Basics of Event Generators III

Leif Lönnblad

Department of Theoretical Physics
Lund University

Terascale Monte Carlo School
DESY 08.04.22

Outline of Lectures

- Lecture I: Basics of Monte Carlo, the event generator strategy, matrix elements, LO/NLO, ...
- Lecture II: Parton showers, Sudakov formfactors, initial/final state, angular ordering, $k_\perp$-factorization, ...
- Lecture III: Underlying events, multiple interactions, minimum bias, pile-up, hadronization, decays, ...

Outline of Lecture III

Underlying Events
- Multiple Interactions
- Minimum Bias and Pile-Up
- The small-x problem revisited

Hadronization
- Local Parton–Hadron Duality
- Cluster Hadronization
- String Hadronization

Particle Decays
- Standard Hadronic Decays
- Decays of heavy resonances

General Purpose Event Generators

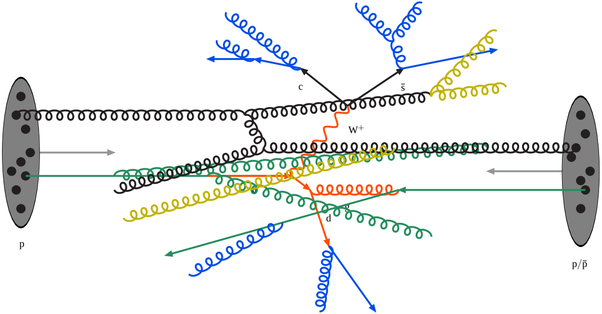
Now we have hard partons and in addition softer and more colliniear partons added with a parton shower, surely we should be able to compare a parton jet with a jet measured in our detector.

Now we have hard partons and in addition softer and more colliniear partons added with a parton shower, surely we should be able to compare a parton jet with a jet measured in our detector.

NO!

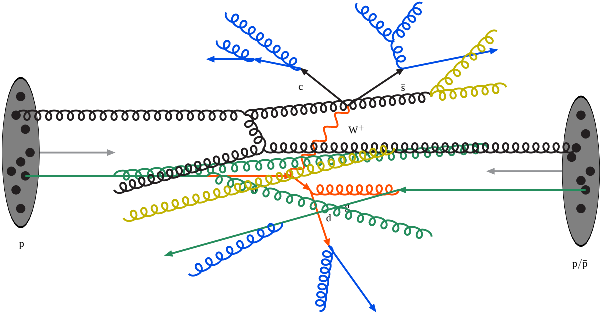
We also have to worry about hadronization, underlying events and pile-up.

What is the underlying event?



Everything except the hard sub-process?

What is the underlying event?



Everything except the hard sub-process
and initial- and final-state showers?

The typical *pp* collision

The underlying event is assumed to be mostly soft, like most of the *pp* collisions are.

- low-$p_\perp$ parton–parton scatterings ($d\hat{\sigma}_{gg} \propto 1/\hat{t}^2$)
- Elastic scattering $pp \to pp$ ($\sim$ 20% at the Tevatron, $\to$ half the cross section for asymptotic energies)
- Diffractive excitation $pp \to N^*p$, $pp \to N^*N'^*$

Particles are distributed more or less evenly in (η, ϕ).

Maybe we can measure the typical *pp* collisions and then add random low-$p_\perp$ particles at random to our generated events.

The typical *pp* collision

The underlying event is assumed to be mostly soft, like most of the *pp* collisions are.

- low-$p_\perp$ parton–parton scatterings ($d\hat{\sigma}_{gg} \propto 1/\hat{t}^2$)
- Elastic scattering $pp \to pp$ ($\sim$ 20% at the Tevatron, $\to$ half the cross section for asymptotic energies)
- Diffractive excitation $pp \to N^*p$, $pp \to N^*N'^*$

Particles are distributed more or less evenly in (η, ϕ).

Maybe we can measure the typical *pp* collisions and then add random low-$p_\perp$ particles at random to our generated events.

We want to do better than that.

