Monte Carlo Event Generators

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MCnet-LPCC Summer School

on Monte Carlo Event Generators for LHC

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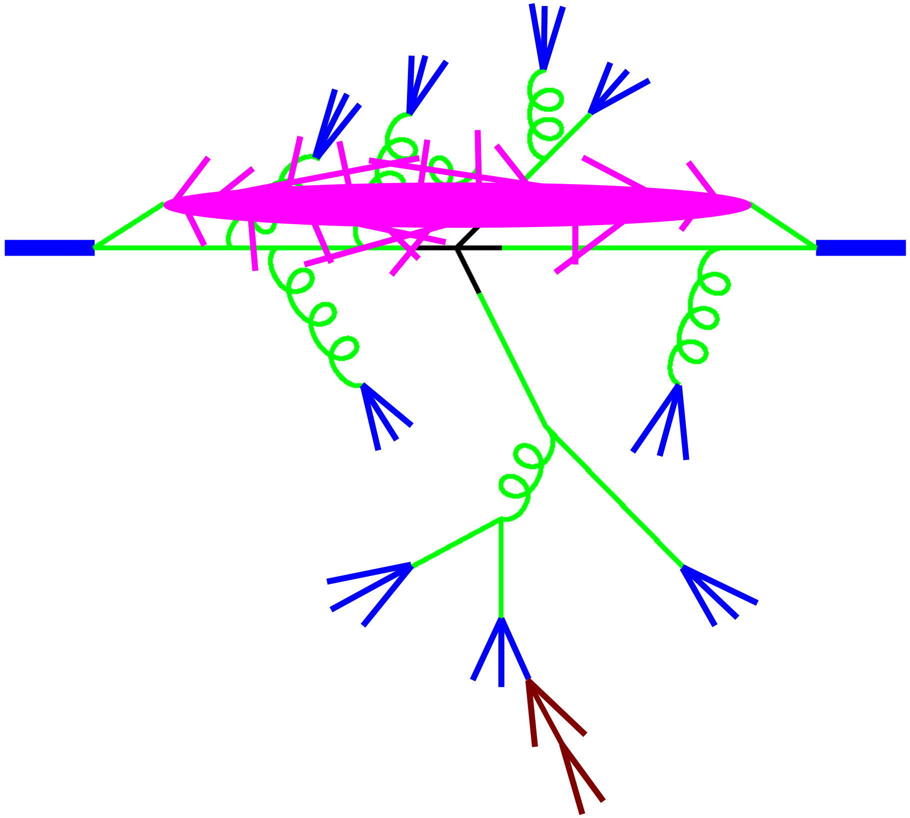
LPCC

LHC Physics Centre at CERN

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.

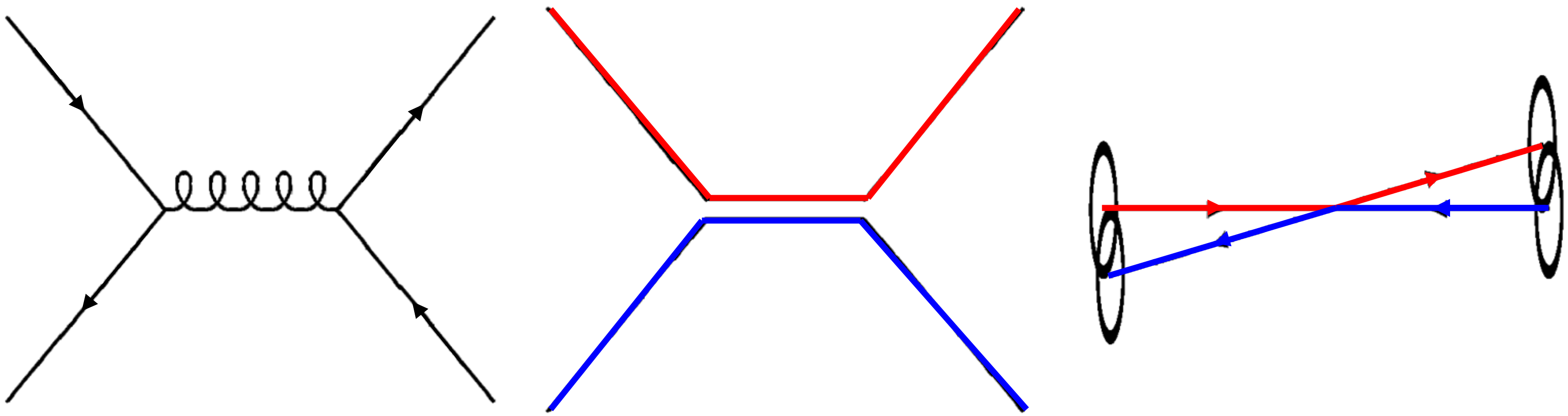
= parton shower.

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.

Hard Scattering

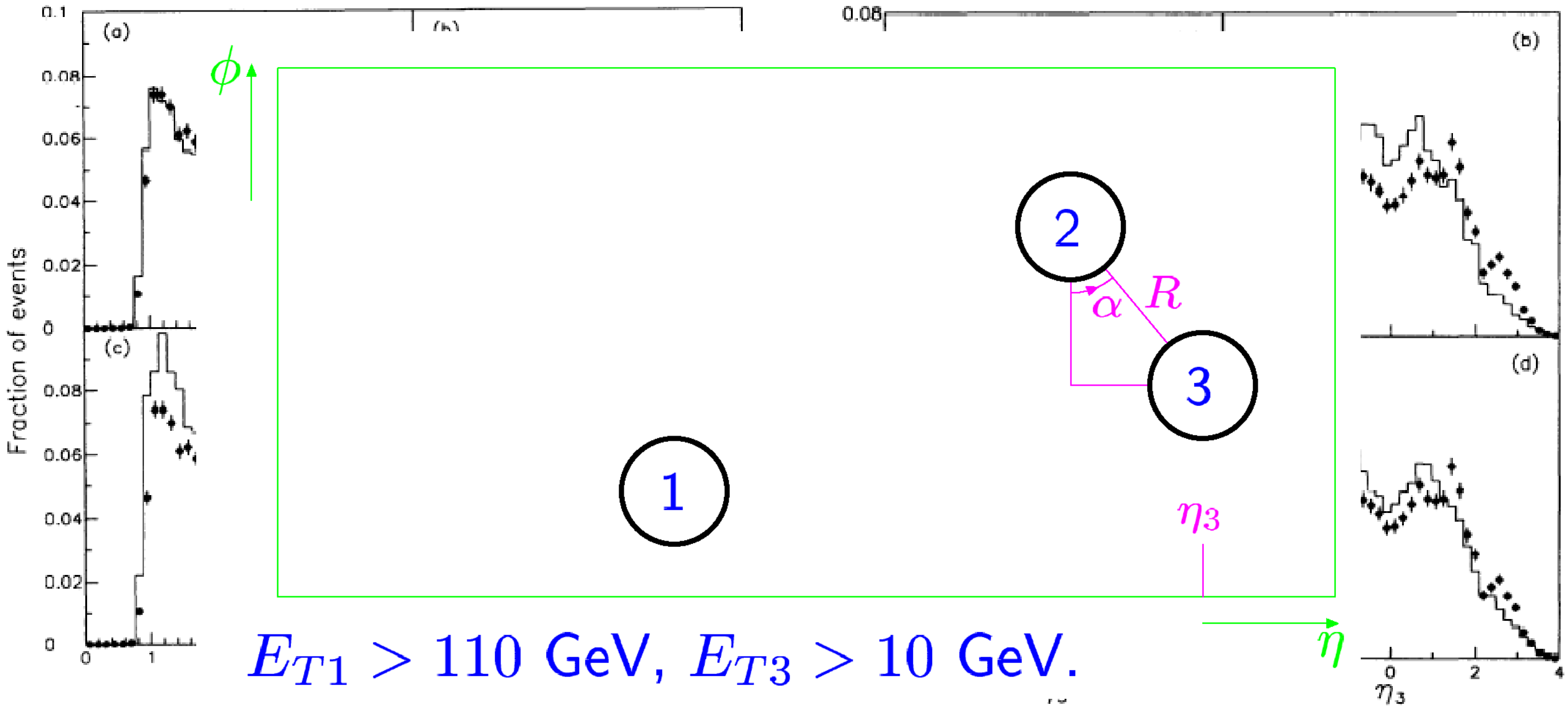
Sets up initial conditions for parton showers.

