Monte Carlo Event Generators

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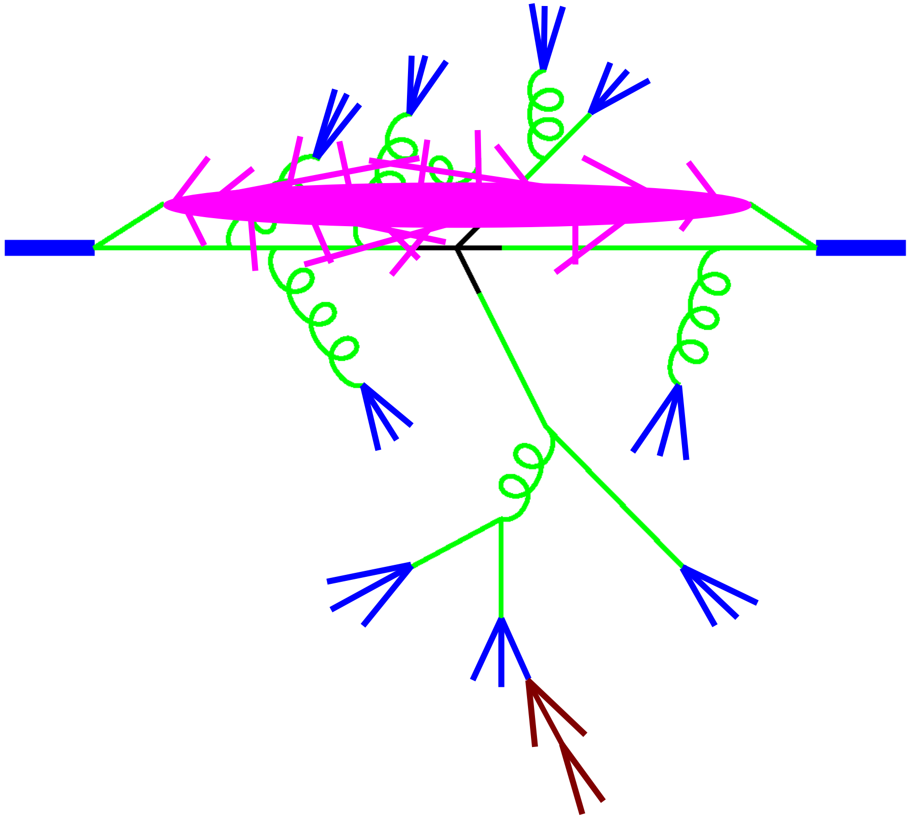
Structure of LHC Events

1. Hard process
2. Parton shower
3. Hadronization
4. Underlying event
5. Unstable particle decays



Parton Showers: Introduction

QED: accelerated charges radiate.

QCD identical: accelerated colours radiate.

gluons also charged.

→ cascade of partons.

= parton shower.

1. e^+e^-annihilation to jets.
2. Universality of collinear emission.
3. Sudakov form factors.
4. Universality of soft emission.
5. Angular ordering.
6. Initial-state radiation.
7. Hard scattering.
8. Heavy quarks.
9. Dipole cascades.

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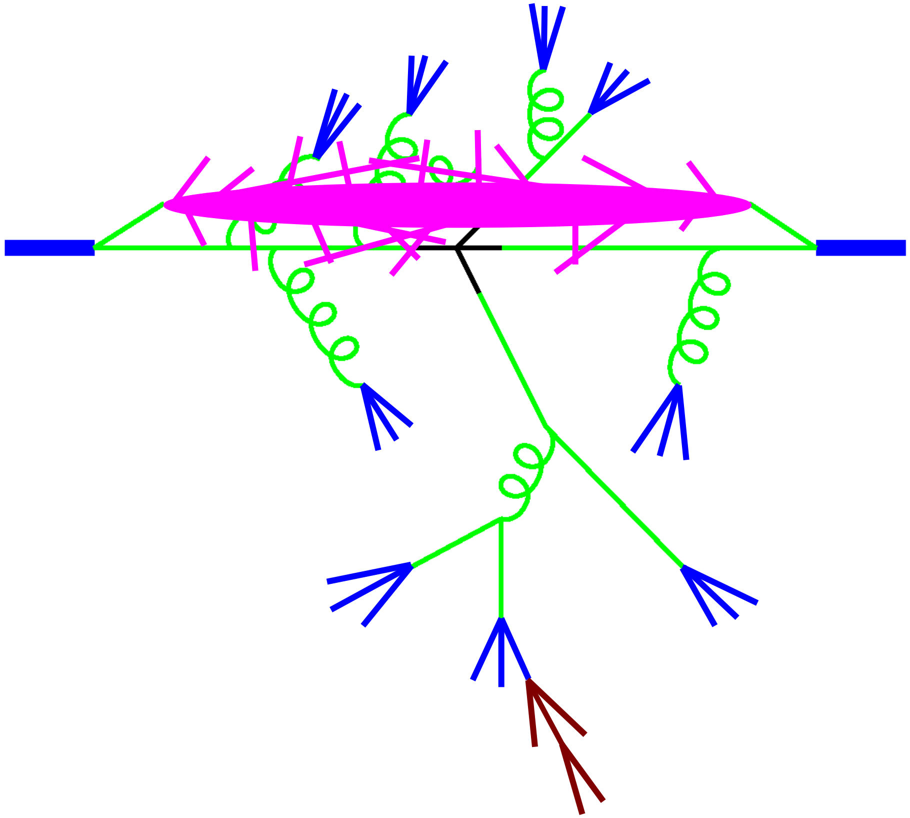