Multiple Interactions

Based upon the eikonalization of the jet cross section.

$$\sigma_{\mathrm{hard}}(p^2_{\perp\mathrm{min}}) = \int_{p^2_{\perp\mathrm{min}}} \frac{d\sigma_{\mathrm{hard}}(p^2_\perp)}{dp^2_\perp} dp^2_\perp$$

Diverges faster than $1/p^4_{\perp\mathrm{min}}$ as $p^2_{\perp\mathrm{min}} \to 0$ and eventually exceeds the total inelastic (non-diffractive) cross section.

The average number of scatterings are given by

$$\langle n \rangle = \sigma_{\mathrm{hard}}(p_{\perp\mathrm{min}})/\sigma_{\mathrm{nd}}$$

Secondary interactions are not very hard, but PYTHIA models also soft scatterings with partons. Instead of a cut, the partonic cross section is regularized with

$$\frac{d\hat{\sigma}}{dp_\perp^2} \to \frac{d\hat{\sigma}}{dp_\perp^2} \times \frac{p_\perp^4}{(p_{\perp 0}^2 + p_\perp^2)^2}$$
$$\alpha_s(p_\perp^2) \to \alpha_s(p_{\perp 0}^2 + p_\perp^2)$$

where $p_{\perp 0} \sim 1$ GeV and depends on the total energy.

Secondary interactions are not very hard, but PYTHIA models also soft scatterings with partons. Instead of a cut, the partonic cross section is regularized with

$$\frac{d\hat{\sigma}}{dp_\perp^2} \to \frac{d\hat{\sigma}}{dp_\perp^2} \times \frac{p_\perp^4}{(p_{\perp 0}^2 + p_\perp^2)^2}$$
$$\alpha_s(p_\perp^2) \to \alpha_s(p_{\perp 0}^2 + p_\perp^2)$$

where $p_{\perp 0} \sim 1$ GeV and depends on the total energy.

HERWIG has another strategy based more explicitly on the saturation of the gluon density for small x and $p_\perp$.

Secondary interactions are not very hard, but PYTHIA models also soft scatterings with partons. Instead of a cut, the partonic cross section is regularized with

$$\frac{d\hat{\sigma}}{dp_\perp^2} \to \frac{d\hat{\sigma}}{dp_\perp^2} \times \frac{p_\perp^4}{(p_{\perp 0}^2 + p_\perp^2)^2}$$

$$\alpha_s(p_\perp^2) \to \alpha_s(p_{\perp 0}^2 + p_\perp^2)$$

where $p_{\perp 0} \sim 1$ GeV and depends on the total energy.

(More on multiple interactions tomorrow.)

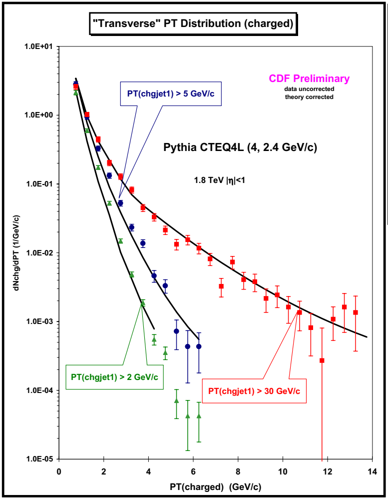
Including an impact parameter dependence we now get the probability for the hardest emission:

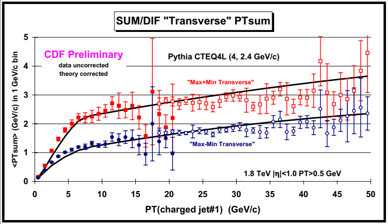
$$\frac{dP_{\text{hardest}}(b,p_\perp)}{d^2b\,dp_\perp} \propto e(b)\frac{d\sigma(p_\perp)}{dp_\perp}\exp\left\{-\int_{p_\perp} e(b)\frac{d\sigma(p'_\perp)}{dp'_\perp}dp'_\perp\right\}$$

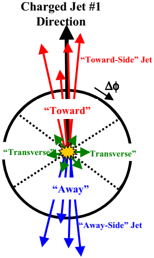
$e(b)$ is an overlap function.