Colour coherence important here too.



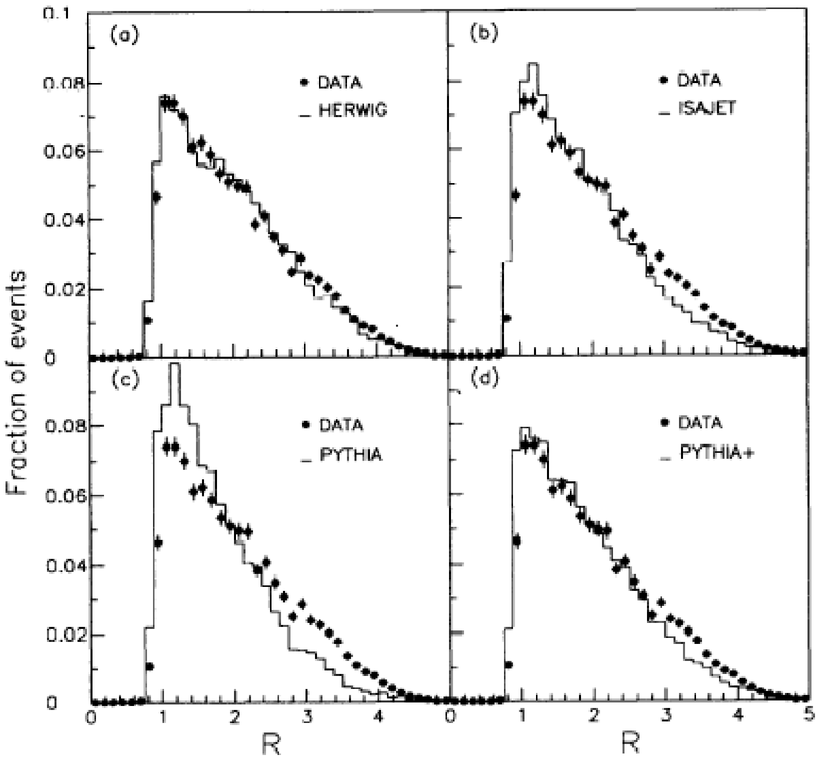
Emission from each parton confined to cone stretching to its colour partner

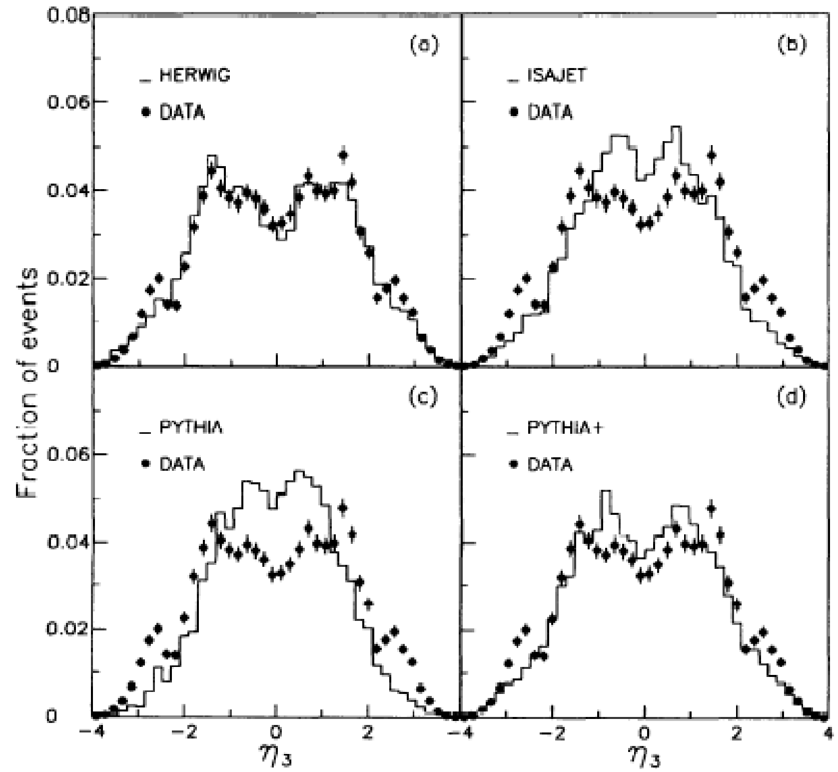
Essential to fit Tevatron data…



$E_{T1} > 110$ GeV, $E_{T3} > 10$ GeV.

