

Discovery of Pions and Kaons in Cosmic Rays in 1947

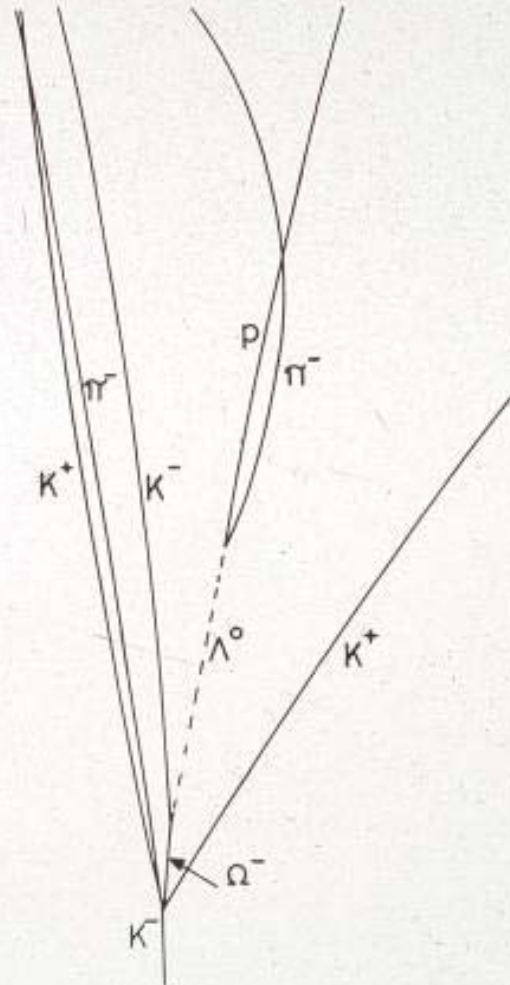
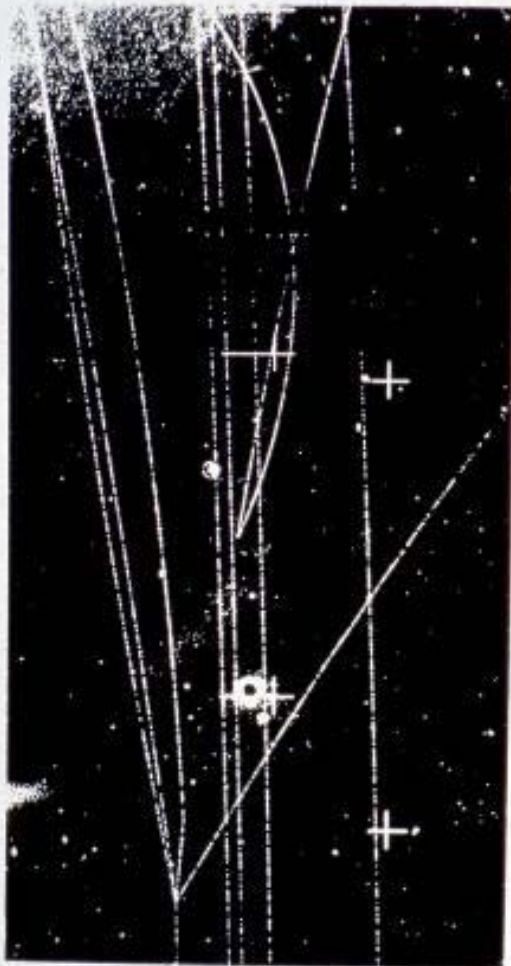
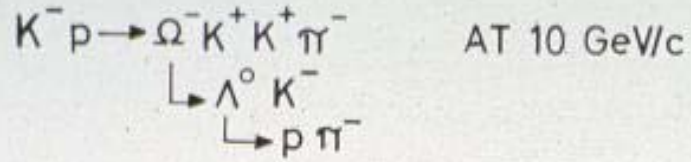


$\pi^+ \rightarrow \mu^+ \rightarrow e^+$ (cosmic rays)

Points to note:

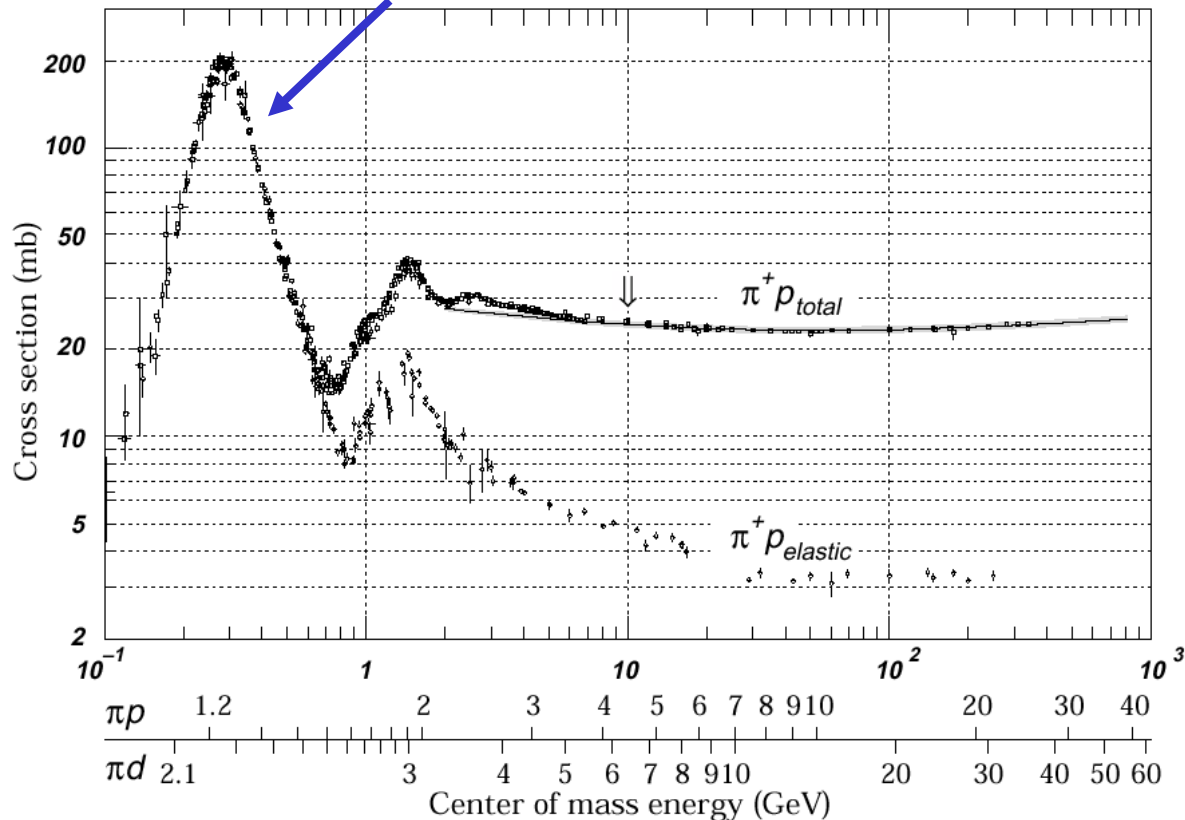
- dE/dx – Bragg Peak
- Low dE/dx for fast e^+
- Constant range ($\sim 600\mu\text{m}$)
(i.e. 2-body decay)
- small angle scattering

Strange Particles

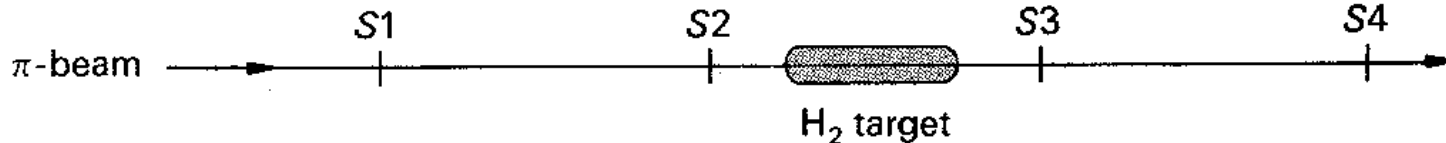


Protons Have Inner Structure

Δ -resonance



First measurements studied total absorption cross section using a 4-fold coincidence



Quarks

The name was coined in 1964 by Murray Gell-Mann, who said that he was strongly influenced by a poem from James Joyce's book, *Finnegans Wake*:

Three quarks for muster Mark!
Sure he hasn't got much of a bark
And sure any he has it's all beside the mark.

