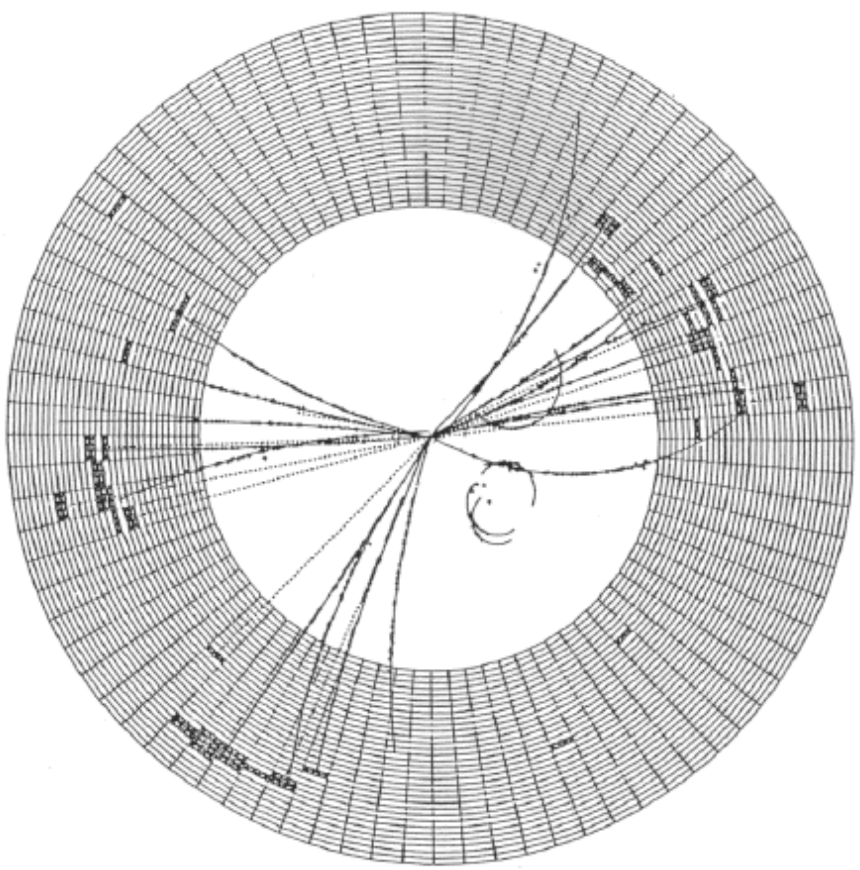
Particle Physics

Dr Victoria Martin, Spring Semester 2013

Lecture 10: QCD at Colliders



- ★ Jets
- ★ Renormalisation in QCD
- ★ Asymptotic Freedom and Confinement in QCD
- ★ Lepton and Hadron Colliders
- ★ $\mathbf{R} = (e^+e^- \rightarrow \text{hadrons})/(e^+e^- \rightarrow \mu^+\mu^-)$
- ★ Measuring Jets
- ★ Fragmentation

QCD Summary

- QCD: Quantum Chromodymanics is the quantum description of the strong force.
- Quarks are colour charged: red, green or blue
- Anti-quarks are colour charged: anti-red, anti-green, anti-blue
- Gluons are the propagators of the QCD and carry colour and anti-colour, described by 8 Gell-Mann matrices, λ.

Internal Lines (propagators)

spin 1 gluon

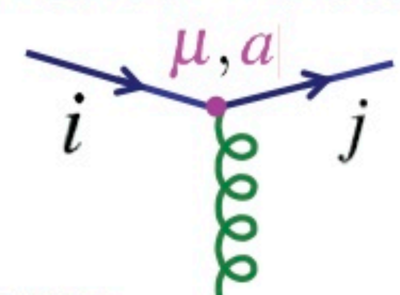
$$\boxed{\frac{g_{\mu\nu}}{q^2}\delta^{ab}}$$

a, b = 1,2,…,8 are gluon colour indices

Vertex Factors

spin 1/2 quark

$$\boxed{g_s \tfrac{1}{2}\lambda^a_{ji}\gamma^\mu}$$



i, j = 1,2,3 are quark colours,

λ^a **a = 1,2,..8 are the Gell-Mann SU(3) matrices**

- $\mathcal{M}$ includes a colour factor, f, calculable from the λ matrices.
- The QCD coupling constant is $\alpha_S = g_S^2/4\pi$

From lecture 6: Running Coupling Constant in QED

- Renormalise α, and correct for all possible fermion types in the loop:

$$\alpha(q^2) = \alpha(0)\left(1 + \frac{\alpha(0)}{3\pi} z_f \ln(\frac{-q^2}{M^2})\right)$$

- z_f is the sum of charges over all possible fermions in the loop
  - ➡ At $q^2 \sim 1$ **MeV** only electron, $z_f = 1$
  - ➡ At $q^2 \sim 100$ **GeV**, $f = e, \mu, \tau, u, d, s, c, b$ $z_f = 60/3$

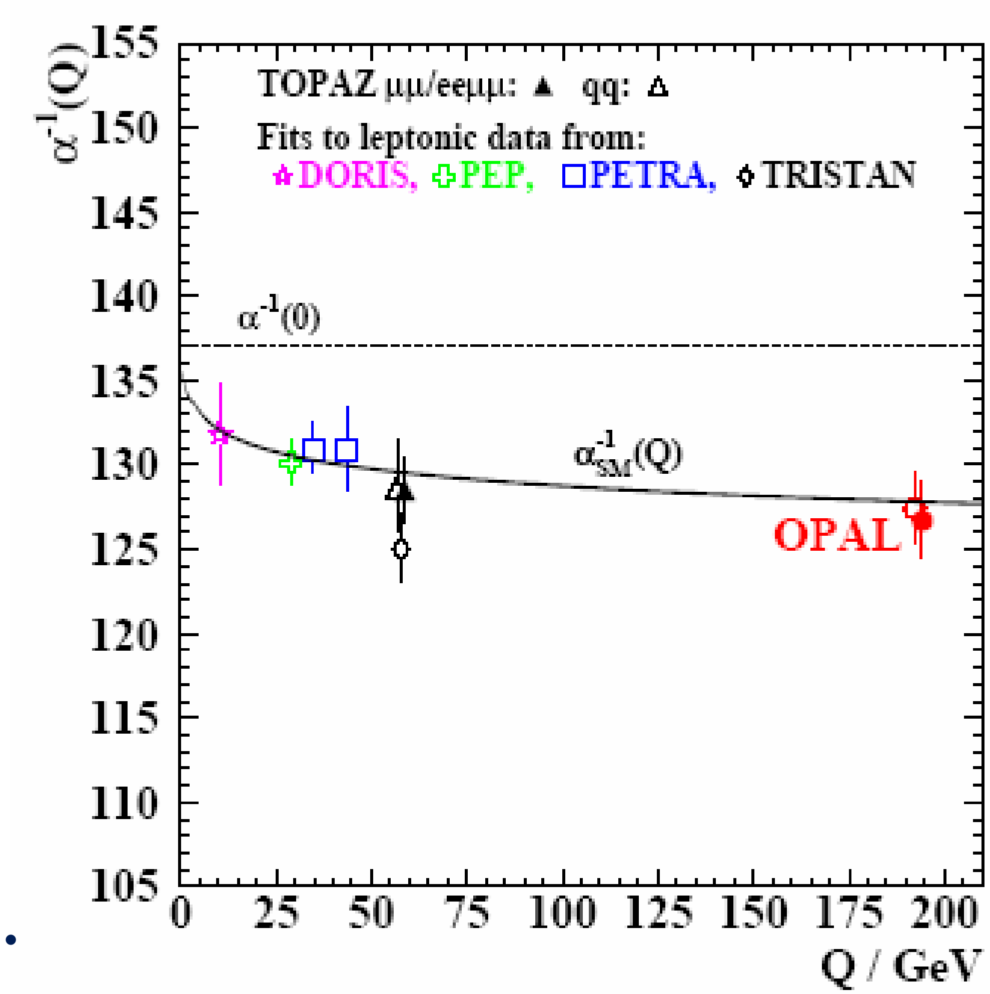
$$z_f = \sum_f Q_f^2$$

- Instead of using M^2 dependence, replace with a reference value μ^2:

$$\alpha(q^2) = \alpha(\mu^2)\left(1 - \frac{\alpha(\mu^2)}{3\pi} z_f \ln(\frac{q^2}{\mu^2})\right)^{-1}$$

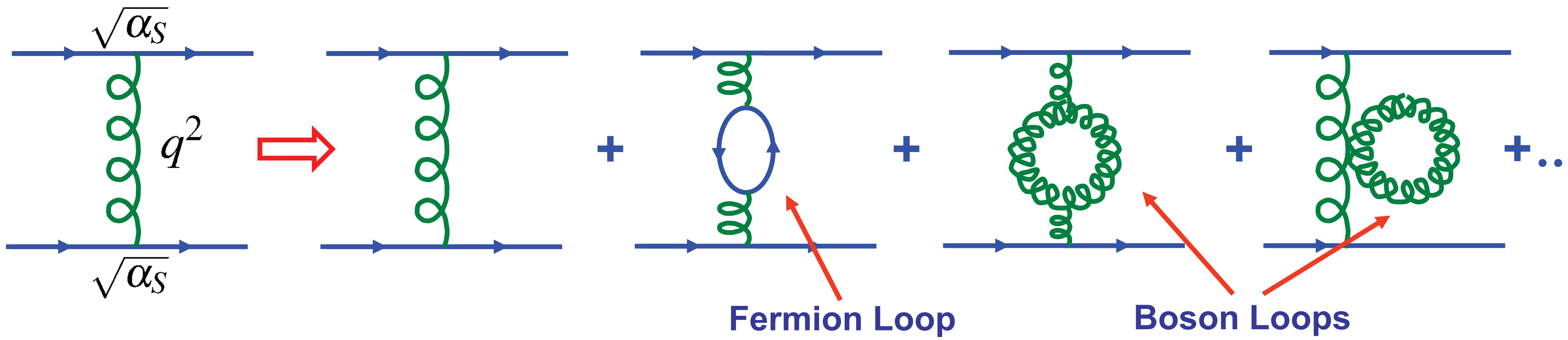
- Usual choices for μ are **1 MeV** or $m_Z \sim$ **91 GeV.**
  - ➡ $\alpha(\mu^2 = 1\ \mathrm{MeV}^2) = 1/137$
  - ➡ $\alpha(\mu^2 = (91\ \mathrm{GeV})^2) = 1/128$

- We choose a value of μ where make a initial measurement of α, but once we do the evolution of the values of α are determined by the above eqn.