Hadronization: Introduction

Partons are not physical particles: they cannot freely propagate.

Hadrons are.

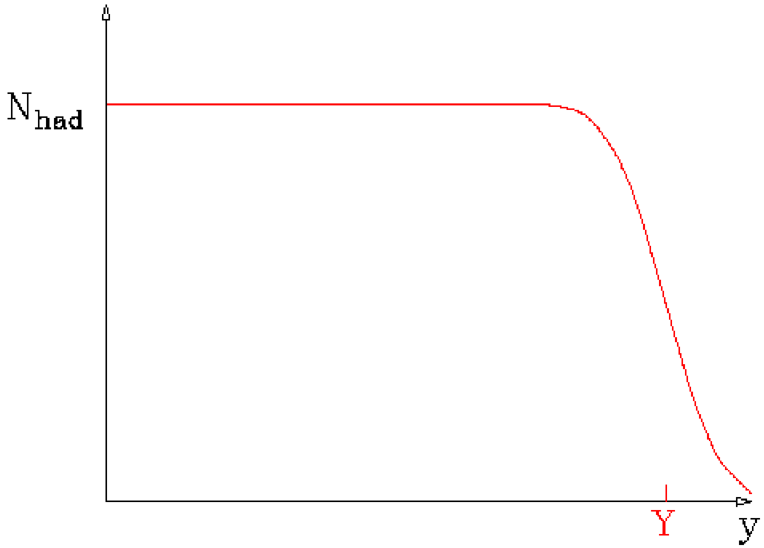
Need a model of partons' confinement into hadrons: hadronization.

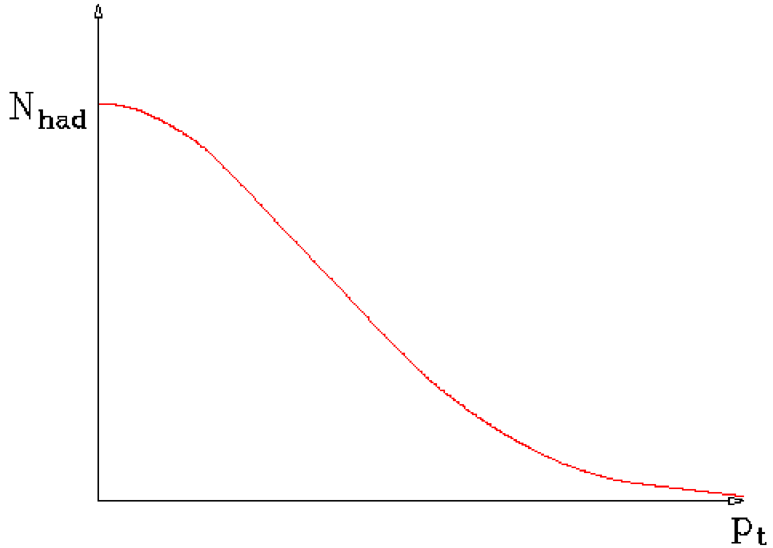
1. Phenomenological models.
2. Confinement.
3. The string model.
4. Preconfinement.
5. The cluster model.
6. Secondary decays.
7. Underlying event models.

Phenomenological Models

Experimentally, $e^+e^- \rightarrow$ two jets:

Flat rapidity plateau and limited p_t, $\rho(p_t^2) \sim e^{-p_t^2/2p_0^2}$





Estimate of Hadronization Effects

Using this model, can estimate hadronization correction to perturbative quantities.

Jet energy and momentum:

$$E = \int_0^Y dy\, d^2p_t\, \rho(p_t^2)\, p_t\, \cosh y = \lambda \sinh Y$$

$$P = \int_0^Y dy\, d^2p_t\, \rho(p_t^2)\, p_t\, \sinh y = \lambda(\cosh Y - 1) \sim E - \lambda,$$

with $\lambda = \int d^2p_t\, \rho(p_t^2)\, p_t,$ mean transverse momentum.

Estimate from Fermi motion $\lambda \sim 1/R_{had} \sim m_{had}$.

Jet acquires non-perturbative mass: $M^2 = E^2 - P^2 \sim 2\lambda E$

Large: ~ 10 GeV for 100 GeV jets.

