Theory of Strong Interactions

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Outline

Emergence of Quantum ChromoDynamics (QCD) as the theory of strong interactions

Part I

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The thesis

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- Hadrons are not elementary particles, but made of quarks and gluons
- Their static properties and scattering should be understood within QCD

Hadrons are not elementary particles

- Magnetic moments of nucleons should be $\mu_N = \frac{e_N \hbar}{2m_N}$: exp. wrong !

  proton: $\mu_p = 2.79\mu_N$ and neutron $\mu_n = -1.9\mu_N$

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- Issue: if they are very massive, they have to be strongly bound, but too strong a binding would not explain hadron-hadron scattering results

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- Search for quarks: (Gell-Mann about an atomic spectroscopic friend)

> And since most things with curious chemical behaviour in the ocean eventually are eaten by oysters, he is grinding up oysters and looking for quarks in them. He has not yet seen any, nor have any been found at very high energies in cosmic rays. So we must face the likelihood that quarks are not real.

M. Gell-Mann, "Elementary Particles ?", Proceedings of the Royal Institution, 41, no. 189 (1966).

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- Missing factor of 3 in $R = \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}$ (see later)

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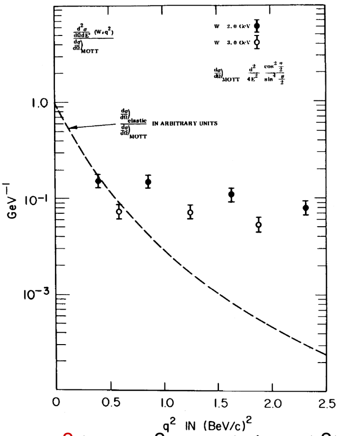

- $Q^2 (= -q^2 = -(k' - k)^2)$ dependence of the DIS cross sections: weak

DIS: Deep Inelastic Scattering

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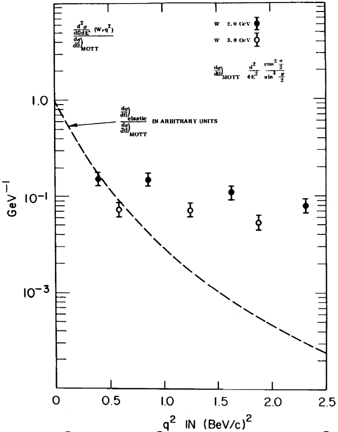

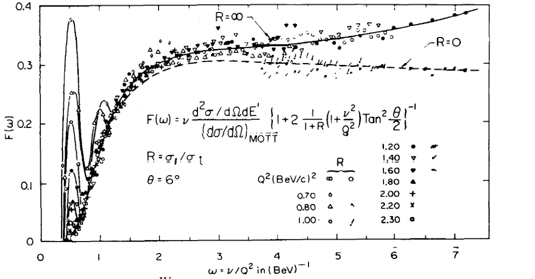

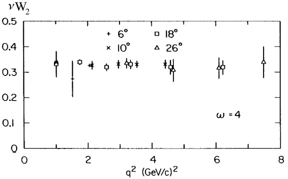

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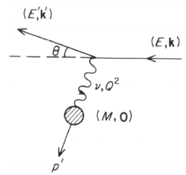
- DIS form factors ($W_{1,2}$) depends unexpectedly only on a single variable

Bjorken scaling and pointlike constituents

Elastic vs Inelastic scatterings



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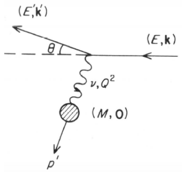

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→ **Elastic** $e\mu \to e\mu$: pointlike μ

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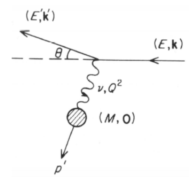

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$(\tau = -q^2/4M^2)$

$$\{\dots\}_{ep\to ep} = \Big(\frac{G_E^2 + \tau G_M^2}{1+\tau}\cos^2\frac{\theta}{2} + 2\tau G_M^2 \sin^2\frac{\theta}{2}\Big)\delta(\nu + \frac{q^2}{2m})$$

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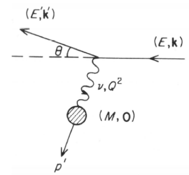

