Event Generators for LHC

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1. (yesterday) Introduction and Overview;
   Parton Showers; Matching Issues

2. (today) Multiple Interactions;
   Hadronization; Generator News & Conclusions
Multiple Interactions
What is minimum bias?

≈ “all events, with no bias from restricted trigger conditions”

\[ \sigma_{\text{tot}} = \sigma_{\text{elastic}} + \sigma_{\text{single-diffractive}} + \sigma_{\text{double-diffractive}} + \ldots + \sigma_{\text{non-diffractive}} \]

reality: \( \sigma_{\text{min-bias}} \approx \sigma_{\text{non-diffractive}} + \sigma_{\text{double-diffractive}} \approx 2/3 \times \sigma_{\text{tot}} \)

What is underlying event?

jet

underlying event

pedestal height
What is multiple interactions?

Cross section for $2 \rightarrow 2$ interactions is dominated by $t$-channel gluon exchange, so diverges like $\frac{d\sigma}{dp_\perp^2} \approx \frac{1}{p_\perp^4}$ for $p_\perp \rightarrow 0$.

integrate QCD $2 \rightarrow 2$

$qq' \rightarrow qq'$
$q\bar{q} \rightarrow q'\bar{q}'$
$q\bar{q} \rightarrow gg$
$qg \rightarrow qg$
$gg \rightarrow gg$
$gg \rightarrow q\bar{q}$

with CTEQ 5L PDF's

Integrated cross section above $p_{T\text{min}}$ for pp at 14 TeV

jet cross section

total cross section
\[
\sigma_{\text{int}}(p_{\perp \text{min}}) = \int \int \int_{p_{\perp \text{min}}} \, dx_1 \, dx_2 \, dp_{\perp}^2 \, f_1(x_1, p_{\perp}^2) \, f_2(x_2, p_{\perp}^2) \frac{d\sigma}{dp_{\perp}^2}
\]

Half a solution to \( \sigma_{\text{int}}(p_{\perp \text{min}}) > \sigma_{\text{tot}} \): many interactions per event

\[
\sigma_{\text{tot}} = \sum_{n=0}^{\infty} \sigma_n
\]

\[
\sigma_{\text{int}} = \sum_{n=0}^{\infty} n \sigma_n
\]

\[
P_n \quad \sigma_{\text{int}} > \sigma_{\text{tot}} \iff \langle n \rangle > 1
\]

\[
\langle n \rangle = 2
\]

If interactions occur independently then Poissonian statistics

\[
P_n = \frac{\langle n \rangle^n}{n!} \, e^{-\langle n \rangle}
\]

but energy–momentum conservation ⇒ large \( n \) suppressed
Other half of solution:
perturbative QCD not valid at small $p_\perp$ since $q, g$ not asymptotic states (confinement!).

Naively breakdown at

$$p_{\perp \text{min}} \approx \frac{\hbar}{r_p} \approx \frac{0.2 \text{ GeV} \cdot \text{fm}}{0.7 \text{ fm}} \approx 0.3 \text{ GeV} \approx \Lambda_{\text{QCD}}$$

...but better replace $r_p$ by (unknown) colour screening length $d$ in hadron

\[ \lambda \sim \frac{1}{p_\perp} \]
so modify

\[
\frac{d\hat{\sigma}}{dp_{\perp}^2} \propto \frac{\alpha_s^2(p_{\perp}^2)}{p_{\perp}^4} \rightarrow \frac{\alpha_s^2(p_{\perp}^2)}{p_{\perp}^4} \theta(p_{\perp} - p_{\perp\text{min}}) \quad \text{(simpler)}
\]

or

\[
\rightarrow \frac{\alpha_s^2(p_{\perp 0}^2 + p_{\perp}^2)}{(p_{\perp 0}^2 + p_{\perp}^2)^2} \quad \text{(more physical)}
\]

where \( p_{\perp\text{min}} \) or \( p_{\perp 0} \) are free parameters, empirically of order 2 GeV

Typically 2 – 3 interactions/event at the Tevatron, 4 – 5 at the LHC, but may be more in “interesting” high-\( p_{\perp} \) ones.
Modelling multiple interactions

T. Sjöstrand, M. van Zijl, PRD36 (1987) 2019: first models for event properties based on perturbative multiple interactions

(1) Simple scenario:
no longer used (no impact-parameter dependence)

(2) More sophisticated scenario:
still in frequent use (Tune A, Tune DWT, ATLAS tune, ...)