Independent Fragmentation Model ("Feynman—Field")

Direct implementation of the above.

Longitudinal momentum distribution = arbitrary fragmentation function: parameterization of data.

Transverse momentum distribution = Gaussian.

Recursively apply $q \to q' + \mathrm{had}.$

Hook up remaining soft q and $\bar{q}$.

Strongly frame dependent.

No obvious relation with perturbative emission.

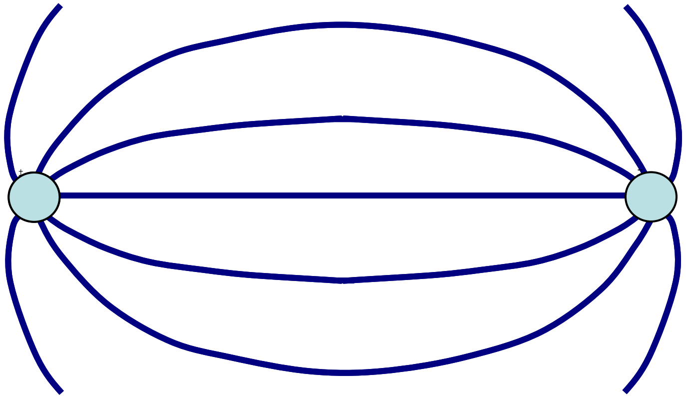
Not infrared safe.

Not a model of confinement.

Confinement

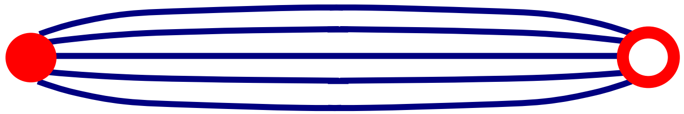
Asymptotic freedom: $Q\bar{Q}$ becomes increasingly QED-like at short distances.

QED:



but at long distances, gluon self-interaction makes field lines attract each other:

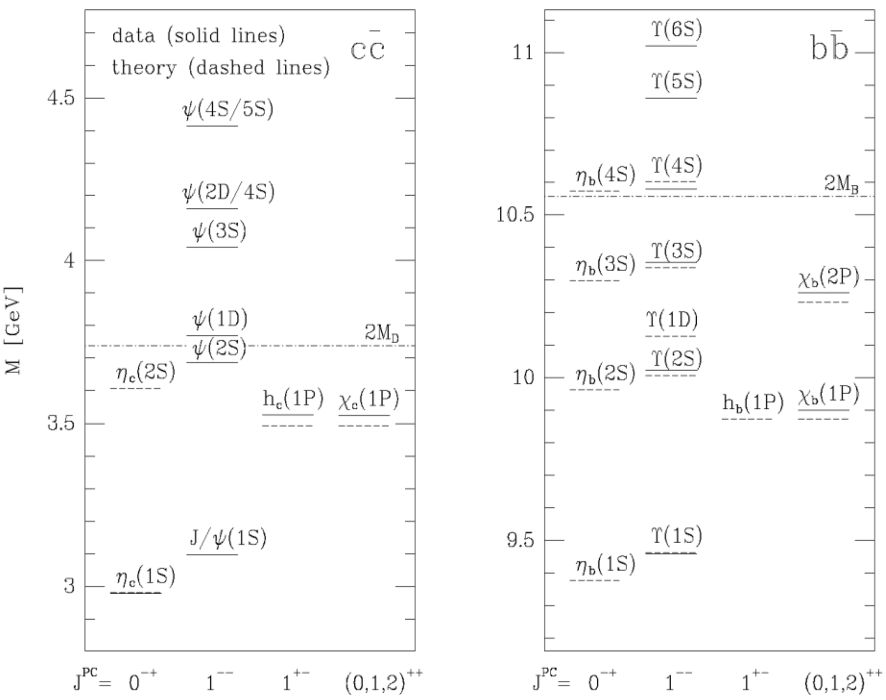
QCD:



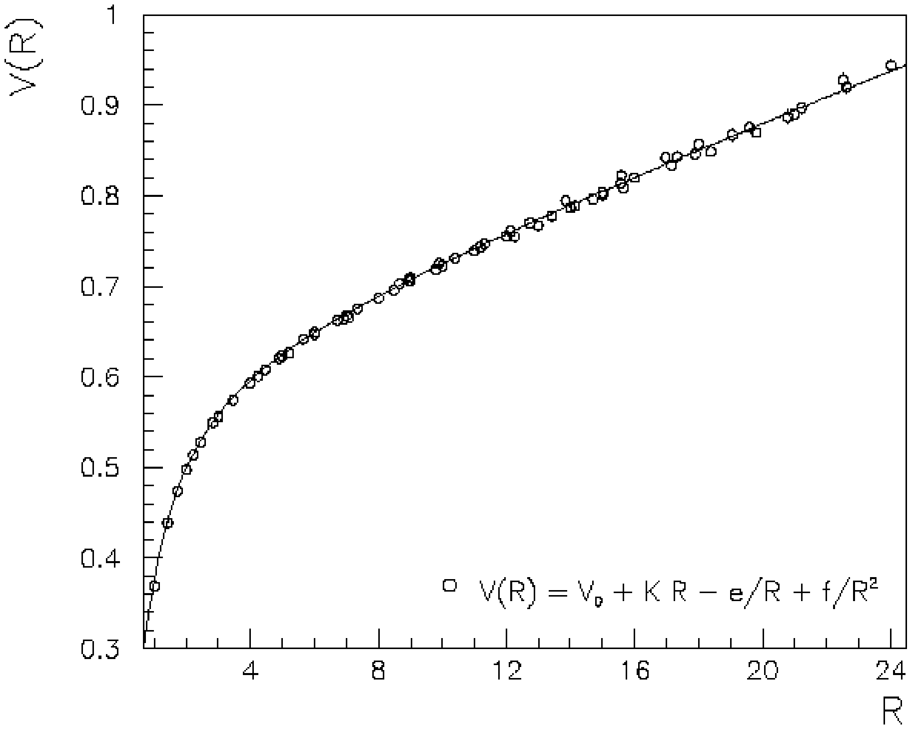
→linear potential → confinement

Interquark potential

Can measure from quarkonia spectra:



or from lattice QCD:



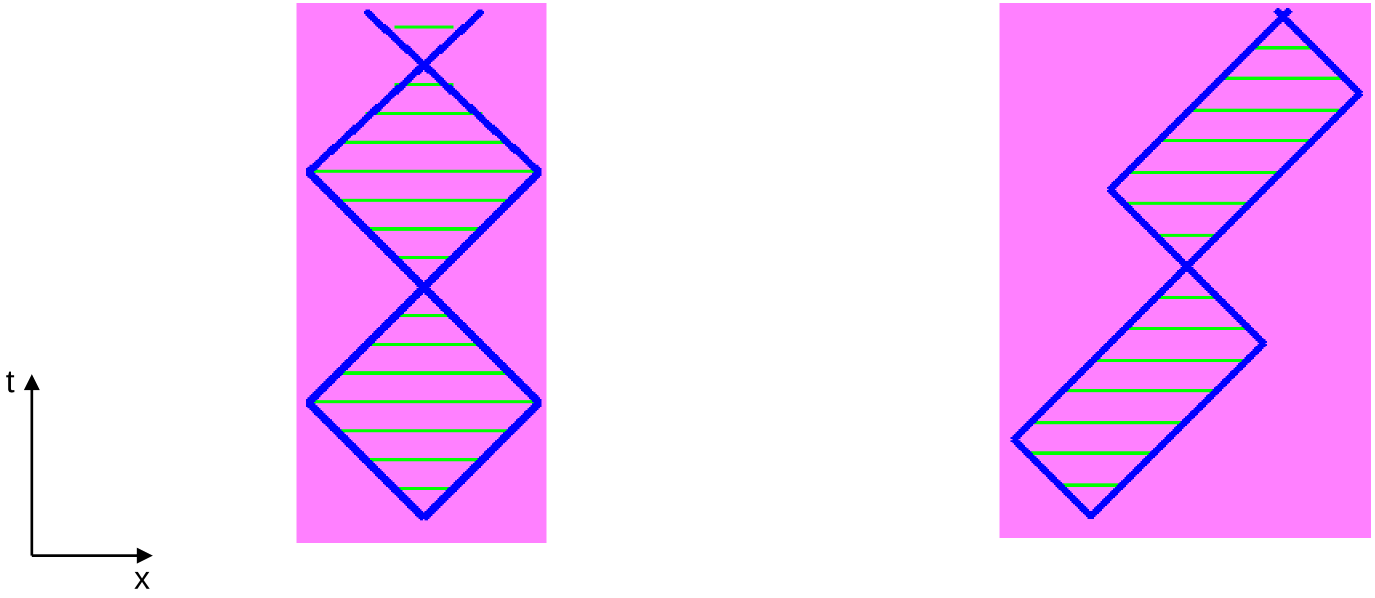
→ String tension

$$\kappa \approx 1\ \mathrm{GeV/fm}.$$

String Model of Mesons

Light quarks connected by string.

