SUSY Phenomenology

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Physics at LHC

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Introduction

- The SM is extremely successful for energies up to ~ 100 GeV; yet some deep questions remain open:

  origin of mass, EWSB, flavour and CP mixing, dark matter, ...

- Any further progress requires physics beyond the SM.

- We expect this new physics to be manifest at the TeV scale:

  motivation to build LHC.

- Of the existing BSM theories, low-scale supersymmetry (SUSY) is the best motivated and best studied one.

  will review some aspects of SUSY relevant for LHC;

  by no means exhaustive

SUSY has an incredibly rich phenomenology:

superpartner spectrum, decay chains, dark matter candidate, R-parity violation, CP violation, lepton flavor violation, *etc, etc.*

Joke at a recent BBQ party:

"Never trust a theorist talking about SUSY ....."

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SUPERSYMMETRY

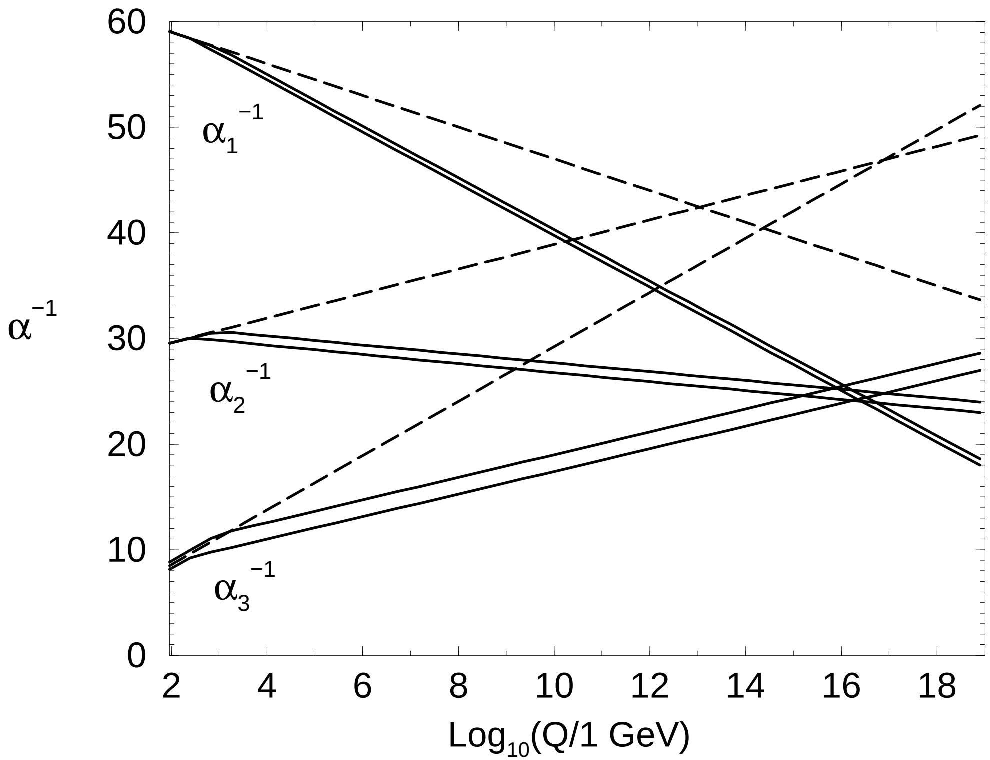
Why we like it:

- symmetry between fermions and bosons
- natural and unique extension of relativistic symmetries
- many theoretical beauties
- rich phenomenology

"The discovery of supersymmetry is tantamount to the discovery of quantum dimensions of space-time"

[David Gross, CERN Colloq. 6 Jul 2004]

Gauge Coupling Unification



Running of the inverse gauge couplings:
dashed lines – SM; full lines – MSSM.

MSSM SPECTRUM

particle	spin	superpartner	spin
quarks	$1/2$	squarks	0
leptons	$1/2$	sleptons	0
gauge bosons	1	gauginos	$1/2$
Higgs bosons	0	higgsinos	$1/2$
graviton	2	gravitino	$3/2$

$$W = h_E H_1 L E^c + h_D H_1 Q D^c + h_U H_2 Q U^c - \mu H_1 H_2$$

$$\ldots\ldots$$

$$m(\text{particle}) \neq m(\text{superpartner})$$

$\Rightarrow$ SUSY must be broken $\Leftarrow$

SOFT-BREAKING TERMS

Terms in the Lagrangian that break SUSY ‘softly’

i.e. they do not (re-)introduce quadratic divergencies

- gaugino masses $M_\lambda \lambda^a \lambda^a$
- scalar (mass)^2 terms $m^2 \phi^* \phi$
- bilinear and trilinear couplings $B\phi^2 + A\phi^3$

We want to generate these terms by spontaneous symmetry breaking, analogous to the SM Higgs mechanism.

