Low Missing Energy and New Physics: To Miss or Not To Miss

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May 1, 2012

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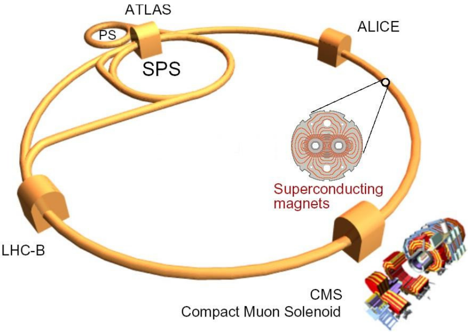
- *But it is important to look for signals with low MET as well, and perhaps without compromise on the dark matter issue*
- *Distinguishing among various scenarios: a challenge*
- *Useful signals to study at the LHC: same-sign tri-and four-leptons*

The LHC...



$$p \Rightarrow \Leftarrow p$$
$$7/8/14 \text{ TeV}$$

Goals of the LHC....

- To discover the Higgs boson and complete the Standard Model of electroweak interactions
- To know more about top and bottom quark properties
- To understand strong interaction better
- To look for quark-gluon plasma
- *Physics beyond the standard electroweak theory*

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- **Higgs mass range narrowed down, with some tantalising but inconclusive hints....**
- **The theory of weak + electromagnetic interactions is almost certainly the proposed $SU(2) \times U(1)$ gauge theory, but the origin of masses not yet certain**
- **The search for new physics is on, mostly accepting the 'Higgs lore', but no positive evidence yet**

BUT....

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- **Why do we think there should be** *new physics* **?**
- **Why should new laws be manifest at the LHC energy ?**

Phenomenological dissatisfactions(unexplained features):

- **Large number of unrelated free parameters**
- **Replication of fermion families**
- **The pattern of fermion masses**
- **Maximal P but small CP violation**

Theoretical/Philosophical questions:

- **No way to unify with strong interaction**
- **No clue on a quantum theory of gravity**
- *Divergent higher-order contributions to the Higgs boson mass*

Sporadic/seasonal/volatile issues:

- **The muon anomalous magnetic moment (3 - 3.5 σ inconsistency)**
- **PAMELA (excess positrons $\sim$ 10 - 80 GeV from galactic halo)**
- **ATIC (excess galactic cosmic-ray electrons $\sim$ 300 -800 GeV)**
- **Tevatron multimuon events (excess multimuons, inexplicable from b-decays)**
- **Top quark forward-backward asymmetry at Tevatron**
- ***Wjj* events in the CDF experiment**

The Standard Model has inadequacies/puzzles...

Concrete and persistent problems:

- **Neutrino masses and mixing**
- **Cold dark matter**
  (no particle physics explanation)
- **Matter-antimatter asymmetry in the universe**
- **A positive cosmological constant (!)**

Effective energy scale to be probed at the LHC: $\simeq$ 1 -2 TeV

Out of the many motivations listed, which ones definitely suggest *'something new'* **at this energy?**

Why new physics at the TeV scale?

- **The issue of Grand Unification**
  (very indirect!)
- **To understand why the Higgs should be within a TeV**
  (relatively pressing!)
- **Finding a cold(warm?) dark matter candidate**
  (Somewhat imperative)

Thus the Dark matter issue is rather central to new physics search at the LHC

Events with large missing-E_T (MET) or resonances are the first to be looked for

Popular belief: dark matter candidates $\Rightarrow$ MET

Theories often proposed with a Z_2 symmetry to accommodate a stable particle (dark matter candidate)

A candidate theory: supersymmetry (SUSY) with R-parity ($R = (-)^{(3B+L+2S)}$)
A lot of progress has taken place in SUSY search— mSUGRA-based cMSSM ruled out upto $\simeq$ 850 GeV (with $4.7 fb^{-1}$)

There can be other Z_2-endowed scenarios: (Universal extra dimensions with KK parity, Little Higgs with T-parity)

Distinguishing among models with Z_2....