L=0 mesons only have 'yo-yo' modes:



Obeys area law: $m^2 = 2\kappa^2 \text{ area}$

The Lund String Model

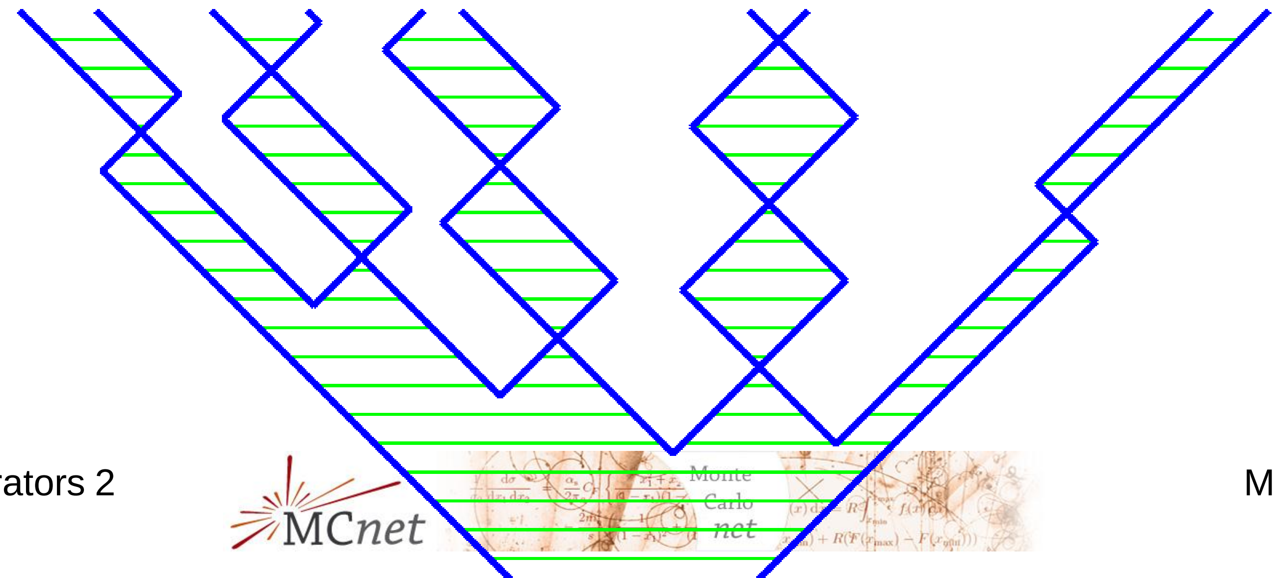
Start by ignoring gluon radiation:

e^+e^- annihilation = pointlike source of $q\bar{q}$ pairs

Intense chromomagnetic field within string → $q\bar{q}$ pairs created by tunnelling. Analogy with QED:

$$\frac{d(\text{Probability})}{dx\ dt} \propto \exp(-\pi m_q^2/\kappa)$$

Expanding string breaks into mesons long before yo-yo point.



Lund Symmetric Fragmentation Function

String picture → constraints on fragmentation function:

- Lorentz invariance
- Acausality
- Left—right symmetry

$$f(z) \propto z^{a_\alpha - a_\beta - 1}(1-z)^{a_\beta}$$

$a_{\alpha,\beta}$ adjustable parameters for quarks α and β.

Fermi motion → Gaussian transverse momentum.

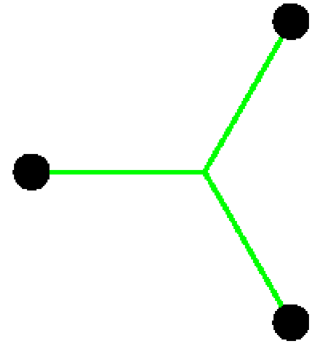
Tunnelling probability becomes

$$\exp\left[-b(m_q^2 + p_t^2)\right]$$

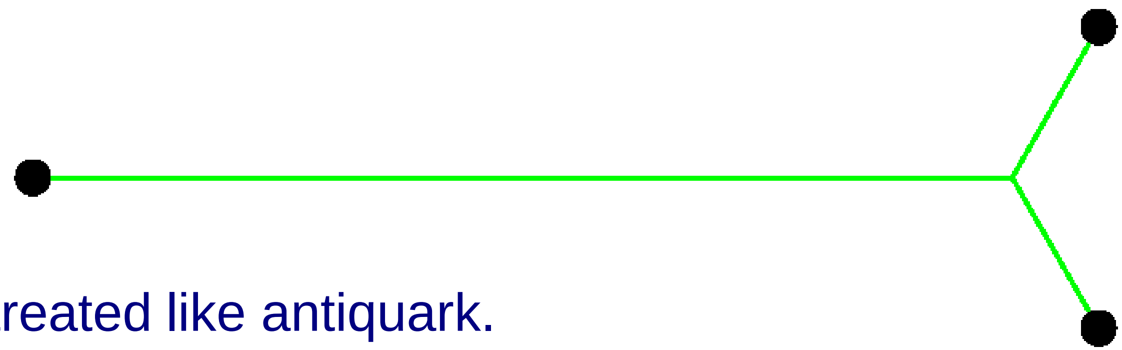
a, b and m_q^2 = main tuneable parameters of model

Baryon Production

Baryon pictured as three quarks attached to a common centre:



At large separation, can consider two quarks tightly bound: diquark



→ diquark treated like antiquark.

