30 years of searches for SUSY at colliders

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This presentation covers the **direct searches for supersymmetric particles** at high-energy colliders performed **in the time period 1980 to 2010**, i.e. until the beginning of LHC data taking.

The colliders in operation during that period were (*):

- **In the eighties**, the e+e- colliders **PEP** at SLAC, **PETRA** at DESY and **TRISTAN** at KEK
  and the **SppS** p-pbar collider at CERN
- **In the nineties**, the **LEP** e+e- collider at CERN
  and the **Tevatron** p-pbar collider at Fermilab
- **In the first 10 years of the XXIst century**
  the upgraded **Tevatron** p-pbar collider at Fermilab.

The results presented are somewhat biased by my participation in the following experiments: CELLO at PETRA, ALEPH at LEP, D0 at the Tevatron and ATLAS at the LHC.

(*): The **SLC** e+e- collider at SLAC and the **HERA** ep collider at DESY did not contribute to the searches reported here: apologies !

The theory of supersymmetry developed rapidly in the seventies.

In the second half of this decade, Pierre published a number of papers that were seminal for the phenomenology of supersymmetry.

In particular:
Supersymmetry and Weak, Electromagnetic and Strong Interactions,
Phys.Lett. 64B (1976) 159
Spontaneously Broken Supersymmetric Theories of Weak, Electromagnetic and Strong Interactions, **Phys.Lett. 69B (1977) 489**
can be regarded as the ancestors of what became known as the MSSM.

Together with Glennys Farrar, he introduced the concept of R-parity, actually in a footnote of *Phenomenology of the Production, Decay, and Detection of New Hadronic States Associated with Supersymmetry,* **Phys.Lett. 76B (1978) 575-579**
a paper where constraints on light gluinos (forming R-hadrons) were derived , mostly from beam-dump experiments.

Next, Glennys and Pierre provided some food for experimentalists with
Searching for the spin-0 leptons of supersymmetry, **Phys.Lett. 89B (1980) 191-194**
… and this closes the list of theoretical references in this talk.

Progelomena

The phenomenology of supersymmetry is extremely diverse, depending on the SUSY breaking mechanism, on whether R-parity is conserved or not, on the nature of the lightest supersymmetric particle (LSP)… And even within each SUSY model, there are a possibly large number of unknown parameters (the soft-breaking terms).

In this talk, given the amount of time allocated,

- the **SUSY breaking** mechanism is **inspired by supergravity**,
- the **LSP** is the **lightest neutralino** (actually a pure **photino** in the early days),
- there is **no source of CP-violation** beyond that present in the CKM matrix, and
- **R-parity** is assumed to be **conserved**.

Alternative frameworks, such as GMSB or R-parity violation, were actually also studied in detail. Therefore, the set of results presented here, although fairly representative, does not do appropriate justice to the ingenuity invested by the experimentalists in their searches for SUSY over more than three decades.

The eighties

In the early eighties, the hot topics for searches were:

- The gluon and the top quark
- The W and Z bosons

Nevertheless, the interest in searches for supersymmetry increased gradually…

Searches at e+e- high-energy colliders

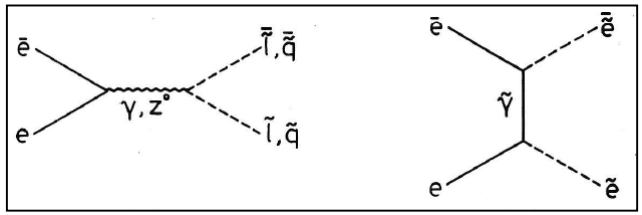
e+e- high-energy colliders and experiments in the eighties:

PEP:	29 GeV	- MARK 2, MAC, ASP
PETRA:	35 – 46.6 GeV	- CELLO, JADE, MARK J, PLUTO, TASSO
TRISTAN:	52 – 60 GeV	- AMY, TOPAZ, VENUS

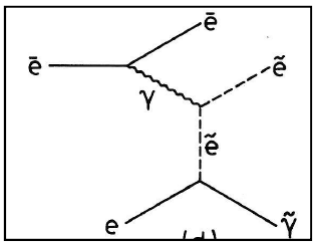
In e+e- collisions, all SUSY particles, except for the gluino, are produced in a democratic way via electroweak interactions. The search is therefore naturally directed toward the lightest ones, typically assumed to be the NLSP, and the results are interpreted in a fairly model-independent way.

As instructed by Glennys and Pierre, experiments at PEP and PETRA undertook immediately searches for spin-0 leptons.

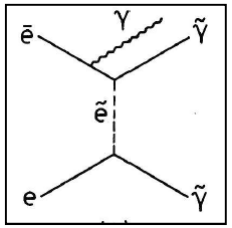
Because of t-channel exchange processes, searches for **selectrons** were the most sensitive, with $\tilde{e} \rightarrow e\,\tilde{\gamma}$.



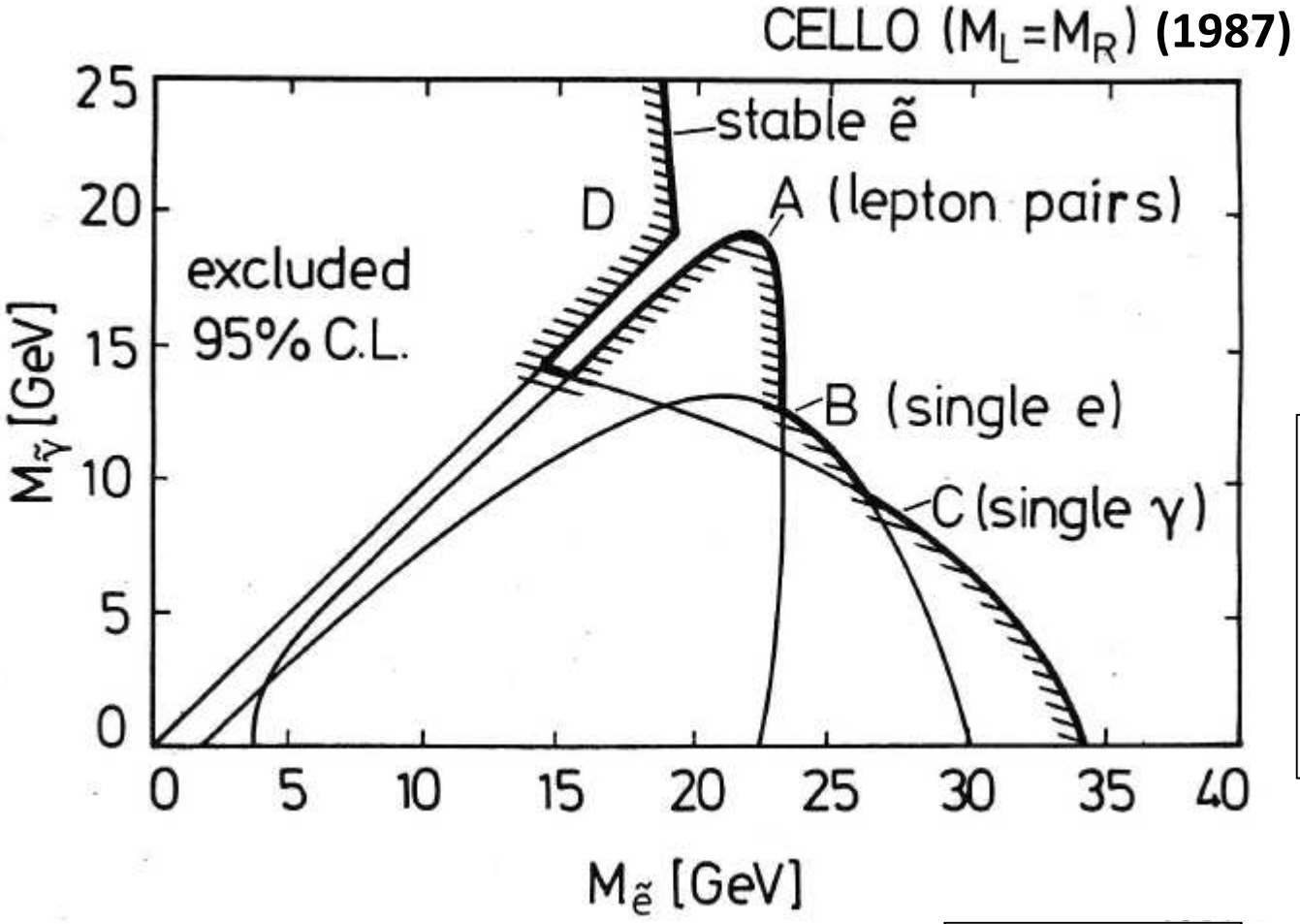
Here the final state is an acoplanar pair of electrons with missing energy carried away by the photinos.
The mass reach is limited to the beam energy



Here the spectator electron is undetected and the visible final state is a single electron.
The cross section is lower than for pair production,
but the mass reach extends beyond the beam energy.

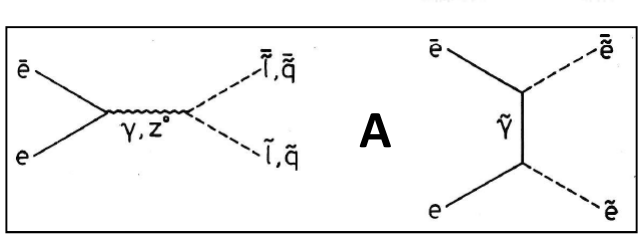


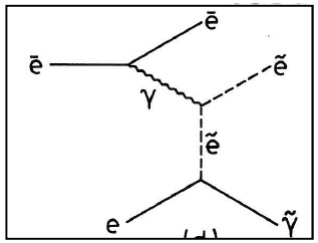
Here, tagging by an ISR photon is necessary as the final state is otherwise invisible.
The cross section is even lower than for single selectron production and the requirements on the detector (hermetic calorimetry) are especially challenging.