In Joyce's poem, the word's meaning seems to be a kind of squawk or birdlike sound, but Gell-Mann simply liked the sound of it.

Hadrons: Bound States of the Strong Interaction

Hadrons
(Composite Particles)

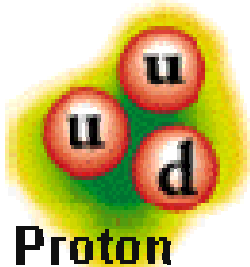
Fermions

Bosons

Baryons

Anti-Baryons

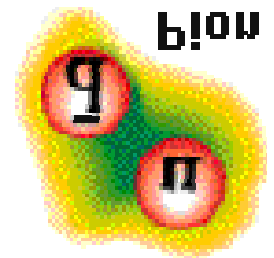
Mesons



qqq

$\bar{q}\bar{q}\bar{q}$

$q\bar{q}$



Baryons: 3 Quarks

Mesons (Quark/Anti-Quark)

Quarks and Color

Discovery of the Δ^{++} -baryon by Fermi et al. in 1951

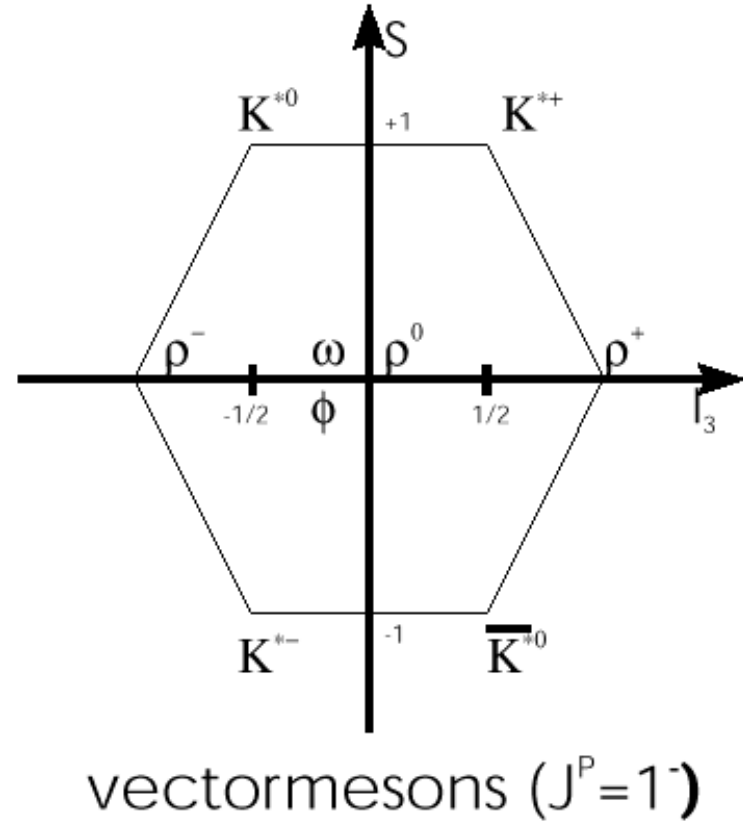
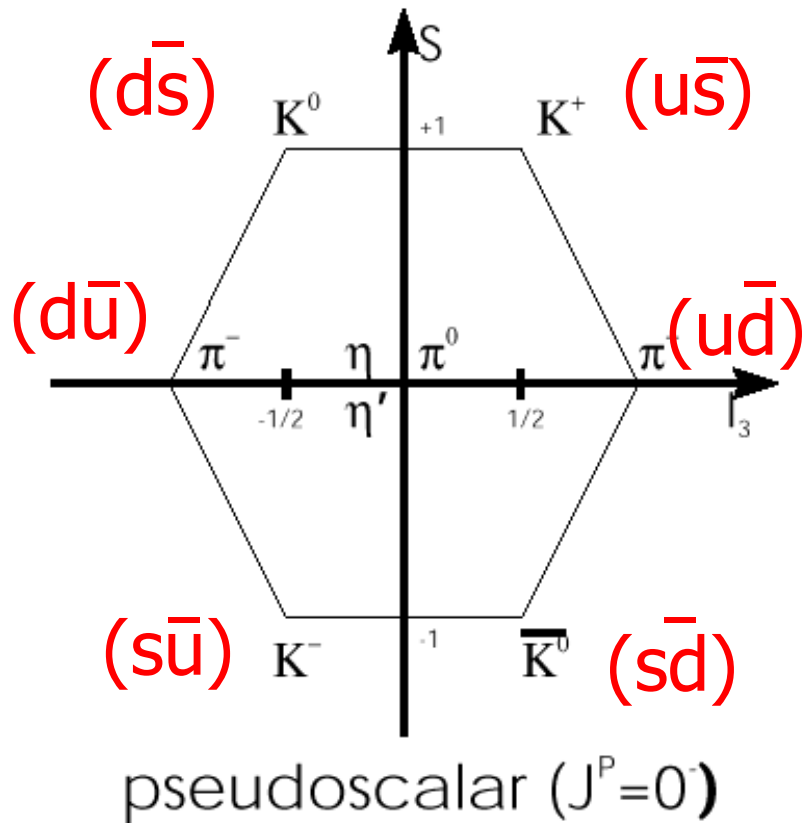
$$p = uud$$

$$n = udd$$

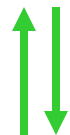
$$\Delta^{++} = uuu \quad (J=3/2)$$

Not only forbidden by Pauli principle, but no qq or q states observed. Therefore, introduce color charge. Hadrons must be colorless or else many states must exist (e.g. $u_R u_R d_G$, $u_R u_B d_G$). There must be 3 color charges (RGB, and the corresponding anti-charges) for baryons and mesons to be colorless.

