QCD Physics and HERA - Lecture I

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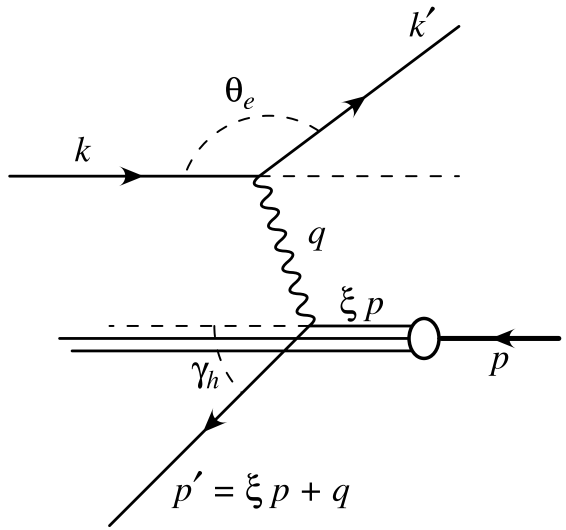
8/2/2005.

- *QCD Introduction.*
- *HERA Accelerator.*
- *Experiments.*
- *Deep Inelastic Scattering.*
- *Proton Structure.*
- *Photon Structure.*
- α_S *measurements.*
- *Beyond the SM.*



The Strong Interaction I

- *4 fundamental Interactions: Weak, Electromagnetic, Gravity, Strong*
- *Strong interaction posited to account for cohesion of nuclei.*
  - *Must be strong (stronger than EM).*
  - *Must only be effective over short distances.*
- *Original Theory: Yukawa interaction (1935).*
  - *Model on QED.*
  - *Use a massive* $\mathcal{O}(100\ \mathrm{MeV})$ *gauge boson to account for finite range.*
  - *Ideal candidate* π *discovered in cosmic ray + accelerator experiments in the 1940s.*
  - *Theorists made renormalisable field theories where nucleons interacted with each other via the exchange of pions, conserving isospin + strangeness.*
- *However perturbation expansions of QFTs of strong interaction broke down.*

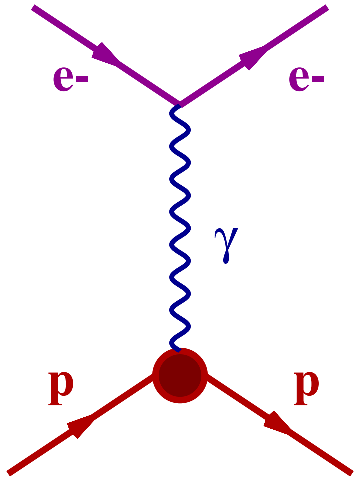
The Strong Interaction II

- *In QED, succesive complicated diagrams for a process are suppressed by a factor* $e^2 = \left(\frac{1}{137}\right)^2$ *per loop. Meaning that only the simplest diagrams make an appreciable contribution to the total cross section.*
- *Strong interaction coupling* g_S^2 *was measured at around 15 for hadrons, so that extra loops make a very large contribution.*
- *Thus perturbative theories broke down, the first term could not be replied upon since its magnitude was so much smaller than subsequent terms.*
- *To make any prediction from theory one must sum the whole series, which is not possible.*

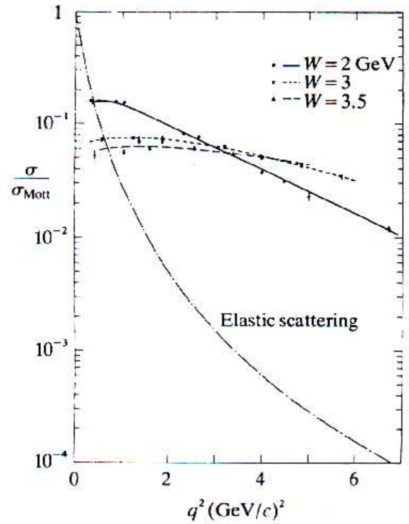
Aces and Quarks

- *In 1964 Gell-Mann and Zweig independently proposed that hadrons such as the proton were composite particles built from three basic blocks now known as up, down and strange.*
- *The proposed particles had very unusual properties:*
  - spin $\frac{1}{2}$ and baryon number $\frac{1}{3}$
  - u and d form an isospin doublet with 0 strangeness.
  - s an isospin 0 singlet with unit strangeness.
  - non-integral charge: $Q_u = +\frac{2}{3}$, $Q_{d,s} = -\frac{1}{3}$
- *Mesons formed by $q\bar{q}$, nine combinations available, octet and singlet.*
- *Baryons formed by qqq, in SU(3) only decuplets, octets and singlets available.*

ep scattering



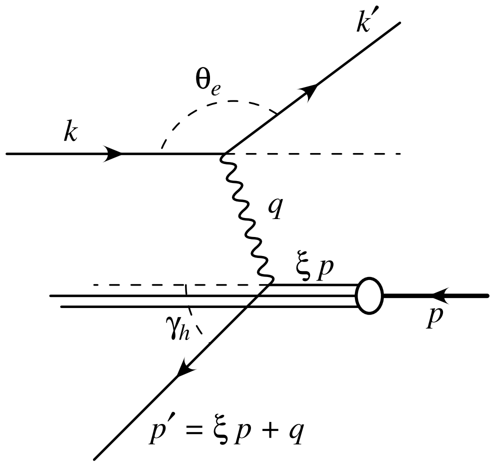
- *In the late 1960s a new phenomenon was observed at SLAC: scaling.*
- *SLAC used a 22 GeV linear electron accelerator.*
- *Accelerated electrons were scattered off protons and elastic ep scattering observed.*
- *Elastic ep scattering can be understood entirely in terms of QED as the exchange by proton and electron of a single photon. Electrons are structureless particles whereas protons are extended objects that should show structure.*
- *First measurements showed that cross sections at large angles in ep scattering were much smaller than in ee scattering.*
  - *Electrons seemed to act as 'hard' objects, bouncing off one another.*
  - *Protons seemed to be diffuse large objects that exerted a smaller impulse on passing particles.*

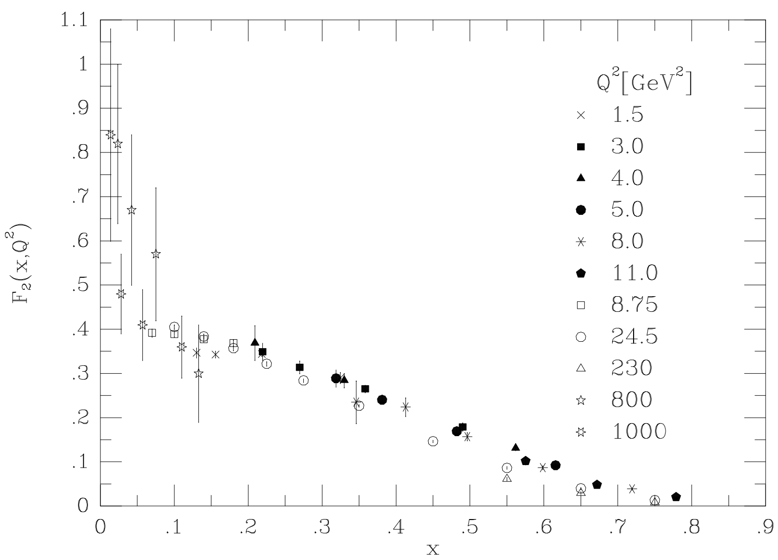


Scaling in inelastic ep scattering

- *Inelastic ep scattering was also thought to be mediated by single photon exchange between proton and electron, and it was thought that the most important process would be resonance production.*
- *analysis of the data at low electron scattering angle showed the expected behaviour.*
- *at large angles there remained a large measured cross section, despite the disappearance of individual resonance peaks.*
- *The inelastic ep cross section was behaving as though the proton contained: hard, point-like scattering centres.*

Scaling in inelasic ep scattering





- *In high energy ep scattering we can define the following variables:*

$$q{=}k{-}k', \quad Q^2 = -q^2, \quad M^2 = p^2$$
$$x = \frac{Q^2}{2p.q}, \quad y = \frac{q.p}{k.p}$$

- *Structure functions F_1 and F_2 are defined in terms of the cross section:*

$$\frac{d^2\sigma}{dxdQ^2} = \frac{4\pi\alpha^2}{Q^4}\{[1+(1-y)^2]F_1 + \frac{(1-y)}{x}(F_1 - 2xF_2)\}$$