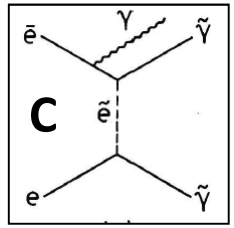


A increased by ~6 GeV at TRISTAN

C extended @90% CL to 51.5 GeV by CELLO, to 58 GeV by ASP@PEP, and to **68.5 GeV** by CELLO/MARK J/ASP/MAC for massless photinos







Z.Phys. C35 (1987) 181

Searches at hadron colliders

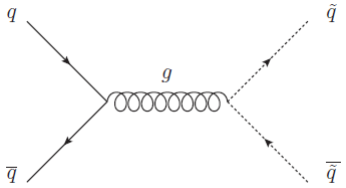
The **hadron collider** in operation in the eighties was the **SppS** (*say* "*SppbarS*"**),**
with two large experiments: **UA1 and UA2.**
The center-of-mass energy was **630 GeV.**

At hadron colliders, the most copiously produced SUSY particles are expected to be the colored ones, namely **squarks and gluinos**.

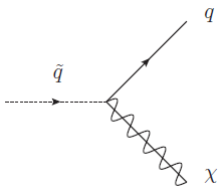
The pattern of lighter SUSY particles, however, plays a role in the interpretation of the search results, as it has an impact on the squark and gluino decay chains.

This complication was generally ignored at the time.

Topologies for squark and gluino searches



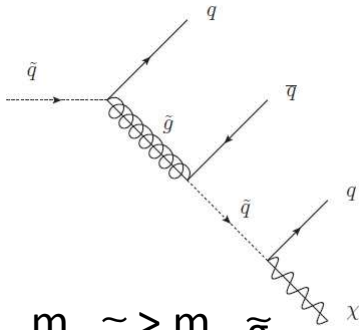
with



$m_{\tilde{q}} < m_{\tilde{g}}$

Acoplanar jets

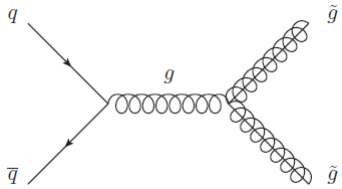
or



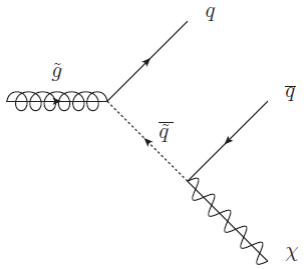
$m_{\tilde{q}} > m_{\tilde{g}}$

Multijets + MET

Squark pair production

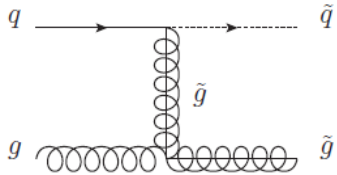


with



≥ 4 jets + MET

Gluino pair production

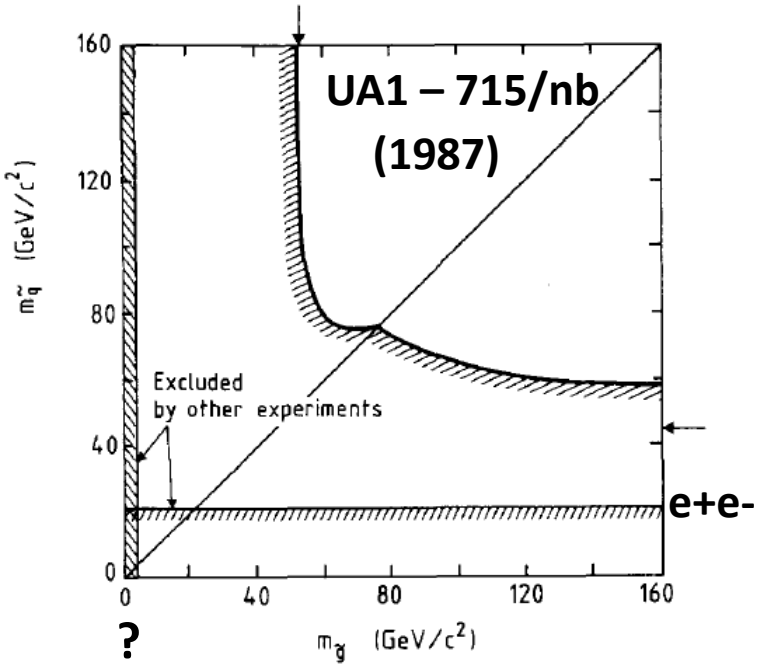


Associated production

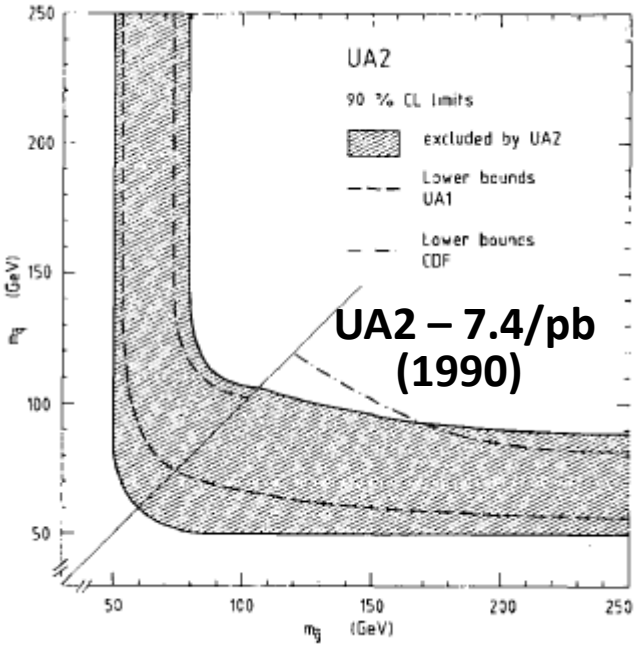
≥ 3 jets + MET

Main background: multijet with jet mismeasurement, reduced by topological cuts , e.g., $\Delta\varphi$(MET, jets)

Phys.Lett. B198 (1987) 261-270



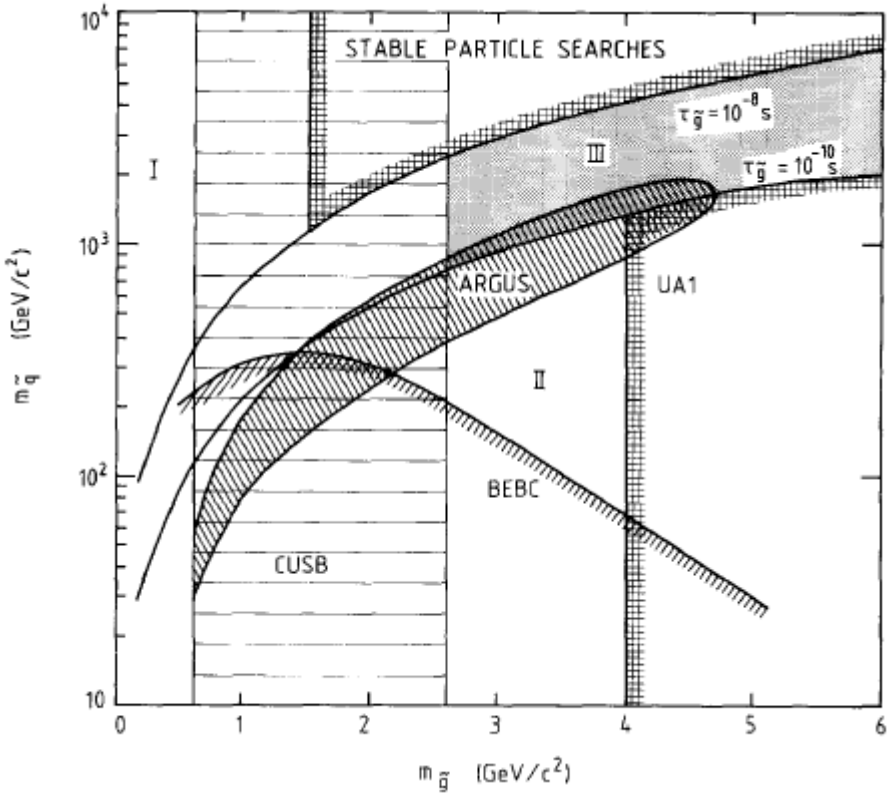
Phys.Lett. B235 (1990) 363-372



$m_{\tilde{g}} = m_{\tilde{q}}$ > 106 GeV

Results shown for $m_{\tilde{\gamma}} = 0$ (little change up to 20 GeV)
Cascade decays are ignored.
Five x 2 (L-R) flavors of mass degenerate squarks.

What about light gluinos ?



