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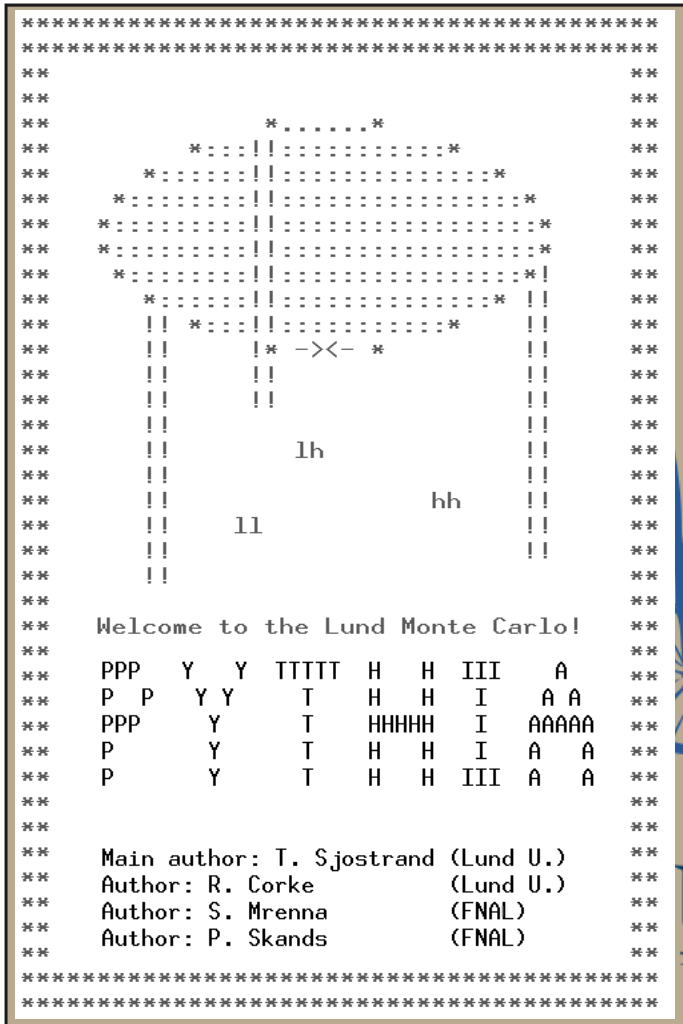
# Status of BSM in Pythia 8




## MC4BSM 09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**Outline:**

- Overview
- BSM overview, available processes and related features
- Development within SUSY
- Development within extra dimensions and unparticles

April 3–4, 2009

UC DAVIS
UNIVERSITY OF CALIFORNIA

Website: http://particle.physics.ucdavis.edu/workshops/doku.php
Email: mc4bsm@particle.physics.ucdavis.edu
Organizers: Hsin-Chia Cheng, John Conway, Robin Erbacher, Christophe Grojean, Jack Gunion, Markus Luty, Konstantin Matchev, Steve Mrenna, Maxim Perelstein, Peter Skands, John Terning