- Is only a model for nondiffractive events, i.e. for $\sigma_{\text{nd}} \simeq (2/3)\sigma_{\text{tot}}$
- Smooth turn-off at $p_{\perp 0}$ scale
- Require $\geq 1$ interaction in an event
- Interactions generated in ordered sequence $p_{\perp 1} > p_{\perp 2} > p_{\perp 3} > \ldots$
  by “Sudakov” trick (what happens “first”?)

$$\frac{d\mathcal{P}}{dp_{\perp i}} = \frac{1}{\sigma_{\text{nd}}} \frac{d\sigma}{dp_{\perp}} \exp \left[ - \int_{p_{\perp}}^{p_{\perp(i-1)}} \frac{1}{\sigma_{\text{nd}}} \frac{d\sigma}{dp_{\perp}'} dp_{\perp}' \right]$$

- After each interaction rescaled new PDF’s for momentum conservation
- Leads to $n_{\text{int}}$ narrower than Poissonian, except that ...
Hadrons are extended, e.g. double Gaussian (“hot spots”):

\[ \rho_{\text{matter}}(r) = N_1 \exp \left( -\frac{r^2}{r_1^2} \right) + N_2 \exp \left( -\frac{r^2}{r_2^2} \right) \]

where \( r_2 \neq r_1 \) represents “hot spots”

- Events are distributed in impact parameter \( b \)
- Overlap of hadrons during collision

\[ \mathcal{O}(b) = \int d^3x \, dt \, \rho_{\text{boosted}}^{1,\text{matter}}(x, t) \rho_{\text{boosted}}^{2,\text{matter}}(x, t) \]

- Average activity at \( b \) proportional to \( \mathcal{O}(b) \)
  \( \Rightarrow \) central collisions normally more active
  \( \Rightarrow \) \( \mathcal{P}_n \) broader than Poissonian

- Time-consuming \((b, p_\perp)\) generation
- Problems if many valence quarks kicked out
  \( \Rightarrow \) Simplify after first interaction:
  only \( gg \) or \( q\bar{q} \) outgoing, no showers, …
(3) HERWIG
Soft Underlying Event (SUE), based on UA5 Monte Carlo

- Distribute a (~ negative binomial) number of clusters independently in rapidity and transverse momentum according to parametrization/extrapolation of data
- modify for overall energy/momentum/flavour conservation
- no minijets; correlations only by cluster decays

(4) Jimmy (HERWIG add-on)
- similar to PYTHIA (2) above; but details different
- matter profile by electromagnetic form factor
- no $p_\perp$-ordering of emissions, no rescaling of PDF: abrupt stop when (if) run out of energy

(5) Phojet/DTUjet
- comes from “historical” tradition of soft physics of “cut Pomerons” $\approx p_\perp \rightarrow 0$ limit of multiple interactions
- extended also to “hard” interactions similarly to PYTHIA

(6) SHERPA: based on PYTHIA (2), with CKKW added
FIG. 3. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs simple models: dashed low $p_T$ only, full including hard scatterings, dash-dotted also including initial- and final-state radiation.

FIG. 4. Forward-backward multiplicity correlation at 540 GeV, UA5 results (Ref. 33) vs simple models; the latter models with notation as in Fig. 3.
FIG. 5. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs impact-parameter-independent multiple-interaction model: dashed line, $p_{T_{\min}} = 2.0$ GeV; solid line, $p_{T_{\min}} = 1.6$ GeV; dashed-dotted line, $p_{T_{\min}} = 1.2$ GeV.

FIG. 6. Forward-backward multiplicity correlation at 540 GeV, UA5 results (Ref. 33) vs impact-parameter-independent multiple-interaction model; the latter with notation as in Fig. 5.
Direct observation of multiple interactions


Order 4 jets $p_{\perp 1} > p_{\perp 2} > p_{\perp 3} > p_{\perp 4}$ and define $\varphi$ as angle between $p_{\perp 1} \mp p_{\perp 2}$ and $p_{\perp 3} \mp p_{\perp 4}$ for AFS/CDF

Double Parton Scattering

Double BremsStrahlung

AFS 4-jet analysis (pp at 63 GeV): observe 6 times Poissonian prediction, with impact parameter expect 3.7 times Poissonian, but big errors $\Rightarrow$ low acceptance, also UA2
CDF 16 GeV $\gamma/\pi^0 + 3$ Jets
1-Vertex Events

- Data
- Yellow region = double parton scattering (DPS)
- The rest = PYTHIA showers

CDF 3-jet + prompt photon analysis

Yellow region =
double parton
scattering (DPS)

The rest =
PYTHIA showers

\[
\sigma_{\text{DPS}} = \frac{\sigma_A \sigma_B}{\sigma_{\text{eff}}} \quad \text{for} \ A \neq B \quad \implies \sigma_{\text{eff}} = 14.5 \pm 1.7^{+1.7}_{-2.3} \text{ mb}
\]

Strong enhancement relative to naive expectations!
Jet pedestal effect

Events with hard scale (jet, W/Z, . . .) have more underlying activity!
Events with \( n \) interactions have \( n \) chances that one of them is hard, so “trigger bias”: hard scale \( \Rightarrow \) central collision
\( \Rightarrow \) more interactions \( \Rightarrow \) larger underlying activity.
Centrality effect saturates at \( p_\perp^{\text{hard}} \sim 10 \) GeV.

