3$$

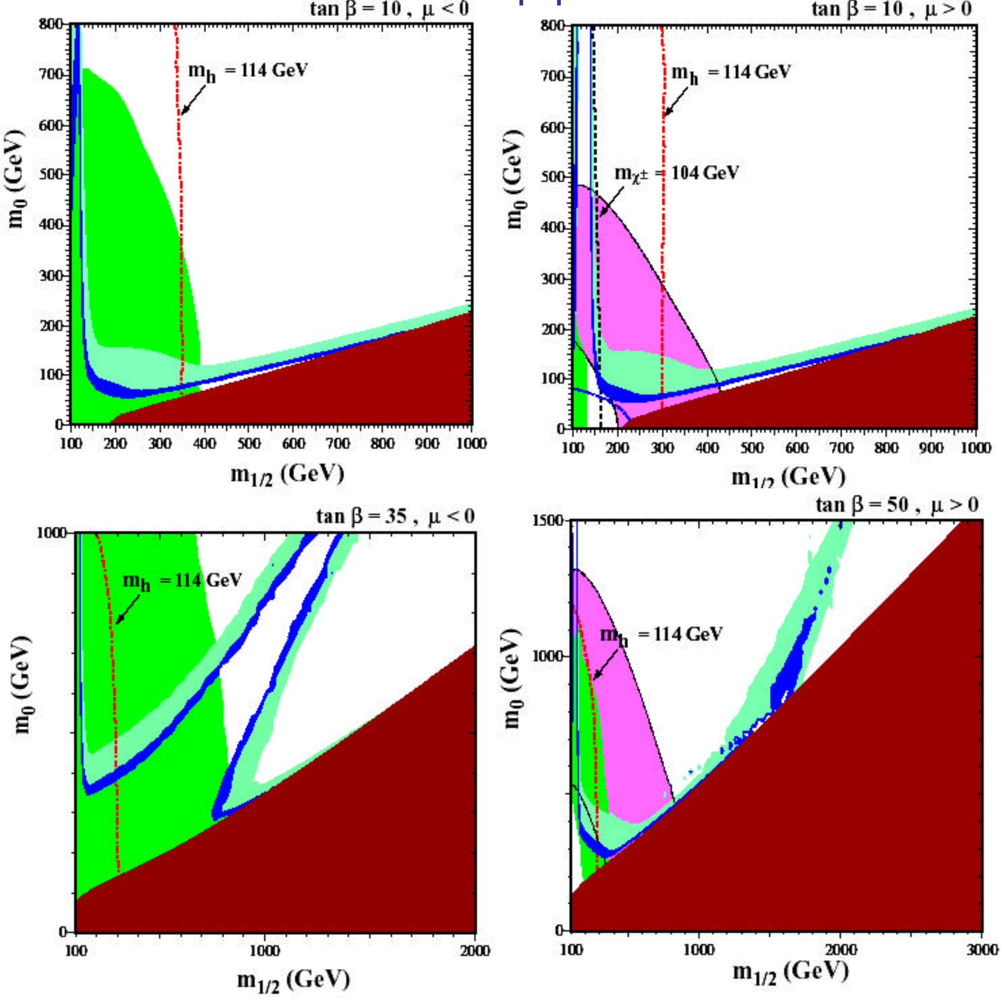
-**blue**: CDM constraint:

$$0.094 \le \Omega h^2 \le 0.129$$

-**pink**: region preferred by

(g_μ-2) of Davier02

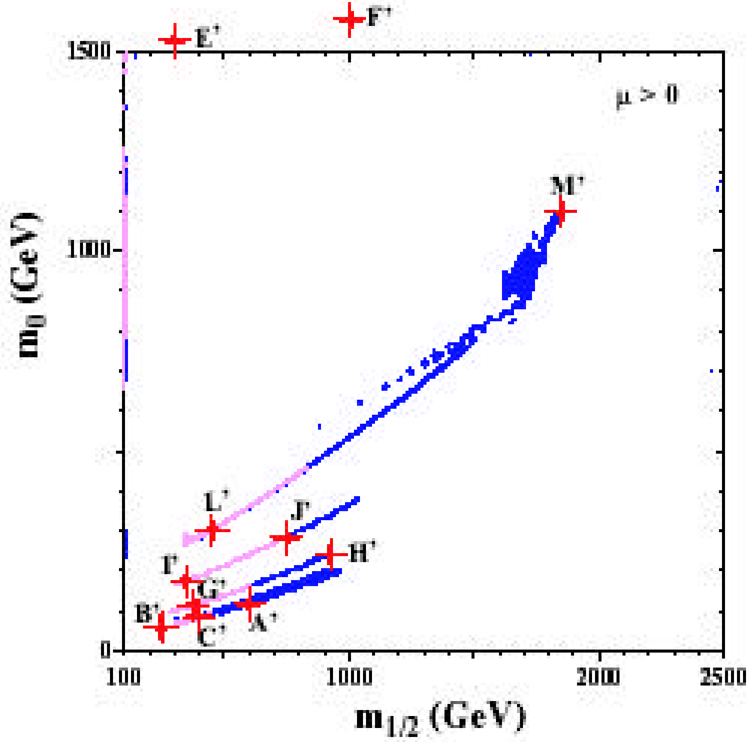
J.Ellis et al.,hep-ph/0303043



CMSUGRA allowed “lines”

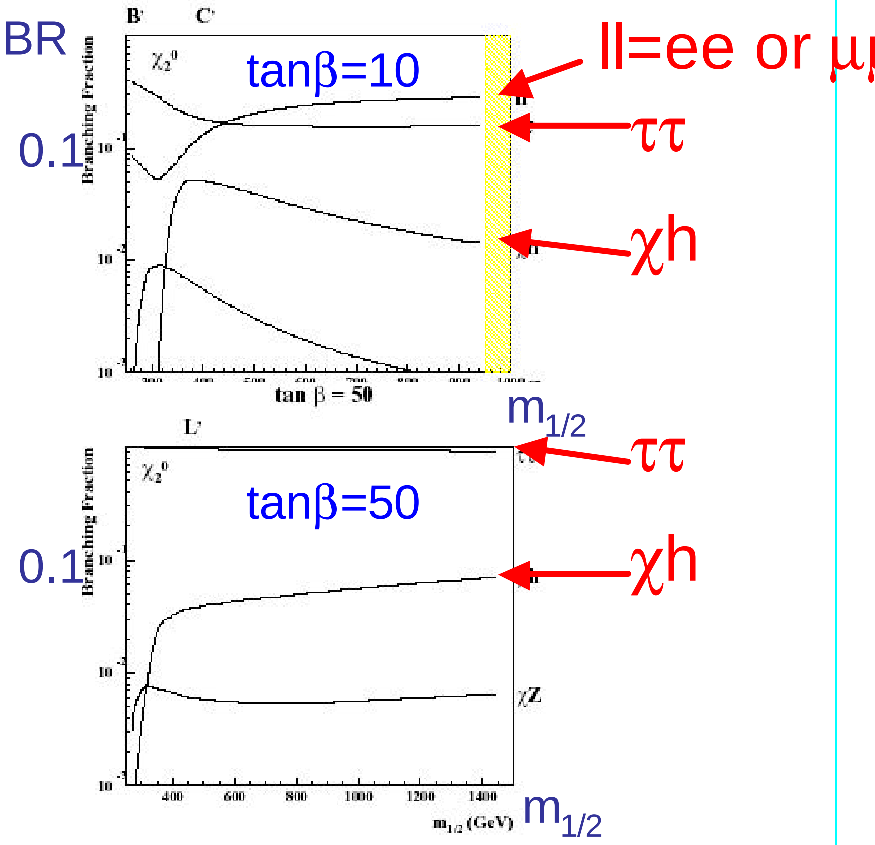
- With WMAP: narrow tanβ dependent lines

J.Ellis et al.,hep-ph/0303043



- Main χ_2^0 decays:dileptons

Battaglia et al.,hep-ph/0306219



Importance of ττ decays (at large tanβ)

Zuoz Summer school
16-20/08/04

Luc Pape, CERN

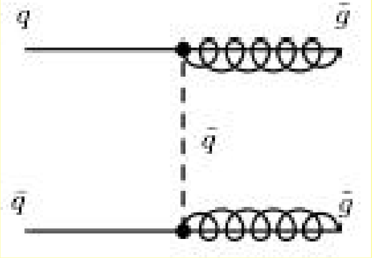
Sparticle production at LHC

- Contents
  - Squark and gluino production
  - Stop production
  - Slepton production
  - Direct chargino/neutralino production

