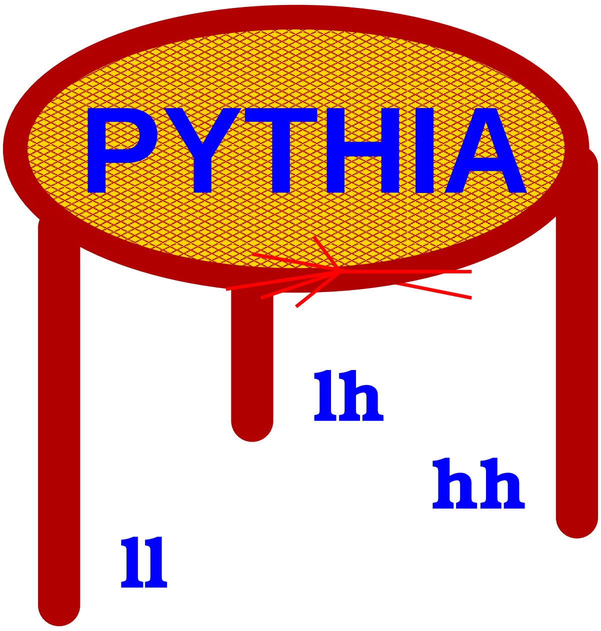
ECFA/DESY Linear Collider Workshop
Oxford 20–23 March 1999

A PYTHIA Update



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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
$\sim$ 46.800 lines Fortran 77

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

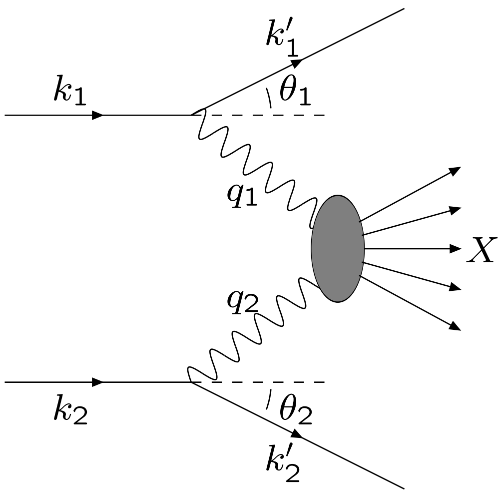
PYTHIA 6.1 main news

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

Virtual photon processes

(C. Friberg & TS, in preparation)

The photon flux



$$W^2 = (q_1 + q_2)^2$$

$$Q_i^2 = -q_i^2$$

$$y_i = \frac{q_i k_j}{k_i k_j} \quad j=2(1) \text{ for } i=1(2)$$

$$x_i = \frac{q_i(k_1 + k_2)}{k_i(k_1 + k_2)}$$

$$y_i \approx x_i + \frac{Q_i^2}{s}$$

$$Q_i^2 \approx \frac{x_i^2}{1 - x_i} m_i^2 + (1 - x_i) s \sin^2(\theta_i/2)$$

$$\mathrm{d}\sigma(\mathrm{ee} \to \mathrm{ee}X) = \sum_{\xi_1,\xi_2=\mathrm{T,L}} \int \mathrm{d}y_1 \, \mathrm{d}Q_1^2 \, \mathrm{d}y_2 \, \mathrm{d}Q_2^2$$

$$\times \; f_{\gamma/\mathrm{e}}^{\xi_1}(y_1, Q_1^2) \; f_{\gamma/\mathrm{e}}^{\xi_2}(y_2, Q_2^2) \; \mathrm{d}\sigma(\gamma_{\xi_1}^* \gamma_{\xi_2}^* \to X)$$

with

$$f_{\gamma/\mathrm{e}}^{\mathrm{T}}(y, Q^2) = \frac{\alpha_{\mathrm{em}}}{2\pi} \left(\frac{(1 + (1 - y)^2}{y} \frac{1}{Q^2} - \frac{2m_{\mathrm{e}}^2 y}{Q^4} \right)$$

$$f_{\gamma/\mathrm{e}}^{\mathrm{L}}(y, Q^2) = \frac{\alpha_{\mathrm{em}}}{2\pi} \frac{2(1 - y)}{y} \frac{1}{Q^2}$$

