Introduction

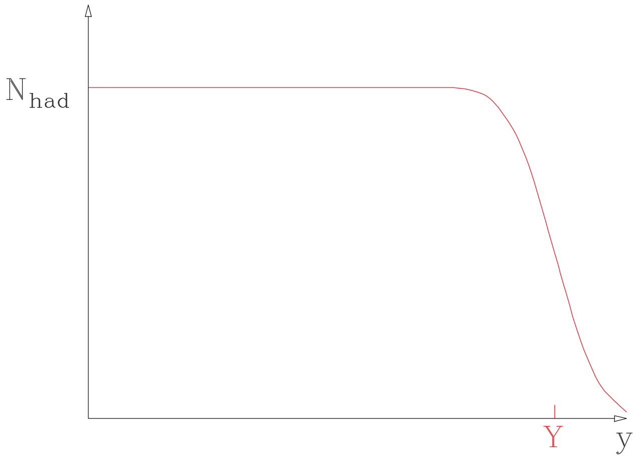
Partons are not physical particles:
they cannot freely propagate.
Hadrons are.

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

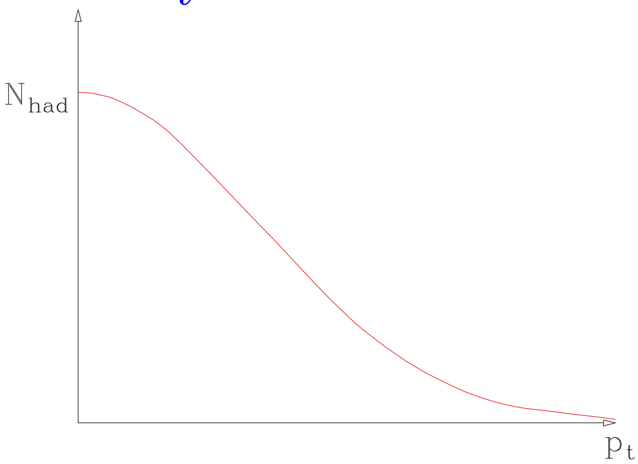
1) Phenomenological models.
2) Confinement.
3) The string model.
4) Preconfinement.
5) The cluster model.
6) Outstanding problems.

Phenomenological Models

Experimentally, $e^+e^- \to$ 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:

$$
\begin{aligned}
E &= \int_0^Y dy\, d^2p_t\, \rho(p_t^2)\, p_t\, \cosh y \\
&= \lambda \sinh Y \\
P &= \int_0^Y dy\, d^2p_t\, \rho(p_t^2)\, p_t\, \sinh y \\
&= \lambda(\cosh Y - 1) \sim E - \lambda,
\end{aligned}
$$

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

a.k.a. Feynman-Field

Direct implementation of above.

Longitudinal mtm distribution = arbitrary fragmentation function: parametrization of data.
Transverse mtm distribution = Gaussian.

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

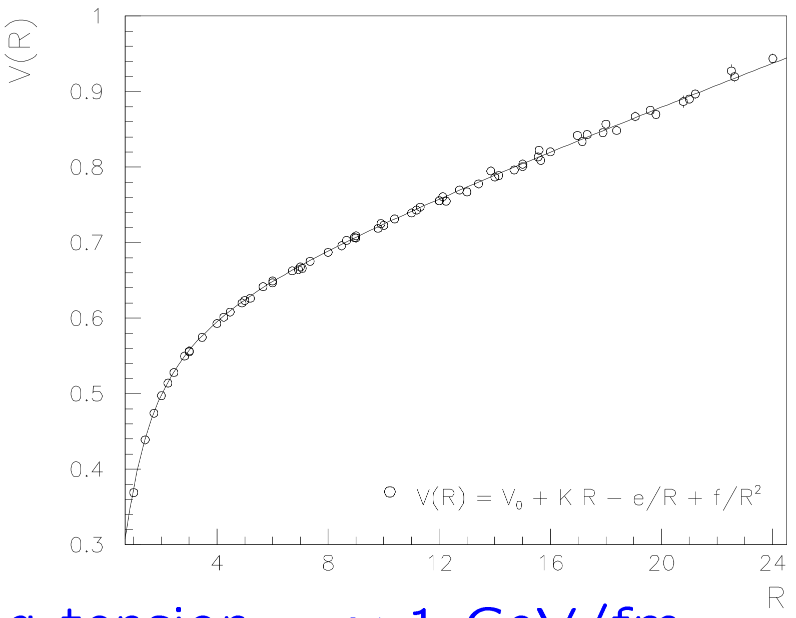
QCD:

$\rightarrow$ linear potential $\Rightarrow$ confinement.