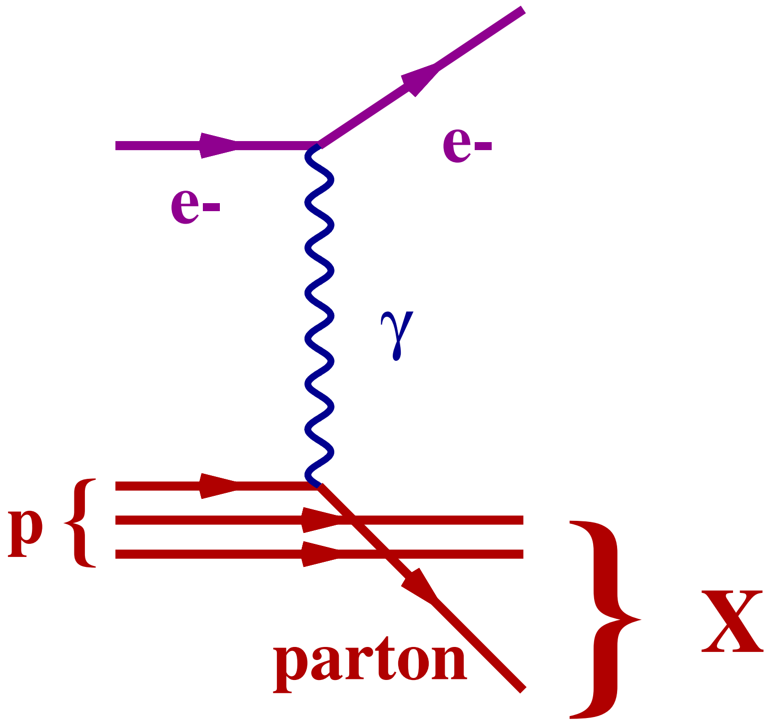
- *F_1 and F_2 are functions of x,Q^2. Björken predicted that for $Q^2 \to \infty$, and x fixed the structure functions depend only on x.*

$$F_i(x, Q^2) = F_i(x)$$

- *Björken scaling $\longrightarrow \gamma$ scatters off (charged) point-like proton constituents.*

Scaling and the Quark-Parton Model

- *The Quark-Parton Model (QPM) was developed by Feynman to account for scaling.*
- *The Proton constituents are called partons.*
- *Björken scaling $\rightarrow \gamma$ scatters off (charged) point-like proton constituent.*
- *Partons are Quasi-free, and regarded as being independent over the time of collisions.*
- *Deep Inelastic Scattering (DIS) takes place in the QPM as single photon exchange between the incoming electron and a parton.*
- *F_1, F_2 measure the momentum distribution of the charged partons within the proton in terms of x (momentum fraction of proton).*
- *Parton Model predicts scaling.*



The Quark Parton Model I

- *Successes:*
  - *Provides a method to deal with strong interactions by focusing on their effect on parton distributions.*
  - *With parton distributions, electron-hadron processes became calculable in terms of first order QED processes.*
- *Questions:*
  - *What are the partons? Are they Quarks?*
  - *Partons must be Quasi-free to account for scaling, but constituent quark model requires strong inter-quark forces.*
- *Need an extra QPM assumption to stop quarks flying out of the proton after scattering. (No quarks observed in remnants of collisions).*
- *Feynman showed that scaling would be observed in DIS irrespective of parton nature.*

The Quark Parton Model II

- *Subsequent work focused on the attributes of partons.*
- *We can express the contribution of each quark to F_i using the fact that the interactions are from QED:*

$$F_2(x) = \sum_{q,\bar{q}} e_q^2 x q(x)$$

Where $q(x)$ is the probability of finding a parton with momentum fraction between q and $q + \mathrm{d}x$

- *Relative magnitudes of F_1 and F_2 are determined by spin.*
- *$R = F_1 - 2xF_1$ was measured as approximately 0 (Callan-Gross relation), as would be expected in the spin $\frac{1}{2}$ case.*
- *3 quark (uud) model of protons overestimated the measured size of the structure functions by approximately 2.*
- *Break down quark component into:*
  - *"Valence" component: comprising minimum SU(3) composition of the hadron.*
  - *"Sea" component: SU(3) singlet cloud containing indefinite number of quarks.*

Sea Quarks and Sum Rules

- *When probed at a scale Q^2, the sea contains all flavours with $M \ll Q$.*
- *at $Q \approx 1GeV$ appropriate pdf's are:*

$$u(x) = u_V x + u_S(x), u(x) = d_V x + d_S(x), s(x) = s_S(x)$$

expect that $\bar{u}(x) = \bar{d}(x) = s(x) = \bar{s}(x)$

- *Expect the proton momentum sum rules, to hold:*

$$\int_0^1 u_V(x)\,\mathrm{d}x = 2 \text{ and } \int_0^1 d_V(x)\,\mathrm{d}x = 1$$

- *It was measured that:*

$$\sum_q \int_0^1 q(x) + \bar{q}(x) \sim 0.5$$

- *50% of proton momentum is not carried by quarks.*

Gluons and QPM

- *Other 50 % of proton momentum must be carried by neutral particles.*
- *Natural solution: neutral boson exchanged by quarks in strong interactions.*
- *QPM modified to include a nuclear glue-particle responsible for the inter-quark force: The Gluon*
- *Inclusion of a gluonic component reduced structure functions, improving description of the SLAC data.*

Strong Interactions and QFT

- *In QFT no realistic interacting theory existed predicting scaling.*
- *The success of the parton model and scaling phenomena in DIS was explained with the demonstration of the asymptotic freedom property of gauge theories.*
- *Gauge theories are invariant under local transformations of the fields and thus the predictions of the theory are unchanged by such transformations.*
- *Asymptotic freedom means that at high momenta gauge theories behave as free, non-interacting field theories.*
- *important steps:*
  - *1972: Gross and Coleman demonstrate that no renormalisable field theory except gauge theories, could account for scaling.*
  - *1973: Politzer and Wilczek demonstrate asymptotic freedom of gauge theories.*
  - *1973: Gross and Coleman demonstrate that no theory without gauge fileds asymptotically free.*
- *A field theory of the strong interaction must be a gauge theory.*

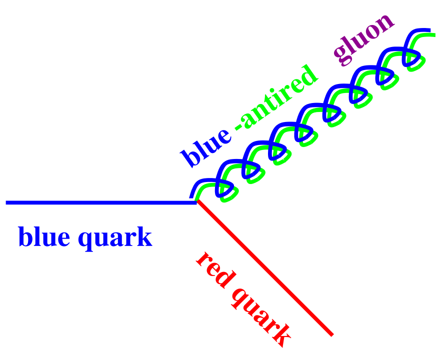
QCD: A Gauge Theory of the Strong Interaction.

- *Assume that the fundamental gauge fields are the quarks interacting via the exchange of gauge vector fields (gluons).*
- *since quarks are fermions, the total wave function must be antisymmetric under quark-interchange. Wave functions of quarks were represented by three components.*

$$\Psi_q = \psi_{SU(3)_F}\phi_{\text{spin}}\psi_{\text{space}}$$

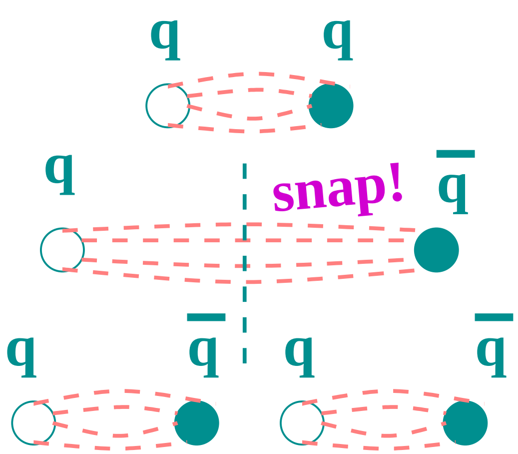
Which is symmetric overall under exchange of quarks.