Note that if we have a high-$p_\perp$ scattering we bias ourselves towards small impact parameters and larger overlaps.

Larger overlap gives more additional scatterings and more active underlying event. Hence, the underlying event is correlated with the hard sub-process.

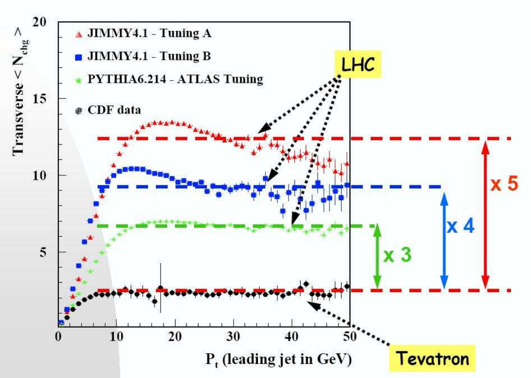

"Transverse" PT Distribution (charged)
CDF Preliminary
data uncorrected
theory corrected
PT(chgjet1) > 5 GeV/c
Pythia CTEQ4L (4, 2.4 GeV/c)
1.8 TeV |η|<1
PT(chgjet1) > 2 GeV/c
PT(chgjet1) > 30 GeV/c
dNchg/dPT (1/GeV/c)
PT(charged) (GeV/c)
1.0E+01
1.0E+00
1.0E-01
1.0E-02
1.0E-03
1.0E-04
1.0E-05
0
2
4
6
8
10
12
14


SUM/DIF "Transverse" PTsum
CDF Preliminary
data uncorrected
theory corrected
Pythia CTEQ4L (4, 2.4 GeV/c)
"Max+Min Transverse"
"Max-Min Transverse"
1.8 TeV |η|<1.0 PT>0.5 GeV
<PTsum> (GeV/c) in 1 GeV/c bin
PT(charged jet#1) (GeV/c)
0
1
2
3
4
5
0
5
10
15
20
25
30
35
40
45
50


Charged Jet #1
Direction
"Toward-Side" Jet
Δφ
"Toward"
"Transverse"
"Transverse"
"Away"
"Away-Side" Jet

How much underlying event will there be at LHC?

No UE model claims to be able to predict the energy dependence.



Minimum Bias and Pile-Up

Minimum Bias events is not no-bias typical *pp* collisions. You still need a trigger.

But if we look at a pile-up event overlayed with a triggered event, surely that is a no-bias *pp* collision.

Minimum Bias and Pile-Up

Minimum Bias events is not no-bias typical *pp* collisions. You still need a trigger.

But if we look at a pile-up event overlayed with a triggered event, surely that is a no-bias *pp* collision.

No, even pile-up events may be correlated with the trigger collision.

Nature is efficient

Consider trigger on a calorimeter jet with $E_\perp > E_{\perp cut}$.

This can either be accomplished by a parton–parton scattering with $p_\perp > E_{\perp cut}$

Or by a parton–parton scattering with lower $p_\perp$(which has a higher cross section $\propto (E_{\perp cut}/p_\perp)^4$ and some random particles coming from the underlying event or pile-up events which happens to fluctuate upwards.

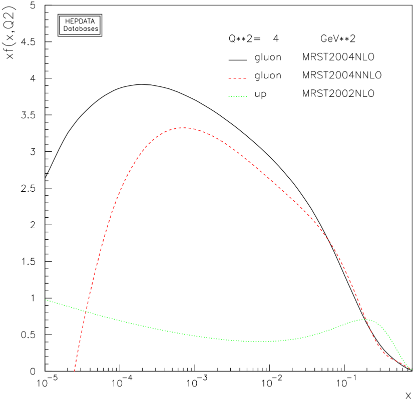
We bias ourselves towards pile-up events with higher activity than a no-bias pp collision.

The standard MI models assume that additional scatterings can be treated with collinear factorization and DGLAP-based initial-state showers.