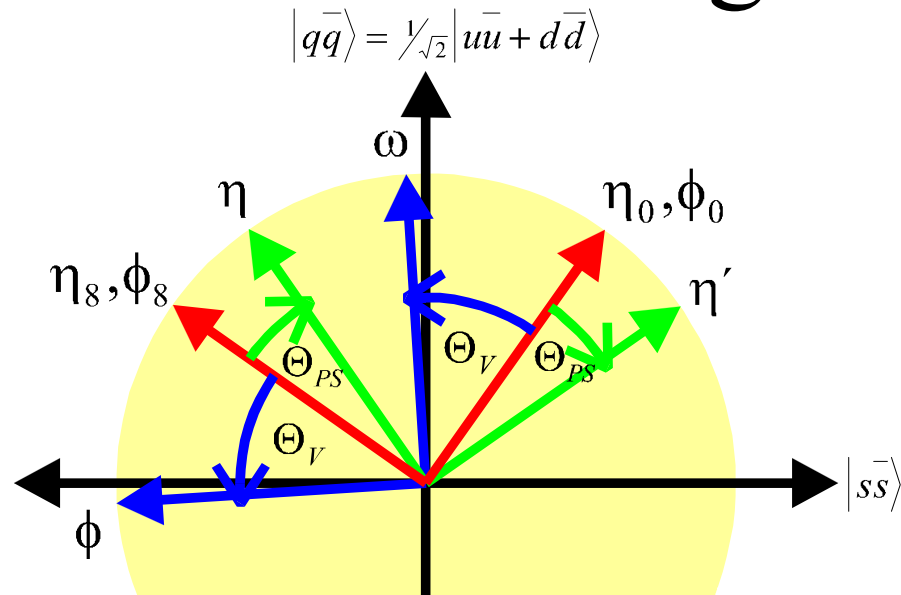
Mesons with u, d, and s Quarks



Spin



Mesons and Mixing Angles



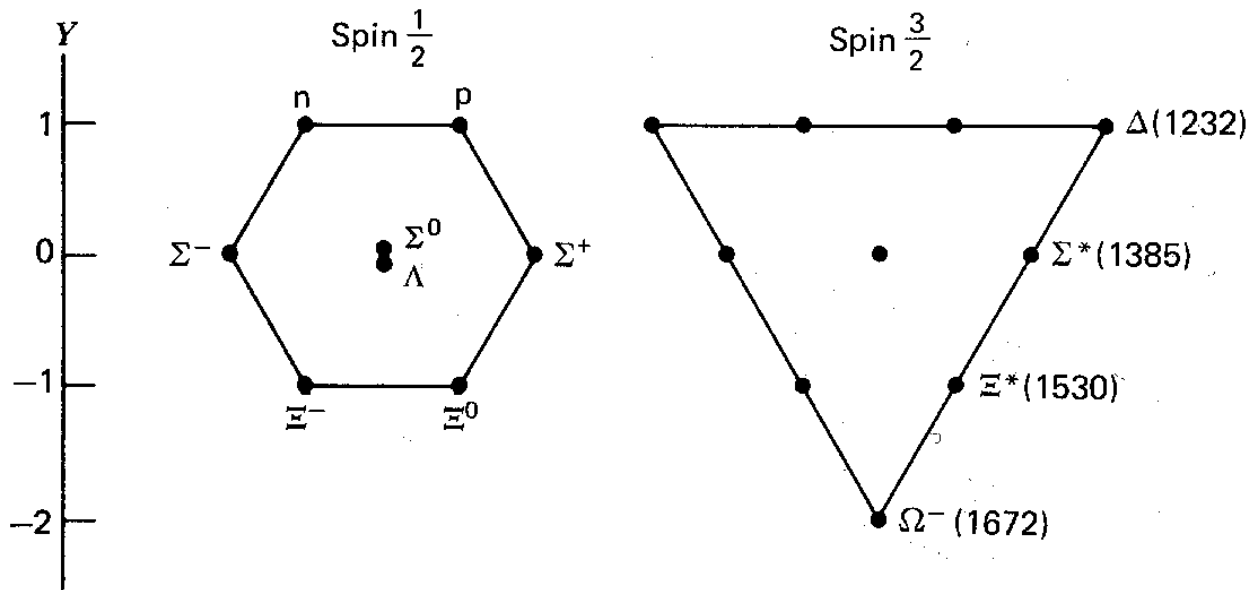
$$|\eta_8\rangle = \frac{1}{\sqrt{6}}|u\bar{u} + d\bar{d} - 2s\bar{s}\rangle = \sqrt{\frac{1}{3}}|q\bar{q}\rangle - \sqrt{\frac{2}{3}}|s\bar{s}\rangle$$

$$|\eta_0\rangle = \frac{1}{\sqrt{3}}|u\bar{u} + d\bar{d} + s\bar{s}\rangle = \sqrt{\frac{2}{3}}|q\bar{q}\rangle + \sqrt{\frac{1}{3}}|s\bar{s}\rangle$$

$$\begin{pmatrix} \eta' \\ \eta \end{pmatrix} = \begin{pmatrix} \cos(\Theta_{PS}) & \sin(\Theta_{PS}) \\ -\sin(\Theta_{PS}) & \cos(\Theta_{PS}) \end{pmatrix} \begin{pmatrix} \eta_0 \\ \eta_8 \end{pmatrix} \quad \begin{matrix} \Theta_V = 37^\circ \\ \Theta_{PS} = -10^\circ \dots -23^\circ \end{matrix}$$

Small deviation from ideal mixing angle in the ϕ/ω system: \rightarrow decoupling of the light and strange quarks

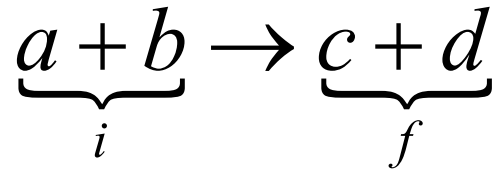
Baryons with u, d, and s Quarks



uuu,ddd,sss states missing for $S=1/2$: Pauli principle

Determination of Quantum Numbers in Hadron-Hadron Interactions

Cross sections and decay rates



$$\Gamma = \frac{2\pi}{\hbar} |M_{if}|^2 \rho_f$$

$$\rho_f = \frac{dn}{dE}$$

$$\frac{d\sigma}{d\Omega} = \left(\frac{\hbar c}{8\pi} \right)^2 \frac{g_f |M_{if}|^2}{s} \frac{|\vec{p}_f|}{|\vec{p}_i|}$$

(g_f spin/isospin degeneracy)

Determining the Pion Spin

Using $\pi^+d \rightarrow p+p$ (1951) and $p+p \rightarrow \pi^+d$ data and the principle of **Detailed Balance**

$$|M_{if}|^2 = |M_{fi}|^2$$

$$\frac{\sigma(pp \rightarrow \pi^+d)}{\sigma(\pi^+d \rightarrow pp)} = 2 \frac{(2s_\pi + 1)(2s_d + 1)}{(2s_p + 1)^2} \frac{p_\pi^2}{p_p^2}$$

Factor 2 because
two identical p

Data from 1951-1953 show clearly that $s_\pi = 0$

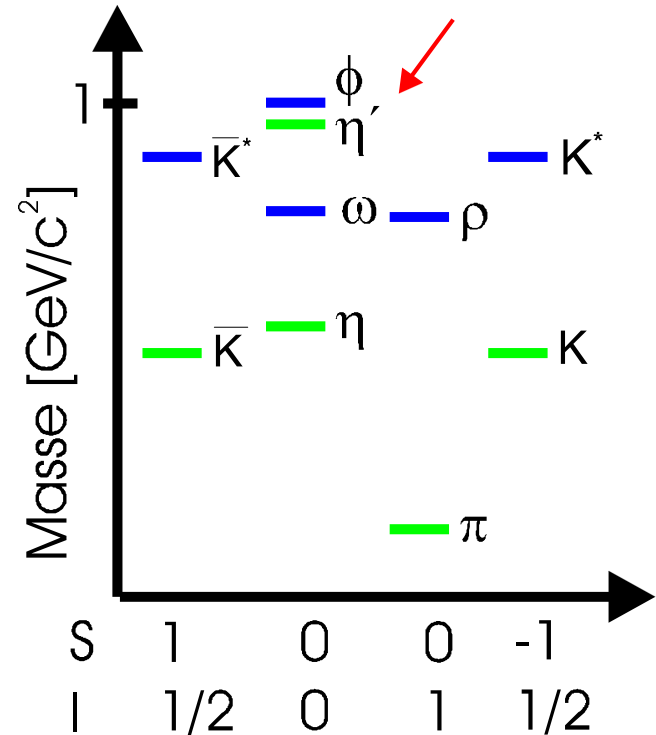
Mass Formulas and Hyperfine Interaction

$$M_{Meson} = m_{Quark} + m_{\overline{Quark}} + \Delta M_{SS}$$

$$\Delta M_{SS}(q\bar{q}) = \frac{8\pi}{9} \alpha_s \frac{\sigma_i \bullet \sigma_j}{m_i m_j} |\Psi(0)|^2$$

$$\sigma_i \bullet \sigma_j = -3 \frac{\hbar^3}{c^3} (\textit{Pseudoscalar})$$

$$= +1 \frac{\hbar^3}{c^3} (\textit{Vector})$$



Equivalent formulas for baryons

Magnetic Moments

$$\mu_i = Q_i \left(\frac{e}{2m_i} \right)$$

Dirac (pointlike) particle

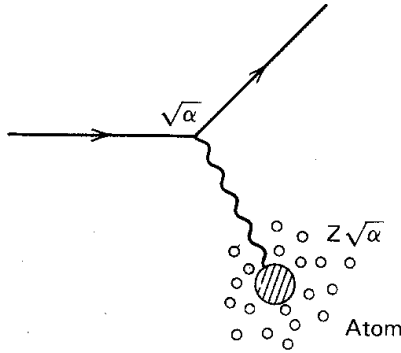
$$\Psi\left(\frac{1}{2}, \frac{1}{2}\right) = \sqrt{\frac{2}{3}} \chi(1,1) \varphi\left(\frac{1}{2}, \frac{1}{2}\right) - \sqrt{\frac{1}{3}} \chi(1,0) \varphi\left(\frac{1}{2}, \frac{1}{2}\right)$$

$$\mu_p = \frac{2}{3}(2\mu_u - \mu_d) + \frac{1}{3}(\mu_d)$$

$$\mu_u = -2\mu_d \quad (\text{For } m_u = m_d)$$

Baryon	Magnetic moment in quark model	Prediction, n.m.	Observed, n.m.
p	$\frac{4}{3}\mu_u - \frac{1}{3}\mu_d$	2.79	2.793
n	$\frac{4}{3}\mu_d - \frac{1}{3}\mu_u$	-1.86	-1.913
Λ	μ_s	-0.58	-0.614 ± 0.005
Σ^+	$\frac{4}{3}\mu_u - \frac{1}{3}\mu_s$	2.68	2.33 ± 0.13
Σ^0	$\frac{2}{3}(\mu_u + \mu_d) - \frac{1}{3}\mu_s$	0.82	—
Σ^-	$\frac{4}{3}\mu_d - \frac{1}{3}\mu_s$	-1.05	-1.00 ± 0.12
Ξ^0	$\frac{4}{3}\mu_s - \frac{1}{3}\mu_u$	-1.40	-1.25 ± 0.014
Ξ^-	$\frac{4}{3}\mu_s - \frac{1}{3}\mu_d$	-0.47	-1.85 ± 0.75