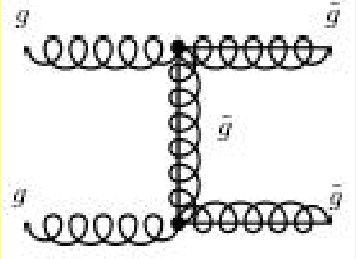
Squark and gluino production

- Contributing LO processes:

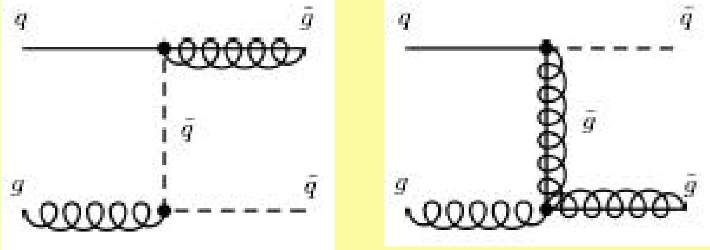
$q\bar{q}$ ® $\tilde{g}\tilde{g}$



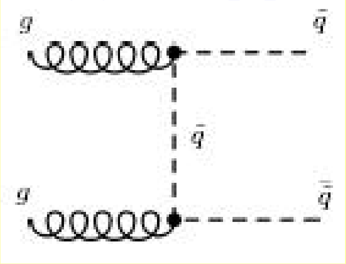
gg ® $\tilde{g}\tilde{g}$



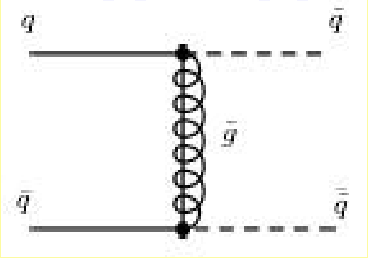
qg ® $\tilde{q}\tilde{g}$



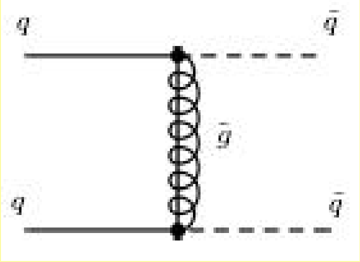
gg ® $\tilde{q}\bar{\tilde{q}}$



$q\bar{q}$ ® $\tilde{q}\bar{\tilde{q}}$



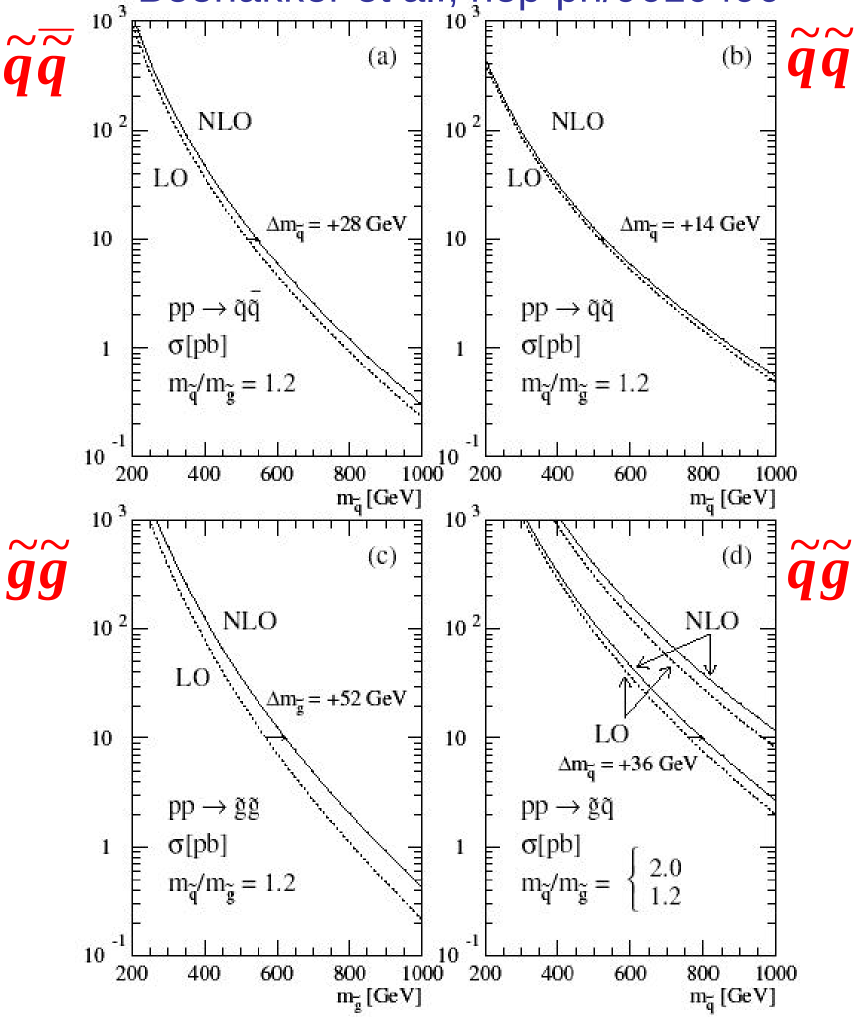
qq ® $\tilde{q}\tilde{q}$



Squark/gluino cross sections

- NLO cross sections at LHC
  - NLO calculation is important: σ_{NLO} ~(1.1-1.9) σ_{LO}
  - Remaining scale dependence ~15% (uncertainty)
  - At 1 TeV, summed σ > 1 pb
  - 1 fb at ~2.5 TeV

Beenakker et al., hep-ph/9610490



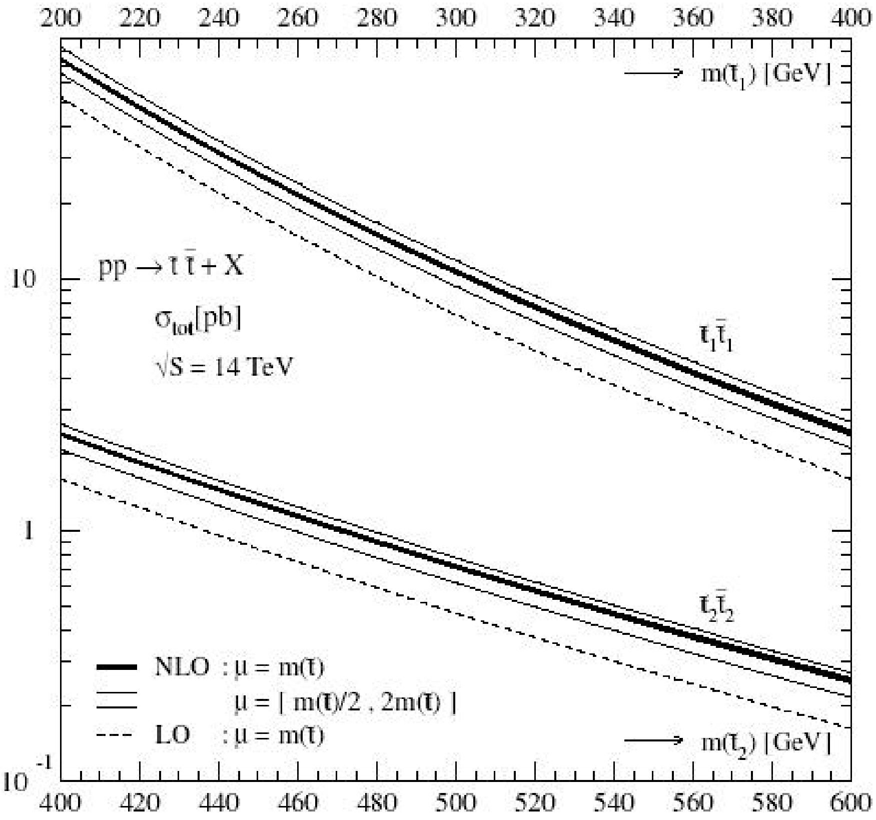
Stop cross section

- NLO cross section at LHC
  - SUSY-QCD corrections

    $\sigma_{NLO} \sim 1.4.\ \sigma_{LO}$
  - remaining scale dependence

    ~10-15% (uncertainty)
  - Only diagonal production is relevant,
  - At 1 TeV, summed $\sigma \sim 20$ fb