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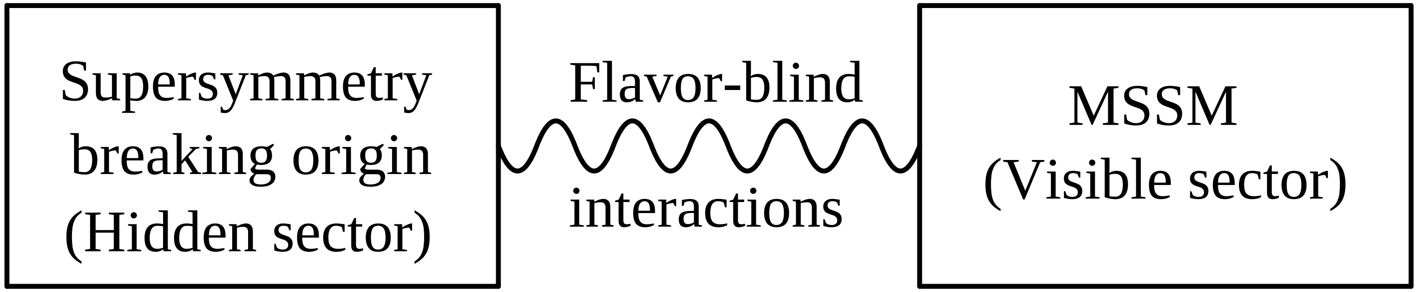
Unfortunately ...

... this does not work with the MSSM fields alone

... it would not lead to a viable spectrum :-(

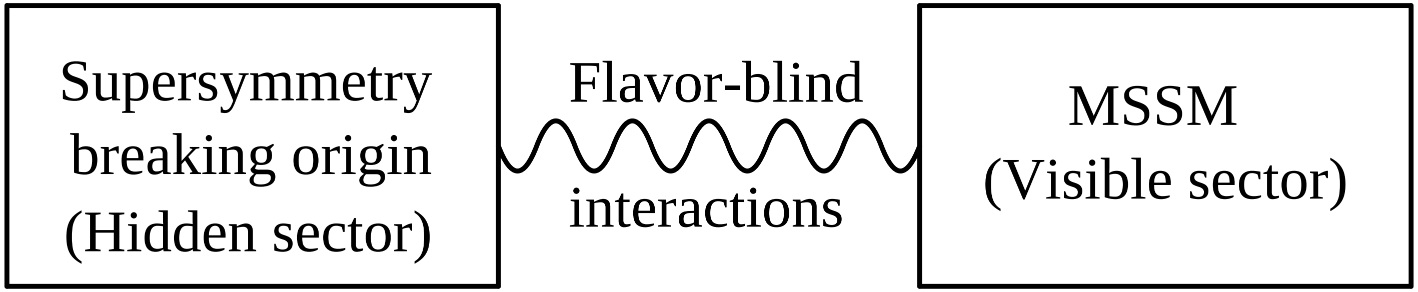
Hidden-Sector SUSY Breaking



- In the hidden sector, the F component of some non-MSSM field acquires a non-zero VEV, which breaks SUSY.
- This breakdown of SUSY is then communicated to the visible sector (the MSSM) by flavor-blind interactions.

Even so it is a very tricky business to achieve viable SUSY breaking, beyond the scope of this talk ....

HIDDEN-SECTOR SUSY BREAKING



Fortunately, how SUSY is broken in the hidden sector is largely irrelevant for phenomenology :-)

Far more important are the mediation mechanism and the associated scale of SUSY breaking !

gravity, gauge, gaugino, anomaly ... mediation,
string inspired models, ...

$\longrightarrow$ Boundary conditions for soft parameters at a high scale.

THE SCALE OF SUSY BREAKING

- In gravity-mediated SUSY breaking the hidden sector communicates with the MSSM through gravitational interactions

VEV of hidden sector field

$$m_{soft} \sim \frac{\langle F \rangle}{M_P} \quad \longrightarrow \quad \sqrt{\langle F \rangle} \sim 10^{11}\ \mathrm{GeV}.$$

$\mathcal{O}$(weak scale)

- In gauge-mediated SUSY breaking the MSSM soft terms arise from loop diagrams involving some *messenger* particles

$$m_{soft} \sim \frac{\langle F \rangle}{M_{mess}}$$

and $\sqrt{\langle F \rangle}$ can be as low as $10^4 - 10^5$ GeV!

GOLDSTINO AND GRAVITINO

- Spontaneous breaking of a global symmetry leads to a massless Nambu-Goldstone mode

  with the same quantum numbers as the broken symmetry generator.

- In SUSY, the broken generator is the fermionic charge Q_α.

- Hence the Nambu-Goldstone mode is a massless neutral Weyl fermion, the goldstino.

- In local SUSY, the longitudinal components of the goldstino are absorbed by the gravitino, which thus acquires a mass.