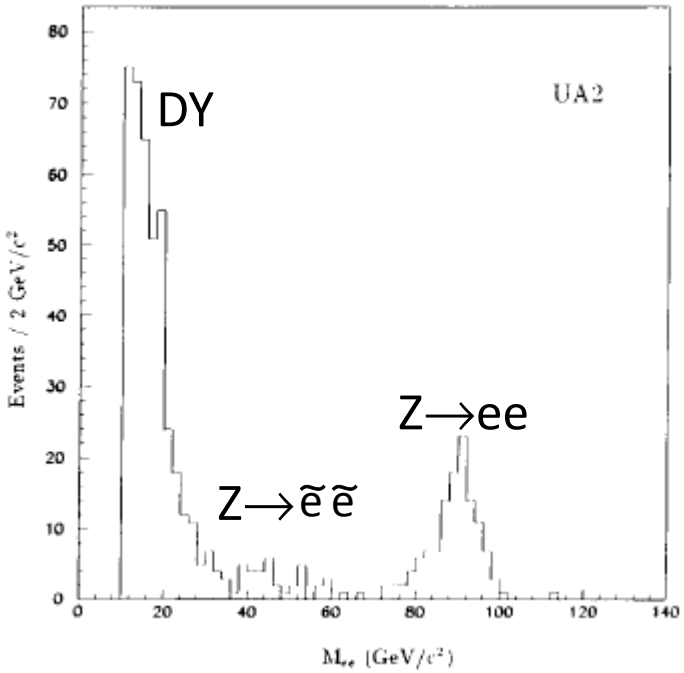
Pre-SppS searches for a light gluino : in Υ and χ_b decays, beam dump experiments, stable particle searches. Regions I and II are unexcluded.

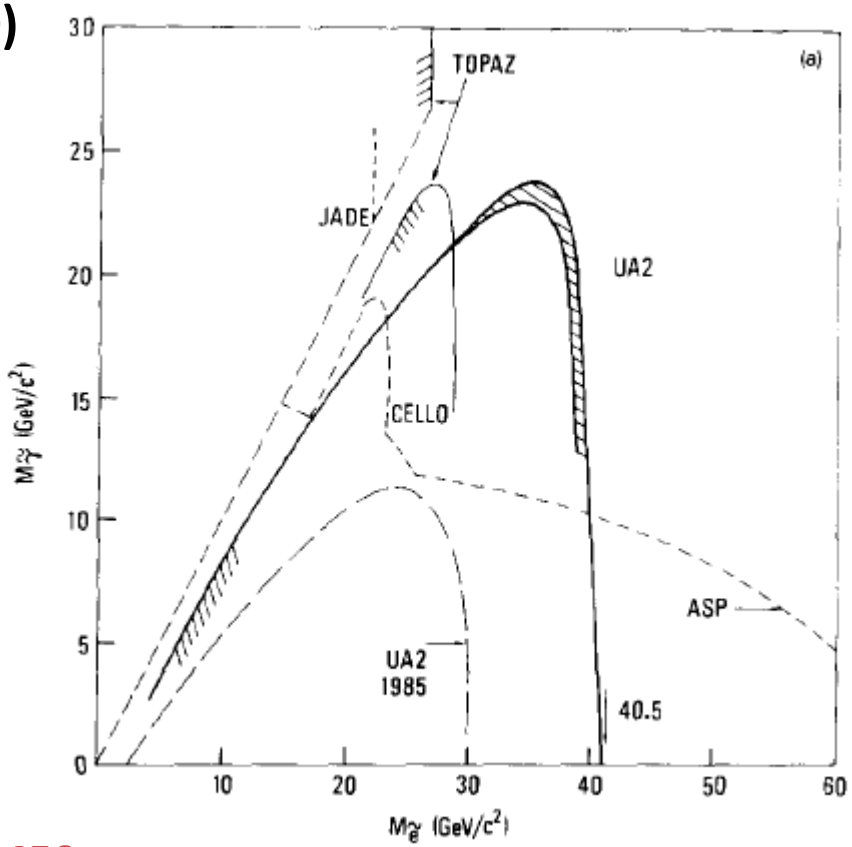
Issue settled at LEP1 (ALEPH, P. Janot): running of α_s, color factors from event shapes, Z hadronic width $\Rightarrow$ **$m_{\tilde{g}}$ > 6.3 GeV**

Phys.Lett. B198 (1987) 261-270

At the SppS, also **selectrons** were searched **in Z decays**
as lepton pairs with masses intermediate between DY and Z→ee.
The selectron mass reach was extended to **~40 GeV**.

UA2 (1990)





Phys.Lett. B238 (1990) 442-450

Legacy of the eighties (with a photino LSP)

- m_selectron > ~40 GeV (m_photino < 20 GeV)
- m_selectron > ~68 GeV (m_photino = 0)
- m_wino/smuon > ~21 GeV (m_photino < 10 GeV) [not shown here]
- m_squark/gluino > ~75/80 GeV (m_photino < 20 GeV and no cascade decay)

The nineties

In the early nineties, the hot topics for searches were:

- The top quark
- The Higgs boson

Nevertheless, the interest in searches for supersymmetry was already well established…
With the increase in mass reach, the interpretation of experimental results was often lead to invoke less simplistic models, typically some flavor of the MSSM including unification assumptions.

Searches at LEP

Four large experiments: ALEPH, DELPHI, L3, OPAL

Two main running periods:

- LEP1 at and near the Z peak
- LEP2 up to 209 GeV

As previously, searches for SUSY particles initially targeted the lightest ones, typically assumed to be the NLSP, and the results were interpreted in a fairly model-independent way.

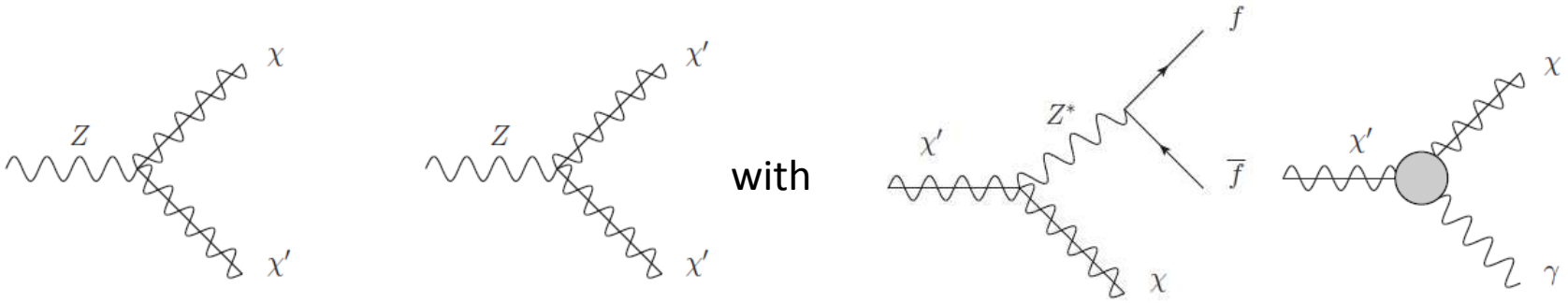
Further specifying the model, various search results were next combined to obtain constraints on the model parameters.

Searches for the Higgs bosons of the MSSM became an integral component of the searches for supersymmetry.

First SUSY results at LEP1

Mass limits close to **m_Z/2** were rapidly obtained at LEP1 for **sleptons** and **charginos** from searches for acoplanar lepton or jet pairs.

A novelty was the search for **neutralinos** in **Z→χχ'** and **Z→χ'χ'**, where χ is the lightest one, no longer a pure photino, and χ' is any heavier one.

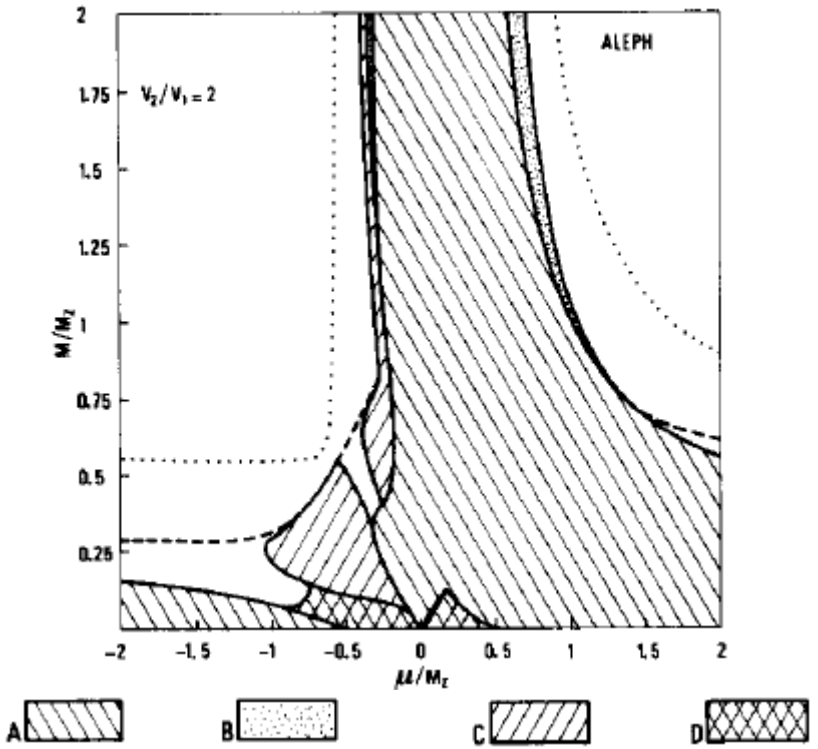


The final states considered were acoplanar leptons, jets or photons, monojets and single photons.

First SUSY results at LEP1 (1990)

The results were interpreted in the MSSM with **gaugino mass unification** and presented as exclusion regions in the (M,μ) plane for various values of tanβ = v2/v1.

