Monte Carlo event generation

The '*Fun-ny*' tutorial

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Lectures and tutorials on Monte Carlo event generation

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The model - compositeness and dark matter

Modelling composite theories with dark matter and partial compositeness

- Top mass achieved from mixing with vector-like partners
  → bottom quark massless

$$Q^0_{L,R} = \begin{pmatrix} T^0_{L,R} \\ B^0_{L,R} \end{pmatrix} \quad \text{and} \quad \tilde{T}^0_{L,R}$$

- A scalar dark matter candidate X

- Quite simple Lagrangian:
  → Yukawa couplings y between the partners and the Higgs $\mathbf{\Phi}$
  → Mass mixings $\mathbf{\Delta}$ [origin not relevant]
  → Yukawa couplings λ between X, the partners and the SM

$$\begin{aligned}\mathcal{L}_{\rm BSM} = & - M_Q \overline{Q^0_L} Q^0_R - M_{\tilde{T}} \overline{\tilde{T}^0_L} \tilde{T}^0_R - \frac{1}{2} M_X X^2 \\ & - \Big(y^* (\overline{Q^0_L} \cdot \Phi^\dagger) \widetilde{T}^0_R + \Delta_L \overline{q^0_L} Q^0_R + \Delta_R \overline{t^0_R} \widetilde{T}^0_L + \text{H.c.} \Big) \\ & + \Big(\hat{\lambda}_{\mathbf{Q}} \ \overline{Q^0_R} \ q^0_L X + \hat{\lambda}_{\mathbf{T}} \ \overline{\tilde{T}^0_L} \ t^0_R X + \text{H.c.} \Big)\end{aligned}$$

Simplified model

- 3 mediators and 1 dark matter (mass eigenstates ≡ gauge eigenstates)

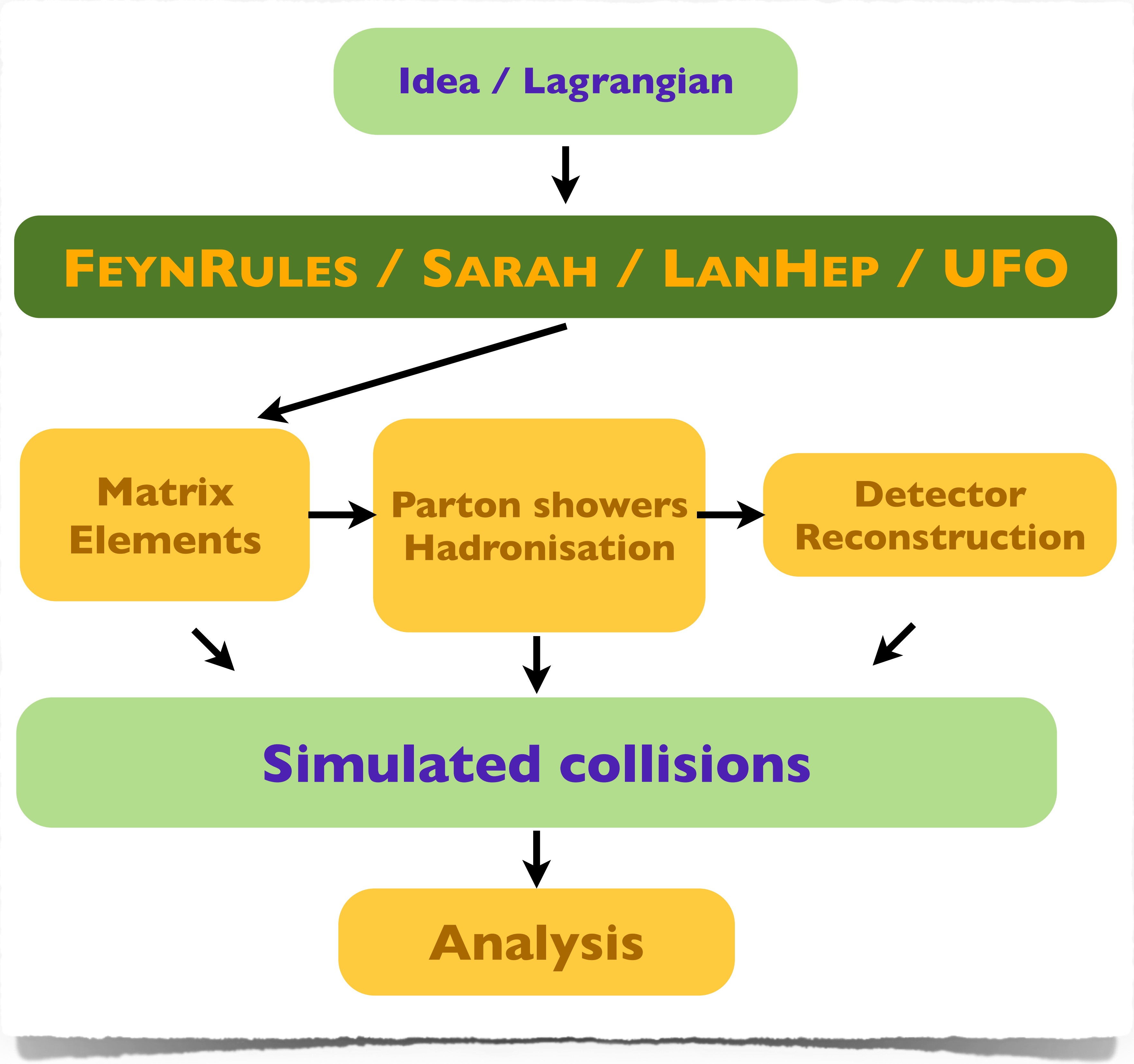
$$T_{L,R}\,, \quad \tilde{T}_{L,R}\,, \quad B_{L,R} \quad \text{and} \quad X$$

