# *Beyond the SM at the LHC with Pythia8*

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# General Introduction

***Pythia v8.1 (C++)***

First released: Oct 2007

Current version: Pythia v8.135

The physics content should be at the same level or improved with respect to Pythia 6.

However, tuning from experimental data just started!

The initial focus has been on SM (QCD) physics and to provide large flexibility to use it with external (specialised) programs.

BSM processes can hence be simulated by using external programs together with Pythia8, but as a complement Pythia8 will also contain an internal library of common BSM processes.

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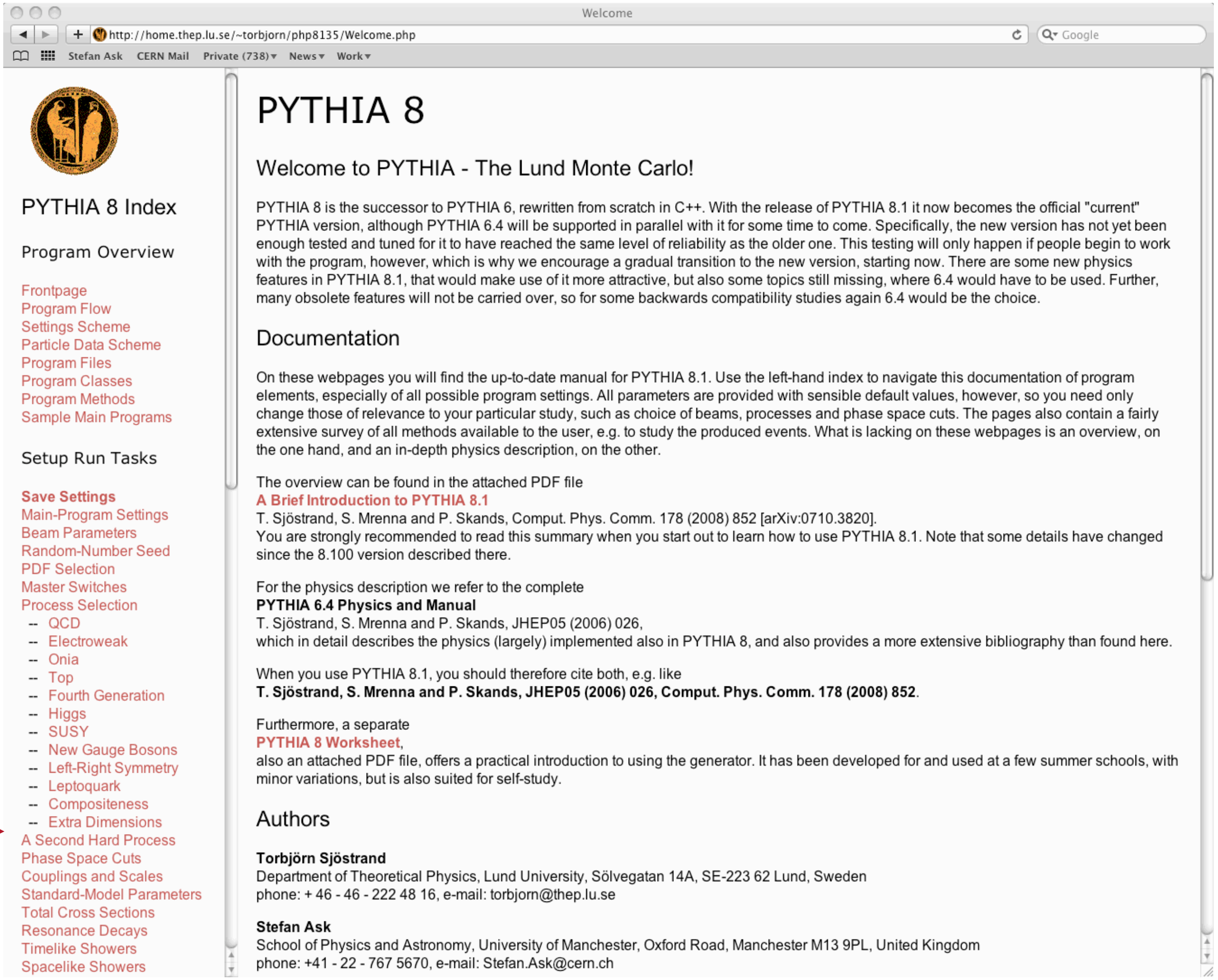
# Documentation and Online Manual

