The Lund Hadronization Model

(Hadronization in HEP Event Generators)

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HEP event generators include dynamical models of hadronization (cluster or string). These models strongly depend on "good" starting conditions for the hadronization.

Cluster traditional: Sophisticated perturbative QCD + simple fragmentation.

String traditional: Sophisticated hadronization + simple parton shower.

Both no longer true today.

Keep in mind: Almost all HEP hadronization studies done in $e^+e^- \to h$ at $s > 10$ GeV, or in pp collisions at multi-TeV energies.

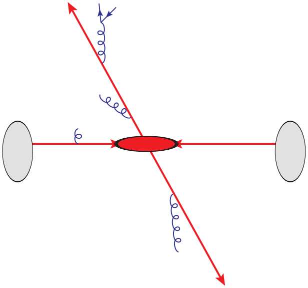
The Lund string model is (now) mostly synonymous with the PYTHIA event generator.

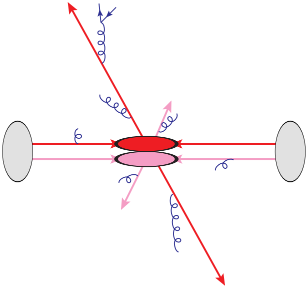
PYTHIA is one of the most used event generators. PYTHIA 8 offers

- Beams: $p/\bar{p}$, $n/\bar{n}$, $\pi^{0\pm}$, γ, $e^{\pm}$, $\mu^{\pm}$, $\nu_\ell/\bar{\nu}_\ell$, ${}^{4}He$, ${}^{6}Li$, ${}^{12}C$, heavy ions. ${}^{X}Y$ only together with p, ${}^{X}Y$. Only scattering energies sensible for partonic processes.
- Perturbative QCD: May combine multiple NLO calculations of different parton multiplicity consistently w/o overlap. Moving to higher-order showers.
- Multiparton interactions: Regularized partonic $2 \to 2$ scatters competing with showers for phase space. Fully embedded with diffraction.
- Fragmentation: Lund string hadronization with two tunneling options, collective string effects, hadronic decay MEs & fits, and hadron rescattering.
- Nuclear structure: Ion beams only. Woods-Saxon + nucleon position fluctuations from Glauber MC, *and also* x-section fluct^{ns} à la Glauber-Gribov.

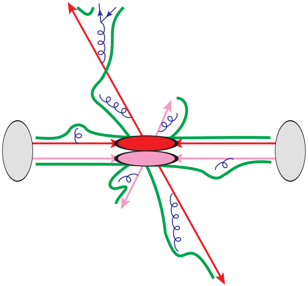
$\Rightarrow$ More mature than PYTHIA 6; exception: ep-DIS and γp have not been combined into one mixed-process framework.

Hard interaction
+ Radiative cascade



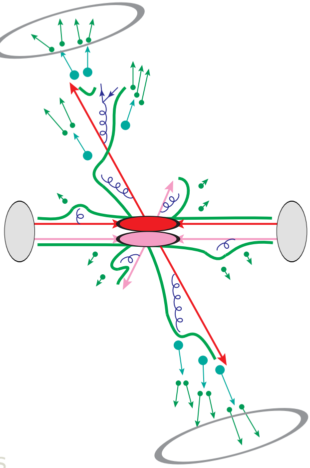


Hard interaction
+ Radiative cascade
+ Multiple interactions of initiators



Hard interaction
+ Radiative cascade
+ Multiple interactions of initiators
+ Hadron formation

Structure of PYTHIA event generation



Hard interaction
+ Radiative cascade
+ Multiple interactions of initiators
+ Hadron formation
+ Hadron decays (& rescattering)
+ Beam spectrum, detector & material effects

Well-defined (perturbative) starting conditions I: Factorization

Partonic (e.g. DIS) calculations rely on factorization of long-distance (hadronic) effects from short-distance (partonic) physics:

$$\sigma = \int d\sigma_{(ab \to X+N \text{ partons})}(\text{high energy}) \otimes f_{a\in \mathrm{A}}(\{x\}_a, \text{high energy}) \otimes f_{b\in \mathrm{B}}(\{x\}_b, \text{high energy}) \otimes \mathcal{D}(p_A, p_B, p_1, \ldots, p_N)$$

$f(\{x\}, \text{energy}) \,\widehat{=}\,$ Parton density in colliding hadron at "resolution" $1/$energy
$\mathcal{D} \,\widehat{=}\,$ Fragmentation mechanism

Measure f and $\mathcal{D}$ where radiative corrections are small (low energy).

