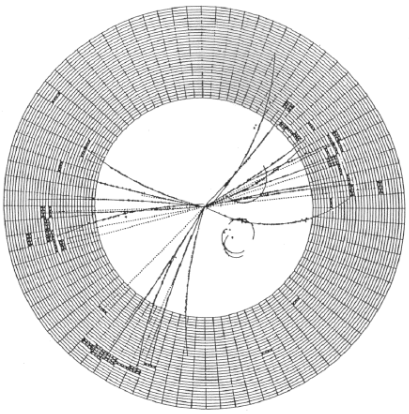
Particle Physics

Dr Victoria Martin, Spring Semester 2012

Lecture 10: QCD at Colliders



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

From Last Lecture: QCD Summary

- QCD: Quantum Chromodymanics is the quantum description of the strong force.
- 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

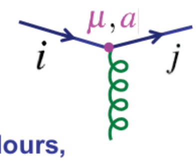
$$\frac{g_{\mu\nu}}{q^2}\delta^{ab}$$

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

Vertex Factors

spin 1/2 quark

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



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

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

- For $\mathcal{M}$ calculate the appropriate colour factor from the λ matrices.
- The coupling constant α_S is large at small q^2 (confinement) and large at high q^2 (asymptotic freedom).
- Mesons and baryons are held together by QCD.
- In high energy collisions, jets are the signatures of quark and gluon production.

From Last Lecture: Jets

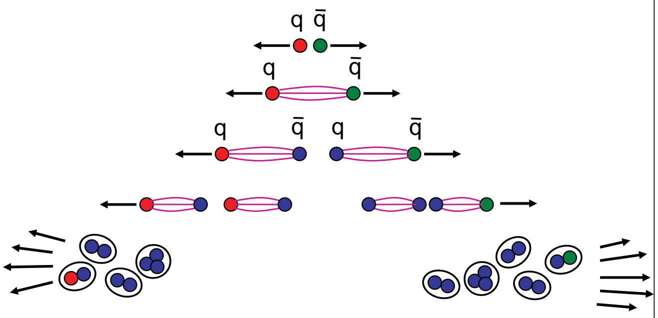
- Consider a quark and anti-quark produced in electron positron annihilation

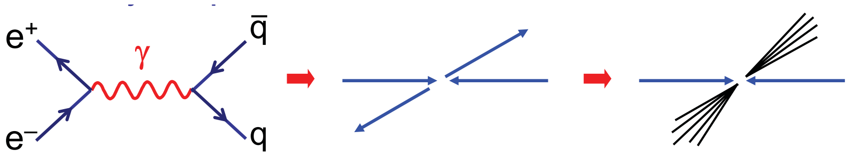
(i) Initially Quarks separate at high velocity

(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

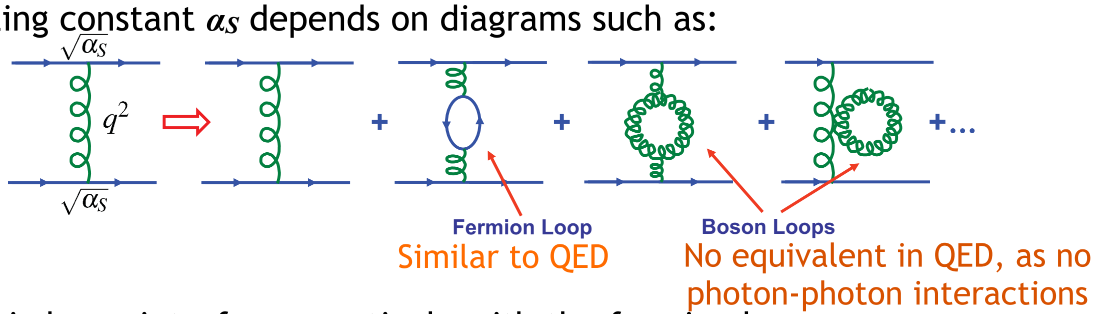




- This process is called **hadronisation**. It is not (yet) calculable.
- The main consequence is that at collider experiments quarks and gluons observed as **jets** of particles

Running Coupling

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



- Bosonic loops interfere negatively with the fermion loops.
- α_S can be written terms of the value at a reference scale μ:

$$\alpha_S(q^2) = \frac{\alpha_S(\mu^2)}{1 + \frac{\alpha_S(\mu^2)}{12\pi}(11n_C - 2n_f)\ln\left(\frac{q^2}{\mu^2}\right)}$$

