Event Generator Physics

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Introduction
Generator Overview
Subprocess Survey
Parton Showers
Hadronization
Beam Remnant Physics
Multiple Interactions
QCD Interconnection
Outlook
Higgs candidates from ALEPH

\[ m_h = 112.4 \text{ GeV}, \ m_Z = 93.3 \text{ GeV} \]

\[ m_h = 109.8 \text{ GeV}, \ m_Z = 93.2 \text{ GeV} \]
Distributions of Reconstructed Mass Sequence: "Loose", "Medium" and "Tight" selection

Events / 3 GeV/c^2 √s = 200-210 GeV

LEP S/B=0.3 background hZ Signal (m_H=115 GeV)

LEP S/B=1.0 background hZ Signal (m_H=115 GeV)

LEP S/B=2.0 background hZ Signal (m_H=115 GeV)

-2 ln(Q) ... REF, DELTA, TOTAL

LEP REF

LEP DELTA

LEP TOTAL

Minimum @m_H ≈ 115 GeV

Agreement with SM Higgs cross-sect. for

m_H = 115.0^{+1.3}_{-0.9} GeV
True Theory: \[ \mathcal{L} = i \bar{\psi} \gamma^\mu D_\mu \psi - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \ldots \]

Applied Theory:

Phenomenology:

Reality:

Event Discussion (4-jet)

Run: event 13978: 6299
Date 000627
Time 111338

E beam 102.70
Ev is 210.0
Em is 4.6
V tx (-0.05, 0.04, -1.07)

B z = 4.350
Bunchlet 1/1
Thrust = 0.8614
A plan = 0.0601
Oblat = 0.1396
Sph er = 0.2098

C trk (N = 91)
Sum p = 119.6
E cal (N = 102)
Sum E = 105.7
H cal (N = 26)
Sum E = 43.0
Muon (N = 2)
Sec V tx (N = 11)
F det (N = 0)
Sum E = 0.0

Y X Z 200.0 cm.
Centre of screen is (0.0000, 0.0000, 0.0000)

50 GeV
20
10
5

27 June
m_h = 112.6 GeV

B-tag(1) = 0.345
B-tag(2) = 0.960
$p = 205.4$ GeV
$L = 0.999$
$s/b(105 GeV) = 0.2844$
$s/b(110 GeV) = 1.1355$
$s/b(115 GeV) = 0.5234$

Highest weight

OPAL candidate

LEPC Seminar 3 November 2000, Results from the OPAL Experiment, Arnulf Quadt

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Event Generator Position

“real life”

Machine, interactions ⇒ events

produce events

“virtual reality”

Event Generator

observe & store events

Detector, Data Acquisition

Detector Simulation

what is knowable?

compare real and simulated data

Event Reconstruction

Physics Analysis

“quick and dirty” feasibility studies

conclusions, articles, talks, ...
Why Generators?

- Allow theoretical and experimental studies of complex multiparticle physics
- Large flexibility in physical quantities that can be addressed
- Vehicle of ideology to disseminate ideas from theorists to experimentalists

Can be used to
- predict event rates and topologies
  ⇒ can estimate feasibility
- simulate possible backgrounds
  ⇒ can devise analysis strategies
- study detector requirements
  ⇒ can optimize detector/trigger design
- study detector imperfections
  ⇒ can evaluate acceptance corrections

God does not throw dice . . .
. . . but Mother Nature does!
Which Generators?

Large spectrum, from big to small

“Lund family” and Lund-based
PYTHIA (⇐ JETSET): general-purpose
ARIADNE: dipole showers (Lönnblad)
LEPTO: leptoproduction (Ingelman et al.)
and many more: RAPGAP, SPHINX, . . .

HERWIG: general-purpose (Webber et al.)

ISAJET: pp & general-purpose (Paige et al.)

Specialized QCD: NLLjet, heavy ions, . . .

Single- or multiprocess parton-level only:
KORALZ, EXCALIBUR, PANDORA,
SUSYGEN, HERACLES, JETVIP,
VECBOS, NJETS, . . .

Generators of generators:
CompHEP, GRACE, HELAS, MADGRAPH,
O’Mega/WHIZARD, . . .

Many more documented in workshops: LEP 1,
LEP 2, HERA, LHC, linear colliders, . . .
Event Physics Overview

Structure of the basic generation process:

1) Hard subprocess: 
\( \frac{d\sigma}{d\hat{t}} \), 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 (PYTHIA: string; HERWIG: cluster; ISAJET: independent).

8) Normal decays: hadronic, \( \tau \), charm, \ldots

9) QCD interconnection effects:

a) colour rearrangement \((\Rightarrow \text{rapidity gaps?})\);
b) Bose-Einstein.

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

<table>
<thead>
<tr>
<th>Process</th>
<th>PYT</th>
<th>HER</th>
<th>ISA</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>QCD &amp; related</strong></td>
<td></td>
<td></td>
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<tr>
<td>Soft QCD</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Hard QCD</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Heavy flavour</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Top threshold</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>$\gamma\gamma$ physics</td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DIS</td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\gamma^<em>\gamma^</em>$ physics</td>
<td></td>
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<td></td>
</tr>
<tr>
<td><strong>Electroweak SM</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Single $\gamma^*/Z^0/W^\pm$</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>$(\gamma/\gamma^*/Z^0/W^\pm/f/g)^2$</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Light SM Higgs</td>
<td>*</td>
<td>*</td>
<td>*</td>
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<tr>
<td>Heavy SM Higgs</td>
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<td></td>
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<tr>
<td><strong>SUSY BSM</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$h^0/H^0/A^0/H^\pm$</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>SUSY</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>$\mathbb{R}$ SUSY</td>
<td></td>
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<tr>
<td><strong>Other BSM</strong></td>
<td></td>
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<tr>
<td>Technicolor</td>
<td>*</td>
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<td>*</td>
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<tr>
<td>New gauge bosons</td>
<td>*</td>
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</tr>
<tr>
<td>Compositeness</td>
<td>*</td>
<td></td>
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<tr>
<td>Leptoquarks</td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H^{\pm\pm}$ (from LR-sym.)</td>
<td>*</td>
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</tr>
<tr>
<td>Extra dimensions</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

