LHC Physics
Event Generators

Torbjörn Sjöstrand
Department of Theoretical Physics
Lund University

Introduction
Generator Overview
Subprocess Survey
Matrix Elements vs. Parton Showers
Hadronization
Multiple Interactions
Generator Standards
How To Run PYTHIA
(Beam Remnant Physics)
(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

-2 ln(Q)

Observed
Expected background
Expected signal + background

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 Generator Position

“real life”

Machine, interactions \( \Rightarrow \) 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
  \[\Rightarrow\] can estimate feasibility
- simulate possible backgrounds
  \[\Rightarrow\] can devise analysis strategies
- study detector requirements
  \[\Rightarrow\] can optimize detector/trigger design
- study detector imperfections
  \[\Rightarrow\] 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, LDC: dipole showers (Lönnblad)
LEPTO: leptoproduction (Ingelman)
and many more: RAPGAP, SPHINX, . . .

HERWIG: general-purpose (Webber et al.)

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

Specialized: TAUOLA, HDECAY, DTUjet, NLLjet, . . .

Single- or multiprocess parton-level only:
ALPGEN, MadCUP, VECBOS, NJETS,
SUSYGEN, KORALZ, PANDORA, . . .

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

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

Structure of the basic generation process:

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

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, …

9) QCD interconnection effects:
   a) colour rearrangement (⇒ 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>
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<tbody>
<tr>
<td><strong>QCD &amp; related</strong></td>
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<td>Soft QCD</td>
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<td>Hard QCD</td>
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<td>Heavy flavour</td>
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<td><strong>Electroweak SM</strong></td>
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<td>Single $\gamma^*/Z^0/W^\pm$</td>
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<td>$(\gamma/\gamma^*/Z^0/W^\pm/f/g)^2$</td>
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<td>Light SM Higgs</td>
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<tr>
<td>Heavy SM Higgs</td>
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<td><strong>SUSY BSM</strong></td>
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<td>$h^0/H^0/A^0/H^\pm$</td>
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<td>SUSY</td>
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<td><strong>Other BSM</strong></td>
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<td>Technicolor</td>
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<td>New gauge bosons</td>
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<td>Compositeness</td>
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<td>Leptoquarks</td>
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<td>$H^{\pm\pm}$ (from LR-sym.)</td>
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<td>Extra dimensions</td>
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<td><strong>User-defined processes</strong></td>
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<td>Les Houches accord</td>
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* = yes, (⋆) = partial/in progress, — = no
Cross sections and kinematics

\[ \sigma = \sum_{i,j} \int \int \int d\mathbf{x}_1 d\mathbf{x}_2 d\tilde{t} f_i(x_1, Q^2) f_j(x_2, Q^2) \frac{d\tilde{\sigma}_{ij}}{d\tilde{t}} \]

\[ f_i(x, Q^2) \text{: parton distribution functions at characteristic scale } Q^2 \approx p_{\perp}^2 = \tilde{t}\tilde{u}/\tilde{s} \]

luminosity \[ \mathcal{L} \propto \frac{N_1 N_2 f}{A} \]

counting rate \[ \frac{dN_{\text{event}}}{dt} = \sigma \mathcal{L} \]

total rate \[ N_{\text{event}} = \sigma \int \mathcal{L}(t) \, dt \]
Higher Order Matrix Elements

$\mathcal{O}(1)$

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

$\mathcal{O}(\alpha_s)$

$\mathcal{O}(\alpha_s L^2)$

$L \sim -\ln y$

$y \sim \min \frac{m_{ij}^2}{E_{\text{cm}}^2}$

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

collinear and soft emission divergences $\Rightarrow$ large higher orders

$\mathcal{O}(\alpha_s^2)$

$\mathcal{O}(\alpha_s^2)$

$\mathcal{O}(\alpha_s^2)$
From ME’s to Parton Showers

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

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

rewrite for \( x_2 \rightarrow 1 \):

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

\[ x_1 \approx z \]

\[ x_3 \approx 1 - z \]

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

generalizes to

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

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

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

\[ P_{g\rightarrow q\bar{q}} = \frac{n_f}{2} (z^2 + (1 - z)^2) \]
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); compensated by subsequent branchings

