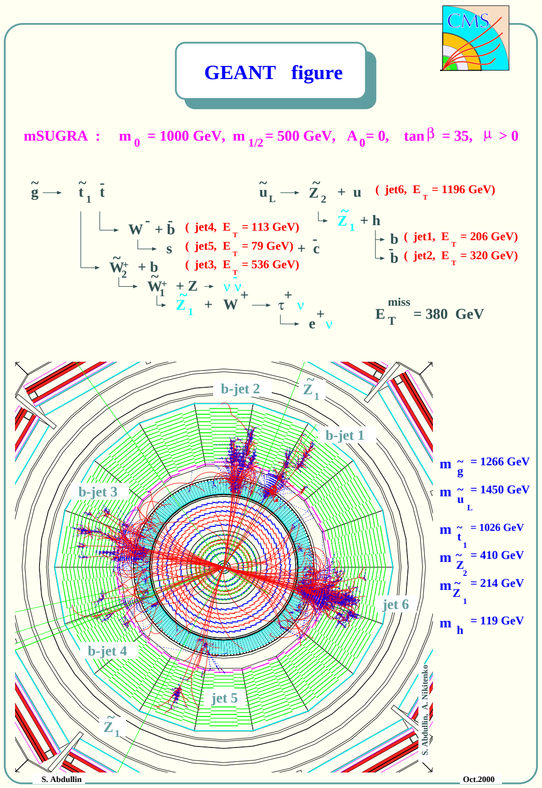
# Supersymmetry at the LHC

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

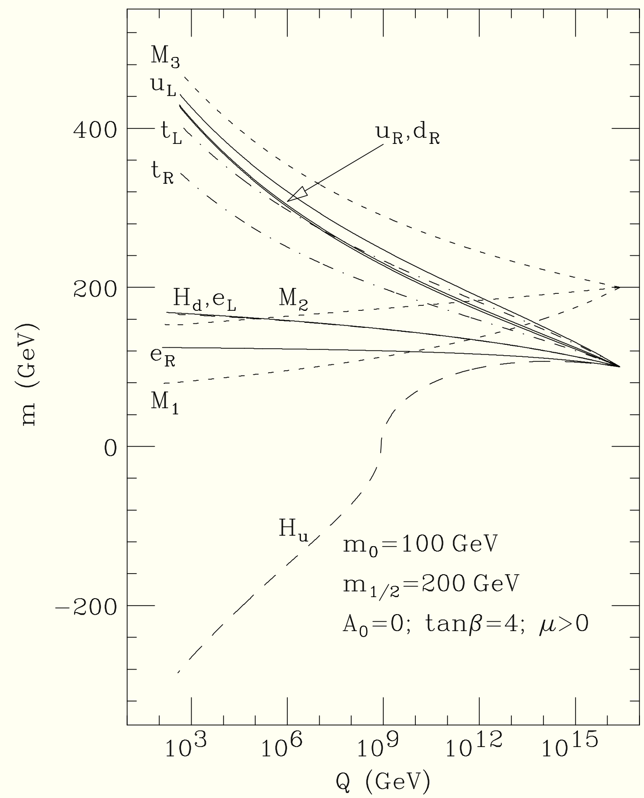
- ⋆ Spontaneous breaking of SUSY phen. inconsistent within MSSM
- ⋆ Hidden sector models (HS)
- ⋆ HS is arena for SUSY breaking; how to communicate SUSY breaking to visible sector (VS)?
  - gravity mediation: supergravity (SUGRA) and local SUSY: minimal messenger sector: $m_{3/2} \sim$ TeV: LSP=bino/higgsino/wino/gravitino?
  - 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

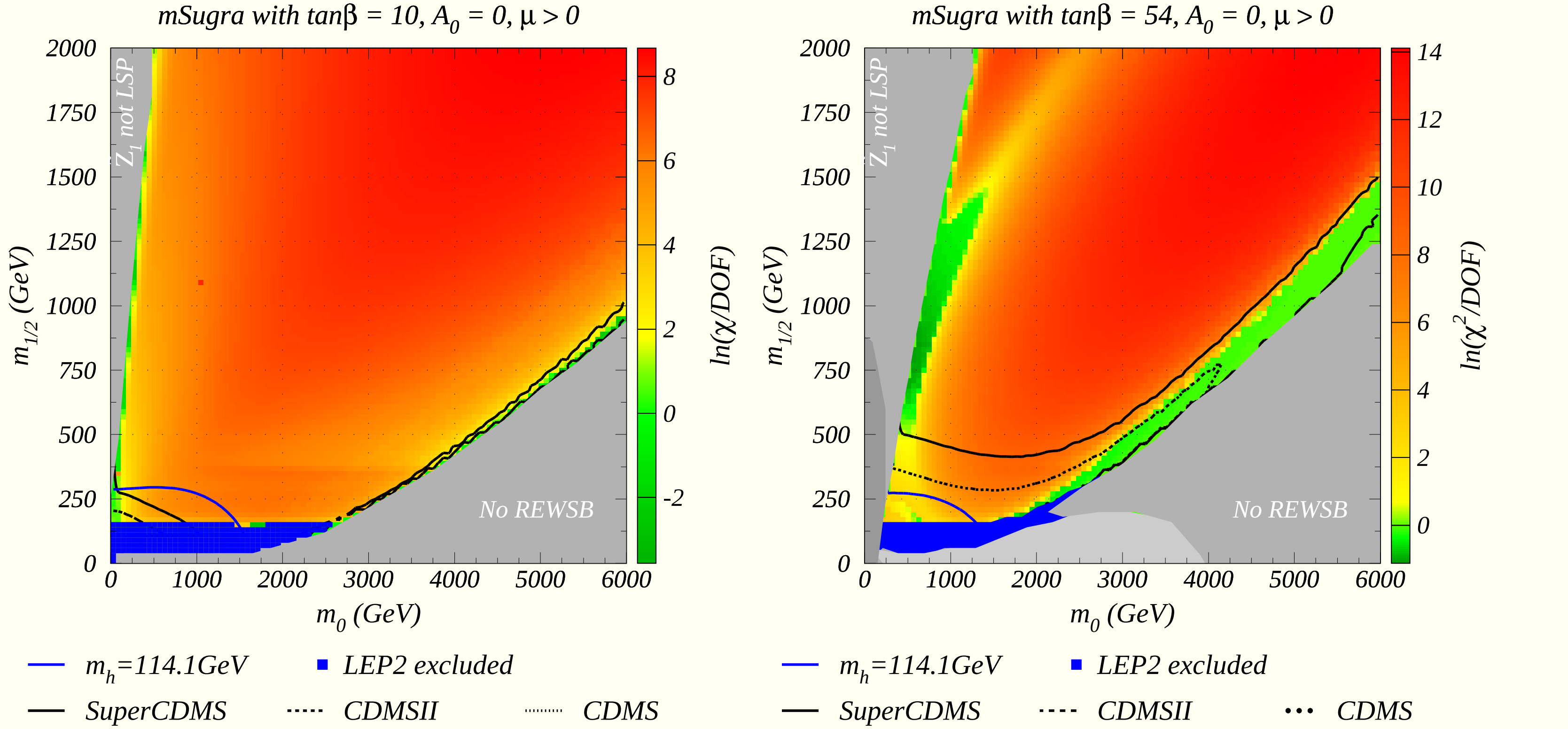
- ⋆ MSSM: weak scale inputs (no RGE running)
- ⋆ mSUGRA
  - $m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ sign(\mu)$
  - non-universal SUGRA
- ⋆ gauge mediated SUSY breaking (GMSB)
  - $\Lambda,\ M,\ n_5,\ \tan\beta,\ sign(\mu),\ C_{grav}$
  - non-minimal GMSB
- ⋆ anomaly-mediated SUSY breaking (AMSB)
  - $m_0,\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

# Sparticle mass spectra

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



# Results of $\chi^2$ fit using $\tau$ data for $a_\mu$:




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

# Parton model of hadronic reactions

For a hadronic reaction,

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

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

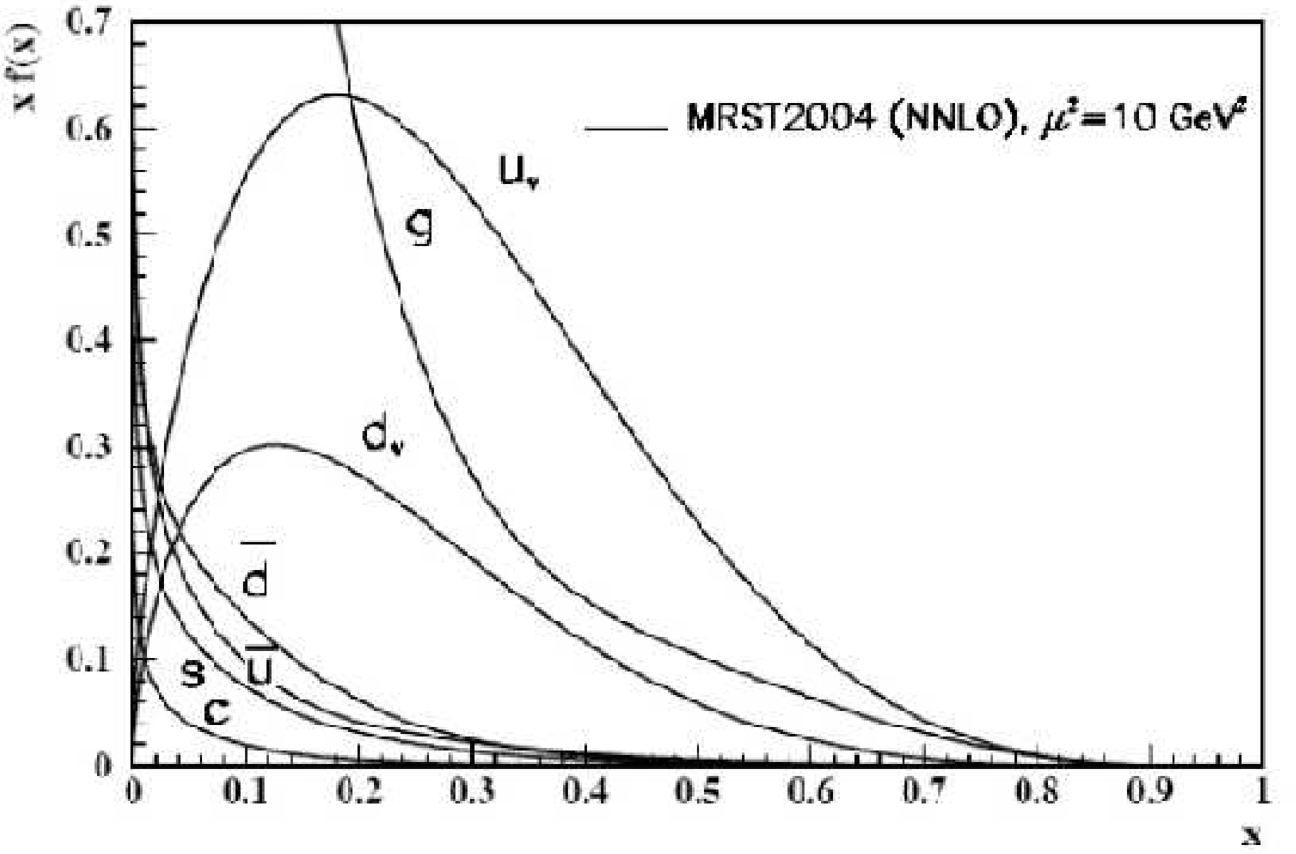
$$a + b \to c + d,$$

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:

