

Monte Carlo event generators for LHC physics

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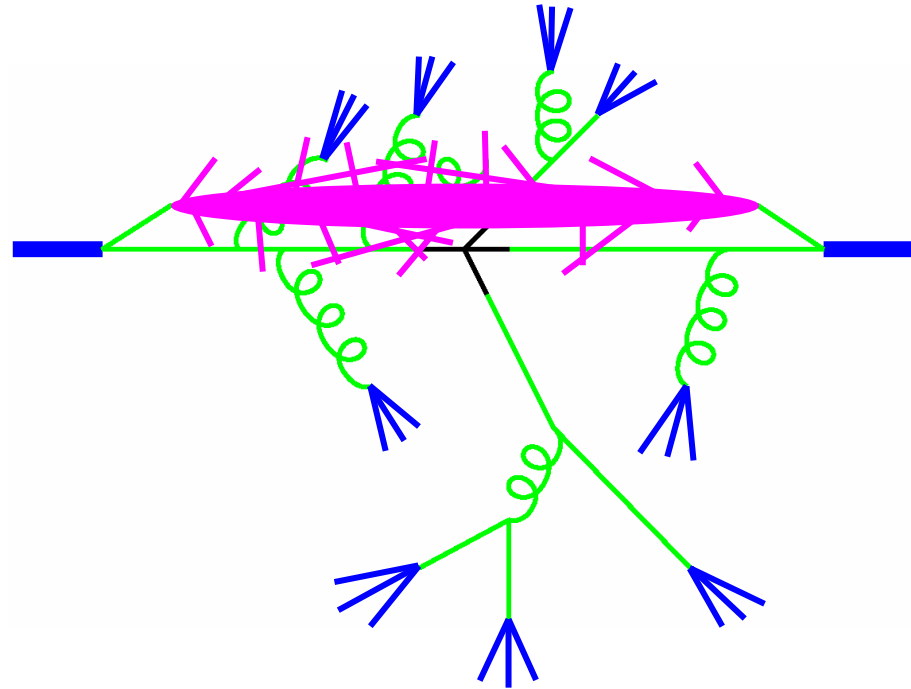
CERN Academic Training Lectures

July 7th – 11th 2003

<http://seymour.home.cern.ch/seymour/slides/CERNlectures.html>

Structure of LHC Events

1. Hard process
2. Parton shower
3. Hadronization
4. Underlying event



Monte Carlo for the LHC

1. Basic principles
2. Parton showers
3. Hadronization
4. Monte Carlo programs in practice
5. Questions and answers

Hadronization: Introduction

Partons are not physical particles: they cannot freely propagate.

Hadrons are.

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

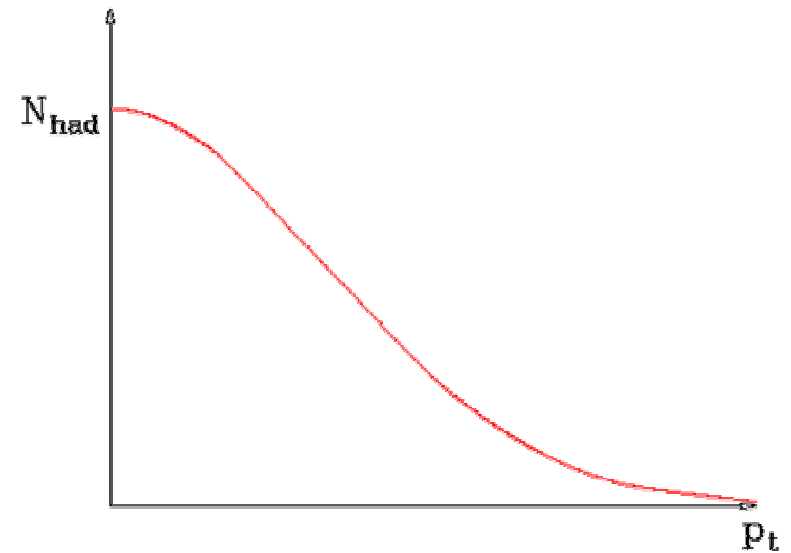
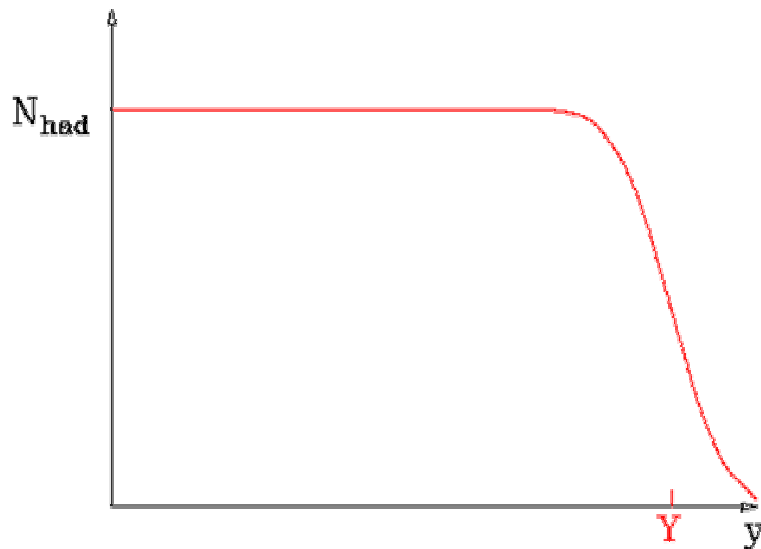
1. Phenomenological models.
2. Confinement.
3. The string model.
4. Preconfinement.
5. The cluster model.
6. Underlying event models.

