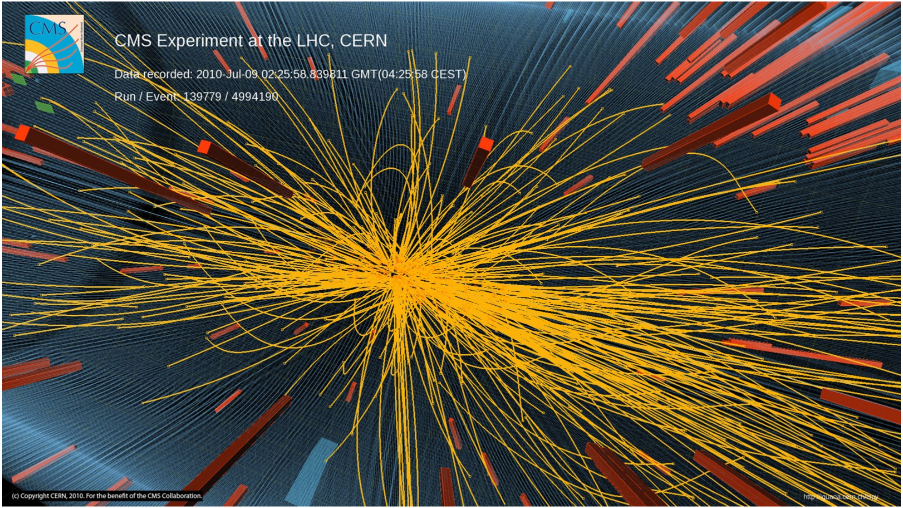
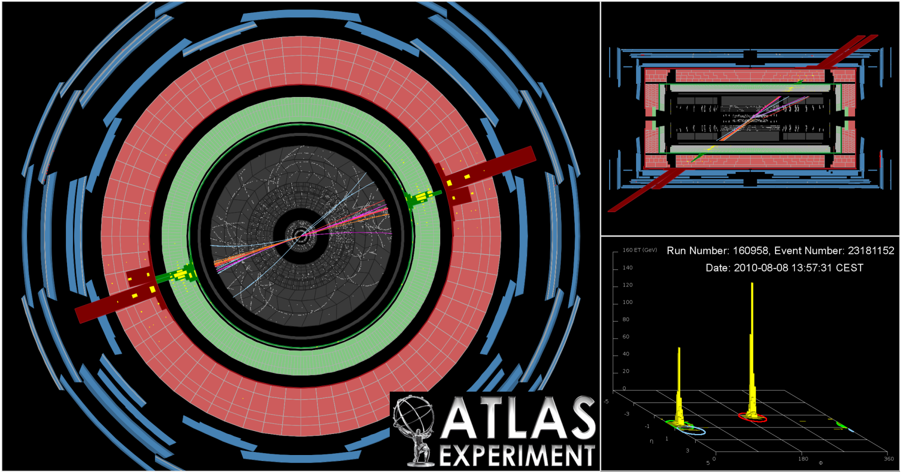
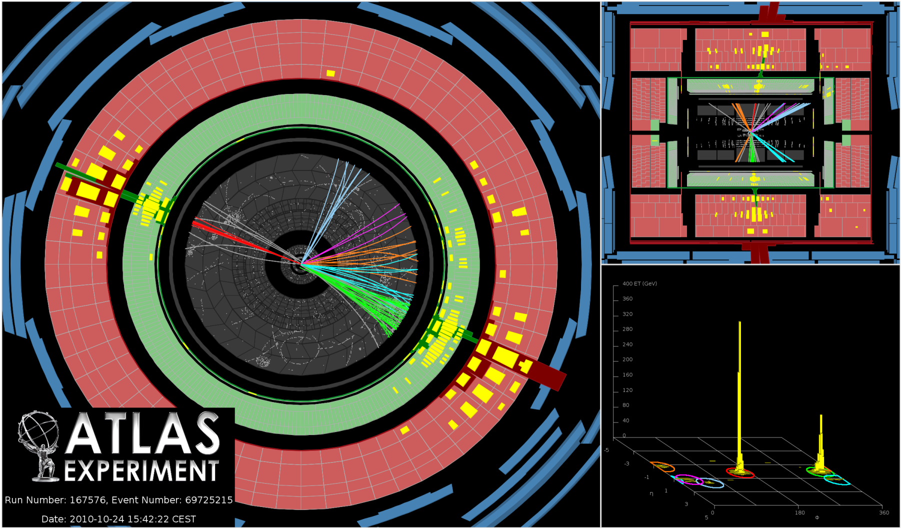
# LHC pp: normal high multiplicities



