Torbjörn Sjöstrand
Lund University

Introduction
Virtual Photon Processes
The photon flux • Photon processes
Parton distributions • Other model aspects
Some results • Program particulars
Photon ISR in $Z^0$ production
Doubly-charged Higgses
Other news
On to C++
Introduction

JETSET 7.4
PYTHIA 5.7
SPYTHIA

} 4 March 1997 : PYTHIA 6.1

General-purpose generator:

- Hard subprocess “library”
- Convolution with parton distributions
  (cross sections, kinematics)
- Resonance decays (process-dependent)
- Initial-state QCD (& QED) showers
- Final-state QCD & QED showers
- Multiple parton–parton interactions
- Beam remnants
- Hadronization (string fragmentation)
- Decay chains
- Analysis & utility routines

Currently PYTHIA 6.125 of 21 February 1999
~ 46,800 lines Fortran 77

Code, manuals, sample main programs:
http://www.thep.lu.se/~torbjorn/Pythia.html
PYTHIA 6.1 main news

- JETSET routines renamed:
  LUxxxx → PYxxxx + some more
- All real variables in **DOUBLE PRECISION**
- New SUSY processes and improved SUSY simulation; new PDG codes for sparticles
- New processes for Higgs, technicolour, ...
- Alternative Higgs mass shape
- Newer parton distributions (but ...)
- Several improved resonance decays
- Initial-state showers matched to (some) matrix elements
- QED radiation off an incoming muon
- New machinery to handle real and virtual photon fluxes and cross sections
- Energy-dependent \( p_{\perp \text{min}} \) in multiple interactions
- Colour rearrangement options for \( W^+W^- \)
- Expanded Bose-Einstein algorithm
- New baryon production scheme (optional)
- One-dimensional histograms (GBOOK)
Virtual photon processes

(C. Friberg & TS, in preparation)

The photon flux

\[ W^2 = (q_1 + q_2)^2 \]
\[ Q_i^2 = -q_i^2 \]
\[ y_i = \frac{q_i k_j}{k_i k_j} \quad j=2(1) \text{ for } i=1(2) \]
\[ x_i = \frac{q_i (k_1 + k_2)}{k_i (k_1 + k_2)} \]
\[ y_i \approx x_i + \frac{Q_i^2}{s} \]
\[ Q_i^2 \approx \frac{x_i^2}{1 - x_i} m_i^2 + (1 - x_i) s \sin^2(\theta_i/2) \]

\[ d\sigma(ee \rightarrow eeX) = \sum_{\xi_1, \xi_2 = T, L} \int d y_1 \ d Q_1^2 \ d y_2 \ d Q_2^2 \]
\[ \times f_{\gamma/e}^{\xi_1}(y_1, Q_1^2) \ f_{\gamma/e}^{\xi_2}(y_2, Q_2^2) \ d \sigma(\gamma_{\xi_1}^* \gamma_{\xi_2}^* \rightarrow X) \]

with

\[ f_{\gamma/e}^{T}(y, Q^2) = \frac{\alpha_{\text{em}}}{2\pi} \left( \frac{1 + (1 - y)^2}{y} \frac{1}{Q^2} - \frac{2m_e^2 y}{Q^4} \right) \]
\[ f_{\gamma/e}^{L}(y, Q^2) = \frac{\alpha_{\text{em}}}{2\pi} \frac{2(1 - y)}{y} \frac{1}{Q^2} \]
Photon processes

So far only jet production, i.e. not low-$p_\perp$.

Three main process classes:
1. **direct x direct**
   \[ \gamma^* \gamma^* \rightarrow q\bar{q} \]
   \[ \gamma^* \gamma_L \rightarrow q\bar{q} \]
   \[ \gamma_L^* \gamma_L^* \rightarrow q\bar{q} \]

2. **direct x resolved**, resolved = VMD or anomalous
   \[ \gamma^*_T g \rightarrow q\bar{q} \]
   \[ \gamma^*_L g \rightarrow q\bar{q} \]
   \[ \gamma^* q \rightarrow qg \]
   \[ \gamma^*_L q \rightarrow qg \]

