Status of UED Simulations

Asesh K Datta

Harish-Chandra Research Institute
Allahabad INDIA

MC4BSM-2014, Daejeon, South Korea
May 23, 2014

Plan

- Introduction
- Universal Extra Dimensions (very basics)
  - The mass spectrum
  - The working scenario
  - MUED vs SUSY
- **Status of mUED simulation**
- **Beyond mUED; status of simulation**
- Conclusion

Introduction

- First phase of LHC run discovered the Higgs boson
  - Opened up a new world (to be pursued over decades to come):

    *** so many ways it can be studied now**
  - Having so tantalizing a mass-value; saying so many things
  - But with it brought its share of "dispair"
  - **A real mixed bag**
- A blessing in disguise?
  - A very efficient filtering away of what things are not like
  - Has already made us alert and a lot more focussed
- At MC4BSM we gather to gauge our preparedness to meet any eventuality

TeV scale flat extra dimensions
(The original proposals)

When accessible by SM particles

- New mechanism of SUSY breaking: Antoniadis (1990)
- Gauge coupling unifications: Dienes, Dudas, Gherghetta (1998)
- Fermion mass hierarchy: Arkani-Hamed, Schmaltz (1999)
- Two Higgs doublets: Arkani-Hamed, Chen, Dobrescu, Hall (2000)

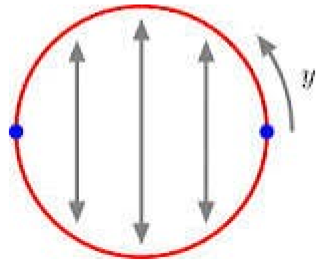
  - Extra dimensions to be compactified at a scale $R^{-1} \sim \mathrm{a\ few\ TeV}$

    ** *(as some of the quarks and leptons are confined to 4D branes)*

Unlikely to be accessible at present-day collider(s)

Universal Extra Dimensions (UED)
(Basic Features)

- Problems of compactifying on a circle
  - Absence of chiral fermions
  - 5-component gauge fields



- Orbifolding as a solution
  - Identifying two diametrically opposite points on a circle

UED
(Basic Features)

- Allow all SM particles access the extra dimensions

  (Appelquist, Cheng, Dobrescu)

  - Universal Extra Dimensions (UED)
  - Key element: momentum conservation in the extra dimension
  - Implies 'KK-number' conservation in the equivalent 4D theory

- Consequences
  - No allowed tree-level vertices involving only one non-zero KK mode
  - Hence, no tree-level contribution to electroweak observables

- Implications
  - Bounds on R^{-1} from tree-level contributions to EW observables evaded
  - Bounds on R^{-1} from single KK productions at colliders evaded

** Relaxed bounds come down to around 500 GeV (1 extra dimension) **

UED (excitations) may become accessible to colliders

UED (Basic Features)

- **Energy momentum relation in 5D**
  - $E^2 = p_1^2 + p_2^2 + p_3^2 + p_y^2 + m^2$

- Compactify the extra-dim on a circle
  - $p_y = \frac{2\pi}{\lambda}, \quad \lambda = \frac{2\pi}{n} \quad \Rightarrow p_y = \frac{n}{R}$
  - $E^2 = p_1^2 + p_2^2 + p_3^2 + \frac{n^2}{R^2} + m^2$

$$m_n = \sqrt{\frac{n^2}{R^2} + m^2}$$

Orbifolding & KK decomposition

- A 5D field has a definite parity under $P_5 : y \to -y$
- Scalars:
  - Even: $$\phi^+(x,y) = \frac{1}{\sqrt{\pi R}}\,\phi_0^+(x) + \frac{2}{\sqrt{\pi R}}\,\phi_n^+(x)\cos\frac{ny}{R}$$
    Obeys Neumann BC: $\left(\frac{\partial\phi^+(x,y)}{\partial y}\right)_{y=0} = \left(\frac{\partial\phi^+(x,y)}{\partial y}\right)_{y=\pi R} = 0$
  - Odd: $$\phi^-(x,y) = \frac{2}{\sqrt{\pi R}}\,\phi_n^-(x)\sin\frac{ny}{R}$$
    Obeys Dirichlet BC: $\phi^-(x,0) = \phi^-(x,\pi R) = 0$
- Gauge Bosons: Odd:
  - Even: $$A_\mu(x,y) = \frac{1}{\sqrt{\pi R}}\left\{A_\mu^0(x) + \sqrt{2}A_\mu^n(x)\cos(\frac{ny}{R})\right\}$$
  - Odd: $$A_\mu(x,y) = \frac{1}{\sqrt{\pi R}}\left\{A_\mu^0(x) + \sqrt{2}A_\mu^n(x)\cos(\frac{ny}{R})\right\}$$

Orbifolding & KK decomposition

- Fermions:
  - SU(2) weak doublet:
    - Even: $\Psi_L^+(x,y) = \frac{1}{\sqrt{2\pi R}}\Psi_L^0(x) + \frac{1}{\sqrt{\pi R}}\Psi_L^n(x)\cos\frac{ny}{R}$
    - Odd: $\Psi_L^-(x,y) = \frac{1}{\sqrt{\pi R}}\Psi_R^n(x)\sin\frac{ny}{R}$
  - SU(2) weak singlet:
    - Even: $\psi_R^+(x,y) = \frac{1}{\sqrt{2\pi R}}\psi_R^0(x) + \frac{1}{\sqrt{\pi R}}\psi_R^n(x)\cos\frac{ny}{R}$
    - Odd: $\psi_R^-(x,y) = \frac{1}{\sqrt{\pi R}}\psi_L^n(x)\sin\frac{ny}{R}$

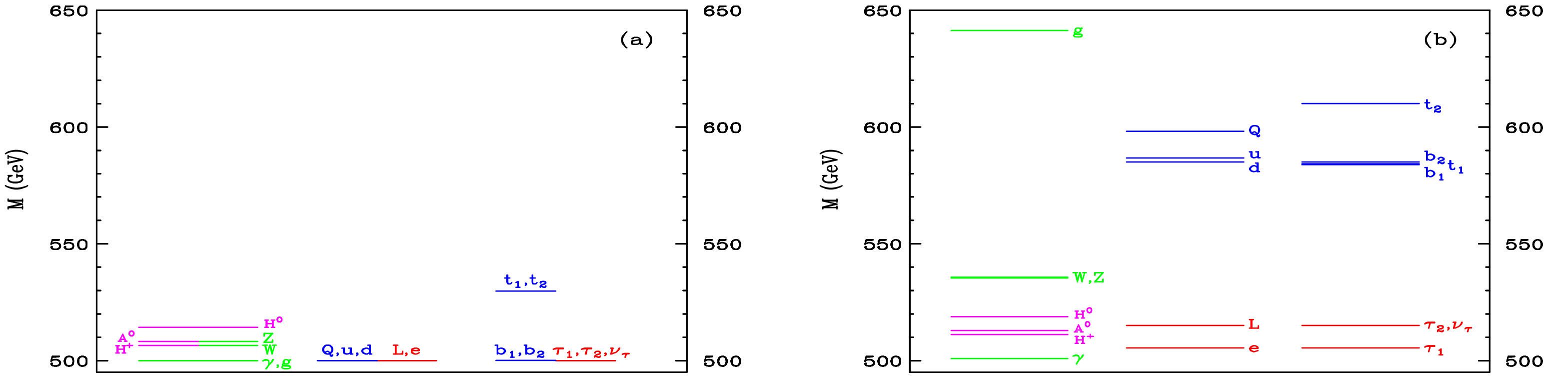
$\Psi_L^n(x)\ ,\ \Psi_R^n(x) \Rightarrow$ Components of vector-like SU(2) doublet KK fermion at level 'n'

