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# BSM physics at the LHC

Winter School on
Strings, Supergravity and Gauge Theories

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# Plan of the lectures

1. A critical overview of the SM
2. Bottom-up approaches to BSM
3. SUSY: if so, which incarnation?
4. Other BSM ideas for the LHC

# Why supersymmetry?

- More general symmetry of local relativistic Q.F.T.
- Linearly realized, it gives a rationale for elementary scalars, living in N=1 multiplets with chiral fermions
- Local version, supergravity, contains Einstein's general relativity, fits naturally in superstrings

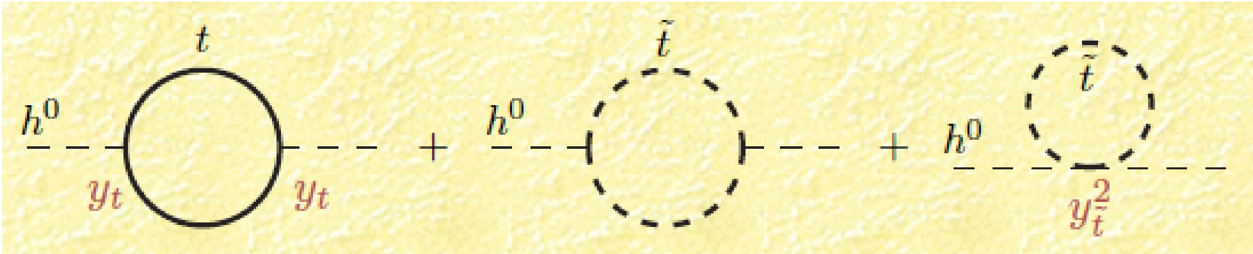
Need N=1 in D=4 because of chirality of EW theory

However, in any realistic model it must be broken [O($10^2$ GeV) lower bounds on charged sparticles]

none of above arguments points to LHC scale as preferred scale for superparticle masses

# Why at the weak scale?

SUSY can solve the ("big") hierarchy problem
thanks to its special renormalization properties




[qualitative here,
more details below]

$$\delta m_H^2 \sim -\frac{3\,h_t^2}{8\pi^2} m_{\tilde{t}}^2 \log\frac{\Lambda^2}{m_{\tilde{t}}^2}$$

Power-dependence on SUSY-breaking masses
only mild logarithmic dependence on cutoff

Naturalness preserved up to very high scales
if superparticle masses are at the weak scale

# The MSSM

(more on possible variations later)

- Gauge group SU(3) x SU(2) x U(1)

  **gauginos** $(\widetilde{g},\ \widetilde{W},\widetilde{B})$

- 3 SM generations, 2 Higgs doublets

  squarks $(\widetilde{q})$, sleptons $(\widetilde{l})$, higgsinos $(\widetilde{H}_{1,2})$

- R-parity conserving superpotential

$$W = Qh^U U^c H_2 + Qh^D D^c H_1 + Lh^E E^c H_1 + \mu H_1 H_2$$

- Explicit soft supersymmetry breaking

$$-\mathcal{L}_{soft} = \varphi^\dagger m^2 \varphi + \Big[(1/2) M_A \lambda_A \lambda_A + m_3^2 H_1 H_2 + \widetilde{q} A^U \widetilde{u}^c H_2 + \widetilde{q} A^D \widetilde{d}^c H_1 + \widetilde{l} A^E \widetilde{e}^c H_1 + h.c.\Big]$$

(the source of many troubles: # parameters, flavour)

# MSSM Higgs sector and EW breaking

2 Higgs doublets: chargino, q & l masses; anomalies

$$H_1 \equiv \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix} \sim (1, 2, -1/2) \qquad H_2 \equiv \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix} \sim (1, 2, +1/2)$$

Special 2-Higgs model with natural FCNC suppression
(only one neutral Higgs couples to each charge sector)

The MSSM tree-level potential ($m_{1,2}^2 = \mu^2 + m_{H_{1,2}}^2 \quad m_3^2 \equiv B\mu$)

$$V_0 = m_1^2|H_1|^2 + m_2^2|H_2|^2 + m_3^2(H_1H_2 + h.c.) + \frac{g^2}{8}(H_2^\dagger\sigma^a H_2 + H_1^\dagger\sigma^a H_1)^2 + \frac{g'^2}{8}(|H_2|^2 - |H_1|^2)^2$$

