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 ATLAS experiment
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 $c + d$. 
The fundamental calculable object in QM is the amplitude $M$ for a process to occur.

A pictorial representation of $M$ 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 $M$ is sum of all different ways a process can occur.

$M$ is a complex number; $|M|^2$ 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

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

- 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

\( d \rightarrow w^- \tilde{\chi}_j \)

\( \bar{u} \rightarrow \tilde{\chi}_j \tilde{w}_1^- \) (1)

\( d \rightarrow \tilde{\chi}_j \tilde{d}_L \)

\( \bar{u} \rightarrow \tilde{\chi}_j \tilde{w}_1^- \) (2)

\( d \rightarrow \tilde{\chi}_j \tilde{u}_L \)

\( \bar{u} \rightarrow \tilde{\chi}_j \tilde{w}_1^- \) (3)

\[ \sqrt{s} = 14 \text{ TeV} \]

\[ \mu = m_{\tilde{g}} = m_{\tilde{g}} \]

CTEQ5L PDFs

\[ m_{\tilde{g}} \text{ (GeV)} \]
Neutralino pair production

$q \rightarrow \tilde{z}_i 
\tilde{z}_j \rightarrow q L, R
\bar{q} \rightarrow \tilde{z}_j 
\bar{q} \rightarrow \tilde{z}_i$
Slepton pair production

\[ \begin{align*}
q & \rightarrow \gamma, z, \tilde{\ell}_{L,R} \\
\bar{q} & \rightarrow \tilde{\ell}_{L,R} \\
n & \rightarrow \tilde{\nu}_L \\
\bar{n} & \rightarrow \tilde{\nu}_L \\
n & \rightarrow \tilde{\tau}_1 \\
\bar{n} & \rightarrow \tilde{\tau}_2 \\
n & \rightarrow d, w^-, \tilde{\ell}_L \\
\bar{n} & \rightarrow \bar{u}, \tilde{\nu}_L
\end{align*} \]
Slepton pair cross section

$\sqrt{s} = 2$ TeV

$\sqrt{s} = 14$ TeV

$\sigma_{N0}$ (pb)

$m_\tau$ (GeV)
Gluino pair production

\[ g \rightarrow \tilde{g} \rightarrow g \]

\[ q \rightarrow \tilde{g} \rightarrow q \]

\[ \bar{q} \rightarrow \tilde{g} \rightarrow \bar{q} \]

\[ a) \]

\[ b) \]
Squark pair production

\[ q \rightarrow \tilde{q} \quad q^\prime \rightarrow \tilde{q}^\prime \]
\[ q \rightarrow \tilde{g} \quad \tilde{q} \rightarrow q^\prime \]
\[ q^\prime \rightarrow \tilde{g} \quad \tilde{q}^\prime \rightarrow q \]

(a)

\[ q \rightarrow \tilde{q} \quad g \rightarrow \tilde{g} \quad \tilde{q} \rightarrow q \]
\[ q \rightarrow \tilde{g} \quad g \rightarrow \tilde{q} \quad \tilde{q} \rightarrow q \]

(b)

\[ q \rightarrow \tilde{q} \quad g \rightarrow \tilde{q} \quad \tilde{q} \rightarrow q \]
\[ q \rightarrow \tilde{q} \quad g \rightarrow \tilde{q} \quad \tilde{q} \rightarrow q \]
\[ q \rightarrow g \quad \tilde{q} \rightarrow \tilde{q}^\prime \]

(c)
Gluino-squark associated production

\[
\begin{align*}
q & \rightarrow \tilde{g} \rightarrow q \\
\tilde{g} & \rightarrow \tilde{q} \rightarrow q \\
\end{align*}
\]
Gluino and squark pair production

\[ \sqrt{s} = 14 \text{ TeV} \]
\[ \mu = +m_{\tilde{g}} = m_{\tilde{q}} \]
CTEQ5L PDFs

\[ \sigma \text{ (fb)} \]

\[ m_{\tilde{g}} \text{ (GeV)} \]

Diagram showing the production cross-section for gluino and squark pair production with different masses and couplings, with annotations for \( \tilde{g}\tilde{q} \), \( \tilde{q}\tilde{q} \), and \( \tilde{g}\tilde{g} \) interactions.
ino-gluino associated production

\[ q \rightarrow \tilde{z}_i \rightarrow g \quad \bar{q} \rightarrow \tilde{g} \]

\[ q \rightarrow \tilde{q} \rightarrow \tilde{d}_L \rightarrow \bar{u} \rightarrow \tilde{w}_i \]

\[ q \rightarrow \tilde{q} \rightarrow \tilde{g} \rightarrow \bar{u} \rightarrow \tilde{w}_i \]

\[ d \rightarrow \tilde{g} \rightarrow \bar{u} \rightarrow \tilde{w}_i \]
μ = m_{\bar{g}} = m_{\tilde{g}}
CTEQ5L PDFs
\sqrt{s} = 14 \text{ TeV}
-ino-squark associated production
Production at LHC

$\sigma (fb)$ vs $m_g (GeV)$

Graph a) $m_{\tilde{q}} = m_g$  
$tan\beta = 3$  
$\mu = m_g$  
CTEQ5L PDFs  
$\sqrt{s} = 14$ TeV

Graph b) $m_{\tilde{q}} = 2m_g$

$\tilde{g}\tilde{g} + \tilde{g}\tilde{q} + \tilde{q}\tilde{q}$
Gluino decays: $\tilde{g} \rightarrow q\bar{q}$ or 3-body