- Lagrangian → Free parameters: 4 masses and 2 couplings

$$\begin{aligned}\mathcal{L}_{\rm BSM} = & \ \mathcal{L}_{\rm kin} - M_T \overline{T}\ T - M_B \overline{B}\ B - M_{\tilde{T}} \overline{\tilde{T}}\ \tilde{T} - \frac{1}{2} M_X X^2 \\ & + \Big(\lambda_Q \big[\ \overline{T_R}\ t_L + \overline{B_R}\ b_L\ \big] X + \lambda_T\ \overline{\tilde{T}_L}\ t_R\ X + \text{H.c.} \Big)\end{aligned}$$

Connecting ideas to simulations...

[Christensen, de Aquino, Degrande, Duhr, BF, Herquet, Maltoni & Schumann (EPJC`11)]



- Model building → UFO
- Hard scattering → MG5_aMC
  - ⋆ Feynman diagram and amplitude generation
  - ⋆ Monte Carlo integration
  - ⋆ Event generation
- QCD environment → Pythia
  - ⋆ Parton showering
  - ⋆ Hadronisation
  - ⋆ Underlying event
- Detector simulation → Rivet
  - ⋆ Simulation of the detector response
  - ⋆ Object reconstruction
- Event analysis → Rivet

Feynman diagram determination

Determine the diagrams of all new physics signals of the model (with MG5aMC@NLO)

```
import model DMSimp_t-F3S_VLQ --modelname
```

```
MG5_aMC>import model DMSimp_t-F3S_VLQ --modelname
INFO: Restrict model DMSimp_t-F3S_VLQ with file models/DMSimp_t/restrict_F3S_VLQ.dat .
INFO: Run "set stdout_level DEBUG" before import for more information.
Kept definitions of multiparticles p / j / l+ / l- / vl / vl~ unchanged
Defined multiparticle all = g ghg ghg~ u c d s b u~ c~ d~ s~ b~ a gha gha~ ve vm vt e- mu- ve~ vm~ vt~ e+ mu+ ys3qu1 ys3qu2 ys3q
u3 ys3qd1 ys3qd2 ys3qd3 ys3u1 ys3u2 ys3u3 ys3d1 ys3d2 ys3d3 ys3qu1~ ys3qu2~ ys3qu3~ ys3qd1~ ys3qd2~ ys3qd3~ ys3u1~ ys3u2~ ys3u3~
 ys3d1~ ys3d2~ ys3d3~ t yf3qu1 yf3qu2 yf3qu3 yf3qd1 yf3qd2 yf3qd3 yf3u1 yf3u2 yf3u3 yf3d1 yf3d2 yf3d3 t~ yf3qu1~ yf3qu2~ yf3qu3~
 yf3qd1~ yf3qd2~ yf3qd3~ yf3u1~ yf3u2~ yf3u3~ yf3d1~ yf3d2~ yf3d3~ z w+ ghz ghwp ghwm h xs xc xv xw w- ghz~ ghwp~ ghwm~ xc~ xw~
ta- xm xd ta+ xd~
MG5_aMC>
```

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u3 ys3qd1 ys3qd2 ys3qd3 ys3u1 ys3u2 ys3u3 ys3d1 ys3d2 ys3d3 ys3qu1~ ys3qu2~ ys3qu3~ ys3qd1~ ys3qd2~ ys3qd3~ ys3u1~ ys3u2~ ys3u3~
