QCD and the quark Model

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Outline

- Strong interactions and QCD
- Historical origin: parton model
- Electron proton elastic and inelastic scattering
- Bjorken scaling
- Scaling violation and a related Feynman diagram with quark-quark-gluon vertex
- Colour charge.
- Path integrals of QCD; lattice gauge theory.
- Quark potential model
- Physics beyond the quark model: “QCD effects”.

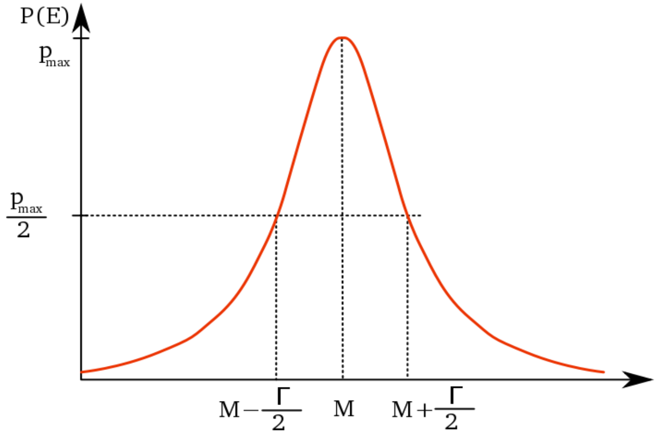
Strong Interactions and QCD

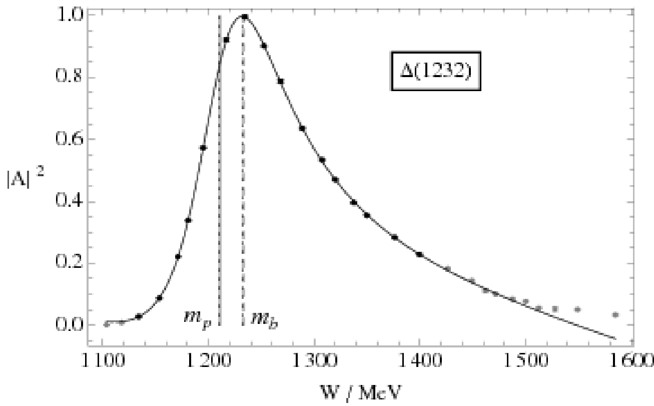
- QCD (Quantum Chromodynamics) is said to be the theory of strong interactions.
- It is said that "The strong interaction is the force that binds protons and neutrons together to form the nucleus." It is also "it is the force that holds quarks together to form protons, neutrons,..".
- Above can be a good popular presentation or motivation of ideas, but not any experimental signature in actual working science, like photon and neutrino detection are for electromagnetic and weak interaction respectively.

Possible definitions of strong interactions in working science.

- If a process is not electromagnetic or weak, it happened through the strong interaction.
- If the interaction time (inversely proportional to the energy width) is $\sim 10^{-23}$ seconds, it happened due to strong interactions.

The Breit-Wigner Distribution: interaction or life time is inversely proportional to (energy) width Γ.

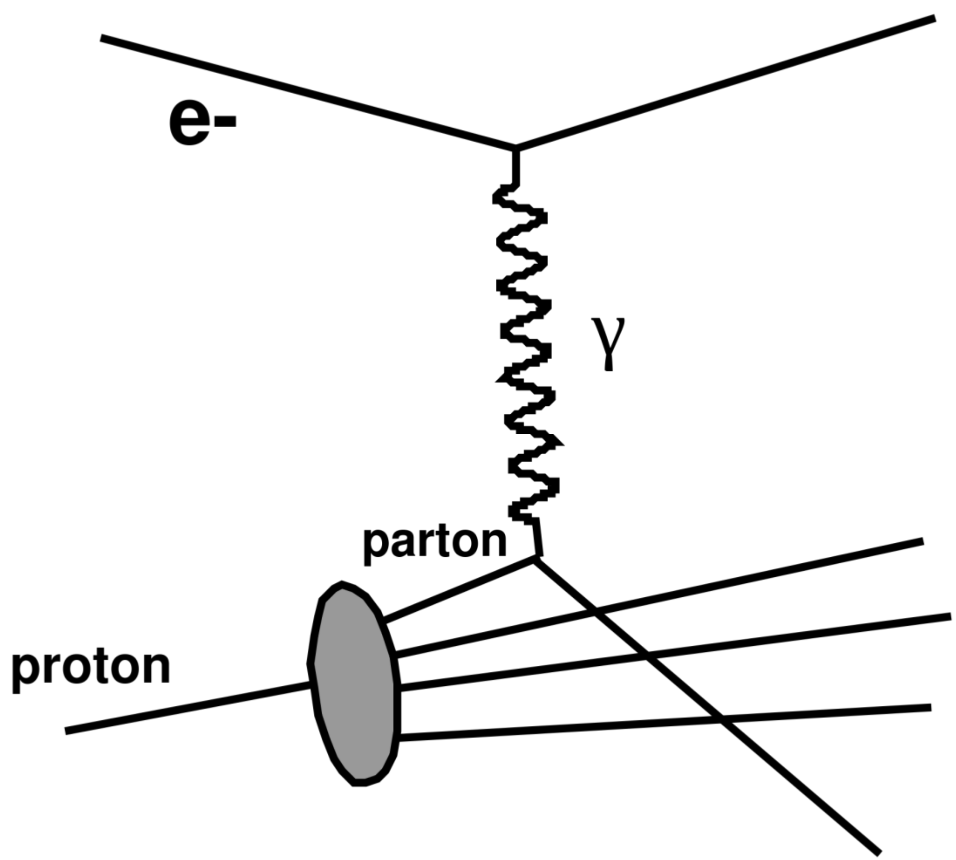




No one-to-one correspondence of processes and theory (QED or QCD)?