(1) $\tilde{g} \rightarrow \tilde{u}_L \tilde{d} \tilde{W}_j$

(2) $\tilde{g} \rightarrow \tilde{d}_L \tilde{u} \tilde{W}_j$

$\tilde{g} \rightarrow \tilde{u}_{L,R} \tilde{u} \tilde{Z}_i$

$\tilde{g} \rightarrow \tilde{u}_{L,R} u \tilde{Z}_i$
Gluino decays: branching fractions

For $\mu=200$ GeV
$\tan\beta=5$
$m_{\tilde{q}}=1$ TeV

$m_0=600$ GeV
$m_{1/2}=250$ GeV
$A_0=0; \mu>0$

Howie Baer, TASI 2008: Sparticle production, decay, event gen., June 17, 2008
Squark decays

\[ \tilde{u}_L \rightarrow u\tilde{Z}_i, \ d\tilde{W}_j^+, \ u\tilde{g}, \]
\[ \tilde{d}_L \rightarrow d\tilde{Z}_i, \ u\tilde{W}_j^-, \ d\tilde{g}, \]
\[ \tilde{u}_R \rightarrow u\tilde{Z}_i, \ u\tilde{g}, \]
\[ \tilde{d}_R \rightarrow d\tilde{Z}_i, \ d\tilde{g}. \]
Slepton decays

\[ \tilde{e}_L \rightarrow e \tilde{Z}_i, \nu_e \tilde{W}_j^- , \]
\[ \tilde{\nu}_e \rightarrow \nu_e \tilde{Z}_i, e \tilde{W}_j^+ , \]
\[ \tilde{e}_R \rightarrow e \tilde{Z}_i . \]
Charginos may decay to a lighter neutralino via

\[ \tilde{W}_j \rightarrow \tilde{Z}_i + f \tilde{f}', \]  

(1)
Decay of $\tilde{W}_1$ versus $\tan \beta$

- $m_0 = 200$ GeV
- $m_{1/2} = 200$ GeV
- $A_0 = 0$
- $\mu > 0$

Branching fraction

- $\tilde{W}_1 \rightarrow \tau \nu \tilde{Z}_1$
- $e \nu \tilde{Z}_1$

$tan \beta$

- $0.0$
- $0.2$
- $0.4$
- $0.6$
- $0.8$
- $1.0$
Neutralino decays

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

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

\[ \tilde{Z}_i \rightarrow \tilde{Z}_i' + f\bar{f} \] (2)
Decay of $\tilde{Z}_2$ versus $\tan \beta$

- $m_0 = 200$ GeV
- $m_{1/2} = 200$ GeV
- $A_0 = 0$
- $\mu > 0$

Branching fraction

$\tilde{Z}_2 \rightarrow \tau \tau \tilde{Z}_1$

$qq\tilde{Z}_1$

$b\bar{b}\tilde{Z}_1$

$ee\tilde{Z}_1$
Decays of SUSY Higgs boson $h$

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

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

Also

- $h \rightarrow Wf\bar{f}'/Zf\bar{f}$
- $h \rightarrow gg, \gamma\gamma, Z\gamma$
Decays of SUSY Higgs boson $H$

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

where $i, i' = 1 - 4$ and $j, j' = 1, 2$. 
Decays of SUSY Higgs boson $A$

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

where $i, i' = 1 - 4$ and $j, j' = 1, 2$. 
Decays of SUSY Higgs boson $H^+$

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

where $i, i' = 1 - 4$ and $j, j' = 1, 2$. 
• $t \rightarrow bW^+$
• $t \rightarrow bH^+$
• $t \rightarrow \tilde{t}_{1,2} \tilde{Z}_i$, $\tilde{b}_{1,2} \tilde{W}_j$

where $i = 1 - 4$ and $j = 1, 2$. 
Decays to gravitino or axino?

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

Couplings can be extracted from SUGRA Lagrangian:

see e.g. *Weak Scale Supersymmetry*

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

Mass scale (GeV) vs. $\text{Br}$ (%)

- $\tilde{g}$ (2060)
- $\tilde{q}^+_L$ (~1857)
- $\tilde{b}^+_L$ (~1770)
- $\tilde{t}^+_L$ (1697)
- $\tilde{b}^+_R$ (~1619)
- $\tilde{t}^+_R$ (1449)
- $W^+\tilde{q}$ (~1067)
- $Z\tilde{q}$ (1056)
- $Z\tilde{t}$ (1056)
- $Z\tilde{b}$ (1056)
- $Z\tilde{t}$ (1056)
- $Z\tilde{b}$ (1056)
- $Z\tilde{t}$ (1056)
- $Z\tilde{b}$ (1056)

Branching ratios:
- $\tilde{Z}_{qq}$ (27.8 %)
- $\tilde{Z}_{τ\nu\nu}$ (12.1 %)
- $\tilde{Z}_{ττ\nu}$ (8.4 %)
- $\tilde{Z}_{W\nu\nu}$ (7.4 %)
- $\tilde{Z}_{τ\nu\nu}$ (5.9 %)

Howie Baer, TASI 2008: Sparticle production, decay, event gen., June 17, 2008
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 $2 \rightarrow n$ 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 in LL - QCD

1) Hard scattering / convolution with PDFs
2) Initial / 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 Pythia

★ SHERPA (Gleisberg, Hoche, krauss, Schalicie, Schumann, Winter)
  - $C++$ code for various $2 \rightarrow n$ processes

★ CompHEP, CalcHEP, Madgraph: for automatic Feynman diagram evaluation: interface via LHA
Briefly: particle interactions with detector
SUSY event with 3 lepton + 2 Jets signature

- $m_0 = 100$ GeV, $m_{1/2} = 300$ GeV, $\tan\beta = 2$, $A_0 = 0$, $\mu < 0$,
- $m(q) = 686$ 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
- $p_T(\tau^-) = 43.9$ 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+$E_T$

★ 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