SUSY ➔ quartic Higgs couplings related to gauge couplings

Stability:

$$m_1^2 + m_2^2 - 2|m_3^2| \geq 0$$

Breaking:

$$m_1^2\, m_2^2 - m_3^4 \leq 0$$

# The MSSM spectrum

$$\langle H_1^0 \rangle = v_1 \neq 0 \quad \langle H_2^0 \rangle = v_2 \neq 0 \qquad v^2 = v_1^2 + v_2^2 \quad \tan\beta = \frac{v_2}{v_1}$$

Fermi scale

Higgs: (tree-level)

$G^{\pm}$ $G^0$ Goldstone

$H^{\pm}$ charged

$(h, H)$ CP-even

$A$ CP-odd

(mixing angle $\alpha$ in the neutral CP-even sector)

Measured SM parameters + two more, e.g. $(m_A, \tan\beta)$

$$m_W, m_A < m_{H^\pm} \qquad m_h < m_Z |\cos 2\beta| < m_Z < m_H \qquad m_h < m_A < m_H$$

SM particles:

$M_{W,Z} \sim v \qquad M_t \sim v_2 \qquad M_b \sim v_1 \qquad M_{tau} \sim v_1$

S-particles:

- Sfermions can mix both in family space and in L-R space
- EW gauginos & higgsinos give charginos and neutralinos

# Radiative corrections to MSSM Higgs sector

Dominated for moderate tan(beta) by top and stop loops
can drastically change tree-level spectrum and couplings
(and indeed save the MSSM from being ruled out already)

Approximate one-loop formula
[moderate tan(beta), decoupling limit, negligible stop mixing]

$$\Delta m_h^2 \sim \frac{3\, g^2\, m_t^4}{16\pi^2\, m_W^2} \log \frac{m_{\tilde{t}_1}^2\, m_{\tilde{t}_2}^2}{m_t^4}$$

After many refinements, typically: $m_h^{max} \sim 130$ GeV

Main corrections to couplings absorbed in running param.s

# The bonuses of R-parity

- Avoids many dangers already at tree-level
  (proton decay, flavour tests, EW tests)

- Only pair (not single) production of sparticles

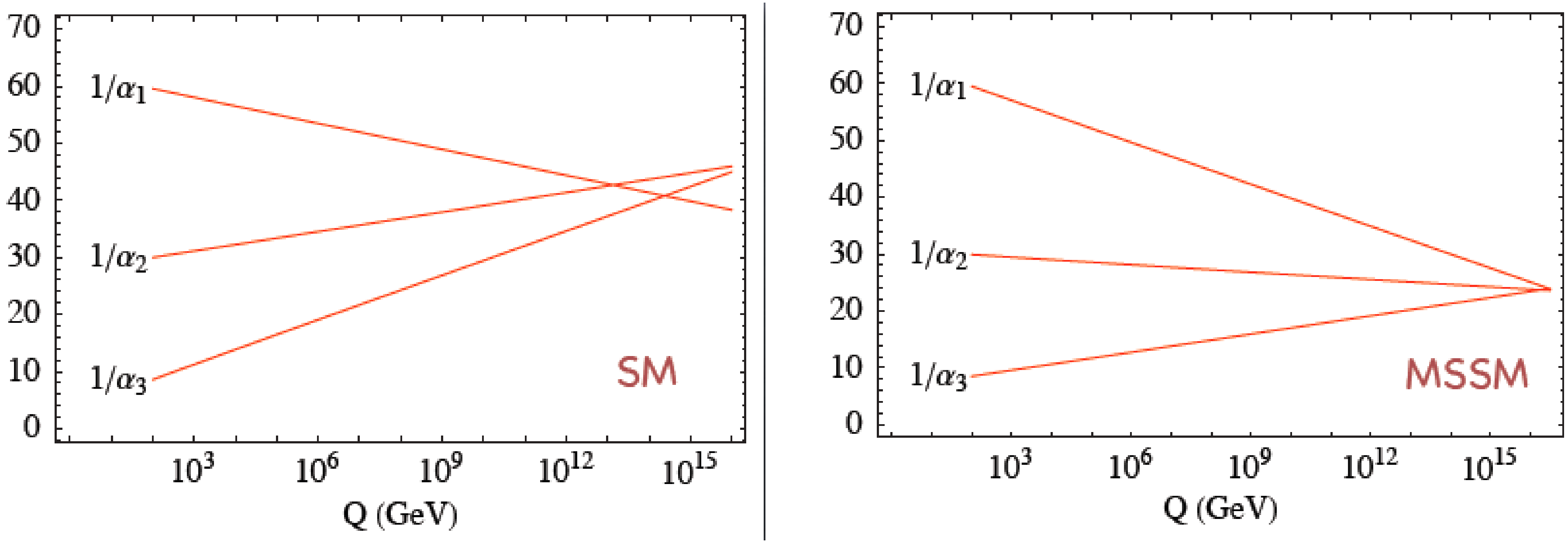
- Lightest Supersymmetric Particle (LSP)
  typically a neutralino (gaugino/higgsino)
  absolutely stable ➔ DARK MATTER candidate