* = yes, (*) = partial/in progress, —— = no
<table>
<thead>
<tr>
<th>No.</th>
<th>Subprocess</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>$f_1 f_2 \rightarrow f_1 f_1$</td>
</tr>
<tr>
<td>12</td>
<td>$f_1 f_2 \rightarrow f_2 f_1$</td>
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<tr>
<td>13</td>
<td>$f_1 f_2 \rightarrow f_1 f_3$</td>
</tr>
<tr>
<td>28</td>
<td>$f_1 g \rightarrow f_1 g^0$</td>
</tr>
<tr>
<td>53</td>
<td>$g g \rightarrow f_1 f_3$</td>
</tr>
<tr>
<td>68</td>
<td>$g g \rightarrow g g^0$</td>
</tr>
<tr>
<td>91</td>
<td>elastic scattering</td>
</tr>
<tr>
<td>92</td>
<td>single diffusion (X B)</td>
</tr>
<tr>
<td>93</td>
<td>single diffusion (X A)</td>
</tr>
<tr>
<td>94</td>
<td>double diffusion</td>
</tr>
<tr>
<td>95</td>
<td>4-39 production</td>
</tr>
</tbody>
</table>

**Open heavy flavour**

<table>
<thead>
<tr>
<th>No.</th>
<th>Subprocess</th>
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</thead>
<tbody>
<tr>
<td>81</td>
<td>$f_1 f_2 \rightarrow Q_1 Q_2$</td>
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<tr>
<td>82</td>
<td>$g g \rightarrow Q_1 Q_2$</td>
</tr>
<tr>
<td>83</td>
<td>$q_1 j \rightarrow Q_1 j$</td>
</tr>
<tr>
<td>84</td>
<td>$g g \rightarrow Q_1 Q_3$</td>
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<tr>
<td>85</td>
<td>$g g \rightarrow f_1 f_3$</td>
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**BSM Neutral Higgs**

<table>
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<td>151</td>
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<tr>
<td>152</td>
<td>$g g \rightarrow H^0$</td>
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<tr>
<td>153</td>
<td>$\gamma \gamma \rightarrow H^0$</td>
</tr>
<tr>
<td>154</td>
<td>$f_1 f_2 \rightarrow Z^0 H^0$</td>
</tr>
<tr>
<td>155</td>
<td>$f_1 f_2 \rightarrow Z^0 A^0$</td>
</tr>
<tr>
<td>156</td>
<td>$f_1 f_2 \rightarrow H^0 A^0$</td>
</tr>
</tbody>
</table>

**W/Z production**

<table>
<thead>
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<th>Subprocess</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>$f_1 f_2 \rightarrow \gamma \gamma Z/\gamma \gamma W$</td>
</tr>
<tr>
<td>2</td>
<td>$f_1 f_2 \rightarrow W^+ W^-$</td>
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<tr>
<td>22</td>
<td>$f_1 f_2 \rightarrow Z^0 W^+ W^-$</td>
</tr>
<tr>
<td>23</td>
<td>$f_1 f_2 \rightarrow Z^0 W^+ W^-$</td>
</tr>
<tr>
<td>25</td>
<td>$f_1 f_2 \rightarrow W^+ W^-$</td>
</tr>
<tr>
<td>15</td>
<td>$f_1 f_2 \rightarrow Z^0$</td>
</tr>
<tr>
<td>16</td>
<td>$f_1 f_2 \rightarrow g g^0$</td>
</tr>
<tr>
<td>30</td>
<td>$f_1 g \rightarrow f_1 g$</td>
</tr>
<tr>
<td>31</td>
<td>$f_1 g \rightarrow f_1 g$</td>
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<tr>
<td>20</td>
<td>$f_1 f_2 \rightarrow W^+ W^-$</td>
</tr>
<tr>
<td>35</td>
<td>$f_1 f_2 \rightarrow f_1 Z^0$</td>
</tr>
<tr>
<td>36</td>
<td>$f_1 f_2 \rightarrow f_1 W^+ W^-$</td>
</tr>
<tr>
<td>69</td>
<td>$\gamma \gamma \rightarrow W^+ W^-$</td>
</tr>
<tr>
<td>70</td>
<td>$W^+ W^- \rightarrow Z^0 W^+ W^-$</td>
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</table>

**Prompt photons**

<table>
<thead>
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<td>14</td>
<td>$f_1 f_2 \rightarrow g g$</td>
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<tr>
<td>15</td>
<td>$f_1 f_2 \rightarrow \gamma$</td>
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<tr>
<td>17</td>
<td>$f_1 f_2 \rightarrow \gamma$</td>
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<tr>
<td>29</td>
<td>$f_1 f_2 \rightarrow g g$</td>
</tr>
<tr>
<td>114</td>
<td>$g g \rightarrow g g$</td>
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</tbody>
</table>

**Deep inelastic scalt**

<table>
<thead>
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<th>Subprocess</th>
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<td>10</td>
<td>$f_1 f_2 \rightarrow f_1 f_1$</td>
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<tr>
<td>99</td>
<td>$f_1 f_2 \rightarrow f_1 f_1$</td>
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</tbody>
</table>

