PYTHIA Status Report

Torbjörn Sjöstrand

Currently PYTHIA 6.158 of 5 April 2001
\sim 53, 100 lines Fortran 77

Code, manuals, sample main programs:

www.thep.lu.se/~torbjorn/Pythia.html

short writeup in T. Sjöstrand, P. Edén, C. Friberg,
L. Lönnblad, G. Miu, S. Mrenna and E. Norrbin
[hep-ph/0010017]
Event physics overview

Structure of the basic generation process:

1) Hard subprocess:
\[ d\hat{\sigma}/d\hat{t}, \text{ Breit-Wigners.} \]

2) Resonance decays:
includes correlations.

3) Final-state
parton showers:
(or matrix elements).

4) Initial-state
parton showers:
(or matrix elements).

5) Multiple
parton–parton
interactions.
6) Beam remnants: colour-connected to rest of event

7) Hadronization

8) Normal decays: hadronic, τ, charm, …

9) QCD interconnection effects:
   a) colour rearrangement (⇒ rapidity gaps?);
   b) Bose-Einstein (within & between strings).

10) The forgotten/unexpected: a chain is never stronger than its weakest link!
### Subprocesses

<table>
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<th>No.</th>
<th>Subprocess</th>
<th>Description</th>
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<td>4</td>
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</tbody>
</table>

**Notes:**
- Subprocesses are described in detail in the accompanying text or diagram.
- Each sub-process is assigned a unique number for easy reference.
- The process is likely a part of a larger system or a specific scientific study.

**Legend:**
- **QCD:** Quantum Chromodynamics
- **QFT:** Quantum Field Theory
- **QY:** Quantum Chemistry
- **QG:** Quantum Geophysics

**Additional Details:**
- Sub-processes 50-110 are specifically highlighted for detailed analysis or further exploration.
- Process 111 is marked for inclusion in a new study or database entry.
## Subprocess summary

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<tr>
<td>Hard QCD</td>
<td>$qg \rightarrow qg$</td>
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<tr>
<td>Open heavy flavour</td>
<td>$q\bar{q} \rightarrow t\bar{t}$</td>
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<tr>
<td>Closed heavy flavour</td>
<td>$gg \rightarrow gJ/\psi$</td>
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<tr>
<td>$\gamma\gamma$ physics</td>
<td>$\gamma q \rightarrow qg$</td>
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<td>DIS</td>
<td>$\gamma^* q \rightarrow q$</td>
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<tr>
<td>$\gamma^<em>\gamma^</em>$ physics</td>
<td>$\gamma^<em>_\perp \gamma^</em>_{\perp} \rightarrow q\bar{q}$</td>
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<td><strong>Electroweak SM</strong></td>
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<td>Single $\gamma^*/Z^0/W^\pm$</td>
<td>$q\bar{q} \rightarrow \gamma^*/Z^0$</td>
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<tr>
<td>$(\gamma/\gamma^*/Z^0/W^\pm/f/g)^2$</td>
<td>$q\bar{q} \rightarrow W^+W^-$</td>
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<tr>
<td>Light SM Higgs</td>
<td>$gg \rightarrow h^0$</td>
</tr>
<tr>
<td>Heavy SM Higgs</td>
<td>$Z_0^0 Z_0^0 \rightarrow W_+^+ W^-_-$</td>
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<td><strong>SUSY BSM</strong></td>
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<tr>
<td>$h^0/H^0/A^0/H^\pm$</td>
<td>$q\bar{q} \rightarrow h^0 A^0$</td>
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<td>SUSY</td>
<td>$q\bar{q}' \rightarrow \tilde{\chi}_i^0 \tilde{\chi}_j^{\pm}$</td>
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<td>RSUSY (Lin progress)</td>
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<td><strong>Other BSM</strong></td>
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<td>Technicolor</td>
<td>$q\bar{q}' \rightarrow \pi_0^{tc} \pi_{tc}^\pm$</td>
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<td>New gauge bosons</td>
<td>$q\bar{q} \rightarrow \gamma^*/Z_0^0/Z_0^0$</td>
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<tr>
<td>Compositeness</td>
<td>$q\bar{q} \rightarrow e^\pm e^{*\mp}$</td>
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<td>Leptoquarks</td>
<td>$qg \rightarrow \ell L_Q$</td>
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<tr>
<td>$H^{\pm\pm}$ (from LR-sym.)</td>
<td>$q\bar{q} \rightarrow H^{++} H^{--}$</td>
</tr>
<tr>
<td>Extra dimensions</td>
<td>$gg \rightarrow G^* \rightarrow e^+ e^-$</td>
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</table>
Beyond the Standard Model