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

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

# Parton Distribution Functions (PDFs)



## Calculating subprocess cross sections/decay rates in QFT

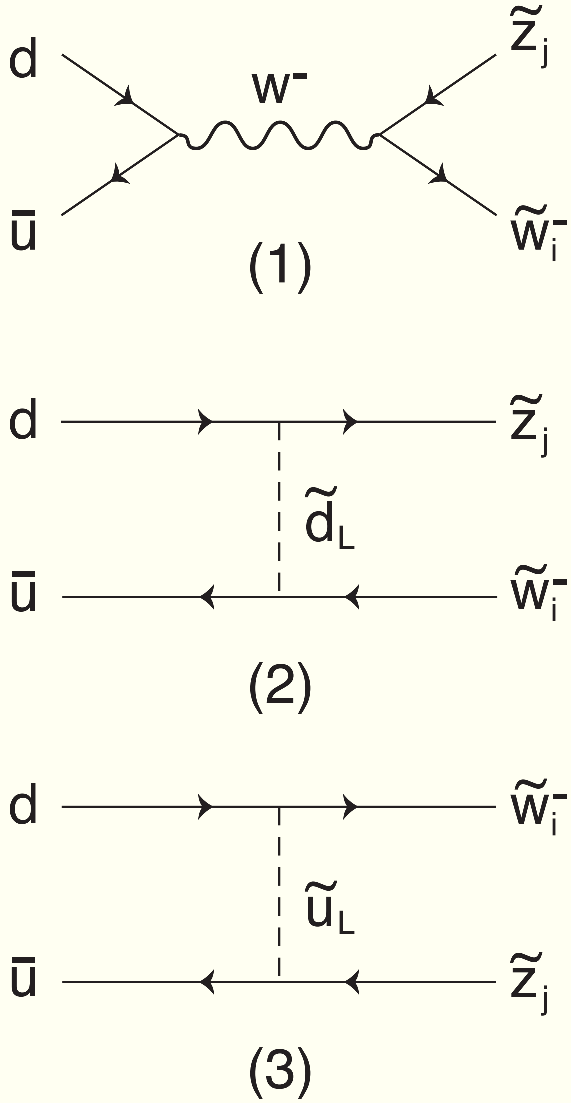
- The fundamental calculable object in QM is the *amplitude* $\mathcal{M}$ for a process to occur
- A pictorial representation of $\mathcal{M}$ is given by a *Feynman diagram*
- Feynman rules for many theories can be found in standard texts: *e.g.* Peskin& Schroeder, *Introduction to Quantum Field Theory*
- In the MSSM, an additional complication occurs due to presence of *Majorana* spinors
- Methods for handling these given *e.g.* in *Weak Scale Supersymmetry* (HB, X. Tata), or book by M. Drees, Godbole& Roy
- total amplitude $\mathcal{M}$ is sum of all different ways a process can occur
- $\mathcal{M}$ is a complex number; $|\mathcal{M}|^2$ gives probability
- must normailze and sum (integrate) over all momentum configurations to gain cross section, usually in *femtobarns*:

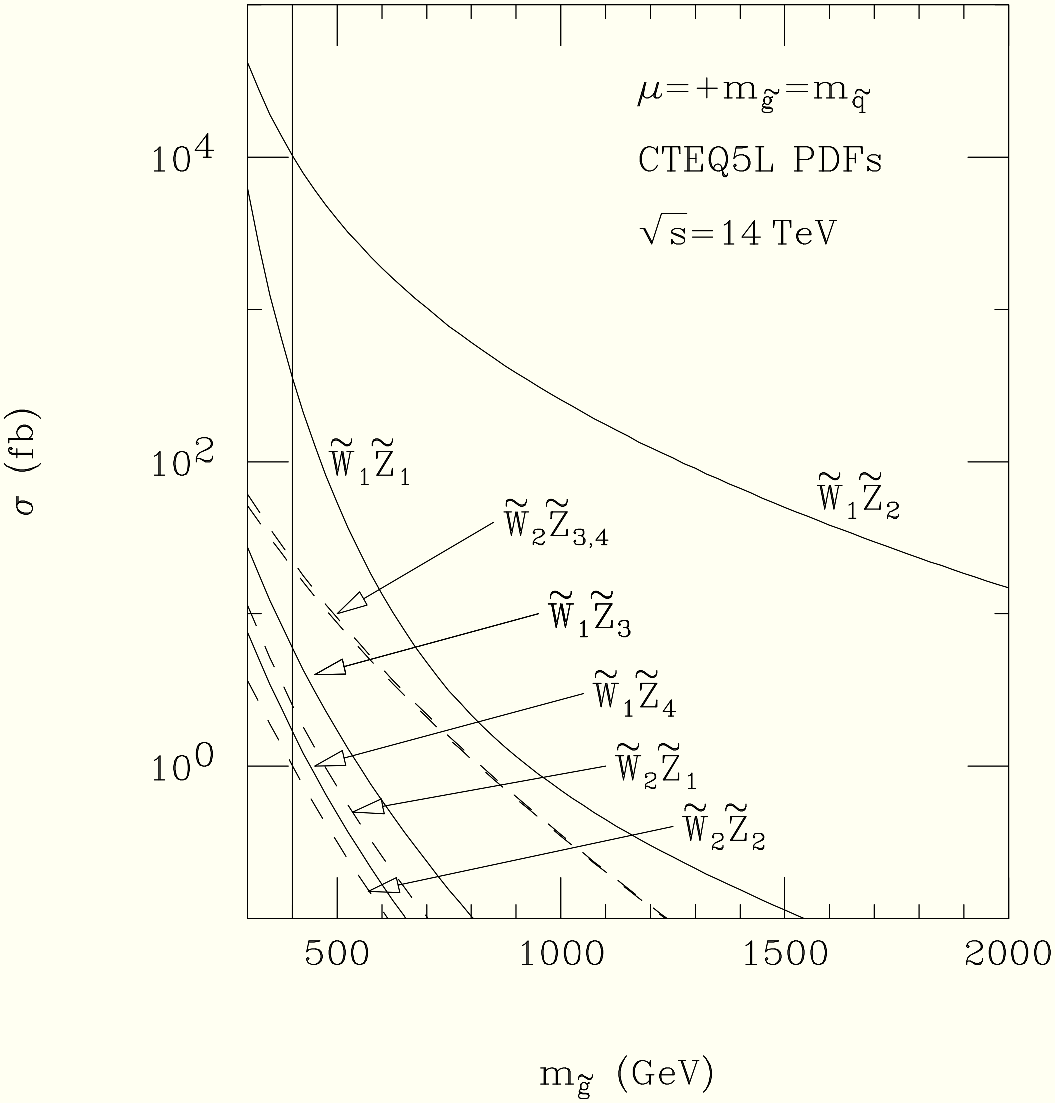
## Calculating subprocess cross sections/decay rates in QFT

$$d\hat{\sigma} = \frac{1}{2\hat{s}}\frac{1}{(2\pi)^2}\int \frac{d^3p_c}{2E_c}\frac{d^3p_d}{2E_d}\delta^4(p_a+p_b-p_c-p_d)\cdot F_{\rm color}F_{\rm spin}\sum|\mathcal{M}|^2,$$

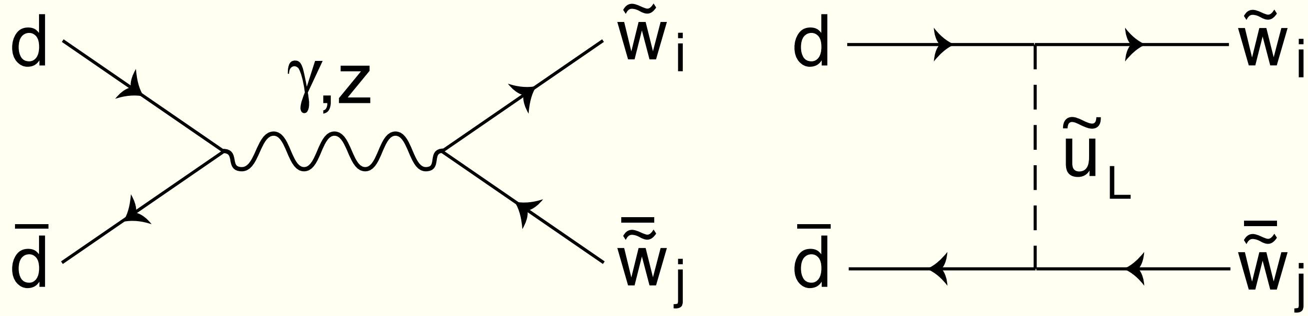
- Must sum (integrate) over all final state momentum configurations
- May be done analytically for simple processes *e.g.* $2 \rightarrow 2$
- Usually done using Monte Carlo method for $n \geq 3$
- Monte Carlo well suited for adding on particle decays so one has really $2 \rightarrow n$ processes where $n$ can be very large
- Convolution of subprocess cross section with PDFs must be done numerically, since PDFs distributed as *subroutines*