Two quarks can tunnel nearby in phase space: baryon—antibaryon pair

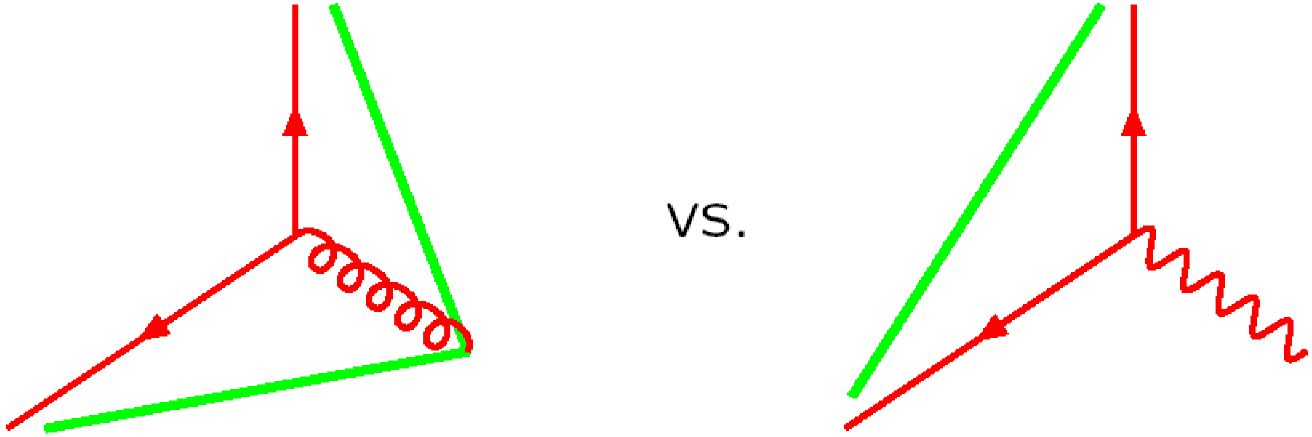
Extra adjustable parameter for each diquark!

Three-jet Events

So far: string model = motivated, constrained independent fragmentation!

New feature: universal

Gluon = kink on string → the string effect



Infrared safe matching with parton shower: gluons with $k_\perp <$ inverse string width irrelevant.

String Summary

- String model strongly physically motivated.
- Very successful fit to data.
- Universal: fitted to e^+e^- little freedom elsewhere.

- How does motivation translate to prediction?
  ~ one free parameter per hadron/effect!

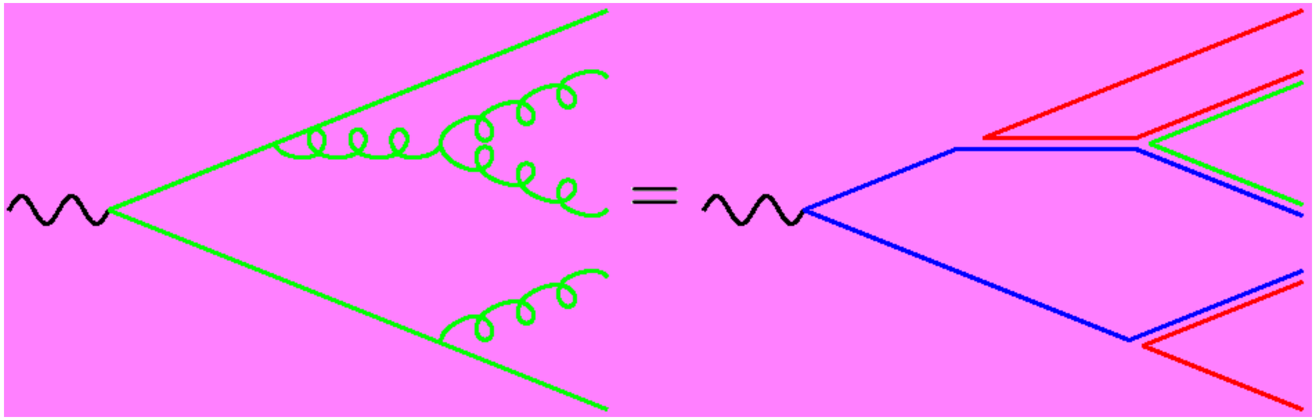
- Blankets too much perturbative information?

- Can we get by with a simpler model?

Preconfinement

Planar approximation: gluon = colour—anticolour pair.