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→ **Inelastic** $ep \to eX$:

$$\{\dots\}_{ep\to eX} = \left(W_2(q^2,\nu)\cos^2\frac{\theta}{2} + 2W_1(q^2,\nu)\sin^2\frac{\theta}{2}\right)$$

Reminder: $d\sigma^{DIS} \sim L^e_{\mu\nu} W^{\mu\nu}$ where Gauge invariance and symmetries give:

$$W_{\mu\nu} = (-g_{\mu\nu} + \frac{q_\mu q_\nu}{q^2})W_1 + \frac{\mathcal{P}_\mu \mathcal{P}_\nu}{P.q}\frac{W_2}{M^2}$$ (hadronic current)

$\mathcal{P} = P_\mu - \frac{P.q}{q^2}q_\mu$

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$$\sin^2\frac{\theta}{2} : 2W_1^{point}(\nu, Q^2) = \frac{Q^2}{2m}\delta(\nu - \frac{Q^2}{2m}) \to \boxed{2mW_1^{point}(\nu, Q^2) = \frac{Q^2}{2m\nu}\delta(1 - \frac{Q^2}{2m\nu})}$$

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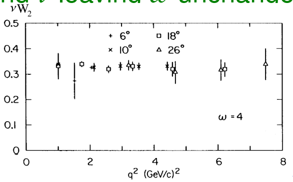
- W_1^{point} and νW_2^{point} are now only functions of $\frac{Q^2}{2m\nu} \equiv \omega$: they scale !

→ if one changes Q^2 and ν leaving ω unchanged, W_i does not change !



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- Let's proceed with some definitions:

$$MW_1(\nu, Q^2) \overset{large\ Q^2}{\longrightarrow} F_1(\omega) \quad \& \quad \nu W_2(\nu, Q^2) \overset{large\ Q^2}{\longrightarrow} F_2(\omega)$$

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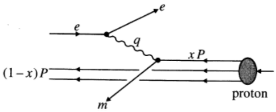
	Proton	Parton
Energy	E	xE
Momenta	P_L	xP_L
	$P_T = 0$	$P_T = 0$
Mass	M	$m = \sqrt{x^2 E^2 - x^2 P_L^2} = xM$



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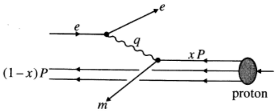
$$MW_1(\nu, Q^2) \xrightarrow{large\ Q^2} F_1(\omega) \quad \& \quad \nu W_2(\nu, Q^2) \xrightarrow{large\ Q^2} F_2(\omega)$$

	Proton	Parton
Energy	E	xE
Momenta	P_L	xP_L
	$P_T = 0$	$P_T = 0$
Mass	M	$m = \sqrt{x^2 E^2 - x^2 P_L^2} = xM$



- For one collision with a parton with a momentum xp_L:

$$F_1(\omega) = MW_1(\nu, Q^2) = \frac{m}{x}\frac{Q^2}{4m^2}\delta(1 - \frac{Q^2}{2m\nu}) = \frac{1}{2x^2\omega}\delta(1 - \frac{1}{\omega x})$$

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Bjorken scaling and the parton model

Putting the partons together in proton

- Previous slide: Scattering on a pointlike particle exhibits scaling
- The scaling is kept intact if the scattered particle is moving along the proton direction with a momentum fraction x: we called it parton
- Indeed we can show that $x = 1/\omega (= \frac{2M\nu}{Q^2})$: x fixed $\leftrightarrow$ ω fixed
- Let's proceed with some definitions:

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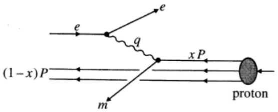

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→ ω identifies to $1/x$

Bjorken scaling and the parton model

Parton Distribution and Callan-Gross relations

Bjorken scaling and the parton model

Parton Distribution and Callan-Gross relations

- Let's recall what we have for one parton with momentum xp_L :
  $F_1(\omega) = \frac{1}{2}\delta(x - \frac{1}{\omega})$ & $F_2(\omega) = x\delta(x - \frac{1}{\omega})$

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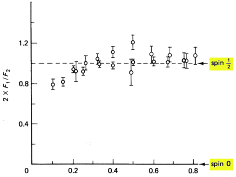