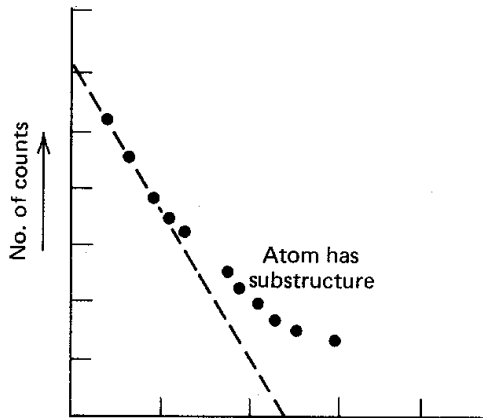
Do Quarks Really Exist?



Probability $Z^2 \alpha^2$

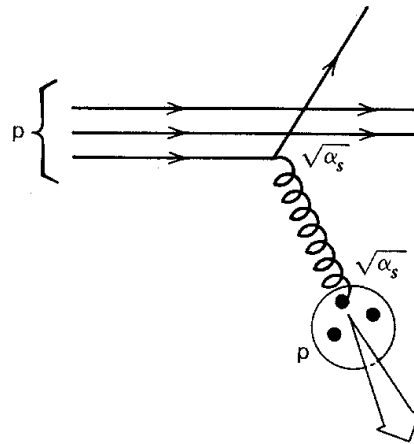
(a)

Au target *Phil. Mag.* xxi, 669 (1911)



Atom has substructure

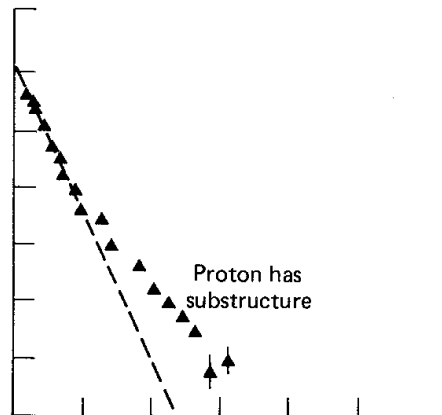
Transverse momentum
or scattering angle



Probability α_s^2

(b)

Proton target *Phys. Lett.* 46B, 471 (1973)

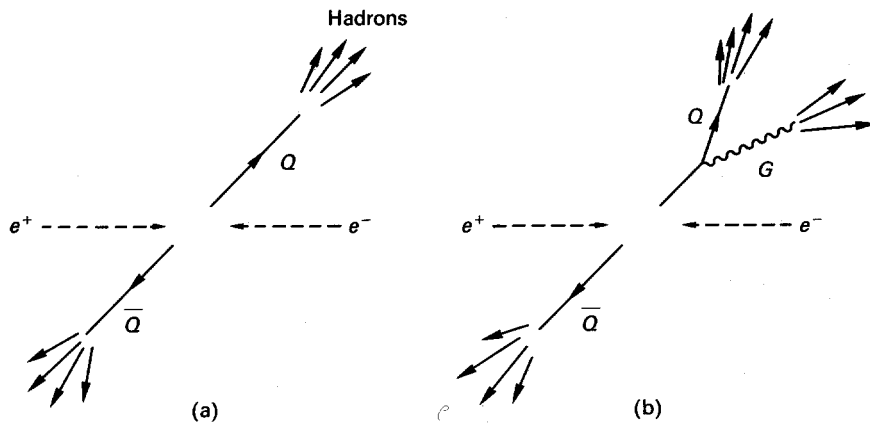


Proton has substructure

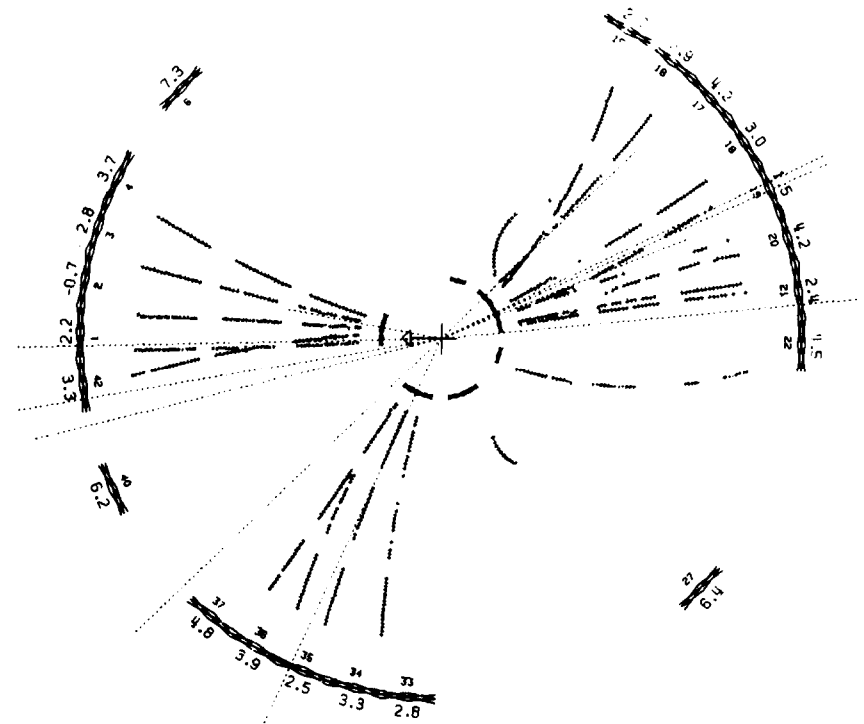
Enhancement of the scattering cross section at backward angles (or large momentum transfers q^2) indicate substructure

Gluons Exist as Well

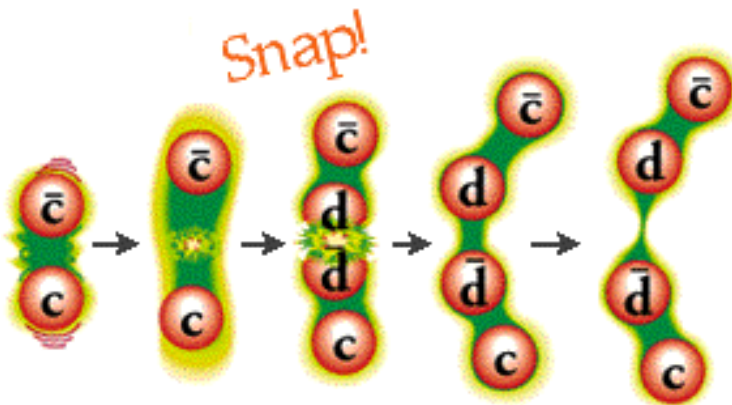
$e^+e^- \rightarrow q \bar{q}$ gluon bremsstrahlung