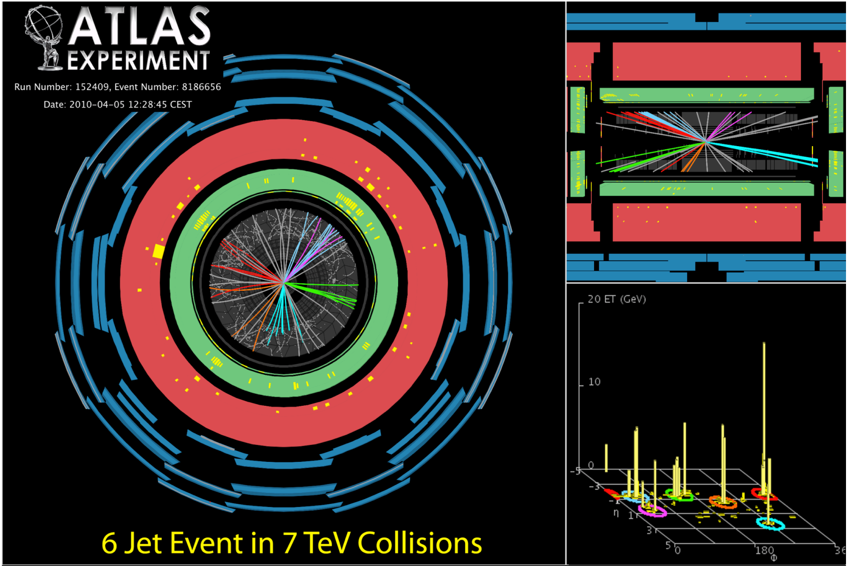
# LHC pp: QCD 2-jet



# LHC pp : QCD 2+-jet

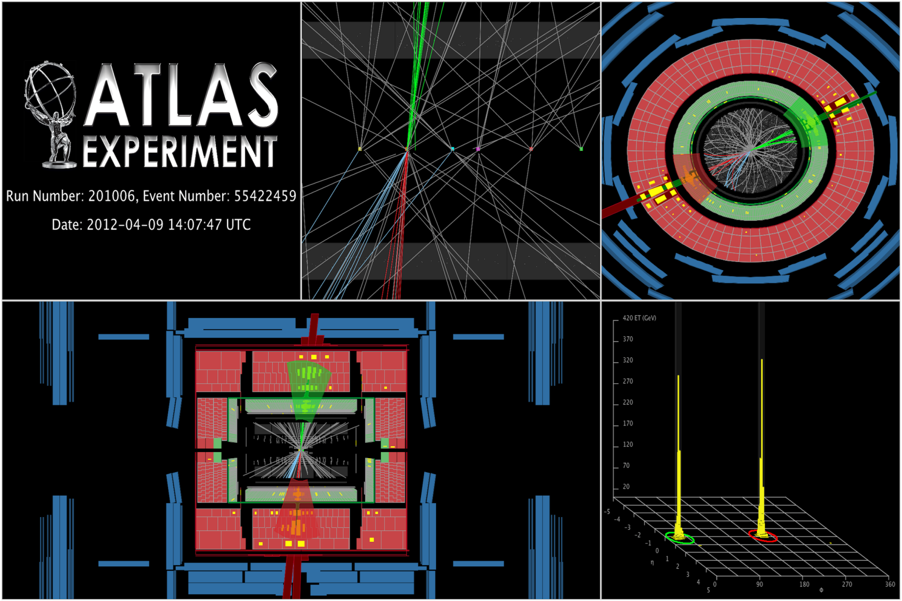


# LHC pp : QCD 6-jet

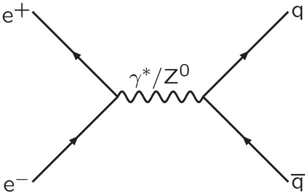



An event with 6 jets taken on April 4th, 2010. The jets have calibrated transverse momenta between 30 GeV and 70 GeV and are well separated in the detector. 12