Studied in detail by Rick Field, comparing with CDF data:
“MAX/MIN Transverse” Densities

- Define the **MAX and MIN “transverse” regions** on an event-by-event basis with MAX (MIN) having the largest (smallest) density.
Plot shows the “Transverse” charged particle density versus $P_T$ (charged jet#1) compared to the QCD hard scattering predictions of two tuned versions of Pythia 6.206 (CTEQ5L, Set B (PARP(67)=1) and Set A (PARP(67)=4)).
Compares the average “transverse” charge particle density (|\(\eta|<1, P_T>0.5 \text{ GeV}\)) versus \(P_T(\text{charged jet#1})\) and the \(P_T\) distribution of the “transverse” density, \(dN_{\text{chg}}/d\eta d\phi dP_T\) with the QCD Monte-Carlo predictions of two tuned versions of PYTHIA 6.206 (\(P_T(\text{hard}) > 0\), CTEQ5L, Set B (PARP(67)=1) and Set A (PARP(67)=4)).
Leading Jet: “MAX & MIN Transverse” Densities

**PYTHIA Tune A**

**HERWIG**

Charged particle density and PTsum density for “leading jet” events versus $E_T(jet#1)$ for PYTHIA Tune A and HERWIG.
Shows the $\Delta \phi$ dependence of the “associated” charged particle density, $dN_{\text{chg}}/d\eta d\phi$, $p_T > 0.5$ GeV/c, $|\eta| < 1$, $\text{PTmaxT} > 2.0$ GeV/c (not including $\text{PTmaxT}$) relative to $\text{PTmaxT}$ (rotated to 180°) and the charged particle density, $dN_{\text{chg}}/d\eta d\phi$, $p_T > 0.5$ GeV/c, $|\eta| < 1$, relative to jet#1 (rotated to 270°) for “back-to-back events” with $30 < E_T(\text{jet#1}) < 70$ GeV.
For PTmaxT > 2.0 GeV both PYTHIA and HERWIG produce slightly too many “associated” particles in the direction of PTmaxT!

But HERWIG (without multiple parton interactions) produces too few particles in the direction opposite of PTmaxT!
Colour correlations

\( \langle p_\perp \rangle (n_{\text{ch}}) \) is very sensitive to colour flow

long strings to remnants \( \Rightarrow \) much 
\( n_{\text{ch}}/\text{interaction} \Rightarrow \langle p_\perp \rangle (n_{\text{ch}}) \sim \text{flat} \)

short strings (more central) \( \Rightarrow \) less 
\( n_{\text{ch}}/\text{interaction} \Rightarrow \langle p_\perp \rangle (n_{\text{ch}}) \) rising

FIG. 27. Average transverse momentum of charged particles in \( |\eta| < 2.5 \) as a function of the multiplicity. UA1 data points (Ref. 49) at 900 GeV compared with the model for different assumptions about the nature of the subsequent (nonhardest) interactions. Dashed line, assuming \( q\bar{q} \) scatterings only; dotted line, \( gg \) scatterings with “maximal” string length; solid line \( gg \) scatterings with “minimal” string length.
Look at the \( <p_T> \) of particles in the "transverse" region \( (p_T > 0.5 \text{ GeV/c}, |\eta| < 1) \) versus the number of particles in the "transverse" region: \( <p_T> \) vs \( \text{N}_{\text{chg}} \).

Shows \( <p_T> \) versus \( \text{N}_{\text{chg}} \) in the "transverse" region \( (p_T > 0.5 \text{ GeV/c}, |\eta| < 1) \) for "Leading Jet" and "Back-to-Back" events with \( 30 < \text{E}_T(\text{jet}\#1) < 70 \text{ GeV} \) compared with "min-bias" collisions.
Initiators and Remnants

Need to assign:
- correlated flavours
- correlated \( x_i = p_{zi}/p_{z\text{tot}} \)
- correlated primordial \( k_{\perp i} \)
- correlated colours
- correlated showers

**PDF after preceding MI/ISR activity:**

0) Squeeze range \( 0 < x < 1 \) into \( 0 < x < 1 - \sum x_i \) (ISR: \( i \neq i_{\text{current}} \))

1) Valence quarks: scale down by number already kicked out

2) Introduce companion quark \( q/\bar{q} \) to each kicked-out sea quark \( \bar{q}/q \), with \( x \) based on assumed \( g \rightarrow q\bar{q} \) splitting