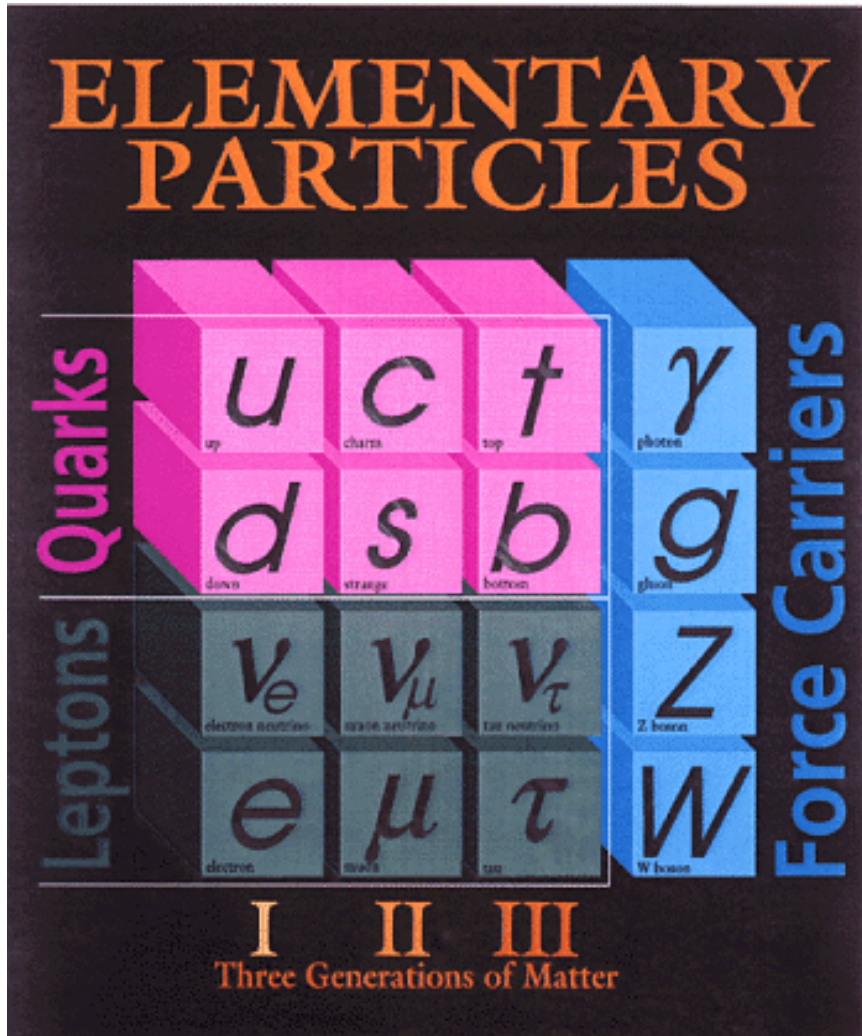
3-jet event (Petra-DESY)



Hadronization



Development of the Standard Model



Important distinction between current quarks and constituent quarks

Flavor	Mass(GeV/c ²)	Elect. Charge
u up	.005	+2/3
d down	.01	-1/3
c charm	1.5	+2/3
s strange	0.2	-1/3
t top	180	+2/3
b bottom	4.7	-1/3

Origin of the masses: Higgs Mechanism \Rightarrow different lecture

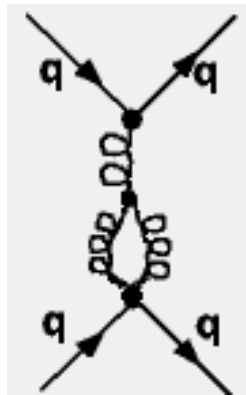
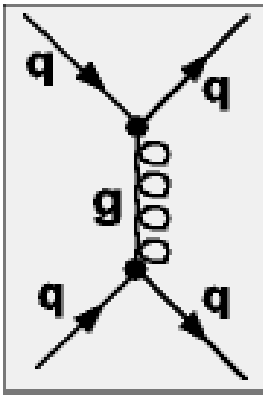
Quantum Chromodynamics (QCD): the Theory of the Strong Interaction

Fundamental gauge theory, like QED

Symmetry group $SU(3)$ (3 color charges)

8 exchange bosons (Gluons) (no color singlet)

Gluons carry color charge



Self interaction of the gluons

Coupling constant α_s is strongly energy dependent

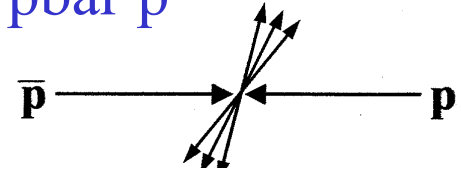
at low energies (hadron structure) perturbation theory does not work!

=> Lattice calculations

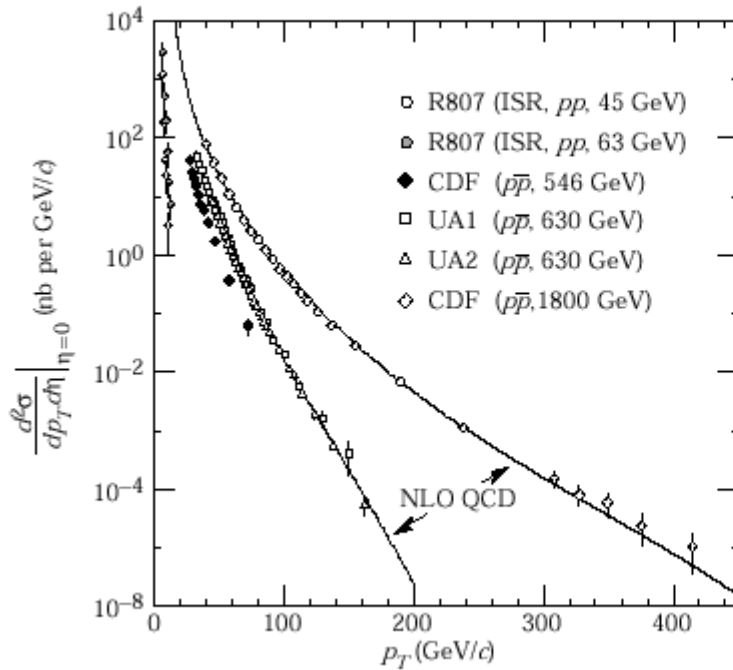
=> Models with effective degrees of freedom (Baryons, Mesons)

QCD at Short Distances $\alpha_s \ll 1$

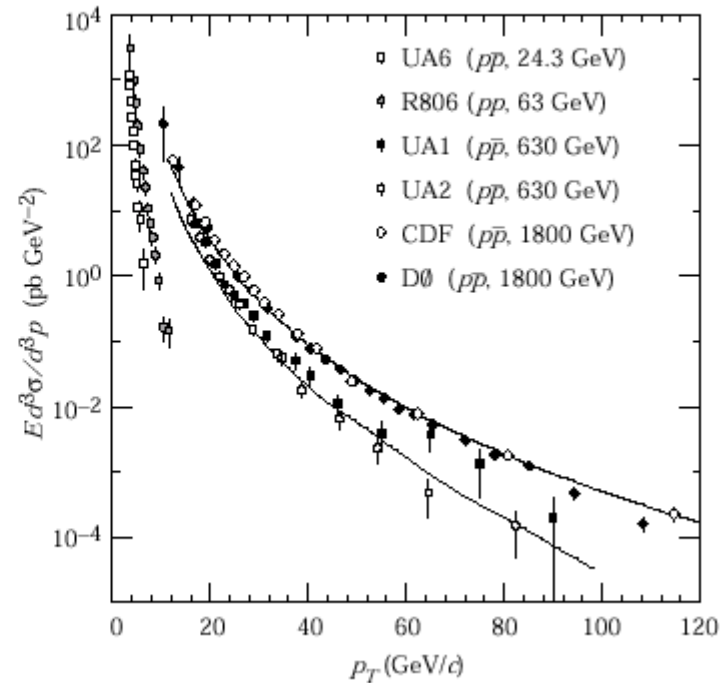
Perturbative treatment: example, jet production in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV (Fermilab)