$\psi_R^n(x)\ ,\ \psi_L^n(x) \Rightarrow$ Components of vector-like SU(2) singlet KK fermion at level 'n'

Fermionic states

$SU(2)_W$ representations	SM mode	KK modes
Quark doublet	$q_L(x) = \begin{pmatrix} U_L(x) \\ D_L(x) \end{pmatrix}$	$Q_L^n(x) = \begin{pmatrix} U_L^n(x) \\ D_L^n(x) \end{pmatrix}$, $Q_R^n(x) = \begin{pmatrix} U_R^n(x) \\ D_R^n(x) \end{pmatrix}$
Lepton doublet	$L_L(x) = \begin{pmatrix} \nu_L(x) \\ E_L(x) \end{pmatrix}$	$L_L^n(x) = \begin{pmatrix} \nu_L^n(x) \\ E_L^n(x) \end{pmatrix}$, $L_R^n(x) = \begin{pmatrix} \nu_R^n(x) \\ E_R^n(x) \end{pmatrix}$
Quark Singlet	$u_R(x)$	$u_R^n(x)$, $u_L^n(x)$
Quark Singlet	$d_R(x)$	$d_R^n(x)$, $d_L^n(x)$
Lepton Singlet	$e_R(x)$	$e_R^n(x)$, $e_L^n(x)$

The mass spectrum



$R^{-1} = 500\,\mathrm{GeV}\ ,\ \Lambda = 20\ ,\ m_h = 120\,\mathrm{GeV}$

- Tree level mass: $m_n^2 = \dfrac{n^2}{R^2} + m_0^2$
- Radiative corrections: (Cheng, Matchev, Schmaltz)
  - Renormalized mass (via bulk interactions; fixed by SM gauge & Yukawa couplings)
  - Contributions from terms localized at the boundary points (can be the new free parameters)
    - Ansatz: Vanishing at the cut-off scale $(\Lambda > R^{-1})$
    - Radiatively generated via running

Brought UED in the limelight at colliders: The minimal UED

Minimal UED (mUED)

The original working scenario

- Practically Rinv is the sole important free parameter (others are Λ & m_h)

- KK partners of SM states at each levels (similar to SUSY partners)

- KK-parity is conserved (similarity with R-parity in SUSY)
  - $K_P = (-1)^n$ (for the n-th KK level)
  - Lightest KK particle (LKP) is a DM candidate (Kong, Matchev ; Kribs, Burnell)
  - WIMP LKP is the missing energy carrier at collider (generic signature of mUED)

- At tree level KK-number is conserved
  - Can be violated at loop level (though KK-parity remain conserved)
    - Non-vanishing 2-0-0 effective coupings

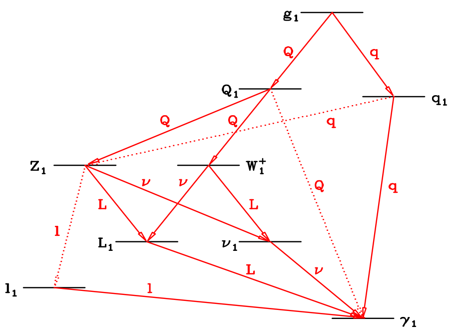
- Couplings are SM-like

mUED vs SUSY

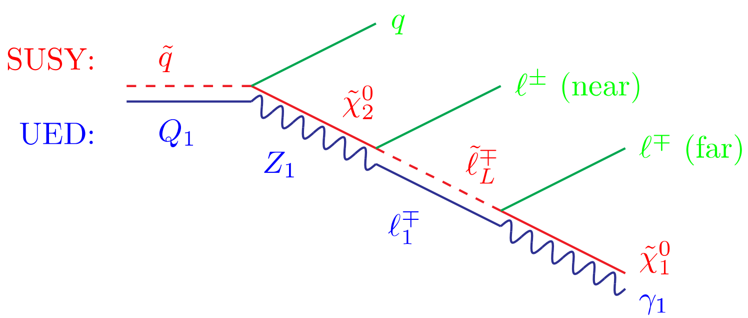
- Faking SUSY!

  (Bosonic SUSY !!)

  (Cheng, Matchev, Schamltz)



- Compare with SUSY with a somewhat compressed spectra



- Simulate mUED at colliders

mUED Vs SUSY

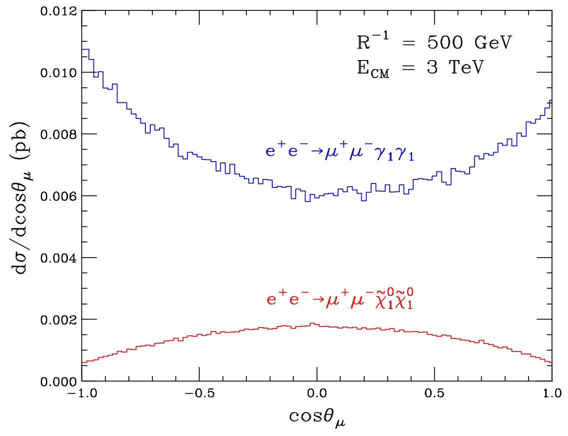
- **Spin**
  - Distinction rather complicated at the LHC
  - An e+e- collider will be a good option

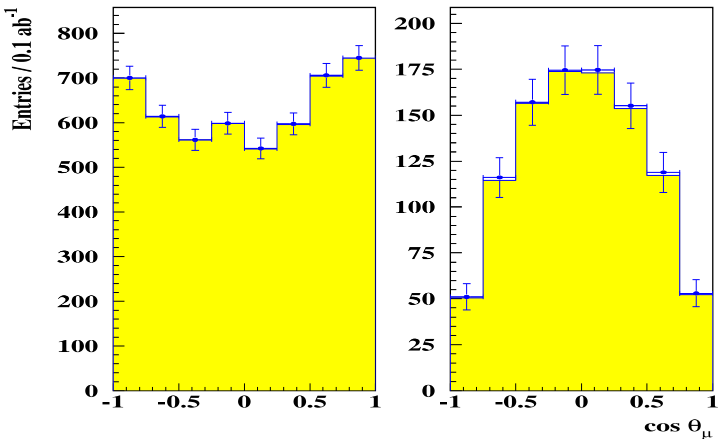
Battaglia, AD, De Roeck, Kong, Matchev (2005)