Running Coupling in QCD

- The observed (renormalised) value of the coupling constant α_S depends on diagrams such as:



Similar to QED

No equivalent in QED, as no photon-photon interactions

- The measured value of α_S at a energy scale q^2 can be written as:

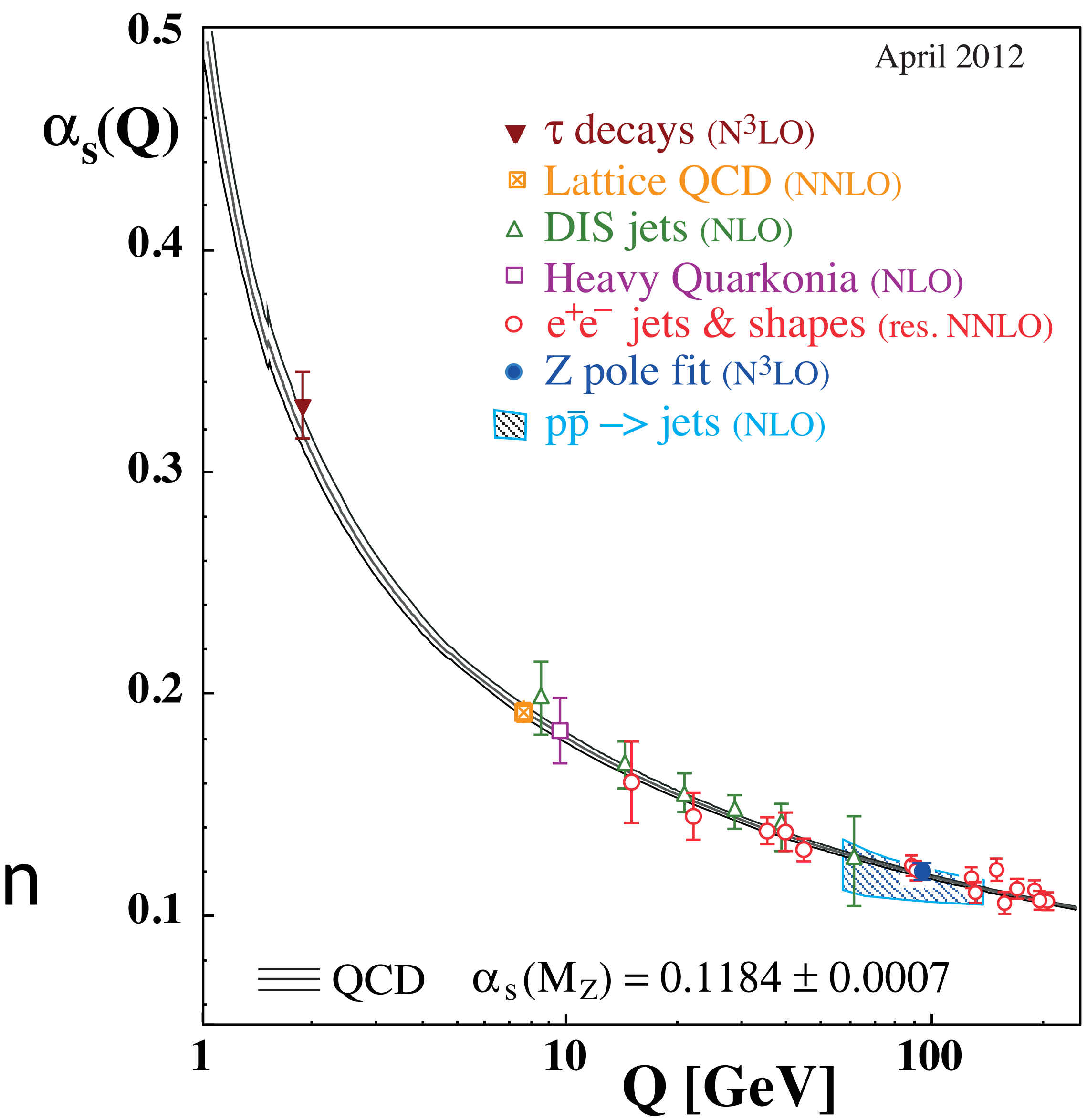
$$\alpha_S(q^2) = \frac{\alpha_S(\mu^2)}{1 + B\alpha_S(\mu^2)\ln\left(\frac{q^2}{\mu^2}\right)}$$

- B can be calculated to be $B = \dfrac{11N_c - 2N_f}{12\pi}$
  - with n_C=3 number of colours, n_f=6 number of quark flavours
- Measuring α_S at a known energy scale μ^2 determine uniquely the value of α_S for all other energies, q^2.

Running of α_S

$$\alpha_S(q^2) = \frac{\alpha_S(\mu^2)}{1 + B\alpha_S(\mu^2)\ln\left(\frac{q^2}{\mu^2}\right)}$$

This calculation won the Nobel Prize for Physics 2004 for Gross, Politzer and Wilczek



Measured values of α_S as a function of q

(from pdg.lbl.gov)

- α_S decrease with increasing q^2
  - ➡ The more energetic the interaction (high q^2), the weaker α_S.

    $\alpha_S\,(q^2=m_Z^2) =\sim 0.12$
  - ➡ The less energetic the interaction (low q^2), the stronger α_S.

    $\alpha_S\,(q^2=1\ \mathrm{GeV}^2) \sim O(1)$

Asymptotic Freedom and Confinement

- At high energy, $q^2 >> \mathbf{1\ GeV}$, α_S is small, *e.g.* $\alpha_S\ (q^2 = m_Z^2) \sim \mathbf{0.12.}$
  - ➡Quarks and gluons behave like free objects at high energy or short distances.
  - ➡This is known as **asymptotic freedom**.
  - ➡*e.g.* At high q^2 consider the scattering from the individual quarks.
  - ➡Use perturbation theory to calculate processes. However due to moderately large α_S need to calculate the more than just the simplest diagrams.
    - ➡Leading order (α_S^2), Next-to-leading order (α_S^4), Next-to-next-to-leading order (α_S^6)

- At low energy, $q^2 \sim \mathbf{1\ GeV}$, α_S is large, *e.g.* $\alpha_S\ (q = 1\ \mathrm{GeV}) \sim \mathbf{1.}$
  - ➡Quarks and gluons are locked (**confined**) inside mesons and baryons.
  - ➡Cannot use perturbation theory to obtain sensible results.
  - ➡Many approaches to calculating QCD non-perturbatively, e.g. lattice QCD, MC techniques.

Jets

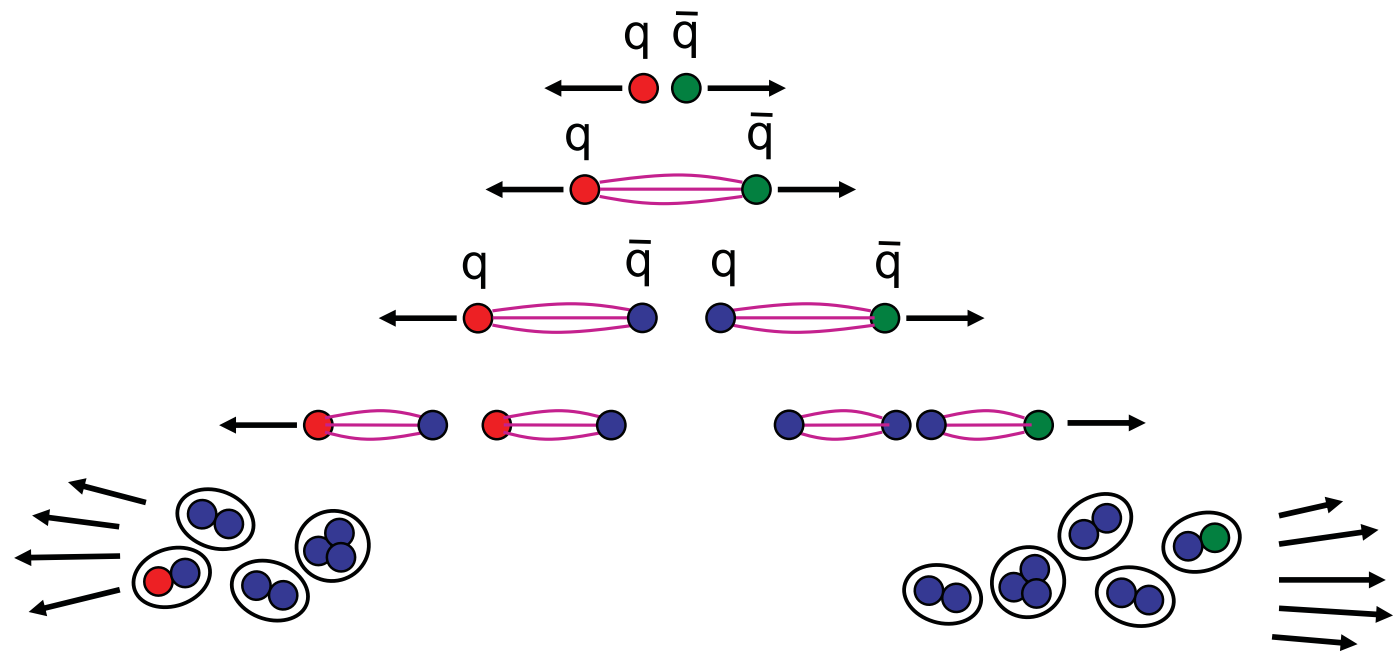
- Consider a quark and anti-quark produced in electron positron annihilation