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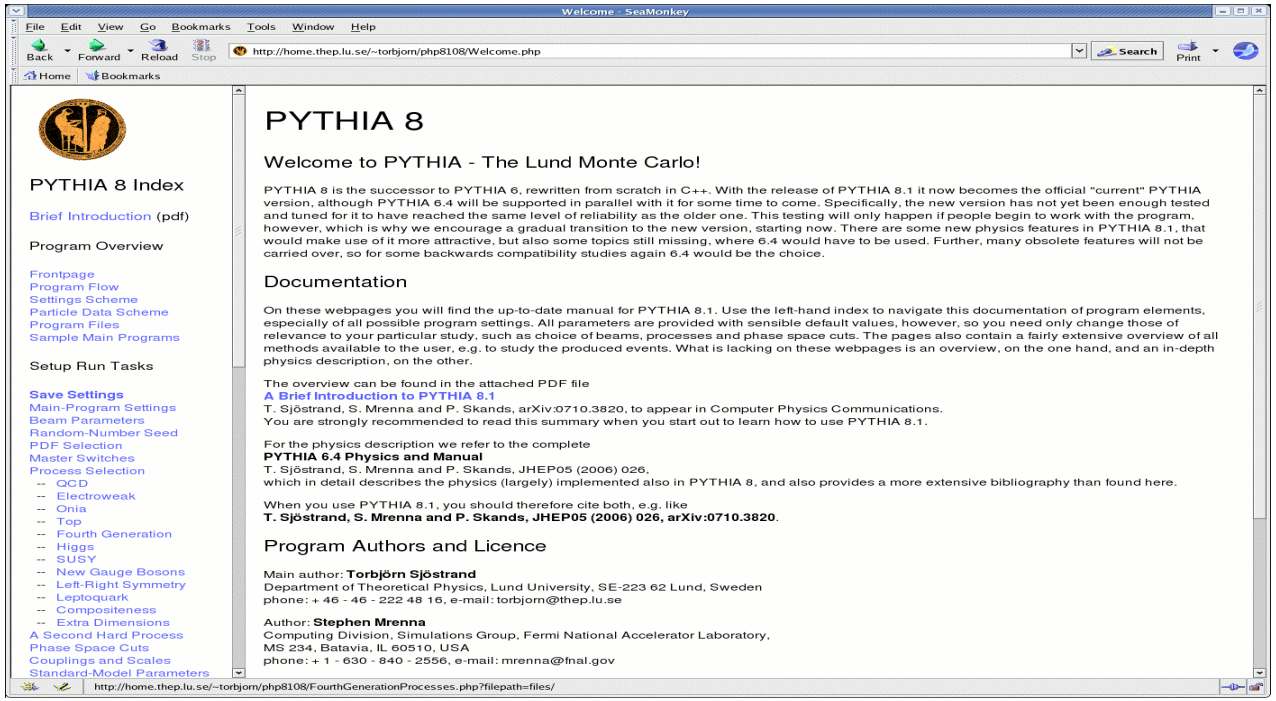
# Overview

- Pythia v8.1 (C++) was released Oct 2007.
- Latest version: Pythia v8.120 (11 March 09).
- The physics content should be at the same level or improved with respect to Pythia 6.
- However, tuning from experimental data remains!
- The initial focus have been on SM physics.
- This talk will focus on the BSM processes and especially the most recent BSM developments.

Process Selection
- QCD
- Electroweak
- Onia
- Top
- Fourth Generation
- Higgs
- SUSY
- New Gauge Bosons
- Left-Right Symmetry
- Leptoquark
- Compositeness
- Extra Dimensions

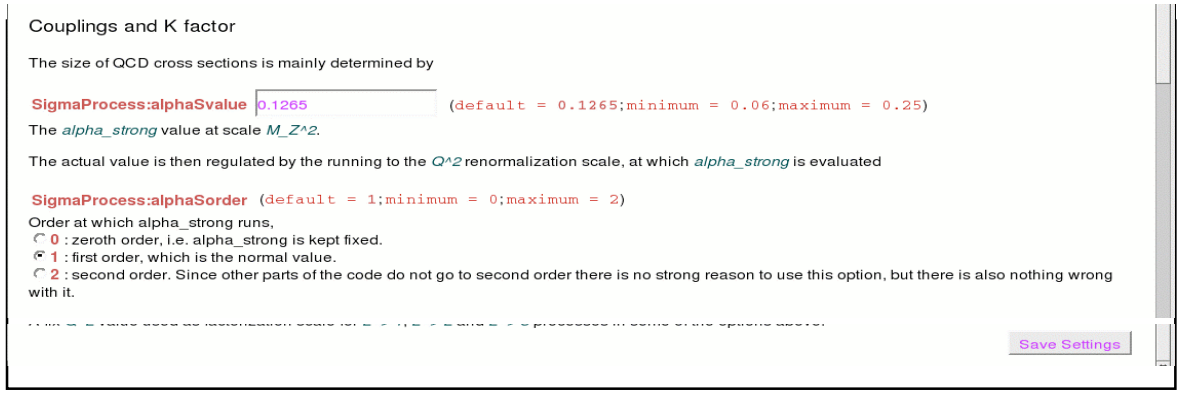
# Interactive Online Manual




Available on the pythia webpage and distributed with the code.

When generated, the parameters and default settings are taken from the same (.xml) source as by the program when running.

Can be used to produce setting files interactively.



# BSM Overview

- Currently a little bit of each, ~ Pythia 6 - SUSY - TC + ED/U.
- Recent BSM developments are mainly in SUSY and extra dimension/unparticle (ED/U) sections.

- BSM processes are mainly based on LO matrix elements.
- Higher order corrections are often available to produce dedicated samples for the high-$p_T$ tail region.
- These normally implies double counting if they are combined with unbiased bulk processes.
- Proper matching between ISR and LO + 1 jet ME exist in some cases.