But for small $p_\perp \sim$ a few GeV we have $x \lesssim 10^{-4}$ which means we need to worry about resumming large logarithms of x

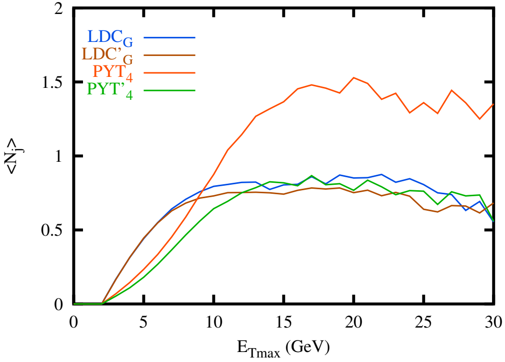
DGLAP-based shower cannot reproduce HERA final states at small x.

The number of gluons is large, and uncertainties are large



There are probably recombination effects and *saturation*

With proper small-x treatment we may get more reliable predictions. Eg. preliminary model based on Linked Dipole Chains



LDCMC $k_{\perp 0}$: 0.99 $\rightarrow$ 1.3 GeV

PYTHIA $p_{\perp 0}$: 2.1 $\rightarrow$ 2.5 GeV

Hadronization

Now that we are able to generate partons, both hard, soft, collinear and from multiple scatterings, we need to convert them to hadrons.

This is a non-perturbative process, and all we can do is to construct models, and try to include as much as possible of what we know about non-perturbative QCD.

Local Parton–Hadron Duality

An analytic approach ignoring non-perturbative difficulties.

Run shower down to scales $\sim \Lambda_{\mathrm{QCD}}$.

Each parton corresponds to one (or 1.something) hadron.

Can describe eg. momentum spectra surprisingly well.

Can be used to calculate power corrections to NLO predictions for event shapes,

- $\langle 1 - T \rangle = c_1 \alpha_{\mathrm{s}}(E_{\mathrm{cm}}) + c_2 \alpha_{\mathrm{s}}^2(E_{\mathrm{cm}}) + c_p / E_{\mathrm{cm}}$

Local Parton–Hadron Duality

An analytic approach ignoring non-perturbative difficulties.

Run shower down to scales $\sim \Lambda_{\mathrm{QCD}}$.

Each parton corresponds to one (or 1.something) hadron.

Can describe eg. momentum spectra surprisingly well.

Can be used to calculate power corrections to NLO predictions for event shapes,

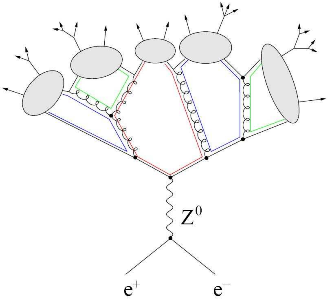
- $\langle 1 - T \rangle = c_1 \alpha_{\mathrm{s}}(E_{\mathrm{cm}}) + c_2 \alpha_{\mathrm{s}}^2(E_{\mathrm{cm}}) + c_p / E_{\mathrm{cm}}$

Cannot generate real events with this though.

Cluster Hadronization

Close to local parton–hadron duality in spirit. Based on the idea of Preconfinement:

The pattern of perturbative gluon radiation is such that gluons are emitted mainly between colour-connected partons. If we emit enough gluons the colour-dipoles will be small.

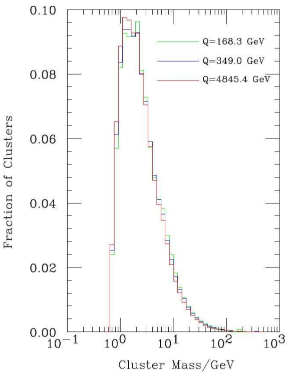


After the shower, force $g \to q\bar{q}$ splittings giving low-mass, colour-singlet clusters

Decay clusters isotropically into two hadrons according to phase space weight $\sim (2s_1+1)(s_2+1)(2p/m)$

Cluster hadronization is very simple and clean.
Maybe too simple. . .