3) Gluon and other sea: rescale for total momentum conservation
Interleaved Multiple Interactions

$p_{\perp}$

$p_{\perp \text{max}}$

$p_{\perp 1}$

$p'_{\perp 1}$

ISR

$p_{\perp 2}$

ISR

$p_{\perp 3}$

$p_{\perp 23}$

$p_{\perp 4}$

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

interaction number

1 2 3 4

hard int.
mult. int.
mult. int.
mult int.
Multiple Interactions: A New Evolution Equation

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<th>time</th>
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<td>backwards</td>
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<td>conditional</td>
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<tr>
<td>MI</td>
<td>simultaneous</td>
<td>$p_\perp \to 0$</td>
<td>conditional</td>
</tr>
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ISR + MI: PDF competition $\Rightarrow$ interleaving (PYTHIA 6.3)
FSR: previously at end, now also interleaved (PYTHIA 8.1):

$$\frac{d\mathcal{P}}{dp_\perp} = \left( \frac{d\mathcal{P}_{\text{MI}}}{dp_\perp} + \sum \frac{d\mathcal{P}_{\text{ISR}}}{dp_\perp} + \sum \frac{d\mathcal{P}_{\text{FSR}}}{dp_\perp} \right)$$

$$\times \exp \left( -\int_{p_\perp}^{p_{\perp,i-1}} \left( \frac{d\mathcal{P}_{\text{MI}}}{dp_\perp'} + \sum \frac{d\mathcal{P}_{\text{ISR}}}{dp_\perp'} + \sum \frac{d\mathcal{P}_{\text{FSR}}}{dp_\perp'} \right) dp_\perp' \right)$$

“resolution evolution”
Monte Carlo: winner takes all
+ many other assumptions/models
Extrapolation to LHC

Energy dependence of $p_{\perp \text{min}}$ and $p_{\perp 0}$:

Larger collision energy
⇒ probe parton ($\approx$ gluon) density at smaller $x$
⇒ smaller colour screening length $d$
⇒ larger $p_{\perp \text{min}}$ or $p_{\perp 0}$

Post-HERA PDF fits steeper at small $x$
⇒ stronger energy dependence

Current PYTHIA 8 default, tied to CTEQ 5L, is

$$p_{\perp 0}(s) = 2.15 \text{ GeV} \left( \frac{s}{(1.8 \text{ TeV})^2} \right)^{0.08}$$
LHC predictions: pp collisions at $\sqrt{s} = 14$ TeV

PYTHIA6.214 - tuned
PYTHIA6.214 - default
PHOJET1.12

$\frac{dN_{\text{chg}}}{d\eta}$ at $\eta = 0$

PYTHIA models favour $\ln^2(s)$;
PHOJET suggests a $\ln(s)$ dependence.

CDF data

Central Region
(min-bias $\frac{dN_{\text{chg}}}{d\eta} \sim 7$)

LHC

Tevatron

$\frac{dN_{\text{chg}}}{d\eta} \sim 30$
$\frac{dN_{\text{chg}}}{d\eta} \sim 15$

A. M. Moraes

Minimum-bias and the Underlying Event at the LHC

5th November 2004
LHC predictions: JIMMY4.1 Tunings A and B vs. PYTHIA6.214 – ATLAS Tuning (DC2)

![Graph showing LHC predictions with CDF data and various tuning comparisons.](image)

- **JIMMY4.1 - Tuning A**
- **JIMMY4.1 - Tuning B**
- **PYTHIA6.214 - ATLAS Tuning**
- **CDF data**

**Axes:**
- **Transverse \(< N_{\text{chge}} >**
- **\(P_t\) (leading jet in GeV)**

**Legend:**
- **Tevatron**
- **LHC**

**Scale Multipliers:**
- **x 3**
- **x 4**
- **x 5**
UE tunings: Pythia vs. Jimmy

PTJIM = 4.9
\[ = 2.8 \times \left( \frac{14}{1.8} \right)^{0.27} \]

- energy dependent PTJIM generates UE predictions similar to the ones generated by PYTHIA6.2 – ATLAS.

\[
\langle N_{\text{dij}} \rangle \text{ - transverse region}
\]

\[
P_{T, \text{leading jet}} \text{ (GeV)}
\]
Multiple Interactions Outlook

Issues requiring further thought and study:

- Multi-parton PDF’s \( f_{a_1a_2a_3}\ldots(x_1, Q^2_1, x_2, Q^2_2, x_3, Q^2_3, \ldots) \)
- Close-packing in initial state, especially small \( x \)
- Impact-parameter picture and \((x, b)\) correlations  
  e.g. large-\( x \) partons more central!, valence quarks more central?
- Details of colour-screening mechanism
- Rescattering: one parton scattering several times
- Intertwining: one parton splits in two that scatter separately
- Colour sharing: two FS–IS dipoles become one FS–FS one
- Colour reconnection: required for \( \langle p_\perp \rangle (n_{\text{charged}}) \)
- Collective effects (e.g. QGP, cf. Hadronization above)
- Relation to diffraction: eikonalization, multi-gap topologies, …

Action items:

- Vigorous experimental program at LHC
- Study energy dependence: RHIC (pp) → Tevatron → LHC
- Develop new frameworks and refine existing ones

Much work ahead!
Hadronization/Fragmentation models

Perturbative → nonperturbative → not calculable from first principles!