Coherence ⇒ angular ordering

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

Soft/collinear cut-off \( m_0 = \min(m_{ij}) \approx 1 \text{ GeV} \) at hadronic mass scales
Parton Shower approach

\[ 2 \rightarrow n = (2 \rightarrow 2) \oplus \text{ISR} \oplus \text{FSR} \]

\[ 2 \rightarrow 2 = \text{hard scattering (on-shell)} \]

\[ \sigma = \iiint dx_1 \, dx_2 \, d\hat{t} \, f_i(x_1, Q^2) \, f_j(x_2, Q^2) \, \frac{d\tilde{\sigma}_{ij}}{d\hat{t}} \]

FSR = Final-State Radiation; timelike shower
\[ Q_i^2 = M^2 > 0 \text{ decreasing + coherence} \]

ISR = Initial-State Radiation; spacelike shower
\[ Q_i^2 = -M^2 > 0 \text{ increasing + } \sim \text{ coherence} \]

backwards evolution: start at hard scattering

Do not doublecount! \[ Q^2 > Q_1^2, Q_2^2, Q_3^2, Q_4^2 \]

\[ 2 \rightarrow 2 = \text{most virtual = shortest distance} \]
Parton Distribution Functions

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 \hspace{2cm} parton distributions

Resolution dependence by DGLAP:

\[ \frac{df_b(x, Q^2)}{d(\ln Q^2)} = \sum_a \int_x^1 \frac{dz}{z} f_a(x', Q^2) \frac{\alpha_s}{2\pi} P_{a \rightarrow bc} \left( z = \frac{x}{x'} \right) \]

Absolute normalization at small \( Q_0^2 \) unknown:

- first principles: lattice QCD
- reality: data from DIS, p\( \bar{p} \)
useful pdf plotting facility at
http://durpdg.dur.ac.uk/HEPDATA/
Initial-state showers

- Parton cascades are continually born, and are subsequently recombined.
- A hard scattering at scale $Q^2$ probes fluctuations up to that scale.
- The hard scattering inside a fluctuation inhibits full recombination of the cascade.
- Convenient reinterpretation:

\[ m^2 = 0 \quad \Rightarrow \quad m^2 = 0 \]
\[ m^2 < 0 \quad \Rightarrow \quad m^2 > 0 \]
\[ m^2 > 0 \quad \Rightarrow \quad m^2 = 0 \]

\[ Q^2 = -m^2 > 0 \quad \text{and increasing} \]

Monte Carlo approach: recast

\[ \frac{df_b}{dt} = \sum_a \int_x^1 \frac{dz}{z} f_a(x', Q^2) \frac{x}{2\pi} \frac{\alpha_s}{P_{a\to bc}(z)} \]

with $t = \ln\left(\frac{Q^2}{\Lambda^2}\right)$ and $z = x/x'$ to

\[ dP_b = \frac{df_b}{f_b} = |dt| \sum_a \int dz \frac{x'}{x} \frac{x' f_a(x', t)}{x' f_b(x, t)} \frac{\alpha_s}{2\pi} P_{a\to bc}(z) \]

then solve by backwards evolution, starting at high $Q^2$ and moving towards lower, with Sudakov form factor
Ladder representation combines whole event:

\[
\begin{align*}
Q_1^2 &> Q_2^2 > Q_{\text{max}}^2 > Q_3^2 > Q_4^2 > Q_5^2 \\
&\sim Q_0^2
\end{align*}
\]

DGLAP: \( Q_{\text{max}}^2 > Q_1^2 > Q_2^2 \sim Q_0^2 \)

BFKL/CCFM: go beyond \( Q^2 \) ordering;
important at small \( x \) and \( Q^2 \)

(Ideal) Monte Carlo order:
1) Hard scattering
2) Initial-state shower from center outwards
3) Final-state shower
Initial- vs. final-state showers

Both controlled by same evolution equations
\[
\frac{dP_{a \to bc}}{2\pi} \frac{dQ^2}{Q^2} P_{a \to bc}(z) \, dz \quad \text{(Sudakov)}
\]

but

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

\[ E_0, m_0^2 \quad E_2, m_2^2 \quad \text{decreasing } E \]
\[ E_1, m_1^2 \quad \text{decreasing } m^2 \quad \text{decreasing } \theta \]

daughters on equal footing, both \( m^2 \geq 0 \)
\( Q^2, z, \ldots \) choice gives several algorithms

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

\[ E_0, Q_0^2 \quad E_2, m_2^2 \quad \text{decreasing } E \]
\[ E_1, Q_1^2 \quad \text{increasing } Q^2 \quad \text{increasing } \theta \]

daughters unequal, one \( m^2 \geq 0 \), one \( m^2 < 0 \)

\[ \Rightarrow \text{kinematics & coherence more complicated} \]
\[ + \text{more messy hadronic environment} \]
gives many attempts: BFKL, CCFM, GLR, \ldots
ME vs. PS

