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Science & Technology Facilities Council

Beyond the SM in Pythia8

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MONTE CARLO TOOLS FOR PHYSICS BEYOND THE STANDARD MODEL

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Pythia 8 (C++)

First version: 8.1 Oct 2007.

Current version: 8.162

Physics content is better than Pythia6 (Fortran) in most areas.

Only Pythia8 is being developed and starts to get competitive tunes wrt LHC data.

Recent developments in several of the main Pythia8 physics areas,

- *ME/PS matching, e.g. showers, CKKW-L.*
- *Multiparton interactions, e.g. re-scattering.*
- *Diffractive processes.*
- *Polarisation in tau production and decay.*
- *Tunes wrt LHC data.*

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Concentrate here on BSM related areas!

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Documentation and Getting Started

Pythia Webpage *http://home.thep.lu.se/~torbjorn/Pythia.html*

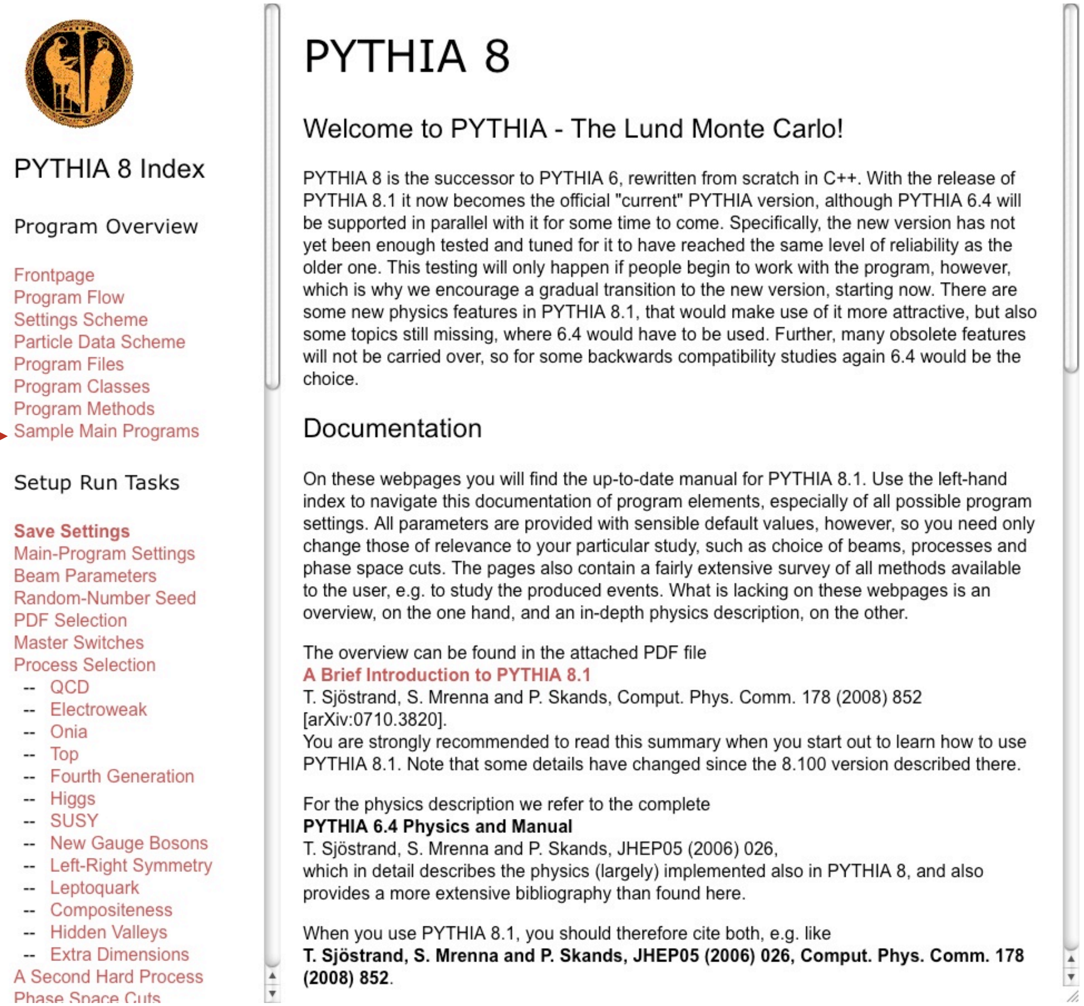
- *Online manual, available on the Pythia webpage as well as distributed with the code.*

- *Manual generated from same (.xml) files as the program takes its parameters from.*

- *Examples of main programs, distributed with the code.*

- *Selection of previous Pythia8 presentations (webpage).*

- *Selection of instructions from different tutorials (webpage).*



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PYTHIA 8

Welcome to PYTHIA - The Lund Monte Carlo!