(relic abundance very sensitive to model parameters,
special regions of parameter space are selected:
MSSM compatible with abundance, does not predict it)

# Another bonus: gauge coupling unification

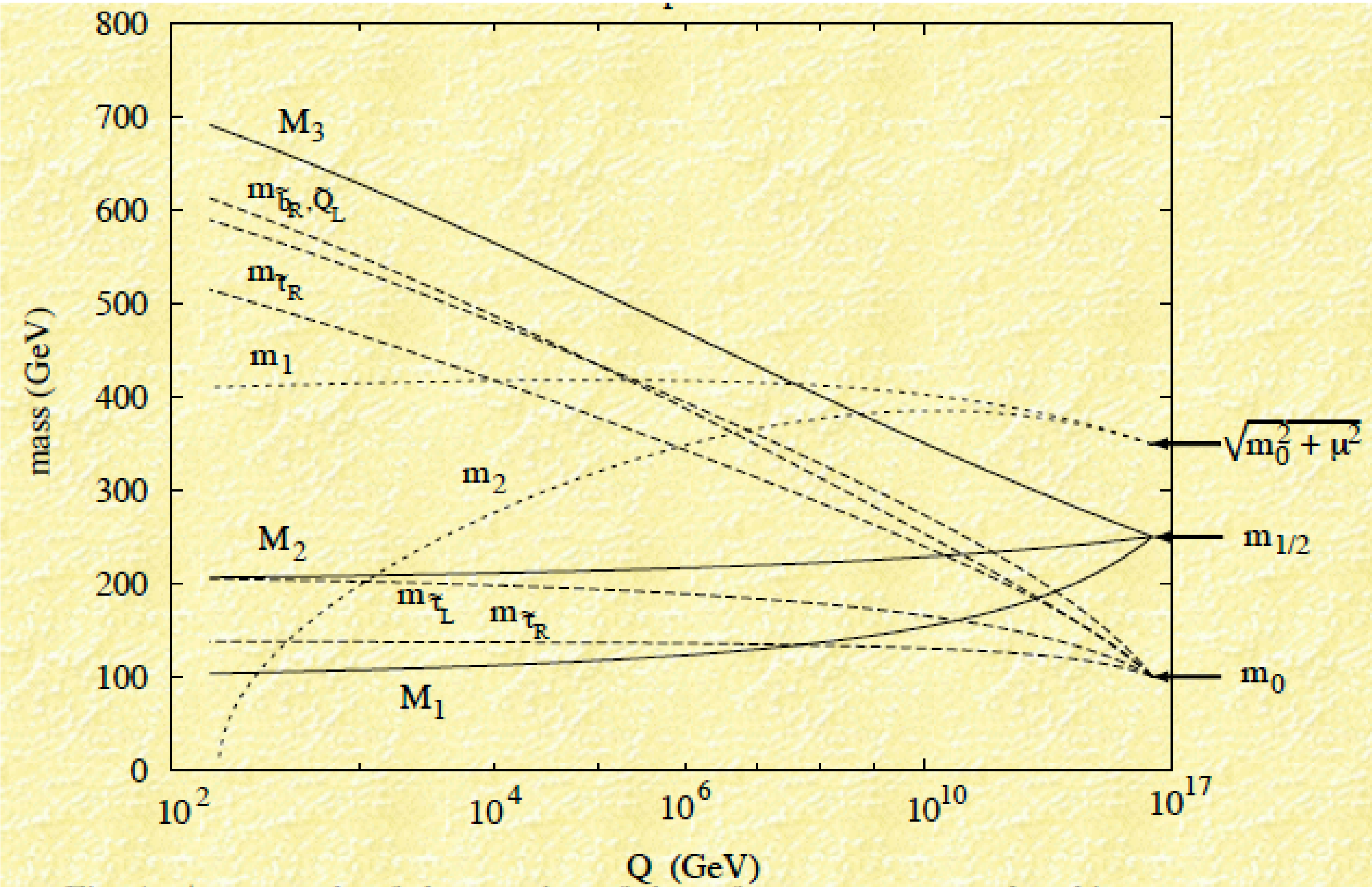
## Effective unification of gauge coupling constants

