International Workshop on Linear Colliders
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PYTHIA and HERWIG for linear collider physics

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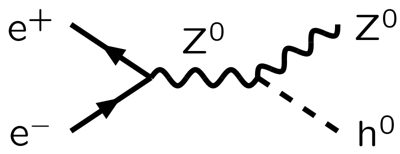
(HERWIG input from
M.H. Seymour, RAL)

Event physics overview
General-purpose generators
Subprocess survey
PYTHIA status
HERWIG status
Photon ISR in Z^0 production
QCD radiation in top decay
(Virtual Photon Processes)
On to C++

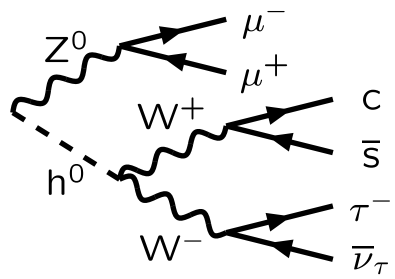
Event physics overview

Structure of the basic generation process:

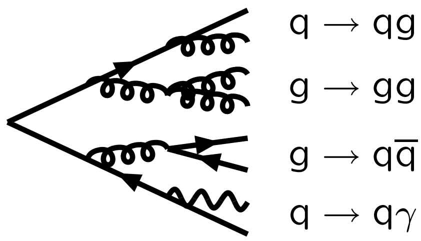
1) Hard subprocess:
$d\hat{\sigma}/d\hat{t}$, Breit-Wigners.



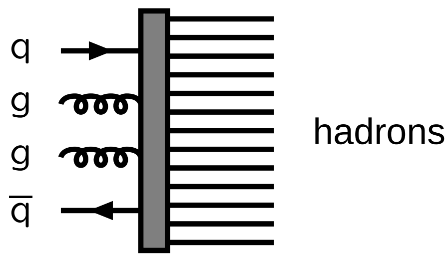
2) Resonance decays:
includes correlations.



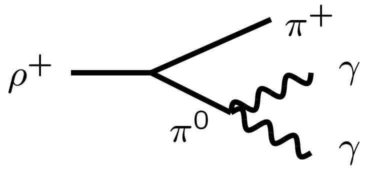
3) Parton showers:
(or matrix elements).



4) Hadronization
(PYTHIA: string;
HERWIG: cluster;
ISAJET: independent).



5) Normal decays:
hadronic, τ, charm, . . .



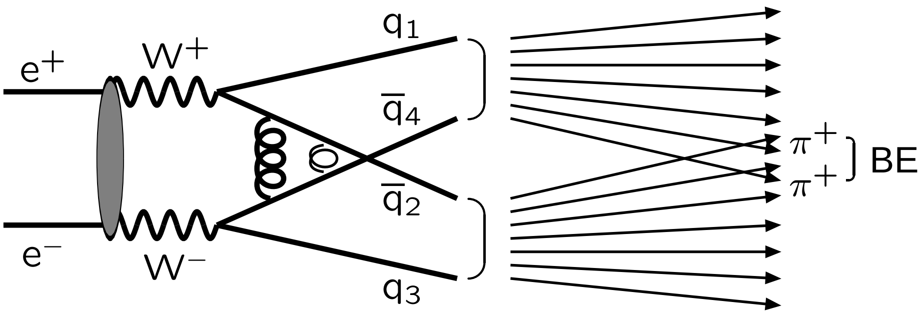
Additional aspects:

6) Beamstrahlung: CIRCE (T.Ohl) interface.

7) Initial-state QED radiation: showers.

8) Hadronic behaviour of photons:
a) $\gamma^{(*)} \longleftrightarrow \rho^0, \ldots$ (VMD)
or $\gamma^{(*)} \longleftrightarrow$ $q\overline{q}$ (anomalous);
b) $f_i^{\gamma^{(*)}}(x, Q^2; P^2)$ (subdivided as above)
and total cross sections;
c) initial-state QCD radiation;
d) beam remnants;
e) multiple parton–parton interactions.

9) QCD interconnection effects:



a) colour rearrangement;
b) Bose-Einstein.

(TS: talk in session P2 (top + QCD).)

