Lecture 2. Sparticle production, decay, event generation

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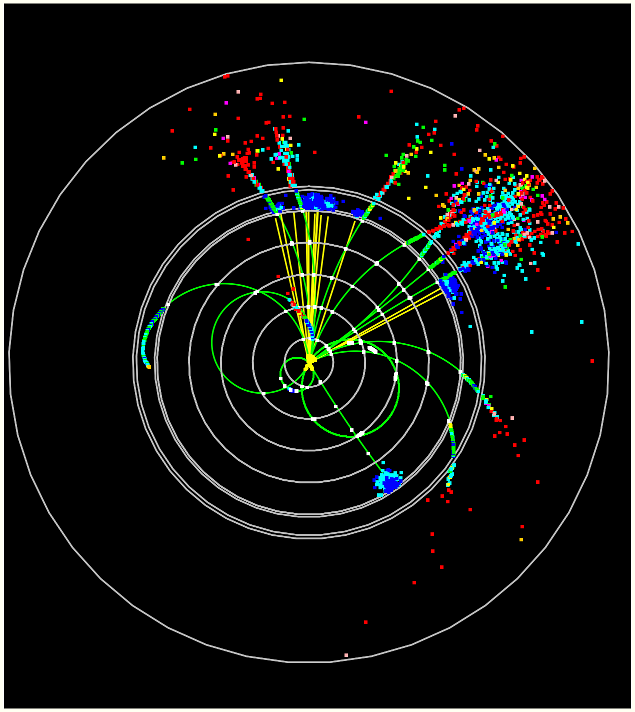
⋆ Outline

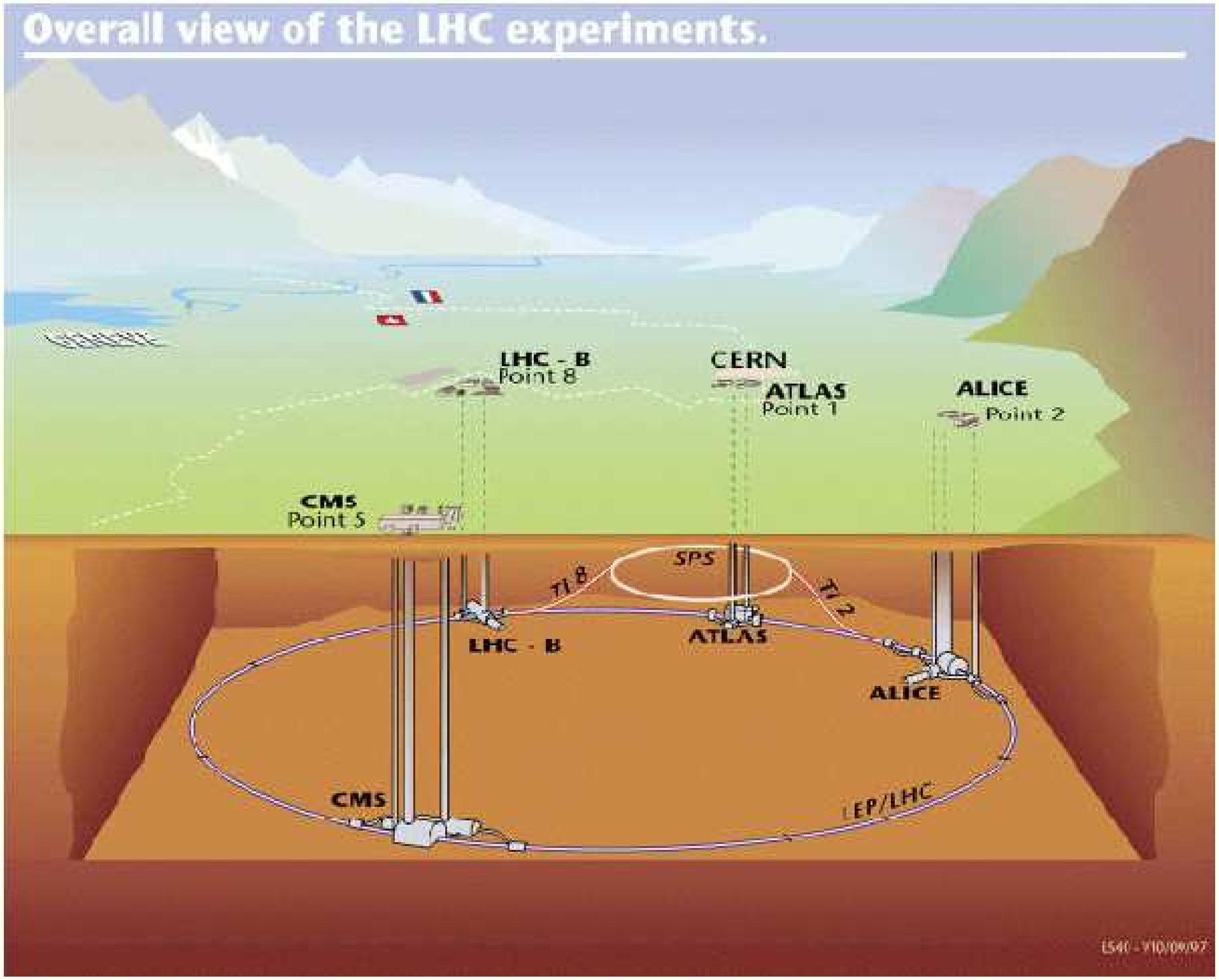
- LHC basics
- Parton model and cross sections
- Sparticle production at LHC
- Sparticle decays
- SUSY event generators
- Event generator demo?



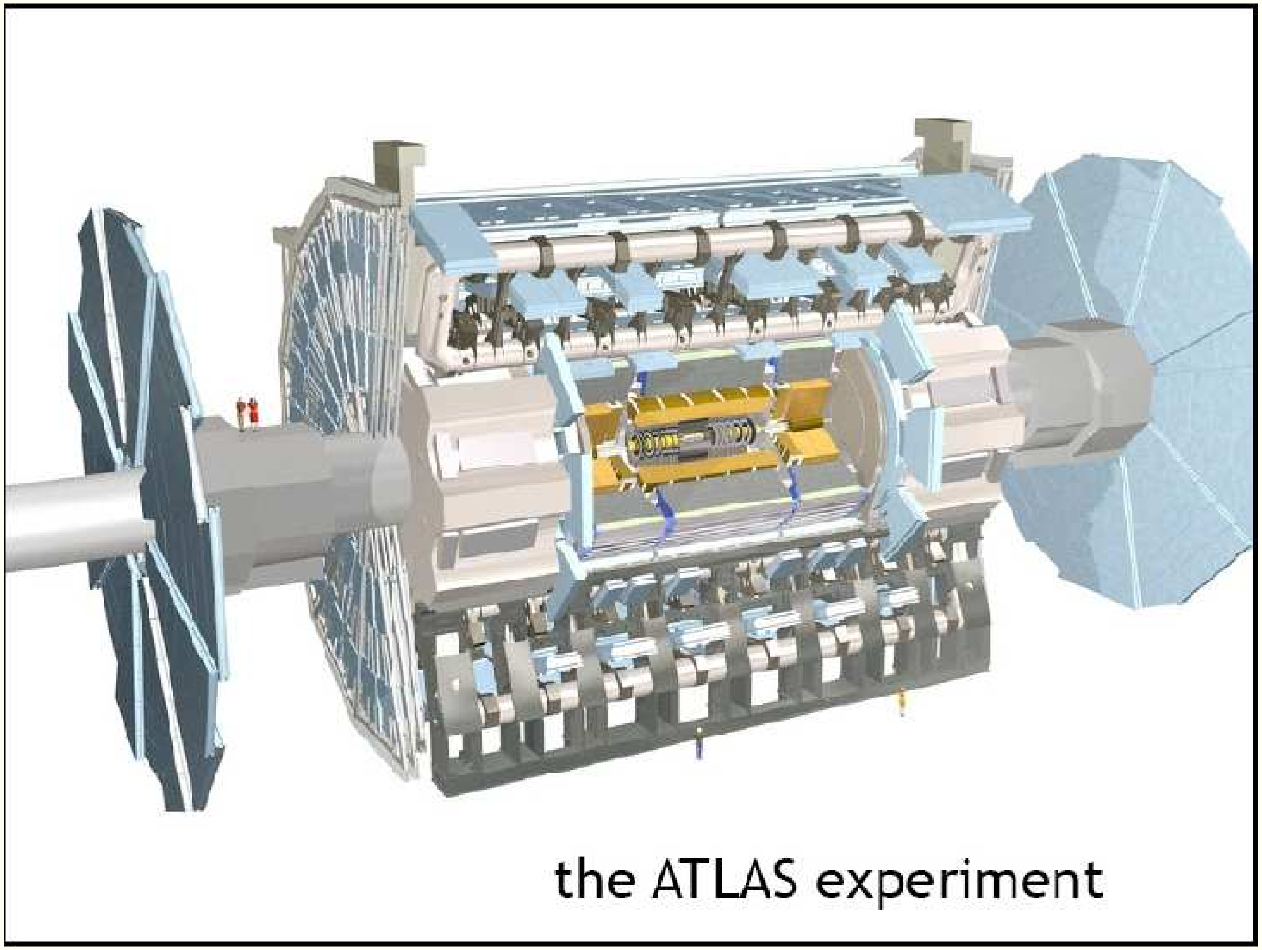
The role of the CERN Large Hadron Collider (LHC)

- The LHC is a proton-proton collider (pp)
- Each beam will have $E = 7$ TeV (trillion electron volts)
- Center-of-mass energy $E \equiv \sqrt{s} = 10 - 14$ TeV
- The collider is on a circular tunnel 27 km in circumference
- It is nearly completed: turn-on expected in May 2008!
- Protons are not fundamental particles: made of quarks q and gluons g
- The quark and gluon collisions should have enough energy to produce TeV-scale superparticles at a large enough rate that they should be detectable above SM background processes
- LHC should be able to discover SUSY or other new physics: but probably can't rule SUSY out if just a Higgs or nothing new is found

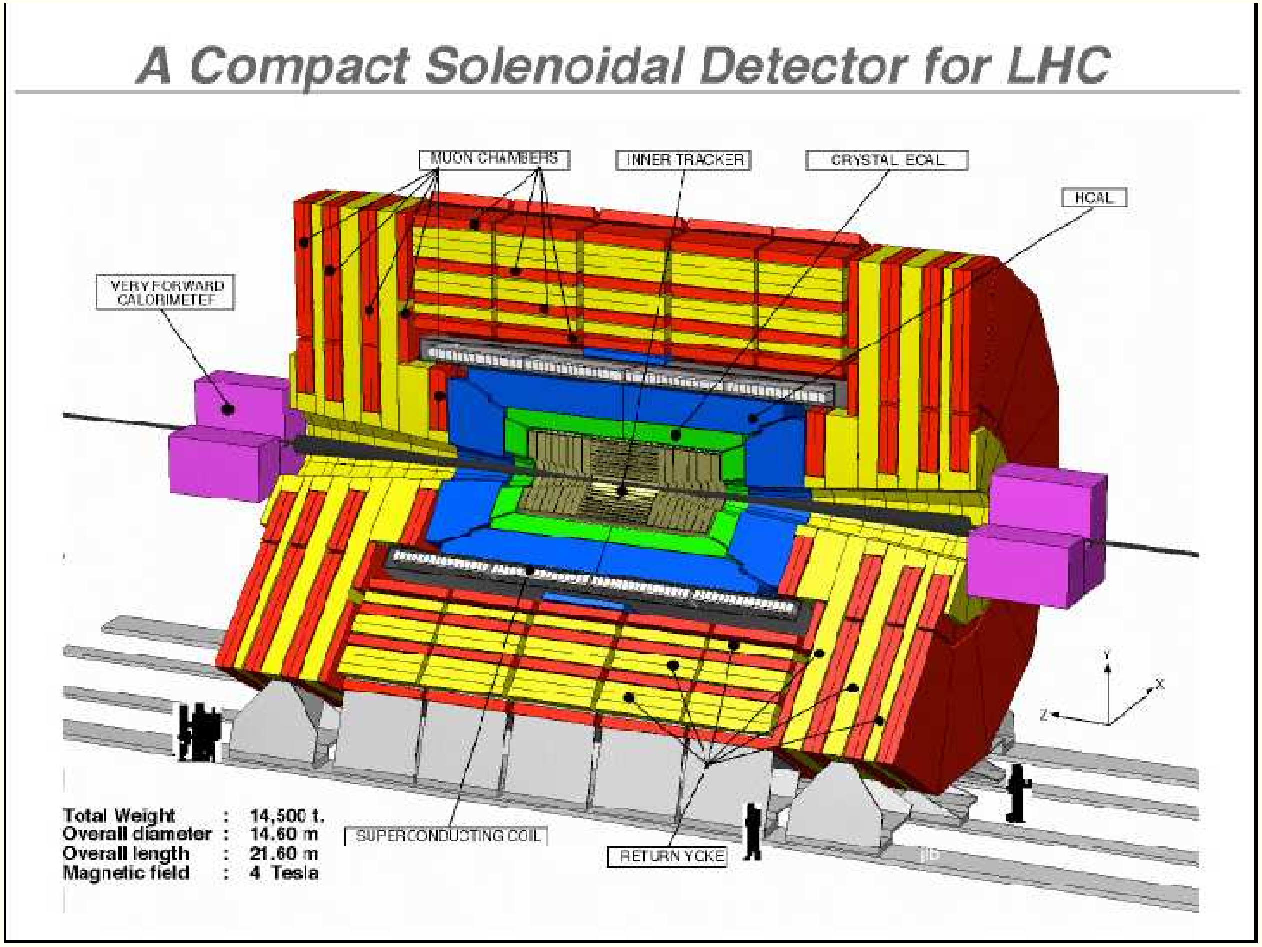
Layout of the LHC:two main detectors: Atlas and CMS



