MC for BSM with Pythia 8

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**    Welcome to the Lund Monte Carlo!    **
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**                                         **
** Main author: T. Sjostrand (Lund U.)    **
**                                         **
** Author:      S. Mrenna (FNAL)          **
**                                         **
** Author:      P. Skands (CERN/FNAL)     **
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Introduction

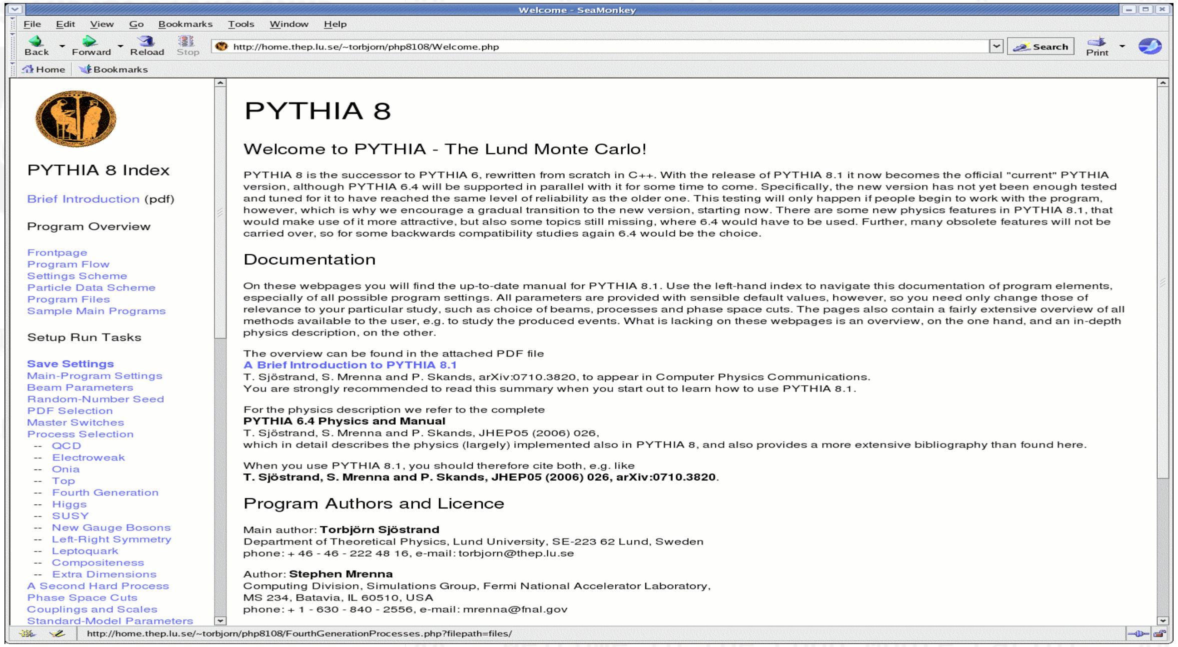
- Pythia v8.1 (C++) was released Oct 2007
- The physics content should be at the same level or improved with respect to Pythia 6
- However, tuning from experimental data remains!
- The initial focus was on SM physics (QCD / EW)
- This talk will focus on the BSM processes and high-light feature relevant to BSM use cases
- Reminder: the implementation of several BSM scenarios have just started !

Pythia 8: Interactive Online Manual

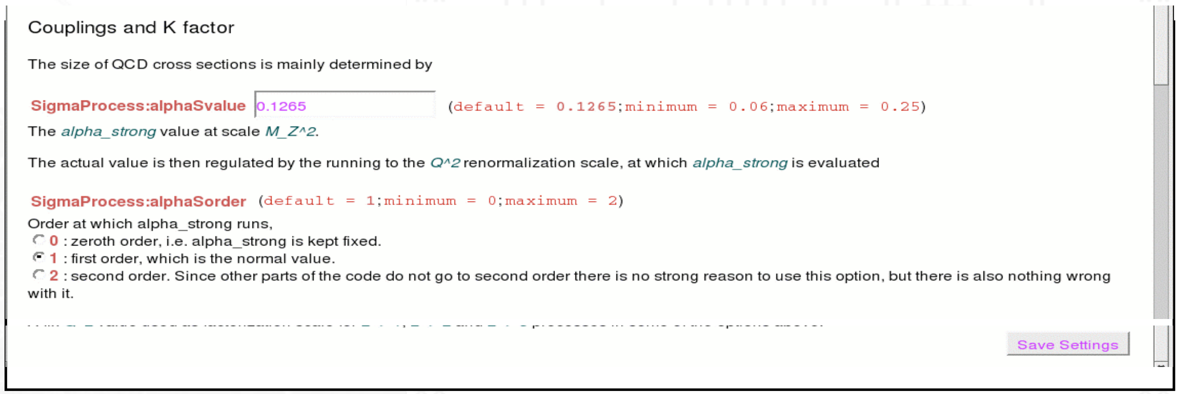
Linked to the code of the current version