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

General-purpose generators

Why?

- Some processes needed as starting point to develop and study relevant QCD physics: initial- & final-state cascades, hadronization, underlying event, . . .
- Generalization to other processes requires corresponding QCD expertise — and, to first approximation, less of other expertise.

Which?

- PYTHIA.
- HERWIG.
- ISAJET.

Complete list!?

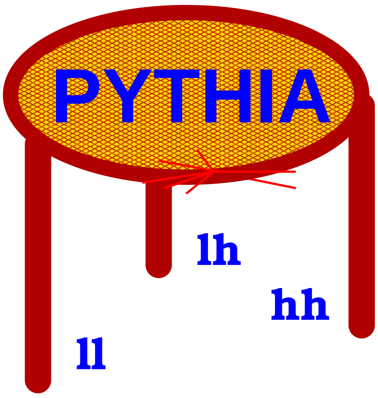
Limitations:

- Normally only leading-order processes; approximate QCD/QED corrections by showers, but no weak corrections at all.
- Hadronization and other aspects are described by models, not theory.
- Amplitudes versus probabilities: interference terms between different colour flows, etc.

Subprocess survey

Process	PYTHIA	HERWIG
QCD & related		
Soft QCD	$\star$	$\star$
Hard QCD	$\star$	$\star$
Heavy flavour	$\star$	$\star$
Top threshold	—	—
$\gamma\gamma$ physics	$\star$	$\star$
DIS	$\star$	$\star$
$\gamma^*\gamma^*$ physics	$(\star)$	$(\star)$
Electroweak SM		
Single $\gamma^*/Z^0/W^\pm$	$\star$	$\star$
$(\gamma/\gamma^*/Z^0/W^\pm/f/g)^2$	$\star$	$\star$
Light SM Higgs	$\star$	$\star$
Heavy SM Higgs	$(\star)$	$\star$
SUSY BSM		
$h^0/H^0/A^0/H^\pm$	$\star$	$\star$
SUSY	$\star$	$(\star)$
$\not{R}$SUSY	—	$(\star)$
Other BSM		
Technicolor	$\star$	—
New gauge bosons	$\star$	—
Compositeness	$\star$	—
Leptoquarks	$\star$	—
$H^{\pm\pm}$ (from LR-sym.)	$(\star)$	—

$\star$ = yes, $(\star)$ = partial/in progress, — = no



status

Authors: TS, S. Mrenna

JETSET 7.4
PYTHIA 5.7
SPYTHIA

} 4 March 1997 : $\longrightarrow$ PYTHIA 6.1

Currently PYTHIA 6.125 of 21 February 1999
$\sim$ 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` $\longrightarrow$ `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, . . .
- Several improved resonance decays

- Newer parton distributions (but . . .)
- 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 $p_{\perp\mathrm{min}}$ in multiple interactions
- Colour rearrangement options for W^+W^-
- Expanded Bose-Einstein algorithm
- New baryon production scheme (optional)
- One-dimensional histograms (GBOOK)

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

```
  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)
```

Pij : relative probability that first (second) fermion is paired with i'th (j'th) antifermion.

PTOP : absolute probability for $t\bar{t}$ event. If $t\bar{t}$ is selected, the Pij are not used. The b&$\bar{b}$ must be first fermion pair.

HERWIG status

Authors: G. Marchesini, B.R. Webber,
G. Abbiendi, I.G. Knowles, M.H. Seymour,
and L. Stanco

Currently HERWIG 5.9 of 22 July 1996
$\sim$ 21.400 lines Fortran 77

Code, manuals, related programs:
`http://hepwww.rl.ac.uk/theory/seymour/herwig/`

Version 6.1 to be released by end of April (?!):
+G. Corcella, S. Moretti, K. Odagiri, P. Richardson

- SUSY production and decay (in hadron collisions) including R-parity violation
- many new Higgs processes
- matrix element corrections to top decay (and W/Z production in hadron collisions)
- $e^+e^- \to$ 4 jets matrix element option
- incorporation and improvement of JIMMY generator for multiparton scattering
- improved treatments of $\gamma^*\gamma^*$ and γ remnant
- beamstrahlung (interface to CIRCE)

