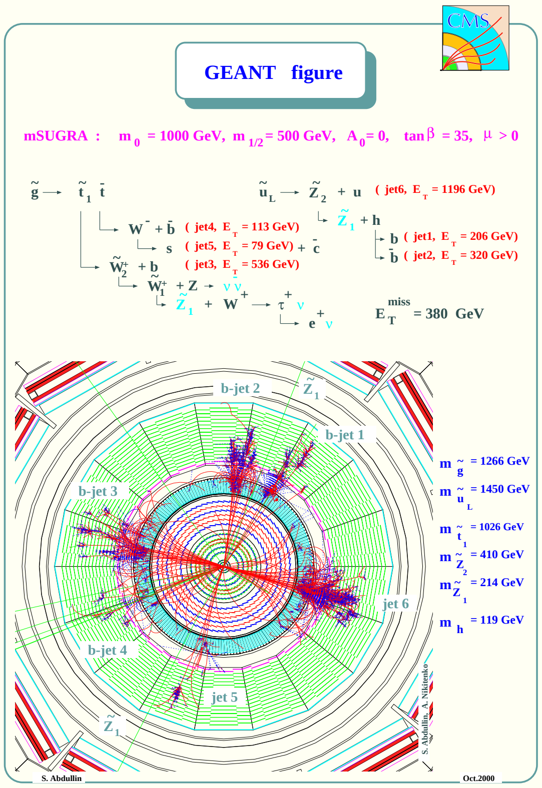
Supersymmetry at the LHC

Howard Baer

Florida State University

★ SUSY at LHC

- SUSY models
- sparticle production
- sparticle decay
- event generation
- searches at LHC
- precision measurements



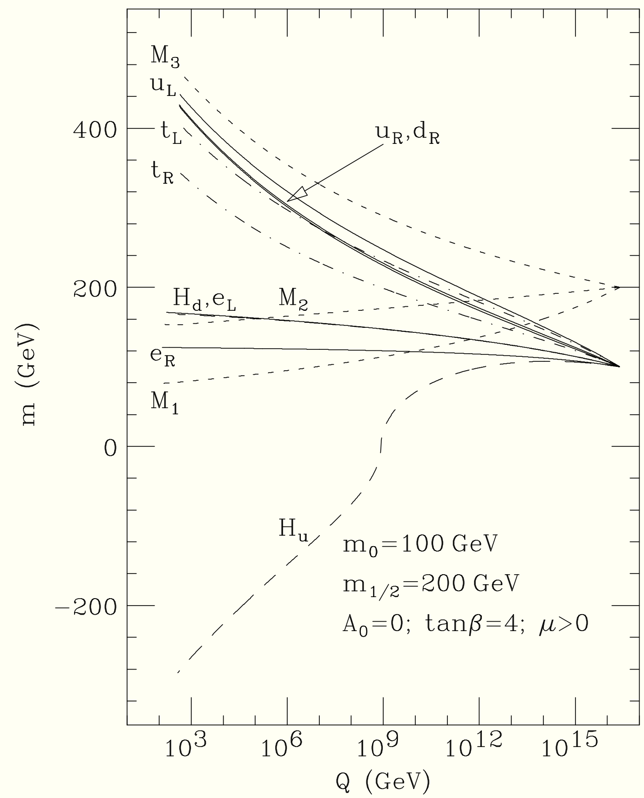
Models of SUSY breaking

- ⋆ Spontaneous breaking of SUSY phen. inconsistent within MSSM
- ⋆ Hidden sector models (HS)
- ⋆ HS is arena for SUSY breaking; how to communicate SUSY breaking to visible sector (VS)?
  - gravity mediation: supergravity (SUGRA) and local SUSY: minimal messenger sector: $m_{3/2} \sim$ TeV: LSP=bino/higgsino/wino/gravitino?
  - gauge mediation (GMSB): introduce messenger sector fields as intermediary between HS and VS: $m_{3/2} \ll$ TeV: LSP=gravitino
  - anomaly mediation (AMSB): $m_{3/2} >$ TeV: LSP=wino
- ⋆ role of extra dimensions? compactification? sequestered sector and AMSB; gaugino mediation; GUTs; $\cdots$

Calculate spectra using Isajet/Isasugra

- ⋆ MSSM: weak scale inputs (no RGE running)
- ⋆ mSUGRA
  - $m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ sign(\mu)$
  - non-universal SUGRA
- ⋆ gauge mediated SUSY breaking (GMSB)
  - $\Lambda,\ M,\ n_5,\ \tan\beta,\ sign(\mu),\ C_{grav}$
  - non-minimal GMSB
- ⋆ anomaly-mediated SUSY breaking (AMSB)
  - $m_0,\ m_{3/2},\ \tan\beta,\ sign(\mu)$
  - non-minimal AMSB
- ⋆ mixed modulus-AMSB
  - $\alpha,\ m_{3/2},\ \tan\beta,\ sign(\mu)$, modular weights

Sparticle mass spectra

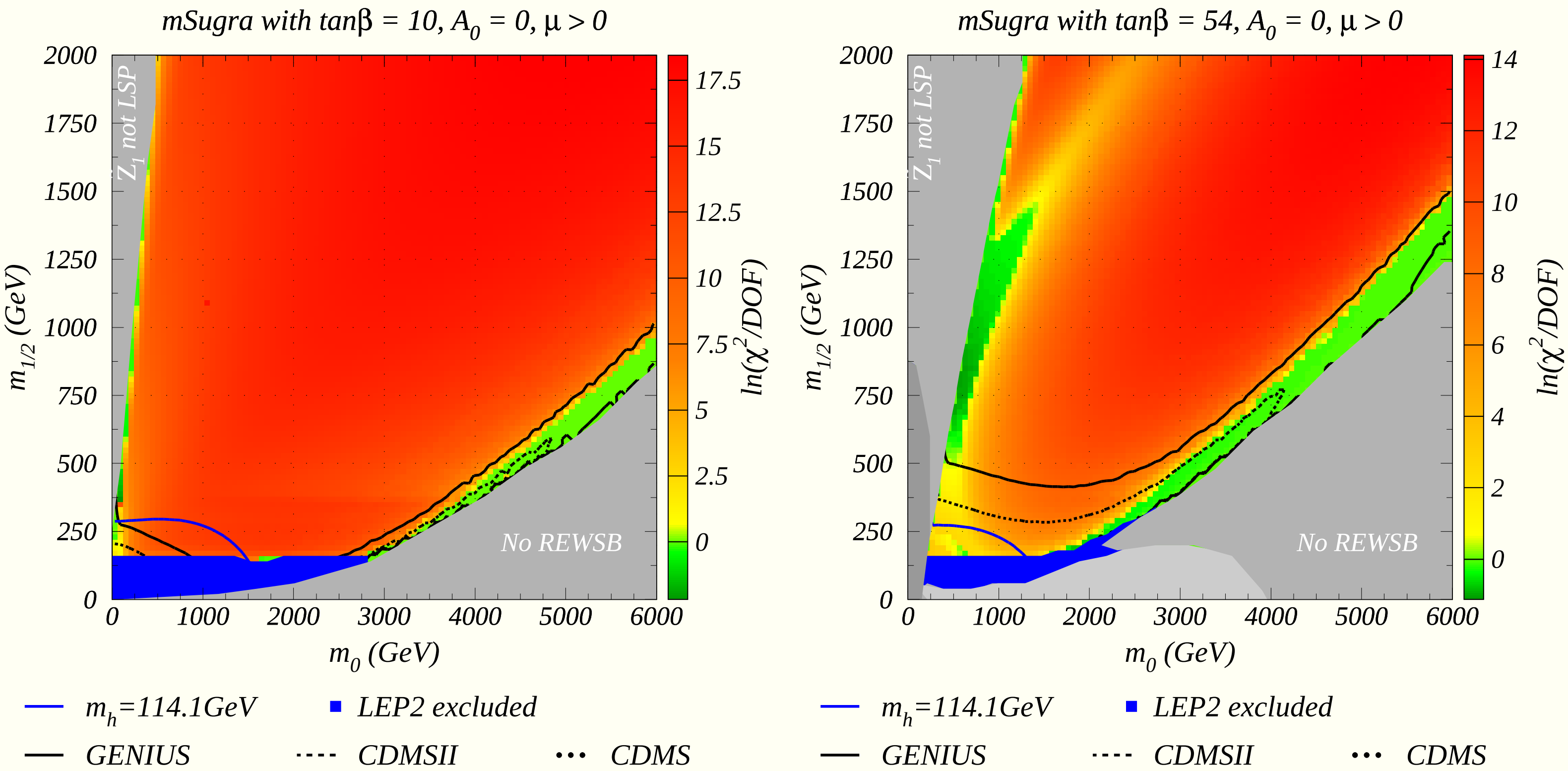


- ⋆ Mass spectra codes
- ⋆ RGE running: $M_{GUT} \to M_{weak}$
  - Isajet (HB, Paige, Protopopescu, Tata)
    - ∗ $\geq$7.72: Isatools
  - SuSpect (Djouadi, Kneur, Moultaka)
  - SoftSUSY (Allanach)
  - Spheno (Porod)
- ⋆ Comparison (Belanger, Kraml, Pukhov)
- ⋆ Website: `http://kraml.home.cern.ch/kraml/comparison/`

Constraints on SUSY models

- ⋆ LEP2:
  - $m_h > 114.4$ GeV for SM-like h
  - $m_{\widetilde{W}_1} > 103.5$ GeV
  - $m_{\tilde{e}_{L,R}} > 99$ GeV for $m_{\tilde{\ell}} - m_{\widetilde{Z}_1} > 10$ GeV
- ⋆ $BF(b \to s\gamma) = (3.25 \pm 0.54) \times 10^{-4}$ (BELLE, CLEO, ALEPH)
  - SM theory: $BF(b \to s\gamma) \simeq 3.3 - 3.7 \times 10^{-4}$
- ⋆ $a_\mu = (g-2)_\mu/2$ (Muon $g-2$ collaboration)
  - $\Delta a_\mu = (27.1 \pm 9.4) \times 10^{-10}$ (Davier et al. e^+e^-)
  - $\Delta a_\mu^{SUSY} \propto \frac{m_\mu^2 \mu M_i \tan\beta}{M_{SUSY}^4}$
- ⋆ $BF(B_s \to \mu^+\mu^-) < 1.5 \times 10^{-7}$ (CDF-new!)
  - constrains at very large $\tan\beta \gtrsim 50$
- ⋆ $\Omega_{CDM} h^2 = 0.113 \pm 0.009$ (WMAP)

Results of χ^2 fit using τ data for a_μ:



HB, C. Balazs: JCAP 0305, 006 (2003)

Parton model of hadronic reactions

For a hadronic reaction,

$$A + B \rightarrow c + d + X,$$

where c and d are superpartners and X represents assorted hadronic debris, we have an associated subprocess reaction

