Performance of LHC searches with MET for models of Universal Extra Dimensions

Luca Panizzi

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Outline

1. Dark Matter in UED
2. A toy model
3. A realistic scenario: UED in the RP^2

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Universal extra-dimensions

All SM fields can propagate in the full D-dimensional background

Assumption 1: compact extra-dimension

$x_{5,6,\ldots}$ are limited to a finite interval $\{0, 2\pi R_{5,6,\ldots}\}$

effective 4D theory up to distance scales of the order of the compactification radii $R_{5,6,\ldots}$

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A field that propagates in D-dimensions can be Fourier-expanded

$$\Phi(x_\mu, x_5, x_6, \ldots) = \sum_{k_5, k_6, \ldots} \phi^{(k_5, k_6, \ldots)}(x_\mu) e^{i\left(\frac{k_5}{R_5} x_5 + \frac{k_6}{R_6} x_6 + \ldots\right)}$$

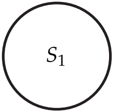
$$0 = \tilde{p}^2 = p^2 - \sum_i p_i^2 = p^2 - \frac{k_5^2}{R_5^2} - \frac{k_6^2}{R_6^2} - \ldots \longrightarrow \text{KK-mass: } m^2_{k_5, k_6} = \frac{k_5^2}{R_5^2} + \frac{k_6^2}{R_6^2} + \ldots$$

Compactification

example in 5D

Compactification on a circle

$x_5 \in \{0, 2\pi R\}$



Clifford algebra in 5D contains γ_5

$$\{\Gamma_\mu, \Gamma_\nu\} = 2\eta_{\mu\nu}$$

with

$\Gamma_\mu \equiv \gamma_\mu$ and $\Gamma_5 \equiv -i\gamma_5$

A chirality projector is missing

Fermions are
4-component Dirac spinors

After KK expansion
no chiral 4D modes

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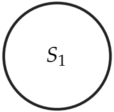

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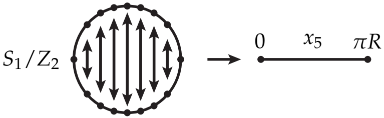
Compactification on an interval (orbifold)

Identification of opposite points



Parity operator

$$P(x_5) = -x_5 \qquad \Phi(x^\mu, -x_5) = P(\Phi)(x^\mu, x_5)$$

Invariance of the action requires

$$P(\Psi_L) = +\Psi_L \qquad P(\Psi_R) = -\Psi_R$$

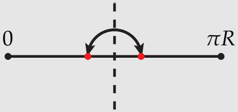
After KK expansion
$$\begin{cases} \Psi_L(x, x_5) \sim \sum_{n=0}^{\infty} \psi_L^{(n)}(x) \cos\left(\frac{n}{R} x_5\right) \\ \Psi_R(x, x_5) \sim \sum_{n=1}^{\infty} \psi_R^{(n)}(x) \sin\left(\frac{n}{R} x_5\right) \end{cases}$$

Zero-mode chiral fermions

KK-parity and Dark Matter

example in 5D

KK symmetry



Discrete symmetry around the midpoint of the interval

$$x_5 \to \pi R - x_5$$

Under this symmetry

$$\begin{cases} \cos\left(\frac{n}{R}(x_5+\pi R)\right) \\ \sin\left(\frac{n}{R}(x_5+\pi R)\right) \end{cases} = (-1)^n \begin{cases} \cos\left(\frac{n}{R}x_5\right) \\ \sin\left(\frac{n}{R}x_5\right) \end{cases}$$

Modes with odd n flip sign

Invariance of the action under KK symmetry $\longrightarrow$ Interactions must contain an even number of modes with odd n

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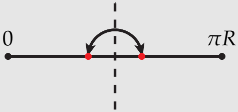

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The lightest KK-odd level is stable $\longrightarrow$ Dark Matter candidate!