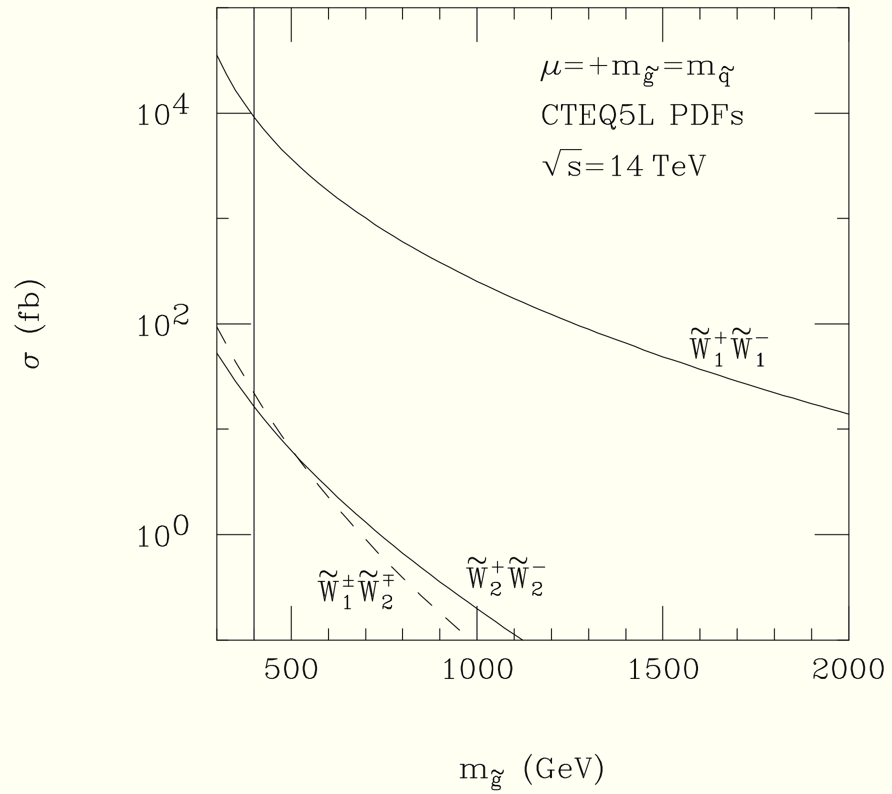
# Chargino-neutralino production



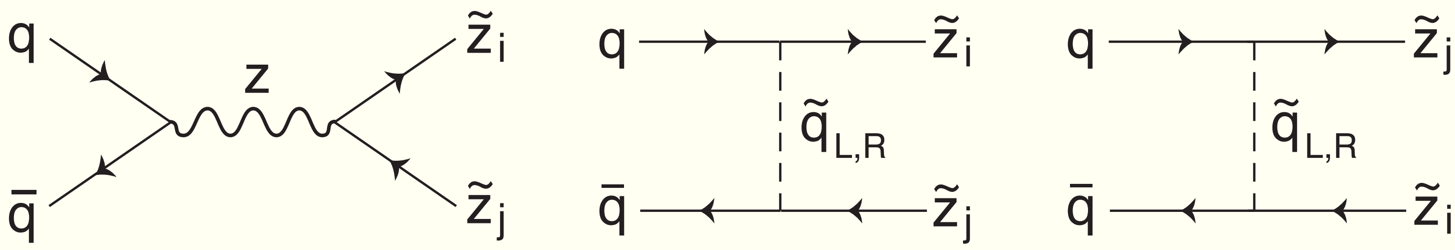



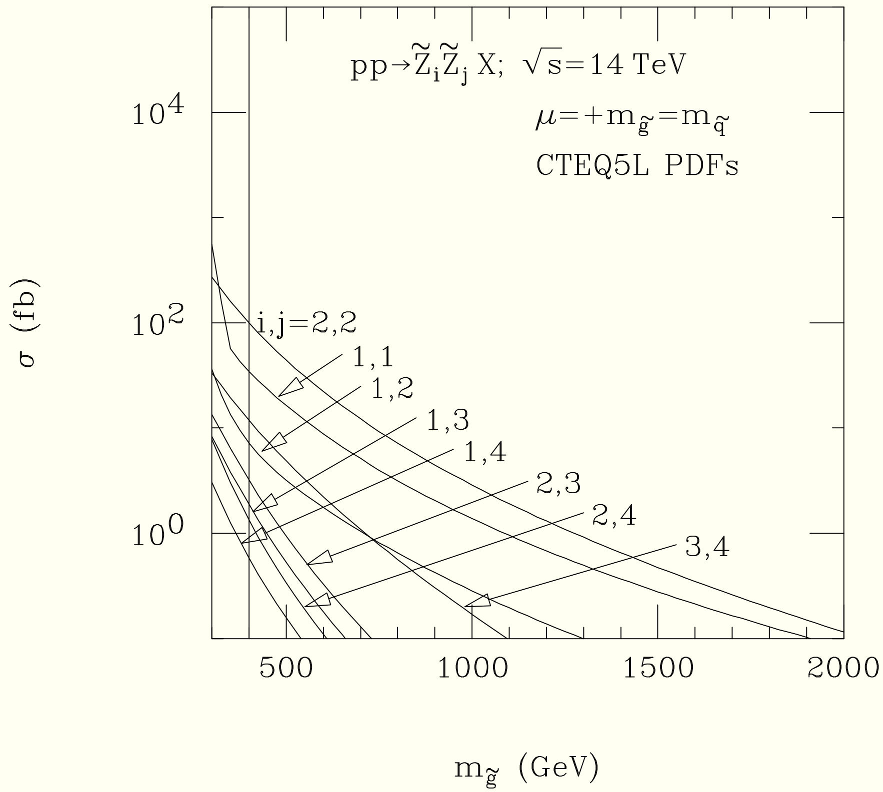
# Chargino pair production



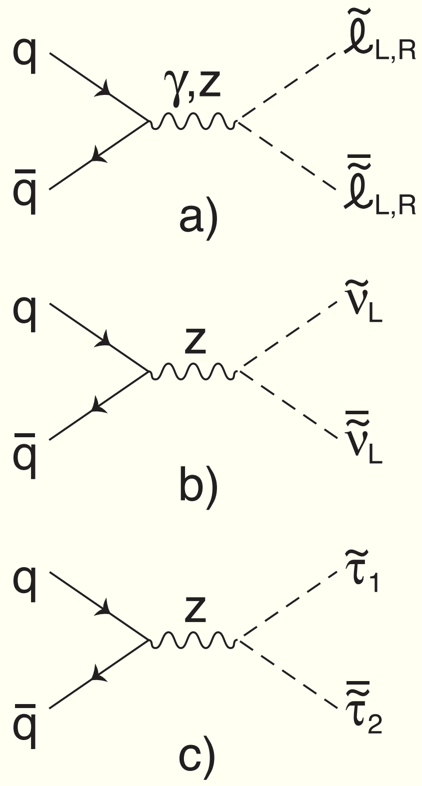



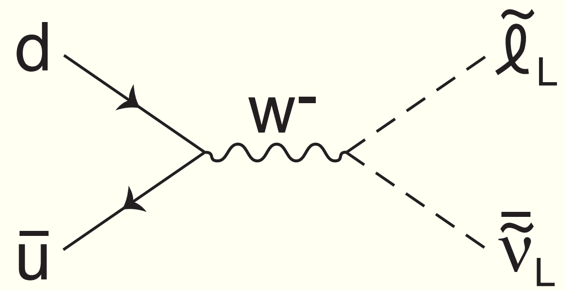
# Neutralino pair production



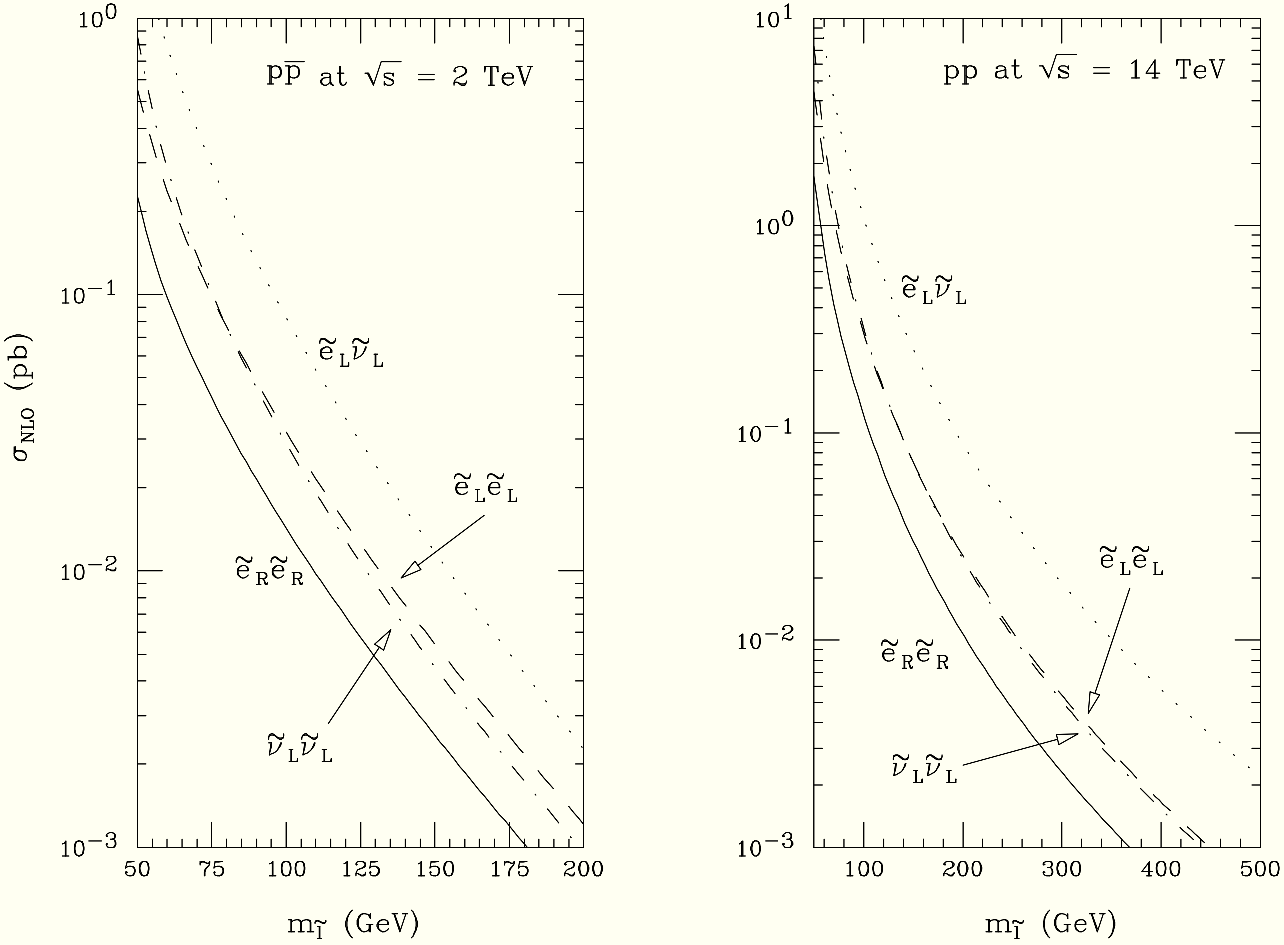



## Slepton pair production

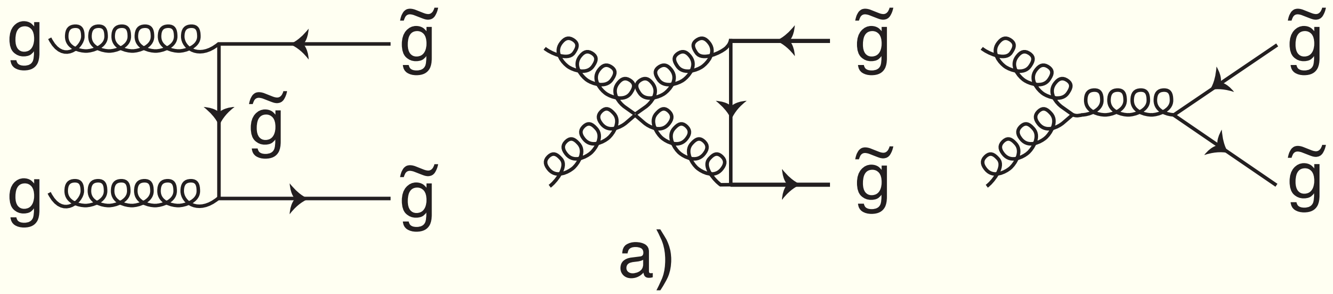