Available from the Pythia webpage and distributed with the code.

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.

Different sections of the manual



***Currently a little bit of each***

*Pythia8 BSM ~ Pythia 6 - SUSY - TC + ED/U*

This corresponds to a relatively large variety of BSM processes.

Recent BSM developments are mainly in SUSY and extra dimension (ED) sections.

Will mainly focus on extra dimension section, which also include some related unparticle processes.

**Pythia8**

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

BSM Related Sections

# Overview of BSM in Pythia8

***The processes contains***

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 rare cases.

Couplings and masses normally have to be determined externally. In order to separate processes and models.

**Pythia8**

Process Selection
- -- QCD
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- -- Extra Dimensions

BSM Related Sections

# 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…

# *---- General BSM Updates ----*

## In Progress!

- Only groups of processes can be turned ON/OFF.
- All masses and couplings are given to Pythia 8 by SLHA1 or SLHA2 files.
- Currently gluino, squark, neutralino and chargino pair production (LO) is available, e.g.
  **SUSY:gg2gluinogluino**
  **SUSY:qqbar2gluinogluino**
  **SUSY:qg2squarkgluino**
  etc.

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

- Allows for non-minimal flavour and/or CP violation.

*G. Bozzi et al., NPB 787 (2007) 1.*

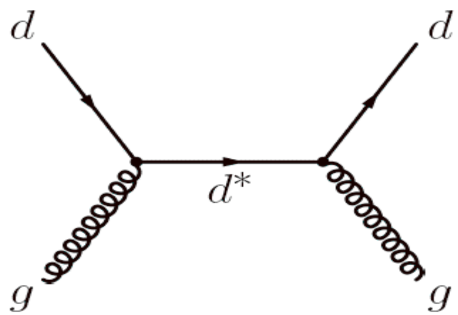
### *Remaining*

- Direct slepton production processes, using the same general SUSY 2->2 structure as developed for the above 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.

# *Compositeness*

### *Already Available*

Available since 8.100, production of excited leptons and quarks.




Excited fermion produced either by gauge or contact interactions.

### *In Progress!*

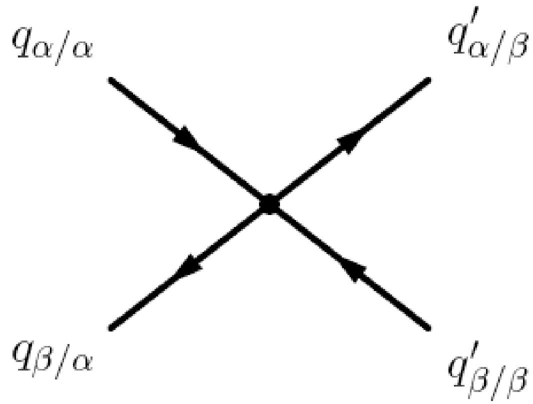
***Contact Interactions from Quark Compositeness*** (*Tomas Davidek*)

Including all 2 to 2 quark scattering processes with u,d,s,c,b in final state.