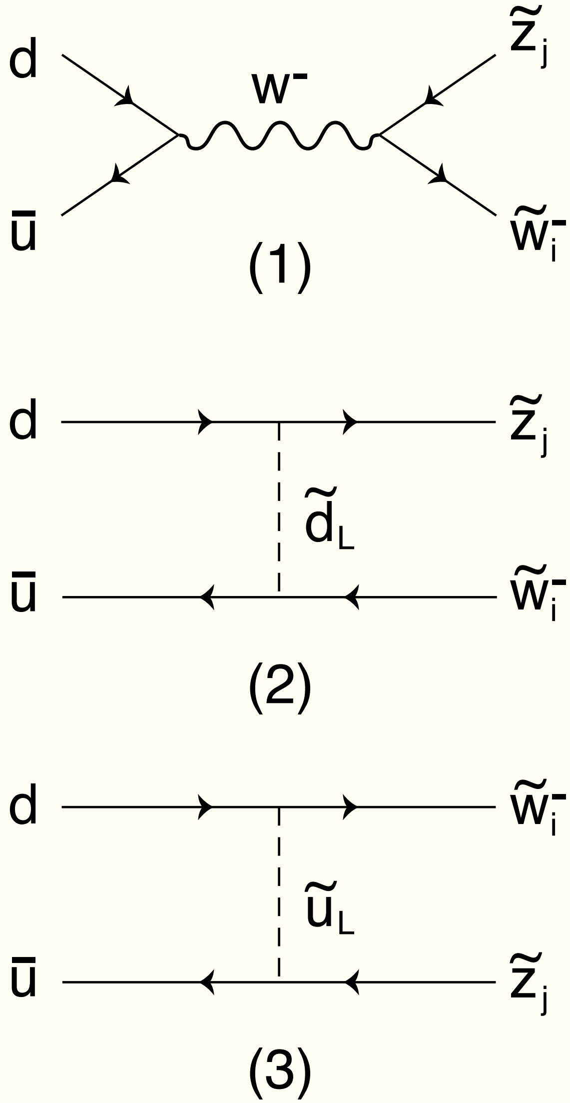
$$a + b \rightarrow c + d,$$

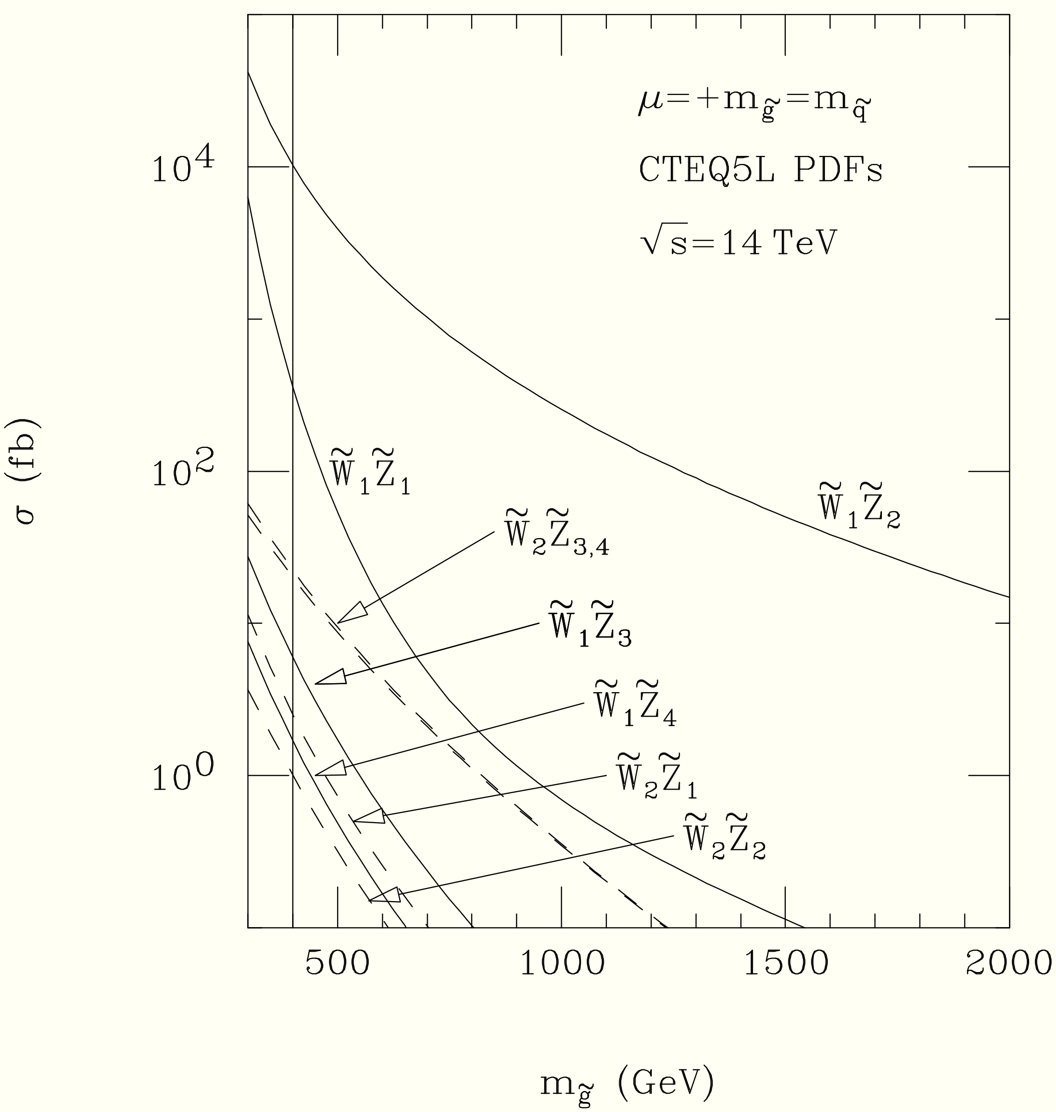
whose cross section can be computed using the Lagrangian for the MSSM. To obtain the final cross section, we must convolute the appropriate subprocess production cross section $d\hat{\sigma}$ with the parton distribution functions:

$$d\sigma(AB \to cdX) = \sum_{a,b} \int_0^1 dx_a \int_0^1 dx_b f_{a/A}(x_a, Q^2)\ f_{b/B}(x_b, Q^2)\ d\hat{\sigma}(ab \to cd). \tag{1}$$

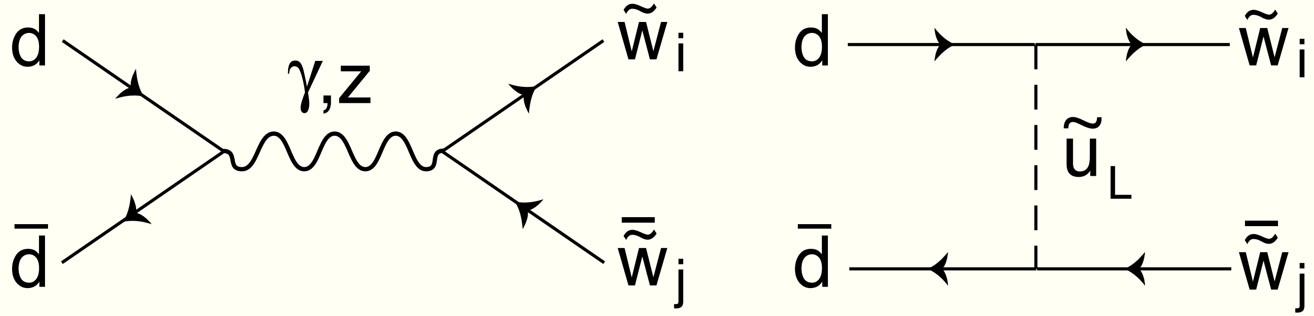
where the sum extends over all initial partons a, b whose collisions produce the final state $c + d$.