The Atlas detector



The CMS (Compact Muon Solenoid) detector



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

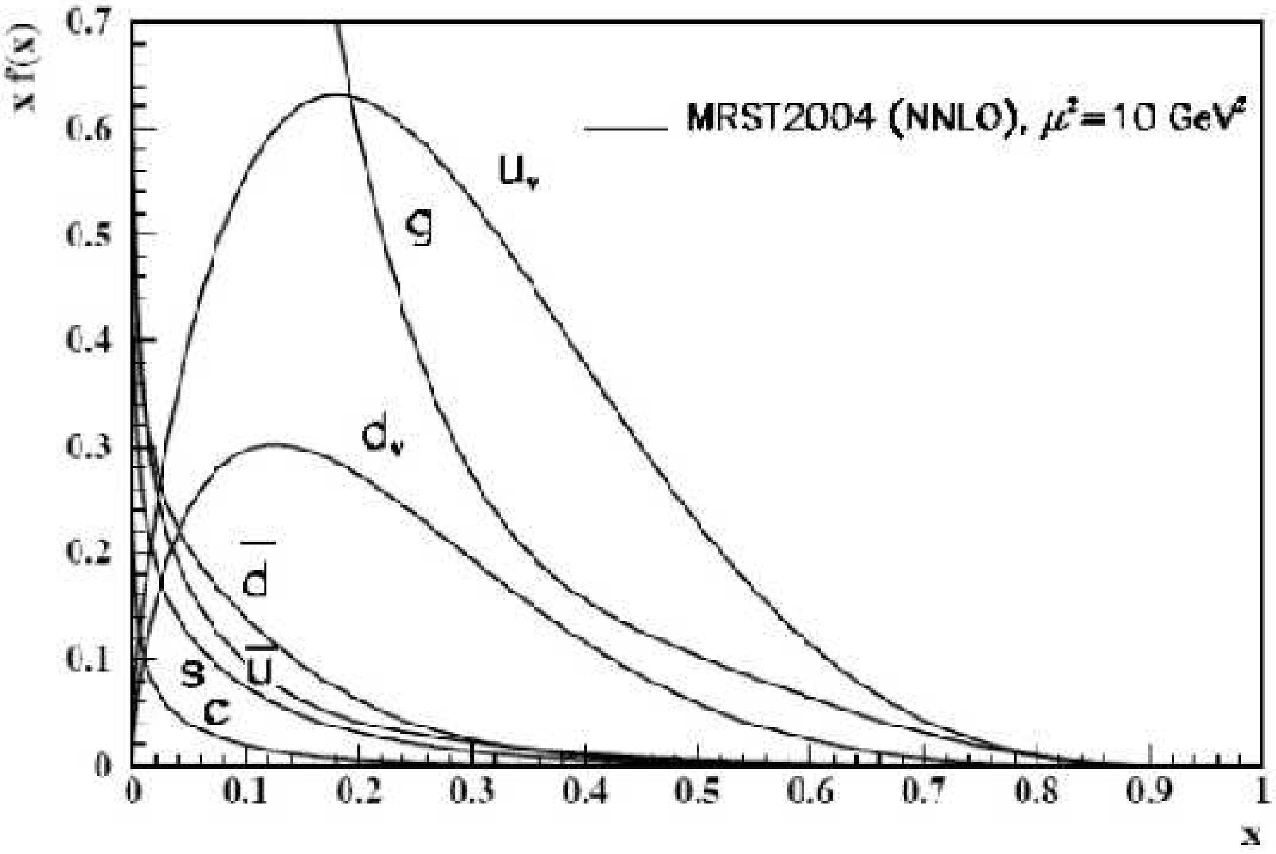
$$a \;+\; b \;\rightarrow\; c \;+\; d,$$

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:

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

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

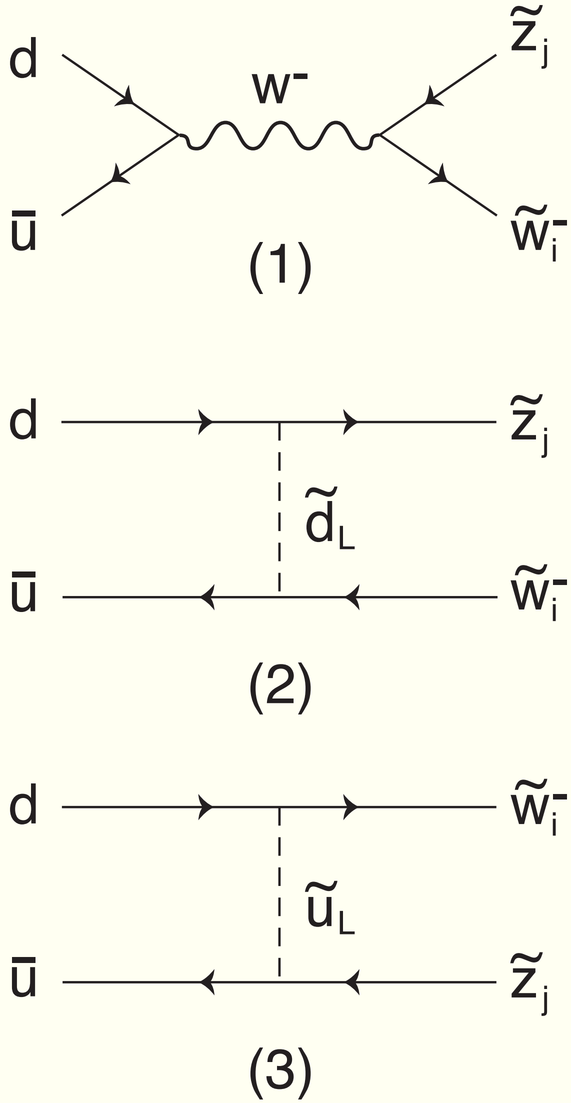
- The fundamental calculable object in QM is the *amplitude* $\mathcal{M}$ for a process to occur
- A pictorial representation of $\mathcal{M}$ is given by a *Feynman diagram*
- Feynman rules for many theories can be found in standard texts: *e.g.* Peskin& Schroeder, *Introduction to Quantum Field Theory*
- 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 normalize and sum (integrate) over all momentum configurations to gain cross section, usually in *femtobarns*:

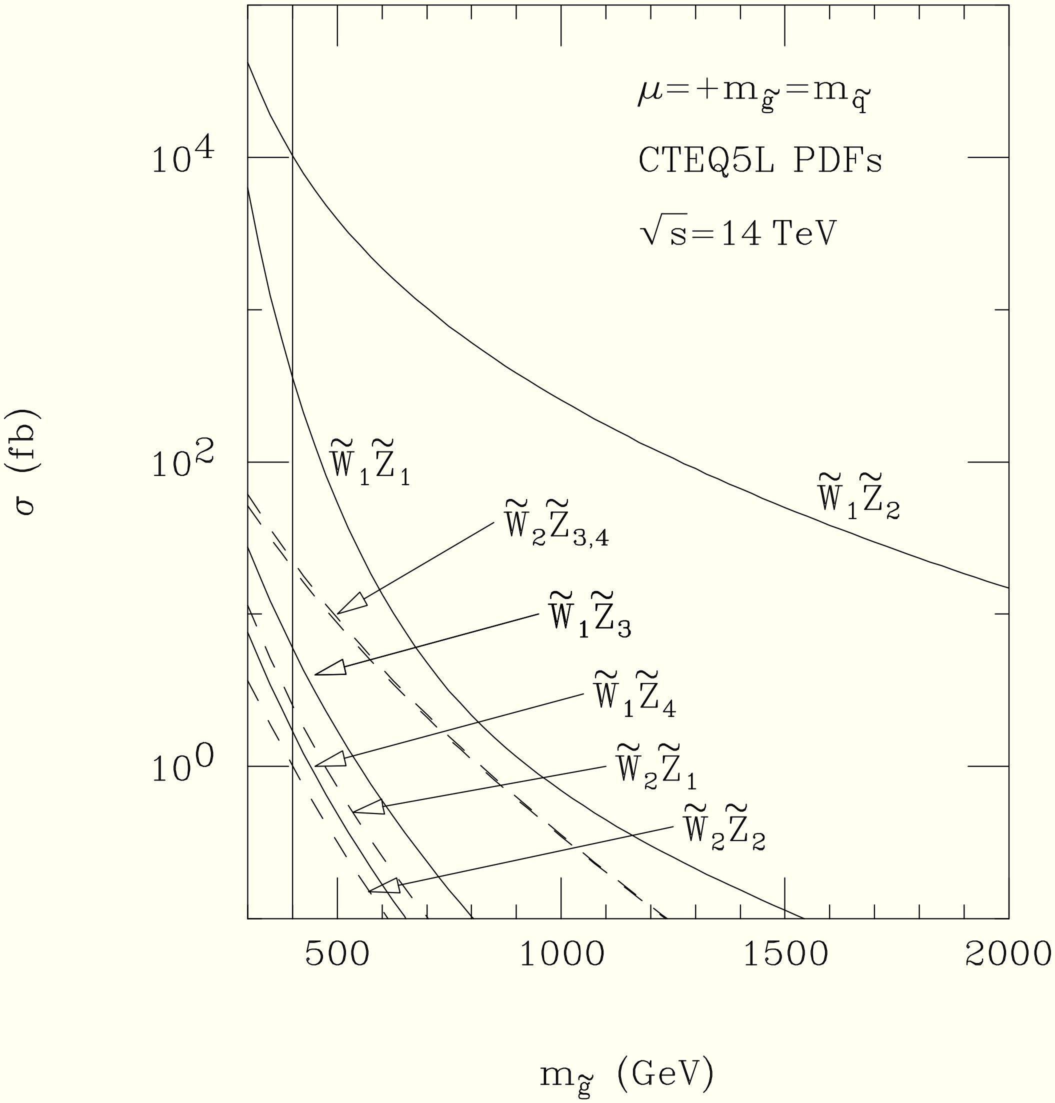
Calculating subprocess cross sections/decay rates in QFT

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

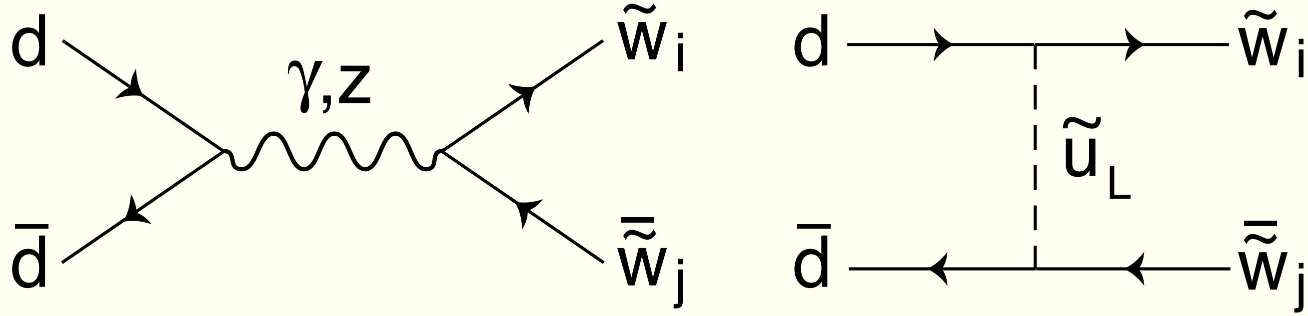
- Must sum (integrate) over all final state momentum configurations
- May be done analytically for simple processes $e.g.$ $2 \to 2$
- Usually done using Monte Carlo method for $n \geq 3$
- Monte Carlo well suited for adding on particle decays so one has really $2 \to n$ processes where n can be very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