- *Solution : Introduce a new Quantum number* $\longrightarrow$ *Colour*
- *Hence the gauge theory of strong interactions describing the strong interactions between quarks and gluons within the SU(3) group of colour is known as Quantum Chromo Dynamics (QCD).*
- *3 Colour charges, conserved at each vertex, are used:*
  - *quarks are singly charged.*
  - *gluons doubly charged.*



QCD and Confinement

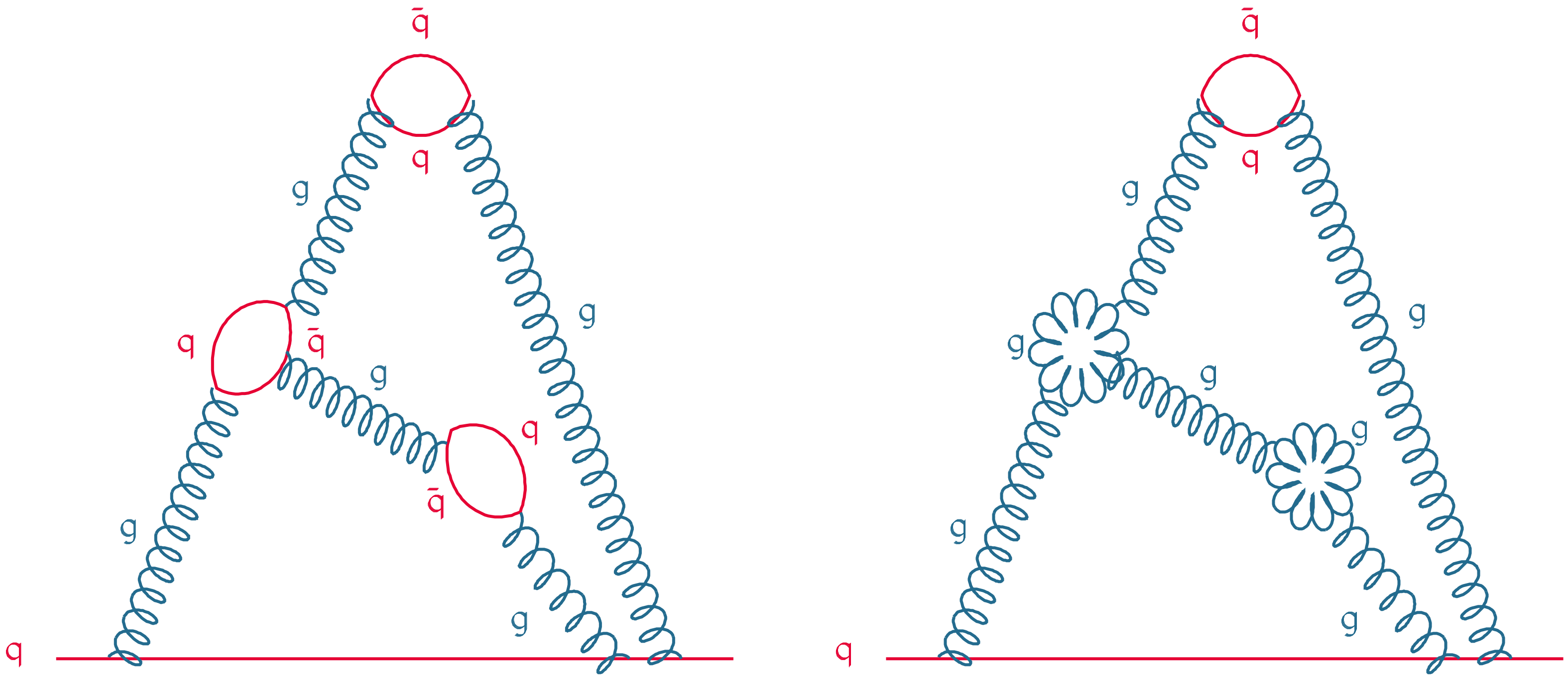
- *QCD exhibits the two most important properties of quark and gluon interactions: aymptotic freedom and confinement.*
- *Confinement offers a solution to the problem of the lack of observation of free quarks.*
- *Since gluons also carry colour charge, they can couple directly to other gluons.*
- *The potential energy required to separate quarks increase linearly with their distance.*



- *Quarks and gluons are only seen in colourless hadrons.*
- *Large amounts of energy to break up hadrons.*
- *This energy is needed to create quark-anti-quark pairs.*

Asymptotic Freedom

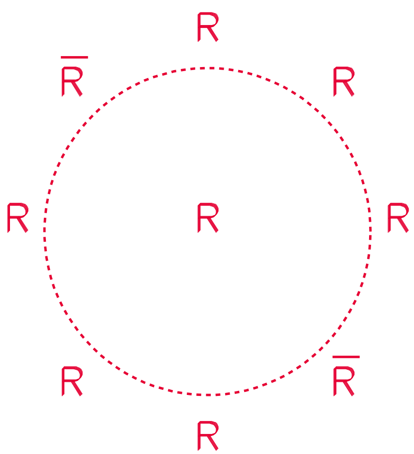
- *In QFT a quark can emit a gluon, the gluon can decay to a $q\bar{q}$ pair and so on.*

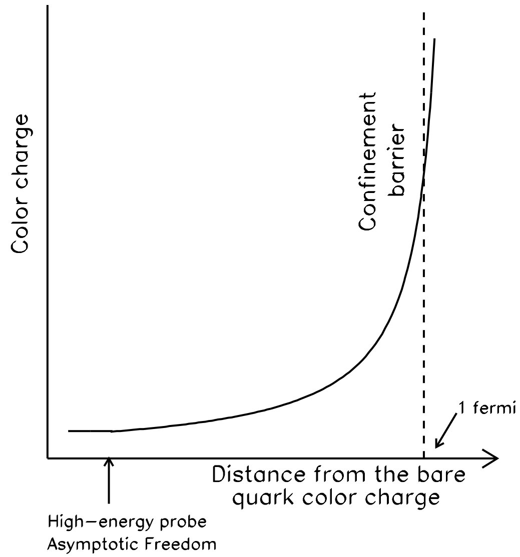


- *The $\bar{q}q$ pairs surround the quark and diffuse the effective colour of the quark.*

Asymptotic Freedom

- *A red charge for example is surrounded by a cloud of colour dipoles antiscreening the colour charge.*
- *To determine the charge, measure the force experienced by a test charge.*
- *moving the test charge towards the quark leads to decrease in measured charge!*
- *This antiscreening results in asymptotic freedom.*
- *When very close together, the quarks interact through colour fields of reduced strength, and behave as free non-interacting particles.*

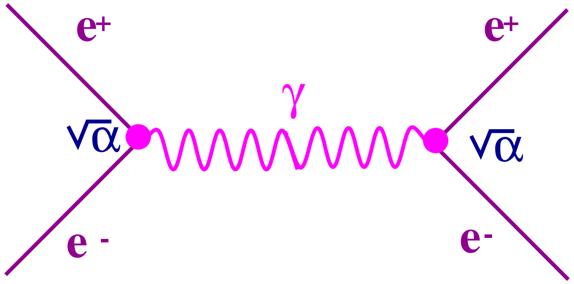




α_S the QCD Coupling Constant

- α *is a measure of the strength of the EM interaction.* $\alpha = \frac{e^2}{4\pi}$

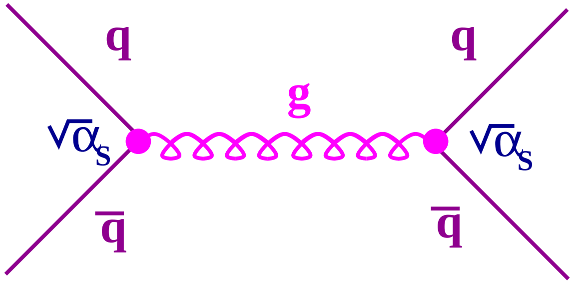
- *In QED,* α *gives the probability of emitting a photon.*



- *a factor* $\sqrt{\alpha}$ *is associated with each absorption or emission of a photon by a charge* e*.*

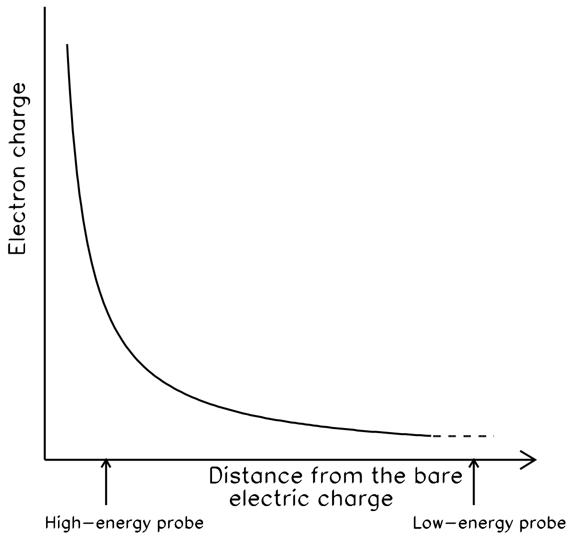
- α_S *is the QCD analogue to* α*:* $\alpha_S = \frac{g_S^2}{4\pi}$ *where* g_S *is the colour charge.*