- This corresponds to a relatively large variety of BSM processes. Where normally the couplings and masses have to be determined externally (separates processes and models).

-- Fourth Generation
-- Higgs
-- SUSY
-- New Gauge Bosons
-- Left-Right Symmetry
-- Leptoquark
-- Compositeness
-- Extra Dimensions

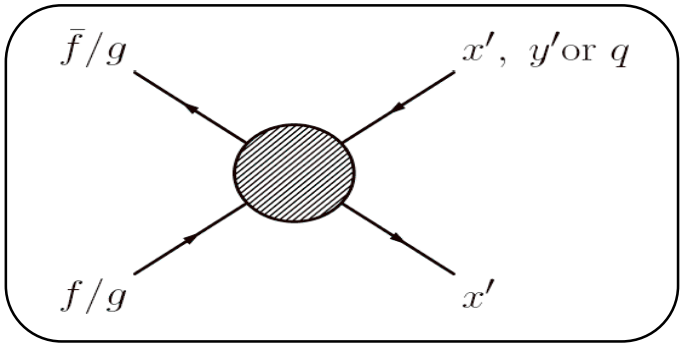
# Available BSM Processes

## Fourth Generation

Production of fourth generation quarks and leptons

Provide a template for models with new particles with similar characteristics

Include most quark scenarios (x = t,b):




and one lepton scenario: $f\bar{f} \to \tau'\nu'$

Parameters:
- Masses
- 4th generation CKM matrix elements

## One/Two Higgs Doublets

($H_{i=1-3}$ = physical states of the h, H and A fields)

Contains:
- The standard set of SM processes
- Single $H_i$ and $H^{+/-}$ production
- $H_i$ and $H^{+/-}$ pair production
- Higher order processes for high-$p_T$ samples

Parameters:
- Higgs mass(es)

(SM)
- Higgs width parameters (**cubicWidth** and **runningLoopMass**)

(BSM)
- Individual couplings to the SM particles
- SUSY couplings will be given by SLHA
- tan(β)
- Scalar / pseudo-scalar mixing, including CP violating interference

# Available BSM Processes

## New Gauge Bosons

From a new SU(2) or U(1) gauge group

### Z':

Z' production with Z and/or $\gamma^*$ interference

No dedicated high-pT processes, but proper matching of ISR to the Z'+1 jet ME

Parameters:
- $g_v$ / $g_a$ couplings for any fermion
- WW coupling + decay-angle parameter

### W':

Same as for Z' but with less $g_v$ / $g_a$ flexibility

### $R^0$ ("Horizontal" gauge boson):

Only mass parameter

## Left-Right Symmetry

New SU(2)_R gauge group and extended Higgs sector

Contains:
- Production of $W_R$ and $Z_R$
- Production of $H^{++/--}$
- Allow for right handed neutrino decays and cascade decays depending on mass hierarchy

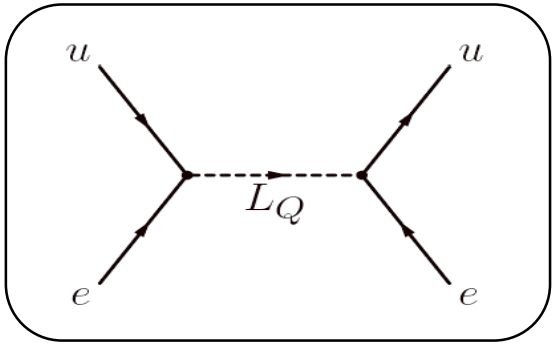
Other Higgs processes controlled by 2HD category

Parameters:
- Masses
- $g_L$, $g_R$ and Higgs couplings
- $v_L$ Vacuum Expectation Value

# Available BSM Processes

## Leptoquark

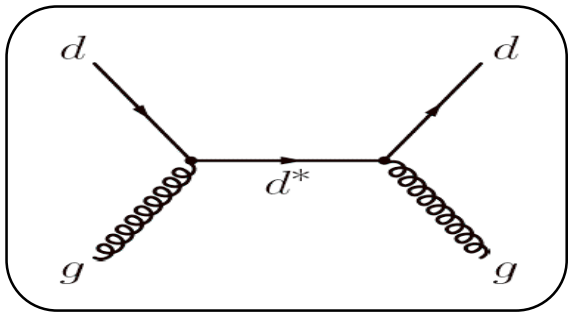
Production of a scalar leptoquark
(Conserved, but variable flavors)




Parameters:
- Mass
- Coupling

## Compositeness

Production of excited leptons and quarks
(and anomalous couplings)




Parameters:
- Masses
- Coupling
- Compositeness scale

# Links to External Programs

## Les Houches Accord (LHA)

- Interface for parton-level event files from ME event generators, using Les Houches Event File (LHEF) standard, *J. Alwall et al., CPC 176 (2007) 300.*
- Then Pythia 8 takes care of the following parton- and hadron-level generation.