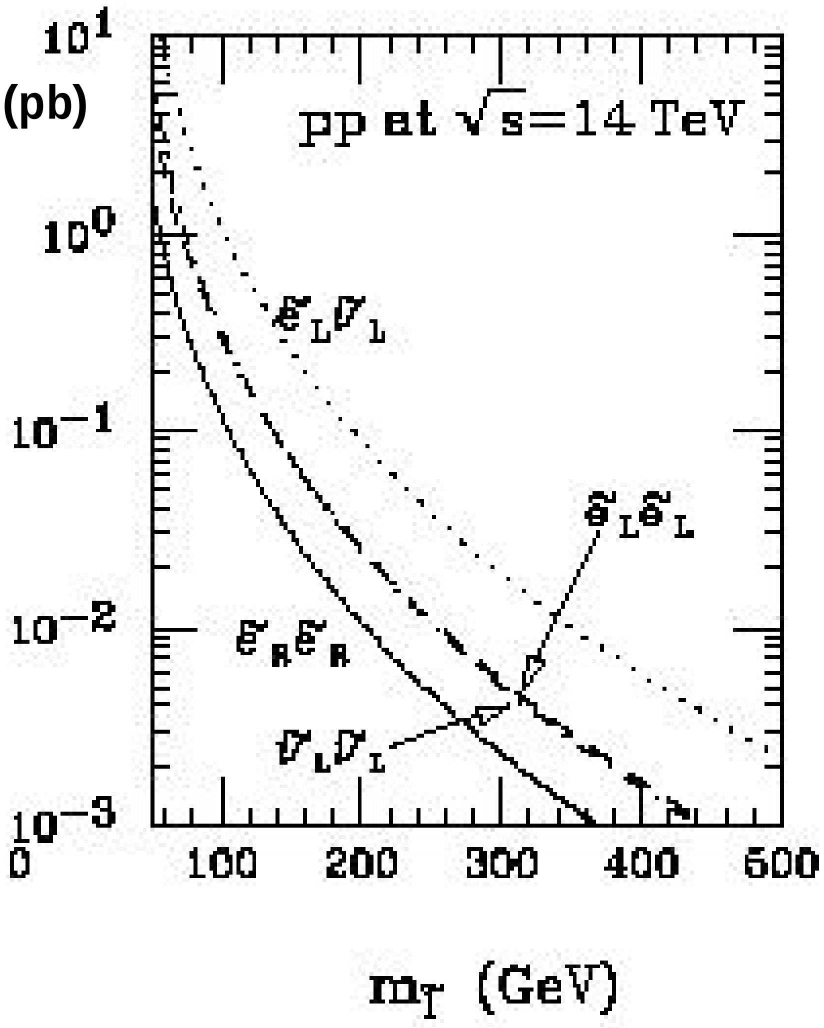
Beenakker et al., hep-ph/9906298



Slepton pair production

- Slepton pair production at NLO
  - Drell-Yan process mediated by Z* or W*
  - With QCD corrections at LHC σ_{NLO} ~(1.25-1.35) σ_{LO}
  - Cross section is small <1 fb at ~500 GeV

Baer et al., hep-ph/9712315

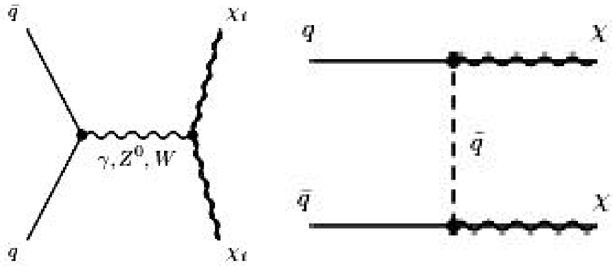


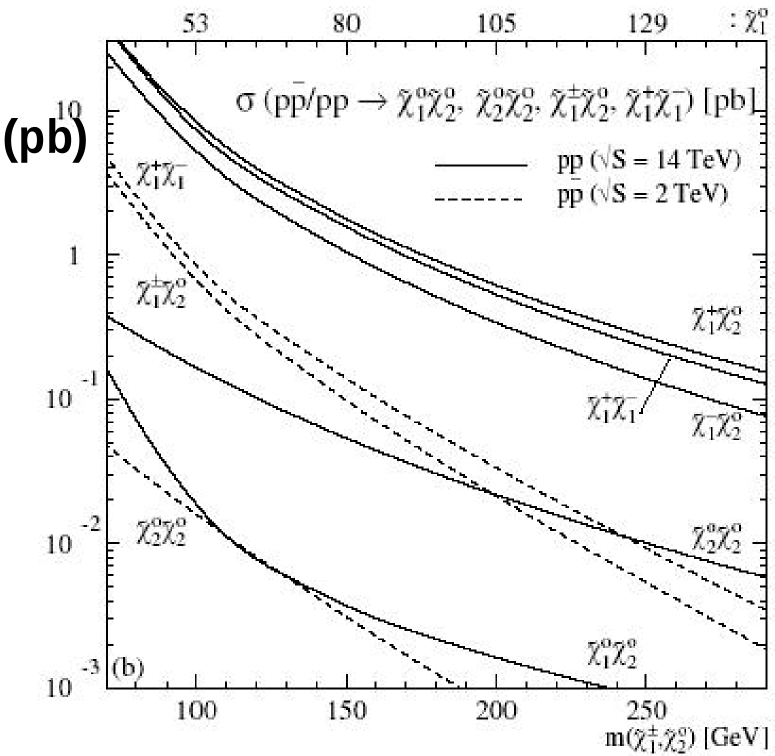
Chargino/neutralino production

- Chargino/neutralino direct production
  - With QCD corrections at NLO

    σ_{NLO} ~(1.1-1.4) σ_{LO}
  - Interesting: $c_2^0 c_1^\pm$

    with c_2^0 ® $c_1^0 l^+ l^-$ $c_1^\pm$ ® $c_1^0 l^\pm n$
  - ➔ trilepton final state





Beenakker et al., hep-ph/9906298

Future Searches

- Contents
  - At LHC (discovery reach + mass reconstruction)
  - At e+e- Linear Colliders (precision measurements)
  - Extrapolation to the GUT scale

Sparticle production at LHC

- Region 1 $m(\tilde{g}) > m(\tilde{q})$

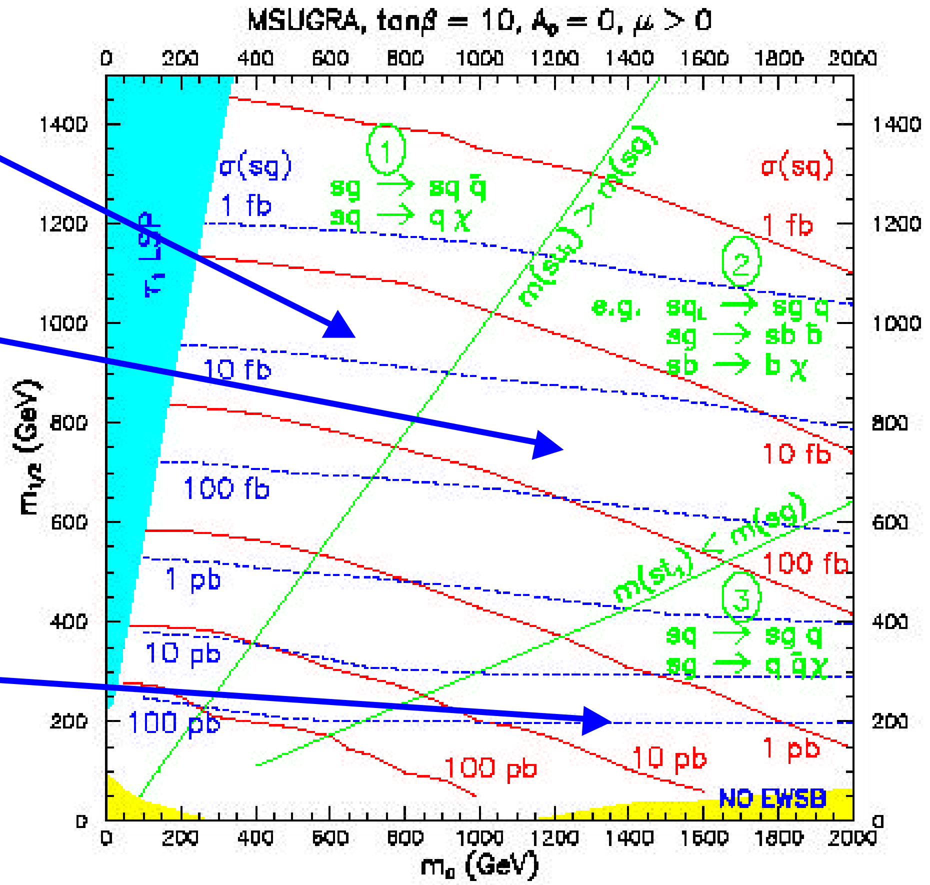
  $\tilde{g} \to \tilde{q}\bar{q}, \tilde{q} \to qc$

- Region 2, e.g.

