Supersymmetry –
Experimental Searches

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Collider Seminar, 2.07.2001

- Introduction:
  SUSY models and experimental signatures
- Results from
  LEP and Tevatron
- Prospects for
  Tevatron Run 2 & LHC
  - Search strategies
  - SUSY id
- Summary

General Comments

SUSY searches are wide & complex field. Could be split into

$$N_{susy}^{flavs} \times \quad N_{models/pars} \times \quad N_{exp}$$

$$\approx 10 \qquad \approx 10 \qquad \approx 3 \quad \Rightarrow \text{few } 100 \text{ talks}$$

One 45 min talk can only give a crude illustrative overview.

Further reading:

- L. Pape, “Search for New Particles in the Context of SUSY”, `http://wwweth.cern.ch/teilchenIV/susytalk.ps.gz`
- LEP SUSY WG: `http://lepsusy.web.cern.ch/lepsusy/`
- Tevatron run II SUSY page, `http://fnth37.fnal.gov/susy.html`
- M. Dittmar, various lecture proceedings, e.g. “SUSY discovery strategies at LHC”, hep-ex/9901004.
- Atlas Technical Design Report, `http://atlasinfo.cern.ch/Atlas/GROUPS/PHYSICS/TDR/access.html`
- homepages of LEP/LHC/Tevatron expts

and references therein.

This talk available on

`http://www.physik.uni-muenchen.de/~gduckeck/susy_exp.ps.gz`

Particles and Sparticles

Spin	0	1/2		1
	$\left.\tilde{\ell}^{\pm}_{L,R}\right\}\ \tilde{\ell}^{\pm}_{1,2}$	$\ell^{\pm}_{L,R}$		
	$\left.\tilde{q}^{\pm}_{L,R}\right\}\ \tilde{q}^{\pm}_{1,2}$	$q^{\pm}_{L,R}$		
		$\tilde{g}$		g
		$\tilde{\gamma}$	$\left.\right\}\ \tilde{\chi}^0_i$	γ
	h^0, H^0, A^0	$\tilde{h}, \tilde{H}$		
		$\tilde{Z}$		Z
	$H^{\pm}$	$\tilde{H}^{\pm}$	$\left.\right\}\ \tilde{\chi}^{\pm}_j$	$W^{\pm}$
		$\tilde{W}\pm$		

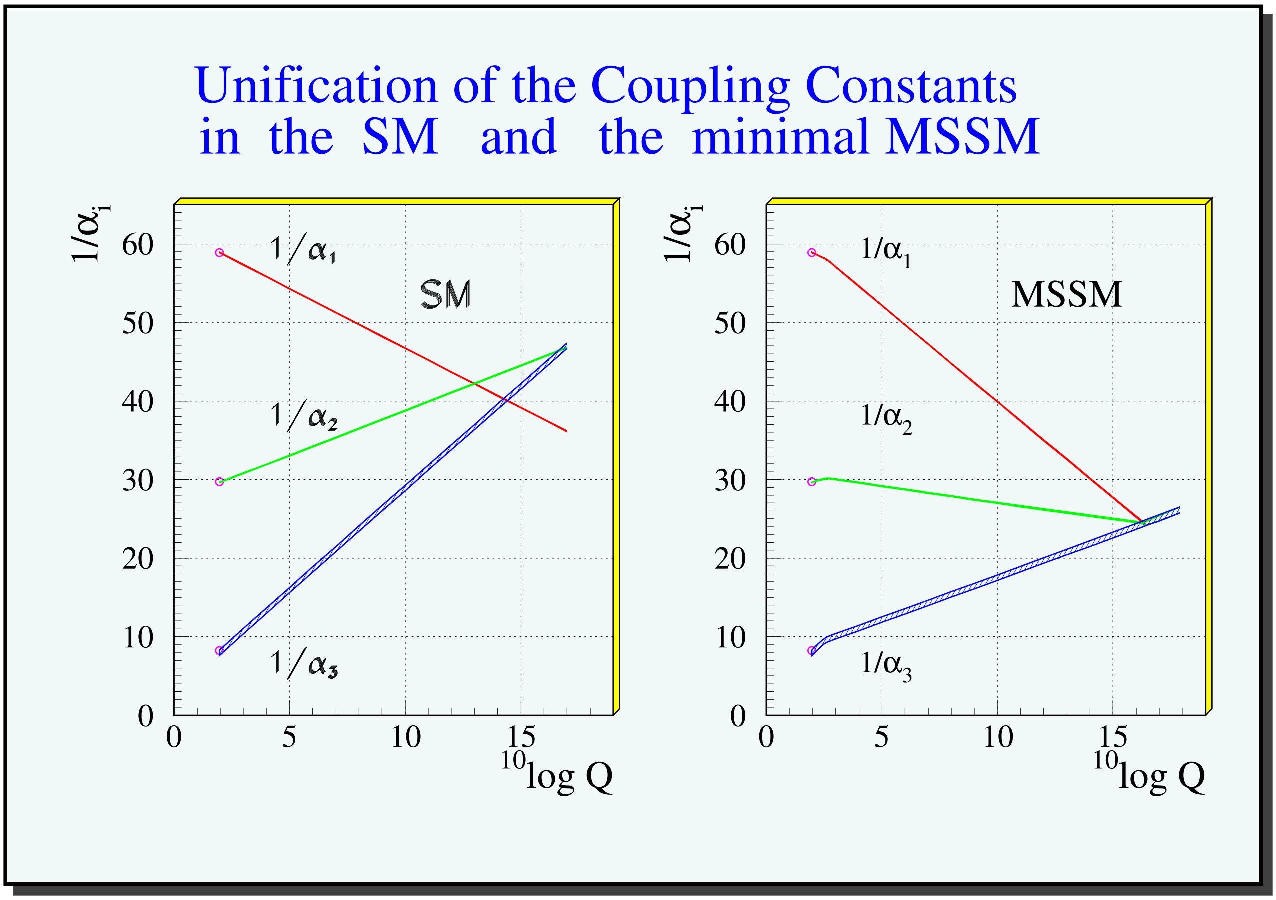
Pros:

- Hierarchy problem
- Coupling unification
- Largely decoupled from SM
  consistent with e-weak precision results

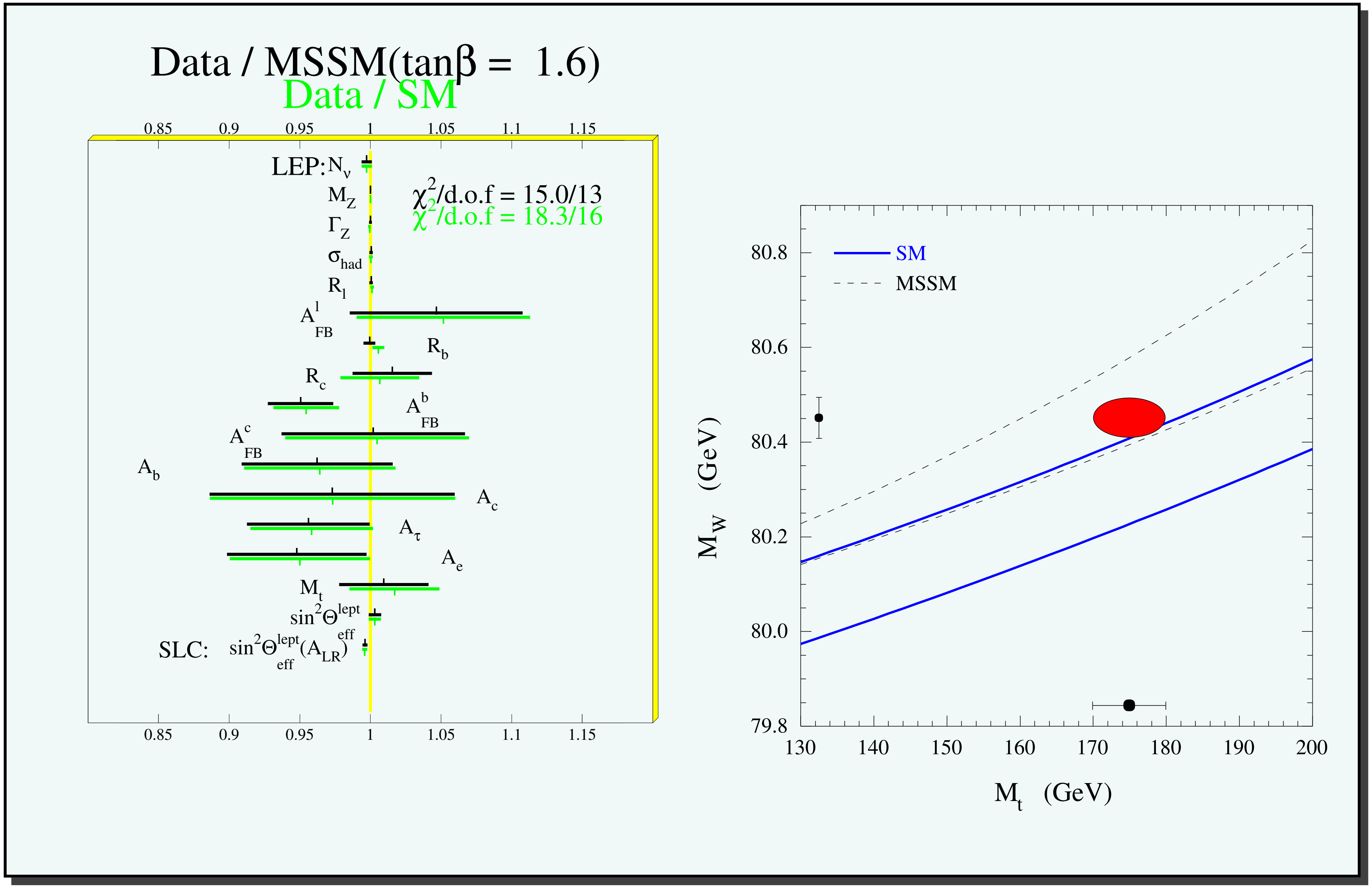
Cons:

- >100 additional parameters in MSSM

Unification of couplings



SUSY and e-weak precision data



SUSY models

Restrict parameter space with additional assumptions.
2 main models commonly used by experiments:

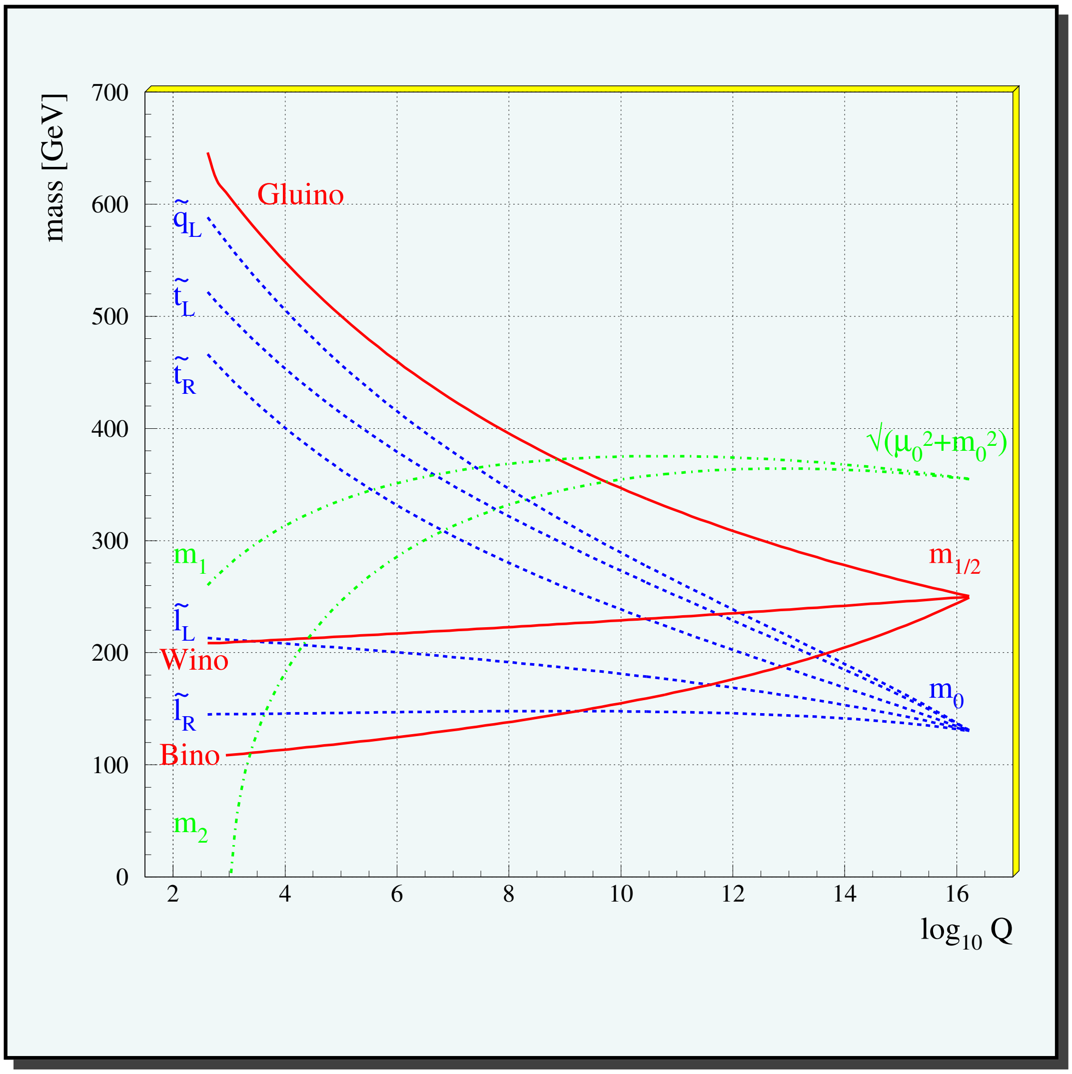
mSUGRA or CMSSM (≈ 4.5 parameters)

- $m_{1/2}$ common gaugino/higgsino mass at Λ_{GUT}
- m_0 common scalar (sfermions, Higgses) at Λ_{GUT}
- $\tan\beta = v_u/v_d$, A_0, $sgn\mu = \pm 1$
- R-parity conserved, e.g. decay chain always ends in $\tilde{\chi}_1^0$ which is the **LSP**: stable, neutral, no interaction with matter

GMSB (Gauge mediated Susy breaking)

- Alternative model, with different SUSY breaking mechanism at lower scale
- main phenomenological consequence: Gravitino mass $m_{\tilde{G}} \leq 1$ GeV (≥ 2 TeV in SUGRA)
- $\Rightarrow \tilde{G}$ is **LSP**
- Exp signature depends on NLSP ($\tilde{\tau}$ or $\tilde{\chi}_1^0$) and its lifetime