(at a scale $M_U \sim 2\times10^{16}$ GeV not very far from $M_P$)




Crucial role in the RGE is of gaugino-higgsino sector
[squarks and sleptons come in complete SU(5) reps]

# One more bonus: radiative EW breaking



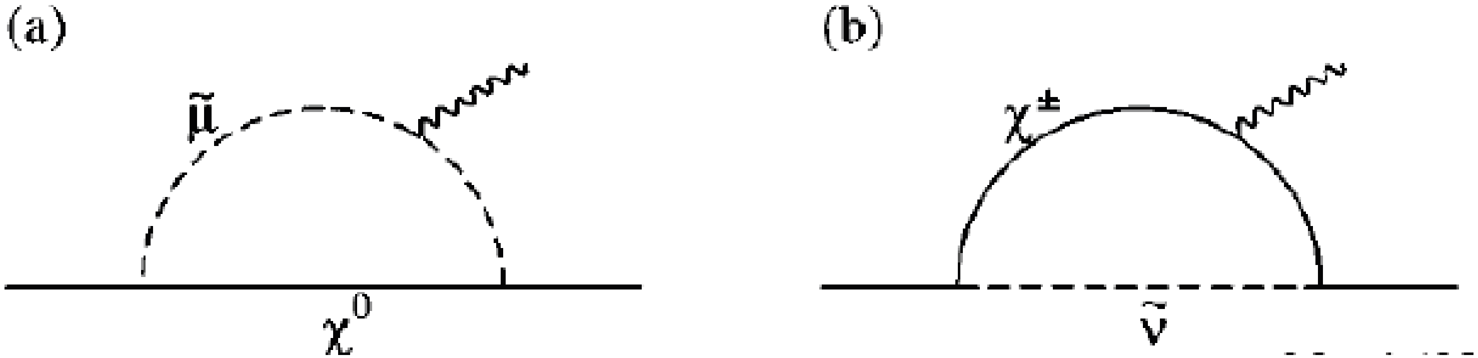

Explains SU(2)xU(1) broken with charge and colour unbroken

# SUSY vs. EW precision tests

SUSY = decoupling physics: SM results for heavy spectrum

For light spectrum, agreement with data in wide par. regions

## SUSY and the (g-2) puzzle

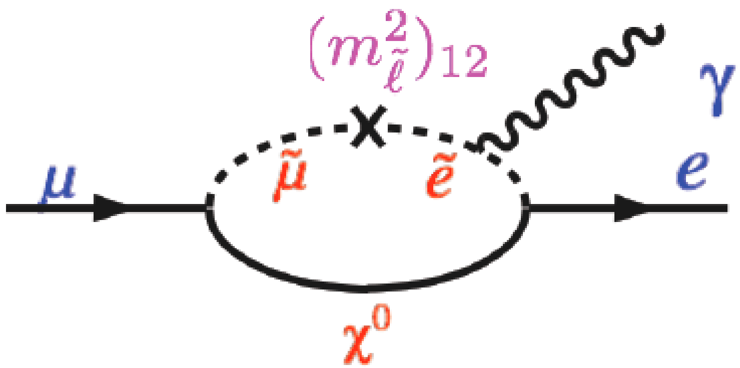


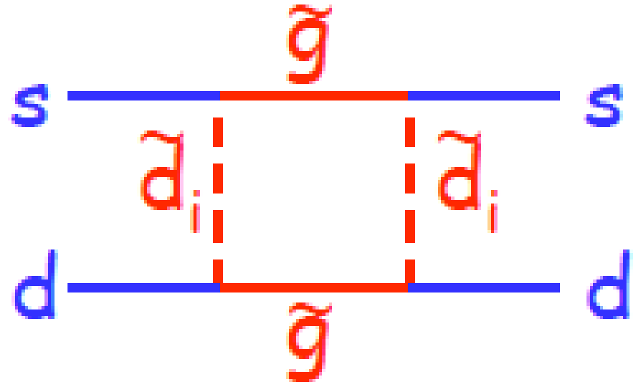

$$\Delta a_\mu^{\rm MSSM} \approx 130 \times 10^{-11} \tan\beta \, \mathrm{sign}(\mu) \left(\frac{100\ \mathrm{GeV}}{M_{\rm SUSY}}\right)^2$$

$$a_\mu^{EXP} - a_\mu^{SM} = (27.7 \pm 9.3) \times 10^{-10}$$

# The SUSY flavour problem

Generic flavour structure of soft terms: sfermion/fermion mass matrices diagonalized by different transformations. Strong constraints from 1-loop FCNC processes, e.g.:




bounds similar to those derived in the effective theory

Phenomenological way out (constrained MSSM): universal b. cond. on soft masses at some large scale, e.g.