  - n_C=3 is the number of colours
  - n_f=6 is the number of quark flavours
- Conventional to choose a reference of Λ, defined by:

$$\ln \Lambda^2 = \ln \mu^2 - \frac{12\pi}{(11n_C - 2n_f)\alpha_S(\mu^2)}$$

$\Lambda \sim 220$ MeV

Running of α_S

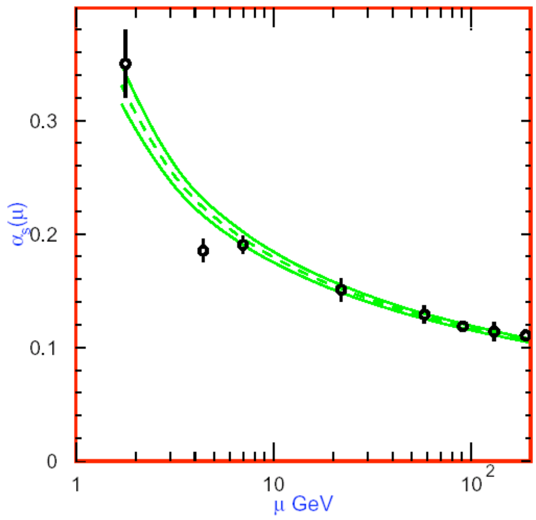
$$\alpha_S(q^2) = \frac{12\pi}{(11n_C - 2n_f)\ln\left(\frac{q^2}{\Lambda^2}\right)}$$

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

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

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

    α_S (q^2=1 GeV^2) ~ 1



Predicted shape of the running versus measurements

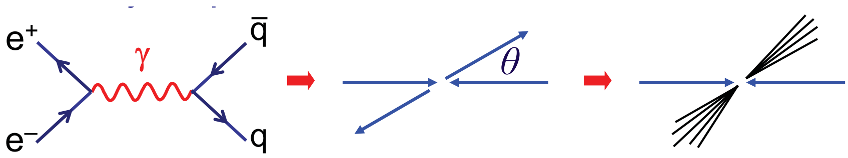
Asymptotic Freedom and Confinement

- At high energy, $q^2 >> \Lambda^2$, α_S is small, *e.g.* α_S (q=m_Z) ~ 0.12.
  - ➡Quarks and gluons behave like free objects at high energy or short distances.
  - ➡This is known as **asymptotic freedom**.
  - ➡*e.g.* in electron-proton scattering with high q^2 we found that we could consider the scattering from the individual quarks.
  - ➡Use pertubation 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, $q^2 \sim \Lambda^2$, α_S is large, *e.g.* α_S (q=1 GeV) ~ 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.

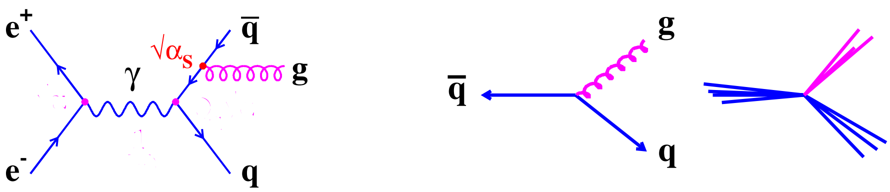
Colliders

- Collider experiments collide beams of particles e.g. e^+e^-, $p\bar{p}$, e^-p, pp
- Key parameters (see also lecture 4)
  - 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