Model building = ideology + “cookbook”

Common approaches:

1) **String** Fragmentation  
   (most ideological)

2) **Cluster** Fragmentation  
   (simplest?)

3) **Independent** Fragmentation  
   (most cookbook)

4) Local Parton–Hadron Duality  
   (limited applicability)

Best studied in  
\( e^+e^- \rightarrow \gamma^*/Z^0 \rightarrow q\bar{q} \)
The Lund String Model

In QED, field lines go all the way to infinity

since photons cannot interact with each other.

Potential is simply additive:

\[ V(x) \propto \sum_i \frac{1}{|x - x_i|} \]
In QCD, for large charge separation, field lines seem to be compressed to tubelike region(s) ⇒ string(s)

by self-interactions among soft gluons in the “vacuum”.
(Non-trivial ground state with quark and gluon “condensates”.
Analogy: vortex lines in type II superconductor)

Gives linear confinement with string tension:
\[ F(r) \approx \text{const} = \kappa \approx 1 \text{ GeV/fm} \quad \iff \quad V(r) \approx \kappa r \]

Separation of transverse and longitudinal degrees of freedom
⇒ simple description as 1+1-dimensional object – string – with Lorentz invariant formalism
Linear confinement confirmed e.g. by quenched lattice QCD

\[ V(R) = V_0 + K R - \frac{a}{R} + \frac{f}{R^2} \]

\[ V(r) \approx -\frac{4 \alpha_s}{3} \frac{\kappa r}{r} + \frac{0.13}{r} + r \]

(for \( \alpha_s \approx 0.5 \), r in fm and V in GeV)

\( V(0.4 \text{ fm}) \approx 0 \): Coulomb important for internal structure of hadrons, not for particle production (?)
Real world (??, or at least unquenched lattice QCD) \( \Longrightarrow \) nonperturbative string breakings \( gg \ldots \rightarrow q\bar{q} \)

\[ V(r) \]

\( r \)

quenched QCD

full QCD

Coulomb part

simplified colour representation:
Repeat for large system ⇒ *Lund model* which neglects Coulomb part:

\[
\left| \frac{dE}{dz} \right| = \left| \frac{dp_z}{dz} \right| = \left| \frac{dE}{dt} \right| = \left| \frac{dp_z}{dt} \right| = \kappa
\]

Motion of quarks and antiquarks in a q\(\bar{q}\) system:

\[
\text{gives simple but powerful picture of hadron production (with extensions to massive quarks, baryons, \ldots)}
\]
How does the string break?

$m_{\perp q'} = 0$

String breaking modelled by tunneling:

\[ \mathcal{P} \propto \exp \left( -\frac{\pi m_{\perp q}^2}{\kappa} \right) = \exp \left( -\frac{\pi p_{\perp q}^2}{\kappa} \right) \exp \left( -\frac{\pi m_{\perp q'}^2}{\kappa} \right) \]

1) common Gaussian $p_{\perp}$ spectrum
2) suppression of heavy quarks $u\bar{u} : d\bar{d} : s\bar{s} : c\bar{c} \approx 1 : 1 : 0.3 : 10^{-11}$
3) diquark $\sim$ antiquark $\Rightarrow$ simple model for baryon production

Hadron composition also depends on spin probabilities, hadronic wave functions, phase space, more complicated baryon production, . . .

$\Rightarrow$ “moderate” predictivity (many parameters!)
Fragmentation starts in the middle and spreads outwards:

but breakup vertices causally disconnected
⇒ can proceed in arbitrary order
⇒ *left–right symmetry*

\[
P(1, 2) = P(1) \times P(1 \rightarrow 2)
\]

⇒ Lund symmetric fragmentation function

\[
f(z) \propto (1 - z)^a \exp(-b m_T^2 / z) / z
\]
The iterative ansatz

\[ q_0, p_{\perp 0}, p_+ \rightarrow q_0 \bar{q}_1, p_{\perp 0} - p_{\perp 1}, z_1 p_+ \]

\[ q_1 \bar{q}_1 \rightarrow q_1 \bar{q}_2, p_{\perp 1} - p_{\perp 2}, z_2 (1 - z_1) p_+ \]

\[ q_2 \bar{q}_2 \rightarrow q_2 \bar{q}_3, p_{\perp 2} - p_{\perp 3}, z_3 (1 - z_2)(1 - z_1) p_+ \]

and so on until joining in the middle of the event

Scaling in lightcone \( p_{\pm} = E \pm p_z \) (for \( q\bar{q} \) system along \( z \) axis)
implies flat central rapidity plateau + some endpoint effects:

\[ \langle n_{ch} \rangle \approx c_0 + c_1 \ln E_{cm}, \sim \text{Poissonian multiplicity distribution} \]
The most characteristic feature of the Lund model