$$\mathcal{L} \supset \frac{2\pi}{\Lambda}\ \eta_{\alpha\beta}\ (\bar{q}\gamma^{\mu}P_{\alpha}q)(\bar{q}\gamma_{\mu}P_{\beta}q)$$

$$\eta_{\alpha\beta} = 0,\ 1,\ -1$$

$$\alpha,\ \beta = L,\ R$$




***Parameters***

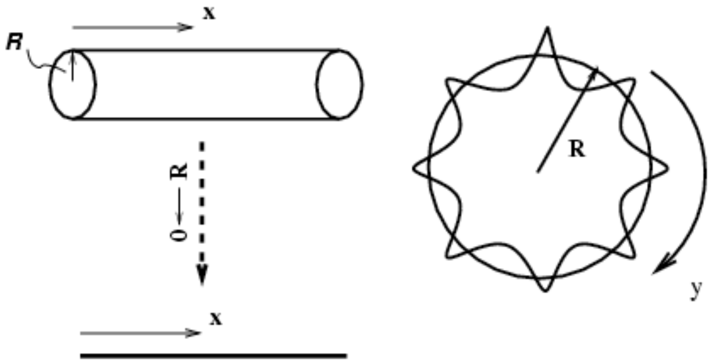
- Helicity parameters: **`etaLL, etaRR, etaLR`**
- Compositeness scale: **`Lambda`**

*---- Extra Dimensions ----*

*(and their relation to Unparticles)*

# Large Extra Dimension (LED) Scenario

## Reminder: Compactified Extra Dimension




- Momentum modes in ED give KK tower.
- Large ED give dense KK states, i.e. effectively continuous mass distribution.
- ED phase space could compensate small gravitational coupling (aka ADD scenario).

*N. Arkani-Hamed, S. Dimopoulos, G. Dvali, PLB 429 (1998) 263*

## LED model parameters in Pythia8

n = integer nr of large extra dimensions.
$M_D$ = scale of gravity in D = 4 + n dimensions.
$\Lambda_T$ = cut-off scale for virtual G exchange.

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

## other popular conventions

$$M^{n+2} = 2M_D^{n+2}$$

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

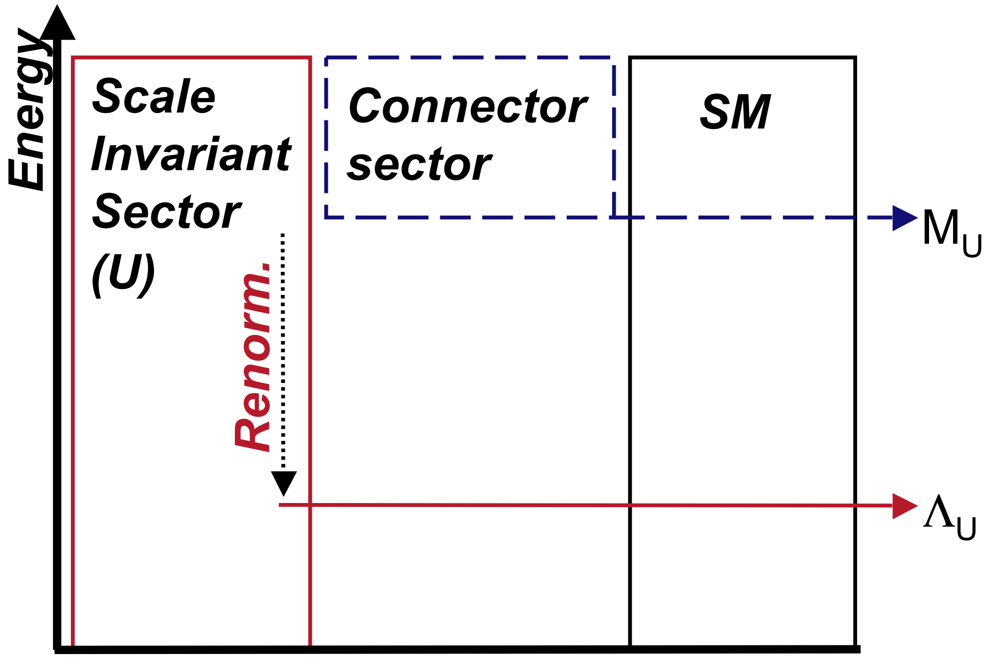
$$M_S^{n+2} = 8\pi^{1-\frac{n}{2}}\Gamma\left(\frac{n}{2}\right)M_D^{n+2}$$