$\longrightarrow$ *super-Higgs mechanism*

Gravitino Mass

$$m_{\tilde{G}} = m_{3/2} = \frac{\langle F \rangle}{\sqrt{3} M_P}$$

- In gravity/anomaly mediated SUSY breaking, this gives

$$m_{\tilde{G}} \sim m_{soft} \sim \mathcal{O}(100)\ \mathrm{GeV}$$

$\longrightarrow$ $\tilde{G}$ does not play any role in collider physics.

.....

- In gauge mediation with $M_{mess} << M_P$, the gravitino turns out to be the lightest SUSY particle (LSP), $m_{\tilde{G}} \sim$ eV – keV.

$\longrightarrow$ Phenomenology characterized by NLSP $\longrightarrow \tilde{G}$ decays !

Gravity Mediation

mSUGRA: $\boldsymbol{m_0, m_{1/2}, A_0, \tan\beta}$, sgn($\boldsymbol{\mu}$)

GRAVITY MEDIATION

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

Gaugino masses (GUT relation):

$$M_1 : M_2 : M_3 \sim 1 : 2 : 7, \qquad M_1 \sim 0.4\, m_{1/2}$$

Higgsino mass parameter

$$|\mu|^2 \sim 0.03\, m_0^2 + 1.2\, m_{1/2}^2 - 2A_0 m_{1/2} - 0.9 A_0^2$$

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Therefore $|\mu| > M_2$ in most benchmark scenarios ($A_0 \leq 0$) and

$$\begin{array}{lll} \tilde{\chi}_1^0 & \sim \tilde{B} & : \quad m_{\tilde{\chi}_1^0} \sim M_1 \\ \tilde{\chi}_2^0, \tilde{\chi}_1^\pm & \sim \tilde{W}^0, \tilde{W}^\pm & : \quad m_{\tilde{\chi}_2^0}, m_{\tilde{\chi}_1^\pm} \sim M_2 \\ \tilde{\chi}_{3,4}^0, \tilde{\chi}_2^\pm & \sim \tilde{H}^0, \tilde{H}^\pm & : \quad m_{\tilde{\chi}_{3,4}^0}, m_{\tilde{\chi}_2^\pm} \sim |\mu| \end{array}$$

MSUGRA

Sleptons and squarks:

$$m_L^2 \sim m_0^2 + 0.5\, m_{1/2}^2, \qquad m_Q^2 \sim m_0^2 + 6.3\, m_{1/2}^2,$$
$$m_E^2 \sim m_0^2 + 0.15\, m_{1/2}^2, \qquad m_{U,D}^2 \sim m_0^2 + 5.8\, m_{1/2}^2.$$

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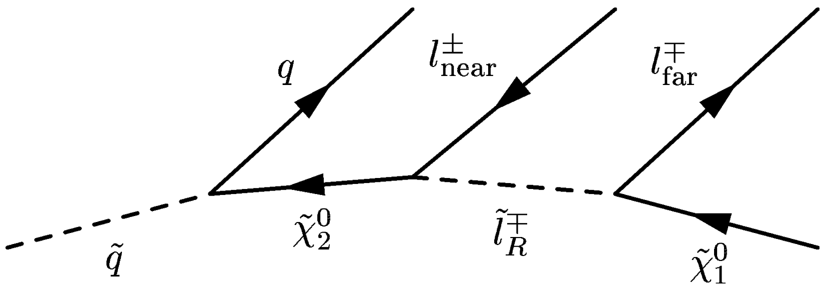
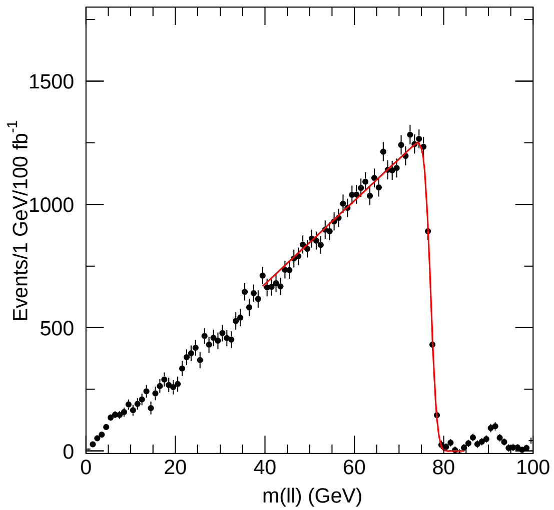
Typical mass pattern for not too large m_0:

$$m_{\tilde{\chi}_1^0} < m_{\tilde{\ell}_R} < m_{\tilde{\ell}_L}, m_{\tilde{\chi}_2^0} \ll m_{\tilde{t}_1} \lesssim m_{\tilde{q}_R} < m_{\tilde{q}_L}$$

Golden LHC SUSY signature:



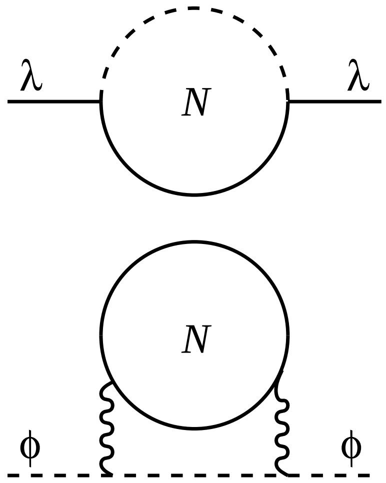


→ **talk by Frank Paige**

I. Hinchliffe, F.E. Paige, et al.; G. Polesello, ...

GAUGE MEDIATION

In GMSB, SUSY is broken by a gauge-singlet chiral supermultiplet S. This breaking is communicated to the visible sector by messenger particles N which have ordinary gauge interactions. Scale = M_{mess}.



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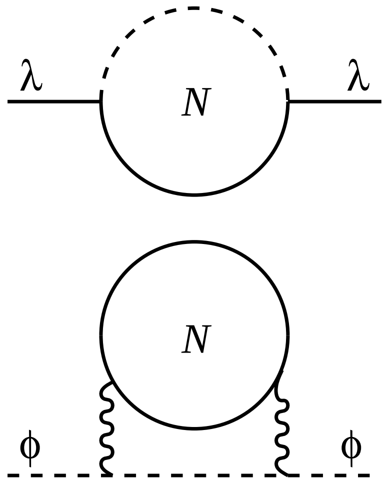


- GUT relation holds for gaugino masses.
- Squark/slepton flavors are a priori degenerate.
- Sleptons and Higgses are typ. much lighter than the squarks.
- LSP = gravitino.

Typical mass ordering:

$$m_{\tilde{B}}, m_{\tilde{l}_R} < m_{\tilde{W}}, m_{\tilde{l}_L} << m_{\tilde{g}}, m_{\tilde{q}}$$

Gauge Mediation

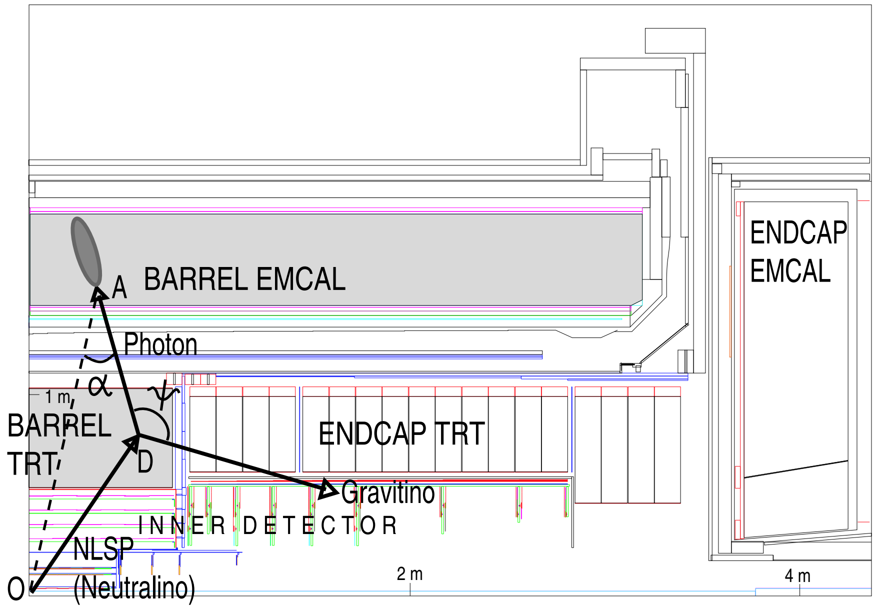
LSP = gravitino, $m_{\tilde{G}} = \text{eV} - \text{keV}$

Phenomenology characterized by *nature and lifetime* of the NLSP!

(NLSP $\tilde{X} \to X\tilde{G}$ decays; prompt / macroscopic / outside detector)

NLSP	decay mode
gaugino-like neutralino	$\tilde{\chi}_1^0 \to (\gamma, Z)\,\tilde{G}$
higgsino-like neutralino	$\tilde{\chi}_1^0 \to h\,\tilde{G}$
stau	$\tilde{\tau}_1 \to \tau\,\tilde{G}$
slepton	$\tilde{\ell}_R \to \ell\,\tilde{G}$
squark	$\tilde{q} \to (q,\, q'W)\,\tilde{G}$
gluino	$\tilde{g} \to g\,\tilde{G}$

also co-NLSP's in degenerate cases.....