- A process, namely electron-proton inelastic scattering (strong or electromagnetic?) is explained with the help of *both* QED and QCD.
- First the simpler explanation (QED) was tried and when that failed to fully understand the relevant experiments, the help turned out to be the theory called Quantum Chromodynamics (QCD).

Parton Model, QED, which was corrected by QCD.

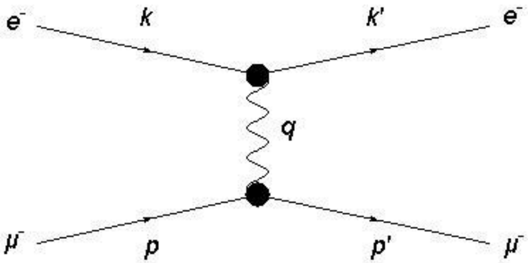


Educational Background:
Simpler e Muon and e proton scatterings

$$S_{fi} = \delta_{fi} + (2\pi)^4 \delta^{(4)}\left(\sum p'_f - \sum p_i\right) \prod_i \left(\frac{1}{2VE_i}\right)^{1/2} \prod_f \left(\frac{1}{2VE'_f}\right)^{1/2} \prod_l (2m_l)^{1/2} \mathcal{M}$$

$$d\sigma = \lim_{T\to\infty} \frac{|S_{fi}|^2}{T} \frac{V}{v_{rel}} \prod_f \frac{V d^3 p'_f}{(2\pi)^3}$$

$$= \frac{1}{4ME} \frac{d^3k'}{(2\pi)^3 2E'} \frac{d^3P'}{(2\pi)^3 2P'_0} \left\{\frac{e^4}{q^4} (L^e)^{\mu\nu} L^{muon}_{\mu\nu}\right\} (2\pi)^4\, \delta^{(4)}(P + q - P').$$

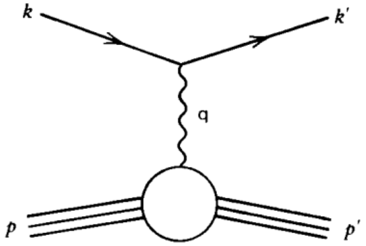


6 Integrations, two Dirac deltas. Net: two integrations.

$$\left(\frac{d\sigma}{dE'\, d\Omega}\right)_{e\mu\to e\mu} = \frac{4\alpha^2 E'^2}{q^4}\left\{\left(Cos^2\frac{\theta}{2} - \frac{q^2}{2m^2} Sin^2\frac{\theta}{2}\right) \delta\left(v + \frac{q^2}{2m}\right)\right\},$$

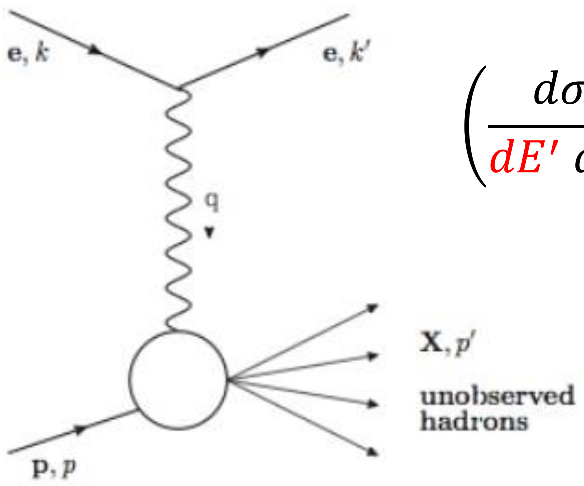
with $\nu = \frac{P.q}{M}$ ($=\frac{P_0 q_0}{M} = k'_0 - k_0 = E' - E$ in the rest frame of target muon).

$$\left(\frac{d\sigma}{dE'\, d\Omega}\right)_{ep\to ep} = \frac{4\alpha^2 E'^2}{q^4}\left\{\left(\frac{G_E^2(q^2) + \tau G_M^2(q^2)}{1+\tau} cos^2\frac{\theta}{2} + 2\tau G_M^2(q^2) sin^2\frac{\theta}{2}\right) \delta\left(v + \frac{q^2}{2M}\right)\right\},$$



$\tau \equiv -q^2/4M^2$; the mass of the target, proton, is now M replacing m for muon.

Inelastic electron-proton scattering



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

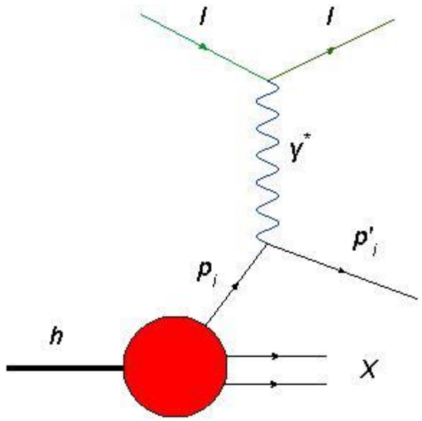
No $\delta^4\left(p^2 - m_0{}^2\right)$ constraint on *X*.