SUSY: see talk by Stephen Mrenna

Technicolor: interferences included, e.g.

\[
\begin{align*}
\bar{q} & \rightarrow q' & \text{e}^+ & \text{e}^- \\
\rho_{tc}^0/\omega_{tc}^0/Z^0/\gamma^* & \rightarrow q' & \text{e}^+ & \nu_e
\end{align*}
\]

gives new set of pair production of

\[
\begin{align*}
\pi_{tc}^+ & \rightarrow \pi_{tc}^0 & \pi_{tc}^0 & \rightarrow W_L^+/Z_L^0/W_L^+/Z^0/\gamma, \text{ e.g.}
\end{align*}
\]

Left-right symmetry: Higgs triplets

\[
\begin{align*}
H_{L,R}^\pm & \rightarrow \ell^\pm \ell^\pm /W_{L,R}^\pm W_{L,R}^\pm \\
W_R^+ & \rightarrow q_i \bar{q}_j /\ell^+ \nu_R
\end{align*}
\]

Higgs: pair production, e.g. $h^0 A^0$ or $h^0 H^\pm$

(earlier partly as $\gamma^*/Z^0/Z^0$ decays)

$Z^0$: flavour-dependent couplings

Compositeness: a few further $e^*/q^*$ processes
Extra dimensions: only begun; now: Randall-Sundrum graviton excitation $G^*$

(J. Bijnens, P. Eerola, M. Maul, A. Månsson, TS $\Rightarrow$ PLB)

lowest order:
$q\bar{q} \rightarrow G^*$
$gg \rightarrow G^*$

$\gamma^*/Z^0$ backgr.

Higher $p_\perp$ for $gg$ fusion $\Rightarrow$ extra signal/check
(in addition to angular decay distribution)

also NLO:
$q\bar{q} \rightarrow gG^*$
$qg \rightarrow qG^*$
$gg \rightarrow gG^*$

confirms PS
Objective: “complete” framework for $\gamma\gamma/\gamma^*/\gamma^*/\gamma^*$ interactions at all $Q_i^2$, especially transition region $Q_i^2 \sim m_\rho^2$.

New machinery for flux of bremsstrahlung $\gamma$’s (transverse and longitudinal).

Real photons can be of three kinds (with further subdivisions):

- **Direct**: point-like
- **Resolved**: hadronic state
- **All**: ‘high’-$p_\perp$ jets;
- **Resolved**: also soft physics

Virtual photon: add the DIS process $\gamma^*q \rightarrow q$, e.g. $q$ in (VMD) $\rho^0$

- $\gamma\gamma$: 9 combinations = $(\text{dir}+\text{VMD}+\text{GVMD})^2$
- $\gamma^*\gamma^*$: + 4 combinations = 2 sides $\times$ $(\text{VMD}+\text{GVMD})$

Have to include dampening factors to remove double-counting (reasonably) consistently.
Small-$x$ evolution

(summary by L. Lönnblad)

There are no reliable generators for small-$x$ evolution. In fact there is no reliable description at all of small-$x$ evolution.

In the limit of asymptotically large energies (>> 2 TeV) the right description is given by BFKL evolution.

After ten years of hard work by Fadin–Lipatov, the next-to-leading log corrections to the BFKL evolution turned out to be HUGE.

CCFM: interpolation between DGLAP and BFKL, more likely to be relevant at finite energies. Includes gluon coherence.

There are three generators which implement CCFM evolution.
SMALLX (Hannes Jung, previously Marchesini and Webber) implements forward evolution, initial-state emissions only and interfaced to PYTHIA for hadronization.

CASCADE (Hannes Jung) implements backward evolution, initial-state emissions only and interfaced to PYTHIA for hadronization.

LDCMC (Leif Lönnblad, Hamid Kharraziha) implements forward–backward symmetric initial-state evolution (according to the Linked Dipole Chain model), final-state dipole cascade and interfaced to PYTHIA for hadronization.