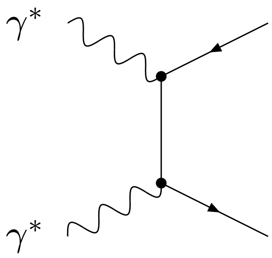
Photon processes

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

Three main process classes:

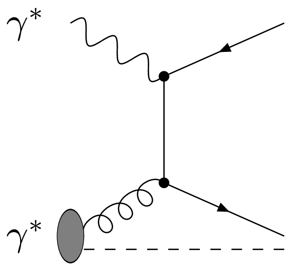
1. direct×direct

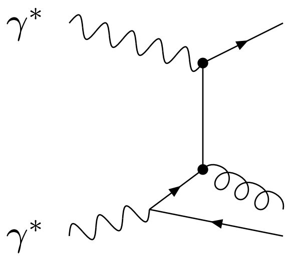
$\gamma^*_\mathrm{T}\gamma^*_\mathrm{T} \to \mathrm{q}\overline{\mathrm{q}}$
$\gamma^*_\mathrm{T}\gamma^*_\mathrm{L} \to \mathrm{q}\overline{\mathrm{q}}$
$\gamma^*_\mathrm{L}\gamma^*_\mathrm{L} \to \mathrm{q}\overline{\mathrm{q}}$



2. direct×resolved , resolved = VMD or anomalous

$\gamma^*_\mathrm{T}\mathrm{g} \to \mathrm{q}\overline{\mathrm{q}}$
$\gamma^*_\mathrm{L}\mathrm{g} \to \mathrm{q}\overline{\mathrm{q}}$
$\gamma^*_\mathrm{T}\mathrm{q} \to \mathrm{qg}$
$\gamma^*_\mathrm{L}\mathrm{q} \to \mathrm{qg}$

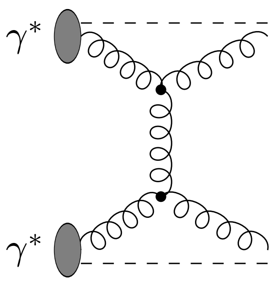


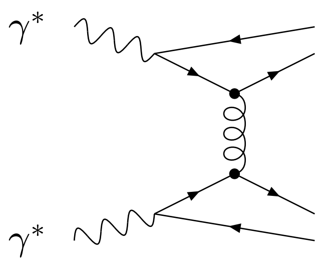


etc.

3. resolved×resolved

$\mathrm{qq}' \to \mathrm{qq}'$
$\mathrm{q}\overline{\mathrm{q}} \to \mathrm{q}'\overline{\mathrm{q}}'$
$\mathrm{q}\overline{\mathrm{q}} \to \mathrm{gg}$
$\mathrm{qg} \to \mathrm{qg}$
$\mathrm{gg} \to \mathrm{gg}$
$\mathrm{gg} \to \mathrm{q}\overline{\mathrm{q}}$





etc.

$$\mathrm{d}\sigma(\gamma^*\gamma^* \to X) = \left(\int \mathrm{d}\widehat{x}_1 \, f_i^{\gamma^*}(\widehat{x}_1, \mu^2, Q_1^2) \right)$$

$$\times \left(\int \mathrm{d}\widehat{x}_2 \, f_j^{\gamma^*}(\widehat{x}_2, \mu^2, Q_2^2) \right) \int \mathrm{d}\widehat{t} \, \frac{\mathrm{d}\widehat{\sigma}}{\mathrm{d}\widehat{t}}(\widehat{s} = \widehat{x}_1 \widehat{x}_2 W^2)$$

Parton distributions

SaS γ^* distributions extended from γ ones by inclusion of dipole damping factors,

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

$$\sum_V \frac{4\pi\alpha_{\mathrm{em}}}{f_V^2} \left(\frac{m_V^2}{m_V^2 + Q^2} \right)^2 f_a^{\gamma,V}(x, \mu^2; \tilde{Q}_0^2) +$$

$$\frac{\alpha_{\mathrm{em}}}{2\pi} \sum_{\mathrm{q}} 2e_{\mathrm{q}}^2 \int_{Q_0^2}^{\mu^2} \frac{\mathrm{d}k^2}{k^2} \left(\frac{k^2}{k^2 + Q^2} \right)^2 f_a^{\gamma,\mathrm{q\overline{q}}}(x, \mu^2; k^2) ,$$

reduction of evolution range: $Q_0 < \tilde{Q}_0 < \mu$,
and matching $f_a^{\gamma^*}(x, \mu^2, Q^2) \to 0$ for $\mu^2 \to Q^2$.