Follow colour structure of parton shower: colour-singlet pairs end up close in phase space

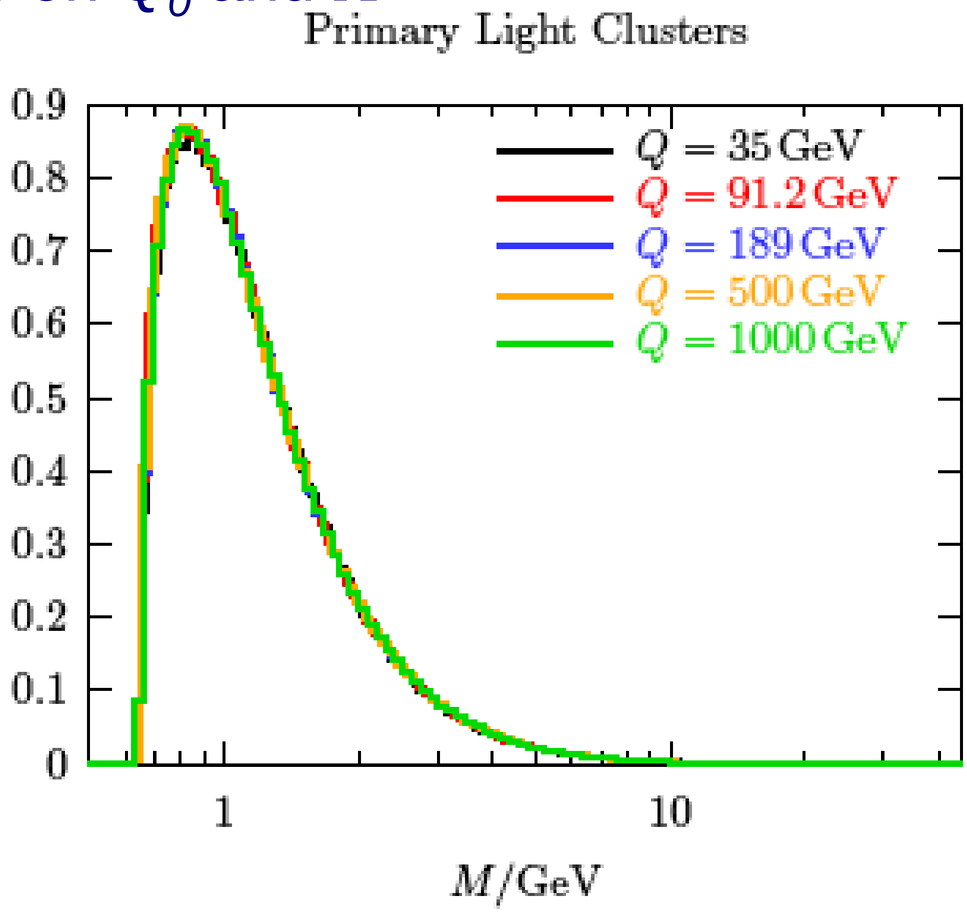


Mass spectrum of colour-singlet pairs asymptotically independent of energy, production mechanism, …

Peaked at low mass $\sim Q_0$.

Cluster mass distribution

- Independent of shower scale Q
  - depends on Q_0 and Λ



The Naïve Cluster Model

Project colour singlets onto continuum of high-mass mesonic resonances (=clusters). Decay to lighter well-known resonances and stable hadrons.

Assume spin information washed out:

decay = pure phase space.

→ heavier hadrons suppressed

→ baryon & strangeness suppression 'for free' (i.e. untuneable).

Hadron-level properties fully determined by cluster mass spectrum, i.e. by perturbative parameters.

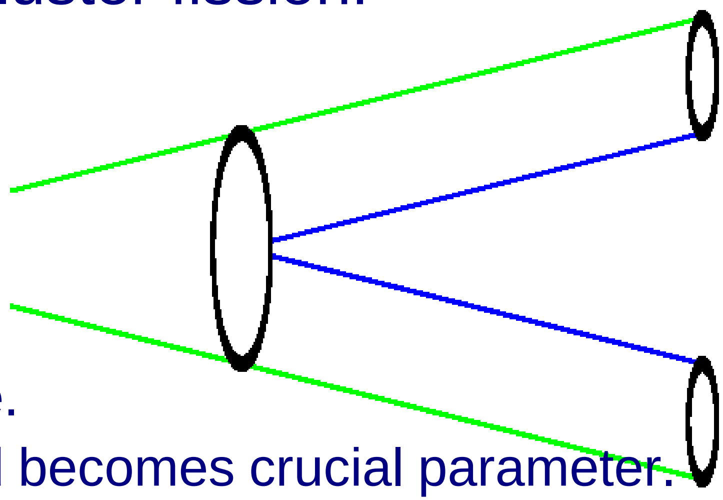
Q_0 crucial parameter of model.

The Cluster Model

Although cluster mass spectrum peaked at small m, broad tail at high m.

“Small fraction of clusters too heavy for isotropic two-body decay to be a good approximation”.

Longitudinal cluster fission:



Rather string-like.

Fission threshold becomes crucial parameter.

~15% of primary clusters get split but ~50% of hadrons come from them.