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:

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

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

with $\lambda = \int d^2 p_t \rho(p_t^2) p_t$, 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 $q \rightarrow q' + \text{had.}$

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

Strongly frame dependent.

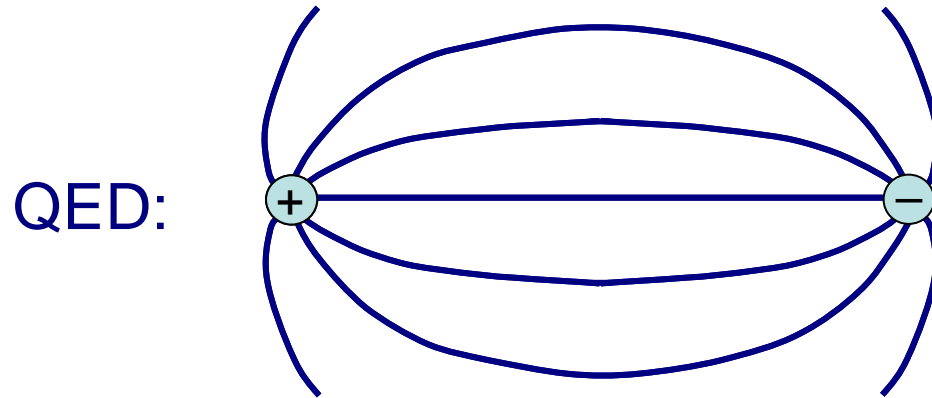
No obvious relation with perturbative emission.

Not infrared safe.

Not a model of confinement.

Confinement

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



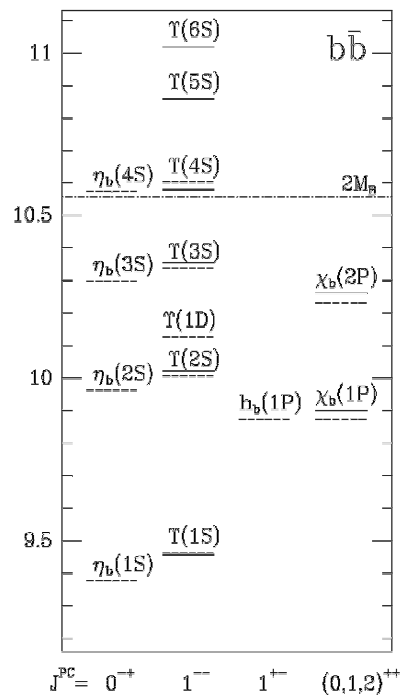
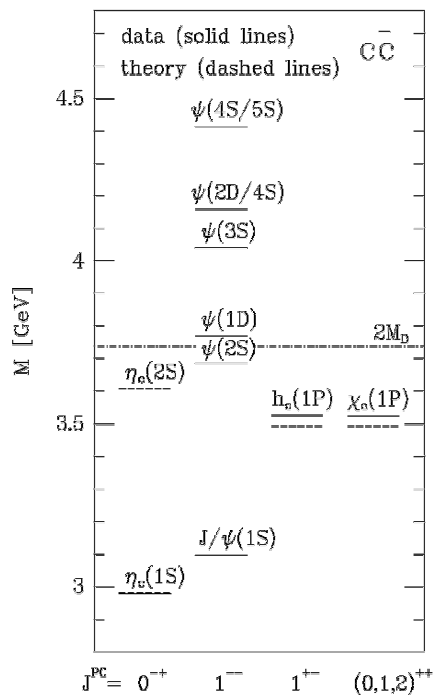
but at long distances, gluon self-interaction makes field lines attract each other:



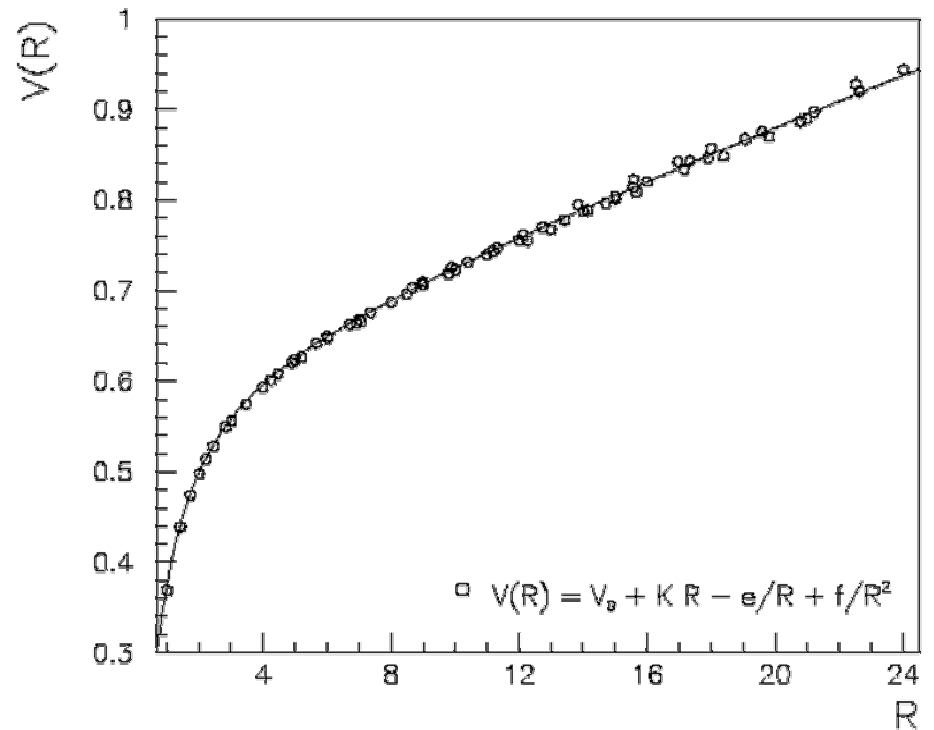
à linear potential à confinement

Interquark potential

Can measure from
quarkonia spectra:



or from lattice QCD:



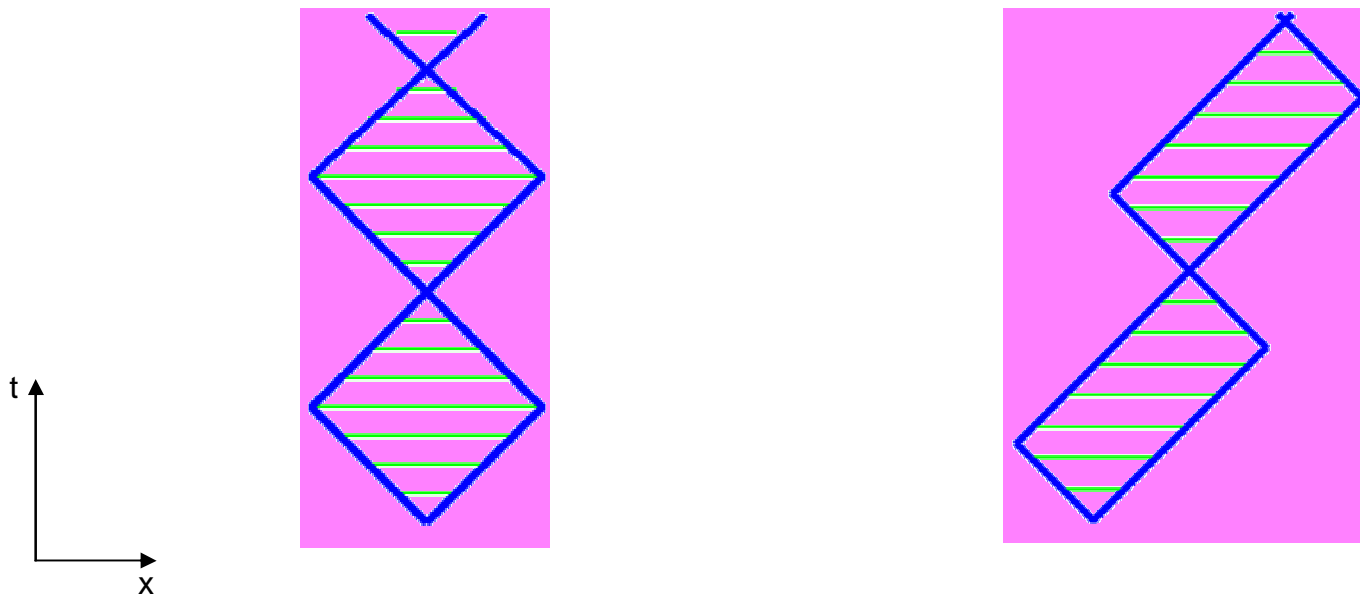
à String tension

$$K \approx 1 \text{ GeV/fm.}$$

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

The Lund String Model

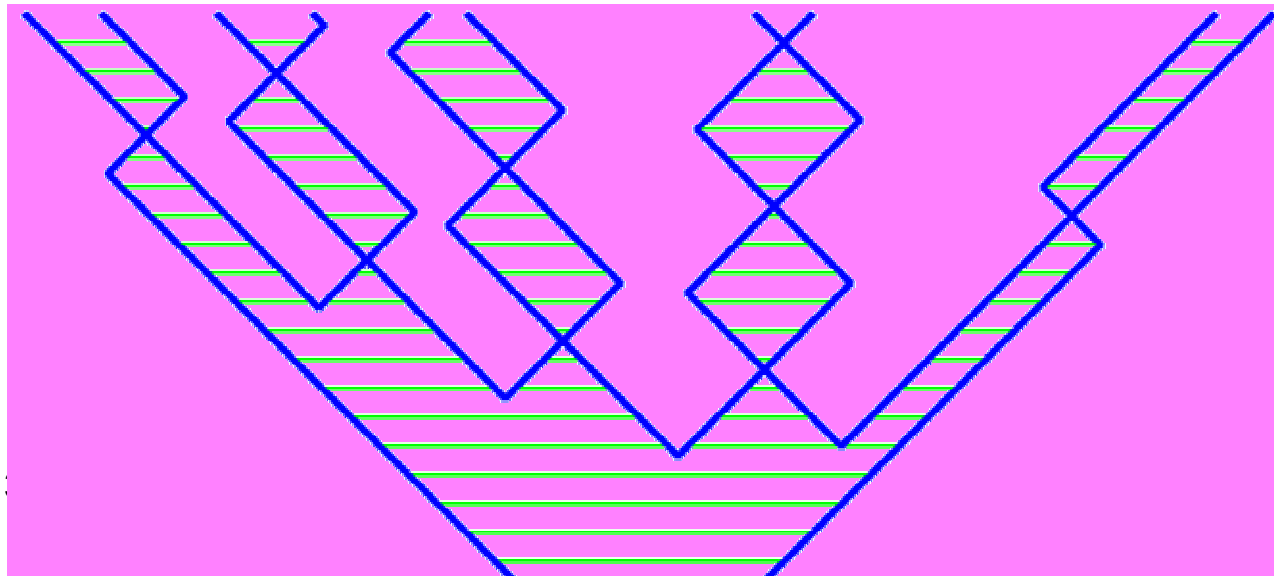
Start by ignoring gluon radiation:

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

Intense chromomagnetic field within string à $q\bar{q}$ 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 à 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 à Gaussian transverse momentum.