μ^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

$$\mu^2 = p_\perp^2 \, \frac{\hat{s} + Q_1^2 + Q_2^2}{\hat{s}} \qquad \left(\sim \frac{-\hat{t}\hat{u}}{\hat{t} + \hat{u}} \right) .$$

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 $Q_0^{\mathrm{sh}} = 1$ 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 $\gamma^* \to \mathrm{q\overline{q}}$ is allowed to radiate, from a scale k to $m_0^{\mathrm{sh}} = 1$ GeV, while a VMD beam remnant cannot.

Primordial $k_\perp$: Gaussian 'small' for VMD,
$\sim \mathrm{d}k_\perp^2/k_\perp^2$ for anomalous.

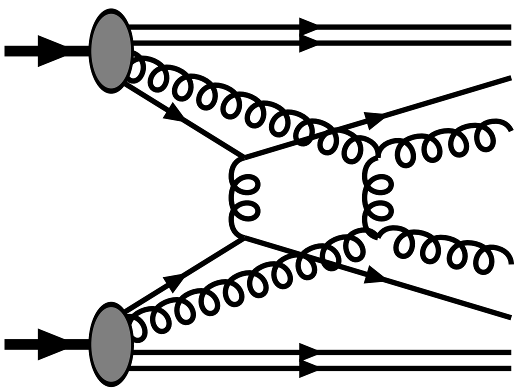
Multiple parton–parton interactions:
only affects VMD$\times$VMD.

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

Ansatz for γ^*:

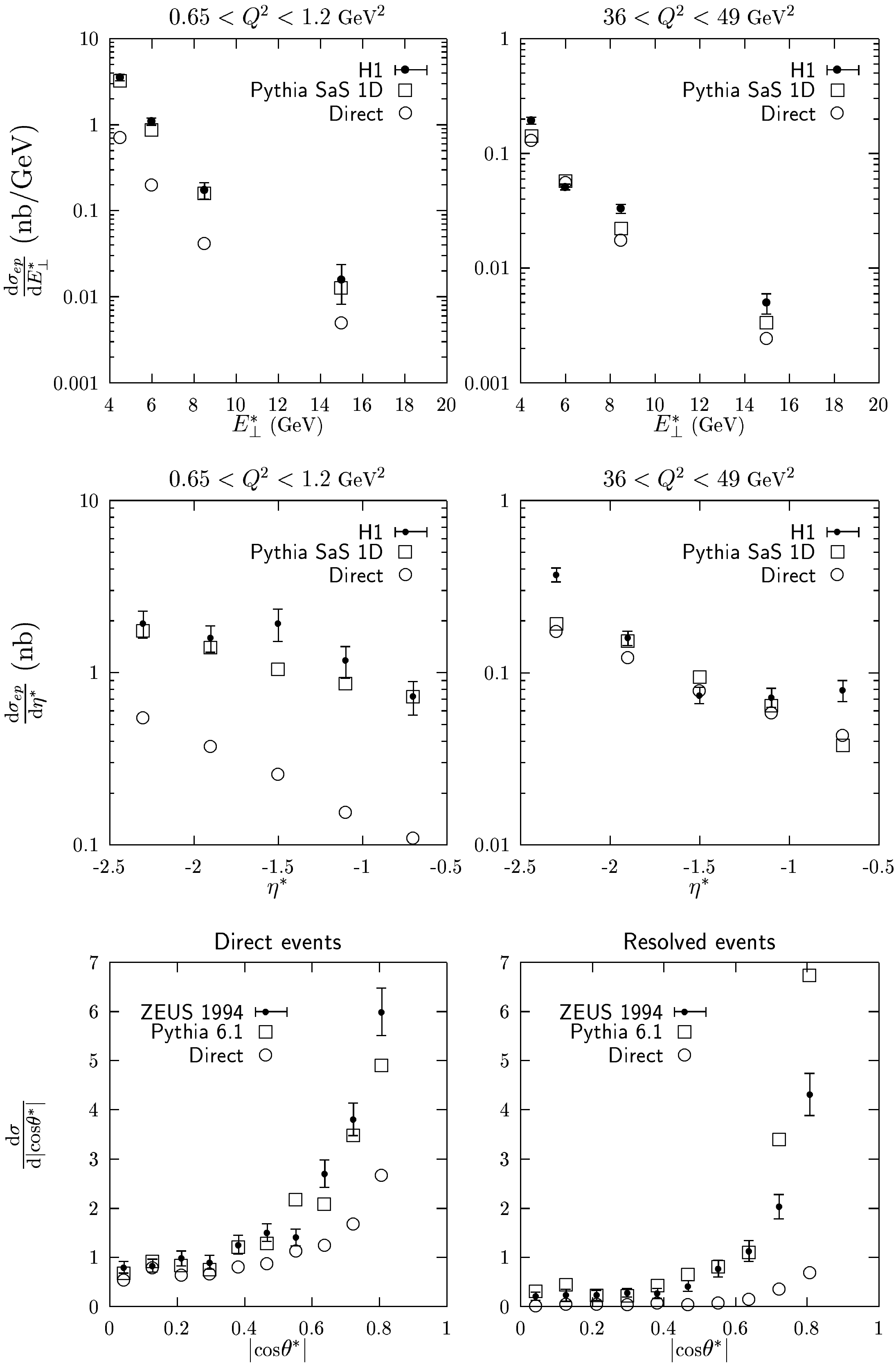
$$\sigma_{\mathrm{tot}} \propto \frac{m_V^2}{m_V^2 + Q^2}$$