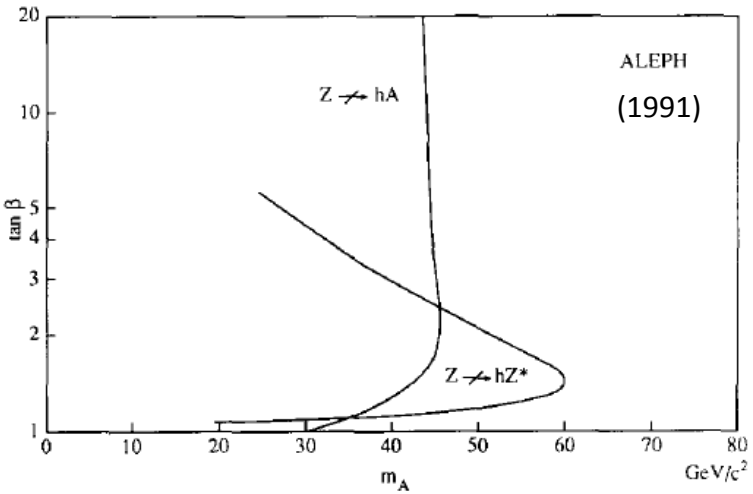
(A) is excluded by the Z line shape,
(B) by chargino searches,
(C) by neutralino searches with $\chi' \rightarrow \chi f \bar{f}$, and
(D) by neutralino searches with $\chi' \rightarrow \chi\gamma$.



Sleptons and squarks are assumed to be heavy enough to be ignored.
Sneutrinos are constrained by the invisible Z width measurement.

Phys.Lett. B244 (1990) 541-550

Early results on the Higgs bosons of the MSSM



Searches for the SM Higgs boson in the Z→HZ* channel were reinterpreted as searches for **Z→hZ***, where **h is the lighter CP-even** Higgs boson, with appropriately modified couplings.

The main decay channels were **h→bb/ττ**, but a novel decay mode, **h→AA** , had to be taken into account, where **A is the CP-odd** Higgs boson.

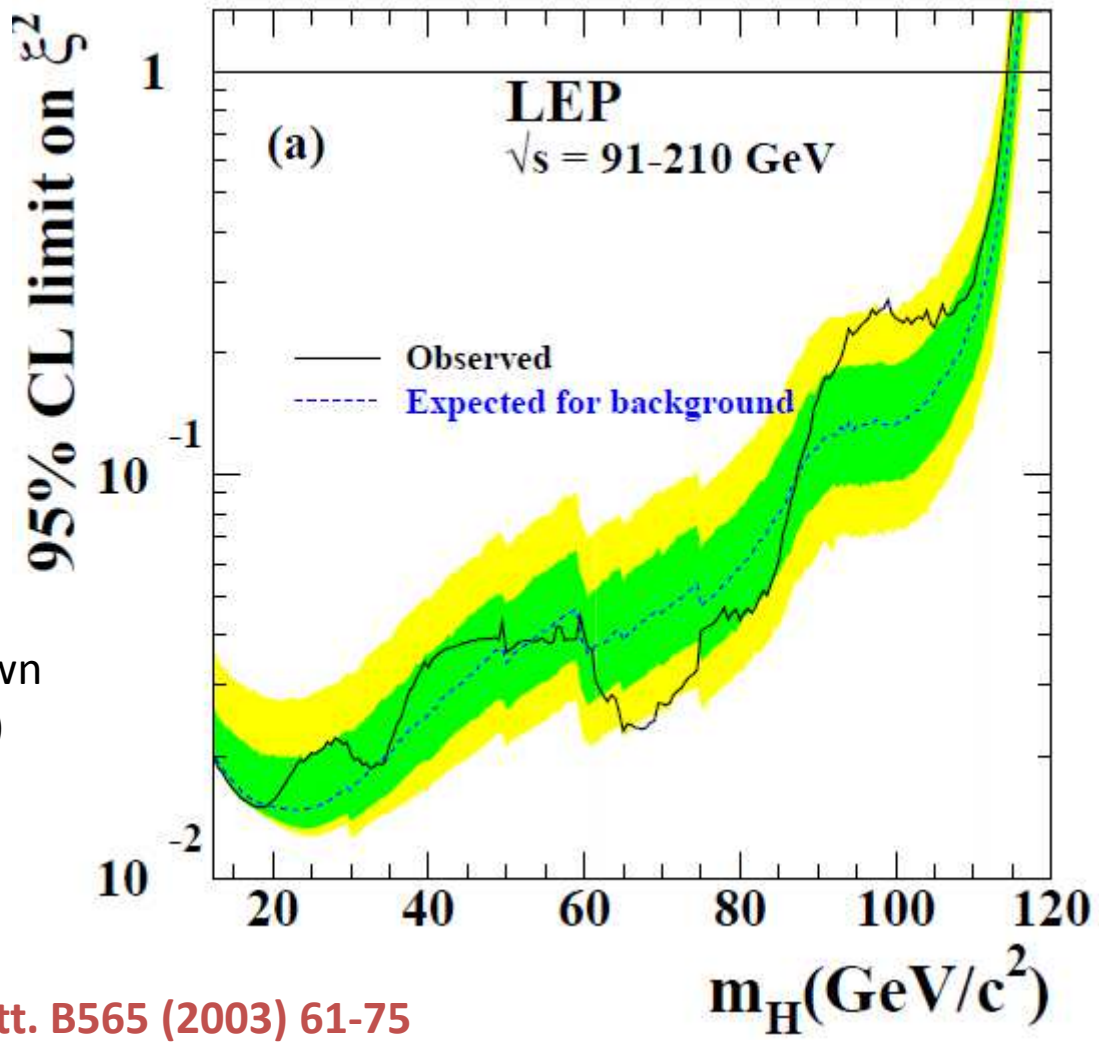
This channel became open for some parameter choices once the large **radiative corrections governed by the top and stop masses** had been taken into account. The main decay modes for the A boson were **A→bb/ττ**.

In addition, searches for the associated production **Z→hA** were performed, especially relevant for large values of tanβ

Phys.Lett. B265 (1991) 475-486

Final LEP results

Results from SM Higgs boson searches in e+e- → ZH



ξ is also known as $\sin(\beta-\alpha)$

Phys.Lett. B565 (2003) 61-75

Here SM BRs are assumed (mostly H→bb; also H→ττ)

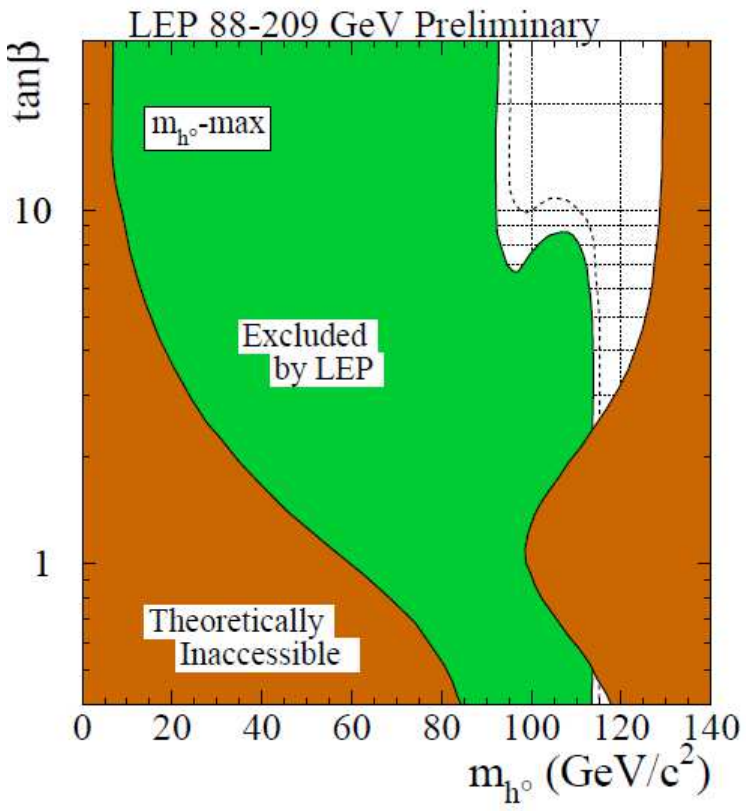
Similar results were obtained for flavor-independent or invisible decays.