'Inverse problem' within SUSY— mapping from signature space to parameter space
Arkani-Hamed *et al.* (2006)
Larger number of observables studied
$\Rightarrow$ degeneracy in the parameter space better lifted

SUSY vs. other scenarios with large MET
General distinction strategies (LHC, dark matter search....):

A.K. Datta, G. Kane, M. Toharia (2005)
D. Hooper, G. Zaharijas (2006)
A. K Datta, P. Dey, S. Gupta, BM, A. Nyffeler (2007)
J. Hubisz *et al.* (2008)
M. Burns *et al.*, 2008
W. Ehrenfeld *et al.* (2009)
B. Bhattacharjee it et al. (2009)

But is is also important to remember that....

So long as large MET signals elude us,

One needs to think of scenarios where such Z_2 symmetry is broken

Some of the resulting theories may still accommodate dark matter candidates

Also, some scenarios with Z_2 still yield low MET

We need criteria to point towards them
and to discriminate among various low-MET scenarios in general

Examples....

(a) SUSY with R-parity violation (SUSY-RPV)
(b) Little Higgs theories with broken T-parity (LHT-TPV)
(c) Universal extra dimensions with conserved Kaluza-Klein parity (UED-KKC)
(d) Universal extra dimensions with Kaluza-Klein parity violated (UED-KKV)
(e) SUSY with a compressed spectrum

The present discussion includes cases (a) - (d)

The MSSM superpotential:
(source of interaction of all chiral $(f, \tilde{f})$ supermultiplets)
$W_{MSSM} = Y^{l}_{ij} L_i H_1 E^c_j + Y^{d}_{ij} Q_i H_1 D^c_j + Y^{u}_{ij} Q_i H_1 U^c_j$
(Assuming that baryon and lepton number are conserved)

When $R = (-)^{L+3B+2S}$ **violated via L or B, one can write**

$W = W_{MSSM} + W_{RPV}$**, with**
$W_{RPV} = \lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k + \epsilon_i L_i H_2 + \lambda''_{ijk} U^c_i D^c_j D^c_k$

We consider here L-violating W_{RPV} **:** $\lambda''_{ijk} = 0$

Offers mechanisms for neutrino mass generation

SUSY-RPV....

Most phenomenological studies: one type of R-parity violating coupling at a time

Result: the MSSM-LSP (say, the lightest neutralino) has two/three body decays with at least one lepton in the final state

The gravitino or the axino may be the dark matter candidate

The Higgs is the pesudo-goldstone boson of a broken approximate global symmetry

The breaking scale stabilises the electroweak scale

In a minimal (littlest) form, SU(5) $\rightarrow$ SO(5)
Underlying electroweak gauge group : $[SU(2) \times U(1)]^2$, with an exchange symmetry (T-parity) – a Z_2 symmetry (stabilises, for example, the m_W/m_Z ratio)

Result: a division into T-even (SM) and T-odd (new) particles
$[SU(2) \times U(1)]^2 \longrightarrow SU(2) \times U(1)$ **at scale** f
New particles include heavy T-odd fermions (Q_H, L_H), heavy gauge bosons (W_H, Z_H, A_h), a Higgs triplet......
The lightest T-odd particle (LTP) is stable: (Usually the A_H)

Z_2 **symmetry** $\Rightarrow$ **LTP is the dark matter candidate**
(A neutral, weakly interacting particle)
The spectrum and the interactions are controlled by
$f = \mathcal{O}(TeV)$, $f\kappa_{ij}$ = matrix deciding heavy fermion masses

But T-parity can be broken...
by Wess-Zumino-Witten anomaly terms
Results: terms $\sim \frac{N\ v^2}{48\pi^2 f^2}\epsilon_{\mu\nu\alpha\beta} V_H^\mu V^\nu \partial^\alpha V^\beta$
The LTP becomes unstable:
For example, $A_H \longrightarrow WW^{(*)}, ZZ^{(*)}$
leading to tree-level or loop-induced decays
such as $\ell\nu\ell\nu, \quad \ell\ell, \ldots$

At least one spacelike compact extra dimension, of radius R, where all fields can propagate

New particles are Kaluza-Klein towers, with same spin as in the zero-mode SM states

The extra dimension 'orbifolded' about the axis from $\phi = 0 - \pi$: a Z_2 symmetry (for ensuring proper fermion chiralities) $\Rightarrow$ A conserved 'Kaluza-Klein parity'