ME : Matrix Elements
+ systematic expansion in $\alpha_s$ (‘exact’)
+ powerful for multiparton Born level
+ flexible phase space cuts
  – loop calculations very tough
  – negative cross section in collinear regions
    $\Rightarrow$ unpredictable jet/event structure
  – no easy match to hadronization

PS : Parton Showers
  – approximate, to LL (or NLL)
  – main topology not predetermined
    $\Rightarrow$ inefficient for exclusive states
+ process-generic $\Rightarrow$ simple multiparton
+ Sudakov form factors/resummation
  $\Rightarrow$ sensible jet/event structure
+ easy to match to hadronization

Marriage desirable! But how?

Problems:
  ● gaps in coverage?
  ● doublecounting of radiation?
  ● Sudakov?
  ● NLO consistency?
Merging

= smooth transition ME/PS, no sharp edge.
+ emissions can cover full phase space
– coherence not straightforward

Want to reproduce

\[ W^{ME} = \frac{1}{\sigma(LO)} \frac{d\sigma(LO + g)}{d(\text{phasespace})} \]

by shower generation + correction procedure

\[
\begin{align*}
\hat{W}^{ME} &= \frac{\hat{W}^{PS}}{\hat{W}^{ME}} \\
\end{align*}
\]

Comments:

● Do not normalize \( W^{ME} \) to \( \sigma(\text{NLO}) \), since extra work without clear gain (expect radiation also in events added by \( K \)-factor \( \geq 1 \))

● Exponentiate ME correction by shower Sudakov form factor:

\[
W^{PS}_{\text{actual}}(Q^2) = \exp \left( -\int_{Q^2}^{Q_{\text{max}}^2} W^{ME}(Q'^2) \, dQ'^2 \right)
\]

● Normally several shower histories

\[ \Rightarrow \] alternative approaches, largely equivalent
Final-state showers merging

Merging with $\gamma^*/Z^0 \to q\bar{q}g$ since long

... but problems with $\gamma^*/Z^0 \to b\bar{b}g$ noted:
$Q_{i}^2 = m_{i}^2$ gives wrong singularity structure,
$Q_{i}^2 = m_{i}^2 - m_{i,\text{onshell}}^2$ is relevant propagator!

\[
W^{\text{ME}} = \frac{ (...) }{ Q_{1}^2 Q_{2}^2 } - \frac{ (...) }{ Q_{1}^4 } - \frac{ (...) }{ Q_{2}^4 }
\]
(also weight from splitting kernels in PS)

Coloured decaying particle also radiates:

ME $\frac{1}{Q_{0}^2 Q_{1}^2}$ matches PS $b \to bg$

$\Rightarrow$ can merge PS with generic $a \to bcg$ ME
(E. Norrbin & TS, NPB603 (2001) 297)

Subsequent branchings $q \to qg$: also matched to ME, with reduced energy of system
$W^{\text{ME}}(x_1, x_2)$

g emission rate
for different
colour, spin and
parity structures

$R_{3}^{bl}(y_c)$

$E_{\text{cm}} = 91 \text{ GeV}$

$m_b = 4.8 \text{ GeV}$

ratio of 3-jets
in $b$ and $uds (=l)$
events

$R_{3}^{bl}(y_c)$

$E_{\text{cm}} = \frac{m_h}{H/A} = 120 \text{ GeV}$

$m_b = 4.8 \text{ GeV}$

reference light $q$
from $\gamma^*/Z^*$
Initial-state showers merging

\[
\frac{d\sigma}{dp_{\perp Z}}
\]

\[Z + 1 \text{ jet ‘exact’}\]

LO ‘exact’

NLO virtual

resummation: physical \(p_{\perp Z}\) spectrum

shower: ditto + accompanying jets (exclusive)

Merged with matrix elements for

\[q\bar{q} \rightarrow (\gamma^*/Z^0/W^\pm)g \text{ and } qg \rightarrow (\gamma^*/Z^0/W^\pm)q':\]

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

\[
\left(\frac{W^{ME}}{W^{PS}}\right)_{q\bar{q}' \rightarrow gW} = \frac{\hat{t}^2 + \hat{u}^2 + 2m_W^2\hat{s}}{\hat{s}^2 + m_W^4} \leq 1
\]

\[
\left(\frac{W^{ME}}{W^{PS}}\right)_{qg \rightarrow q'W} = \frac{\hat{s}^2 + \hat{u}^2 + 2m_W^2\hat{\bar{t}}}{(\hat{s} - m_W^2)^2 + m_W^4} < 3
\]
Problem: requires large primordial $k_\perp \approx 2$ GeV
⇒ need BFKL/CCFM non-ordered evolution?