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- In its Nobel lecture, D. Gross said:

> *the vanishing of the effective coupling at short distances, latter called asymptotic freedom, was necessary to explain scaling [...] One might suspect that this is the only way to get pointlike behavior at short distances*
> **D. Gross, Rev. Mod. Phys, 77 (2005) 837**

Summary of yesterday's lecture

- Hadrons are made of quarks and gluons
- They carry a ”new” quantum number: the color
- Bjorken Scaling in DIS indicates that the proton is made of pointlike constituents
- These are spin 1/2 particles following the Callan-Gross relation experimentally verified (Remember: photon do not probe gluons)
- Asymptotic freedom (weak coupling at short distances) is needed to explain scaling

Outline

Emergence of Quantum ChromoDynamics (QCD) as the theory of strong interactions

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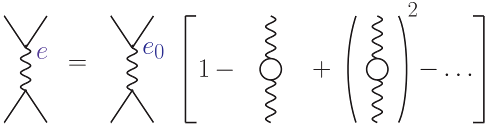
- Formally, if we look at a charge in a scattering process, we have something like:



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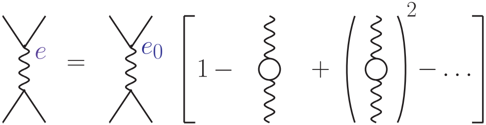
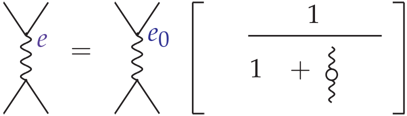


- Thinking in terms of a geometric serie, we can draw:



$$\rightarrow \alpha(Q^2) = \frac{\alpha(\mu^2)}{1 - \frac{\alpha(\mu^2)}{3\pi}\log(\frac{Q^2}{\mu^2})} (\alpha = \frac{e^2}{4\pi})$$

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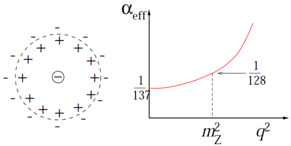

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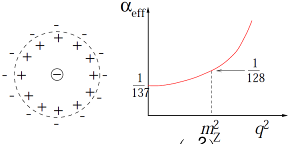

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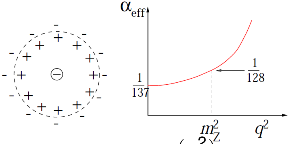

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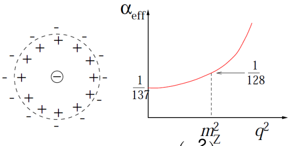

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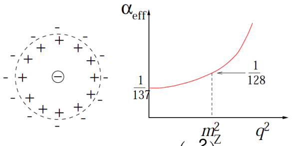

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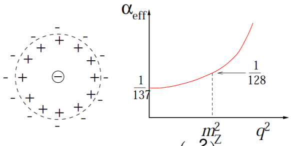

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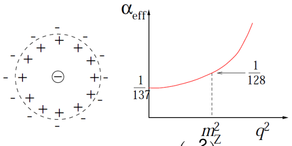

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- Justification of the idea that the partons in the proton are

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The discovery of heavy quarks: the quarks become real !

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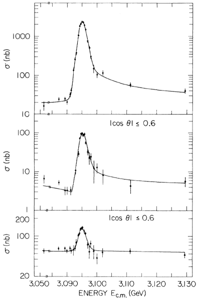

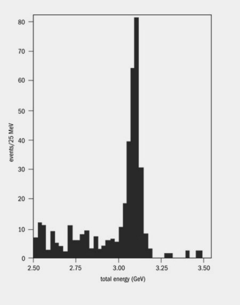

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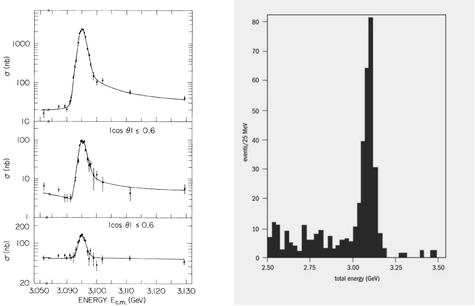