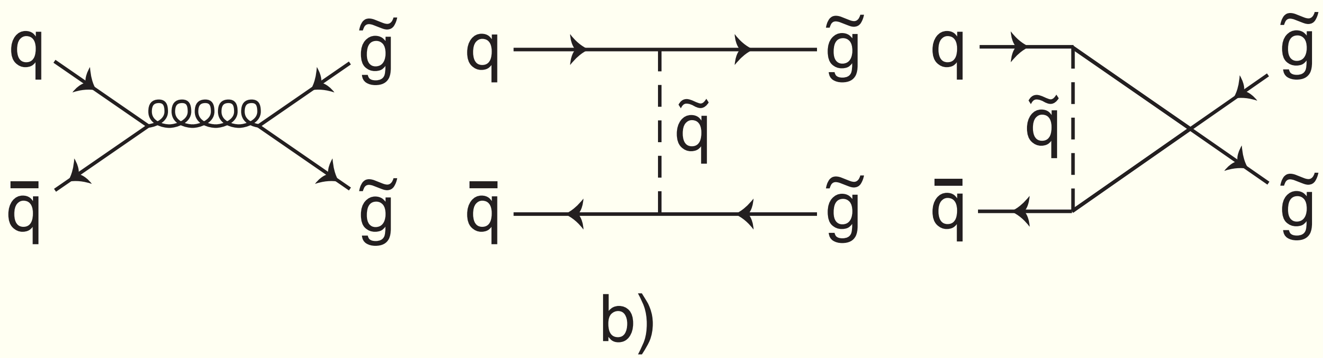



# Slepton pair cross section

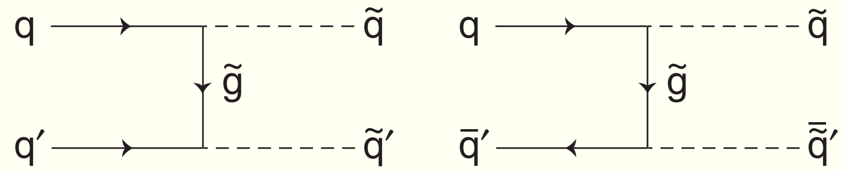


## Gluino pair production

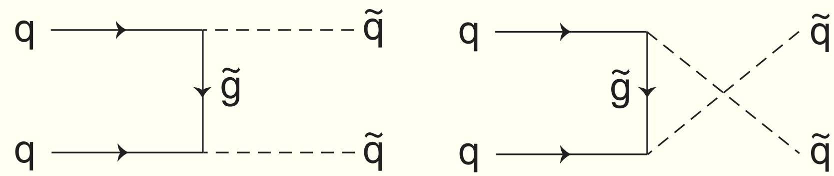


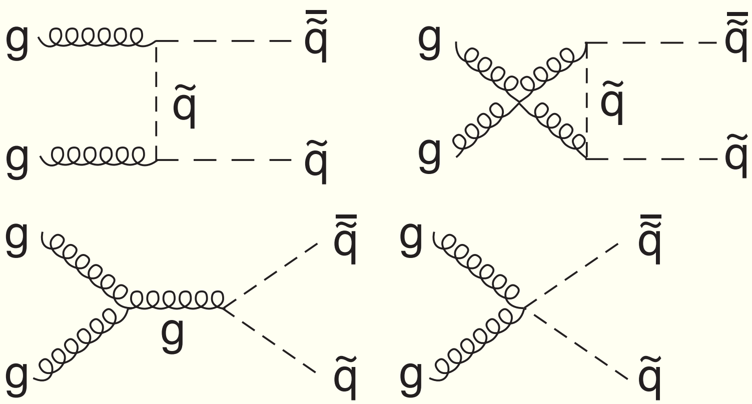
# Squark pair production

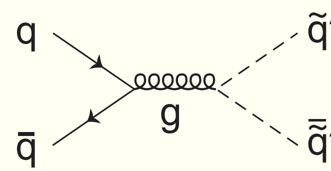



a)



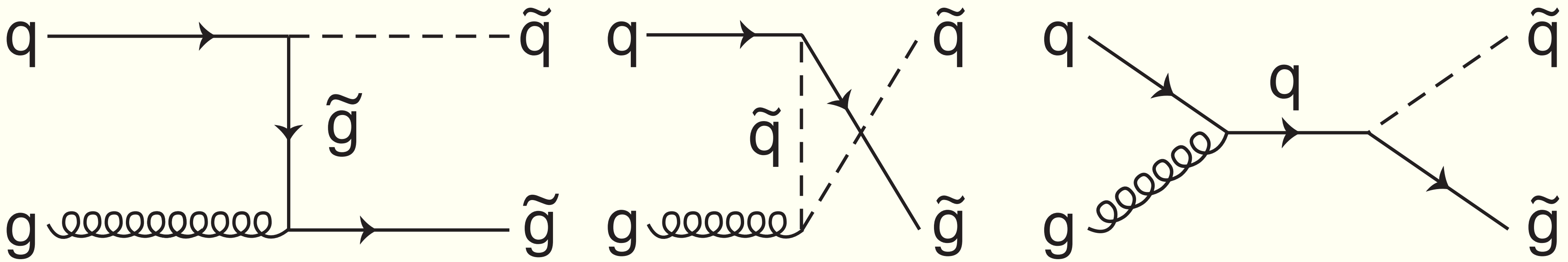

b)



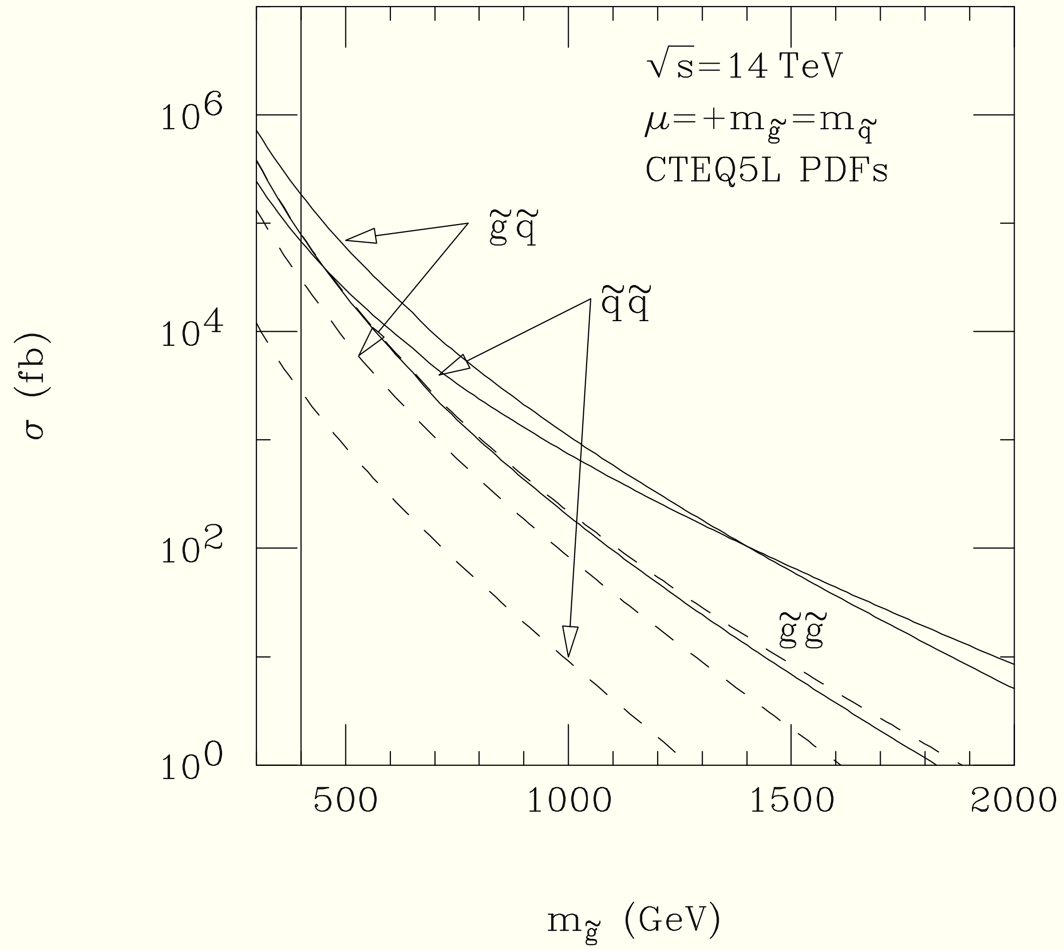




c)