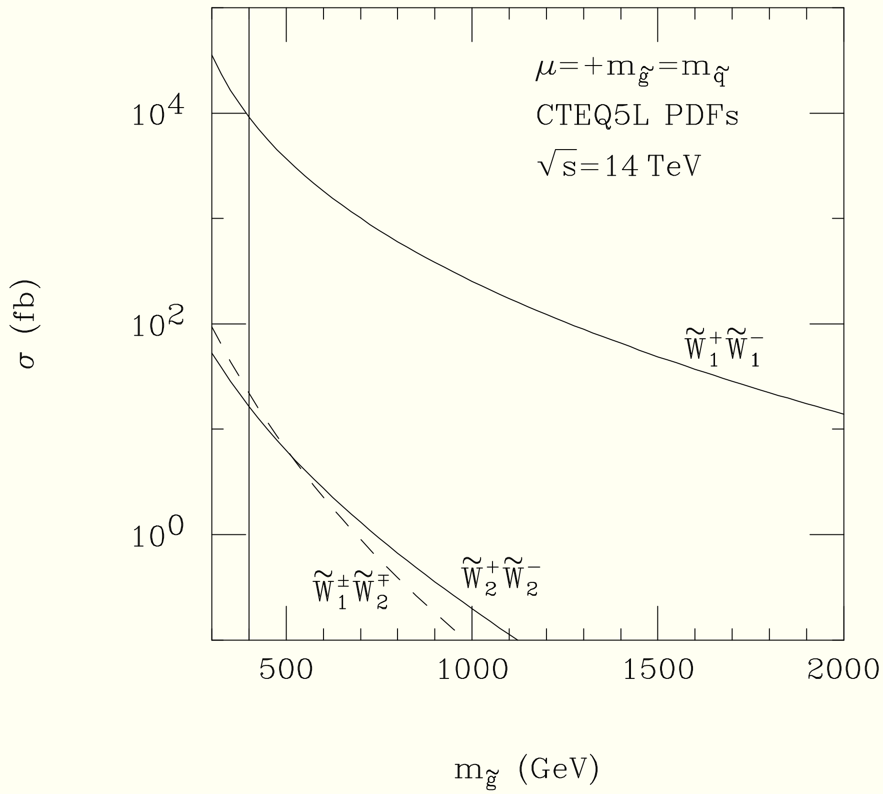
Chargino-neutralino production



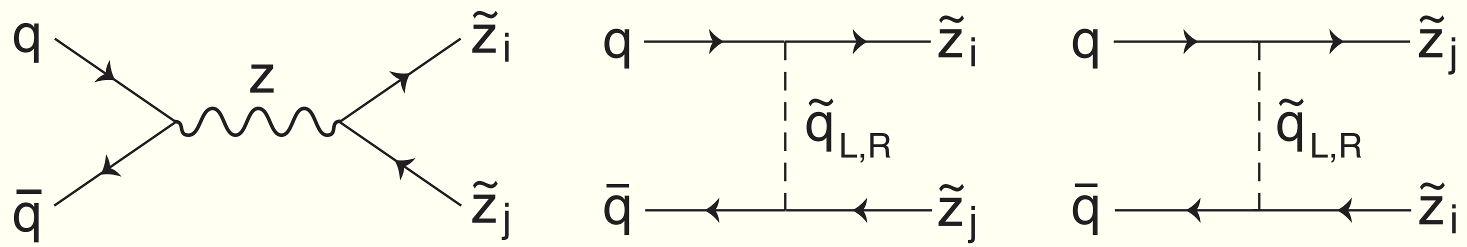


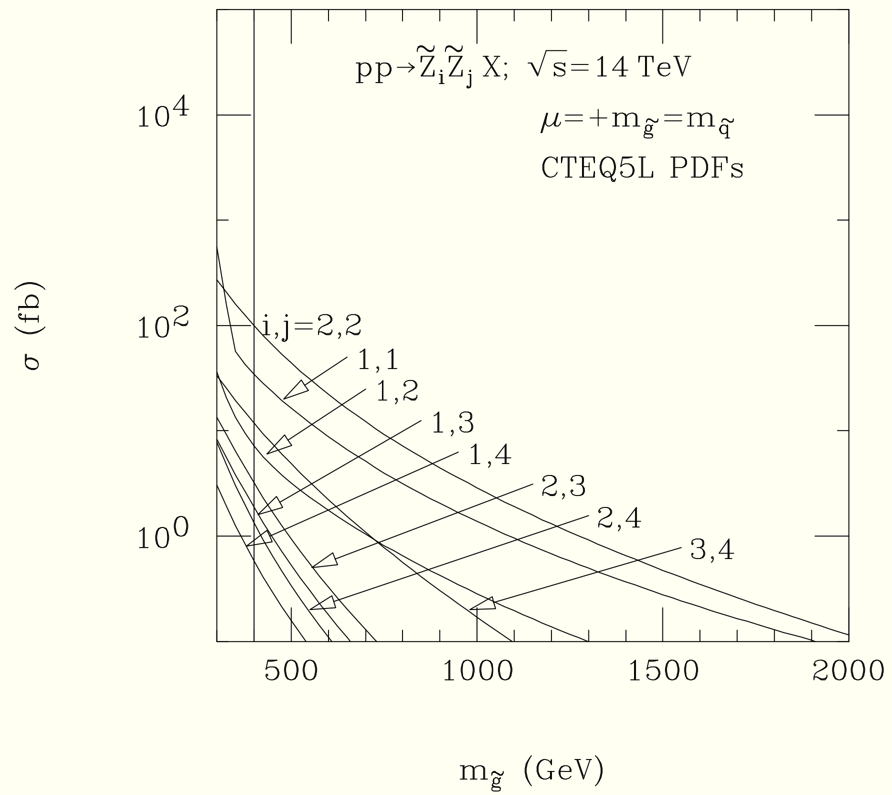
Chargino pair production



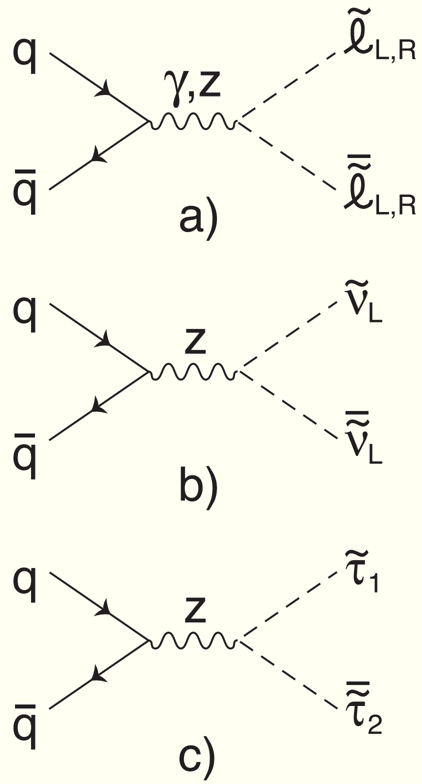


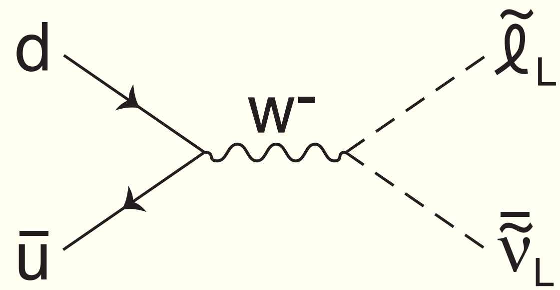
Neutralino pair production



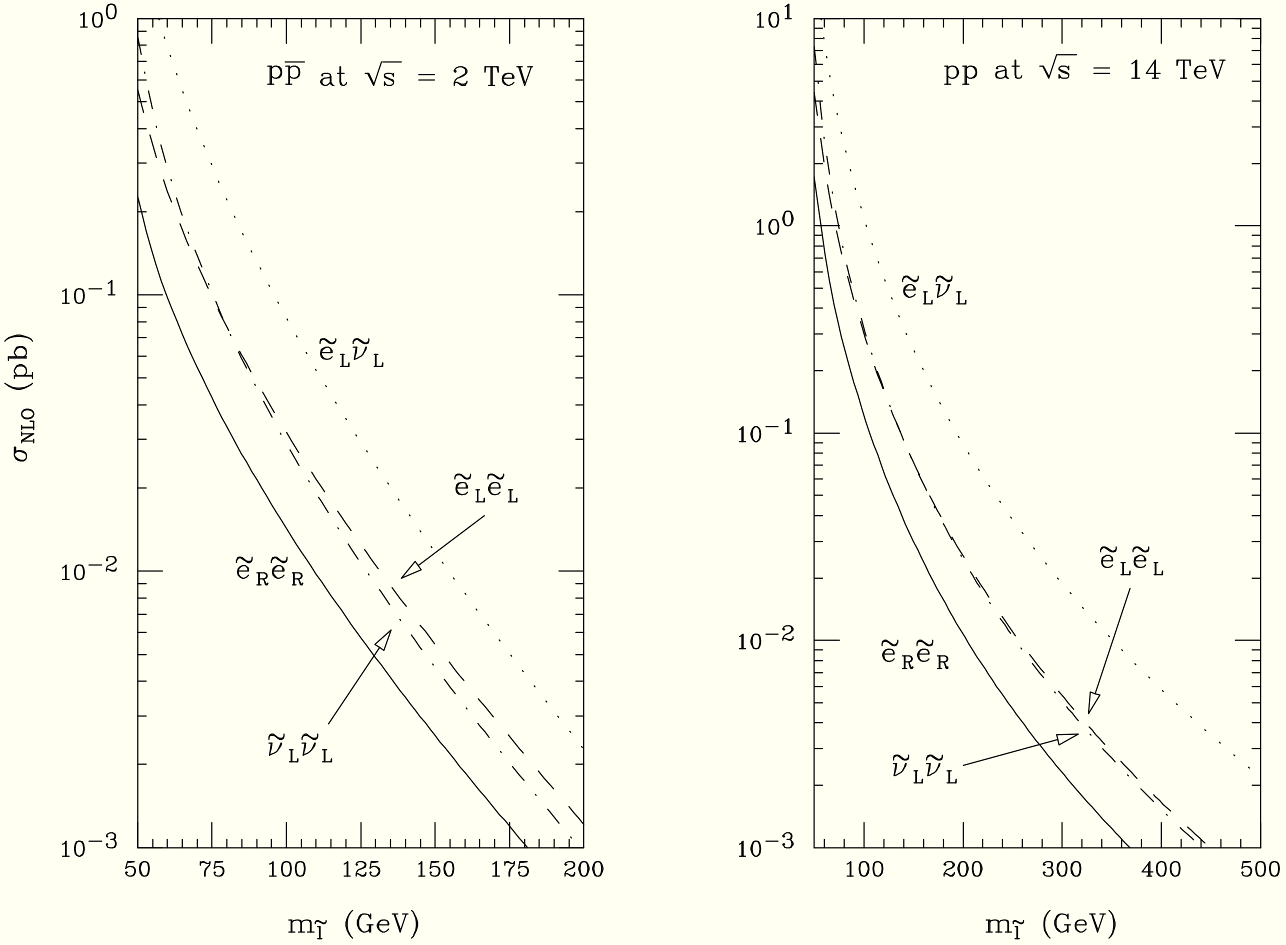


Slepton pair production

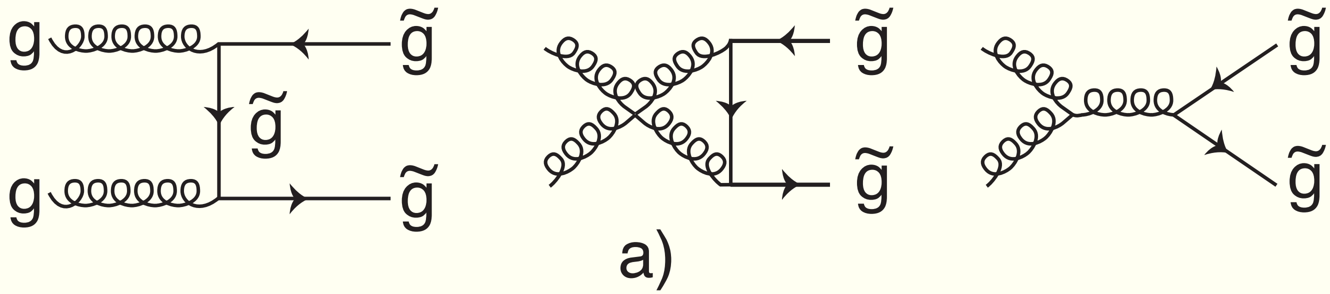