$$p_{\perp\mathrm{min}} \propto \sqrt{1 + \frac{Q^2}{m_V^2}}$$



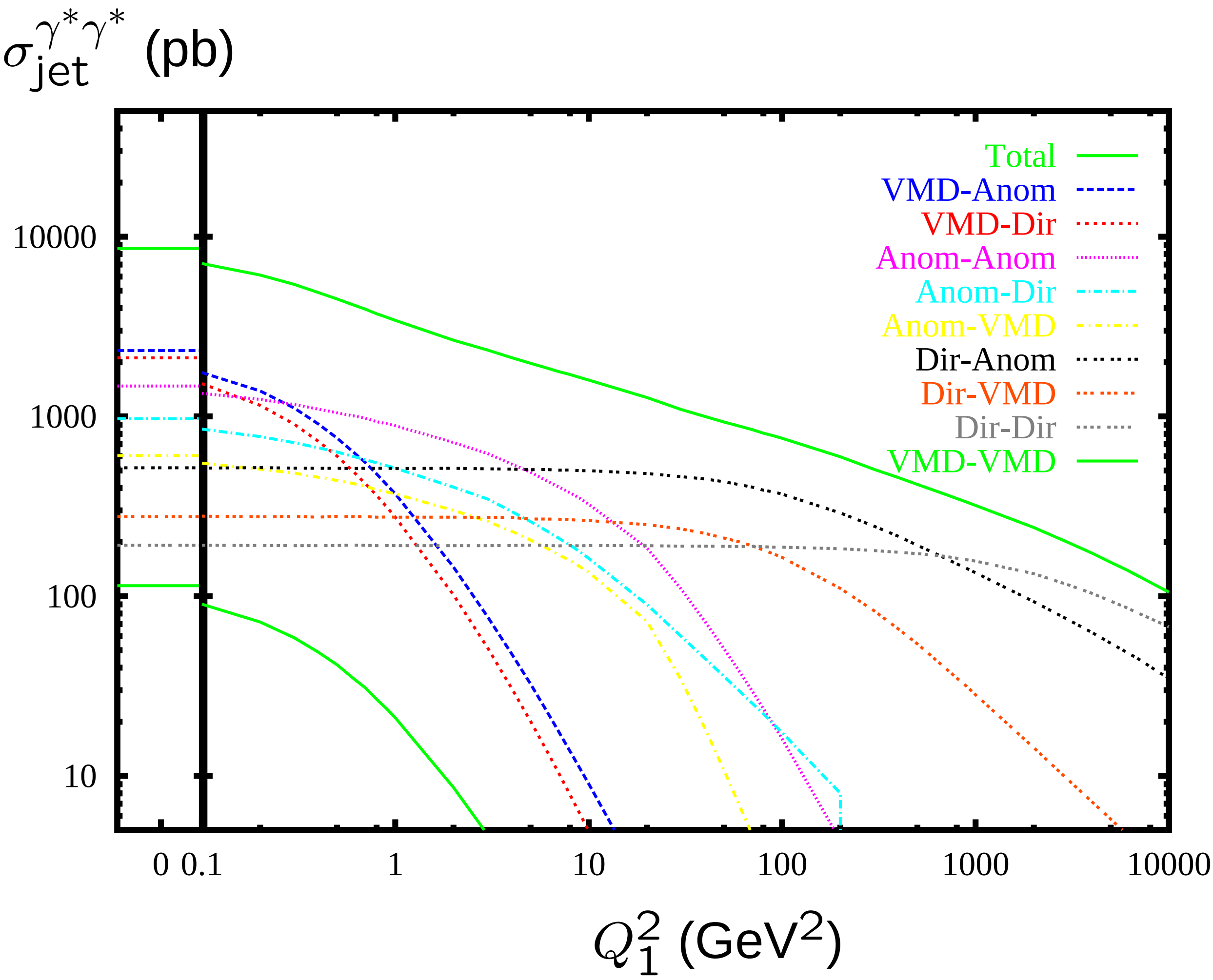
$$\text{Hadronic data}: \; p_{\perp\mathrm{min}} \approx (1.9 \text{ GeV}) \left(\frac{s}{1 \text{ TeV}^2} \right)^{0.08}$$