BSM Categories

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

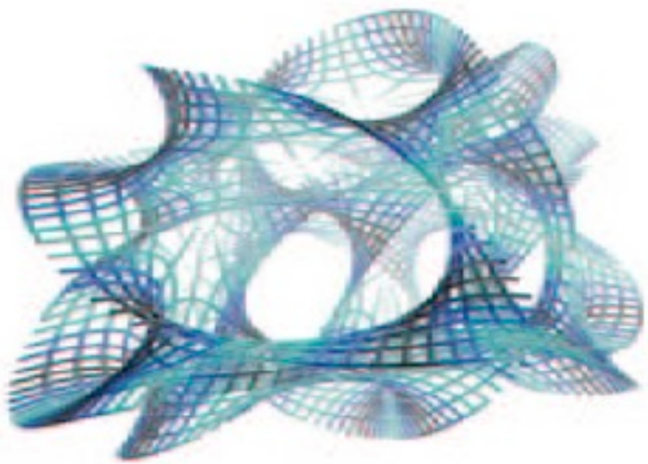


Can be used to produce setting files interactively



BSM Processes

- Currently a little bit of each ~ Pythia 6 - SUSY - TC
- Mainly LO matrix elements
- Higher order corrections to the LO are often available to produce dedicated samples for the high-pT 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
- Next in line in the BSM development:
  - SUSY
  - Technicolor
  - Extra Dimensions (Unparticles)



Status of the BSM Processes

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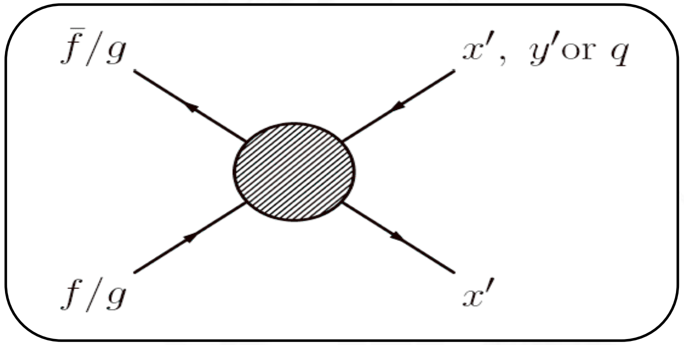
Fourth Generation

Production of fourth generation quarks and leptons

Provide a template for models with new particles with similar characteristics

Example:
FourthBottom:gg2bPrimebPrimebar = on/off

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



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

Parameters:
- Masses
- 4th generation CKM matrix elements

SUSY

SUSY category contain SUSY particle production except for the Higgs sector

Have just started !

Will only allow switching on production of groups of SUSY particles

Example (only one available right now!):
SUSY:qqbar2chi0chi0 = on/off

Parameters:
Pythia 8 will not include any SUSY spectrum calculator to renormalize and interpret SUSY Lagrangian parameters at the GUT scale

SUSY processes will be based directly on the masses and couplings, provided in SUSY Les Houches Accord (SLHA) files

First implementation, also using SLHA2, is planned to be available before end of this year

Status of the BSM Processes

One Higgs Doublet (SM)

Contains:

- The standard set of SM processes
- Higher order processes for high-p_T samples

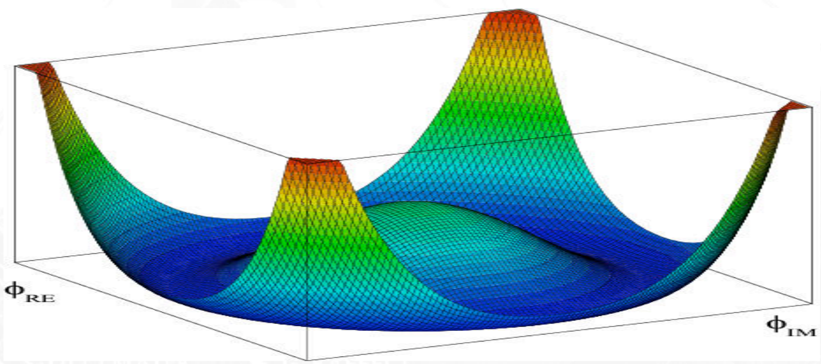
Example:

HiggsSM:ffbar2H = on/off

HiggsSM:qg2Hq = on/off

Parameters:

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



Two Higgs Doublets (BSM)

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

Contains:

- Single H_i and $H^{+/-}$ production
- H_i and $H^{+/-}$ pair production
- Higher order processes for high-p_T samples

Example:

HiggsBSM:ffbar2H1 = on/off
HiggsBSM:ffbar2H+-H1 = on/off

HiggsBSM:qg2H1q = on/off

Parameters:

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

Status of the BSM Processes

New Gauge Bosons

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

Z':

Z' production with Z and/or γ^* interference

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

Example:
NewGaugeBoson:ffbar2gmZZprime = on/off

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

Example:
LeftRightSymmetry:ffbar2ZR = on/off

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

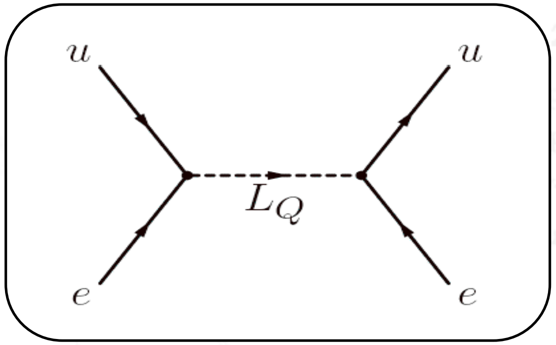
Status of the BSM Processes

Leptoquark

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

Example:
LeptoQuark:ql2LQ = on/off

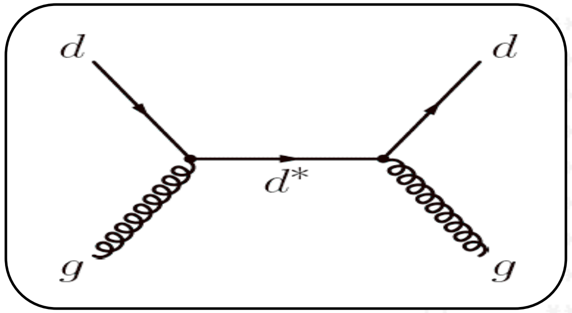
Parameters:
- Mass
- Coupling



Compositeness

Production of excited leptons and quarks
(and anomalous couplings)

Example:
ExcitedFermion:dg2dStar = on/off



Parameters:
- Masses
- Coupling
- Compositeness scale

Extra Dimensions

Have just started!

Randall-Sundrum KK Graviton resonance

Higher order processes for high-p_T samples

Example:
ExtraDimensionsG*:gg2G* = on/off

ExtraDimensionsG*:gg2G*g = on/off

Parameters:
- G mass
- kappaMG (curvature parameter)

More in example below!

Links to External Programs

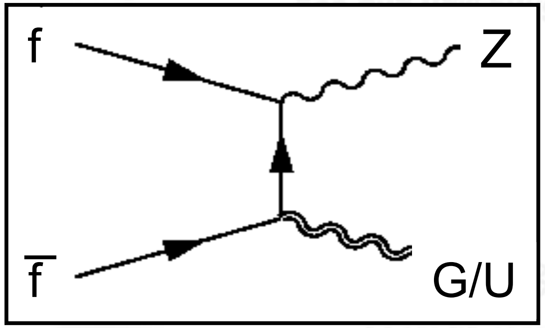
- Les Houches Accord (LHA):
  - Interface for parton-level event files from ME event generators, using Les Houches Event File (LHEF) standard (hep-ph/0609017)
  - For example from MadGraph etc.
  - Then Pythia 8 takes care of the following parton-level and hadron-level generation

- 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 $d\sigma/dt$
  - Pythia then also takes care of the phase space selection etc.
  - **More details in the example below !**

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

Example: Using a Semi-Internal Process



Study of the Z + G (U) cross section at the LHC

Main experimental signatures from graviton emission in large extra dimensions are single jet and single photon events

Hence Z+G would only be a possible complement if a signal is observed in the main channels

The cross section is not expected to be very large, but can it compete with ZZ → $ll\nu\nu$?

