LHC Introduction, General Experimental Considerations, and Model-Independent Searches for SUSY

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Outline

- LHC and CMS/ATLAS
- Preparations for early data taking
- MSSM SUSY searches and mass reach
- New Monte Carlo tools
- Cosmology and SUSY
- Generalized SUSY search
What and Where is CERN, LHC, CMS?

European Center for Nuclear Research (CERN)

Large Hadron Collider (LHC) – 14 TeV, 100 fb⁻¹/year at design L
25 nsec bx, 40 MHz
1 GHz (25 int/bx)

Compact Muon Solenoid (CMS). 3 GJ magnet.
Calorimetry inside.
All silicon tracker (high rates)
PbWO4 crystals (precision ECAL)

Major Step in energy and L
Cooled down. Insert HCAL late March. Plan is for a pilot run in late 2007 with first physics run in 2008 (1 fb⁻¹).
An initial set of calibration constants for HCAL - exists based on test beams in 2004 and radioactive sources. Good to ~ 5%. Similar for ECAL, using cosmic ray muons and sources.
**CMS HCAL: Cosmic Rays at SX5**

1) time shift of \( \frac{1}{2} \) bin due to transit time of cosmic ray.

40 MHz clock
Muon Endcap - Status

- Endcap installation finished
- Pre-operations ongoing
- Get initial alignment using cosmic rays.
- Check for movement during full power magnet test in 2006 on the surface.
Already running multiple coincidences between muon planes to get initial relative alignment.
Si Tracker - Testing at CERN

200 m² of Si strips and 65 Million pixels. Assembly and commissioning complete by the end of CY2006. Installation then prior to first collisions.
The LHC is a discovery machine. Therefore we must be ready on “day one” using pre-calibrations (test beams) and commissioning, e.g. “slice tests” with cosmics. Clearly see enormous increase in mass range at the LHC. Will be in “terra incognita” with dijets very soon. Must establish SM cross sections, resolutions, angular distributions, and mass scales for dijets, W, Z and top, otherwise a search result is just not credible.

(100 pb/GeV) (400 GeV) = 40 nb, 4 Hz at 1% of design L beyond Tevatron kinematic limit
V. Buscher – Run II at CDF and D0 shows that with all the preparation it still will be hard. Try to use top pairs as a benchmark. Top samples will have jets, leptons and MET. Need to establish MET before searching for SUSY.
Standard Z Candle?

Use $Z \rightarrow \mu + \mu$ as second “standard candle” ($W$ is the first) to determine the LHC luminosity.

Expect ~ (2-5)% accuracy in cross section prediction.

The cross section for $Z \rightarrow \mu + \mu$ decay with $|y| < 2.5 \times Pt > 15$ GeV is ~ 600 pb at the LHC. This is 6 Hz at design luminosity.
Use data to establish lepton momentum scale and resolution. Look at high mass isolated dileptons to assess backgrounds. Tevatron limit of ~ 500 GeV in tail. No evidence of F/B asymmetry which deviates from SM. If Z', then $A_{FB} \rightarrow \sim 0$. Also use dilepton data to evaluate irreducible contributions to MET in Z + jets events.
Muons should be the cleanest signal at the LHC:
Momentum in tracker * momentum in muon chambers * match in \((\theta, \phi)\)

Multiple redundant measurements for rare processes. Find the Higgs in a (10-100) fb\(^{-1}\) exposure.
Why SUSY?

- GUT Mass scale - unification works with SUSY
- Improved Weinberg angle prediction
- \( p \) decay rate slowed consistent with present limits.
- Mass hierarchy protected Planck/EW
- Dark matter candidate
- String connections, gravity.

MSSM has ~ SM light \( h \) and ~ mass degenerate \( H, A \). LSP is a neutralino. Squarks and gluinos are heavy, sleptons are light.
The SUSY cross sections for squarks and gluinos are large because they have strong couplings. R parity means cascade decays to LSP. Simplest signature is jets and MET, independent of specific SUSY model.

Dimensionally

\[ \sigma \sim \alpha_s^2/(2M)^2 \]

or \( \sim 1 \text{ pb} \) for \( M = 1 \text{ TeV} \).
SUSY Signatures

The gluino pair production cascade decays to jets + leptons + missing Et. Gluino is a Majoran, like sign ~ same sign for dileptons

The gaugino pairs cascade decay to missing Et + 3 leptons which is a very clean signature, but with smaller cross section
Use SUSY cascades to the stable LSP to sort out the new spectroscopy.

Decay chain used is:

\[
\tilde{\ell}^{+-} \rightarrow \tilde{\chi}^0_1 + \ell^{+-}
\]

\[
\tilde{\chi}^0_2 \rightarrow \tilde{\ell}^+ + \ell^-
\]

\[
\tilde{b} \rightarrow \tilde{\chi}^0_2 + b
\]

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

Final state is

\[
b + b + \ell^- + \ell^+ + \tilde{\chi}^0_1
\]
SUSY Reconstruction

\[ \tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 + \ell^+ + \ell^- \quad \tilde{b} \rightarrow \tilde{\chi}_2^0 + b \quad \tilde{g} \rightarrow \tilde{b} + b \]

Mass of \( \tilde{\chi}_1^0 \) from MET, then others from observed decay products. Earliest searches are with jets + MET, semi-inclusive. Here use dilepton end point? Note plots are for 1 year at 10% of design luminosity.
SUSY – Mass “Reach”

1 month at 1/10 design luminosity, or first physics run in 2008 covers > 1 TeV gluino mass.

SUSY discovery could happen quickly.

WMAP
C.M. energy is the most important variable for SUSY discovery searches over most of the MSSM parameter space. However, fully understanding the discovery will be difficult as will be discussed.