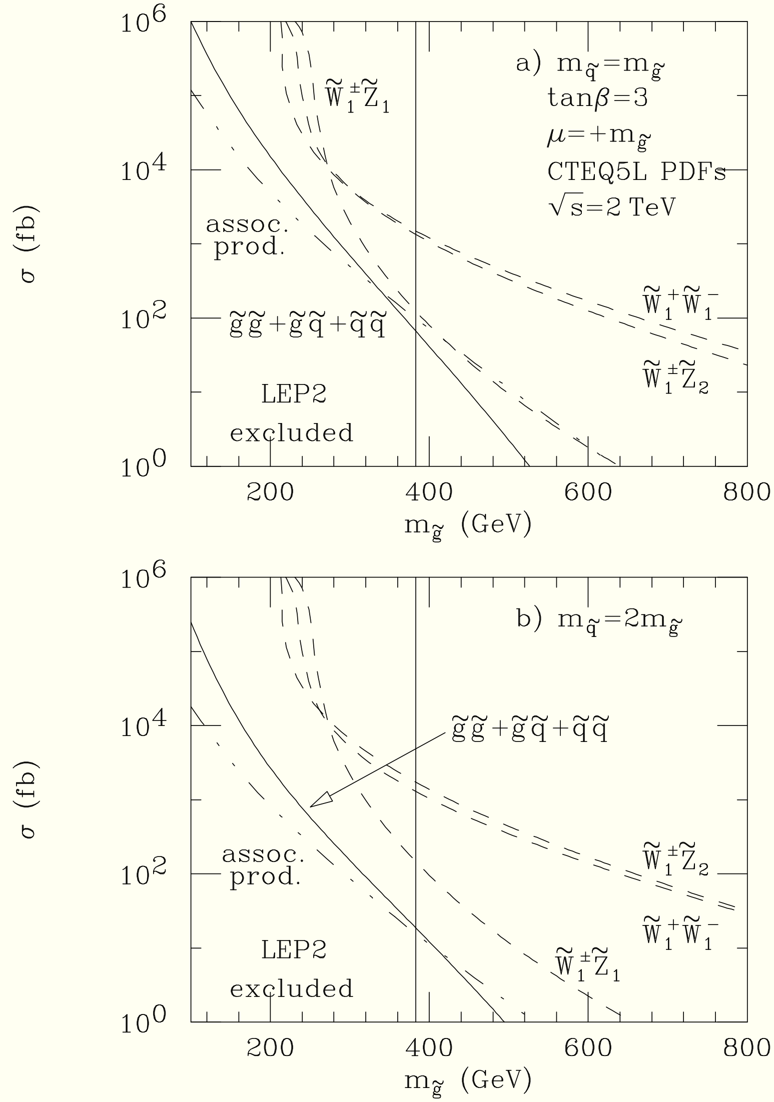
## Gluino-squark associated production



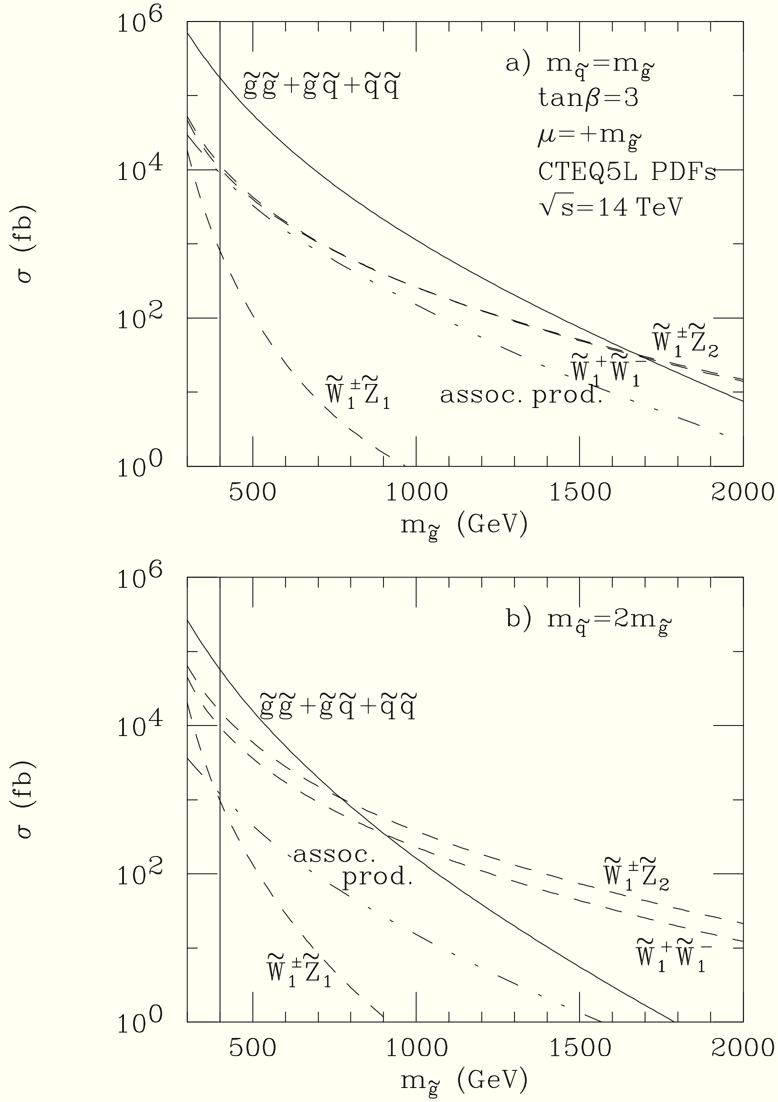
# Gluino and squark pair production



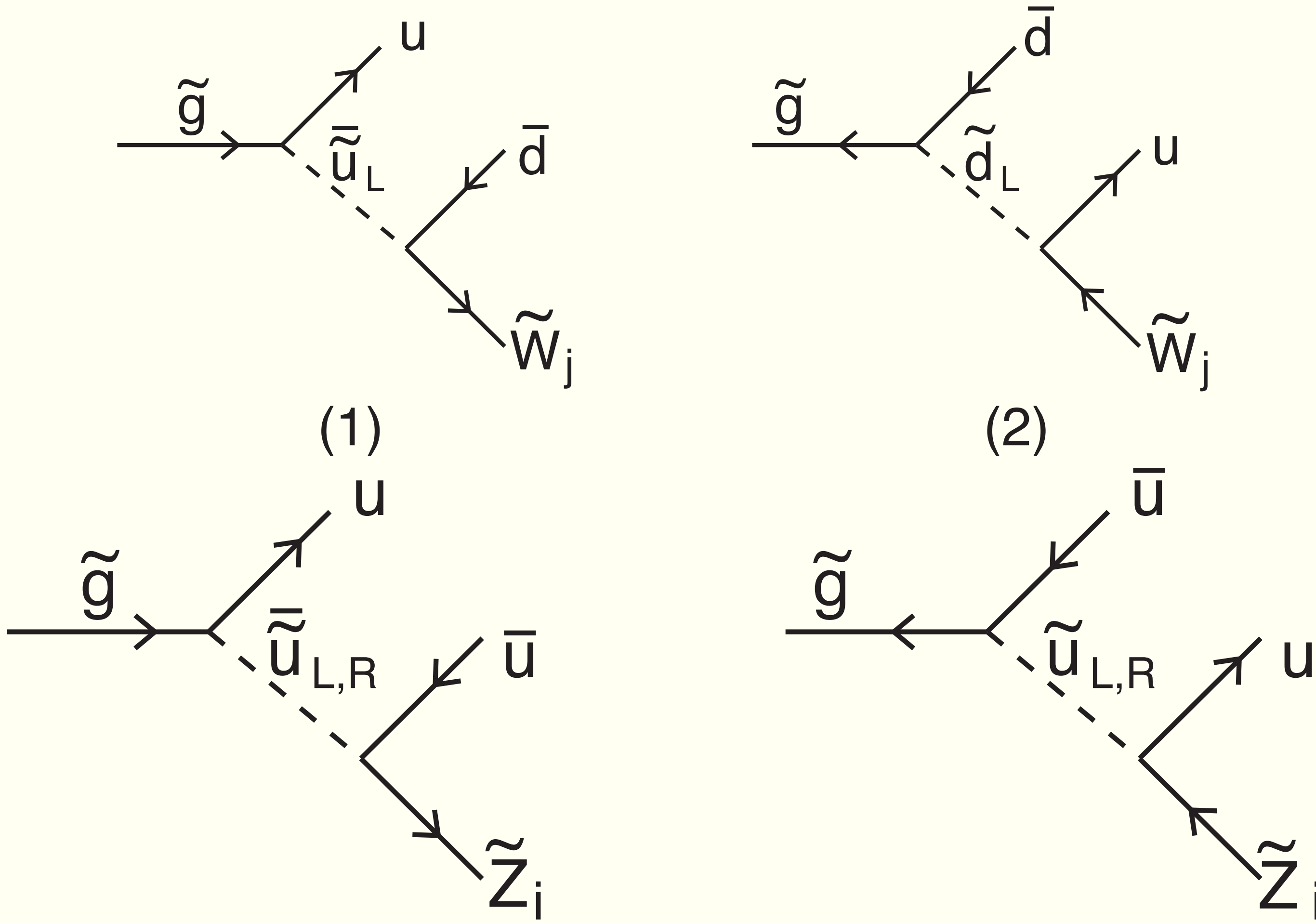
# Production at Tevatron



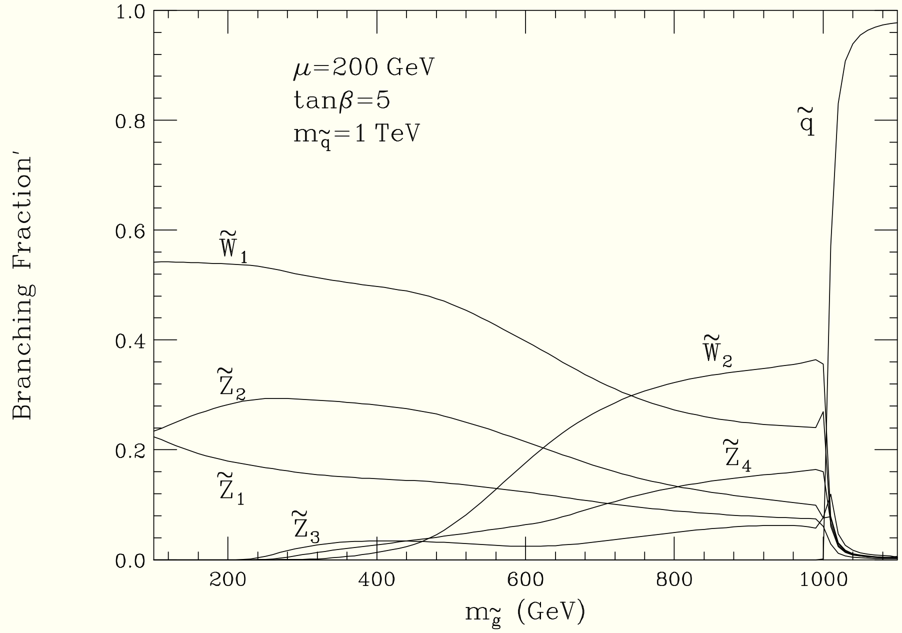
# Production at LHC

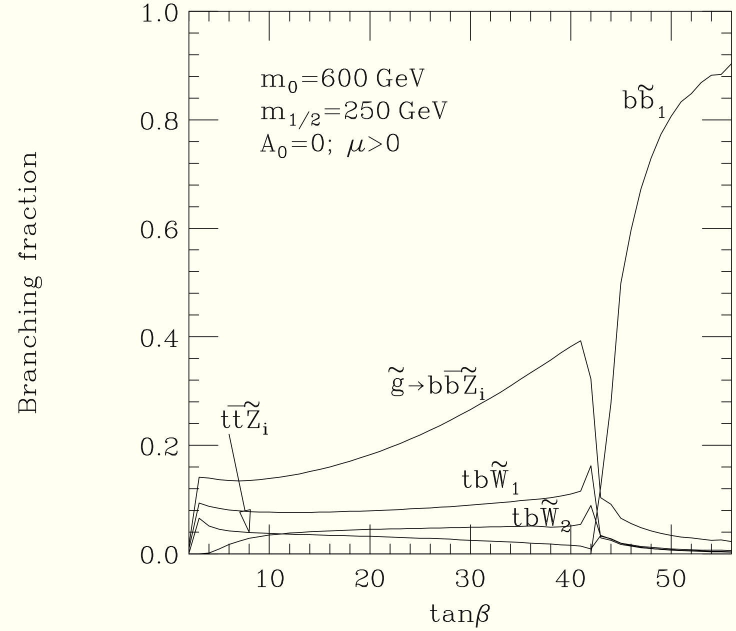


## Gluino decays: $\tilde{g} \to q\tilde{q}$ or 3-body



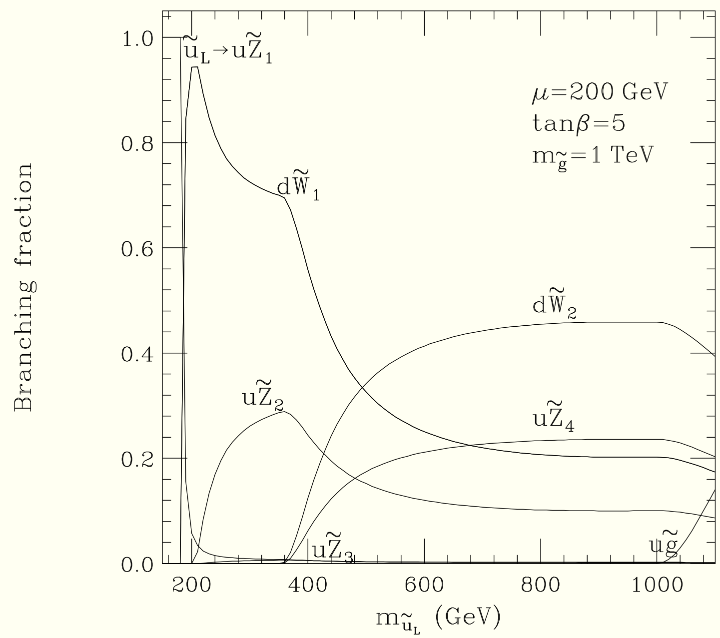
# Gluino decays: branching fractions

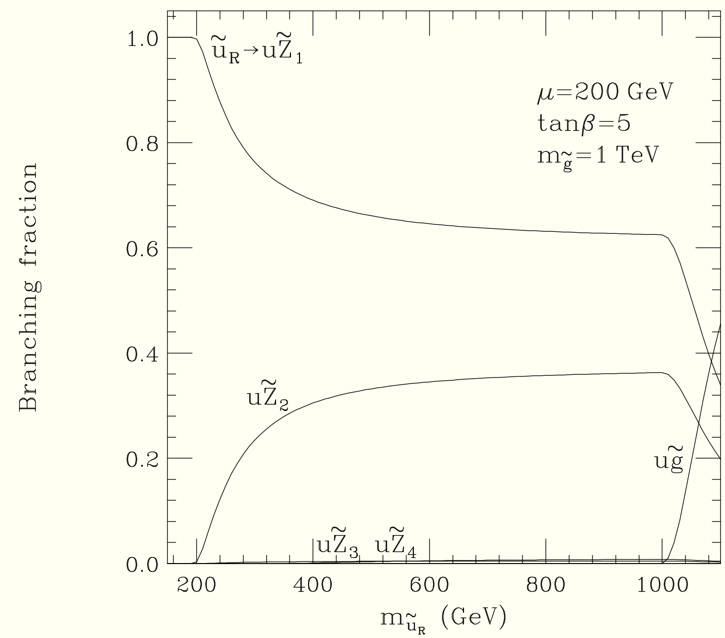


# Squark decays

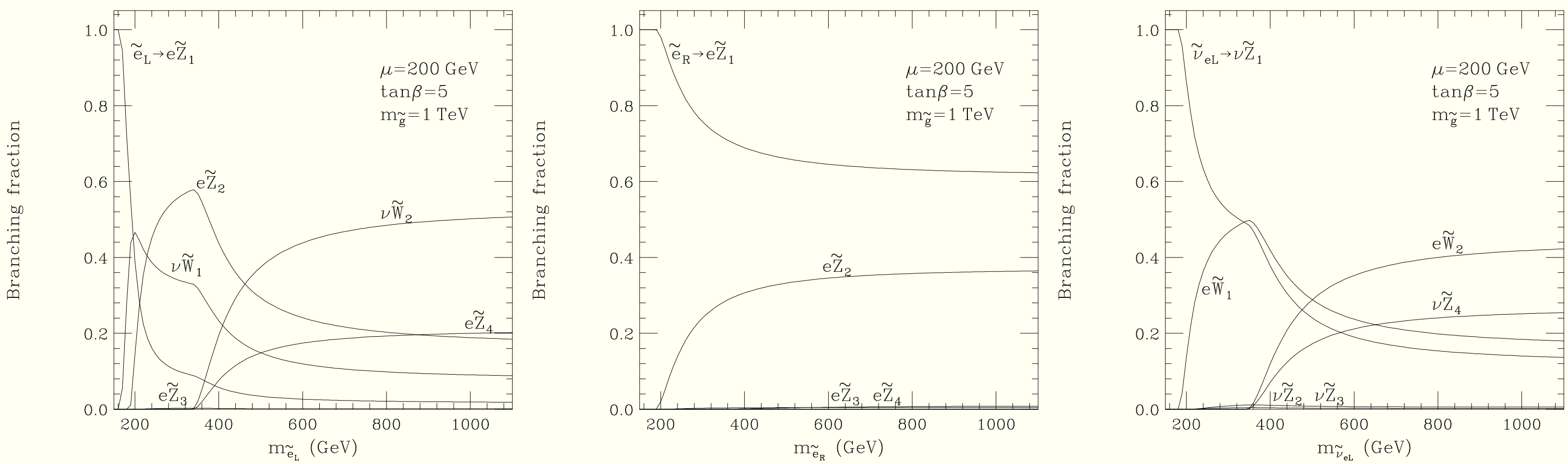
$$\begin{aligned}
\tilde{u}_L &\rightarrow u\widetilde{Z}_i,\ d\widetilde{W}_j^+,\ u\tilde{g}, \\
\tilde{d}_L &\rightarrow d\widetilde{Z}_i,\ u\widetilde{W}_j^-,\ d\tilde{g}, \\