  $\tilde{q}_L \to \tilde{g}q, \tilde{g} \to \tilde{b}\bar{b}, \tilde{b} \to bc$

- Region 3 $m(\tilde{q}) > m(\tilde{g})$

  $\tilde{q} \to \tilde{g}\bar{q}, \tilde{g} \to q\bar{q}c$

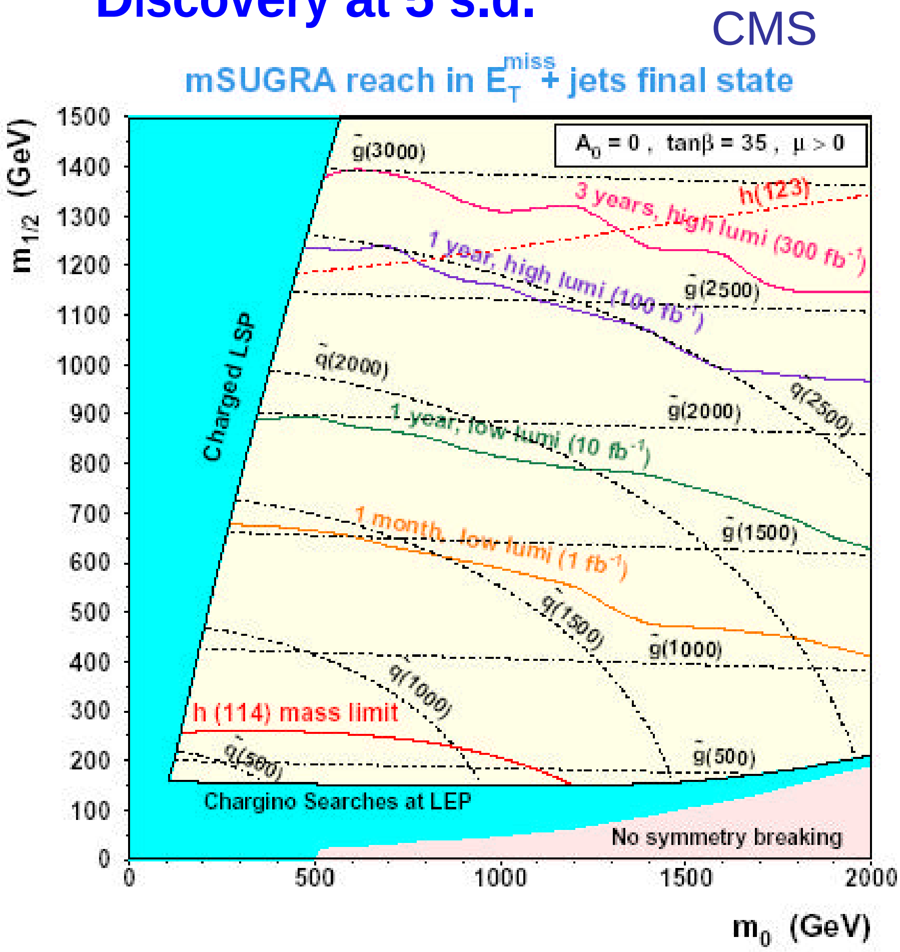


LHC inclusive reach (1)

- **Using E_T^{miss} + jets signature:**
- **s ~1 pb at 1 TeV**
- **After 1 year: ~10 fb^{-1}/year**
  at "low luminosity"
  ➔ already significant reach
- **"High lumi" ~100 fb^{-1}/year**
- **With 300 fb^{-1},**

squarks and gluinos up to ~ 2.5 TeV

Discovery at 5 s.d.



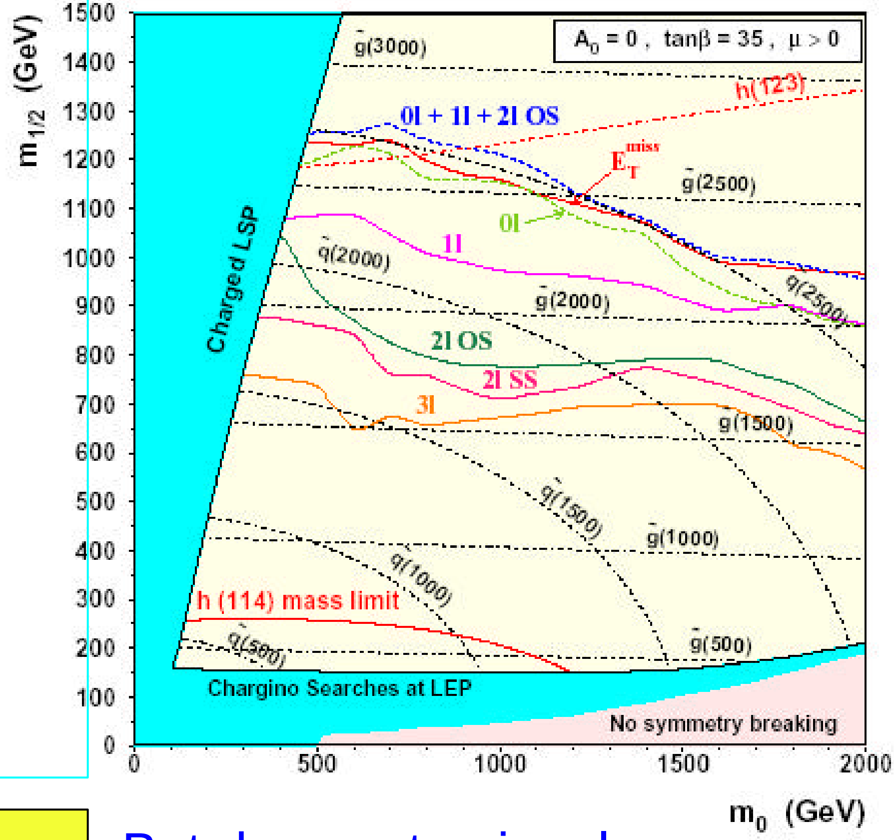
LHC inclusive reach (2)

- **Using E_T^{miss} + leptons signature:**
- **In large area,**

Several topologies are simultaneously observable

CMS

mSUGRA reach in various final states for 100 fb^{-1}



E_T^{miss} likely to be a first hint

But does not uniquely identify SUSY

Decay signatures in $(m_0,m_{1/2})$

- To prove SUSY: (MSUGRA)