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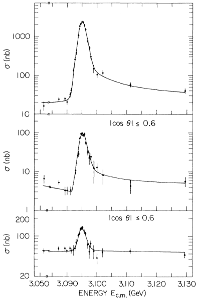

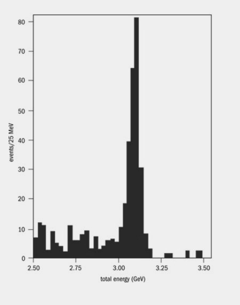

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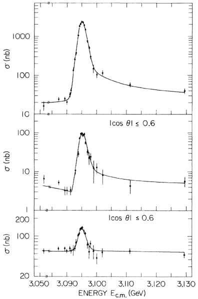
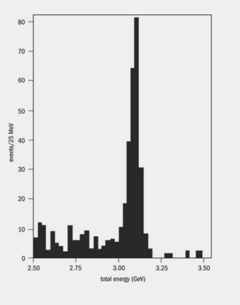
- This 4th quark, the charm quark with a charge $2/3$, was expected from the Glashow-Iliopoulos-Maiani (GIM) mechanism to explain $K \to \mu^+\mu^-$

The discovery of heavy quarks: the quarks become real !

The November revolution (in 1974)

- Simultaneous discovery of a sharp resonnance at SLAC (e^+e^-) and BNL (p-nucleus) at $\sqrt{s} = 3.1$ GeV





- Quickly intepreted as a bound state of a new quark ($m_c \sim 1.5$ GeV)
- This 4th quark, the charm quark with a charge $2/3$, was expected from the Glashow-Iliopoulos-Maiani (GIM) mechanism to explain $K \to \mu^+\mu^-$
- Additional heavier resonances were subsequently discovered

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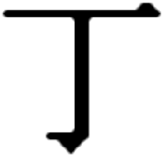

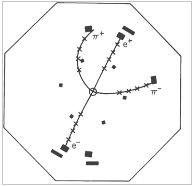

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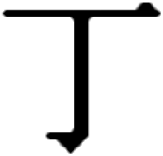

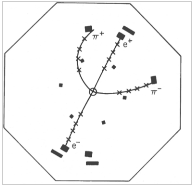

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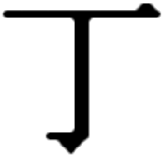

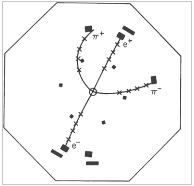

- The quarks acquire a physical existence !
- B. Richter (SLAC) and S. Ting (BNL) got the Nobel prize in 1976

The ratio R: $\frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$

→ Let's look at $\sigma(e^+e^- \to \text{hadrons})$ without color

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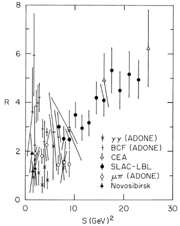
→ great confusion in 1974



B. Richter, ICHEP 1974, London, England, July 1-10, 1974

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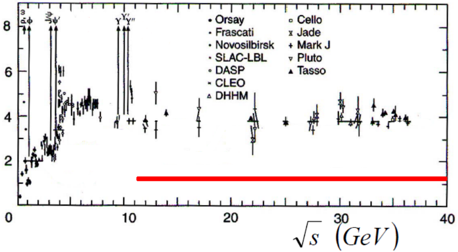
→ Some years later

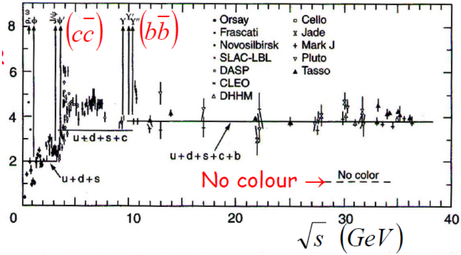


This clearly does not work without colour: *steps but normalisation is off*

The ratio R: $\frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$

→ with coloured quarks: R is 3 times larger

- 3 quarks: $R = 2$
- 4 quarks: $R = 10/3$
- 5 quarks: $R = 11/3$



This clearly works better

The tiny gap about 3 GeV can be accounted by QCD corrections

(see later : $e^+e^- \to q\bar{q}g$)

2-jet events in e^+e^- annihilation: "seeing" the quarks

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- → e^+e^- annihilation may produce a $q\bar{q}$ pair with opposite momenta
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- → We say that they hadronise and we expect to observe
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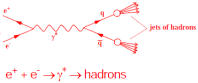

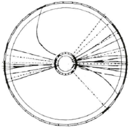

Two-jet event recorded by the Jade experiment at PETRA.