(It was for proton in the elatic case.)

Inelastic form factors *W'*s are functions of two scalar variables that can be constructed from *p* and *q*. Chosen to be q^2 and $\nu = \frac{p.q}{M}$.

The Parton Model Limit: If the struck particle has a rest mass…

- That is, if the scattered particle (other than electron) has some rest mass *m* that is apparently unknown,



$$2W_1^{point}(\nu,Q^2) = \frac{Q^2}{2m^2}\delta\left(\nu - \frac{Q^2}{2m}\right) = \frac{1}{M}\frac{1}{2\omega x^2}\delta\left(1-\frac{1}{x\omega}\right)$$

$$W_2^{point}(\nu,Q^2) = \delta\left(\nu-\frac{Q^2}{2m}\right) = \frac{1}{\nu}\delta\left(1-\frac{1}{x\omega}\right)$$

$Q^2 \equiv -q^2, \omega \equiv \frac{2q.p}{Q^2} = \frac{2M\nu}{Q^2}$ and $(defintion \quad x\equiv \frac{m}{M})$.

But then this constraint *itself* would tell an experimentalist the value of mass m through the equation

$$\frac{p.q}{M} = \nu = \frac{Q^2}{2m}$$

because p is for proton and $q = k' - k$ is experimentally knowable through electron. ($Result\ x = \frac{1}{\omega}$.)

Structure Functions and Momentum Distributions

- (For Bjorken scaling) $\nu W_2^{point}(\nu,Q^2) \equiv F_2(x) \equiv \sum_i e_i^2\, x f_i(x)$

and $MW_1^{point}(\nu,Q^2) \equiv F_1(x)$.

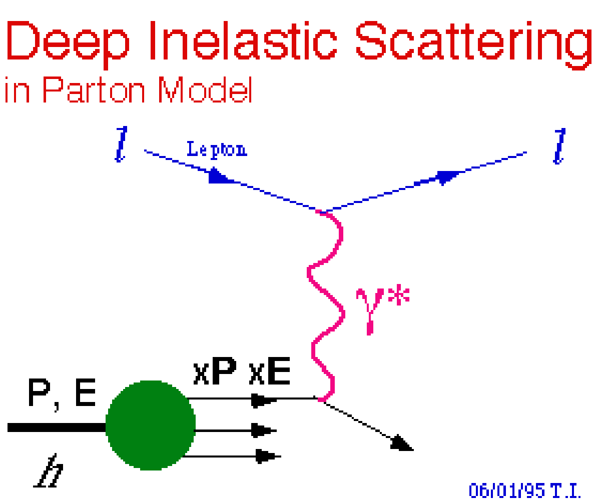
$x = \frac{1}{\omega}$ gives $F_1(x) = \frac{1}{2x}F_2(x)$.

$F_1(x)$ and $F_2(x)$ are dimensionless structure functions of proton.

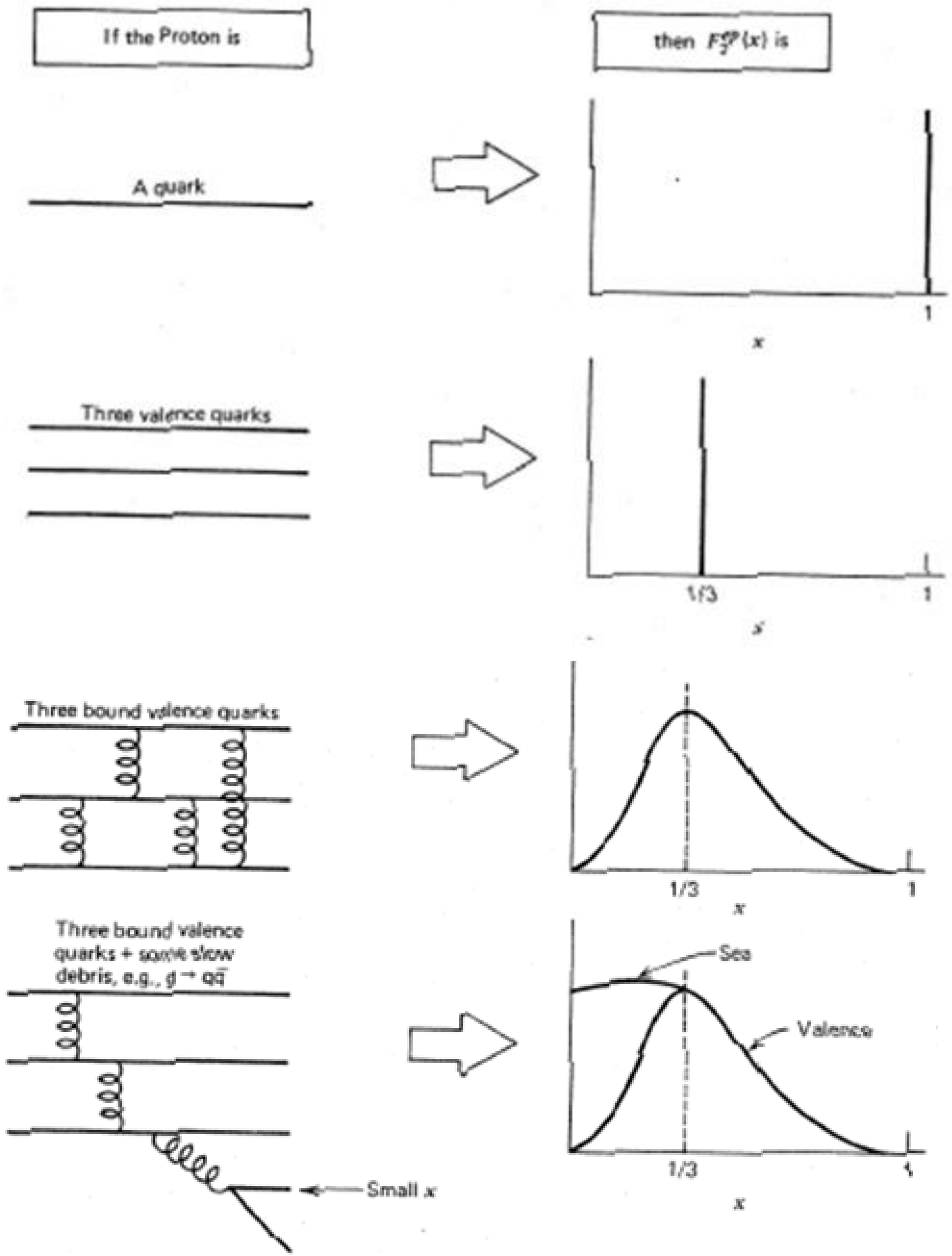
$f_i(x)$ are parton momentum distributions.