- Snapshots of string position
- Strings stretched from $q$ (or $\bar{q}q$) endpoint via a number of gluons to $\bar{q}$ (or $qq$) endpoint

Gluon = kink on string, carrying energy and momentum

Force ratio gluon/ quark = 2, cf. QCD $N_C/C_F = 9/4$, $\rightarrow 2$ for $N_C \rightarrow \infty$

No new parameters introduced for gluon jets!, so:

- Few parameters to describe energy-momentum structure!
- Many parameters to describe flavour composition!
Independent fragmentation

Based on a similar iterative ansatz as string, but

\[ g \rightarrow q = q + g + \text{corrections in middle} \]

String effect (JADE, 1980)
\[ \approx \text{coherence in nonperturbative context} \]

Further numerous and detailed tests at LEP favour string picture . . .

. . . but much is still uncertain when moving to hadron colliders.
The HERWIG Cluster Model

“Preconfinement”: colour flow is local in coherent shower evolution

1) Introduce forced \( g \rightarrow q\bar{q} \) branchings
2) Form colour singlet clusters
3) Clusters decay isotropically to 2 hadrons according to phase space weight \( \sim (2s_1 + 1)(2s_2 + 1)(2p^*/m) \)

simple and clean, but ...
1) Tail to very large-mass clusters (e.g. if no emission in shower); if large-mass cluster → 2 hadrons then incorrect hadron momentum spectrum, crazy four-jet events

⇒⇒⇒ split big cluster into 2 smaller along “string” direction; daughter-mass spectrum ⇒ iterate if required;

\sim 15\% of primary clusters are split, but give \sim 50\% of final hadrons

2) Isotropic baryon decay inside cluster

⇒⇒⇒ splittings \( g \rightarrow qq + \bar{\text{w}} \)

3) Too soft charm/bottom spectra

⇒⇒⇒ anisotropic leading-cluster decay

4) Charge correlations still problematic

⇒⇒⇒ all clusters anisotropic (?)

5) Sensitivity to particle content

⇒⇒⇒ only include complete multiplets
### String vs. Cluster

**Diagram:**
- **Left:** Diagram showing hadrons and various particles like $\pi^-$, $K^+$, $\phi$, $K^{*-}$, $\pi^+$, $\eta$, $n$, $\bar{\Lambda}^0$, $D_s^-$.
- **Right:** Diagram showing the scattering process in QED, initial/final state, radiation, partonic decays, etc.

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“There ain’t no such thing as a parameter-free good description”
Local Parton–Hadron Duality

Analytic approach:
Run shower down to to \( Q \approx \Lambda_{QCD} \)
(or \( m_{\text{hadron}}, \text{if larger} \))

“Hard Line”: each parton \( \equiv \) one hadron

“Soft Line”: local hadron density
\( \propto \) parton density
describes momentum spectra \( d\eta/\eta p \)
and semi-inclusive particle flow,
but fails for identified particles

+ “renormalons” (power corrections)
\[ \langle 1 - T \rangle = a \alpha_s(E_{\text{cm}}) + b \alpha_s^2(E_{\text{cm}}) + c/E_{\text{cm}} \]

Not Monte Carlo, not for arbitrary quantities
Decays

Unspectacular/ungrateful but necessary: this is where most of the final-state particles are produced!
Involves hundreds of particle kinds and thousands of decay modes.

\[ \text{e.g.} \]

\[ B^0 \rightarrow B^0 \gamma \]: electromagnetic decay
\[ B^0 \rightarrow \bar{B}^0 \] mixing (weak)
\[ \bar{B}^0 \rightarrow D^{*+} \bar{\nu}_e e^- \]: weak decay, displaced vertex, \( |M|^2 \propto (p_{B^0} p_{\bar{\nu}}) (p_e p_{D^{*+}}) \)
\[ D^{*+} \rightarrow D^0 \pi^+ \]: strong decay
\[ D^0 \rightarrow \rho^+ K^- \]: weak decay, displaced vertex, \( \rho \) mass smeared
\[ \rho^+ \rightarrow \pi^+ \pi^0 \]: \( \rho \) polarized, \( |M|^2 \propto \cos^2 \theta \) in \( \rho \) rest frame
\[ \pi^0 \rightarrow e^+ e^- \gamma \]: Dalitz decay, \( m(e^+ e^-) \) peaked