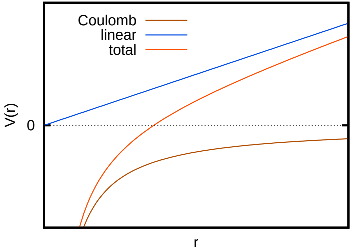
Cluster hadronization is very simple and clean.
Maybe too simple. . .



- Cluster masses can be large (finite probability for no gluon emission): Introduce *string-like* decays of heavy clusters into lighter ones (with special treatment of proton remnant).
- In clusters including a heavy quark (or a di-quark) the heavy meson (or baryon) should go in this direction: introduce anisotropic cluster decays.
- . . .

String Hadronization

What do we know about non-perturbative QCD?



- At small distances we have a Coulomb-like asymptotically free theory
- At larger distances we have a linear confining potential

For large distances, the field lines are compressed to vortex lines like the magnetic field in a superconductor

1+1-dimensional object $\sim$ a massless relativistic string

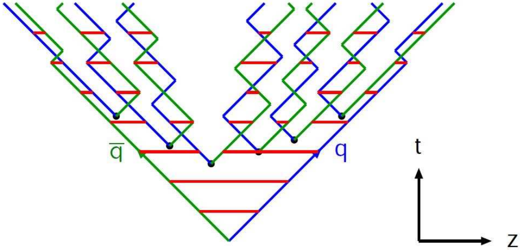
As a $q\bar{q}$-pair moves apart, they are slowed down and more and more energy is stored in the string.

In the energy is small, the $q\bar{q}$-pair will eventually stop and move together again. We get a "YoYo"-state which we interpret as a meson.

If high enough energy, the string will break as the energy in the string is large enough to create a new $q\bar{q}$-pair.

The energy in the string is given by the string tension

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



The quarks obtain a mass and a transverse momentum in the breakup through a tunneling mechanism

$$\mathcal{P} \propto e^{-\frac{\pi m_{q\perp}^2}{\kappa}} = e^{-\frac{\pi m_q^2}{\kappa}} e^{-\frac{\pi p_\perp^2}{\kappa}}$$

Gives a natural supression of heavy quarks

$\mathrm{d\bar{d}} : \mathrm{u\bar{u}} : \mathrm{s\bar{s}} : \mathrm{c\bar{c}} \approx 1 : 1 : 0.3 : 10^{-11}$

The break-ups starts in the middle and spreads outward, but they are causually disconnected. So we should be able to start anywhere.

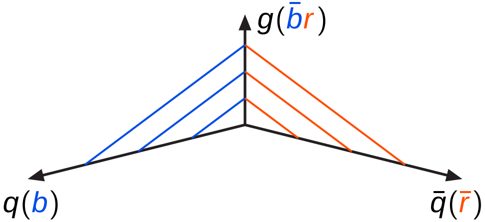
In particular we could start from either end and go inwards.

Requiring left-right symmetry we obtain a unique *fragmentation function* for a hadron taking a fraction z of the energy of a string end in a breakup

$$p(z) = \frac{(1-z)^a}{z} e^{-bm_\perp^2/z}$$

The Lund symmetric fragmentation function.

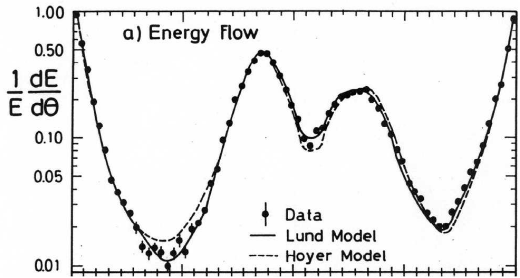
Gluons complicates the picture somewhat. They can be interpreted as a “kinks” on the string carrying energy and momentum



The gluon carries twice the charge ($N_C/C_F \to 2$ for $N_C \to \infty$)

A bit tricky to go around the gluon corners, but we get a consistent picture of the energy–momentum structure of an event with no extra parameters.