\tilde{u}_R &\rightarrow u\widetilde{Z}_i,\ u\tilde{g}, \\
\tilde{d}_R &\rightarrow d\widetilde{Z}_i,\ d\tilde{g}.
\end{aligned}$$



# Slepton decays

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

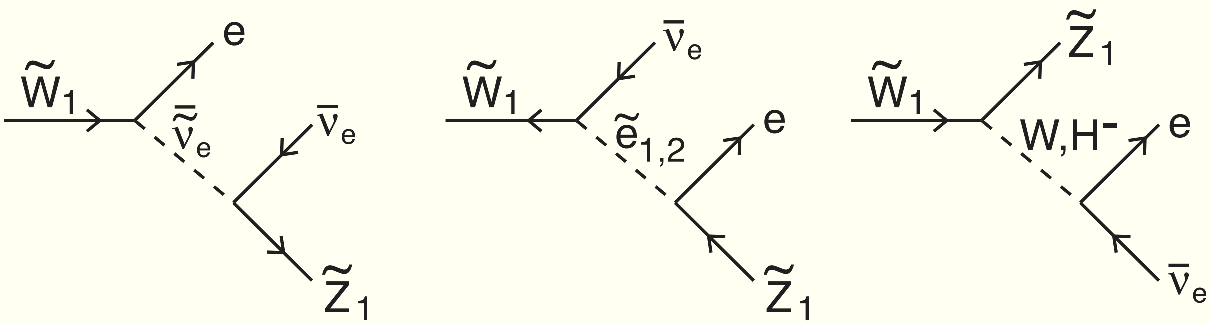


# Chargino decays

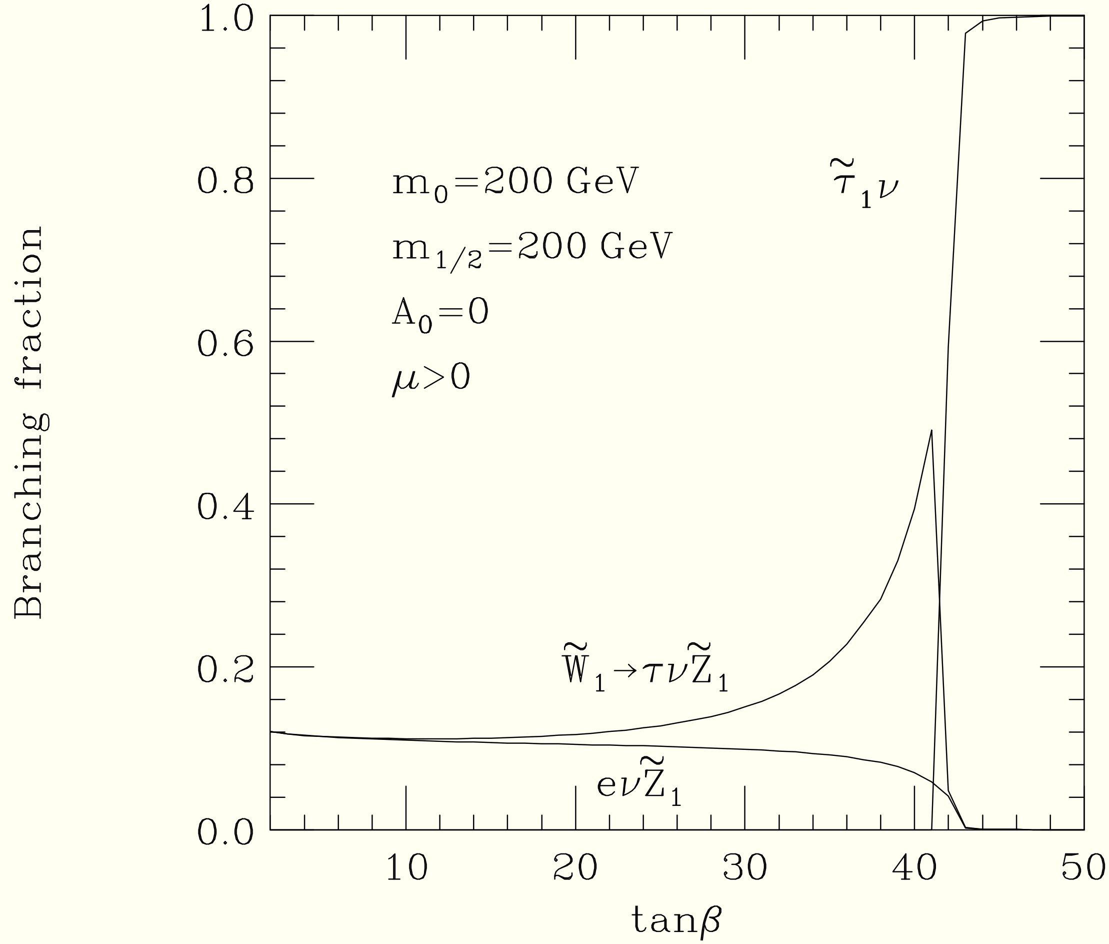
$$
\begin{aligned}
\widetilde{W}_j &\to W\widetilde{Z}_i,\ H^-\widetilde{Z}_i, \\
&\to \tilde{u}_L\bar{d},\ \bar{\tilde{d}}_L u,\ \tilde{c}_L\bar{s},\ \bar{\tilde{s}}_L c,\ \tilde{t}_{1,2}\bar{b},\ \tilde{b}_{1,2}t, \\
&\to \tilde{\nu}_e\bar{e},\ \bar{\tilde{e}}_L\nu_e,\ \tilde{\nu}_\mu\bar{\mu},\ \bar{\tilde{\mu}}_L\nu_\mu,\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