SUSY vs UED

Renormalisation group equations

SUSY: renormalisable theory

10^{15-16} GeV (GUT scale)

TeV (EWSB scale)

Typically **large** mass gap between strongly- and weakly-interacting particles

UED: effective theory

$\mathcal{O}$(10TeV) (cutoff scale)

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Neutralino (**fermion**)

Lightest KK-odd recurrence (**scalar or vector**)

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SUSY particles are **only odd** under R-parity and necessarily decay into DM

KK-even tiers may decay directly into SM or into 2 odd states (and then to DM)

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Signals with MET from SUSY or UED may have different properties

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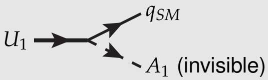
The model and its signature

Ingredients

- 1 heavy up-type quark U_1 (representative of the KK quark recurrences)
- 1 neutral scalar particle A_1 (the Dark Matter candidate)

$$M(U_1) > M(A_1) \quad \Longrightarrow$$



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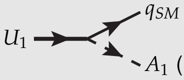
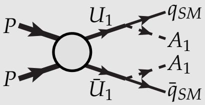


(invisible)

Production process

QCD pair production



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(relevance of ISR and FSR: boosted events, unbalance in MET)

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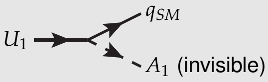

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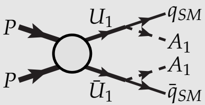

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How to test this signal against available SUSY-tuned searches?

The exclusion confidence level

Let's consider a fictional search with 1 bin

Observation	Background
310 events	300 events

The exclusion confidence level

Let's consider a fictional search with 1 bin

Observation

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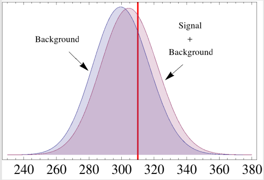
Background

300 events

Signal

Case I: 5 events



Exclusion CL $\simeq$ 14%

$$\text{Exclusion CL} = 1 - \frac{\text{CL(s+b)}}{\text{CL(b)}} = 1 - \frac{\text{p-value(s+b)}}{1 - \text{p-value(b)}}$$

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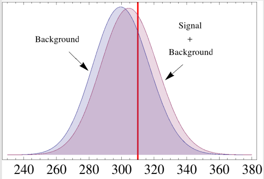

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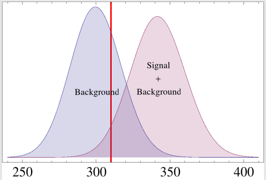
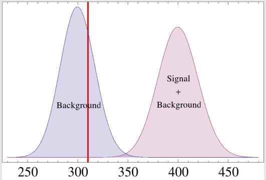
Case II: 42 events



Exclusion CL $\simeq$ 94%

Case III: 100 events



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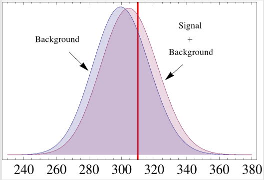

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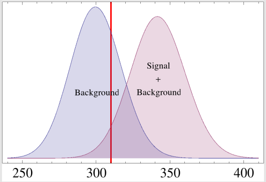

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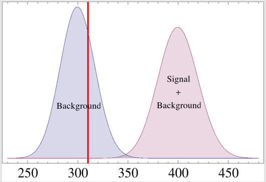

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Simulate the signal, apply the cuts used in the search
and find the exclusion confidence level of the tested scenario

A SUSY-inspired search

CMS α_T search at 7 TeV

Definition of α_T

di-jet event
with less energetic jet j_2

$$\alpha_T = \frac{p_T(j_2)}{M_{jj}} = \frac{p_T(j_2)}{\sqrt{H_T^2 - \not{H}_T^2}} \quad \text{where} \quad \not{H}_T = |\sum_{i=1}^{N_{jet}} \vec{p}_T|$$

- QCD events have typically $\alpha_T < 0.5$: powerful to discriminate SM background
- effective in events with large MET (typical in SUSY)!