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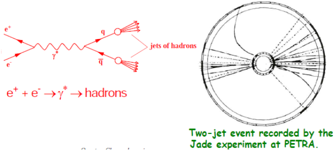

→ (Polar) Angular distributions: info on the nature of the particles involved

- (Spin 1/2) muons and quarks: $d\sigma(e^+e^- \to \mu^+\mu^-)/d\cos\theta \propto 1 + \cos^2\theta$
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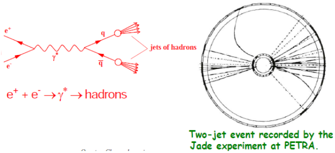

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→ October 1975: *"Evidence for Jet Structure in Hadron Production by e^+e^- Annihilation"*

jets of spin 1/2 quarks

We have found evidence for jet structure in $\sigma(e^+e^- \to \mathrm{hadrons})$ at center-of-mass energies of 6.2 and 7.4 GeV. At 7.4 GeV the jet-axis angular distribution integrated over azimuthal angle was determined to be proportional to $1 + (0.78 \pm 0.12)\cos^2\theta$. **G. Hanson et al. , PRL 35 1609 (1975)(SPEAR)**

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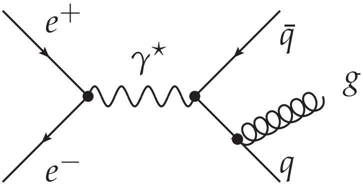

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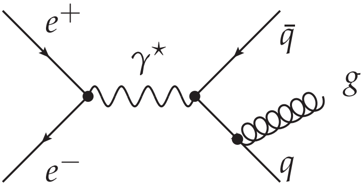
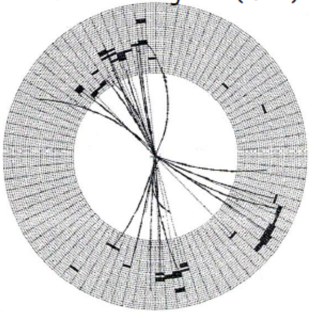


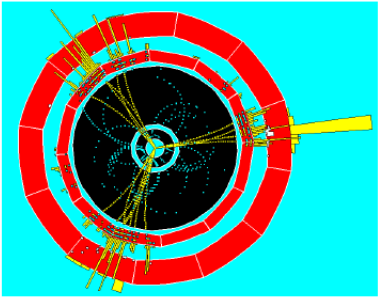
- Contribution of $e^+e^- \to q\bar{q}g$ to R: $R = 3\sum_q e_q^2(1 + \alpha_s(Q^2)/\pi)$

3-jet event in e^+e^- annihilation: "seeing" the gluon

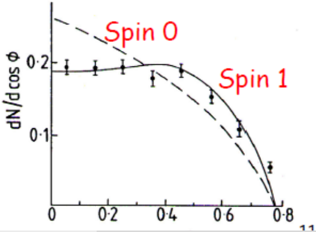
JADE Event $\sqrt{s} = 31 GeV$
Direct evidence for gluons (1978)



ALEPH Event $\sqrt{s} = 91 GeV$ (1990)



Distribution of the angle, ϕ, between the highest energy jet (assumed to be one of the quarks) relative to the flight direction of the other two (in their cms frame).
ϕ depends on the spin of the gluon.



⇒ GLUON IS SPIN 1

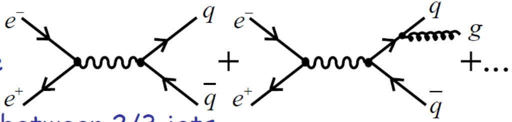
Slide borrowed from V. Gibson lectures on QCD

Measurement of α_S

α_s can be measured in many ways. The cleanest is from the ratio

$$R = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}.$$

In practise, measure



i.e. don't distinguish between 2/3 jets.