Modified algorithm also affects other processes
- prefer $Q_{\text{max}}^2 = s$ where no doublecounting
  ⇒ more radiation at large $p_\perp$
- require $\tilde{u} = Q^2 - \tilde{s}(1 - z) < 0$ in branchings
  ⇒ fewer but harder emissions

Similarly for Higgs production in $m_t \to \infty$ limit:
- $gg \to gh^0$ and $qg \to qh^0$ simple
- $q\bar{q} \to gh^0$ nonsingular & small ⇒ add

Challenges:
- gauge boson pairs
- QCD $2 \to 2$ with ISR+FSR+interference
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

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

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 $g \rightarrow q\bar{q}$

can break string

simplified colour representation

$V(r)$

quenched QCD

full QCD
Repeat for large system ⇒ *Lund model* which neglects Coulomb part:

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

**Motion of quarks and antiquarks:**

\[\overline{q} \quad t \quad q\]

gives simplified picture of hadron production:

\[\overline{q} \quad t \quad q\]

with Lorentz contraction for fast hadrons
Fragmentation properties and parameters:

String breaking modelled by tunneling:

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

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

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

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:

Gluon = kink on string, carrying \((E, p)\)

Force ratio gluon/ quark = 2,

\(\text{cf. QCD } N_C/C_F = 9/4\)

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

\(\text{(JADE figure omitted since bitmap too large to print easily)}\)
HERWIG Cluster Model

![Diagram of HERWIG Cluster Model]

Fraction of Clusters

Cluster Mass/GeV
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: $p_{\perp \text{min}}$

$$\frac{1}{2} \sigma_{\text{jet}} = \int_{p_{\perp \text{min}}^2}^{s/4} \frac{d\sigma}{dp_{\perp}^2} dp_{\perp}^2 \leq \int_0^{s/4} \frac{d\sigma}{dp_{\perp}^2} \frac{p_{\perp}^4}{(p_{\perp 0}^2 + p_{\perp}^2)^2} dp_{\perp}^2$$

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

\[ \sim \frac{r_p}{N_{\text{partons}}} \quad \text{with correlations?} \]

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

Olden days:

\[ xg(x, Q_0^2) \rightarrow \text{const. for } x \rightarrow 0 \]

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

Post-HERA:

\[ xg(x, Q_0^2) \sim x^{-\epsilon} \text{ for } x \rightarrow 0, \quad \epsilon \gtrsim 0.08 \]

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

\[ \Rightarrow p_{\perp \text{min}} \sim \frac{1}{\langle d \rangle} \sim N_{\text{partons}} \sim s^{\epsilon} \]
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
PDG Particle Codes

first published 1988; regular updates

A. Fundamental objects

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<td>1</td>
<td>d</td>
<td>11</td>
<td>e⁻</td>
<td>21</td>
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<tr>
<td>2</td>
<td>u</td>
<td>12</td>
<td>νₑ</td>
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</tr>
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<td>3</td>
<td>s</td>
<td>13</td>
<td>μ⁻</td>
<td>23</td>
</tr>
<tr>
<td>4</td>
<td>c</td>
<td>14</td>
<td>νₑ</td>
<td>24</td>
</tr>
<tr>
<td>5</td>
<td>b</td>
<td>15</td>
<td>τ⁻</td>
<td>25</td>
</tr>
<tr>
<td>6</td>
<td>t</td>
<td>16</td>
<td>νₜ</td>
<td>26</td>
</tr>
</tbody>
</table>

add – sign for antiparticle, where appropriate

B. Mesons

100 |q₁| + 10 |q₂| + (2s + 1) with |q₁| ≥ |q₂|

particle if heaviest quark u, s, c, b; else anti-

<p>| | | | | |</p>
<table>
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<tr>
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</thead>
<tbody>
<tr>
<td>211</td>
<td>π⁺</td>
<td>413</td>
<td>D*⁺</td>
<td>111</td>
</tr>
<tr>
<td>311</td>
<td>K⁰</td>
<td>423</td>
<td>D⁺</td>
<td>221</td>
</tr>
<tr>
<td>321</td>
<td>K⁺</td>
<td>433</td>
<td>D⁺</td>
<td>331</td>
</tr>
</tbody>
</table>