**Photon-induced**

<table>
<thead>
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<th>Subprocess</th>
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<tbody>
<tr>
<td>33</td>
<td>$f_1 f_2 \rightarrow f_1 g$</td>
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<tr>
<td>34</td>
<td>$f_1 f_2 \rightarrow f_1 g$</td>
</tr>
<tr>
<td>54</td>
<td>$g g \rightarrow f_1 f_1$</td>
</tr>
<tr>
<td>58</td>
<td>$\gamma \gamma \rightarrow f_1 f_1$</td>
</tr>
<tr>
<td>131</td>
<td>$f_1 f_2 \rightarrow f_1 f_2$</td>
</tr>
<tr>
<td>132</td>
<td>$f_1 f_2 \rightarrow f_1 f_2$</td>
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<tr>
<td>133</td>
<td>$f_1 f_2 \rightarrow f_1 f_2$</td>
</tr>
<tr>
<td>134</td>
<td>$f_1 f_2 \rightarrow f_1 f_2$</td>
</tr>
<tr>
<td>135</td>
<td>$g g \rightarrow f_1 f_1$</td>
</tr>
<tr>
<td>136</td>
<td>$g g \rightarrow f_1 f_1$</td>
</tr>
<tr>
<td>137</td>
<td>$\gamma \gamma \rightarrow f_1 f_1$</td>
</tr>
<tr>
<td>138</td>
<td>$\gamma \gamma \rightarrow f_1 f_1$</td>
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</tbody>
</table>

**Heavy SM Higgs**

<table>
<thead>
<tr>
<th>No.</th>
<th>Subprocess</th>
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</thead>
<tbody>
<tr>
<td>80</td>
<td>$q_1 q_2 \rightarrow H^0, H^0$</td>
</tr>
<tr>
<td>81</td>
<td>$Z^0 Z^0 \rightarrow H^0, H^0$</td>
</tr>
<tr>
<td>82</td>
<td>$W^+ W^- \rightarrow H^0, H^0$</td>
</tr>
<tr>
<td>83</td>
<td>$Z^0 Z^0 \rightarrow Z^0, Z^0$</td>
</tr>
<tr>
<td>84</td>
<td>$Z^0 Z^0 \rightarrow Z^0, Z^0$</td>
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<tr>
<td>85</td>
<td>$Z^0 Z^0 \rightarrow Z^0, Z^0$</td>
</tr>
<tr>
<td>86</td>
<td>$W^+ W^- \rightarrow Z^0, Z^0$</td>
</tr>
<tr>
<td>87</td>
<td>$W^+ W^- \rightarrow Z^0, Z^0$</td>
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</tbody>
</table>

**Higgs pairs**

<table>
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<tr>
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<th>Subprocess</th>
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<tbody>
<tr>
<td>297</td>
<td>$f_1 f_2 \rightarrow H^+ H^-$</td>
</tr>
<tr>
<td>298</td>
<td>$f_1 f_2 \rightarrow H^+ H^-$</td>
</tr>
<tr>
<td>299</td>
<td>$f_1 f_2 \rightarrow A^+ A^-$</td>
</tr>
<tr>
<td>300</td>
<td>$f_1 f_2 \rightarrow A^+ A^-$</td>
</tr>
<tr>
<td>311</td>
<td>$f_1 f_2 \rightarrow H^+ H^-$</td>
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</table>

**Double-charged Higgs**

<table>
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<th>No.</th>
<th>Subprocess</th>
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<tbody>
<tr>
<td>341</td>
<td>$f_1 f_2 \rightarrow H^{++}$</td>
</tr>
<tr>
<td>342</td>
<td>$f_1 f_2 \rightarrow H^{++}$</td>
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<tr>
<td>343</td>
<td>$f_1 f_2 \rightarrow H^{++}$</td>
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<td>344</td>
<td>$f_1 f_2 \rightarrow H^{++}$</td>
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<td>345</td>
<td>$f_1 f_2 \rightarrow H^{++}$</td>
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<td>$f_1 f_2 \rightarrow H^{++}$</td>
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<td>347</td>
<td>$f_1 f_2 \rightarrow H^{++}$</td>
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<td>348</td>
<td>$f_1 f_2 \rightarrow H^{++}$</td>
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<tr>
<td>349</td>
<td>$f_1 f_2 \rightarrow H^{++}$</td>
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<tr>
<td>350</td>
<td>$f_1 f_2 \rightarrow H^{++}$</td>
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</table>

**New gauge bosons**

<table>
<thead>
<tr>
<th>No.</th>
<th>Subprocess</th>
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</thead>
<tbody>
<tr>
<td>141</td>
<td>$f_1 f_2 \rightarrow \gamma \gamma Z^*/Z^0$</td>
</tr>
<tr>
<td>142</td>
<td>$f_1 f_2 \rightarrow W^{+} W^{-}$</td>
</tr>
<tr>
<td>144</td>
<td>$f_1 f_2 \rightarrow R$</td>
</tr>
</tbody>
</table>
Parton Showers

\[ \mathcal{O}(1) \]
\[ \mathcal{O}(\alpha_s) \]
\[ \mathcal{O}(\alpha_s) \]
\[ \mathcal{O}(\alpha_s^2) \]
\[ \mathcal{O}(\alpha_s^2) \]
\[ \mathcal{O}(\alpha_s^2) \]

Matrix Elements exact to given order... but blind to higher orders

\[ \mathcal{O}(\alpha_s L^2) \]
\[ \mathcal{O}(\alpha_s^2 L^4) \]

\[ L \approx -\ln y \]
\[ y \approx \min \frac{m_{ij}^2}{E_{cm}^2} \]

collinear and soft emission divergences \[ \Rightarrow \text{large} \]
higher orders
From Matrix Elements to Parton Showers:

![Diagram](image)

\[ x_j = \frac{2E_j}{E_{\text{cm}}} \quad \Rightarrow \quad x_1 + x_2 + x_3 = 2 \]

\[ m_q = 0 : \quad \frac{1}{\sigma_0} \frac{d\sigma_{\text{ME}}}{dx_1 \, dx_2} = \frac{\alpha_s}{2\pi} \frac{4}{3} \frac{x_1^2 + x_2^2}{(1-x_1)(1-x_2)} \]

rewrite for \( x_2 \rightarrow 1 \):

\[ 1 - x_2 = \frac{m_{13}^2}{E_{\text{cm}}^2} = \frac{Q^2}{E_{\text{cm}}^2} \]

\[ x_1 \approx z \]

\[ x_3 \approx 1 - z \]

\[ \Rightarrow \quad d\mathcal{P} = \frac{d\sigma}{\sigma_0} \approx \frac{\alpha_s}{2\pi} \frac{dQ^2}{Q^2} \frac{4}{3} \frac{1 + z^2}{1 - z} \, dz \]

generalizes to

\[ d\mathcal{P}_{a \rightarrow bc} = \frac{\alpha_s}{2\pi} \frac{dQ^2}{Q^2} P_{a \rightarrow bc}(z) \, dz \]

\[ P_{q \rightarrow qg} = \frac{4}{3} \frac{1 + z^2}{1 - z} \]

\[ P_{g \rightarrow gg} = 3 \frac{(1 - z(1 - z))^2}{z(1 - z)} \]

\[ P_{g \rightarrow q\bar{q}} = \frac{n_f}{2} (z^2 + (1 - z)^2) \]
Iteration gives

final-state

parton showers

Sudakov form factor

$$\mathcal{P}^{\text{corr}}(Q^2) = \frac{d\mathcal{P}}{dQ^2} \exp \left(-\int_{Q^2}^{Q_{\text{max}}^2} \frac{d\mathcal{P}}{dQ^2} dQ^2\right)$$

(cf. radioactive decay; ‘time’ ordering)

Coherence $\Rightarrow$ angular ordering

$$\left| \begin{array}{c} \text{a} \\ \text{b} \\ \text{c} \end{array} \right| + \left| \begin{array}{c} \text{d} \\ \text{e} \end{array} \right| = \left| \begin{array}{c} \text{f} \\ \text{g} \end{array} \right|$$

Loop corrections $\Rightarrow \alpha_s(p_{\perp}^2)$

Soft/collinear cut-off $m_0 = \min(m_{ij}) \approx 1$ GeV

Matching of PS to ME (first emissions): if $d\sigma_{\text{ME}} \leq d\sigma_{\text{PS}}$ then generate events by PS and retain branchings with probability $d\sigma_{\text{ME}}/d\sigma_{\text{PS}}$
Initial-state showers:

Hadrons are composite, with time-dependent structure:

\[ f_i(x, Q^2) = \text{number density of partons } i \text{ at momentum fraction } x \text{ and probing scale } Q^2 \]

\[ F_2(x, Q^2) = \sum_i e_i^2 x f_i(x, Q^2) \]

structure function parton distributions

Resolution dependence by DGLAP

\[ \frac{\partial f_i(x, Q^2)}{\partial \ln Q^2} = \sum_j \int_x^1 \frac{dy}{y} f_j(y, Q^2) \frac{\alpha_s}{2\pi} P_{j\rightarrow i} \left( \frac{x}{y} \right) \]

Hard scattering on one branch inhibits cascade recombination. Convenient reinterpretation:

\[ m^2 = 0 \]
\[ m^2 < 0 \]
\[ m^2 > 0 \]
\[ Q^2 = -m^2 > 0 \]

and increasing
Initial- vs. final-state showers:

Both controlled by same evolution equations

$$dP_{a\to bc} = \frac{\alpha_s}{2\pi} \frac{dQ^2}{Q^2} P_{a\to bc}(z) \, dz \cdot \text{ (Sudakov)}$$

but

Final-state showers: $Q^2$ timelike ($\approx m^2$)

\[
\begin{array}{c}
E_0, m_0^2 \\
\end{array} \rightarrow \begin{array}{c}
\theta \\
E_2, m_2^2 \\
E_1, m_1^2
\end{array}
\]

- Decreasing $E$
- Decreasing $m^2$
- Decreasing $\theta$

Daughters on equal footing, both $m^2 \geq 0$

$Q^2, z, \ldots$ choice gives several algorithms

Initial-state showers: $Q^2$ spacelike ($\approx -m^2$)

\[
\begin{array}{c}
E_0, Q_0^2 \\
\end{array} \rightarrow \begin{array}{c}
\theta \\
E_2, m_2^2 \\
E_1, Q_1^2
\end{array}
\]

- Decreasing $E$
- Increasing $Q^2$
- Increasing $\theta$

Daughters unequal, one $m^2 \geq 0$, one $m^2 < 0$

$\Rightarrow$ kinematics & coherence more complicated

$+$ more messy hadronic environment
gives many attempts: BFKL, CCFM, GLR, \ldots
Gluon emission off heavy particles:
(E. Norrbin & TS, LUTP 00-42 [hep-ph/0010012])

Objective:
- improved parton shower description,
- including mass effects (“dead cone”), and
- matched to process-specific $O(\alpha_s)$ ME’s

$Q^2$: evolution variable, $= m^2$ in PYTHIA
$z$: energy/momentum sharing in branching

3-jet events in $e^+e^- \rightarrow \gamma^*/Z^* \rightarrow q\bar{q} \rightarrow q\bar{q}g$: map PS variables on to ME ones:

\[
\frac{1}{\sigma_0} \frac{d\sigma_{\text{ME}}}{dx_1 dx_2} \leq \frac{1}{\sigma_0} \frac{d\sigma_{\text{PS}}}{dQ^2 dz} \quad \text{for } m_q = 0
\]

so can generate events with PS
and correct first branching by ME/PS

Fails for $m_q > 0$ in part of phase space
\Rightarrow have had exaggerated dead cone effect