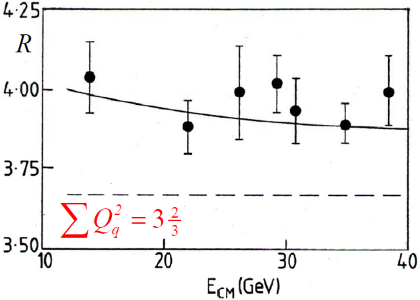
When gluon radiation is included:

$$R = 3\sum Q_q^2\left(1+\frac{\alpha_s}{\pi}\right)$$

Therefore,

$$\left(1+\frac{\alpha_s}{\pi}\right) \approx \frac{3.9}{3.66}$$

$$\alpha_s\left(q^2 = 25^2\right) \approx 0.2$$

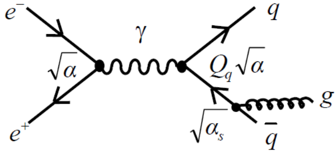


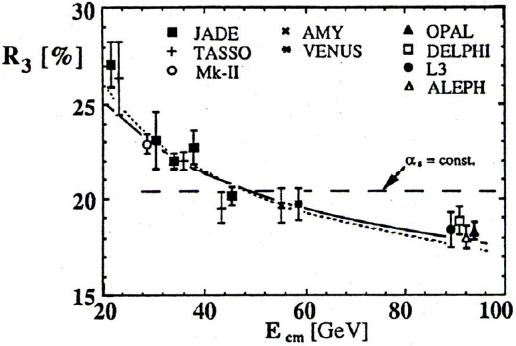
Slide borrowed from V. Gibson lectures on QCD

Measurement of α_S

Example: 3 jet rate $e^+e^- \to q\bar{q}g$

$$R_3 = \frac{\sigma(e^+e^- \to 3\ jets)}{\sigma(e^+e^- \to 2\ jets)} \propto \alpha_s$$



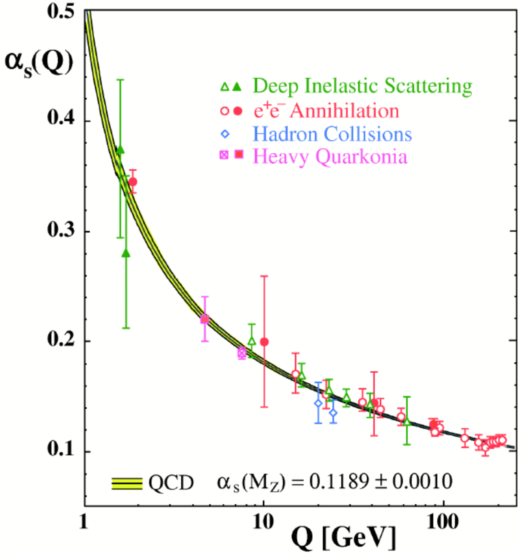


α_s decreases with energy

α_s RUNS !

Slide borrowed from V. Gibson lectures on QCD

Measurement of α_s



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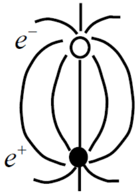
Qualitatively, compare QCD with QED:

QCD
Colour field



QED
Electric field

Self interactions of the gluons squeezes the lines of force into a narrow tube or STRING. The string has a "tension" and as the quarks separate the string stores potential energy.

Energy stored per unit length in field ~ constant $V(r) \propto r$

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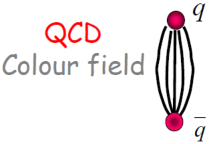

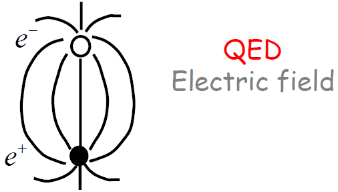

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Energy stored per unit length in field ~ constant $V(r) \propto r$