PYTHIA 8 is the successor to PYTHIA 6, rewritten from scratch in C++. With the release of PYTHIA 8.1 it now becomes the official "current" PYTHIA version, although PYTHIA 6.4 will be supported in parallel with it for some time to come. Specifically, the new version has not yet been enough tested and tuned for it to have reached the same level of reliability as the older one. This testing will only happen if people begin to work with the program, however, which is why we encourage a gradual transition to the new version, starting now. There are some new physics features in PYTHIA 8.1, that would make use of it more attractive, but also some topics still missing, where 6.4 would have to be used. Further, many obsolete features will not be carried over, so for some backwards compatibility studies again 6.4 would be the choice.

Documentation

On these webpages you will find the up-to-date manual for PYTHIA 8.1. Use the left-hand index to navigate this documentation of program elements, especially of all possible program settings. All parameters are provided with sensible default values, however, so you need only change those of relevance to your particular study, such as choice of beams, processes and phase space cuts. The pages also contain a fairly extensive survey of all methods available to the user, e.g. to study the produced events. What is lacking on these webpages is an overview, on the one hand, and an in-depth physics description, on the other.

The overview can be found in the attached PDF file
A Brief Introduction to PYTHIA 8.1
T. Sjöstrand, S. Mrenna and P. Skands, Comput. Phys. Comm. 178 (2008) 852 [arXiv:0710.3820].
You are strongly recommended to read this summary when you start out to learn how to use PYTHIA 8.1. Note that some details have changed since the 8.100 version described there.

For the physics description we refer to the complete
PYTHIA 6.4 Physics and Manual
T. Sjöstrand, S. Mrenna and P. Skands, JHEP05 (2006) 026,
which in detail describes the physics (largely) implemented also in PYTHIA 8, and also provides a more extensive bibliography than found here.

When you use PYTHIA 8.1, you should therefore cite both, e.g. like
T. Sjöstrand, S. Mrenna and P. Skands, JHEP05 (2006) 026, Comput. Phys. Comm. 178 (2008) 852.

Overview of BSM in Pythia8

Today's Standard: *Use ME program, then interface to Pythia8 through LHE files.*

However, internal library with common / special BSM processes is still maintained.

Hard (BSM) processes are mainly based on LO matrix elements.

New couplings and masses normally have to be determined externally, in order to separate processes and models.

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 LO processes.

Process Selection

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

BSM Processes

Beyond the SM Resonances

New EW gauge bosons (Z', W', R)

	`NewGaugeBoson:ffbar2gmZZprime, ffbar2Wprime, ffbar2R0.`	*spin-0*
[*Hui97*]	`LeftRightSymmetry: ffbar2ZR, ffbar2WR, (+ 12 including HL/HR).`	*spin-1*

Leptoquark models (QL)

	`LeptoQuark:ql2QL, qg2QLl, gg2QLQLbar, qqbar2QLQLbar.`	*spin-0*

Extra dimension models (KK graviton, gluon or gamma/Z)

	`ExtraDimensionsG*: gg2G*, ffbar2G*, gg2G*g, qg2G*q, qqbar2G*g`	*spin-1*
	`ExtraDimensionsG*: qqbar2KKgluon*`	*spin-2*
[*Bel10*]	ExtraDimensionsTEV: ffbar2ddbar (+ 11, $\mathrm{gamma}_{KK}/Z_{KK}$ -> ffbar).	

Excited fermion models (compositeness, f*)

[*Bau90*]	`ExcitedFermion:dg2dStar, qq2dStarq, (+ 17, different fStar).`	*spin-1/2*

Higgs (two-doublet) models

	`HiggsBSM: ffbar2H1, qg2H1q, (+13 others).`	
	`HiggsBSM: ffbar2H2, qg2H2q, (+13 others).`	*spin-0*
	`HiggsBSM: ffbar2A3, qg2A3q, (+13 others).`	
	`HiggsBSM: ffbar2H+-, ffbar2A3H1, (+ 5 others).`	

Large variety of spin and colour configurations.

Kaluza Klein Graviton Resonance

Graviton resonance based on partial widths for decays to any pair of SM particles.

Include correct angular distribution for G decay, whereas subsequent decays are isotropic.*