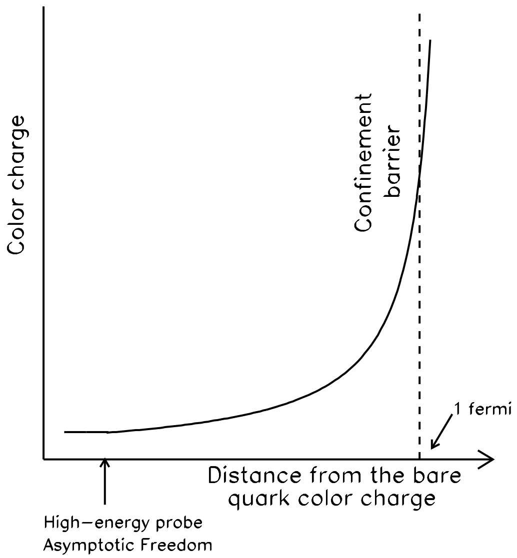
- *In QCD,* α_S *gives the probability of emitting a gluon.*



- *a factor* $\sqrt{\alpha_S}$ *is associated with each absorption or emission of a gluon by a colour charge* g_S*.*

Running of Coupling Constants

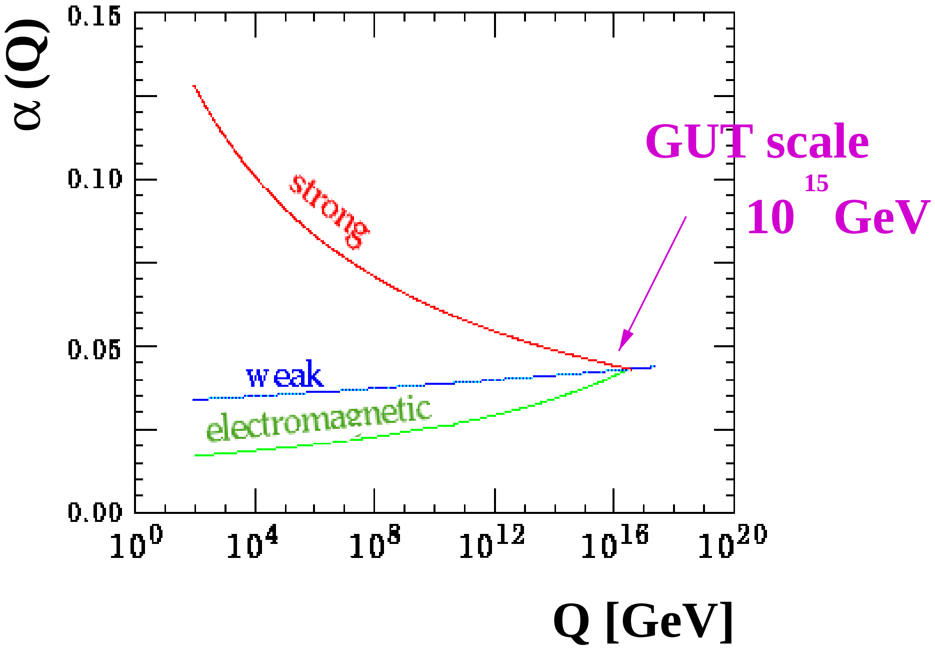


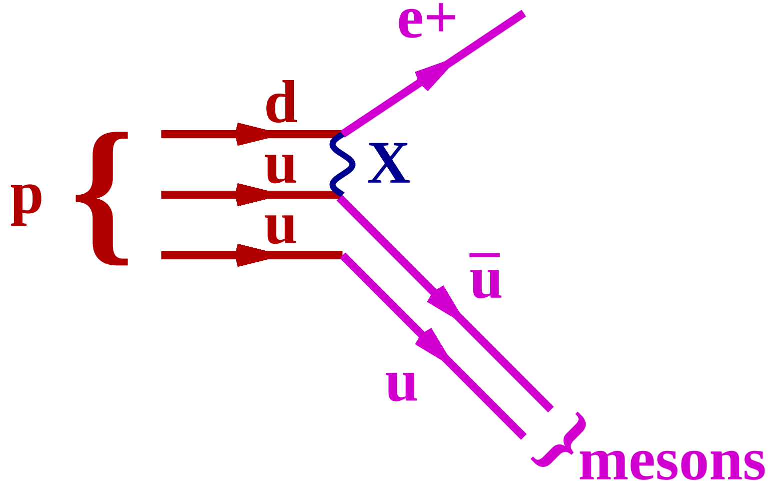


- *In QED the electric charge seen depends on the distance from the particle, due to screening.* α *depends on the scale, and is said to run.*
- *In QCD the magnitude of the strength also depends on the scale at which we view the particle. So* α_S *also runs.*
- *In QCD the value of* α_S *is small at short distances, this is the scale at which perturbation theory works.*

Grand Unification

- *We expect all couplings to merge at a very large (10^{15} GeV) energy scale.*
- *At this stage a Grand Unification theory (GUT) would unify the strong, weak and EM interactions, making them all aspects of the same interaction.*
- *Several models have been proposed, none are entirely satisfactory, so far.*
- *GUT's predict lifetime of 10^{31} years for the proton.*
- *Hitherto there has been no detection of proton decay, (but nice results on neutrino mass!)*





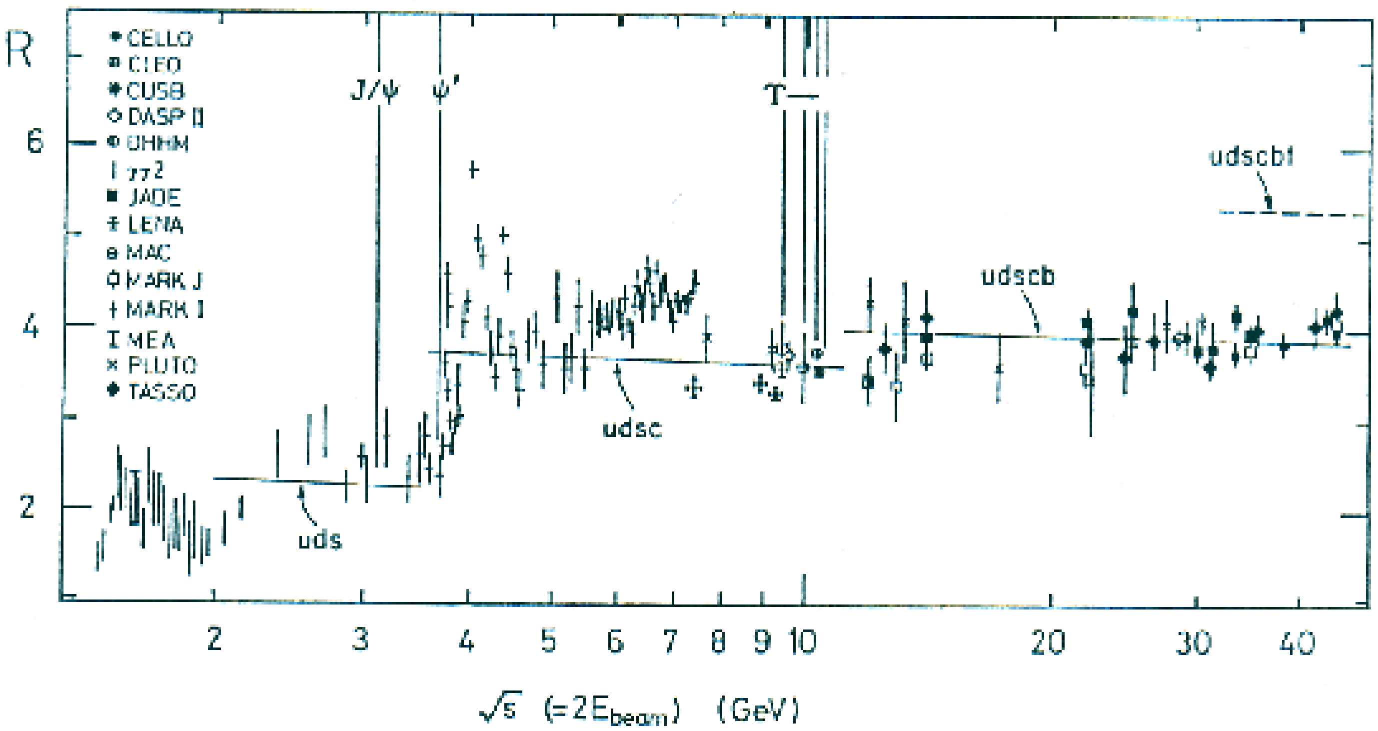
Can QCD Account for Strong Interactions?