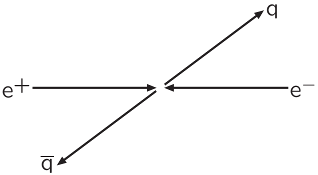
# LHC pp: QCD 2-jet with pileup



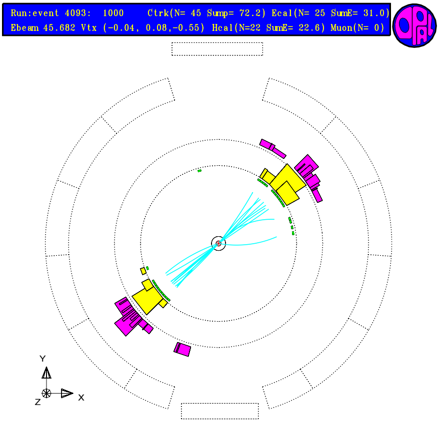
# LEP $e^+e^-$: 2-jet



e+
e−
γ*/Z0
q
q̄

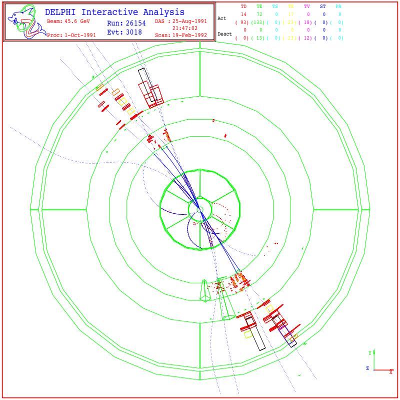



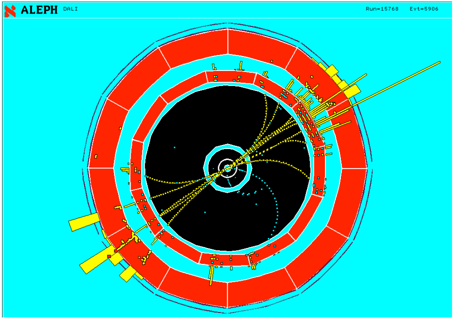
e+
e−
q
q̄

Run:event 4093: 1000 Ctrk(N= 45 Sump= 72.2) Ecal(N= 25 SumE= 31.0)
Ebeam 45.682 Vtx (-0.04, 0.08,-0.55) Hcal(N=22 SumE= 22.6) Muon(N= 0)
Y
Z
X

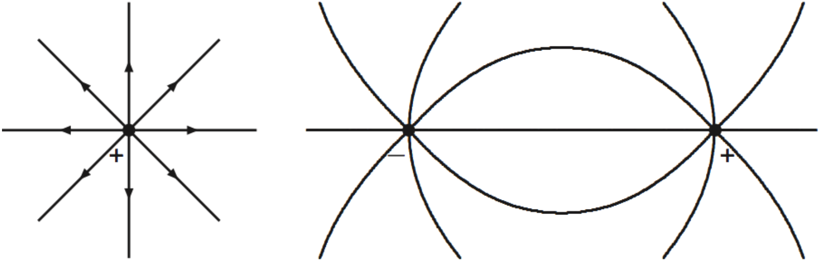
# LEP $e^+e^-$: more 2-jet



# The QED potential

In QED, field lines go all the way to infinity



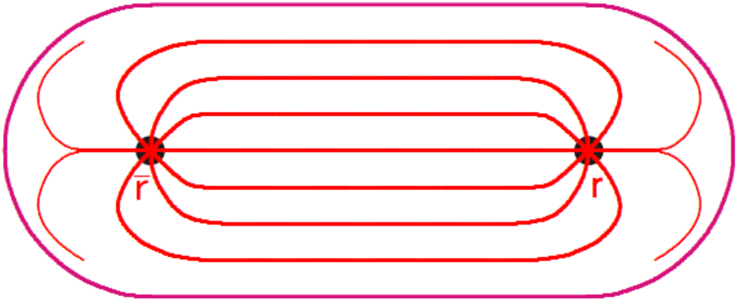

since photons cannot interact with each other.

Potential is simply additive:

$$V(\mathbf{x}) \propto \sum_i \frac{Q_i}{|\mathbf{x} - \mathbf{x}_i|}$$

# The QCD potential – 1

In QCD, for large charge separation, field lines are believed to be compressed to tubelike region(s) $\Rightarrow$ **string(s)**




by self-interactions among soft gluons in the “vacuum”.

(Analogy: vortex lines in type II superconductor.)