Restore by $Q_j^2 = m_{j,\text{offshell}}^2 - m_{j,\text{onshell}}^2$

Also works for decaying coloured state,
e.g. ME for $t \rightarrow bWg$ matches PS for $b \rightarrow bg$

\Rightarrow can match PS to generic $a \rightarrow bcg$ ME
...but often ME $\ll$ PS
$\implies$ need ME input for good description

Calculate for $1 \rightarrow 2$ processes in SM + MSSM:
\[
\frac{1}{\sigma(a \rightarrow bc)} \frac{d\sigma(a \rightarrow bcg)}{dx_1 dx_2}
\]

Depends on mass ratios, colour and spin structure, and parity ($\gamma_5$)

<table>
<thead>
<tr>
<th>colour</th>
<th>spin</th>
<th>$\gamma_5$</th>
<th>example</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1 \rightarrow 3 + 3$</td>
<td>—</td>
<td>—</td>
<td>(eikonal)</td>
</tr>
<tr>
<td>$1 \rightarrow 3 + 3$</td>
<td>$1 \rightarrow \frac{1}{2} + \frac{1}{2}$</td>
<td>$1, \gamma_5, 1 \pm \gamma_5$</td>
<td>$Z^0 \rightarrow q\bar{q}$</td>
</tr>
<tr>
<td>$3 \rightarrow 3 + 1$</td>
<td>$\frac{1}{2} \rightarrow \frac{1}{2} + 1$</td>
<td>$1, \gamma_5, 1 \pm \gamma_5$</td>
<td>$t \rightarrow bW^+$</td>
</tr>
<tr>
<td>$1 \rightarrow 3 + 3$</td>
<td>$0 \rightarrow \frac{1}{2} + \frac{1}{2}$</td>
<td>$1, \gamma_5, 1 \pm \gamma_5$</td>
<td>$H^0 \rightarrow q\bar{q}$</td>
</tr>
<tr>
<td>$3 \rightarrow 3 + 1$</td>
<td>$\frac{1}{2} \rightarrow \frac{1}{2} + 0$</td>
<td>$1, \gamma_5, 1 \pm \gamma_5$</td>
<td>$t \rightarrow bH^+$</td>
</tr>
<tr>
<td>$1 \rightarrow 3 + 3$</td>
<td>$1 \rightarrow 0 + 0$</td>
<td>1</td>
<td>$Z^0 \rightarrow q\bar{q}$</td>
</tr>
<tr>
<td>$3 \rightarrow 3 + 1$</td>
<td>$0 \rightarrow 0 + 1$</td>
<td>1</td>
<td>$q \rightarrow q'W^+$</td>
</tr>
<tr>
<td>$1 \rightarrow 3 + 3$</td>
<td>$0 \rightarrow 0 + 0$</td>
<td>1</td>
<td>$H^0 \rightarrow q\bar{q}$</td>
</tr>
<tr>
<td>$3 \rightarrow 3 + 1$</td>
<td>$0 \rightarrow 0 + 0$</td>
<td>1</td>
<td>$q \rightarrow q'H^+$</td>
</tr>
<tr>
<td>$1 \rightarrow 3 + 3$</td>
<td>$\frac{1}{2} \rightarrow \frac{1}{2} + 0$</td>
<td>$1, \gamma_5, 1 \pm \gamma_5$</td>
<td>$\chi \rightarrow q\bar{q}$</td>
</tr>
<tr>
<td>$3 \rightarrow 3 + 1$</td>
<td>$0 \rightarrow \frac{1}{2} + \frac{1}{2}$</td>
<td>$1, \gamma_5, 1 \pm \gamma_5$</td>
<td>$q \rightarrow q\chi$</td>
</tr>
<tr>
<td>$3 \rightarrow 3 + 1$</td>
<td>$\frac{1}{2} \rightarrow 0 + \frac{1}{2}$</td>
<td>$1, \gamma_5, 1 \pm \gamma_5$</td>
<td>$t \rightarrow \bar{t}\chi$</td>
</tr>
<tr>
<td>$8 \rightarrow 3 + 3$</td>
<td>$\frac{1}{2} \rightarrow \frac{1}{2} + 0$</td>
<td>$1, \gamma_5, 1 \pm \gamma_5$</td>
<td>$g \rightarrow q\bar{q}$</td>
</tr>
<tr>
<td>$3 \rightarrow 3 + 8$</td>
<td>$0 \rightarrow \frac{1}{2} + \frac{1}{2}$</td>
<td>$1, \gamma_5, 1 \pm \gamma_5$</td>
<td>$q \rightarrow qg$</td>
</tr>
<tr>
<td>$3 \rightarrow 3 + 8$</td>
<td>$\frac{1}{2} \rightarrow 0 + \frac{1}{2}$</td>
<td>$1, \gamma_5, 1 \pm \gamma_5$</td>
<td>$t \rightarrow \bar{t}g$</td>
</tr>
</tbody>
</table>
Universal gluon radiation patterns (≈ no spin dependence) for small gluon energies . . .

(a) $r_1 \approx r_2 = 0.2, x_3 = 0.02$

(b) $r_1 \approx r_2 = 0.2, x_3 = 0.1$

(with textbook dead cone)
... but very process-dependent for large gluon energies ...