Distributions of third-hardest jet in multi-jet events



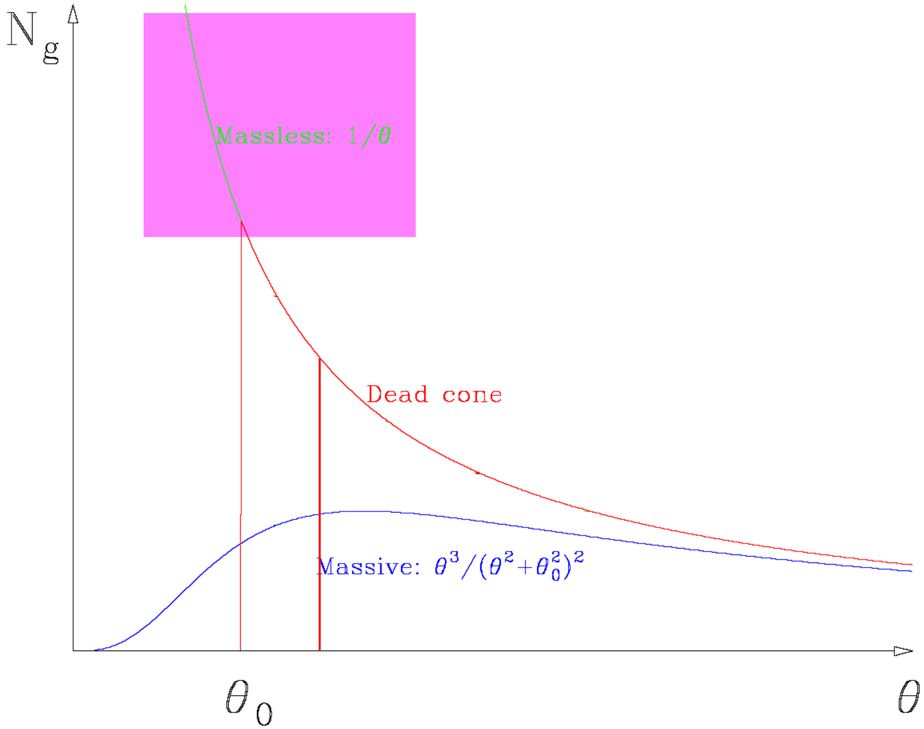


Distributions of third-hardest jet in multi-jet events

HERWIG has complete treatment of colour coherence, PYTHIA+ has partial

Heavy Quarks/Spartons

look like light quarks at large angles, sterile at small angles:



approximated as energy-dependent cutoff: $\theta > \theta_0 = \frac{m_q}{E_q}$.

The 'dead cone'. Too extreme?

Heavy Quarks/Spartons

More properly treated using quasi-collinear splitting:

$$\mathrm{d}\mathcal{P}_{\widetilde{ij}\to ij} = \frac{\alpha_S}{2\pi}\,\frac{\mathrm{d}\tilde{q}^2}{\tilde{q}^2}\,\mathrm{d}z\,P_{\widetilde{ij}\to ij}\left(z,\tilde{q}\right),$$

$$\begin{aligned}
P_{q\to qg} &= \frac{C_F}{1-z}\left[1+z^2-\frac{2m_q^2}{z\tilde{q}^2}\right],\\
P_{g\to gg} &= C_A\left[\frac{z}{1-z}+\frac{1-z}{z}+z\left(1-z\right)\right],\\
P_{g\to q\bar{q}} &= T_R\left[1-2z\left(1-z\right)+\frac{2m_q^2}{z\left(1-z\right)\tilde{q}^2}\right],\\
P_{\tilde{g}\to\tilde{g}g} &= \frac{C_A}{1-z}\left[1+z^2-\frac{2m_{\tilde{g}}^2}{z\tilde{q}^2}\right],\\
P_{\tilde{q}\to\tilde{q}g} &= \frac{2C_F}{1-z}\left[z-\frac{m_{\tilde{q}}}{z\tilde{q}^2}\right],
\end{aligned}$$

$\rightarrow$ smooth suppression in forward region

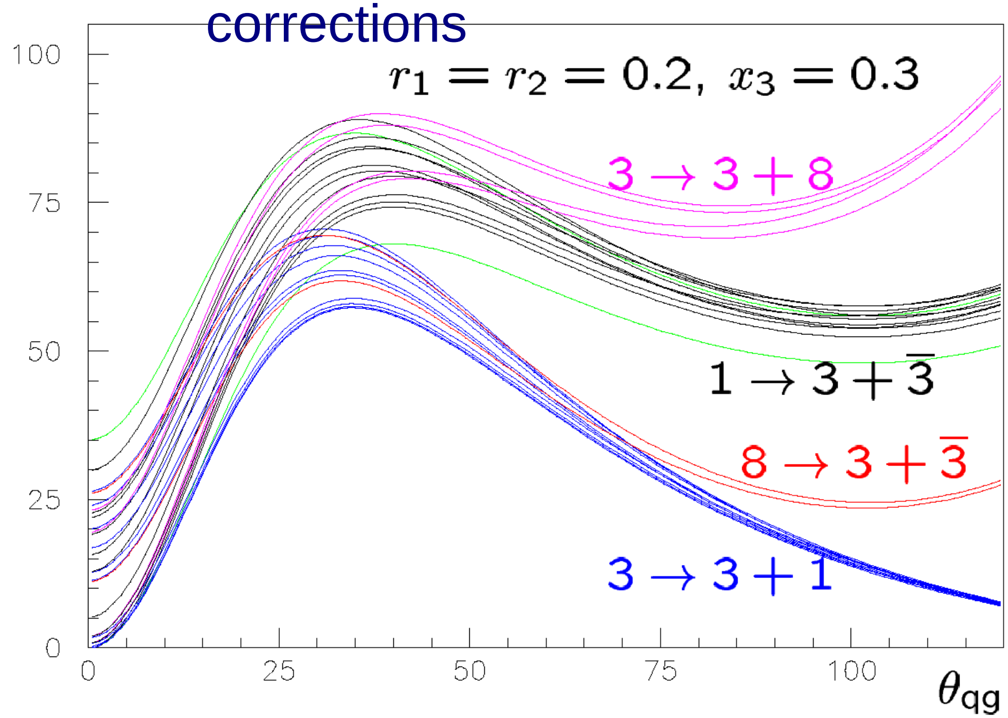
Heavy Quarks/Spartons

- Dead cone only exact for
  - emission from spin-0 particle, or
  - infinitely soft emitted gluon

- In general, depends on
  - energy of gluon
  - colours and spins of emitting particle and colour partner

→ process-dependent mass corrections

colour	spin	γ_5	example
$1 \to 3+\bar{3}$	—	—	(eikonal)
$1 \to 3+\bar{3}$	$1 \to \frac{1}{2}+\frac{1}{2}$	$1, \gamma_5, 1 \pm \gamma_5$	$Z^0 \to q\bar{q}$
$3 \to 3+1$	$\frac{1}{2} \to \frac{1}{2}+1$	$1, \gamma_5, 1 \pm \gamma_5$	$t \to bW^+$
$1 \to 3+\bar{3}$	$0 \to \frac{1}{2}+\frac{1}{2}$	$1, \gamma_5, 1 \pm \gamma_5$	$H^0 \to q\bar{q}$
$3 \to 3+1$	$\frac{1}{2} \to \frac{1}{2}+0$	$1, \gamma_5, 1 \pm \gamma_5$	$t \to bH^+$
$1 \to 3+\bar{3}$	$1 \to 0+0$	1	$Z^0 \to \tilde{q}\bar{\tilde{q}}$
$3 \to 3+1$	$0 \to 0+1$	1	$\tilde{q} \to \tilde{q}'W^+$
$1 \to 3+\bar{3}$	$0 \to 0+0$	1	$H^0 \to \tilde{q}\bar{\tilde{q}}$
$3 \to 3+1$	$0 \to 0+0$	1	$\tilde{q} \to \tilde{q}'H^+$
$1 \to 3+\bar{3}$	$\frac{1}{2} \to \frac{1}{2}+0$	$1, \gamma_5, 1 \pm \gamma_5$	$\chi \to q\bar{\tilde{q}}$
$3 \to 3+1$	$0 \to \frac{1}{2}+\frac{1}{2}$	$1, \gamma_5, 1 \pm \gamma_5$	$\tilde{q} \to q\chi$
$3 \to 3+1$	$\frac{1}{2} \to 0+\frac{1}{2}$	$1, \gamma_5, 1 \pm \gamma_5$	$t \to \tilde{t}\chi$
$8 \to 3+\bar{3}$	$\frac{1}{2} \to \frac{1}{2}+0$	$1, \gamma_5, 1 \pm \gamma_5$	$\tilde{g} \to q\bar{\tilde{q}}$
$3 \to 3+8$	$0 \to \frac{1}{2}+\frac{1}{2}$	$1, \gamma_5, 1 \pm \gamma_5$	$\tilde{q} \to q\tilde{g}$
$3 \to 3+8$	$\frac{1}{2} \to 0+\frac{1}{2}$	$1, \gamma_5, 1 \pm \gamma_5$	$t \to \tilde{t}\tilde{g}$