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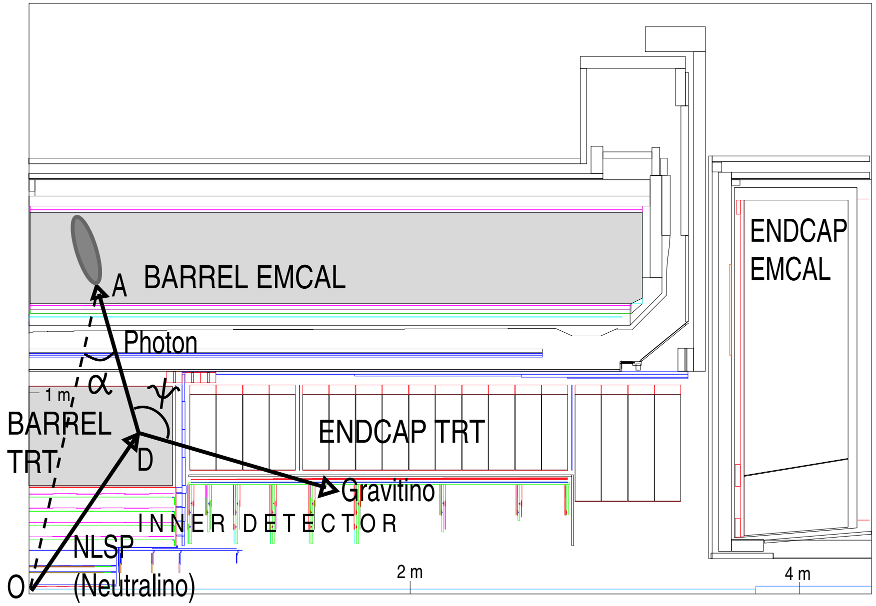
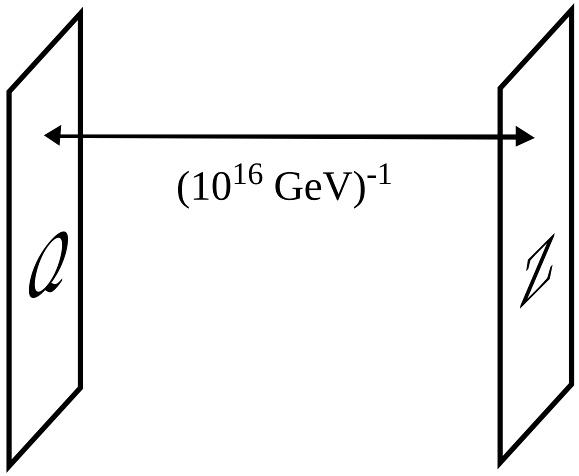


GMSB adds a vast variety of possible signals

Baer et al., 1998; Hinchliffe, Paige, 1998; Ambrosanio et al., 2000;
Diaz-Cruz, Ghosh, Moretti, 2003; Kawagoe et al., 2003.

Anomaly Mediation

In AMSB, SUSY-breaking fields are placed on one 3-brane and MSSM fields on another. Supergravity contributions are thus suppressed geometrically.



The MSSM soft terms are then generated by loop-suppressed contributions of order $\sim (1/16\pi^2)\langle F\rangle/M_P$ arising from the 'super-Weyl anomaly'.

Anomaly Mediation

Peculiar gaugino mass spectrum: $M_2 \sim \frac{1}{3} M_1$. The lightest states are hence a triplet of Winos

$$\text{NLSP:} \qquad \tilde{\chi}_1^{\pm} \approx \tilde{W}^{\pm}$$

$$\text{LSP:} \qquad \tilde{\chi}_1^{0} \approx \tilde{W}^{0}$$

with a typical mass splitting of $\mathcal{O}(100)$ MeV ! $\quad \tilde{\chi}_1^{\pm} \to \tilde{\chi}_1^{0} \pi^{\pm}$

Another unique feature is the near-degeneracy of $\tilde{l}_L$ and $\tilde{l}_R$.

$\longrightarrow$ yet another new class of SUSY signatures.

F.E. Paige, J.D. Wells, hep-ph/0001249,
H. Baer, J.K. Mizukoshi, X. Tata, hep-ph/0007073,
A.J. Barr, et al., hep-ph/0208214; A. Datta, K. Huitu, hep-ph/0211319.

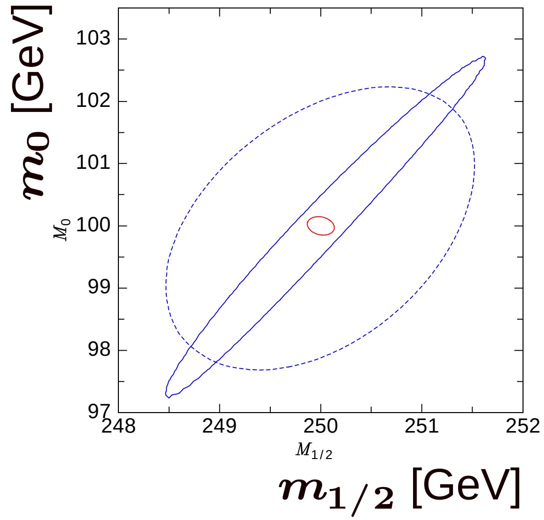
Parameter Determination

- Different models feature different (though sometimes similar) characteristics of the sparticle spectrum

  $\longrightarrow$ few parameters, predictive, good for benchmarking, etc.