The lightest KK-odd particle (LKP) is stable due to the Z_2 symmetry: dark matter candidate (A neutral, weakly interacting particle): Usually the first excitation (A_1) of the photon

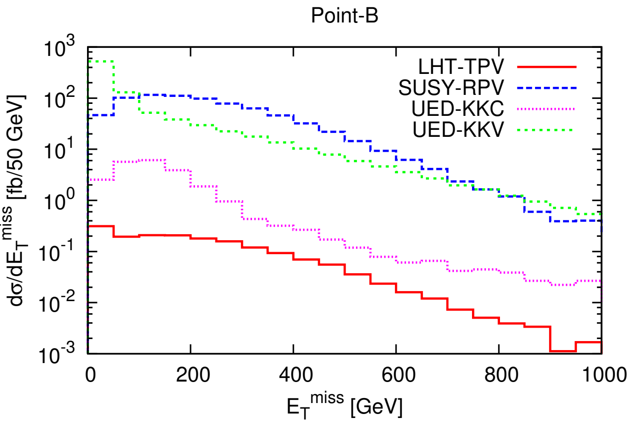
The spectrum is decided by R^{-1}, and the cut-off scale

A highly compressed spectrum in general

KK-parity can be broken by additional asymmetric operators at the orbifold fixed points
$\Rightarrow$ The LKP is again unstable

Claim: all of these four scenarios, including UED-KKC, can lead to similar MET signals at the LHC
How to distinguish?
K. Ghosh, S. Mukhopadhyay, BM (2010)

MET distributions for all four scenarios...



M_s = Strongly interacting particle mass $\simeq$ 1 TeV
SUSY-RPV: λ-type with one coupling

Distinguishing among the various scenarios...

Prescription: use multileptons $\ell = e, \mu$
Dileptons: limited discriminating power
Trileptons: sometimes effective, but....
four-and five-lepton final states can be useful discriminators

Isolated and central leptons, with
appropriate transverse momentum requirements

Sufficient statistics required for discrimination:
14 TeV run necessary
For M_s = 600 GeV, 5 fb^{-1} at 14 TeV is enough
For M_s = 1 TeV, 30 fb^{-1} is required for 5σ significance for all scenarios

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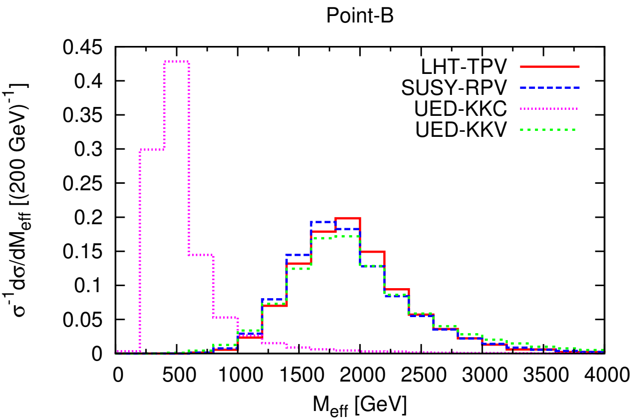


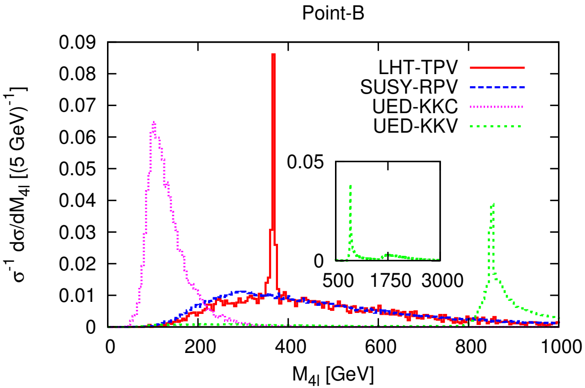
Effective mass distribution with $M_s = 1$ TeV: UED-KKC stands out

$(M_{eff} = \Sigma_i p_T^i + MET)$

Four-lepton invariant mass...

$M_{4l} = (p_{l_1} + p_{l_2} + p_{l_3} + p_{l_4})^2$
If the 4ℓ all come from one particle,
then M_{4l} = mass of the parent particle

Four-lepton invariant mass...