$f_i(x)$ is the probability density $\frac{dP_i}{dx}$ that the struck parton *i* carries a fraction *x* of the proton's four momentum *p.*

$$\sum_{i'} \int dx\, x f_{i'}(x) = 1.$$



	Proton		Parton
	↓	↓	
Energy	xE	E	
Momentum	xp_L	p_L	
		$p_T = 0$	$p_T = 0$
Mass		M	$m = (x^2E^2 -$

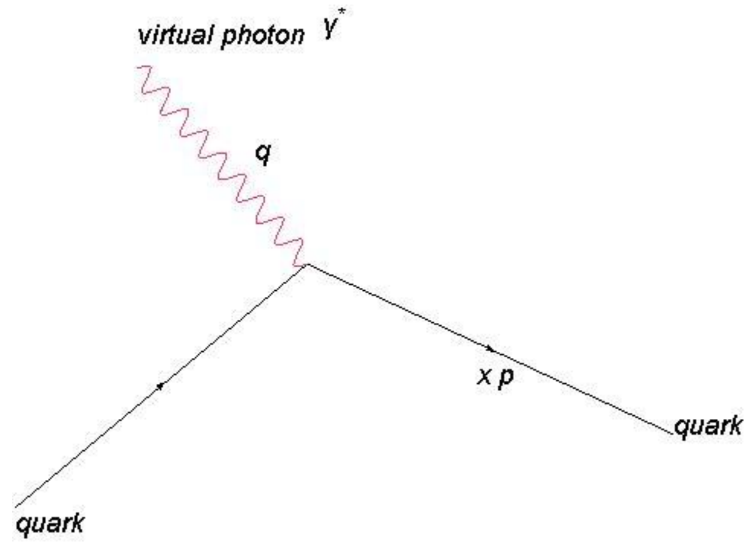


Only QED!

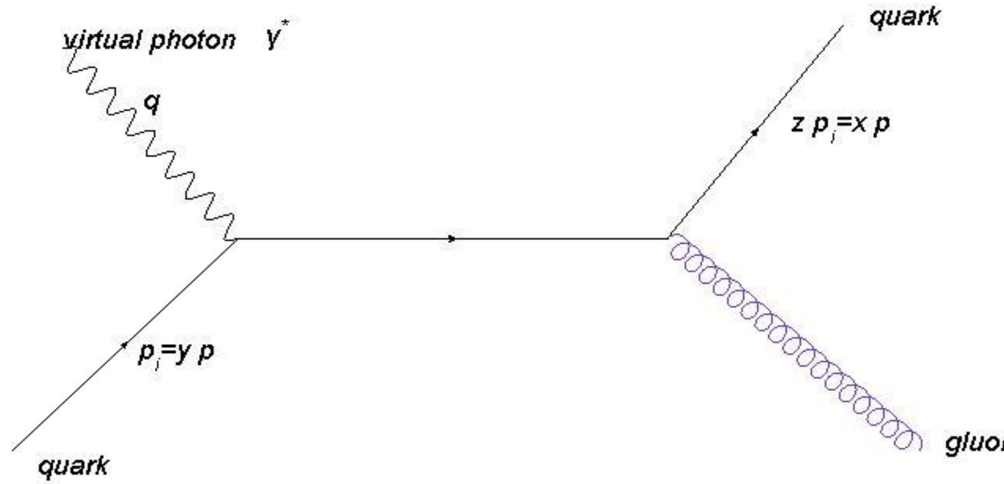
H*ere,* we need QCD!

Bjorken Scaling (a Parton model, QED result) is verified but only approximately; further improvement by QCD

- Changing



to "Compton Scattering"



Writing in terms of “cross-sections”

- $\sigma^{tot}(\gamma p \to X) = \frac{4\pi^2\alpha}{K}\varepsilon^{\mu *}\varepsilon^{\nu}W_{\mu\nu}$

with $W_{\mu\nu}$ being the hadronic tensor in $d\sigma \sim L^{e}_{\mu\nu}W^{\mu\nu}$. For real photons, sum over two transverse polarizations of the incident photon.