Interquark potential

Can ‘measure’ from quarkonia spectra:

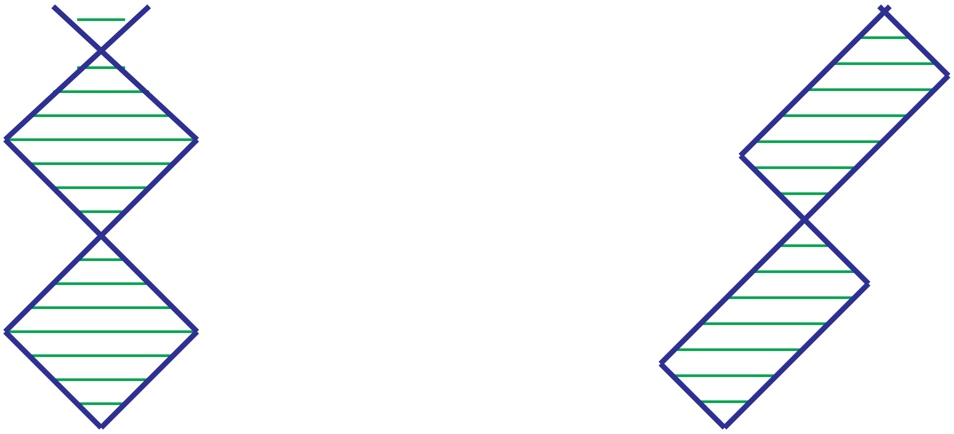
or from lattice QCD:



$\rightarrow$ string tension, $\kappa \approx 1$ GeV/fm.

String Model of Mesons

Light quarks connected by string.
$L = 0$ mesons only have 'yo-yo' modes:



Obeys area law: $m^2 = 2\kappa^2$ area

Find the energy and momentum carried by the string as a function of time in an arbitrary frame. Check the mass relation. Show that the string tension is Lorentz invariant.

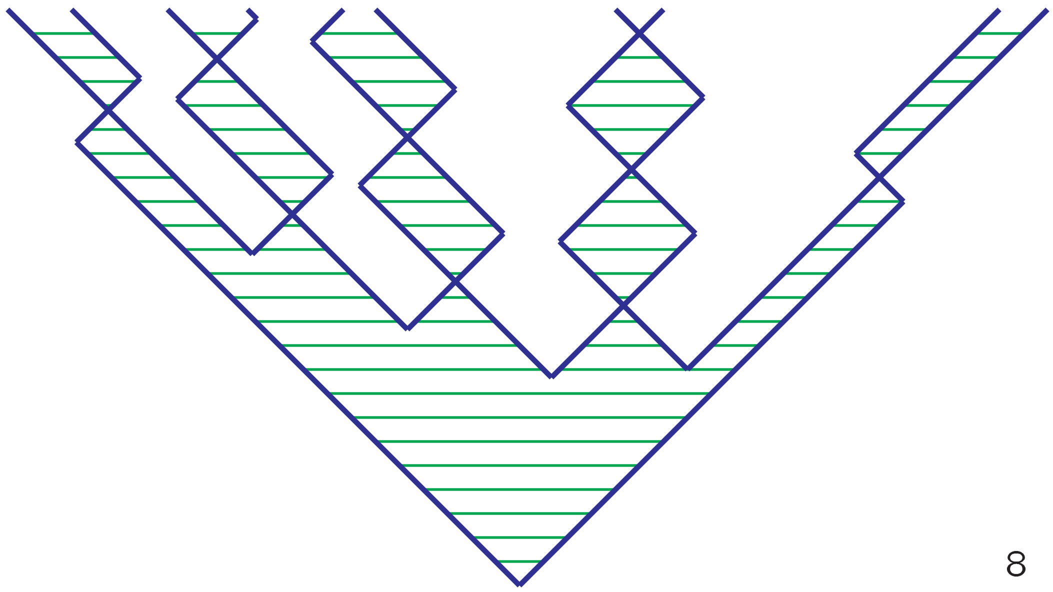
The Lund String Model

Start by ignoring gluon radiation:
e^+e^- annihilation = pointlike source of $q\bar{q}$ pairs

Intense chromomagnetic field within string
$\rightarrow$ quark-antiquark pairs created by tunnelling.
Analogy with QED:

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

Expanding string breaks up into hadrons long before its yo-yo point.