 ys3d1~ ys3d2~ ys3d3~ t yf3qu1 yf3qu2 yf3qu3 yf3qd1 yf3qd2 yf3qd3 yf3u1 yf3u2 yf3u3 yf3d1 yf3d2 yf3d3 t~ yf3qu1~ yf3qu2~ yf3qu3~
 yf3qd1~ yf3qd2~ yf3qd3~ yf3u1~ yf3u2~ yf3u3~ yf3d1~ yf3d2~ yf3d3~ z w+ ghz ghwp ghwm h xs xc xv xw w- ghz~ ghwp~ ghwm~ xc~ xw~
ta- xm xd ta+ xd~
MG5_aMC>
```

Tasks

- Determine the ensemble of relevant new physics particles
- Determine the list of new physics processes
  - → Beware: the signal must be visible
- How many diagrams per process ?
  - → Distinguish the different channels (initial states)
  - → Try to guess before using MG5aMC to cross check
  - → Are all diagrams equal? Can some be neglected?

$$\mathcal{L}_{\rm BSM} = \mathcal{L}_{\rm kin} - M_T \overline{T}\, T - M_B \overline{B}\, B - M_{\tilde{T}} \overline{\tilde{T}}\, \tilde{T} - \frac{1}{2} M_X X^2 + \Big(\lambda_Q \big[\, \overline{T_R}\, t_L + \overline{B_R}\, b_L \,\big] X + \lambda_T\, \overline{\tilde{T}_L}\, t_R\, X + \text{H.c.} \Big)$$

Feynman diagram determination

Solution

- Abbreviations make life easy:
  - ➙ yy ≡ all top partners

```
MG5_aMC>define VLQT = yf3qu3; define VLQT~ = yf3qu3~;
Defined multiparticle vlqt = yf3qu3
Defined multiparticle vlqt~ = yf3qu3~
MG5_aMC>define VLQB = yf3qd3; define VLQB~ = yf3qd3~;
Defined multiparticle vlqb = yf3qd3
Defined multiparticle vlqb~ = yf3qd3~
MG5_aMC>define VLQTtilde = yf3u3; define VLQTtilde~ = yf3u3~;
Defined multiparticle vlqttilde = yf3u3
Defined multiparticle vlqttilde~ = yf3u3~
MG5_aMC>define VLQ = VLQT VLQB VLQTtilde
Defined multiparticle vlq = yf3qu3 yf3qd3 yf3u3
MG5_aMC>define VLQ~ = VLQT~ VLQB~ VLQTtilde~
Defined multiparticle vlq~ = yf3qu3~ yf3qd3~ yf3u3~
MG5_aMC>define yy = VLQ VLQ~
Defined multiparticle yy = yf3qu3 yf3qd3 yf3u3 yf3qu3~ yf3qd3~ yf3u3~
```

- Process generation
  - ⋆ Use the '*exclude*' option to remove the irrelevant particles
  - ⋆ Browse the generated folder to get the diagrams