- **Presence of multiple KK levels in mUED**
  - More cousins of an SM excitation
  - Level 2 gauge bosons

Datta, Kong, Matchev (2005)

mUED Vs SUSY



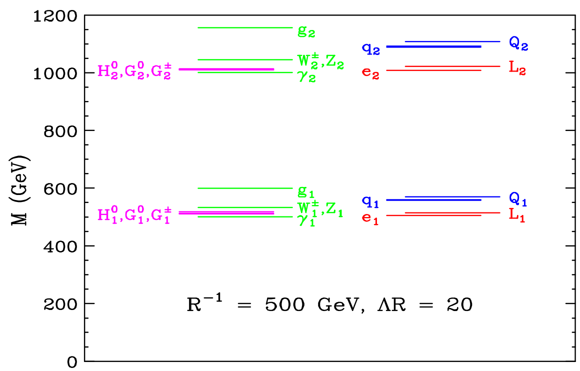


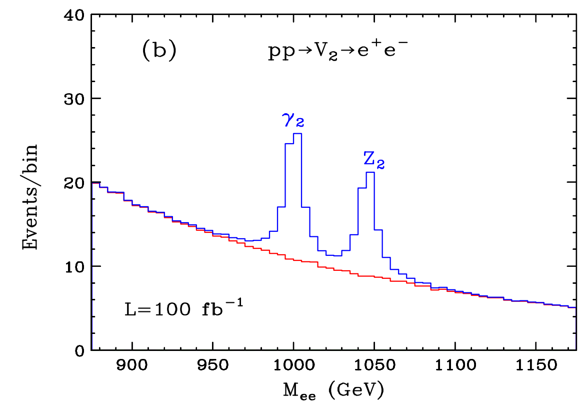
Battaglia, Datta, De Roeck, Kong, Matchev (2005)

- Spin
  - Distinction rather complicated at the LHC
  - An e+e- machine will be a good place

$$(1-\cos^2\theta)_{SUSY} \text{ Vs } (1+\cos^2\theta)_{UED}$$

MUED Vs SUSY

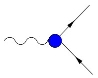


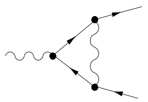


AD, Kong, Matchev (2005)

- Presence of (infinitely) many KK levels
  - Only a couple of them may at best be accessible though
  - More cousins of various SM states

  - KK-number violating (but KK-parity conserving) loop-level couplings $V^{(2)} - f^{(0)} - f^{(0)}$





Tools for mUED

Early Days (2002-2006)

Macesanu, McMullen, Nandi (2002)

- Rate calculations for strongly interacting level '1' KK pairs

- Pre-C-M-S work
  - Too degenerate a spectrum
  - Quasi-stable lighter KK excitations

- Fat-brane scheme: Decays to Gravitons (missing energy)

- Squared matrix-elements were provided

- **Implementation originally limited to private codes**

Tools for mUED

Early Days (2002-2006)

First ever implementation of mUED in an event-generator (CalcHEP/CompHEP)

AD, Kong, Matchev (2005)

http://home.fnal.gov/~kckong/mued/

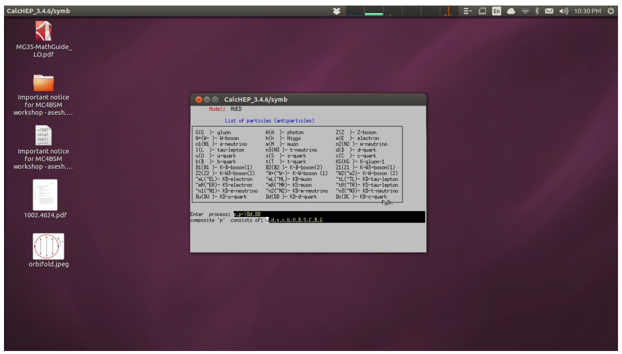
arxiv : 1002.4624

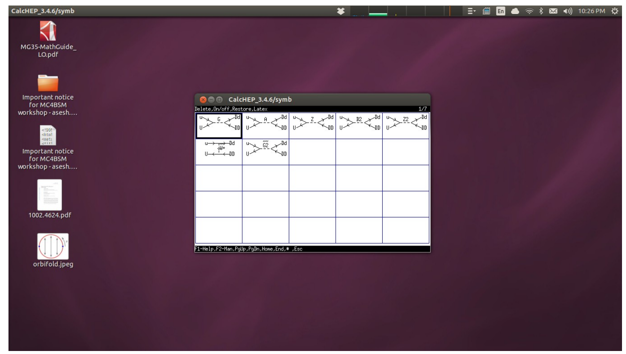
- Complete spectrum up to KK level '2' including the radiative corrections to the masses (a la CMS) (except for the Higgs excitations)

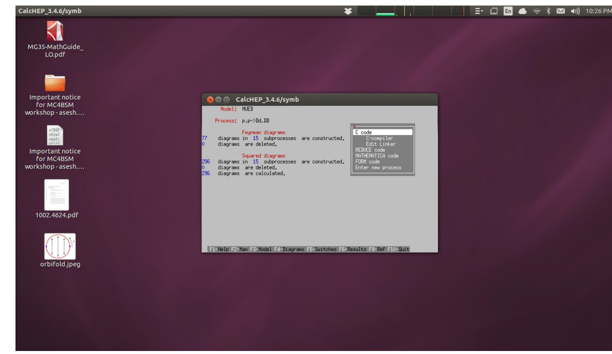
- Full tree level Lagrangian incorporated (unitary gauge)
- Effective interaction vertices incorporated for leve '2' gauge bosons $V^{(2)} f^{(0)} f^{(0)}$
- Option to have running coupling constants

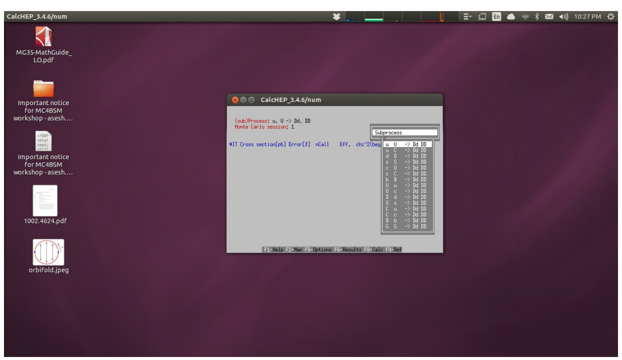
Main inputs: $\mathbf{R^{-1}}$, $\mathbf{\Lambda R}$