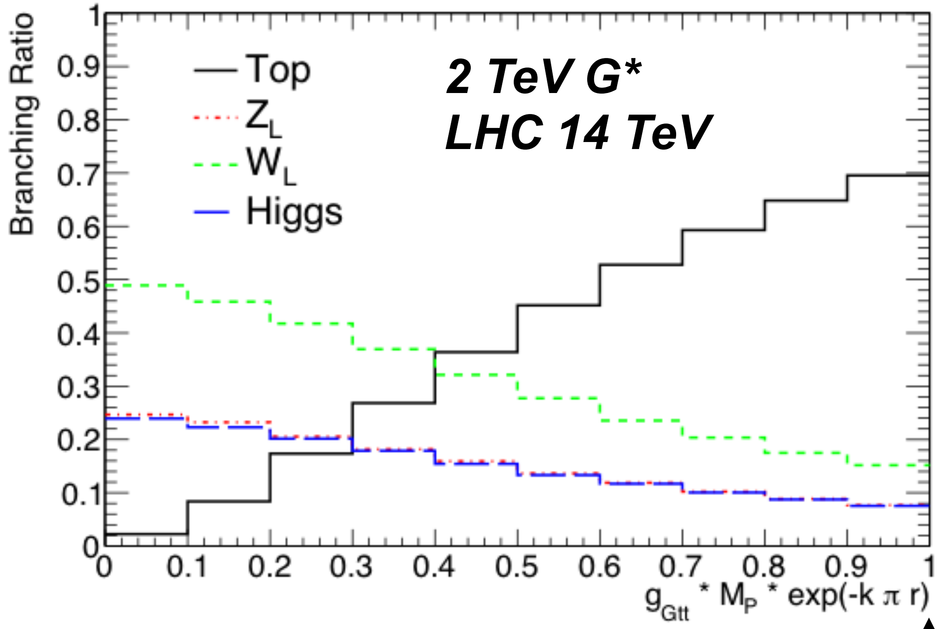
Supports two RS inspired scenarios,

- *Universal G* (kappa) coupling to SM particles (RS with SM on the TeV brane").*
- *Particle / flavour dependent G* couplings (RS with SM in the bulk").*

Scenario two also allows for dominant coupling to longitudinal component of Z and W.

Documentation [Bij01]

"SM in Bulk" a'la Randall et al. [Fit07]



(top on the TeV brane)

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

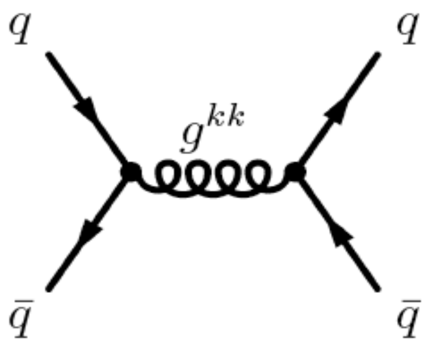
Kaluza Klein Gluon Resonance

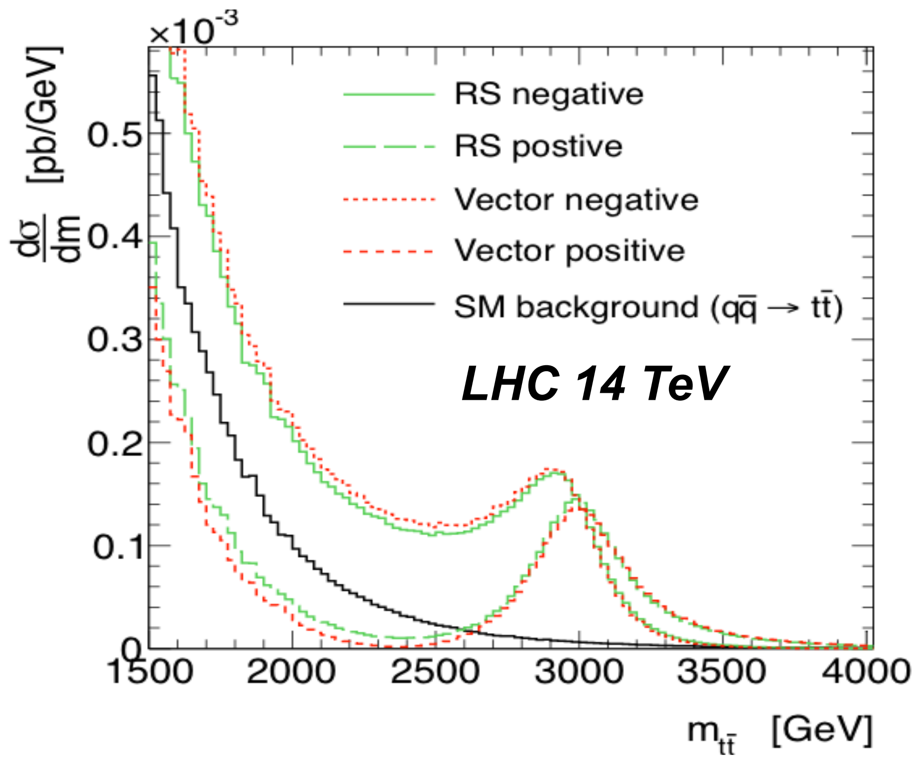
KK gluon (g^{KK}) resonance is almost as flexible as the Z' process!

Documentation [Ask11]

$$\Gamma(g^{kk} \to q_j \bar{q}_j) = \frac{\alpha_S \; \beta \; \sqrt{s}}{6} \left((g_v^j)^2 A_j + (g_a^j)^2 \beta^2 \right);$$

$$A_j = 1 + 2\frac{m_j^2}{s}; \qquad \beta^2 = 1 - 4\frac{m_j^2}{s}.$$





Allows for flavour as well as helicity dependent g^{KK} couplings.

Mass and helicity dependent angular distributions of g^{KK} decay.

Possible to include interference with SM gluon amplitude.