## SUSY LHA

- Provide interface for SUSY spectrum and couplings.
- For example from Isasusy, Spheno, SoftSusy, Suspect.

## Semi-internal processes (or decays)

- Possibility to implement a new parton-level process.
- Based on the differential cross section, $d\sigma/dt$.

## Runtime interfaces

- Possibility to use both Fortran and C++ programs

Also possible to use external PDFs, external decay and/or parton shower software, so-called user-hooks, external random generators, HepMc format etc…

# Semi-Internal Process

```
class Sigma2ffbar2UZ : public Sigma2Process {

public:
  //+++ Constructor.
  Sigma2ffbar2UZ( int, bool, double, double, double, double );
  //+++ Destructor.
  ~Sigma2ffbar2UZ(){};

  //+++ Initialize process.
  virtual void initProc();
  ……

  //+++ Info on the subprocess.
  virtual string name()       const {return "f fbar -> U Z";}
  virtual int    code()       const {return 10001;}
  virtual string inFlux()     const {return "ffbarSame";}
  virtual int    id3Mass()    const {return 39;}    // G-code
  virtual int    id4Mass()    const {return 23;}
  virtual int    resonanceA() const {return 23;}
  virtual int    gmZmode()    const {return 2;}

private:
……

};
```

```
int main() {

  ……

  //+++ Pythia generator.
  Pythia pythia;

  SigmaProcess* sigma2ffbar2UZ = new Sigma2ffbar2UZ(spin, GRAVITON, dU, LambdaU, lambda, ratio);
  pythia.setSigmaPtr(sigma2ffbar2UZ);
  ……
  …

}
```

Inherits from a 2-to-2 scattering base class.

The user code is conveniently separated from the main Pythia library.

The class structure of the parton level process is the same as the internal processes.

Therefore it is used just as an internal Pythia process.

And the internal processes serves as nice templates/examples!

# Supersymmetry

## Available in v8.120

**P. Skands**

- Only groups of processes can be turned ON/OFF.
- All masses and couplings are given to Pythia 8 by SLHA1 or SLHA2 files.
- Currently only gaugino pair production (LO) is available,

```
SUSY:qqbar2chi0chi0 ◯ On ◉ Off (default = off)
SUSY:qqbar2chi+-chi0 ◯ On ◉ Off (default = off)
SUSY:qqbar2chi+chi- ◯ On ◉ Off (default = off)
```

Processes related to an extended Higgs sector is kept in the Higgs section

- Allows for non-minimal flavour and/or CP violation.
  Follows the conventions of, *G. Bozzi et al., NPB 787 (2007) 1.*

## In Progress

- Squark, gluino and slepton production processes, using the same general SUSY 2->2 structure as developed for the gaugino processes.
- Decays, initially based only on phase space and externally computed total widths from BSM-LHEF or SLHA DECAY tables. Later including the matrix elements.
- Only R-parity conserving processes to start with.

# LED Graviton and Unparticle Processes

From a phenomenology point of view, unparticle emission and virtual unparticle exchange is often a generalization of the similar graviton processes in large extra dimensions (LED). So both can be covered by the same implementation!

**Unparticle (U) model parameters in Pythia8**

*K.Cheung, W.Y.Keung & T.C.Yuan, PRD 76 (2007) 055003.*

$d_U$ = scale dimension parameter.
$\Lambda_U$ = unparticle renormalization scale.
$\lambda$ = universal coupling between U and SM operators.