  Need more specific signatures

  $\tilde{q}_R \rightarrow q c_1^0$ 100%

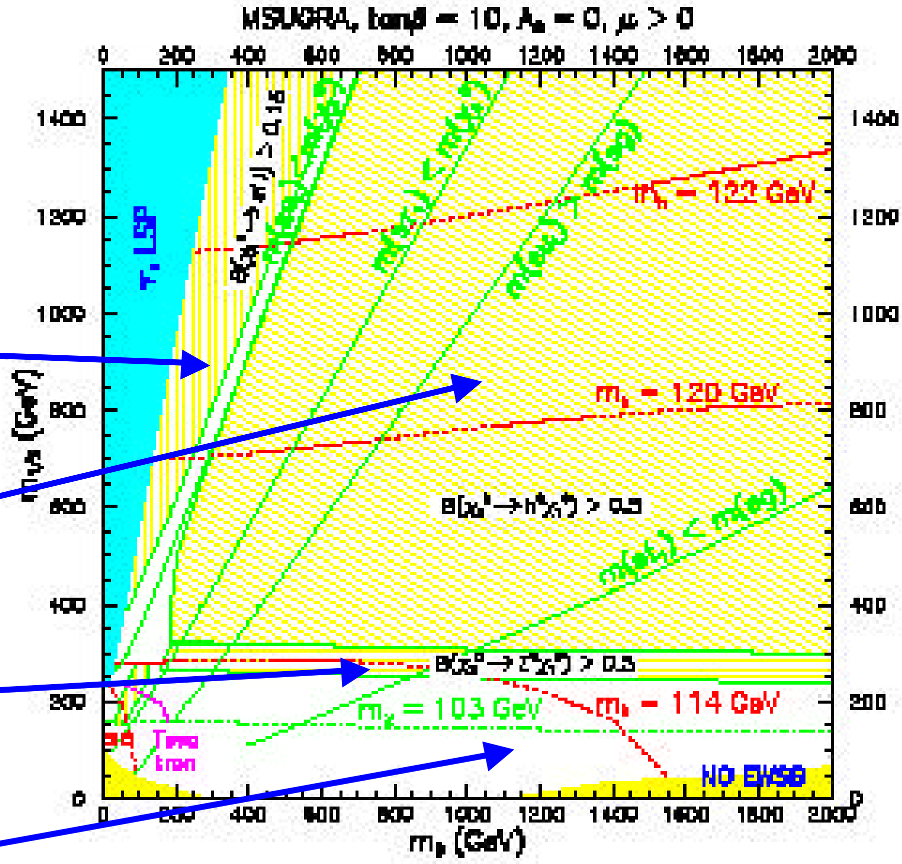
  $\tilde{q}_L \rightarrow q c_2^0$ significant

$(l\,j\,y)$ $\boxed{c_2^0 \rightarrow \tilde{l}^{\pm} l^{\mp}}$

$(l\,j\,y)$ $\boxed{c_2^0 \rightarrow h^0 c_1^0}$

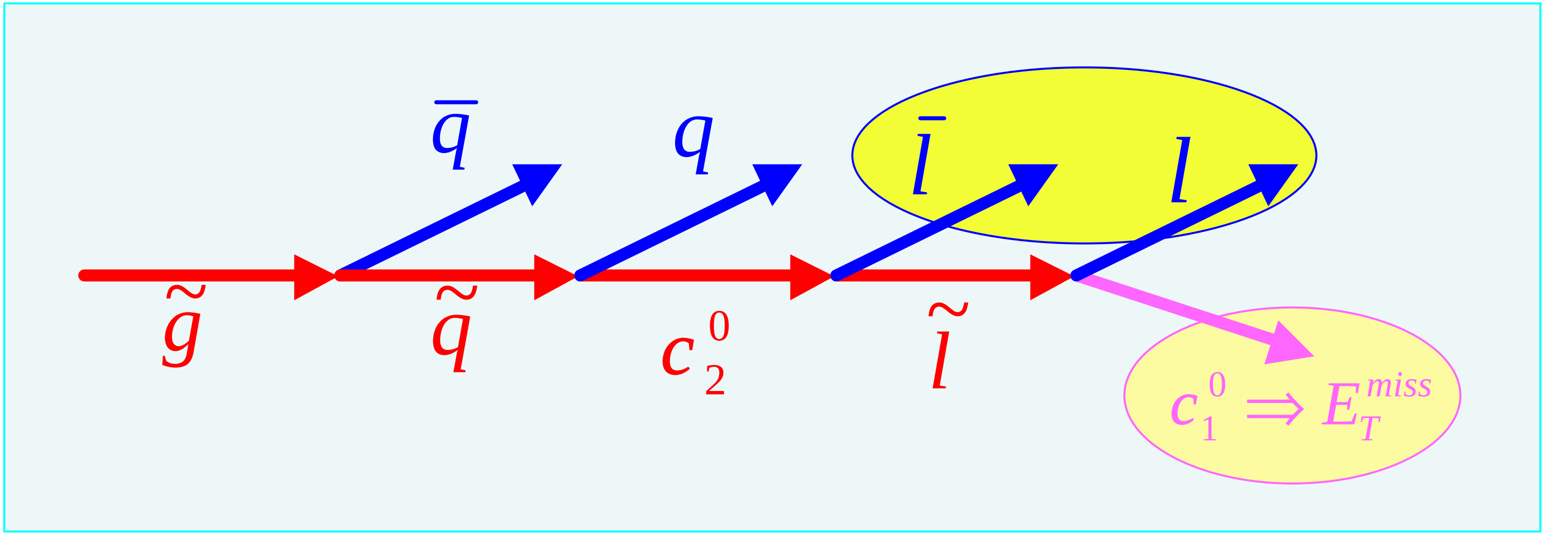
$(A y\,y)$ $\boxed{c_2^0 \rightarrow Z^0 c_1^0}$

$\boxed{c_2^0 \rightarrow l^+ l^- c_1^0}$



More general than strict MSUGRA

Decay chain to dileptons



Final states with dileptons (1)

- **M(ll):** very sharp end point

$$M_{ll}^{\max} = M_{\tilde{\chi}_2^0}\sqrt{\left(1-\frac{M_{\tilde{l}}^2}{M_{\tilde{\chi}_2^0}^2}\right)\left(1-\frac{M_{\tilde{\chi}_1^0}^2}{M_{\tilde{l}}^2}\right)}$$

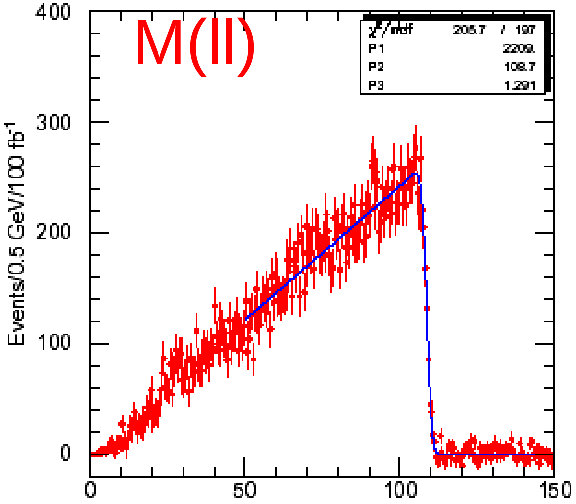
➔ $\Delta M / M \approx 0.1\%$

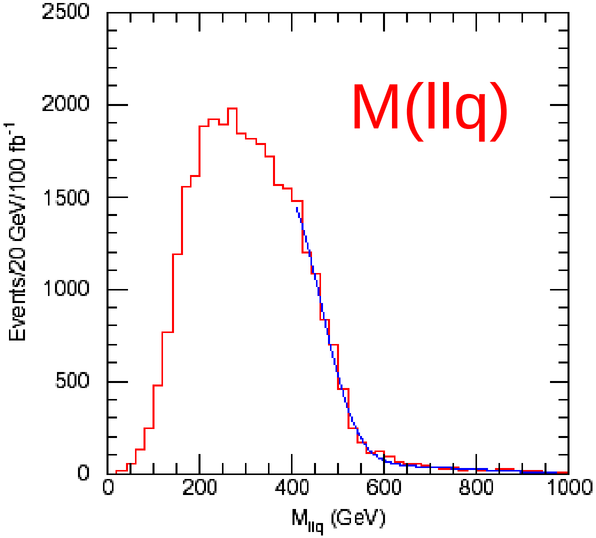
- **M(llq)** softer edge,
  Obtained by extrapolation

$$M_{llq}^{\max} = M_{\tilde{q}}\sqrt{\left(1-\frac{M_{\tilde{\chi}_2^0}^2}{M_{\tilde{q}}^2}\right)\left(1-\frac{M_{\tilde{\chi}_1^0}^2}{M_{\tilde{\chi}_2^0}^2}\right)}$$

➔ $\Delta M / M \approx 1\%$

ATLAS

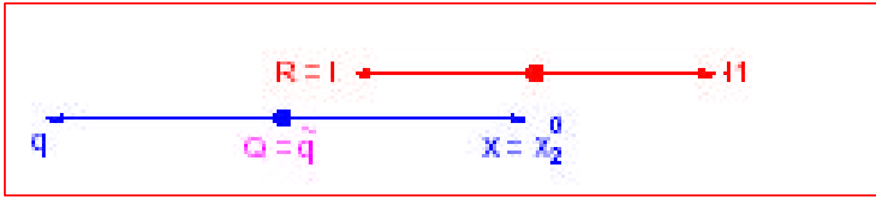




Final states with dileptons (2)