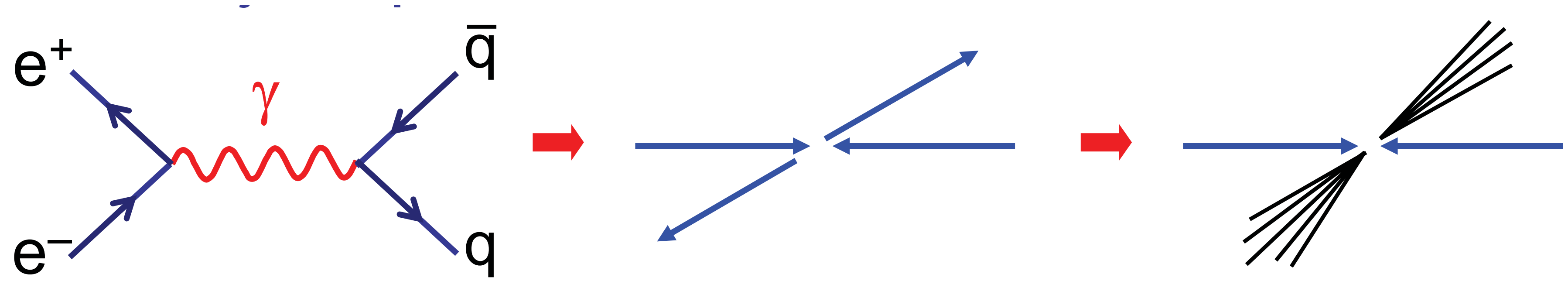
(i) Initially Quarks separate at high velocity

(ii) Colour flux tube forms between quarks

(iii) Energy stored in the flux tube sufficient to produce $q\overline{q}$ pairs

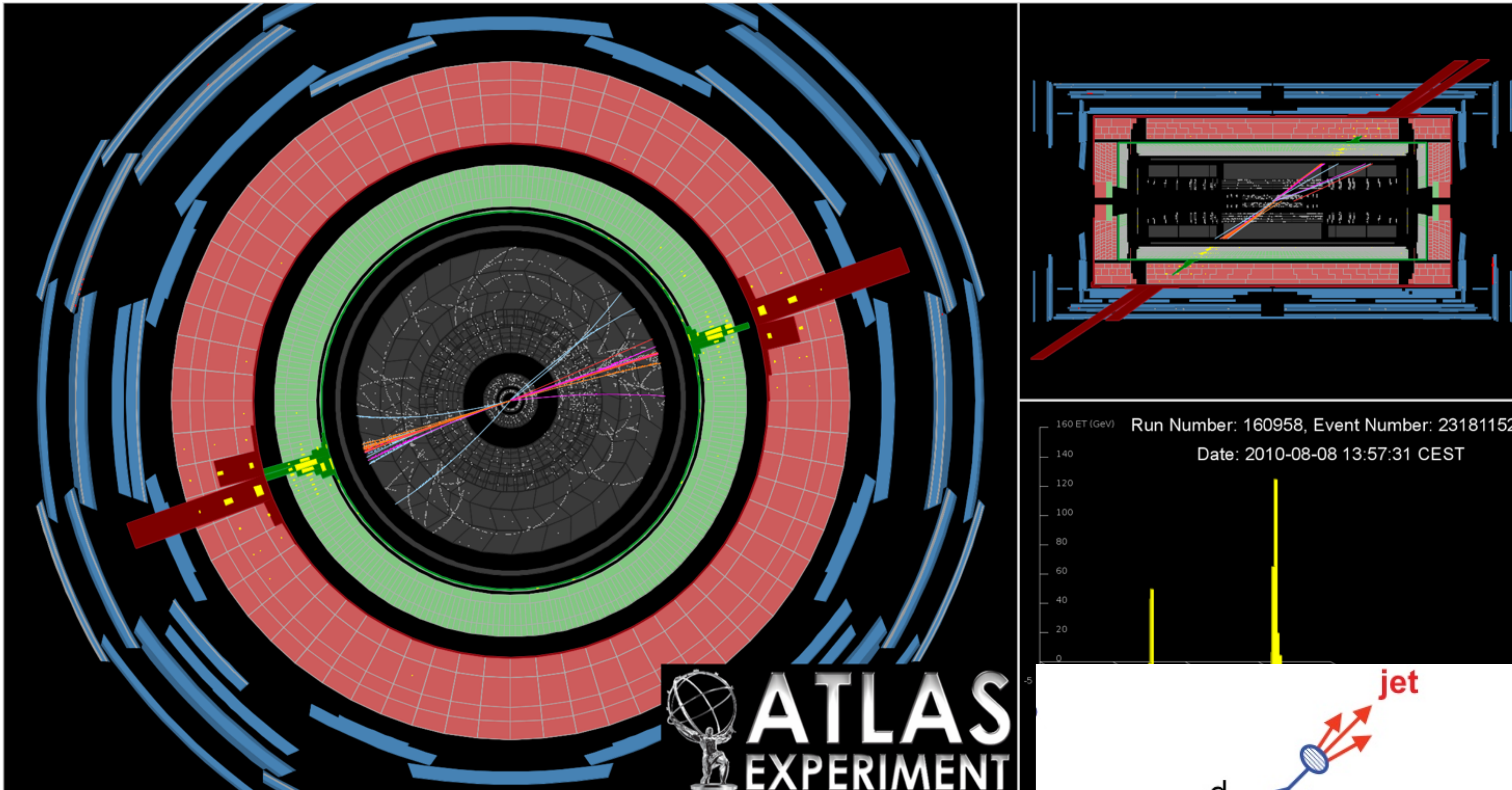
(iv) Process continues until quarks pair up into jets of colourless hadrons