HB, Belyaev, Krupovnickas, Tata: JHEP 0402, 007 (2004)
Searches for recoils in LSP + Nucleus scattering. Synergy with LHC searches with accelerator produced dark matter.
LHC mass vs recoil cross section (SCDMS). LHC Mass determined from LSP MET and cascade decay products. Direct search recoil data measures mass from recoil energy $E_{\text{recoil}}$

$$< E_{\text{recoil}} > \sim 2v^2 M /[1 + M / M_\chi]^2$$

But you must know the velocity and density of the LSP. Indirect searches?
New Monte Carlo Tools

New tools – hard explicit extra jets with matches at low Et to showering MC. Background estimates, e.g. Z + Js, in SM rise a lot and SM shapes now mimic the harder SUSY shapes.

Becomes a “counting experiment”. Must then have normalization systematics under very good control.

S. Asai and T, Sasaki – TeV4LHC

Jet + MET

Effective Mass(GeV) = m_{\tilde{g}, \tilde{q}} + \Sigma P_T(4jets)
Lepton(s) + Jet + MET

Too much SM background in Jets + MET. Go to lepton(s) + Jets + MET. Top is still a major background along with W + jets and Z + jets. Need to understand leptons well (Z as standard candle – and DY tail). Note that di leptons in gluino decays are 50% like sign because gluino is a Majoran. Thus asking for like sign dileptons improves sensitivity, with reduced rate.
At lower cross section there are more spectacular topologies, such as MET + 3 leptons or MET + 2 jets + 2 leptons. If you see an enhancement above the SM is it MSSM SUSY?
LEP2 Higgs

$g-2$

WMAP (LSP is dark matter)

LSP is neutral

$b \rightarrow s + \gamma$

$B_s \rightarrow \mu^+ \mu^-$

Taken at face value, the MSSM is excluded for almost all values of the parameters. "SUSY" is more complex than the MSSM?
The universe is flat and composed largely of dark energy (75%) and dark matter (25%). What are they? We understand only about 5% of the Universe by weight. Assume that DM is a fact and that some form of SUSY with R parity is the most likely thermal relic candidate.
Dark Matter and SUSY

\[ \frac{dY}{dx} = -x <\sigma_A \nu > s[Y^2 - Y_{EQ}^2] \]

\[ Y = n/s, \quad x = M/T, \quad Y_{EQ} \big|_{NR} \sim x^{3/2} e^{-x} \]

\[ \Gamma_A(T_F) \sim H(T_F) \]

\[ \sigma_A \sim \alpha_w^2/2M_W^2[y/(1+y)^2] \]

\[ y = s/M_W^2 \]

\[ q + \bar{q} \rightarrow \tilde{\chi}_1^0 + \tilde{\chi}_1^0 \]

Boltzmann Eq.
Freezout of relic when annihilation rate \( \sim \) expansion rate.

Neutralino annihilation rate into quark pairs. A weakly interacting particle with a mass \((100, 1000)\) GeV has the correct relic density to be dark matter. Thus DM (lensing, rotation curves), plus cosmology (thermal relic) implies a weakly interacting, TeV scale stable (R parity) object. Can we be more incisive? What is the thermally averaged annihilation cross section times velocity?
The annihilations have many branches which makes exact calculations impossible given the plethora of SUSY parameters. Limited parameter space in MSSM SUSY if the LSP neutralino is a mixture dominated by Higgsino. In general not sharply constrained in mass.

Edsjo and Gondolo, hep-ph/9704361
DM gives confidence that SUSY search at LHC is crucial and should be generalized. Assume non-universal gaugino masses, M1, M2, M3. Evade the constraints on the MSSM. (H. Baer). Implies a “model independent” search for SUSY signals using Jets + MET + leptons. Experimentally it is best to look at the simplest final states arising from cascades to LSP, but leptons appear to be needed to improve S/B ratios.
All BSM Looks Alike (J. Lykken)

Same signature – Jets + MET + lepton(s)

Difficult to distinguish SUSY from UED or little Higgs, or ..... (spin?)
The LHC experiments – ATLAS and CMS - are preparing for the 2007 “pilot” and the early 2008 physics runs.

It is critical to be prepared for discoveries at the LHC – “day 1” occurs at the pb level in cross section. M signals.

The LHC provides a greatly enhanced SUSY reach.

Given the MSSM constraints, and guided by DM it is best to look for “generic” SUSY where cascades to LSP imply jets + lepton(s) + MET final states. Leptons are necessary to enhance S/B ratios.

Exploring the spectroscopy will be difficult.

Data will make us smarter……..
What can colliders say about DM?

The missing energy signature

Models of EWSB \(\rightarrow\) predicts new heavy QCD interacting particles

Jets + leptons + \(E_T\) at hadron colliders

• It is likely that the LHC will find evidence of DM, but it is unlikely that we will be able to reveal the precise identity of the WIMP (spin, quantum numbers)

• The ILC via angular distributions and threshold shape of the reaction can give information of the underlying theory.
Cosmological Higgs?

\[ V(<\phi>) = \lambda <\phi>^4 \]
\[ \rho_c = \frac{3H_o^2}{8\pi G_N} \]
\[ ratio \sim 10^{56} \]

or

\[ <\phi> = 174 \text{ GeV}, \rho_c^{1/4} = 3 \text{ meV} \]
\[ ratio \sim 10^{13} \]

Spectacular mismatch in estimates/measurements of dark energy. Why is the Higgs field not gravitationally effective?

Only comparable HEP scale is solar neutrino oscillation, mass \( \sim 9 \) meV.