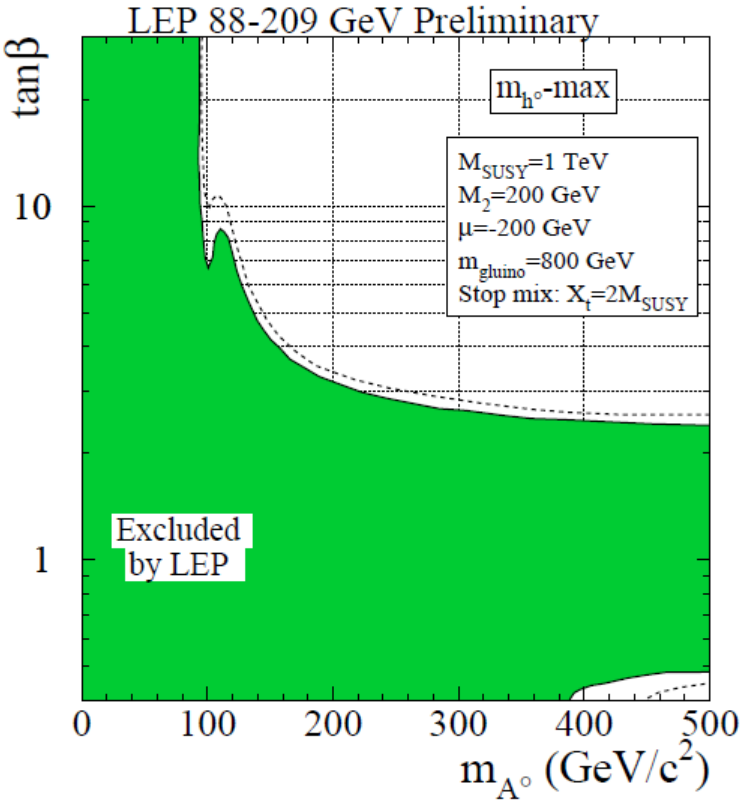
The region around 95 GeV remains exciting for some…

Results from the MSSM Higgs boson searches

e+e- → Zh and e+e- → Ah

A is the CP-odd state (A→ 90% bb/ 10% ττ)

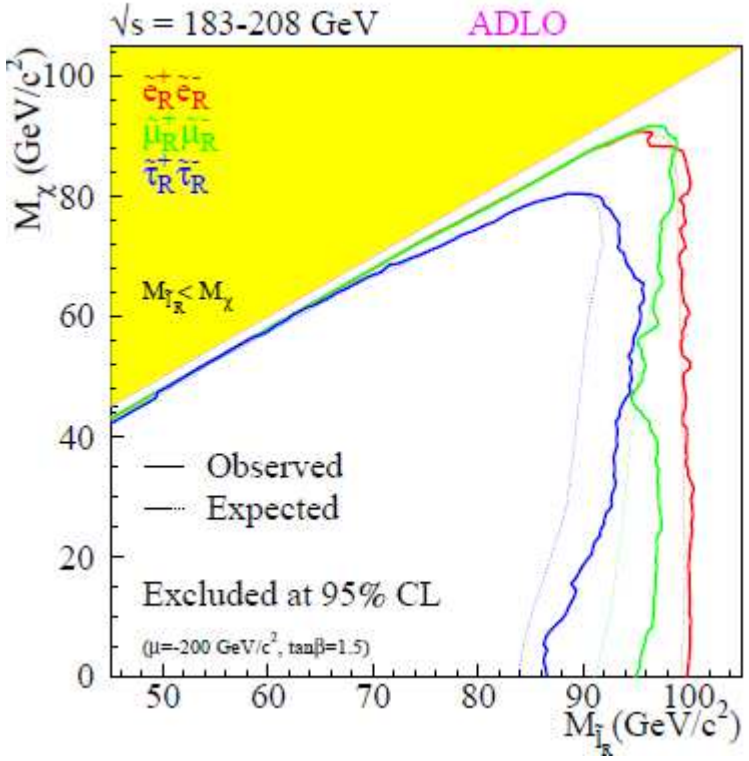




The exclusion at low tanβ comes from Zh, and at high tanβ from Ah.

arXiv:hep-ex/0107030

Sleptons



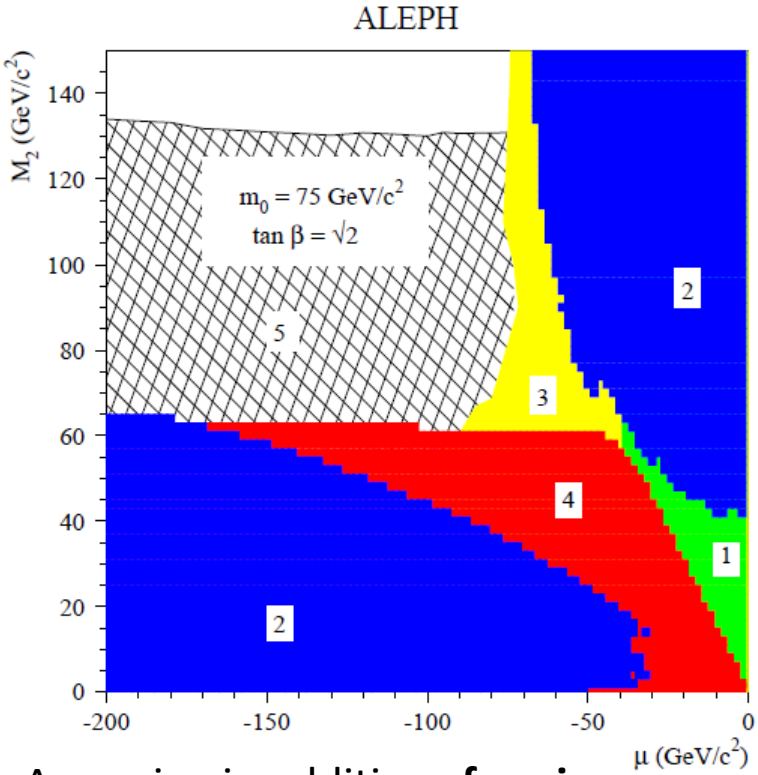
At LEP, less minimal models are considered. Here, the LSP is the lightest neutralino, rather than a pure photino.

In this plot, t-channel exchange of heavier neutralinos is included in the case of selectron pair production, and decays to χ' are also possible at low m_χ. Hence the specification of μ and tanβ, with gaugino mass unification assumed.

LEPSUSYWG/04-01.1

Charginos and neutralinos

Eur.Phys.J. C11 (1999) 193-216

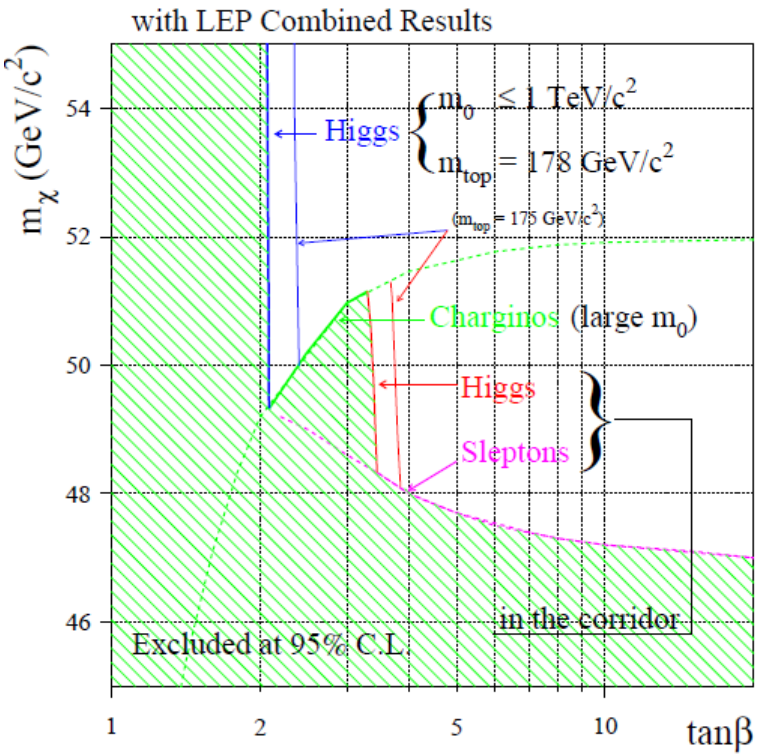


- Chargino masses up to **103 GeV** are excluded by direct searches with heavy sneutrinos (thus avoiding the destructive interference).
- Assuming **gaugino mass unification**, the regions excluded at LEP1 (1) and by direct chargino searches at LEP2 (2) are extended by the neutralino searches at LEP2 (3).
- Assuming in addition **sfermion mass unification**, slepton mass limits can be transalted into limits on M_2 for given values of m_0 and tanβ (4)
- Finally, the **constraints from Higgs boson searches** can be used in the low tanβ region (5): Basically (and oversimplifying), the Higgs mass limit provides a constraint on the stop mass. The stop mass depends on m_0 and M_3. For given values of m_0 and tanβ, a lower limit on M_3 is obtained, which is turned into a limit on M_2 using gaugino mass unification.

The LSP mass limit

- There is **no absolute mass limit on a χ LSP**: the production cross section vanishes for an appropriate choice of couplings; e.g. a pure photino with heavy selectrons.
- With **gaugino mass unification**, indirect limits result from , e.g., chargino searches. A chargino mass limit of 103 GeV holds for heavy sfermions , in which case the χ mass limit is 52 GeV at large tanβ.
- For lighter sfermions, a "corridor" opens up for small $\chi^{\pm}$ - $\tilde{\nu}$ mass differences, but this region is rescued by direct searches for sleptons under the assumption of **sfermion mass unification**.
- Finally, the **constraints from Higgs boson searches** can be used in the low tanβ region as explained in the previous slide.