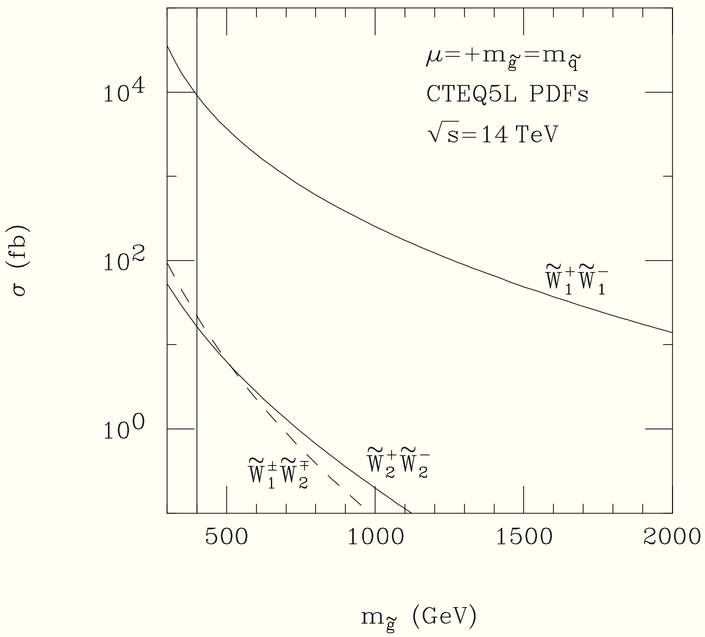
Chargino-neutralino production



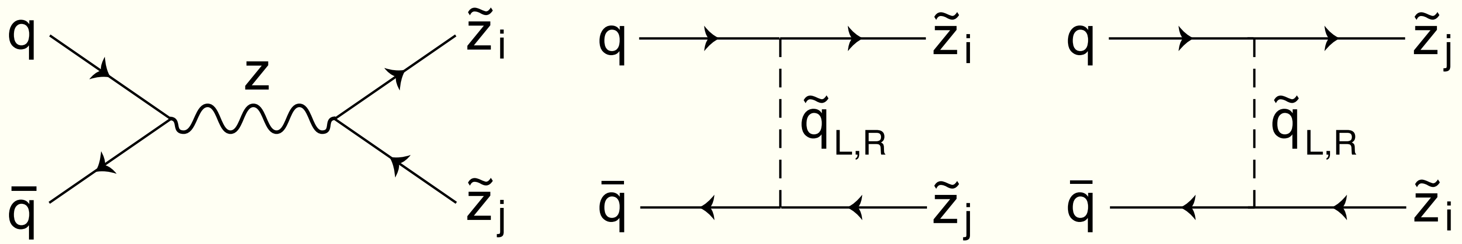


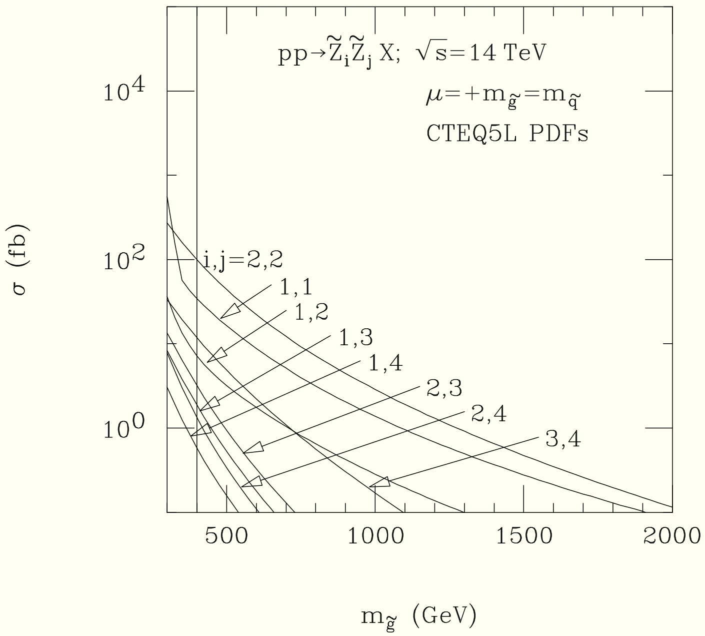
Chargino pair production



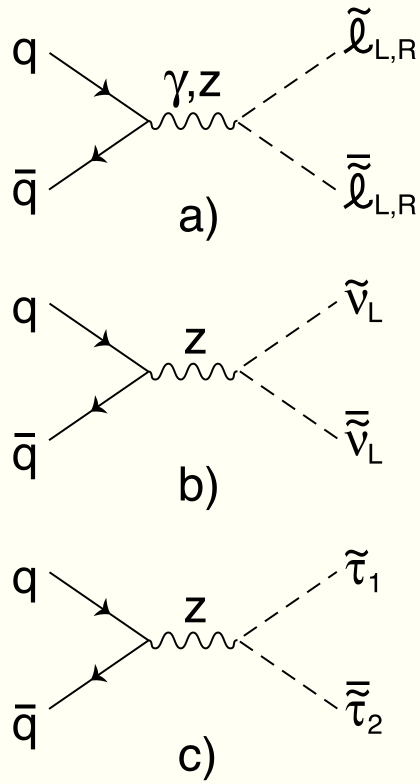


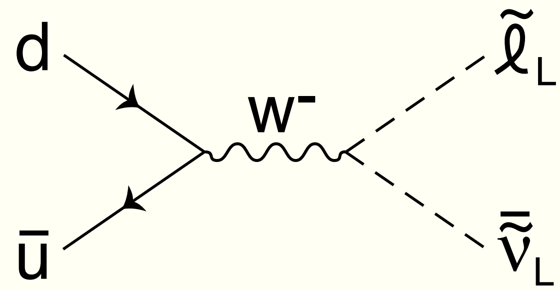
Neutralino pair production



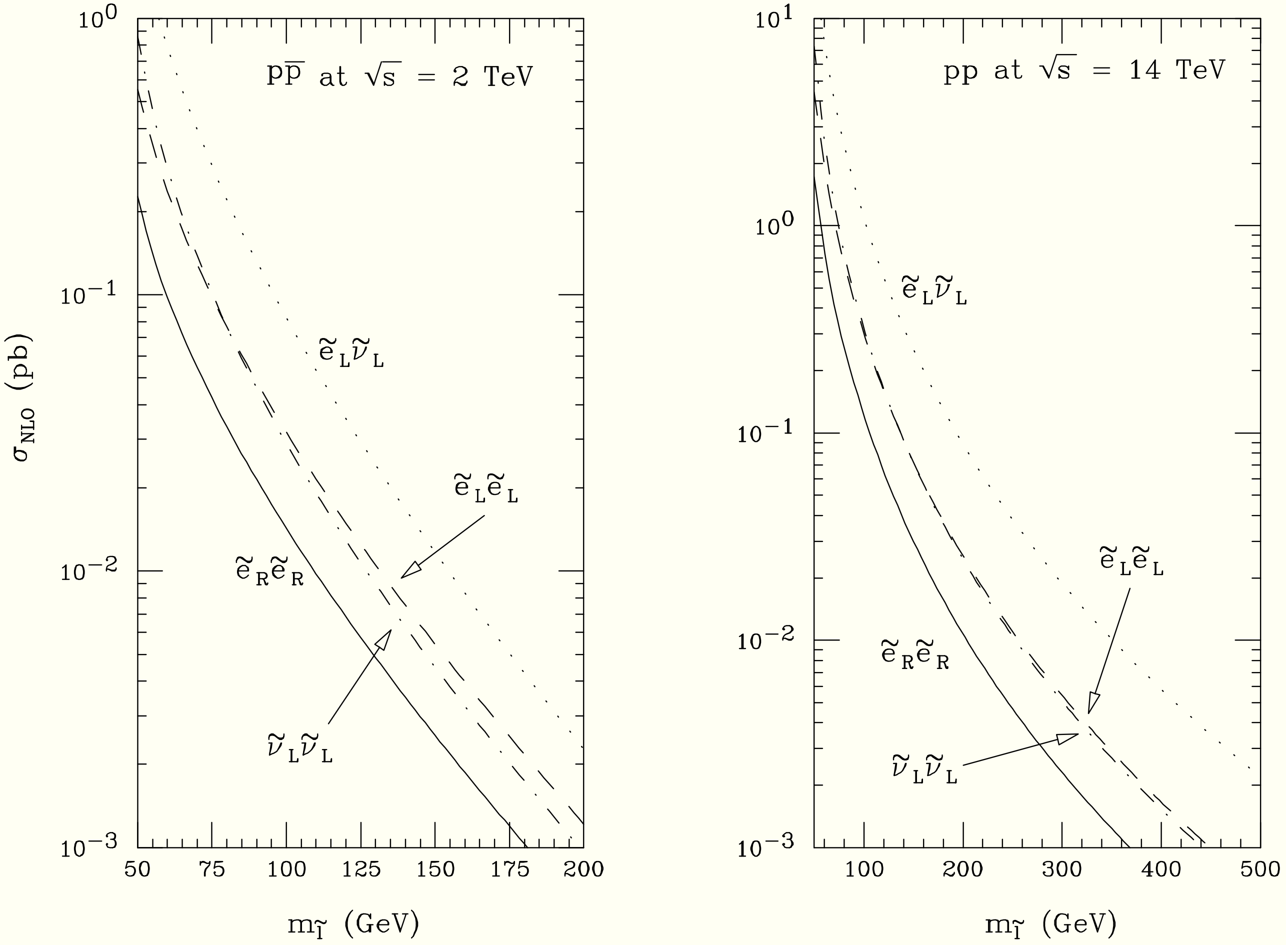


Slepton pair production

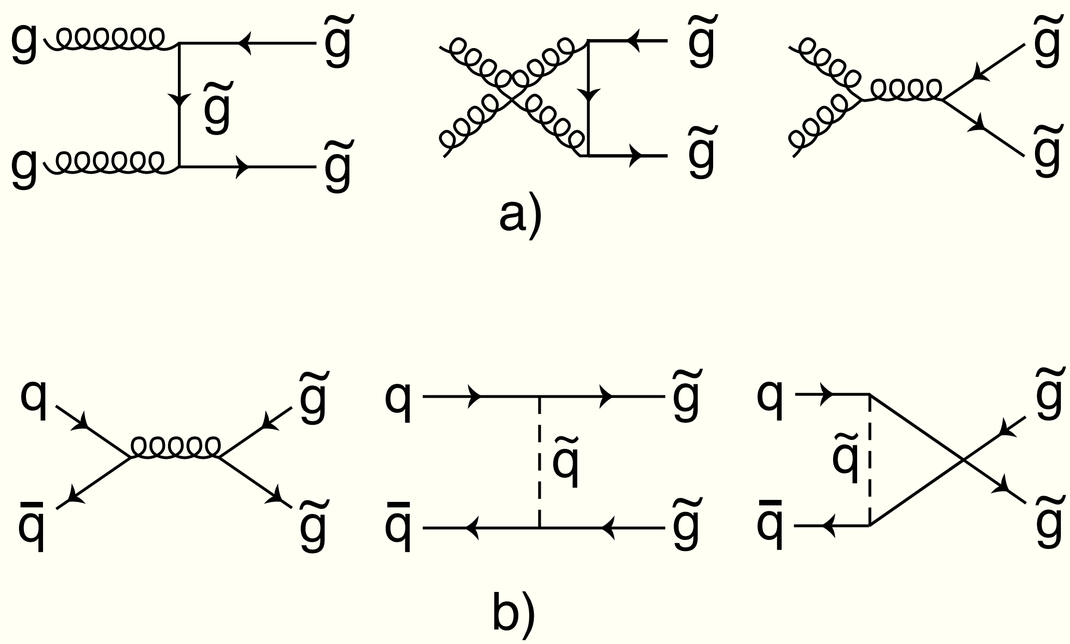




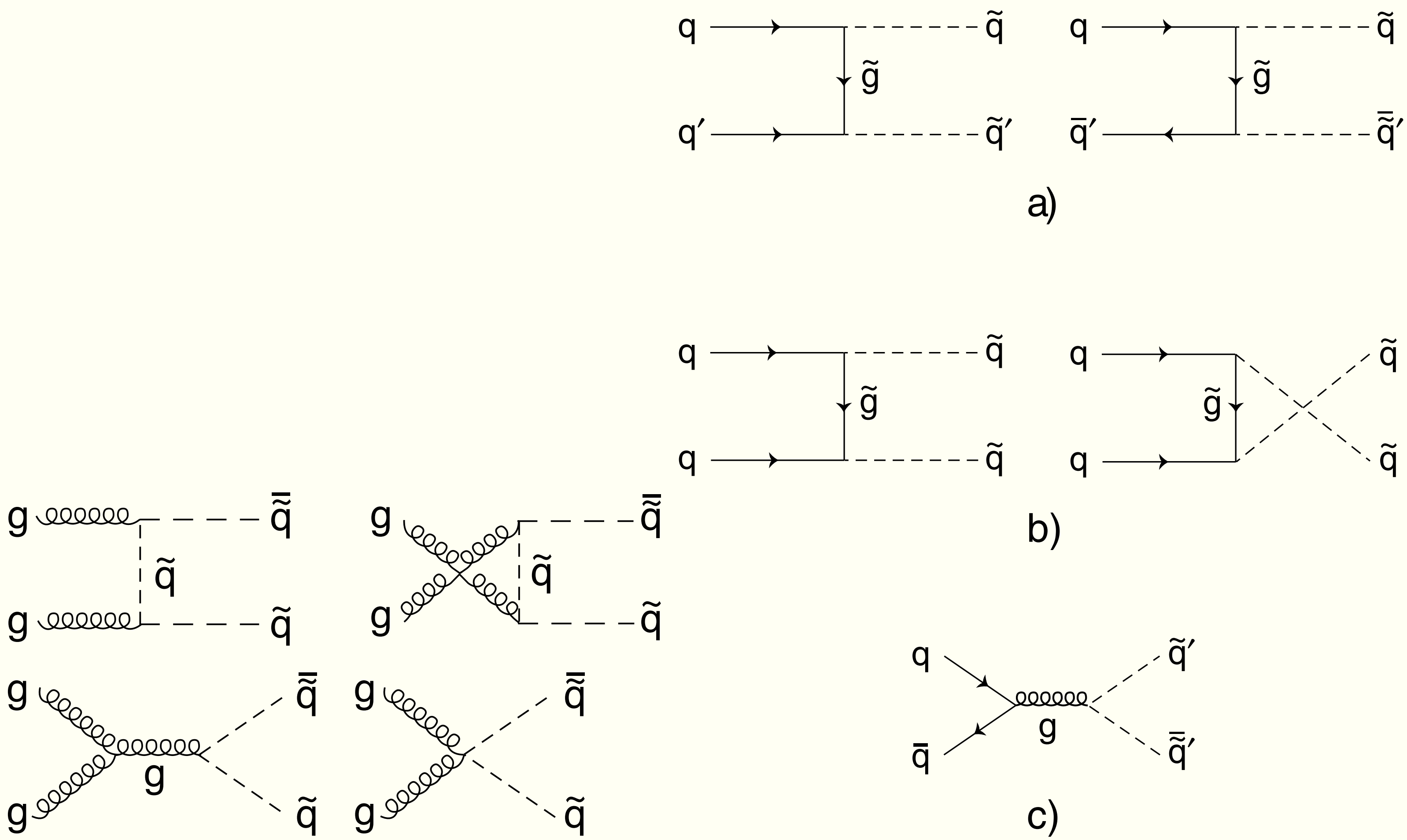
Slepton pair cross section



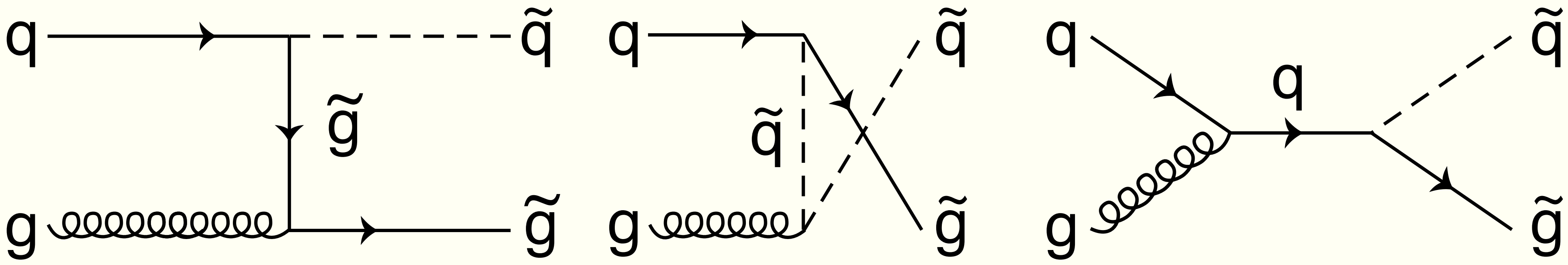
Gluino pair production



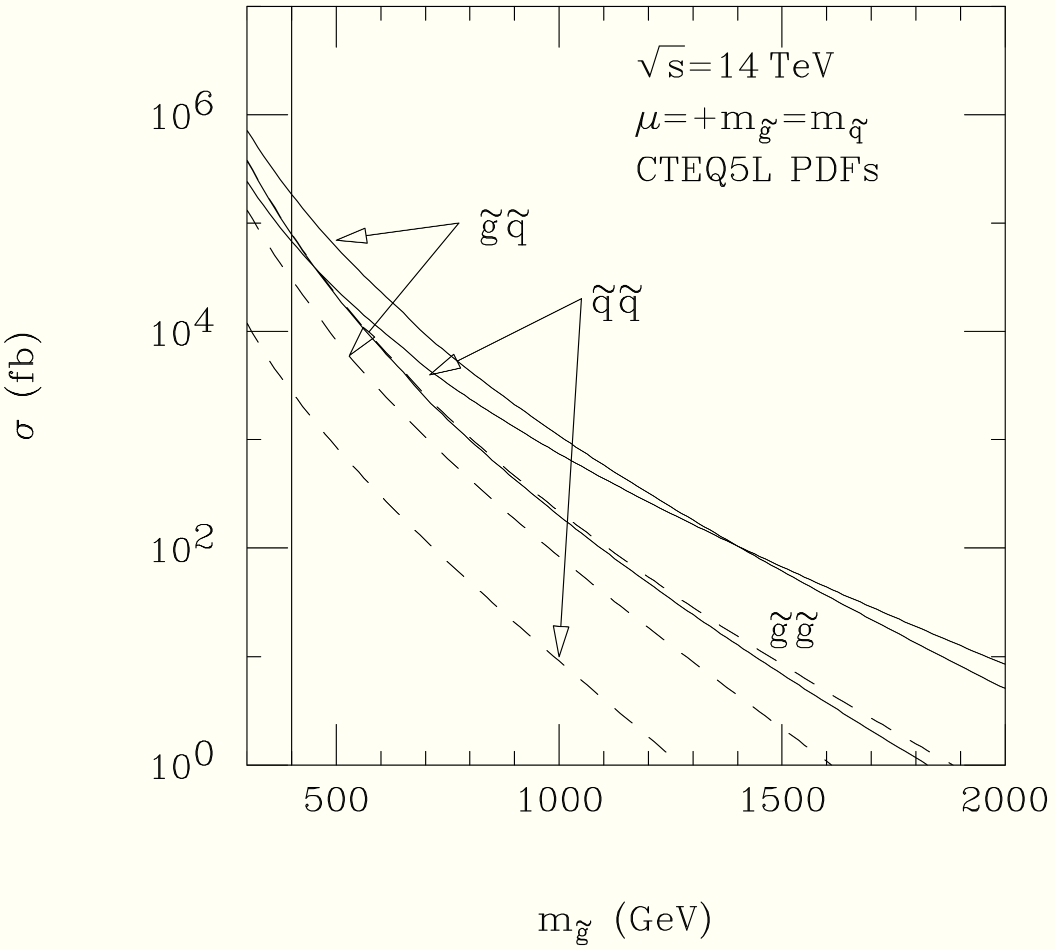