All three give compatible results for small-$x$ final states at HERA DIS. Estimates of NLL corrections are more favorable than for straight BFKL (much thanks to energy–momentum conservation). But still, all three are very sensitive to the treatment of non-leading terms.
Using only the pole terms in the gluon splitting function, a good description of e.g. forward jet rates is obtained. Also with the un-integrated gluon densities from SMALLX and off-shell ME’s, one obtains a good description of $F_2$ and $F_C^2$ at HERA, heavy quark cross-sections at the Tevatron, etc.

But using the full gluon splitting destroys at least some of the nice results.

Should we worry about small-$x$ effects at the Tevatron?

Yes, for low $E_\perp$ jets. But there we also have problem with multiple scatterings etc.

Yes, for heavy quark production.

Yes, for $\delta \eta \gtrsim 4$

Yes

None of the generators are available for $p\bar{p}$ (There are plans but don’t hold your breath)
Beam Remnant Physics


Strings normally ‘large’ mass, but at times small because of beam remnant structure or by $g \to q\bar{q}$ in shower. Thus three hadronization mechanisms (regions):

1. Normal string fragmentation:
   continuum of phase-space states.

2. Cluster decay:
   low mass $\Rightarrow$ exclusive two-body state.

3. Cluster collapse:
   very low mass $\Rightarrow$ only one hadron.

If collapse:
- $\bar{c}d$: $D^-, D^{*-}, \ldots$
- $cud$: $\Lambda_c^+, \Sigma_c^+, \Sigma_c^{*+}, \ldots$
  $\Rightarrow$ flavour asymmetries
- $p\bar{p}$; $p$ side: $\Lambda_b^0, B^+, B^0$

Can give $D$ ‘drag’ to larger $x_F$ than $c$ quark in all three cases

But many parameters: $\Rightarrow$ tune
Improved description of when collapse occurs (mass spectrum $\leftrightarrow$ constituent quark masses)

**example:**
charm
string
in $\pi p$ collision

and
1-body collapse: energy-momentum shuffling
2-body decay: smoother joining to string picture (matched anisotropic decay)

$$A(x_F) = \frac{\#D^- - \#D^+}{\#D^- + \#D^+}$$
in $\pi^- p$
Bottom production at the Tevatron

Rapidity distribution
full: b quarks
dashed: B hadrons

Average rapidity shift
\( \Delta y = y_B - y_b \)
as function of \( y_b \)
above different \( p_{\perp b} \) thresholds

B asymmetry
\( A = \frac{\sigma(B^0) - \sigma(\bar{B}^0)}{\sigma(B^0) + \sigma(\bar{B}^0)} \)
as function of \( y_B \)

Only pair production for simplicity
Multiple Interactions

(TS & M. van Zijl, PRD36 (1987) 2019,
J. Dischler & TS, EPJdir C2 (2001) 1)

Consequence of composite nature of hadrons:

Evidence:

- direct observation: AFS, UA1, CDF
- implied by width of multiplicity distribution + jet universality: UA5
- forward–backward correlations: UA5
- pedestal effect: UA1, H1

One new free parameter: $p_{\perp \text{min}}$

\[
\frac{1}{2} \sigma_{\text{jet}} = \int_{p_{\perp \text{min}}^2}^{s/4} \frac{d\sigma}{dp_{\perp}^2} dp_{\perp}^2
\]

\[
\ll \int_0^{s/4} \frac{d\sigma}{dp_{\perp}^2} \left( \frac{p_{\perp}^4}{(p_{\perp 0}^2 + p_{\perp}^2)^2} \right) dp_{\perp}^2
\]

Measure of colour screening length $d$ in hadron $p_{\perp \text{min}} \langle d \rangle \approx 1 (\equiv \hbar)$
The resolved and screened scenarios are illustrated with the expression $\lambda \sim 1/p_\perp$.

The average distance $\langle d \rangle$ is estimated as:

$$\langle d \rangle \sim \frac{r_p}{\sqrt{N_{\text{partons}}}}$$

or

$$\sim \frac{r_p}{N_{\text{partons}}}$$

with or without correlations, respectively.

