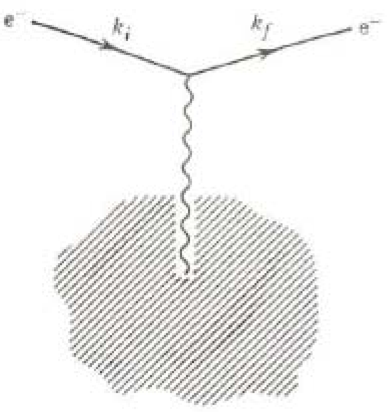
Quarks, Gluons, QCD

- Quarks: from a concept of classification to physics reality
- Deep inelastic electron scattering
  - Pointlike constituents: ‘partons’
  - Quantitative analysis: partons have spin ½ and fractional charge
- e^+e^- annihilation:
  - Number of quarks; color charge of quarks
  - Discovery of gluons
- QCD Lagrangian
  - Difference to QED
  - Quark-Gluon Plasma

Probing the size of the proton

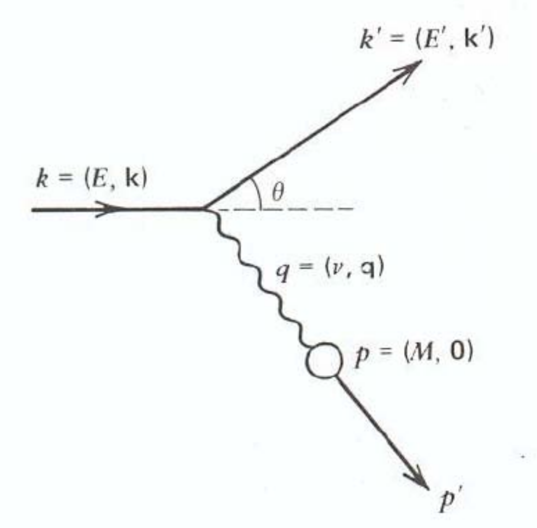
- Probing the charge distribution, shown in figure



- Approach; measure the angular distribution of electrons and compare to pointlike distribution
- $\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{point} |F(q)|^2$ with $q = k_i - k_f$; $|F(q)|$...Form factor
- Example: scattering of unpolarized electrons from static charge distribution $Ze\rho(\vec{x})$
- For a static target: $F(\vec{q}) = \int \rho(\vec{x})\, e^{i\vec{q}\bullet\vec{x}}\, d^3x$ ... Fourier transform of charge distribution
- Form factor is Fourier transform of charge distribution
- Lorentz invariant four-momentum transfer
  $$q^2 = (E - E')^2 - (\vec{p} - \vec{p}')^2 \cong -4\, E\, E' \sin^2(\theta/2)$$

$e^-\mu^- \rightarrow e^-\mu^-$

- Reaction is relevant for understanding lepton scattering on constituents
- Scattering cross section in Lab frame (muon at rest, mass M)



$$\left(\frac{d\sigma}{d\Omega}\right)_{lab} = \frac{\alpha^2}{4E^2 \sin^4 \theta/2} \frac{E'}{E} \left(\cos^2 \theta/2 - \frac{q^2}{2M^2} \sin^2 \theta/2 \right)$$

- Scattering cross section of electron on spin ½ particle
- Electron beam used to study dimension and internal structure of protons

Charge distribution of proton

- For $|q|$ small; (small energy transfer, large 'equivalent' wavelength of electron)

$$F(\vec{q}) = \int \left(1 + i\vec{q}\cdot\vec{x} - \frac{(\vec{q}\cdot\vec{x})^2}{2} + \ldots \right) \rho(\vec{x})\, d^3x = 1 - \frac{1}{6}|\vec{q}|^2 \left\langle r^2 \right\rangle$$

  assuming that charge distribution is spherically symmetric
- Low $|q|$, i.e. small angle scattering measures the mean square charge radius
- Cannot directly be applied to protons
  - Need to consider magnetic moment; proton not static, will recoil
- Reference point-like cross-section is same as eμ scattering with M_P

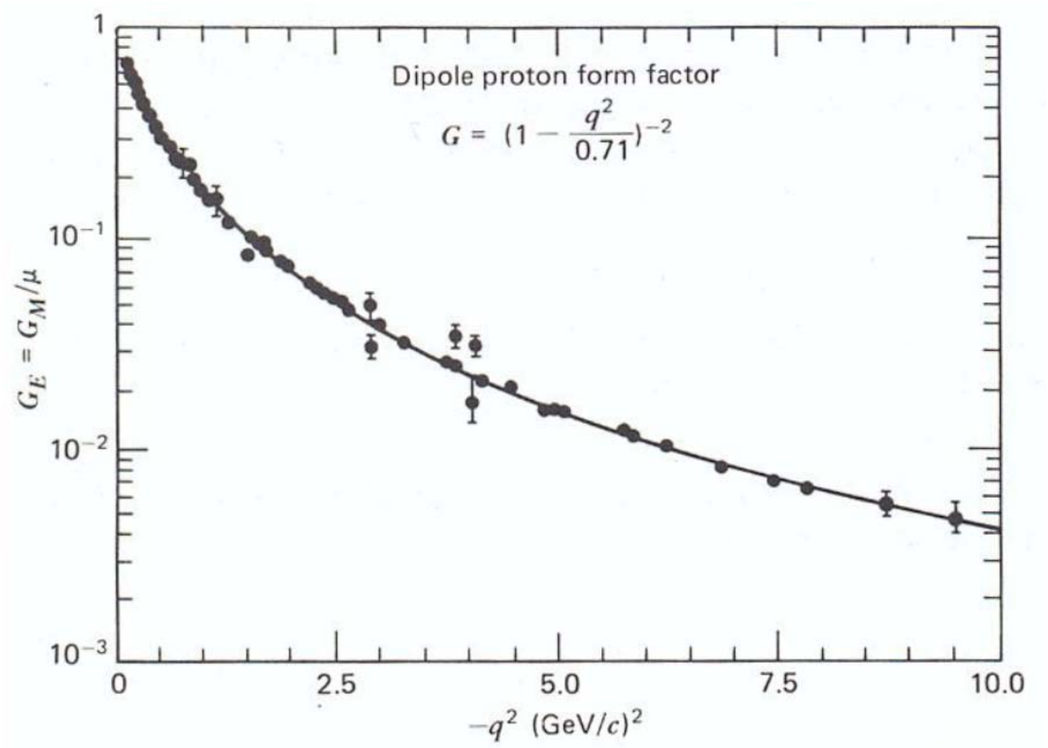
$$\left(\frac{d\sigma}{d\Omega}\right)_{lab} = \frac{\alpha^2}{4E^2 \sin^4 \theta/2} \frac{E'}{E} \left(A\cos^2 \theta/2 - B\frac{q^2}{2M^2} \sin^2 \theta/2 \right)$$

where A, B = 1 for point-like proton; E/E' from proton recoil

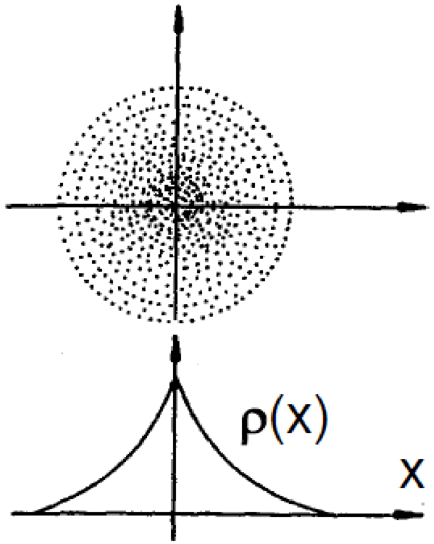
Charge distribution of proton

- Generalizing to extended source, one obtains two form factors (electric and magnetic) with κ being the anomalous magnetic moment with the result
- $$A = \left(F_1^2 - \frac{\kappa^2}{4M^2} F_2^2\right) \quad , \quad B = -\frac{q^2}{2M^2}\left(F_1 + \kappa F_2\right)^2$$
- 'Rosenbluth' formula; the two form factors $F_{1,2}(q^2)$ summarize the structure of the proton; determined experimentally; formula reduces to pointlike formula for κ=0 and $F_1(q^2) = 1$
- In practise $G_E = F_1 + \frac{\kappa q^2}{4M^2} F_2 \qquad G_M = F_1 + \kappa F_2$
- For protons: $\left\langle r^2 \right\rangle = (0.81 * 10^{-13}\,\text{cm})^2$
- Nobel prize for Hofstaedter in 1961

Proton form factor versus q^2

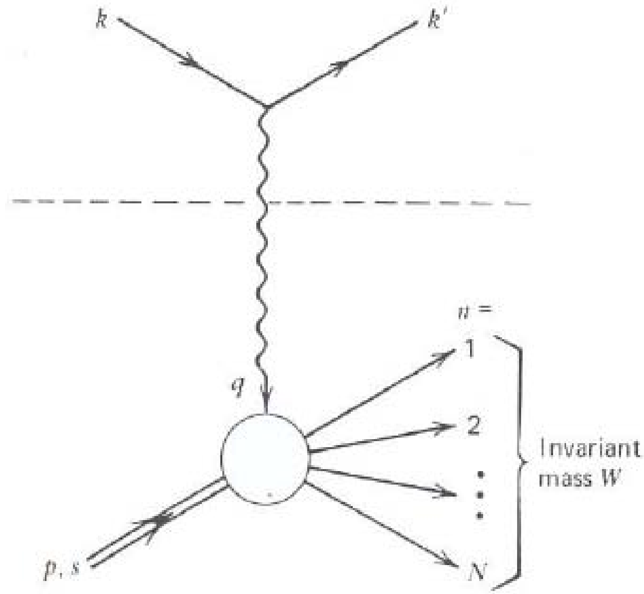


Fourier transform of this
Form factor is exponential
Charge distribution
$\rho\ (r) = \rho_0 \exp(- q_0/\ r)$