Charginos may decay to a lighter neutralino via

$$\widetilde{W}_j \to \widetilde{Z}_i + f\bar{f}' \ , \tag{1}$$



# Decay of $\widetilde{W}_1$ versus $\tan\beta$

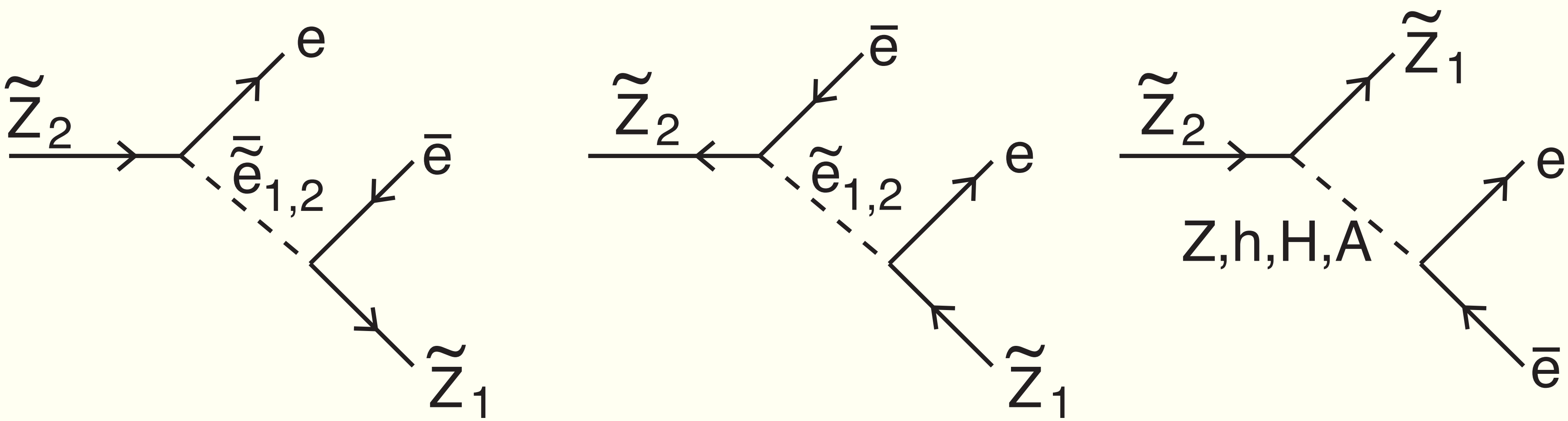


# Neutralino decays

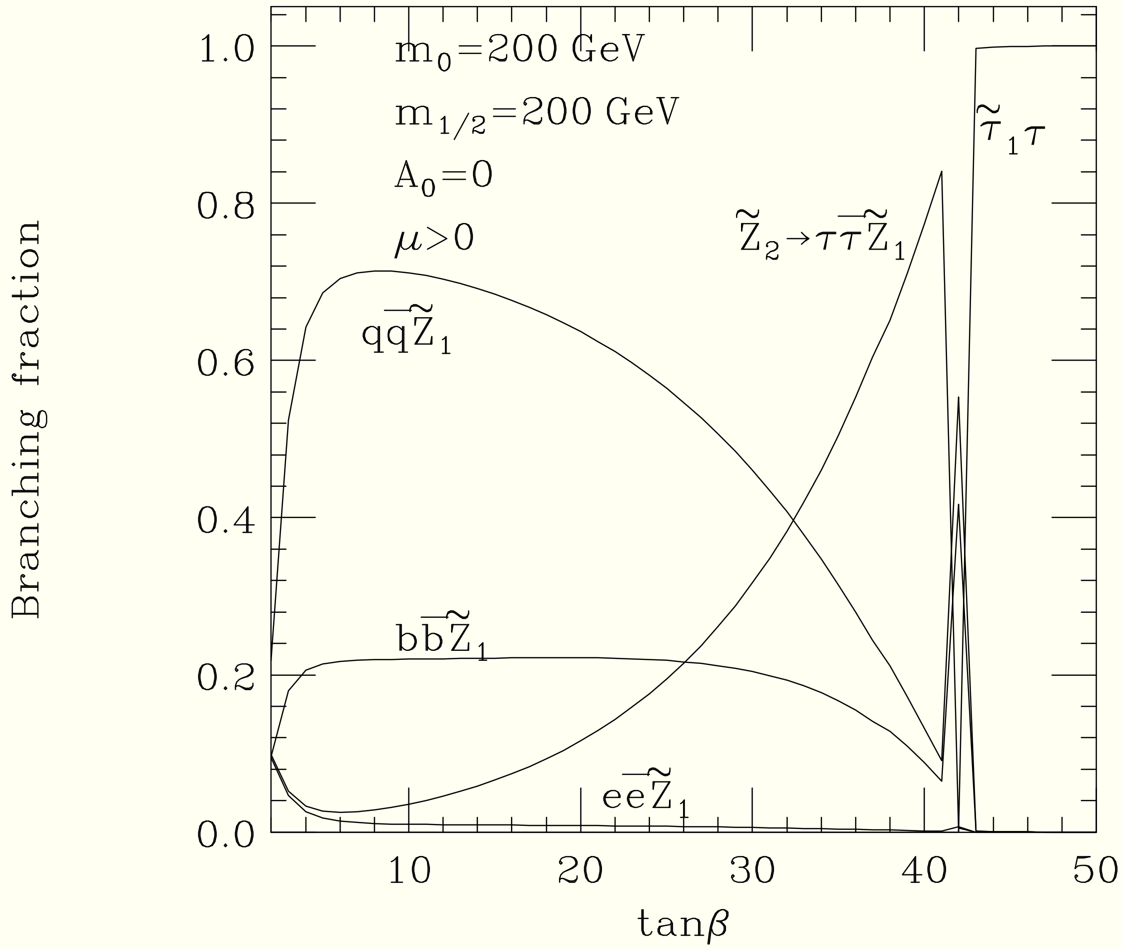
$$\widetilde{Z}_i \rightarrow W\widetilde{W}_j,\ H^-\widetilde{W}_j,\ Z\widetilde{Z}_{i'},\ h\widetilde{Z}_{i'},\ H\widetilde{Z}_{i'},\ A\widetilde{Z}_{i'}$$
$$\rightarrow \tilde{q}_{L,R}\bar{q},\ \bar{\tilde{q}}_{L,R}q,\ \tilde{\ell}_{L,R}\bar{\ell},\ \bar{\tilde{\ell}}_{L,R}\ell,\ \tilde{\nu}_\ell\bar{\nu}_\ell,\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

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

$$\widetilde{Z}_i \rightarrow \widetilde{Z}_{i'} + f\bar{f} \tag{2}$$



# Decay of $\widetilde{Z}_2$ versus $\tan\beta$



## Decays of SUSY Higgs boson $h$

- $h \to u\bar{u},\ d\bar{d},\ s\bar{s},\ c\bar{c},\ b\bar{b},\ e\bar{e},\ \mu\bar{\mu},\ \tau\bar{\tau}$
- $h \to \widetilde{Z}_i \widetilde{Z}_{i'},\ \widetilde{W}_j^+ \widetilde{W}_{j'}^-,\ \tilde{f}\bar{\tilde{f}}$
- $h \to AA$

where $i, i' = 1-4$ and $j, j' = 1, 2$.

Also

- $h \to W f \bar{f}' / Z f \bar{f}$
- $h \to gg,\ \gamma\gamma,\ Z\gamma$

# Decays of SUSY Higgs boson $H$

- $H \to u\bar{u},\ d\bar{d},\ s\bar{s},\ c\bar{c},\ b\bar{b},\ t\bar{t},\ e\bar{e},\ \mu\bar{\mu},\ \tau\bar{\tau}$
- $H \to WW,\ ZZ$
- $H \to \widetilde{Z}_i\widetilde{Z}_{i'},\ \widetilde{W}_j^+\widetilde{W}_{j'}^-,\ \tilde{f}\bar{\tilde{f}}$
- $H \to hh,\ AA,\ H^+H^-,\ AZ$
- $H \to gg,\ \gamma\gamma,\ Z\gamma$

where $i, i' = 1-4$ and $j, j' = 1, 2$.

# Decays of SUSY Higgs boson $A$

- $A \to u\bar{u},\ d\bar{d},\ s\bar{s},\ c\bar{c},\ b\bar{b},\ t\bar{t},\ e\bar{e},\ \mu\bar{\mu},\ \tau\bar{\tau}$
- $A \to \widetilde{Z}_i \widetilde{Z}_{i'},\ \widetilde{W}_j^+ \widetilde{W}_{j'}^-,\ \tilde{f}\bar{\tilde{f}}$
- $A \to hZ$
- $A \to gg,\ \gamma\gamma$

where $i, i' = 1 - 4$ and $j, j' = 1, 2$.

## Decays of SUSY Higgs boson $H^+$

- $H^+ \to u\bar{d},\ c\bar{s},\ t\bar{b},\ \nu_e\bar{e},\ \nu_\mu\bar{\mu},\ \nu_\tau\bar{\tau}$
- $H^+ \to \widetilde{Z}_i\widetilde{W}_j^+,\ \tilde{f}\bar{\tilde{f}}'$
- $H^+ \to hW$

where $i, i' = 1 - 4$ and $j, j' = 1, 2$.

## Decay of top to SUSY?

- $t \rightarrow bW^+$
- $t \rightarrow bH^+$
- $t \rightarrow \tilde{t}_{1,2}\widetilde{Z}_i,\ \tilde{b}_{1,2}\widetilde{W}_j$

where $i = 1 - 4$ and $j = 1, 2$.