Jet Production in pp and $p\bar{p}$ Interactions



Direct γ Production in $p\bar{p}$ Interactions

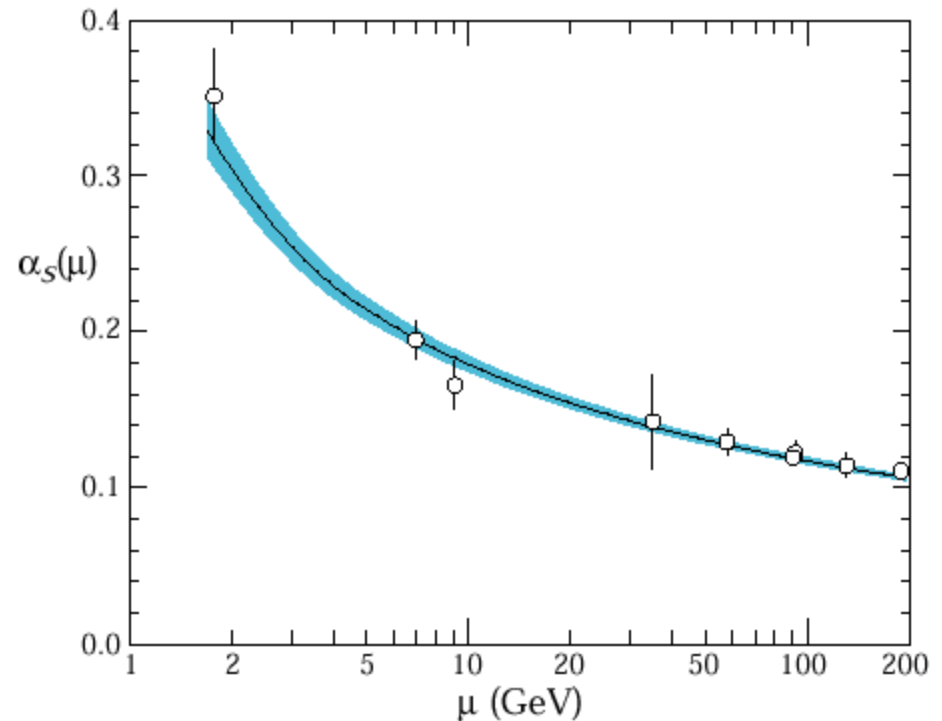


Quantitative description of the data over 10 orders of magnitude by perturbative QCD!

Strong QCD: Nonperturbative Regime

Running coupling constant

$$a_s(Q^2) = \frac{12 \pi}{(33 - 2n_f) \log(Q^2 / \Lambda^2)}$$

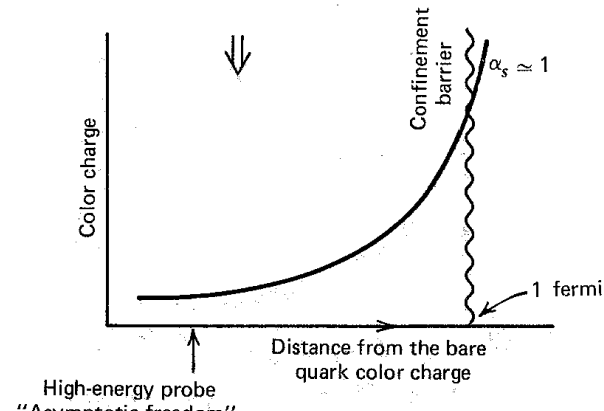
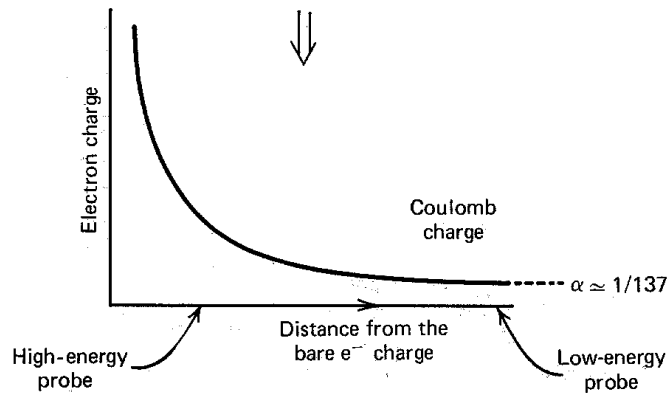
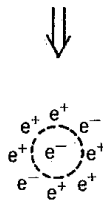
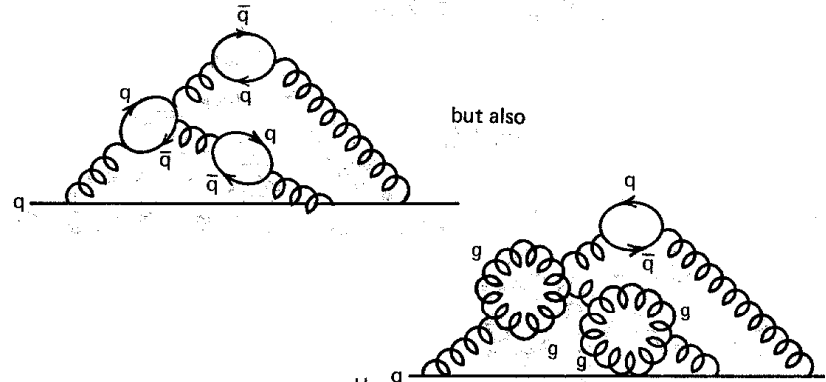
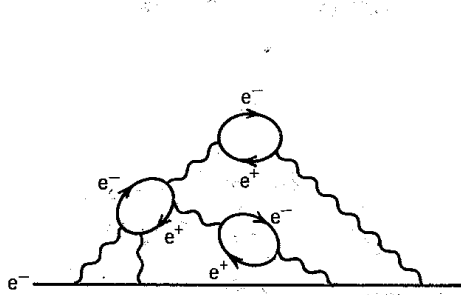


Λ is the mass scale (i.e. renormalization) where α_s get very large

Charge Screening and Quark Confinement

Quantum electrodynamics (QED)

Quantum chromodynamics (QCD)



(a)

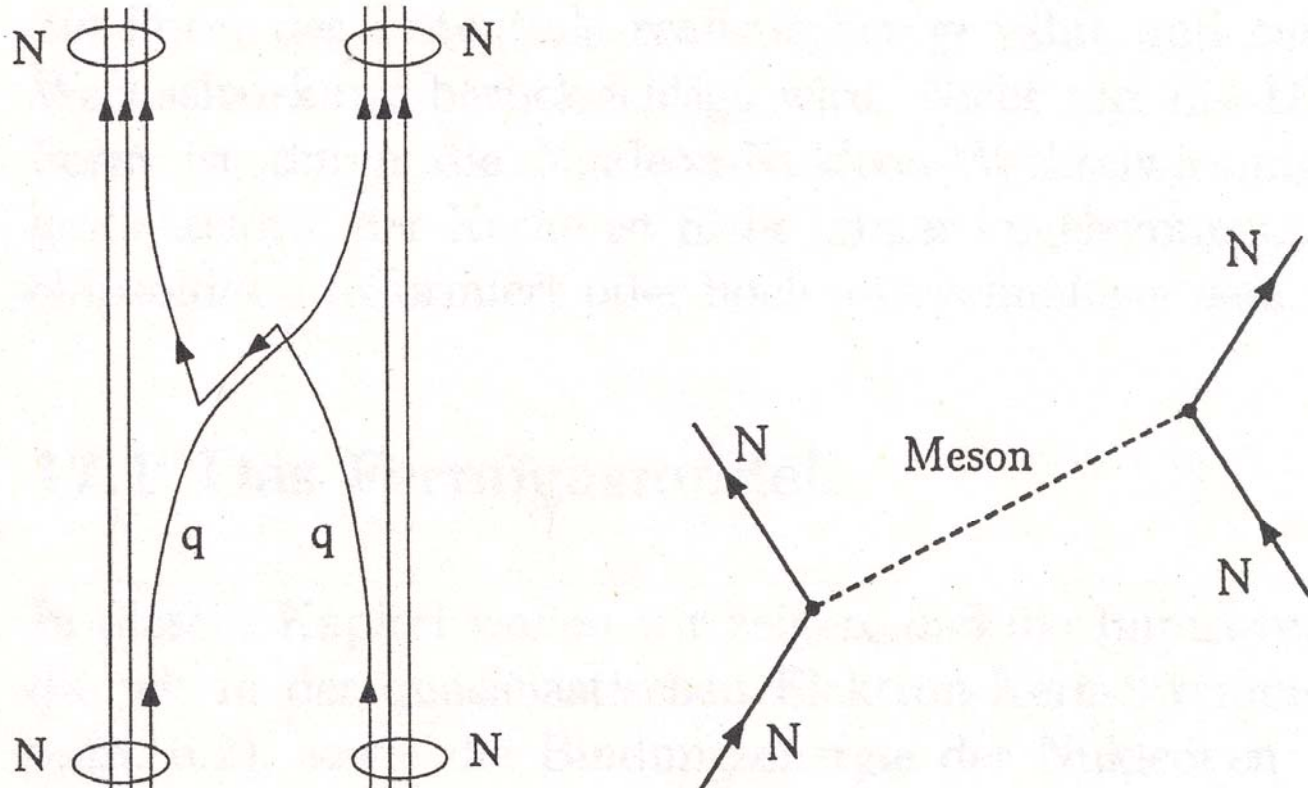
(b)

