PHYSICS BEYOND THE STANDARD MODEL WITH PYTHIA 8

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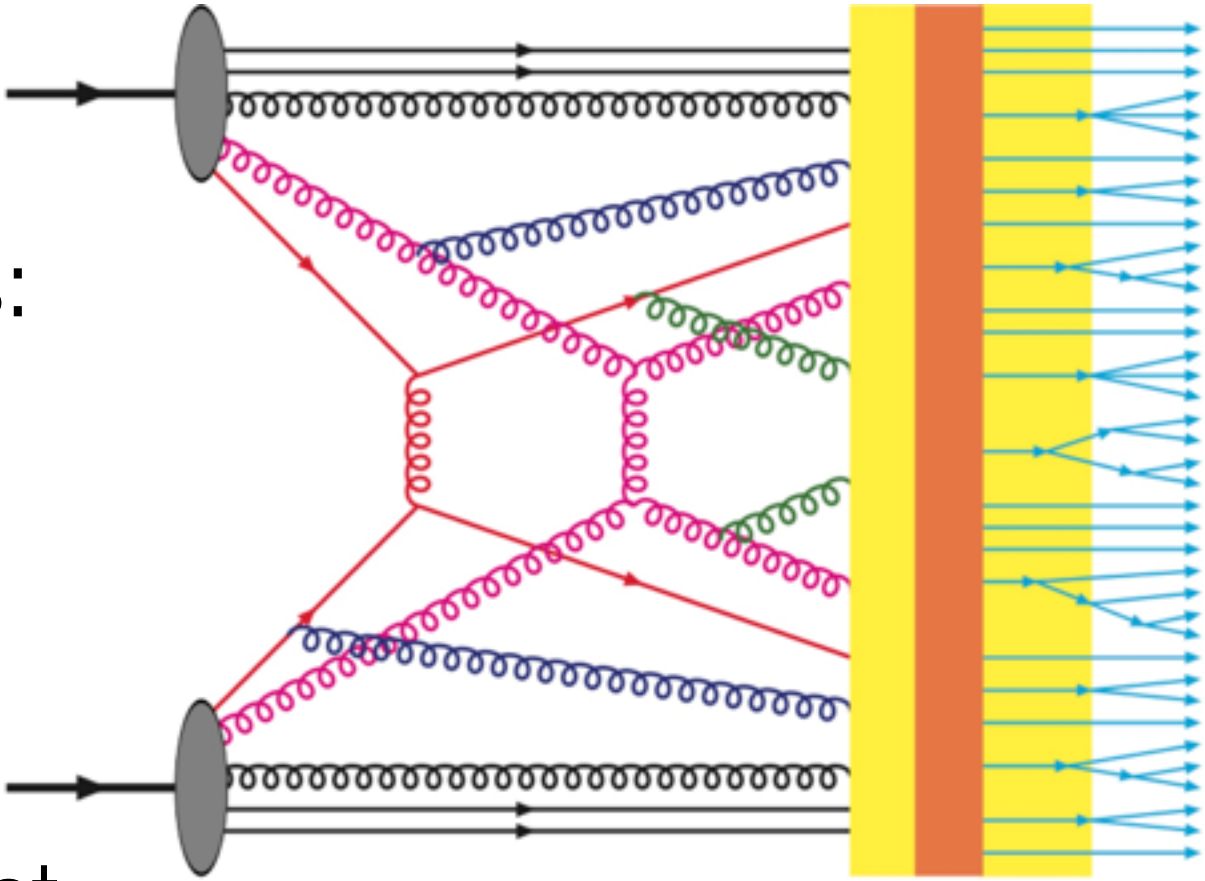
What is Pythia 8?

- General purpose Monte-Carlo generator
- Simulates collision events: hard process, showering, hadronisation, multiple interactions, underlying event ...
- Version 8.1 released in Oct 2007. Current version 8.175



Download and online manual from http://home.thep.lu.se/~torbjorn/Pythia.html

Support for Pythia 6 has stopped!

...
Development of Pythia 6 now stops. **We will still provide support and urgent fixes to the code, if necessary, until 1 March 2013. At this point, the Pythia 6 code will be frozen, and a final legacy version will be released later in 2013.** We will then continue to answer questions regarding the behavior of Pythia 6 until 1 July 2013, after which only Pythia 8 will be actively developed and supported.
...

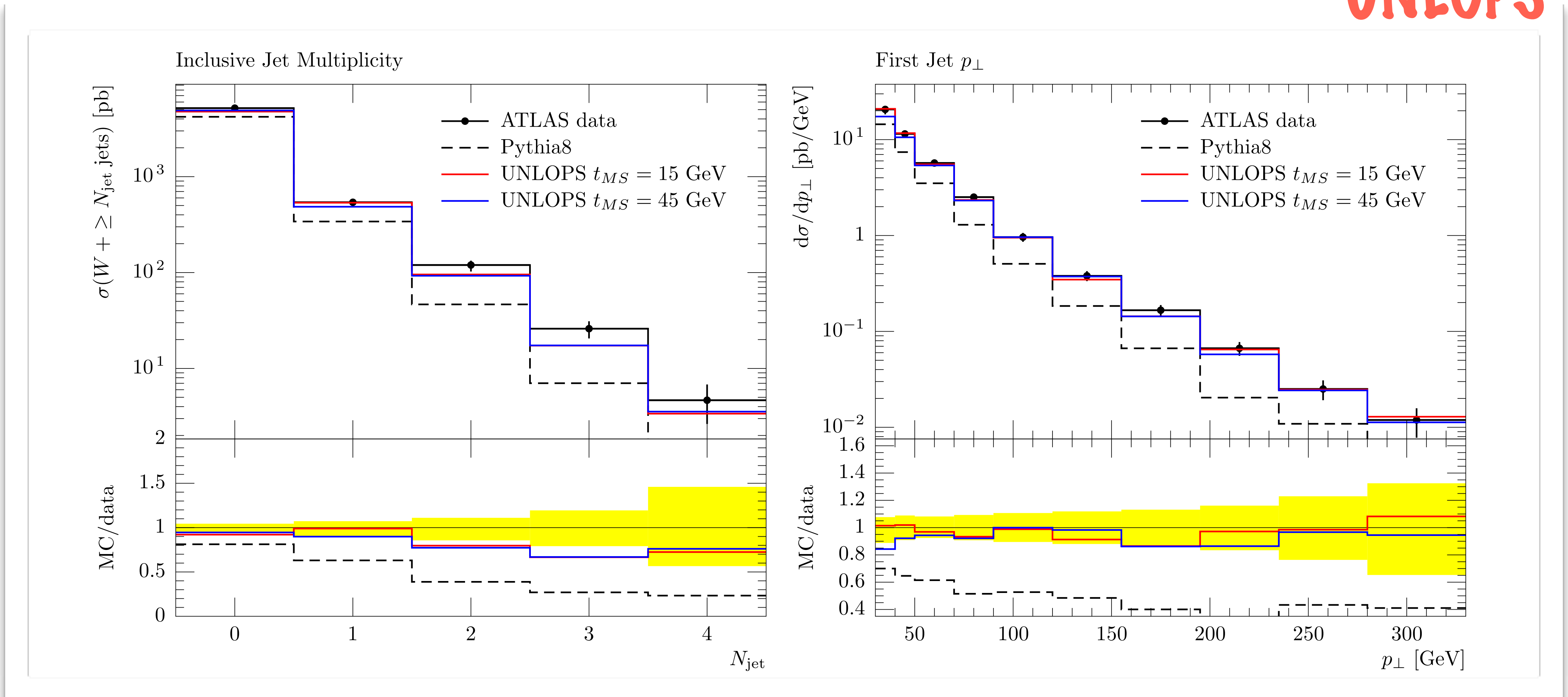
Full effort to make Pythia 8 better than Pythia 6 in all respects.