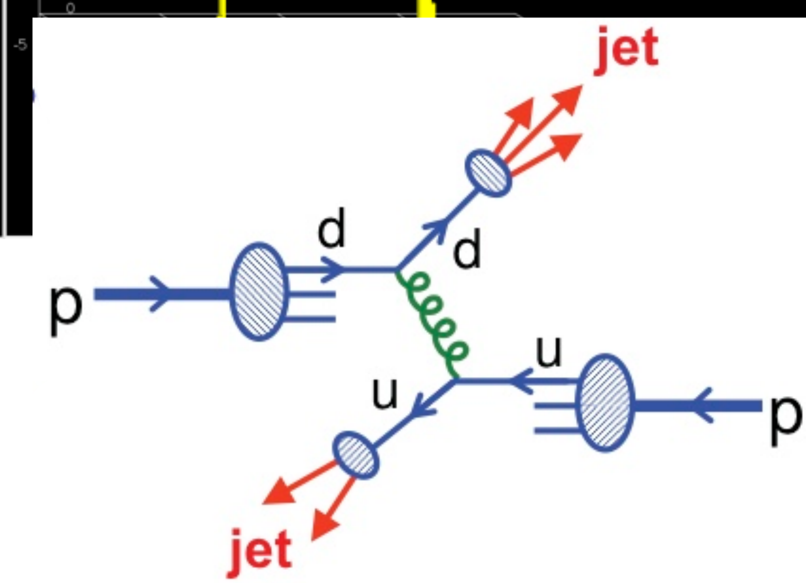




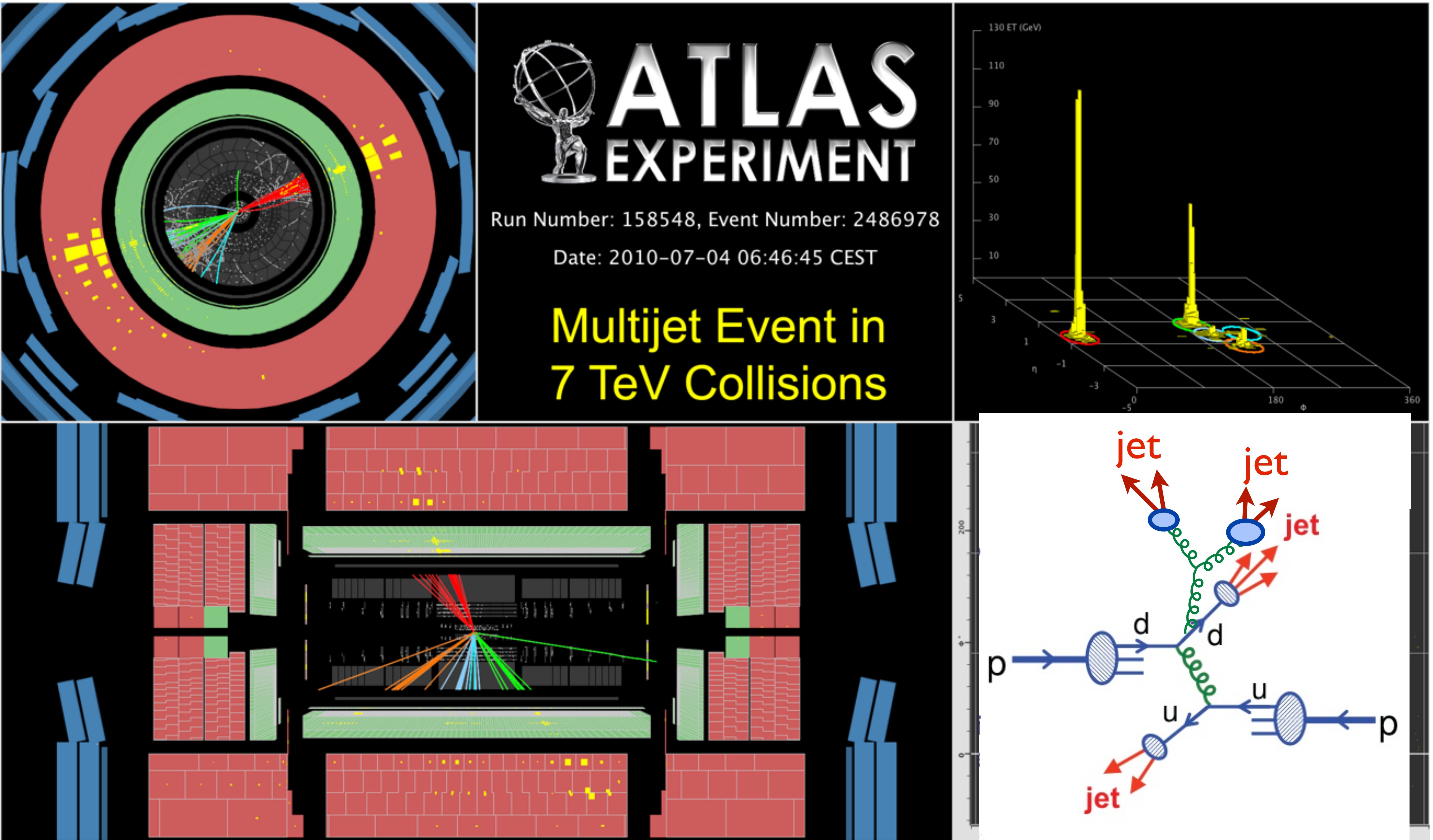
- This process is called **hadronisation**. It is not (yet) calculable.
- The main consequence is that at collider experiments quarks and gluons observed as **jets** of particles

LHC Event with Two Jets





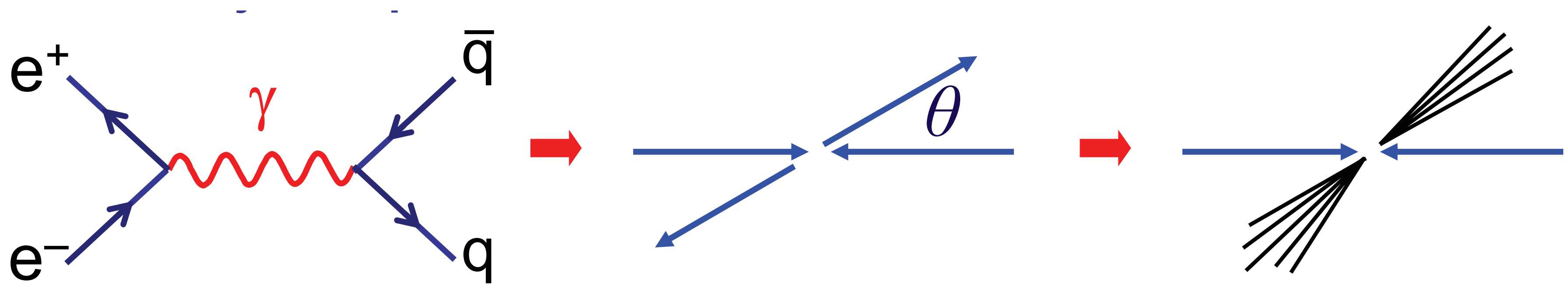
LHC Event with Multi Jets



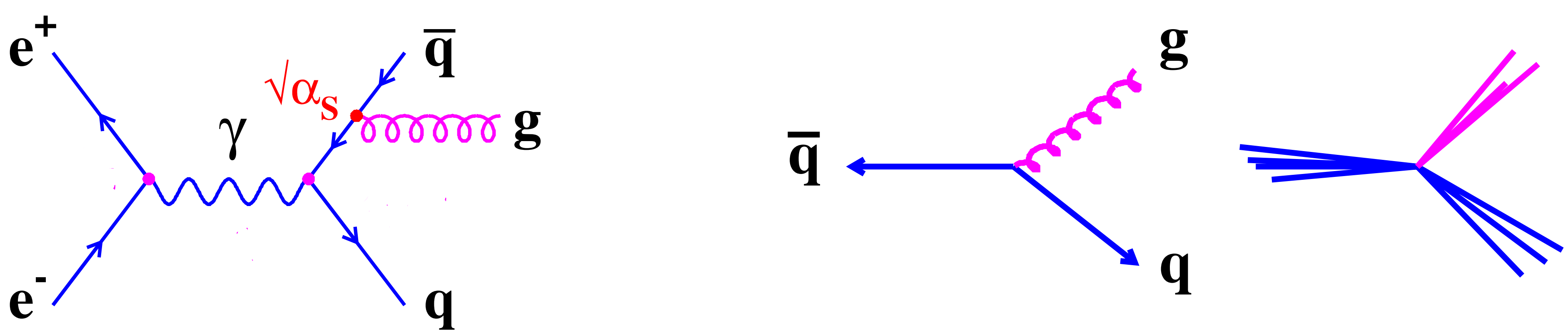
Colliders

- Collider experiments collide beams of particles e.g. e^+e^-, $p\bar{p}$, e^-p, pp
- Key parameters:
  - centre of mass energy: $\sqrt{s} = \sqrt{(p_a + p_b)^2}$
  - Integrated luminosity $\int \mathscr{L}\, dt = \mathscr{L} \times$ time to run experiment

$e^+e^- \to$ hadrons



- Electromagnetic production of quark pair: $\mathbf{q\bar{q}}$
    - $\mathbf{q}$ and $\mathbf{\bar{q}}$ hadronise into **two jets**
- In CM frame jets are produced back-to-back.
- Angular distribution $(\mathbf{1+cos^2\theta})$, same as $e^+e^-\to\mu^+\mu^-$



- Emission of a hard gluon in final state gives three jets (rate measures α_s)
- Observation of three jet events is direct evidence for gluons