- *To test the validity of any theory, it's predictions must confront experimental data. Important predictions:*
  - *3 Colour States per Quark: Cross sections should yield evidence that there are 3 colour degrees of freedom for each quark in a final state.*
  - *Scaling Violations: With increasing Q^2, $F_2(x, Q^2)$ should increase at small x and decrease at large x.*
  - *Running of α_S: α_S should decrease with increasing Q^2.*
  - *Hadronic Jets: Since quarks and gluons cannot be seen in isolation, we should only directly observe hadronic jets.*
  - *Gluon Jets: Some jets should originate from gluons.*
  - *Gluon Self Coupling: Evidence for a ggg vertex should be observed.*

Measuring Quark Colour Species

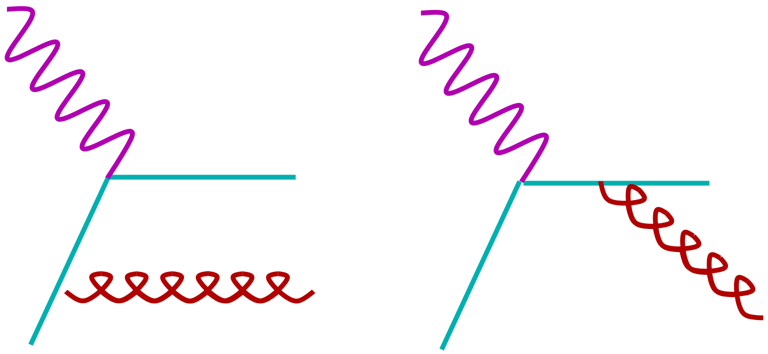
$$\sigma(e^+e^- \rightarrow \mu^+\mu^-) = \frac{4\pi\alpha^2}{3s}, \quad \sigma(e^+e^- \rightarrow q\bar{q}) = n_c \sum_q e_q^2 \frac{4\pi\alpha^2}{3s}$$

- *Expect* $R = \frac{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}{\sigma(e^+e^- \rightarrow q\bar{q})} = n_c \sum_q e_q^2$
- *Well measured muonic cross section makes it possible to confirm number, colour states and electromagnetic charge of quarks.*
- *R=2*(u,d,s)*, 10/3*(u,d,s,c)*, 11/3*(u,d,s,c,b)*, 15.3*(u,d,s,c,b,t)*,* $n_c = 3$

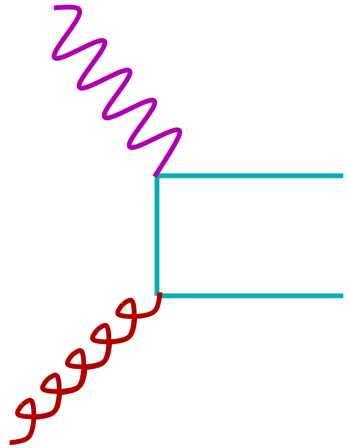


Scaling Violation

- *The QPM predicts exact scaling.*
- *QCD predicts that exact scaling is broken by:*



And



Gluon emission by a quark (QCD compton process)

DIS with initial gluons (Boson-Gluon Fusion Process).

- *These give rise to terms* $\propto \alpha_S \ln Q^2$ *which break scaling.*
- *Such logarithmic scaling violations are a property of gauge theories with point like fermion-vector boson couplings.*

Scaling Violation

- *QCD gives the quark parton distribution in the proton to* $\mathcal{O}(\alpha_S)$ *as:*

$$q(x,Q^2) = q_0(x) + \frac{\alpha_S}{2\pi}\left\{q_0(x) \otimes P_{qq}(x)\ln\frac{Q^2}{\kappa^2} + g_0(x) \otimes P_{qg}(x)\ln\frac{Q^2}{\kappa^2}\right\}$$

where P_{ij} *are the splitting functions.*

- *The* Q^2 *evolution of* $q(x,Q^2)$ *is governed by the DGLAP evolution equations.*

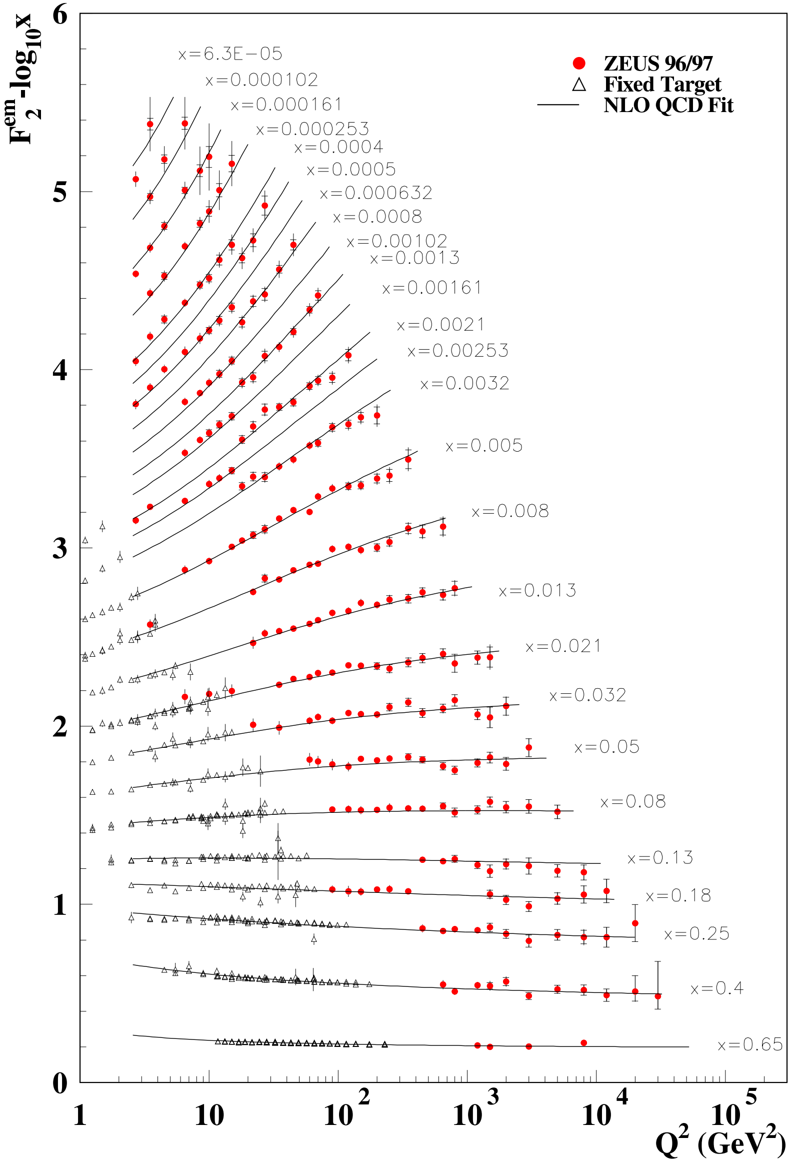
$$\frac{\partial q_{NS}}{\partial \ln Q^2} = \frac{\alpha_S(Q^2)}{2\pi} P_{qq}^{NS} \otimes q_{NS},$$

$$\frac{\partial}{\partial \ln Q^2}\begin{pmatrix} q_S(x,Q^2) \\ g(x,Q^2) \end{pmatrix} = \frac{\alpha_S(Q^2)}{2\pi}\begin{pmatrix} P_{qq} & P_{qg} \\ P_{gq} & P_{gg} \end{pmatrix} \otimes \begin{pmatrix} q_S(x,Q^2) \\ g(x,Q^2) \end{pmatrix},$$

$$q_S = q + \bar{q},\ q_S = q - \bar{q}$$

- *Solutions mean that as* Q^2 *increases the NS distribution function decreases at large* x *and increases at small* x*, so that the phase space for gluon emission by quarks increases as* Q^2 *increases.*