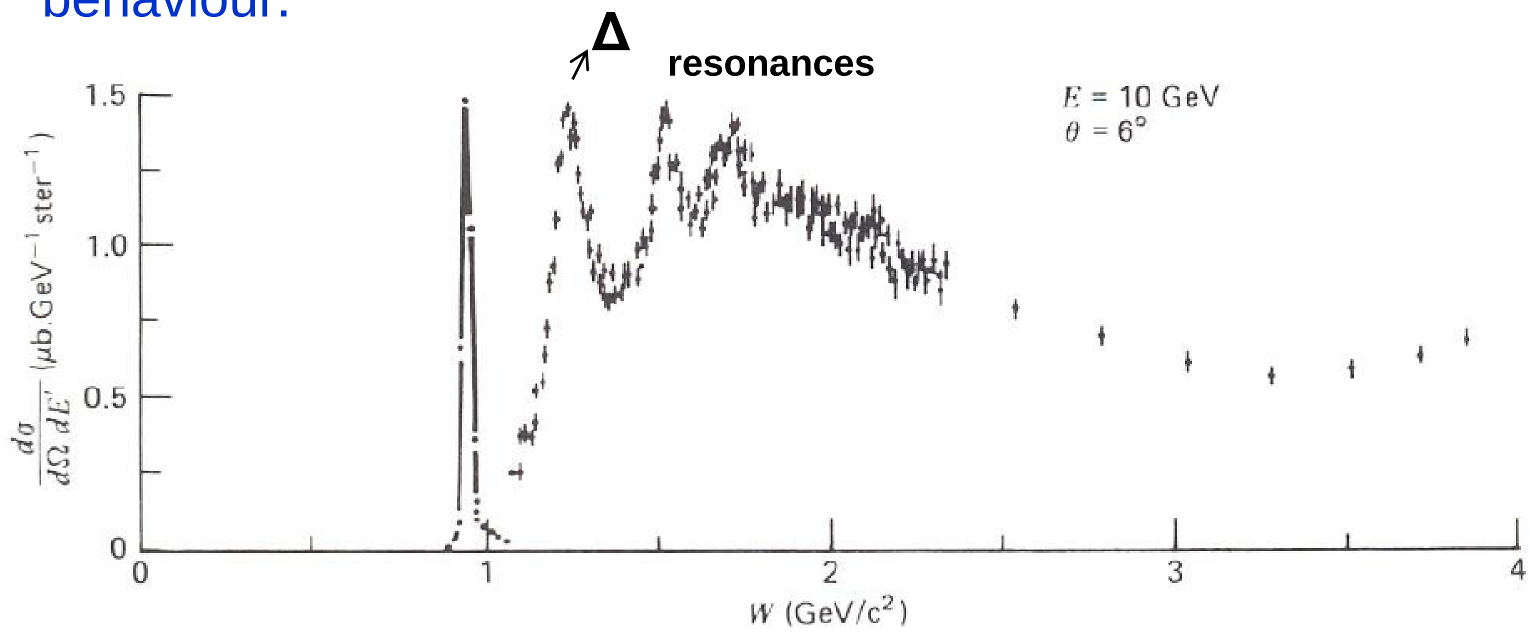
Inelastic Electron-Proton scattering

- Probing the internal structure of the proton
  - Increase the momentum transfer q^2 of the photon, equivalent to photons of shorter wavelength
  - However, if proton is composite object, it will get excited, break up under large momentum transfer, producing system of particles with invariant mass W



The ep -> eX cross section

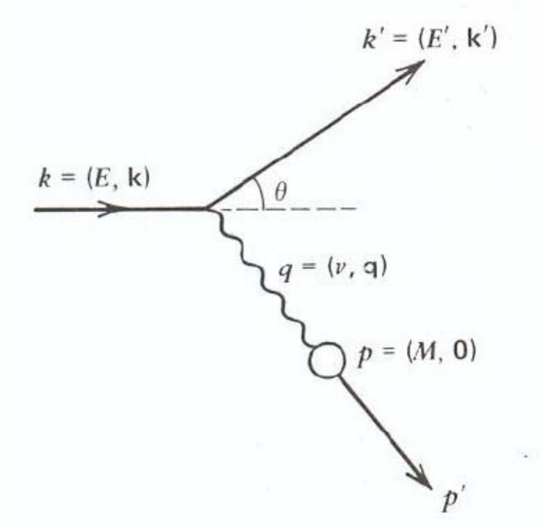
- The ep-> eX cross section as a function of the invariant mass of the particle system produced. The peak at W≈ M corresponds to scattering which does not breakup the proton; the peaks at higher W correspond to excited states of the proton; beyond the resonances multiparticle states with large invariant mass result in a smooth behaviour.



(elastic peak at W=M_p is reduced by factor 8.5)

$e^- \mu^- \rightarrow e^- \mu^-$

- Reaction is relevant for understanding lepton scattering on constituents
- Scattering cross section in Lab frame (muon at rest, mass M)



$$\left(\frac{d\sigma}{d\Omega}\right)_{lab} = \frac{\alpha^2}{4E^2 \sin^4 \theta/2} \frac{E'}{E} \left(\cos^2 \theta/2 - \frac{q^2}{2M^2} \sin^2 \theta/2 \right)$$

- Scattering cross section of electron on spin ½ particle
- Electron beam used to study dimension and internal structure of protons

Deep inelastic scattering

- Generalization of the inelastic scattering process follows the formalism for $e^- \mu^- \rightarrow e^- \mu^-$, but requires a more complicated description of the proton interaction, with two independent variables
  - q^2 , v = p•q/ M, q…four-momentum of virtual photon;
    M ..proton mass;
  - or alternatively
  - x = - q^2 / 2 p•q ; y = p•q/ p•k
  - Invariant mass of final hadronic system
    $W^2 = (p+q)^2 = M^2 + 2\nu M + q^2$
- Giving the final result

$$\left(\frac{d\sigma}{dE'd\Omega}\right)_{lab} = \frac{4\alpha^2 E'^2}{q^4}\left(W_2(\nu,q^2)\cos^2\theta/2 + 2W_1(\nu,q^2)\sin^2\theta/2\right)$$

with W_1 and W_2 to be determined experimentally… see later

Summary: electron scattering

- The differential cross section for eμ-> eμ, ep -> ep (elastic) and ep -> eX can written as $$\left(\frac{d\sigma}{dE'd\Omega}\right)_{lab} = \frac{4\alpha^2 E'^2}{q^4}\{\ldots\}$$
- For eμ-> eμ $$\{\ldots\} = \left(\cos^2\theta/2 - \frac{q^2}{2m^2}\sin^2\theta/2\right)\delta(\nu + \frac{q^2}{2m})$$
- For ep -> ep (elastic) $$\{\ldots\} = \left(\frac{G_E^2 + \tau G_M^2}{1+\tau}\cos^2\theta/2 + 2\tau G_M^2 \sin^2\theta/2\right)\delta(\nu + \frac{q^2}{2M})$$
- Integration over δ-function gives $$\left(\frac{d\sigma}{d\Omega}\right) = \frac{\alpha^2}{4E^2\sin^4\theta/2}\frac{E'}{E}(\ldots)$$
- For ep -> eX very similar; see expression on previous slide

Studying the sub-structure of the proton

- The formalism developed for deep inelastic scattering ep-> eX can be applied to the special case of probing a possible proton sub-structure
  - Using sufficiently small wavelength (i.e. sufficiently large q^2) it is possible to resolve a possible substructure, i.e. constituents
  - The breaking-up of the proton is described by the inelastic form factors W_1 and W_2
  - The scattering formalism is applied to electron scattering on the constituents, assuming certain properties

Probing the proton composition

- Assuming **pointlike** constituents ('partons') with **spin ½**, the scattering cross section is related to eμ-scattering with (for convenience $Q^2 = - q^2$)

$$2W_1^{point}(\nu, Q^2) = \frac{Q^2}{2m^2}\delta(\nu - \frac{Q^2}{2m})$$

$$W_2^{point}(\nu, Q^2) = \delta(\nu - \frac{Q^2}{2m})$$

- m is the mass of the parton (or quark); pointlike: structureless Dirac particle
- Using the identity δ (x/a) = a δ (x) one finds

$$2mW_1^{point}(\nu, Q^2) = \frac{Q^2}{2m\nu}\delta(\nu - \frac{Q^2}{2m\nu}) \qquad \nu W_2^{point}(\nu, Q^2) = \delta(\nu - \frac{Q^2}{2m\nu})$$

- With the intriguing result that these functions depend only on the ratio Q^2/ 2mv and not on Q^2 and v independently

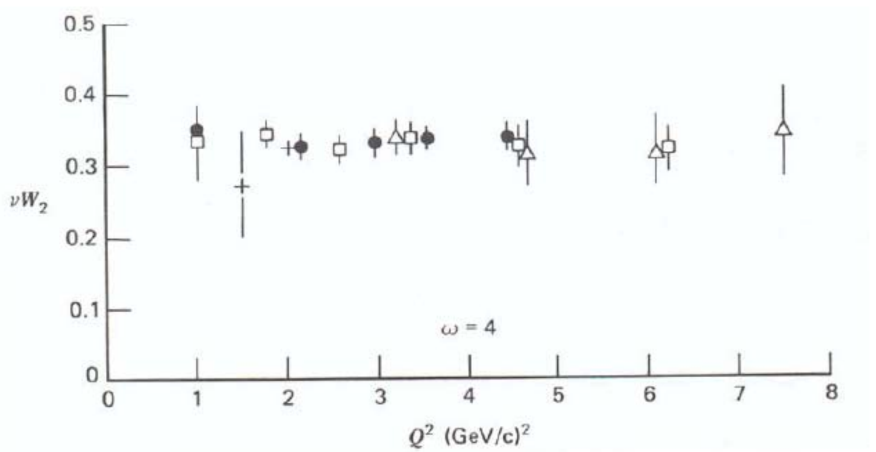
Probing the proton composition

- Summarizing and replacing the parton mass scale with the proton mass scale M

$$MW_1^{point}(\nu,Q^2) \rightarrow F_1(\omega) \qquad \nu W_2(\nu,Q^2) \rightarrow F_2(\omega)$$

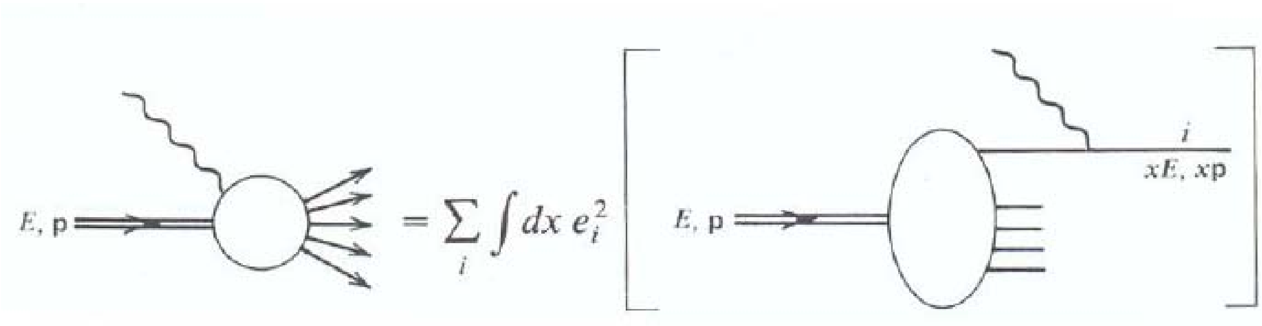
for large Q^2 and $\omega = 2M\nu/Q^2$; at a given ω, the structure functions **are measured** to be independent of Q^2

- Inelastic structure functions are independent on Q^2 -> constituents are pointlike and quasi-free (inside the proton)
- One experimental example
- Structure function = Fourier Transform of charge distribution→ St.F. is constant → charge distrib. is pointlike!