Squark pair production



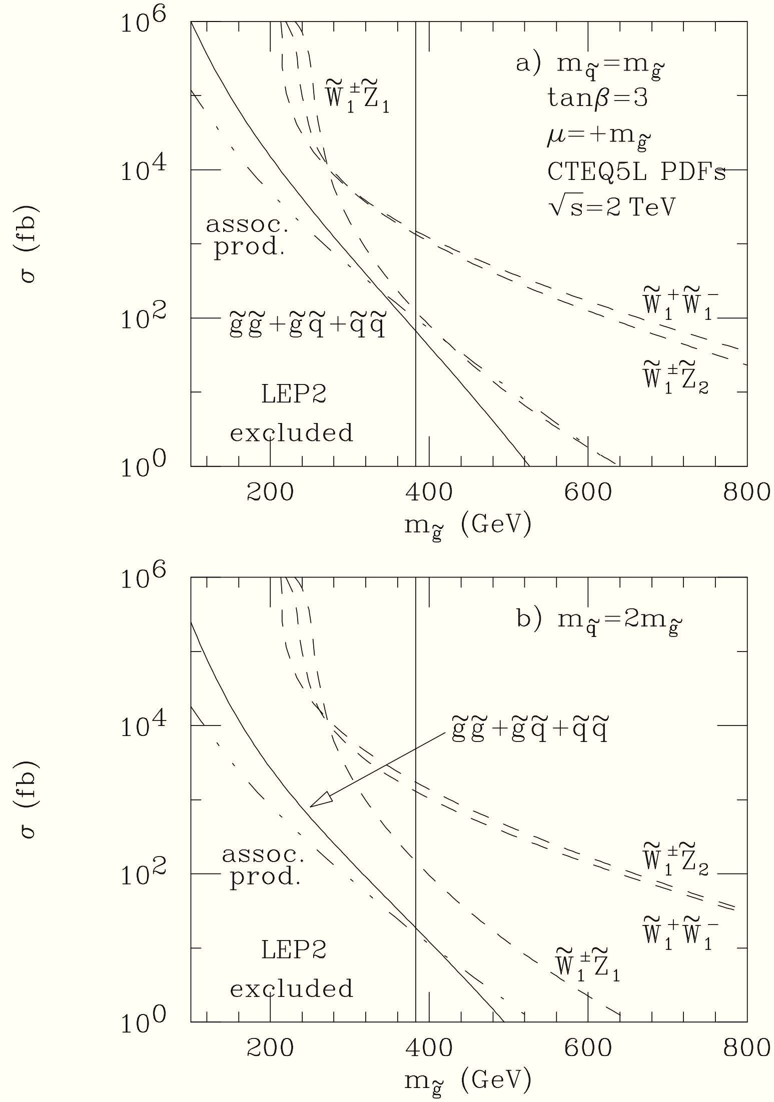
Gluino-squark associated production



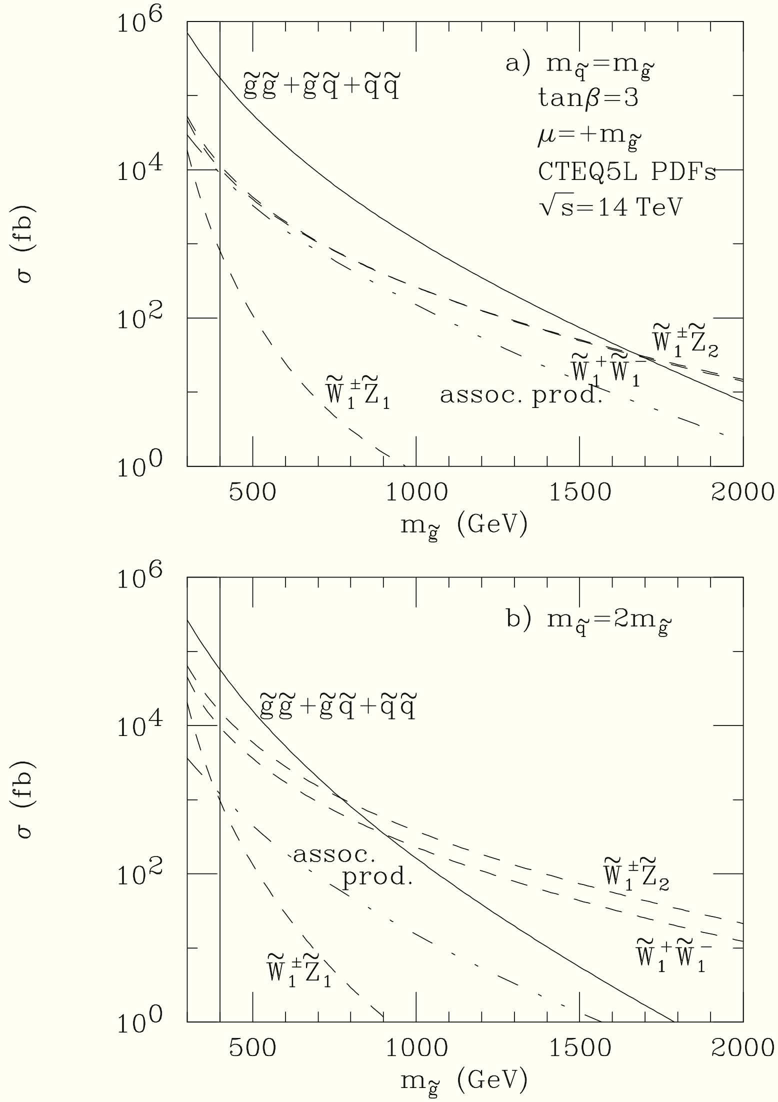
Gluino and squark pair production



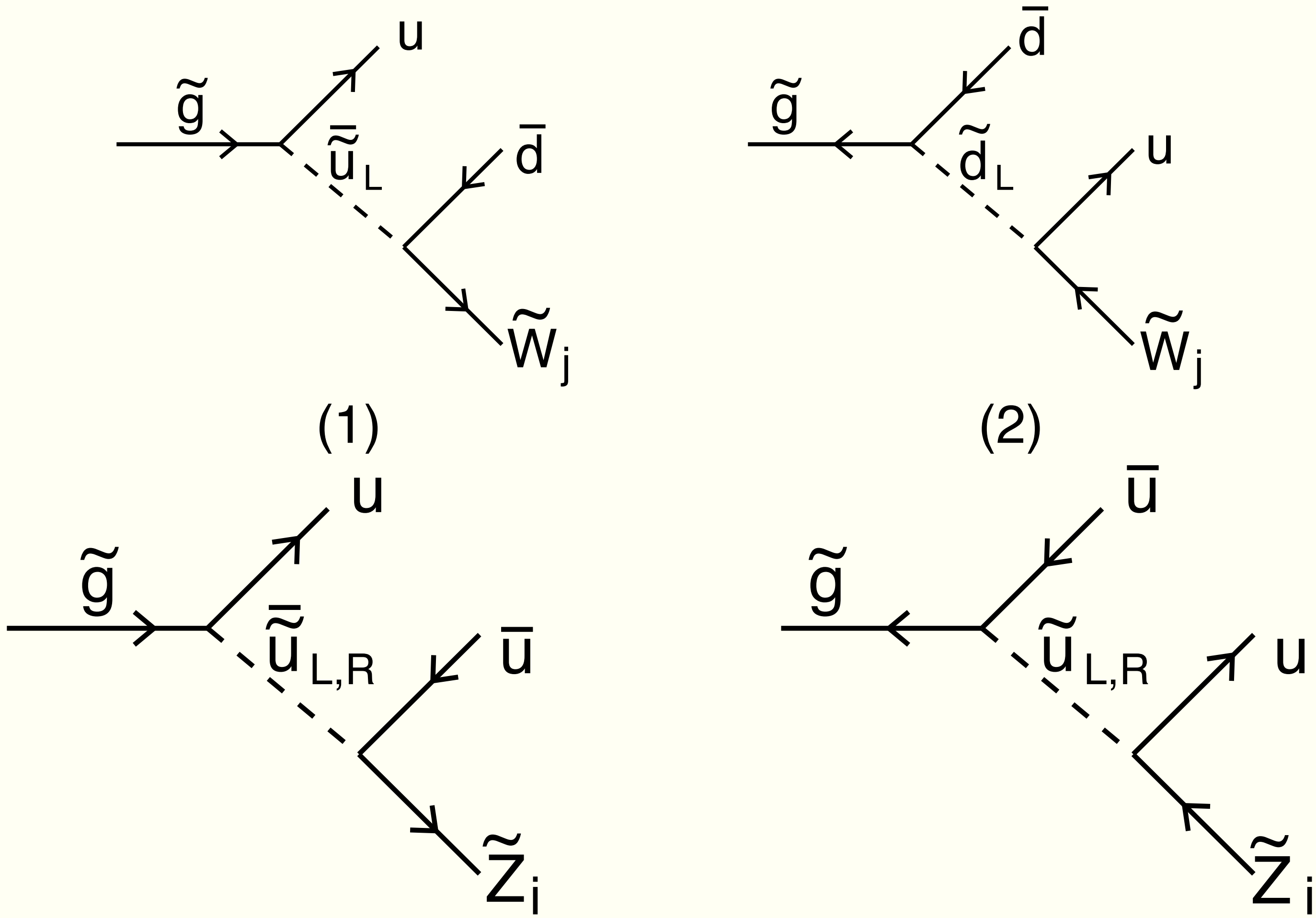
Production at Tevatron



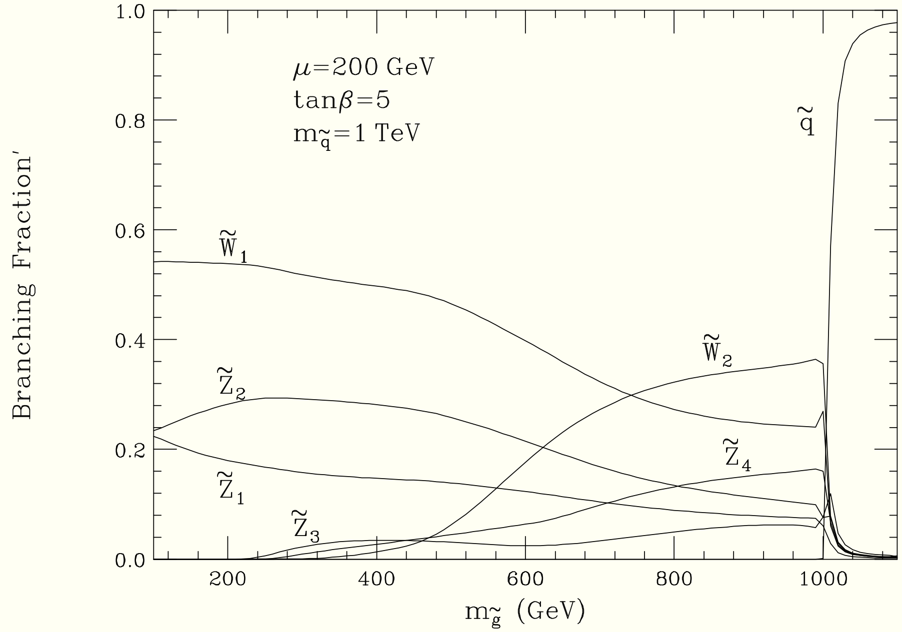
Production at LHC

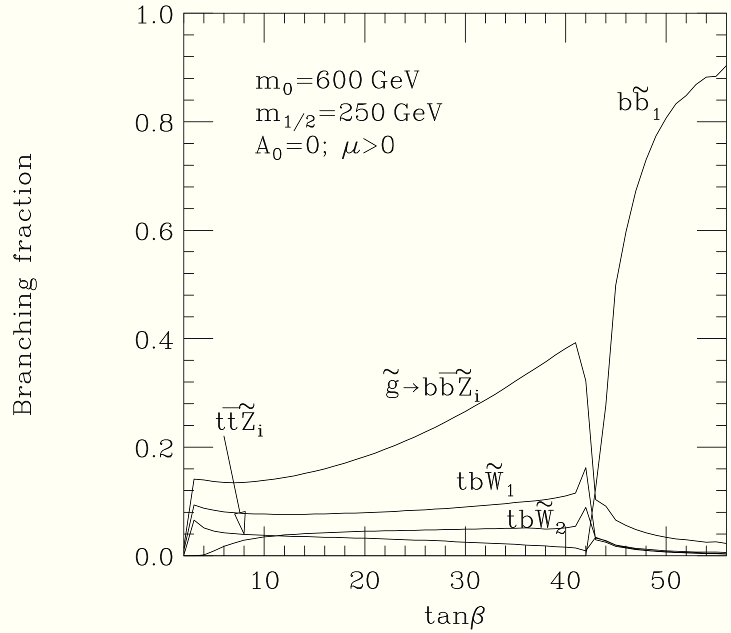


Gluino decays: $\tilde{g} \to q\tilde{q}$ or 3-body



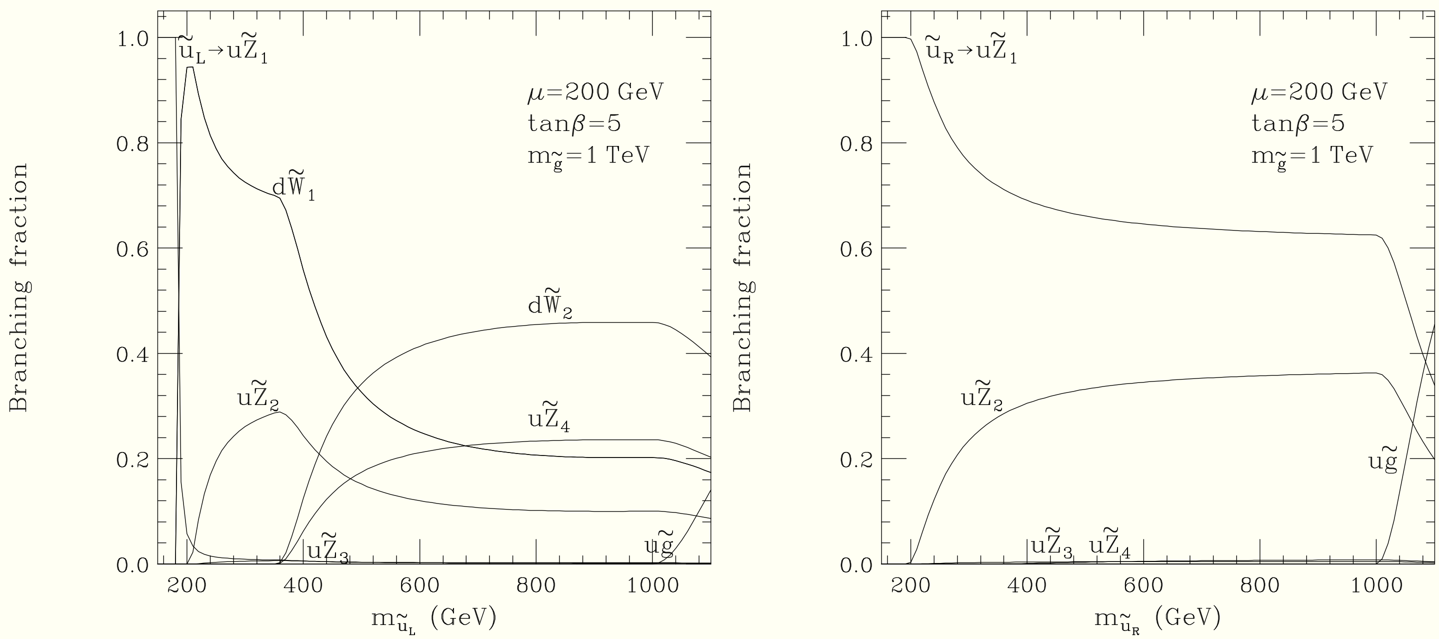
Gluino decays: branching fractions





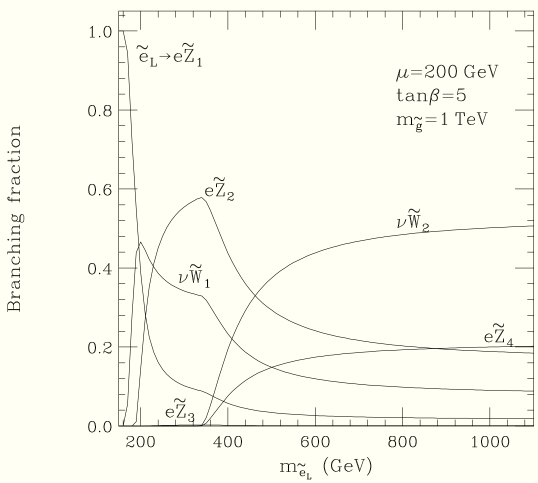
Squark decays

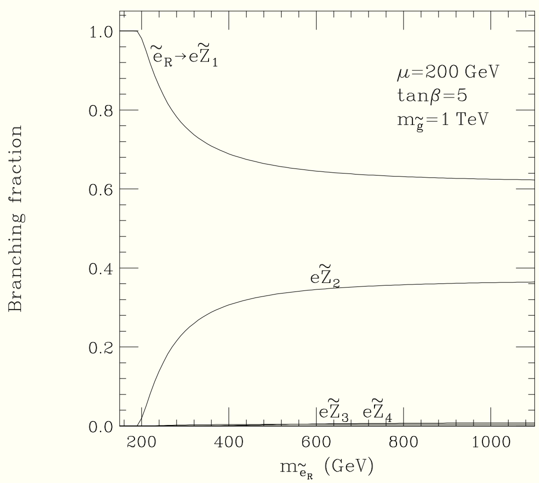