The Colour Dipole Model

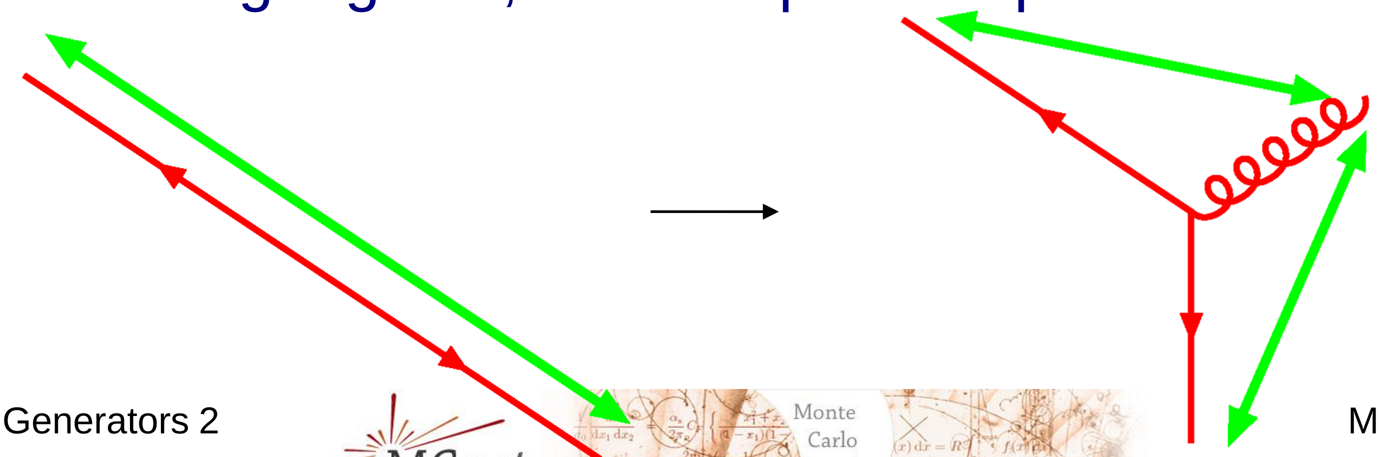
Conventional parton showers: start from collinear limit, modify to incorporate soft gluon coherence

Colour Dipole Model: start from soft limit

Emission of soft gluons from colour-anticolour dipole universal (and classical):

$$d\sigma \approx \sigma_0 \, \tfrac{1}{2} C_A \frac{\alpha_s(k_\perp)}{2\pi} \frac{dk_\perp^2}{k_\perp^2} \, dy, \qquad y = \text{rapidity} = \log \tan \theta/2$$

After emitting a gluon, colour dipole is split:

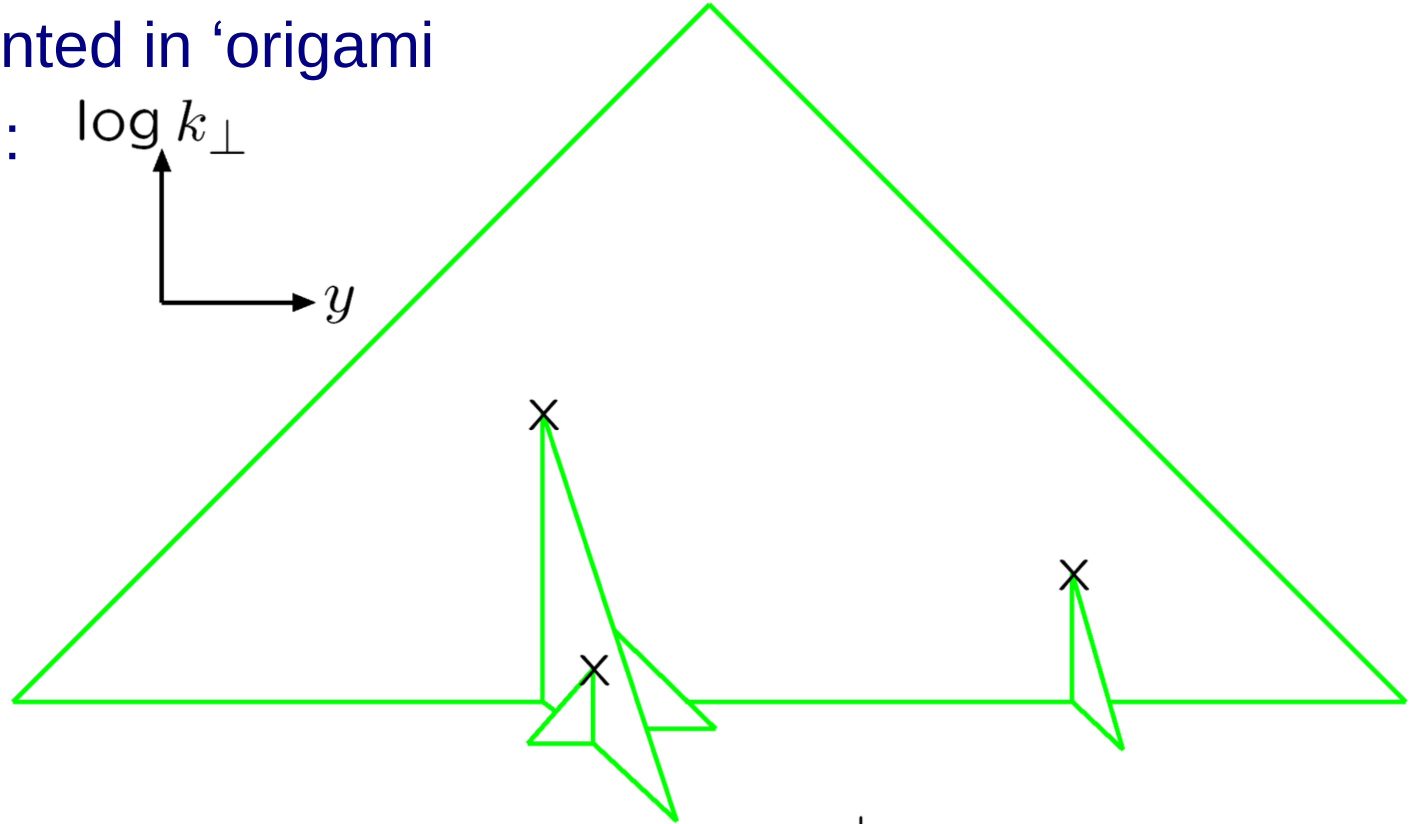


Subsequent dipoles continue to cascade

c.f. parton shower: one parton → two

CDM: one dipole → two = two partons → three

Represented in 'origami diagram':