# The QCD potential – 2

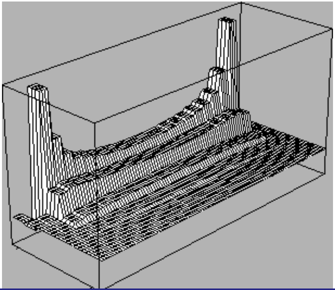
Gives force/potential between a $\mathrm{q}$ and a $\overline{\mathrm{q}}$:

$F(r) \approx \mathrm{const} = \kappa \quad \Longleftrightarrow \quad V(r) \approx \kappa r$

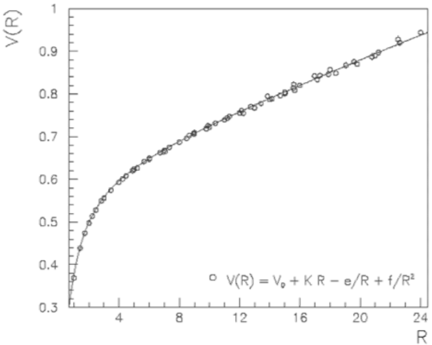
$\kappa \approx 1\ \mathrm{GeV/fm} = 1.6 \cdot 10^{-19}\mathrm{J} \cdot 10^{9} \cdot 10^{15}/\mathrm{m} = 1.6 \cdot 10^{5}\mathrm{J/m}$
$\approx$ potential energy gain lifting a 16 ton truck.
Cf. proton mass is $\approx 1$ GeV and its size $\approx 1$ fm.

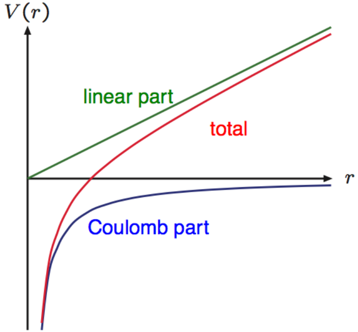
Flux tube parametrized by center location as a function of time
$\Rightarrow$ simple description as a 1+1-dimensional object – a **string**.

Linear confinement confirmed e.g. by lattice QCD calculation of gluon field between a static colour and anticolour charge pair:



# The QCD potential – 3




At short distances also Coulomb potential:

$$V(r) \approx -\frac{4}{3}\frac{\alpha_s}{r} + \kappa r$$

Coulomb correction important for internal structure of hadrons, but not for particle production (?).

# String motion – 1

**The Lund Model: core idea**

Use only linear potential $V(r) \approx \kappa r$ to trace string motion and let string fragment by repeated $\mathrm{q}\overline{\mathrm{q}}$ breaks.

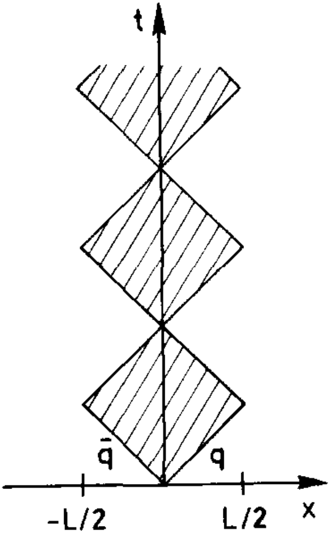
Assume negligibly small quark masses.
Then linearity between space–time and energy–momentum gives

$$\left|\frac{\mathrm{d}E}{\mathrm{d}z}\right| = \left|\frac{\mathrm{d}p_z}{\mathrm{d}z}\right| = \left|\frac{\mathrm{d}E}{\mathrm{d}t}\right| = \left|\frac{\mathrm{d}p_z}{\mathrm{d}t}\right| = \kappa$$

($c = 1$) for a $\mathrm{q}\overline{\mathrm{q}}$ pair flying apart along the $\pm z$ axis.
But signs relevant: the $\mathrm{q}$ moving in the $+z$ direction has $\mathrm{d}z/\mathrm{d}t = +1$ but $\mathrm{d}p_z/\mathrm{d}t = -\kappa$.

Conservation of total energy:
$E_{\mathrm{kinetic}}(t) + E_{\mathrm{potential}}(t) = E_{\mathrm{total}}(t) =$ constant.

# String motion – 2




Consider decay $Z^0 \to q\overline{q}$ at rest:

$t = 0$: $E_{\mathrm{potential}}(0) = V(0) = 0$
$\Rightarrow E_{\mathrm{kinetic}}(0) = E_{\mathrm{q}}(0) + E_{\overline{\mathrm{q}}}(0) = m_{\mathrm{Z}}$.

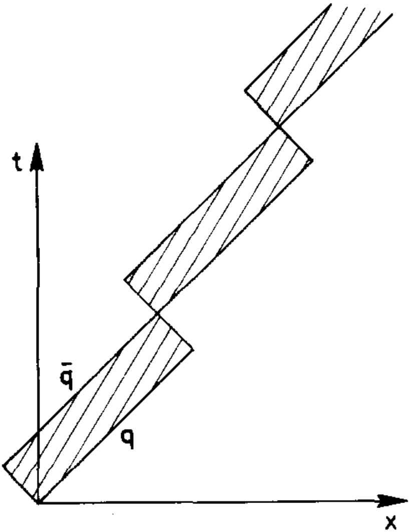
As the $\mathrm{q}$ and a $\overline{\mathrm{q}}$ fly apart, kinetic energy turns into potential.