$$m_0 \quad A_0 \quad M_{1/2} \quad \mu_0 \quad (B\mu)_0$$

# The MSSM tuning problem

concrete MSSM realization poses a tuning problem,
especially when extrapolating the MSSM to high scales

$$m_Z^2 \sim -2m_H^2 = -2\mu^2 + \frac{3\lambda_t^2}{2\pi^2} m_{\tilde{t}}^2 \log\frac{M_P}{m_{\tilde{t}}} + \ldots \sim -2\mu^2 + O(1) m_{\tilde{t}}^2 + \ldots$$

naturalness suggests light SUSY: $m_{\tilde{t}} \sim \mu \sim m_Z$

Things are made worse by the upper bound on the Higgs mass

$$m_h^2 < m_Z^2 + m_t^2 \frac{3\lambda_t^2}{2\pi^2} \log\frac{m_{\tilde{t}}}{m_t} \;\; \& \;\; m_h > 114.4\, GeV \quad \Rightarrow \quad m_{\tilde{t}} > 500\text{-}1000\, GeV$$

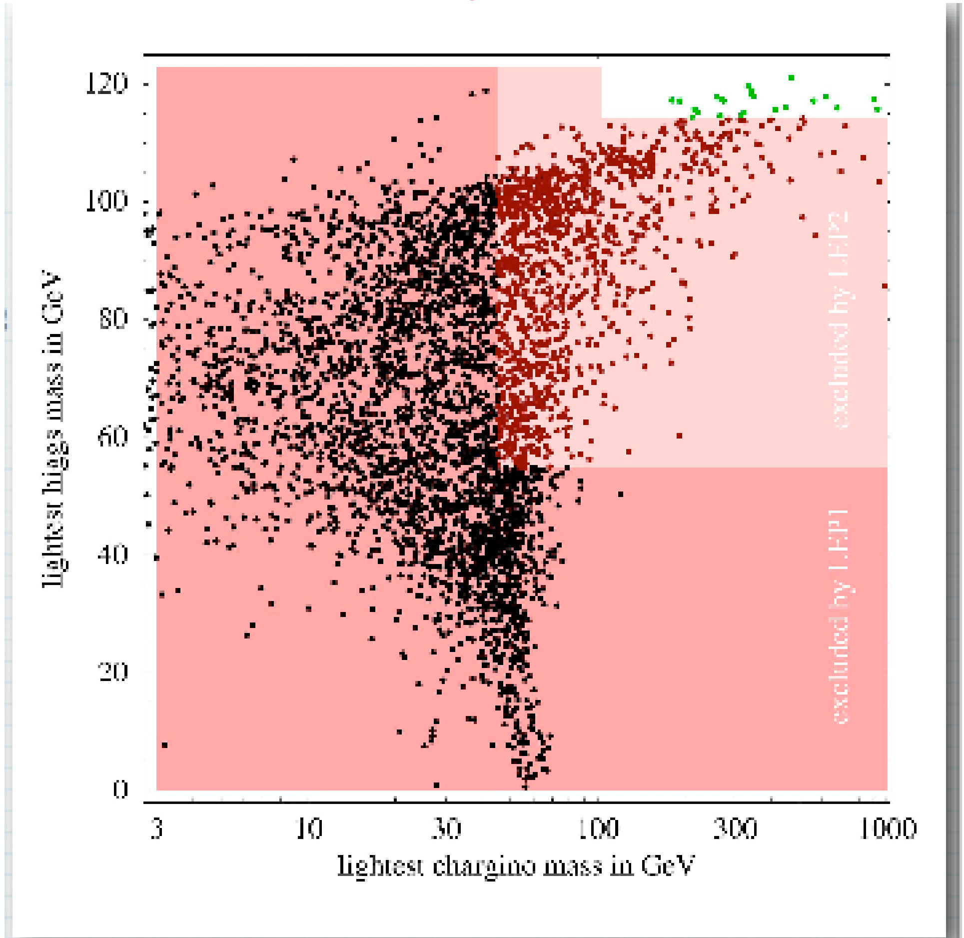
O(few%) fine-tuning required without further theoretical input

There are ways to do better, e.g. adding a singlet (NMSSM),
(complicating the analysis of Higgs and neutralino sectors)
and/or lowering the MSSM cutoff (but gauge unification?)