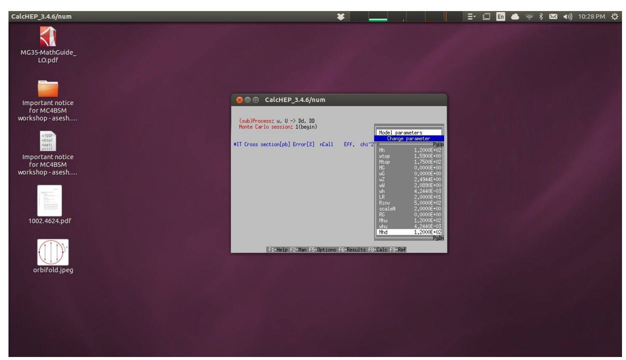
MUED in CalcHEP at work

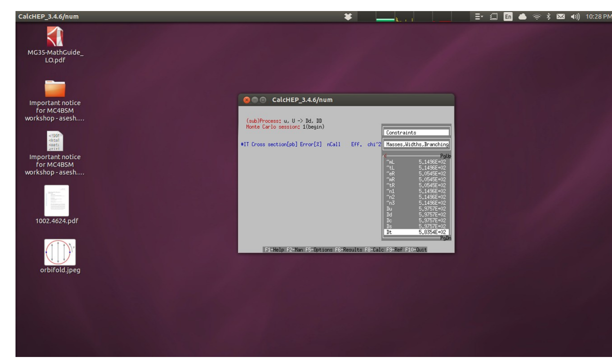












Tools for mUED

(Implementation in CalcHEP/CompHEP)

Validation

- Spectrum numerically checked with C-M-S work
- Vertices cross-checked against LanHEP
- Very many random checks of the analytical formulae *(arxiv:1002.4624)*
- Cross-checks against formulae in literature
- Cross-checks of coannihilation formulae against available literature

Recently validated exhaustively against Feynrules implementation

Tools for mUED

Intermediate phase (2006-2009)

- **Pythia v6.4.17 incorporated mUED**

  Elkacimi, Goujdami, Przysiezniak, Skands [hep-ph/0602198, arXiv:0901.4087]

- Radiative corrections to masses included a la C-M-S

- Gravity mediated decay only for $\gamma^{(1)}\,(\sim B^{(1)}) \rightarrow \gamma\, G$

  (a la de Rujula et al., Macesanu et al.)

- No KK level '2' excitation yet incorporated
- Scope for closer validation

Tools for mUED

Pythia 6.4

PDG Convention		Pythia Convention	
$d_L^{(1)}$	5100001	$d*_D$	5100001
$u_L^{(1)}$	5100002	$u*_D$	5100002
$e_L^{(1)-}$	5100011	$e*_D-$	5100011
$\nu_{eL}^{(1)}$	5100012	$nue*_D$	5100012
$g^{(1)}$	5100021	$g*$	5100021
$\gamma^{(1)}$	5100022	$gamma*$	5100022
$Z^{(1)0}$	5100023	$Z*0$	5100023
$W^{(1)+}$	5100024	$W*+$	5100024
$d_R^{(1)}$	6100001	$d*_S$	6100001
$u_R^{(1)}$	6100002	$u*_S$	6100002
$e_R^{(1)-}$	6100011	$e*_S$	6100011

Tools for mUED

Pythia 6.4

```
  COMMON/PYPUED/IUED(0:99),RUED(0

IUED(1) = The main UED ON(=1)/OFF(=0) switch
          Default value = 0
IUED(2) = The number of large extra dimensions
          into which only the graviton propagates
          Default value = 6
IUED(3) = The number of quark flavour KK excitations
          Default value = 5
RUED(0) = The curvature 1/R of the delta extra dimensions
          Default value = 1000 GeV
RUED(1) = The cutoff scale Lambda
          Default value = 5000 GeV
 N.B. The Higgs mass is also a free parameter
 of the UED theory but is set through pmas(25,1).
```

```
ISUB  production process (ref: hep-ph/0201300 and Azuelos-Beauchemin)
---- --------------------------------
 311 g   + g      -> g*    + g*
 312 g   + q      -> g*    + q*_D/q*_S
 313 q_i + q_j    -> q*_Di + q*_Dj
                  -> q*_Si + q*_Sj
 314 g   + g      -> q*_D  + q*_Dbar
                  -> q*_S  + q*_Sbar
 315 q   + qbar   -> q*_D  + q*_Dbar
                  -> q*_S  + q*_Sbar
 316 q_i + q_barj -> q*_Di + q*_Sbarj
 317 q_i + q_barj -> q*_Di + q*_Dbarj
                  -> q*_Si + q*_Sbarj
 318 q_i + q_j    -> q*_Di + q*_Sj
 319 q_i + q_bari -> q*_Dj + q*_Dbarj
```

```
(ref: hep-ph/0205314):
     l*_S  -> l   + gamma*
     q*_S  -> q   + gamma*
     q*_S  -> q   + Z*
     l*_D  -> l   + gamma*
     nu*_D -> nu  + gamma*
     q*_D  -> q   + gamma*
     q*_D  -> q   + Z*
     q*_Di -> q_j + W*
     W*+-  -> l+- + nu*_D
           -> nu  + l*_D+-
     Z*    -> nu_bar + nu*_D
           -> l-+ + l*_D+-
     g*    -> q   + q*_Dbar
           -> q   + q*_Sbar
```

Tools for mUED

Pythia 6.4

```
Four new subroutines have been added to handle UED-specific tasks:
      SUBROUTINE PYXDIN   to initialize Universal Extra Dimensions
      SUBROUTINE PYUEDC   to compute UED mass radiative corrections
      SUBROUTINE PYXUED   to compute UED cross sections
      SUBROUTINE PYGRAM   to generate UED graviton mass spectrum
```

```
In addition, several Pythia routines have been modified to include the
UED implementation. These modified routines include
      SUBROUTINE PYGIVE   now accepts input also for IUED and RUED
      SUBROUTINE PYINIT   added call to PYXDIN to initialize UED
      SUBROUTINE PYMAXI   small extension for UED overestimates
      SUBROUTINE PYPTFS   small extension for showering KK gluons
      SUBROUTINE PYRAND   extented to choose flavours in UED processes
      SUBROUTINE PYRESD   added call to PYGRAM to choose graviton mass
                          from continuous spectrum in UED decays to
                          gravitons
      SUBROUTINE PYSCAT   extented to include UED processes
      SUBROUTINE PYSIGH   small extension to call PYXUED for UED
      SUBROUTINE PYWIDT   extented to compute KK decay widths
```

Tools for mUED
Implementation in Feynrules
(2010 onwards)

https://feynrules.irmp.ucl.ac.be/wiki/MUED

Author: Priscila de Aquino

Instructions

* The MUED is implemented in unitary gauge.

* The switch FeynmanGauge (future devlopments) must thus be set to False,

* To run it in CalcHEP the switch FeynmanGauge must be set to True when asking the CalcHEP output, and then to False before any run.

* In MadGraph, the maximal number of particles must be increased to run the model:

* Increase the value of max_particles in params.inc in the MadGraphII directory from 2**7-1 to 2**8-1

* Remove all excecutables in the MadGraphII directory (rm -rf *.o).

* Recompile MadGraph by typing make in the MadGraph main directory.

Validations

(MG-FR vs SH-FR vs CH-FR vs CH-Standard)

Comparison of the built-in Madgraph Standard-Model and FeynRules generated Madgraph MUED for Standard Model processes. This comparison was done using squared matrix element at given phase-space points.