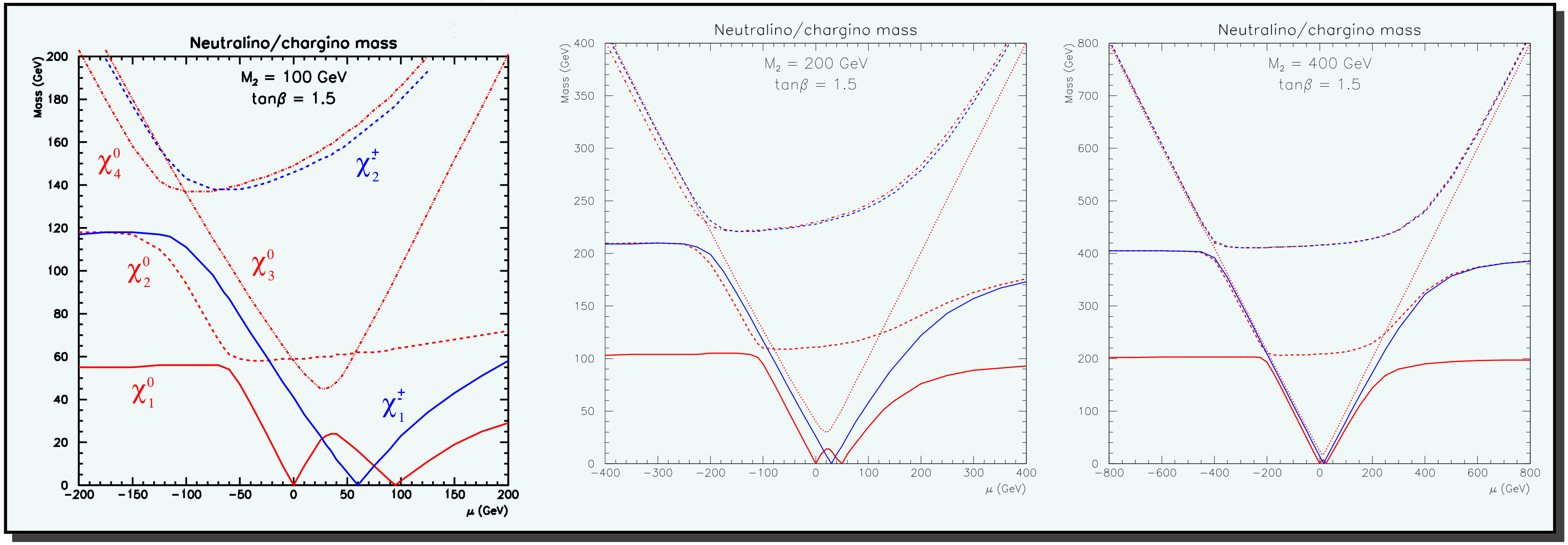
mSUGRA



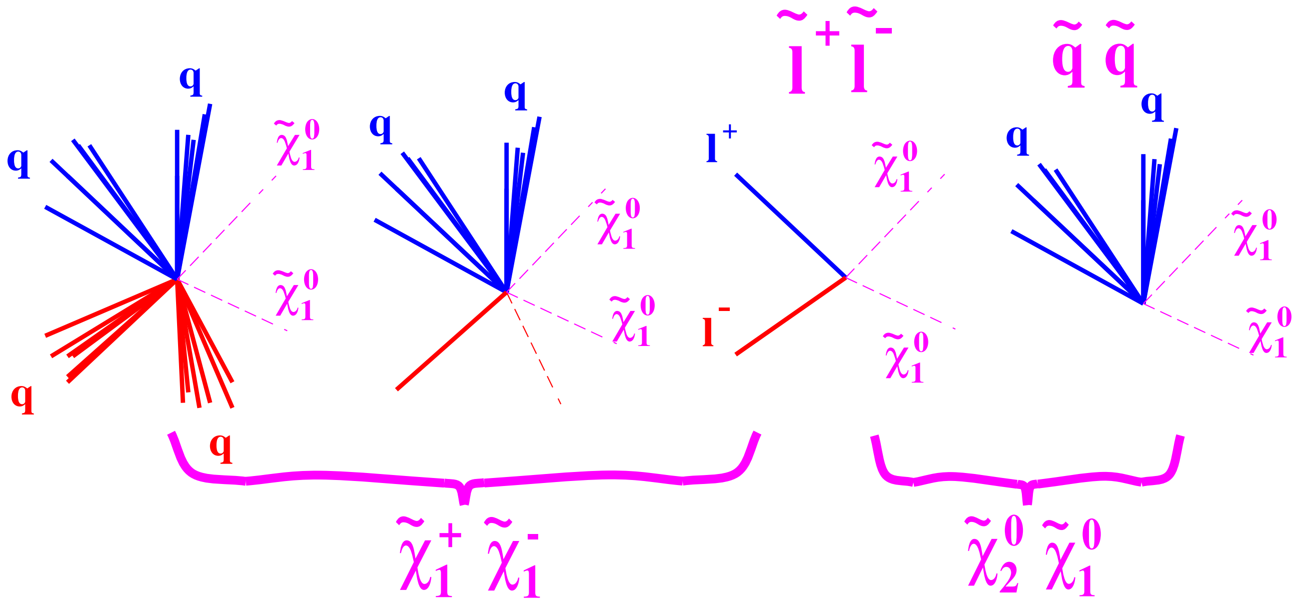
- Mass evolution by RGE from Λ_{GUT} to EW scale.
- mass spectrum, mixing of LR-sfermions and gauginos/higgsinos strongly depend on parameters
- $\Rightarrow$ Spectroscopy & exp signatures strongly depend on parameters

Example:

Chargino/neutralino masses as funciton of μ, M_2

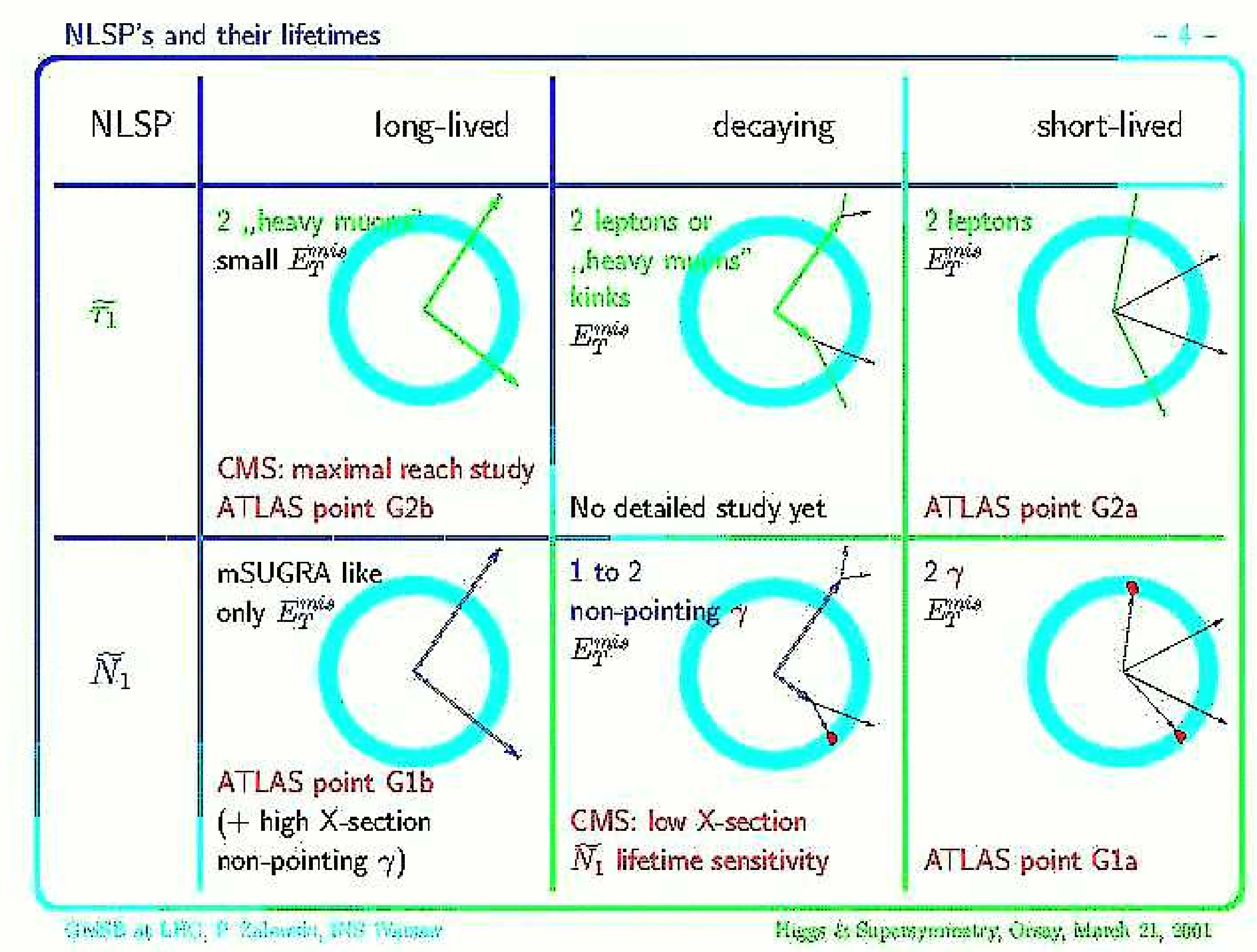


mSUGRA search topologies



- Basic signature: **Missing Energy**
- Categorization based on
  - n_{jets}
  - $n_{leptons}$ (same sign, opposite sign)

GMSB – signatures



NLSP's and their lifetimes

– 4 –

NLSP	long-lived	decaying	short-lived
$\tilde{\tau}_1$	2 „heavy muons" small E_T^{mis} CMS: maximal reach study ATLAS point G2b	2 leptons or „heavy muons" kinks E_T^{mis} No detailed study yet	2 leptons E_T^{mis} ATLAS point G2a
$\tilde{N}_1$	mSUGRA like only E_T^{mis} ATLAS point G1b (+ high X-section non-pointing γ)	1 to 2 non-pointing γ E_T^{mis} CMS: low X-section $\tilde{N}_1$ lifetime sensitivity	2 γ E_T^{mis} ATLAS point G1a

GMSB at LHC; P. Zalewski, INS Warsaw

Higgs & Supersymmetry, Orsay, March 21, 2001

Experimental requirements for SUSY

Large variety of possible signatures
⇒ large variety of detector requirements

Main focus on

- coverage of large solid angle
- good hermeticity
- jet reconstruction
- lepton id

In general less critical:

- mass reconstruction/resolution
- secondary vertices/lifetime

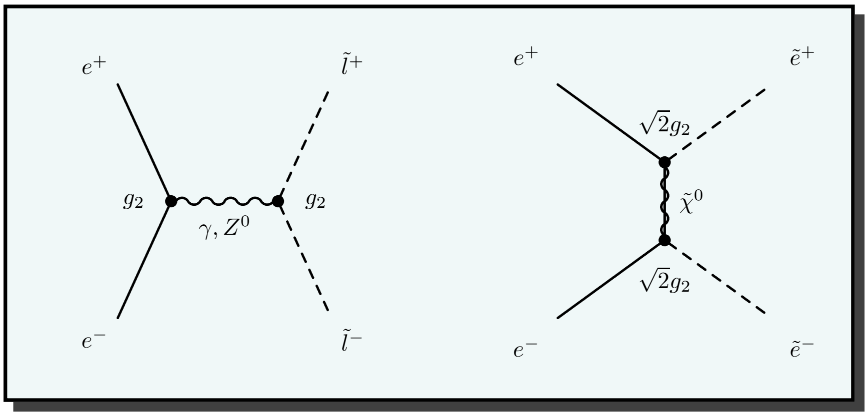
Also “exotic” detector features could become crucial

- direction determination for calorimeter showers
- dE/dx in outer detectors (⇒ ADC readout ATLAS μ-chambers)
- calorimetry in muon system

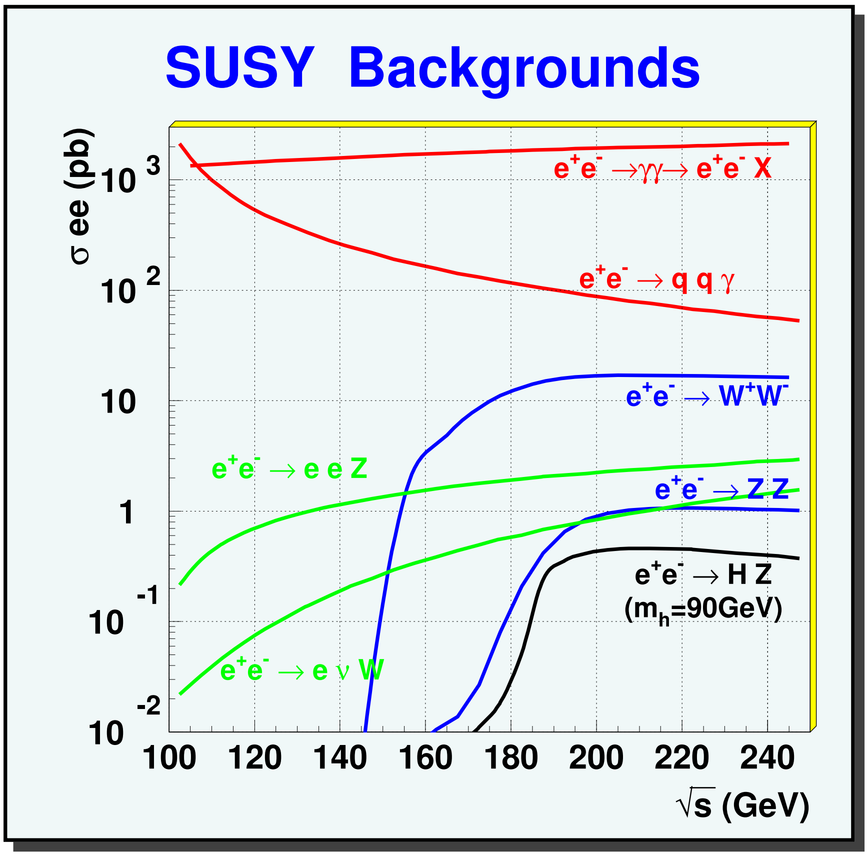
SUSY at LEP

e^+e^- collider LEP at CERN

- LEP1 1989–1995 at 91 ± 3 GeV with 150 pb^{-1}/exp
- LEP2 1996–2000 from 161 – 208 GeV with 650 pb^{-1}/exp



Production in s- or t-channel ($\tilde{e}$, $\tilde{\nu_e}$) $\sigma_{susy} = \mathcal{O}(1\,pb)$