# An empirical measure of fine-tuning

After LEP-2

lightest Higgs mass (GeV)




After LEP-1

[Giunti-Romanino-Strumia]

lightest chargino mass (GeV)

# Split supersymmetry

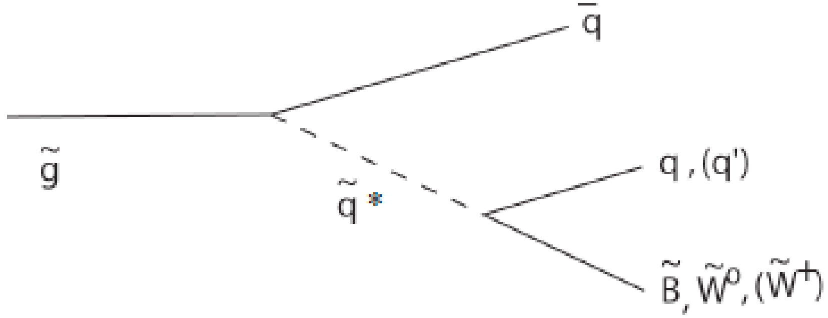
[ArkaniHamed-Dimopoulos, Giudice-Romanino,…]

If you feel ready to throw naturalness away
(not only "little", but also "big" hierarchy problem)
Keep the good: DM, unification, EW tests, light Higgs
Throw the bad: susy flavour problem, too light Higgs

Can be easily achieved by sending
all the scalars but SM Higgs to very high mass scales
while keeping gauginos and higgsinos at TeV scale

A limiting case of the MSSM worth exploring

LHC signature:
long-lived gluino



# Beyond the MSSM

Taking the MSSM at face value, its appealing properties

- Solution of “big” hierarchy problem
- Effective unification of gauge couplings
- A good candidate for dark matter

come with a number of unanswered questions:

- Special flavour structure of soft terms
- Relative scale of different soft terms

and, at a deeper level:

- Absolute scale of soft terms
- Vacuum energy problem (as any other realistic model)

To answer, study spontaneous breaking in the microscopic theory (for the first two issues, enough to know mediation mechanism from the susy-breaking sector to the MSSM)

# The need for supergravity

Minimal framework for spontaneous breaking in local N=1 SUSY (supergravity) : MSSM + goldstino multiplet +

gravitational multiplet $\begin{pmatrix} e_\mu^m \\ \psi_\mu \end{pmatrix}$ spin-2 / spin-3/2 gauge fermion of SUGRA ↓ GRAVITINO

A crucial difference with global supersymmetry:

$$V_{sugra} = ||F||^2 + ||D||^2 - ||H||^2$$ only in SUGRA $\quad ||H||^2 = 3\, m_{3/2}^2 M_P^2$

$$\Lambda_{SUSY}^4 = \langle ||F||^2 + ||D||^2 \rangle > M_{weak}^4$$ no sparticle observed

$$\Lambda_{cosm} = \langle V_{sugra} \rangle^{1/4} < M_{weak}^2 / M_P$$ limits on vacuum energy

phenomenology →
gravitational effects crucial for vacuum selection
(only afterwards we can take the global limit)
if not, we implicitly accept anthropic attitude…

# Heavy vs. Light Gravitino

No detailed model of SUSY breaking is fully convincing

Two broad scenarios for the effective theory at the LHC scale

$\Lambda_{SUSY}^4 = 3\,m_{3/2}^2 M_P^2$ $\quad m_{3/2}(\Lambda_{SUSY})_{\text{model dependent}}$ $\quad \Delta m_{SUSY} \sim M_{weak}$

- o Heavy gravitino (weak scale mass)
- • MSSM + soft terms
- • MSSM LSP stable (WIMP dark matter)

- o Light gravitino (mass < keV)
- • MSSM + goldstino multiplet
- • MSSM LSP ➔ particle + (goldstino)

What else is needed to do phenomenology?
(too) many mass parameters in terms of a few
"models" of susy-breaking "mediation"