- Once SUSY is discovered: want to relate observations to the underlying model parameters and ultimatly determine the high-scale structure of the theory !

  - good strategy, relevant measurements
  - sophisticated computational tools
  - careful assessment of uncertainties



Top-down fit [ATLAS TDR],

Discrimination analysis [Allanach, Grellscheid]

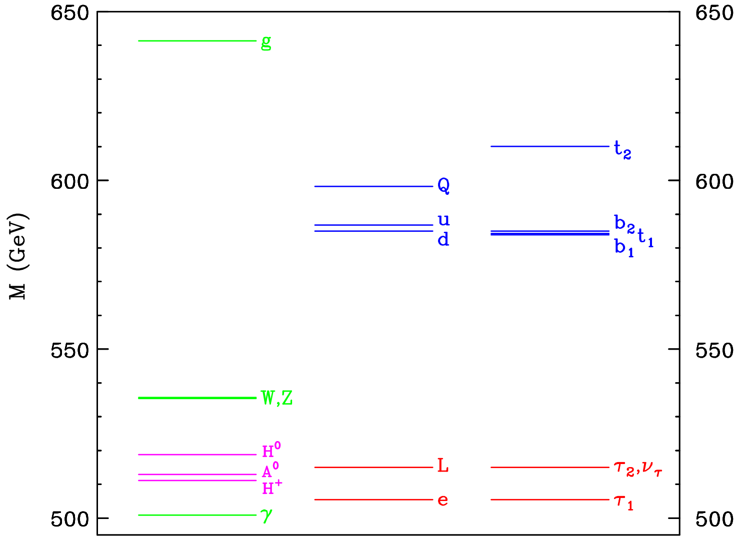
Bottom-up reconstruction [Blair, Porod, Zerwas]

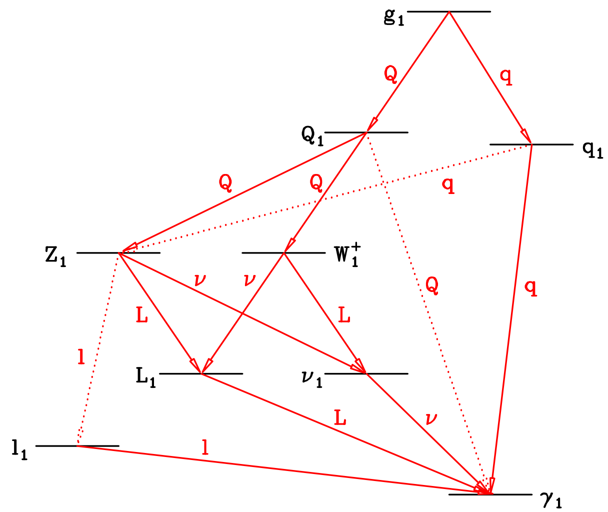
Sfitter, Fittino, SPA project ...

$\longrightarrow$ **Tilman Plehn's talk in the SUSY session.**

FAKE SUSY ?

Universal extra dimensions:
1st level of KK modes may look like SUSY
(except for spin)





[Cheng, Matchev, Schmaltz, hep-ph/0205314]

SUSY Dark Matter

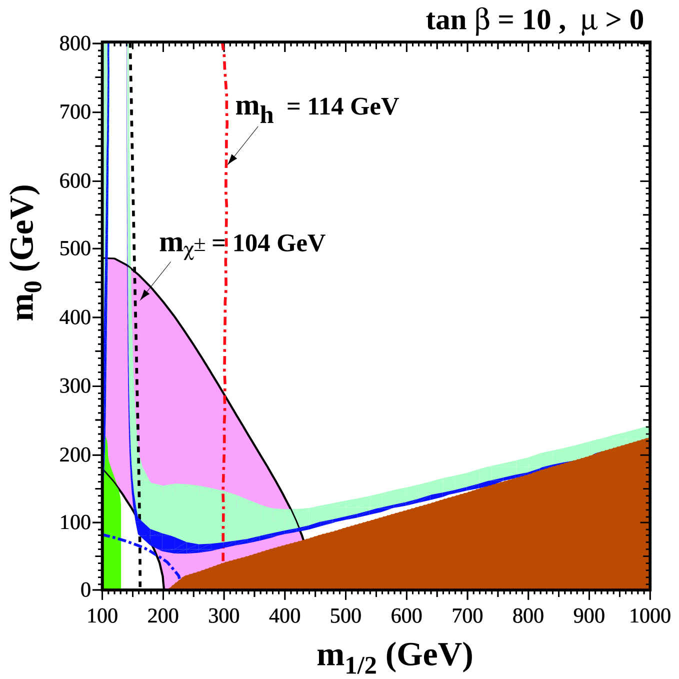
LSP is a very good CDM candidate

- neutralino
- gravitino
- axino

WMAP: $0.094 < \Omega h^2 < 0.129$

hot topic, flood of papers
constraining SUSY this way

mSUGRA, $A_0 = 0$, $\tan\beta = 10$



Ellis, Olive, Santoso, Spanos
hep-ph/0303043

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WMAP: $0.094 < \Omega h^2 < 0.129$