Needs more users and feedback.

- Important to model backgrounds correctly to observe BSM signatures.
- Current state-of-the-art SM calculations use ME generators + PS with matching followed by hadronisation.
  - ➡ Pythia 8 provides various interfaces to external ME generators
  - ➡ LO/NLO matching for processes available

ME + PS matching at NLO!

UNLOPS



Lonnblad and Prestel; arXiv:1211.7278

Also available LO matching via new Unitarised ME+PS merging (UMEPS), MLM and CKKW-L.

Interfaces

- Interface to LHAPDF or other external PDF libraries.
- Les Houches Accord (LHA) files for reading events or runtime LHA interface.
- Semi-internal processes for programs like Madgraph 5.
- HepMC output for programs like RIVET, Delphes etc.
- Can be compiled as a plugin to ROOT.
- Generalised SLHA input for any BSM model.

Other major improvements:

- ✦ Improvements to parton showers; possibility to use external PS programs (e.g. Vincia)
- ✦ Improvements to MPI
- ✦ Showering to take into account colour-epsilon topologies, sextets.
- ✦ Hadronisation in presence of coloured exotic particles (R-hadrons [*M. Fairbairn et al.,Phys. Rep. 438 (2007)*], long-lived triplets or octets, ...)
- ✦ Tau polarisation in both production and decay [*P. Ilten, arXiv:1211.6730 [hep-ph]*]

Example card file

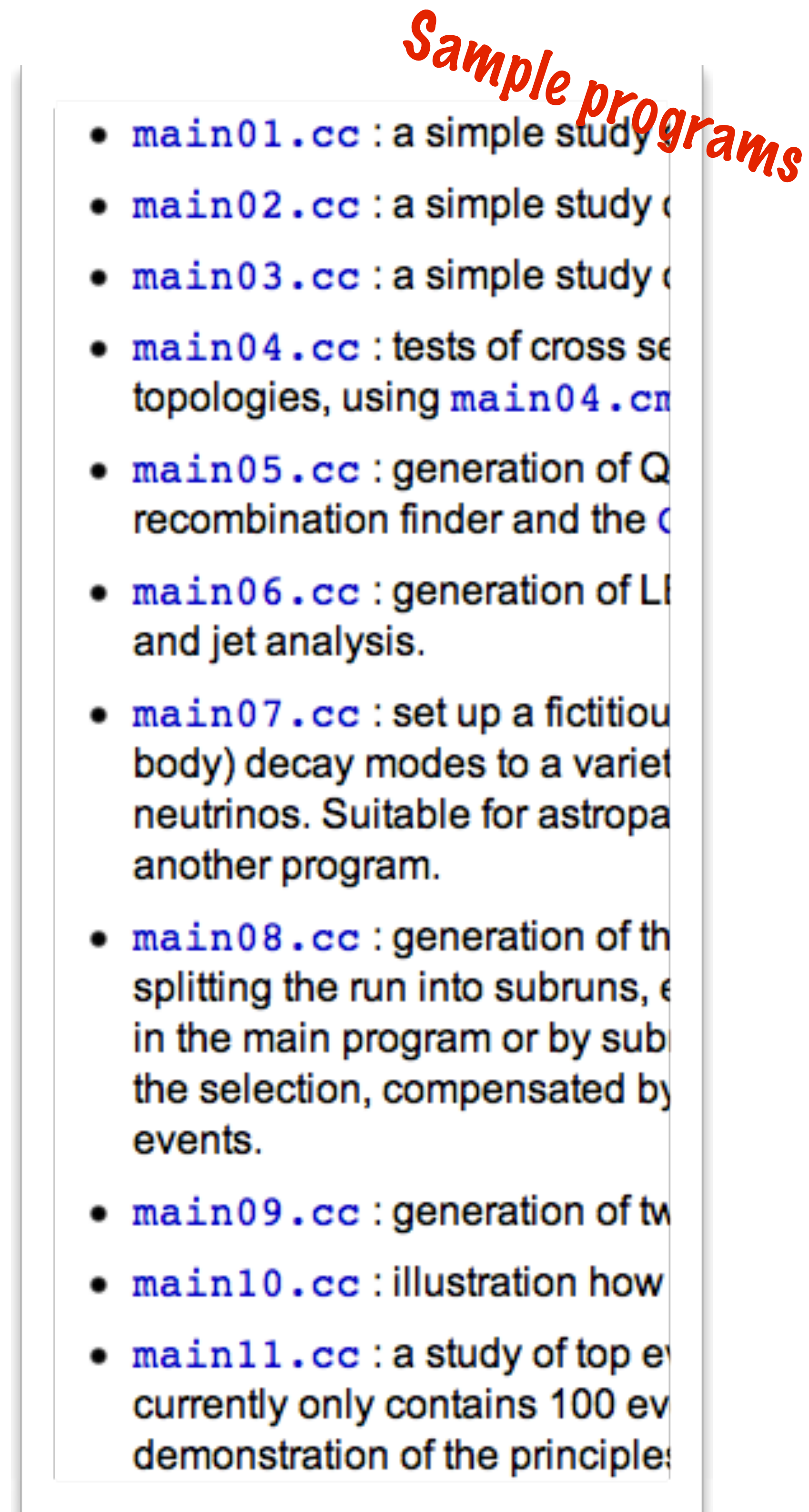
```
! 1) Settings that are used in the main program.
Main:numberOfEvents = 1000          ! number of events to generate
Main:timesAllowErrors = 10          ! abort run after this many flawed events

! 2) Settings related to output in init(), next() and stat().
Init:showChangedSettings = on       ! list changed settings
Init:showChangedParticleData = on   ! list changed particle data
#Init:showChangedResonanceData = on ! also print changed resonance data
Init:showOneParticleData = 25       ! print data for this particular particle
Next:numberCount = 100              ! print message every n events
Next:numberShowInfo = 1             ! print event information n times
Next:numberShowProcess = 1          ! print process record n times
Next:numberShowEvent = 0            ! print event record n times
Stat:showPartonLevel = on           ! more statistics on MPI

! 3) Beam settings.
Beams:idA = 2212                    ! first beam, p = 2212, pbar = -2212
Beams:idB = 2212                    ! second beam, p = 2212, pbar = -2212
Beams:eCM = 14000.                  ! CM energy of collision, LHC

! 4) Settings for hard-process generation internal to Pythia8.
HiggsSM:gg2H = on                   ! Higgs production by gluon-gluon fusion
25:m0 = 125.4                       ! Higgs mass

! 5) Switch off some key components of the simulation, for comparisons.
#PartonLevel:all = off               ! stop after hard process
#PartonLevel:MPI = off               ! no multiparton interactions
#PartonLevel:ISR = off               ! no initial-state radiation
#PartonLevel:FSR = off               ! no final-state radiation
#HadronLevel:all = off               ! stop after parton level
#HadronLevel:Hadronize = off         ! no hadronization
```