The Lund string model predicted the string effect measured by Jade.



In a three-jet event there are more energy between the $\mathrm{g}-\mathrm{q}$ and $\mathrm{g}-\bar{\mathrm{q}}$ jets than between $\mathrm{q}-\bar{\mathrm{q}}$.

For the flavour structure the picture becomes somewhat messy.

Baryons can be produced by having $\mathrm{qq}-\bar{\mathrm{q}}\bar{\mathrm{q}}$-breakups (diquarks behaves like an anti-colour), but more complicated mechanisms (“popcorn”) needed to describe baryon correlations.

We also need special suppression of strange mesons, baryons. Parameters for different spin states, . . .

There are *lots* of parameters i PYTHIA.

The Ninth Commandment of Event Generation

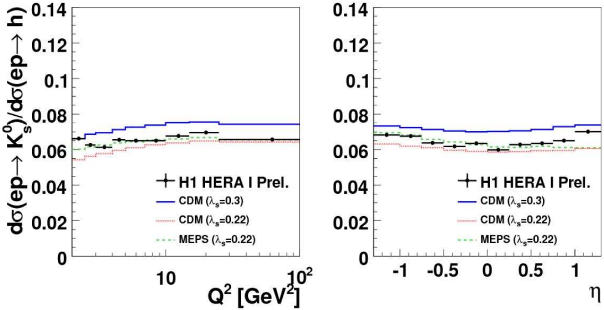
Strings vs. Clusters

Model	string (PYTHIA)	cluster (HERWIG)
energy–momentum picture	powerful, predictive few parameters	simple, unpredictive many parameters
flavour composition	messy, unpredictive many parameters	simple, reasonably predictive few parameters

There will always be parameters. . .

Most hadronization parameters have been severely constrained by LEP data. Does this mean we can use the models directly at LHC?

Something Strange at HERA



Jet universality

There may be problems with flavour and meson/baryon issues.

Also at LEP there were mainly quark jets, gluon jets are softer and not very well measured.

At LHC there will be very hard gluon jets.

We need to check that jet universality works.

The PDG decay tables

The Particle Data Group has machine-readable tables of decay modes.

But they are not complete and cannot be used directly in an event generator.

- Branching ratios need to add up to unity.
- Some decays are listed as $B^{\star 0} \to \mu^+\nu_\mu X$.
- ...

Most decays need to be coded by hand

Particle Decays

Not the most sexy part of the event generators,
but still essential.

$$
\begin{aligned}
& B^{\star 0} \to \gamma \;\; B^0 \\
& \qquad\qquad \hookrightarrow \overline{B}^0 \to e^- \bar{\nu}_e \;\; D^{\star +} \\
& \qquad\qquad\qquad\qquad\qquad \hookrightarrow \pi^+ \;\; D^0 \\
& \qquad\qquad\qquad\qquad\qquad\qquad\quad \hookrightarrow K^- \;\; \rho^+ \\
& \qquad\qquad\qquad\qquad\qquad\qquad\qquad\quad \hookrightarrow \pi^+ \;\; \pi^0 \\
& \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\quad \hookrightarrow e^+ e^- \gamma
\end{aligned}
$$

Particle Decays

Not the most sexy part of the event generators, but still essential.

$$B^{\star 0} \rightarrow \gamma \;\; B^0$$

$$\hookrightarrow \overline{B}^0 \rightarrow e^- \bar{\nu}_e \;\; D^{\star +}$$

$$\hookrightarrow \pi^+ \;\; D^0$$

$$\hookrightarrow K^- \;\; \rho^+$$

$$\hookrightarrow \pi^+ \;\; \pi^0$$

$$\hookrightarrow e^+ e^- \gamma$$

EM decays

Particle Decays

Not the most sexy part of the event generators,
but still essential.