(c) $r_1 = r_2 = 0.2$, $x_3 = 0.3$

(d) $r_1 = r_2 = 0.2$, $x_3 = 0.6$

(and no dead cone except for spin $0 \rightarrow 0 + 0$)
ME matching of initial-state showers:
(G. Miu & TS, PLB449 (1999) 313)

2 → 1 process $q(1) + q'(2) \rightarrow W(0)$ starting point for backwards shower evolution:

Alternatively 2 → 2 matrix element processes
$q(3) + q'(2) \rightarrow g(4) + W(0)$ and mirror
$q(1) + q'(5) \rightarrow g(6) + W(0)$:

$$R_{q\bar{q}' \rightarrow gW}(\hat{s}, \hat{t}) = \frac{(d\hat{\sigma}/d\hat{t})_{\text{ME}}}{(d\hat{\sigma}/d\hat{t})_{\text{PS}}} = \frac{\hat{t}^2 + \hat{u}^2 + 2m_W^2\hat{s}}{\hat{s}^2 + m_W^4}$$

$$\frac{1}{2} < R_{q\bar{q}' \rightarrow gW}(\hat{s}, \hat{t}) \leq 1$$

Similarly for $q(1) + g(5) \rightarrow q'(6) + W(0)$:

$$R_{qg \rightarrow q'W}(\hat{s}, \hat{t}) = \frac{(d\hat{\sigma}/d\hat{t})_{\text{ME}}}{(d\hat{\sigma}/d\hat{t})_{\text{PS}}} = \frac{\hat{s}^2 + \hat{u}^2 + 2m_W^2\hat{t}}{(\hat{s} - m_W^2)^2 + m_W^4}$$

$$1 < R_{qg \rightarrow q'W}(\hat{s}, \hat{t}) \leq \frac{\sqrt{5} - 1}{2(\sqrt{5} - 2)} < 3$$
Improve PS:

- $Q_{\text{max}}^2 = s$, not $Q_{\text{max}}^2 \approx m_W^2$ (intermediate)
- MC correction by $R(\hat{s}, \hat{t})$ for first ($\approx$ hardest) emission on each side (new)

Same for all colourless vector gauge bosons: $\gamma^*, Z^0, Z'^0, W'^\pm, \ldots$

Complete simulation at 1.8 TeV:

Requires large primordial $k_\perp$, around 2 GeV.
(4 GeV in plot; miscorrection in data.)
In line with resummation descriptions, etc.
Solved by better understanding of soft part of showers: BFKL, CCFM, \ldots?
Hadronization

In QED field lines go all the way to infinity

since photons cannot interact with each other

In QCD, for large charge separation, field lines seem to be compressed to tubelike region

by nonperturbative self-interaction among infinitely many soft gluons forming the field.

Analogy: vortex lines in type II superconductor
Lattice QCD — in quenched approximation — confirms large-distance behaviour

\[ F(r) \approx \text{const} = \kappa \quad \iff \quad V(r) \approx \kappa r \]

Input from hadronic spectroscopy gives string tension
\[ \kappa \approx 1 \text{ GeV/fm} (= 160 \text{ kJ/m} = 16 \text{ ton/m}) \]

Consider LEP1 events:
\[ E_{cm} = m_Z \]
\[ \approx 90 \text{ GeV} \]

Should give stable oscillating system

but experimental reality is jet production

with transverse width \(\approx 0.4 \text{ GeV}\)
Extra: nonperturbative splittings \( g \to q\bar{q} \)

\[
\begin{align*}
\bar{q} & \quad + \quad \bar{q} \\
\text{can break string} & \\
\bar{r} & \quad \downarrow \quad \bar{r} \\
q & \quad \downarrow \quad q \\
\bar{r} & \quad \downarrow \quad \bar{r} \\
\bar{r} & \quad \downarrow \quad \bar{r} \\
\end{align*}
\]

simplified colour representation

\[ V(r) \]

quenched QCD

full QCD
Repeat for large system \( \Rightarrow \text{Lund model} \) which neglects Coulomb part:

\[
\left| \frac{dE}{dx} \right| = \left| \frac{dp}{dx} \right| = \left| \frac{dE}{dt} \right| = \left| \frac{dp}{dt} \right| = \kappa
\]

Motion of quarks and antiquarks:

\[
\bar{q} \quad q
\]

gives simplified picture of hadron production:

with Lorentz contraction for fast hadrons
Fragmentation properties and parameters:

String breaking modelled by tunneling:

\[ \mathcal{P} \propto \exp \left( -\frac{\pi m_1^2}{\kappa} \right) = \exp \left( -\frac{\pi p_1^2}{\kappa} \right) \exp \left( -\frac{\pi m_2^2}{\kappa} \right) \]

1) common Gaussian \( p_\perp \) spectrum
2) suppression of heavy quarks
\[ u\bar{u} : d\bar{d} : s\bar{s} : c\bar{c} \approx 1 : 1 : 0.3 : 10^{-11} \]

Hadron composition also depends on spin probabilities, hadronic wave functions, phase space, \( \ldots \Rightarrow \) moderate predictivity

Spacelike separation of breakups \( \Rightarrow \) arbitrary order, iterative ansatz from endpoints.
Left–right symmetry \( \Rightarrow \)
Lund symmetric fragmentation function

\[ \mathcal{P}(z) \propto \frac{1}{z} (1 - z)^a \exp \left( -\frac{bm_1^2}{z} \right) \]

where \( z = \frac{(E+p_z)_{\text{hadron}}}{(E+p_z)_{\text{remaining}}} \) or \( z = \frac{(E-p_z)_{\text{hadron}}}{(E-p_z)_{\text{remaining}}} \)
and \( a \approx 0.3, \ b \approx 0.6 \ \text{GeV}^{-2} \).
Scale by \((E\pm p_z)_{\text{remaining}} \Rightarrow \) flat rapidity plateau
The Lund gluon picture:

\[ g (\bar{r}b) \]

\[ \bar{q} (\bar{b}) \]

Gluon = kink on string, carrying \( (E, p) \)
Force ratio gluon/ quark = 2,
cf. QCD \( N_C/C_F = 9/4 \)

String effect (JADE) \( \approx \) coherence:

(JADE figure omitted for technical reasons)
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.