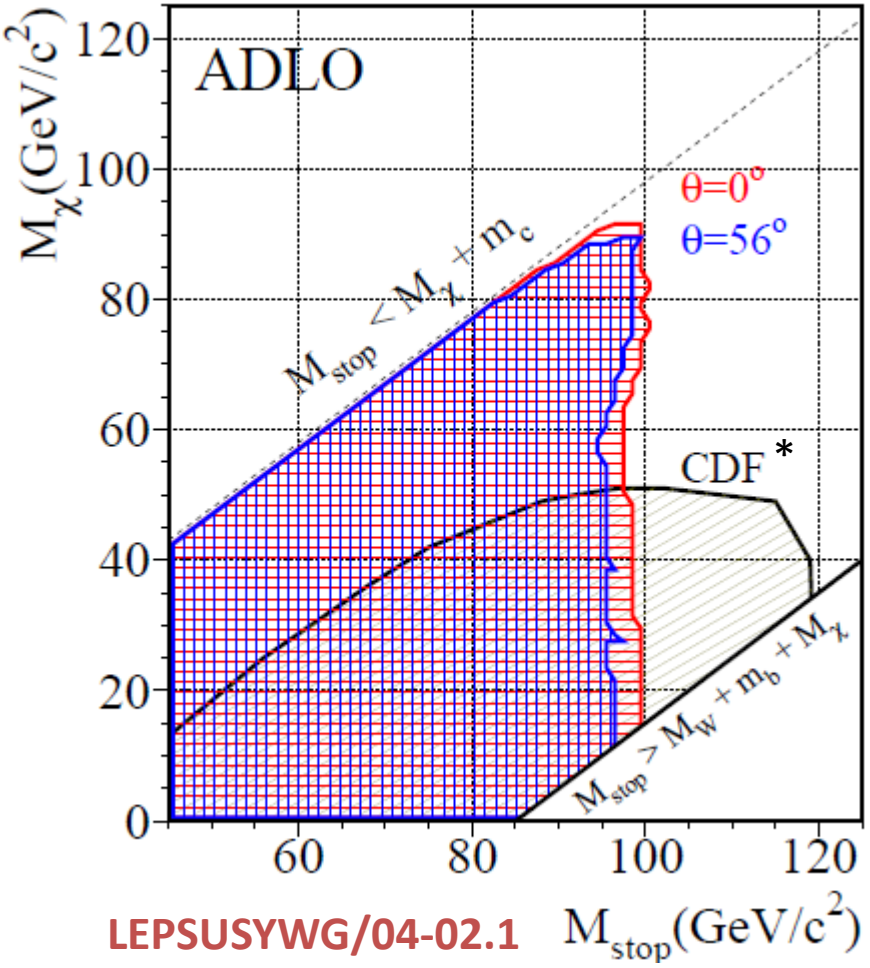
LEPSUSYWG/04-07.1



Parameters of the scan:
m_0, $m_{1/2}$, A_t, μ, tanβ, m_A

- In the end, the limit is set at **47 GeV** by slepton searches in the corridor at large tanβ.
- In **mSUGRA**, where $|\mu|$ and mA are not free parameters, a slightly tighter limit of **50 GeV** is obtained.

stop



LEPSUSYWG/04-02.1

(* This CDF limit was later updated.)

A limit on **generic squark** masses is set at **100 GeV**. For stop, L-R mixing is taken into account, including the case of vanishing coupling to the Z.

$\tilde{t} \rightarrow t\chi$ is kinematically forbidden.
Here, only **c**χ(loop decay) is shown,
but **bff'**χ was also considered.

For the smallest mass differences, searches for long-lived hadrons were performed, with stop hadronisation and stop-hadron interactions included in the simulation. This search lead to an **absolute mass limit** of **63 GeV**.

Phys.Lett. B537 (2002) 5-20

Searches at the Tevatron

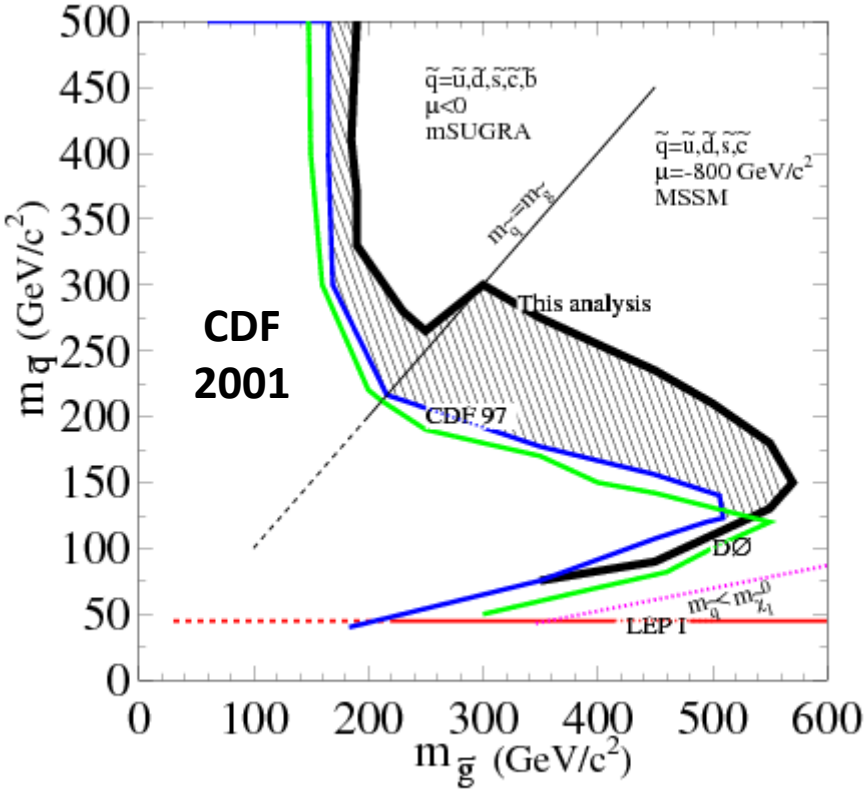
Run 1: $p\bar{p}$ @ 1.8 TeV

Two large experiments: **CDF** and **D0**

Essentially: colored SUSY particles

Occasional temporary excitements,
e.g., the ee$\gamma\gamma$event of CDF.

squarks and gluinos



With squark and gluino masses substantially larger than at the SppS, **cascade decays** can no longer be ignored and a model has to be used, here **mSUGRA** where a solution exists. (If not, for $m_{\tilde{q}} < m_{\tilde{g}}$, a simplified MSSM is used.)

$m_{\tilde{g}} = m_{\tilde{q}}$ > 300 GeV

Phys.Rev.Lett. 88 (2002) 041801

The early XXIst century

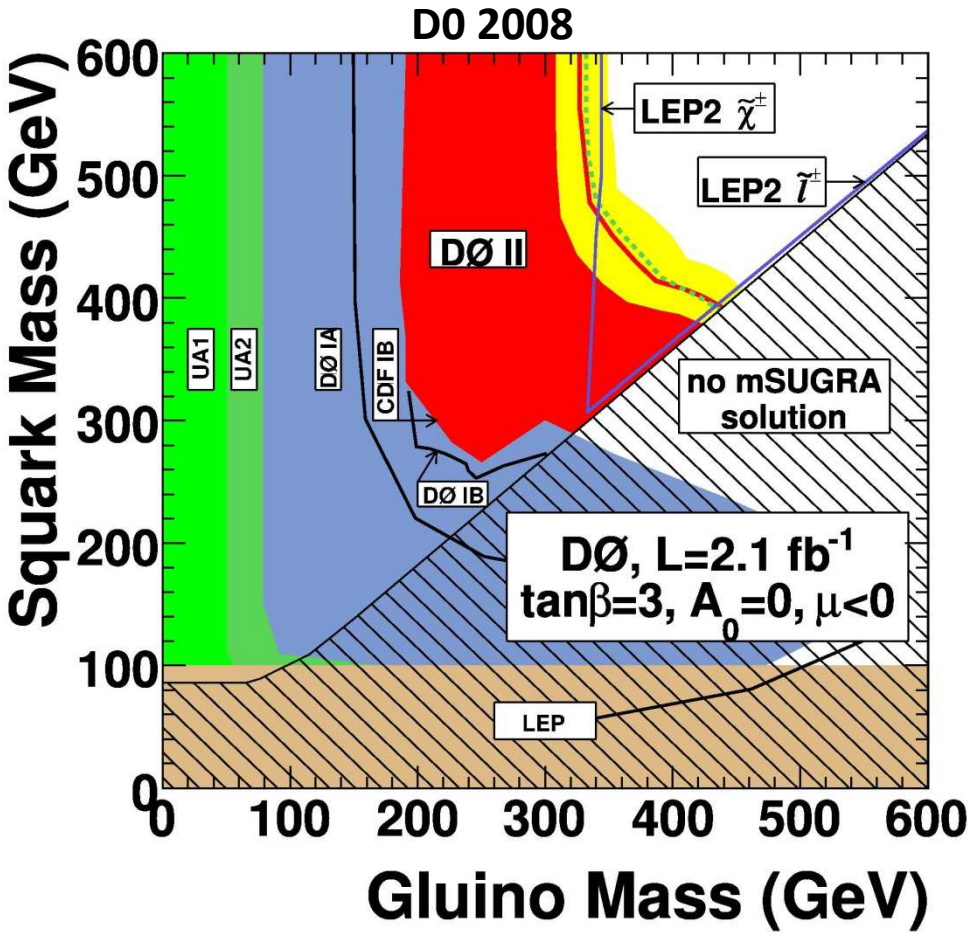
The high energy frontier was the upgraded Tevatron operating at 1.96 TeV.
The CDF and D0 detectors had also been upgraded.

The hot topic for searches was the Higgs boson.

Searches for supersymmetry were fully mature.

Squarks and gluinos

As always at a hadron collider, colored SUSY particles were the priority.



Results presented in the **mSUGRA** framework.

Within this framework, the LEP limits on chargino and slepton masses can be translated into limits in the squark-gluino mass plane.