Max separation when $E_{\mathrm{kinetic}} = 0$, i.e. $E_{\mathrm{potential}} = \kappa L = m_{\mathrm{Z}} \Rightarrow L = m_{\mathrm{Z}}/\kappa$.

From this point the string pulls the $\mathrm{q}$ and $\overline{\mathrm{q}}$ back together, i.e. potential energy turns into kinetic.

Continued oscillations: "yo-yo mode".

# String motion – 3




System with net motion
in one direction
is boosted version
of system at rest.

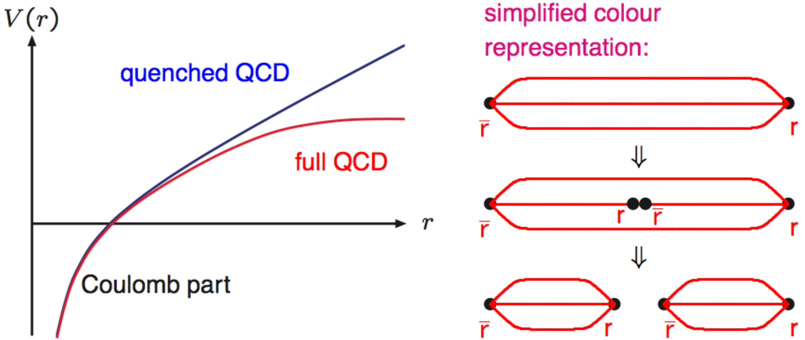
Each crossing point
is appropriately shifted
in direction of motion.

Quarks move longer times
in “right” direction
and shorter in “wrong”.

Reminder: “simultaneous”
frame-dependent for
spatially separated events.

# The QCD potential – 4

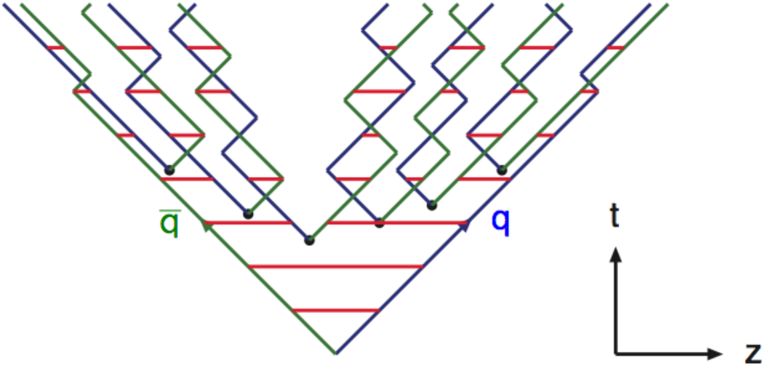
Full QCD = gluonic field between charges ("quenched QCD")
plus virtual fluctuations $\mathrm{g} \to \mathrm{q}\overline{\mathrm{q}}\,(\to \mathrm{g})$
$\Longrightarrow$ nonperturbative string breakings $\mathrm{gg}\ldots \to \mathrm{q}\overline{\mathrm{q}}$



# The Lund Model

Combine yo-yo-style string motion with string breakings!

Motion of quarks and antiquarks with intermediate string pieces:

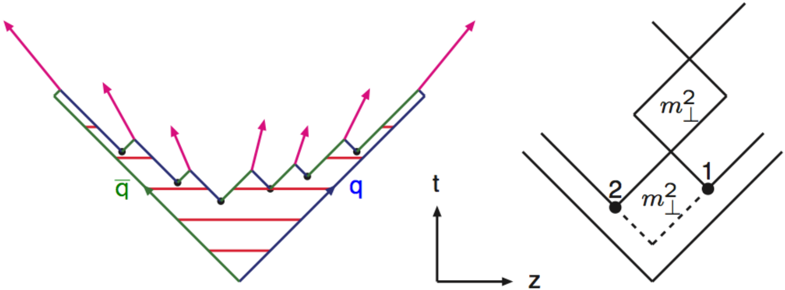



A $q$ from one string break combines with a $\overline{q}$ from an adjacent one.

Gives simple but powerful picture of hadron production.

# Where does the string break? – 1

Fragmentation starts in the middle and spreads outwards:




Corresponds to roughly same invariant time of all breaks, $\tau^2 = t^2 - z^2 \sim$ constant.

Hadrons at outskirts are more boosted.