C. Baryons

1000 q₁ + 100 q₂ + 10 q₃ + (2s + 1)

with q₁ ≥ q₂ ≥ q₃, or Λ-like q₁ ≥ q₃ ≥ q₂

<p>| | | | | |</p>
<table>
<thead>
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</tr>
</thead>
<tbody>
<tr>
<td>2112</td>
<td>n</td>
<td>3122</td>
<td>Λ⁰</td>
<td>3214</td>
</tr>
<tr>
<td>2212</td>
<td>p</td>
<td>3212</td>
<td>Σ⁰</td>
<td>3334</td>
</tr>
</tbody>
</table>

+ diquarks, SUSY, technicolor, . . .
HEPEVT Event Record

PARAMETER (NMXHEP=4000)
COMMON/HEPEVT/NEVHEP,NHEP,
&ISTHEP(NMXHEP),IDHEP(NMXHEP),
&JMOHEP(2,NMXHEP),JDAHEP(2,NMXHEP),
&PHEP(5,NMXHEP),VHEP(4,NMXHEP)
DOUBLE PRECISION PHEP, VHEP

NMXHEP = maximum number of entries
NEVHEP = event number
NHEP = number of entries in current event
ISTHEP = status code of entry
  0 = null entry
  1 = existing entry
  2 = fragmented/decayed entry
  3 = documentation entry
  + some internal
IDHEP = PDG particle identity
  + some internal, e.g. 92 = string
JMOHEP = mother position(s)
JDAHEP = first and last daughter position
PHEP = momentum \((p_x, p_y, p_z, E, m)\) in GeV
VHEP = production vertex \((x, y, z, t)\) in mm
User-Defined Processes

Les Houches accord May 2001 ⇒
E Boos et al., hep-ph/0109068

CompHEP !?
Grace
MadGraph
AlpGen !!
MadCup !!
...

{ HERWIG !!
ISAJET ??
PYTHIA !!

Two steps in run:

1) at initialization, e.g. from inside PYINIT,
CALL UPINIT
to define character of run in
COMMON/HEPRUP/

2) for each new event, e.g. from inside PYEVNT,
CALL UPEVNT
to define next event, with weight etc., in
COMMON/HEPEUP/
Initialization

```fortran
INTEGER MAXPUP
PARAMETER (MAXPUP=100)
INTEGER IDBMUP,PDFGUP,PDFSUP,IDWTUP,NPRUP,
&LPRUP
DOUBLE PRECISION EBMUP,XSECUP,XERRUP,XMAXUP
COMMON/HEPRUP/IDBMUP(2),EBMUP(2),PDFGUP(2),
&PDFSUP(2),IDWTUP,NPRUP,XSECUP(MAXPUP),
&XERRUP(MAXPUP),XMAXUP(MAXPUP),LPRUP(MAXPUP)
```

- **IDBMUP**: incoming beam particles
- **EBMUP**: incoming beam energies
- **PDFGUP**, **PDFSUP**: parton distributions (PDFLIB)
- **IDWTUP**: weighting strategy
  - = 1: PYTHIA mixes and unweights events, according to known $d\sigma_{\text{max}}$
  - = 2: PYTHIA mixes and unweights events, according to known $\sigma_{\text{tot}}$
  - = 3: unit-weight events, given by user
  - = 4: weighted events, given by user
  - = -1, -2, -3, -4: also allow negative $d\sigma$
- **NPRUP**: number of separate user processes
- **XSECUP(i)**: $\sigma_{\text{tot}}$ for each user process
- **XERRUP(i)**: error on $\sigma_{\text{tot}}$ for each u.p.
- **XMAXUP(i)**: $d\sigma_{\text{max}}$ for each u.p.
- **LPRUP(i)**: integer identifier for each u.p.
The event

INTEGER MAXNUP
PARAMETER (MAXNUP=500)
INTEGER NUP,IDPRUP,IDUP,ISTUP,MOTHUP,ICOLUP
DOUBLE PRECISION XWGTUP,SCALUP,AQEDUP,
 &AQCDUP,PUP,VTIMUP,SPINUP
COMMON/HEPEUP/NUP,IDPRUP,XWGTUP,SCALUP,
 &AQEDUP,AQCDUP,IDUP(MAXNUP),ISTUP(MAXNUP),
 &MOTHUP(2,MAXNUP),ICOLUP(2,MAXNUP),
 &PUP(5,MAXNUP),VTIMUP(MAXNUP),SPINUP(MAXNUP)