**Graviton (G) process obtained from spin-2 U formulas**

- Uses the same cross section and ME code (whenever possible).
- Only change (two) constant factors,
  e.g. G emission,

$$d_U = \frac{n}{2} + 1$$ n = integer nr of extra dimensions

$$A(d_U) \leftrightarrow S(n)$$ phase space factors fixed by $d_U$ or n

$$\Lambda_U = M_D$$ scale of gravity in D = 4 + n dimensions

$$\lambda_1 = \lambda_2 = 1$$

# Z/gamma + G/U Emission

## Available in v8.120

**ExtraDimensions LED / Unpart :**
**ffbar2GZ, ffbar2Ggamma,**
**ffbar2UZ, ffbar2Ugamma,**

$$\frac{d\sigma}{dm_U^2 dt} = \frac{|M|^2}{2 \cdot 16\pi^2 \cdot s^2} \frac{A_{d_U}}{\Lambda_U^2} \left(\frac{m_U^2}{\Lambda_U^2}\right)^{d_U - 2} \theta(p_U^0)\theta(m_U^2)$$

Checked against LED papers

*G.F. Giudice, R. Rattazzi, J.D. Wells, NPB 544 (1999) 3.*

*E.A. Mirabelli, M. Perelstein, M.E Peskin, PRL 82 (1999) 2236.*

*G.F. Giudice, T. Plehn, A. Strumia, NPB 706 (2005) 455.*

- The variable U/G mass spectrum solved by re-weighting a Breit-Wigner (BW) spectrum available in Pythia. The MC efficiency depends on how well the BW shape overlaps with the cross section (only affect generation speed!).
- Production of gamma + G/U events corresponds to the photon limit of the Z + G/U process.
- A truncation switch was implemented to check the validity of the effective theory.

Further documentation of how G/U emission was implemented in Pythia 8 is found in:

*SA, EPJC 60 (2009) 509.*

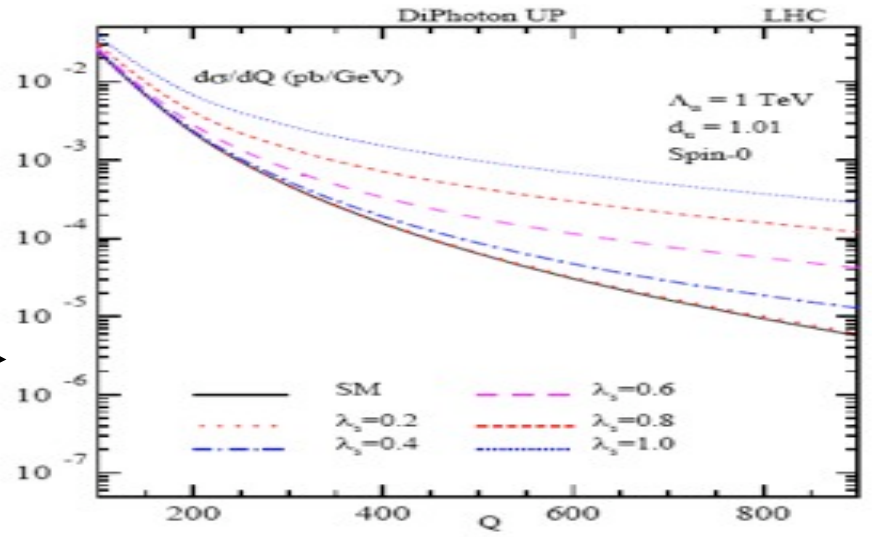
# 2 gamma from virtual G*/U* exchange

## Available in v8.120

**ExtraDimensions LED / Unpart:**
**ffbar2gammagamma, gg2gammagamma**

- Uses the U matrix elements in,

*M.C. Kumar, P. Mathews, V. Ravindran, A. Tripathi, PRD 77 (2008) 055013.*

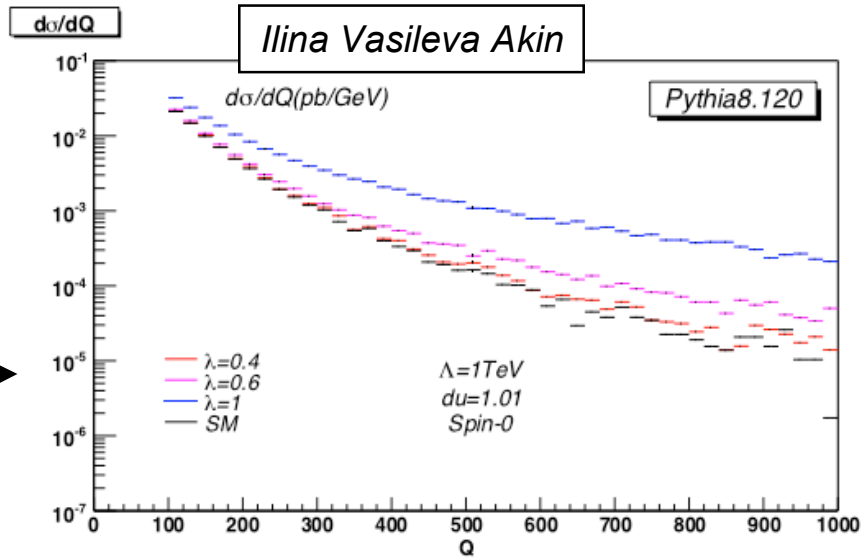



- Graviton ME obtained by,

$$d_U = 2$$
$$\Lambda_U = \Lambda_T$$
$$\lambda^2 \cdot \chi = 4\pi$$

*G.F. Giudice, R. Rattazzi, J.D. Wells, NPB 544 (1999) 3.*

- Validation of these processes was done by Ilina Vasileva Akin (CMS).



# (mono) Jet + G/U Emission

## G: Available in v8.120

**ExtraDimensionsLED:**
**gg2Gg**, **qg2Gq**, **qqbar2Gg**

## U: In progress

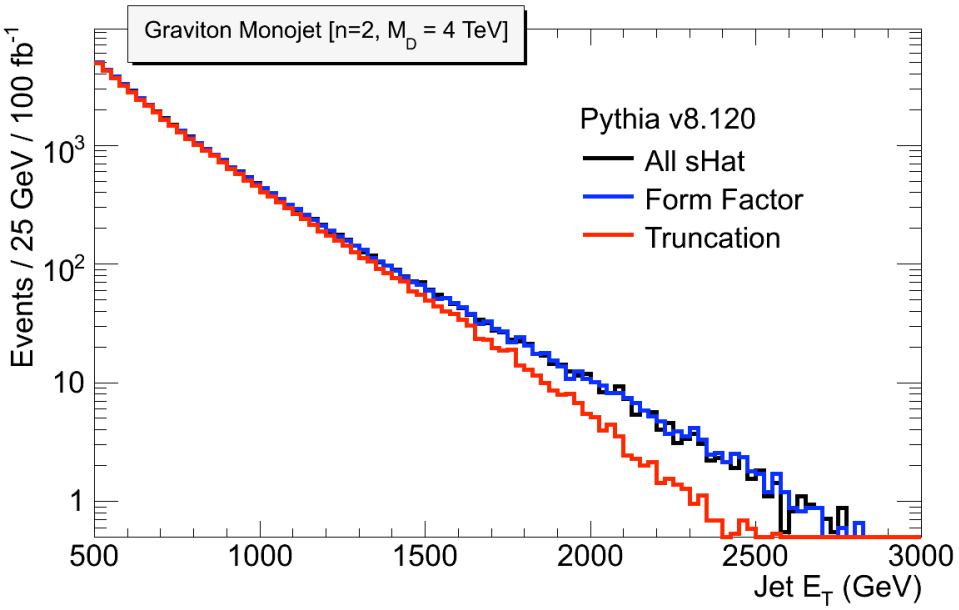
**ExtraDimensionsUnpart:** (spin-1 and spin-0)
**gg2Ug**, **qg2Uq**, **qqbar2Ug**

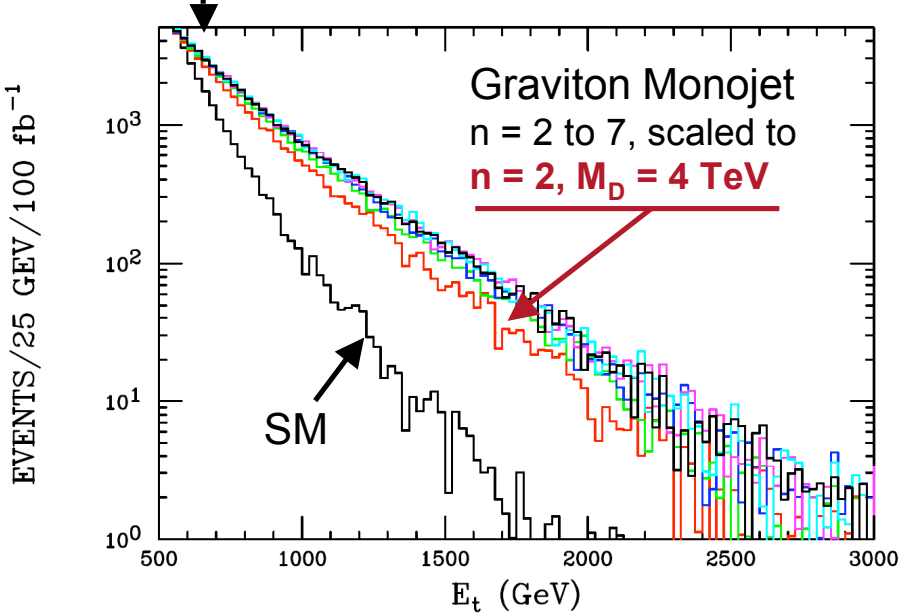
- No spin-2 U ME available (as far as I know ?), so only, G / spin-1 U / spin-0 U, will be implemented.
- Validation just started in collaboration with Albert De Roeck et al. (CMS).