- ✦ Pythia 8 has a basic library of BSM processes that can be used for quick studies.
  - BSM Higgses (2HDM)
  - Fourth generation quarks
  - New Gauge Bosons
  - Left-Right symmetric models
  - Leptoquarks
  - Compositeness
  - Hidden Valley
  - Extra Dimensions
  - SUSY
- ✦ More exotic processes may be implemented via external programs.

BSM Higgses (2HDM):

Start with two complex Higgs doublets (eight d.o.f.), three are “eaten”, left with five: two CP-even, neutral; one CP-odd neutral and pair of charged Higgses.

Many 2HDM possibilities depending on which doublet couples to which fermions.

- Type I: all fermions couple only to second doublet
- Type II: up-type quarks couple to first, down-type and charged leptons to second (like in SUSY)
- Type III: up-type quarks and charged leptons to first, down-type to second
- Type IV: all quarks couple to first, all charged leptons to second.

HiggsBSM:all = on

Common switch for the group of Higgs production beyond the Standard Model

HiggsBSM:ffbar2H1 = on

Scattering *f fbar -> h^0(H_1^0)*, where *f* sums over available flavours except top.

HiggsBSM:gg2H1 = on

Scattering *g g -> h^0(H_1^0)* via loop contributions primarily from top.

Can be turned on using

parm **HiggsH1:coup2d** (default = **1.**)
The *h^0(H_1)* coupling to down-type quarks.

parm **HiggsH1:coup2u** (default = **1.**)
The *h^0(H_1)* coupling to up-type quarks.

parm **HiggsH1:coup2l** (default = **1.**)
The *h^0(H_1)* coupling to (charged) leptons.

parm **HiggsH1:coup2Z** (default = **1.**)
The *h^0(H_1)* coupling to *Z^0*.

parm **HiggsH1:coup2W** (default = **1.**)
The *h^0(H_1)* coupling to *W^+-*.

parm **HiggsH1:coup2Hchg** (default = **0.**)

...

Set couplings

CPX scenario possible

mode **HiggsH1:parity** (default = **1**; minimum = 0; maximum = 3)
possibility to modify angular decay correlations in the decay of a *h^0(H_1)* decay *Z^0 Z^0* or *W^+ W^-* to four fermions. Currently it does not affect the partial width of the channels, which is only based on the above parameters.

option **0** : isotropic decays.
option **1** : assuming the *h^0(H_1)* is a pure scalar (CP-even), as in the MSSM.
option **2** : assuming the *h^0(H_1)* is a pure pseudoscalar (CP-odd).
option **3** : assuming the *h^0(H_1)* is a mixture of the two, including the CP-violating interference term.

Extra Gauge Bosons

NewGaugeBoson:ffbar2gmZZprime = on
Scattering *f fbar ->Z'^0*. [..]

mode **Zprime:gmZmode** (default = **0**; minimum = 0; maximum = 6)
Choice of full *gamma^*/Z^0/Z'^0* structure or not in the above process. [...]
option **0** : full *gamma^*/Z^0/Z'^0* structure, with interference included.
option **1** : only pure *gamma^** contribution.
option **2** : only pure *Z^0* contribution.
option **3** : only pure *Z'^0* contribution.
option **4** : only the *gamma^*/Z^0* contribution, including interference.
option **5** : only the *gamma^*/Z'^0* contribution, including interference.
option **6** : only the *Z^0/Z'^0* contribution, including interference.

Can be turned on with full interference with gamma/Z

flag **Zprime:universality** (default = **on**)
If on then you need only set the first-generation couplings below, and these are automatically also used for the second and third generation. If off, then couplings can be chosen separately for each generation.

parm **Zprime:vd** (default = **-0.693**)
vector coupling of *d* quarks.

parm **Zprime:ad** (default = **-1.**)
axial coupling of *d* quarks.

parm **Zprime:vu** (default = **0.387**)
vector coupling of *u* quarks.

parm **Zprime:au** (default = **1.**)
axial coupling of *u* quarks.

Versatile assignment of couplings

Extra Gauge Bosons

NewGaugeBoson:ffbar2Wprime = on

[T]here is no equally compelling case for *W^+-/W'^+-* interference effects being of importance for discovery, and such interference has therefore not been implemented for now.

The couplings of the *W'^+-* are here assumed universal, i.e. the same for all generations. One may set vector and axial couplings freely, separately for the *q qbar'* and the *l nu_l* decay channels. [...] [F]or simplicity, the same Cabibbo--Kobayashi--Maskawa quark mixing matrix is assumed as for the standard *W^+-*. [...]

`parm` **Wprime:vq** `(default = 1.)`
vector coupling of quarks.

`parm` **Wprime:aq** `(default = -1.)`
axial coupling of quarks.