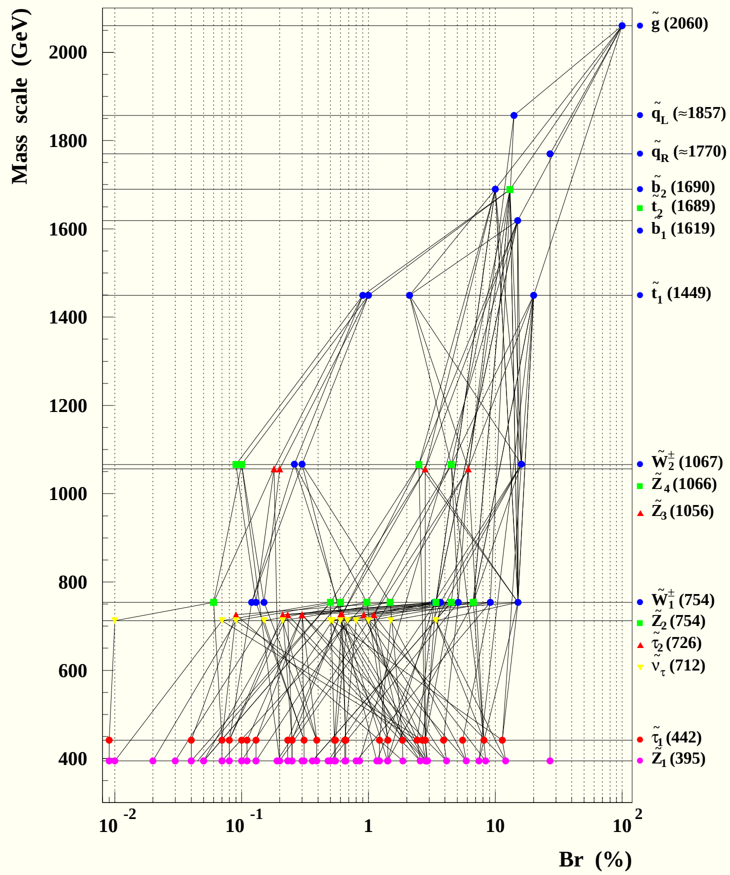
# Decays to gravitino?

- $\widetilde{Z}_1 \to \gamma\tilde{G}$
- $\widetilde{Z}_1 \to \tilde{G} + (h,\ H,\ A$ or $Z)$
- $\tilde{f} \to f\tilde{G}$

Couplings can be extracted from SUGRA Lagrangian:

see *e.g. Weak Scale Supersymmetry*

# Sparticle cascade decays

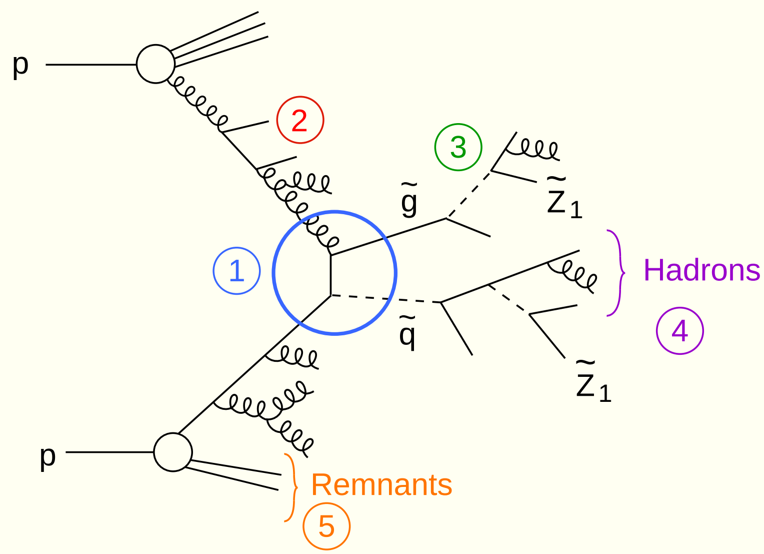



| | | | |
|---|---|---|---|
| $\tilde{Z}_1$ qq | (27.0 %) | $\tilde{Z}_1$ $\tau\nu$WWWbb | (4.1 %) |
| $\tilde{Z}_1$ $\tau\nu$Wbb | (12.1 %) | $\tilde{Z}_1$ $\tau\tau$bb | (2.9 %) |
| $\tilde{Z}_1$ $\tau\tau$WWbb | (8.4 %) | $\tilde{Z}_1$ $\tau\tau$qq | (2.9 %) |
| $\tilde{Z}_1$ WWbb | (7.4 %) | $\tilde{Z}_1$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

# A realistic picture of what SUSY matter looks like at LHC

- ⋆ Counting different flavor states (which are potentially measurable), there are well over 1000 subprocess reactions expected at LHC from the MSSM
- ⋆ on average, each sparticle has 5-20 decay modes
- ⋆ rough estimate of distinct SUSY $2 \to n$ processes:
  - $\sim 100 \times 10 \times 10 \sim 10^5$
  - this is actually a gross underestimate since each daughter of a produced sparticle has multiple decay modes, and so on...
- ⋆ the way forward: Monte Carlo program
  - calculate $all$ prod'n cross sections: generate according to relative weights
  - calculate all branching fractions, and generate decays according to them
  - interface with parton shower, hadronization, underlying event
  - computer generated events should look something like what we would expect from the MSSM at the LHC

# 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,...)

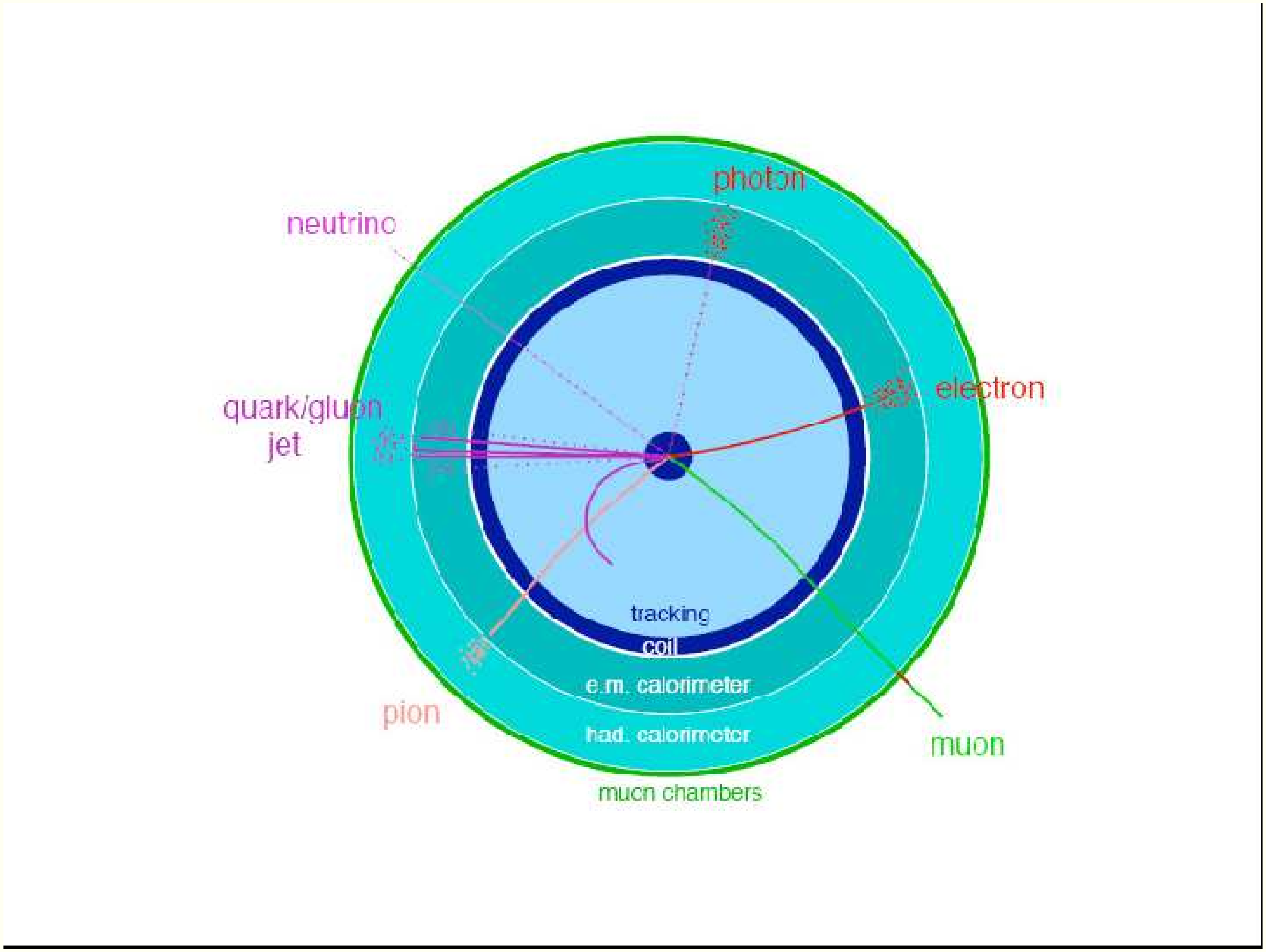
- CH, AO-PS, Phen. model UE, Isawig

⋆ SUSYGEN (Ghodbane, Katsanevas, Morawitz, Perez)

- mainly for $e^+e^-$; interfaces to Pytha

⋆ CompHEP, CalcHEP, Madgraph: for automatic Feynman diagram evaluation

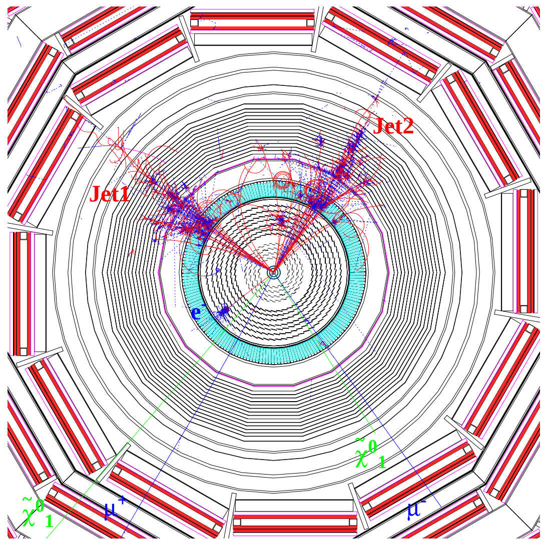
# Briefly: particle interactions with detector



# 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, $\mu$ < 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.**

## Conclusions

- ⋆ sparticle production
  - generally, $\tilde{g}\tilde{g}$, $\tilde{g}\tilde{q}$ $\tilde{q}\tilde{q}$ dominate at LHC if $m_{\tilde{g},\tilde{q}} \lesssim 1$ TeV
- ⋆ sparticle decays
  - multi-step cascade decays lead to multi-jets+multi-leptons+$\not\!\!E_T$
- ⋆ event generation
  - combine numerous production processes with multi-step sparticle cascade decays, initial/final state parton showering, hadronization and a modeling of underlying event, and hopefully we get a pretty good picture of what production of SUSY matter will look like in the environment of an LHC detector