Comparison of the existing CalcHEP MUED (CH-ST) with the FeynRules generated ones in **CalcHEP, Madgraph and Sherpa**: CH-FR, MG-FR and SH-FR, through the calculation of several 2-to-2 cross-sections. **All the checks performed were conclusive.**

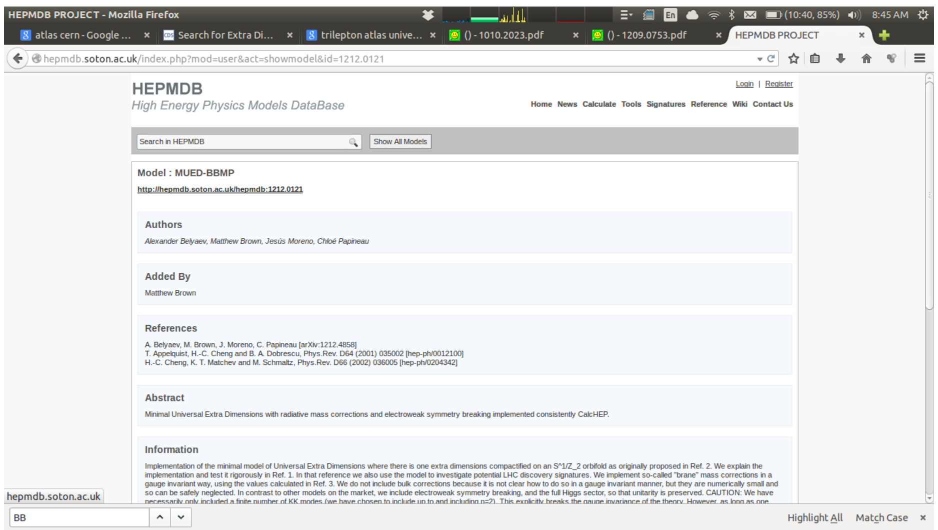
Process	MG-FR	CH-FR	CH-ST	Comparison
Z1,Z1>W-,W+	2.8557×10^{1}	2.8544×10^{1}	2.8545×10^{1}	δ = 0.0453702 %
W1+,W1->Z,Z	8.39996	8.4077	8.4078	δ = 0.0933024 %
W1+,W1->Z,A	5.07653	5.074	5.074	δ = 0.0497819 %
Z1,A>W+,W1-	1.89587×10^{2}	1.8975×10^{2}	1.8975×10^{2}	δ = 0.0860381 %
Z,A>W1+,W1-	3.1847	3.185	3.185	δ = 0.00954049 %
W1+,W1->W+,W-	8.70656	8.7135	8.7135	δ = 0.079644 %
W+,W->Z1,Z1	6.00463	6.0042	6.0042	δ = 0.00715757 %
W+,W1->Z,Z1	4.92433×10^{2}	4.9258×10^{2}	4.9258×10^{2}	δ = 0.0299393 %
W1+,W1->W1+,W1-	2.20282×10^{3}	2.2023×10^{3}	2.2023×10^{3}	δ = 0.0237219 %
Z1,Z1>W1+,W1-	1.90534×10^{3}	1.9046×10^{3}	1.9046×10^{3}	δ = 0.0388589 %
W+,W1->Z1,A	1.27772×10^{2}	1.2783×10^{2}	1.2783×10^{2}	δ = 0.0452054 %
Z,Z1>W+,W1-	4.94142×10^{2}	4.9443×10^{2}	4.9443×10^{2}	δ = 0.058226 %
G1,G1>G1,G1	1.45954×10^{5}	1.4616×10^{5}	1.4622×10^{5}	δ = 0.182272 %
G1,G>G1,G	9.53441×10^{4}	9.5424×10^{4}	9.5394×10^{4}	δ = 0.0837291 %

W1+,W1->e-,e+	1.55845×10^{-1}	1.5571×10^{-1}	1.5571×10^{-1}	δ = 0.0865344 %
G1,B1>u,u~	3.70629×10^{-1}	3.7095×10^{-1}	3.7103×10^{-1}	δ = 0.108077 %
G1,B1>d,d~	1.09204×10^{-1}	1.0907×10^{-1}	1.091×10^{-1}	δ = 0.122737 %
G1,Z1>u,u~	6.86623×10^{-1}	6.8809×10^{-1}	6.8824×10^{-1}	δ = 0.235185 %
G1,Z1>d,d~	6.89026×10^{-1}	6.8809×10^{-1}	6.8824×10^{-1}	δ = 0.136008 %
B1,e1R->A,e-	1.63934×10^{-1}	1.6393×10^{-1}	1.6393×10^{-1}	δ = 0.002401 %
Du1,Z1>G,u	2.06835	2.068	2.0683	δ = 0.0170034 %
Dd1,Z1>G,d	2.07017	2.068	2.0683	δ = 0.104961 %
Du1,Du1>u,u	9.13152	9.1361	9.1392	δ = 0.084122 %
Dd1,Dd1>d,d	9.13821	9.1361	9.1392	δ = 0.0339256 %
Du1,Du1~>u,u~	7.99093	7.9862	7.9893	δ = 0.0592671 %
Dd1,Dd1~>d,d~	7.97718	7.984	7.9871	δ = 0.124315 %
Su1,Su1>u,u	7.14921	7.1468	7.1495	δ = 0.037772 %
Sd1,Sd1>d,d	5.85953	5.8576	5.86	δ = 0.040964 %
Su1,Su1~>u,u~	8.38504	8.3857	8.3888	δ = 0.0447872 %
Sd1,Sd1~>d,d~	9.08126	9.0999	9.1031	δ = 0.240191 %
t1R-,t1R+>u,u~	1.10552×10^{-1}	1.1094×10^{-1}	1.1094×10^{-1}	δ = 0.350093 %
t1R-,t1R+>d,d~	3.27702×10^{-2}	3.2795×10^{-2}	3.2795×10^{-2}	δ = 0.0757631 %
t1R-,t1R+>tt-,tt+	2.55448×10^{-1}	2.5536×10^{-1}	2.5537×10^{-1}	δ = 0.0344615 %
t1R-,t1R+>A,A	2.07877×10^{-1}	2.0788×10^{-1}	2.0788×10^{-1}	δ = 0.00136955 %
t1R-,m1R->tt-,m-	6.58407×10^{-1}	6.5817×10^{-1}	6.5818×10^{-1}	δ = 0.0360216 %
e1R-,t1R+>e-,tt+	4.76616×10^{-1}	4.7681×10^{-1}	4.7681×10^{-1}	δ = 0.0407535 %
n13,n13~>t,t~	1.50282×10^{-1}	1.5043×10^{-1}	1.5043×10^{-1}	δ = 0.0983645 %
n12,n12~>c,c~	1.63453×10^{-1}	1.6354×10^{-1}	1.6354×10^{-1}	δ = 0.0531901 %

Tools for mUED

CalcHEP (again)

Belyaev, Brown, Moreno, Papineau (2013)



- Both in Feynman-'t Hooft gauge and unitary gauge
- KK states up to level '2'
- Complete Higgs sector