Experimental Evidence for Scaling Violation

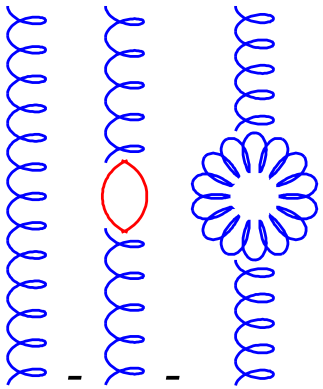


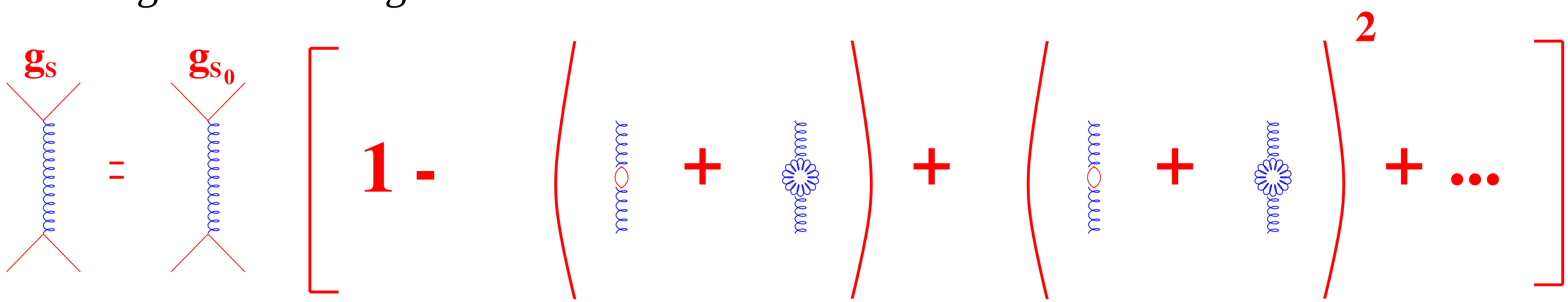
Plot showing measurements of $F_2(x, Q^2)$ in DIS from collider (ZEUS) and fixed target (E666,NMC,BCDMS) experiments.

Here we see that F_2 is increasing with Q^2 for small x and decreasing at large x.

Note the large increase in Q^2 and x ranges due to the HERA experiment.

Running of α_S

- *The magnitude of the colour charge is modified by antiscreening.*
- *The gluon propagator*  *is modified to*  *at leading order.*
- *Summing to all orders gives:*



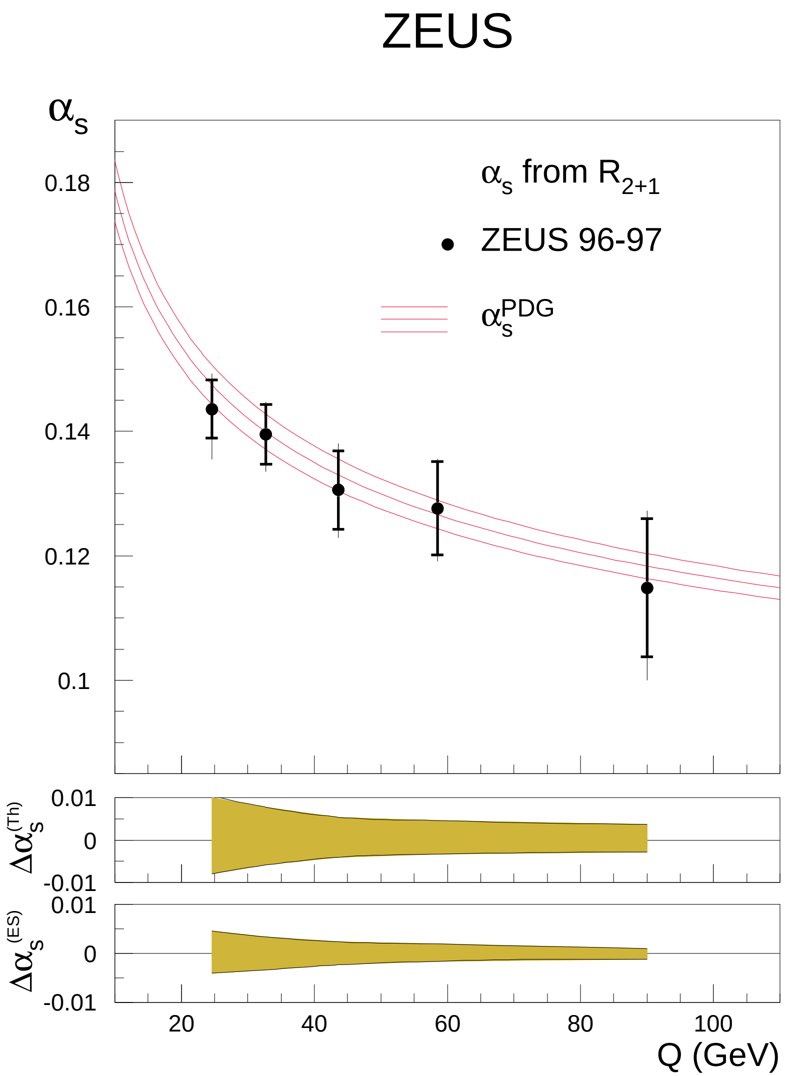
- *The sum of a geometric series giving* $g_S^2 = g_{S_0}^2 \left(\frac{1}{1+I(Q^2)}\right)$
- *We expect that* α_S *will run with* Q^2.

Running of α_S

- *For QCD,* $I(Q^2) = \frac{\alpha_S(\mu^2)}{12\pi}(33 - 2N_F)\ln\frac{Q^2}{\mu^2}$*, ($\mu$ is a reference scale)*
- *At sufficiently low Q^2, the effective coupling becomes large. The scale at which this happens is* $\Lambda^2 = \mu^2 \exp\left[\frac{-12\pi}{(33-2N_F)\alpha_S(\mu^2)}\right]$
- *Then:* $\alpha_S(Q^2) = \frac{12\pi}{(33-2N_F)\ln\frac{Q^2}{\mu^2}}$
- $\alpha_S(Q^2)$ *decreases with increasing Q^2 and is small fo r short distance interactions.*
- *for $Q^2 \gg \Lambda^2$, perturbative description in terms of quarks and gluons interacting weakly is possible.*
- *for $Q^2 \approx \Lambda^2$, the quarks and gluons are tightly bound in hadronic states and perturbation theory is inapplicable.*
- *The important parameter Λ is not predicted by theory and must be determined by experiment. Recent measurements give $\Lambda = 208^{+25}_{-23}$ MeV.*

Running of α_S

α_S from jet rates in DIS at HERA:

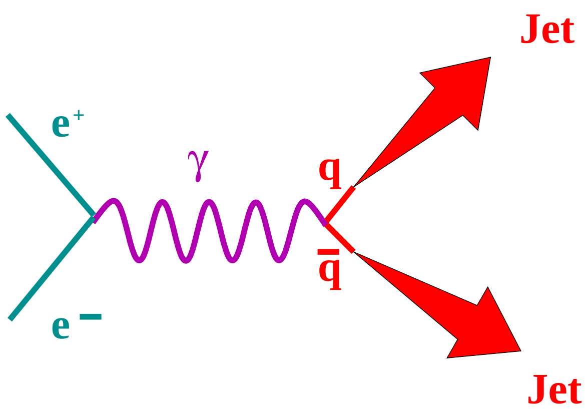


The fraction of DIS events containing 2 jets relative to the fraction containing 1 jet is proportional to α_S.

$$\alpha_S(M_Z) = 0.1166 \pm 0.0019(\text{Stat})$$
$$^{+0.0024}_{-0.0033}(\text{Exp})\ ^{+0.0057}_{-0.0044}(\text{Theo})$$