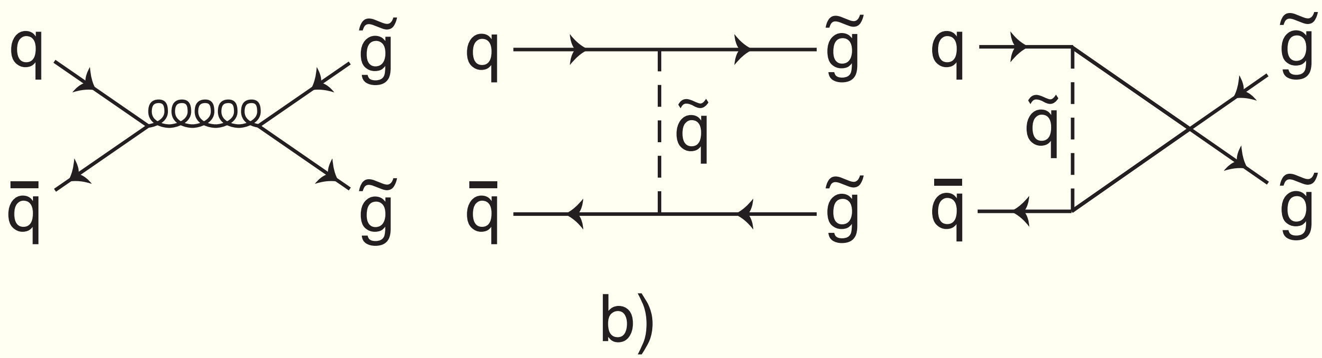


Slepton pair cross section

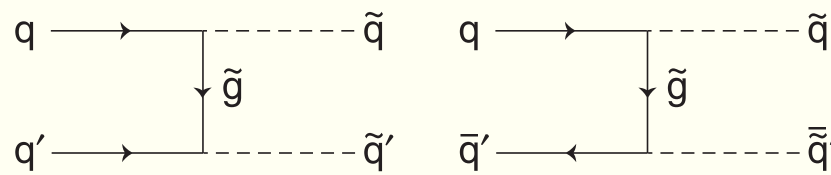


Gluino pair production

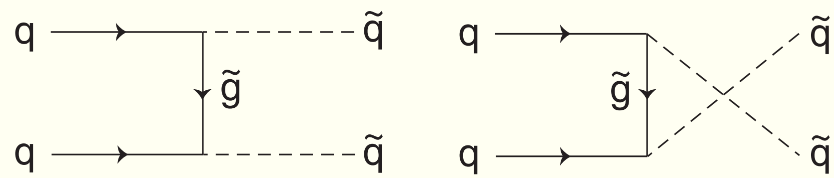




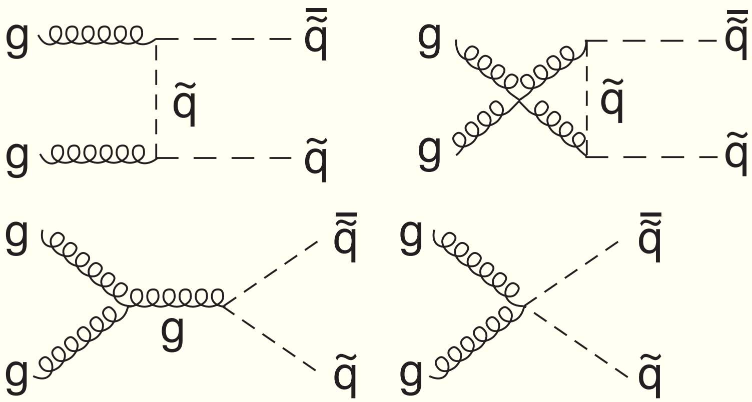
Squark pair production

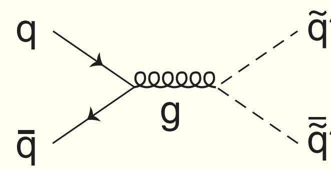


a)



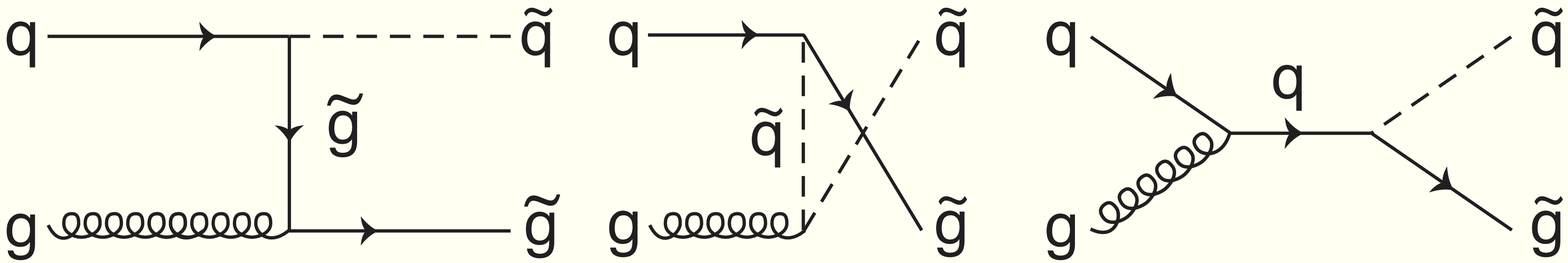
b)



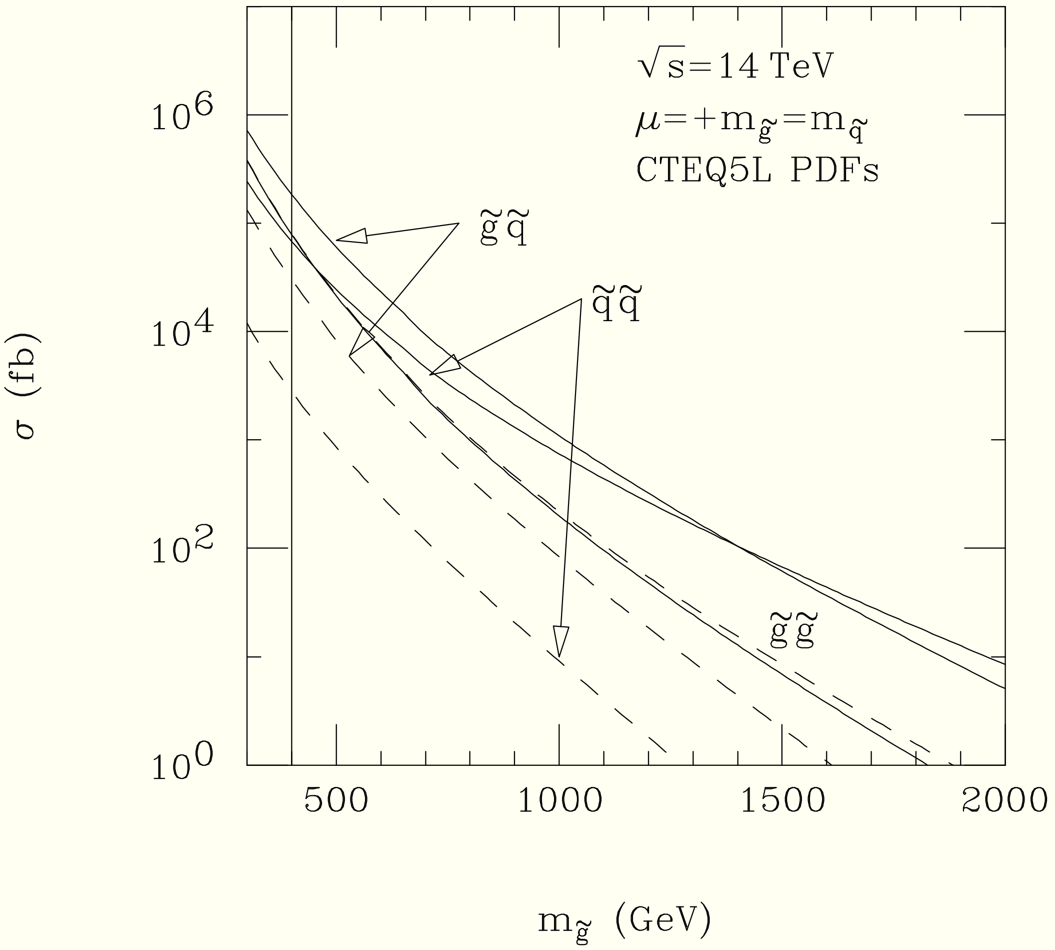


c)