IDPRUP: identity of current process
XWGTUP: event weight
SCALUP: scale $Q$ of parton distributions etc.
AQEDUP: $\alpha_{em}$ used in event
AQCDUP: $\alpha_s$ used in event
NUP: number of particles in event
IDUP(i): PDG identity code for particle $i$
ISTUP(i): status code (incoming, final-state,
intermediate resonances with preserved $m$)
MOTHUP(j,i): position of one or two mothers
ICOLUP(j,i): colour and anticolour indices
PUP(j,i): $(p_x, p_y, p_z, E, m)$
VTIMUP(i): invariant lifetime $c\tau$
SPINUP(i): spin (helicity) information
Example 1: hadronic $t\bar{t}$ production

Example 2: baryon number violation
PYTHIA Status

JETSET 7.4
PYTHIA 5.7
SPYTHIA

} 4 March 1997 : PYTHIA 6.1

Currently PYTHIA 6.210
of 25 September 2002
~ 58, 900 lines Fortran 77

Code, manual, sample main programs, more:

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]

long writeup in T. Sjöstrand,
L. Lönnblad, S. Mrenna and P. Skands,
LU TP 01-21 [hep-ph/0108264],
second edition April 2002
with 430 new or revised pages!
User program structure

1) Initialization step
- select process(es) to study
- modify physics parameters: \( m_t, m_h, \ldots \)
- set kinematics constraints
- modify generator performance
- initialize generator
- book histograms

2) Generation loop
- generate one event at a time
- analyze it (or store for later use)
- add results to histograms
- print a few events

3) Finishing step
- print deduced cross-sections
- print/save histograms etc.

HERWIG, ISAJET: generator contains main program, user writes subroutines
PYTHIA: generator is subroutine package, user writes main program
Higgs production with PYTHIA

C...Arithmetic in double precision; integer functions; PYDATA.
IMPLICIT DOUBLE PRECISION(A-H, O-Z)
INTEGER PYK,PYCHGE,PYCOMP
EXTERNAL PYDATA
C...The event record and other common blocks.
COMMON/PYJETS/N,NPAD,K(4000,5),P(4000,5),V(4000,5)
COMMON/PYDAT2/KCHG(500,4),PMAS(500,4),PARF(2000),VCKM(4,4)
COMMON/PYSUBS/MSEL,MSELPD,MSUB(500),KFIN(2,-40:40),CKIN(200)
COMMON/PYPARS/MSTP(200),PARP(200),MSTI(200),PARI(200)
C...Physics scenario.
MSEL=0 ! Mix subprocesses freely
MSUB(102)=1 ! g + g -> h0
MSUB(123)=1 ! f + f' -> f + f' + h0
MSUB(124)=1 ! f + f' -> f" + f"' + h0
PMAS(25,1)=300D0 ! Nominal Higgs mass.
C...Run parameters.
NEV=1000 ! Number of events
ECM=14000D0 ! CM energy of run
CKIN(1)=200D0 ! Minimum Higgs mass.
CKIN(2)=400D0 ! Maximum Higgs mass.
C...Switch off unnecessary aspects (for faster simulation).
MSTP(61)=0 ! No initial-state showers
MSTP(71)=0 ! No final-state showers
MSTP(81)=0 ! No multiple interactions
MSTP(111)=0 ! No hadronization
C...Initialize and book histogram(s).
CALL PYINIT(’CMS’,’p’,’p’,ECM)
CALL PYBOOK(1,’Higgs mass distribution’,80,200D0,400D0)
C...Generate events and look at first few.
DO 200 IEV=1,NEV
   CALL PYEVNT
   IF(IEV.LE.1) CALL PYLIST(1)
C...Find Higgs and fill its mass. End event loop.
   DO 150 I=7,9
      IF(K(I,2).EQ.25) CALL PYFILL(1,P(I,5),1D0)
   150 CONTINUE
   200 CONTINUE
C...Final output.
   CALL PYSTAT(1) ! Print cross section table
   CALL PYHIST ! Print histogram(s)
END
Outlook

Generators in state of continuous development
- new physics processes
- more precise parton showers
- improved models soft physics
- moving to C++
⇒ 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?:

\[ H \rightarrow ZZ^* \rightarrow 4 \text{ electrons} \]

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