# Hadronization

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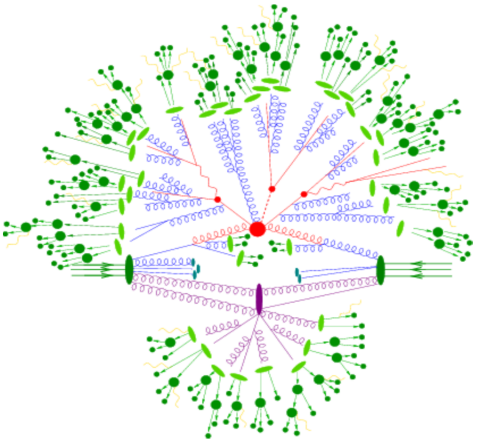

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# Challenge

1 Challenge

Parton shower terminates at scale around 1 GeV. However, we are not able to see partons directly because of the colour confinement. Degrees of freedom in the detector are hadrons. In this stage, there is not first principle for hadronization/fragmentation.

Two famous models: the String Model and the Cluster Model.

A model should:

- Obey relevant observation laws and symmetries.
- Enforce confinement.
- Implement as many phenomenological properties of QCD as possible.

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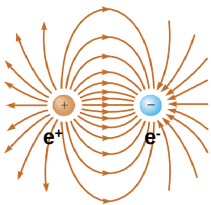
## Strings in QCD

**Analogy to QED**



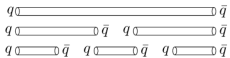

**Electric dipol**

**EM field → infinity**

**QCD**

**Color flux tube = string**

**Due to the quark confinement - in QCD strings can breake!**



**→ Hadron production by string breaking**

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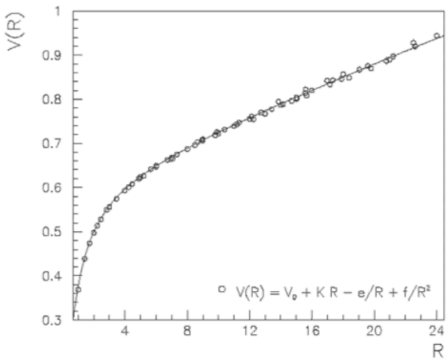
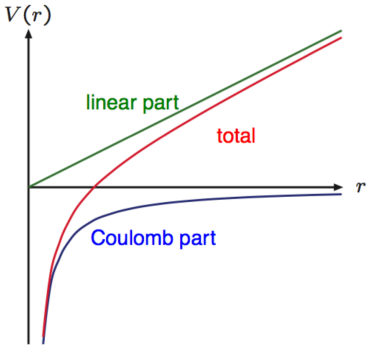
[E. Bratkovskaya's Lecture]

# The String Model

## 2 The String Model




The potential between a static quark-antiquark pair is given by:

$$V(r) \sim \frac{\alpha_S}{r} + \kappa r$$

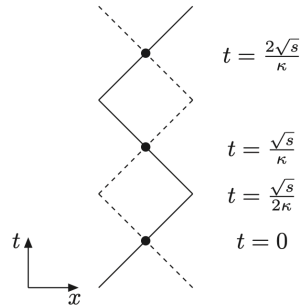
# The String Model

## 2 The String Model

String model neglect the Coulumn part of the potential

$$V(r) \sim \cancel{\frac{\alpha_s}{r}} + \kappa r$$

This gives a so-called Yoyo mode. With the maximal distance between quark is $L$, a hadron with mass $m = \kappa L$ can be produced.



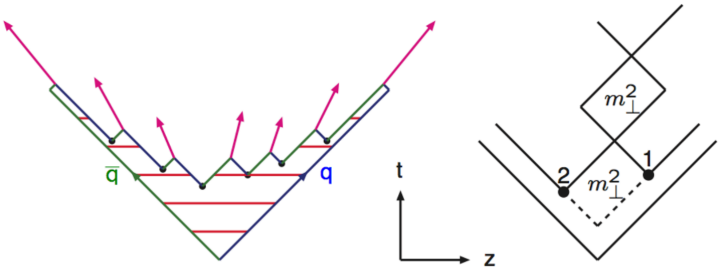

(a)

[C. Bierlich *et al.*, 2022]

# The String Model

## 2 The String Model

A string can be broken to two strings if $L_1 + L_2 < L$, by producing a (di-)$q\bar{q}$ from vacuum.