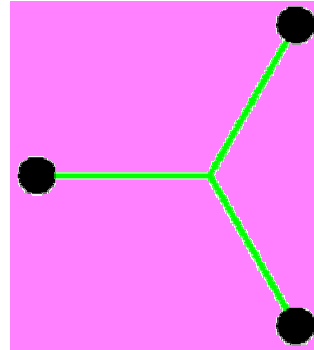
Tunnelling probability becomes

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

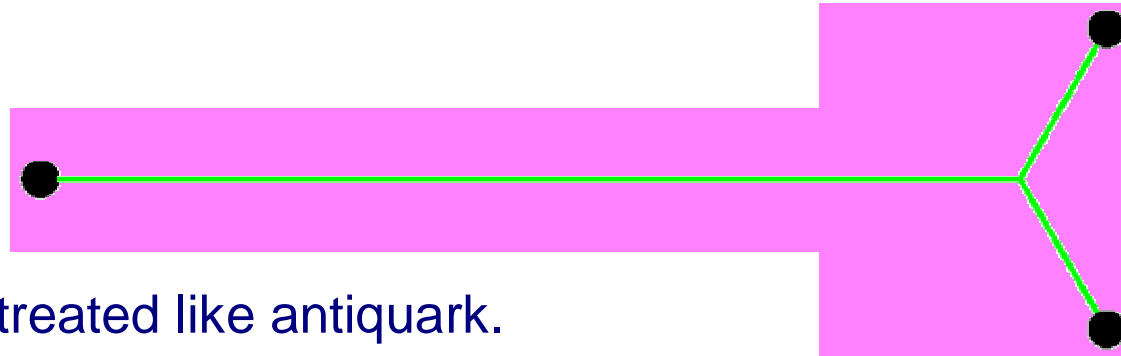
a, b and m_q^2 = main tuneable parameters of model

Baryon Production

Baryon pictured as three quarks attached to a common centre:



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



à diquark treated like antiquark.

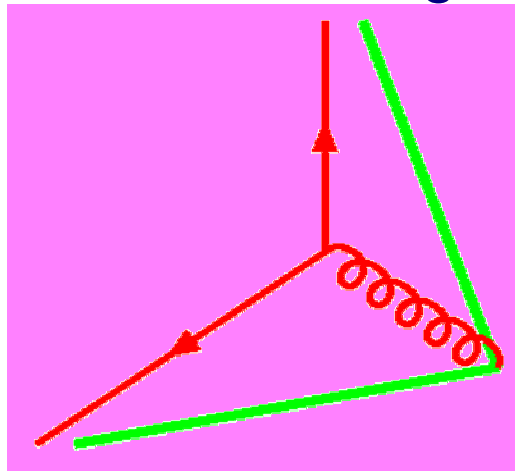
Two quarks can tunnel nearby in phase space: baryon—antibaryon pair
Extra adjustable parameter for each diquark!

Three-jet Events

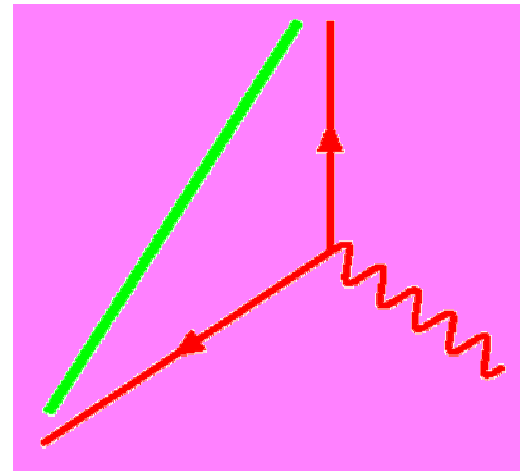
So far: string model = motivated, constrained independent fragmentation!

New feature: universal

Gluon = kink on string à the string effect



vs.



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

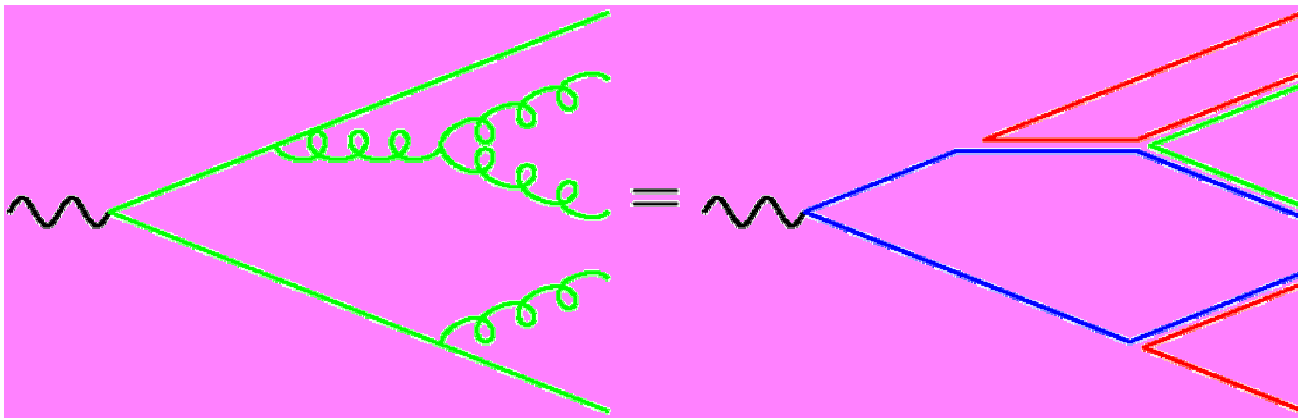
String Summary

- 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 $\sim Q_0$.