Other Beyond the SM 2-to-2 Processes

Fourth generation fermions (b', t', tau' or nu')

```
FourthBottom: gg2bPrimebPrimebar (+ 5).
FourthTop: gg2tPrimetPrimebar (+ 4)
FourthPair: ffbar2tPrimebPrimebar, ffbar2tauPrimenuPrimebar
```

Contact interactions (compositeness)

```
ContactInteractions: QCqq2qq, QCqqbar2qqbar, QCffbar2llbar.
```

Dijet or llbar production from contact interactions, based on [Eic83]

$$\mathfrak{L}_{\psi\psi} = (g^2/2\Lambda^2)[\eta_{LL}\bar{\psi}_L\gamma_\mu\psi_L\bar{\psi}_L\gamma^\mu\psi_L + \eta_{RR}\bar{\psi}_R\gamma_\mu\psi_R\bar{\psi}_R\gamma^\mu\psi_R + 2\eta_{RL}\bar{\psi}_R\gamma_\mu\psi_R\bar{\psi}_L\gamma^\mu\psi_L].$$

with, $g^2 = 4\pi; \quad \eta_{\alpha\beta} = -1, 0, 1$

Pythia8 contains a relatively large set of generic BSM processes.

Supersymmetry

The SUSY implementation supports,

Documentation [Des11]

- *nMSSM, i.e. with one additional neutralino.*
- *CP as well as flavour violation in the squark sector.*
- *R-parity violation, including resonant squark production.*

Chargino and neutralino production	qqbar2chi0chi0, qqbar2chi+-chi0, qqbar2chi+chi-.
Gaugino squark production	qg2chi0squark, qg2chi+-squark.
Gluino production	gg2gluinogluino, qqbar2gluinogluino.
Squark-gluino production	qg2squarkgluino
Squark-pair production	gg2squarkantisquark, qqbar2squarkantisquark qq2squarksquark
RPV resonant squark production	qq2antisquark

Generally includes gaugino, squark and gluino production, grouped into 12 classes, however, with options to choose specific processes.

All parameters, i.e. masses, mixing etc., are provided through SLHA(2) files.

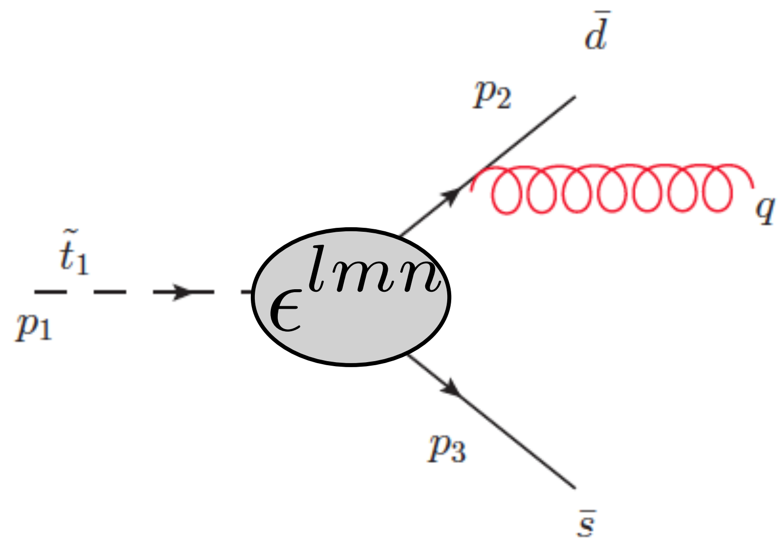
Decay widths by default taken from SLHA input, however, also possible to use the widths calculated by Pythia, e.g. ME based widths available for SUSY two body decays.

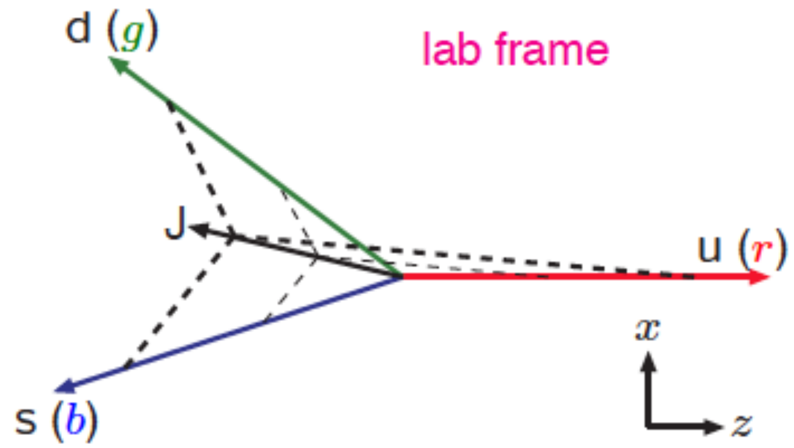
SUSY and Exotic Colour Configurations

RPV models can imply unusual colour configurations.