$\sigma_{\lambda}^{tot} = \frac{4\pi^2\alpha}{K}\varepsilon_{\lambda}^{\mu *}\varepsilon_{\lambda}^{\nu}W_{\mu\nu}$ for virtual photons as well.

$$\sigma_T = \frac{1}{2}(\sigma_{+}^{tot} + \sigma_{-}^{tot}) = \frac{4\pi^2\alpha}{K}W_1(\nu, Q^2)$$

$$\sigma_L = \sigma_0^{tot} = \frac{4\pi^2\alpha}{K}\left[\left(1 + \frac{\nu}{Q^2}\right)W_2(\nu, Q^2) - W_1(\nu, Q^2)\right]$$

In the deep inelastic limit, $2F_1 = 2MW_1 = \frac{\sigma_T}{\sigma_0}$ and $\frac{F_2}{x} = \nu\frac{W_2}{x} = \frac{\sigma_T + \sigma_L}{\sigma_0}$.

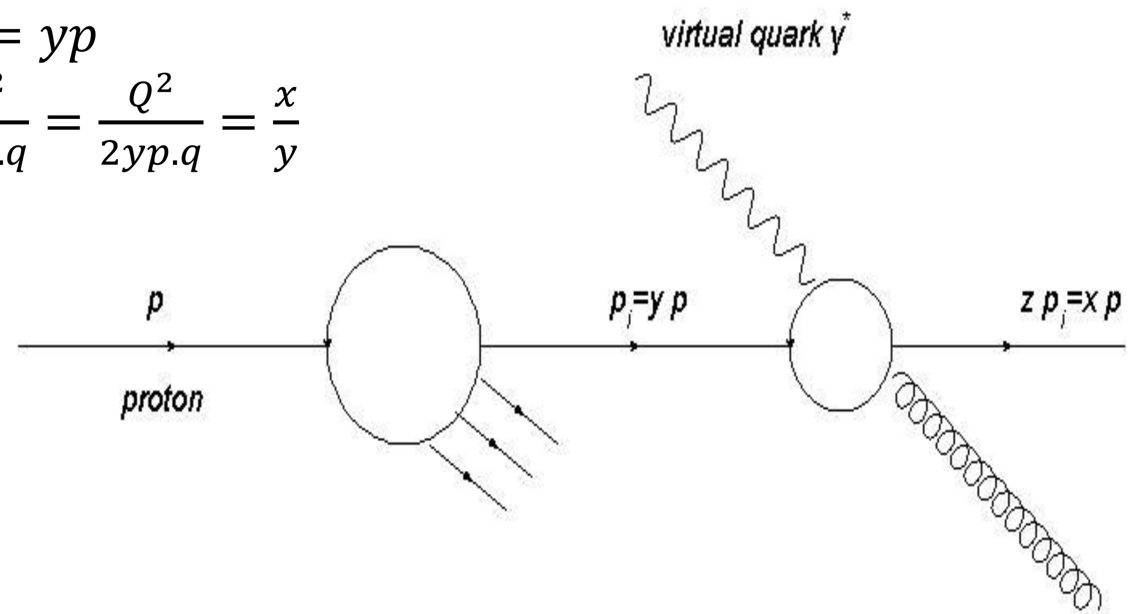
Proton and Partons

- $\left(\frac{\sigma_T(x,Q^2)}{\sigma_0}\right)_{\gamma^* p} = \sum_i \int_0^1 dz \int_0^1 dy f_i(y)\delta(x - zy)\left(\frac{\hat{\sigma}_T(z,Q^2)}{\sigma_o}\right)_{\gamma^* i}$

γ^*−proton frame $\quad$ γ^* − parton frame

$p \qquad p_i = yp$

$x = \frac{Q^2}{2p.q} \qquad z = \frac{Q^2}{2p_i.q} = \frac{Q^2}{2yp.q} = \frac{x}{y}$

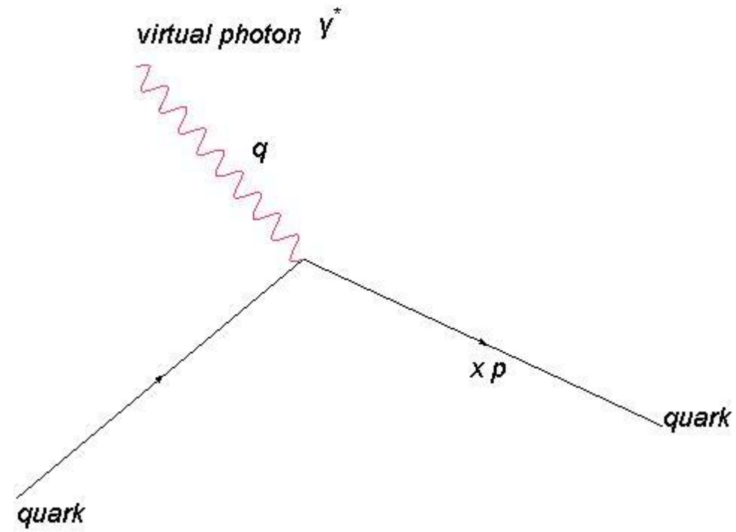


$$\left(\frac{\sigma_T(x,Q^2)}{\sigma_0}\right) = \sum_i \int_x^1 \frac{dy}{y} f_i(y)\left(\frac{\hat{\sigma}_T(x/y,Q^2)}{\hat{\sigma}_0}\right).$$