Since the Yoyo motion should be in a boosted frame, we have:

$$\frac{m_i^2}{\kappa^2} = (x_i - x_{i-1})^2 - (t_i - t_{i-1})^2$$

# The String Model



A hadron can take a fraction (z) of total momentum. The distribution of $z$ is given by the fragmentation function:

$$f(z) \propto \frac{(1-z)^a}{z} \exp(-\frac{bm_\perp^2}{z}),$$

where $a$ and $b$ are two free parameters in $[0.0, 2.0]$.
Principlely, $a$ can be different for each flavour. Going from flavour $i$ to flavour $j$, the fragmentation function is modified to

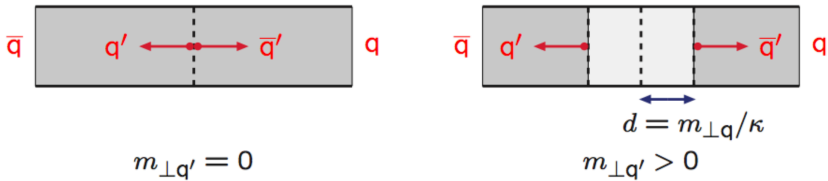
$$f(z) \propto \frac{z^{a_i}}{z} \frac{(1-z)^{a_j}}{z} \exp(-\frac{bm_\perp^2}{z}).$$

For massive quarks, we have:

$$f(z) \propto \frac{z^{a_\alpha}}{z^{1+r_Q bm_Q^2}} \frac{(1-z)^{a_\beta}}{z} \exp(-\frac{bm_\perp^2}{z}).$$

# The String Model

A massive $q\bar{q}$ cannot be produced in a single vertex, but can tunnel to real quark pair by tunneling a distance $m_\perp/\kappa$.




The tunneling probability is given by

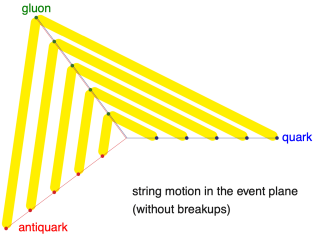
$$P \propto \exp(-\pi m_\perp^2) = \exp(-\pi m^2/\kappa)\exp(-\pi p_\perp/\kappa).$$

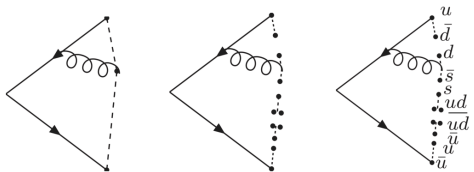
Suppressions of heavy quarks are:

$$P(u\bar{u}, d\bar{d}) : P(s\bar{s}) : P(c\bar{c}) \approx 1 : 0.3 : 10^{-11}$$

# The String Model

## 2 The String Model




Gluon is a kink on string, carrying energy and momentum.
No new parameters are introduced for gluon jets.

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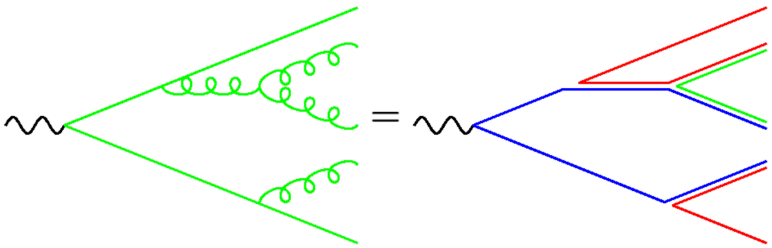
# The Cluster Model



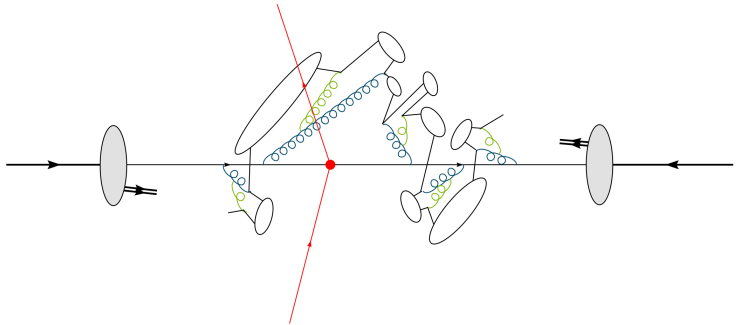
Colour preconfinement:



Parton shower organizes partons in colour space. Colour partners (=colour singlet pairs) end up close in phase space.