Comparison with HERA data



e^+e^- cross sections

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



Program particulars

To access new γ^* 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×V = V×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 : $\gamma^*\gamma^* \to \ell^+\ell^-$ included in dir×dir if not switched off (automatic when mixing).

Possible to specify cuts on x_i, y_i, Q_i^2, θ_i, W^2
in `CKIN(61) - CKIN(78)`.
Phase space sampled according to

$$\prod_i (\mathrm{d}Q_i^2/Q_i^2)\,(\mathrm{d}x_i/x_i)\,\mathrm{d}\varphi_i$$

$\Rightarrow$ full efficiency for x_i and Q_i^2 cuts.

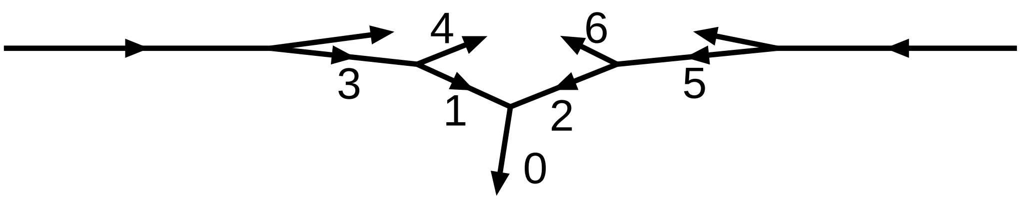
Photon ISR in Z^0 production

(G. Miu & TS, hep-ph/9812455 $\rightarrow$ 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 $e^+(3) + e^-(2) \rightarrow \gamma(4) + Z^0(0)$:

$$
\begin{aligned}
\hat{s} = (p_3 + p_2)^2 &= \frac{(p_1 + p_2)^2}{z} = \frac{m_Z^2}{z} \\
\hat{t} = (p_3 - p_4)^2 &= p_1^2 = -Q^2 \\
\hat{u} = m_Z^2 - \hat{s} - \hat{t} &= Q^2 - \frac{1-z}{z} m_Z^2
\end{aligned}
$$

