New Physics with Low Missing Energy: Identification and Discrimination at the LHC

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November 3, 2011

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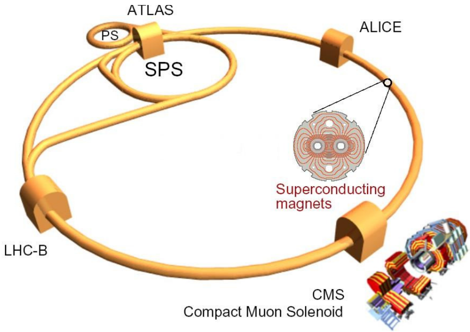
- *K. Ghosh, BM, S. Mukhopadhyaya, JHEP 1010,096 (2010)*
  S. Mukhopadhyay, BM, Phys. Rev. D82, 031501 (2010)
  S. Mukhopadhyay, BM, arXiv:1108.4921 [hep-ph]
  (To appear in Phys. Rev. D)

The LHC...


ATLAS
PS
SPS
ALICE
Superconducting magnets
LHC-B
CMS
Compact Muon Solenoid

Goals of the LHC....

- To discover the Higgs boson and complete the Standard Model
- 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*

BUT....

- **Why do we think there should be** *new physics* **?**

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

The Standard Model has inadequacies/puzzles...

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*

The Standard Model has inadequacies/puzzles...

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**
  (Quite 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

Dark matter candidates produced $\Rightarrow$ Events with MET

A candidate theory: supersymmetry (SUSY)
A lot of progress has taken places in SUSY search— mSUGRA-based cMSSM ruled out upto about a TeV

Theories often proposed with a Z_2 symmetry to accommodate a stable particle fitting in as dark matter candidate

One also studies how to distinguish among various such scenarios
(SUSY with R-parity, 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:

A.K. Datta, G. Kane, M. Toharia (2005)
A. K Datta, P. Dey, S. Gupta, BM, A. Nyffeler (2007)
J. Hubisz *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

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:

$W_{MSSM} = Y^l_{ij} L_i H_1 E^c_j + Y^d_{ij} Q_i H_1 D^c_j + Y^u_{ij} Q_i H_1 U^c_j$

When $R = (-)^{L+3B+2J}$ **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} **:** $\lambda''_{ijk} = 0$

A relevant mechanism 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
In the minimal (littlest) form,
Underlying electroweak gauge group : $[SU(2) \times U(1)]^2$ **,**
with an exchange symmetry (T-parity) – a Z_2 **symmetry**
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 $\sim \epsilon_{\mu\nu\alpha\beta} V_H^{\mu} V^{\nu} \partial^{\alpha} V^{\beta}$
The LTP becomes unstable:
For example, $A_H \longrightarrow W^{(*)} W^{(*)}$**,**
leading to tree-level or loop-induced decays

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

New particles are Kaluza-Klein towers in the 4D projections,
with same spin as in the zero-mode SM states

Two orbiforld fixed points in the extra dimension:
a Z_2 symmetry (for ensuring proper fermion chiralities)
$\Rightarrow$ A conserved Kaluza-Klein parity

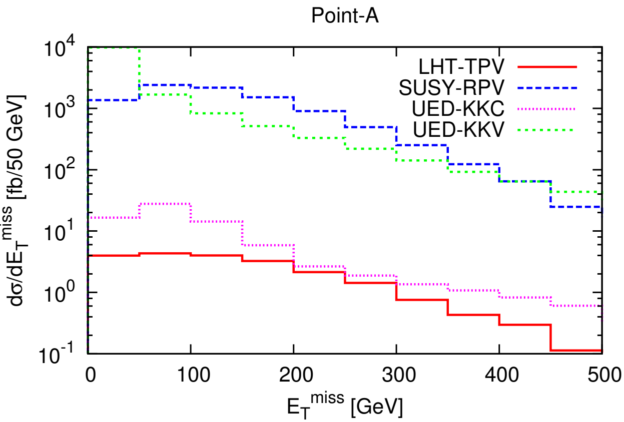
The lightest KK-odd particle (LKP) is stable
due to the Z_2 symmetry: dark matter candidate
(A neutral, weakly interacting particle):
Usually the excited photon A_1