$e^+e^- \rightarrow$ hadrons



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



- 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

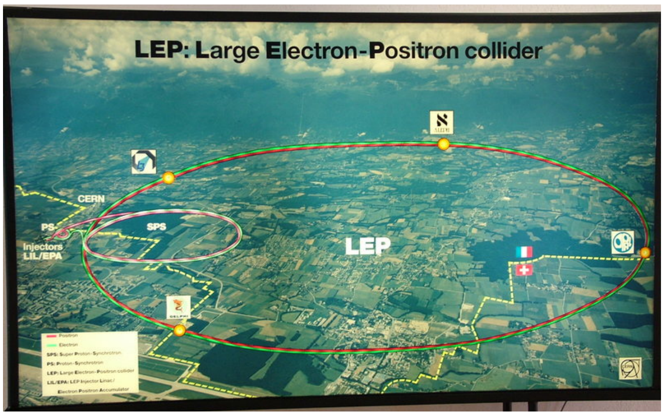
Lepton Colliders

PETRA: Positron-Elektron-Tandem-Ring-Anlage

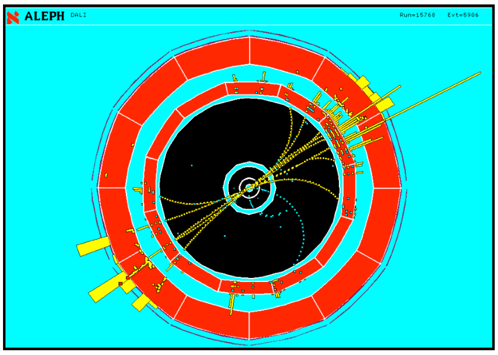
- At DESY, Hamburg
- ran 1978 to 1986
- e^+e^- collider, 2.3 km
- $\sqrt{s}$ = 14 to 46 GeV.
- Two experimental collision points: TASSO and JADE.
- Highlight: discovery of the gluon!

LEP: Large Electron Positron Collider

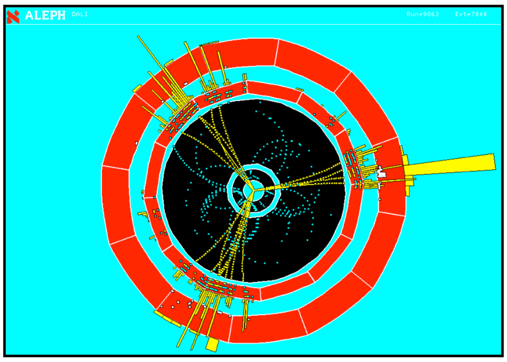
- At CERN
- The world's highest energy e^+e^- collider, 27 km circumference.
- LHC was built in LEP tunnel
- Ran from 1989 to 2000
- Centre of mass energy, $\sqrt{s}$=89 to 206 GeV
- Four experimental collision points: Aleph, Delphi, L3, Opal
- Highlight: beautiful confirmation of the electroweak model



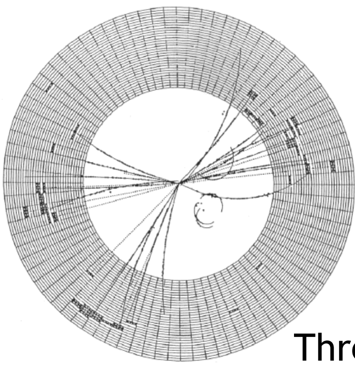
Jet Events at Lepton Colliders



Two jet event from LEP

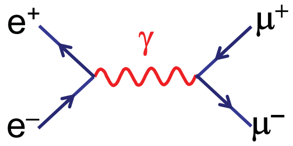


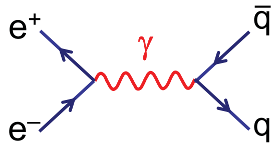
Three jet event from LEP



Three jet event from Petra

Rate for $e^+e^- \rightarrow$ 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:

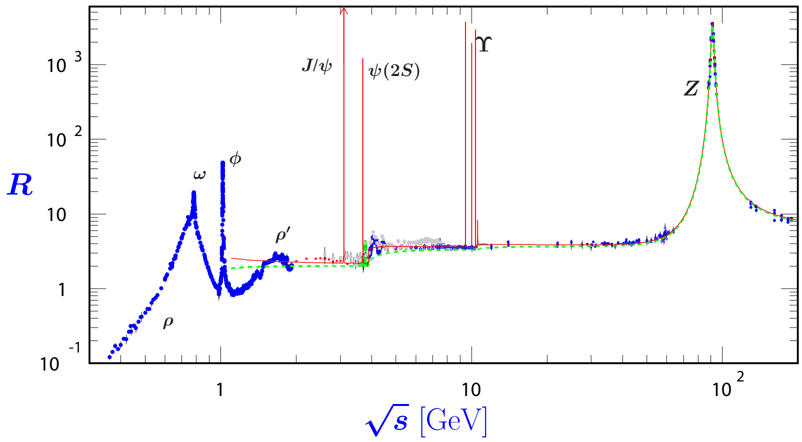
$$\mathbf{R} = \frac{\sigma(e^+e^- \to \mathrm{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} = N_c \frac{e_q^2}{e^2}$$

- N_c**=3** is the number of quark colours
- $e_q = +⅔, −⅓$ 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.