Example: acoplanar di-leptons

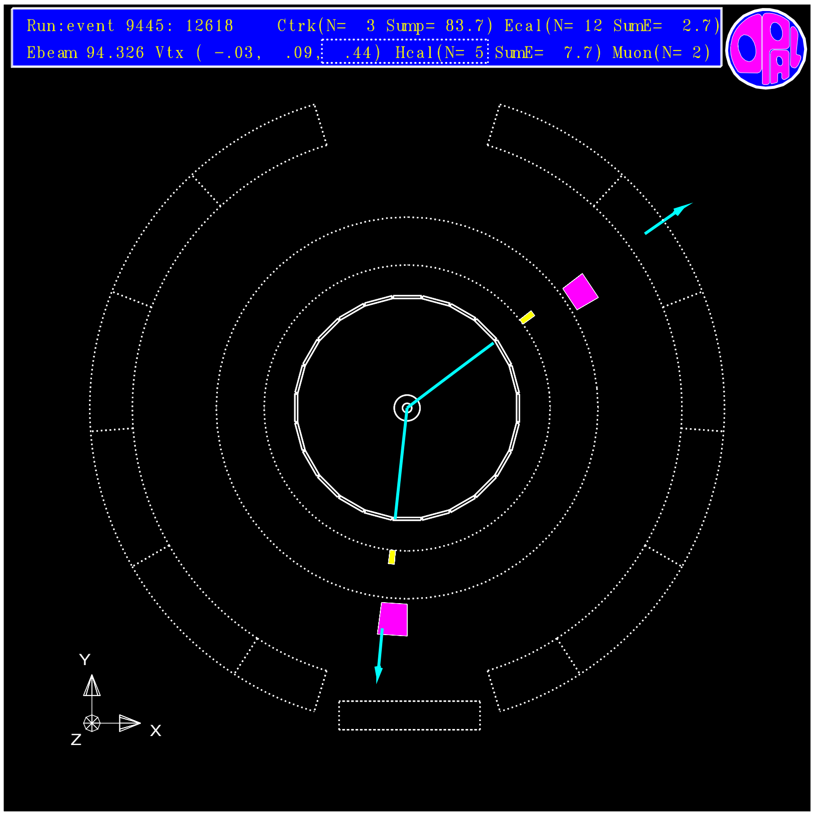
Characteristic signature for

- slepton $\tilde{\ell}^+ \to \tilde{\chi}_1^0 \ell^+$
- chargino $\tilde{\chi}_1^+ \to \tilde{\chi}_1^0 W^+$ or $\tilde{\ell}^+ \nu_\ell$

Kinematics depends critically on $\Delta M = M_{\tilde{\ell}^+} - M_{\tilde{\chi}_1^0}$

Low ΔM: two-photon background

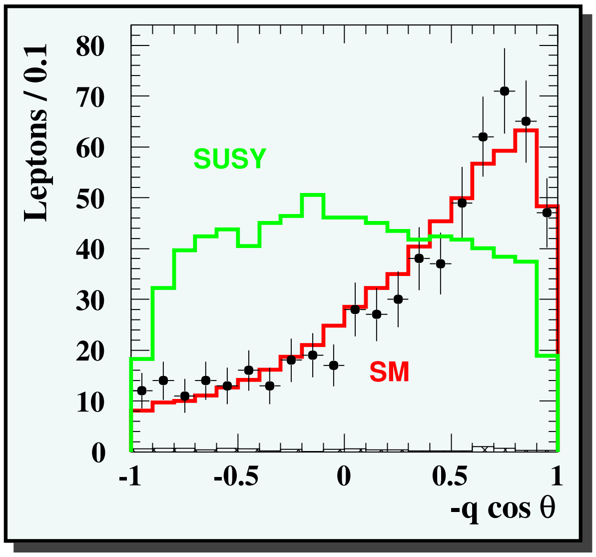
Large ΔM: $\ell^+ \ell^-$ and $W^+ W^-$

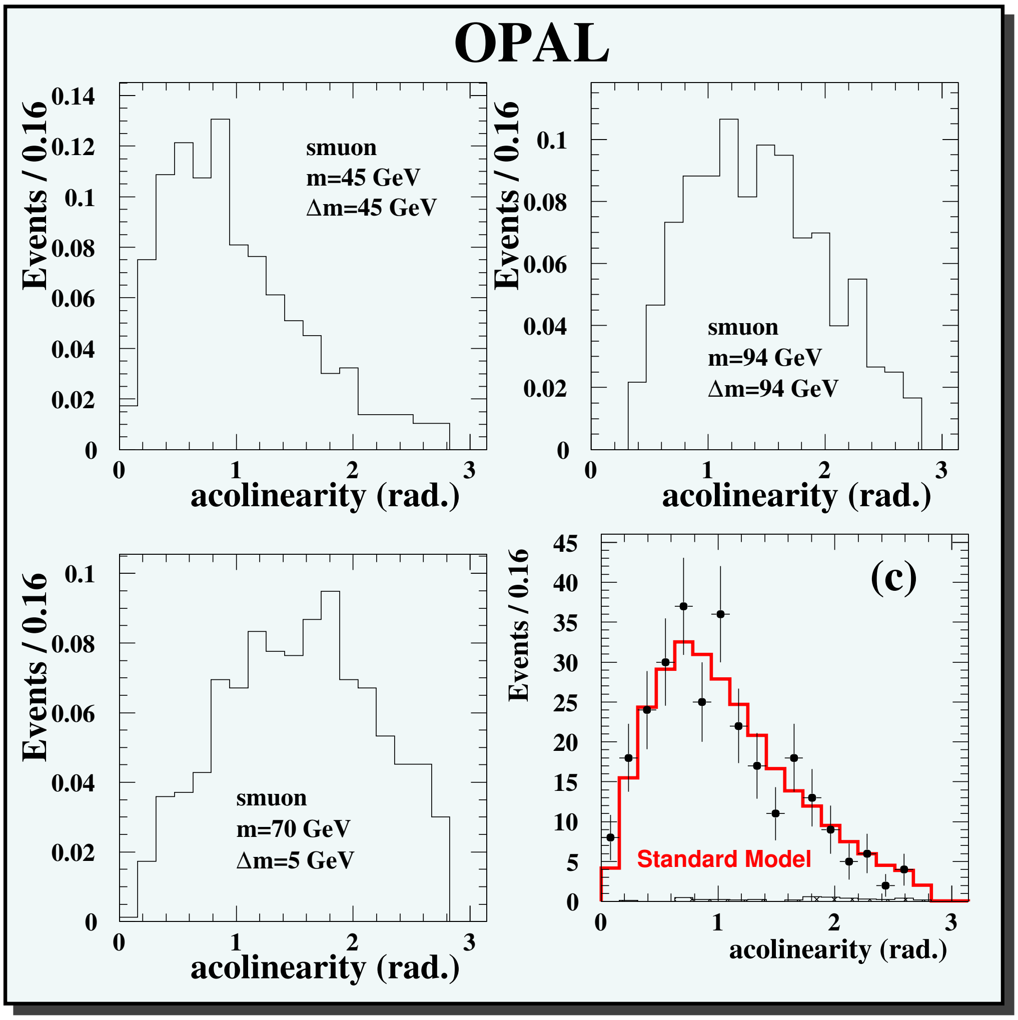


$\mu^+ \mu^-$ with large missing p_t, consistent with

$W^+ W^- \to \mu^+ \nu_\mu \, \mu^- \bar{\nu}_\mu$

Separation of SUSY signal and SM background:





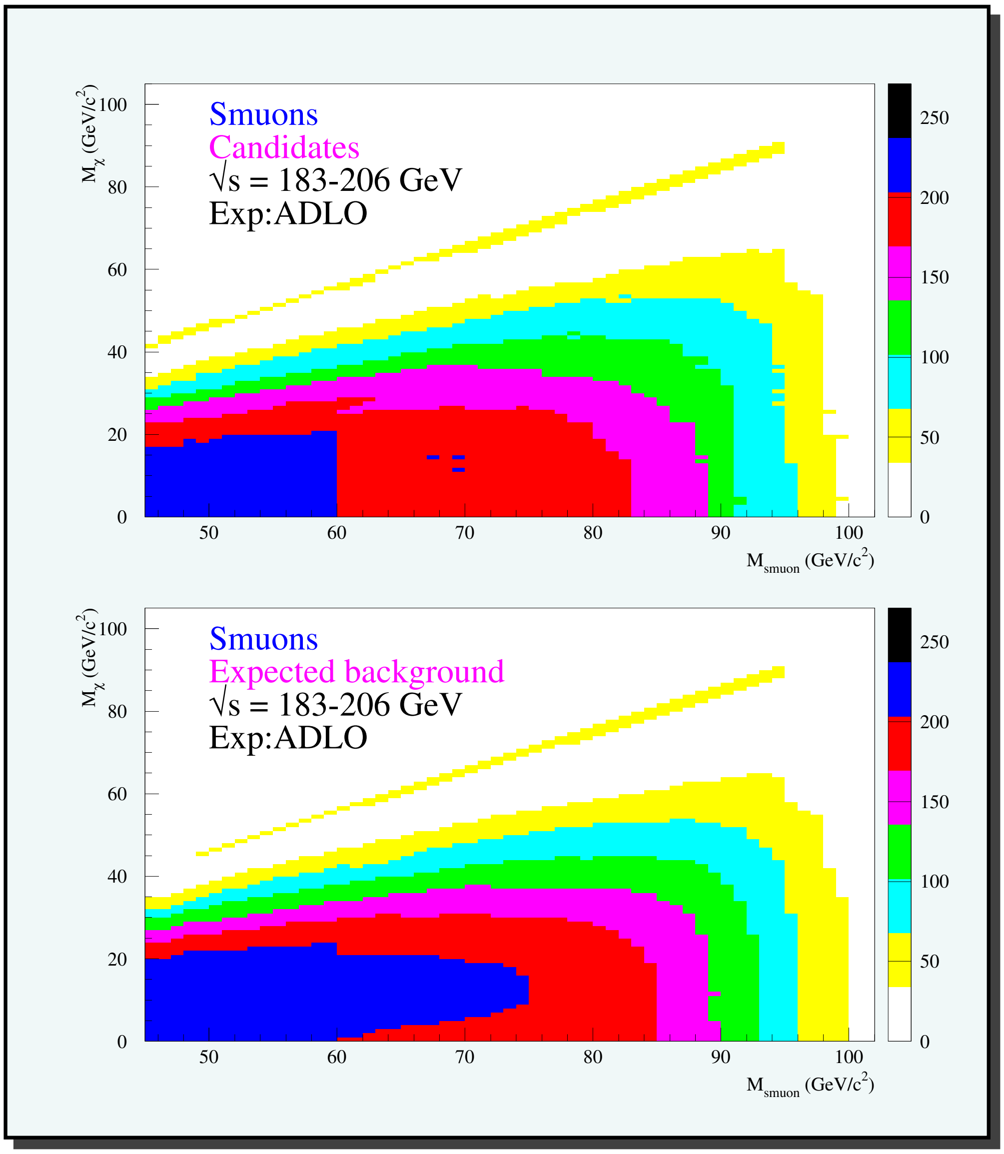
Procedure for deriving limits:

1. Test compatibility of each event with SUSY masses:

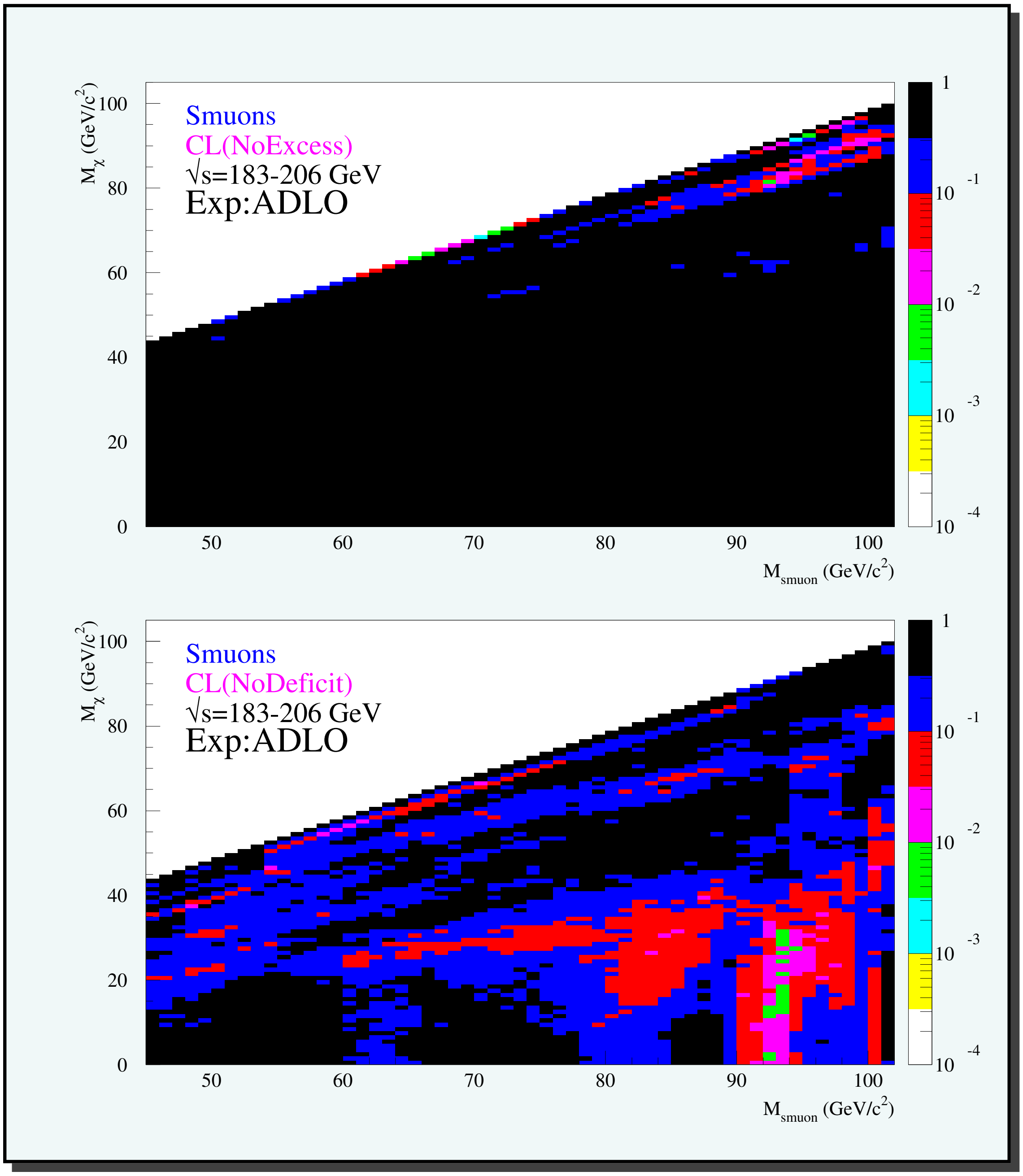
$$E_\ell^{max,min} = \frac{E_b}{2}\left(1 - \frac{M^2_{\tilde{\chi}^0_1}}{M^2_{\tilde{\ell}+}}\right)\left[1 \pm \sqrt{1 - \frac{M^2_{\tilde{\ell}+}}{E_b^2}}\right]$$