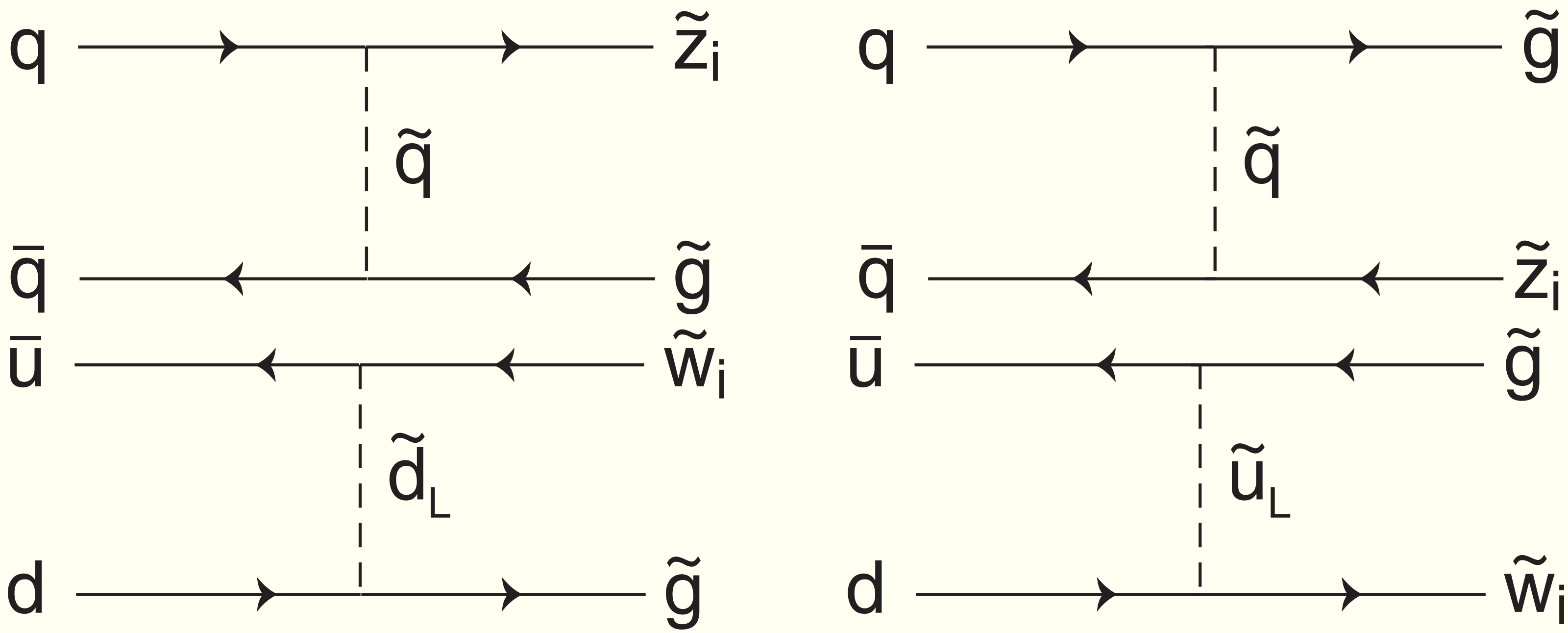
Gluino-squark associated production

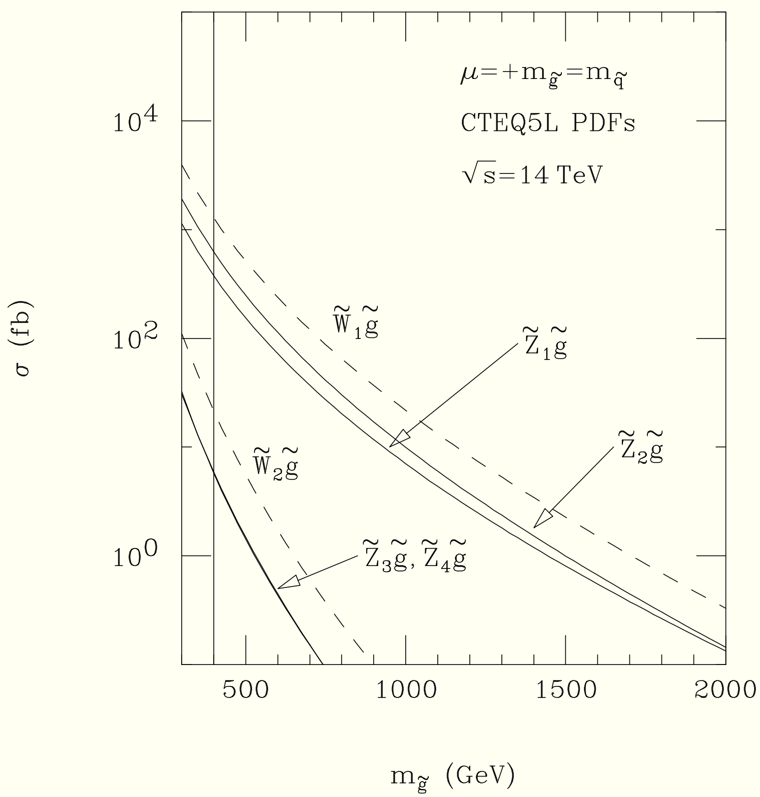


Gluino and squark pair production



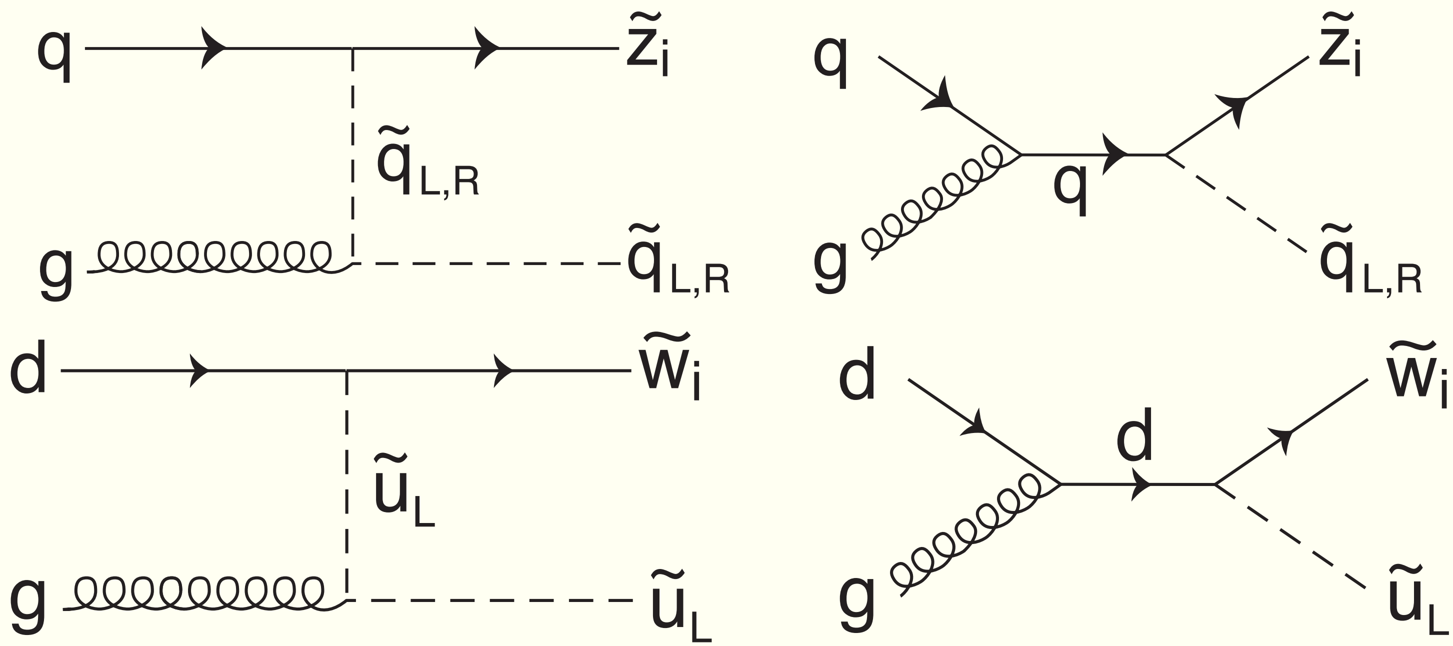
-ino-gluino associated production

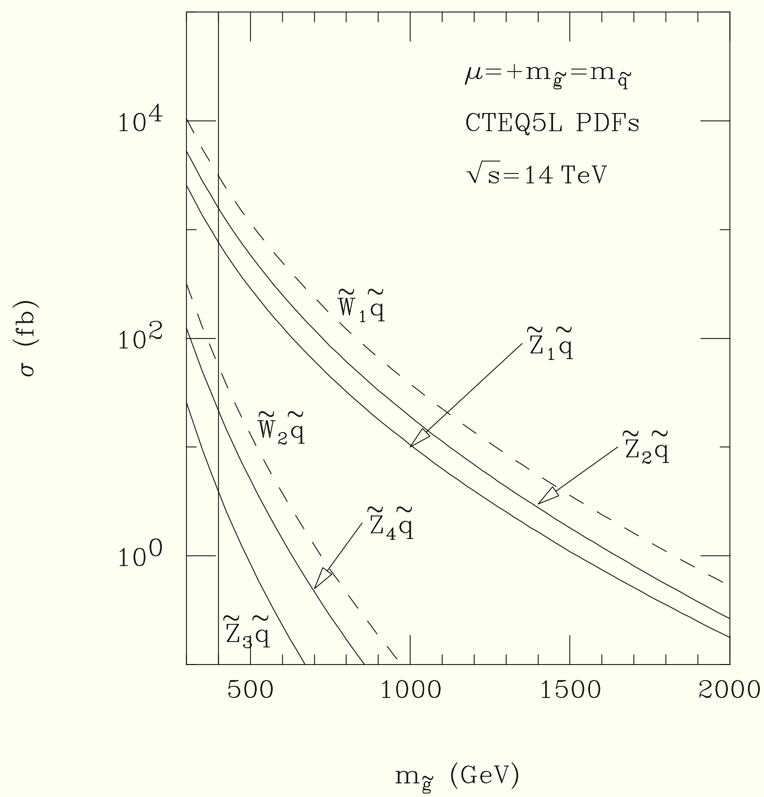




$\mu=+m_{\tilde g}=m_{\tilde q}$
CTEQ5L PDFs
$\sqrt{s}=14$ TeV
10^4
10^2
10^0
σ (fb)
$\widetilde W_1\tilde g$
$\widetilde Z_1\tilde g$
$\widetilde Z_2\tilde g$
$\widetilde W_2\tilde g$
$\widetilde Z_3\tilde g$, $\widetilde Z_4\tilde g$
500
1000
1500
2000
$m_{\tilde g}$ (GeV)

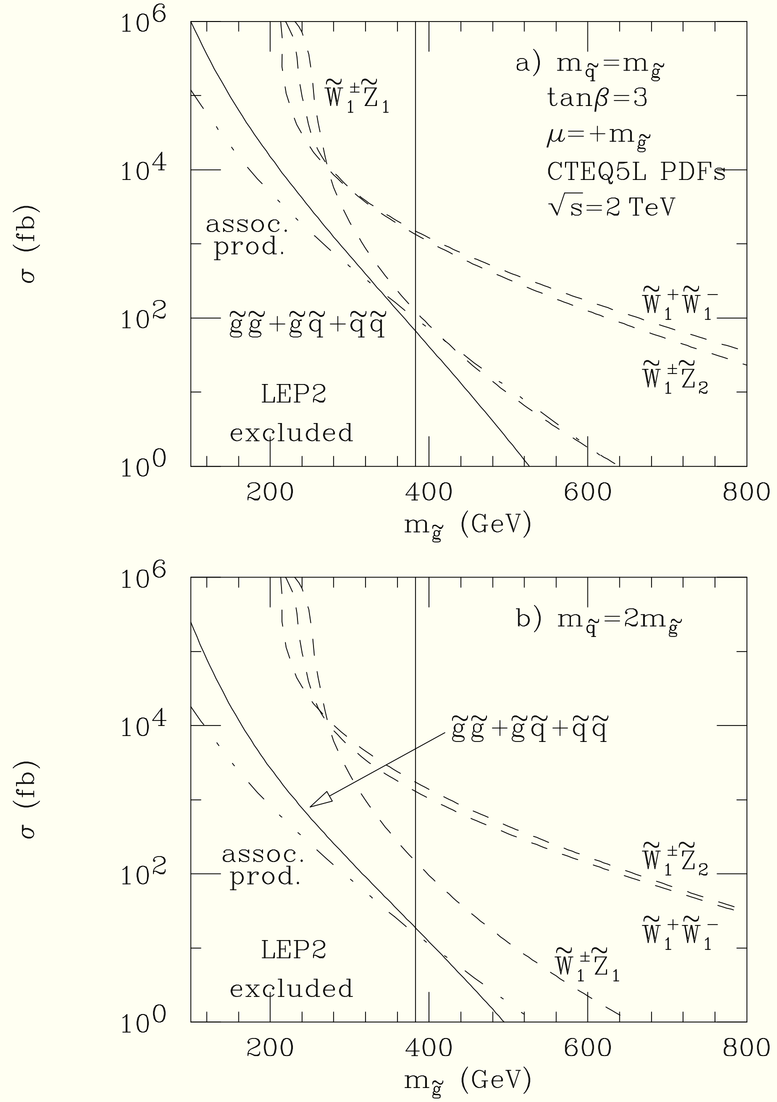
-ino-squark associated production



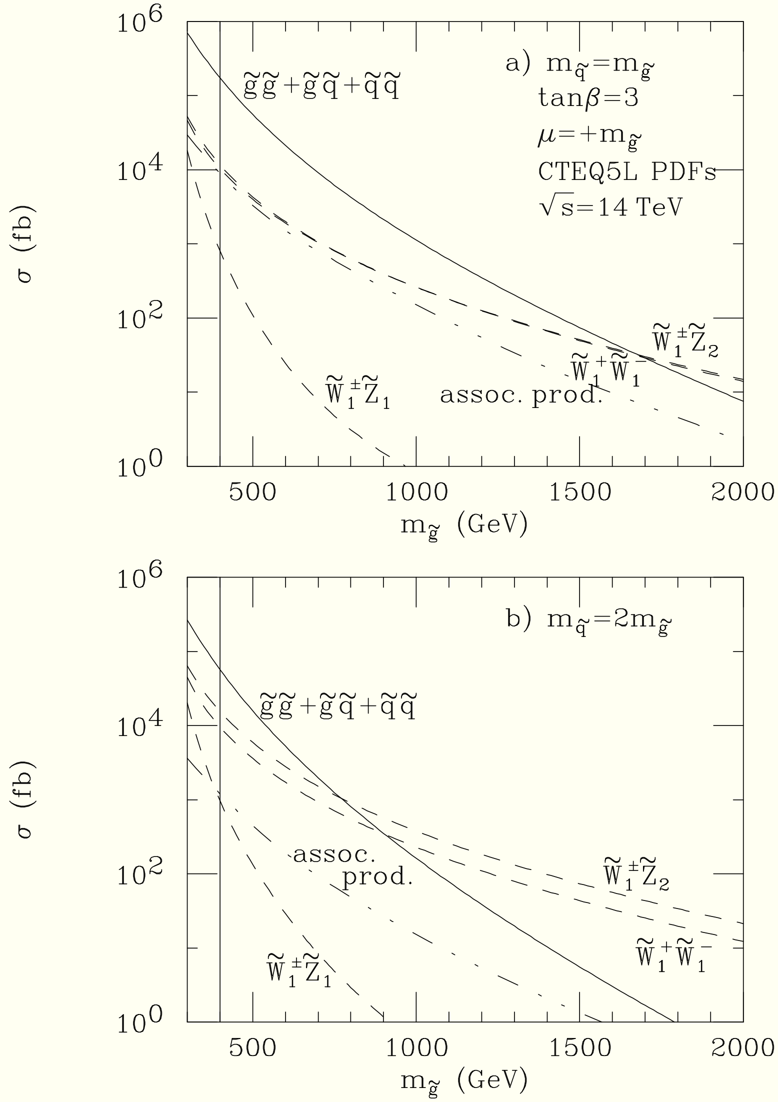


$\mu=+m_{\tilde g}=m_{\tilde q}$
CTEQ5L PDFs
$\sqrt{s}=14$ TeV
10^4
10^2
10^0
σ (fb)
$\widetilde{W}_1\tilde{q}$
$\widetilde{Z}_1\tilde{q}$
$\widetilde{W}_2\tilde{q}$
$\widetilde{Z}_2\tilde{q}$
$\widetilde{Z}_4\tilde{q}$
$\widetilde{Z}_3\tilde{q}$
500
1000
1500
2000
$m_{\tilde g}$ (GeV)