*T. Han, J.D. Lykken, R.-J. Zhang, PRD 59 (1999) 105006*

$$\Lambda_H^4 = \frac{2}{\pi}\Lambda_T^4$$

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

# Analogous Unparticle Scenario




Unpartices (U) belong to a scale invariant sector, only interacting with the SM via a connector sector at a high energy scale.

*H. Georgi, PRL 98 (2007) 221601*

***Gives rise to***

- Continuous U mass spectrum.
- Non-integer $d_U$-body phase space.

***Similar to LED*** $d_U = \frac{n}{2} + 1$

Particle with access to one ED appears with a 1.5 particle phase space.

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

***Unparticle model parameters in Pythia8***

Spin = 0, 1 or 2.
$d_U$ = scale dimension parameter.
$\Lambda_U$ = unparticle renormalization scale.
$\lambda$ = coupling between U and SM (related to $M_U$).

# Common LED / Unparticle Processes

Common implementation, based on unparticle formulae, where the G process is obtained (when possible) from spin-2 unparticle matrix elements.

These common implementations simplifies for comparisons between the similar processes.

**Doc: arXiv:0912.4233v1 [hep-ph]**

MAN/HEP/2009/20
MCnet/09/20
DESY 09-214
Dec 2009

arXiv:0912.4233v1 [hep-ph] 21 Dec 2009

Real Emission and Virtual Exchange of Gravitons and Unparticles in Pythia8

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Abstract

Models with large extra dimensions as well as unparticle models could give rise to new phenomena at collider experiments due to real emission or virtual exchange of gravitons or unparticles. In this paper we present the common implementation of these processes in the Monte Carlo generator PYTHIA8, using relations between the parameters of the two models. The program offers several options related to the treatment of the UV region of the effective theories, including the possibility of using a form factor for the running gravitational coupling. Characteristic results obtained with PYTHIA8 have been used to validate the implementations as well as to illustrate the key features and effects of the model parameters. The results presented in this paper are focused on mono-jet, di-photon and di-lepton final states at the LHC.

***U to G Emission***

$$d_U = \frac{n}{2} + 1$$

$$A(d_U) \leftrightarrow S(n)$$

$$\Lambda_U = M_D$$

$$\lambda_1 = \lambda_2 = 1$$

(phase space factors)

***U to G Exchange***

$$d_U = 2$$

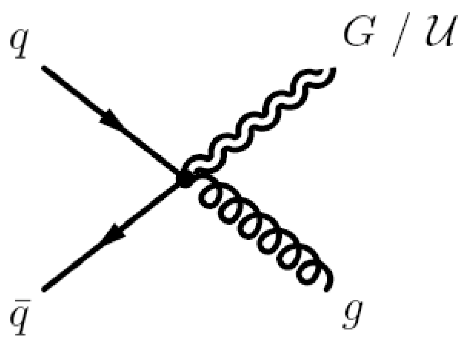
$$\Lambda_U = \Lambda_T$$

$$\lambda^2 \cdot \chi = 4\pi$$

(factor from U propagator)