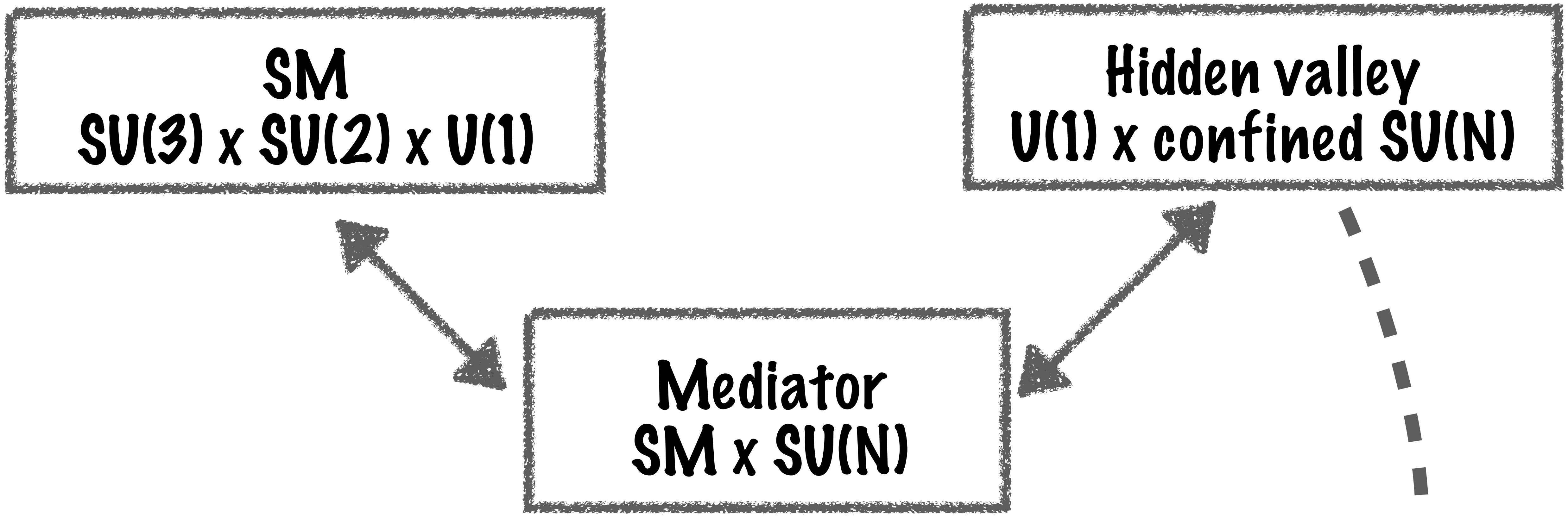
`parm` **Wprime:vl** `(default = 1.)`
vector coupling of leptons.

`parm` **Wprime:al** `(default = -1.)`
axial coupling of leptons.

Hidden Valleys

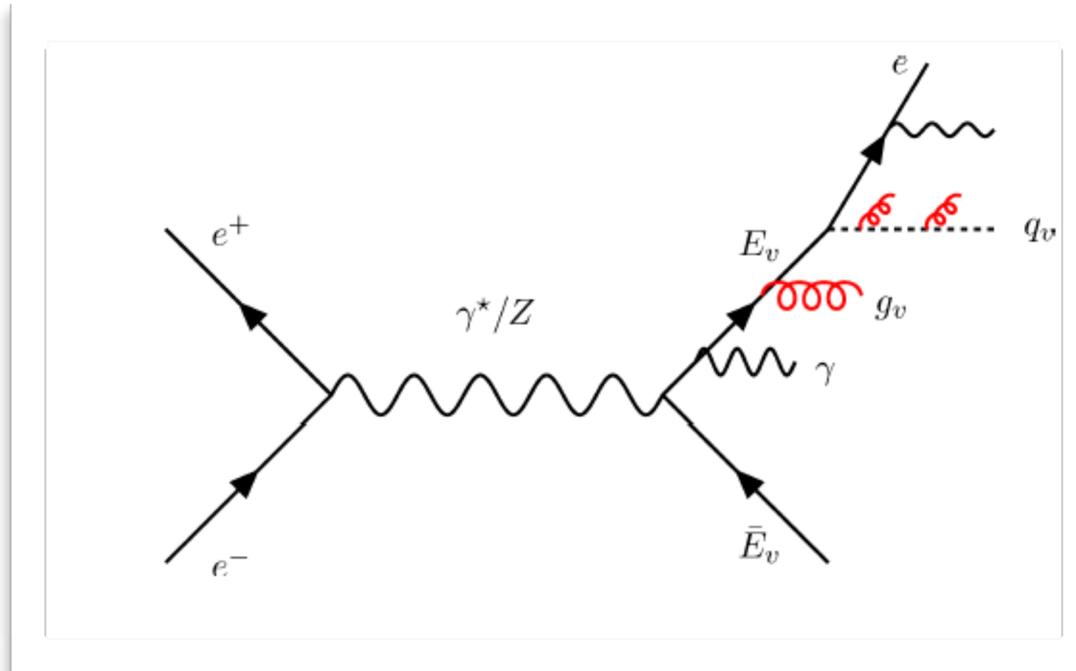
L. Carloni and T. Sjöstrand, JHEP 1009 (2010) 105

L. Carloni, J. Rathsman and T. Sjöstrand, JHEP 1104 (2011) 091



- ✦ Hidden valley photon: mixes with SM photon, Z
- ✦ New (hidden) mesons; flavour singlets can decay to SM

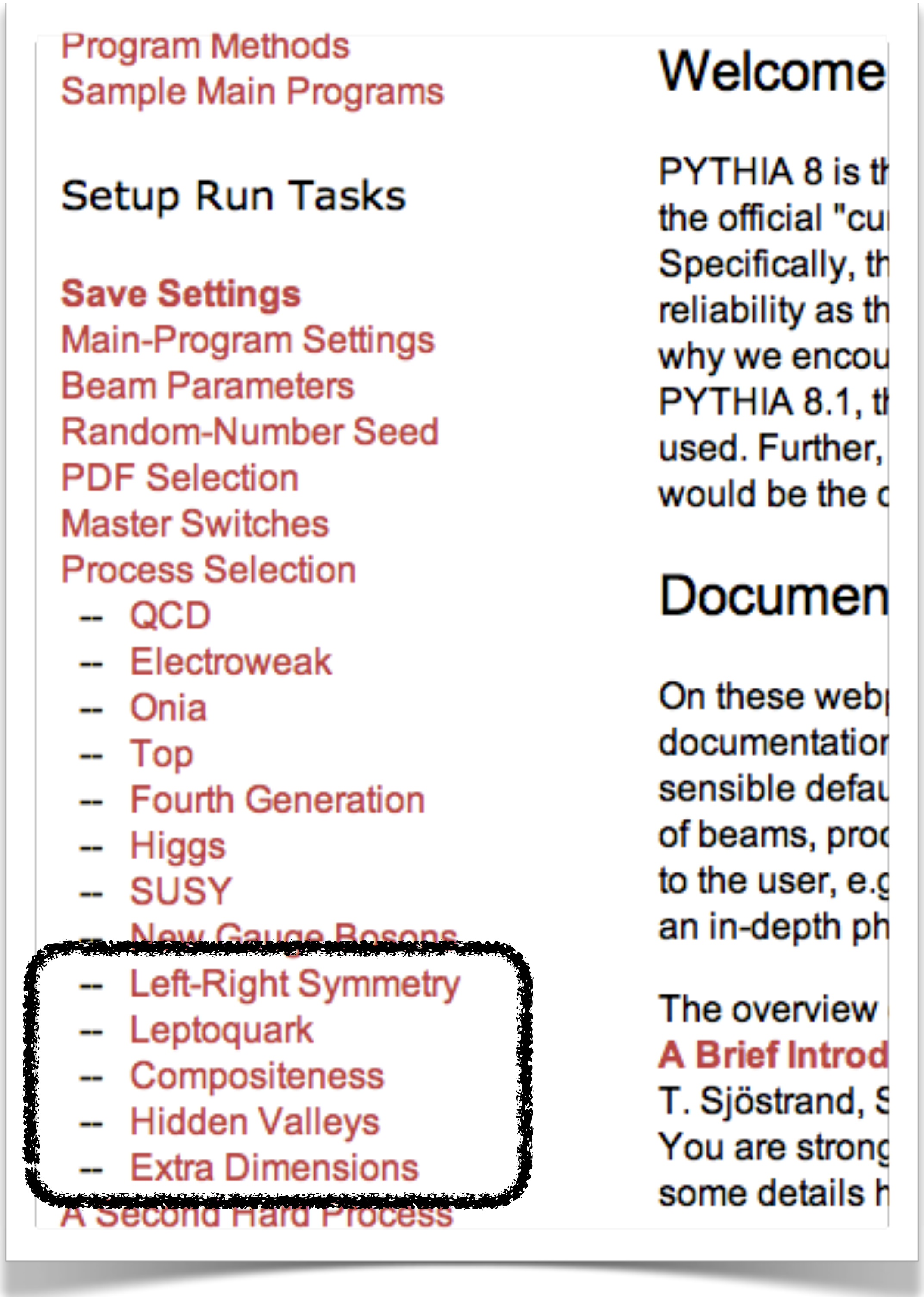
FSR of new sector:



- ✦ Mediator particles charged under both groups
- ✦ Normal QCD, QED radiation
- ✦ Radiation into hidden valley photons (which then decay to SM via mixing with SM gauge bosons
- ✦ Radiation into hidden valley gluons which forms hidden sector mesons

See online manual for:

- ✦ Left-Right models
- ✦ Leptoquarks
- ✦ Compositeness
- ✦ Extra dimensions:
  - Randall-Sundrum
  - Universal ED
  - Large ED
  - Unparticles


Program Methods
Sample Main Programs

Setup Run Tasks

Save Settings
Main-Program Settings
Beam Parameters
Random-Number Seed
PDF Selection
Master Switches
Process Selection
-- QCD
-- Electroweak
-- Onia
-- Top
-- Fourth Generation
-- Higgs
-- SUSY
-- New Gauge Bosons
-- Left-Right Symmetry
-- Leptoquark
-- Compositeness
-- Hidden Valleys
-- Extra Dimensions
A Second Hard Process

Welcome

PYTHIA 8 is th
the official "cu
Specifically, th
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why we encou
PYTHIA 8.1, th
used. Further,
would be the c

Documen

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to the user, e.g
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The overview
A Brief Introd
T. Sjöstrand, S
You are strong
some details h

Supersymmetry

ND and P. Skands, Eur. Phys. J. C72 (2012) 2238

Idea: Space-time + new fermionic co-ordinates
= Superspace!

➡Writing field theory in this space requires superfields

➡Each superfield has both bosonic and fermionic components

➡If we write SM using superfields, we get a new "superpartner" for each field

SUSY in Pythia 8

- ✦ Can read in files SUSY Les Houches v2 (SLHA2) format (more later...)

- ✦ 6x6 squark matrices allow processes with
  - CP violation
  - Flavour violation
  - R-parity violation

$$\begin{pmatrix} \tilde{u}_1 \\ \tilde{u}_2 \\ \tilde{u}_3 \\ \tilde{u}_4 \\ \tilde{u}_5 \\ \tilde{u}_6 \end{pmatrix} = R^u \begin{pmatrix} \tilde{u}_L \\ \tilde{c}_L \\ \tilde{t}_L \\ \tilde{u}_R \\ \tilde{c}_R \\ \tilde{t}_R \end{pmatrix} ; \begin{pmatrix} \tilde{d}_1 \\ \tilde{d}_2 \\ \tilde{d}_3 \\ \tilde{d}_4 \\ \tilde{d}_5 \\ \tilde{d}_6 \end{pmatrix} = R^d \begin{pmatrix} \tilde{d}_L \\ \tilde{s}_L \\ \tilde{b}_L \\ \tilde{d}_R \\ \tilde{s}_R \\ \tilde{b}_R \end{pmatrix}$$

- ✦ Cross sections
  - Pair production of all strongly charged superparticles
  - Pair production of Neutralinos and Charginos

Production processes

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

Slepton-pair, neutralino/chargino - gluino currently being validated

Sparticle Decays

✦ Calculate all decay widths for 2-body decays of squarks, sleptons, gluino, neutralinos and charginos.

- $\tilde{g} \to \tilde{q}_i q_j$
- $\tilde{\chi}_i^0 \to \tilde{q}_i q_j,\ \tilde{l}_i l_j\ \tilde{\chi}_j^0 Z,\ \tilde{\chi}_j^+ W^-, \tilde{\chi}_j^0 H_k, \tilde{\chi}_j^+ H^-$
- $\tilde{\chi}_i^+ \to \tilde{q}_i q_j,\ \tilde{l}_i l_j\ \tilde{\chi}_j^+ Z,\ \tilde{\chi}_j^0 W^+, \tilde{\chi}_j^+ H_k, \tilde{\chi}_j^0 H^+$
- $\tilde{q}_i \to q_j \tilde{\chi}_k^0,\ q_j \tilde{\chi}_k^+,\ \tilde{q}_j Z,\ \tilde{q}_j W^+, \tilde{q}_j H_k, \tilde{q}'_j H^+$

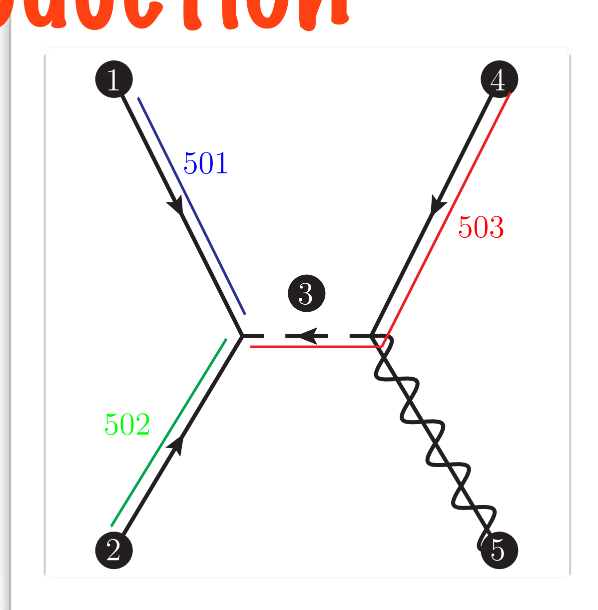
Three body widths should be supplied via SLHA