Pythia8's parton shower and hadronisation machinery capable of handling several unconventional colour scenarios,

- *Radiation related to UDD-type interactions including colour-epsilon topologies, i.e. non-zero baryon number.*
- *Hadronisation related to string topologies with colour junctions.*
- *Also, capable of handling colour-sextet states, represented by two colour triplet charges.*





Documentation [Sjo03]

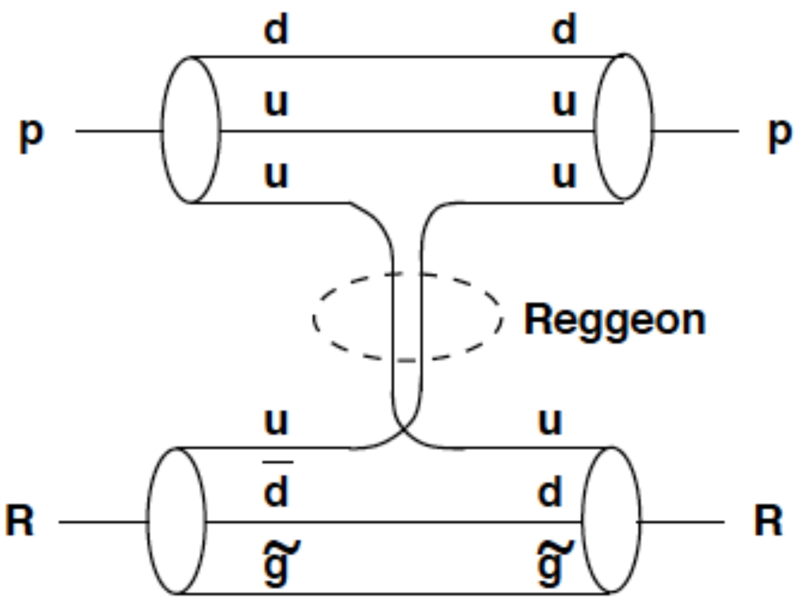
Supersymmetry R-hardons

For scenarios with long lived squarks or gluinos, it is possible to produce R-hadrons.

Documentation [Kra04]

Implementation also applies to non-SUSY long lived “hadrons”.

However, R-hadrons are to a large extent also a matter for the detector simulation.



- ⋆ Formation of R-hadrons

$\tilde{g}q\bar{q}$	$\tilde{t}_1\bar{q}$	“mesons”
$\tilde{g}qqq$	$\tilde{t}_1 qq$	“baryons”
$\tilde{g}g$		“glueballs”

- ⋆ Conversion between R-hadrons by “low-energy” interactions with matter: $\tilde{g}u\bar{d} + p \to \tilde{g}uud + \pi^+$ irreversible
- ⋆ Displaced vertices if finite lifetime, or else
- ⋆ punch-through: $\sigma \approx \sigma_{\text{had}}$ but $\Delta E \lesssim 1$ GeV $\ll E_{\text{kin},R}$

Large Extra Dimensions and Unparticles

Large extra dimension (LED) model

```
ExtraDimensionsLED: gg2Gg, qg2Gq, qqbar2Gg
ExtraDimensionsLED: ffbar2Ggamma, ffbar2GZ
ExtraDimensionsLED: ffbar2gammagamma, gg2gammagamma
ExtraDimensionsLED: ffbar2llbar, gg2llbar

ExtraDimensionsLED: gg2DJgg, (+ 5)
```

Real G (first two lines)

*Virtual G** (remaining lines)

Unparticle model

```
ExtraDimensionsUnpart: gg2Gg, qg2Gq, qqbar2Gg
ExtraDimensionsUnpart: ffbar2Ggamma, ffbar2GZ
ExtraDimensionsUnpart: ffbar2gammagamma, gg2gammagamma
ExtraDimensionsUnpart: ffbar2llbar, gg2llbar
```

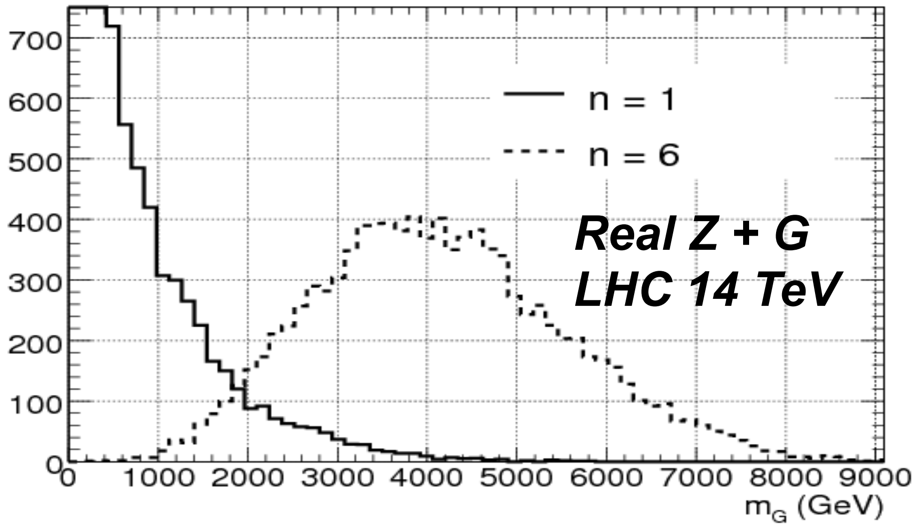
Unparticle processes kept in the same (extra dimension) section, due to the strong similarities.