# Real G / U Emission (LED/U)

***Already Available***




***Processes***

Mono-jet: **`gg2Gg, qg2Gq, qqbar2Gg`**

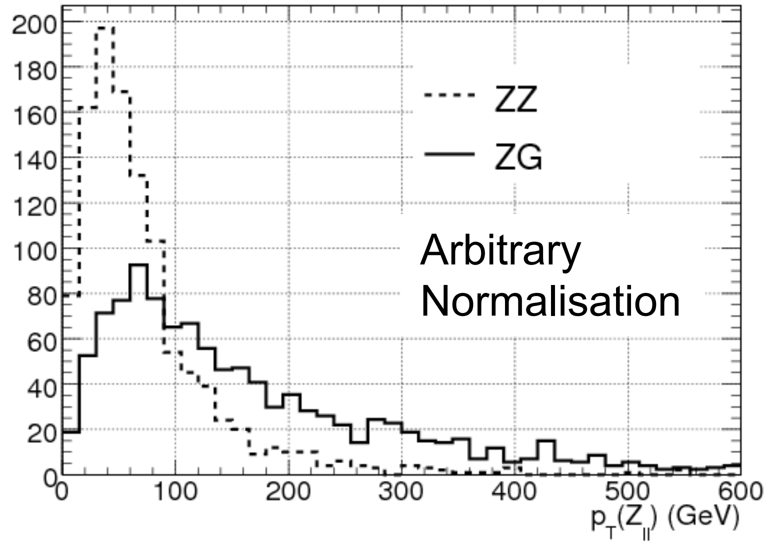
Mono-photon: **`ffbar2Ggamma`**

Mono-Z: **`ffbar2GZ`**

G and U options separated into **`ExtraDimensionsLED`** and **`ExtraDimensionsUnpart`** sections and name differ with **`G`** replaced by **`U`**.

*SA, EPJC 60 (2009) 509.*

- Mono-photon process corresponds to the photon limit of the mono-Z process.
- No interference between photon/Z.
- The Z decays isotropically.
- No spin-2 U Matrix elements for mono-jet processes, i.e. G only spin-2 mono-jet scenario.



# G / U Mass Distributions (LED/U)

• The G / U mass spectrum depends on *n* or $d_U$ value.

• In order to maximize the MC efficiency the events are sampled according to a Breit-Wigner (BW) spectrum.

• For maximum generation speed the BW shape should overlap as much as possible with the cross section, i.e. be tuned to the particular mass spectrum.