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

A highly compressed spectrum in general

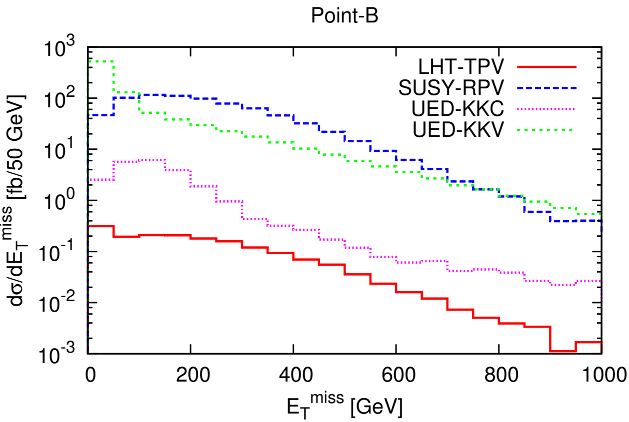
KK-parity can be broken by additional operators at the orbifold fixed points
$\Rightarrow$ The LKP is again unstable

Claim: all of these four scenarios, including UED-KKC, can lead to similar MET signals at the LHC
How to distinguish?



M_s = *Strongly interacting particle mass* $\simeq$ *600 GeV*
SUSY-RPV: λ*-type with one coupling*

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...

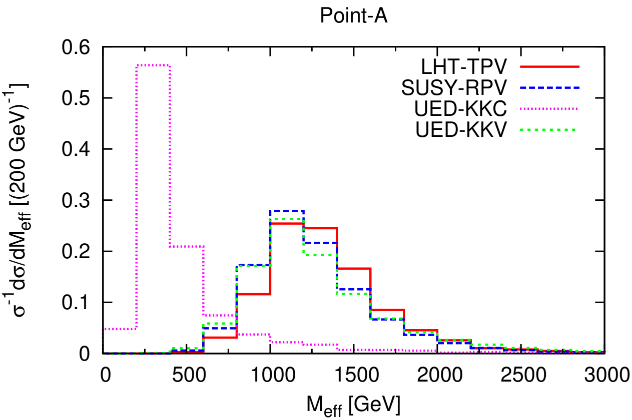
In addition to di-and tri-leptons,
four-and five-lepton final states can be useful discriminators

Isolated and central leptons

A p_T-cut of 10 GeV on the two softest leptons keeps away backgrounds

$M_{l^+l^-} \geq 20 GeV$ for all opposite-sign lepton pairs keep away γ^* backgrounds

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



Effective mass distribution with $M_s = 600$ GeV: UED-KKC stands out
$(M_{eff} = \Sigma_i p_T^i + MET)$

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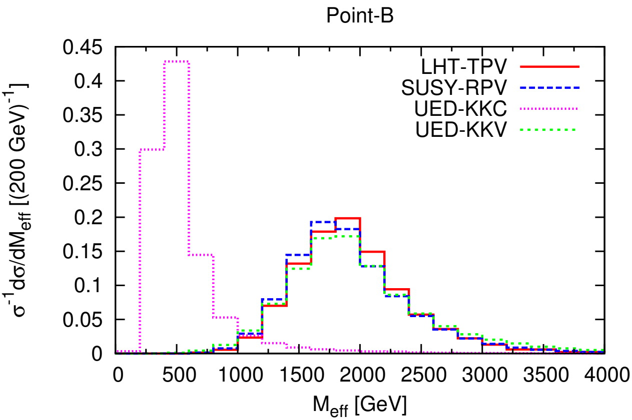
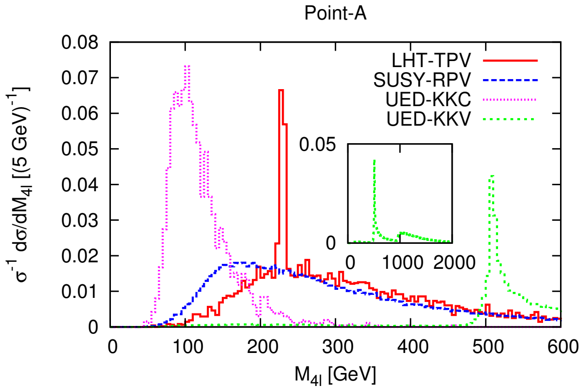


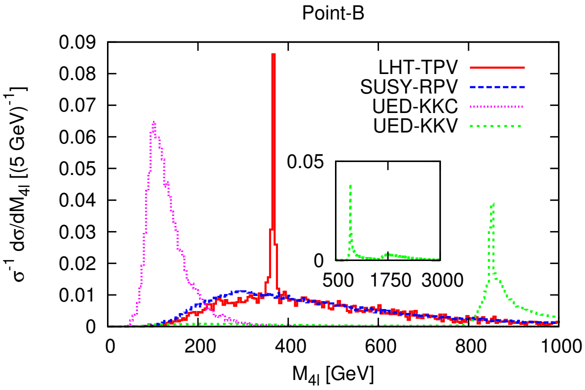
Effective mass distribution with $M_s = 1$ TeV: UED-KKC stands out

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

Four-lepton invariant mass...