HERWIG 6.1 main SUSY features

- General MSSM (incl. goldstino): e.g., mSUGRA with $\tilde{\chi}_1^0$ LSP, GMSB with $\tilde{G}$ LSP.
- Mass and decay spectra not generated intrinsically: read in from data file, e.g. generated by ISAJET/ ISASUSY.
- All R-parity conserving $2 \to 2$ sparticle production subprocesses.
- Comprehensive range of $2 \to 1$, $2 \to 2$ and $2 \to 3$ Higgs production subprocesses.
- All resonant R-parity violating $2 \to 2$ production subprocesses and decay.

  $\Rightarrow$ B-violating: non-trivial colour structure.

  Observable effects?
- Sparton, in particular gluino and stop, showering/ hadronisation not included (yet).
- Isotropic decay, spin correlation not systematically included. Finite width effect included.
- Only hadronic collisions so far. e^+e^- forthcoming.

Comparison with ISAJET & PYTHIA

- Mass and decay spectra calculated intrinsically in ISAJET and PYTHIA, but taken as input in HERWIG.
- e^+e^- available in ISAJET and PYTHIA.
- R-parity violating production processes not yet included in ISAJET and PYTHIA.
- Production cross sections agree between all three programs for sparton pair, slepton pair and associated sparton+gaugino processes. Discrepancy for the gaugino pair cross section with PYTHIA (wrong sign of interference terms?).

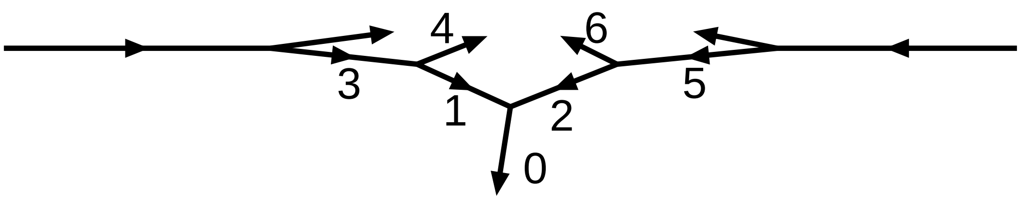
Photon ISR in Z^0 production

(G. Miu & TS, PLB449 (1999) 313)

By-product of a 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:

$$\left.\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}\hat{t}}\right|_{\mathrm{ME}} = \frac{\sigma_0}{\hat{s}} \frac{\alpha_{\mathrm{em}}}{2\pi} \frac{\hat{t}^2 + \hat{u}^2 + 2m_{\mathrm{Z}}^2 \hat{s}}{\hat{t}\hat{u}}$$

$$\xrightarrow{Q^2 \to 0} \sigma_0 \frac{\alpha_{\mathrm{em}}}{2\pi} \frac{1+z^2}{1-z} \frac{1}{Q^2} = \left.\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}Q^2}\right|_{\mathrm{PS1}}$$

$$\left.\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}\hat{t}}\right|_{\mathrm{PS1}} = \frac{\sigma_0}{\hat{s}} \frac{\alpha_{\mathrm{em}}}{2\pi} \frac{\hat{s}^2 + m_{\mathrm{Z}}^4}{\hat{t}(\hat{t}+\hat{u})}$$

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

$$\left.\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}\hat{t}}\right|_{\mathrm{PS}} = \left.\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}\hat{t}}\right|_{\mathrm{PS1}} + \left.\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}\hat{t}}\right|_{\mathrm{PS2}} = \frac{\sigma_0}{\hat{s}} \frac{\alpha_{\mathrm{em}}}{2\pi} \frac{\hat{s}^2 + m_{\mathrm{Z}}^4}{\hat{t}\hat{u}}$$

$$R_{\mathrm{ee}\to\gamma\mathrm{Z}}(\hat{s},\hat{t}) = \frac{(\mathrm{d}\hat{\sigma}/\mathrm{d}\hat{t})_{\mathrm{ME}}}{(\mathrm{d}\hat{\sigma}/\mathrm{d}\hat{t})_{\mathrm{PS}}} = \frac{\hat{t}^2 + \hat{u}^2 + 2m_{\mathrm{Z}}^2 \hat{s}}{\hat{s}^2 + m_{\mathrm{Z}}^4}$$