Virtual "Cross-Sections" in the Parton Model Limit

Neglecting the mass of the outgoing quark i.e. $(q + p_i)^2 = 0$

$z = \frac{Q^2}{2p_i.q} = 1.$

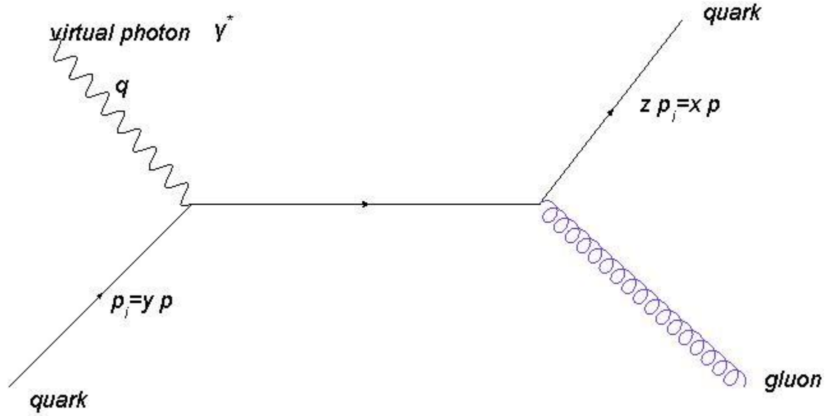


$$\frac{\hat{\sigma}_T\,(z, Q^2)}{\sigma_0} = e_i^2 \delta(1 - z)$$

Bjorken scaling

$$\frac{F_2(x,Q^2)}{x} = \frac{\sigma_T(x,Q^2)}{\sigma_0} = \sum_i e_i^2 \int_x^1 \frac{dy}{y} f_i(y) \delta\left(1 - \frac{x}{y}\right) = \sum_i e_i^2 f_i(x).$$

Modification to Virtual Differential Cross-Sections by Gluon Scattering



- For (Compton) $\gamma^* e \rightarrow \gamma e$

$\overline{|\mathcal{M}|^2}=32\pi^2\alpha^2\left(-\frac{u}{s}-\frac{s}{u}+\frac{2tQ^2}{su}\right).$

- For $\gamma^* q \rightarrow gq$

$\overline{|\mathcal{M}|^2}=32\pi^2(e_i{}^2\alpha\alpha_s)\frac{4}{3}\left(-\frac{\hat{t}}{\hat{s}}-\frac{\hat{s}}{\hat{t}}+\frac{2\hat{u}Q^2}{\widehat{s\hat{t}}}\right)$

with $\hat{s}= x\ s, \hat{u}= x\ u$ and $\hat{t}=t.$

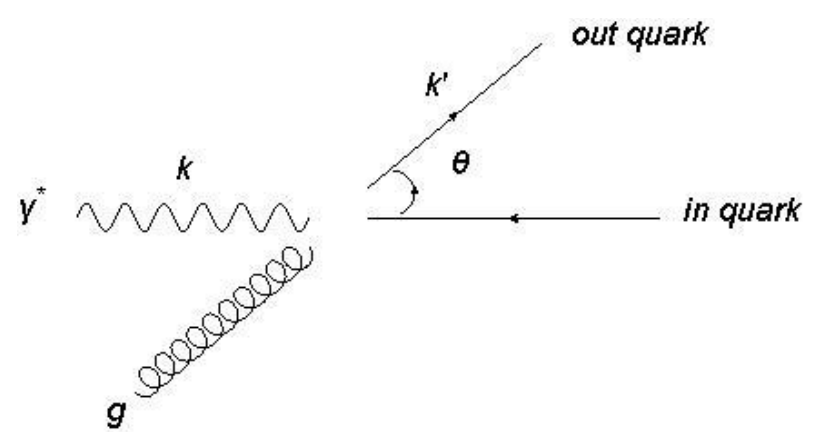
$p_T^2=\frac{\hat{s}\hat{t}\hat{u}}{(\hat{s}+Q^2)^2}$, $\quad d\Omega=\frac{4\pi}{\hat{s}}dp_T^2$

$\frac{\hat{s}}{4\pi}\frac{d\hat{\sigma}}{d\Omega}=\frac{d\hat{\sigma}}{dp_T^2}=\frac{1}{16\pi\hat{s}^2}\overline{|\mathcal{M}|^2}=\frac{8\pi e_i{}^2\alpha\alpha_s}{3\hat{s}^2}\left(\frac{1}{-\hat{t}}\right)\left[\hat{s}+\frac{2(\hat{s}+Q^2)Q^2}{\hat{s}}\right]=\frac{1}{p_T^2}e_i{}^2\hat{\sigma}_0\frac{\alpha_s}{2\pi}P_{qq}(z)$