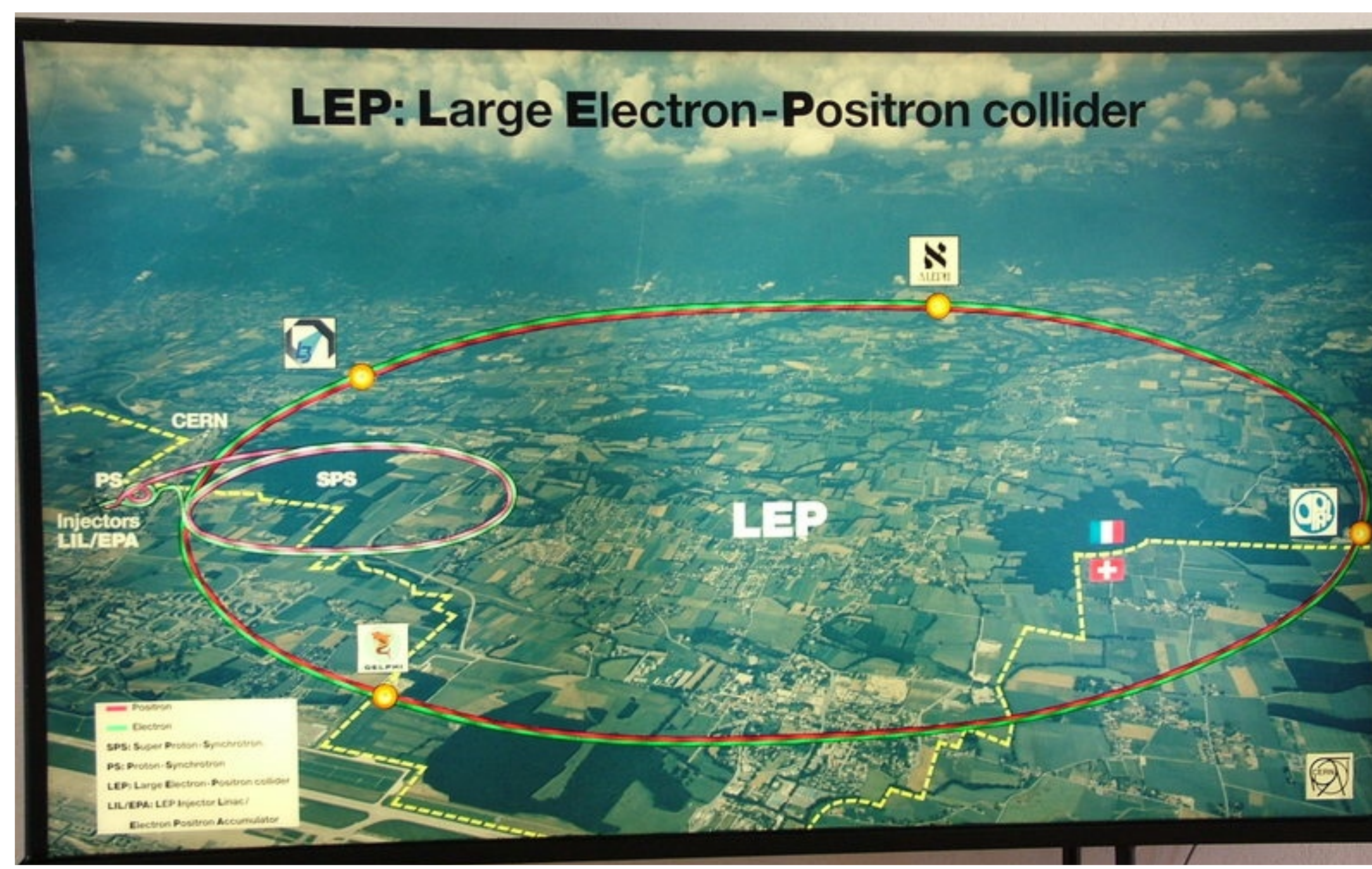
Lepton Colliders

PETRA: Positron-Elektron-Tandem-Ring-Anlage

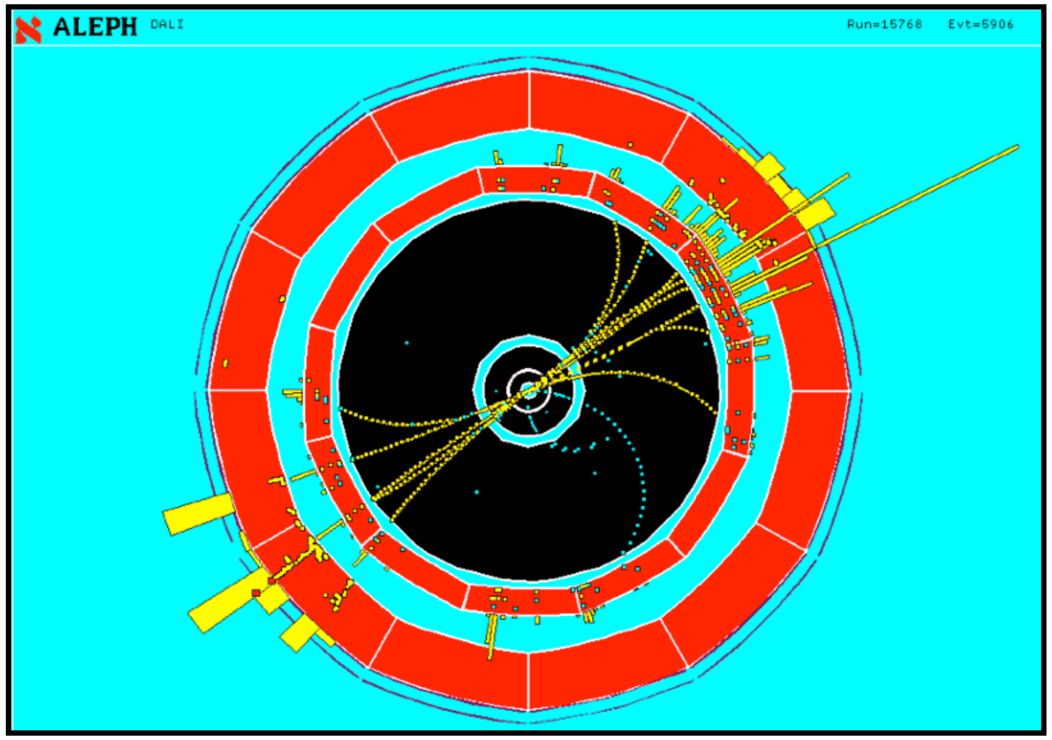
- At DESY, Hamburg
- ran 1978 to 1986
- e^+e^- collider, 2.3 km
- $\sqrt{s}$ = **14 to 46 GeV.**
- Two experimental collision points: TASSO and JADE.
- Highlight: discovery of the gluon!

LEP: Large Electron Positron Collider

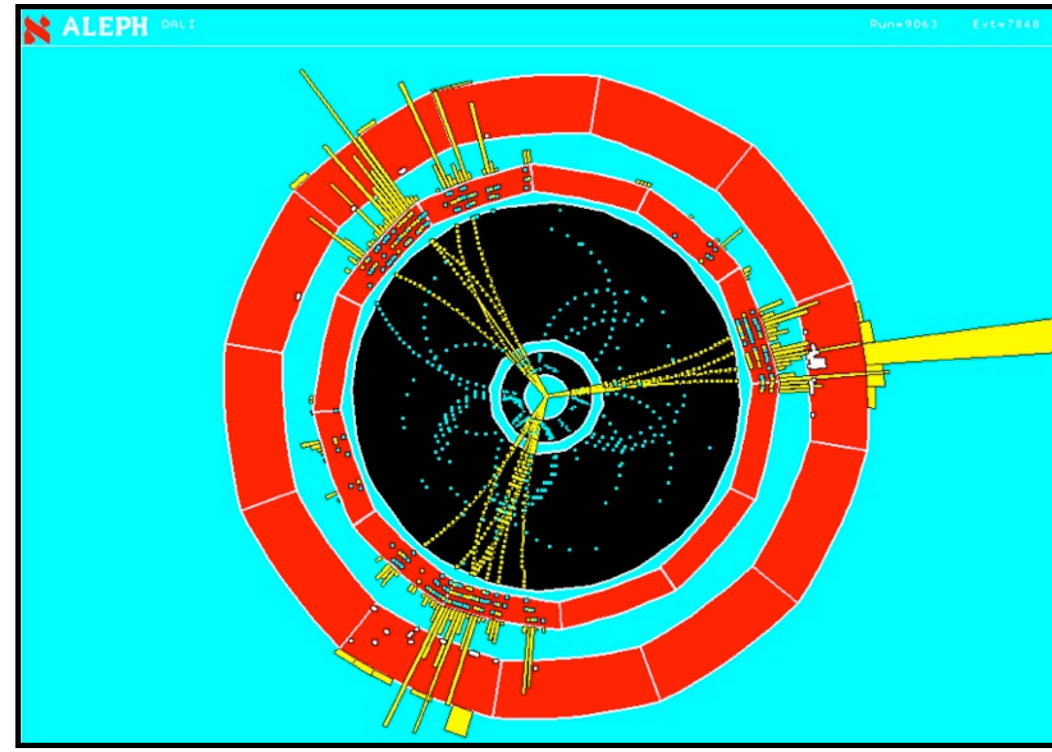
- At CERN
- The world's highest energy e^+e^- collider, 27 km circumference.
- LHC was built in LEP tunnel
- Ran from 1989 to 2000
- Centre of mass energy, $\sqrt{s}$=**89 to 206 GeV**
- Four experimental collision points: Aleph, Delphi, L3, Opal
- Highlight: beautiful confirmation of the electroweak model