Lund Symmetric Fragmentation Function

String picture $\rightarrow$ constraints on fragmentation function:

– Lorentz covariance

– 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 $\rightarrow$ Gaussian transverse mtm.
Tunnelling probability becomes

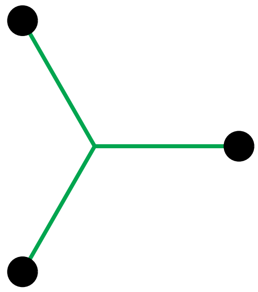
$$\exp\left[-b(m_q^2 + p_t^2)\right]$$

a, b main tunable parameters of model.
Also quark masses.

Show that Lund symmetric fragmentation function is symmetric.

Baryon Production

Baryon pictured as three quarks attached to a common centre:



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

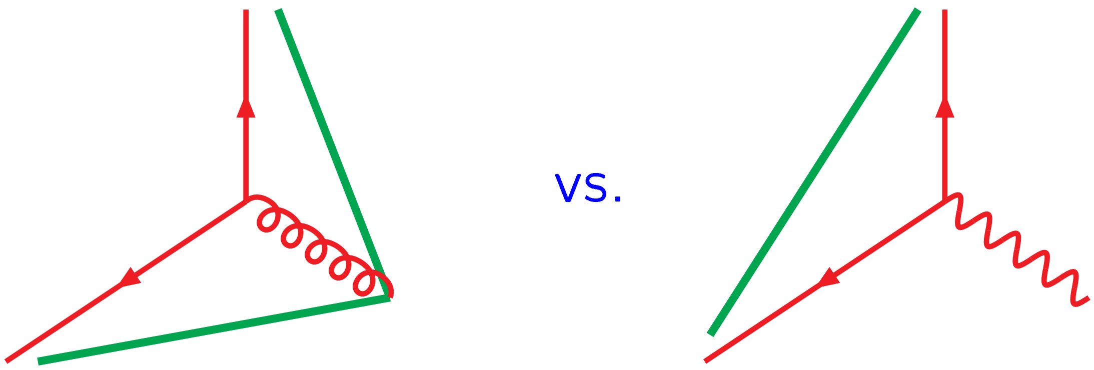
$\Rightarrow$ diquark treated like antiquark.

Two quarks can tunnel nearby in phase space – produce 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: gluons with $k_\perp <$ 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?
$\sim$ one free parameter per hadron/effect!

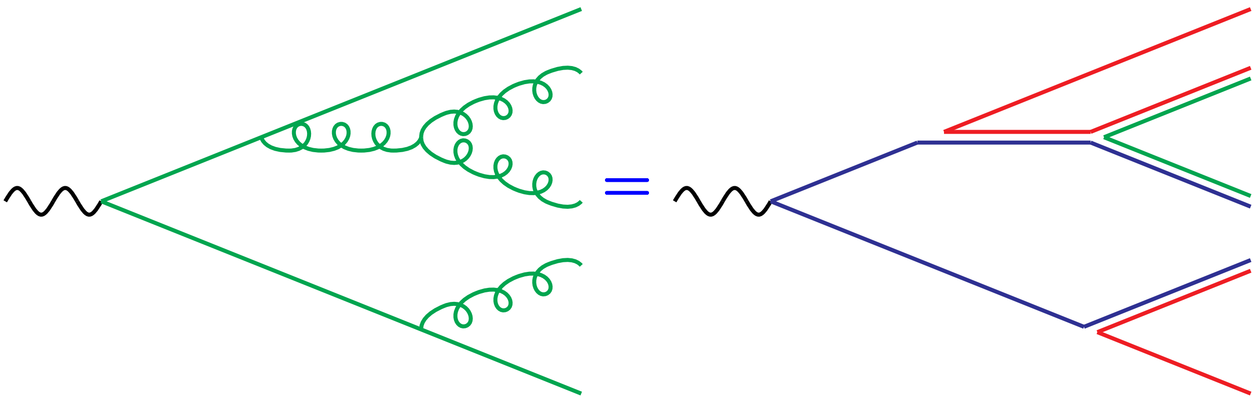
Blankets too much perturbative information?

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 $\sim Q_0$.

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.

$\Rightarrow$ heavier hadrons suppressed
$\rightarrow$ baryon & strangeness suppression
'for free' (i.e. untunable).