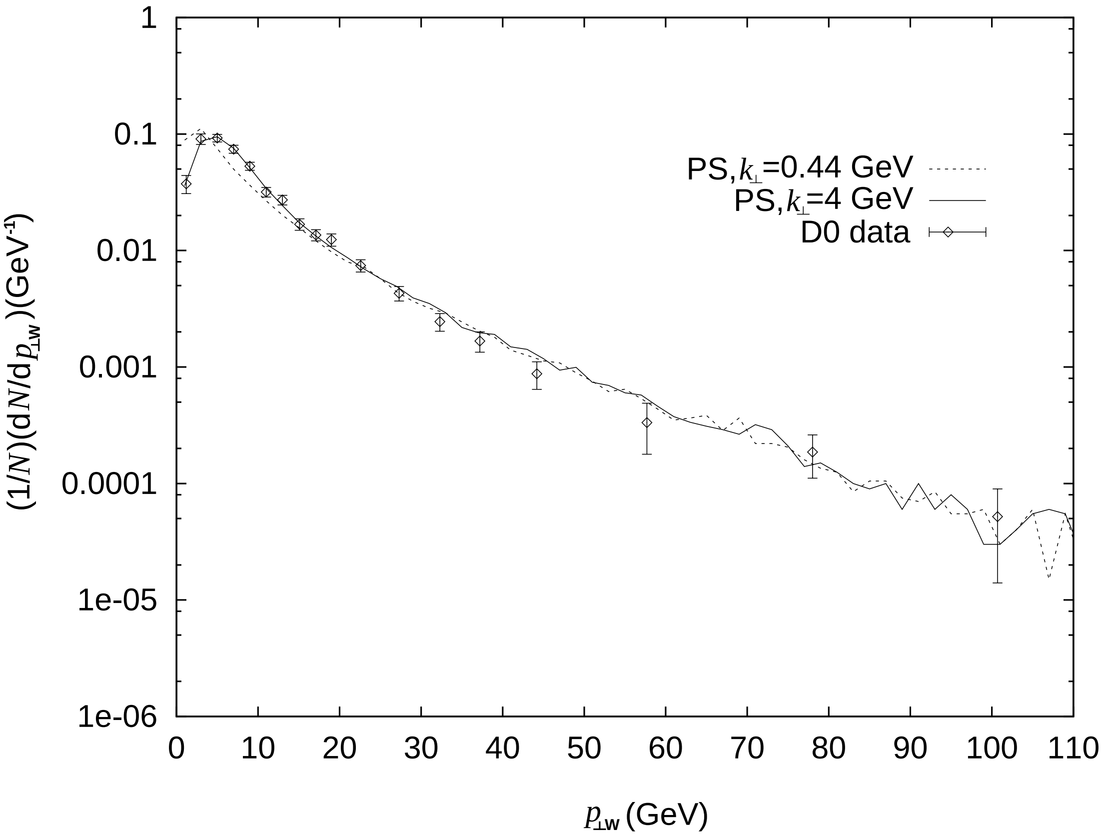
$$\frac{1}{2} < R_{\mathrm{ee}\to\gamma\mathrm{Z}}(\hat{s},\hat{t}) \leq 1$$

Improve PS:

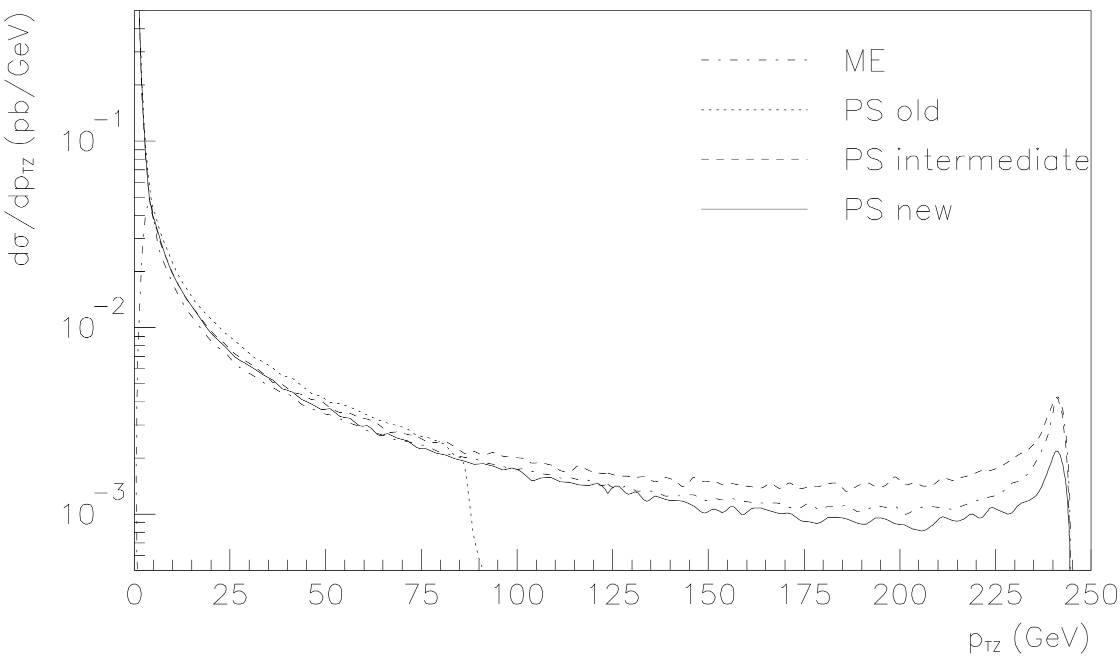
- $Q^2_{\mathrm{max}} = s$, not $Q^2_{\mathrm{max}} \approx m_{\mathrm{Z}}^2$ (intermediate)
- MC correction by $R(\hat{s},\hat{t})$ for first ($\approx$ hardest) emission on each side (new)

Now default.

$p\overline{p} \to W^{\pm}$ at 1.8 TeV:



$e^+e^- \to Z^0$ at 500 GeV,
80 GeV $< \sqrt{\hat{s}} <$ 100 GeV:



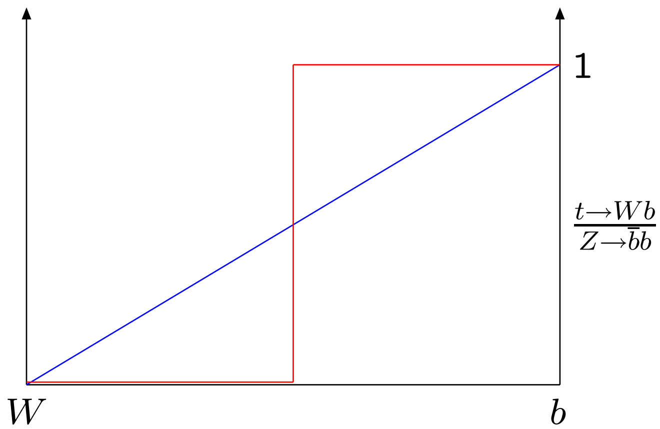
Matrix element correction to top decay

(G. Corcella & M.H. Seymour, PLB 442 (1998) 417)

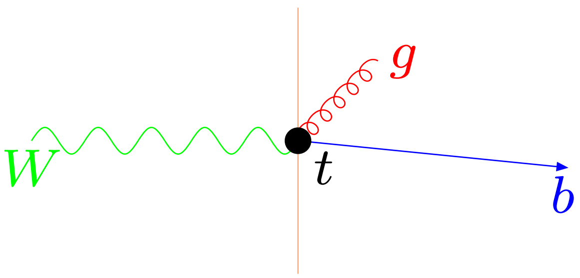
parton shower reliable for soft/collinear gluons
needs to be supplemented by exact tree-level matrix elements to describe full range

generally small corrections but. . .
top decay special case:
HERWIG algorithm frame-dependent:
showering of top decay done in top rest frame