# The Cluster Model

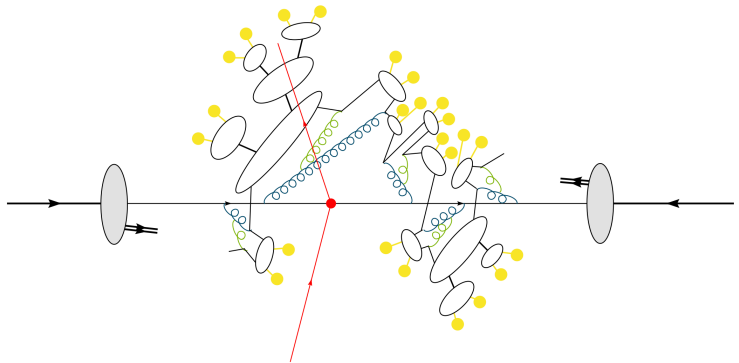
## 3 The Cluster Model



- Gluons are decayed to $q\bar{q}$ nonperturbatively.
- Colour singlet clusters are forms by colour connected parton pairs.

# The Cluster Model





- Heavy clusters (with mass $M$) are splitted to light clusters when

$$M^P \quad \geq \quad C^P + (m_1 + m_2)^P,$$

where $C$ and $P$ are model parameters.

# The Cluster Model



When a heavy cluster is splitted, a $q\bar{q}$ ($q = u, d, s$ with mass $m_q$) pair is selected to be popped from the vacuum. Masses of new clusters are given by

$$M_i = m_i + (M - m_i - m_q)R_i^{1/x}, (i = 1, 2)$$

where $R_i$ is a random number in $[0, 1]$, and $x$ is a parameter.
If the cluster contains a remnant of the beam particles, the mass is given by

$$M_i = m_i + m_q + y,$$

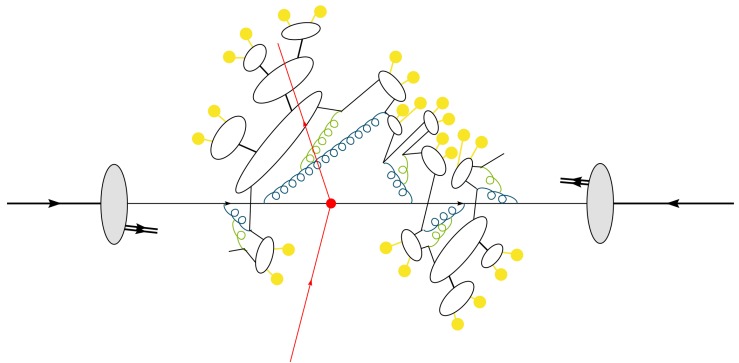
where $y$ is distributed between 0 and $M - m_1 - m_2 - 2m_q$ according to

$$\frac{dP}{dy^2} = \exp(-by)$$

where $b$ is a parameter.

# The Cluster Model





- A cluster is decayed to two hadrons, based on the available phase space, spin and flavour.
- If the energy of cluster is not sufficient to decay to two hadron, it decays to one.

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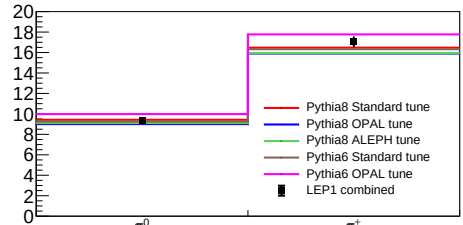
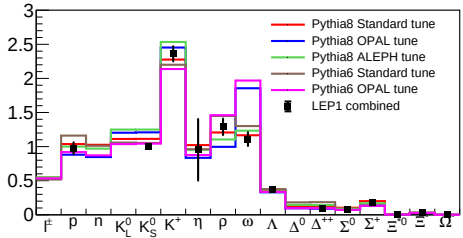
# Tuning

4 Tuning

- Perturbative parton shower only few parameters.
- In contrast, non-perturbative Hadronization has many parameters.
- We have to optimize paramaters based on well-measured data.



# Tuning

4 Tuning

Tuning methods:

- Manual Tuning
- Automatic method: Professor [A. Buckley *et al.*, 2010]

A good tune should have:

- Physically sensible parameter values, with good universality.
- Good agreement with data.
- Reliable uncertainties.
- Best fit for our observables.

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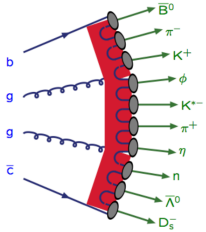
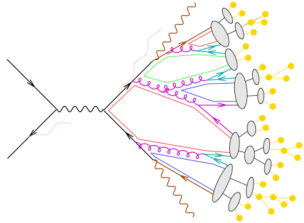
# Summary





| program | PYTHIA | Herwig |
|---|---|---|
| model | string | cluster |
| energy–momentum picture | powerful | simple |
| | predictive | unpredictive |
| parameters | few | many |
| flavour composition | messy | simple |
| | unpredictive | in-between |
| parameters | many | few |

# Q&A

*Thank you for listening!*
*Your feedback will be highly appreciated!*