Four-lepton invariant mass...



Some more criteria for discrimination....

- *Pairwise opposite-sign lepton invariant masses and their correlations in 4ℓ events*

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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*

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: 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 σ(SS3ℓ):
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

Very little competition from other scenarios...

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

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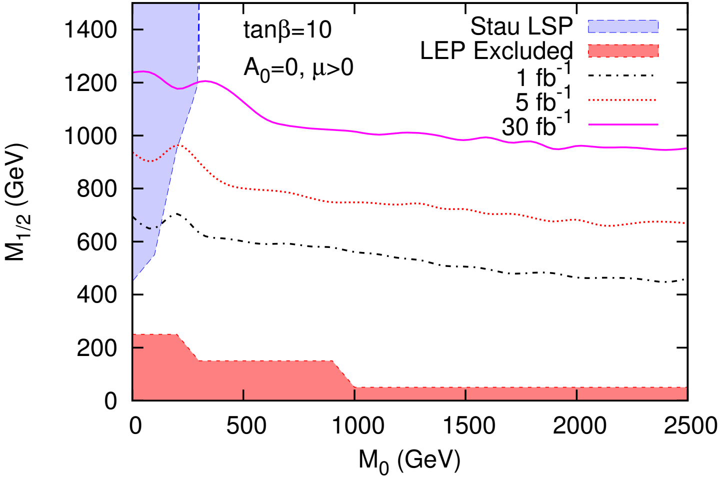
- *SUSY with compressed spectrum: rates even lower*
- *LHT-TPV: Decay of the LKP to one charged lepton has low branching ratio*
- *UED: SS3ℓ occurs even more rarely*
- *Thus SUSY-RPV stands out*

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 event rates

BP	M_1 (GeV)	M_2 (GeV)	$M_{\chi_1^0}$ (GeV)	$M_{\chi_1^\pm}$ (GeV)	$M_{\tilde{e}_L}$ (GeV)	$M_{\tilde{\tau}}$ (GeV)
1	150	150	146.54	154.80	254.13	180.91
2	160	150	154.08	154.80	254.13	217.69
3	100	300	97.69	395.30	254.10	180.68
4	125	250	121.65	254.35	156.76	217.52

BP	$\sigma_{7\,Tev}$ (fb)	$L_{7\,TeV}$ (fb^{-1})	$\sigma_{14\,Tev}$ (fb)	$L_{14\,TeV}$ (fb^{-1})
1	0.91	5.49	4.60	1.09
2	0.41	12.20	1.62	3.09
3	2.81	1.78	20.67	0.24
4	8.78	0.57	42.93	0.12

$L_{7\,TeV}, L_{7\,TeV}$: **luminosities (in fb^{-1}) at thse energies required for five signal events**

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

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

Table: Results for the same-sign trilepton search in terms of the effective cross-sections (in fb) and the expected signal significance (in Gaussian σs). The results are shown for $7 TeV$ LHC and 1 fb^{-1} of integrated luminosity.

After lepton selection + MET cut, 3 events with zero "real" background, with $\sim 1.25 fb^{-1}$

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

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: Results for the same-sign dilepton search in terms of the effective cross-sections (in fb) and the expected signal significance (in Gaussian σs). The results are shown for $7 TeV$ LHC and $1\,\text{fb}^{-1}$ of integrated luminosity.

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

General conclusion: same-sign trileptons (SS3ℓ) with enhanced rate are smoking gun signals of SUSY with L-violation

S. Mukhopadhyay, BM (2010, 2011)

If the lightest neutralino is the LSP, its decays in pair can yield two leptons of identical sign

A third lepton of the same sign can come from the cascade

Similar happening with same-sign four-leptons (SS4ℓ), too

At the same time, one has mixed-sign tri-and four-lepton events (MS3ℓ, MS4ℓ)

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

For λ-type coupling,

$x \simeq 0.12$

In actual simulations, $x = 0.11 \pm 0.2$

To identify the dynamics...

With λ'-type coupling,

A χ_1^0-LSP can decay into $l^{\pm} q\bar{q}'$ or $\nu q\bar{q}$

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

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 %)

Concluding remarks...

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- *Multilepton final states can help in distinguishing among different scenarios*
- *Same-sign trileptons: a very clear signal of SUSY with L-violation*
- *The early run has interesting prospects*
- *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