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.

à heavier hadrons suppressed

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

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

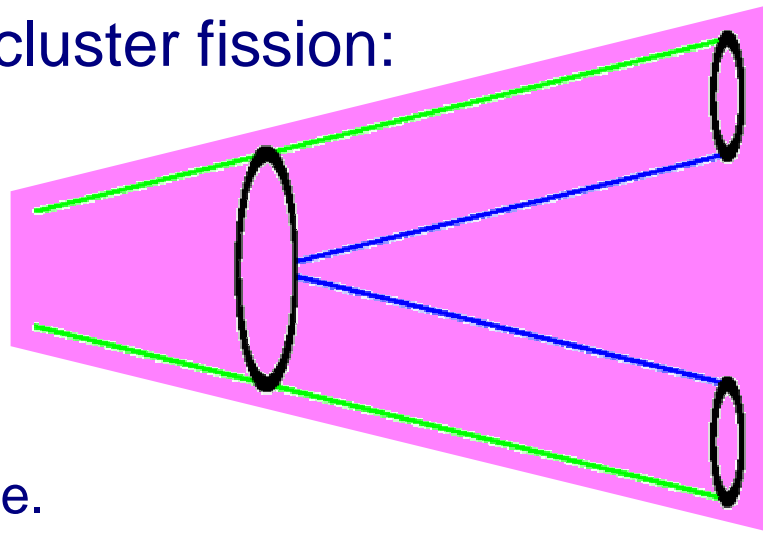
Q_0 crucial parameter of model.

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”

à ‘perturbative’ quarks remember their direction somewhat

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

Rather string-like.

Extra adjustable parameter.

Strings

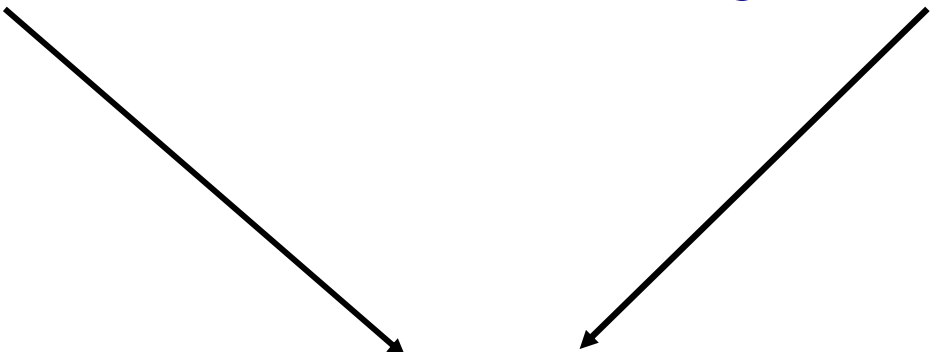
“Hadrons are produced by hadronization: you must get the non-perturbative dynamics right”

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”

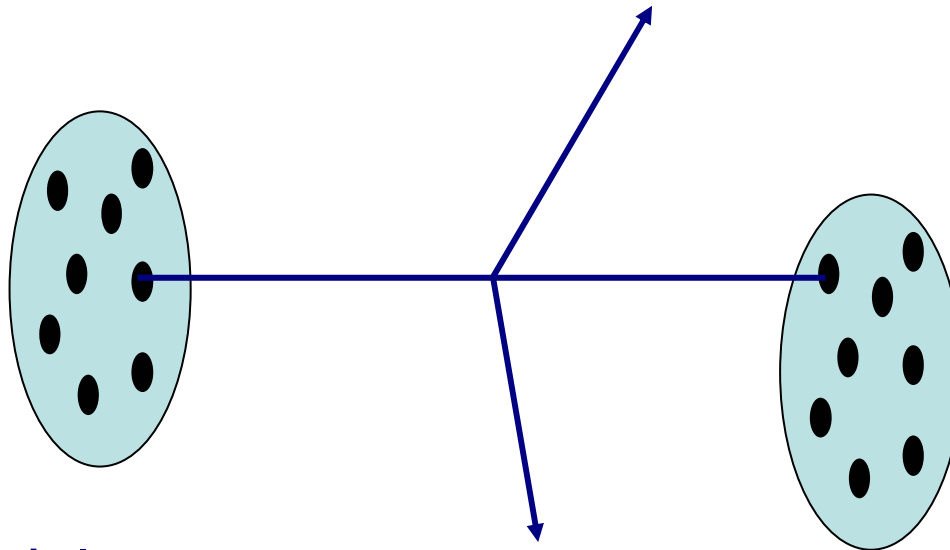
Improving data has meant successively making non-perturbative phase more string-like...