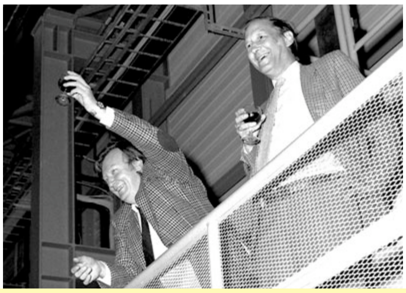


- Consistent with N_C**=3**, this is one of the key pieces of evidence for three quark colours.
- At quark thresholds, $\sqrt{s} \sim 2m_q$ "resonances" occur as bound states of $\mathrm{q\bar{q}}$ more easily produced.
- Steps at **~4** and **~10 GeV** due to charm and bottom quark threshold
- At $\sqrt{s}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

Hadron Colliders

Sp$\bar{p}$S

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



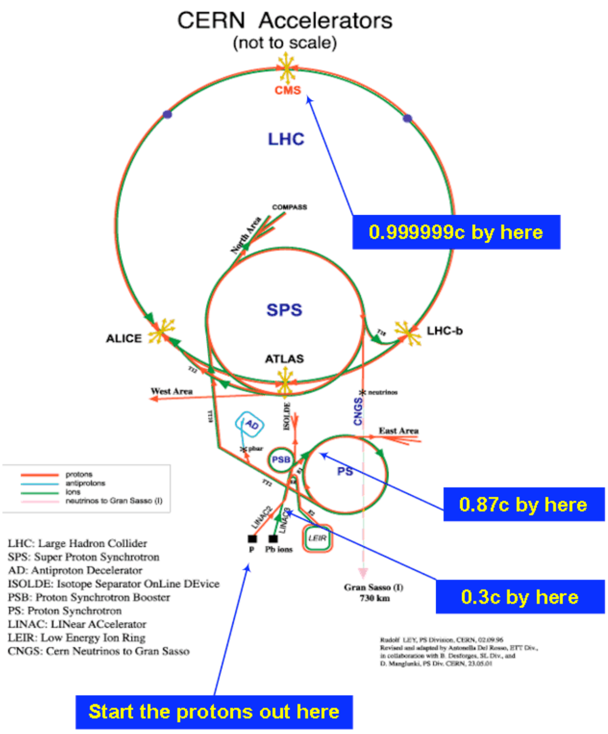
Nobel Prize for Physics 1984
Carlo Rubbia and Simon van der Meer, from CERN
"For their decisive contributions to large projects, which led to the discovery of the field particles W and Z, communicators of the weak interaction."

TeVatron

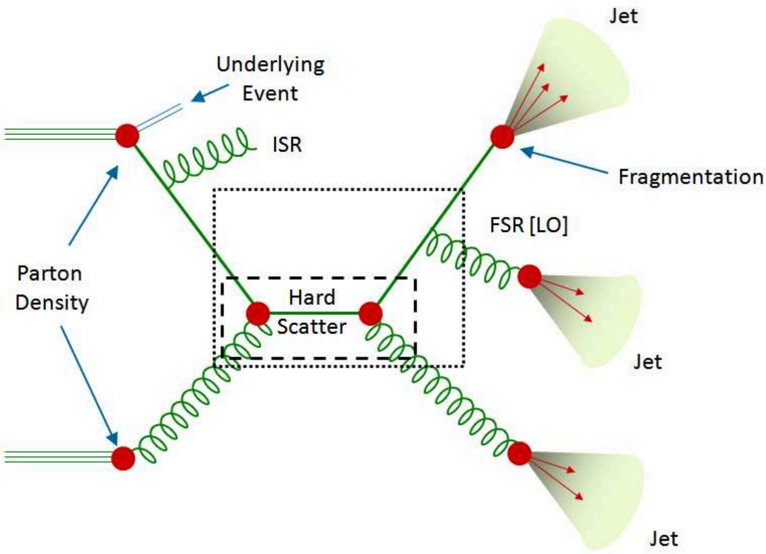
- At Fermilab, near Chicago
- Proton anti-proton collider, 6.3 km
- Run 1: 1987 - 1995
  - $\sqrt{s} = 1.80$ TeV
- Run 2: 2000 - 2011
  - $\sqrt{s} = 1.96$ TeV
- Two experimental collision points: CDF and DØ
- Highlight: discovery of the top quark!

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



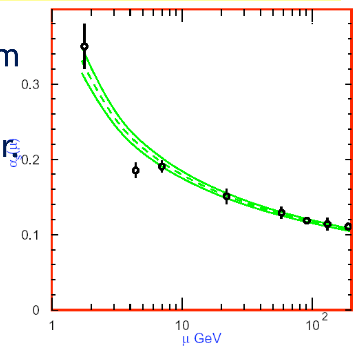
QCD production at Hadron Colliders



- 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.

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

- Next lecture: mesons and baryons! Griffiths chapter 5.