Similar to angular-ordered parton shower for e^+e^- annihilation

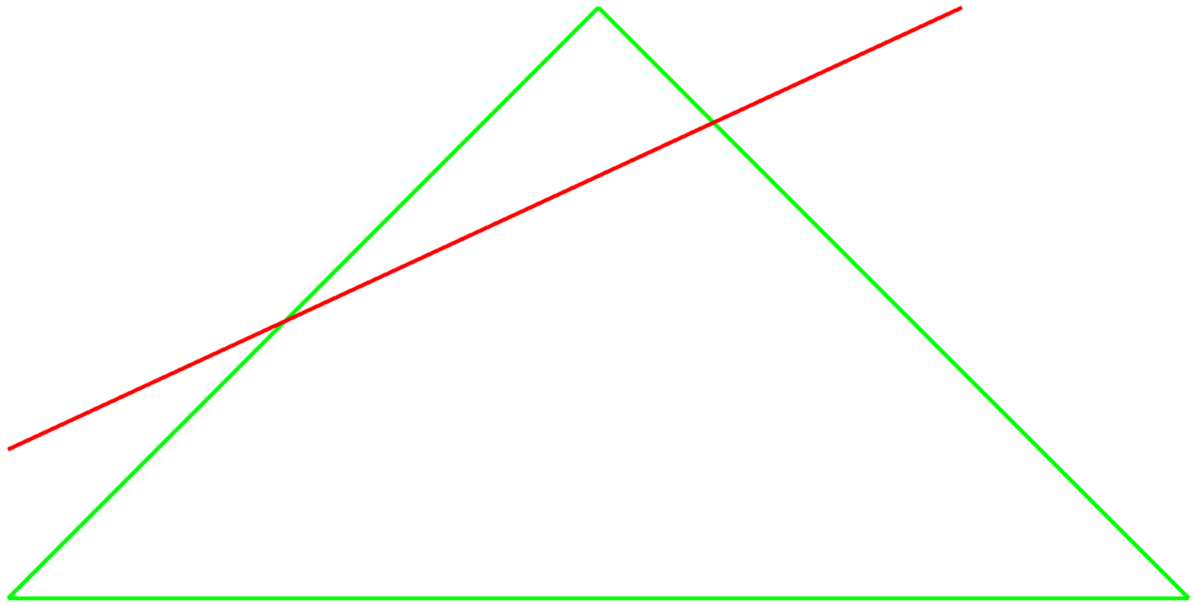
Initial-state radiation in the CDM

There is none!

Hadron remnant forms colour dipole with scattered quark.

Treated like any other dipole.

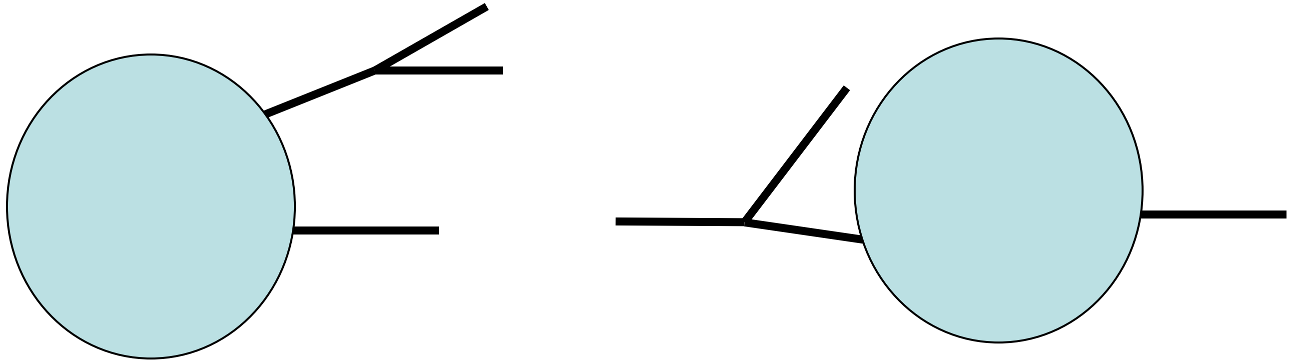
Except remnant is an extended object: suppression



Biggest difference relative to angular-ordered → more radiation at small x

Dipole Cascades

- Most new implementations based on dipole picture:
  - Catani & MHS (1997)
  - Kosower (1998)
  - Nagy & Soper (May 2007)
  - Giele, Kosower & Skands (July 2007) VINCIA
  - Dinsdale, Ternick & Weinzierl (Sept 2007)
  - Schumann & Krauss (Sept 2007) SHERPA
  - Winter & Krauss (Dec 2007) SHERPA



Matrix Element Matching

Parton shower built on approximations to QCD matrix elements valid in **collinear** and **soft** approximations

$\rightarrow$ describe bulk of radiation well $\rightarrow$ hadronic final state

$\rightarrow$ but …

- searches for new physics
- top mass measurement
- *n* jet cross sections
- …

$\rightarrow$ hard, well-separated jets

- described better by fixed ("leading") order matrix element
- would also like next-to-leading order normalization

$\rightarrow$ need matrix element matching

Older Programs, still sometimes seen

- PYTHIA 6.2: traditional q^2ordering; veto of non-ordered final state emission; partial implementation of angular ordering in initial state; big range of hard processes.

- HERWIG 6: complete implementation of colour coherence; NLO evolution for large x; smaller range of hard processes.

- ARIADNE: complete implementation of colour dipole model; best fit to HERA data; interfaced to PYTHIA for hard processes.

Supported Programs

- PYTHIA 6.3: p_T-ordered parton showers, interleaved with multi-parton interactions; dipole-style recoil; matrix element for first emission in many processes.
- PYTHIA 8: new program with many of the same features as PYTHIA 6.3, many 'obsolete' features removed.
- SHERPA: new program built from scratch; p_T-ordered dipole showers; multi-jet matching scheme (CKKW) to AMAGIC++ built in.
- Herwig++: new program with similar parton shower to HERWIG (angular ordered) plus quasi-collinear limit and recoil strategy based on colour flow; spin correlations.