To get a first indication of the Z + G/U cross section, a relative comparison was made at generator level between the ZZ → $ll\nu\nu$ and ZG → llG processes

In order to get an indication of experimental effects it was also guided by a detailed ATLAS study of the ZZ → $ll\nu\nu$ cross section measurement

A paper documenting this study and the implementation in Pythia 8 is in preparation

Only the process implementation will be addressed here!

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);
  ……
  …

}
```

The Z+G/U process was implemented as a semi-internal process to Pythia 8.1

It 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 !

Unparticle vs Graviton (in LED) Emission

H. Georgi, PRL 98 (2007) 221601;

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

Unparticle (U) model parameters:

d_U = scale dimension parameter

Λ_U = unparticle renormalization scale

λ = coupling to the SM (depend on connector sector)

Low energy U-SM interactions are described by effective operators:

Spin-0: Disregarded (based on "conventional wisdom")

Spin-1: Defined by the 3 parameters above (at least for an unpolarized beam)

Spin-2: Can have two operators with different $\lambda_{i=1,2}$

From a phenomenology point of view, unparticle emission is a generalization of graviton emission. So both can be covered by the same implementation!

Spin-2 U and G emission (in LED) cross sections are equivalent by changing:

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

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

$$\Lambda_U = M_D$$

$$\lambda_1 = \lambda_2 = 1$$

Cross Section and G/U Mass Spectrum

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

mass spectrum (KK)

- The variable U/G mass spectrum gave rise to the main difference with respect to the internal Pythia processes
- This could, however, be conveniently solved by re-weighting a Breit-Wigner spectrum available in Pythia
- Production of γ + G/U events is also possible by the photon limit of the Z + G/U process
- A truncation switch was implemented to check the validity of the effective theory (truncates part of the cross section with $\hat{s} > M_D$ or Λ_U)
- The different parts of the implementation was cross checked against other graviton emission results, e.g. $e^+e^- \rightarrow \gamma G$ (see back up slides for details)

Trying Out Pythia 8

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