*G.F. Giudice, R. Rattazzi, J.D. Wells, NPB 544 (1999) 3.*

*K.Cheung, W.Y.Keung, T.C.Yuan, PRD 76 (2007) 055003.*

*T. G. Rizzo, PLB 665 (2008) 361.*



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# Form Factor for the Gravity Coupling

## In progress

- A realistic alternative for the G emission (G* exchange) processes when sHat approaches $M_D$.
- Obtained from RGEs in a particular scenario of quantum gravity.
- Could restore unitarity of G scattering at high energy and possibly also be tested at the LHC in the case of a signal.

$$F(t, M_D) = \left[1 + \left(\frac{\mu^2}{t^2 M_D^2}\right)^{1+\frac{n}{2}}\right]^{-1}$$

*J. L. Hewett, T. G. Rizzo, JHEP 0712 009 (2007)*

Gravitational coupling damped at higher energies (μ).

**Configurable parameters**

μ = renormalization scale,

- **SigmaProcess:renormScale2**, e.g. $p_T^2 + min(m_3^2, m_4^2)$, $\sqrt{\hat{s}}$ ...
- In the case of G emission also possible to use, $E^*_{jet}$ (* = center-of-mass frame)

t = O(1) "free" parameter (related to the RGE details).
Should be < 2 to preserve unitarity in 2-to-2 G scattering.

For U*/G* exchange: $tM_D \rightarrow t'\Lambda_T$

# KK Graviton Resonance

## G: Available since pre-v8.120

**ExtraDimensionsG*:**
**gg2G***, **ffbar2G***
**gg2G*g**, **qg2G*q**, **qqbar2G*g** (for the high-$p_T$ tail)

- KK Graviton resonance in the traditional RS model with the SM on the TeV brane.

**Two parameters**

Graviton mass, $m_G$

Graviton - SM coupling, $\kappa_{mG} = \frac{\sqrt{2}xk}{\bar{M}_P} = \frac{e^{kr\pi}}{\bar{M}_P} \cdot \sqrt{2}m_G$

- Plan to extend this for models with SM in the bulk (**just started**).
- Flavor dependent coupling to the graviton.
- Other resonances…

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# Trying Out Pythia 8

- Goto: http://home.thep.lu.se/~torbjorn/Pythia.html

- Download the file: `pythia8120.tgz` and follow the instructions (both given at the webpage and in the README file provided with the code).
- It contains:
  - The interactive online manual.
  - **More than 30 "main program" examples** including, standalone running, how to use external programs, semi-internal processes etc…
  - and more…

- Further documentation:
  - T. Sjostrand, S. Mrenna and P. Skands, *A Brief Introduction to PYTHIA 8.1*, Comp. Phys. Comm. 178 (2008) 852. [arXiv:0710.3820]
  - T. Sjostrand, S. Mrenna and P. Skands, *PYTHIA 6.4 Physics and Manual*, JHEP 0605 (2006) 026. [hep-ph/0603175]

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# Conclusions

- Pythia 8.120 contains approximately the BSM physics in Pythia 6 - SUSY - TC + ED/U.

- SUSY in progress. Allow NMFV and CPV processes.
- LED and U processes implemented together whenever possible.
- G/U emission and G*/U* exchange processes available in Pythia v8.120.

- In addition, there are several possibilities to use it together with external programs, e.g. external BSM input from
  - LHA interface for parton-level event files from ME generators.
  - SUSY LHA interface for spectrum and couplings.
  - Semi-internal process to implement a new parton-level process based on $d\sigma/dt$ formula.