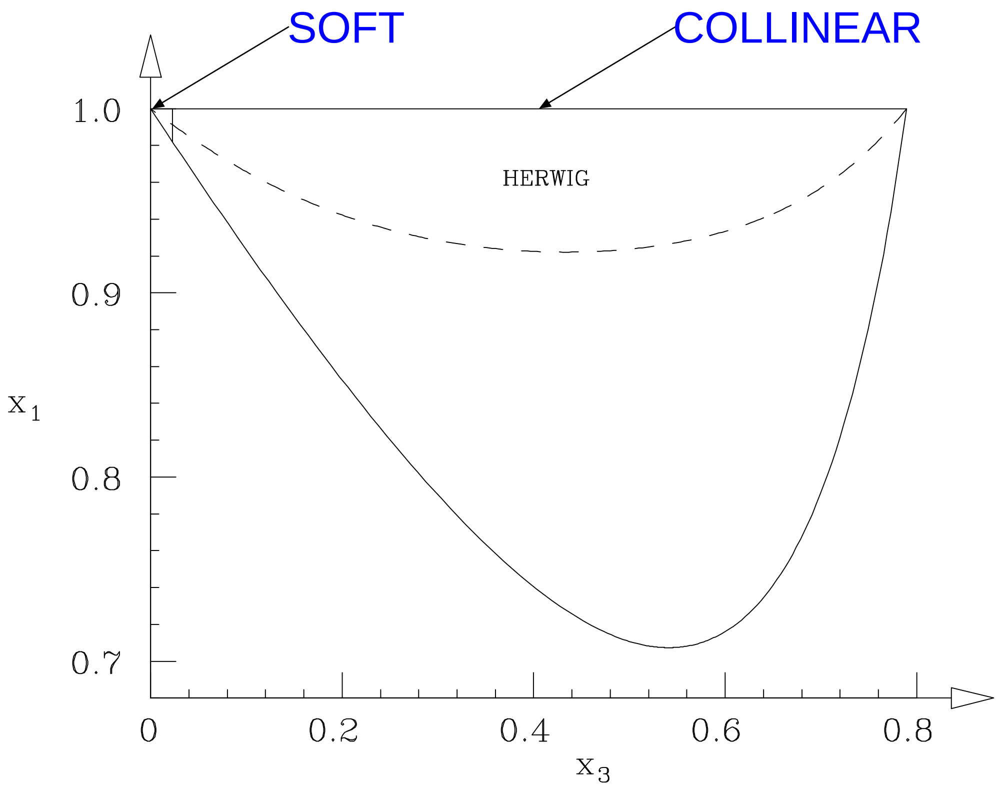
Gluon emission pattern smoothly suppressed at large angles
HERWIG approximates this by sharp step
"dead cone approximation"



(gets total amount of radiation about right, but angular distribution badly wrong)



W hemisphere empty!



HARD correction:

Uses tree-level matrix element to generate events in the ‘dead’ region (∼ 3% of decays)

SOFT correction:

Ensures that hardest emission in parton shower region agrees with tree-level matrix element

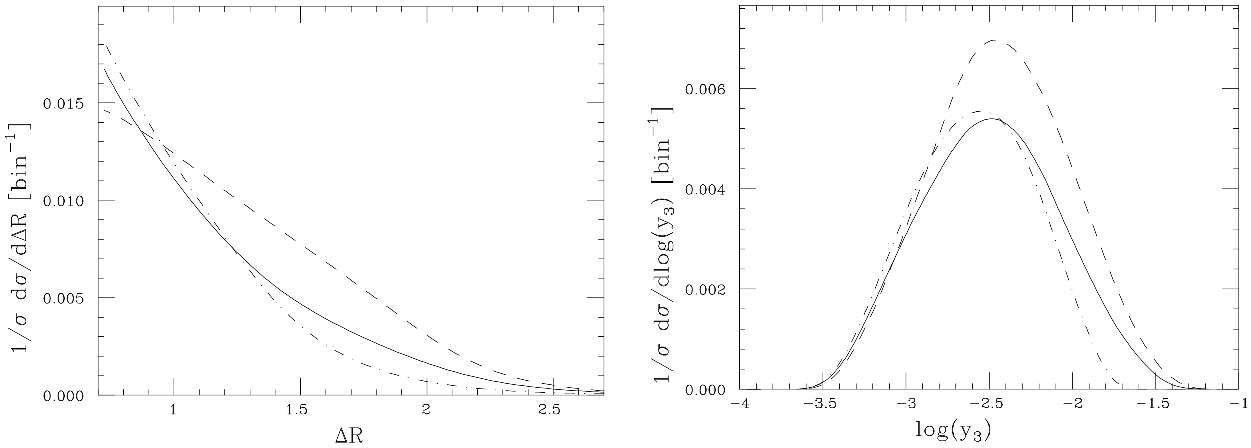
(M.H. Seymour, CPC 90 (1995) 95)