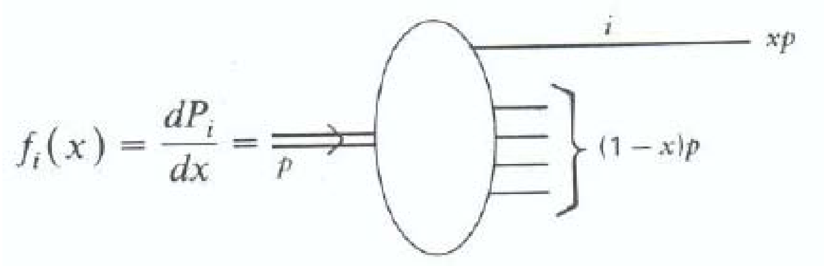


What are the properties of the 'partons' ?

- Partons are spin ½, electrically charged pointlike particles



- This picture recognizes that there are various partons in the proton: e.g. u, d quarks with different charges; uncharged gluons, with which the photon does not react; they carry different fraction x of the parent proton's momentum and energy ->
- Parton momentum distribution



Parton momentum distribution functions

- $f_i(x)$ gives probability that parton i carries fraction x of the proton's momentum p; all the fractions have to add up to 1

$$\sum \int dx\, x\, f_i(x) = 1$$

- Which leads to the following expressions for the structure functions

$$\nu W_2(\nu, Q^2) \rightarrow F_2(x) = \sum_i e_i^2 x\, f_i(x)$$

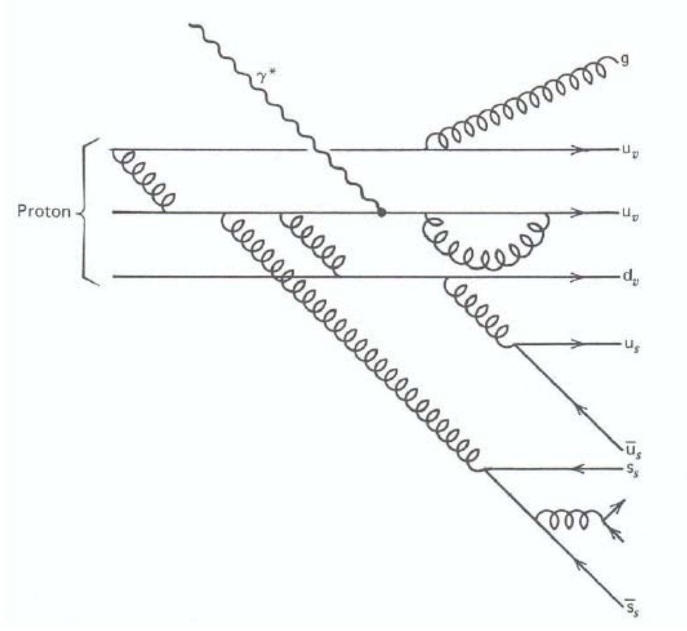
$$M W_1(\nu, Q^2) \rightarrow F_1(x) = \frac{1}{2x} F_2(x)$$

with $x = 1/\omega = Q^2/2M\nu$, only dependent on x

- The momentum fraction is found to be identical to the kinematical variable x of the virtual photon: the virtual photon must have the right value of x to be absorbed by the parton with momentum fraction x

Looking at quarks inside the proton

- Proton is composed of the constituent quarks (u,d quarks) (or ‘valence’ quarks), gluons, and quark-antiquark pairs (‘sea’ quarks)



- For the proton

$$\frac{1}{x}F_2^p(x)=\left(\frac{2}{3}\right)^2\left[u^p(x)+\bar{u}^p(x)\right]+\left(\frac{1}{3}\right)^2\left[d^p(x)+\bar{d}^p(x)\right]+\left(\frac{1}{3}\right)^2\left[s^p(x)+\bar{s}^p(x)\right]$$

Looking at quarks inside the proton

- Six unknown quark structure functions; additional information is provided by measuring electron-deuteron scattering, providing information on the corresponding neutron structure functions

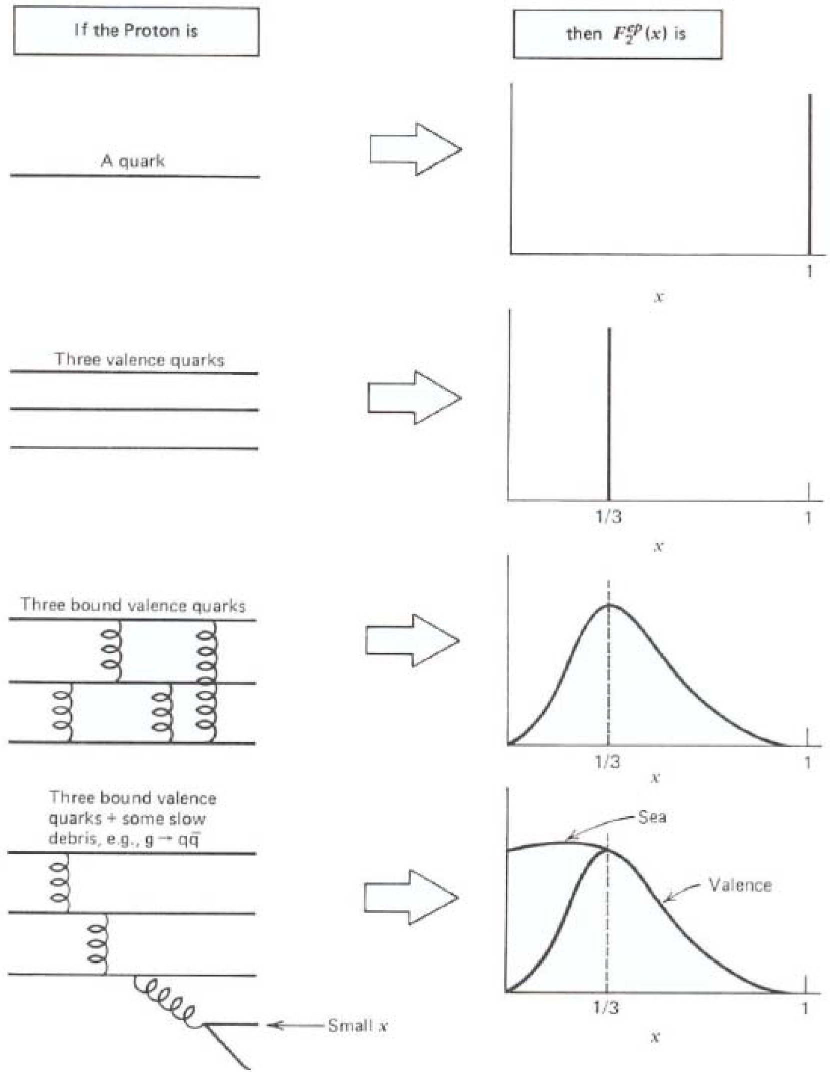
$$\frac{1}{x}F_2^n(x)=\left(\frac{2}{3}\right)^2\left[u^n(x)+\bar{u}^n(x)\right]+\left(\frac{1}{3}\right)^2\left[d^n(x)+\bar{d}^n(x)\right]+\left(\frac{1}{3}\right)^2\left[s^n(x)+\bar{s}^n(x)\right]$$

- Due to isospin invariance their quark content is related
  - There are as many u quarks in the proton as d quarks in the neutron

$$u^p(x)=d^n(x)\equiv u(x) \qquad d^p(x)=u^n(x)\equiv d(x) \qquad s^p(x)=s^n(x)\equiv s(x)$$

- Additional constraints: quantum numbers of proton must be those of the uud combination
- Measurement of F_2 (x) confirms charge assignment of the u and d quarks

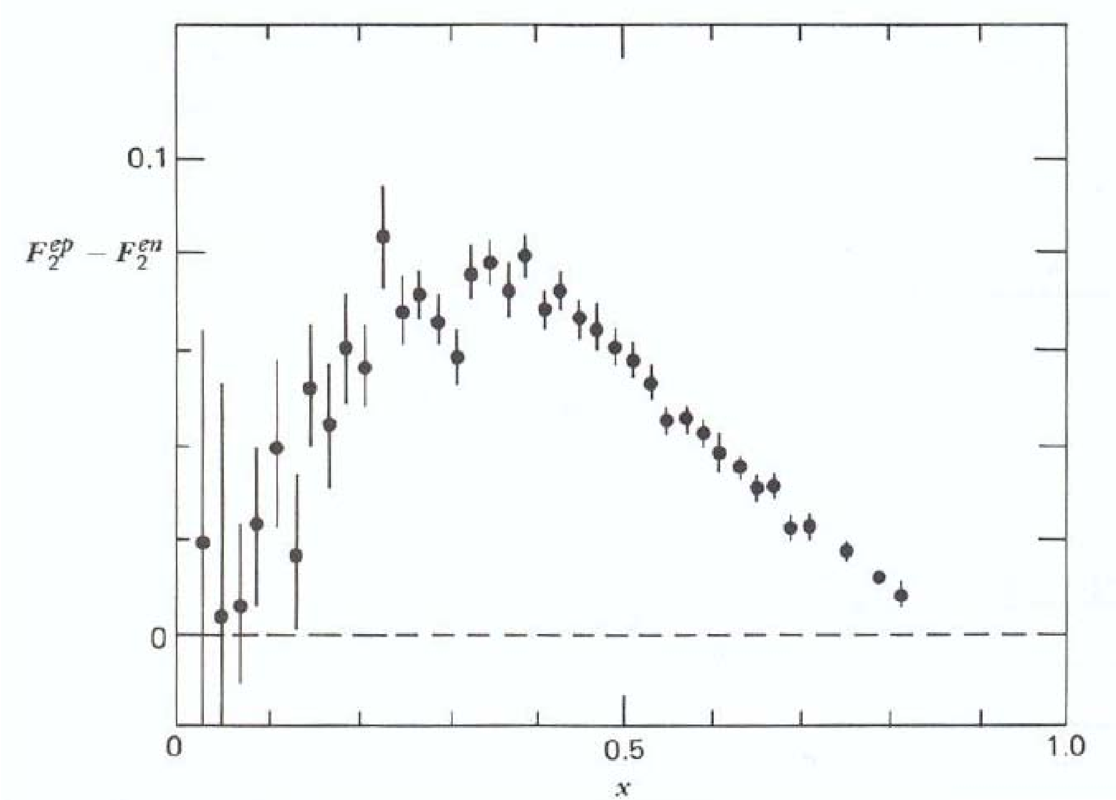
Conceptual form of the structure functions