4ℓ invariant mass distributions: explanation

- *UED-KKC:*
  $M_{4\ell} \leq \sqrt{2\frac{(M_{Z_1}^2 - M_{L_1}^2)(M_{L_1}^2 - M_{\gamma_1}^2)}{M_{L_1}^2} + 4(E_1E_3 + E_1E_4 + E_2E_3 + E_2E_4)}$
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- *SUSY-RPV: no peak at all*

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- *Angular correlation of each lepton with the nearest jet (for SUSY-RPV, there is often peaking in the forward direction)*
- $N(5\ell)/N(4\ell)$*: SUSY-RPV and LHT-TPV show higher ratios than the two other cases*
  Reason : compressed spectrum tends to soften leptons from cascade

Same-sign trileptons(SS3ℓ): unexplored potential...

Lepton sign: seriously used in the search for same-sign dilepton (SSD) events
Majorana fermions enhance SSD rates, p_T + isolation cuts reduce backgrounds (mostly from $t\bar{t}$)

Leptons of higher multiplicity and same sign: SM backgrounds extremely small

Theories with L-violation + self-conjugate fields: unsuppressed signals

A very discriminating check on scenarios with low-MET

SUSY-RPV stands out by contributing to SS3ℓ (and also SS4ℓ) (Even in the early run)

Also, the dynamics of R-parity violation can be probed thereby
S. Mukhopadhyay, BM (2010, 2011)

Same-sign trileptons(SS3ℓ): unexplored potential...

Standard model contribution to $\sigma(\text{SS}3\ell)$:
with appropriate cuts,
$\simeq 2.5 \times 10^{-3}$ fb ($\simeq 7.0 \times 10^{-4}$ fb) at 14 (7) TeV
Even smaller backgrounds for SS4ℓ

If high-MET new physics signals continue to elude us,
Low-MET ones must be looked for
SS3ℓ $\Rightarrow$ a discriminating signature of specific scenario(s)
In SUSY-RPV, LSP-pair decays (with no branching ratio suppression) can yield two same-sign leptons,
and one more comes from the cascade

- *SUSY with R-parity: rates are always very low due to lack of L-violation and branching fraction suppression*

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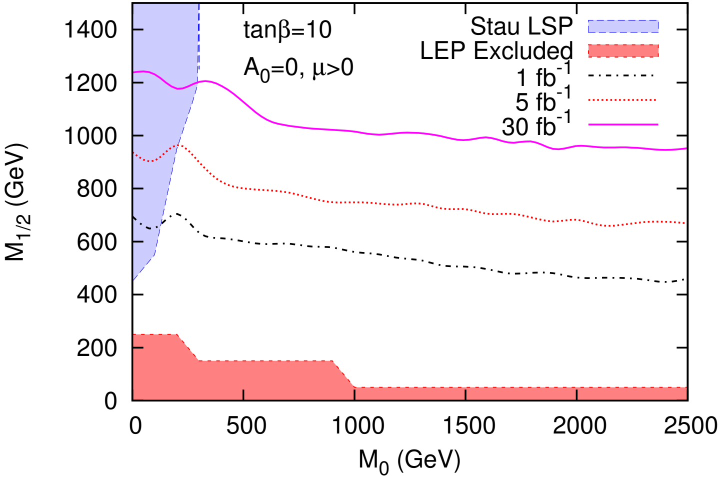
- *UED: SS3ℓ occurs even more rarely*
- *Thus SUSY-RPV stands out*

Coverage in mSUGRA parameter space at 14 TeV



5-event contours with background $<< 1$: One λ-type coupling included

Rates at 7 TeV

Case	$\sigma_{SS3\ell}$ (fb)
λ-type: $m_{\tilde{g}} \simeq 660\,GeV, neutralinoLSP$	19.82
λ-type: $m_{\tilde{g}} \simeq 1\,TeV, neutralinoLSP$	4.29
λ-type: $m_{\tilde{g}} \simeq 770\,GeV, stauLSP$	30.74
λ-type: $m_{\tilde{g}} \simeq 1\,TeV, stauLSP$	3.35
$\lambda^{'}$-type: $m_{\tilde{g}} \simeq 660\,GeV, neutralinoLSP$	2.07