$\hat{\sigma}\ (\gamma^* q \rightarrow\ gq)=\int_{\mu^2}^{\frac{\hat{s}}{4}}dp_T^2\frac{d\hat{\sigma}}{dp_T^2}=e_i{}^2\hat{\sigma}_0\left(\frac{\alpha_s}{2\pi}P_{qq}(z)\log\frac{Q^2}{\mu^2}\right)$

with $z=\frac{Q^2}{2p_i.q}=\frac{Q^2}{(p_i+q)^2+Q^2}=\frac{Q^2}{\hat{s}+Q^2}$

and $\quad P_{qq}(z)=\frac{4}{3}\left(\frac{1+z^2}{1-z}\right).$



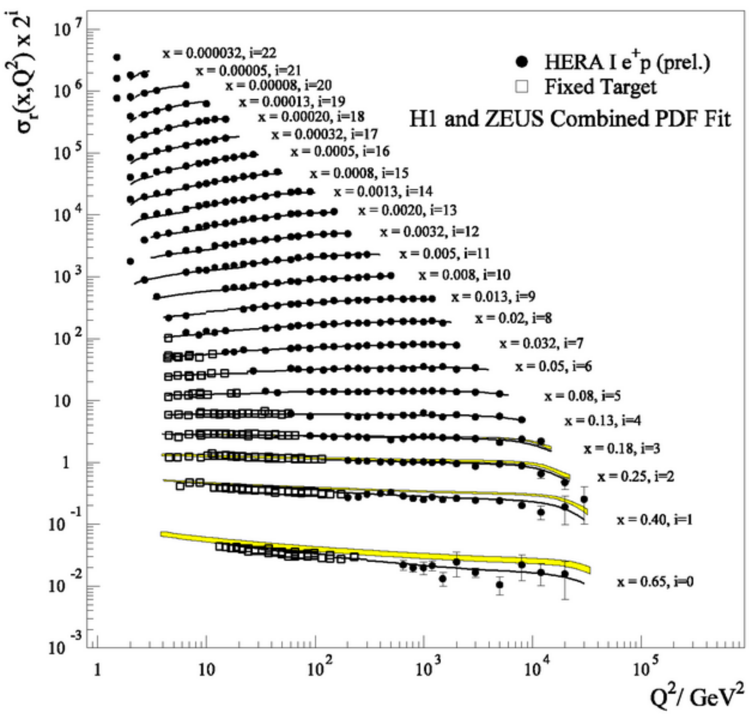
Modification to Virtual (Total) Cross-Sections by Gluon Scattering

- $\hat{\sigma}(\gamma^* q \to gq) = {e_i}^2 \hat{\sigma}_0 \left(\frac{\alpha_s}{2\pi} P_{qq}(z) \log \frac{Q^2}{\mu^2}\right)$

with a cutoff μ used to regularize some infra-red divergence.

Adding this to parton $\frac{\hat{\sigma}(z,Q^2)}{\sigma_0} = e_i^2 \delta(1-z) = e_i^2 \delta\left(1-\frac{x}{y}\right)$ gives

$$\frac{F_2(x,Q^2)}{x} = \frac{\sigma_T(x,Q^2)}{\sigma_0} = \sum_i e_i^2 \int_x^1 \frac{dy}{y} f_i(y) \left[\delta\left(1-\frac{x}{y}\right) + \right.$$

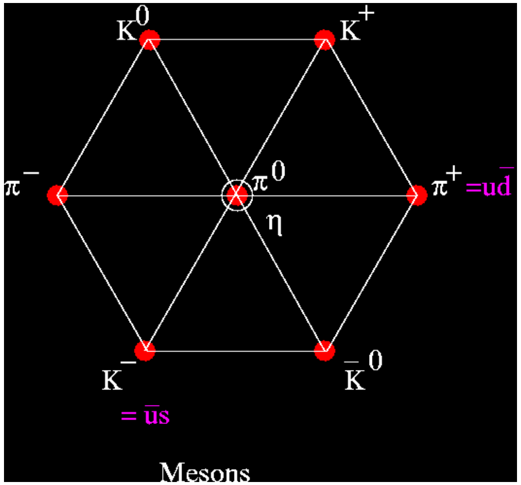


QCD was used in above…

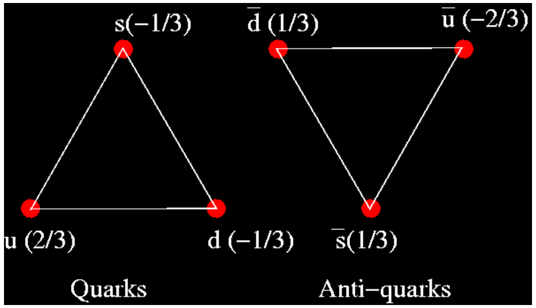
- to replace α by $(\alpha\alpha_s)\frac{4}{3}$

This means: a possibly different value of charge and different number of charges.

These are properties of quarks and quarks where earlier used for a static model of hadrons.