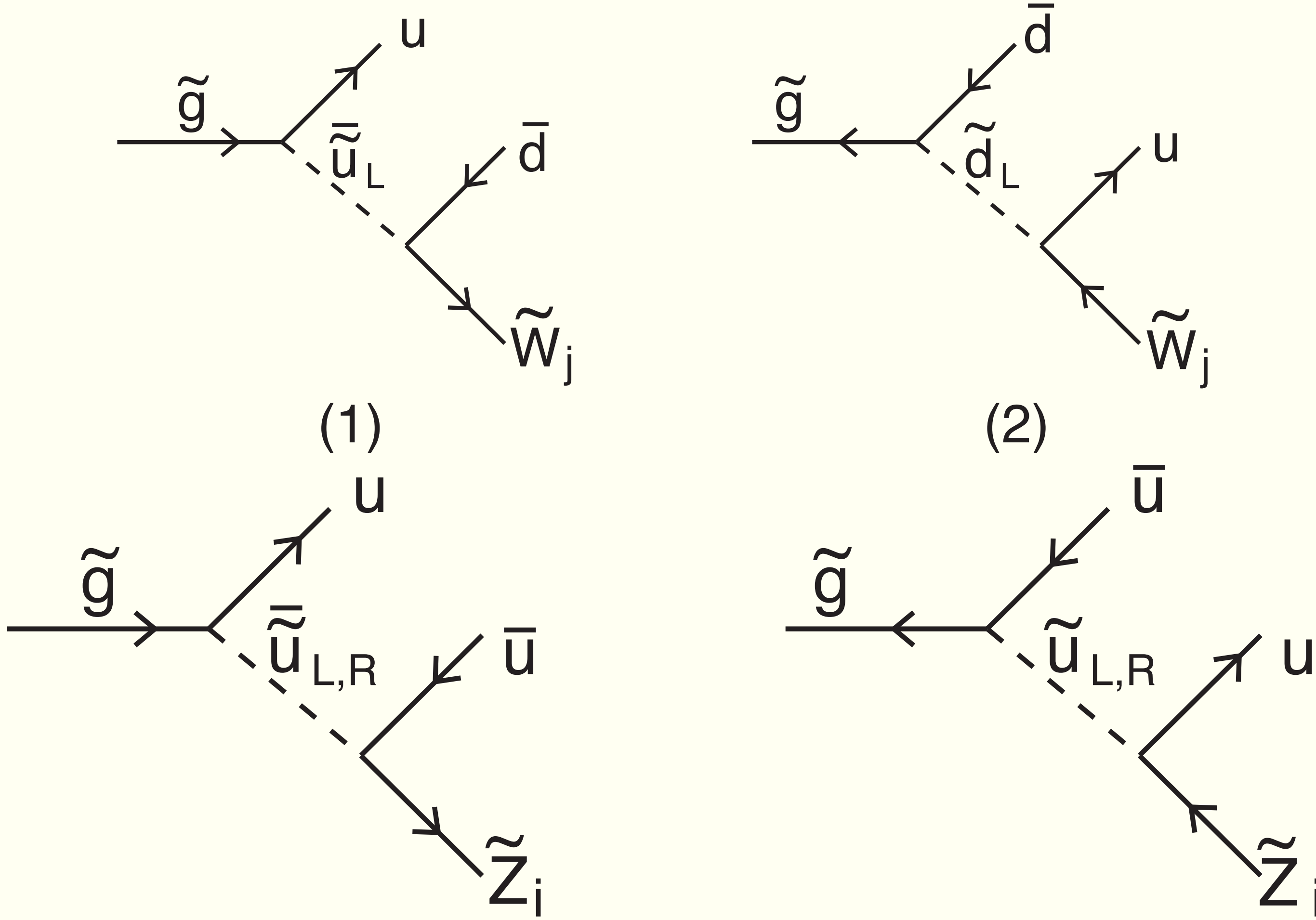
Production at Tevatron



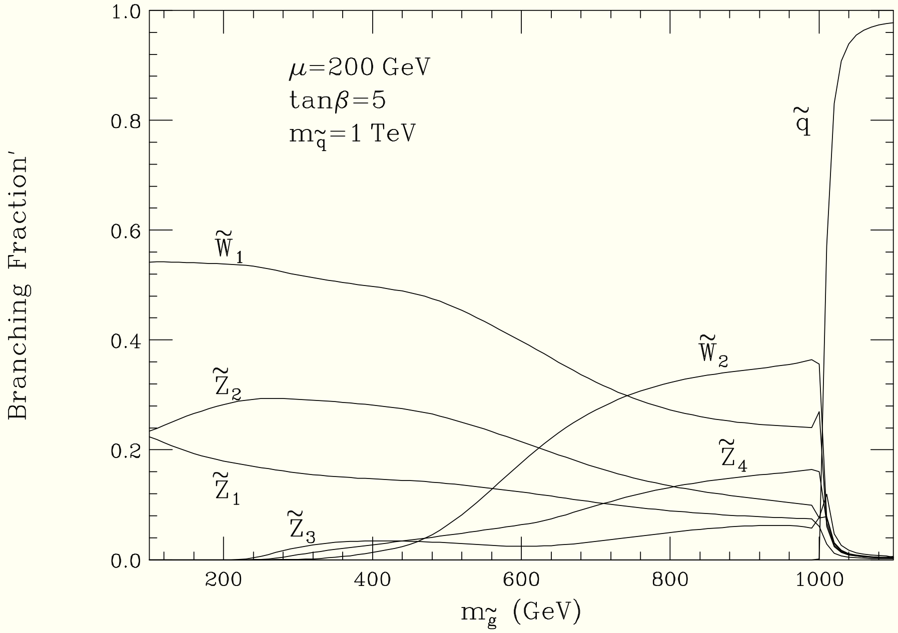
Production at LHC

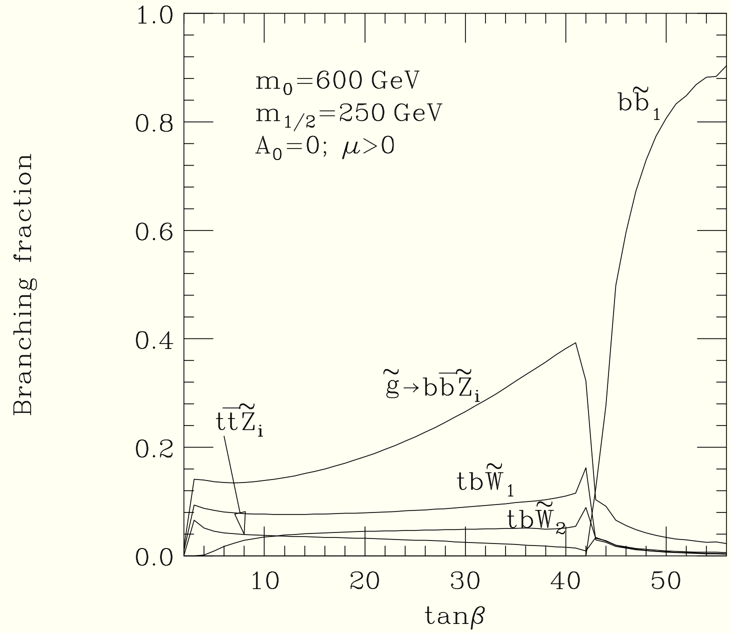


Gluino decays: $\tilde{g} \to q\tilde{q}$ or 3-body



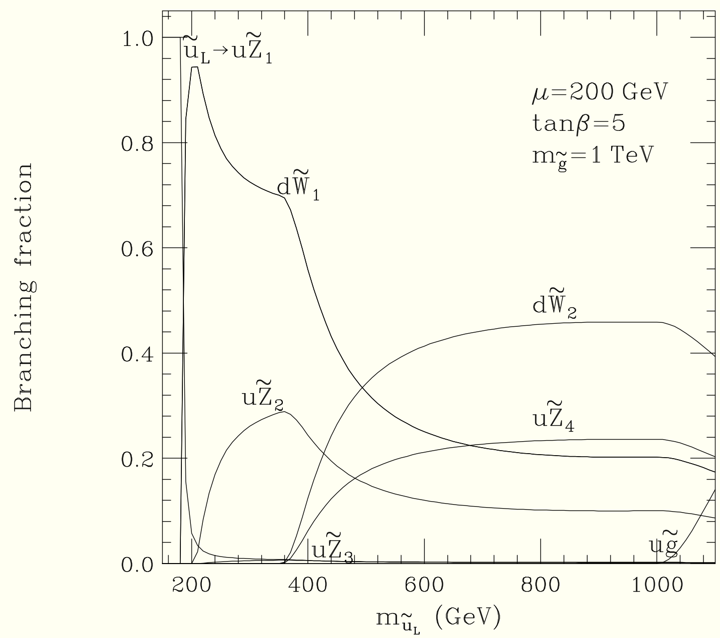
Gluino decays: branching fractions

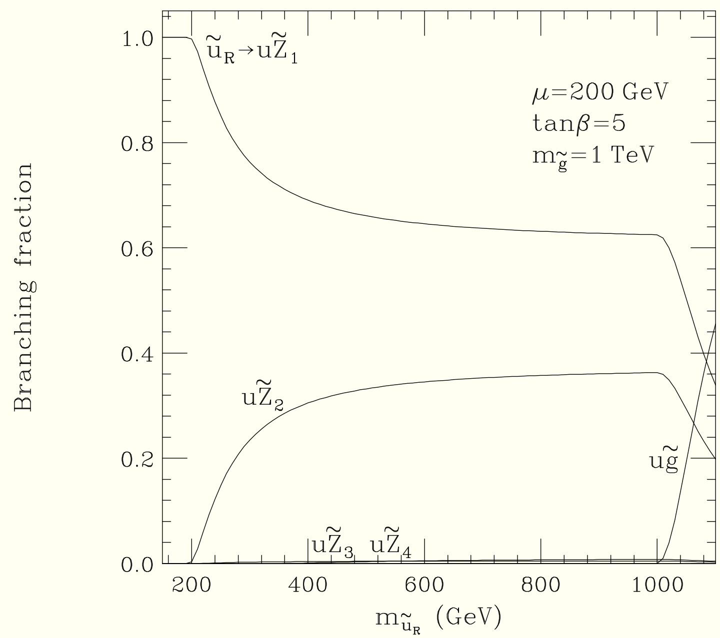




Squark decays

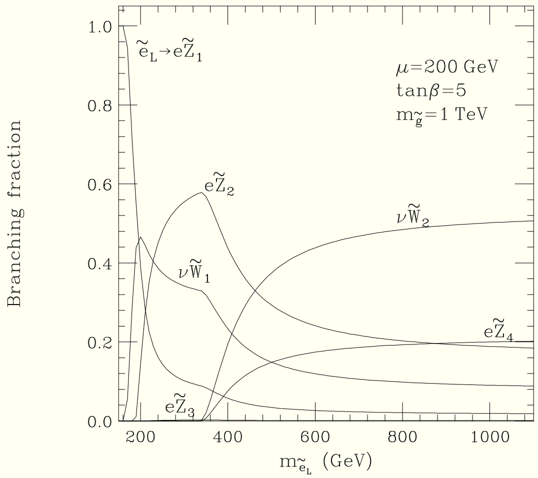
$$\begin{aligned}
\tilde{u}_L &\rightarrow u\widetilde{Z}_i,\ d\widetilde{W}_j^+,\ u\tilde{g}, \\
\tilde{d}_L &\rightarrow d\widetilde{Z}_i,\ u\widetilde{W}_j^-,\ d\tilde{g}, \\
\tilde{u}_R &\rightarrow u\widetilde{Z}_i,\ u\tilde{g}, \\
\tilde{d}_R &\rightarrow d\widetilde{Z}_i,\ d\tilde{g}.
\end{aligned}$$