3. **resolved x resolved**
   \[ qq' \rightarrow qq' \]
   \[ q\bar{q} \rightarrow q'\bar{q}' \]
   \[ q\bar{q} \rightarrow gg \]
   \[ qq \rightarrow qq \]
   \[ gg \rightarrow gg \]
   \[ gg \rightarrow q\bar{q} \]

\[
\frac{d\sigma(\gamma^* \gamma^* \rightarrow X)}{d\hat{s}} = \left( \int d\hat{x}_1 f_i^{\gamma^*}(\hat{x}_1, \mu^2, Q_1^2) \right) \\
\times \left( \int d\hat{x}_2 f_j^{\gamma^*}(\hat{x}_2, \mu^2, Q_2^2) \right) \int d\hat{t} \frac{d\hat{\sigma}}{d\hat{t}}(\hat{s} = \hat{x}_1 \hat{x}_2 W^2)
\]
Parton distributions

SaS $\gamma^*$ distributions extended from $\gamma$ ones by inclusion of dipole damping factors,

$$f_{a}^{\gamma^*}(x, \mu^2, Q^2) =$$

$$\sum_{V} \frac{4\pi \alpha_{em}}{f_{V}^2} \left( \frac{m_{V}^2}{m_{V}^2 + Q^2} \right)^2 f_{a}^{\gamma, V}(x, \mu^2; \tilde{Q}_{0}^2) +$$

$$\frac{\alpha_{em}}{2\pi} \sum_{q} 2e_{q}^2 \int_{Q_{0}^2}^{\mu^2} \frac{dk^2}{k^2} \left( \frac{k^2}{k^2 + Q^2} \right)^2 f_{a}^{\gamma, q\bar{q}}(x, \mu^2; k^2),$$

reduction of evolution range: $Q_{0} < \tilde{Q}_{0} < \mu$, and matching $f_{a}^{\gamma^*}(x, \mu^2, Q^2) \rightarrow 0$ for $\mu^2 \rightarrow Q^2$.

$\mu^2$ scale choice of pdf’s ambiguous. Alternatives range from $p_{\perp}^2$ to $p_{\perp}^2 + Q_{1}^2 + Q_{2}^2$, with preferred one

$$\mu^2 = p_{\perp}^2 \frac{\hat{s} + Q_{1}^2 + Q_{2}^2}{\hat{s}} \left( \sim \frac{-\hat{t}\hat{u}}{\hat{t} + \hat{u}} \right).$$

So far no resolved longitudinal photon, except by multiplicative factor

$$R(\mu^2, Q^2) = 1 + a \frac{4\mu^2 Q^2}{(\mu^2 + Q^2)^2}. $$
Other model aspects

Initial-state shower cut-off: normally $Q_{0}^{sh} = 1$ GeV. If vector meson/anomalous state ‘resolution scale’ $\tilde{Q}_{0}/k$ is above this, shower cut-off is increased correspondingly.

Final-state radiation: the ‘beam remnant’ quark in an anomalous branching $\gamma^{*} \rightarrow q\overline{q}$ is allowed to radiate, from a scale $k$ to $m_{0}^{sh} = 1$ GeV, while a VMD beam remnant cannot.

Primordial $k_{\perp}$: Gaussian ‘small’ for VMD, $\sim dk_{\perp}^{2}/k_{\perp}^{2}$ for anomalous.

Multiple parton–parton interactions: only affects VMD × VMD.

$$\langle n_{int} \rangle \sim \frac{1}{\sigma_{tot}} \int_{p_{\perp min}^{2}}^{s/4} \frac{d\sigma_{jet}}{dp_{\perp}^{2}} dp_{\perp}^{2}$$

Ansatz for $\gamma^{*}$:

$$\sigma_{tot} \propto \frac{m_{V}^{2}}{m_{V}^{2} + Q^{2}}$$

$$p_{\perp min} \propto \sqrt{1 + \frac{Q^{2}}{m_{V}^{2}}}$$

Hadronic data: $p_{\perp min} \approx (1.9 \text{ GeV}) \left( \frac{s}{1 \text{ TeV}^{2}} \right)^{0.08}$
Comparison with HERA data
\( e^+ e^- \) cross sections

\[
\sqrt{s_{\gamma^* \gamma^*}} = 100 \text{ GeV}, \quad Q_2^2 = 1 \text{ GeV}^2, \quad p_\perp > 5 \text{ GeV}:
\]

\( \sigma_{\text{jet}}^{\gamma^* \gamma^*} \) (pb)
Program particulars

To access new $\gamma^*$ flux convolution:
CALL PYINIT('cms','gamma/e-','gamma/e+',500D0)

Also possible to have $\gamma^*\gamma^*$ collisions directly:
CALL PYINIT('five','gamma','gamma',400D0)
with $P(1,J)$ and $P(2,J)$ defining momenta and virtualities ($P(I,5) < 0$ for spacelike ones).