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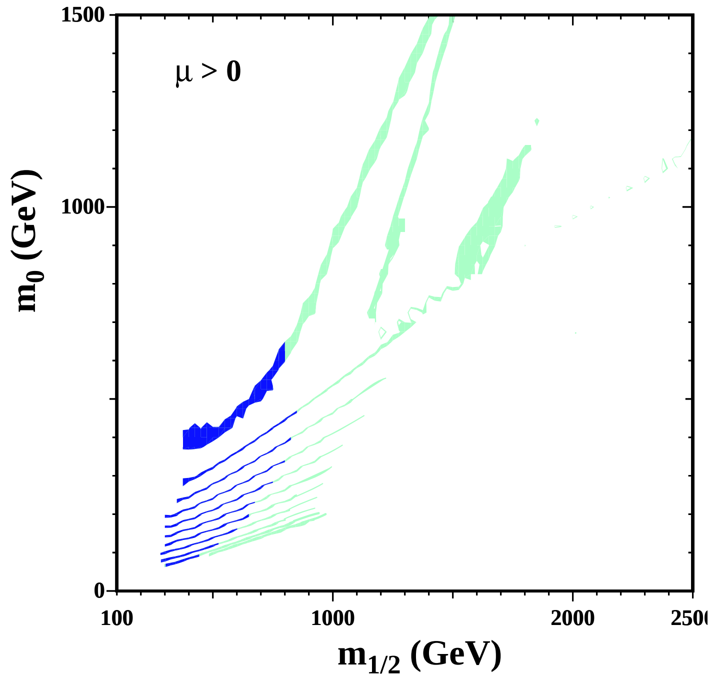
mSUGRA, $A_0 = 0$, $\tan\beta = 5, 10$



Ellis, Olive, Santoso, Spanos
hep-ph/0303043

see also Baltz, Gondolo
hep-ph/0307039

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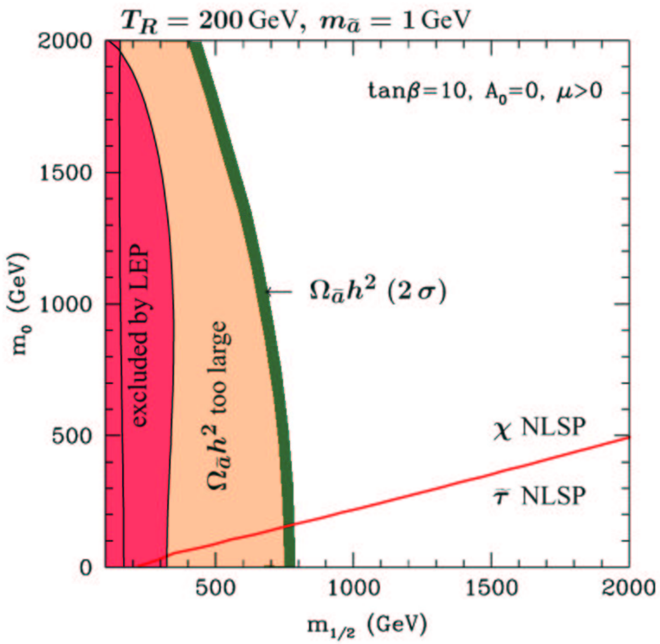
mSUGRA + axino



Covi et al., hep-ph/0402240

axino = LSP

$\tilde{\chi}^0_1 \longrightarrow (\gamma, Z)\, \tilde{a}$

or $\tilde{\tau}_1 \longrightarrow \tau \tilde{a}$

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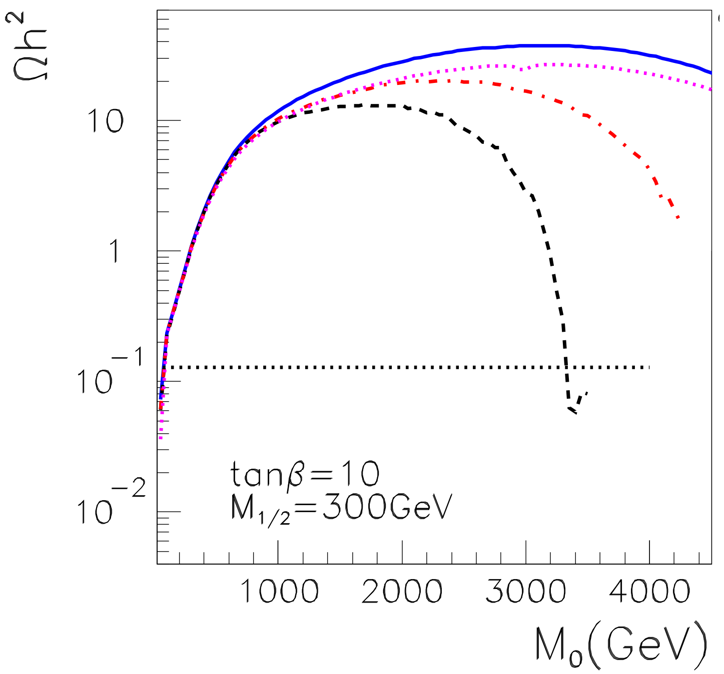
very model/scenario dependent,
uncertainties not taken into account