Important aspect: Hard cross sections can be calculated by third-party tools!

Well-defined (perturbative) starting conditions II: Evolution

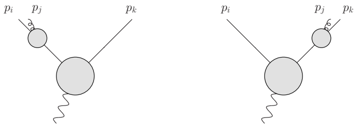
Short distance scattering cross sections can be calculated in fixed-order coupling expansion. Fixed-order expansions apply at a high energy. But distribution functions are extracted at low energy.

→ Transport extracted $f(x,$ low energy$)$ to the desired $f(x',$ high energy$)$ by (DGLAP) evolution equations:

$$\frac{\mathrm{d}}{\mathrm{d}\log(t/\mu^2)} f_q(x,t) \; = \; \int_x^1 \frac{\mathrm{d}z}{z}\frac{\alpha_s}{2\pi}\, P_{qq}(z)\, f_q(x/z,t) + \int_x^1 \frac{\mathrm{d}z}{z}\frac{\alpha_s}{2\pi}\, P_{gq}(z)\, f_g(x/z,t)$$

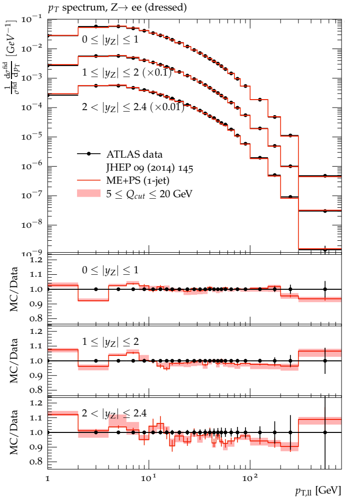
The inversion high energy → low energy is called parton shower.

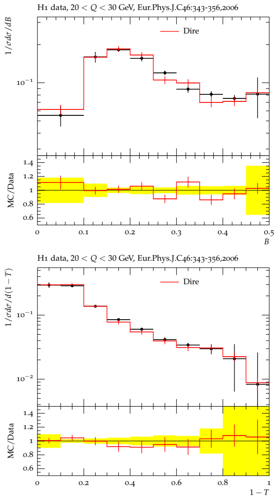
But note: Needs to describe both soft and collinear radiation.



Glue interferes, i.e. naive factorization amended at differential level!

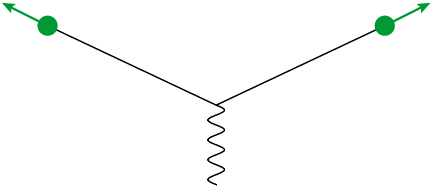
Parton shower predictions





→ Reproduces $p_\perp$-like spectra, based on two types of non-perturbative inputs: collinear PDFs and primordial $k_\perp$ parametrization.

Why bother with showers? Non-perturbative physics!



Color or flavor are not “destroyed” by confinement, only contained.
A parton can never fragment into a hadron.

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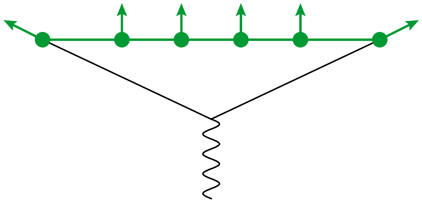

When do partons convert to hadrons?
If they have small relative momenta and a virtuality $\sim \Lambda_{qcd}$.
Widely separated partons cannot couple to hadron vertices and allow $\mathcal{O}(\Lambda_{qcd})$ momentum flow.