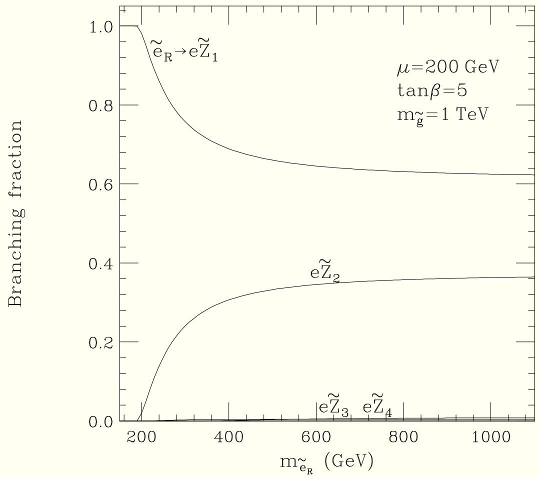


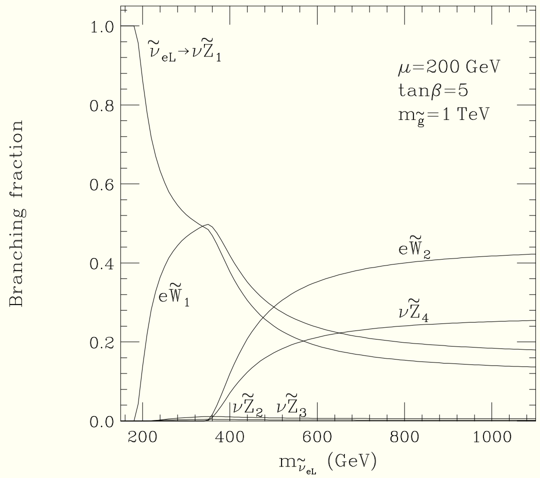


Slepton decays

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





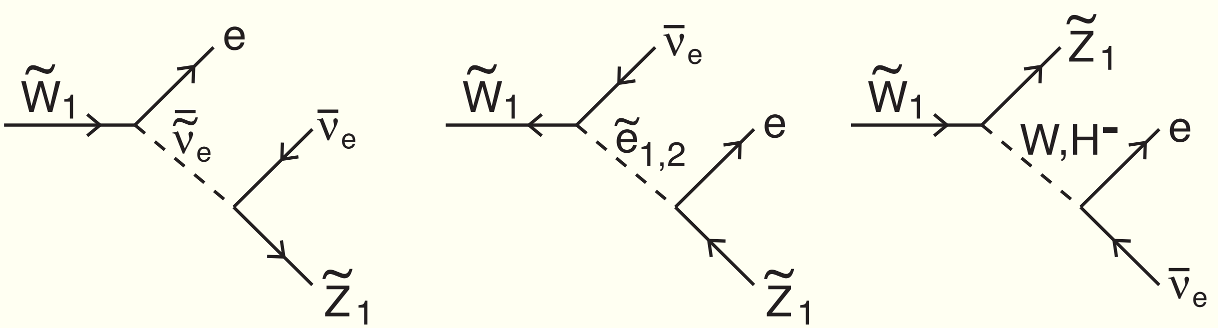


Chargino decays

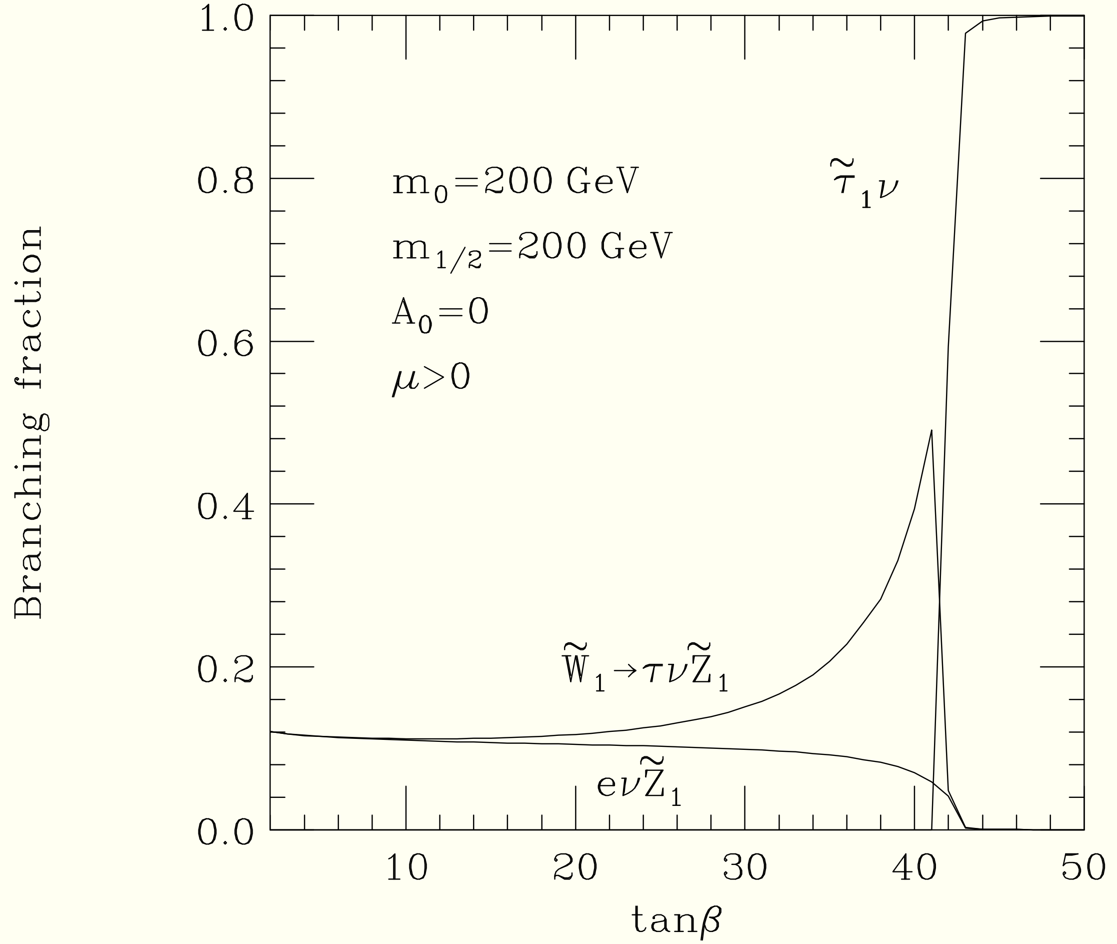
$$
\begin{aligned}
\widetilde{W}_j &\rightarrow W\widetilde{Z}_i,\ H^-\widetilde{Z}_i, \\
&\rightarrow \tilde{u}_L\bar{d},\ \bar{\tilde{d}}_L u,\ \tilde{c}_L\bar{s},\ \bar{\tilde{s}}_L c,\ \tilde{t}_{1,2}\bar{b},\ \tilde{b}_{1,2}t, \\
&\rightarrow \tilde{\nu}_e\bar{e},\ \bar{\tilde{e}}_L\nu_e,\ \tilde{\nu}_\mu\bar{\mu},\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

Charginos may decay to a lighter neutralino via

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



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

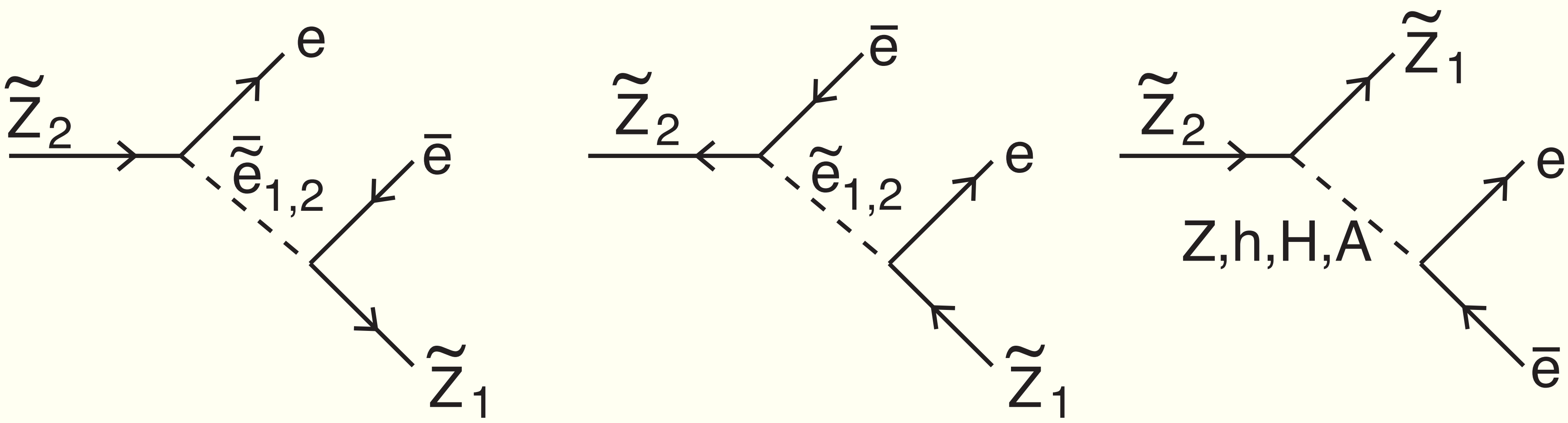


Neutralino decays

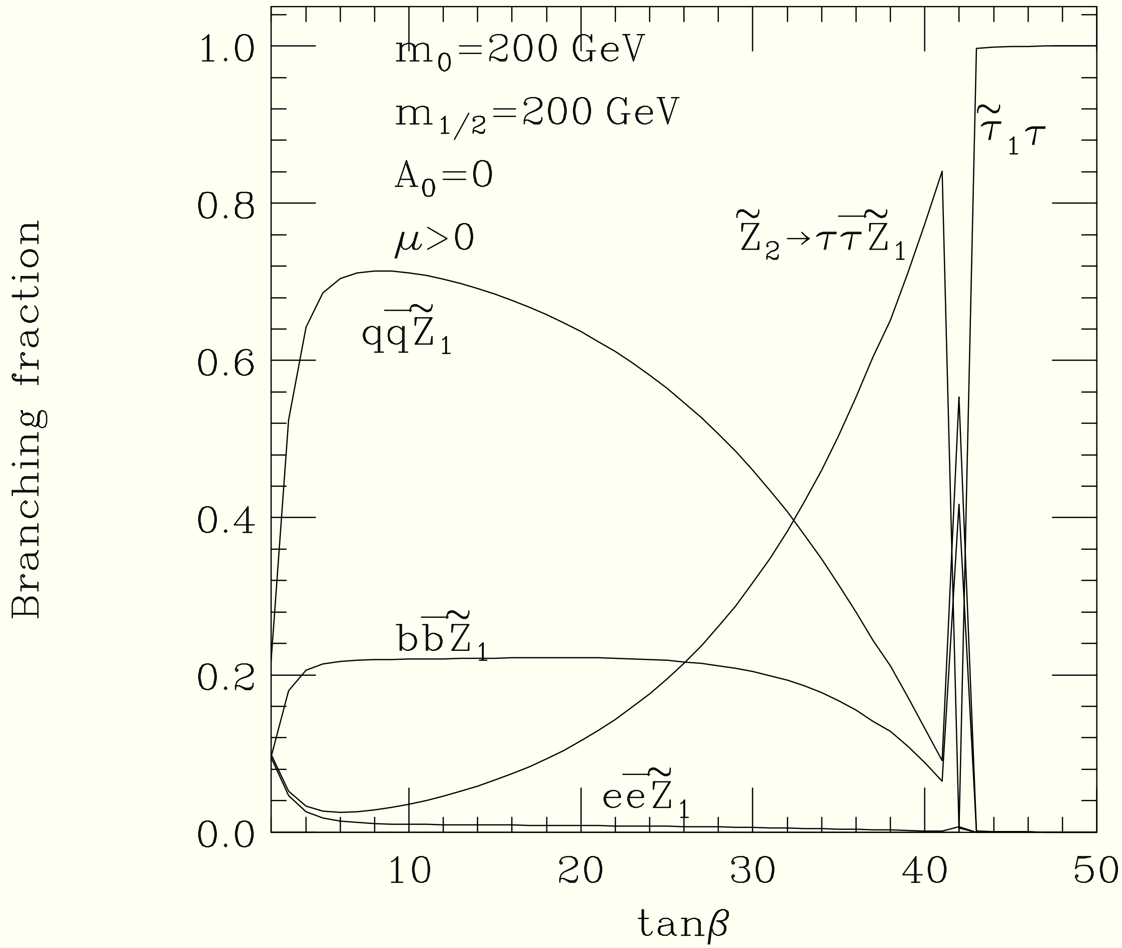
$$\begin{aligned}\widetilde{Z}_i &\to W\widetilde{W}_j,\ H^-\widetilde{W}_j,\ Z\widetilde{Z}_{i'},\ h\widetilde{Z}_{i'},\ H\widetilde{Z}_{i'},\ A\widetilde{Z}_{i'}\\ &\to \tilde{q}_{L,R}\bar{q},\ \bar{\tilde{q}}_{L,R}q,\ \tilde{\ell}_{L,R}\bar{\ell},\ \bar{\tilde{\ell}}_{L,R}\ell,\ \tilde{\nu}_\ell\bar{\nu}_\ell,\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

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

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



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

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

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?