Valence quark distribution

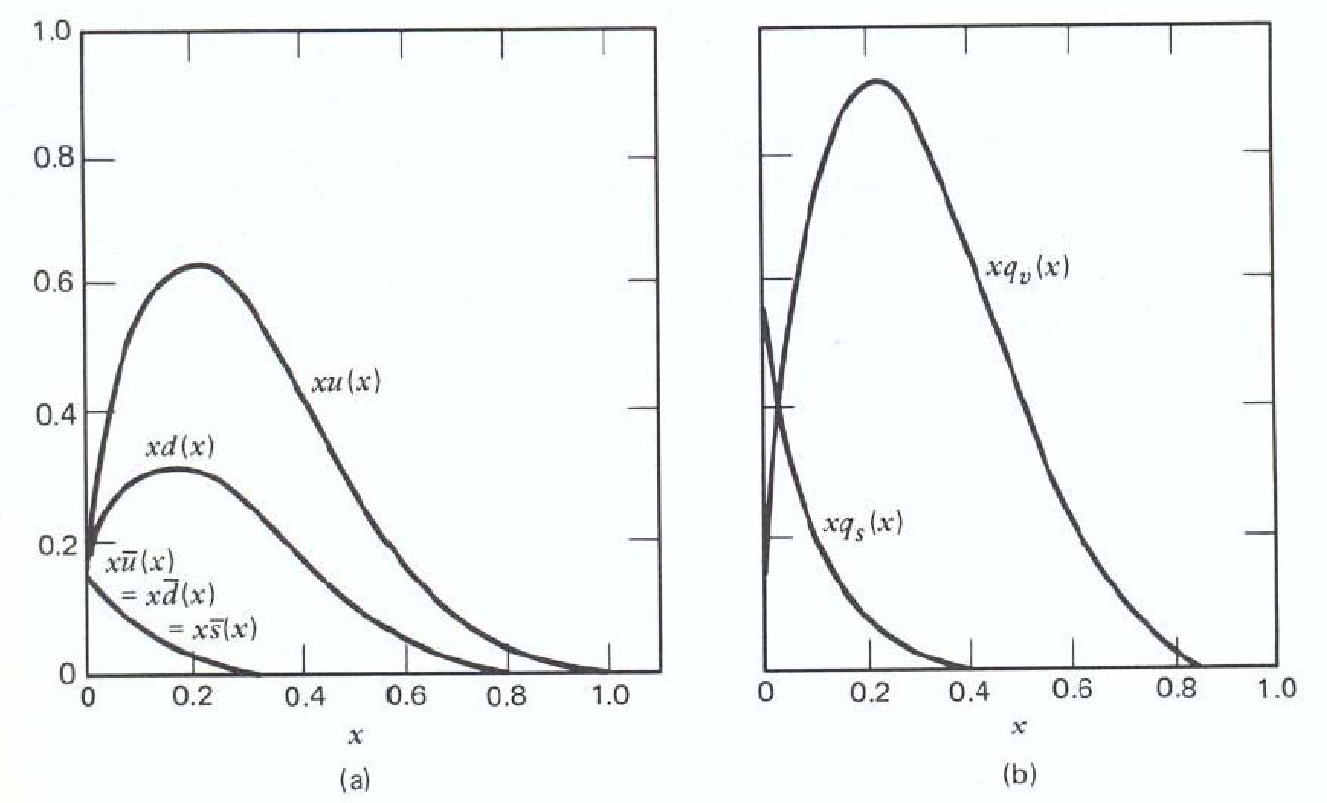
- From $$\frac{1}{x}\left[F_2^p(x) - F_2^n(x)\right] = \frac{1}{3}\left[u\ (x) - d\ (x)\right]$$

  one can directly measure the valence quark distributions

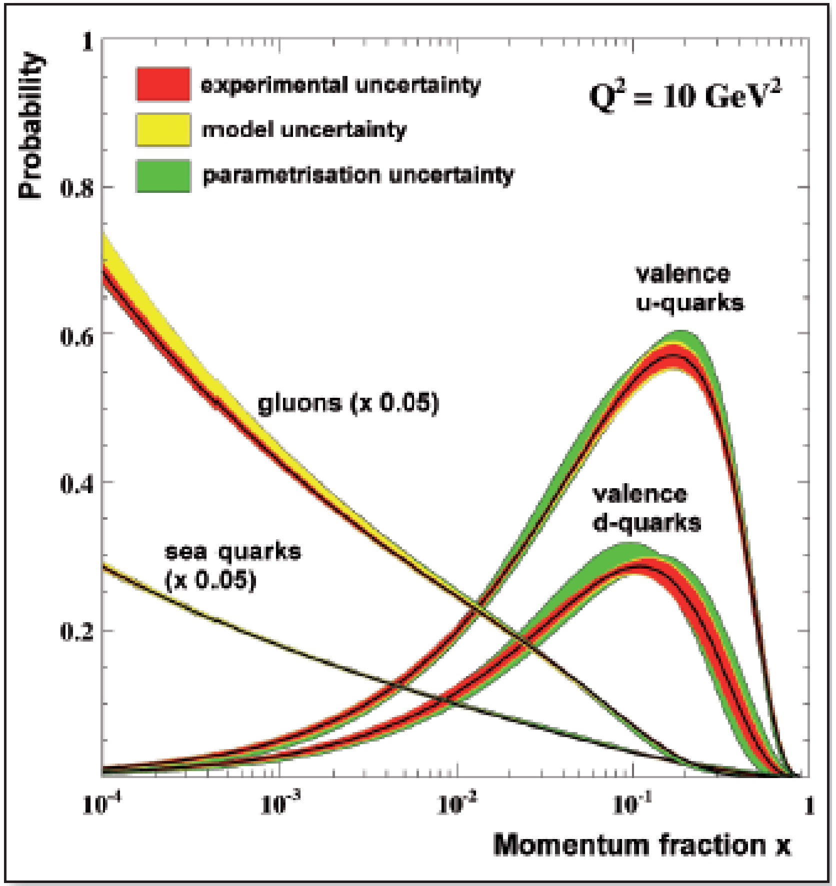


Quark structure functions

- From the analysis of deep inelastic scattering data



Quark structure functions: 'state of the art'



Deep inelastic scattering (DIS) experiments at Stanford Linear Accelerator(SLAC)

- Developed in the late 1960's; was at the time one of the largest experimental facilities
- Originally conceived to study elastic scattering-> extension to inelastic scattering met with some scepticism by the Program Committees: what can one learn?

- Established the quark structure
- Nobel prize (1990) for J.I. Friedman, H.W. Kendall and R.E. Taylor for 'structure of the proton'

Summary: results from DIS

- From structure functions $F_2(x, Q^2) \approx F_2(x)$ -> nucleons are composed from pointlike constituents
- From $2x F_1(x) = F_2(x)$ -> constituents have spin ½
- From experimental data on $F_2(x)$ for protons and neutrons (supplemented with data from DIS neutrino scattering) -> charge assignment for the u and d quarks
- From $\int F_2(x)\, dx$ -> quarks carry approximately 50 % of nucleon momentum; the rest is carried by the gluons; strong evidence for the reality and importance of gluons inside the nucleon
- Quantum numbers of the nucleon can be explained with the quantum number assignment of the quarks

e^+e^- Annihilations to Hadrons

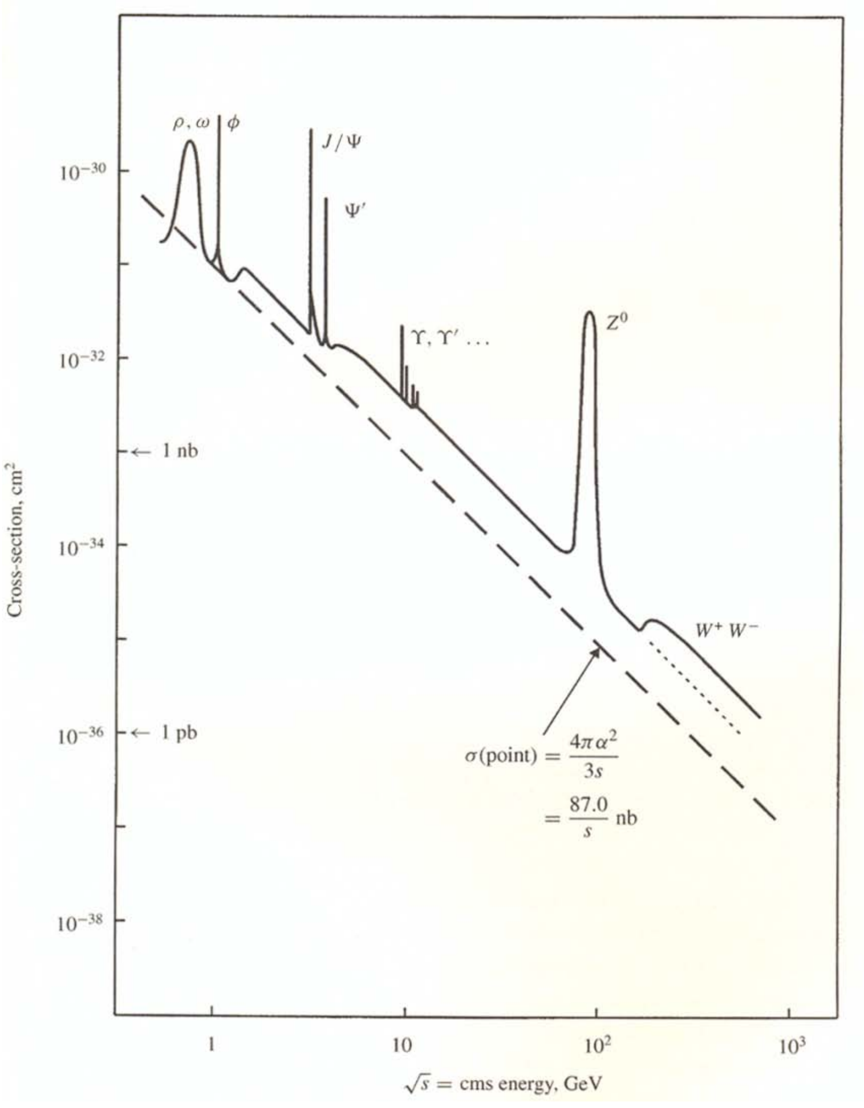
- $e^+e^- \rightarrow Q\overline{Q} \rightarrow Q \rightarrow \text{hadron jet},\ \overline{Q} \rightarrow \text{hadron jet}$