Select jet production with MSEL = 1 (default).

Photon character regulated by MSTP(14):
= 10 : mix direct/VMD/anomalous for real photons; $D \times V = V \times D$ etc. $\Rightarrow$ 6 classes.
= 20 : (default) mix direct/VMD/anomalous for virtual photons; $\Rightarrow$ 9 classes.
= 25 : mix direct/resolved for virtual photons; $\Rightarrow$ 4 classes.
= other numbers : individual classes.

warning : $\gamma^*\gamma^* \rightarrow \ell^+\ell^-$ included in dir$\times$dir if not switched off (automatic when mixing).

Possible to specify cuts on $x_i$, $y_i$, $Q^2_i$, $\theta_i$, $W^2$ in CKIN(61) - CKIN(78).
Phase space sampled according to
$$\prod_i \left( \frac{dQ^2_i}{Q^2_i} \right) \left( \frac{dx_i}{x_i} \right) d\varphi_i$$
$\Rightarrow$ full efficiency for $x_i$ and $Q^2_i$ cuts.
Photon ISR in $Z^0$ production

(G. Miu & TS, hep-ph/9812455 → PLB)

By-product of study on $W^\pm$ production in hadron colliders, attempting to combine matrix-element (ME) and parton-shower (PS) strengths.

Merging strategy: correct hardest emissions in showers so as to reproduce one order higher matrix elements.

$2 \rightarrow 1$ process $e^+(1) + e^-(2) \rightarrow Z^0(0)$ starting point for backwards shower evolution:

$2 \rightarrow 2$ process $e^+(3) + e^-(2) \rightarrow \gamma(4) + Z^0(0)$:

\[ \hat{s} = (p_3 + p_2)^2 = \frac{(p_1 + p_2)^2}{z} = \frac{m_Z^2}{z} \]
\[ \hat{t} = (p_3 - p_4)^2 = p_1^2 = -Q^2 \]
\[ \hat{u} = m_Z^2 - \hat{s} - \hat{t} = Q^2 - \frac{1-z}{z} m_Z^2 \]
Relate ME and PS rates:

\[
\begin{align*}
\left. \frac{d\hat{\sigma}}{d\hat{t}} \right|_{\text{ME}} &= \left. \frac{d\hat{\sigma}}{d\hat{t}} \right|_{\text{PS1}} = \left. \frac{d\hat{\sigma}}{d\hat{t}} \right|_{\text{PS2}} = \frac{\sigma_0}{\hat{s}} \frac{\alpha_{\text{em}}}{2\pi} \frac{\hat{t}^2 + \hat{u}^2 + 2m_Z^2\hat{s}}{\hat{t}\hat{u}} \\
&\quad \overset{Q^2 \to 0}{\approx} \frac{\sigma_0}{\hat{s}} \frac{\alpha_{\text{em}}}{2\pi} \frac{1 + z^2}{1 - z} \frac{1}{Q^2} = \left. \frac{d\hat{\sigma}}{dQ^2} \right|_{\text{PS1}} \\
&\approx \frac{\sigma_0}{\hat{s}} \frac{\alpha_{\text{em}}}{2\pi} \frac{\hat{s}^2 + m_Z^4}{\hat{t}(\hat{t} + \hat{u})} 
\end{align*}
\]

Add mirror \( e^+(1) + e^-(5) \to \gamma(6) + Z^0(0) \):

\[
\begin{align*}
\left. \frac{d\hat{\sigma}}{d\hat{t}} \right|_{\text{PS}} &= \left. \frac{d\hat{\sigma}}{d\hat{t}} \right|_{\text{PS1}} + \left. \frac{d\hat{\sigma}}{d\hat{t}} \right|_{\text{PS2}} = \frac{\sigma_0}{\hat{s}} \frac{\alpha_{\text{em}}}{2\pi} \frac{\hat{s}^2 + m_Z^4}{\hat{t}\hat{u}} \\
R_{ee\to\gamma Z}(\hat{s}, \hat{t}) &= \frac{(d\hat{\sigma}/d\hat{t})_{\text{ME}}}{(d\hat{\sigma}/d\hat{t})_{\text{PS}}} = \frac{\hat{t}^2 + \hat{u}^2 + 2m_Z^2\hat{s}}{\hat{s}^2 + m_Z^4} \\
\frac{1}{2} &< R_{ee\to\gamma Z}(\hat{s}, \hat{t}) \leq 1
\end{align*}
\]