$$\tilde{u}_L \rightarrow u\widetilde{Z}_i,\ d\widetilde{W}_j^+,\ u\tilde{g},$$
$$\tilde{d}_L \rightarrow d\widetilde{Z}_i,\ u\widetilde{W}_j^-,\ d\tilde{g},$$
$$\tilde{u}_R \rightarrow u\widetilde{Z}_i,\ u\tilde{g},$$
$$\tilde{d}_R \rightarrow d\widetilde{Z}_i,\ d\tilde{g}.$$

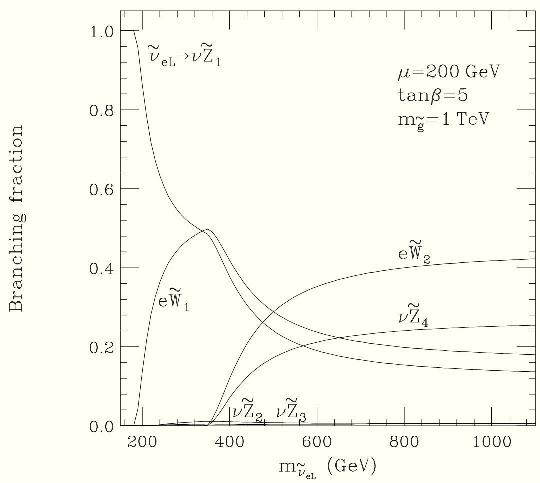


Slepton decays

$$
\begin{aligned}
\tilde{e}_L &\rightarrow e\widetilde{Z}_i,\ \nu_e\widetilde{W}_j^-,\\
\tilde{\nu}_e &\rightarrow \nu_e\widetilde{Z}_i,\ e\widetilde{W}_j^+,\\
\tilde{e}_R &\rightarrow e\widetilde{Z}_i.
\end{aligned}
$$