- $\sigma(e^+e^- \rightarrow anything) \propto \frac{1}{s}\,(as\ for\ \mu^+\mu^-\ production)$

    s…center of mass energy

- Peaks in cross-section are due to boson resonances

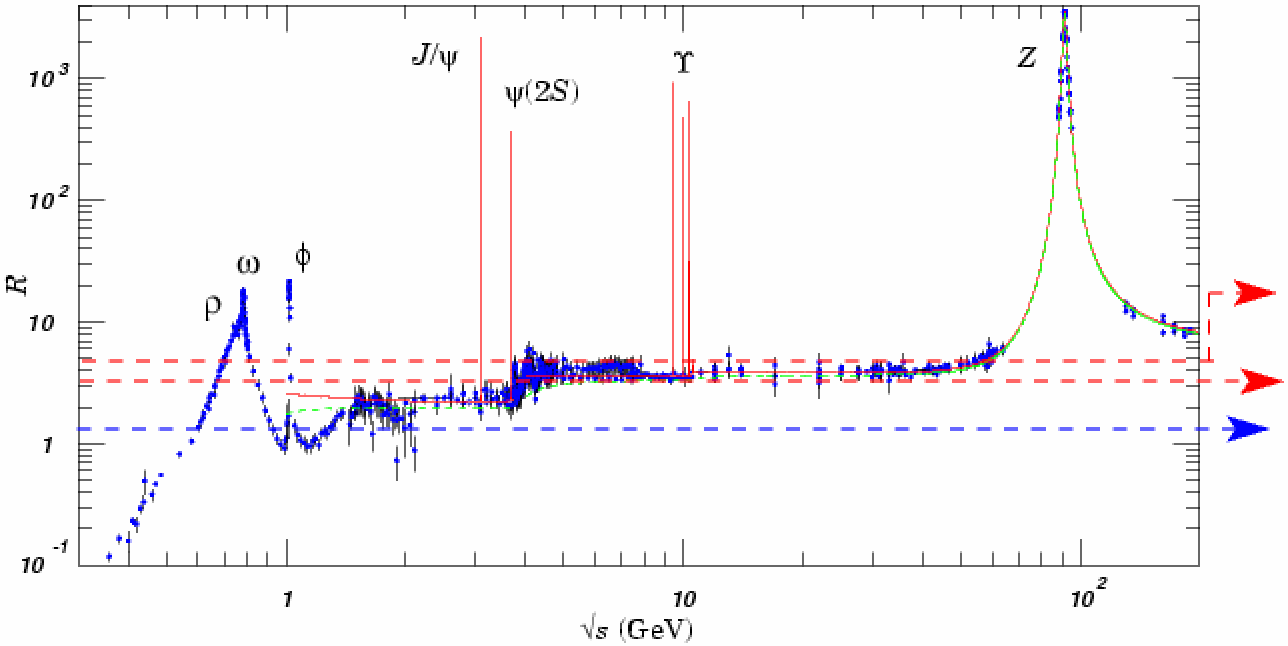
e^+e^- Annihilations to Hadrons vs center of mass energy s



Experimental proof of color charge of quarks

- Measurement of of total cross section σ ($e^+e^- \rightarrow$ hadrons) relative to σ ($e^+e^- \rightarrow \mu^+\mu^-$)
- Total cross section is obtained by summing over all contributing quarks:
$$\sigma(e^+e^- \rightarrow q\bar{q}) = \sigma(e^+e^- \rightarrow \mu^+\mu^-) \bullet N_C \sum_i q_i^2$$
  - N_C is the number of color charges (states)
  - the (three) color states of a quark have the same electric charge
  - The sum is over all energetically possibly produced quarks
- Measurement of the ratio
$$R = \sigma(e^+e^- \rightarrow q\bar{q}) / \sigma(e^+e^- \rightarrow \mu^+\mu^-) = N_C \sum_i q_i^2$$
directly determines the number of color states
- Higher order effects (3 jets,..) modify R
$$R = R_0(1 + \alpha_s(Q^2)/\pi + ...)$$

Measurement of R



6 quarks and three colors 45/9

5 quarks and three colors 33/9

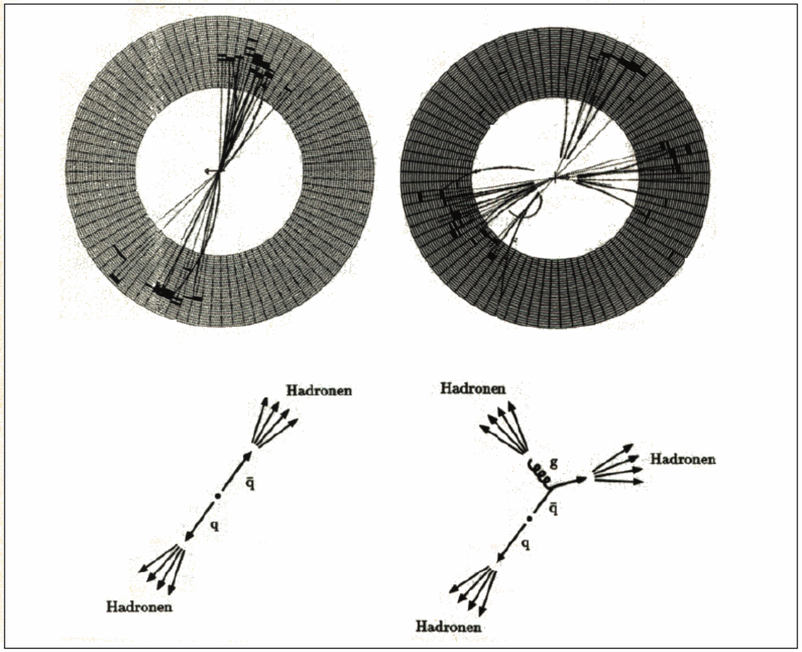
5 quarks and one color 11/9

$$R = N_c \sum_f z_f^2 = N_c \cdot [(\tfrac{2}{3})^2 + (-\tfrac{1}{3})^2 + (-\tfrac{1}{3})^2 + (\tfrac{2}{3})^2 + (-\tfrac{1}{3})^2] = N_c \cdot \frac{11}{9}$$

u d s c b

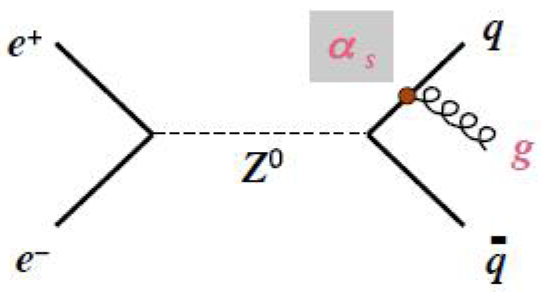
$e^+e^- \rightarrow$ three Jets

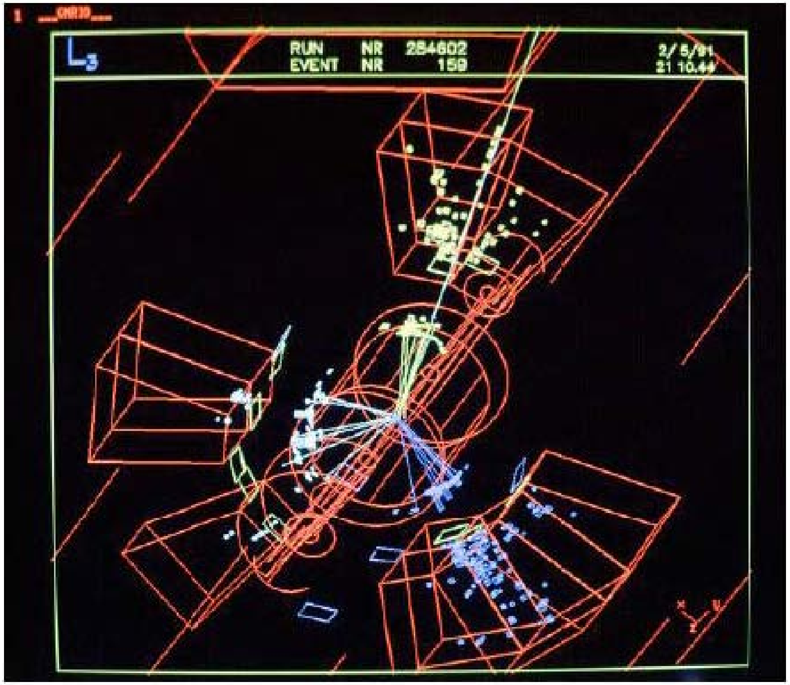
- Discovery of gluons in the observation of $e^+e^- \rightarrow$ three Jets $\rightarrow$ quark jet+ antiquark jet + gluon jet
  - gluon is radiated by a quark (or antiquark)
- Independent confirmation in proton-proton collisions (quark-gluon scattering) and DIS (electrons and neutrinos)



$e^+e^- \rightarrow$ three Jets

- Angular distribution of the gluon jet is sensitive to spin of gluon->
  - Spin of gluon = 1 (vector boson)
- Three-jet events can also be used to determine α_s : rate of gluon radiation is proportional to α_s





Event display of a 3-jet event at LEP

Summary: $e^+e^- \rightarrow$ hadrons

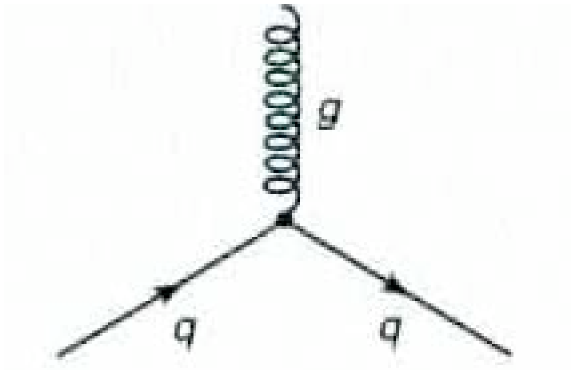
- Measurements are consistent with

  - fractional charge for the quarks and three color states (value of R)
  - Quarks (Antiquarks) can radiate gluons -> gluons have similar reality as quarks
  - Gluon radiation can be quantitatively used to measure α_s and to determine the spin of the gluon (S=1)

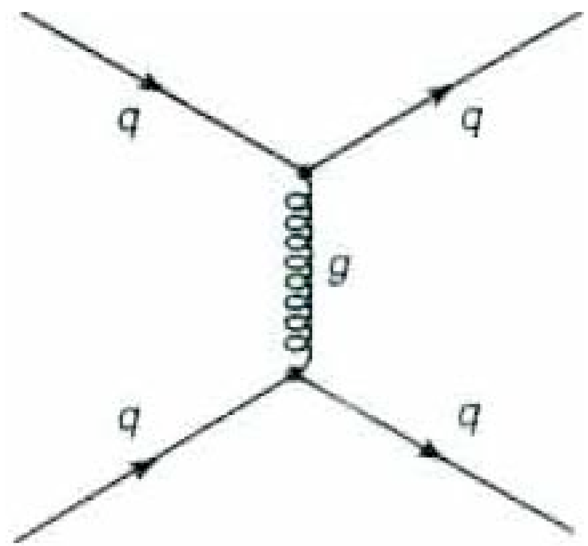
Theory of Strong Interactions: Quantum Chromodynamics (QCD)