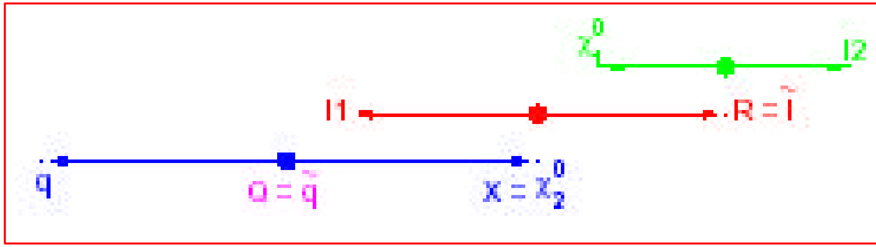
- **M(l1q):**

$$M^{\max}_{l1q} = M_{\tilde{q}}\sqrt{\left(1-\frac{M^2_{\chi^0_2}}{M^2_{\tilde{q}}}\right)\left(1-\frac{M^2_{\tilde{l}}}{M^2_{\chi^0_2}}\right)}$$



- **M(l2q):** leptons in same configuration as for M(ll)$^{\max}$

$$M^{\max}_{l2q} = M_{\tilde{q}}\sqrt{\left(1-\frac{M^2_{\chi^0_2}}{M^2_{\tilde{q}}}\right)\left(1-\frac{M^2_{\chi^0_1}}{M^2_{\tilde{l}}}\right)}$$



➔Can distinguish M(l1q)$^{\max}$ from M(l2q)$^{\max}$

- 4 unknown masses: $M_{\tilde{q}}, M_{\chi^0_2}, M_{\tilde{l}}, M_{\chi^0_1}$

  4 endpoints: $M(ll)^{\max}, M(l1q)^{\max}, M(l2q)^{\max}, M(llq)^{\max}$

  ➔ **all masses can be determined**

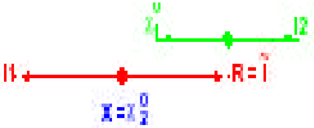
  More information available: constraints (other end points, gluino decay)

End points and configurations

$$\tilde{q} \to q\tilde{\chi}_2^0,\ \tilde{\chi}_2^0 \to \tilde{l}_1 + \bar{l},\ \tilde{l} \to l_2 + \tilde{\chi}_1^0$$

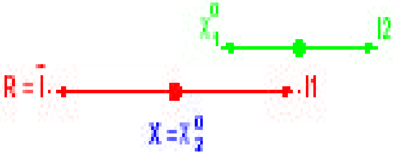
1. $(ll)^{max}$

$$M_{ll}^{max} = M_X\sqrt{(1-\frac{M_R^2}{M_X^2})(1-\frac{M_0^2}{M_R^2})}$$



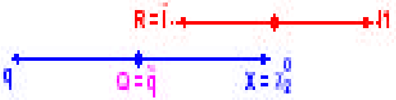
2. $(ll)^{min}$ (parallel leptons)

$$E_{l2}/E_{l1} = (M_R^2 - M_0^2)/(M_X^2 - M_R^2)$$



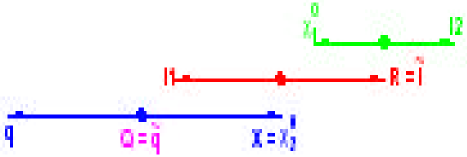
3. $(l1q)^{max}$ (1st lepton)

$$M_{l_1q}^{max} = M_Q\sqrt{(1-\frac{M_X^2}{M_Q^2})(1-\frac{M_R^2}{M_X^2})}$$



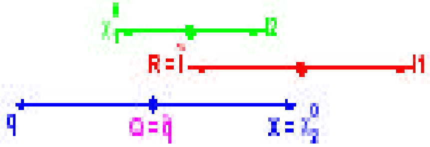
4. $(l2q)^{max}$ (2nd lepton)

$$M_{l_2q}^{max} = M_Q\sqrt{(1-\frac{M_X^2}{M_Q^2})(1-\frac{M_0^2}{M_R^2})}$$

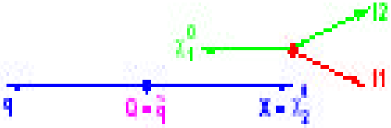


5. $(llq)^{max}$, for $M_X^2 < M_Q M_0$

$$M_{llq}^{max} = M_Q\sqrt{(1-\frac{M_X^2}{M_Q^2})(1-\frac{M_0^2}{M_X^2})}$$

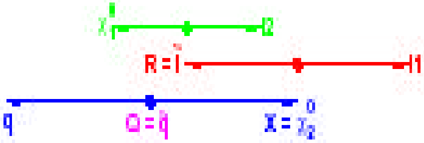


$$M_{llq}^{max} = M_Q - M_0,\ \text{for}\ M_X^2 \geq M_Q M_0$$



6. $(l1q + l2q)^{max}$

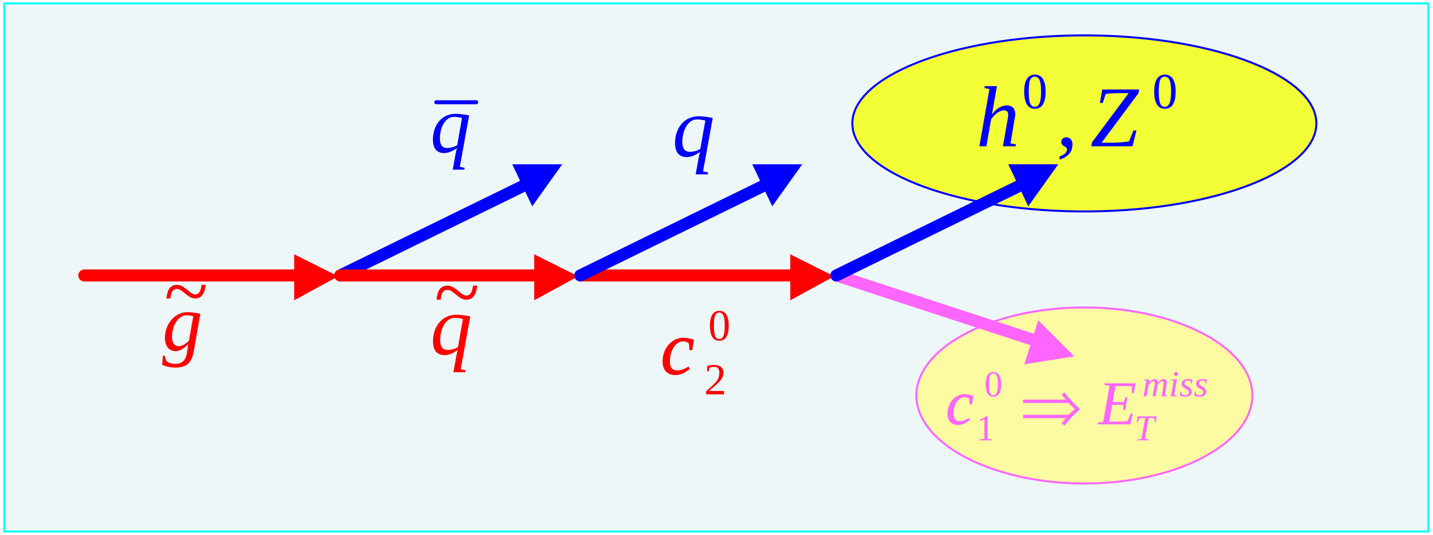
$$(M_{l1q} + M_{l2q})^{max} = M_{l1q}^{max} + \sqrt{(M_{llq}^{max})^2 - (M_{l1q}^{max})^2}$$



7. $(llq)^{min,max}$ versus (ll)

$$(M(llq)^{min,max})^2 = M_Q^2 + M_0^2 - \frac{1}{2}M_Q^2(1+\frac{M_X^2}{M_Q^2})(1+\frac{M_0^2}{M_X^2}) + \frac{M_Q^2}{2M_X^2}(1+\frac{M_X^2}{M_Q^2})M_{ll}^2$$
$$\mp \frac{M_Q^2}{2}(1-\frac{M_X^2}{M_Q^2})\sqrt{(1-\frac{M_0^2}{M_X^2}-\frac{M_{ll}^2}{M_X^2})^2 - 4\frac{M_0^2}{M_X^2}\frac{M_{ll}^2}{M_X^2}}$$