- Download the file: `pythia8108.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, links to 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]

Conclusions

- Pythia 8.1 contains approximately the BSM physics in Pythia 6 - SUSY - TC

- More BSM processes (especially SUSY) are on its way !

- In addition, there are several possibilities to use it together with external programs, e.g. external BSM processes from
  - LHA interface for parton-level event files from ME generators
  - Semi-internal process which is used to implement a parton-level process based on $d\sigma/dt$

- My experience from using the semi-internal process option:
  - It provides a convenient way to implement a new process
  - The full event generation chain (at process-parton-hadron level) is taken care of by Pythia
  - The user code is clearly separated from the main Pythia library

[--- Back Up Slides ---]

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	ql2LQ, qg2LQl, gg2LQLQbar, qqbar2LQLQbar
ExcitedFermion	dg2dStar, qq2uStarq, qqbar2muStarmu, ...
ExtraDimensionsG*	gg2G*, qqbar2G*, ...

The Truncation Option

Example:
ffbar → Z+Graviton in large extra dimensions (ADD)

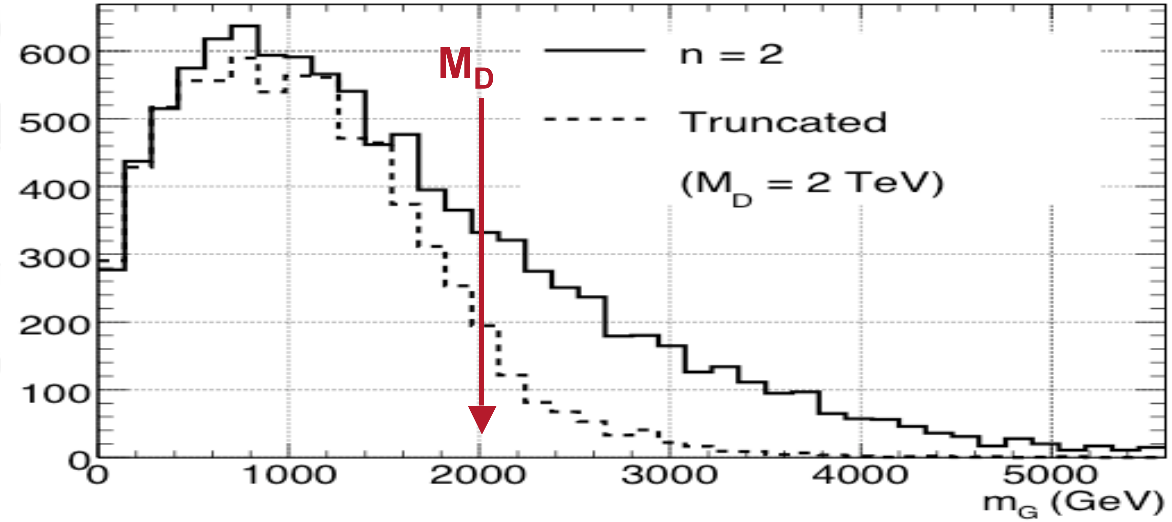
If $\hat{s} > M_D$ the effective theory is not valid

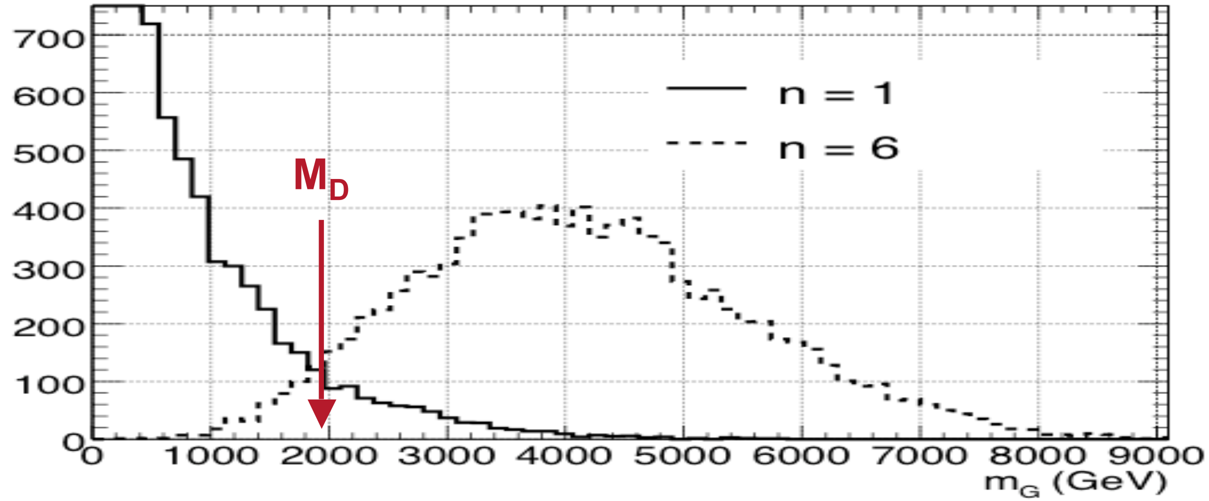
Important to check effect from truncating this region (factor $\hat{s}^2/M^4_D$ used here)

This also truncates mass spectrum at large values

Mass spectrum increasingly peaked at large values (i.e. truncation effect more important) with increasing n

Implemented switch for using this truncation or not





Validation Cross Checks

Photon Limit:

γ + U/G was obtained by the photon limit of the Z process (i.e. all uses the same code / formulas),

$m_Z \rightarrow 0$; $(g^2_A+g^2_V) / 4 \rightarrow Q^2$; $g / \cos(\theta_W) \rightarrow e$,

Validated different parts of the process by re-producing related processes:

- ee or pp → G+γ : Cover most parts (but only in the photon limit and G scenario)

G.F. Giudice, R. Rattazzi & J.D. Wells, NPB 544 (1999) 3;
E.A. Mirabelli, M. Perelstein & M.E. Peskin, RPL 82 (1999) 2236.

- ee → G+Z : Complementary check of full Z ME (cancelation needed for U spin-2 ME to become G ME)

K.Cheung & W.Y. Keung, PRD 60 (1999) 112003;
G.F. Giudice, T. Plehn & A. Strumia, NPB 706 (2005) 455.

- ee → U+γ : Complementary check of U spin-1 ME and U phase space factors

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