Each compatible point in mass-plane ($M_{\tilde{\ell}+}$ vs $M_{\tilde{\chi}^0_1}$) gets an entry

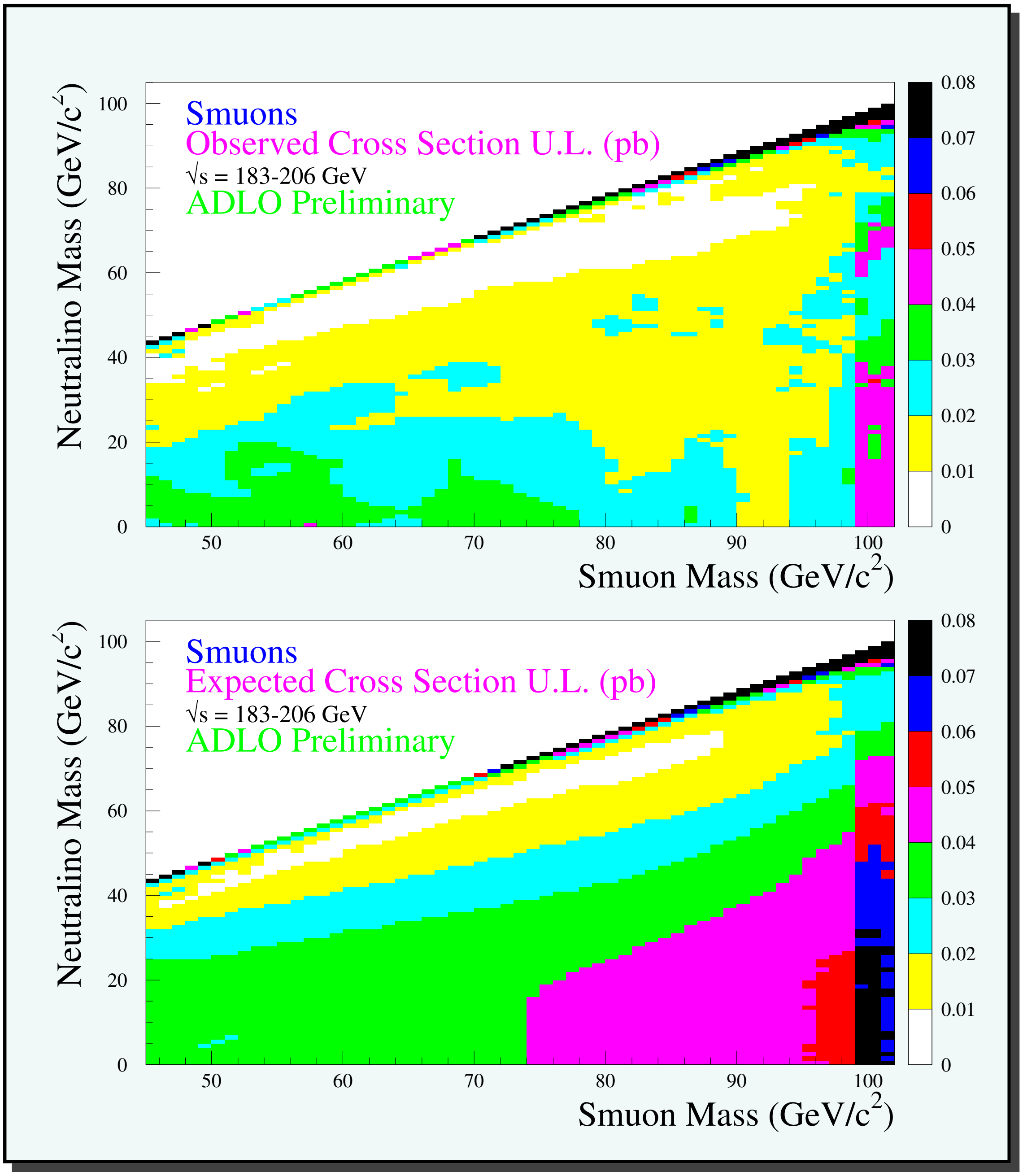
⇒ many entries per event !



2. For each point in $(M_{\tilde{\ell}^+} - M_{\tilde{\chi}_1^0})$ plane the compatibilty with background is calculated (excess and deficit):



3. The cross-section 95 % CL upper limits are calculated in the $(M_{\tilde{\ell}^+} - M_{\tilde{\chi}_1^0})$ plane:

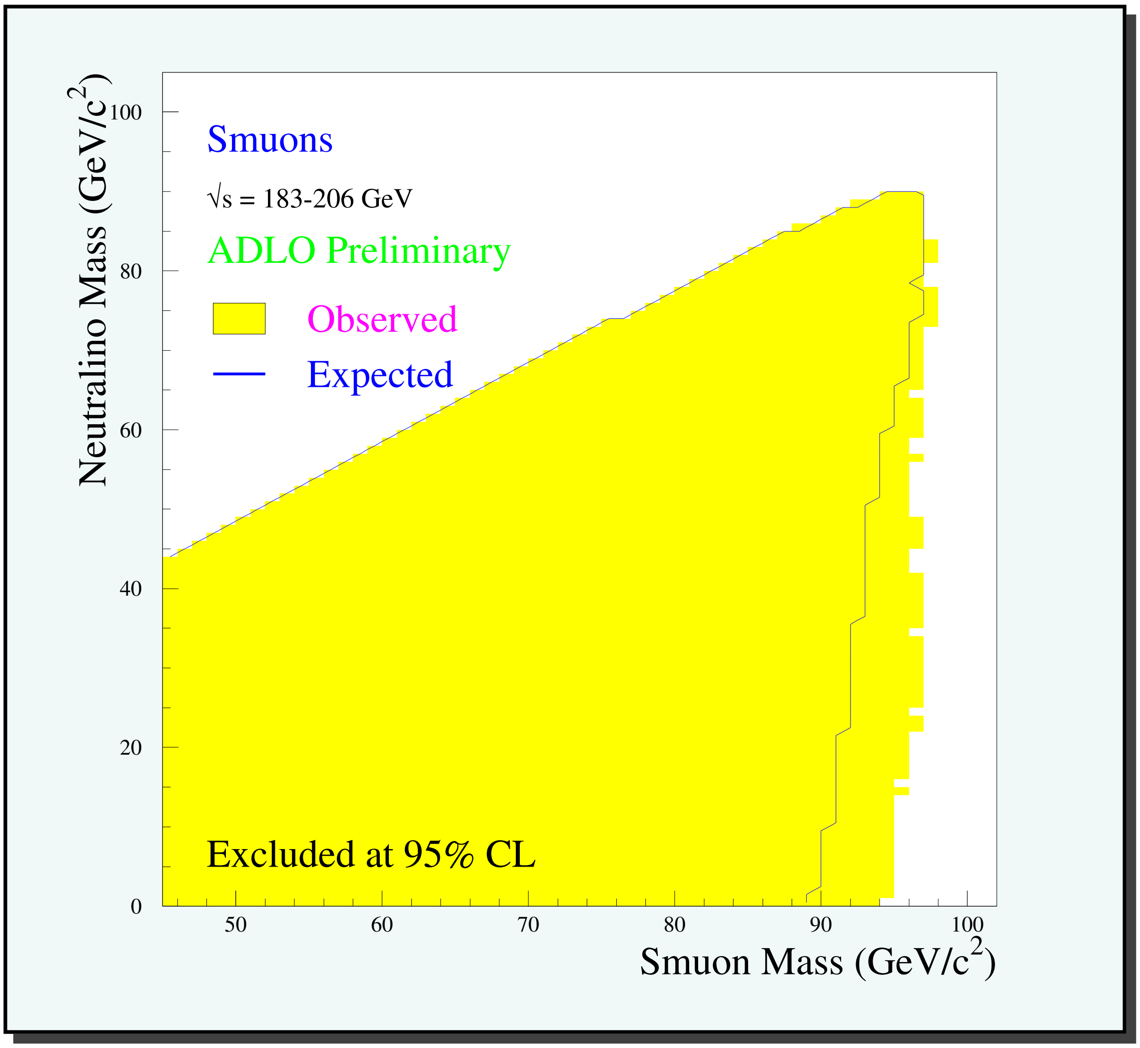


So far model-independent ...

4. Translation into SUSY mass-limits for $M_{\tilde{\ell}+}$ as function of $M_{\tilde{\chi}_1^0}$: Specific SUSY model/parameter set must be choosen for cross-section prediction.

Conservative choice:

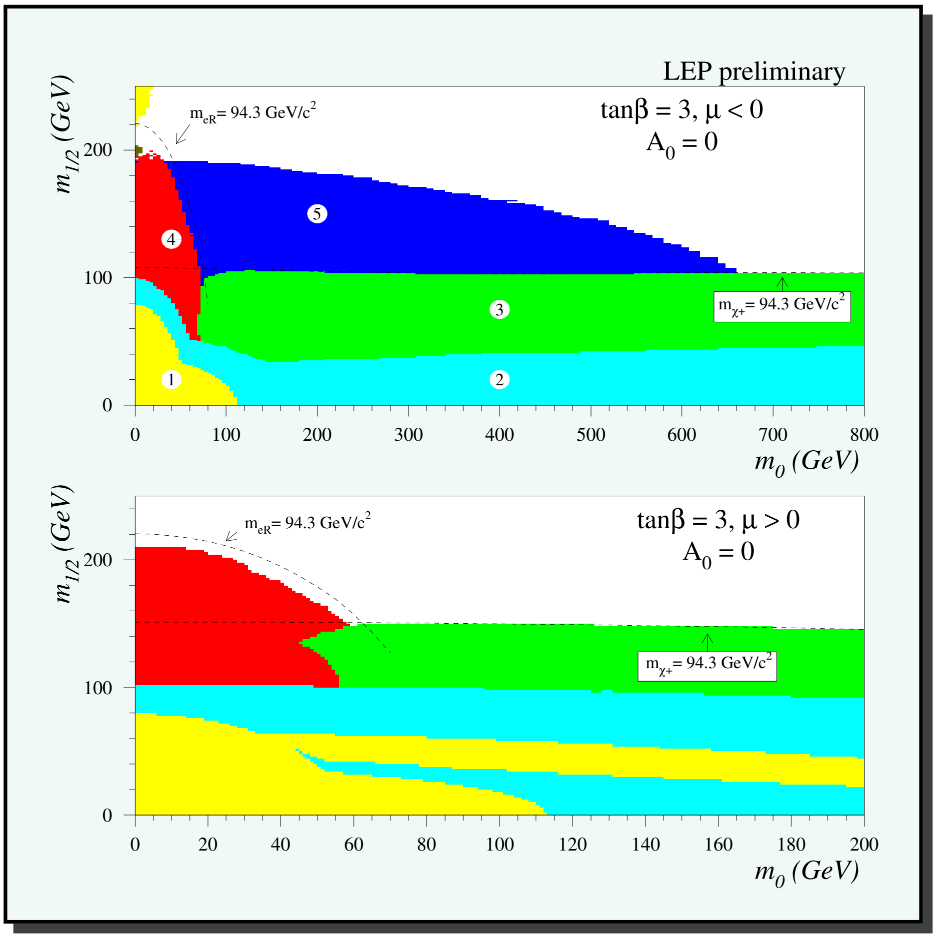
- Only $\tilde{\ell}_R$ production ($< \sigma_{\tilde{\ell}_L}$)
- “un-favourable” parameters: $\mu = -200$ GeV, $\tan\beta = 1.5$



5. Similar procedure for other sparticles:
$\tilde{q}$, $\tilde{g}$, $\tilde{\chi}^0_i$, $\tilde{\chi}^\pm_j$

Overall combination ⇒ Interpretation in SUSY m_0–$m_{1/2}$ plane:

Small $\tan\beta$



1/yellow: theoretically excluded

2/light-blue: excluded by LEP1 limit on Γ_Z

3/green: $\tilde{\chi}$ limits

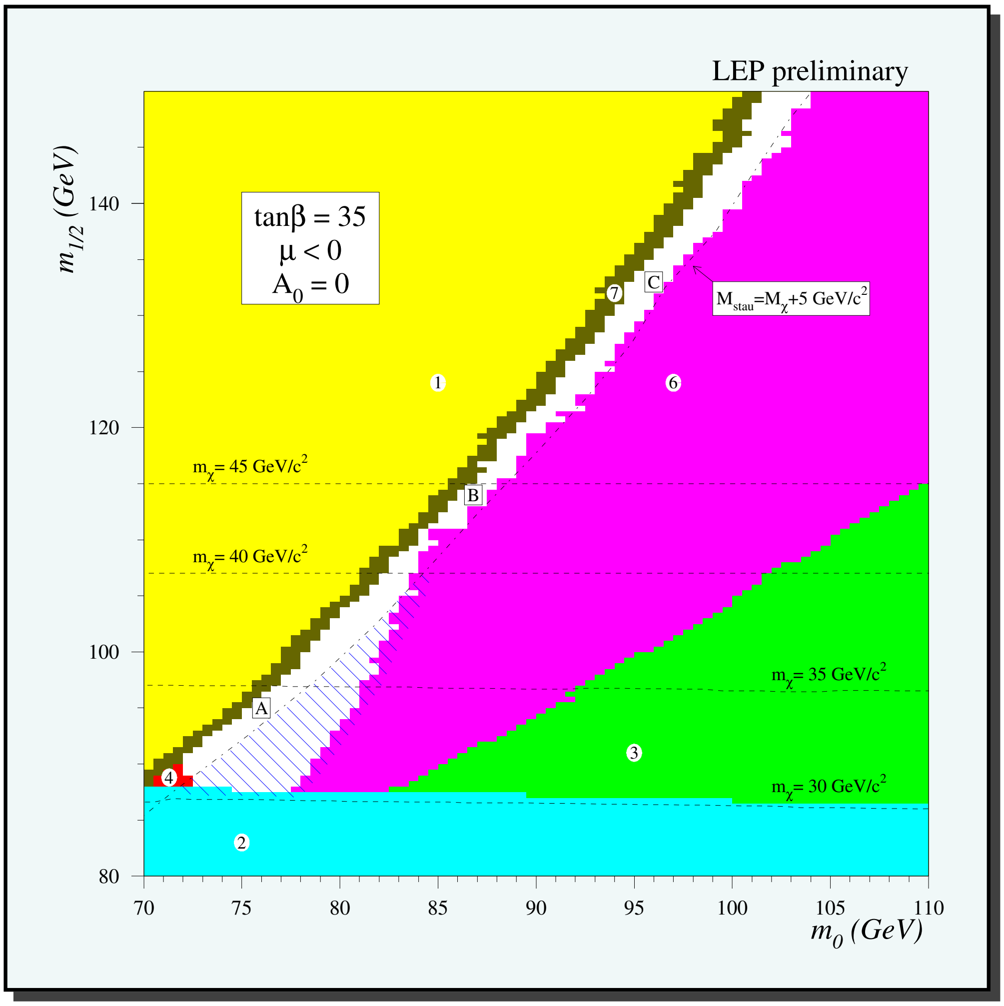
4/red: $\tilde{e}$ limits

5/dark-blue: $h^0 Z^0$ limits

6/magenta: $\tilde{\tau}$ limits

7/brown: heavy stable charged particles

Large $\tan\beta$



Sparticle mass-limits

For large mSUGRA parameter space LEP exclusion close to kinematic limit for pair-production ($= E_{beam}$)