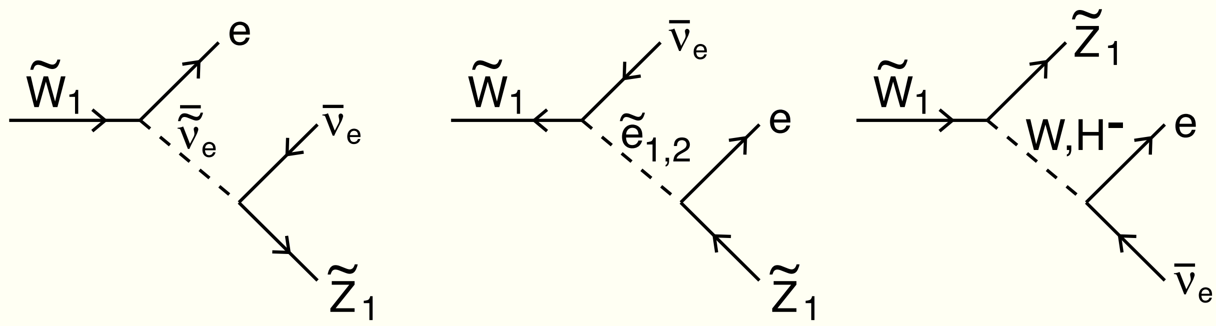


Chargino decays

$$
\begin{aligned}
\widetilde{W}_j &\rightarrow W\widetilde{Z}_i,\ H^-\widetilde{Z}_i,\\
&\rightarrow \tilde{u}_L\bar{d},\ \bar{\tilde{d}}_L u,\ \tilde{c}_L\bar{s},\ \bar{\tilde{s}}_L c,\ \tilde{t}_{1,2}\bar{b},\ \tilde{b}_{1,2}t,\\
&\rightarrow \tilde{\nu}_e\bar{e},\ \bar{\tilde{e}}_L\nu_e,\ \tilde{\nu}_\mu\bar{\mu},\ \bar{\tilde{\mu}}_L\nu_\mu,\ \tilde{\nu}_\tau\bar{\tau},\bar{\tilde{\tau}}_{1,2}\nu_\tau,\ \text{and}\\
\widetilde{W}_2 &\rightarrow Z\widetilde{W}_1,\ h\widetilde{W}_1,\ H\widetilde{W}_1\ \text{and}\ A\widetilde{W}_1.
\end{aligned}
$$

Charginos may decay to a lighter neutralino via

$$\widetilde{W}_j \rightarrow \widetilde{Z}_i + f\bar{f}' \ , \tag{2}$$

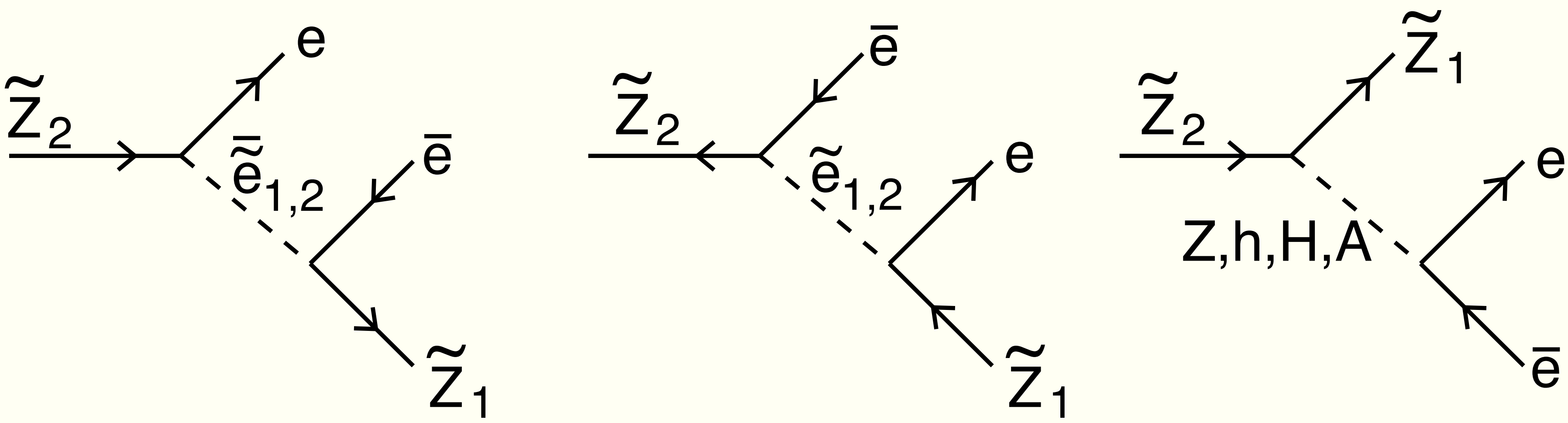


Neutralino decays

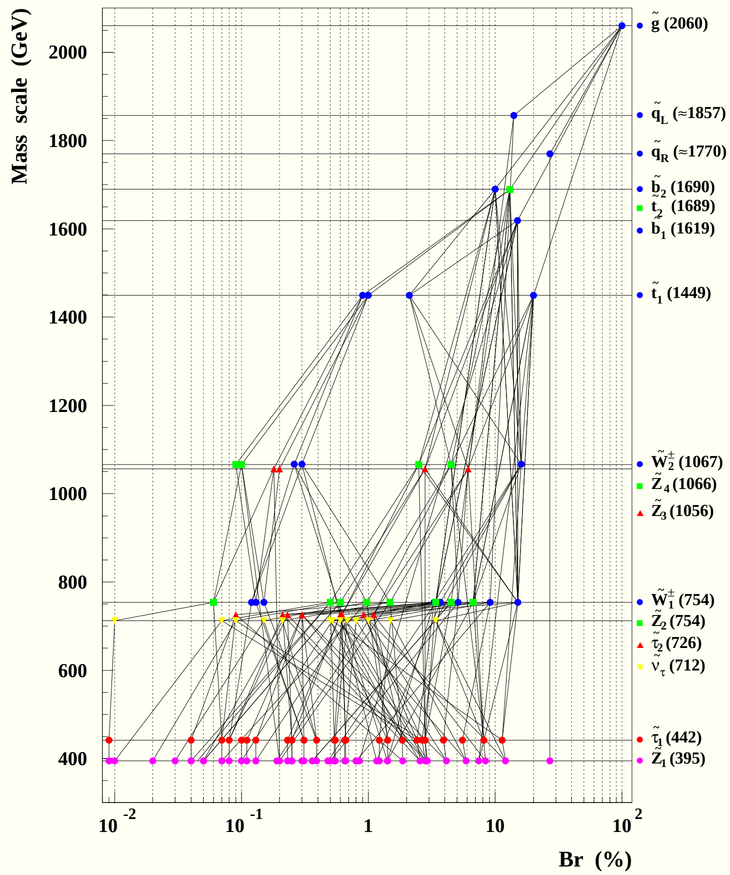
$$\begin{aligned} \widetilde{Z}_i &\rightarrow W\widetilde{W}_j,\ H^-\widetilde{W}_j,\ Z\widetilde{Z}_{i'},\ h\widetilde{Z}_{i'},\ H\widetilde{Z}_{i'},\ A\widetilde{Z}_{i'} \\ &\rightarrow \tilde{q}_{L,R}\bar{q},\ \bar{\tilde{q}}_{L,R}q,\ \tilde{\ell}_{L,R}\bar{\ell},\ \bar{\tilde{\ell}}_{L,R}\ell,\ \tilde{\nu}_\ell\bar{\nu}_\ell,\ \bar{\tilde{\nu}}_\ell\nu_\ell. \end{aligned}$$

If 2-body modes are closed,then the neutralino can decay via

$$\widetilde{Z}_i \rightarrow \widetilde{Z}_{i'} + f\bar{f} \tag{3}$$

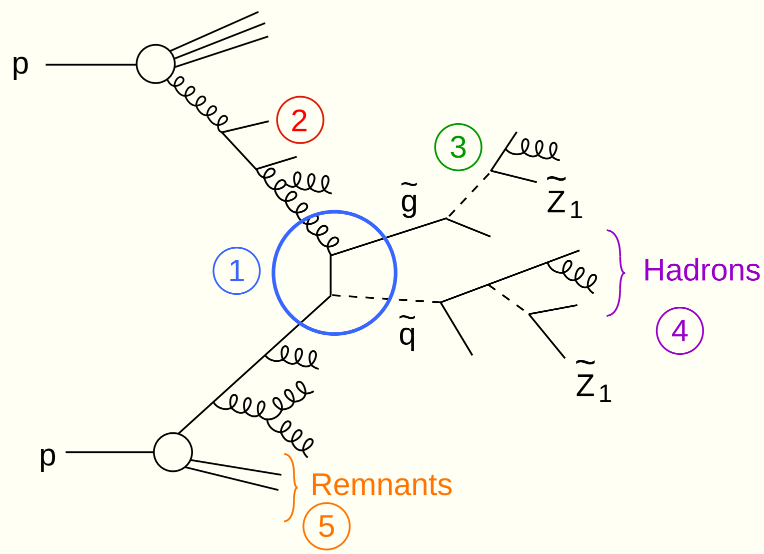


Sparticle cascade decays



$\tilde{Z}_1$ qq	(27.0 %)	$\tilde{Z}_1$ $\tau\nu$WWWbb	(4.1 %)
$\tilde{Z}_1$ $\tau\nu$Wbb	(12.1 %)	$\tilde{Z}_1$ $\tau\tau$bb	(2.9 %)
$\tilde{Z}_1$ $\tau\tau$WWbb	(8.4 %)	$\tilde{Z}_1$ $\tau\tau$qq	(2.9 %)
$\tilde{Z}_1$ WWbb	(7.4 %)	$\tilde{Z}_1$ $\tau\nu$ZWbb	(2.8 %)
$\tilde{Z}_1$ $\tau\nu$qq	(5.9 %)	$\tilde{Z}_1$ $\tau\nu$hWbb	(2.6 %)

Event generation for sparticles



Event generation in LL - QCD

1) Hard scattering / convolution with PDFs

2) Intial / final state showers

3) Cascade decays

4) Hadronization

5) Beam remnants

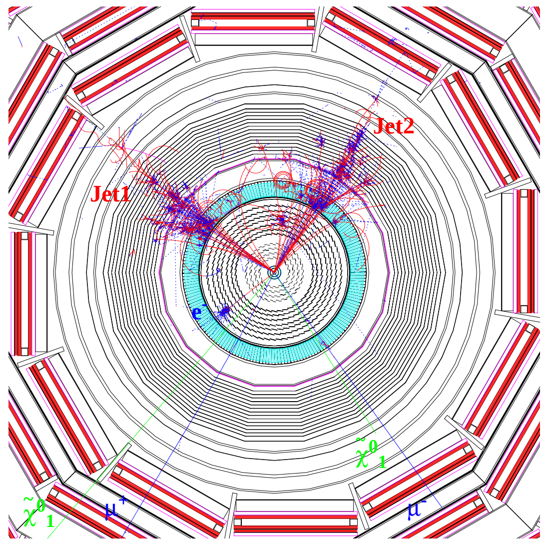
Event generations for SUSY

- ⋆ Isajet (HB, Paige, Protopopsecu, Tata)
  - IH, FW-PS, n-cut Pomeron UE
- ⋆ Pythia (Sjöstrand, Lönnblad, Mrenna)
  - SH, FW-PS, multiple scatter UE, SUSY at low $\tan\beta$ only
- ⋆ Herwig (Marchesini, Webber, Seymour, Richardson,...)
  - CH, AO-PS, Phen. model UE, Isawig

SUSY scattering event: Isajet simulation

SUSY event with 3 lepton + 2 Jets signature

m_0 = 100 GeV, $m_{1/2}$ = 300 GeV, $\tan\beta$ = 2, A_0 = 0, μ < 0,
$m(\tilde{q})$ = 686 GeV, $m(\tilde{g})$ = 766 GeV, $m(\tilde{\chi}^0_2)$ = 257 GeV,
$m(\tilde{\chi}^0_1)$ = 128 GeV.



Leptons:

$p_t(\mu^+)$ = 55.2 GeV

$p_t(\mu^-)$ = 44.3 GeV

$p_t(e^-)$ = 43.9 GeV

Jets:

E_t(Jet1) = 237 GeV

E_t(Jet2) = 339 GeV

Sparticles:

$p_t(\tilde{\chi}^0_1)$ = 95.1 GeV

$p_t(\tilde{\chi}^0_1)$ = 190 GeV

Charged particles with p_t > 2 GeV, $|\eta|$ < 3 are shown;
neutrons are not shown; no pile up events superimposed.