$$
\begin{aligned}
B^{\star 0} &\rightarrow \gamma\ B^0 \\
&\qquad \hookrightarrow \overline{B}^0 \rightarrow e^- \bar{\nu}_e\ D^{\star +} \\
&\qquad\qquad\qquad \hookrightarrow \pi^+\ D^0 \\
&\qquad\qquad\qquad\qquad \hookrightarrow K^-\ \rho^+ \\
&\qquad\qquad\qquad\qquad\qquad \hookrightarrow \pi^+\ \pi^0 \\
&\qquad\qquad\qquad\qquad\qquad\qquad \hookrightarrow e^+ e^- \gamma
\end{aligned}
$$

Weak mixing

Particle Decays

Not the most sexy part of the event generators,
but still essential.

$$B^{\star 0} \to \gamma \; B^0$$
$$\hookrightarrow \overline{B}^0 \to e^- \bar{\nu}_e \; D^{\star +}$$
$$\hookrightarrow \pi^+ \; D^0$$
$$\hookrightarrow K^- \; \rho^+$$
$$\hookrightarrow \pi^+ \; \pi^0$$
$$\hookrightarrow e^+ e^- \gamma$$

Weak decay, displaced vertex, $|\mathcal{M}|^2 \propto (p_{\bar{B}} p_{\bar{\nu}})(p_e p_{D^\star})$

Particle Decays

Not the most sexy part of the event generators,
but still essential.

$$
\begin{aligned}
&B^{\star 0} \rightarrow \gamma \;\; B^0 \\
&\qquad\qquad \hookrightarrow \overline{B}^0 \rightarrow e^- \bar{\nu}_e \;\; D^{\star +} \\
&\qquad\qquad\qquad\qquad\qquad \hookrightarrow \pi^+ \;\; D^0 \\
&\qquad\qquad\qquad\qquad\qquad\qquad\quad \hookrightarrow K^- \;\; \rho^+ \\
&\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad \hookrightarrow \pi^+ \;\; \pi^0 \\
&\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad \hookrightarrow e^+ e^- \gamma
\end{aligned}
$$

Strong decay

Particle Decays

Not the most sexy part of the event generators, but still essential.

$$
\begin{aligned}
&B^{\star 0} \rightarrow \gamma \;\; B^0 \\
&\qquad\qquad \hookrightarrow \overline{B}^0 \rightarrow e^- \bar{\nu}_e \;\; D^{\star +} \\
&\qquad\qquad\qquad\qquad\qquad\quad \hookrightarrow \pi^+ \;\; D^0 \\
&\qquad\qquad\qquad\qquad\qquad\qquad\quad \hookrightarrow K^- \;\; \rho^+ \\
&\qquad\qquad\qquad\qquad\qquad\qquad\qquad\quad \hookrightarrow \pi^+ \;\; \pi^0 \\
&\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad \hookrightarrow e^+ e^- \gamma
\end{aligned}
$$

Weak decay, displaced vertex, ρ mass smeared

Particle Decays

Not the most sexy part of the event generators,
but still essential.

$$B^{\star 0} \to \gamma \; B^0$$
$$\hookrightarrow \overline{B}^0 \to e^- \bar{\nu}_e \; D^{\star +}$$
$$\hookrightarrow \pi^+ \; D^0$$
$$\hookrightarrow K^- \; \rho^+$$
$$\hookrightarrow \pi^+ \; \pi^0$$
$$\hookrightarrow e^+ e^- \gamma$$

ρ polarized, $|\mathcal{M}|^2 \propto \cos^2\theta$ in ρ rest frame

Particle Decays

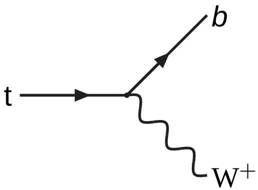
Not the most sexy part of the event generators,
but still essential.

$$B^{\star 0} \to \gamma \; B^0$$
$$\hookrightarrow \overline{B}^0 \to e^- \bar{\nu}_e \; D^{\star +}$$
$$\hookrightarrow \pi^+ \; D^0$$
$$\hookrightarrow K^- \; \rho^+$$
$$\hookrightarrow \pi^+ \; \pi^0$$
$$\hookrightarrow e^+ e^- \gamma$$