The unparticle processes allow for different U spin, i.e. 0, 1 or 2.

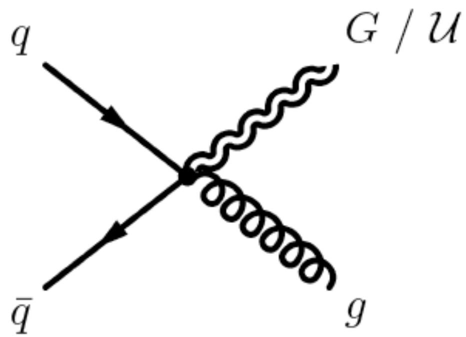
G/U Real Emission and Virtual Exchange

Large extra dimensions predicts graviton (G) emission and virtual exchange processes, with unconventional G mass distributions.

Documentation [Ask09, Ask10]



U to G Conversion

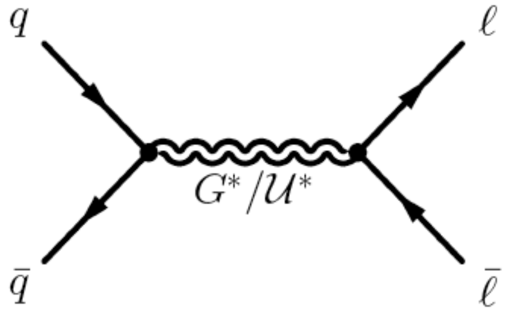


$$d_U = \frac{n}{2} + 1$$
$$A(d_U) \leftrightarrow S(n)$$
$$\Lambda_U = M_D$$
$$\lambda_1 = \lambda_2 = 1$$

(phase space factors)

Unparticle models can be very similar.

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



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

(factor from U propagator)

LED Dijet Processes

Dijet production through G exchange available in two versions.*

1) Traditional amplitude parametrisation.

$$S(s \ll \Lambda^2) = \frac{4\pi}{\Lambda_T^4}$$

(like the other LED G proc.)*

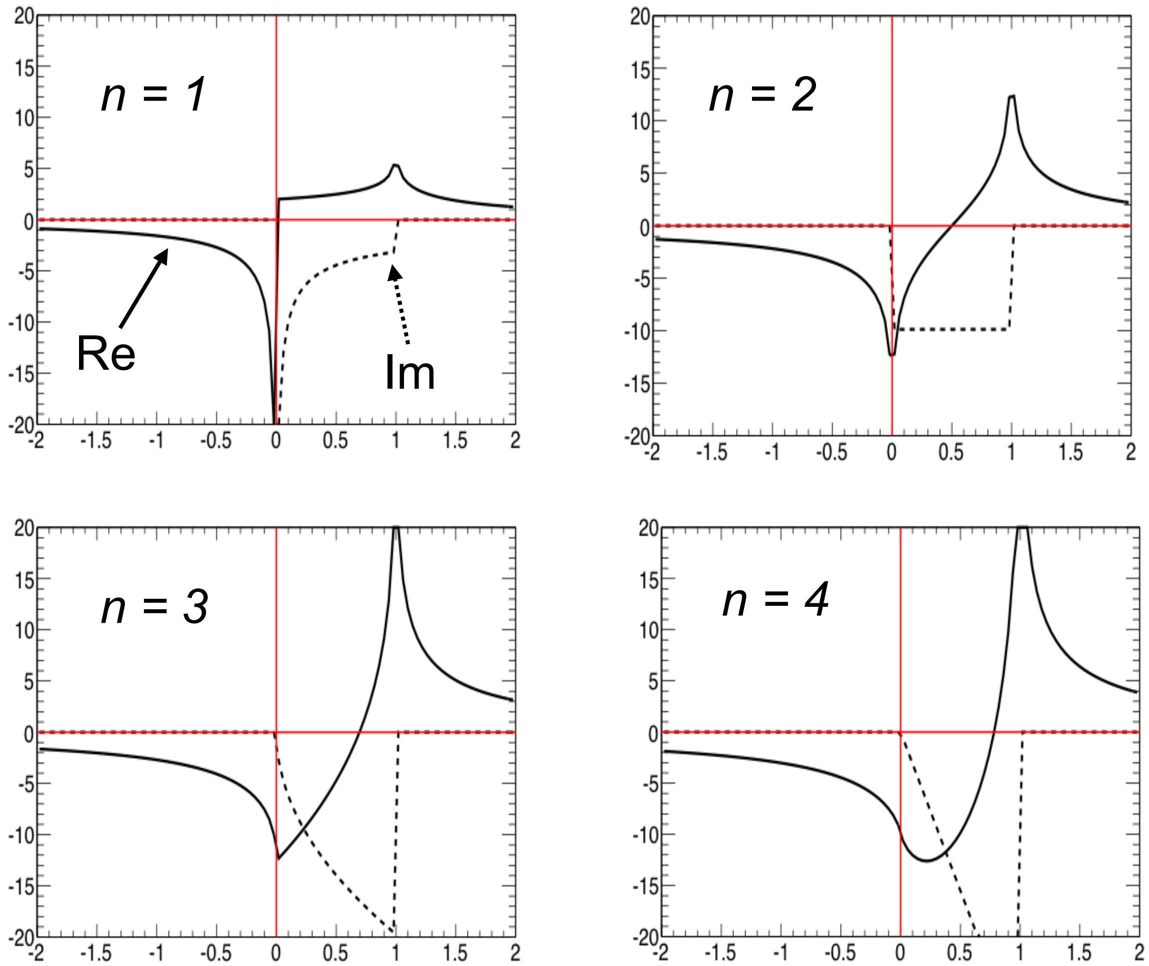
2) Full amplitude, including Lambda cut-off and other parameters.