```
MG5_aMC>generate p p > xs xs j
MG5_aMC>output
```

Feynman diagram determination

Solution

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MG5_aMC>define VLQT = yf3qu3; define VLQT~ = yf3qu3~;
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MG5_aMC>define VLQTtilde = yf3u3; define VLQTtilde~ = yf3u3~;
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MG5_aMC>generate p p > xs xs j
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Processes

- Monojet production (18 diagrams)
  - ➙ gb (and $g\bar{b}$) channel: 12 diagrams
  - ➙ $b\bar{b}$ channel: 6 diagrams

- VLQ pair production (63 diagrams)
  - ⋆ $gg \to T\bar{T}, \tilde{T}\bar{\tilde{T}}, B\bar{B}$
    - ➙ 3x3 QCD diagrams
  - ⋆ $q\bar{q} \to T\bar{T}, \tilde{T}\bar{\tilde{T}}, B\bar{B}$
    - ➙ 3x1 QCD diagram x 5 flavours (gluon exchange)
    - ➙ 3x2 EW diagrams x 5 flavours (photon/Z exchange)
  - ⋆ $b\bar{b} \to B\bar{B}$
    - ➙ 1 t-channel diagram (DM exchange)
  - ⋆ $q\bar{q}' \to B\bar{T} + T\bar{B}$
    - ➙ 2x1 diagrams x 2 flavour assignments (W exchange)
  - ⋆ $bb \to BB$, $\bar{b}\bar{b} \to \bar{B}\bar{B}$
    - ➙ 2x2 *t*-channel diagram (DM exchange)

Feynman diagram determination

Solution

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  - ➙ yy ≡ all top partners

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Processes

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  - ➙ *gb* (and $g\bar{b}$) channel: 12 diagrams
  - ➙ $b\bar{b}$ channel: 6 diagrams
- VLQ pair production (~~63~~ 29 diagrams)
  - $\star\, gg \to T\bar{T}, \tilde{T}\bar{\tilde{T}}, B\bar{B}$
    - ➙ 3x3 QCD diagrams
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Exercise

Tasks

- Simulate the VLQ signal with the decays with MADSPIN
- Edit the MADSPIN card correctly
- Edit the param card accordingly (VLQ widths to be automatically calculated, *i.e.* set to '*Auto*')
- Check the results in the param card
  → Determine the VLQ decay table

Exercise

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Solution

- MG5aMC commands:

```
import model DMSimp_t-F3S_VLQ --modelname
define yy = yf3qu3 yf3qu3~ yf3qd3 yf3qd3~ yf3u3 yf3u3~
generate p p > yy yy QCD=2 DMT=2 QED=0 / xv xm xc xw
output
launch
```

- In the MADSPIN card:

```
decay yy > all xs
```

Exercise

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generate p p > yy yy QCD=2 DMT=2 QED=0 / xv xm xc xw
output
launch
```

- In the MADSPIN card:

```
decay yy > all xs
```

- Branching ratios

$$BR(T \to Xt) \simeq 87.49\%$$
$$BR(T \to WB) \simeq 12.51\%$$

$$BR(B \to Xb) \simeq 96.67\%$$
$$BR(B \to Wt) \simeq 3.34\%$$

$$BR(\tilde{T} \to Xt) = 100\%$$

Exercise

Tasks

- Simulate the VLQ signal with the decays with MADSPIN
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Solution

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```
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```