# The classic SUSY signature at the LHC

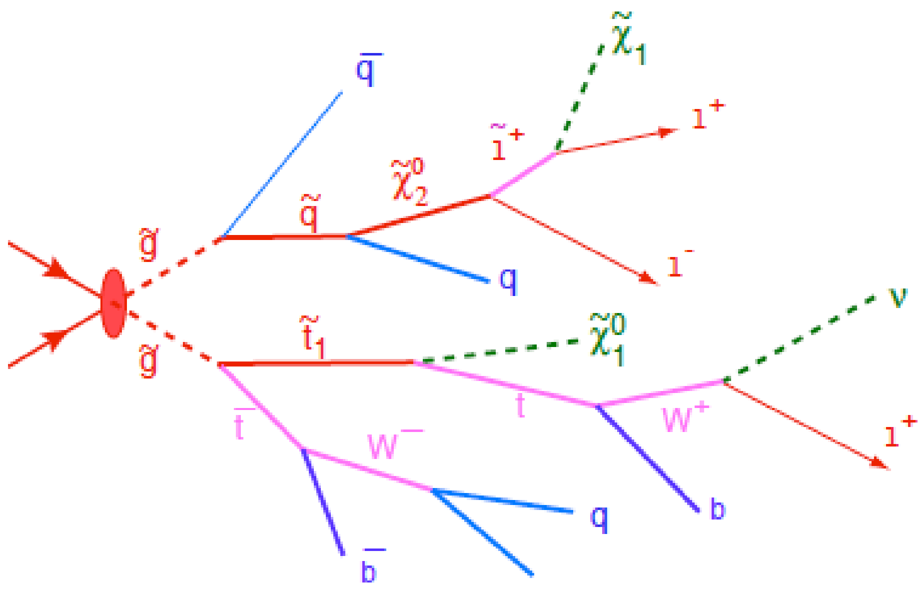
- Gluino/squark pair production (strong) and decay:

Multi-jets + missing $E_T$

(+ possible isolated leptons and/or gauge bosons)

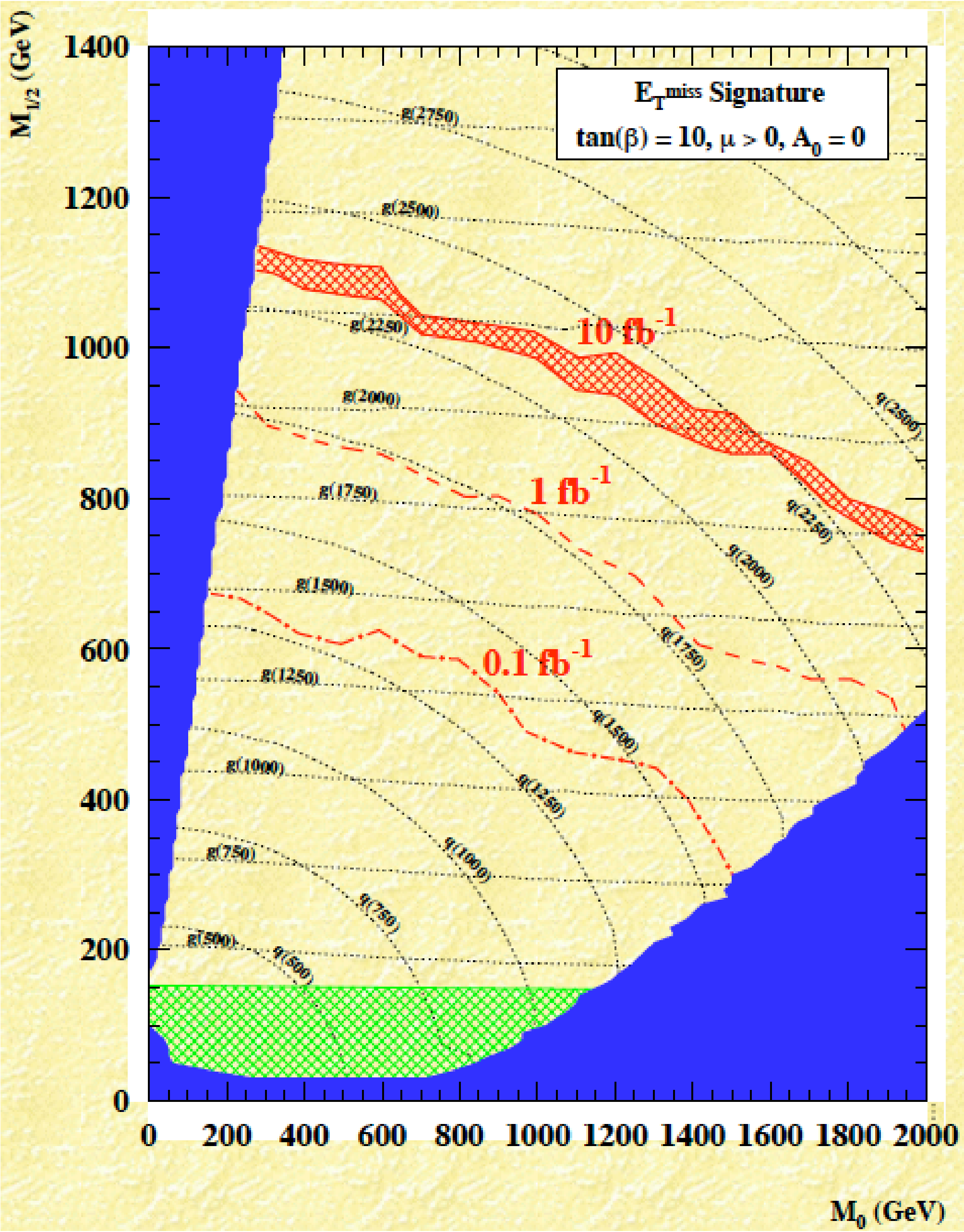
After seeing deviations from SM expectations need efforts to reconstruct SUSY spectrum from data, e.g.:

- Edges in invariant mass distributions
- Methods analogous to W "transverse mass"



Many other possible signals being considered

# LHC discovery potential for SUSY




## SUSY "Easy"

## If:

1) SM background well understood
2) Detector response well understood

## Then:

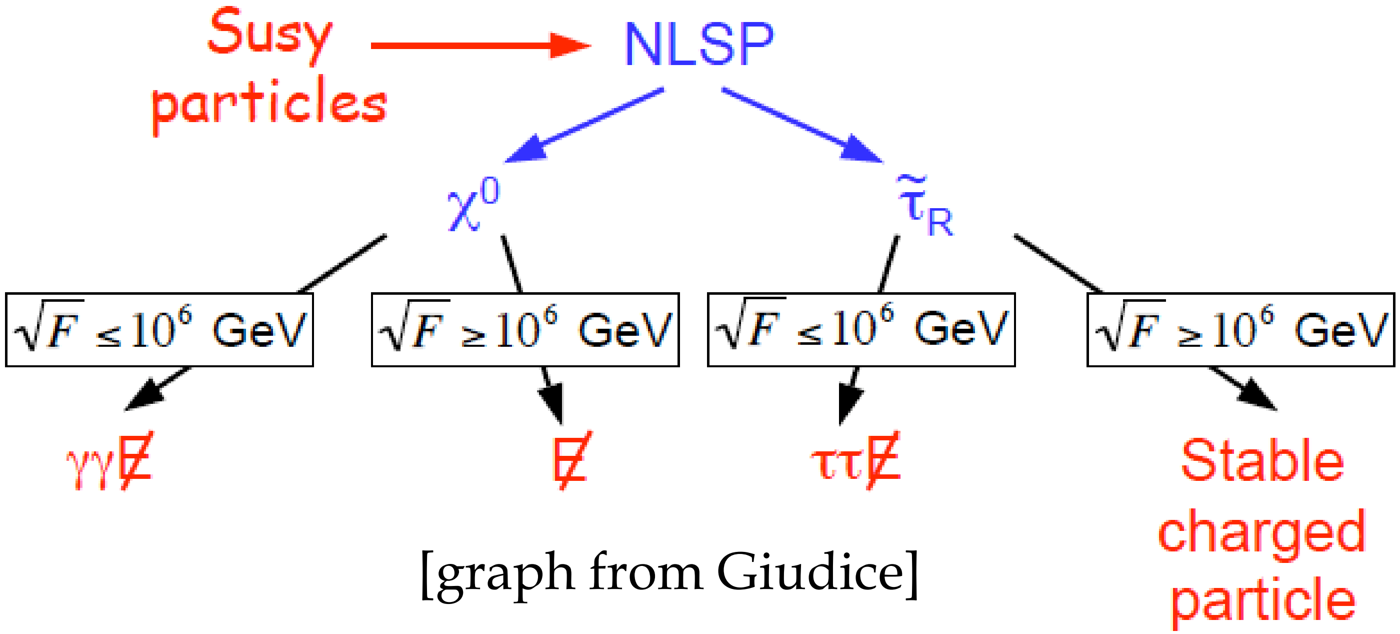
With 10 $fb^{-1}$ at 14 TeV already sensitive to 1-2 TeV gluino/squark masses

$M_g \sim 2.7\, M_{1/2} \quad M_{sq}^2 \sim M_0^2 + 5\, M_{1/2}^2$

# More SUSY signatures at the LHC

- Chargino/neutralino pair-production (weak) and decay:
  Tri-leptons + missing $E_T$
- Top pairs + missing $E_T$ from stop pair production

Signatures of light gravitino scenario (e.g. gauge mediation)




[graph from Giudice]