  (improved unitarity)
- Realising arbitrary mass splittings possible
- No running couplings

Tools for mUED

CalcHEP (again)

	Process	DKM σ [pb]	BBMP σ [pb]
1	$G^{(1)}\,G^{(1)} \to G\,G$	3.952×10^{1}	3.952×10^{1}
2	$G^{(1)}\,G \to G^{(1)}\,G$	7.600×10^{3}	7.600×10^{3}
* 3	$G^{(1)}\,G^{(1)} \to G^{(1)}\,G^{(1)}$	8.619×10^{3}	8.600×10^{3}
* 4	$G^{(1)}\,Z^{(1)} \to c\,\bar{c}$	2.132×10^{-1}	2.037×10^{-1}
* 5	$G^{(1)}\,\gamma^{(1)} \to b\,\bar{b}$	3.651×10^{-2}	3.249×10^{-2}
* 6	$\gamma^{(1)}\,\gamma^{(1)} \to t\,\bar{t}$	2.641×10^{-2}	2.758×10^{-2}
* 7	$Z^{(1)}\,Z^{(1)} \to d\,\bar{d}$	9.098×10^{-2}	9.165×10^{-2}
* 8	$Z^{(1)}\,Z^{(1)} \to W^{+}\,W^{-}$	9.293×10^{0}	9.288×10^{0}
* 9	$W^{+(1)}\,W^{-(1)} \to Z\,Z$	2.744×10^{0}	2.761×10^{0}
10	$W^{+(1)}\,W^{-(1)} \to Z\,\gamma$	1.653×10^{0}	1.653×10^{0}
*11	$W^{+(1)}\,W^{-(1)} \to W^{+}\,W^{-}$	3.152×10^{0}	3.081×10^{0}
12	$W^{+(1)}\,W^{-(1)} \to \gamma\,\gamma$	2.489×10^{-1}	2.489×10^{-1}
13	$Z\,\gamma \to W^{+(1)}\,W^{-(1)}$	1.028×10^{0}	1.028×10^{0}
*14	$Z^{(1)}\,Z^{(1)} \to W^{+(1)}\,W^{-(1)}$	7.240×10^{2}	7.210×10^{2}
*15	$Z\,Z^{(1)} \to W^{+}\,W^{-(1)}$	2.045×10^{2}	2.029×10^{2}
*16	$W^{+(1)}\,W^{-(1)} \to W^{+(1)}\,W^{-(1)}$	3.663×10^{2}	3.661×10^{2}
17	$W^{+}\,W^{-(1)} \to Z^{(1)}\,\gamma$	5.290×10^{1}	$P^{(1)}$ 1.016×10^{-1} $V^{(1)}$ 5.280×10^{1} total 5.290×10^{1}
*18	$W^{+}\,W^{-(1)} \to Z^{(1)}\,Z$	2.041×10^{2}	$P^{(1)}$ 3.940×10^{-1} $V^{(1)}$ 2.026×10^{2} total 2.029×10^{2}

Table 3.5: Sample of processes with two gauge bosons for cross-section comparison (in pb) between previous implementation ([35], DKM) and our implementation (BBMP) for partonic $\sqrt{s} = 2$ TeV. All final state particles are required to have transverse momenta greater than 100 GeV. Cross-sections are accurate to the number of significant figures shown. Asterisks highlight cross-sections that differ between models; differences are explained in the text.

Tools for mUED
WHIZARD

Model type	with CKM matrix	trivial CKM
QED with e,μ,τ,γ	–	`QED`
QCD with d,u,s,c,b,t,g	–	`QCD`
Standard Model	`SM_CKM`	`SM`
SM with anomalous couplings	–	`SM_ac`
SM with K matrix	–	`SM_km`
MSSM	`MSSM_CKM`	`MSSM`
MSSM with gravitino	–	`MSSM_Grav`
NMSSM	`NMSSM_CKM`	`NMSSM`
E_6 SSM	–	`PSSSM`
Littlest Higgs model	–	`Littlest`
Littlest Higgs model (ungauged $U(1)$)	–	`Littlest_Eta`
Simplest Little Higgs model	–	`Simplest`
Simplest Little Higgs (universal coupl.)	–	`Simplest_univ`
UED	–	`UED`
SM with Z'	–	`Zprime`
SM with graviton resonance	–	`Xdim`
SUSY toy model with gravitino	–	`GravTest`
SM as template	–	`Template`
[SM, all unitary gauge, `CompHEP` model	–	`SM_ug`]

Figure 4.2: Summary of models currently supported by `WHIZARD`.

There are more BSM models, whose inclusion into `WHIZARD` started from version 1.51 on:

Bounds on mUED

- Precision data: $R^{-1} \gtrsim 500\,\mathrm{GeV}$

  ACD (2002), Gogoladze, Macasenu (2006)

  Belanger, Belayev, Brown, Kakizaki, Papineau, Pukhov (2012 – 13)

- DM Relic Density: $R^{-1} < 1.3\,\mathrm{TeV}$

  Belanger, Kakizaki, Pukhov (2010)

- LHC (ATLAS): $R^{-1} > 1.4\,\mathrm{TeV}$

  arxiv:1209.0753

  * (from diphoton + MET) study: $\gamma^{(1)} \to \gamma\, G$

  * Fat brane scenario:

  * **Pythia 6 used**

Non-minimal UED

- An effective field theory approach:
  - Include terms consistent with required symmetries at the cut-off scale
- Comes in various forms
  - Non-vanishing BLTs at tree level (kinetic & Yukawa) (del Aguila, Perez-Victoria, Santiago)
  - Non-vanishing Bulk mass terms (split UED) (Park, Shu)
  - Non-vanishing BLT + Bulk mass terms (Flacke, Kong, Park)
  - Non-universal BLTs (Datta, Dey, Shaw, Raychaudhuri)
- Departure from mUED
  - Deviations in masses
  - Deviations in coupling strengths (overlap integrals)
  - Mixing of states from levels with identical KK parity

Non-minimal UED

The Action

$$S_{\text{NMQCD}} = S_{\text{quark}} + S_{\text{gluon}} + S_{\text{Yukawa}},$$

Non-minimal UED

Action

$$S_{\mathrm{NMQCD}} = S_{\mathrm{quark}} + S_{\mathrm{gluon}} + S_{\mathrm{Yukawa}},$$

$$S_{\mathrm{quark}} = \int d^4x \int_{-L}^{L} dy \sum_{i=1}^{3} \left\{ i\overline{U}_i \Gamma^M \mathcal{D}_M U_i + r_Q \Big(\delta(y-L) + \delta(y+L) \Big) \Big[i\overline{U}_i \gamma^\mu \mathcal{D}_\mu P_L U_i \Big] \right.$$

$$S_{\mathrm{gluon}} = \int d^4x \int_{-L}^{L} dy \left\{ -\frac{1}{4} G^a_{MN} G^{aMN} + \Big(\delta(y-L) + \delta(y+L) \Big) \Big[-\frac{r_G}{4} G^a_{\mu\nu} G^{a\mu\nu} \Big] \right\},$$

$$G^a_\mu(x,y) = \sum_{n=0}^{\infty} G^{a(n)}_\mu(x) f_{G_{(n)}}(y)$$

$$C_{X_{(n)}} = \cos\frac{M_{X_{(n)}}\pi R}{2}, \quad S_{X_{(n)}} = \sin\frac{M_{X_{(n)}}\pi R}{2}, \quad T_{X_{(n)}} = \tan\frac{M_{X_{(n)}}\pi R}{2}$$