$\longrightarrow$ **talk by Genevieve Belanger (hep-ph/0402161).**



CP Violation

Soft-breaking parameters can have CP-violating phases, e.g.

$$M_1 = |M_1|\, e^{i\phi_1}, \quad A_t = |A_t|\, e^{i\phi_t}, \quad \ldots.$$

Very interesting possibility since

- CPV is still an open question in the SM
- we *need* additional sources of CPV to explain the observed baryon asymmetry in the Universe

see e.g., Dine, Kusenko, hep-ph/0303065

SUSY CP phases are heavily constrained by EDMs. However, these constraints are model dependent; some phases can still be large.

$\Rightarrow$ can considerably change phenomenology

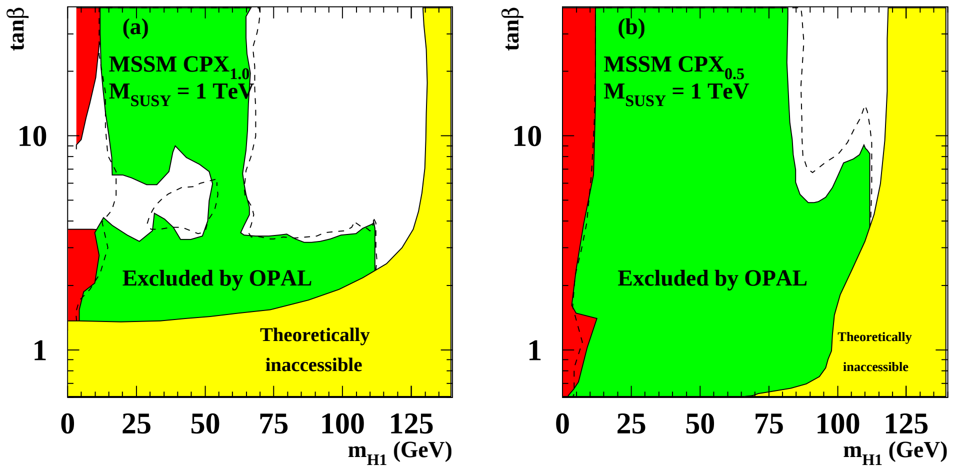
CP Violation

Consequences of CPV phases:

- Higgs-sector CP mixing: $h^0, H^0, A^0 \longrightarrow H_1^0, H_2^0, H_3^0,$ no longer pure scalar or pseudoscalar states !
- cross sections and branching ratios can change significantly, e.g., $gg \to H$, $\tilde{\chi}_2^0 \to H\tilde{\chi}_1^0$, $\tilde{b} \to b\tilde{\chi}^0$, ...
- CP asymmetries, polarization effects (mainly @ LC)

LEP Higgs limits change completely:

OPAL collab., hep-ex/0406057



$\longrightarrow$ **talk by Rohini Godbole**

CP and non-standard Higgs study group, `http://cern.ch/kraml/cpnsh/`

Lepton Flavor Violation

neutrino oscillations $\longrightarrow$ neutrino masses and mixing
first real BSM signal!

In SUSY, neutrino masses can be generated through

- the usual see-saw mechanism, adding a heavy ν_R
- R-parity violation (lepton-neutralino mixing, rad. corr.)

Massive neutrinos in turn

- affect the $\tilde{l}$ mass matrix by RG running and virtual corrections
- lead to LFV in the charged lepton sector ($\tau \longrightarrow \mu\gamma, \mu \longrightarrow e\gamma$,...)
- lead to LFV in processes with sleptons and sneutrinos (SLFV), e.g. $\tilde{\chi}^0_2 \longrightarrow \tilde{\tau}\tau \longrightarrow e\tau\tilde{\chi}^0_1$

Very popular topic, vast literature developing,
large signals possible @ LHC $\longrightarrow$ **talk by Werner Porod**

CONCLUSIONS

SUSY phenomenology is extremely rich:

- Different SUSY-breaking scenarios can lead to quite different characteristics of the spectrum.
- SUSY dark matter: neutralino, gravitino, axino, ... ?
- CP violation, lepton flavor violation, ... ?
- SUSY + extra dimensions ?
- Need to search with an open mind!

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