$$S(s) = \frac{\pi^{n/2}\Lambda^{n-2}}{\Gamma(n/2)M_D^{2+n}} F_n(s/\Lambda^2)$$

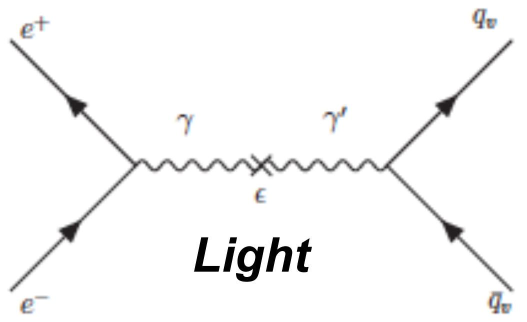
Based on [Fra11]

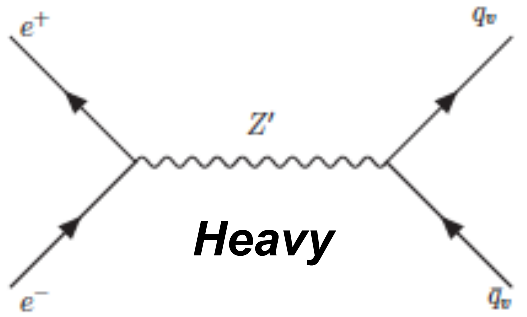
Still being validated!

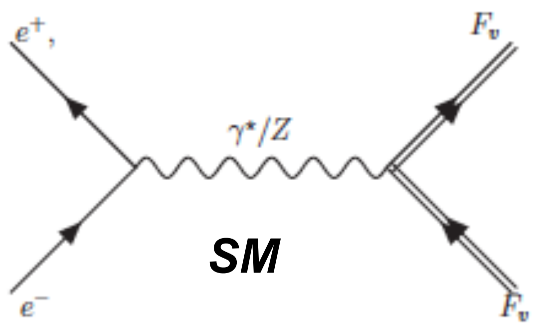
Reproduced S(x) for Lambda = M_D = 1 TeV



Hidden Valley Models







Complete framework to simulate Hidden Valley or Dark Sector scenarios, i.e. new low energy sector hidden by massive mediator or weak couplings.

Documentation [Car10, Car11]

Include three scenarios for producing HV particle pairs (q_v or F_v).

The HV particles can be charged under the HV gauge group only (q_v) or in addition to the SM group (F_v).

F_v assumed to decay to f + q_v , i.e. flavour diagonal wrt SM partner.

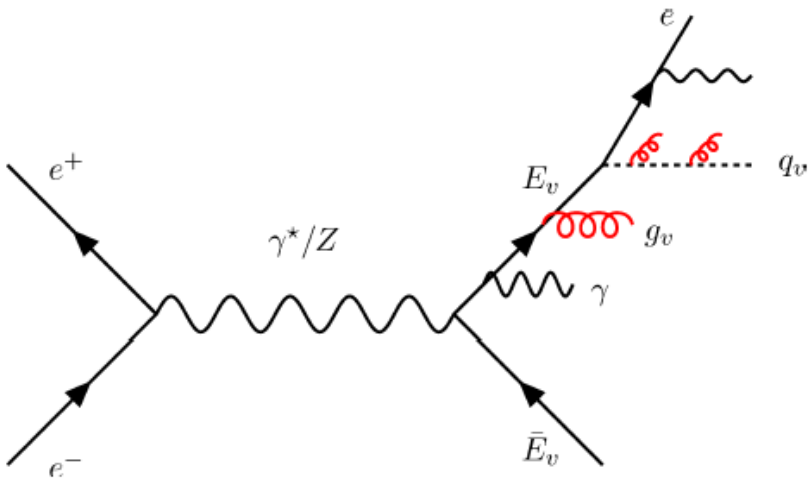
The HV gauge group can be chosen as,

- *Abelian, which allows for massive γ_v.*
- *Non-abelian, only with massless g_v which leads to HV hadronisation.*

Hidden Valley Models

Example, E_v charged under,

$SU(2)_{SM}$ x $U(1)_{SM}$ x $SU(3)_v$



Large variety of phenom. alternatives

Decays back to SM particles possible through kinetic mixing (γ/γ') or a heavy Z'.