Dedicated programs, with special attention to polarization effects:

- EVTGEN: \( B \) decays
- TAUOLA: \( \tau \) decays
Jet Universality

Question: are jets the same in all processes?
Answer 1: no, at LEP mainly quarks jets, often b/c,
        at LHC mainly gluons, if quarks then mainly u/d.
Answer 2: no, perturbative evolution gives calculable differences.
Answer 3: (string) hadronization mechanism assumed universal, but is not quite.

\[ E \frac{d^3\sigma}{d^3p} : \text{Dependence on proton } P_T \]

so discrepancies
\[
\begin{align*}
P_{qq}/P_{q} & = 0.1 \text{ at LEP}, \quad \frac{P_{s}}{P_{u}} = 0.3 \text{ at LEP,} \\
P_{s}/P_{u} & = 0.5 \text{ at HERA,} \\
\end{align*}
\]

Reasons? HERA dominated by “beam jets”, so

- Less perturbative evolution \( \Rightarrow \) strings less “wrinkled”?
- Many overlapping strings \( \Rightarrow \) collective phenomena?

\[ \begin{aligned}
\lambda_s &= 0.3 \\
\lambda_s &= 0.2 \\
\end{aligned} \]
Momentum distribution of charged particles in **gluon jets**. HERWIG 5.6 predictions are in a good agreement with CDF data. PYTHIA 6.115 produces slightly more particles in the region around the peak of distribution.

Momentum distribution of charged particles in **quark jets**. Both HERWIG and PYTHIA produce more particles in the central region of distribution.

Both PYTHIA and HERWIG predict more charged particles than the data for quark jets!
CDF Run 1 data from on the momentum distribution of charged particles ($p_T > 0.5$ GeV and $|\eta| < 1$) within chgjet#1 (leading charged jet) for $P_T$(chgjet#1) > 5 GeV compared with the QCD “hard scattering” Monte-Carlo predictions of HERWIG, ISAJET, and PYTHIA. The points are the charged number density, $F(z) = dN_{\text{chg}}/dz$, where $z = p_{\text{chg}}/P(\text{chgjet#1})$ is the ratio of the charged particle momentum to the charged momentum of chgjet#1.
Event Generator Developments
The Bigger Picture

ME Generator

ME Expression

SUSY/... spectrum calculation

Process Selection

Resonance Decays

Parton Showers

Multiple Interactions

Beam Remnants

Phase Space Generation

PDF Library

τ Decays

B Decays

Hadronization

Ordinary Decays

Detector Simulation

need standardized interfaces (LHA/LHEF, LHAPDF, SUSY LHA, HepMC, …)
On To C++

Currently HERWIG and PYTHIA are successfully being used, also in new LHC environments, using C++ wrappers

Q: Why rewrite?
A1: Need to clean up!
A2: Fortran 77 is limiting

Q: Why C++?
A1: All the reasons for ROOT, Geant4, ... (“a better language”, industrial standard, ...)
A2: Young experimentalists will expect C++ (educational and professional continuity)
A3: Only game in town! Fortran 90

So far mixed experience:
- Conversion effort: everything takes longer and costs more (as for LHC machine, detectors and software)
- The physics hurdle is as steep as the C++ learning curve
C++ Players

PYTHIA 7 project \(\rightarrow\) **ThePEG**
Toolkit for High Energy Physics Event Generation
(L. Lönnblad; S. Gieseke, A. Ribon, P. Richardson)

ARIADNE/LDC: to do ISR/FSR showers, multiple interactions
(L. Lönnblad; N. Lavesson)

**HERWIG++**: complete reimplementation
November 2007: first full-fledged version (2.1; now 2.2.0)
(P. Richardson; M. Bähr, S. Gieseke, M. Gigg, D. Grellscheid,
K. Hamilton, O. Latunde-Dada, S. Plätzer, M.H. Seymour,
A. Sherstnev, B.R. Webber, arXiv:0803:0883)

**SHERPA**: new program, written from scratch
operational since \(\sim\)2006 (now 1.1.0)
(F. Krauss; T. Gleisberg, S. Hoeche, R. Matyszkiewicz,
S. Schumann, F. Siegert, J. Winter)

**PYTHIA 8**: complete reimplementation
October 2007: first full-fledged version (8.100; now 8.108)
(T. Sjöstrand, S. Mrenna, P. Skands, arXiv:0710.3820 \(\rightarrow\) CPC)
MCnet