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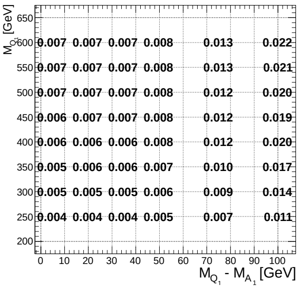
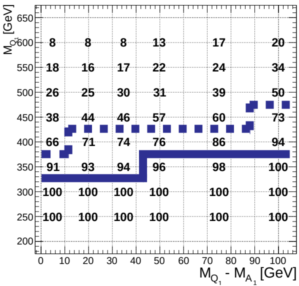
Results in the toy model: more effective with large splitting!

Efficiencies



Exclusion CLs



1σ exclusion

2σ exclusion

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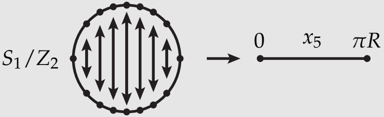
A problem with Dark Matter in 5D

Fixed points of the 5D orbifold



The points 0 and πR are transformed into themselves

KK-parity must be imposed by hand on the physically different fixed points

The Dark Matter candidate is not “natural” in 5D

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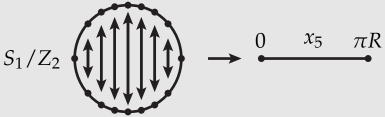

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orbifold without fixed points → KK-parity unbroken globally → Natural Dark Matter candidate

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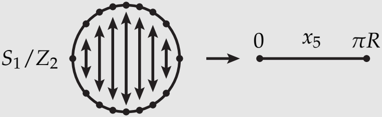

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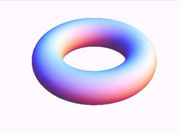
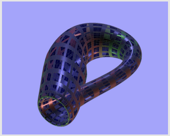
6D orbifolds without fixed points

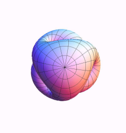
Torus



Klein Bottle



Real Projective Plane



Only in the Real Projective Plane there are 0-mode (i.e. SM) chiral fermions

Spectrum and possible signatures

Particle content (lightest tiers)

Odd tier (1,0)+(0,1): $M = M_{KK}$

Fermions: Q_1, L_1, ν_1
Gauge Scalars: W_1, Z_1, G_1, A_1

Even tier (2,0)+(0,2): $M = 2M_{KK}$

Fermions: Q_2, L_2, ν_2
Gauge Vectors: W_2^μ, Z_2^μ, G_2^μ, A_2^μ
Higgses: H_2, S_2^0, $S_2^\pm$

Mass splittings in the same tier $\lesssim$ 100 GeV for Mkk $\lesssim$ 800 GeV

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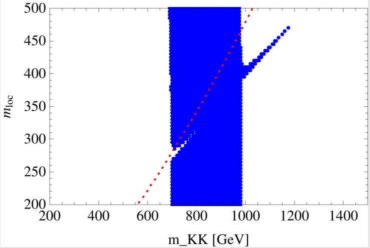
Bounds on M_{KK} from DM relic aboundance



A.Arbey, G.Cacciapaglia, A.Deandrea, B.Kubik, arXiv:1210.0384

The allowed region
is between 700 GeV and 1 TeV

(feature due to localized $H_{(2,0)}$ mass term)

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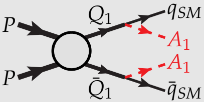
Examples of production processes

Odd tier



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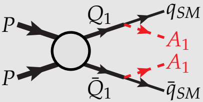

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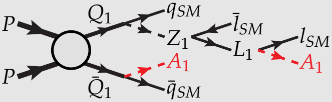
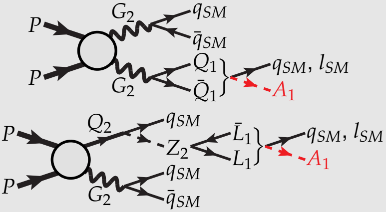