BW shape defined by standard particle data scheme in Pythia8,

**5000039:m0**

**5000039:mWidth**

**5000039:mMin**

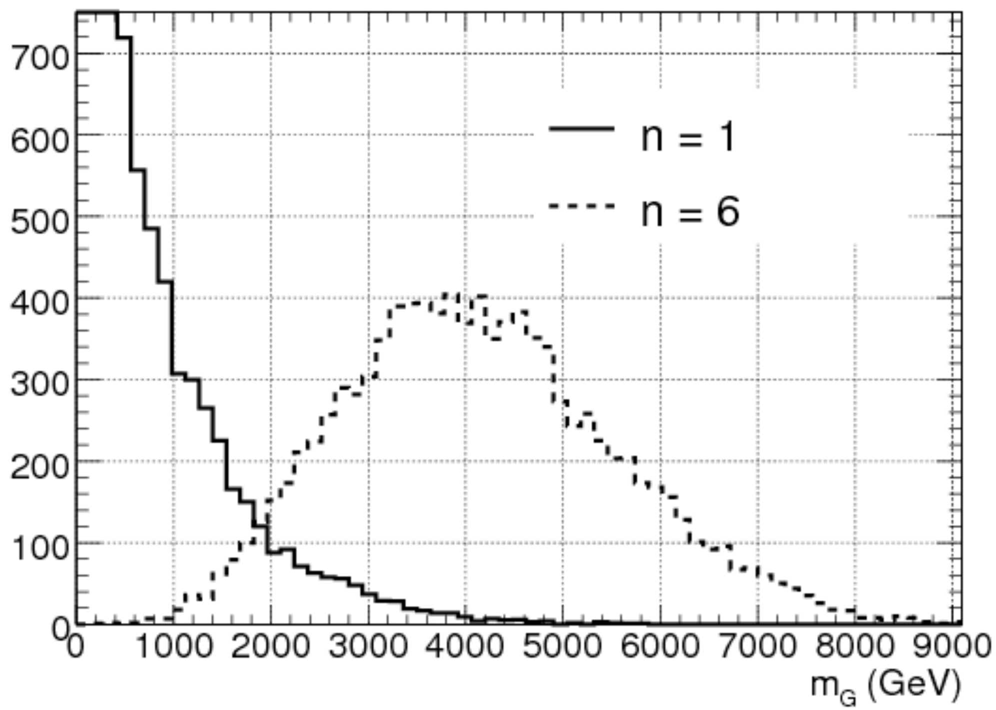
**5000039:mMax**

***(G and U use same id code)***

For example,

• Generate some events and plot mass dist.

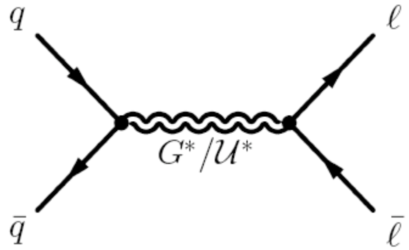
• Adjust the BW shape to roughly cover the bulk of the mass distribution.



# *Virtual G* / U* Exchange (LED/U)*

***Already Available Processes*** Di-lepton: **`gg2llbar, qqbar2llbar`**

Di-photon: **`gg2gammagamma, qqbar2gammagamma`**

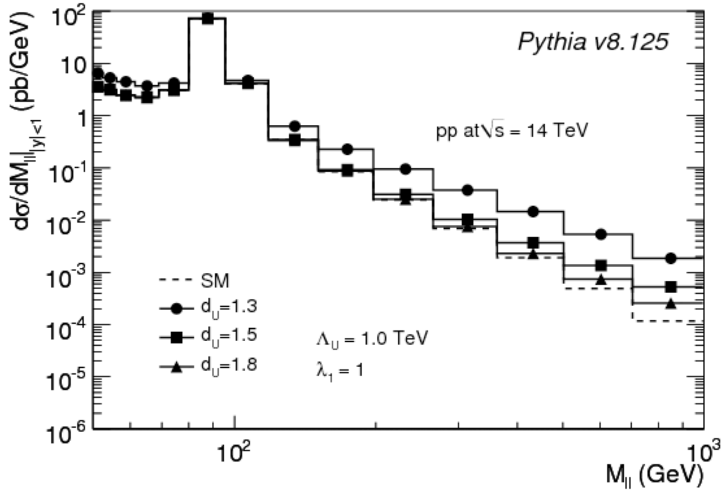



Include helicity dependent couplings between a spin-1 U and fermions (same options as for eta parameter on slide 6).

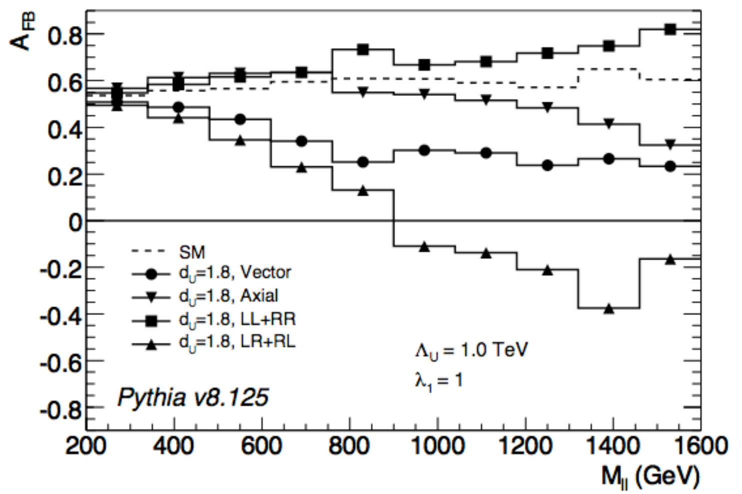
Could lead to interesting interference patterns and effects on the angular distribution.