Very important near threshold. . .

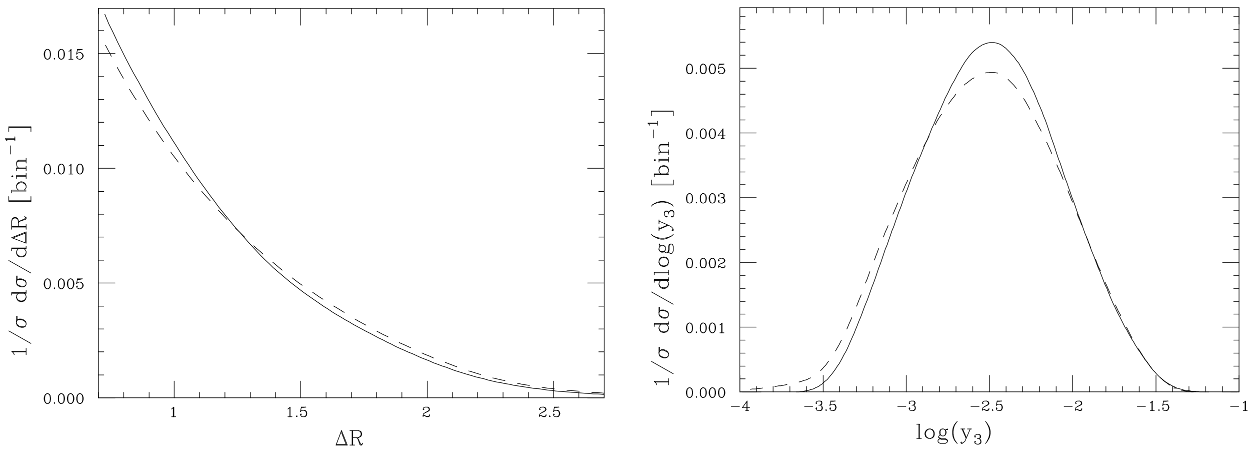
(cf. L.H. Orr, T. Stelzer & W.J. Stirling, PRD56 (1997) 446)

$e^+e^- \to t\bar{t}$ at $\sqrt{s} = 360$ GeV
3-jet events in Durham algorithm

HERWIG 5.9 (dashed): most recent public version, with known bug (initial scale of parton shower set incorrectly),
HERWIG 6.0 (dot-dashed): with bug fix,
HERWIG 6.1 (solid): with matrix element correction



HERWIG 6.1 (solid)
tree-level matrix element (dashed)
(with $\alpha_S = \alpha_S(\langle p_t \rangle = 30\text{GeV}) = 0.145$)



Matrix element corrections to production also important: in progress

On to C++

Why Fortran $\longrightarrow$ C++?

- SLAC $\longrightarrow$, FNAL $\longrightarrow$, CERN $\longrightarrow$ LHC era.
- Industrial standard.
- Educational and professional continuity for students.
- Better to program – for experts.
- User-friendly interfaces – for the rest of us.

PYTHIA 7 milestones:

- January 1998: project formally started.
- 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.
- By summer: “proof of concept” (?).
- End 2000: most of current PYTHIA (?).
- ??: more and better than current PYTHIA.

Manpower: L. Lönnblad, M. Bertini, TS.

(L. Lönnblad, hep-ph/9810208 $\longrightarrow$ CPC; input to `leif@thep.lu.se`.)

HERWIG prospects:
PPARC application for 2 “postdocs”,
to produce a C++ version, also with
significantly improved physics contents.