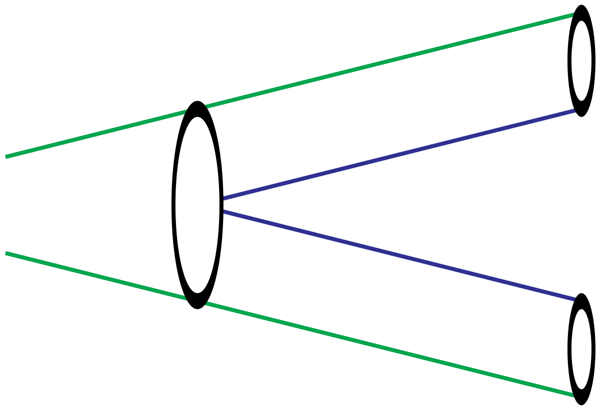
Hadron-level properties fully determined by cluster mass spectrum, i.e. by perturbative parameters.

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 decay to be a good approximation". Longitudinal cluster fission:



Rather stringlike.

Fission threshold becomes crucial parameter.

$\sim$ 15% of primary clusters get split
but $\sim$ 50% of hadrons come from them.

"Leading hadrons are too soft"

$\rightarrow$ 'perturbative' quarks remember their direction somewhat

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

Rather stringlike.

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 stringlike. . .

???

The Programs

ISAJET: Independent fragmentation, coupled with incoherent parton showers.

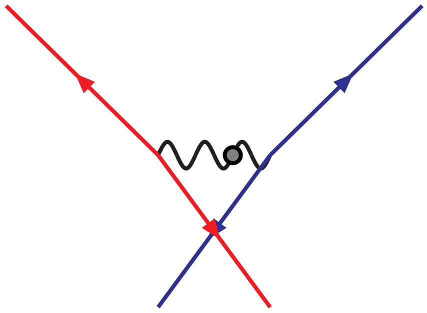
JETSET: THE implementation of the Lund string model. Used by (and now subsumed by) PYTHIA/LEPTO/ARIADNE... Excellent fit to e^+e^- data.

HERWIG: THE implementation of the cluster model. OK fit to e^+e^- data, but problems in several areas.

Outstanding Problems

1) Interconnection Effects in $e^+e^- \to W^+W^-$ and elsewhere.

WW events are a single source of hadrons.
$\tau_W \sim 0.1$ fm vs $\tau_{hadr} \sim 1$ fm.



Colour reconnection: 'strings' can 'unravel'
~ 50 MeV effect for MCs that fit LEP I
~ 100 MeV for J.Ellis and Geiger model???

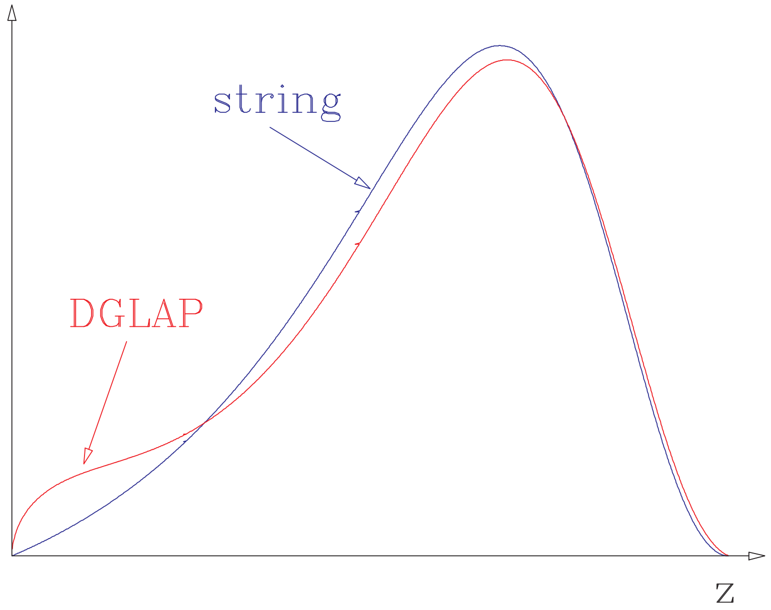
Bose-Einstein correlation:
π^0 are identical bosons $\Rightarrow$ attractive
'Worst case scenario' $\to$ 100 MeV shift.
Realistic?

Devise an experimental test to distinguish different interconnection models, and so improve the measurement of the W mass at LEP.

2) How real are strings?

Can we measure string drag effects uniquely?

eg charm quark spectrum in e^+e^-?



charm-anticharm asymmetries
in photoproduction?

The Future

Continual improvements. . .

Compromise between theoretical justification and phenomenological necessity.

between controllable/understandable models and good simulation of data.

Can better theoretical understanding of power corrections constrain/improve models?

Open up the black box:
when should it be reliable?
what physics is dominating?
is this a bug???