*H. Georgi, PLB 650 (2007) 275*

*Di-lepton production at the LHC*




*Forward-Backward Asymmetry*



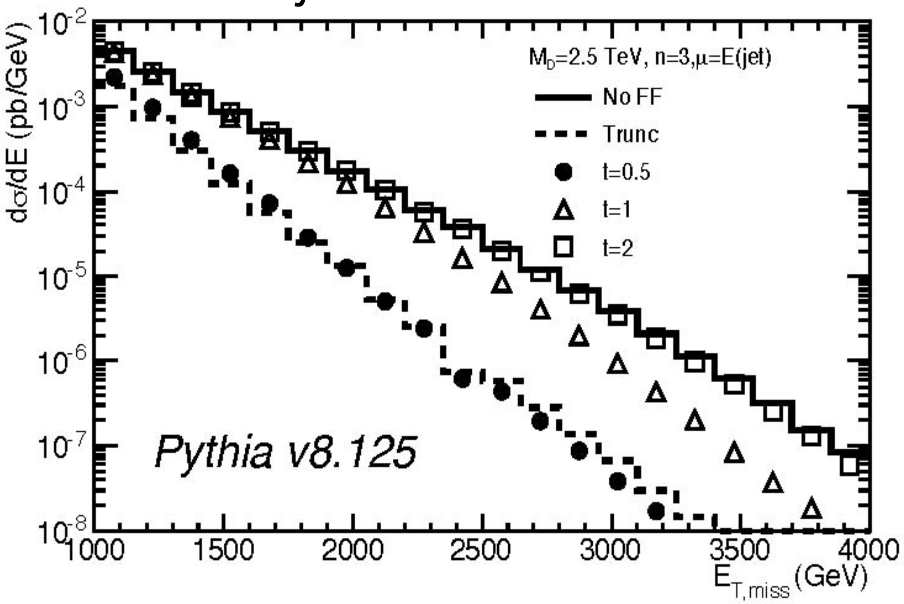
# *Treatment of the UV Region (LED/U)*

***Already Available***

Several options are available related to the treatment of the UV region of the effective theory,

- **CutOffMode = 0**, Do nothing.
- **CutOffMode = 1**, Truncate.
- **CutOffMode = 2/3**, Form factor (G).

*G + jet emission at LHC*




Including a form factor for the gravitational coupling.

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

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

The choice of renormalization scale (μ) follows the general Pythia parameter, **SigmaProcess:renormScale2**

*t* is a O(1) “free” parameter. Should be < 2 to preserve unitarity for G scattering.

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

# Resonances from Extra Dimensions

Smaller extra dimension models often give rise to resonances due the KK modes (smaller size, larger KK mode separation).

***Complementary set of related resonances***

- Graviton resonance,
  - gg and ffbar initiated / spin-2 / colour singlet.
  - Common coupling to all SM particles (RS1 with SM on the TeV brane).
  - Flavour dependent couplongs (RS1 with SM in bulk).

***Already Available***

***in Progress!***

- Z' resonance,
  - ffbar initiated / spin-1 / colour singlet.
  - Possible to specify any combination of couplings and SM interf.

***Already Available***

- $Z_{KK}$ + $gamma_{KK}$ resonances, ***(See Mark Suttons Talk!)***
  - ffbar initiated / spin-1 / colour singlet.
  - Include $Z_{KK}/gamma_{KK}$ interference and multiple KK modes.

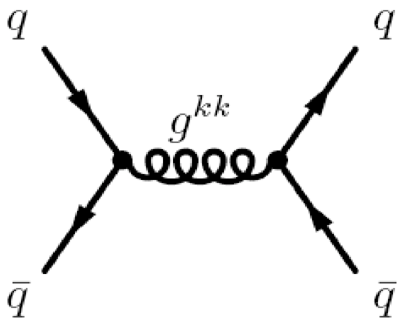
***Next Version***

- Gluon resonance,
  - qqbar initiated / spin-1 / colour octet.