R-parity violating processes

Three types of RPV couplings: LLE, LQD, UDD

$(\lambda_{ijk}, \lambda'_{ijk} \text{ and } \lambda''_{ijk})$

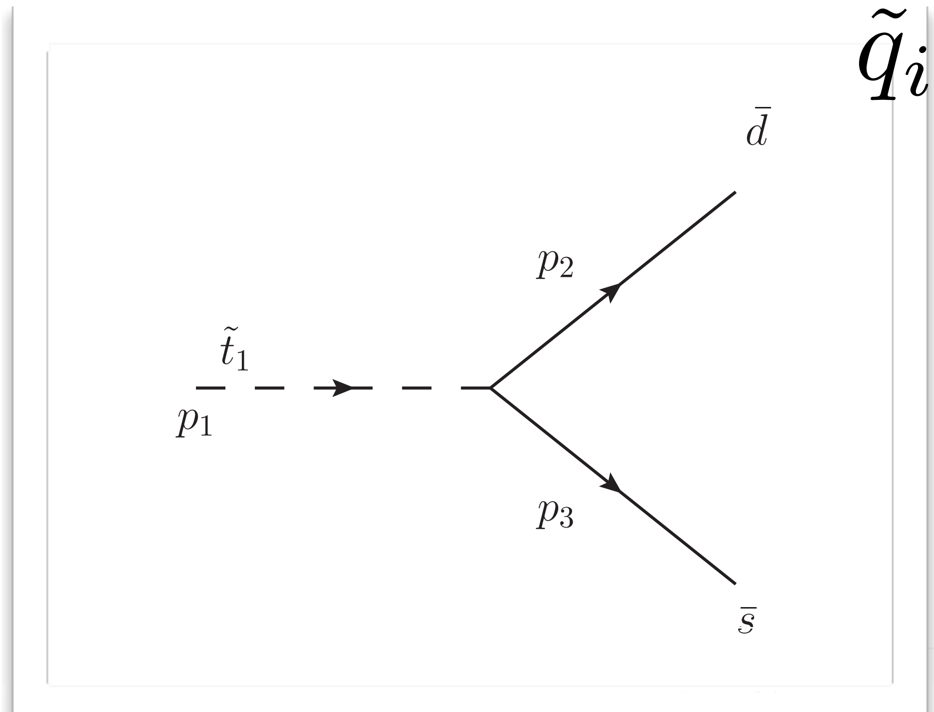
Production



$q_i q_j \to \tilde{q}_k^*$ via λ''_{ijk}

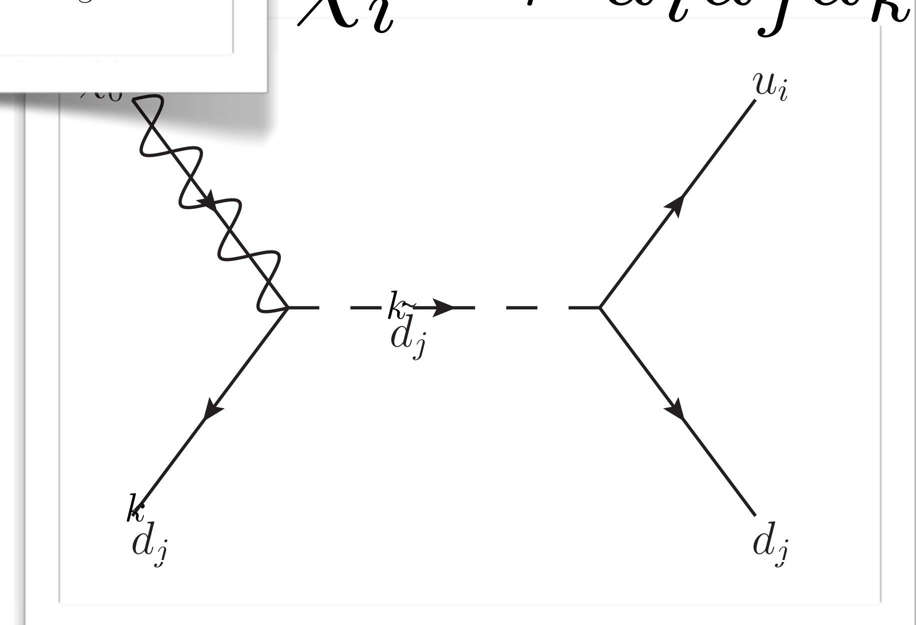
$$\sigma_{\tilde{u}_i^*} = \frac{2\pi}{3m_i^2}\sum_{jk}\sum_{i'}|\lambda''_{i'jk}(R^u)_{ii'}|^2$$