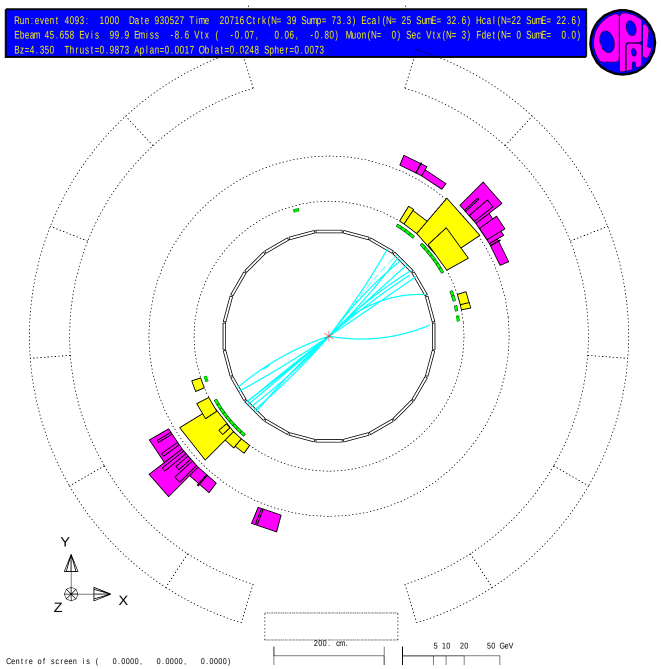
Jets

- *Quarks and Gluons cannot be observed directly.*
- *The collision of very high energy electon + positron beams offers an opportunity to look for direct evidence for quarks.*
- *Photons are produced in* e^+e^- *collisions.*
- *Can produce* $q\bar{q}$
- $q\bar{q}$ *pull apart producing 2 jets travelling in the same direction as the quarks and approximately opposite to each other.*



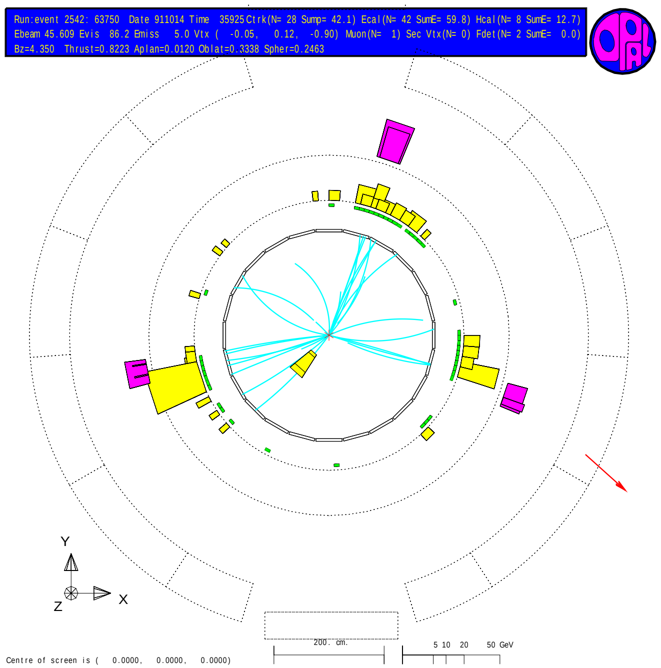
Experimental Evidence For Jets

- *First observation of back to back 2-jet events in* $e^+e^- \rightarrow q\bar{q}$ *at SPEAR in 1975.*
- *The collision of very high energy electon + positron beams offers an opportunity to look for direct evidence for quarks.*
- *Back to back collimated bunches of tracks from charged hadrons seen in the central tracking detector.*
- *Back to back hadronic clusters in the calorimeter.*



Gluons and 3-Jet Events

- $\mathcal{O}(\alpha_S)$ *correction to* $e^+e^- \longrightarrow q\bar{q}$ *gives events with 3 jets in the final state.*
- *Jets are coplanar to conserve momentum.*
- *first direct evidence for gluons by observation of 3 jet events at PETRA in 1979.*



Gluons and 3-Jet Events

- *The leading order cross section:* $\sigma_0(e^+e^- \longrightarrow q\bar{q}) = 3e_q^2\frac{4\pi\alpha^2}{3s}$*,*
where s *is the COM energy squared,*
is modified at $\mathcal{O}(\alpha_S)$ *by gluon emission diagrams.*

- *the modified cross section is:*

$$\sigma(e^+e^- \longrightarrow q\bar{q}) + \sigma(e^+e^- \longrightarrow q\bar{q}g) = \sigma_0(1 + \frac{\alpha_S(s)}{\pi})$$

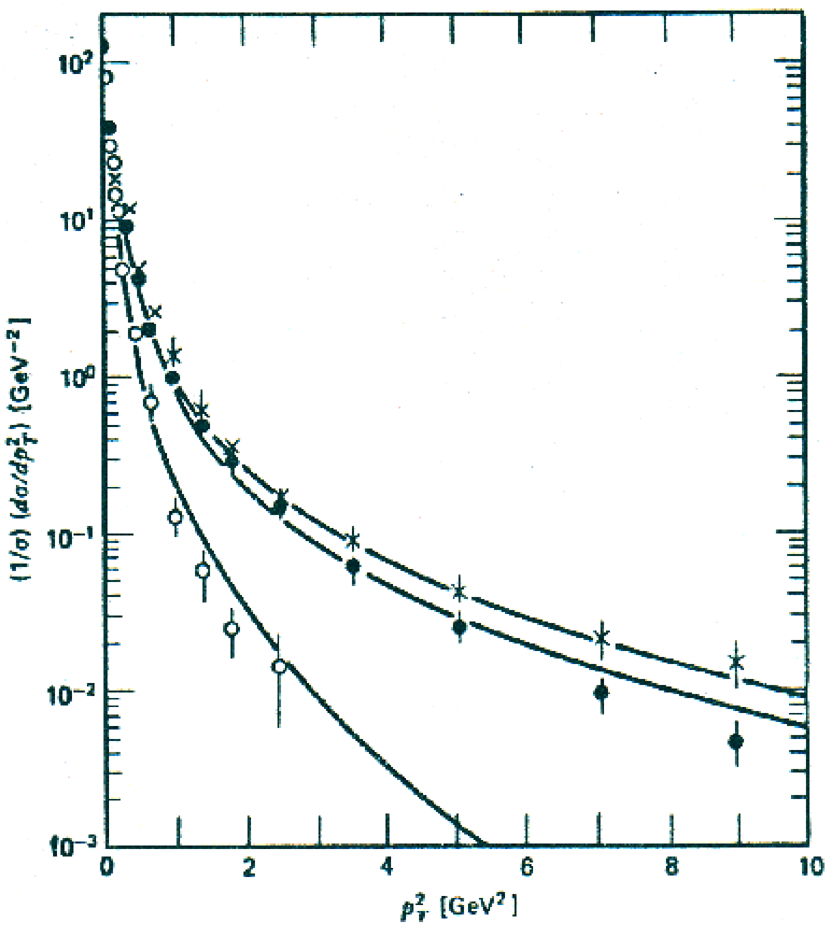
- *This can be written in terms of transverse momentum (*p_T*) between the* q *and* $\bar{q}$

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}p_T} \sim \alpha_S\frac{1}{p_T^2}\ln\left(\frac{s}{4p_T^2}\right)$$

- *For fixed* p_T *the cross section increases with increasing* s*.*

Gluons and 3-Jet Events

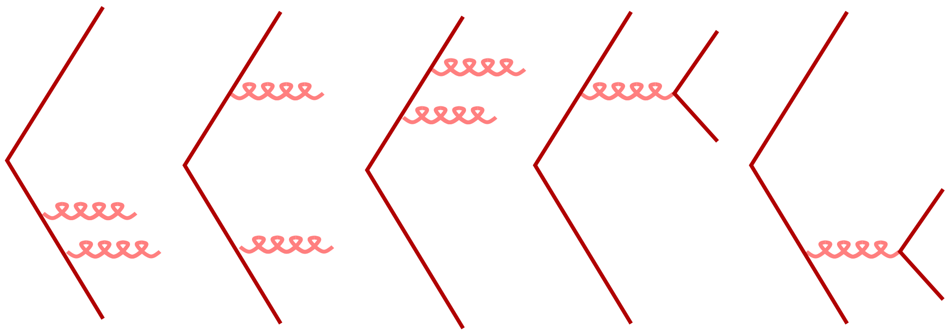
- *p_T is non-zero only when there is gluon-emission.*
- *The hadrons from one of the quarks should also have large p_T.*



- *Measurement of the p_T distribution w.r.t. the thrust axis of hadrons at different s at PETRA.*
- *For fixed p_T the distributiion increases with increasing s.*
- *For s the distribution falls with increasing p_T.*