The Tevatron results extend the region indirectly excluded at LEP.

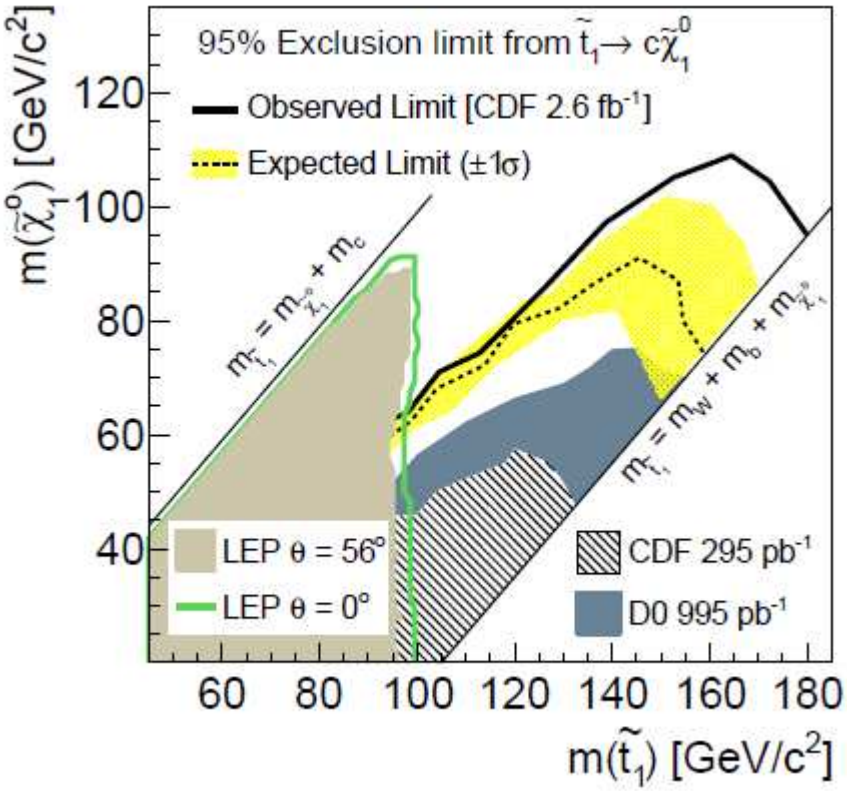
$m_{\tilde{g}} = m_{\tilde{q}} > 390$ GeV

Phys.Lett. B660 (2008) 449-457

stop

Because of L-R mixing and/or the top Yukawa coupling impact in the RGEs, a stop could be much lighter than the five x 2 generic squarks.

CDF 2012



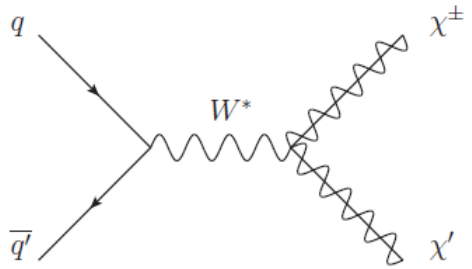
For large $\tilde{t}$ -χ mass splittings, a mass limit of **180 GeV** is set by the CDF search for acoplanar charm jets.

The LEP results remain relevant for smaller mass splittings.

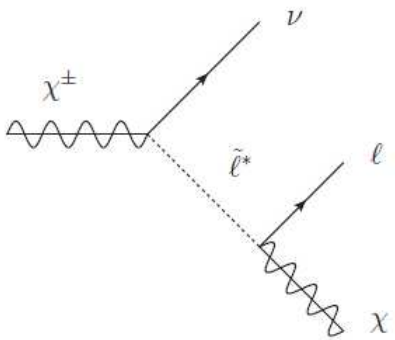
JHEP 1210 (2012) 158

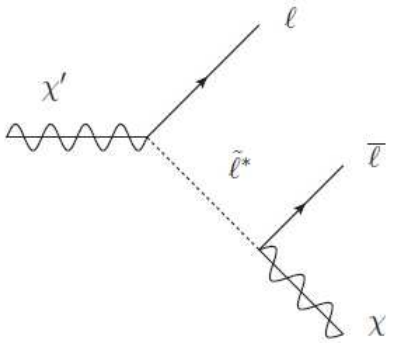
Electroweak gauginos

The searches for squarks and gluinos suffer from large backgrounds, which renders competitive the searches for electroweak gauginos, in spite of lower-production cross sections, for configurations such that multileptonic final states arising from the gaugino decays are enhanced.



with



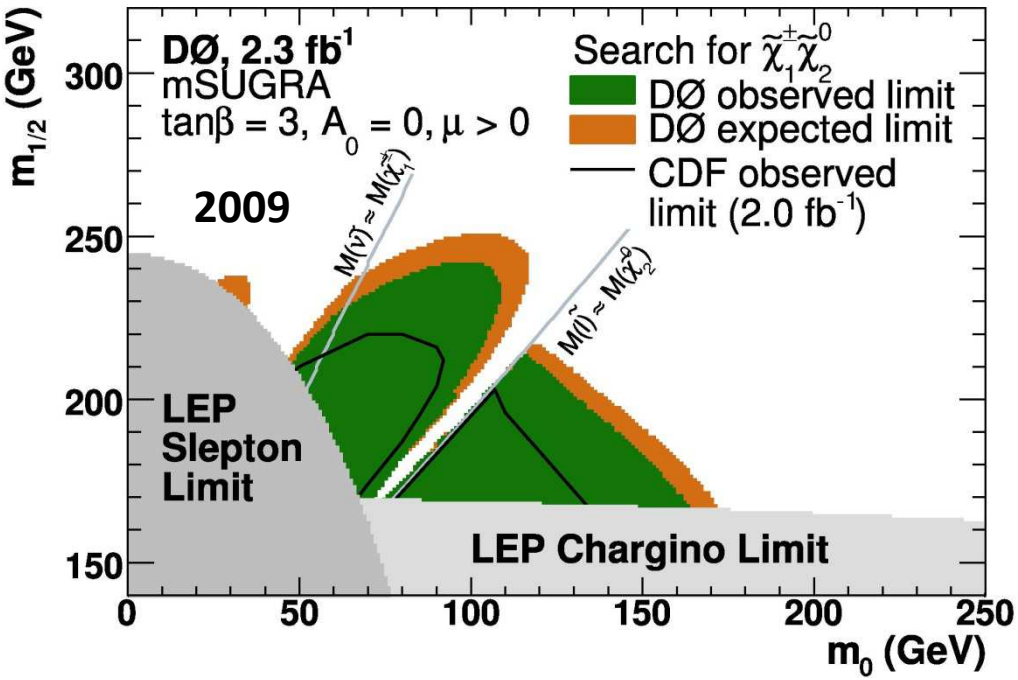


The final state is 3 leptons with MET. (Same-sign dileptons +isolated track included.)

Ultimate background: WZ reduced by m_ll < m_Z

Charginos and neutralinos

The interpretation framework is **mSUGRA**.



Phys.Lett. B680 (2009) 34-43

Gaps:

Slepton mass just below m_χ'

$\Rightarrow$ Soft lepton from $\chi' \rightarrow l \tilde{l}$.

Sneutrino mass below m_χ'

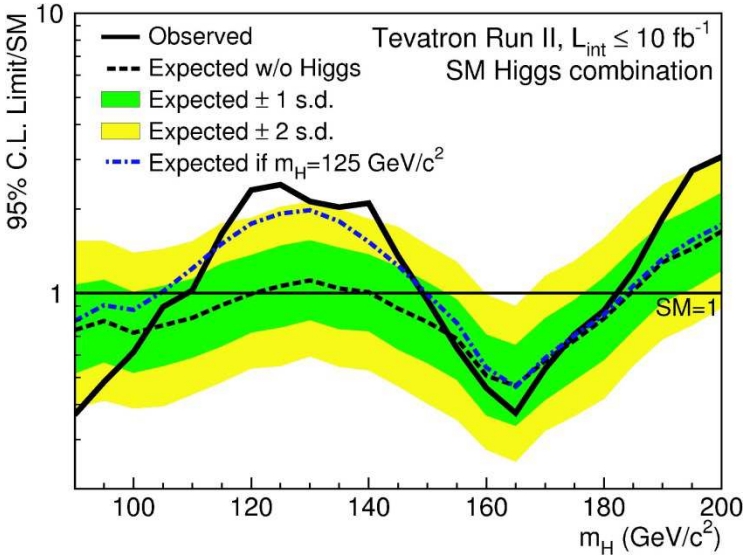
$\Rightarrow$ Invisible χ' decays open up

Sneutrino mass just below m_$\chi^{\pm}$

$\Rightarrow$ Soft lepton from $\chi^{\pm} \rightarrow l \tilde{\nu}$

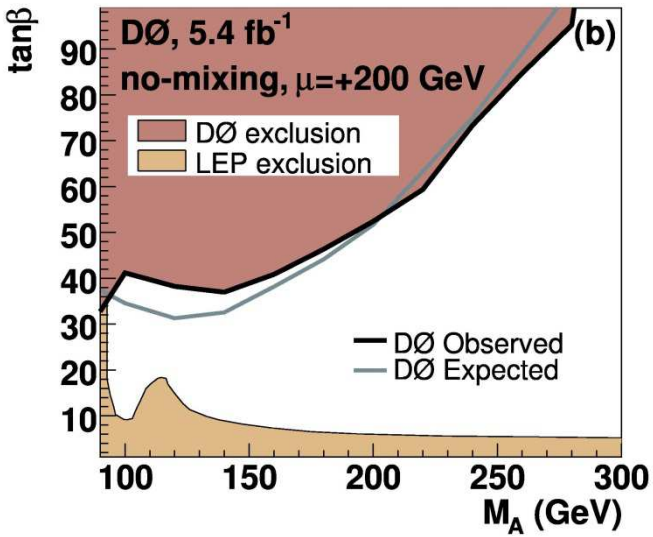
Substantial extension of the regions excluded by LEP.
But LEP results remain relevant, especially at large m_0.