Summary

- Accelerated colour charges radiate gluons.

  Gluons are also charged → cascade.

- Probabilistic language derived from factorization theorems of full gauge theory.

  Colour coherence is a fact of life: do not trust those who ignore it!

- Modern parton shower models are very sophisticated implementations of perturbative QCD, but would be useless without hadronization models…

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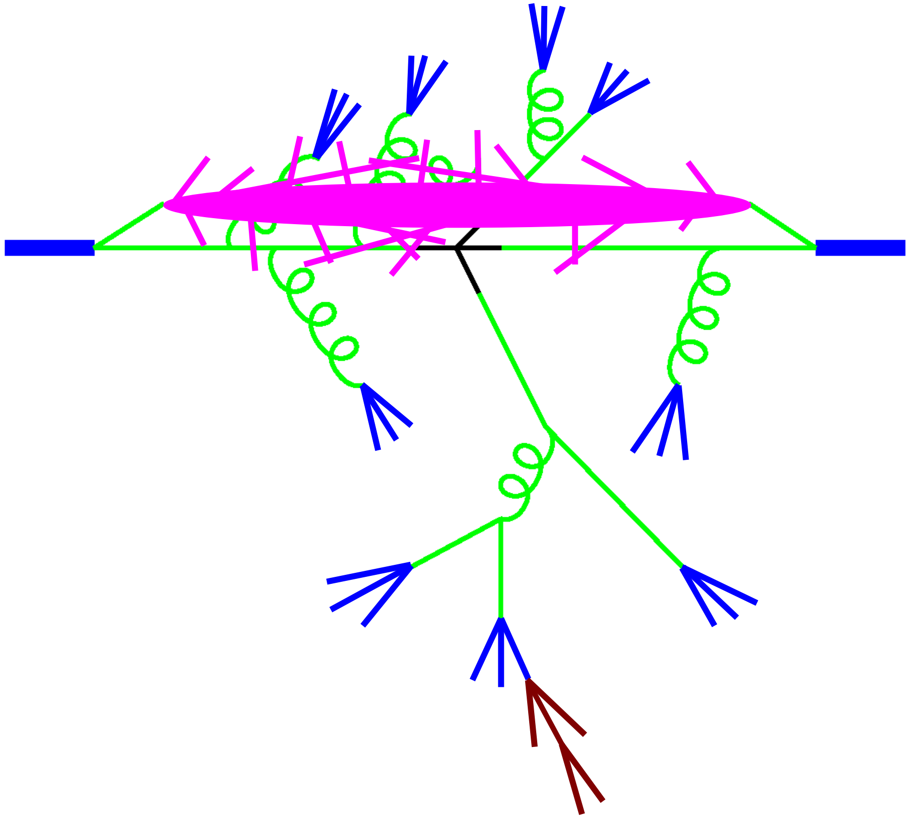


Hadronization: Introduction

Partons are not physical particles: they cannot freely propagate.

Hadrons are.

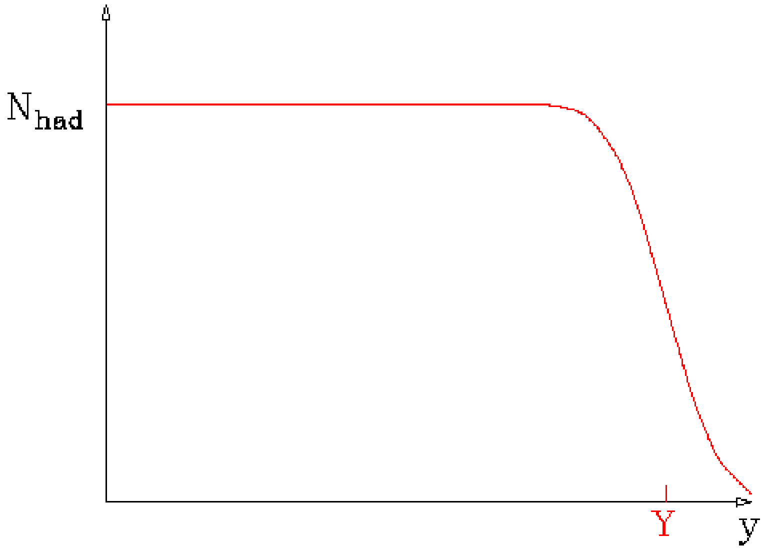
Need a model of partons' confinement into hadrons: hadronization.

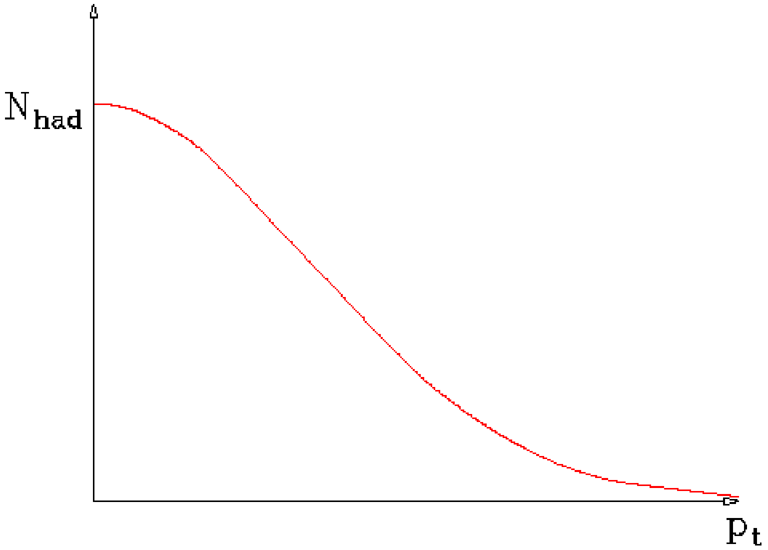
1. Phenomenological models.
2. Confinement.
3. The string model.
4. Preconfinement.
5. The cluster model.
6. Secondary decays.
7. Underlying event models.

Phenomenological Models

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

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

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

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 $q \to q' + \text{had}.$

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

Strongly frame dependent.

No obvious relation with perturbative emission.

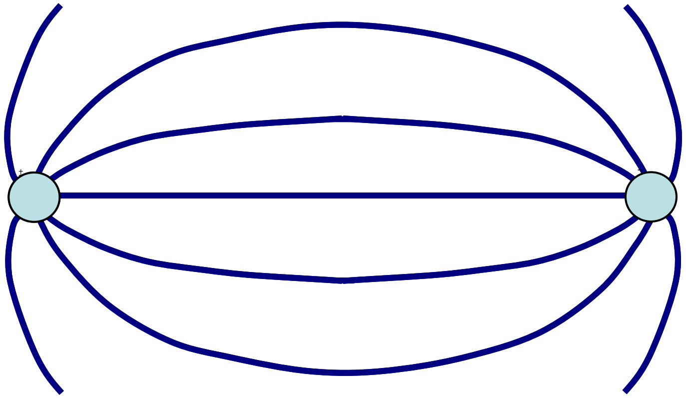
Not infrared safe.