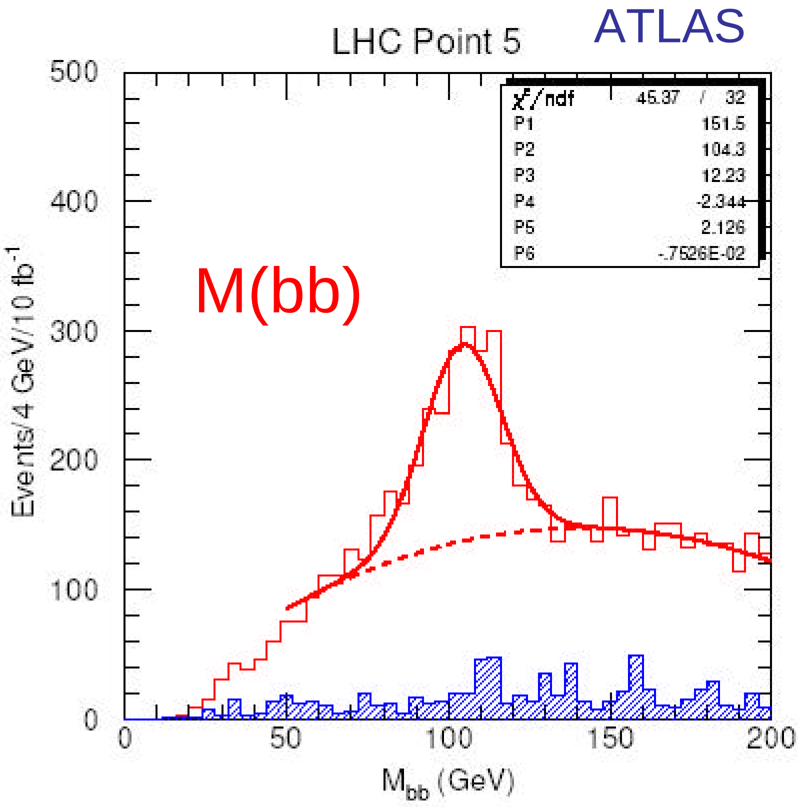
Decay chain to h^0 or Z^0



Final states with h^0 or Z^0

- Higgs can be reconstructed from b-bbar jets
  Could be a **h^0 discovery** channel
- Z^0 reconstructed from di-lepton decay
- Decay chain is shorter than for di-leptons

1. Either need start from gluino $M(q_1h^0)$,$M(q_2h^0)$,$M(qq)$,$M(qqh^0)$ to determine 4 masses
2. Or start from squark and combine with another channel

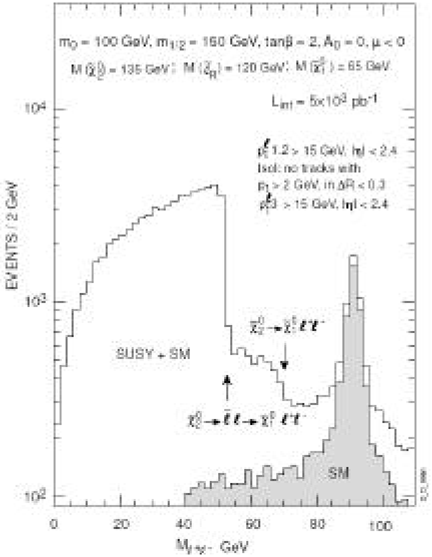


Multiple end points in decays

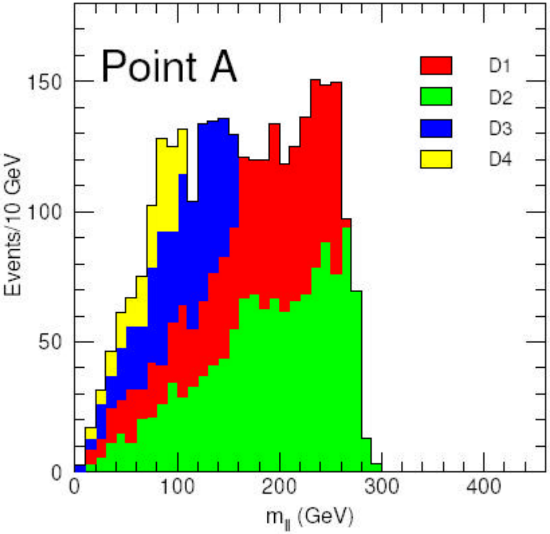
- Multiple decay modes

$$c_2^0 \circledR \tilde{l}\, l, ll c_1^0$$

- Multiple heavy χ^0_i decays
  - D1 $c_4^0 \circledR \tilde{l}_R l \circledR ll c_1^0$
  - D2 $c_4^0 \circledR \tilde{l}_L l \circledR ll c_1^0$
  - D3 $c_4^0 \circledR \tilde{l}_L l \circledR ll c_2^0$
  - D4 $c_2^+ \circledR \tilde{n}_L l \circledR ll c_1^+$
  - ATLAS, Point SPS1A
    (m_0=100, $m_{1/2}$=250, tanβ=10)



CMS



ATLAS

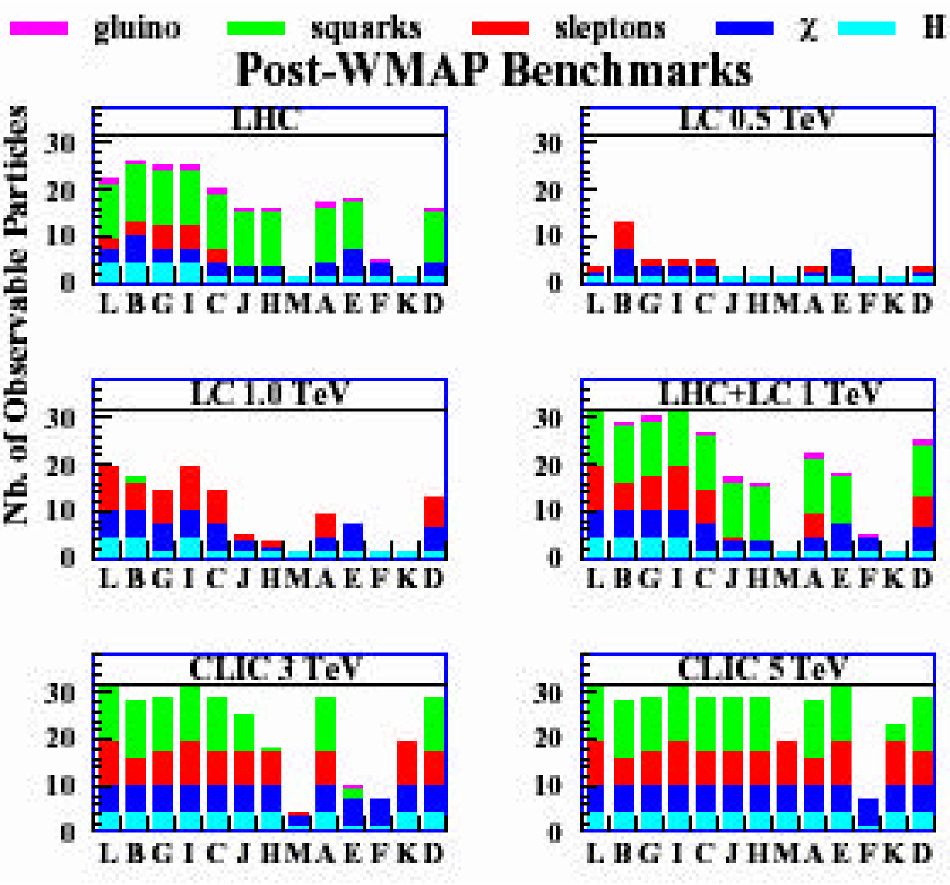
LHC summary

- LHC could discover SUSY quite early
  - With 10 fb^{-1} squarks/gluinos up to 1.5-2 TeV
- Ultimate reach (300 fb^{-1}) up to ~2.5 TeV
- LHC can also reconstruct sparticle masses
  - For all decay modes of χ^0_2, even in $\tau\tau$ decays
- Reasonable accuracy:
  - (ATLAS, Gjelsten et al., ATL-PHYS-2004-007, SPS1A)
  - ΔM ~ 5 GeV for neutralinos and sleptons (2.5-5%)
  - ΔM ~ 10-15 GeV for gluino and squark (jet E-resolution) (2-3%)
- Futher work needed
  - (cross-sections, spin correlations, “flavour” identification, …)