- Status (approx. 1970)
  - Concept of quarks introduced for classification of hadrons
    - The ‘Eightfold Way’ by Gell-Mann; similar concept by Zweig
  - Classification needed another ingredient, ‘color’ charge of quarks
    - Required to avoid problem with Pauli exclusion principle
  - Free quarks were not observed-> are quarks really particles ?
  - DIS showed that proton has a substructure-> partons
    - Detailed experiments confirmed partons to have the properties of quarks(fractional charge, spin ½)
  - Quantum Electrodynamics (QED) confirmed with high experimental accuracy-> local gauge invariance as principle for deriving the Lagrangian of particle interactions
  - Experimental tests of nascent electroweak theory contemplated
- Ingredients prepared for attacking the ‘hardest’ problem: Strong Interactions

Quantum Chromodynamics (QCD)



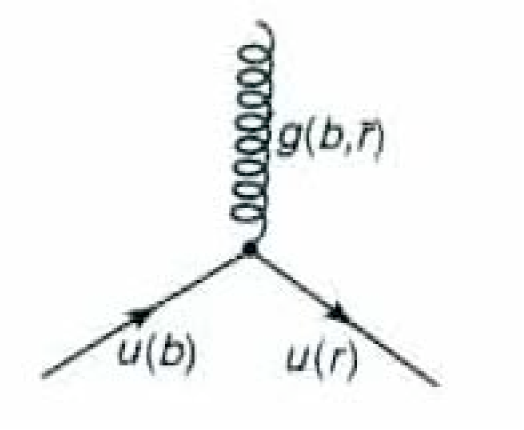
- in QCD: color plays the role of charge
- fundamental vertex
  $q \to q + \text{gluon } g$
- Analogous to $e \to e + \gamma$



- bound state of $q\bar{q}$
- Scattering of two quarks
- force between two quarks is mediated by the exchange of gluons

Quantum Chromodynamics QCD: similarities and differences to QED

- QED: one type of charge, i.e. *one* number (+, -); photon is neutral
- QCD: *three* kinds of color: red, green, blue
  - Fundamental process $q \rightarrow q + g$



: color of quark (not its flavor may change in strong interactions)

e.g.: blue up-quark ⇒ red up-quark

color is conserved ⇒ gluon carries away the difference

gluons are ‘bicolored’ with one positive and negative unit (e.g.: one unit of blueness and minus one unit of redness)

3 x 3 = 9 possibilities ⇒ experimentally only 8 different gluons observed; ninth gluon would be ‘color singlet’ (color neutral) and therefore observable ⇒ not observed, i.e. does not exist

QED and QCD: similarities and differences

- QED Lagrangian derived with the requirement of 'local gauge invariance'; gauge group is U(1)

$$\mathcal{L} = [i\hbar c\overline{\psi}\gamma^{\mu}\partial_{\mu}\psi - mc^2\overline{\psi}\psi] - \left[\tfrac{1}{16\pi}F^{\mu\nu}F_{\mu\nu}\right] - (q\overline{\psi}\gamma^{\mu}\psi)A_{\mu} \quad F^{\mu\nu} = \partial^{\mu}A^{\nu} - \partial^{\nu}A^{\mu}$$

  with A_{μ} a new massless field such that $A_{\mu} \to A_{\mu} + \partial_{\mu}\lambda$

- QCD Lagrangian $\mathcal{L} = i\hbar c\overline{\psi}\gamma^{\mu}\partial_{\mu}\psi - mc^2\overline{\psi}\psi$

  with $\overline{\psi} = (\overline{\psi}_r \overline{\psi}_b \overline{\psi}_g)$, describes interaction of three (equal mass) color states-> require invariance under U(3), with U being a 3x3 matrix which can be written as $U = e^{i\theta}e^{i\overline{\lambda}\cdot\overline{a}}; \overline{\lambda}\cdot\overline{a} = \lambda_1 a_1 + \lambda_2 a_2 + \ldots + \lambda_8 a_8$

- Matrix $e^{i\overline{\lambda}\cdot\overline{a}}$ has determinant 1-> belongs to SU(3) -> want to derive Lagrangian invariant under local SU(3) invariance

- $\psi \to S\psi, where\, S \equiv e^{iq\overline{\lambda}\cdot\Phi(x)/hc}; \Phi \equiv -(\hbar c/g)\overline{a}$; g is coupling constant

- Complete QCD Lagrangian

$$\mathcal{L} = [i\hbar c\overline{\psi}\gamma^{\mu}\partial_{\mu}\psi - mc^2\overline{\psi}\psi] - \left[\tfrac{1}{16\pi}F^{\mu\nu}F_{\mu\nu}\right] - (q\overline{\psi}\gamma^{\mu}\overline{\lambda}\psi)A_{\mu}$$

1st term: free quark; 2nd term: gluon field; 3rd term: quark-gluon interaction

QCD: Gluon-Gluon coupling

gluons, carrying color, (unlike the electrically neutral photon) may couple to other gluons ⇒three and four gluon vertices ⇒ QCD more complicated (but also richer: allows for more possibilities)

- Coupling constant α_s ~> 1 ⇒ higher order diagrams make significant (sometimes even dominant) contributions: a real problem!
- However, triumph of QCD: discovery that α_s is NOT constant, but depends on the separation of the interacting particles ⇒ 'running' coupling constant:
  - α_s is large at large distances (larger than proton) ⇒ 'confinement')
  - α_s is small at very short distances (smaller than proton) ⇒('asymptotic freedom')

QCD Lagrangian:

- Complete QCD Lagrangian

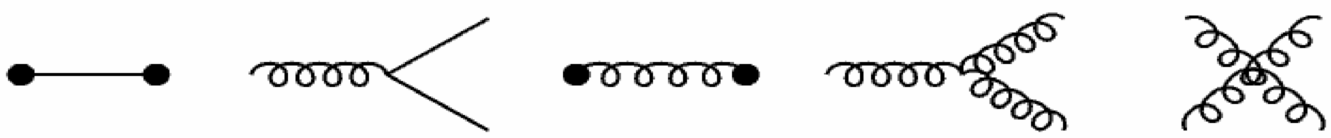
$$\mathcal{L} = [i\hbar c\overline{\psi}\gamma^{\mu}\partial_{\mu}\psi - mc^{2}\overline{\psi}\psi] - \left[\frac{1}{16\pi}F^{\mu\nu}F_{\mu\nu}\right] - (q\overline{\psi}\gamma^{\mu}\vec{\lambda}\psi)A_{\mu}$$

with

$$F^{\mu\nu} = \partial^{\mu}A^{\nu} - \partial^{\nu}A^{\mu} - \frac{2q}{\hbar c}(\vec{A}^{\mu}\times\vec{A}^{\nu})$$

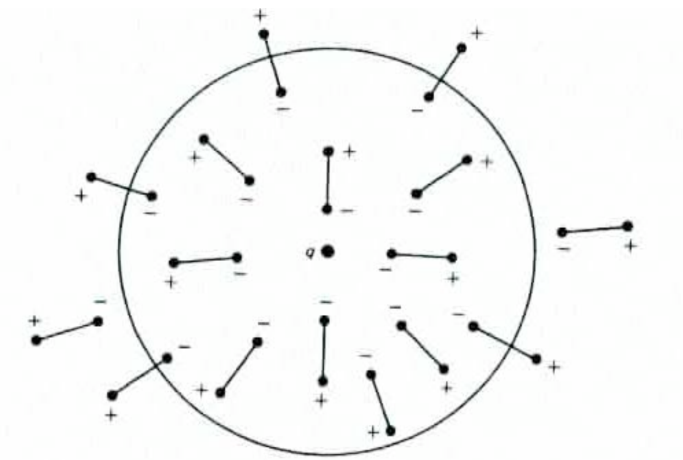
- 1st part is analog to photon field in QED; 2nd term is new: quadratic in gluon field

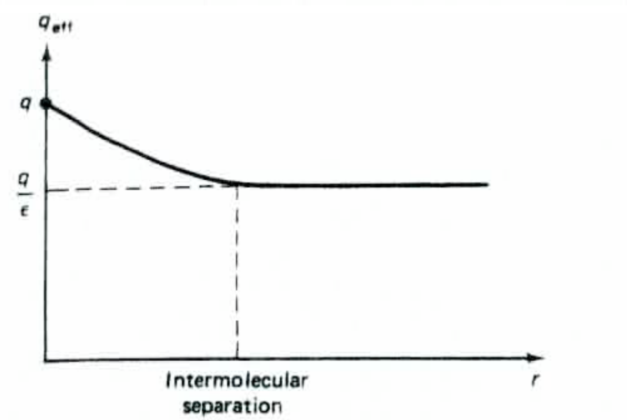
$$\mathcal{L}_{QCD} = (q\overline{q}) + \quad g(q\overline{q}F) + \quad (F^{2}) + \quad g(F^{3}) + \quad g^{2}(F^{4})$$

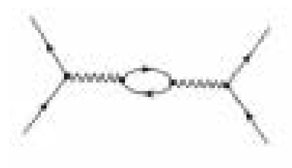
- 
- quarks quark-gluon gluons gluon-gluon self interaction
- Lagrangian describes three equal-mass Dirac fields (the three colors of a given quark flavor) with eight massless vector fields (the gluons)
- Lagrangian applies to one specific quark flavor; need altogether six replicas of ψ for the six quark flavors

Detour to QED

- Also in electrodynamics: effective coupling also depends on distance
  - Charge q embedded in dielectric medium ε (polarizable)
    - medium becomes polarized
    - Particle q acquires halo of negative particles, partially screening the charge q
    - at large distance charge is reduced to q / ε
    - in QED: vacuum behaves like dielectric
    - full of virtual positron-electron pairs
    - virtual electron attracted to q, positron repelled



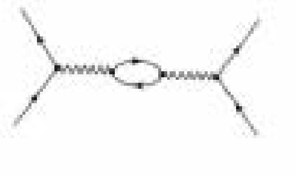


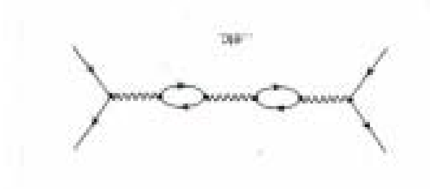


- This vacuum polarization screens partially the charge at distances larger than h/mc= $2.4*10^{-10}$ cm (Compton wavelength of electron)
- Measurable, e.g. in structure of hydrogen levels
- NOTE: we measure the 'screened' charge, not the 'bare' charge