Non-minimal UED

(Input parameters)

- nmUED with BLKTs & BLYTs
  - Coefficients of BLKTs (r_{EW}, r_Q, r_G)
  - Coefficients of BLYTs $(r_Y : \textit{important for the top quark sector})$
  - R^{-1}

- Features
  - Large mass-splits possible without radiative corrections (unlike in muED)
  - Large coupling deviations (w.r.t. mUED) possible
  - Large widths for resonances (fat) are possible

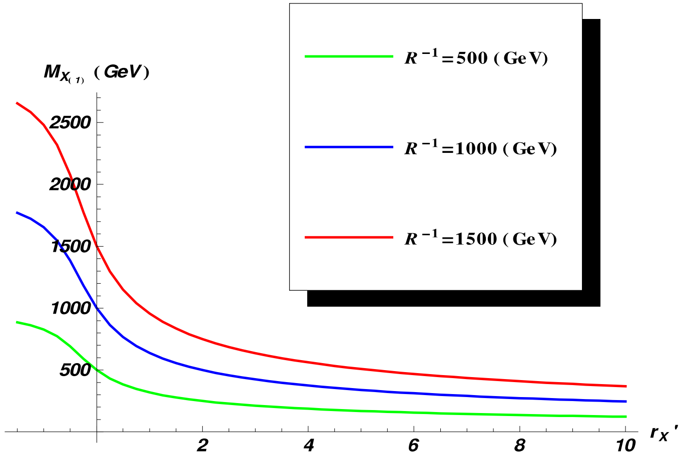
Functions of BLKT, BLYT coefficients & $\mathbf{R}^{-1}$

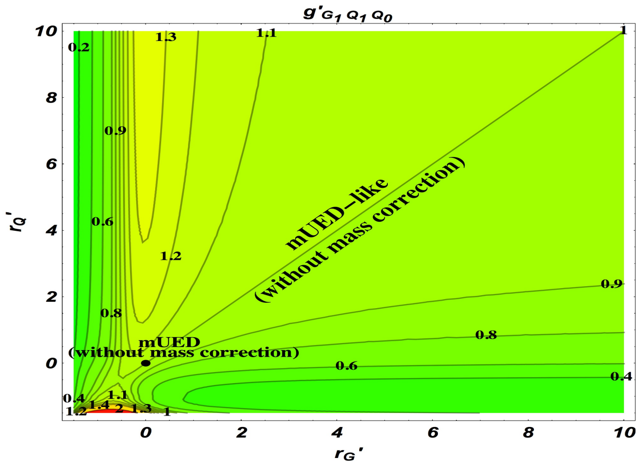
SUSY-UED confusion becomes complete

(modulo observations of a gauge boson resonance)

Non-minimal UED

(Masses & Couplings)





$$r'_X M'_{X_{(n)}} = \begin{cases} -T_{X_{(n)}} & \text{for } n \text{ even} \\ 1/T_{X_{(n)}} & \text{for } n \text{ odd} \end{cases}$$

$$r'_X = r_X R^{-1}, \quad M'_X = M_X/R^{-1}$$

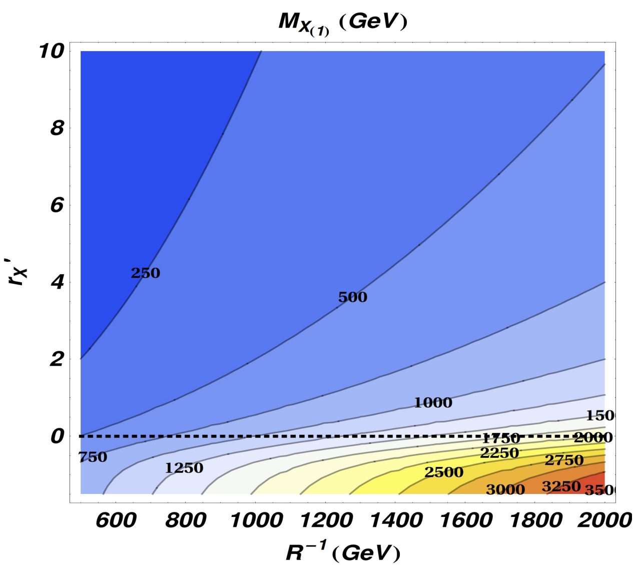
AD, Nishiwaki, Niyogi (2012, 2013)

$$g'_{G_1 Q_1 Q_0} \equiv \frac{1}{N_{G(0)}} \int_{-L}^{L} dy \Big(1 + r_Q \delta(y-L) + \delta(y+L)\Big) f_{G_{(1)}} f_{Q_{(1)}} f_{Q_{(0)}}$$

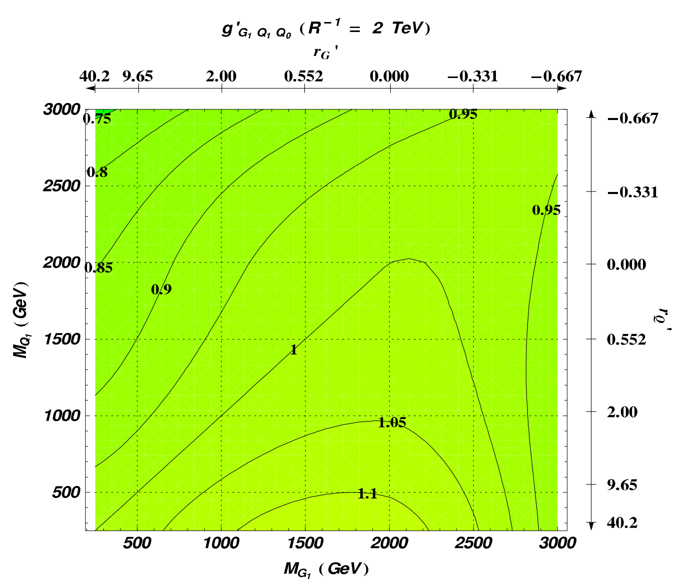
$$= \frac{N_{Q_{(0)}}}{N_{G_{(0)}}} \frac{N_{G_{(1)}} N_{Q_{(1)}}}{S_{G_{(1)}} S_{Q_{(1)}}} \left[2 r_Q S_{G_{(1)}} S_{Q_{(1)}} - \frac{\sin((M_{Q_{(1)}} + M_{G_{(1)}}) \frac{\pi R}{2})}{M_{Q_{(1)}} + M_{G_{(1)}}} + \frac{\sin((M_{Q_{(1)}} - M_{G_{(1)}}) \frac{\pi R}{2})}{M_{Q_{(1)}} - M_{G_{(1)}}} \right]$$