- $\tilde{\chi}_1^{\pm} > 103$ GeV
- $\tilde{e}, \tilde{\mu}, \tilde{\tau} > 89, 85, 71$ GeV for $\Delta M > 15$ GeV
- $\tilde{b}, \tilde{t} \geq$ 80–90 GeV, depending on LR mixing

Generic (model-independent) limits difficult, e.g.:
for sfermions only ≥ 45 GeV indirect limit from LEP Γ_Z

Special case for LSP ($\tilde{\chi}_1^0$):

- no Γ_Z limits
- only indirect limits from excluded parameter-space:
  $M_{\tilde{\chi}_1^0} > 40$ GeV

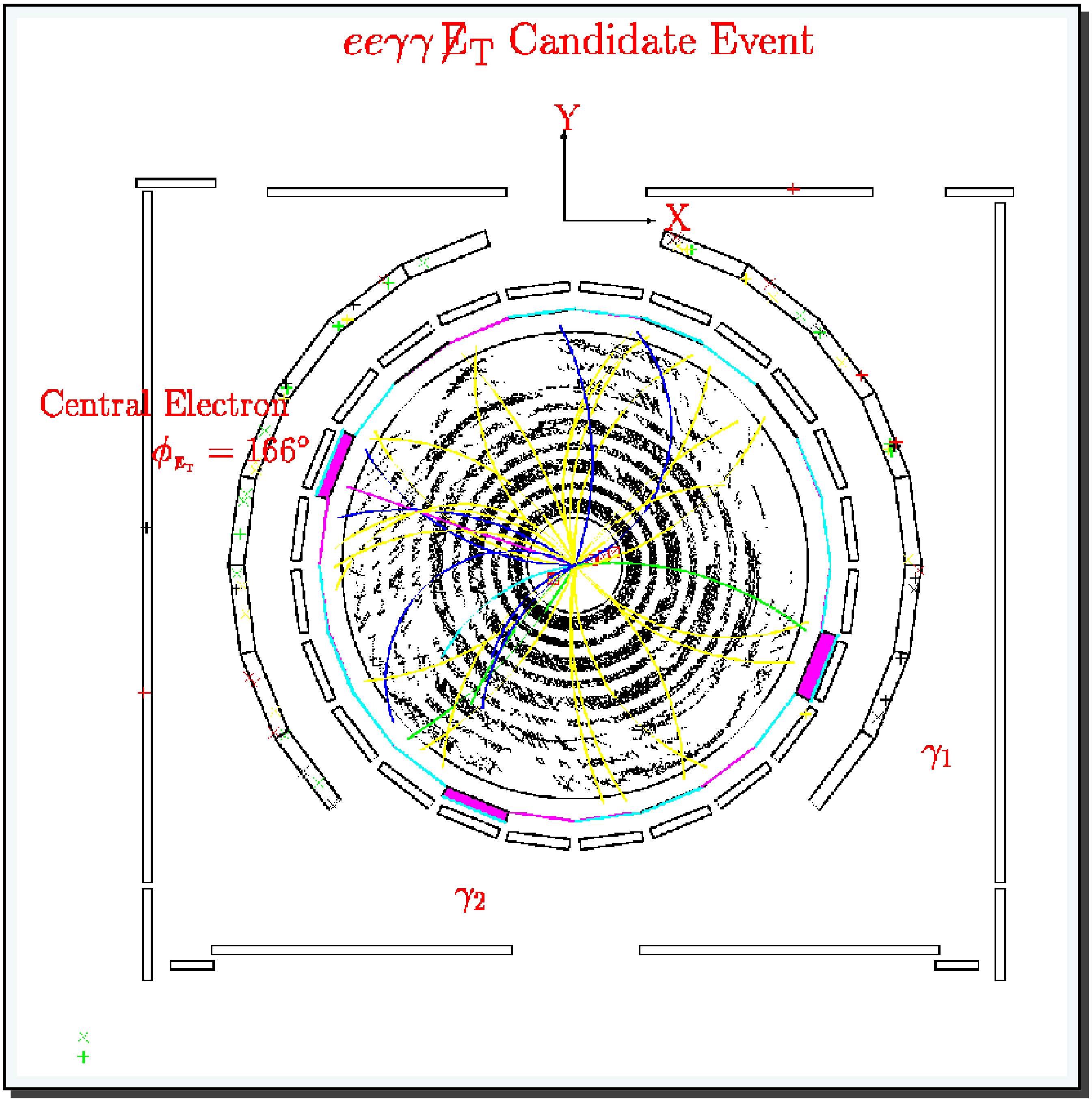
SUSY at Tevatron

General feature (wrt LEP):

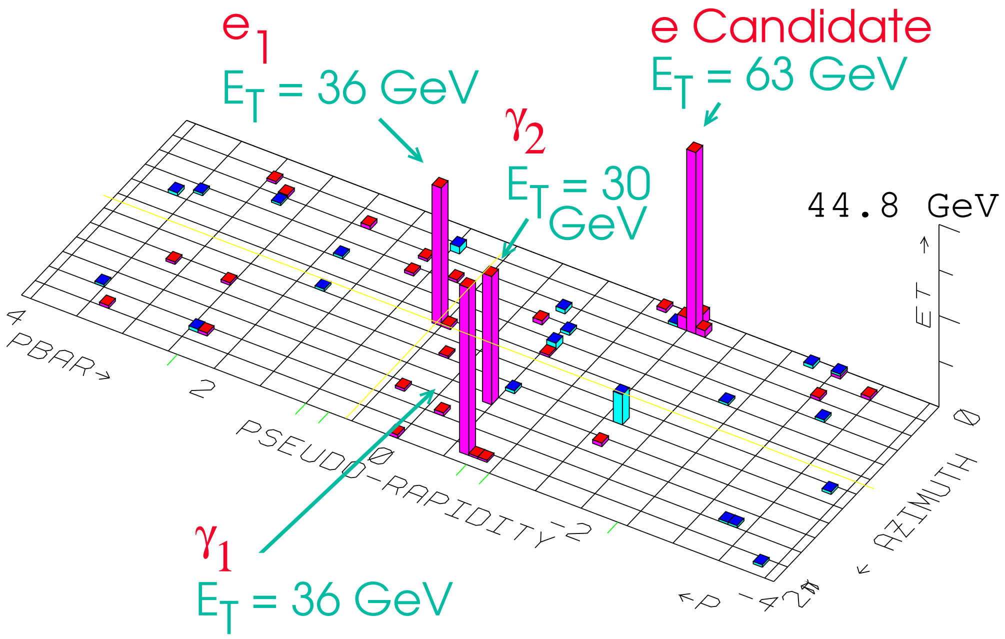
- High reach for
  $\tilde{q}, \tilde{g}, \tilde{\chi}_1^{\pm}$ (150, 180, 140) GeV
  in certain range of SUGRA parameters
- Rather sensitive to parameters
- ⇒ High discovery potential
  ⇒ no/weak generic limits

Most spectacular:
Peculiar CDF event with $\mathrm{e}^+\mathrm{e}^-\gamma\gamma$ final state.
⇒ triggered interest in GMSB SUSY models.

Event Display



$ee\gamma\gamma\not{E}_T$ Candidate Event



e_1
E_T = 36 GeV

γ_2
E_T = 30 GeV

e Candidate
E_T = 63 GeV

γ_1
E_T = 36 GeV

$\not{E}_T$ = 55 GeV

- 2 clear photons
- 1 clear electron
- 2nd electron in plug calorimeter a little “ambiguous”
- SM backg $\approx 10^{-6}$ (main process $WW\gamma\gamma$)

SUSY–GMSB interpretation:

$$
\begin{aligned}
q\bar{q} \longrightarrow\ & \tilde{e}^{+}\tilde{e}^{-} \\
& \hookrightarrow e^{-}\,\tilde{\chi}_1^0 \\
& \qquad\quad \hookrightarrow \gamma\tilde{G}
\end{aligned}
$$

Only one such $e^+e^-\gamma\gamma$ candidate at CDF

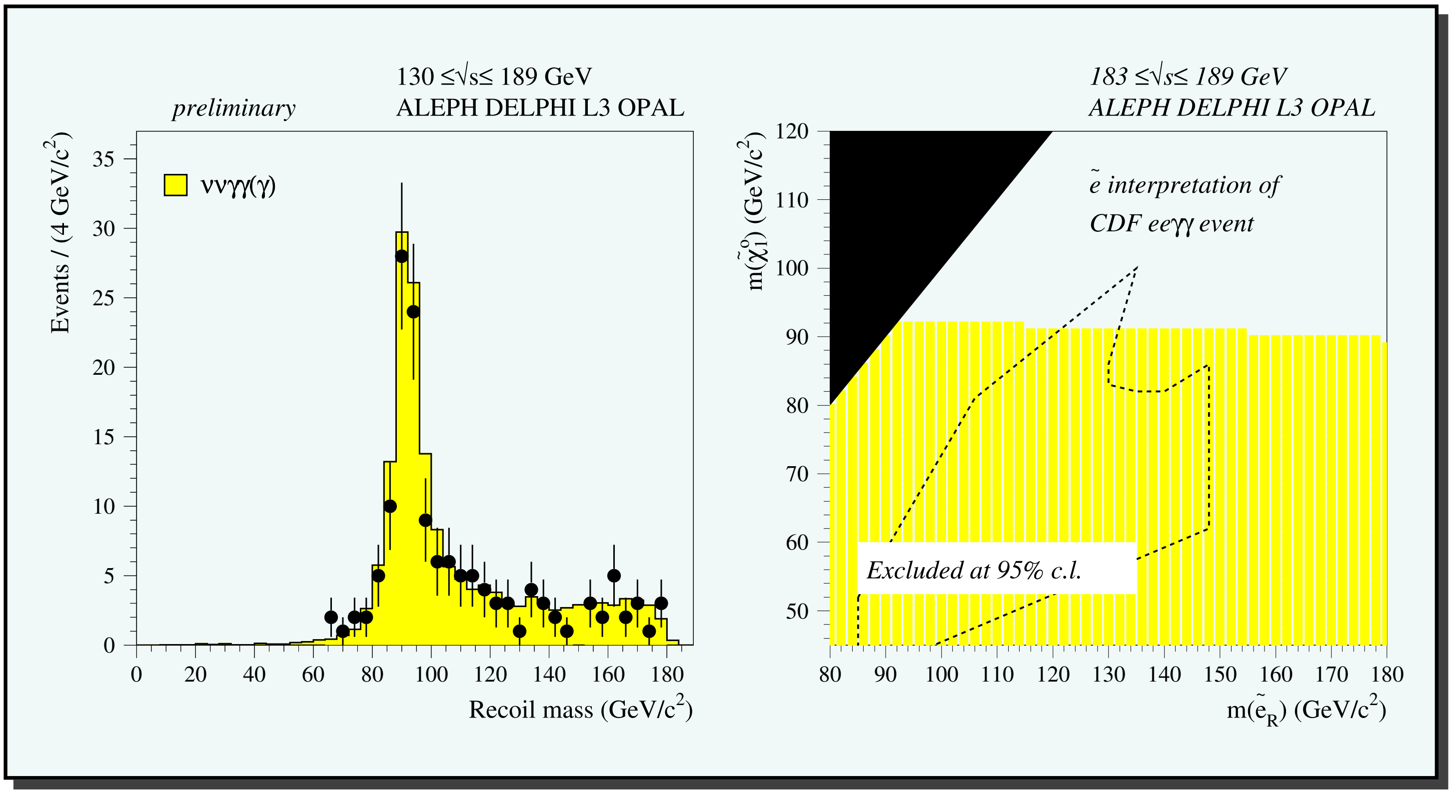
None at D0.

This SUSY process an invitation for LEP:
Large σ and high mass-reach for

$$e^+e^- \longrightarrow \tilde{\chi}_1^0\,\tilde{\chi}_1^0 \longrightarrow \gamma\gamma\,\tilde{G}\tilde{G}$$

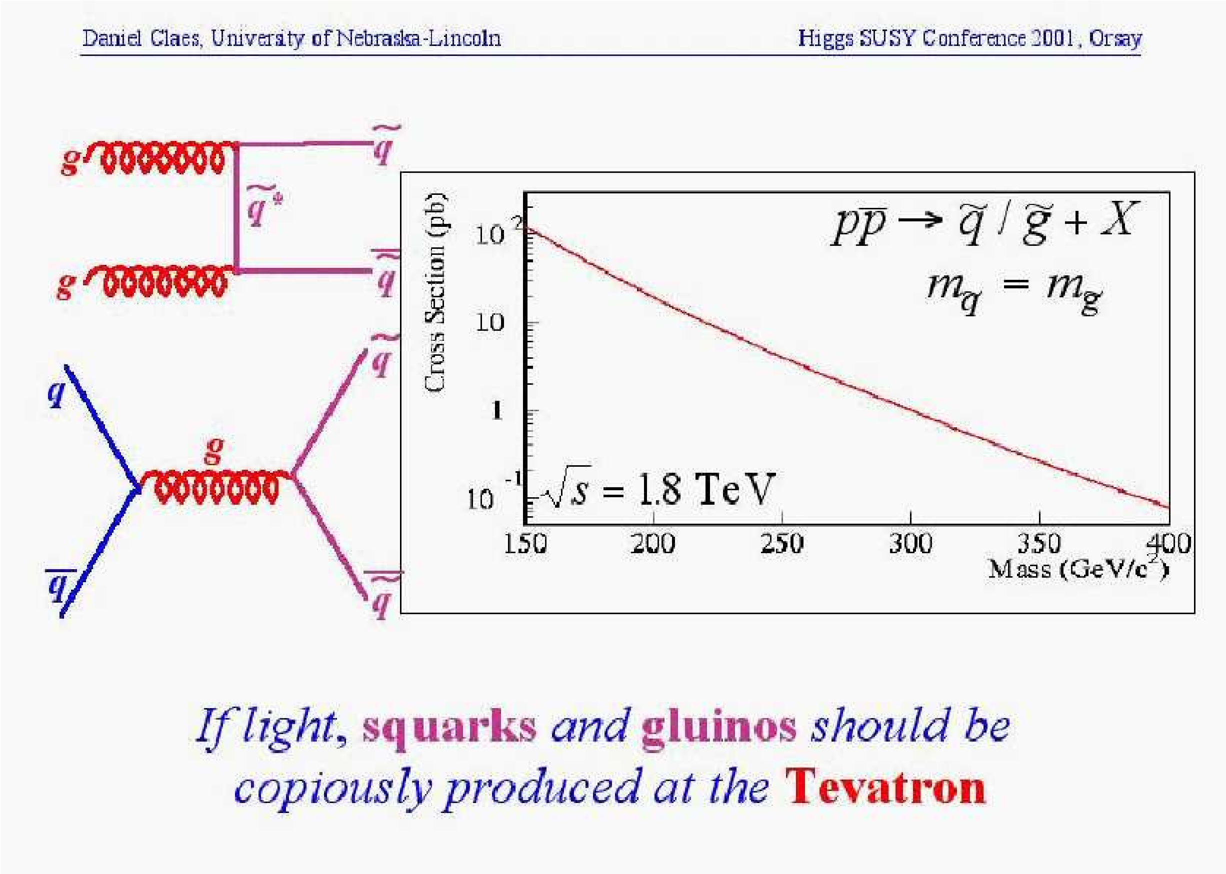
proceeds via $\tilde{e}^-$ exchange in t–channel