Coupling constants: QED vs QCD

- QED : coupling constants modified by virtual effects (‘loop diagrams’)





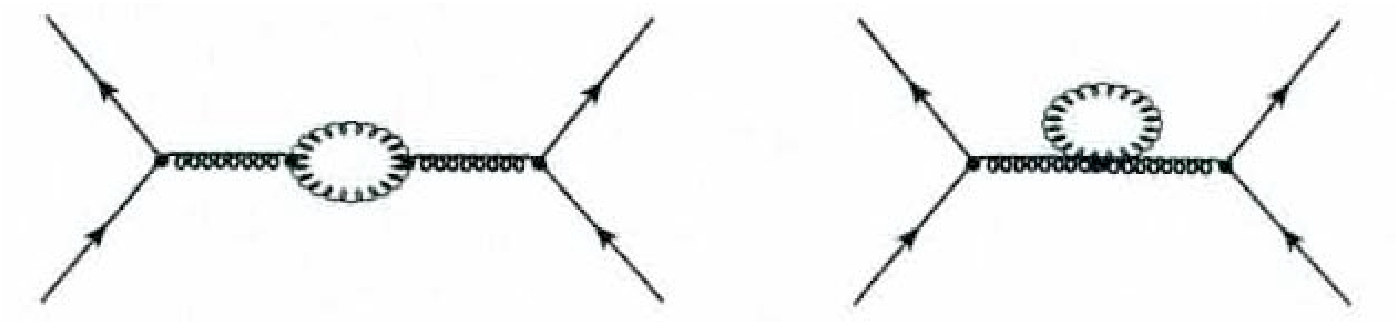
  which ‘screens’ the electric charge and modifies the coupling constant as a function of the distance (or equivalently; of the momentum transfer of a reaction); observable: Lamb shift; anomalous magnetic moment

$$\alpha_{QED} = \frac{\alpha(0)}{1 - [\alpha(0)/3\pi]\ln\left[\left|q^2\right|/(mc)^2\right]} \quad for \left|q^2\right| >> (mc)^2$$

- Coupling constant α_{QED} varies only very weakly with q^2

QCD: More complicated

- Diagrams analogous to QED contribute to vacuum polarization
- *qqg* vertex: contributes to increasing coupling strength at short distance
- In addition: direct *gg* vertex



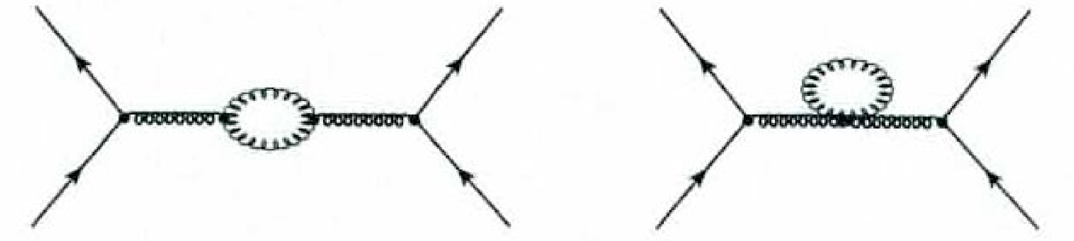
- Competition between quark polarization diagrams, $\alpha_s \uparrow$ and gluon polarization, $\alpha_s \downarrow$ at short distances

QCD vacuum polarization and 'Camouflage'

- In polarized medium quark continuously emits and reabsorbs gluons, changing constantly its color
- Color-charged gluons propagate to appreciable distances, spreading the color charge of the quark, camouflaging the quark, which is source of the color charge
  - The smaller the region around the quark the smaller the effective color charge of the quark→ color charge felt by quark of another color charge approaching the quark will diminish as the quark approaches the first one
- Net effect: competition between screening and camouflage
- QCD: critical parameter $a = 2f$ (of flavors) – $11n$ (number of colors)
  - if a is positive (as in QED), coupling increases at short distance
  - in SM: $n = 3, f = 6; a = -21$; QCD coupling decreases at short distance

Coupling constants: QCD

- The screening effects happen in QCD (quark-antiquark loops), BUT in addition due to gluon couplings



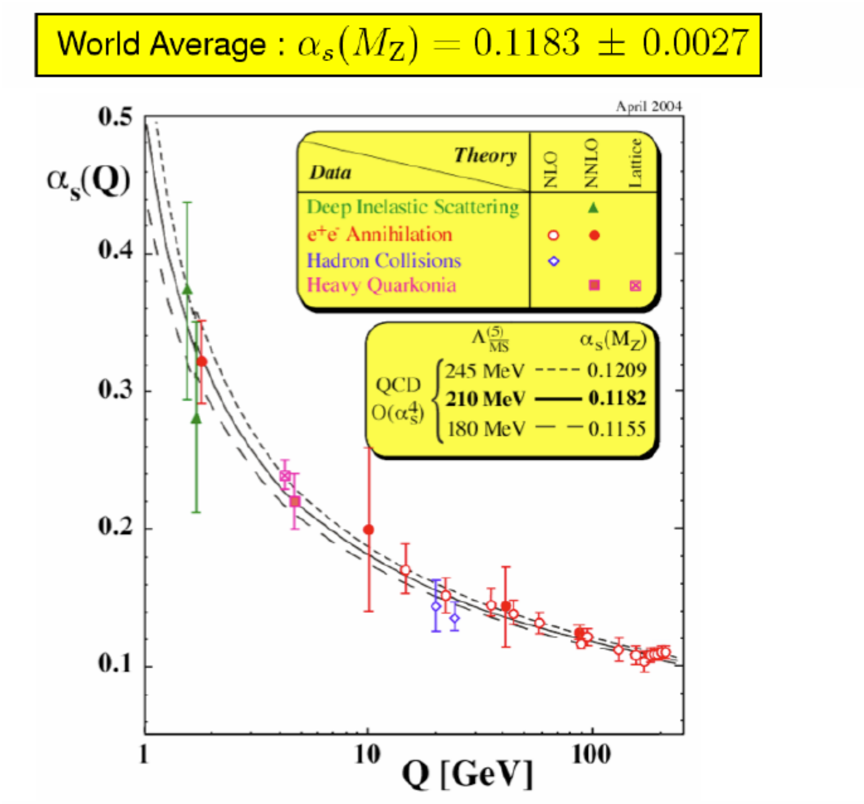
- with the result for the coupling constant

$$\alpha_{QCD} = \alpha_s = \frac{\alpha_s(\mu^2)}{1 + \left[\alpha(\mu^2)/12\pi\right](11n - 2f)\ln\left[\left|q^2\right|/\mu^2\right]} \quad for \left|q^2\right| >> \mu^2$$

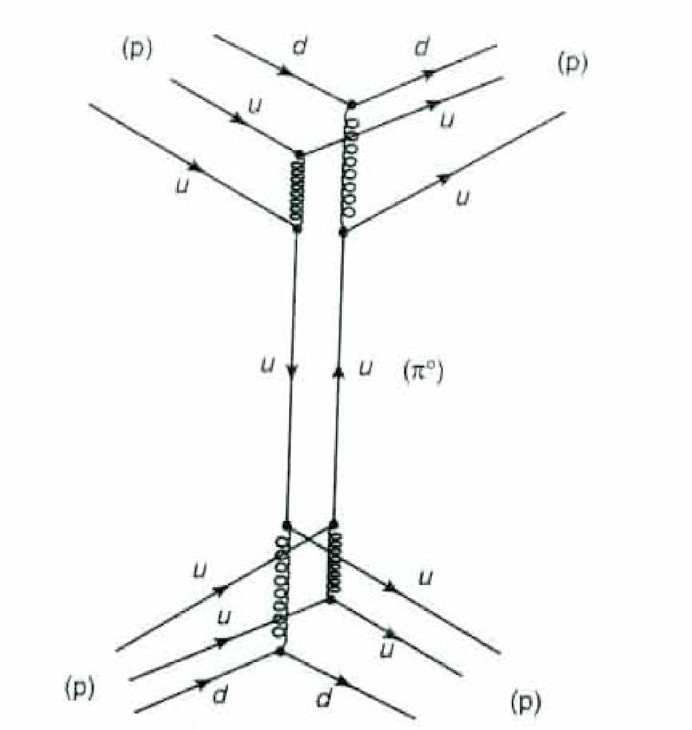
- With n= colors (3 in SM) and f= number of quark flavors (6 in SM); μ is a reference value around which α_s is evaluated.
- At large q^2 α_s becomes less than 1-> perturbation theory is applicable; -> ***Asymptotic Freedom***.
- There are equivalent Feynman rules for quantitative calculations: peturbative QCD is quantitatively tested at the <1% level

Coupling constants: QCD

- At small q^2 α_s becomes very large -> ***confinement***
- The exact proof of confinement is very difficult to demonstrate within the frame work of QCD and is a very active topic of current research in strong interactions



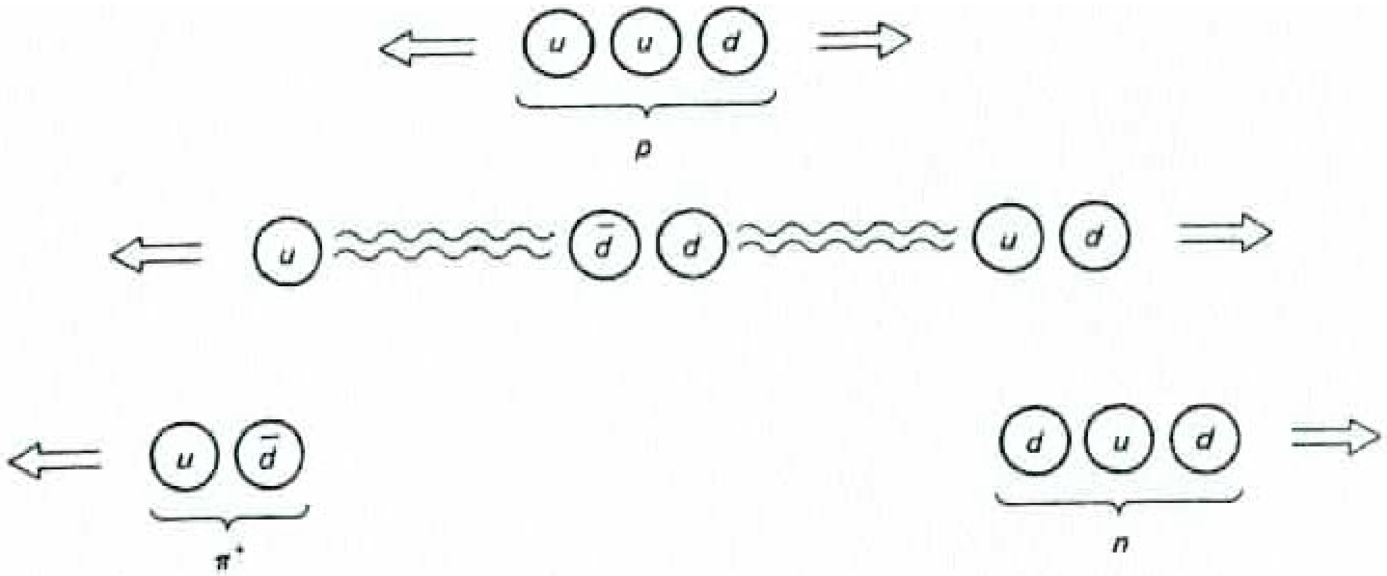
QCD: One more difference



- quarks are confined in colorless packages
- experimental observations are indirect and are complicated manifestations of QCD
- force between two protons involves diagrams of the type shown
- reminiscent of the Yukawa π-exchange model