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

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

Decays to gravitino or axino?

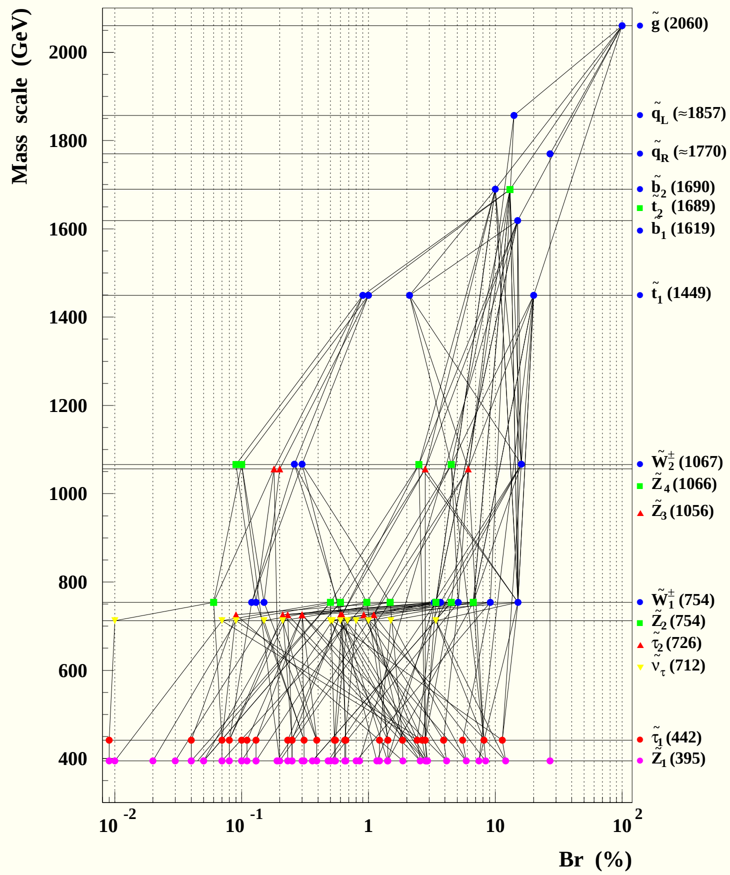
- $\widetilde{Z}_1 \to \gamma\tilde{G}$
- $\widetilde{Z}_1 \to \tilde{G} + (h,\ H,\ A$ or $Z)$
- $\tilde{f} \to f\tilde{G}$

Couplings can be extracted from SUGRA Lagrangian:

see *e.g. Weak Scale Supersymmetry*

- $\widetilde{Z}_1 \to \tilde{a} + \gamma$
- See e.g. Covi, Kim, Kim and Roszkowski, JHEP0105, 033 (2001)

Sparticle cascade decays

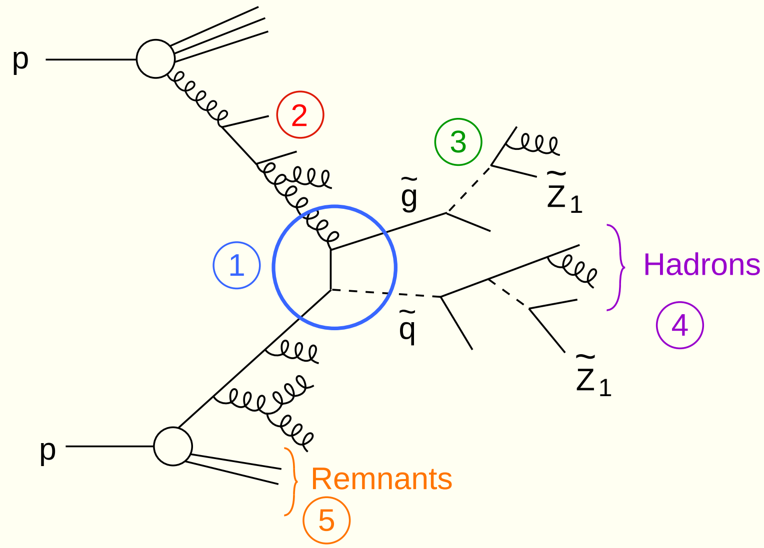


$\tilde{Z}_1$ qq	(27.0 %)	$\tilde{Z}_1$ $\tau\nu$WWWbb	(4.1 %)
$\tilde{Z}_1$ $\tau\nu$Wbb	(12.1 %)	$\tilde{Z}_1$ $\tau\tau$bb	(2.9 %)
$\tilde{Z}_1$ $\tau\tau$WWbb	(8.4 %)	$\tilde{Z}_1$ $\tau\tau$qq	(2.9 %)
$\tilde{Z}_1$ WWbb	(7.4 %)	$\tilde{Z}_1$ $\tau\nu$ZWbb	(2.8 %)
$\tilde{Z}_1$ $\tau\nu$qq	(5.9 %)	$\tilde{Z}_1$ $\tau\nu$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:
  - $\sim 1000 \times 10 \times 10 \sim 10^5$
  - 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, Spin corr.!

⋆ SUSYGEN (Ghodbane, Katsanevas, Morawitz, Perez)

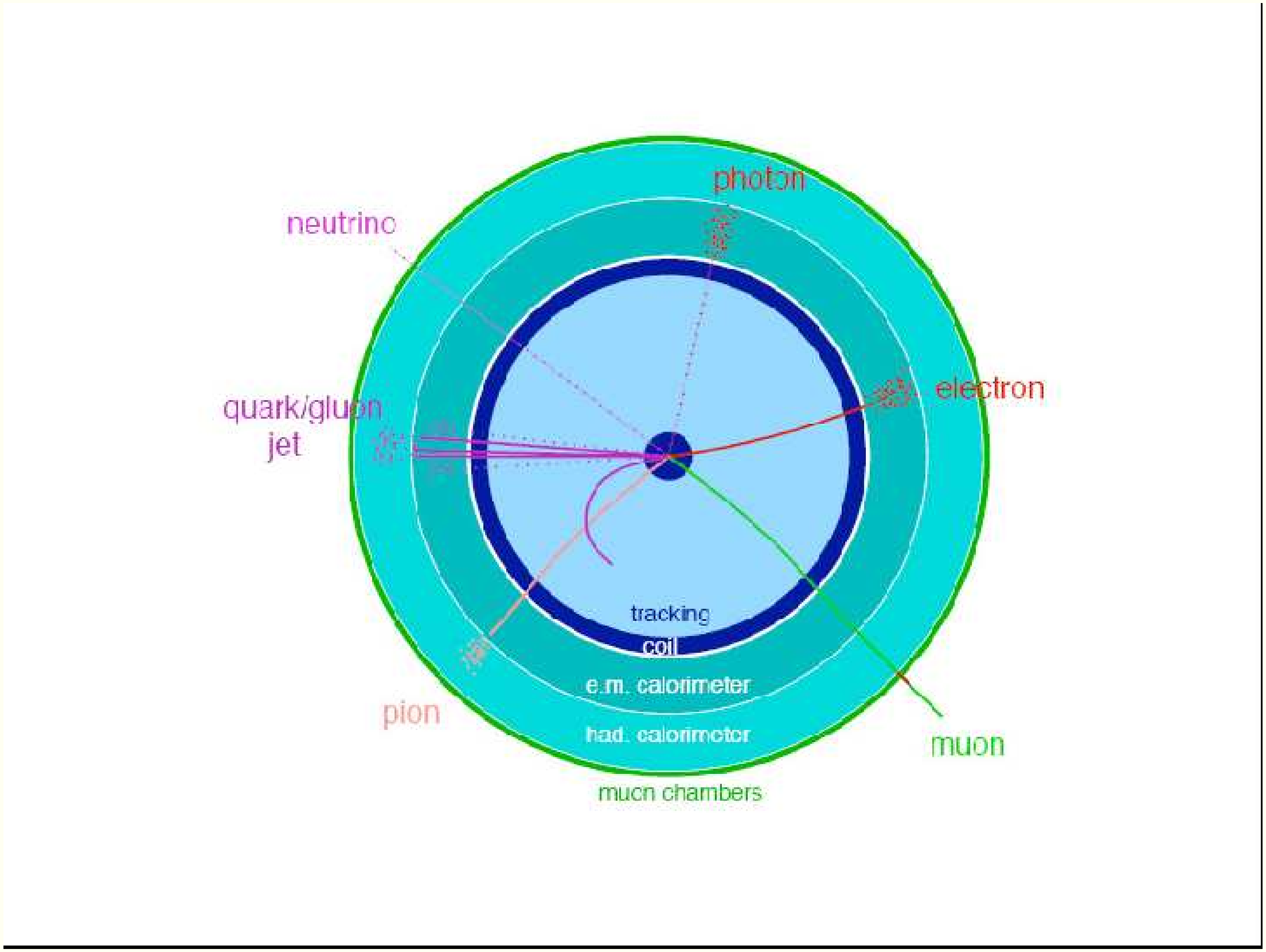
- mainly for e^+e^-; interfaces to Pytha

⋆ SHERPA (Gleisberg, Hoche, krauss, Schalicke, Schumann, Winter)

- $C++$ code for various $2 \to n$ processes

⋆ CompHEP, CalcHEP, Madgraph: for automatic Feynman diagram evaluation: interface via LHA

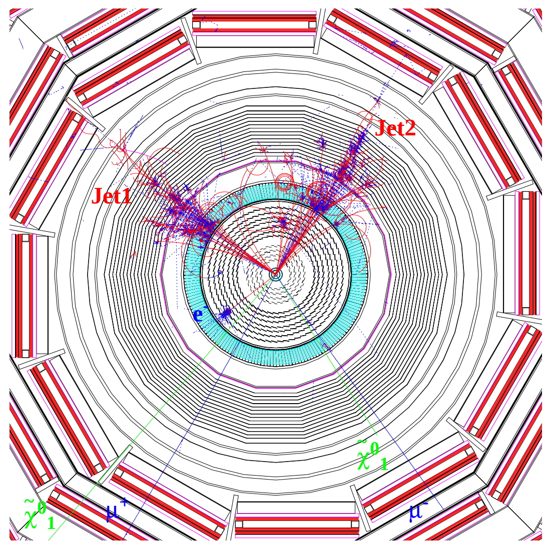
Briefly: particle interactions with detector



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:	Jets:	Sparticles:
$p_t(\mu^+) = 55.2$ GeV	E_t(Jet1) = 237 GeV	$p_t(\tilde{\chi}^0_1) = 95.1$ GeV
$p_t(\mu^-) = 44.3$ GeV	E_t(Jet2) = 339 GeV	$p_t(\tilde{\chi}^0_1) = 190$ GeV
$p_t(e^-) = 43.9$ 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 $m_{\tilde{g},\tilde{q}} \stackrel{<}{\sim} 1$ 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