The number of partons $N_{\text{partons}}$ is given by:

$$N_{\text{partons}} \sim N_g = \int_{4p_{\perp \text{min}}/s}^{1} g(x, \sim p_{\perp \text{min}}^2) \, dx$$

**Olden days:**

For $x \to 0$,

$$xg(x, Q_0^2) \to \text{const.}$$

Therefore,

$$N_{\text{partons}} \sim \ln \frac{4p_{\perp \text{min}}^2}{s} \sim \text{const.}$$

**Post-HERA:**

For $x \to 0$, $xg(x, Q_0^2) \sim x^{-\epsilon}$ with $\epsilon \approx 0.08$,

$$\Rightarrow N_{\text{partons}} \sim \left(\frac{s}{4p_{\perp \text{min}}^2}\right)^\epsilon$$

$$\Rightarrow p_{\perp \text{min}} \sim \frac{1}{\langle d \rangle} \sim N_{\text{partons}} \sim s^\epsilon$$
Mean charged multiplicity in inelastic non-diffractive ‘minimum bias’:

‘New’ PYTHIA default:

\[ p_{\perp \text{min}} = (1.9 \text{ GeV}) \left( \frac{s}{1 \text{ TeV}^2} \right)^{0.08} \]

Importance:
- comparison of data at 630 GeV & 1.8 TeV
- extrapolations to LHC
Other PYTHIA 6.1 news

- JETSET routines renamed: 
  \[LUxxxx \rightarrow PYxxxx + \text{some more}\]
- All real variables in \textsc{double precision}
- Improved resonance decay machinery
- ME/PS matching: \textbf{see separate talk}
- Newer parton distributions (CTEQ5, \ldots)
- QED radiation off an incoming muon
- Colour rearrangement options
- Expanded Bose-Einstein algorithm
- New baryon production scheme (optional)
- One-dimensional histograms (GBOOK)
- Gone: top hadrons, \(gg \rightarrow Z^0b\bar{b}\)

2–, 4– and 6–fermion standard interfaces for showers and hadronization:

\begin{verbatim}
CALL PY2FRM(IRAD,ITAU,ICOM)
CALL PY4FRM(ATOTSQ,A1SQ,A2SQ,ISTRAT,&IRAD,ITAU,ICOM)
CALL PY6FRM(P12,P13,P21,P23,P31,P32,PTOP,&IRAD,ITAU,ICOM)
\end{verbatim}

\(q\bar{q}gg\) and \(q\bar{q}q\bar{q}\) QCD 4–jet standard interface for showers and hadronization:

\begin{verbatim}
CALL PY4JET(PMAX,IRAD,ICOM)
\end{verbatim}
Future Plans

PYTHIA 6.2: before end of summer?

- Completely updated long manual
  (> 370 pp!)
- Lepton-number-violating SUSY decays
  (P. Skands)
- Reversed order resonance decays and showers, e.g. \( t \rightarrow bW \rightarrow bq\bar{q}' \)
  
  **now:**
  
  1. \( t \rightarrow bW \)
  2. \( bW \) cascade
     \( \Rightarrow \) boost \( W \)
  3. \( W \rightarrow q\bar{q}' \)
  4. \( q\bar{q}' \) cascade
  
  **future:**
  
  1. \( t \rightarrow bW \)
  2. \( W \rightarrow q\bar{q}' \)
  3. \( bW \) cascade
     \( \Rightarrow \) boost \( q\bar{q}' \)
  4. \( q\bar{q}' \) cascade

- Improved interfacing of external processes, e.g. with COMPHEP
  
  **now:**
  can predefine
  1) externally

  **future:**
  can predefine
  1) and 2) externally
PYTHIA 6.?

- Steady trickle of new processes?
- Triple gauge boson production?
- Baryon-number-violating SUSY decays?
- ME/PS matching for gauge boson pairs (e.g. $q \bar{q} \rightarrow W^+ W^-$) (S. Burby)?
- ME/PS matching for QCD processes?
- Improved FSR shower algorithm?
- Improved ISR shower algorithm?
- Modified ISR shower to bring in some BFKL/CCFM features?
- Understand primordial $k_\perp$ better?
- Multiple parton–parton interactions with more complicated colour topologies?

PYTHIA 7: see talk by Leif Lönnblad

Onwards C++ Soldiers!