Comparison LHC/LC/CLIC

- Complementary reach
- LHC: h^0, squarks, gluino
- eeCOL: sleptons, gauginos
  - E_{cms} limited
- Not fully representative
  - Precision is also important
- May need >3 TeV to unravel whole spectrum

M.Battaglia et al.,hep-ph/0306219



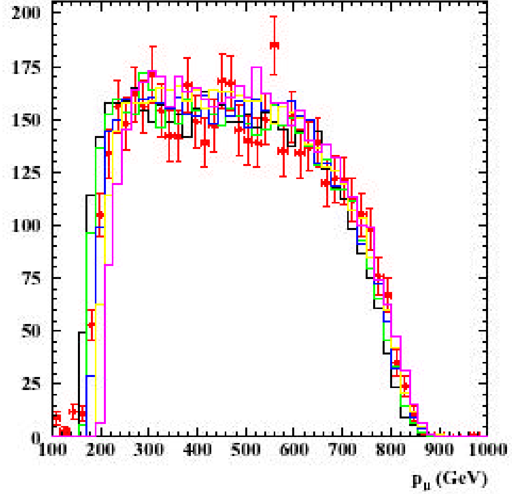
Lepton Colliders

- More precise than LHC
- E.g. smuon pair production

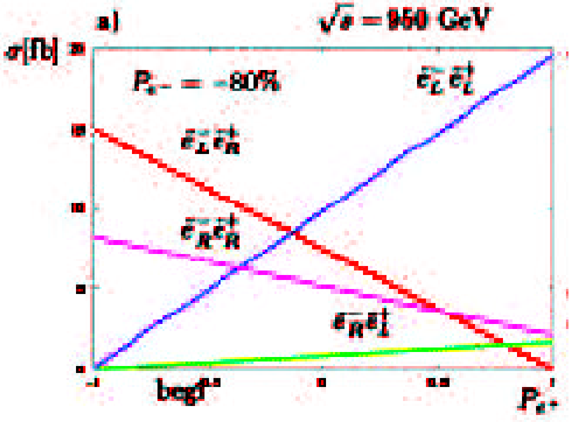
$$E_{\mu}^{\max,\min} = \frac{M_{\tilde{\mu}}}{2}\left(1 - \frac{M_{\chi_1^0}^2}{M_{\tilde{\mu}}^2}\right)\left(1 \pm \sqrt{1 - \frac{M_{\tilde{\mu}}^2}{E_{beam}^2}}\right)$$

  - 2 edges ➔ determines both masses
  - Precision 2-3% at 1 TeV mass
- Threshold scan improves precision further
  - Precision 1-2% at 1 TeV mass
  - Improves over LHC by 5-10 for neutralino and slepton
- Can use beam polarization
  - Increase/decrease cross section selectively for signal and background
- But: **Limited by beam energy**

CLIC 3 TeV



$$M_{\tilde{\mu}} = 1145,\ M_{\chi_1^0} = 652\ GeV$$

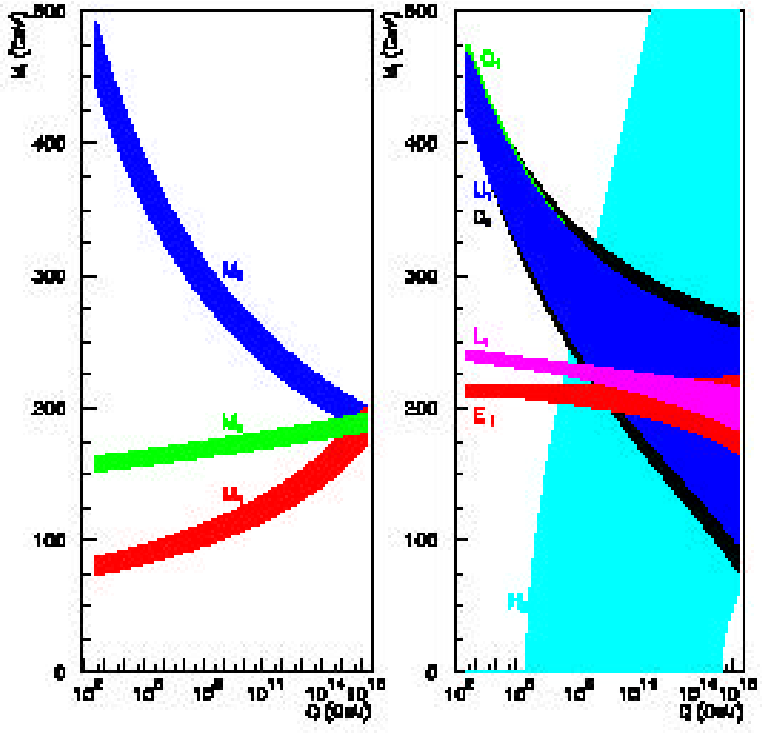


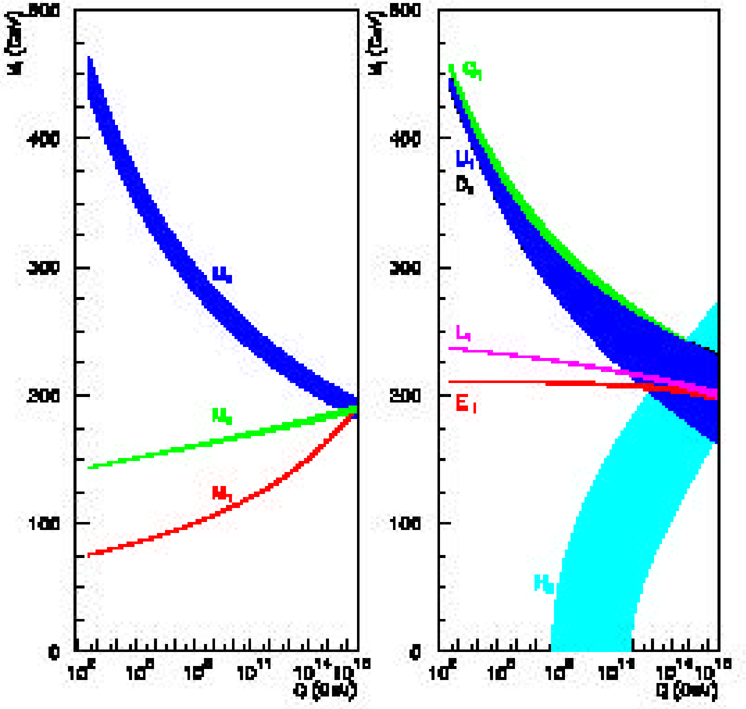
Identifying the model

- Topology: photons, excess leptons or jets, Taus from MSUGRA or GMSB
- Distinguish higgsino-like from AMSB?
- Distinguish MSUGRA from UED?
- Use decay BR? Production cross-sections?

Extrapolation to GUT scale

LHC only LHC + LC





Blair, Porod, Zerwas, hep-ph/0011367

Conclusion

- Today: completely in the dark (SM works too well)
- Something must exist beyond the SM
- But large number of candidate models
- Among them, SUSY is a respectable candidate
- Which SUSY? MSUGRA, GMSB, AMSB, RPV, NMSSM,

Eagerly need experimental guidance

- Hope to see something at LHC (light Higgs!)
- Then, will require another generation of accelerators
  - LC, CLIC, MUCOL, VLHC, …
- It is time that we discover something!

Further reading (biased sample)

- Basic MSSM
  - Perspectives on Supersymmetry, World Scientific, Singapore 1998, ed. G.L.Kane
  - S.P.Martin, A Supersymmetry Primer, hep-ph/9709356 v.3
  - H.Haber and M.Schmitt, Supersymmetry, PDG2004, http://pdg.lbl.gov/
- Higgs
  - The Higgs Hunter's Guide, Addison-Wesley 1990, ed. J.F.Gunion, H.E.Haber, G.Kane, S.Dawson
  - Perspectives on Higgs Physics, World Scientific, Singapore 1993, ed. G.L.Kane
  - M.Spira, P.M.Zerwas, Electroweak symmetry breaking and Higgs physics, hep-ph/9803257