The Cluster Model

"Leading hadrons are too soft"

→ 'perturbative' quarks remember their direction somewhat

$$P(\theta^2) \sim \exp(-\theta^2/2\theta_0^2)$$

Rather string-like.

Extra adjustable parameter.

Strings

"Hadrons are produced by hadronization: you must get the non-perturbative dynamics right"

Improving data has meant successively refining perturbative phase of evolution…

Clusters

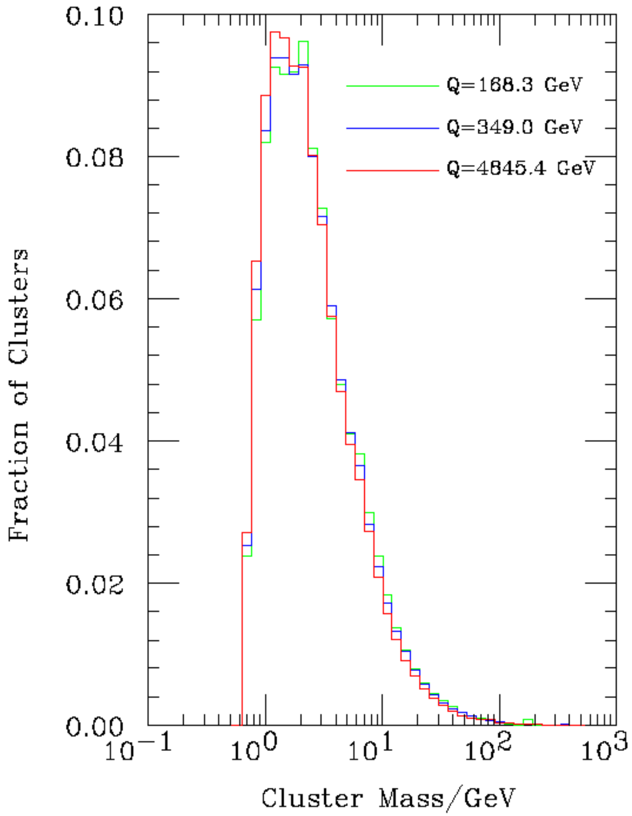
"Get the perturbative phase right and any old hadronization model will be good enough"

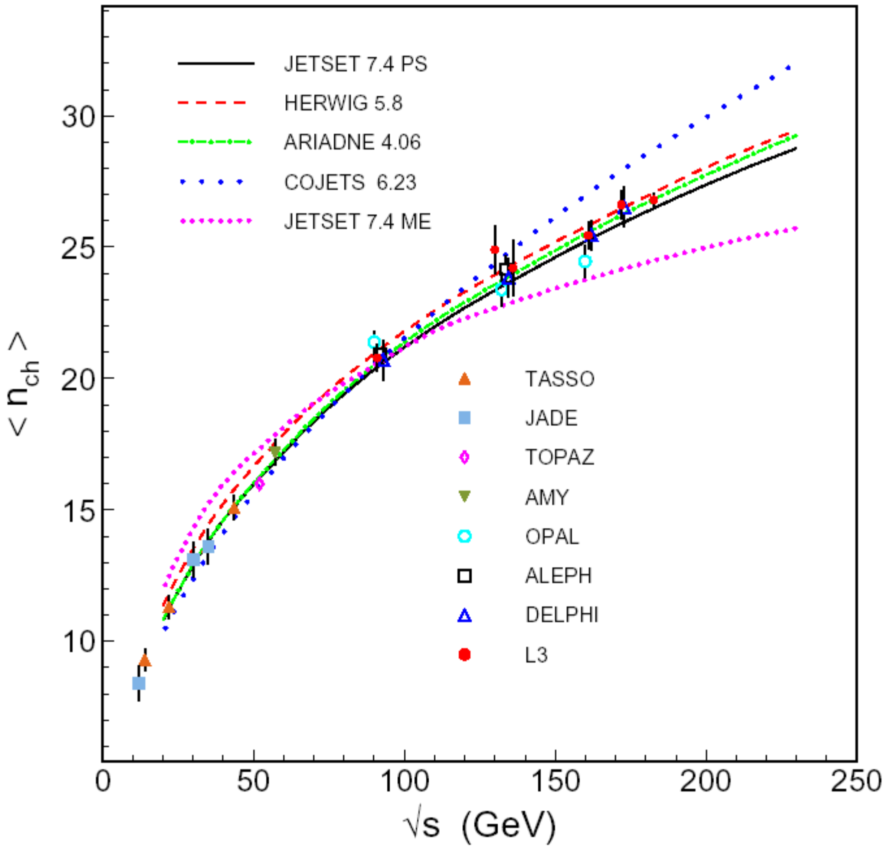
Improving data has meant successively making non-perturbative phase more string-like…

???

Universality of Hadronization Parameters

- Is guaranteed by preconfinement: do not need to retune at each energy





→ Only tune what's new in hadron—hadron collisions