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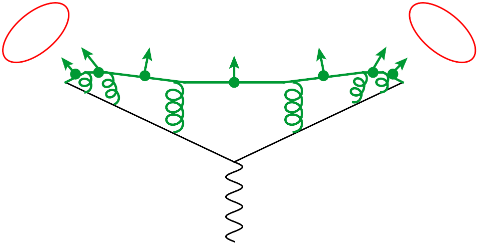
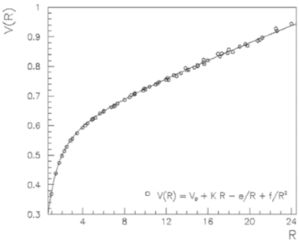
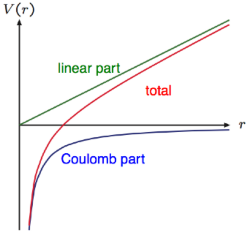


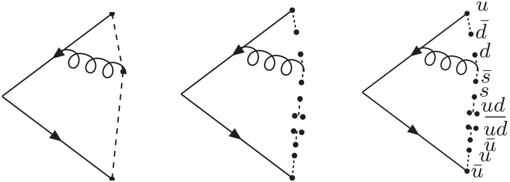
Partons fragment together with their soft/collinear gluon field!
Gluons and soft/collinear partons from evolution make momentum flow small and allow non-perturbative parton-hadron vertices.

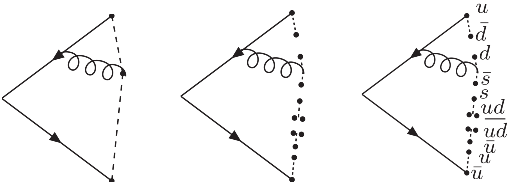




At large distances, the potential between color-anticolor is linear.

$\sim$ 1+1-dim. QED fields which fragment by flux tube breaking

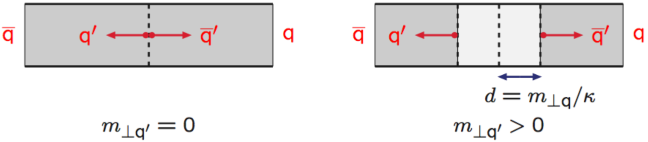




The “vertices” are related to tunneling probabilities that (together with causality) produce the Lund symmetric fragmentation function

$$f(z) = \frac{(1-z)^a}{z} \exp\left(-\frac{bm_{\perp h}^2}{z}\right)$$

Note the $p_\perp$-dependence required by momentum conservation!
Gluons are “just” excitations of the string (no new parameters).



Assume that string breaks by tunneling $\rightarrow$ Gaussian spectrum

$$\mathcal{P}_q \propto \exp\left(-\pi m_{\perp q}^2/\kappa\right) = \exp\left(-\pi p_{\perp q}^2/\kappa\right) \exp\left(-\pi m_q^2/\kappa\right)$$

and thus suppresses heavy (di)quarks ($\mathrm{u\bar{u}} : \mathrm{s\bar{s}} : \mathrm{c\bar{c}} \approx 1 : 0.3 : 0$).

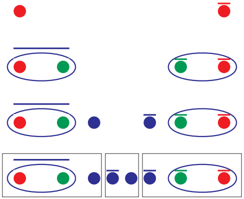
High energies (many hadron states available), also allow a thermodynamic breaking mechanism with

$$\mathcal{P}_h \propto \exp\left(-m_{\perp h}/T\right) = \int d^2 p_{\perp q_1} \int d^2 p_{\perp q_2} \mathcal{P}_{q_1} \mathcal{P}_{q_2} \delta(\vec{p}_{\perp h} - \vec{p}_{\perp q_1} - \vec{p}_{\perp q_1})$$

Mesons: Combine "tunneled" quarks with other quarks.
Baryons: Combine diquarks ($\sim$ antiquark) w/ other quarks.