- If $V(r) > 2m_\pi$, 2 π's pop up from the vacuum and the $q\bar{q}$

Evidence for gluon self interaction

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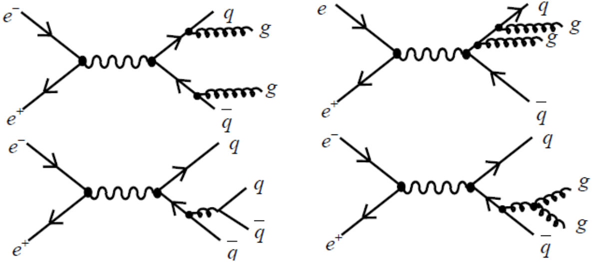
- One way to look at self interaction between gluons is to look at 4 jets, e.g. $e^+e^- \to q\bar{q}gg$



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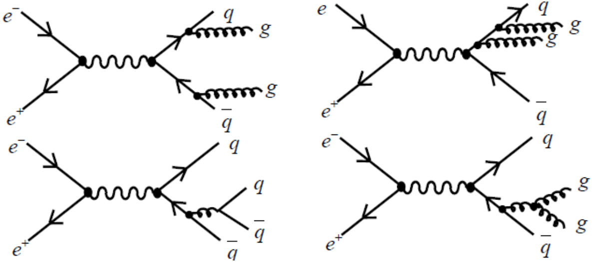

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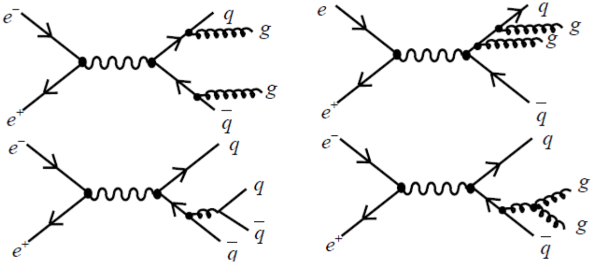
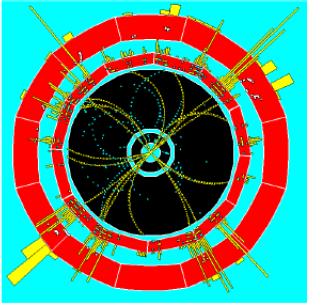
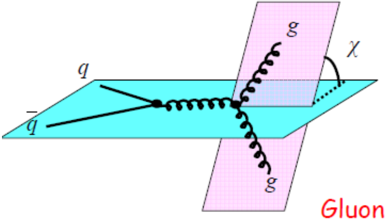


- One type of graphs involves the triple gluon vertex which has a specific Lorentz structure
- It produces a specific angular distribution of the jets

Evidence for gluon self interaction

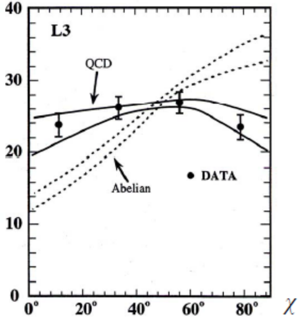
4-JET EVENT (ALEPH)





Experimentally:

- Define the two lowest energy jets as the gluons. (Gluon jets are more likely to be lower energy than quark jets).
- Measure angle between the plane containing the "quark" jets and the plane containing the "gluon" jets, χ.



Gluon self-interactions are required to describe the experimental data.

Slide borrowed from V. Gibson lectures on QCD

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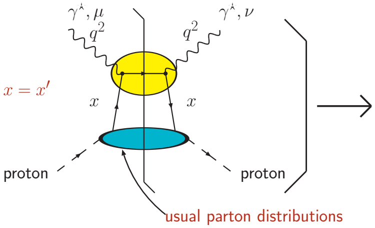
Back to the proton apart . . .

➟ Study of the proton content via (deeply) inelastic scattering (DIS):



$$W_{\mu\nu} = (-g_{\mu\nu} + \frac{q_\mu q_\nu}{q^2}) F_1(x, q^2) + \frac{\mathcal{P}_\mu \mathcal{P}_\nu}{P.q} F_2(x, q^2)$$

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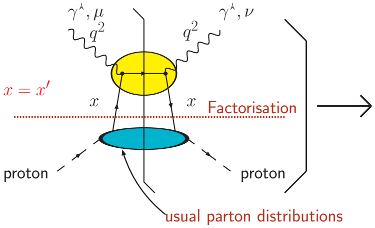