Dalitz decay, $m_{e^+e^-}$ peaked

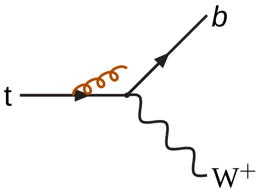
Decays of heavy resonances

May influence the hard sub-process



Decays of heavy resonances

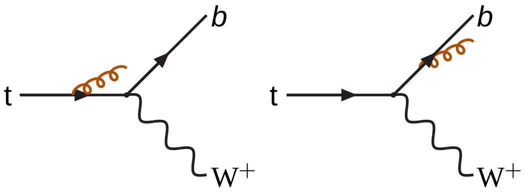
May influence the hard sub-process



But also influences parton showers

Decays of heavy resonances

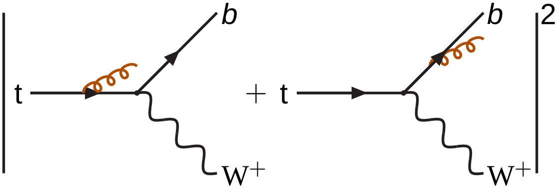
May influence the hard sub-process



But also influences parton showers

Decays of heavy resonances

May influence the hard sub-process



But also influences parton showers
and gives rise to coherence effects

General Purpose Event Generators

There are only a few programs which deals with the whole picture of the event generation

- Hard sub-processes
- Parton showers
- Multiple interactions
- Hadronization
- Decays

Many more programs deal with a specific part of the event generation

- Hard subprocess: AlpGen, MadEvent, . . . can be used with other generators using the Les Houches interface (but be sure to do proper merging)
- Parton Shower: ARIADNE, CASCADE, . . . neet to integrated with a specific general purpose generator
- Multiple interactions: JIMMY (now integrated with HERWIG)
- Hadroniziation (?)
- Decays: Tauola, EvtGen, typically called from within other generators.

PYTHIA version 8

- A few simple MEs, the rest from Les Houches
- $k_\perp$-ordered initial-/final-state DGLAP-based shower
- Multiple interactions interleaved with shower
- Lund String Fragmentation
- Particle decays

`http://home.thep.lu.se/~torbjorn/Pythia.html`

HERWIG++ version 2.2

- Construction of arbitrary MEs using helicity amplitudes, but not automized.
- Angular ordered, DGLAP-based shower
- JIMMY-based multiple interactions
- Cluster hadronization
- Particle decays with correlations
- Open structure based on THEPEG

`http://projects.hepforge.org/herwig`

SHERPA version 1.1

- Built-in automated ME generator
- Virtuality-ordered DGLAP-based shower ($\sim$ old PYTHIA) with CKKW merging
- Multiple interactions ($\sim$ old PYTHIA) with some CKKW features
- Cluster hadronization (string fragmentation via old PYTHIA).
- Standard particle decays.

`http://projects.hepforge.org/sherpa`

All authors of Herwig, Pythia, Sherpa, as well as, ThePEG, Ariadne and Rivet are members of MCnet.

EU-funded research training network with teams in CERN, Durham, Karlsruhe, Lund and UCL.

Four Postocs, two PhD positions, and . . .

Yearly Monte Carlo Schools

Next MCNet Monte Carlo School in August 2008 in Debrecen

Jointly organized with the CTEQ collaboration

More info: `http://www.cteq-mcnet.org`

Short-Term Studentships

Possibility for PhD students to spend 3-6 months in one of the MCnet teams, all expences payed.

Aimed at experimental or theoretical students who needs event generators in their research projects and want to learn to use and understand them.

More info: `http://www.montecarlonet.org` or `Michael.Seymour@cern.ch`

Final Advertisement

LUND UNIVERSITY

Lund University, department of Theoretical High Energy Physics has announced a four-year PhD studentship.

More info: `http://www.thep.lu.se` or `Leif.Lonnblad@thep.lu.se`

The Tenth Commandment of Event Generation

Thou shalt only have nine commandments of event generation