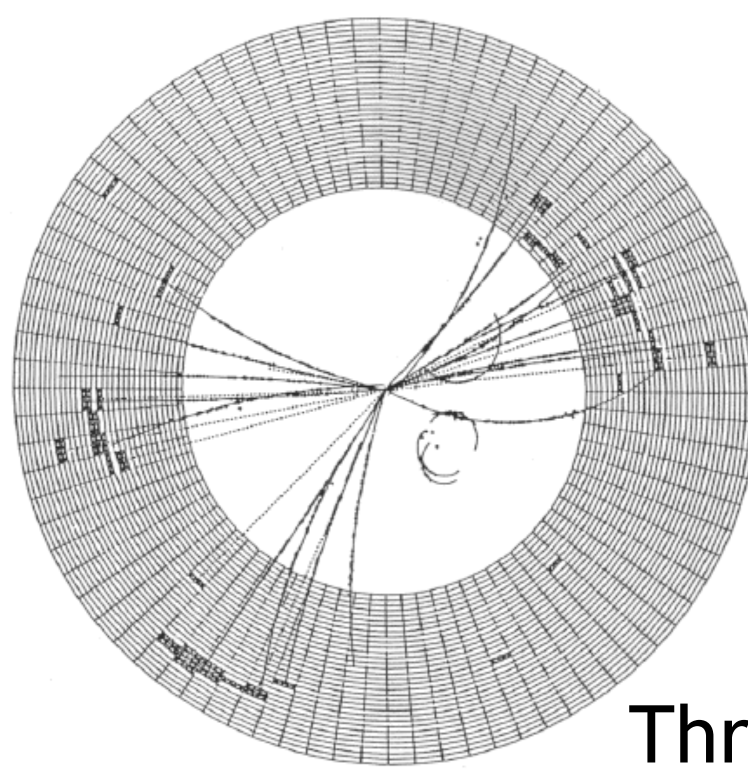
Jet Events at Lepton Colliders



Two jet event from LEP

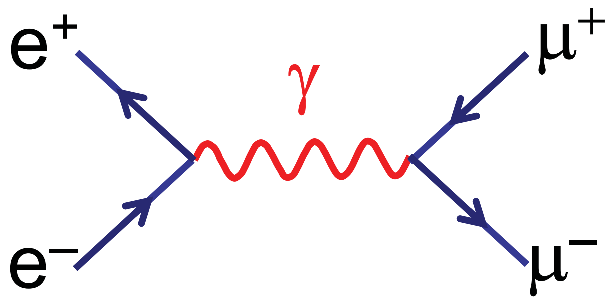


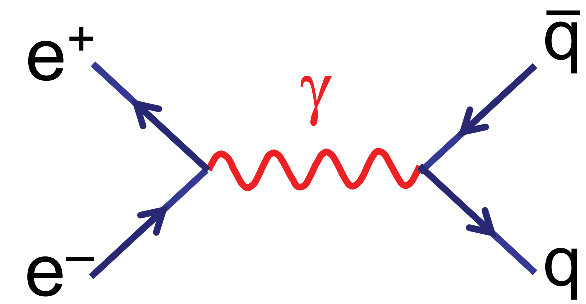
Three jet event from LEP



Three jet event from Petra

Rate for $e^+e^- \to$ hadrons





$$\mathcal{M}(e^+e^- \to \mu^+\mu^-) = \frac{e^2}{q^2}[\bar{v}(e^+)\gamma^\mu u(e^-)][v(\mu^+)\gamma^\mu \bar{u}(\mu^-)]$$

$$\mathcal{M}(e^+e^- \to \mathrm{q\bar{q}}) = \frac{e\,e_q}{q^2}[\bar{v}(e^+)\gamma^\mu u(e^-)][v(\mathrm{\bar{q}})\gamma^\mu \bar{u}(\mathrm{q})]$$

- Ignoring differences in the phase space, ratio, **R** between hadron production and muon production:

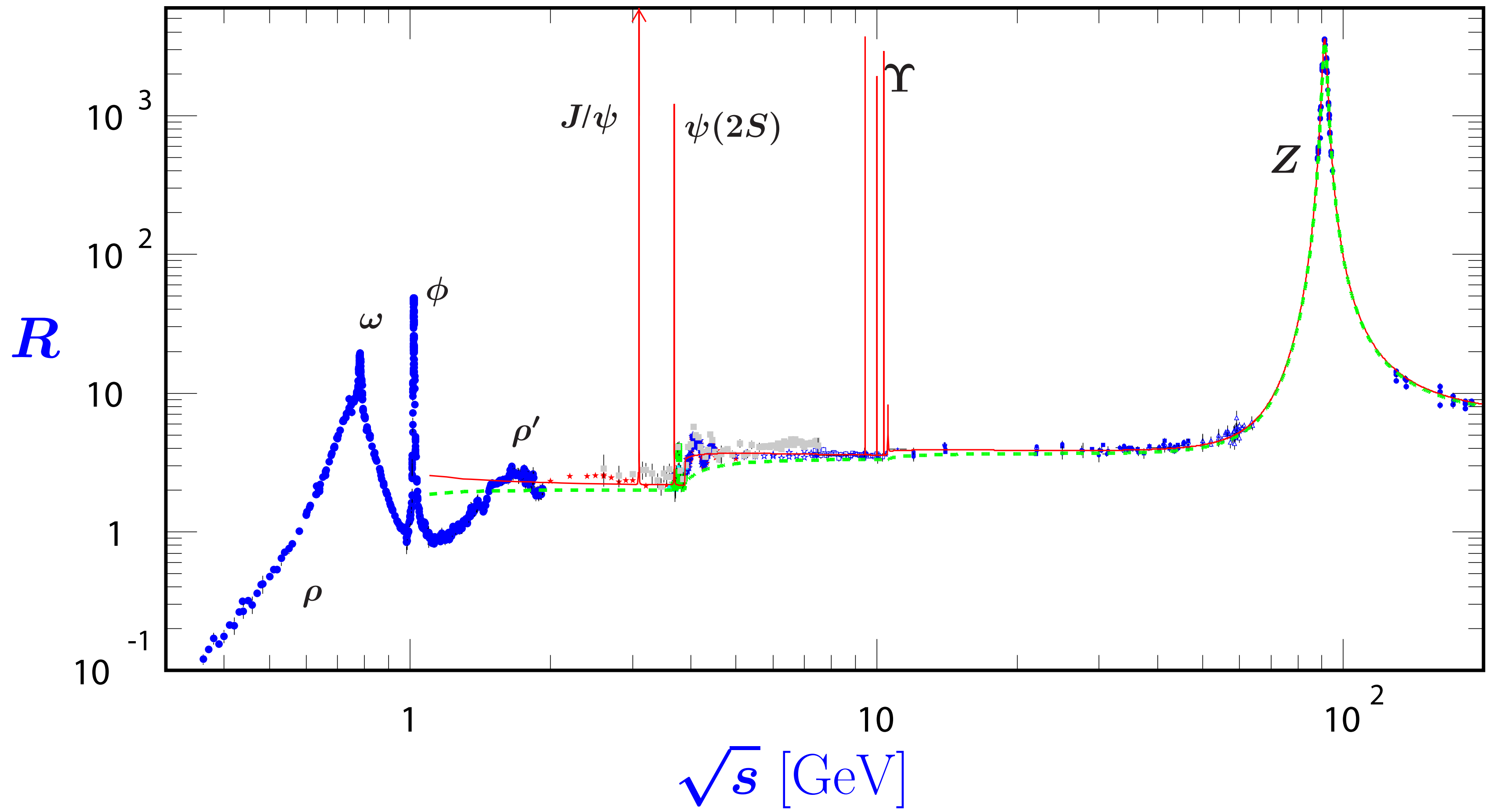
$$\mathbf{R} = \frac{\sigma(e^+e^- \to \mathrm{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} = N_c\frac{e_q^2}{e^2}$$

- N_c=3 is the number of quark colours
- $e_q = +\frac{2}{3}, -\frac{1}{3}$ is the charge of the quark
- The number of available quark flavours depends on the available $s=q^2$
- $\sqrt{s} > 2\,\mathrm{m_q}$ for a quark flavour **q** to be produced.

CM energy (GeV)	Available quark pairs	R
$1 < \sqrt{s} < 3$	u, d, s	2
$4 < \sqrt{s} < 9$	u, d, s, c	10/3
$\sqrt{s} > 10$	u, d, s, c, b	11/3

Measurement of R

- Compendium of measurements from many lepton colliders.



- Consistent with N_C=3, this is one of the key pieces of evidence for three quark colours.
- At quark thresholds, $\sqrt{s} \sim 2m_q$ "resonances" occur as bound states of $q\bar{q}$ more easily produced.
- Steps at ~4 and ~10 GeV due to charm and bottom quark threshold
- At $\sqrt{s} \sim$ 100 GeV, Z-boson exchange takes over.

Hadron Colliders

- **Sp$\bar{\text{p}}$S**: Super Proton anti-Proton Synchrotron at CERN
- 1981 - 1984, 6.9 km, $\sqrt{s} = 400$ GeV
- Two experiments: UA1 and UA2
- Tunnel now used for pre-acceleration for LHC

Nobel Prize for Physics 1984

Carlo Rubbia and Simon van der Meer, from CERN

"For their decisive contributions to large projects, which led to the discovery of the field particles W and Z, communicators of the weak interaction."

- **TeVatron** at Fermilab, near Chicago
- Proton anti-proton collider, 6.3 km
- Run 1: 1987 - 1995 $\sqrt{s} = 1.80$ TeV
- Run 2: 2000 - 2011 $\sqrt{s} = 1.96$ TeV
- Two experiments: CDF and DØ
- Highlight: discovery of the top quark!