$\tilde{q}_i \to \bar{q}_j \bar{q}_k$

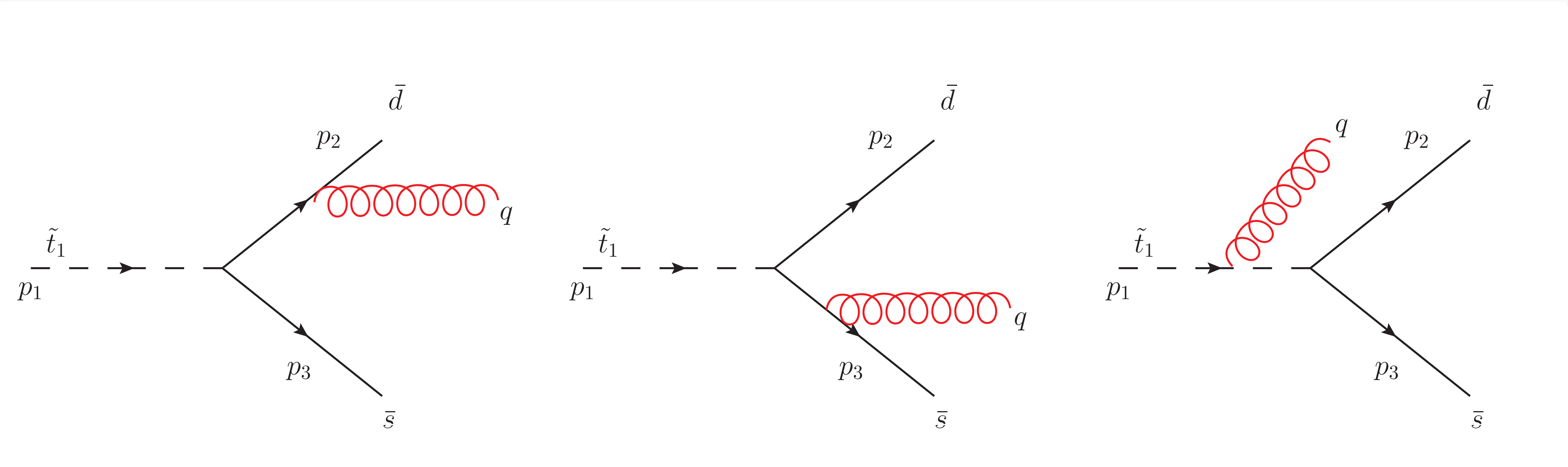


Decays

$\tilde{\chi}_i^0 \to u_i d_j d_k$



Showering in the presence of BNV

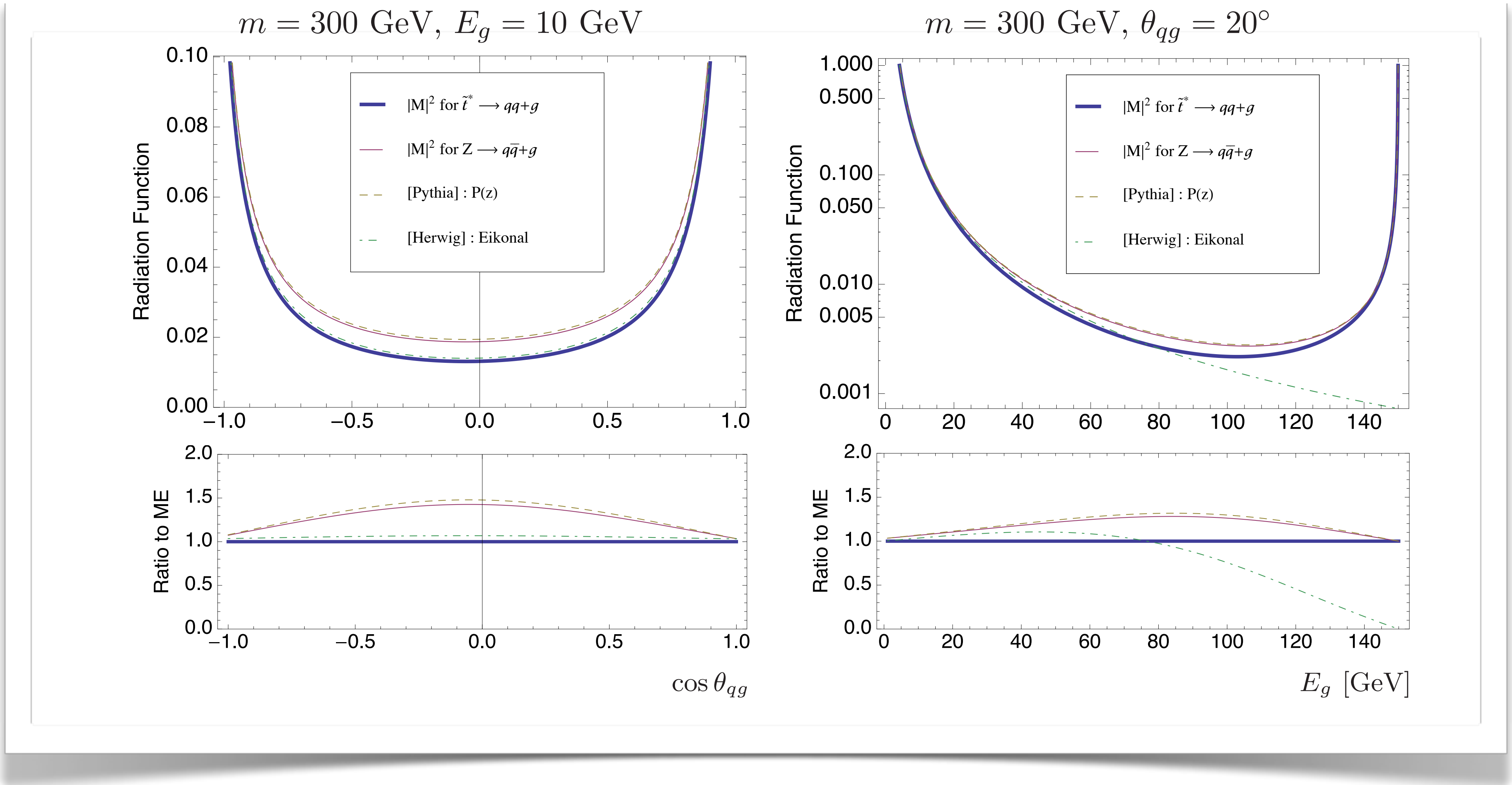


$$\frac{|M_1|^2}{|M_0|^2} = 4\pi\alpha_s C_F \left[\frac{1}{(N_c-1)}\left(\frac{2s_{23}}{s_{2q}s_{3q}} + \frac{2s_{12}}{s_{1q}s_{2q}} + \frac{2s_{13}}{s_{1q}s_{3q}}\right) + \frac{s_{2q}}{ss_{3q}} + \frac{s_{3q}}{ss_{2q}}\right]$$

$$+ \text{finite terms}$$

Case of $\tilde{\chi}_i^0 \to u_i d_j d_k$ is similar, with three half-strength dipoles between the quarks

Showering in the presence of BNV



$$\frac{|M_{Z\to q\bar{q}+g}|^2}{|M_{Z\to q\bar{q}}|^2} = 8\pi\alpha_s C_F\left(\frac{2s_{23}}{s_{2q}s_{3q}} + \frac{s_{2q}}{\hat{s}s_{3q}} + \frac{s_{3q}}{\hat{s}s_{2q}}\right)$$

What about the Higgs sector of SUSY?

- ➡ The 2HDM model is automatically initialised using data read in via SLHA

On going SUSY work:

- ➡ Three body decays
- ➡ Validation of remaining decays.
- ➡ Higgs decays to SUSY particles
- ➡ Production of sleptons
- ➡ Production at leptons colliders (for CLIC/ILC studies)

Improvements to SLHA interface

Was designed for SUSY

```
BLOCK MODSEL  # Model selection
     1     1   sugra
#
BLOCK SMINPUTS  # Standard Model inputs
     1     1.27934000E+02   # alpha_em^-1(M_Z)^MSbar
     2     1.16637000E-05   # G_F [GeV^-2]
     3     1.18000000E-01   # alpha_S(M_Z)^MSbar
     4     9.11876000E+01   # M_Z pole mass
     5     4.25000000E+00   # mb(mb)^MSbar
     6     1.75000000E+02   # mt pole mass
     7     1.77700000E+00   # mtau pole mass
#
BLOCK MINPAR  # Input parameters - minimal models
     1     1.00000000E+02   # m0
     2     2.50000000E+02   # m12
     3     1.00000000E+01   # tanb
     4     1.00000000E+00   # sign(mu)
     5    -1.00000000E+02   # A0
```

Problem with designing a generic interface for all BSM models is how to implement arbitrary blocks

particle ID particle name

```
BLOCK QNUMBERS 7654321 # balleron
      1      0  # 3 times electric charge
      2      2  # number of spin states (2S+1)
      3      8  # colour rep (1: singlet, 3: triplet, 6: sextet, 8: octet)
      4      0  # Particle/Antiparticle distinction (0=own anti)
```

particle name anti-particle name

```
BLOCK QNUMBERS 8765432 # yup yupbar
      1      2  # 3 times electric charge
      2      2  # number of spin states (2S+1)
      3      3  # colour rep (1: singlet, 3: triplet, 6: sextet, 8: octet)
      4      1  # Particle/Antiparticle distinction (0=own anti)

 BLOCK MASS
 #      ID code   pole mass in GeV
        7654321    800.0   # m(balleron)
        8765432    600.0   # m(yup)

 #           ID       WIDTH in GeV
 DECAY    7654321   2.034369169E+00   # balleron decays
 #     BR                  NDA       ID1       ID2       ID3
       9.900000000E-01     3         6           5         3    # BR( -> t b s )
       1.000000000E-02     3         4           5         3    # BR( -> c b s )
```

Use either a **semi-internal process** (your own derived subclass of a Pythia process) to provide production cross section expressions or **read in LHE file** generated externally.