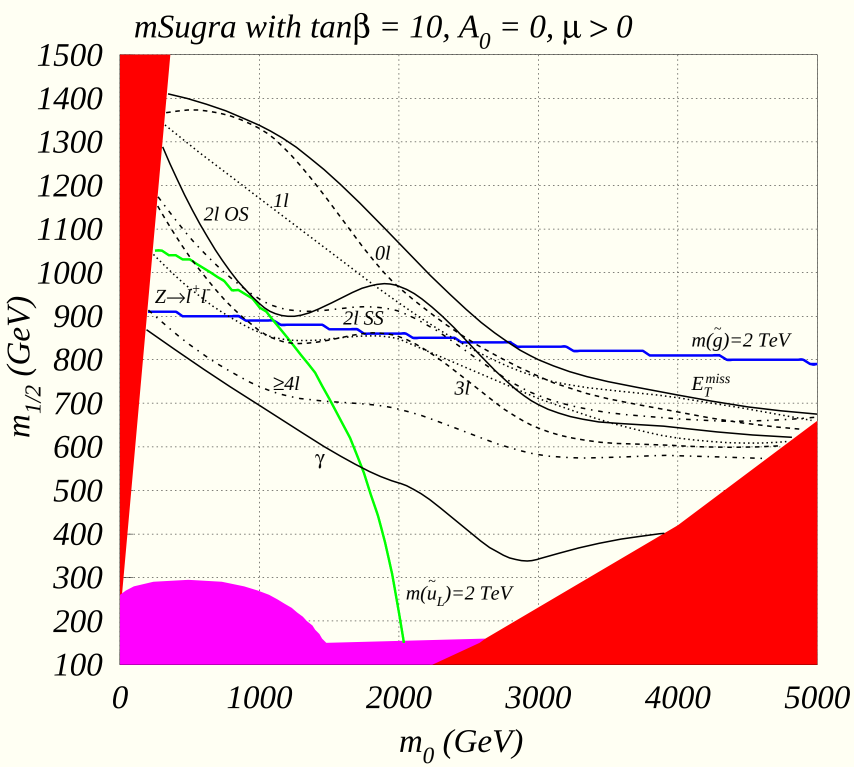
Search for SUSY at CERN LHC

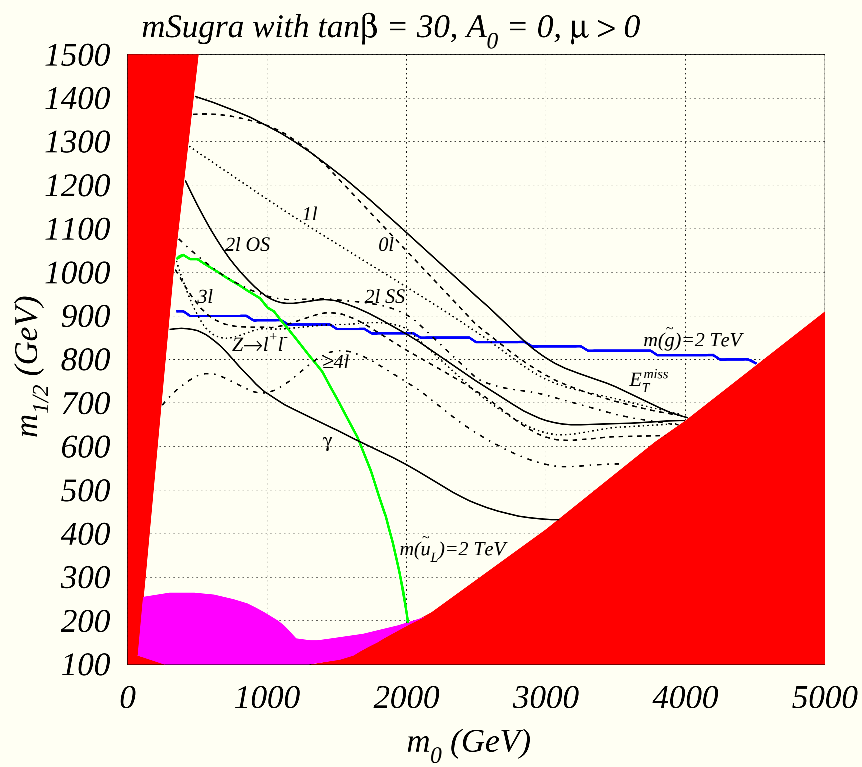
- $\tilde{g}\tilde{g}$, $\tilde{g}\tilde{q}$, $\tilde{q}\tilde{q}$ production dominant for $m \lesssim 1$ TeV
- lengthy cascade decays are likely
  - $\not{E}_T+$ jets
  - $1\ell+ \not{E}_T+$ jets
  - $OS\ 2\ell+ \not{E}_T+$ jets
  - $SS2\ell+ \not{E}_T+$ jets
  - $3\ell+ \not{E}_T+$ jets
  - $4\ell+ \not{E}_T+$ jets
- BG: $W+jets$, $Z+jets$, $t\bar{t}$, $b\bar{b}$, WW, $4t$, $\cdots$
- Grid of cuts gives optimized S/B

Pre-cuts and cuts

- ⋆ $\not\!\!E_T > 200$ GeV
- ⋆ $N_j \geq 2$ (where $p_T(jet) > 40$ GeV and $|\eta(jet)| < 3$
- ⋆ Grid of cuts for optimized S/B:
  - $N_j \geq 2 - 10$
  - $\not\!\!E_T > 200 - 1400$ GeV
  - $E_T(j1) > 40 - 1000$ GeV
  - $E_T(j2) > 40 - 500$ GeV
  - $S_T > 0 - 0.2$
  - muon isolation
- ⋆ $S > 10$ events for 100 fb^{-1}
- ⋆ $S > 5\sqrt{B}$ for optimal set of cuts

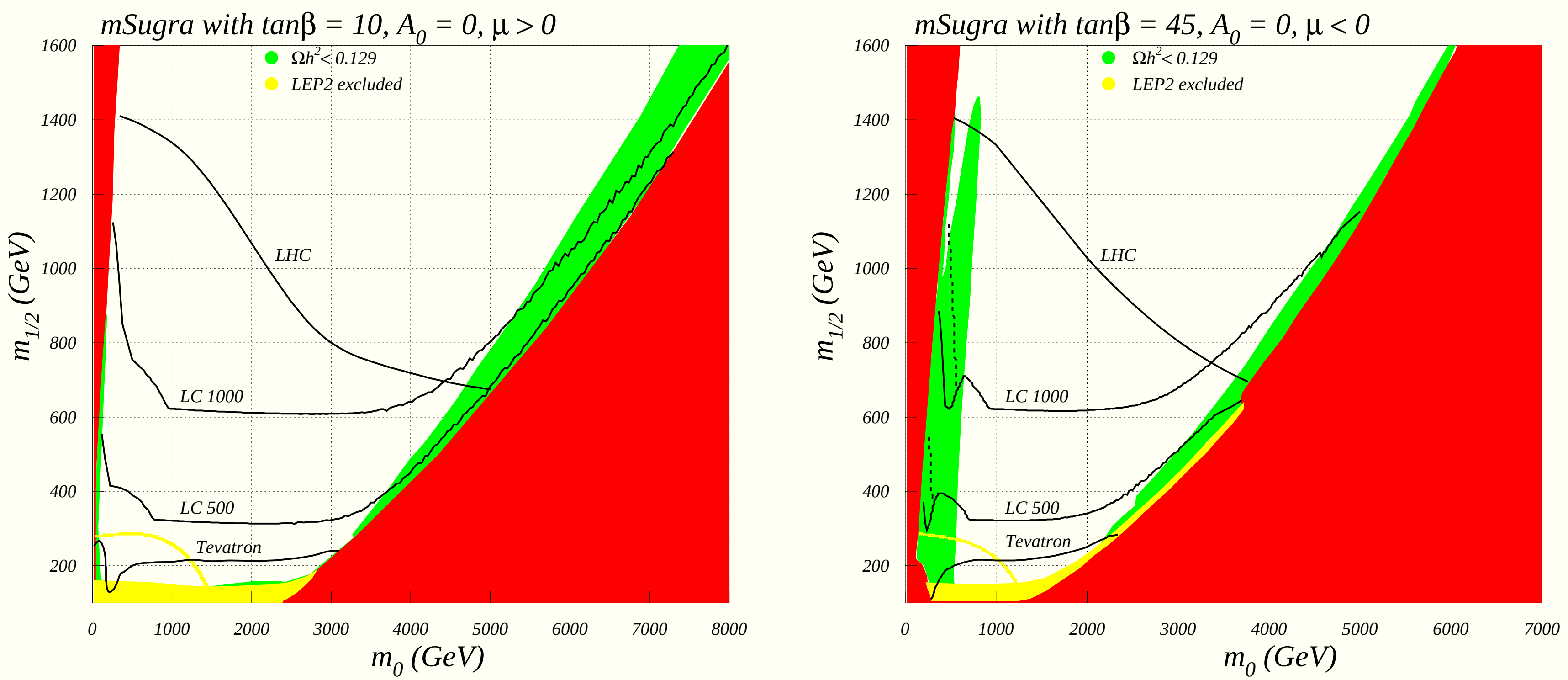
Sparticle reach of LHC for 100^{-1} fb





HB, Balazs, Belyaev, Krupovnickas, Tata: JHEP 0306, 054 (2003)

Sparticle reach of all colliders and relic density



HB, Belyaev, Krupovnickas, Tata: JHEP 0402, 007 (2004)

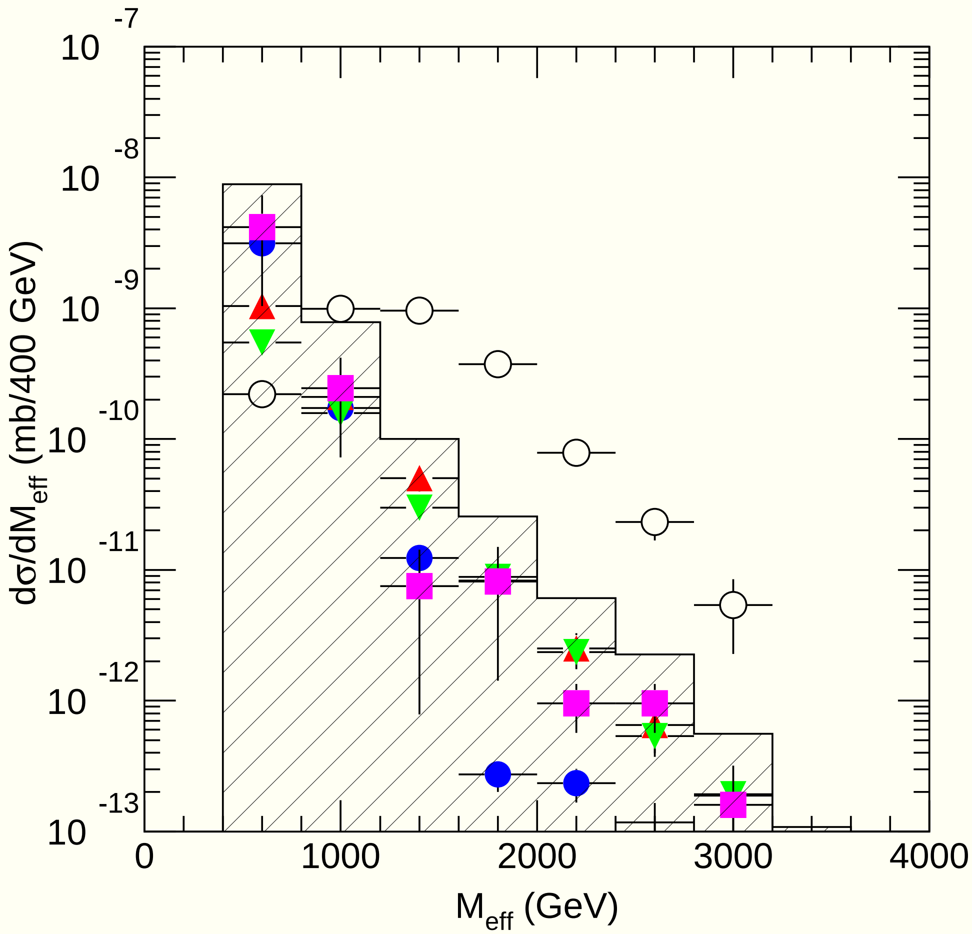
Precision measurements at LHC

- $M_{eff} = \not{E}_T + E_T(j1) + \cdots + E_T(j4)$ sets overall $m_{\tilde{g}},\ m_{\tilde{q}}$ scale
- $m(\ell\bar{\ell}) < m_{\widetilde{Z}_2} - m_{\widetilde{Z}_1}$ mass edge
- $m(\ell\bar{\ell})$ distribution shape
- combine $m(\ell\bar{\ell})$ with jets to gain $m(\ell\bar{\ell}j)$ mass edge: info on $m_{\tilde{q}}$
- further mass edges possible *e.g.* $m(\ell\bar{\ell}jj)$
- Higgs mass bump $h \to b\bar{b}$ likely visible in $\not{E}_T + jets$ events
- in favorable cases, may overconstrain system for a given model