Adjacent breaks have to be separated such that hadron formed with correct mass: area $\propto m_\perp^2 = m^2 + p_\perp^2$.

Breakup vertices causally disconnected!

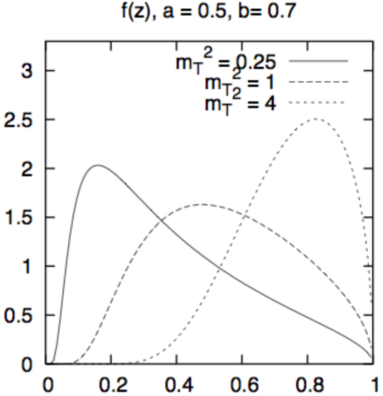
# Where does the string break? – 2

Breakups causally disconnected
⇒ can proceed in arbitrary order
⇒ split off hadrons
from both ends inwards.

Described by probability $f(z)$,
e.g. Lund shape

$$f(z) \propto (1-z)^a \exp(-bm_\perp^2/z)/z$$

where $z$ is fraction of
remaining energy and momentum
that hadron takes,
with $1-z$ left over.




Applied iteratively from both ends, matched in the middle.

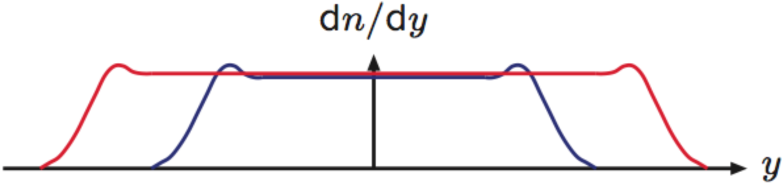
# Where does the string break? – 3

Example: all $z = 1/2$ for jet with energy $E_{\rm jet}$.
Then hadrons obtain energies $E_{\rm jet}/2$, $E_{\rm jet}/4$, $E_{\rm jet}/8$, $E_{\rm jet}/16$, . . . ,
i.e. evenly spaced in $\ln E$.

Proper treatment: evenly spaced in rapidity $y$:

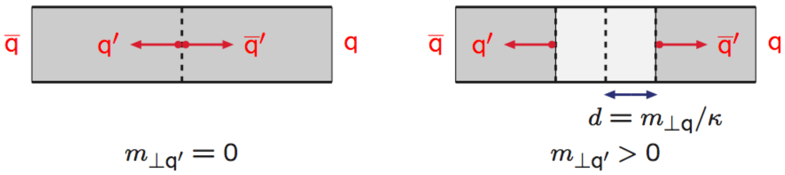
$$y = \frac{1}{2} \ln \left( \frac{E + p_z}{E - p_z} \right)$$

Varying $z$ values $\Rightarrow$ varying spacing, but still on the average
flat rapidity plateau + some endpoint corrections:




and total multiplicity grows proportional to $\ln(E_{\rm jet})$.

# How does the string break?




String breaking modelled by tunneling:

$$\mathcal{P} \propto \exp\left(-\frac{\pi m_{\perp q}^2}{\kappa}\right) = \exp\left(-\frac{\pi p_{\perp q}^2}{\kappa}\right) \exp\left(-\frac{\pi m_{q}^2}{\kappa}\right)$$

- Common Gaussian $p_\perp$ spectrum, $\langle p_\perp \rangle \approx 0.4$ GeV.
- Suppression of heavy quarks,
  $\mathrm{u\bar{u}} : \mathrm{d\bar{d}} : \mathrm{s\bar{s}} : \mathrm{c\bar{c}} \approx 1 : 1 : 0.3 : 10^{-11}$.
- Diquark $\sim$ antiquark $\Rightarrow$ simple model for baryon production.

# Flavour composition

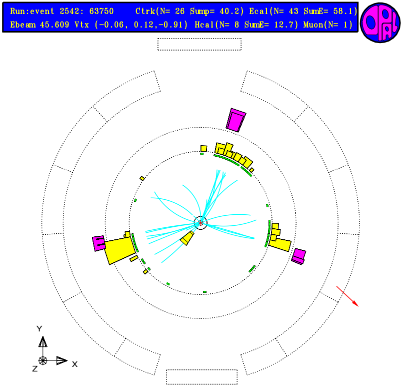
Combination of $\mathrm{q}$ and $\overline{\mathrm{q}}$ ($\mathrm{qq}$) from two adjacent breaks gives meson (baryon).