Not a model of confinement.

Confinement

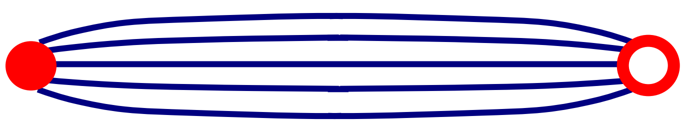
Asymptotic freedom: $Q\bar{Q}$ becomes increasingly QED-like at short distances.

QED:



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

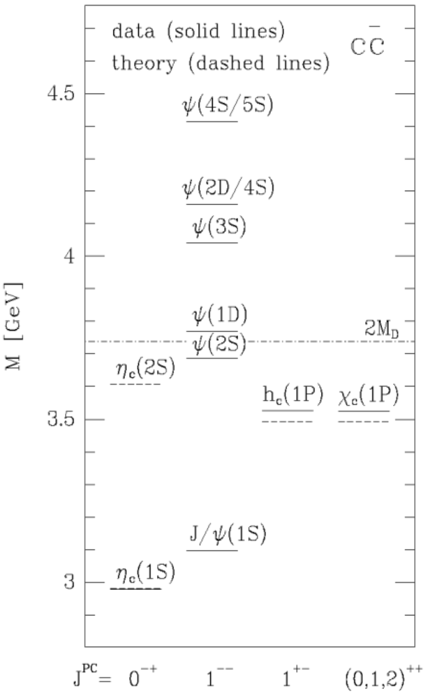
QCD:

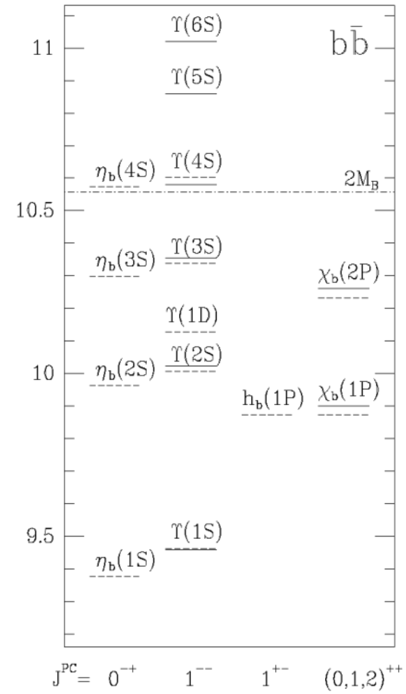


→linear potential → confinement

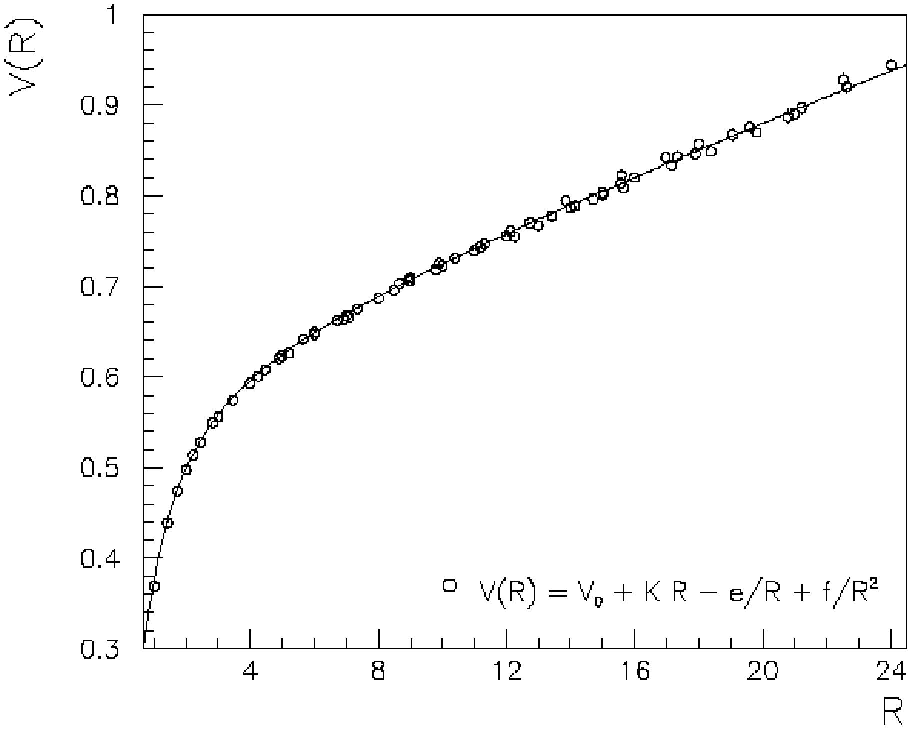
Interquark potential

Can measure from quarkonia spectra:





or from lattice QCD:



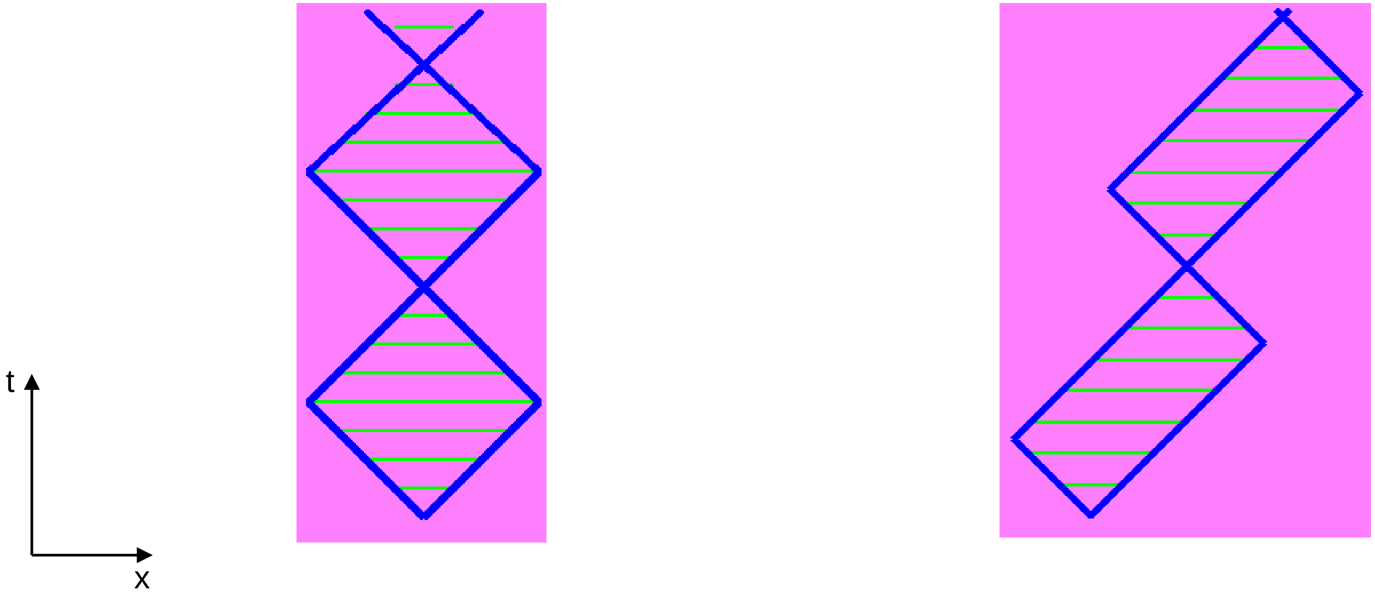
→ String tension

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

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

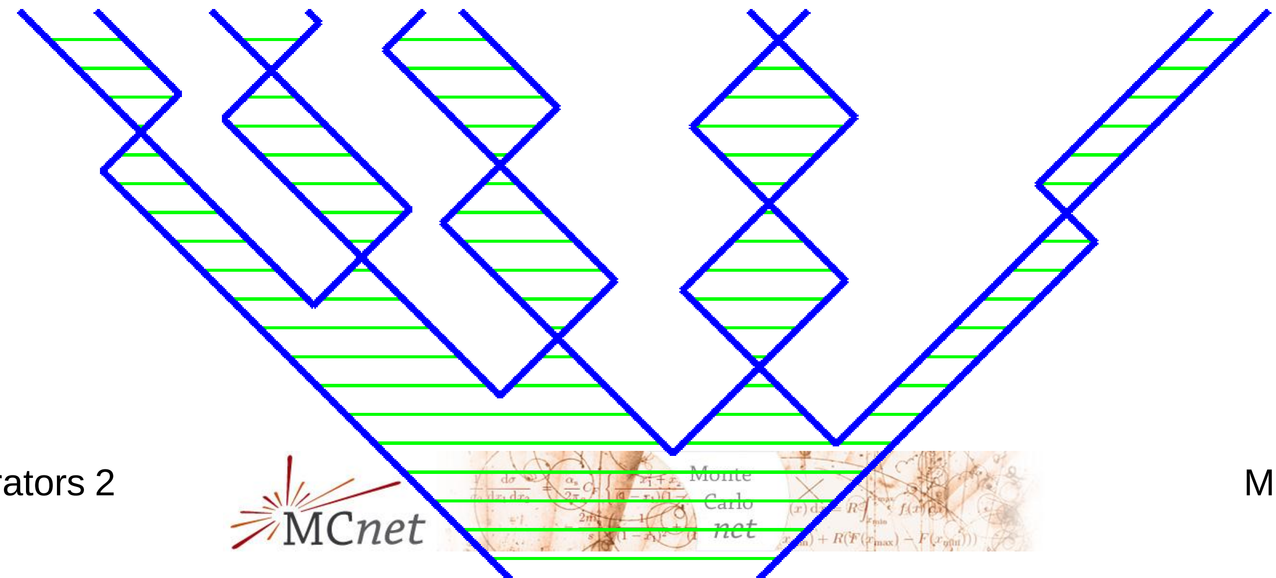
Start by ignoring gluon radiation:

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.

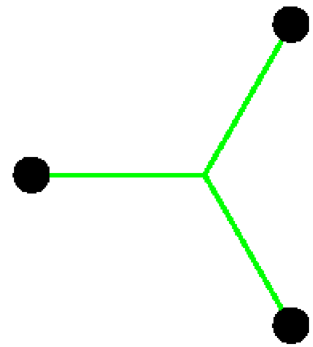
Tunnelling probability becomes

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

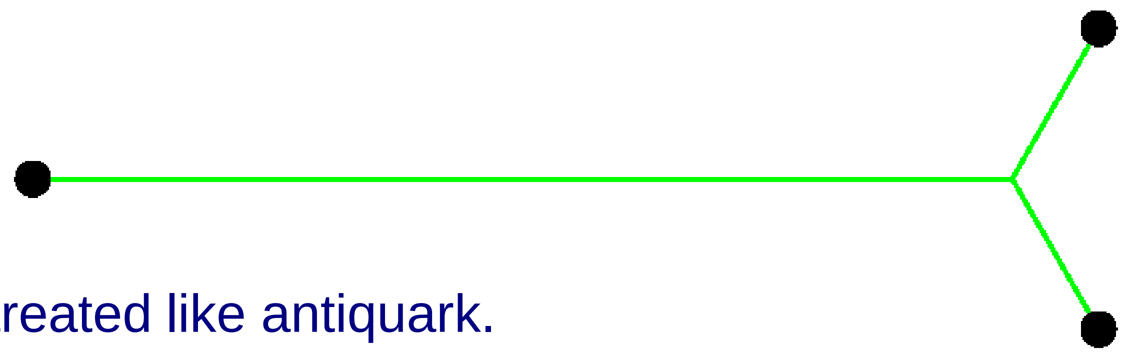
a, b and m_q^2 = main tuneable parameters of model

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

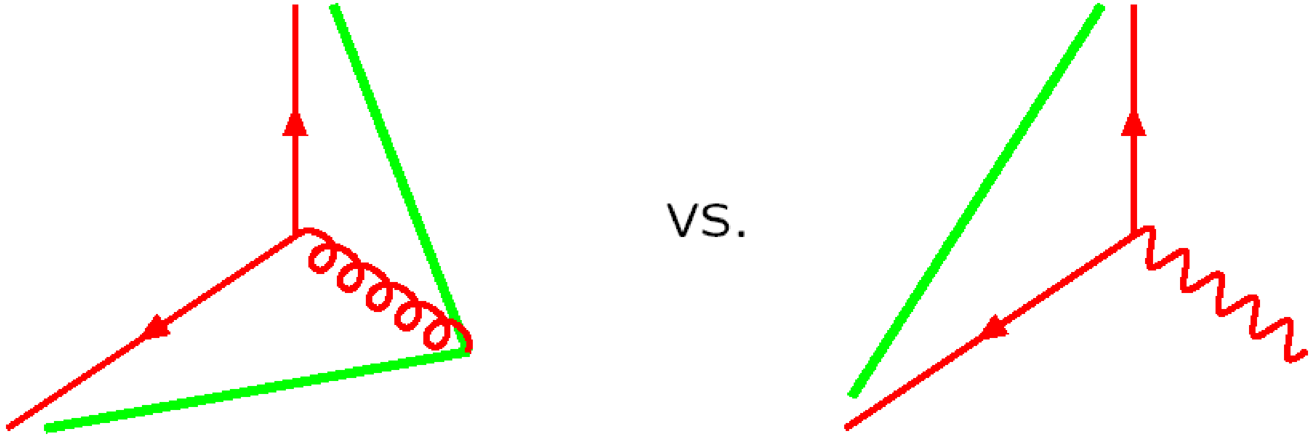
Extra adjustable parameter for each diquark!

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?