\[ \begin{array}{c}
\pi^- & \begin{array}{c} \text{If collapse:} \\
\begin{array}{c} \bar{c}d: D^-, D^{*-}, \ldots \\
cud: \Lambda^+_c, \Sigma^+_c, \Sigma^{*+}_c, \ldots \\
\Rightarrow \text{flavour asymmetries}
\end{array}
\end{array} \\
p^+ & \begin{array}{c} \text{Can give D “drag” to larger } x_F \text{ than } c \text{ quark.}
\end{array}
\end{array} \]

**PYTHIA** predicted qualitative behaviour.
Quantitative one sensitive to details
$\Rightarrow$ develop model & tune
Improved description of when collapse occurs (mass spectrum ⇐ constituent quark masses)

example: charm string in πp collision

and

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

\[
A(x_F) = \frac{\#D^- \#D^+}{\#D^- + \#D^+} \\
\text{in } \pi^- p
\]
But also normal string fragmentation:

\[ p_\pm = E \pm p_z \]
\[ p_{-D} = zp_{-c} \quad 0 < z < 1 \]

\[ \Rightarrow p_{+D} = \frac{m_{1D}^2}{p_{-D}} = \frac{m_{1D}^2}{zp_{-c}} \quad \text{normally} \quad \frac{m_{1c}^2}{zp_{-c}} = \frac{p_{+c}}{z} \]

i.e. again drag.

Technical components of modelling:

- Charm and bottom masses: c and b cross sections \((m_c = 1.5, m_b = 4.8)\)
- Light-quark masses: threshold for cluster mass spectrum, together with \(m_c\) \((m_u = m_d = 0.33, m_s = 0.5)\)
- Beam remnant distribution function: \((p - g = ud_0 + u\) in colour octet state) hadron asymmetries also without collapse (uneven sharing, but not extremely so)
- Primordial \(k_{\perp}\): collapse rate at large \(p_{\perp}\) (Gaussian width 1 GeV)
- Threshold behaviour for non-collapse: all at \(D\pi\) or gradually at \(D\pi, D^*\pi, D\rho, \ldots\)
- Collapse energy–momentum conservation: practical solution to mass \(\delta\) function (several models tried; not very sensitive)
HERA-B predictions

$B^0$ full
$\bar{B}^0$ dashed

$y$ dependence

$$A = \frac{B^0 - \bar{B}^0}{B^0 + \bar{B}^0}$$

$p_\perp$ dependence

$(vary \ beam \ remn \ dist)$
Multiple Interactions


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: $p_{\perp \text{min}}$

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

$$\leq \int_{0}^{s/4} \frac{d\sigma}{dp_{\perp}^2} \frac{p_{\perp}^4}{(p_{\perp 0}^2 + p_{\perp}^2)^2} dp_{\perp}^2$$

Measure of colour screening length $d$ in hadron $p_{\perp \text{min}} \langle d \rangle \approx 1 (\approx \bar{h})$
\[ \langle d \rangle \sim \frac{r_p}{\sqrt{N_{\text{partons}}}} \quad \text{no correlations} \]
\[ \sim \frac{r_p}{N_{\text{partons}}} \quad \text{with correlations?} \]

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

**Olden days:**

\[ xg(x, Q_0^2) \to \text{const. for } x \to 0 \]
\[ \Rightarrow N_{\text{partons}} \sim \ln \frac{s}{4p_{\text{min}}^2} \sim \text{const.} \]

**Post-HERA:**

\[ xg(x, Q_0^2) \sim x^{-\epsilon} \quad \text{for } x \to 0, \quad \epsilon \gtrsim 0.08 \]
\[ \Rightarrow N_{\text{partons}} \sim \left( \frac{s}{4p_{\text{min}}^2} \right)^{\epsilon} \]
\[ \Rightarrow p_{\text{min}} \sim \frac{1}{\langle d \rangle} \sim N_{\text{partons}} \sim s^{\epsilon} \]
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
QCD Interconnection


\[ \Gamma_W, \Gamma_Z, \Gamma_t \approx 2 \text{ GeV} \]
\[ \Gamma_h > 1.5 \text{ GeV for } m_h > 200 \text{ GeV} \]
\[ \Gamma_{\text{SUSY}} \sim \text{ GeV (often)} \]
Not too far from threshold:
\[ \tau = \frac{1}{\Gamma} \approx \frac{0.2 \text{ GeV fm}}{2 \text{ GeV}} = 0.1 \text{ fm} \ll r_{\text{had}} \approx 1 \text{ fm} \]
⇒ hadronic decay systems overlap, between pairs of resonances (WW, ZZ, t\bar{t}, \ldots)
⇒ cannot be considered separate systems!

Three main eras for interconnection:
1. Perturbative: suppressed for \( \omega > \Gamma \) by propagators/timescales ⇒ only soft gluons.
Above topics among unsolved problems of strong interactions: confinement dynamics, $1/N_C^2$ effects, QM interferences, ...,:

- opportunity to study dynamics of unstable particles,
- new ways to probe confinement dynamics in space and time, *but*
- risk to limit/spoil precision mass measurements.

So far mainly studied for $m_W$ at LEP2:

1. **Perturbative:** $\langle \delta m_W \rangle \lesssim 5$ MeV.
2. **Colour rearrangement:** many models, conservatively $\langle \delta m_W \rangle \lesssim 40$ MeV.

3. **Bose-Einstein:** symmetrization of unknown amplitude, wider spread among models, but again conservatively $\langle \delta m_W \rangle \lesssim 40$ MeV.