Improve PS:
- \( Q^2_{\text{max}} = \hat{s} \), not \( Q^2_{\text{max}} \approx m_Z^2 \) (intermediate)
- MC correction by \( R(\hat{s}, \hat{t}) \) for first (\( \approx \) hardest) emission on each side (new)

Now default.
$p\bar{p} \rightarrow W^\pm$ at 1.8 TeV:

\begin{align*}
(1/N)(dN/dp_W)(\text{GeV}^{-1})
\end{align*}

$P_S, k=0.44$ GeV

$P_S, k=4$ GeV

D0 data

$e^+e^- \rightarrow Z^0$ at 500 GeV,

$80 \text{ GeV} < \sqrt{s} < 100 \text{ GeV}$:

\begin{align*}
\frac{d\sigma}{dp_\tau} (\text{pb}/\text{GeV})
\end{align*}

$M_{\tau}$
Doubly-charged Higgses


Based on left–right symmetric scenario.

New particles: $\nu_{iR}$, $W_R^\pm$, $H_L^{\pm\pm}$, $H_R^{\pm\pm}$.

New processes:

341. $\ell_i \ell_j \rightarrow H_L^{\pm\pm}$
342. $\ell_i \ell_j \rightarrow H_R^{\pm\pm}$
343. $\ell_i^\pm \gamma \rightarrow H_L^{\pm\pm} e^\mp$
344. $\ell_i^\pm \gamma \rightarrow H_R^{\pm\pm} e^\mp$
345. $\ell_i^\pm \gamma \rightarrow H_L^{\pm\pm} \mu^\mp$
346. $\ell_i^\pm \gamma \rightarrow H_R^{\pm\pm} \mu^\mp$
347. $\ell_i^\pm \gamma \rightarrow H_L^{\pm\pm} \tau^\mp$
348. $\ell_i^\pm \gamma \rightarrow H_R^{\pm\pm} \tau^\mp$
349. $f_i \bar{f}_i \rightarrow H_L^{++} H_L^{--}$
350. $f_i \bar{f}_i \rightarrow H_R^{++} H_R^{--}$
351. $f_i f_j \rightarrow f_k f_l H_L^{\pm\pm}$
352. $f_i f_j \rightarrow f_k f_l H_R^{\pm\pm}$

Typical decays:

$H_L^{++} \rightarrow \ell_i^+ \ell_j^+, W_L^+ W_L^+$

$H_R^{++} \rightarrow \ell_i^+ \ell_j^+, W_R^+ W_R^+$

$W_R^+ \rightarrow q\bar{q}'$, $\ell_i^+ \nu_{\ell R}$

Status: working, but still a few factors of $\sim 2$ to sort out.
Other news

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}

\( P_{ij} \): relative probability that first (second) fermion is paired with \( i \)’th (\( j \)’th) antifermion.

\( P_{TOP} \): absolute probability for \( tt \) event. If \( tt \) is selected, the \( P_{ij} \) are not used. The \( b\bar{b} \) must be first fermion pair.

Process 36, \( e\gamma \rightarrow \nu W (\Rightarrow ee \rightarrow e\nu W) \):
\( W \) decay angle ME now included.

New function \texttt{PYMRUN} for running \( \overline{\text{MS}} \) masses, e.g. in Higgs production \( \Rightarrow \) PMAS(KC,1) free to use for “on-shell” masses (e.g. for charm production rates).

Technicolour processes upgraded; more to come.

New processes specifically for \( \tilde{b} \) production.

Many bugs fixed, and (no doubt) new ones introduced.
On to C++!

(L. Lörenblad, hep-ph/9810208 → CPC; M. Bertini, TS)

Why Fortran → C++?

- SLAC →, FNAL →, CERN → LHC era.
- Industrial standard.
- Educational and professional continuity for students.
- Better to program — for experts.
- User-friendly interfaces — for the rest of us (cooperation with GEANT4, LHC++).

Milestones:

- January 1998: project formally started (Leif ~half-time).
- Exists today: strategy document, code for the event record and the particle object.
- In progress: particle data and other data base handling, event generation handler structure, string fragmentation.
- Next: decay routines, very simple matrix elements.
- By summer: proof of concept.
- End 2000: most of current PYTHIA functionality (?).
- ??: more and better than current PYTHIA.

Input welcome: leif@thep.lu.se