Comparison: dielectric medium

ferromagnet

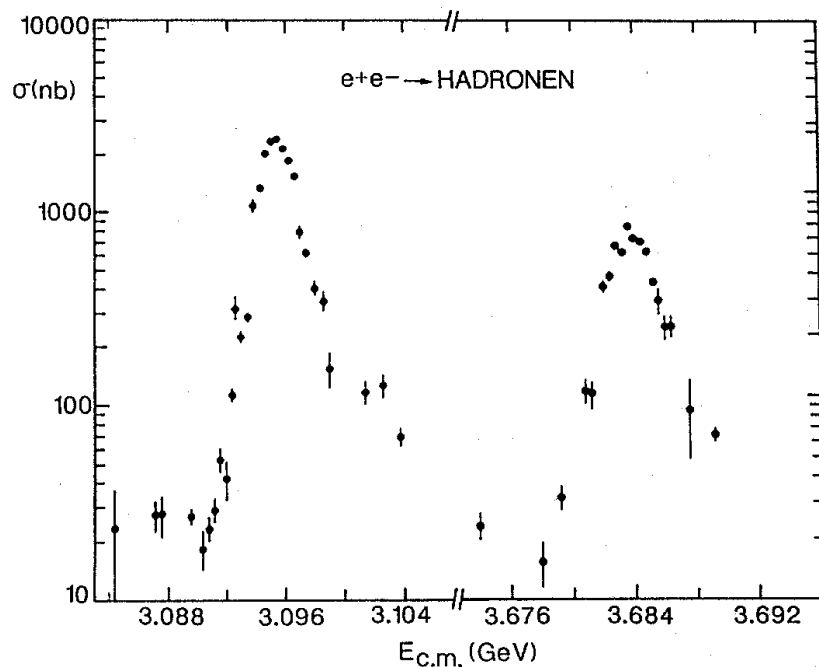
Hadrons as effective degrees of freedom

Only color singlet states at large distances



Production of J/Ψ

$c\bar{c}$ states were discovered in 1974 in both proton induced reactions at BNL and $e^+e^- \rightarrow \gamma^* \rightarrow J/\Psi$ at SLAC (Nobel prize 1976). In e^+e^- reactions there is much less background, but one can only produce states with the same quantum numbers as the (virtual) photon $J^\pi = 1^-$



The states are very narrow, and the resolution is dominated by the detectors / beam.

Width of the J/Ψ

Width determined from Breit-Wigner formula, branching ratios and total cross section:

Breit-Wigner

$$\sigma(E)_{e^+e^- \rightarrow J/\Psi \rightarrow e^+e^-} = \frac{\lambda^2 (2J+1) \Gamma_{e^+e^-}^2 / 4\pi}{(2s_1+1)(2s_2+1) \left[(E - E_R)^2 + \Gamma^2 / 4 \right]}$$

$$\Rightarrow \int_0^\infty \sigma(E) dE = \frac{3\lambda^2}{8} \left(\frac{\Gamma_{e^+e^-}}{\Gamma} \right)^2 \Gamma$$

$$\Gamma_{tot} = 0.088 \text{ MeV}$$

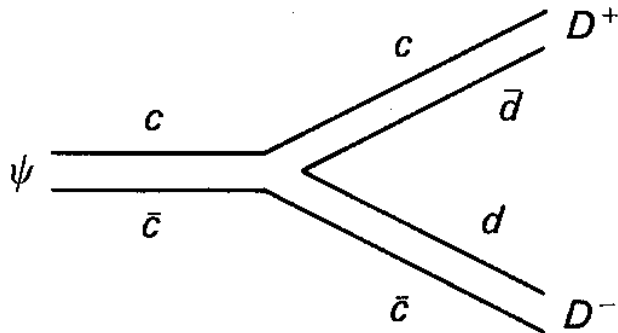
The J/Ψ is so narrow ($\Gamma_p=150 \text{ MeV}$) because it is below the D⁺ D⁻ threshold, and the so called OZI rule (Okubu-Zweig-Iizuka)

(a Breit-Wigner is the Fourier transform of an exponential decay)

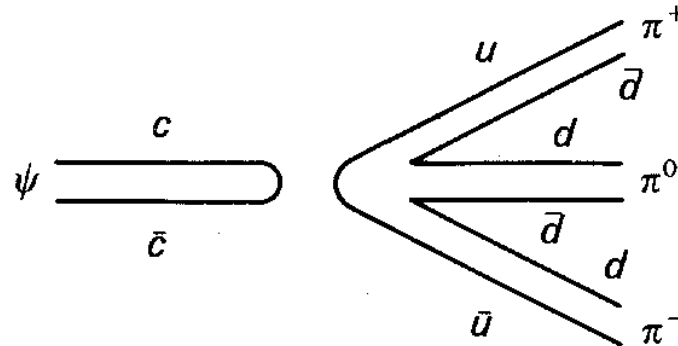
OZI Rule and the Decay of Vector Mesons

Processes with discontinuous quark lines are strongly suppressed.

One needs at least a 3 gluon exchange to annihilate the c-quarks and produce other quark flavors.



OZI allowed, but
below threshold for the J/Ψ

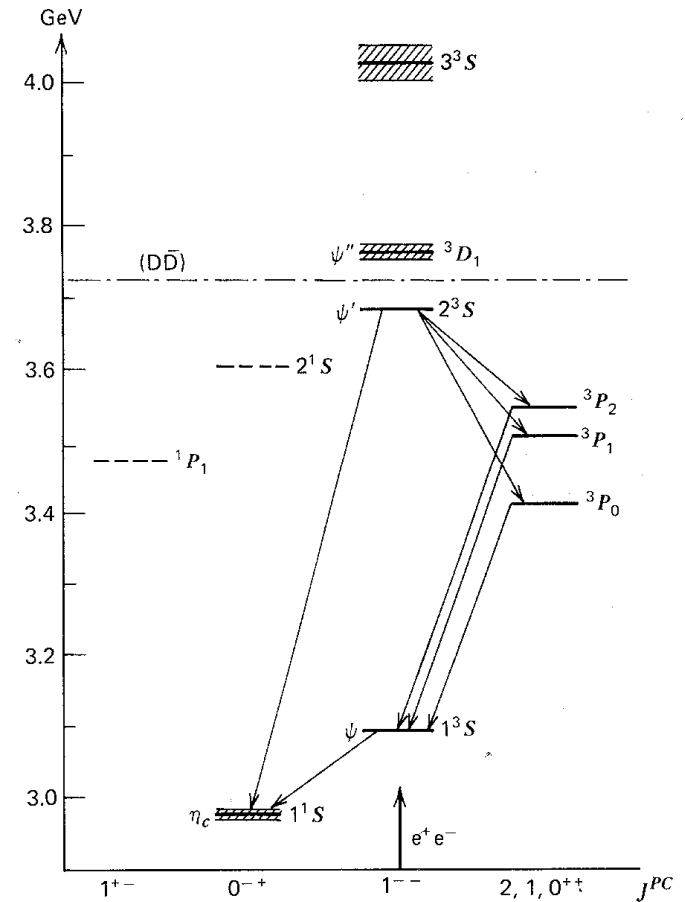
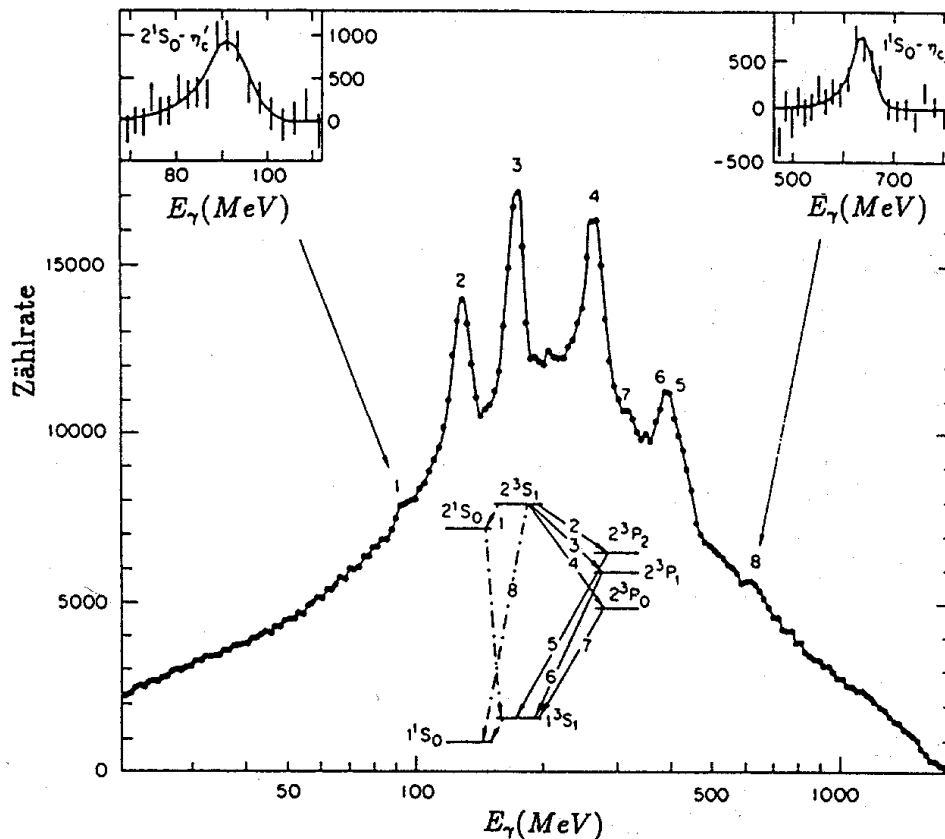