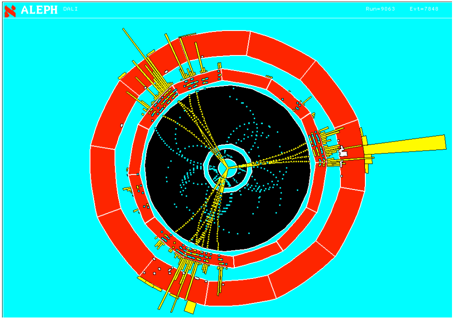
Many uncertainties in selection of hadron species, e.g.:

- Spin counting suggests vector:pseudoscalar = 3:1, but $m_\rho \gg m_\pi$, so empirically $\sim$1:1.
- Also for same spin $m_{\eta'} \gg m_\eta \gg m_{\pi^0}$ gives mass suppression.
- There is one V and one PS for each $\mathrm{q}\overline{\mathrm{q}}$ flavour set, but baryons are more complicated, e.g. $\mathrm{uuu} \Rightarrow \Delta^{++}$ whereas $\mathrm{uds} \Rightarrow \Lambda^0$, $\Sigma^0$ or $\Sigma^{*0}$.
- Simple diquark model too simpleminded; produces baryon–antibaryon pairs too nearby in rapidity space.

String model unpredictive in understanding of hadron mass effects $\Rightarrow$ many parameters, 10–20 depending on how you count.

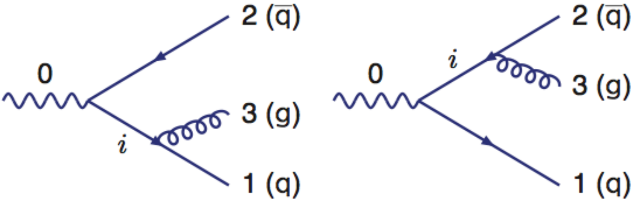
# LEP $e^+e^-$: 3-jet


Run:event 2542: 63750 Ctrk(N= 26 Sump= 40.2) Ecal(N= 43 SumE= 58.1)
Ebeam 45.609 Vtx (-0.06, 0.12,-0.91) Hcal(N= 8 SumE= 12.7) Muon(N= 1)
Y
Z
X


ALEPH
DALI
Run=9063
Evt=7848

# LEP $e^+e^-$: 3-jet matrix elements

$e^+e^- \to Z^0 \to q\bar{q}g$ receives contributions from two Feynman diagrams:

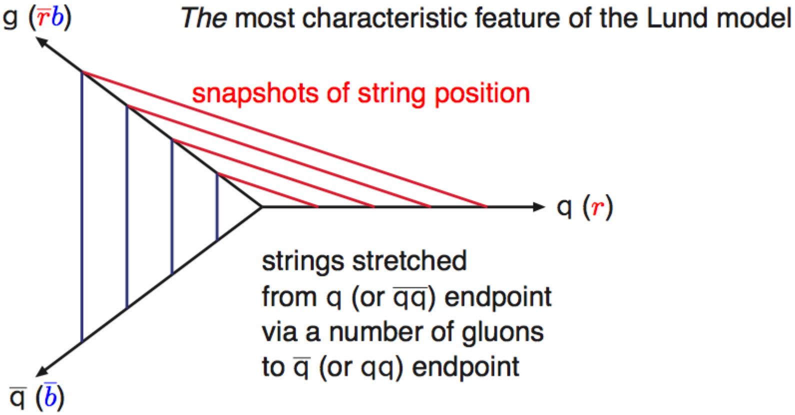



Emission of gluon is a bremsstrahlung process:

$$\mathrm{d}\mathcal{P} \approx k\,\alpha_s \frac{\mathrm{d}E_g}{E_g}\left(\frac{\mathrm{d}\theta_{qg}}{\theta_{qg}} + \frac{\mathrm{d}\theta_{\bar{q}g}}{\theta_{\bar{q}g}}\right)$$

i.e. gluon perfers to have low energy and be close to $q$ or $\bar{q}$, but with smooth tail to large energies and separations.