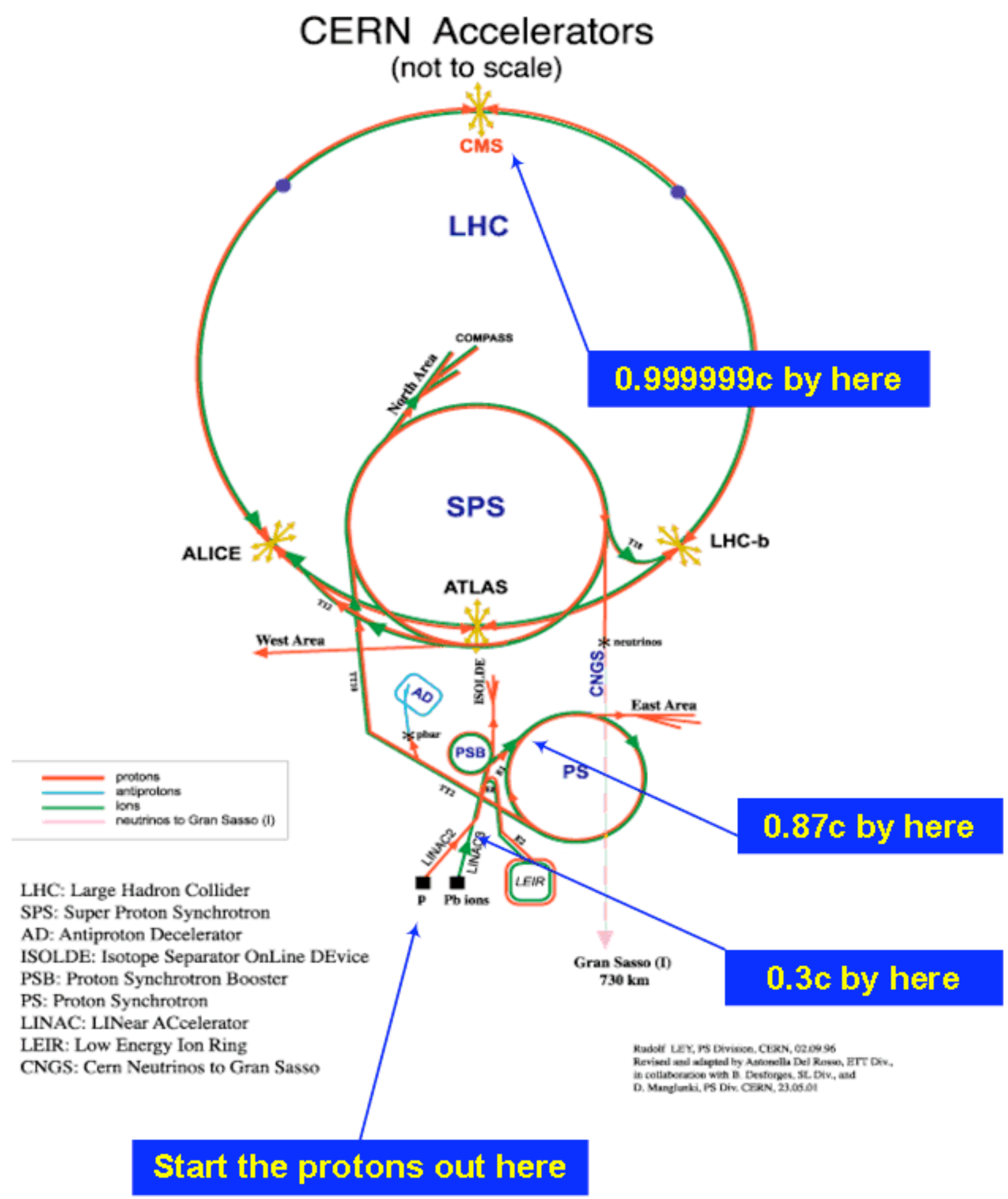
The Large Hadron Collider

- At CERN
- Proton-proton collider, $\sqrt{s} = 7$ **to 14 TeV**
- 2009 – 202X

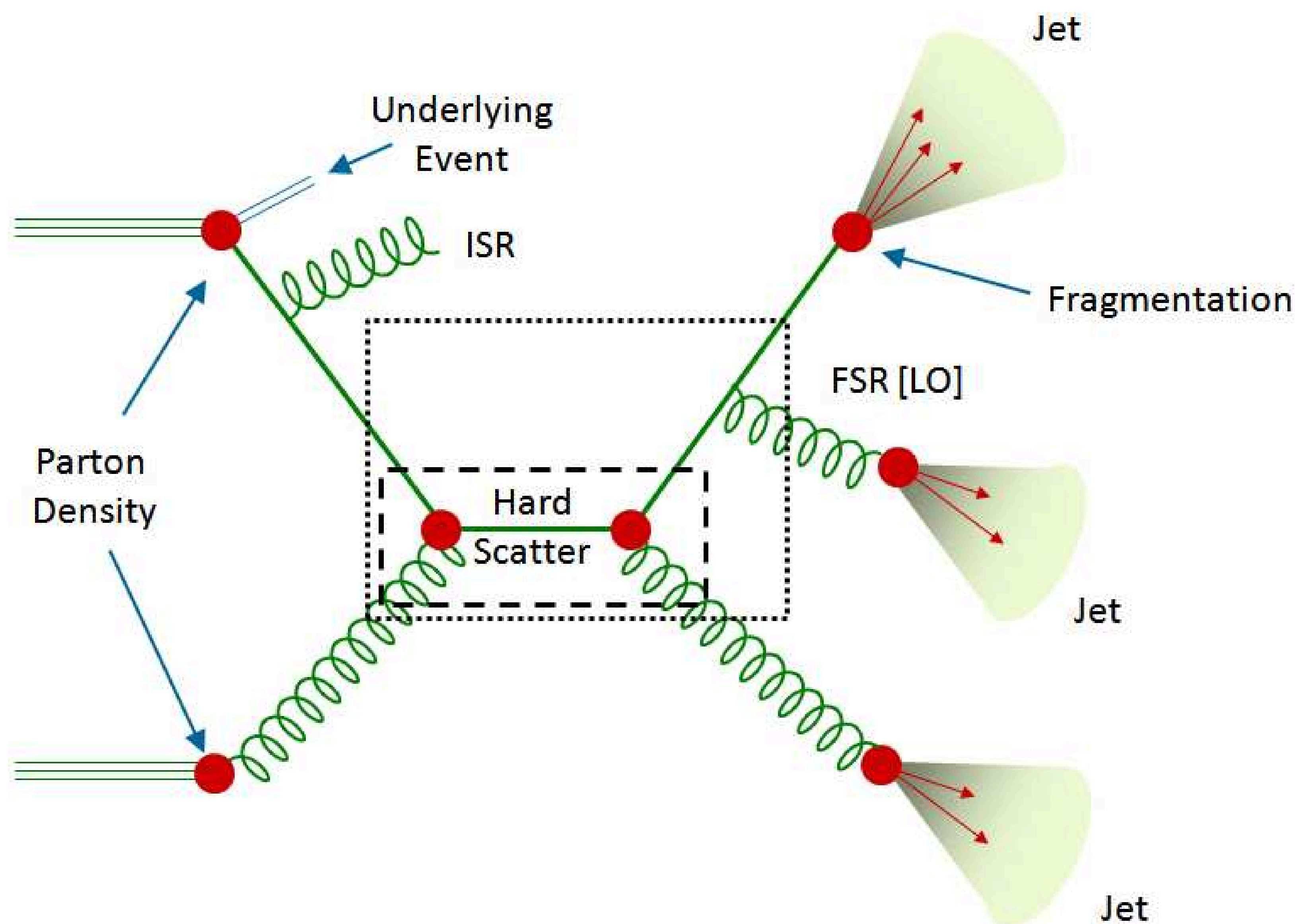
- Relies on network of accelerators

- Four collision points: ATLAS, CMS, LHCb, ALICE

- CMS & ATLAS: general purpose detectors: observation of highest energy collisions
- LHCb: specialist experiment looking at b-hadrons
- ALICE: specialist experiment looking at Pb ion collisions



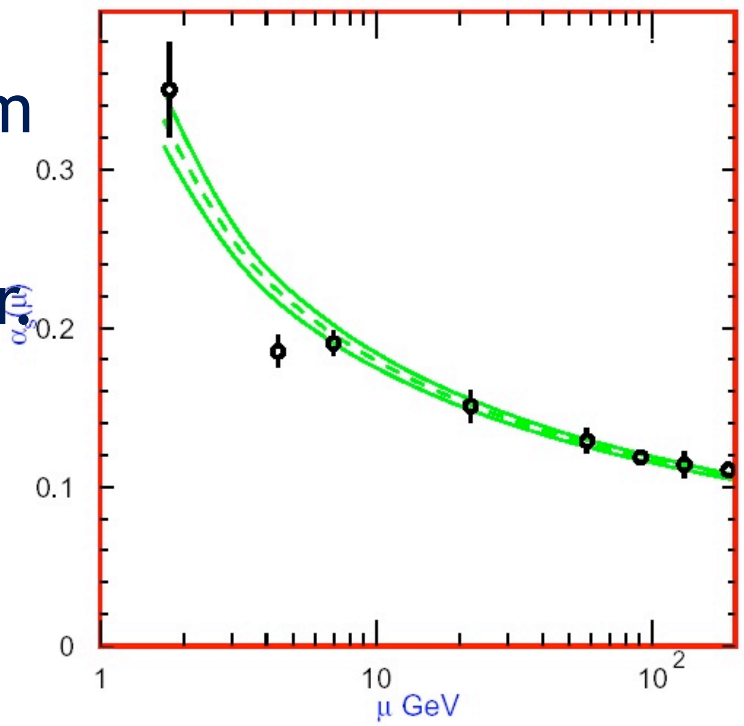
QCD production at Hadron Colliders



- Much more complicated due initial state hadrons not being fundamental particles
- Every object is colour charged: all object can interact with each other.
- QCD is very strong
- Not able to use perturbation theory to describe the interactions with low four momentum transfer q.

Summary

- In QCD, the coupling strength α_S decreases at high momentum transfer (q^2) increases at low momentum transfer.
- Perturbation theory is only useful at high momentum transfer.
- Non-perturbative techniques required at low momentum transfer.



- At colliders, hard scatter produces quark, anti-quarks and gluons.
- Fragmentation (hadronisation) describes how partons produced in hard scatter become final state hadrons. Need non-perturbative techniques.
- Final state hadrons observed in experiments as jets. Measure jet p_T, η, ϕ
- Key measurement at lepton collider, evidence for N_C=3 colours of quarks.

$$\mathbf{R} = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} = N_c \frac{e_q^2}{e^2}$$

Hadron Collider Dictionary

- The **hard scatter** is an initial scattering at high q^2 between partons (gluons, quarks, antiquarks).
- The **underlying event** is the interactions of what is left of the protons after parton scattering.
- **Initial and final state radiation** (ISR and FSR) are high energy gluon emissions from the scattering partons.
- **Fragmentation** is the process of producing final state particles from the parton produced in the hard scatter.
- A hadronic **jet** is a collimated cone of particles associated with a final state parton, produced through fragmentation.
- Transverse quantities are measured transverse to the beam direction.
- An event with high **transverse momentum** (p_T) jets or isolated leptons, is a signature for the production of high mass particles (W,Z,H,t).
- An event with **missing transverse energy** (E_T) is a signature for neutrinos, or other missing neutral particles.
- A **minimum bias** event has no missing energy, and no high mass final states particles ($W,Z,H,\mathrm{b},\mathrm{t}$). At the LHC these are treated as background.