- In the MADSPIN card:

```
decay yy > all xs
```

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$$BR(B \to Wt) \simeq 3.34\%$$

$$BR(\tilde{T} \to Xt) = 100\%$$

- MG5AMC does a lot of other things…

Exercise: cross section calculation

Tasks

- Evaluate the cross section for all signal contributions
  - ➝ Particle widths to be treated correctly
  - ➝ Separate the different VLQ final states

- Same exercise but:
  - ➝ DM mass = 10 GeV
  - ➝ VLQ masses = 1500 GeV
  - ➝ Use NNPDF 4.0 LO (α_s = 0.118)

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- Same exercise but:
  - ➞ DM mass = 10 GeV
  - ➞ VLQ masses = 1500 GeV
  - ➞ Use NNPDF 4.0 LO (α_s = 0.118)

Solution

- Same commands as before, but update of the param and run cards

Processes	Default cards	Modified cards
$pp \to XXj$		
$pp \to T\bar{T}$ with $T \to Xt$		
$pp \to B\bar{B}$ with $B \to Xb$		
$pp \to \tilde{T}\bar{\tilde{T}}$ with $\tilde{T} \to Xt$		

Exercise: cross section calculation

Tasks

- Evaluate the cross section for all signal contributions
  - ➙ Particle widths to be treated correctly
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Solution

- Same commands as before, but update of the param and run cards

Processes	Default cards	Modified cards
$pp \to XXj$	3.1 fb	0.058 fb
$pp \to T\bar{T}$ with $T \to Xt$	12.8 fb	0.78 fb
$pp \to B\bar{B}$ with $B \to Xb$	32.4 fb	0.80 fb
$pp \to \tilde{T}\bar{\tilde{T}}$ with $\tilde{T} \to Xt$	8.9 fb	1.3 fb

Exercise: cross section calculation

Tasks

- Investigate the generate ‘`Events`’ subfolder
  ➞ `<working dir>/Events`
  ➞ Before and after decay
- Understand what an event is

Exercise: cross section calculation

Tasks

- Investigate the generate ‘`Events`’ subfolder
  - ➙ `<working dir>/Events`
  - ➙ Before and after decay
- Understand what an event is

```
<event>
  8      1 +1.2928952e-03 1.60413600e+03 7.81860800e-03 8.35196700e-02
        21 -1    0    0  503  502 +0.00000000000e+00 +0.00000000000e+00 +3.13017792010e+03  3.13017792010e+03  0.00000000000e+00 0.0000e+00 1.0000e+00
        21 -1    0    0  501  503 +0.00000000000e+00 +0.00000000000e+00 -1.34834557820e+03  1.34834557820e+03  0.00000000000e+00 0.0000e+00 -1.0000e+00
   5920006  2    1    2  501    0 +4.48078064695e+02 +3.49232745816e+02 -5.07791554907e+02  1.68254491201e+03  1.50012254662e+03 0.0000e+00 0.0000e+00
        51  1    3    3    0    0 +3.00177956616e+02 +7.64884368497e+02 -7.82834313853e+02  1.13493808895e+03  1.00000000000e+01 0.0000e+00 0.0000e+00
         6  1    3    3  501    0 +1.47900108078e+02 -4.15651622681e+02 +2.75042758946e+02  5.47606823054e+02  1.72000000000e+02 0.0000e+00 1.0000e+00
  -5920006  2    1    2    0  502 -4.48078064695e+02 -3.49232745816e+02 +2.28962389681e+03  2.79597858629e+03  1.50079352456e+03 0.0000e+00 0.0000e+00
        51  1    6    6    0    0 -8.21567914179e+02 -5.75497689643e+02 +2.01834742600e+03  2.25388503709e+03  1.00000000000e+01 0.0000e+00 0.0000e+00
        -6  1    6    6    0  502 +3.73489849484e+02 +2.26264943827e+02 +2.71276470812e+02  5.42093549204e+02  1.72000000000e+02 0.0000e+00 -1.0000e+00
</event>.
```

- Particle identification: PDG codes
- Particle status: initial/intermediate/final states
- Mother/daughter relations
- Momenta