$\gamma\gamma$ production well-studied signal at LEP2:



SUSY at Tevatron Run II

- $p\bar{p}$ collider at 2 TeV $\sqrt{s}$
- Run II data-taking started this March
- 2 fb^{-1} in next 2 years
- 15 fb^{-1} till LHC start



Daniel Claes, University of Nebraska-Lincoln Higgs SUSY Conference 2001, Orsay

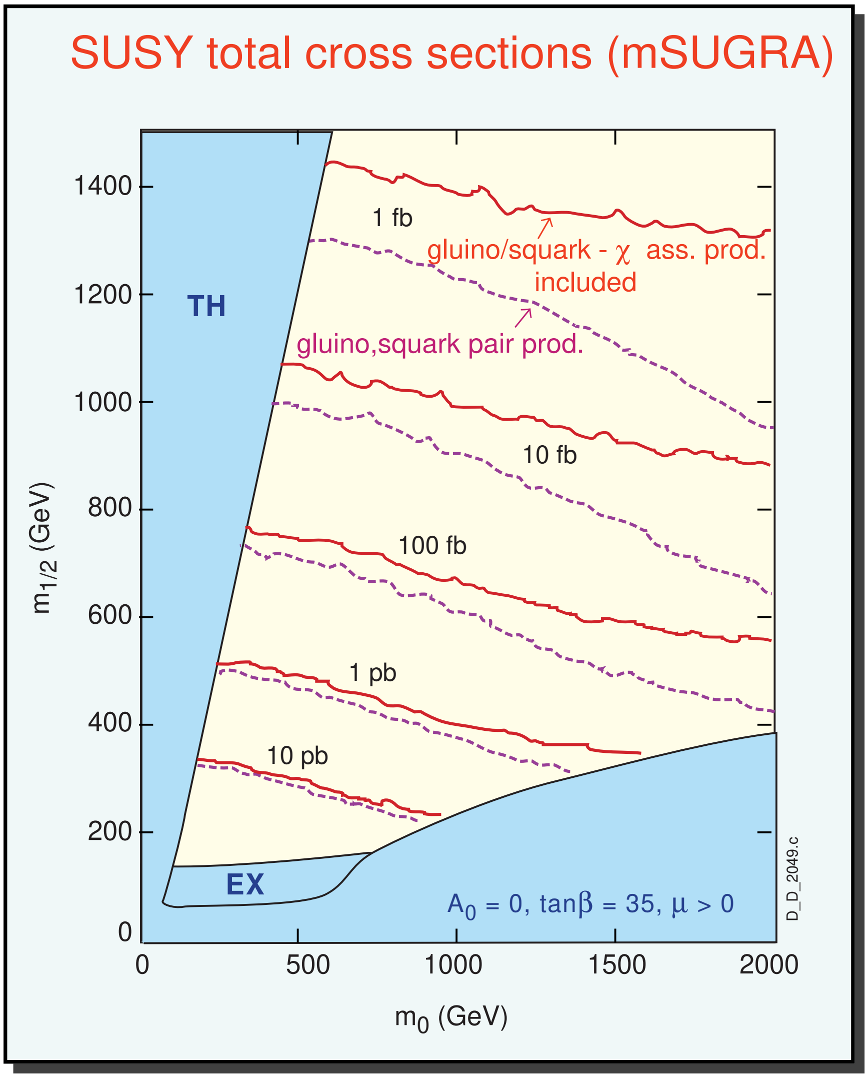
If light, **squarks** *and* **gluinos** *should be copiously produced at the* **Tevatron**

SUSY reach:

find or exclude $\tilde{g}$ and $\tilde{q}$ up to 400 MeV

SUSY at LHC

- pp collider at 14 TeV $\sqrt{s}$
- Data-taking starts 2006
- 100 pb^{-1} in one day
- 30 fb^{-1} in 3 years 300 fb^{-1} in 10 years



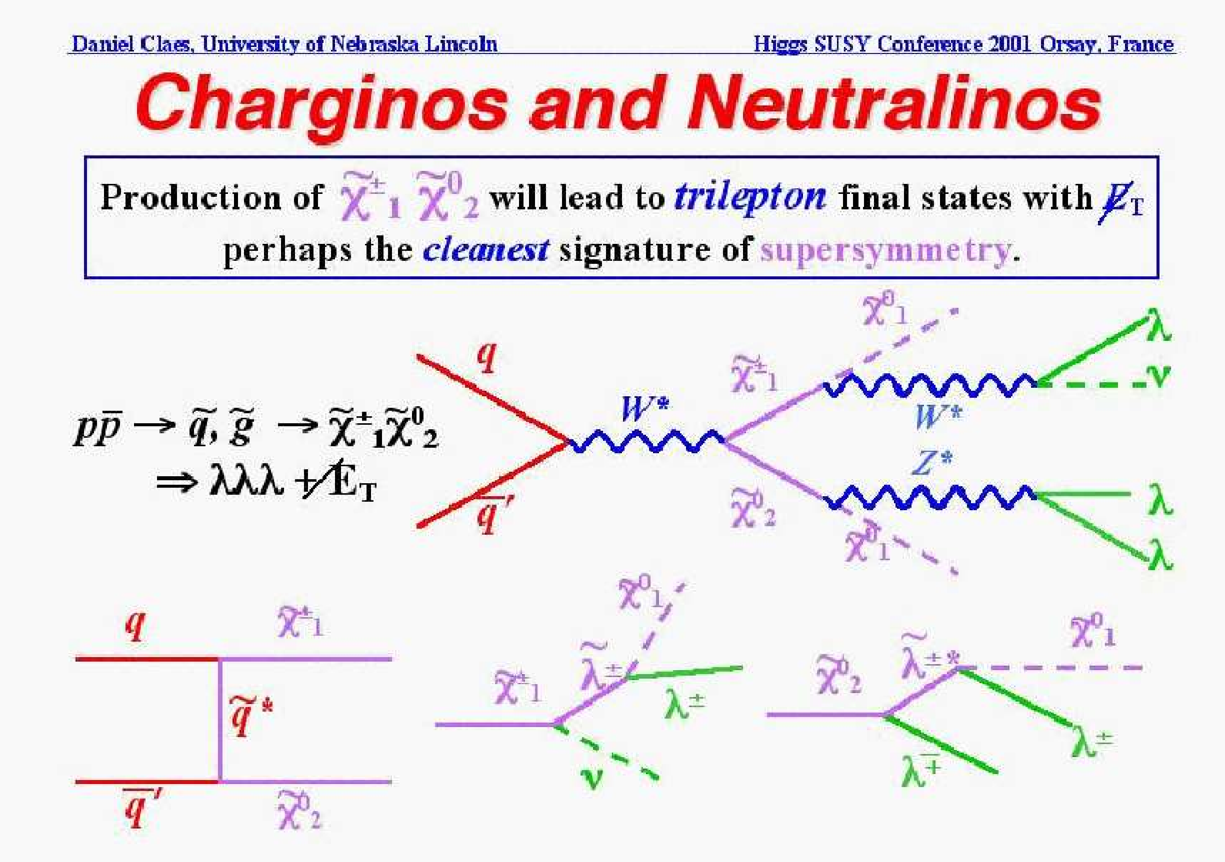
SUSY total cross sections (mSUGRA)

Up to 2 TeV reach for $M_{\tilde{g}}$ and $M_{\tilde{q}}$

Huge σ–SUSY for $M_{\tilde{g}}$, $M_{\tilde{q}} \approx 500$ GeV

⇒ 1–day discovery

Tri-Lepton Signal



Daniel Claes, University of Nebraska Lincoln Higgs SUSY Conference 2001 Orsay, France

Charginos and Neutralinos

Production of $\tilde{\chi}^{\pm}{}_1\ \tilde{\chi}^{0}{}_2$ will lead to *trilepton* final states with $\not{E}_T$ perhaps the *cleanest* signature of supersymmetry.

$$p\bar{p} \to \tilde{q}, \tilde{g} \to \tilde{\chi}^{\pm}{}_1\tilde{\chi}^{0}{}_2 \Rightarrow \lambda\lambda\lambda + \not{E}_T$$

In particular for Tevatron interesting channel:

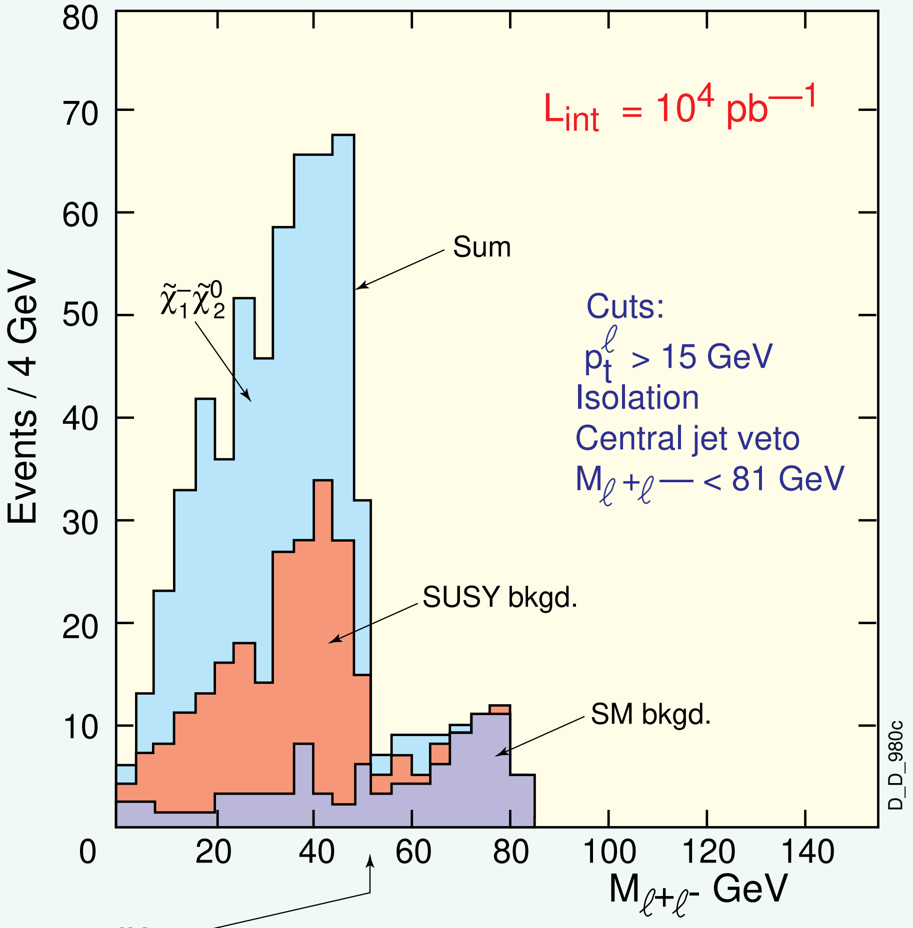
- Very low backgrounds (ZZ, WZ)
- aim to reach $\tilde{\chi}_1^{\pm} \approx$ 200 GeV

... also for LHC ...

$\tilde{\chi}_1^0$ mass determination in $3\ell^-$ + no jets + E_t^{miss} final state from $\tilde{\chi}_1^- \tilde{\chi}_2^0$ production

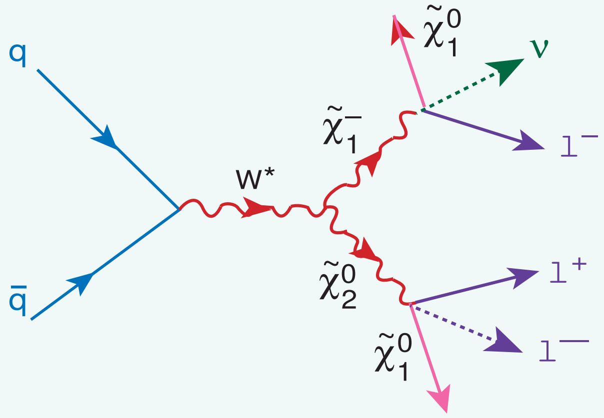
m_0 = 200 GeV, $m_{1/2}$ = 100 GeV, $\tan\beta = 2$, $A_0 = 0$, $\mu < 0$

$M(\tilde{\chi}_2^0) - M(\tilde{\chi}_1^0) \approx M(\tilde{\chi}_1^0) \approx 52$ GeV



$M_{\ell\ell}^{max} = M(\tilde{\chi}_2^0) — M(\tilde{\chi}_1^0) \approx M(\tilde{\chi}_1^0) \rightarrow m_{1/2} \approx 2.5\, M(\tilde{\chi}_1^0)$

in m SUGRA



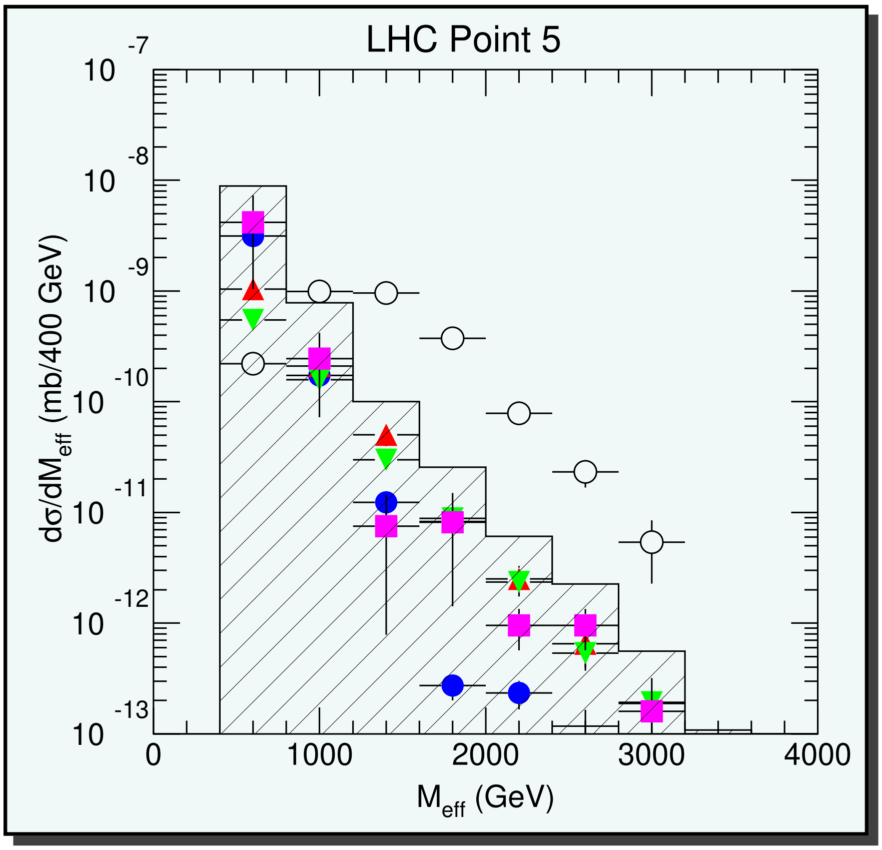
LHC SUSY search

Main focus on $\tilde{g}$ and $\tilde{q}$.