***Next Version***

# KK Gluon Resonance

***Available in next version***



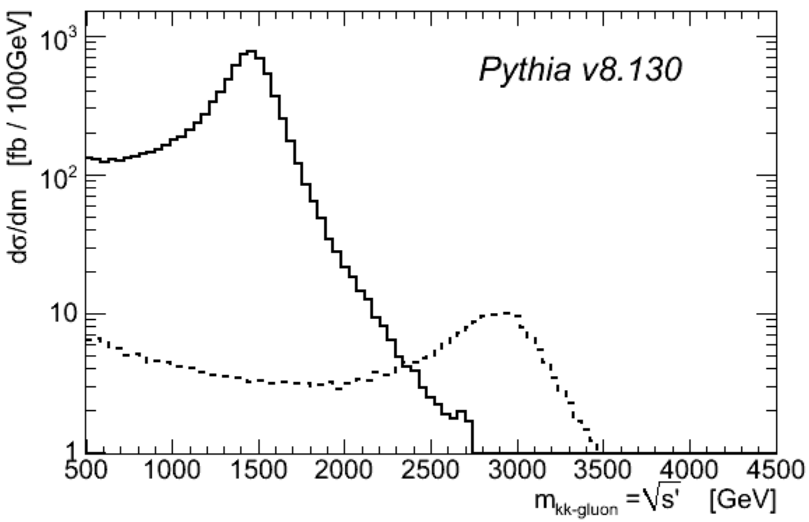

***Process***

KK gluon resonance: **`qqbar2KKgluon*`**

***Parameters***

Mass: **`5100021:m0`**
Couplings: **`gqq, gbb, gtt`**

*KK gluon Production at LHC*




Implemented as a BW resonance, based on the KK gluon width.

$$\Gamma(g^{kk} \to q_i \bar{q}_i) = \frac{\alpha_S \cdot c_i^2 \cdot \beta \cdot m_{g^{kk}}}{6} \left(1 + 2\frac{m_q^2}{m_{g^{kk}}^2}\right)$$

($c_i$, gluon coupling wrt quark flavor *i*)

Currently no interference.

# Couplings On and Off the TeV Brane

### *KK Gluon Resonance*

H. Davoudiasl, J.L. Hewett, T.G. Rizzo, PRD 63 (2001) 075004

Couplings ($c_i = g^{(n)}/g^{SM}$) of the KK gluon follow the conventions in,

Some of the popular RS1 models, with the SM in the ED bulk, implies different couplings to $b_L/b_R$ and $t_L/t_R$.

The process does not allow for separate couplings, but the over all coupling can be approximated by,

$$c_{t/b} = \left( \frac{c^2_{t_L/b_L}}{2} + \frac{c^2_{t_R/b_R}}{2} \right)^{\frac{1}{2}}$$

### *KK Graviton Resonance*

Flavour dependent graviton couplings (***in progress***) will also follow above conventions, related to same RS1 model.

These couplings relate to the common graviton coupling in the old scenario, with the SM on the TeV brane, as

$$\frac{c_G}{\bar{M}_P} \rightarrow \frac{e^{k\pi r}}{\bar{M}_P} = \frac{x \cdot k}{m_G \cdot \bar{M}_P} = \frac{\kappa}{\sqrt{2}}$$

# Conclusions

- Pythia8 supports many possibilities to be used with external programs.
- Recent BSM developments mainly related to SUSY and extra dimensions.
- SUSY section still have missing pieces, but in progress.
- LED graviton (G) and unparticle (U) processes available through common implementation.
- Most common set of G/U emission and G*/U* exchange processes are finished.
- Several ED related resonances available in next Pythia8 version.

*Now follows a practical example based on the LED process,* **`ffbar2Ggamma`**