★ methodology very p-space dependent

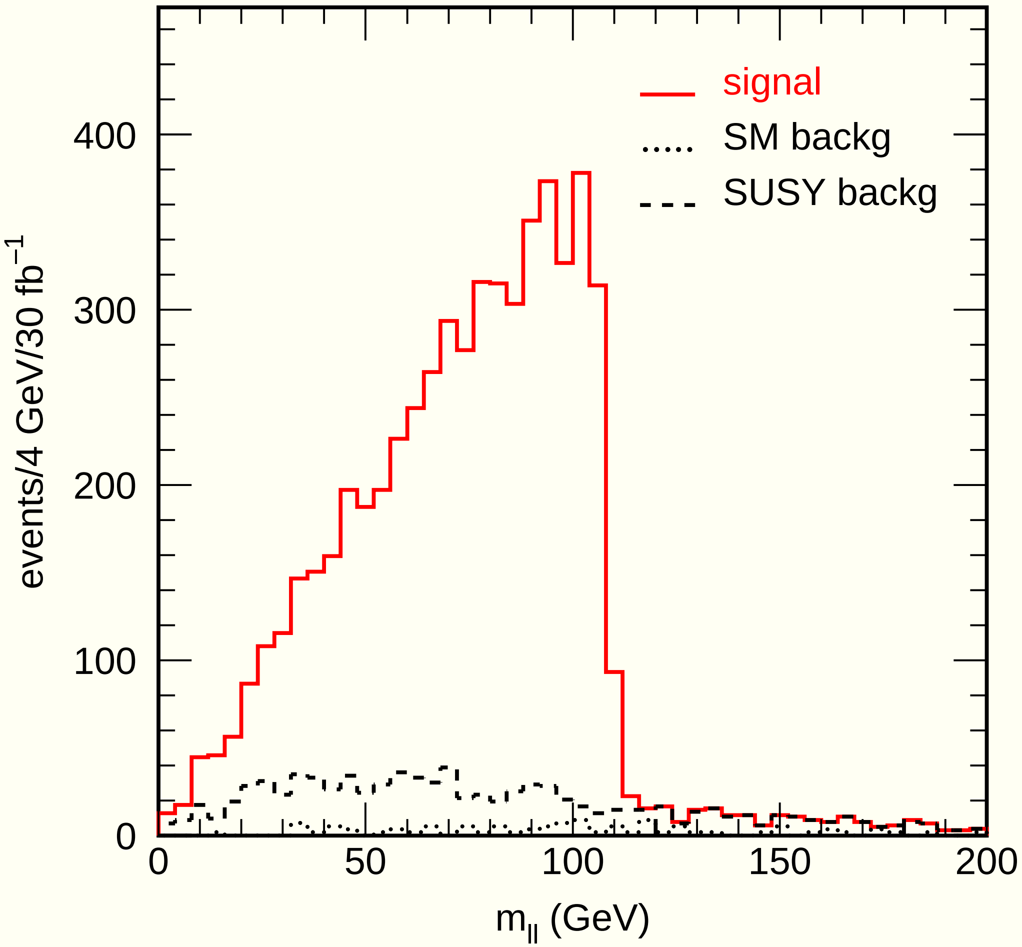
★ some regions are very difficult *e.g.* HB/FP

$$M_{eff} = E_T(j1) + E_T(j2) + E_T(j3) + E_T(j4) + \not{E}_T$$



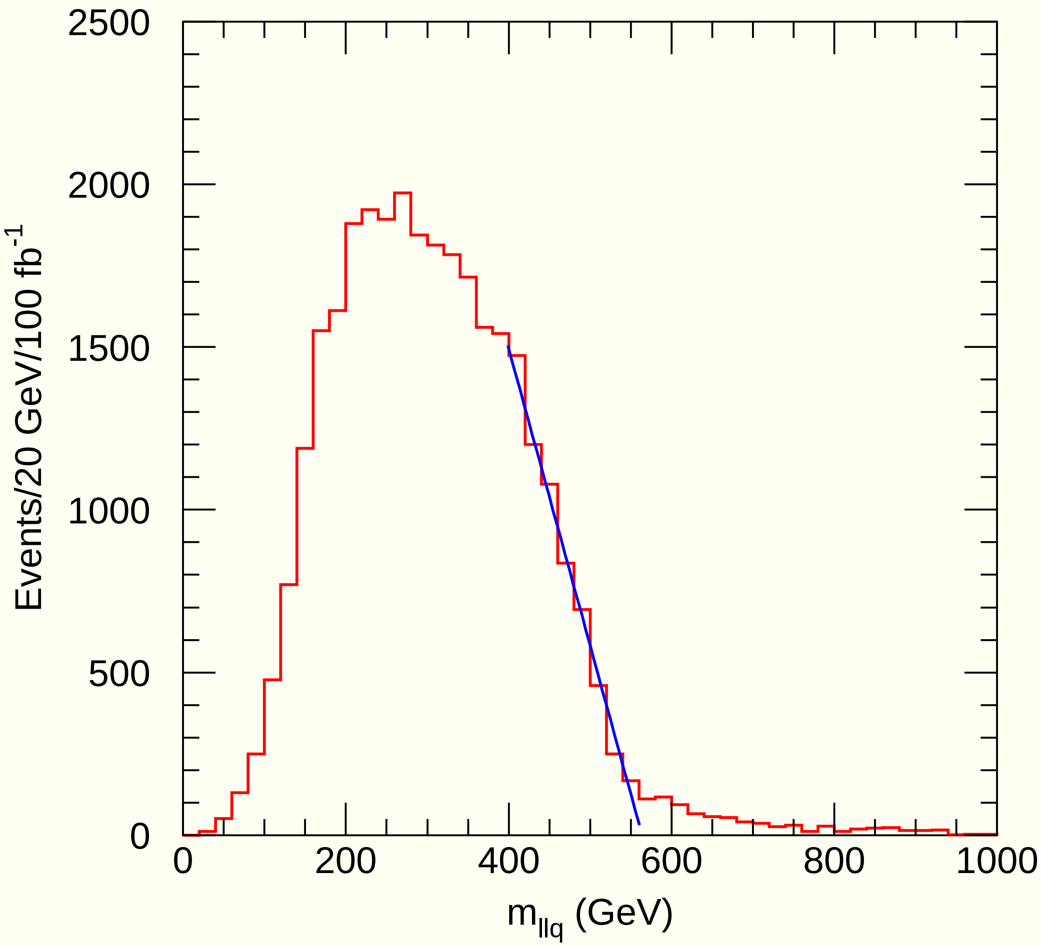
Atlas TDR (F. Paige)

$m(\ell^+\ell^-)$ mass edge from $\widetilde{Z}_2 \to \ell^+\ell^-\widetilde{Z}_1$



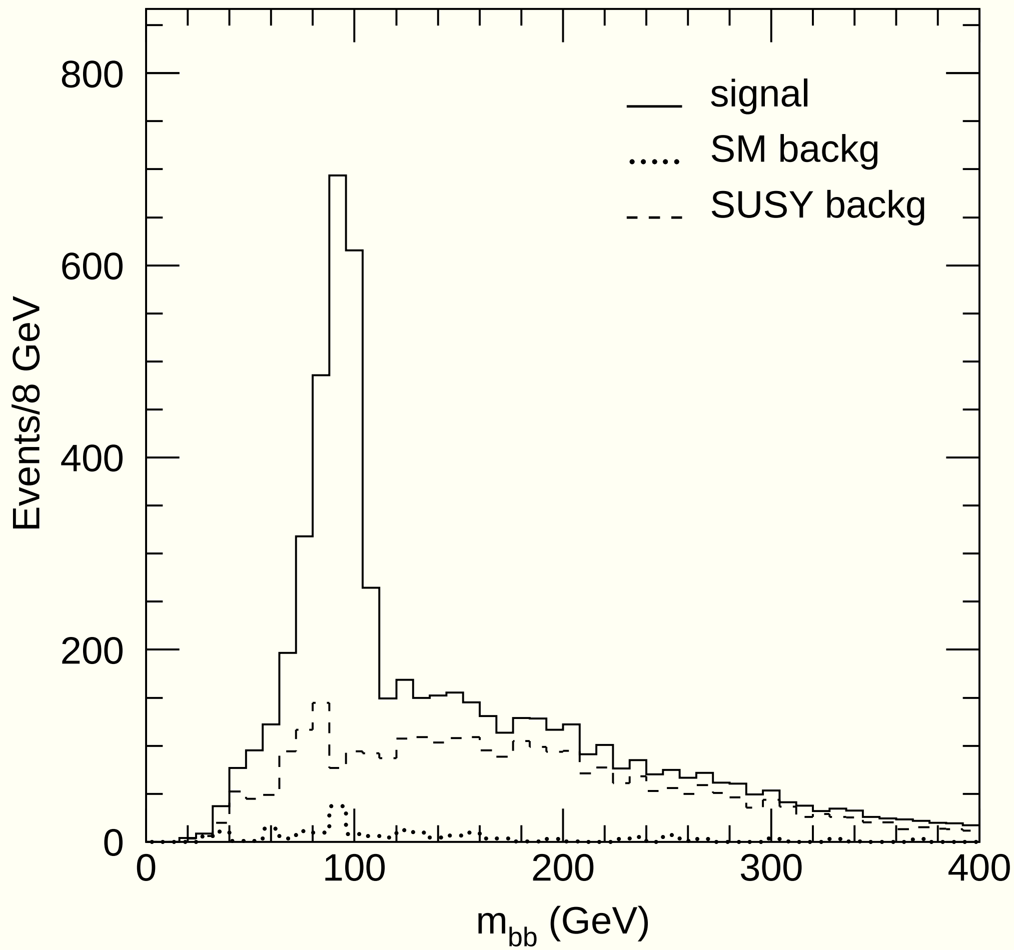
Atlas TDR (F. Paige)

$m(\ell^+\ell^- q)$ **mass edge from** $\tilde{q} \to q\widetilde{Z}_2$



Atlas TDR (F. Paige)

$m(b\bar{b})$ Higgs mass bump in SUSY jets + $\not\!\!E_T$ events



Atlas TDR (F. Paige)

Conclusions

- ⋆ SUSY models
- ⋆ SUGRA models most naturally encompass DM: thermal WIMPS
- ⋆ WMAP bound $\Omega_{\widetilde{Z}_1} h^2 = 0.113 \pm 0.009$ especially constraining
  - bulk, $\tilde{\tau}$ coann., HB/FP, A-funnel, h-funnel, $\tilde{t}_1$ coann.
- ⋆ Various regions $\Rightarrow$ distinct collider/DM signatures
- ⋆ SUSY (SUGRA) at LHC
  - sparticle production
  - sparticle decays
  - event generation
  - studies of when $S > 5\sqrt{B}$ for given int. lum.
  - a variety of precision measurements likely possible if SUSY discovered at LHC