???

The Underlying Event

- Protons are extended objects
- After a parton has been scattered out of each, what happens to the remnants?

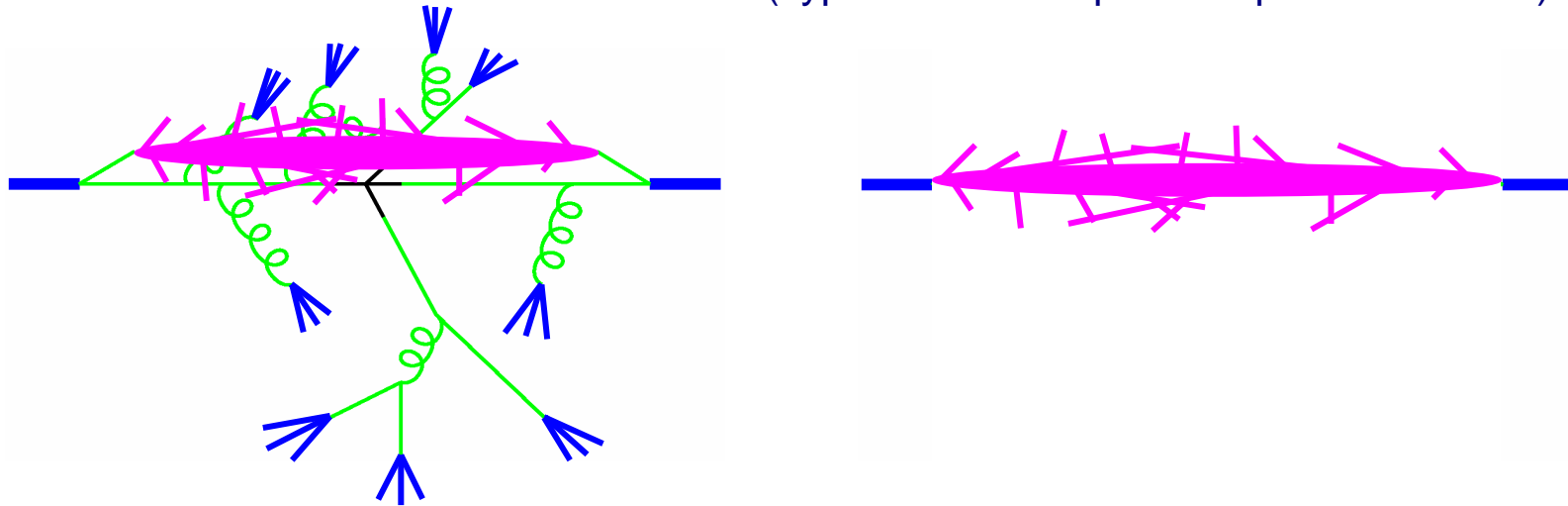


Two models:

- **Non-perturbative:** Soft parton—parton cross section is so large that the remnants always undergo a soft collision.
- **Perturbative:** ‘Hard’ parton—parton cross section huge at low p_t , high energy, dominates inelastic cross section and is calculable.

Soft Underlying Event Model (HERWIG)

Compare underlying event with 'minimum bias' collision
('typical' inelastic proton—proton collision)