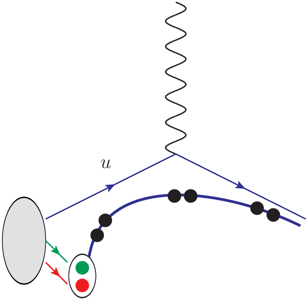
The hadron species is picked based on the quark flavor, but with many unknowns (i.e. parameters):

What is the quark mass, anyway?
Naive spin (vector vs. pseudoscalar) counting not applicable, e.g. because $m_\rho \gg m_\pi$.
Many baryon states, picked from SU(6)$_{flavor \times spin}$.
Naive diquark $\leftrightarrow$ baryon model produces too strongly correlated baryons $\rightarrow$ Popcorn model.



$\Rightarrow \mathcal{O}(20)$ flavor-dependent parameters. Much fewer in thermodynamic model (but also not fully developed)

ℓh scattering is treated either as DIS or as γh, i.e. h is shattered into "hard partons" and a "beam remnant". Remnant is endpoint of some string.



Simplest: Valence parton scattering
→ Remnant may be diquark, just need to fix spin: ud is $\frac{3}{4}ud_0$ and $\frac{1}{4}ud_1$, uu always uu_1 from $SU(6)_{flavor\times spin}$

#Remnants > 1 for q_{sea} or gluons.
$\bar{q}_{sea}$ directly yield baryons.

Remnant composition complicated upon considering parton showers and multiparton interactions.

Hard parton can also have $p_\perp$, which is compensated by remnants.

Physics assumptions/limitations:

Always want to confine previously deconfined color.

Target-m not really present in x-section or q/g kinematics.

Only tested for $W > 4$ GeV, small W in $e^+e^- \to h$ only, last global overview in 1987?

"Jet joining" not well-understood for low hadron multiplicity.

Strong isospin not traced in string.

Strings are traditionally non-interaction.

Parameters allow tuning to describe data sets. Non-global tunes $\Rightarrow$ loss in predictivity: *"Can make it fit, but would we trust it?"*

More measurements needed to understand low-mass hadronization, especially with diquark endpoints!

Optimistic scenario:

- Assume possibility of approximation

$$\sigma_{full} = \sum_{\text{channels}} \int dx f_{\text{nucleon h in nucleus N}}(x) d\sigma(\nu h[xP] \rightarrow X)$$

- Specialized library to obtain probabilities $f_{h/N}(x)$
- Specialized MC generators calculate and write out exclusive processes $d\sigma(\nu h \rightarrow X)$ as (σ-weighted) sets of 4-momenta.
- PYTHIA will process these further (e.g. decay resonances)
- PYTHIA will remove overlap between processes introduced by postprocessing & between exclusive processes.

⇒ HEP-like division of labor. HEP multiparton interaction algorithms as strawman for multi-hadron effects. HEP NLO+PS methods as template for overlap removal.
⇒ Lots of new ideas needed!

First and foremost: Event generators ♡ Data

So if you have data & analysis code, share them publicly!

PYTHIA 8 implements the Lund String Model.
The string model takes a high-energy perspective on hadronization.

Dynamical model of hadron generation with few parameters.

Most parameters due to flavor selection.

Low-energy and low-multiplicity improvements require experimental input, *i.e. need simple way to compare to data in the development process*.

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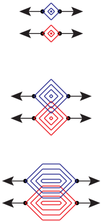
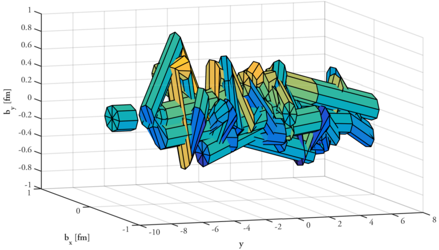
Figures from arxiv:1710.09725 [hep-ph] and C. Bierlich





As color and anti-color move apart, strings will expand
...and at some point overlap.

Typical events for pp scattering at $\sqrt{s} = 7$ TeV are already very dense. Heavy-Ion collisions even more so!

Microscopic model of collective effects implemented in ANGANTYR module.