**And…**

# UED in Pythia 6

- One TeV$^{-1}$ sized universal extra dimension. Covers, *n* = 1, first SM KK excitations.
- *N* eV$^{-1}$ sized extra dimensions where only gravity propagates ($M_D$ = a few TeV).
- Mass spectrum calculated at one-loop level.
- Iso-doublet / -singlet mixing neglected (should only be relevant for top sector).

**One Universal Extra Dimension in PYTHIA**

M. ElKacimi[1], D. Goujdami[1], H. Przysiezniak[2*], P. Skands[3]

[1] Université Cadi Ayyad, Faculté des Sciences Semlalia, B.P. 2390, Marrakech, Maroc
[2] Laboratoire René-J.-A.-Lévesque, Université de Montréal, C.P. 6128, Montréal (Québec), H3C 3J7, Canada, and IN2P3/CNRS, France
[3] Fermilab MS106, Batavia IL-60510-0500, USA

**Abstract**

The Universal Extra Dimensions model has been implemented in the PYTHIA generator from version 6.4.18 onwards, in its minimal formulation with one TeV$^{-1}$ sized extra dimension. The additional possibility of gravity-mediated decays, through a variable number of eV$^{-1}$ sized extra dimensions into which only gravity extends, is also available. The implementation covers the lowest-lying Kaluza-Klein (KK) excitations of Standard Model particles, except for the excitations of the Higgs fields, with the mass spectrum calculated at one loop. $2 \to 2$ tree-level production cross sections and KK number conserving 2-body decays are included. Mixing between iso-doublet and -singlet KK excitations is neglected thus far, and is expected to be negligible for all but the top sector.

*arXiv:0901.4087v1 [hep-ph]*

Plan to start the implementation in Pythia 8 at the 2009 Les Houches meeting


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# Hard Processes

| ProcessGroup | ProcessName |
|---|---|
| SoftQCD | minBias,elastic, singleDiffractive, doubleDiffractive |
| HardQCD | gg2gg, gg2qqbar, qg2qg, qq2qq, qqbar2gg, qqbar2qqbarNew, gg2ccbar, qqbar2ccbar, gg2bbbar, qqbar2bbbar |
| PromptPhoton | qg2qgamma, qqbar2ggamma, gg2ggamma, ffbar2gammagamma, gg2gammagamma |
| WeakBosonExchange | ff2ff(t:gmZ), ff2ff(t:W) |
| WeakSingleBoson | ffbar2gmZ, ffbar2W, ffbar2ffbar(s:gm) |
| WeakDoubleBoson | ffbar2gmZgmZ, ffbar2ZW, ffbar2WW |
| WeakBosonAndParton | qqbar2gmZg, qg2gmZq, ffbar2gmZgm, fgm2gmZf qqbar2Wg, qg2Wq, ffbar2Wgm, fgm2Wf |
| Charmonium | gg2QQbar[3S1(1)]g, qg2QQbar[3PJ(8)]q, ... |
| Bottomonium | gg2QQbar[3S1(1)]g, gg2QQbar[3P2(1)]g, ... |
| Top | gg2ttbar, qqbar2ttbar, qq2tq(t:W), ffbar2ttbar(s:gmZ), ffbar2tqbar(s:W) |
| FourthBottom | gg2bPrimebPrimebar, qq2bPrimeq(t:W) , ... |
| FourthTop | qqbar2tPrimetPrimebar, fbar2tPrimeqbar(s:W), ... |
| FourthPair | ffbar2tPrimebPrimebar(s:W), fbar2tauPrimenuPrimebar(s:W) |
| HiggsSM | ffbar2H, gg2H, ffbar2HZ, ff2Hff(t:WW), ... |
| HiggsBSM | h, H and A as above, charged Higgs, pairs |
| SUSY | qqbar2chi0chi0 (SUSY barely begun) |
| NewGaugeBoson | ffbar2gmZZprime, ffbar2Wprime, ffbar2R0 |
| LeftRightSymmmetry | ffbar2ZR, ffbar2WR, ffbar2HLHL, ... |
| LeptoQuark | q12LQ, qg2LQ1, gg2LQLQbar, qqbar2LQLQbar |
| ExcitedFermion | dg2dStar, qq2uStarq, qqbar2muStarmu, ... |
| ExtraDimensionsG* | gg2G*, qqbar2G*, ... |