Establish SUSY mass-scale using simple & inclusive analysis:

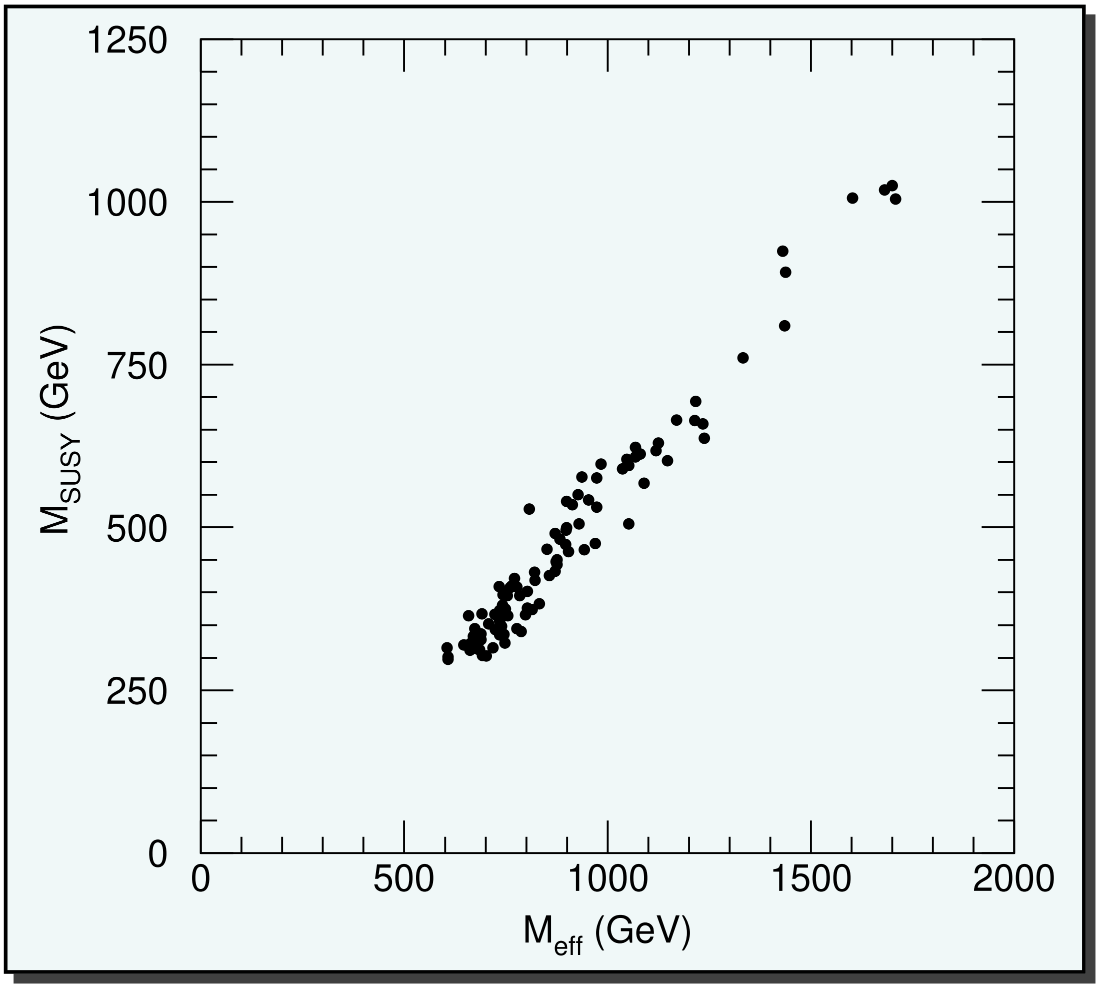
- Select events with
  - 4 jets
  - missing energy
- Construct

$$M_{\text{eff}} = P_{t,1} + P_{t,2} + P_{t,3} + P_{t,4} + E_T^{\text{miss}}$$



- SUSY signal (open points) emerges from backg

- Max. of M_{eff} closely correlated to M_{SUSY} $(= min(M_{\tilde{q}}, M_{\tilde{g}}))$

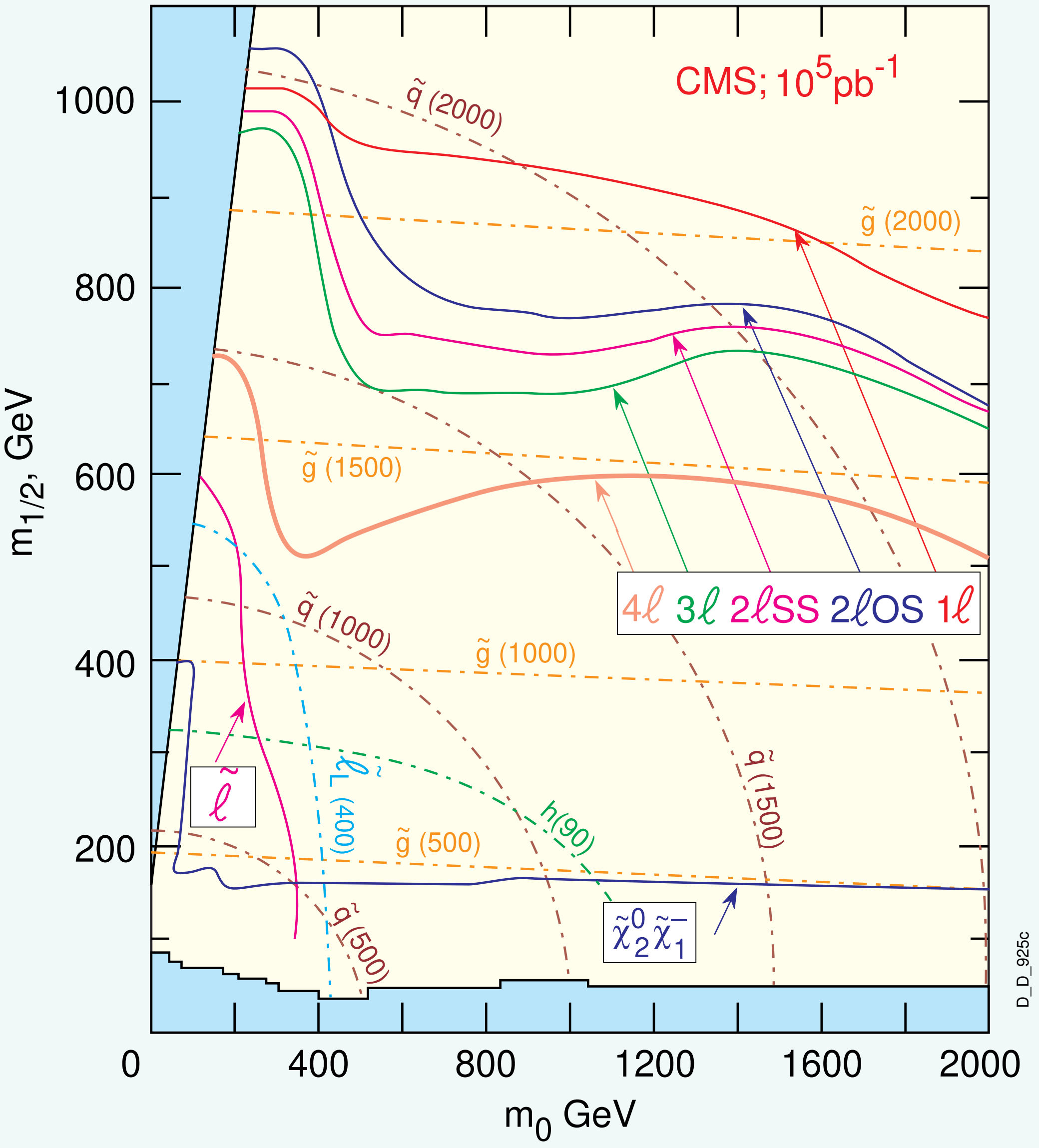


LHC mass reach

Expected sparticle reach in various channels

m SUGRA; tg β = 2 (about the same up to ~ 5), $A_0 = 0$, $\mu < 0$

5 σ contours ($\sigma = N_{sig} / \sqrt{N_{sig} + N_{bkgd}}$) for $10^5 pb^{-1}$



LHC SUSY id

Once SUSY established employ refined analysis

- determine mass–spectrum
- constrain SUSY model

Disentangle decay chain, e.g.

$$\tilde{q}_L \to q_L \, \ell\ell \, \tilde{\chi}^0_1$$

can proceed via gauginos:

$$\begin{aligned} \tilde{q}_L \longrightarrow q_L \; & \tilde{\chi}^0_2 \\ & \hookrightarrow \ell \; \tilde{\ell} \\ & \qquad \hookrightarrow \ell \; \tilde{\chi}^0_1 \end{aligned}$$

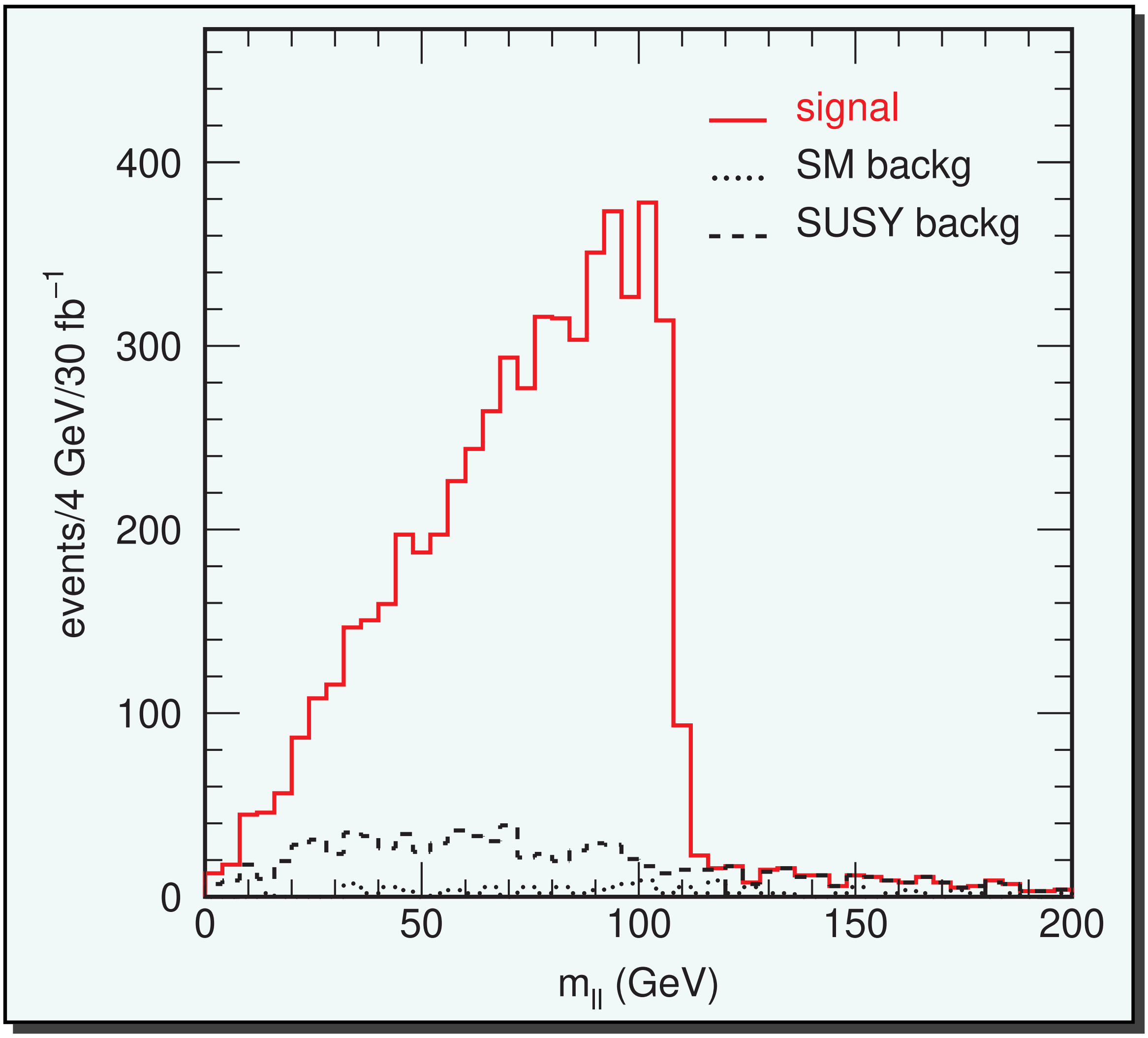
4 unknowns must be determined:

$$M_{\tilde{q}_L}, M_{\tilde{\chi}^0_2}, M_{\tilde{\ell}}, M_{\tilde{\chi}^0_1}$$

Experimental: Endpoints of mass spectra:

1. $M_{\ell\ell}$
2. $M_{\ell\ell q}$
3. $M_{\ell q}$

Endpoint for $M_{\ell\ell}$



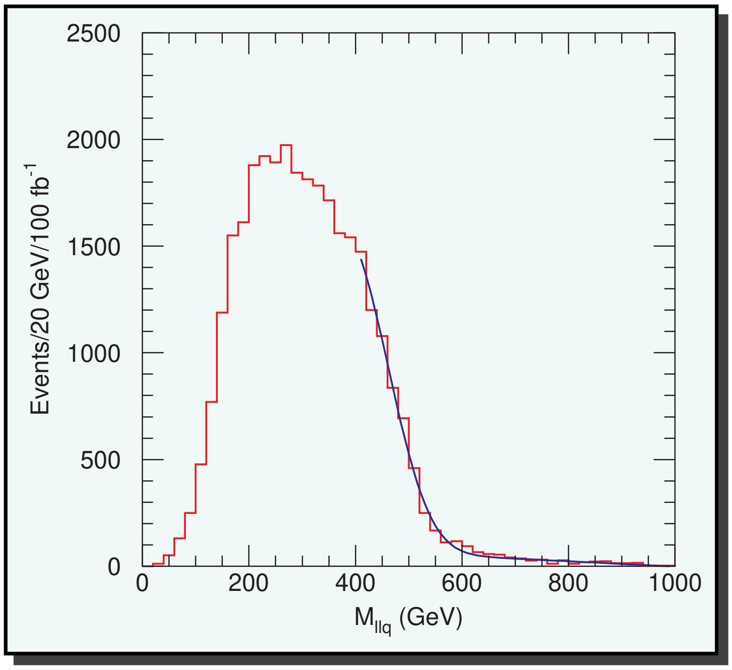
$$M_{\tilde{\chi}_2^0}\sqrt{1-\frac{M_{\tilde{\ell}}^2}{M_{\tilde{\chi}_2^0}^2}}\sqrt{1-\frac{M_{\tilde{\chi}_1^0}^2}{M_{\tilde{\ell}}^2}}$$