Higgs bosons



Mostly:
$qq \to VH$ V=W/Z
$W \to l\nu$ $Z \to ll/\nu\nu$
$H \to bb/WW^*$

Phys.Rev. D88 (2013) no.5, 052014



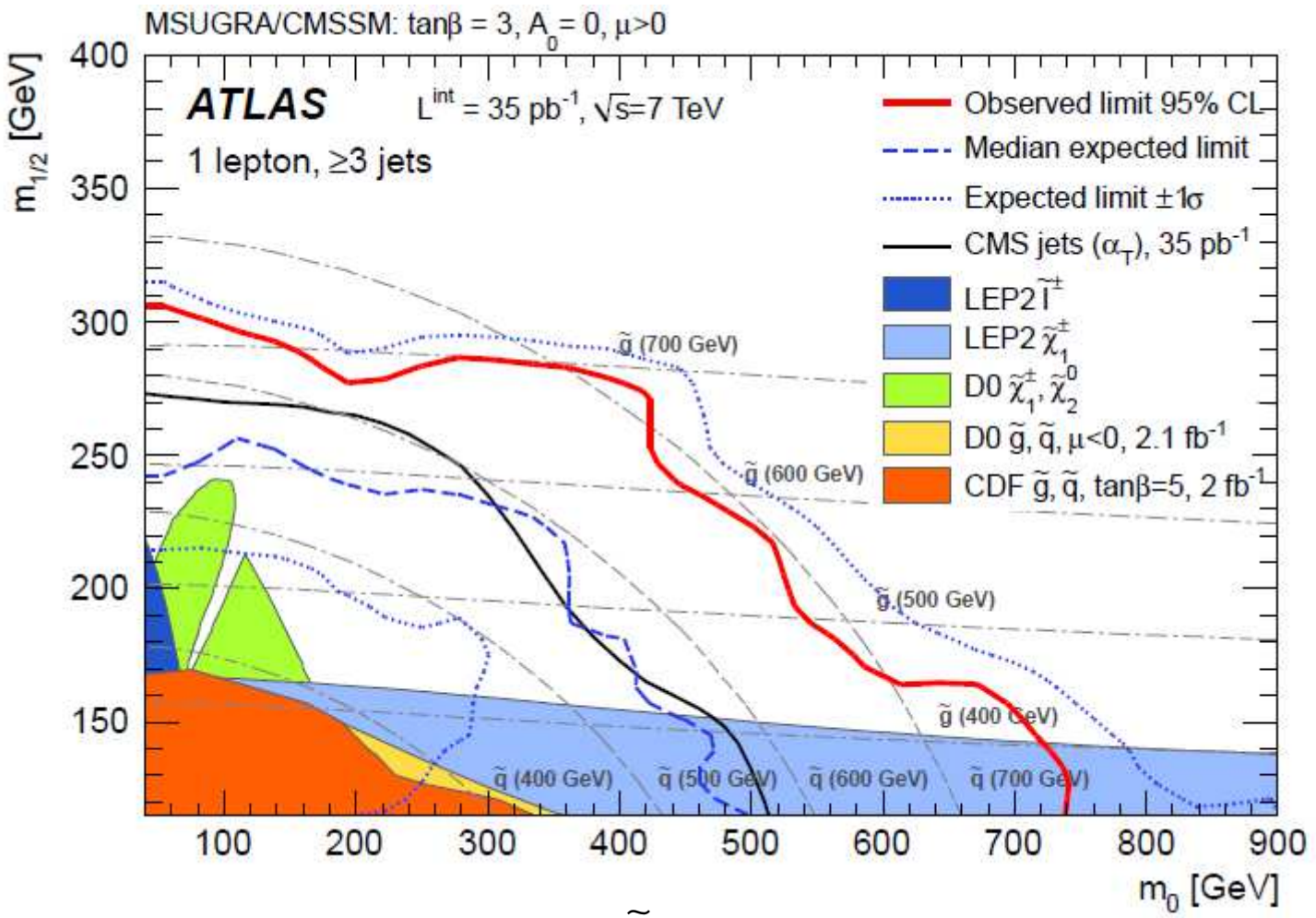
$gg/bb \to \varphi \to \tau\tau$ φ=A/h

(bφ with $\varphi \to \tau\tau$/bb were also studied)

Phys.Lett. B707 (2012) 323-329

And now… the Killer !

2010 data @ 7 TeV – only 35 pb^{-1}



m_ g̃ = m_q̃ > 700 GeV

Phys.Rev.Lett. 106 (2011) 131802

In summary

Approximate limits for equal-mass squarks and gluinos:

- SppS: 100 GeV
- Tevatron Run 1: 300 GeV
- Tevatron Run 2: 400 GeV
- LHC 1st year: 700 GeV

For sleptons and electroweak gauginos, the main constraints are coming from LEP, with mass limits of about 100 GeV.

Next episode tomorrow morning at 9 am with Dirk Zerwas

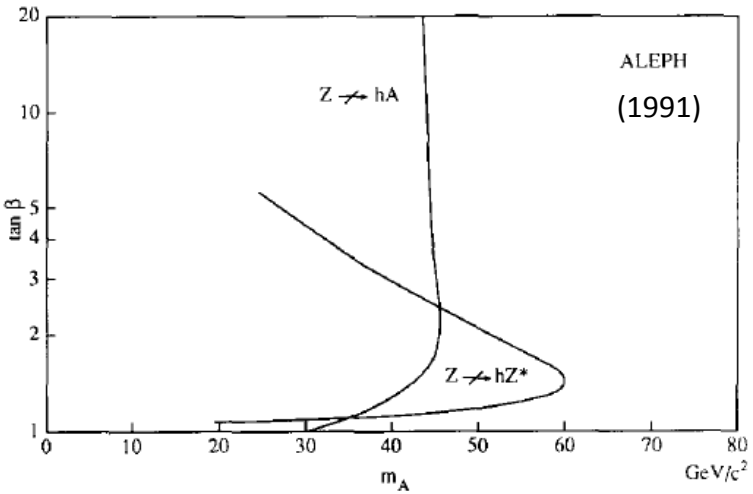
Backup

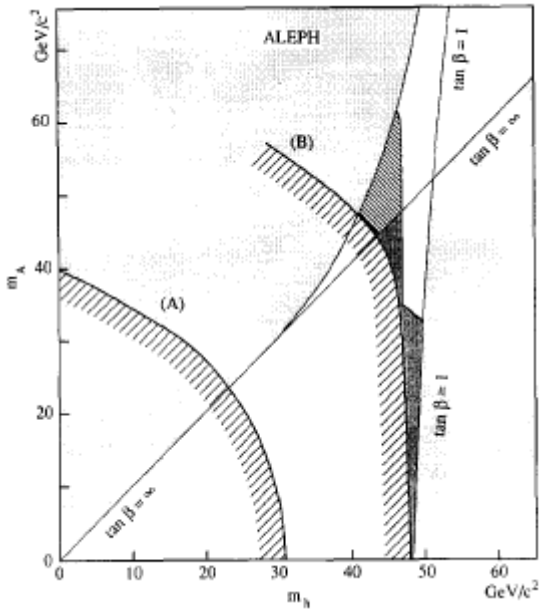
$$M_i = \frac{\alpha_i(M_Z)}{\alpha_U} m_{1/2} \longrightarrow M_3(M_Z) = \frac{\alpha_3(M_Z)}{\alpha_2(M_Z)} M_2(M_Z) = \frac{\alpha_3(M_Z)}{\alpha_1(M_Z)} M_1(M_Z)$$

$$M_1 = \tfrac{5}{3} \mathrm{tg}^2\theta_W M_2 \sim \tfrac{1}{2} M_2$$

$$\begin{aligned}
m^2_{\tilde{u}_L} &= m_0^2 + 6.28 m^2_{1/2} + 0.35 M_Z^2 \cos 2\beta \\
m^2_{\tilde{d}_L} &= m_0^2 + 6.28 m^2_{1/2} - 0.42 M_Z^2 \cos 2\beta \\
m^2_{\tilde{u}_R} &= m_0^2 + 5.87 m^2_{1/2} + 0.16 M_Z^2 \cos 2\beta \\
m^2_{\tilde{d}_R} &= m_0^2 + 5.82 m^2_{1/2} - 0.08 M_Z^2 \cos 2\beta \\
m^2_{\tilde{\nu}_L} &= m_0^2 + 0.52 m^2_{1/2} + 0.50 M_Z^2 \cos 2\beta \\
m^2_{\tilde{e}_L} &= m_0^2 + 0.52 m^2_{1/2} - 0.27 M_Z^2 \cos 2\beta \\
m^2_{\tilde{e}_R} &= m_0^2 + 0.15 m^2_{1/2} - 0.23 M_Z^2 \cos 2\beta
\end{aligned}$$

Early results on the Higgs bosons of the MSSM





Phys.Lett. B265 (1991) 475-486