Measuring Jets

- A jet has a four-momentum $E = \sum_i E_i \quad \vec{p} = \sum_i \vec{p}_i$
  - ➡ Where the constituents (i) are hadrons detected as charged tracks and neutral energy deposits.

- Transverse momentum of jet:

$$p_T^{\mathrm{JET}} = \sqrt{p_x^2 + p_y^2}$$

- Position in the detector in two coordinates:
  - ➡ ***Pseudorapidity*** of jet (η) $\eta^{\mathrm{JET}} = -\ln\left(\tan\frac{\theta}{2}\right)$

    with polar angle, θ $\cos\theta = \frac{\sqrt{p_x^2+p_y^2}}{p_z}$
  - ➡ **Azimuthal angle** of jet (ϕ) $\phi^{\mathrm{JET}} = \tan^{-1}\left(\frac{p_y}{p_x}\right)$

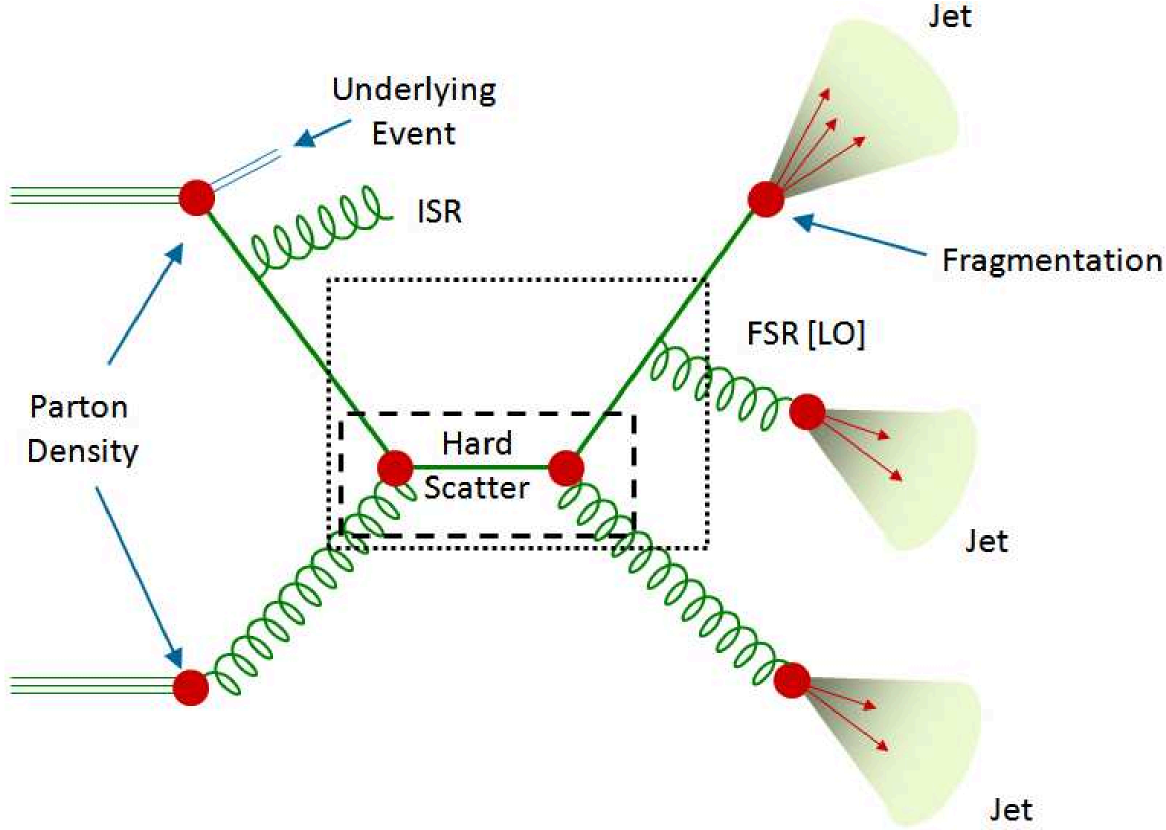
- To assign individual constituents to the jet, simplest algorithm is to define a **cone** around a central value: η^{JET}, ϕ^{JET}.

$$R^2 = (\eta_i - \eta^{\mathrm{JET}})^2 + (\phi_i - \phi^{\mathrm{JET}})^2$$

- All objects with R less than a given value (typically 0.4 or 0.7) are assigned to the jet
- Many sophisticated jet clustering algorithms exist which take into account QCD effects.

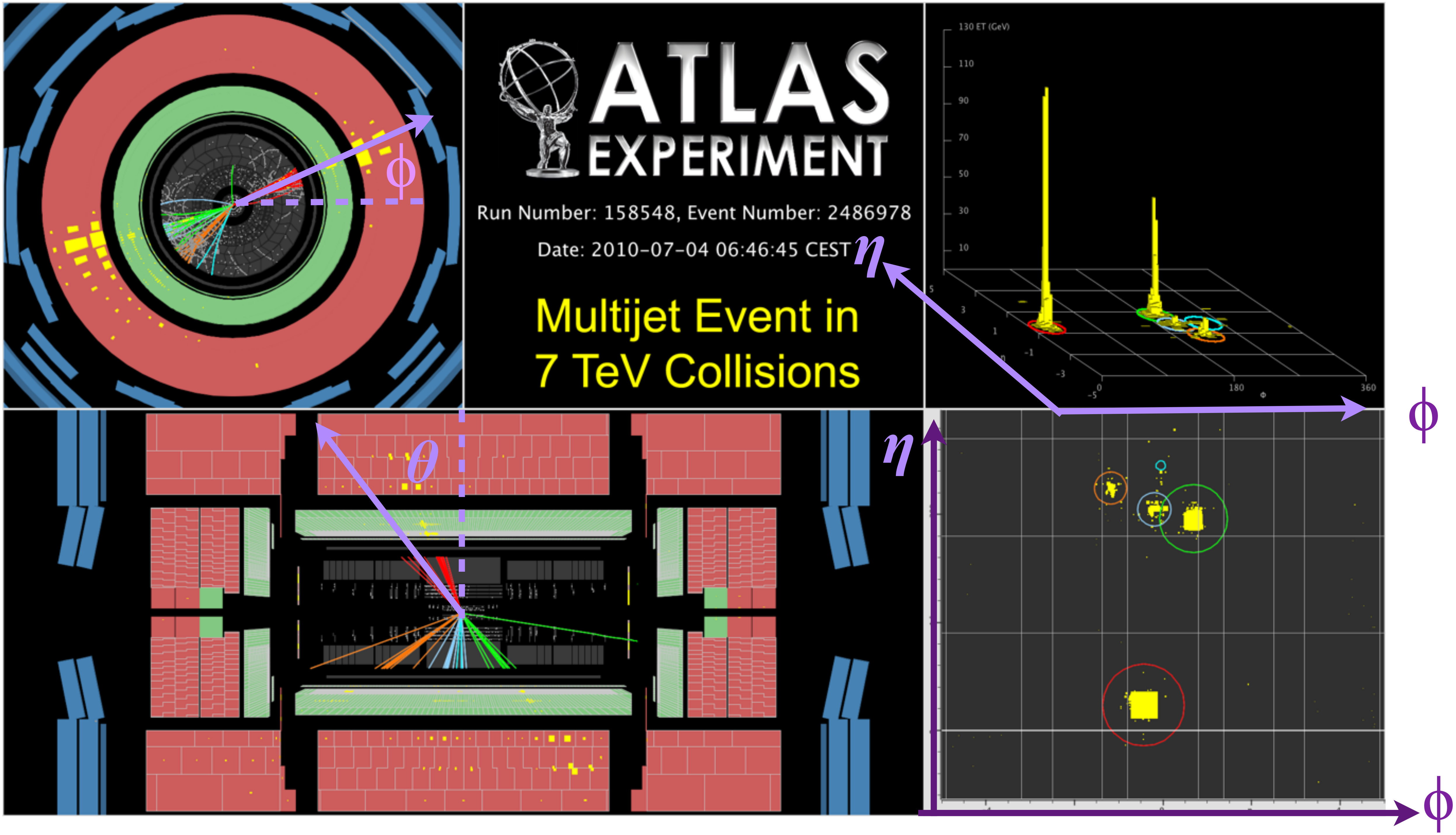
Jet Fragmentation

- **Fragmentation** or **hadronisation** is the process of producing final state particles from the parton produced in the hard scatter.
- Gluon momentum transfer, q, varies
  - ➡ both perturbative and non-perturbative methods are needed to describe/model fragmentation



- Initial parton radiates gluon, which can form quark anti-quark pairs, modeled using perturbative QCD
- Hadrons are formed using non-perturbative models of colour confinement. Several stochastic models exist, with many parameters:
  - PYTHIA, HERWIG, SHERPA
- The jet fragmentation algorithms are tuned to match data

ATLAS Multijet Event



- η and ϕ act as map of activity in the detector