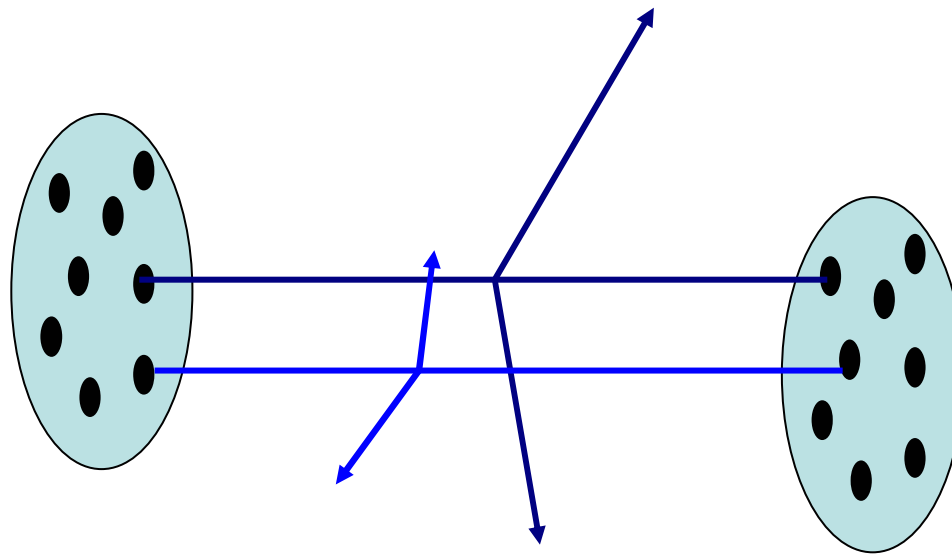


Parameterization of (UA5) data
+ model of energy-dependence

Multiparton Interaction Model (PYTHIA/JIMMY)

For small $p_{t \min}$ and high energy inclusive parton—parton cross section is larger than total proton—proton cross section.

à More than one parton—parton scatter per proton—proton

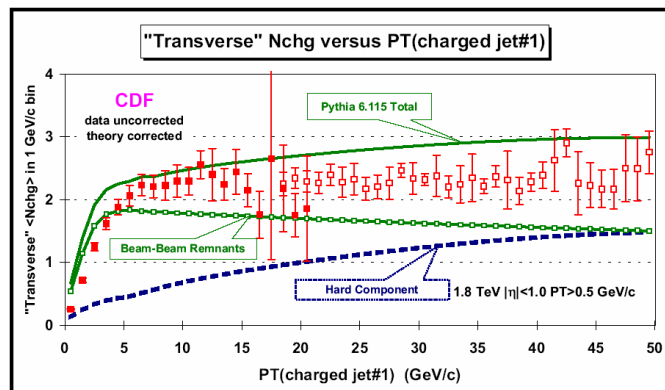
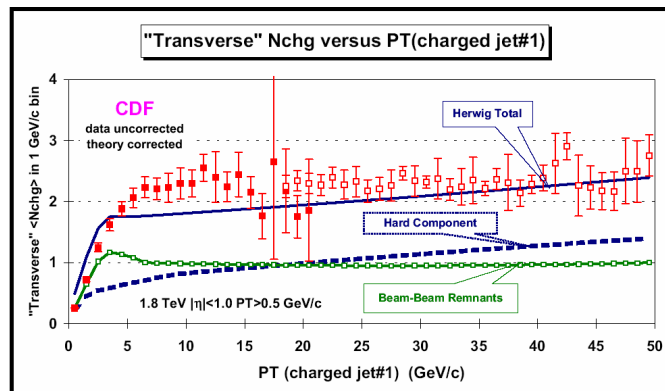
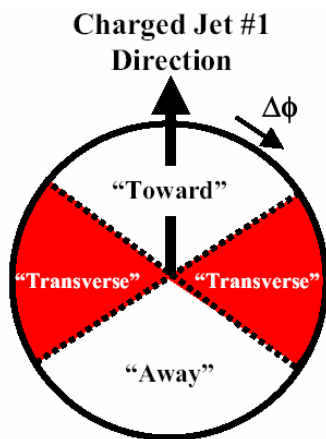


Need a model of spatial distribution within proton

à Perturbation theory gives you n-scatter distributions

Some Warnings

- Not everyone means same thing by “underlying event”
 - Remnant—remnant interaction
 - Everything except hard process final state
- Separation into model components is model dependent



MC for LHC 3

Mike Seymour

Summary

- Hard Process is very well understood: firm perturbative basis
- Parton Shower is fairly well understood: perturbative basis, with various approximations
- Hadronization is less well understood: modelled, but well constrained by data. Extrapolation to LHC ~ reliable.
- Underlying event least understood: modelled and only weakly constrained by existing data. Extrapolation?
- “What physics is dominating my effect?”

Reminder – FAQs

Lecture 5, Friday 11th July:
Question and Answer session

Email questions to: M.H.Seymour@rl.ac.uk

Cutoff: Thursday 10th July, 2pm

<http://seymour.home.cern.ch/seymour/slides/CERNlectures.html>