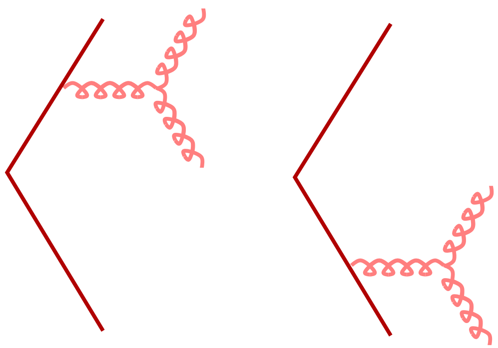
Triple Gluon Vertex

- *QCD is based on the non-abelian SU(3) group which introduces self-coupling of the bosons. QED is based on a non-abelian group U(1).*
- *Due to the gluon self-coupling, the ggg vertex should be observed in events containing at least 4 jets in the final state.*
- *Diagrams contributing to σ for four jet events:*



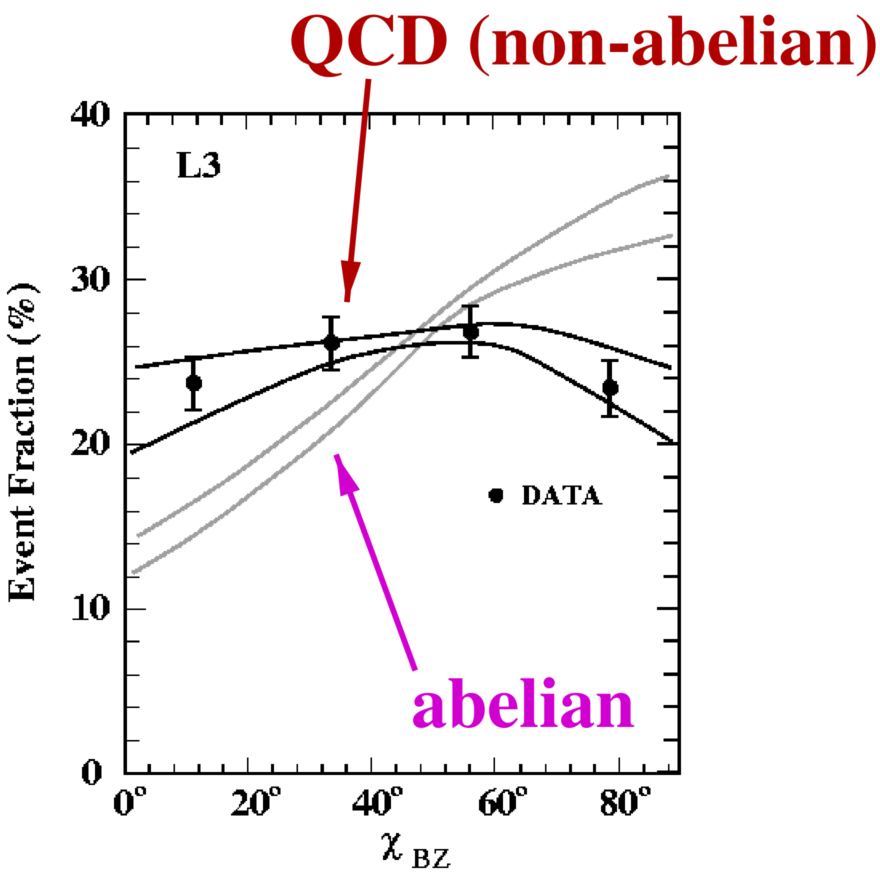
abelian-like diagrams

non-abelian like diagrams



Triple Gluon Vertex

- *Four-jet events have been observed at LEP.*
- *Variables have been devised to highlight the non-abelian nature of QCD in contrast to abelian theories such as the* $[U(1)]^3$ *group.*
- *These variables are:*
  - *Bengtsson-Zerwas angle* $\chi_{\rm BZ}$ *the angle between the planes defined by the two lowest and two highest energy jets.*
  - *Nachtmann-Reiter angle* $\theta^*_{\rm NR}$ *the angle between the momentum vector of the differences of jets 1,2 and jets 3,4.*
  - $alpha_{34}$ *the angle between the two lowest energy jets.*
- *these variables have been measured at LEP.*
- *The data clearly favours a non-abelian theory.*



Colour Factors

- *The dynamics of any gauge theory are completely defined by the commutation relations between its group generators* T^i, $[T^i, T^j] = i\sum_k f^{ijk}T^k$
- *In perturbative calculations the average and sum over all possible colour configurations in the initial and final states lead to the combinatoric factors* C_A, C_F *and* T_F*.*

$$\sum_{k,\eta} T^k_{\alpha\eta}T^k_{\eta\beta} = \delta_{\alpha\beta}C_F, \quad \sum_{\alpha,\beta} T^m_{\alpha\beta}T^n_{\beta\alpha} = \delta^{mn}T_F, \quad \sum_{j,k} f^{jkm}f^{jkn} = \delta^{mn}C_A$$

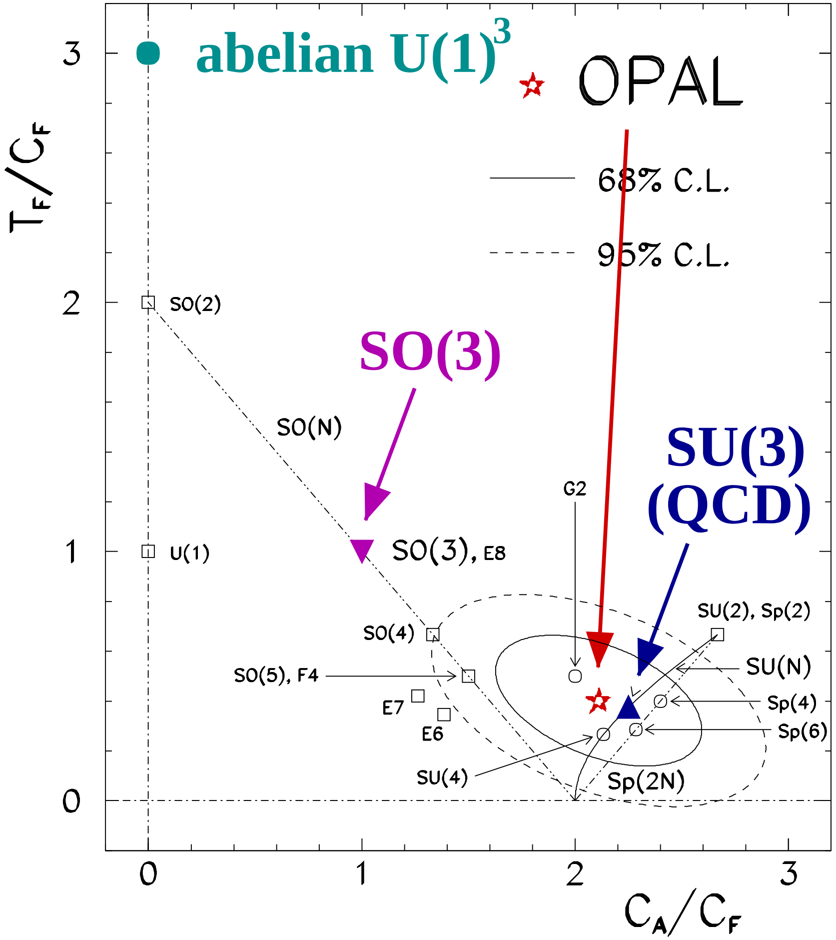
- C_A, C_F *and* T_F *are known as the colour factors and are the physical manifestations of the underlying group structure.*
- *in QCD they represent the relative strength of the processes* $q \longrightarrow qg$, $g \longrightarrow gg$ *and* $g \longrightarrow q\bar{q}$
- *Simulataneous measurement of* C_A/C_F *and* T_F/C_F *at in* e^+e^- *collisions has been made.*

Colour Factors

- *Predictions:*

Group	C_A/C_F	T_F/C_F
$SU(3)$	9/4	3/8
$[U(1)]^3$	0	3
$SO(3)$	1	1

- *Measured values are:*
  $C_A/C_F = 2.11 \pm 0.16(\mathrm{St.}) \pm 0.28\ (\mathrm{Sy.})$
  $T_F/C_F = 0.40 \pm 0.11(\mathrm{St.}) \pm 0.14\ (\mathrm{St.})$
- *SU(3) is clearly favoured*



Lecture I - Summary

- *QCD is a well established theory of the strong interaction.*
- *It explained many known features of the strong interaction.*
- *Many predictions were made and have been confirmed by experiment.*
- *Nobel Prize in Physics 2004: Gross, Politzer, Wilczek*

“For the discovery of asymptotic freedom in the theory of the strong interaction”