OZI suppressed

Charmonium Spectroscopy

Charmonium is the positronium of QCD: one can obtain information about the confining potential from the energy levels

The Crystal Ball Detector



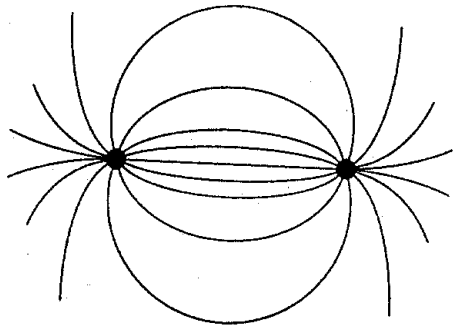
The η'_c was confirmed 20 years later, 80 MeV higher!

Extracting the Potential from the Energy Levels

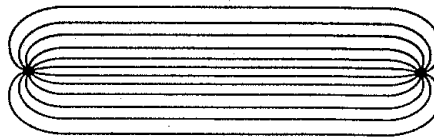
The energy levels are similar to positronium for $n=1,2$

⇒ Coulomb type interaction at small distances

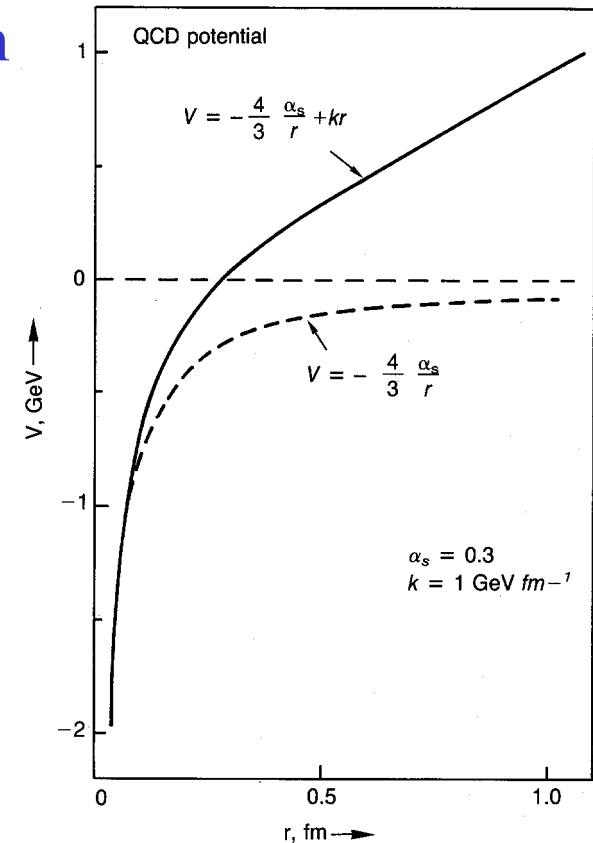
⇒ Deviations at higher energies



Field of 2 el. Charges:
Photons don't couple to themselves



Field from q-qbar :
Self coupling of the gluons
creation of new q-qbar pairs at high energy



Determining α_s at $M(J/\Psi)$

The partial width for decays into e^+e^-

$$\Gamma(J/\Psi \rightarrow \gamma^* \rightarrow e^+e^-) = \frac{16\pi\alpha^2}{M^2} |\psi(0)|^2 |Q|^2 \approx 5keV$$

The partial width for decays into hadrons

$$\Gamma(J/\Psi \rightarrow 3g \rightarrow \text{Hadrons}) = \frac{160(\pi^2 - 9)}{81M^2} \alpha_s^3 |\psi(0)|^2 \approx 70keV$$
$$\Rightarrow \frac{\Gamma(J/\Psi \rightarrow 3g \rightarrow \text{Hadrons})}{\Gamma(J/\Psi \rightarrow \gamma^* \rightarrow e^+e^-)} \propto \frac{\alpha_s^3}{\alpha^2}$$

$$\alpha_s \geq 0.21$$

The Electromagnetic Structure of Hadrons

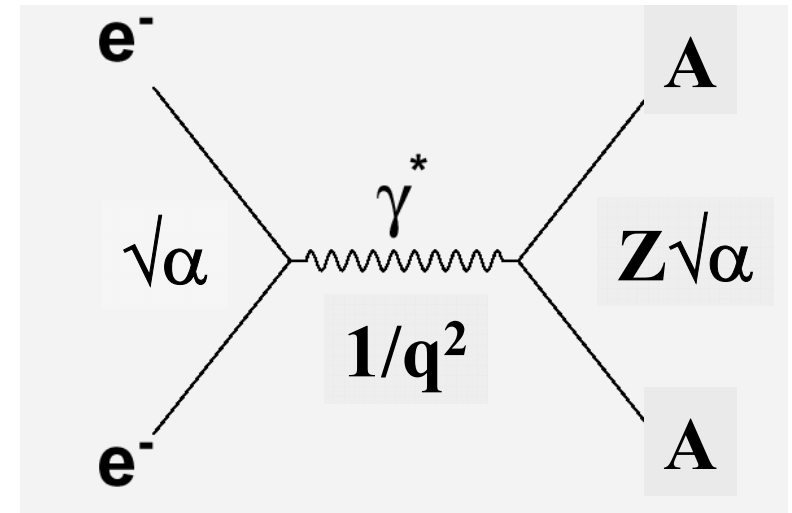
Elastic scattering of spinless electrons by (pointlike) nuclei
(Rutherford scattering)

$$\frac{d\sigma}{d\Omega} = \left(\frac{\hbar c}{8\pi} \right)^2 \frac{g_f |M_{if}|^2 |\vec{p}_f|}{s |\vec{p}_i|}$$

$$M_{if} \propto \sqrt{\alpha} \frac{1}{q^2} Z \sqrt{\alpha}$$

$$\left(q = \vec{p}_i - \vec{p}_f = 2|p| \sin \frac{\Theta}{2} \right)$$

$$E' = \frac{E}{1 + \frac{E}{Mc^2} (1 - \cos \Theta)}$$



$$\left. \frac{d\sigma}{d\Omega} \right]_{\text{Rutherford}} = \frac{4(Z\alpha)^2 E^2}{q^4}$$