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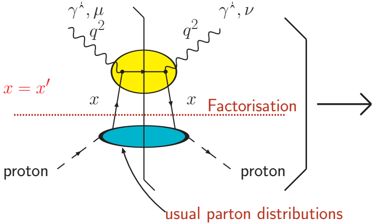

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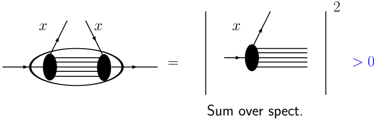

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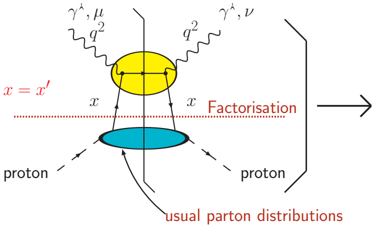

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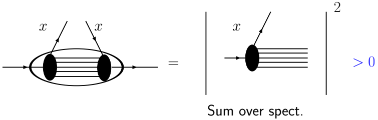


➟ Probability to find a parton with a momentum fraction x: $q(x)$

$$F_2(x, q^2) = x \sum_q e_q^2 \, q(x, q^2)$$

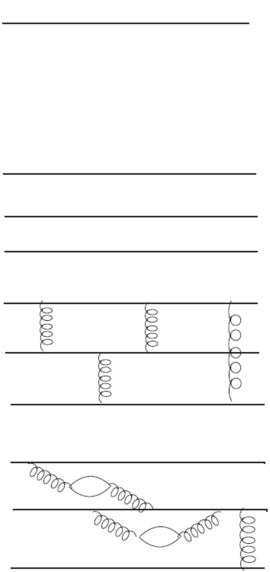
Extreme cases of PDFs. . .

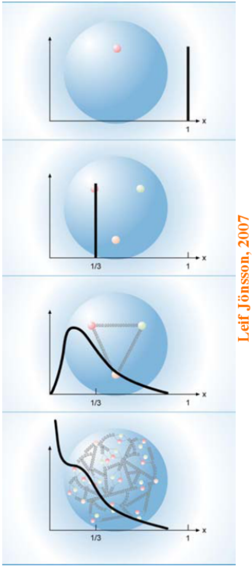
One quark:

Three quarks:

Three interacting quarks:

Valence quarks + sea quarks:





Interferences in the proton. . .

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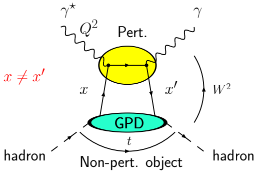

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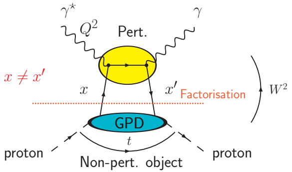

For $Q^2 \gg t$, described in terms of 4 generalised parton distribution: GPDs

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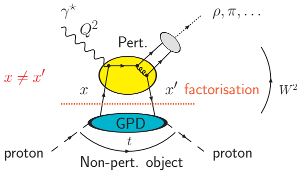

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idem for meson electroproduction

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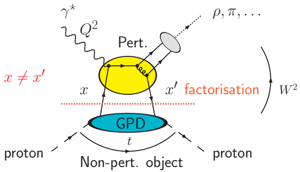

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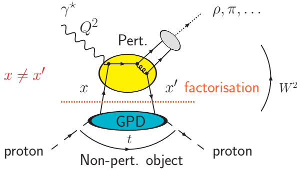

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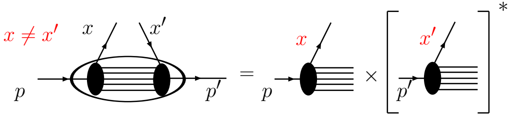

but are **universal !**

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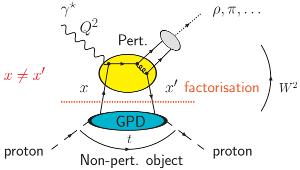

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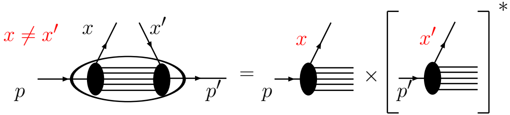

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➠ Interpretration only at the amplitude level

Amplitude of probability

for a proton to emit a quark with x & to absorb another with x'