What if you need extra parameters (blocks)?

➡Pythia provides functionality to retrieve data from arbitrarily named blocks

```
bool slhaPtr->getEntry(string blockName, double& val);
bool slhaPtr->getEntry(string blockName, int indx, double& val);
bool slhaPtr->getEntry(string blockName, int indx, int jndx, double& val);
bool slhaPtr->getEntry(string blockName, int indx, int jndx, int kndx, double& val);
```

In Summary:

- ➡ Pythia 8 provides cutting edge support for matching
- ➡ Tau polarisation and decays now built-in
- ➡ Many BSM models supported
- ➡ Showering/hadronisation with exotic colour states available
- ➡ All SUSY production processes relevant for LHC have been implemented.
- ➡ Arbitrary BSM models can be implemented by the user.

Backup

Param card for merging

```
! main86.cmnd.
! This file contains commands to be read in for a Pythia8 run.
! Lines not beginning with a letter or digit are comments.

// Number of events generated
Main:numberOfEvents         = 1000

// Specify shower options
HadronLevel:all             = on
PartonLevel:MPI             = on

// Core process for merging
Merging:Process             = pp>LEPTONS,NEUTRINOS

// Maximal number of additional LO jets.
Merging:nJetMax             = 2

// Merging scale value.
Merging:TMS                 = 15

// Switch off enforced rapidity ordering
SpaceShower:rapidityOrder   = off

// Since UMEPS is a tree-level merging method, both leading-order and
// next-to-neading order PDFs are allowed. However, from parton shower
// considerations, leading-order PDFs are preferred, since multiparton
// interactions probe the incoming hadron at small momentum scales.
// Example PDF files generated with CTEQ6M PDFs.
PDF:useLHAPDF               = on
PDF:LHAPDFset               = cteq6m.LHpdf
SpaceShower:alphaSvalue     = 0.118
TimeShower:alphaSvalue      = 0.118
```

Param card for SUSY

```
Beams:idA = 2212                    ! first beam, p = 2212, pbar = -2212
Beams:idB = 2212                    ! second beam, p = 2212, pbar = -2212
Beams:eCM = 10000.                  ! CM energy of collision

! 4) Read SLHA spectrum
SLHA:file = cmssm.spc               ! Sample SLHA1 spectrum for CMSSM-10.1.1
#SLHA:file = sps1aWithDecays.spc      ! Older example including DECAY tables

! 5a) Process selection
#SUSY:all = on                       ! Switches on ALL (~400) SUSY processes
#SUSY:gg2gluinogluino  = on
#SUSY:qqbar2gluinogluino  = on
#SUSY:qg2squarkgluino = on
#SUSY:gg2squarkantisquark = on
#SUSY:qqbar2squarkantisquark = on
#SUSY:qq2squarksquark = on
#SUSY:qqbar2chi0chi0  = on
#SUSY:qqbar2chi+-chi0 = on
#SUSY:qqbar2chi+chi-  = on
#SUSY:qg2chi0squark = on
#SUSY:qg2chi+-squark  = on
#SUSY:qqbar2chi0gluino = on
#SUSY:qqbar2chi+-gluino = on
SUSY:qqbar2sleptonantislepton = on

! Optionally select only specific sparticle codes in the final state
SUSY:idA        = 1000015            ! 0: all
SUSY:idB        = 1000015            ! 0: all
```

Fourth generation quarks: t', b'

`flag` **FourthBottom:all** (default = **off**)
Common switch for the group of *b'* production.

`flag` **FourthBottom:gg2bPrimebPrimebar** (default = **off**)
Scatterings *g g -> b' b'bar*. Code 801.

`flag` **FourthBottom:qqbar2bPrimebPrimebar** (default = **off**)
Scatterings *q qbar -> b' b'bar* by gluon exchange.

`flag` **FourthBottom:qq2bPrimeq(t:W)** (default = **off**)
Scatterings *q q' -> b' q''* by *t*-channel exchange of a *W^+-* boson.

`flag` **FourthBottom:ffbar2bPrimebPrimebar(s:gmZ)** (default = **off**)
Scatterings *f fbar -> b' b'bar* by *s*-channel exchange of a *gamma^*/Z^0* boson.

`flag` **FourthBottom:ffbar2bPrimeqbar(s:W)** (default = **off**)
Scatterings *f fbar' -> b' qbar''* by *s*-channel exchange of a *W^+-* boson. Here *q''* is either *u* or *c*.

`flag` **FourthBottom:ffbar2bPrimetbar(s:W)** (default = **off**)
Scatterings *f fbar' -> b' tbar* by *s*-channel exchange of a *W^+-* boson.

Production, similar for t'

`flag` **FourthPair:ffbar2tPrimebPrimebar(s:W)** (default = **off**)
Scatterings *f fbar' -> t' b'bar* by *s*-channel exchange of a *W^+-* boson.

`flag` **FourthPair:ffbar2tauPrimenuPrimebar(s:W)** (default = **off**)
Scatterings *f fbar' -> tau' nu'_taubar* by *s*-channel exchange of a *W^+-* boson.

`parm` **FourthGeneration:VubPrime** (default = **0.001**; minimum = 0.0; maximum = 1.0)
The *V_ub'* matrix element in the 4 * 4 CKM matrix.

`parm` **FourthGeneration:VcbPrime** (default = **0.01**; minimum = 0.0; maximum = 1.0)
The *V_cb'* matrix element in the 4 * 4 CKM matrix.

`parm` **FourthGeneration:VtbPrime** (default = **0.1**; minimum = 0.0; maximum = 1.0)
The *V_tb'* matrix element in the 4 * 4 CKM matrix.

CKM parameters

Why is SUSY so popular?

- ✦ We would expect large loop corrections to Higgs mass which depend on the scale upto which SM is valid. If this is (say) the Planck scale, why is Higgs mass so small?
  - ➡ Loop contribution from bosons and fermions differ in sign. Superpartners would mean a natural cancellation.
- ✦ We need new source of CP to explain baryon asymmetry. SUSY has a large sector unexplored with plenty of possibilities.

Why is SUSY so popular?

- ✦ If there is a Grand Unified Theory, SUSY provides unification of couplings at the GUT scale
- ✦ Problem with proton decay due to scalars that carry lepton or baryon number.
  - ➡Solved by introduction of R-parity gives a bonus: provides a natural DM candidate with the right relic density
- ✦ Possibility of getting neutrino masses.

Looks like a cure for all ills,
BUT ...