Non-minimal UED

(Masses and Couplings)



r'_X	$M'_{X_{(1)}}$	$M_{X_{(1)}}$ (GeV) (for $R^{-1} = 1000\,\text{GeV}$)
-1.5	1.771	1771
-1.0	1.654	1654
-0.5	1.386	1386
0.0	1.000	1000
0.5	0.767	767
1.0	0.638	638
2.0	0.500	500
5.0	0.339	339
10.0	0.246	246



AD, Nishiwaki, Niyogi (2012, 2013)

$g'_{G_1 Q_1 Q_0}$	R^{-1} (TeV)	$M_{G_{(1)}}$ (GeV)	$M_{Q_{(1)}}$ (GeV)
0.85	2	835.1	2724.3
	3	840.9	2407.6
	5	1246.1	2819.1
1.1	2	1820.0	500.0
	3	2019.5	1036.0
	5	2121.7	989.6

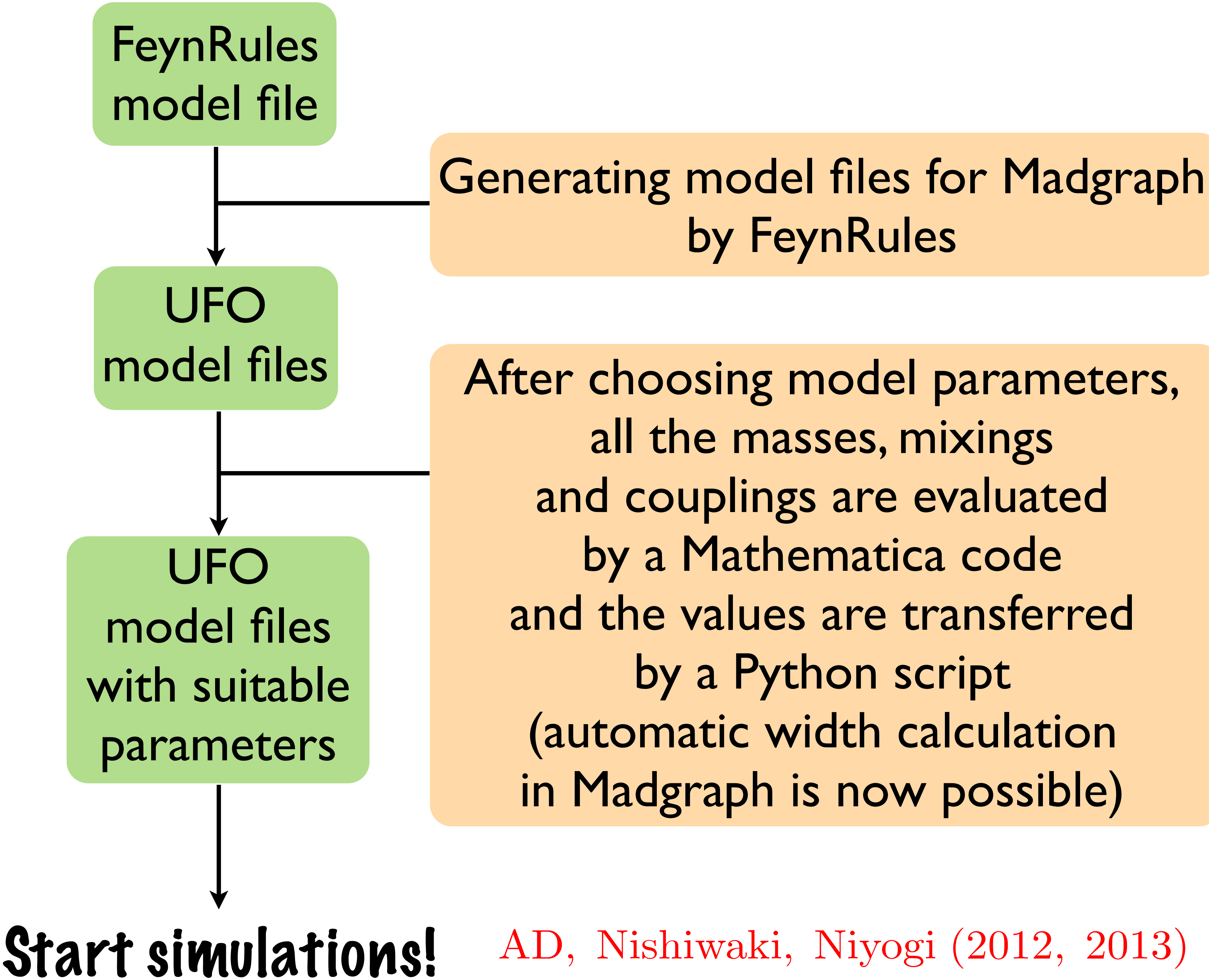
Non-minimal UED

(The case with the EW gauge bosons)

- EWPT constraint $\Rightarrow r_B \simeq r_W \simeq r_{EW}$
  - Leads to near-degenerate spectrum at each KK level
  - Limited implications for colliders

- Radiative corrections could split the masses.
  - Efficient masquerading of SUSY !

- $B^{(2)}, Z^{(2)}, W^{(2)\pm}$ have tree-level couplings to a pair of SM fermions
- May result in large decay widths
  - Large masses, reasonable couplings, large number of possible decay modes



AD, Nishiwaki, Niyogi (2012, 2013)

Non-minimal UED
(Madgraph-5 implementation via Feynrules)

- Already have — AD, Nishiwaki, Niyogi 2012--'13
  - Fermions, gauge and Higgs bosons: upto KK level 2
  - Unitary gauge
  - Tree level couplings including the KK-number violating ones
  - Sequential CKM (a good approximation)
  - Level mixing between level '0' and '2'

- Work in progress
  - Higgs self couplings
  - Treatment for broad level '2' gauge boson resonances
  - Radiative corrections to the level '1' gauge boson masses

UED with Bulk mass and Brane terms

- **A more general setup** (Kong, Flacke, Park ; 2013)
  - Vectorlike masses for the bulk fermion (Split UED)
    - Consistent with 5D Lorentz invariance
  - Boundary (brane) localized terms (non-minimal UED)
    - Consistent with 4D Lorentz symmetry
- **Two additional paramteres** (beyond those in mUED)
  - A universal fermionic bulk mass parameter (increases the masses)
  - A universal brane coefficient (decreases the masses)
- **Studied:**

  * Mass spectra * Interactions * EW, DM and LHC constraints

- **An overall rich phenomenology is recognized**
- **But not yet any public code available**

Conclusions

- Most event generators can now work with mUED
- A general opportunity to validate collider analyses
- Use published LHC (SUSY and other) results to constrain mUED

or

! Simply **reweight** events with correct mUED matrix elements !

Gainer, Lykken, Matchev, Mrenna, Park; arxiv:1404.7129)

- Possible **level '2' resonances** would be very welcome additions
- Non-minimal editions would offer more leg-room to UED
- Keep subjecting analyses to robust and related experimental constraints