Some general conclusions about SS3ℓ :

- $M_{2(1)} \geq 2M_{1(2)} \Rightarrow$ *Signal rate enhanced*
- $M_1 \simeq M_2 \Rightarrow$ *Signal suppressed unless* $M_3 >> M_{1,2}$
- *For* $m_{\tilde{g}}, m_{\tilde{q}} \simeq$ *1 TeV, 5 background-free events possible with 0.6 - 5.5* fb^{-1} *at 7 TeV, and 0.1 - 3.0* fb^{-1} *at 14 TeV*
- *The nature of SUSY-RPV can be extracted for one type of RPV coupling present at a time*

Some numbers in CMSSM with $m_{\tilde{g}} \simeq m_{\tilde{g}} \simeq$1 TeV: ss3l

$\tan\beta = 5$

Cut	SM	S	Sig(S)
Lepton selection + $MET > 30 GeV$	7.01×10^{-4}	2.41	5.9
$MET > 50 GeV$		2.23	5.6
$MET > 100 GeV$		1.65	4.7
$m_{eff}^{\ell} > 100$ GeV		2.39	5.8
$m_{eff}^{\ell} > 200$ GeV		1.57	4.6
$m_{eff} > 150$ GeV		2.40	5.9
$m_{eff} > 250$ GeV		2.10	5.4

Table: Same-sign trilepton rates (in fb) and the expected signal significance, for $7 TeV$ LHC and 1 fb^{-1} of integrated luminosity. $(\lambda_{123} = 10^{-3})$

After lepton acceptance + MET cut, 3 events with $\sim 1.25 fb^{-1}$

Some numbers in CMSSM with $m_{\tilde{g}} \simeq m_{\tilde{g}} \simeq 1$ TeV: SSD

$\tan\beta = 5$

Cut	SM	S	Sig(S)
Lepton selection + $MET > 30 GeV$	10.7	11.61	3.1
$MET > 50 GEV$		10.95	
$MET > 100 GeV$		8.66	
$m^{\ell}_{eff} > 100\ GeV$	6.4	10.59	3.5
$m^{\ell}_{eff} > 200\ GeV$	1.0	5.50	3.7
$m_{eff} > 150\ GeV$	7.4	11.41	3.5
$m_{eff} > 250\ GeV$	1.8	9.46	4.7

Table: Same-sign dilepton rates (in fb) and the expected signal significance, for $7 TeV$ LHC and $1\,\text{fb}^{-1}$ of integrated luminosity. ($\lambda_{123} = 10^{-3}$)

After lepton acceptance + MET cut, 5σ discovery in the SSD channel with $2.6 fb^{-1}$

To identify the dynamics...

Define $x = \sigma_{SS3\ell}/(\sigma_{SS3\ell} + \sigma_{MS3\ell})$,

and $y = \sigma_{SS4\ell}/(\sigma_{SS4\ell} + \sigma_{MS4\ell})$

The dynamics is reflected in x and y

x and y depend only on how charginos and neutralinos decay to leptons of either sign, and are independent of the spectrum
Assumption:
(a) neutralino LSP
(b)only one L-violating coupling at a time

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- **With λ'-type coupling,**

  Let $B(\chi_1^0 \longrightarrow l^\pm q\bar{q}')$ **=** α
  ($\alpha \simeq 0.5$**) Then**

  $x = \alpha^2/4 + 4y(1/\alpha - 1)$

To identify the dynamics...

For the bilinear terms $\epsilon_i L_i H_2$ side by side with $\mu H_1 H_2$,

The ϵ_i can be rotated away from the superpotential,

RPV is then driven by sneutrino vev in the scalar potential

Then correct neutrino masses $\Rightarrow \langle \tilde{\nu} \rangle \simeq 100 keV$ in that basis

$\chi_1^0 \longrightarrow \ell W, \nu Z$
(BR's fixed unless sneutrinos are closely degenerate with the Higgs)

Then
$x = 3.53y + 0.06$

(Including backgrounds, the relations are satisfied upto 10 - 20 %)

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- *SS3ℓ and SS4ℓ can differentiate among various R-parity breaking terms*

Concluding remarks...

"It is the mark of an educated mind to be able to be able to entertain a thought without accepting it"

—Aristotle