(example from SUGRA "Point 5", $M_{\ell\ell}^{max} = 108.1$ GeV)

Endpoints for $M_{\ell\ell q}$

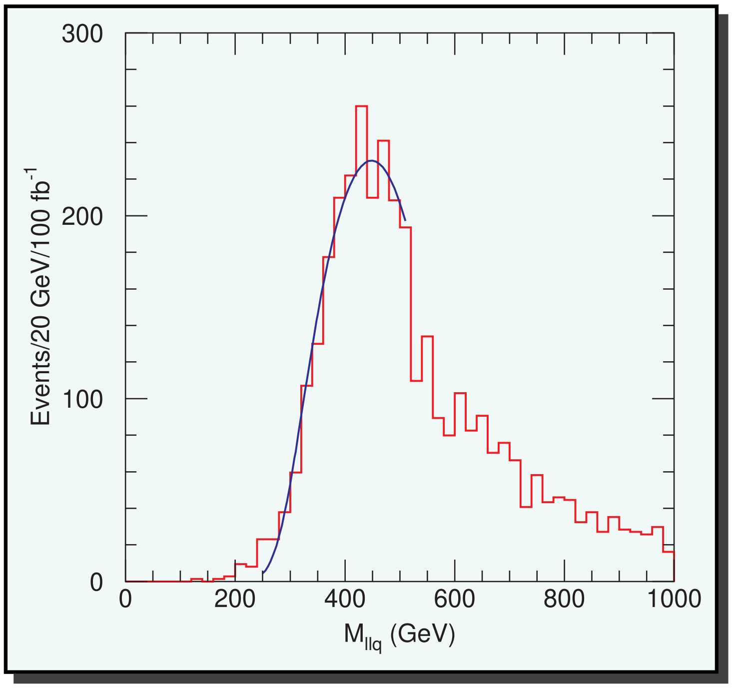
$$M_{\ell\ell q}^{max} = \sqrt{\frac{(M_{\tilde{q}}^2 - M_{\tilde{\chi}_2^0}^2)(M_{\tilde{\chi}_2^0}^2 - M_{\tilde{\chi}_1^0}^2)}{M_{\tilde{\chi}_2^0}^2}}$$

(Point 5, $M_{\ell\ell q}^{max} = 552$ GeV)

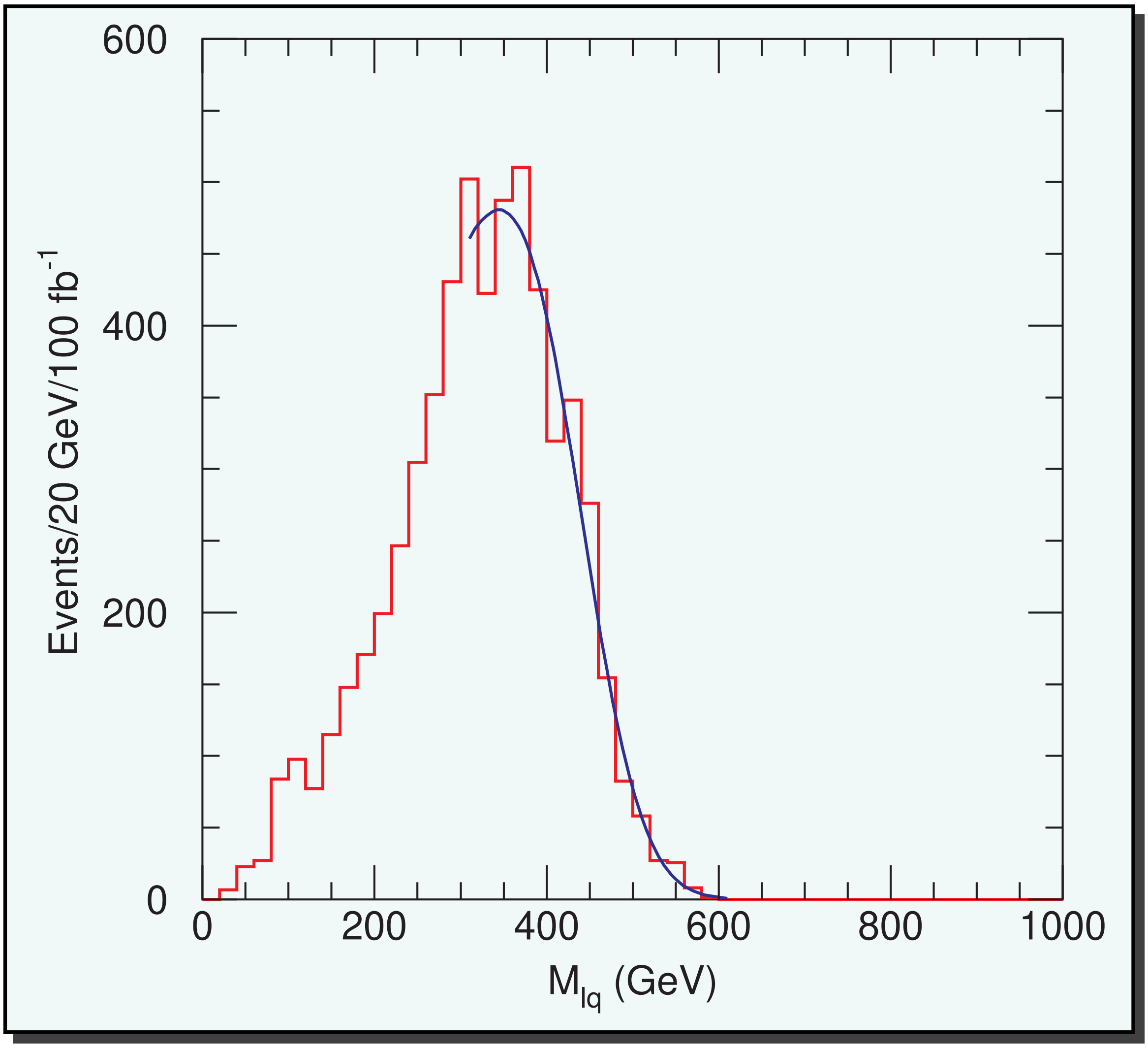


Similar but more complex relation for $M_{\ell\ell q}^{min}$

(Point 5, $M_{\ell\ell q}^{min} = 271$ GeV)



... and finally $M_{\ell q}$



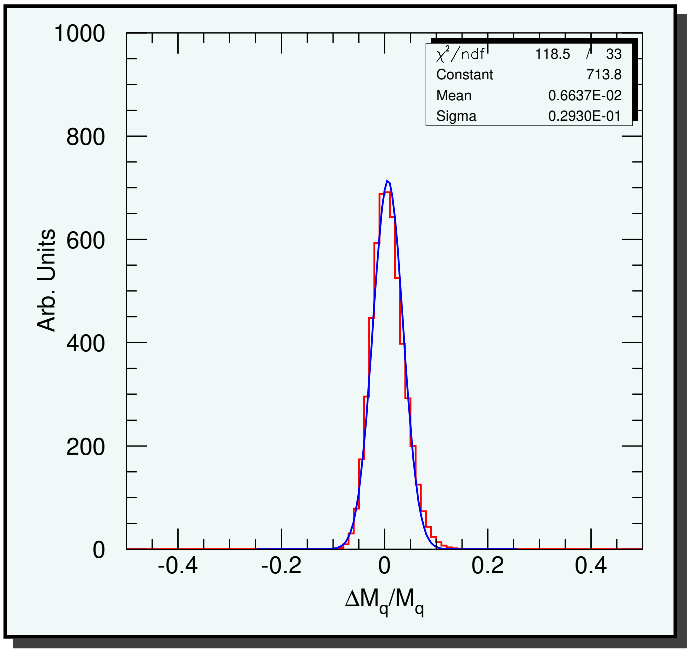
$$M_{\ell q}^{max} = \sqrt{\frac{(M_{\tilde{q}}^2 - M_{\tilde{\chi}_2^0}^2)(M_{\tilde{\chi}_2^0}^2 - M_{\tilde{\ell}2})}{M_{\tilde{\chi}_2^0}^2}}$$

(Point 5, $M_{\ell q}^{max} = 479$ GeV)

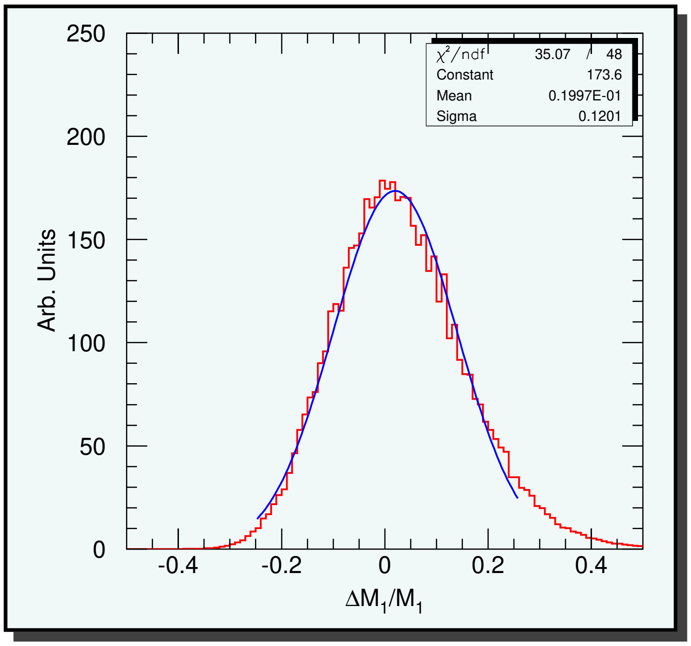
Sparticle reconstruction

Enough constraints for mass reconstruction w/o explicit model at the ≈ few per-cent level

$M_{\tilde{q}}$



$M_{\tilde{\chi}_1^0}$



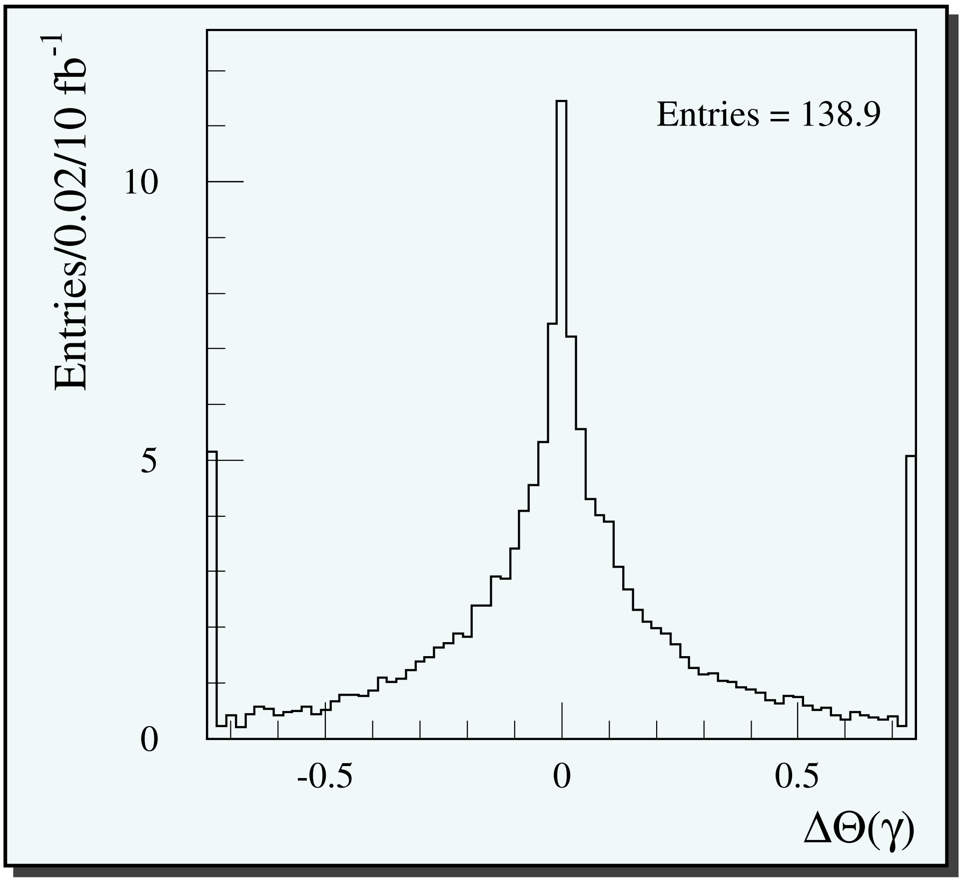
Long-living NLSP in GMSB SUSY

Final, more exotic example for decay

$$\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}$$

with $c\tau_{\tilde{\chi}_1^0} = 1.1$ km

Identification based on non-pointing angle $\Delta\theta$ for photons in the calorimeter.



Typical resolution $\Delta\theta \approx 10$ mrad

Summary

LEP/Tevatron searches give limits for substantial SUSY parameter space

- $\tilde{q} \simeq 150,\ \tilde{g} \simeq 180$ GeV
- $\tilde{\chi}_1^\pm \simeq$ 100–140 GeV
- $\tilde{\ell} \simeq$ 80–90 GeV
- model-independent limits much weaker
- $\tilde{\chi}_1^0$ (=LSP) $\simeq 40$ GeV

Tevatron run II:

- $\tilde{q}, \tilde{g} \rightarrow 400,\ \tilde{\chi}_1^\pm \rightarrow 200$ GeV

LHC

- $\tilde{q}, \tilde{g} \rightarrow 2$ TeV
  $\Rightarrow$ find SUSY if relevant for e-weak symmetry breaking
- main background to SUSY is SUSY
- If SUSY then also
  - measure $M_{\tilde{q}}, M_{\tilde{g}}$ to few %
  - maybe also $M_{\tilde{\ell}}, M_{\tilde{\chi}_1^\pm}, M_{\tilde{\chi}_1^0}$
  - severe constraints for SUSY models/pars
  - Many new particles, interesting fun-work
    $\Rightarrow$ 7th heaven for experimentalists