Even tier



The final state contains MET, jets and leptons: more searches can be tested

Searches with jets, MET and leptons

CMS only

Single lepton

"Lepton projection method" with variable L_P, which measures the component of the lepton p_T that is parallel to that of the reconstructed W it originates from. In the SM typically $L_P > 0.3$

signal region: $L_P < 0.15$ $\qquad S_T^{lep} = p_T(l) + \not{E}_T = \begin{cases} 250 - 350 GeV \\ 350 - 450 GeV \\ 450 - \infty GeV \end{cases}$

Opposite-sign dileptons

Region 1	Region 2	Region 3	Region 4
$H_T > 300GeV$	$H_T > 600GeV$	$H_T > 600GeV$	$125 < H_T < 300GeV$
$\not{E}_T > 275GeV$	$\not{E}_T > 200GeV$	$\not{E}_T > 275GeV$	$\not{E}_T > 275GeV$

Same-sign dileptons

Region 1	Region 2	Region 3	Region 4	Region 5
$H_T > 80GeV$	$H_T > 200GeV$	$H_T > 450GeV$	$H_T > 450GeV$	$H_T > 450GeV$
$\not{E}_T > 120GeV$	$\not{E}_T > 120GeV$	$\not{E}_T > 50GeV$	$\not{E}_T > 120GeV$	$\not{E}_T > 0GeV$

Characterized in general by hard cuts on S_T^{lep}, H_T and/or $\not{E}_T$!

Exclusion CLs for UED in the RPP

	$m_{KK} = 400$ GeV		$m_{KK} = 600$ GeV		$m_{KK} = 700$ GeV	
	ϵ_{total}	CL	ϵ_{total}	CL	ϵ_{total}	CL
α_T	1.4%	100%	1.1%	99%	1.0%	64%
L_p	0.19%	100%	0.11%	83%	0.08%	38%
OS	0.03%	87%	0.02%	3%	0.02%	1%
SS	0.01%	100%	$<$ 0.01%	20%	$<$ 0.01%	5%
Combination		100%		99.9%		72%

Combining the 7 TeV SUSY searches it is possible to put a 2σ bound on $M_{KK} = \min(1/R_5, 1/R_6)$ between 600 and 700 GeV

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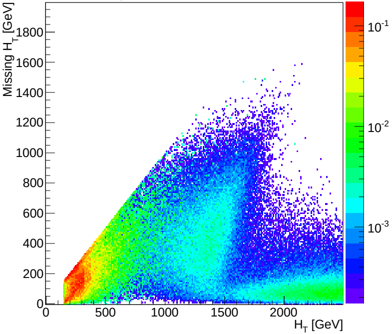
SUSY searches with $\not{E}_T$ already provide strong bounds on non-SUSY models with DM candidates and compressed spectra, but there is still room for improvement!

Possible directions for improvement

Example with α_T

Signal before α_T cuts



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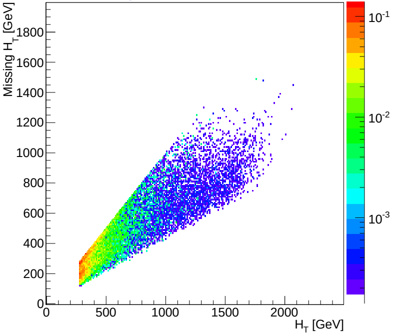

The α_T cuts remove large clusters of UED events

Modifying kinematical cuts to account for compressed spectra may improve the efficiency for different scenarios, increasing the range of application of a given search!

Conclusions and outlook

- Dark Matter candidates in Universal Extra Dimensions have **different properties** with respect to SUSY candidates
  - $\rightarrow$ Small mass gap between DM candidate and other states: **compressed spectra**
  - $\rightarrow$ **Spin** of the DM candidate (vector or scalar)
- Phenomenology at collider exhibits **peculiar features**, but searches with $\not{E}_T$ are mostly tuned for SUSY
- The potentiality of SUSY-tuned searches to constrain UED models is high and there is still **room for improvement!**