- EU Marie Curie training network
- Approved for four years starting 1 Jan 2007
- Involves THEPEG/ARIADNE, HERWIG, SHERPA and PYTHIA
  (CERN, Durham, Lund, Karlsruhe, UC London; leader: Mike Seymour)
- 4 postdocs & 2 graduate students: generator development and tuning
  - short-term studentships: 33 @ 4 months each
  (applications processed every three months; next deadline 30 June)
  - theory or experiment
    - Annual Monte Carlo school:
      Durham, UK, 18 – 20 April 2007
      CTEQ – MCnet, Debrecen, Hungary, 8 – 16 August 2008
      Lund 2009
    - Support for other such schools:
      Physics at the Terascale Monte Carlo School, DESY, 21 – 24 April 2008
    - non-EU participation up to 30%
Key differences between PYTHIA 6.4 and 8.1

Old features definitely removed include, among others:
- independent fragmentation
- mass-ordered showers

Features omitted so far include, among others:
- ep, γp and γγ beam configurations
- several processes, especially SUSY & Technicolor

New features, not found in 6.4:
- interleaved $p_{\perp}$-ordered MI + ISR + FSR evolution
- richer mix of underlying-event processes ($\gamma$, J/ψ, DY, …)
- possibility for two selected hard interactions in same event
- possibility to use one PDF set for hard process and another for rest
- elastic scattering with Coulomb term (optional)
- updated decay data

Preliminary plans for the future:
- rescattering in multiple interactions
- NLO and CKKW-L matching
Trying Out PYTHIA 8.1

For subversion xx (currently 08)

- Download pythia81xx.tgz from
  
  http://home.thep.lu.se/~torbjorn/Pythia.html

- tar xvfz pythia81xx.tgz to unzip and expand

- cd pythia81xx to move to new directory

- ./configure ... needed for external libraries + debug/shared
  (see README, libraries: HepMC, LHAPDF, PYTHIA 6)

- make will compile in ~ 3 minutes
  (for archive library, same amount extra for shared)

- The htmldoc/pythia8100.pdf file contains A Brief Introduction

- Open htmldoc/Welcome.html in a web browser for the full manual

- Install the phpdoc/ directory on a webserver and open
  phpdoc/Welcome.html in a web browser for an interactive manual

- The examples subdirectory contains > 30 sample main programs:
  standalone, link to libraries, semi-internal processes, ...
  (make mainNN and then ./mainNN.exe > outfile)

- A Worksheet (on the web pages) contains step-by-step
  instructions and exercises how to write and run a main program
Outlook

Generators in state of continuous development:

* better & more user-friendly general-purpose matrix element calculators + integrators *
* new libraries of physics processes, also to NLO *
  * more precise parton showers *
* better matching matrix elements ⇔ showers *
* improved models for underlying events / minimum bias *
* upgrades of hadronization and decays *
  * moving to C++ *
  ⇒ always better, but never enough

But what are the alternatives, when event structures are complicated and analytical methods inadequate?
Event Physics Overview

Repetition: from the “simple” to the “complex”,
or from “calculable” at large virtualities to “modelled” at small

Matrix elements (ME):

1) Hard subprocess:
   $|\mathcal{M}|^2$, Breit-Wigners, parton densities.
   $\bar{q} \rightarrow Z^0 \rightarrow qg$
   $q \rightarrow Z^0 \rightarrow qg$

2) Resonance decays:
   includes correlations.
   $Z^0 \rightarrow W^+\mu^-$
   $W^+ \rightarrow c\bar{s}$
   $h^0 \rightarrow W^-\tau^-$
   $W^- \rightarrow \nu_\tau$

Parton Showers (PS):

3) Final-state parton showers.
   $q \rightarrow qg$
   $g \rightarrow gg$
   $g \rightarrow q\bar{q}$
   $q \rightarrow q\gamma$

4) Initial-state parton showers.
5) Multiple parton–parton interactions.

6) Beam remnants, with colour connections.

5) + 6) = Underlying Event

7) Hadronization

8) Ordinary decays: hadronic, $\tau$, charm, …
Read More

These lectures (and more):
http://home.thep.lu.se/~torbjorn/ and click on “Talks”

Frank Krauss, CERN–Fermilab Hadron Collider lectures, June 2007:
http://indico.cern.ch/conferenceOtherViews.py?view=cdsagenda&confId=6238

Bryan Webber, MCnet school, Durham, April 2007:
http://www.hep.phy.cam.ac.uk/theory/webber/

Peter Richardson, CTEQ Summer School lectures, July 2006:
http://www.ippp.dur.ac.uk/~richardn/talks/

Steve Mrenna, CTEQ Summer School lectures, June 2004:
http://www.phys.psu.edu/~cteq/schools/summer04/mrenna/mrenna.pdf

Mike Seymour, Academic Training lectures July 2003:
http://seymour.home.cern.ch/seymour/slides/CERNlectures.html

(update in preparation for Les Houches 2007 proceedings)