In sum: $\langle \delta m_W \rangle_{\text{tot}} < m_\pi$, $\langle \delta m_W \rangle_{\text{tot}}/m_W \lesssim 0.1\%$; a small number that becomes of interest only because we aim for high accuracy.
Connectometry – diagnosing interconnections:

Threshold: low-momentum particles depleted

\(e^\pm \rightarrow q\overline{q} \text{ with } p_T \ll 1 \text{ GeV}/c\)

\(~4\sigma (~2\sigma) \text{ signal/experiment if } 500 \text{ pb}^{-1} \text{ at } 172 \text{ (195) GeV. (Hint in DELPHI data?)}\)

**BE:**
- first promising indication
- from DELPHI (Moriond 99)
- but not agreement between LEP groups

**DELPHI (preliminary)**

\(\sigma^{+}\sigma^{-} \rightarrow W^{+}W^{-} \quad \pi^{+}\pi^{-} \text{ and } \pi^{0}\pi^{0}\)

- **DATA**
- Models with full BE
- Models with inside BE
Top near threshold:
\[e^+e^- \rightarrow t\bar{t} \rightarrow bW^+\bar{b}W^- \rightarrow b\bar{b}\ell^+\nu_{\ell'}\ell'\bar{\nu}_{\ell'}\].

**Hadronic multiplicity as function of \(\theta_{\bar{b}b}\):**

\[
\langle n_{\text{ch}} \rangle \quad \langle n_{\text{ch}}(|p| < 1 \text{ GeV}) \rangle
\]

**Curves:** various scenarios for QCD radiation from \(\widehat{tb}, \widehat{tb}\) and \(\widehat{bb}\) colour dipoles, realistically

\[I \propto \frac{\omega^2}{\Gamma_t^2 + \omega^2} (\widehat{tb} + \widehat{tb}) + \frac{\Gamma_t^2}{\Gamma_t^2 + \omega^2} \widehat{bb}\]

Unrealistic: \(\langle \delta m_t \rangle \approx 100 - 500 \text{ MeV}\).
Realistic: \(\langle \delta m_t \rangle \approx 30 \text{ MeV}\).

(W. Beenakker et al., hep-ph/9902304:) \(\langle \delta m_t \rangle \lesssim 100 \text{ MeV}\).

**Interconnection outlook for hadron colliders:**

- ‘trivial’ to extend from \(W^+W^-\) to any pair of resonances;
- more bookkeeping for ‘triplets’ like \(t\bar{t} \rightarrow b\bar{b}q_1\bar{q}_2q_3\bar{q}_4\);
- extension to \(p\bar{p}\) underlying event requires further thought.

Wild guess: \(\langle \delta m_t \rangle \sim 200 \text{ MeV}\).
\(\gamma^* p\) and \(\gamma^* \gamma^*\) Interactions


Objective: ‘complete’ framework for 
\(\gamma\gamma/\gamma^*\gamma/\gamma^*\gamma^*\) interactions at all \(Q^2_i\), especially transition region \(Q^2_{\pi} \sim m_p^2\)

First step: machinery for flux of virtual \(\gamma\)'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) \(\rho^0\)

\[
\begin{align*}
\gamma\gamma: & \quad 9 \quad \text{combinations} = (\text{dir} + \text{VMD} + \text{GVMD})^2 \\
\gamma^*\gamma^*: & \quad 4 \quad \text{combinations} = 2 \times (\text{VMD} + \text{GVMD}) \\
\text{Total:} & \quad 13 \quad \text{!!}
\end{align*}
\]

Have to include dampening factors to remove doublecounting (reasonably) consistently
PYTHIA Status

JETSET 7.4  
PYTHIA 5.7  
SPYTHIA  
\{ \begin{array}{c}
\text{4 March 1997: PYTHIA 6.1}
\end{array} \}

Currently PYTHIA 6.156 of 16 Nov. 2000  
\sim 53,000 \text{ lines Fortran 77}

Code, manuals, sample main programs:  
\textbf{www.thep.lu.se/\sim torbjorn/Pythia.html}

Short writeup (summary of news):  
TS, P. Edén, C. Friberg, L. Lönnblad, G. Miu,  

Long writeup in preparation (\sim 1 \text{ month})
On to C++

(L. Lönnblad, CPC 118 (1999) 213;
M. Bertini, L. Lönnblad & TS, LUTF 00-23 [hep-ph/0006152];
input to leif@thep.lu.se)

Why Fortran $\rightarrow$ C++?

- SLAC $\rightarrow$, FNAL $\rightarrow$, CERN $\rightarrow$ 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.
- June 2000: “proof of concept” version, with generic event generation machinery, some processes and string fragmentation.
- ??: more and better than current PYTHIA.

HERWIG++ progress:
PPARC funds 2 dedicated “postdocs”, 3-year work started a year ago.
Outlook

Generators in state of continuous development
• new physics processes
• more precise parton showers
• improved models soft physics
• and much more
⇒ always better, but never enough

Physics & bug warning:
Due to the large uncertainties present in any realistic QCD Monte Carlo, physics studies must be based on the use of at least two complete and independent programs.

LEP1 workshop

But what are the alternatives?:

**H \rightarrow ZZ^* \rightarrow 4 electrons**

CMS full GEANT simulation of

\(H(150 \text{ GeV}) \rightarrow ZZ^* \rightarrow 4e\)
Final Words of Warning

The Monte Carlo simulation has become the major means of visualization of not only detector performance but also of physics phenomena. So far so good. But it often happens that the physics simulations provided by the Monte Carlo generators carry the authority of data itself. They look like data and feel like data, and if one is not careful they are accepted as if they were data.

[...] I am prepared to believe that the computer-literate generation (of which I am a little too old to be a member) is in principle no less competent and in fact benefits relative to us in the older generation by having these marvelous tools. They do allow one to look at, indeed visualize, the problems in new ways. But I also fear a kind of “terminal illness”, perhaps traceable to the influence of television at an early age. There the way one learns is simply to passively stare into a screen and wait for the truth to be delivered. A number of physicists nowadays seem to do just this.

J.D. Bjorken

from a talk given at the 75th anniversary celebration of the Max-Planck Institute of Physics, Munich, Germany, December 10th, 1992. As quoted in: Beam Line, Winter 1992, Vol. 22, No. 4