# The Lund gluon picture – 1

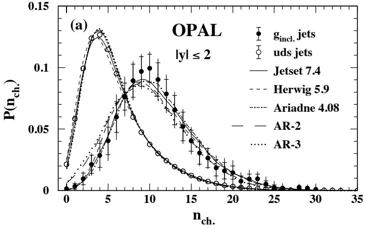


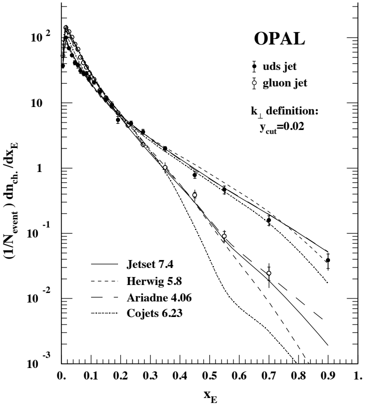

**Gluon = kink on string**

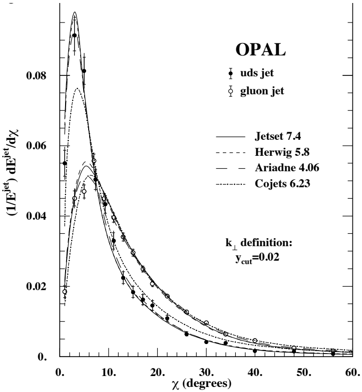
Force ratio gluon/ quark = 2,
cf. QCD $N_C/C_F = 9/4$, $\to 2$ for $N_C \to \infty$
No new parameters introduced for gluon jets!

# The Lund gluon picture – 2

Energy sharing between two strings makes hadrons in gluon jets softer, more and broader in angle:

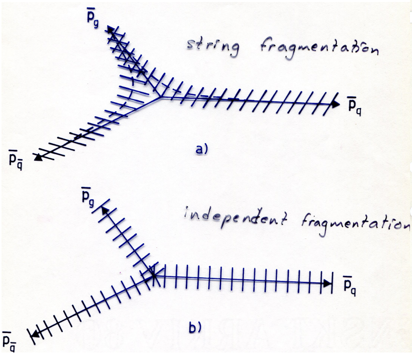


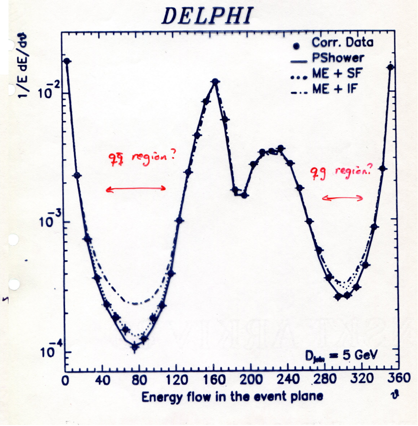



# The Lund gluon picture – 3

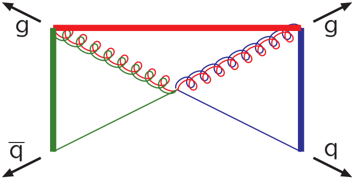
Particle flow in the $q\bar{q}g$ event plane depleted in $q$–$\bar{q}$ region owing to boost of string pieces in $q$–$g$ and $g$–$\bar{q}$ regions:



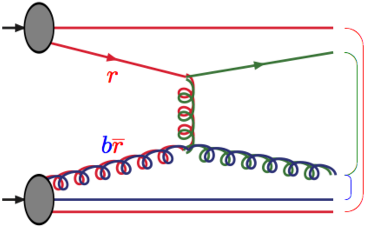



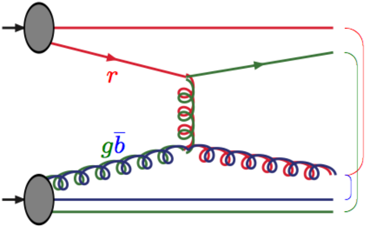
# Building on towards LHC events

Repeated gluon emissions lead to more complicated topologies, but string configurations generalize:




In pp collisions colour flow connects hard scattering with beam remnants:



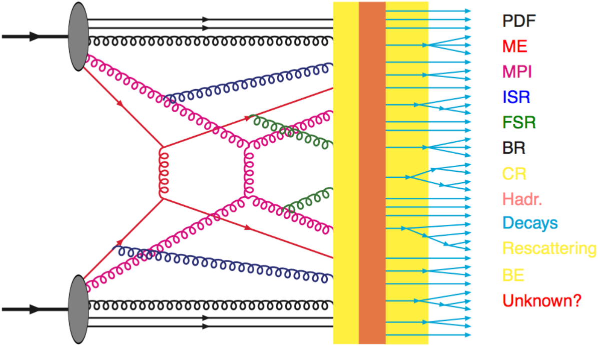




As for $\mathrm{e}^+\mathrm{e}^-$ events there can be further gluon emissions.

Therefore $\geq$ 2 jets at "large" $p_\perp$, plus one along each beam.

# The Lund Monte Carlo PYTHIA

Many further physics components for full LHC story:




PYTHIA generates complete "virtual-reality" LHC events.

Quantum mechanics $\Rightarrow$ random choices (Monte Carlo methods).

Program $\sim$ 100 000 lines of C++ code.

Frequently used by LHC experimentalists.