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

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

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

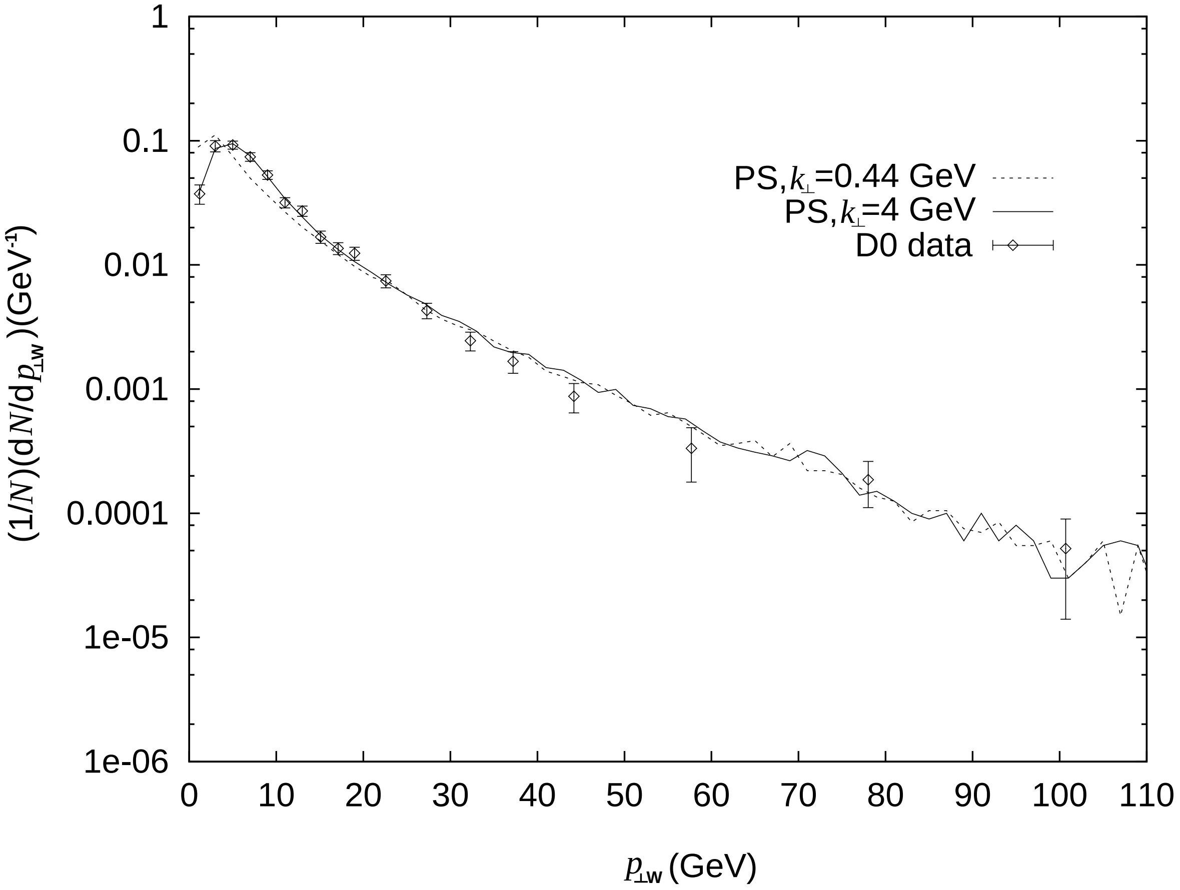
$$\frac{1}{2} < R_{\mathrm{ee}\to\gamma\mathrm{Z}}(\hat{s},\hat{t}) \leq 1$$

Improve PS:

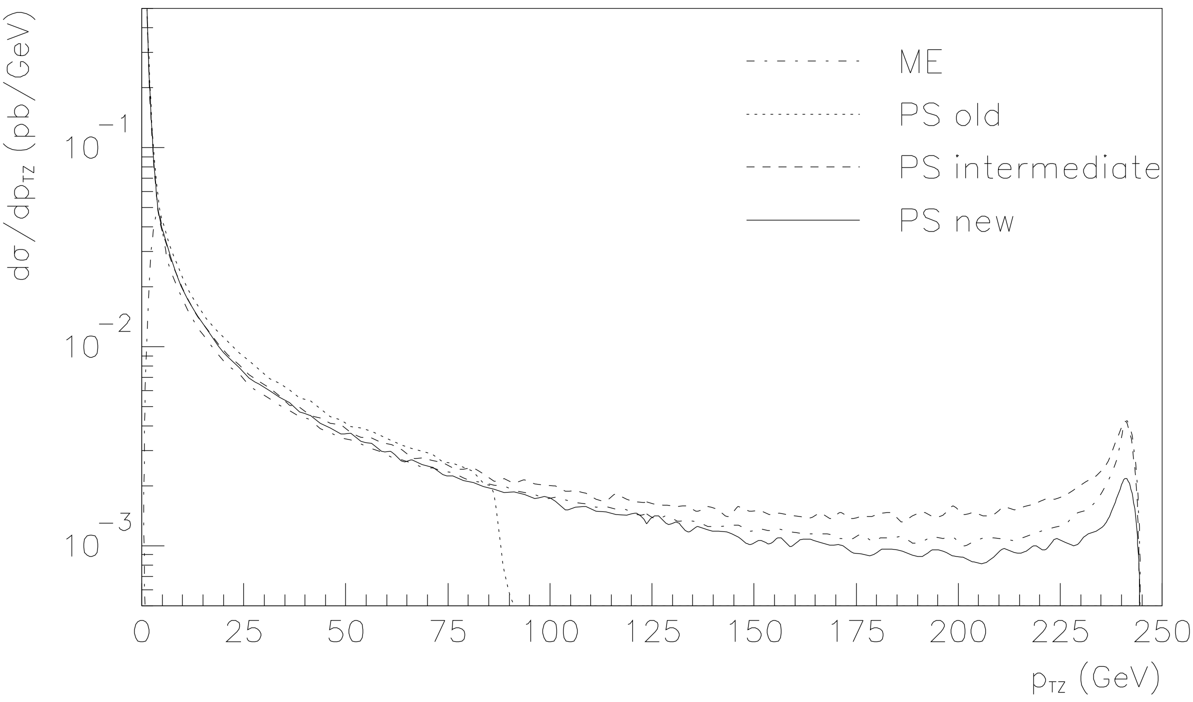
- $Q^2_{\mathrm{max}} = s$, not $Q^2_{\mathrm{max}} \approx m_{\mathrm{Z}}^2$ (intermediate)
- MC correction by $R(\hat{s},\hat{t})$ for first ($\approx$ hardest) emission on each side (new)

Now default.

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



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



Doubly-charged Higgses

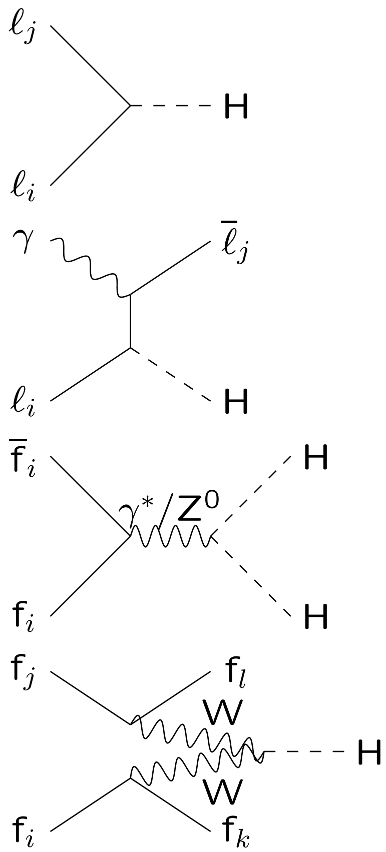
(K. Huitu, J. Maalampi, A. Pietilä, M Raidal, private communication; G. Barenboim, KH, JM, MR, PLB394 (1997) 132)

Based on left–right symmetric scenario.

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

New processes:

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



Typical decays:

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

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

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

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:

```
  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)
```

`P`ij : relative probability that first (second) fermion is paired with i'th (j'th) antifermion.
`PTOP` : absolute probability for $\mathrm{t\bar{t}}$ event. If $\mathrm{t\bar{t}}$ is selected, the `P`ij are not used. The b&$\mathrm{\bar{b}}$ must be first fermion pair.

Process 36, $\mathrm{e}\gamma \to \nu\mathrm{W}$ ($\Rightarrow$ $\mathrm{ee} \to \mathrm{e}\nu\mathrm{W}$) :
W decay angle ME now included.

New function `PYMRUN` for running $\overline{\mathrm{MS}}$ 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 $\tilde{\mathrm{b}}$ production.

Many bugs fixed, and (no doubt) new ones introduced.

On to C++!

(L. Lönnblad, 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`