Decay can be slow, i.e. displaced vertex, and for kinetic mixing (γ BR) leads to lepton pairs.

HV parton shower (interleaved with SM shower) and HV hadronisation allows for different sources of visible / hidden mix of the final state.

Non-abelian case, *(after hadron.)*

- *Only flavour diagonal HV mesons decay in to SM particles.*
- *Allows for up to 8 q_v flavours, implying 64 different HV mesons.*

Abelian case,

- *HV photon radiation can decay to SM.*
- *q_v remains hidden.*

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Links to External Programs

Les Houches Accord (LHA)

- *Interface for parton-level event files from ME event generators, using Les Houches Event (LHE) file standard,*
- *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, dσ/dt.*

Runtime interfaces

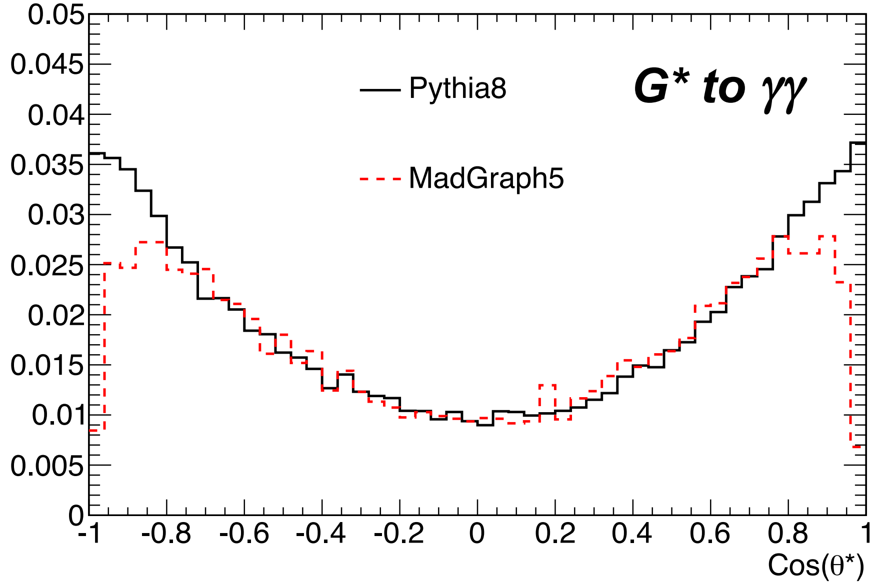
- *Possibility to use both Fortran and C++ programs.*

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

More on Pythia8 and LHA Inputs

Often the most convenient approach for a new (BSM) process [Alw06]

- *Generate parton level BSM events, using an "automatic" ME program.*
- *Feed these events into Pythia8, using the LHA format.*



The LHEF format contains all needed information, initialisation plus events, and therefore very simple to use (see tutorial!).

Also have support for custom made inputs, using the LHA base class frame work.

Since v8.160: [Lon11]

Include support for CKKW-L merging between the PS and MEs with multiple partons.

Using LHEF, where user provides one file per ME based parton multiplicity.

Again convenient support for a number of common merging scale definitions, but also support for customised scale definitions.

Semi-Internal Processes and MadGraph5

Semi-Internal Processes (general)

- *Framework to include a new external processes directly based on cross section formulas.*
- *Inherits 2-to-1/2/3 scattering base classes and the overall class structure, of the parton level process, is the same as the internal processes.*
- *Therefore treated just like any hard Pythia8 process!*

MadGraph5 Processes (new!) *[Alw11, Des11]*

- *MadGraph 5 has an option to output the results of a matrix-element calculation as a set of Pythia 8 C++ classes, based on the semi-internal process interface.*
- *Generates both required processes classes and main program example.*

Benefits / drawbacks wrt LHEFs

- *Easier to mix between Pythia8 processes.*
- *Does not require intermediate (.lhe) event files.*
- *Limited by Pythia8's low (up to 3) final state multiplicity capability.*

Summary and Conclusions

- *Most common Pythia8 use case today when simulating a new BSM process, use automatic ME program for the hard process, then interface with Pythia8 for full event simulations.*

- *However, Pythia8 also contains a relatively large variety of generic, common or special BSM processes.*

- *BSM related updates have recently been included in several areas, often with close connections to parton showers and hadronisation, e.g. RPV vertices, Hidden Valley framework, R-hadrons.*

- *Significant recent updates also wrt interfacing with external programs, e.g. CKKW-L merging capability and possibility to import a hard process produced by MadGraph5.*

Selected References

All references (except the one below) are found in the bibliography of online manual.

Online manual available at: http://home.thep.lu.se/~torbjorn/Pythia.html

[Fit07] A.L. Fitzpatrick et al., JHEP 0709 (2007) 013.