- QCD: theory must *prove* confinement: ongoing major task of theoretical research!
- QCD prediction at very high temperature (short range) phase transition to deconfined 'Quark-Gluon Plasma' -> subject of intense theoretical and experimental current research

Possible Scenario for Quark Confinement



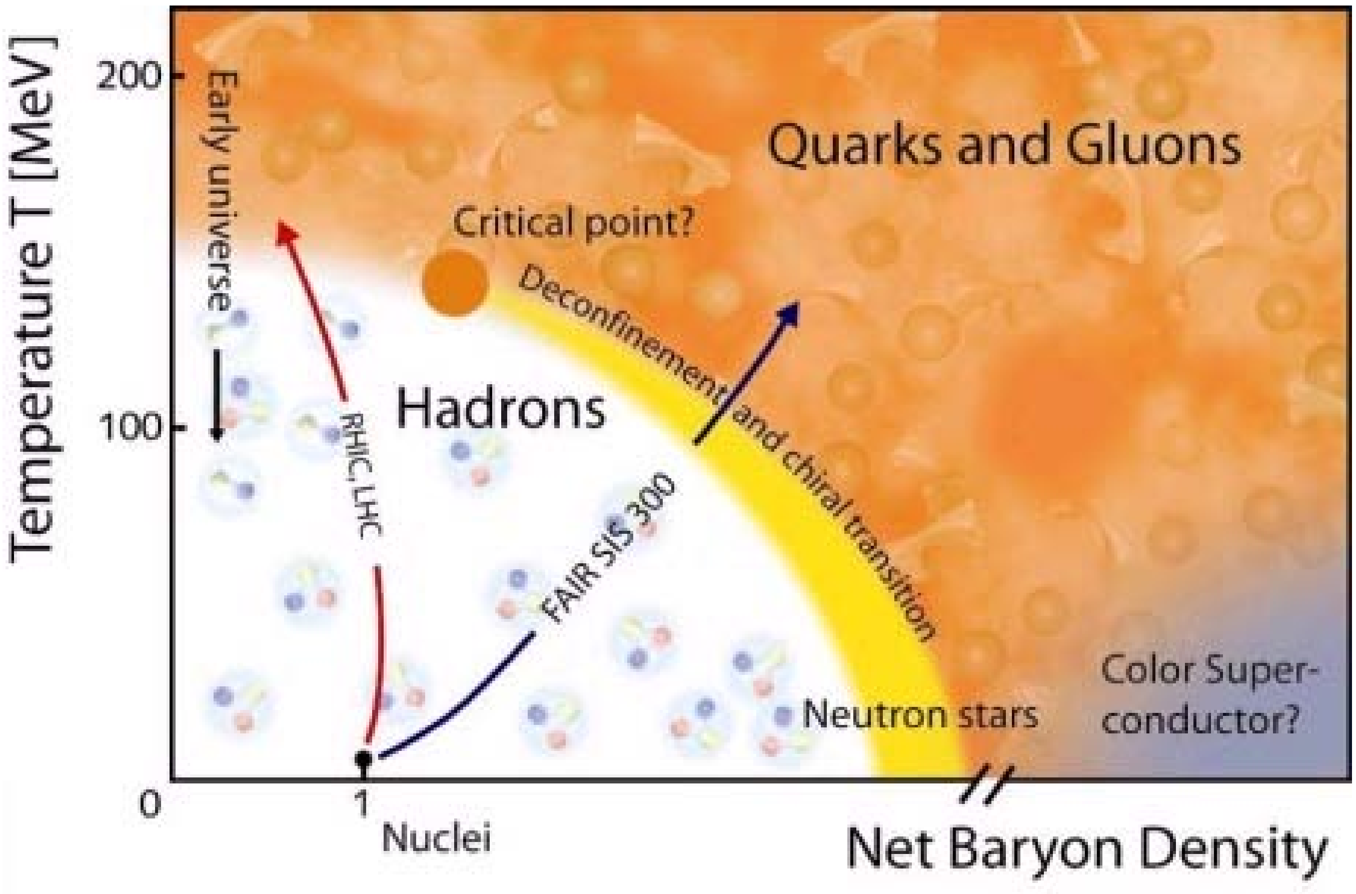
- Concept for *proof* of quark confiment: potential energy increases without limit as quarks are pulled farther and farther apart -> energetically more favorable to produce quark-antiquar pairs
- Conclusive proof for confinement still lacking: long-range interaction difficult to treat theoretically

Quark-Gluon Plasma

- One ‘golden’ prediction of QCD is the ‘Quark-Gluon Plasma’, deconfined quarks and gluons at very high density or temperature
  - T ~ 170 MeV ~ 10^{12} K
  - thought to have been the primordial matter during the first microsecond after the Big Bang
- Considered to be created in very energetic collisions of heavy nuclei (e.g. lead ions)
  - Was an active program at the CERN SPS; now actively being pursued at RHIC (Relativistic Heavy Ion Collider) at Brookhaven, USA
  - Major research activity at the LHC with one dedicated facility

Deconfined quarks in the 'Quark Gluon Plasma'

Phase Diagram of Quark Gluon Plasma



At sufficiently high temperature Nuclear Matter undergoes a phase transition to deconfined quarks and gluons: Quark-Gluon Plasma;

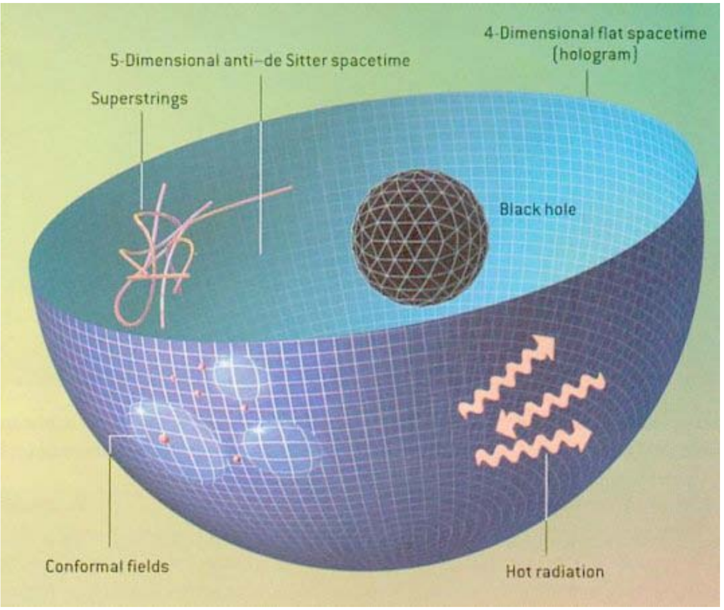
Gravity: a fundamental correspondence

- Most-cited theoretical development of last decade

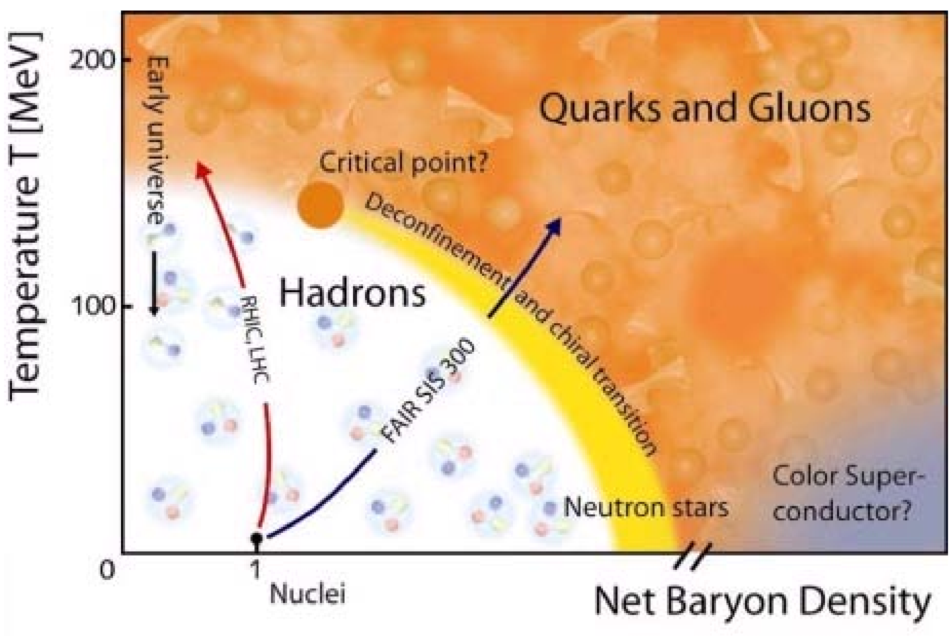
  Correspondence between anti-deSitter Gravity and conformal Quantum Field-Theories: AdS/CFT

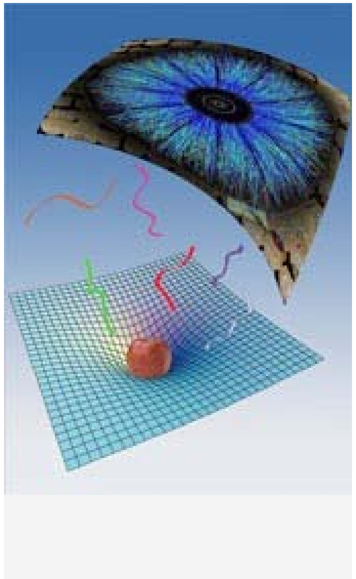
  - Discovery within frame of Superstring-Theory
  - Strongly interacting Quantum Fieldtheorie (z.B. QCD) in 3 space and 1 time dimension →

    equivalently described with 5-dimensional Gravity theory



Applying the AdS/CFT correspondence: Black Holes <-> Quark-Gluon Plasma





- Spectacular application: strongly coupled Quark-Gluon Plasma is described with the physics of black holes in 5 dimensionen (and vice-versa)
- Successful prediction: viscosity of Quark-Gluon Plasma
- Quark-Gluon Plasma is a very active field of study at LHC