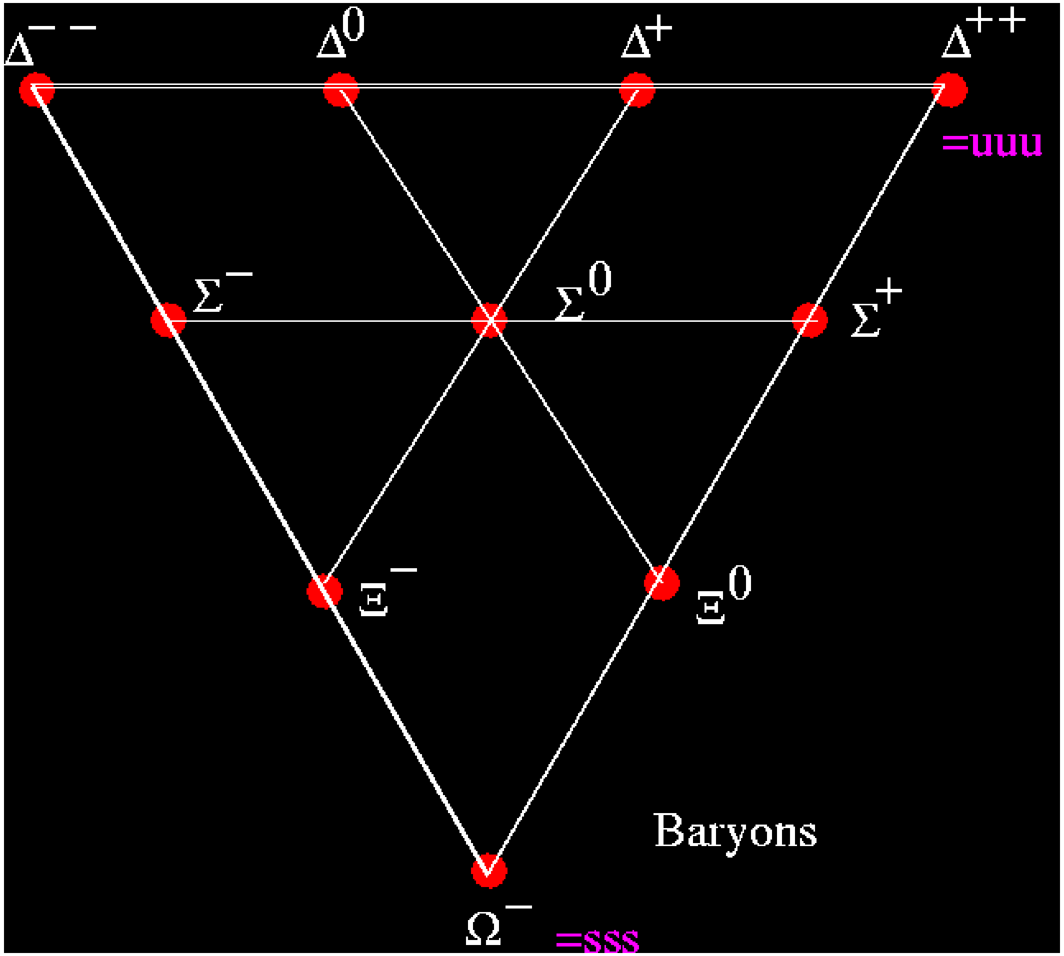


With $$8 \oplus 1 = 3 \otimes \overline{3}$$



$\pi^- + p \rightarrow K^0 + \Lambda^0$ explained as $d\bar{u} + uud \rightarrow d\bar{s} + sud$

Early problems,
3 identical Fermions….

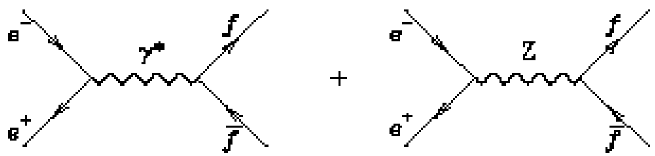


Colour Degree of Freedom…

$$\sigma_0 = \frac{4\pi\alpha^2}{3s} \cdot \sum_{\text{color}} \cdot \sum_f e_f^2 = \frac{4\pi\alpha^2}{3s} \cdot 3 \sum_f e_f^2 \qquad \sigma_0 = \frac{4\pi\alpha^2}{3Q^2} \sum_q e_q^2; \qquad R = \frac{\sigma(e^+e^- \to q\bar{q})}{\sigma(e^+e^- \to \mu^+\mu^-)} = \sum_q e_q^2 = \frac{2}{3}$$

Motivation for Colour SU(3)

- Consider the ratio R of the e^+e^- total hadronic cross section to the cross section for the production of a pair of point-like, charge-one objects such as muons.
- The virtual photon excites all electrically charged constituent-anticonstituent pairs from the vacuum.



- At low energy the virtual photon excites only the u, d and s quarks, each of which occurs in three colours.

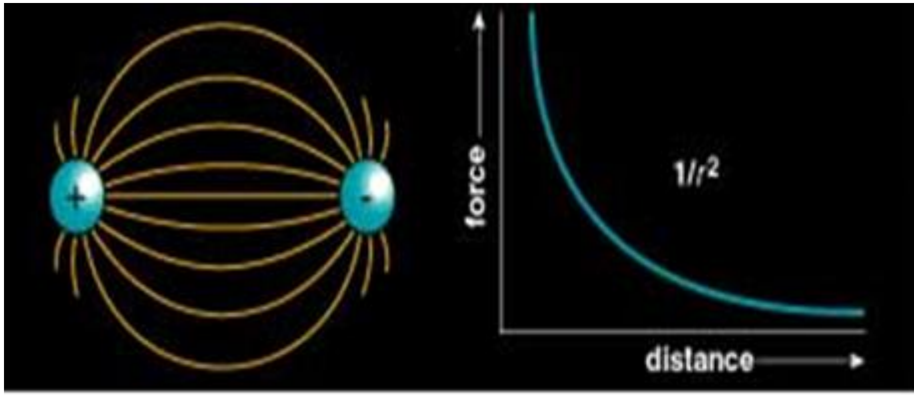
$$\begin{aligned} R &= N_c \sum_i Q_i^2 \\ &= 3\left[\left(\frac{2}{3}\right)^2 + \left(-\frac{1}{3}\right)^2 + \left(-\frac{1}{3}\right)^2\right] = 2\,. \end{aligned}$$

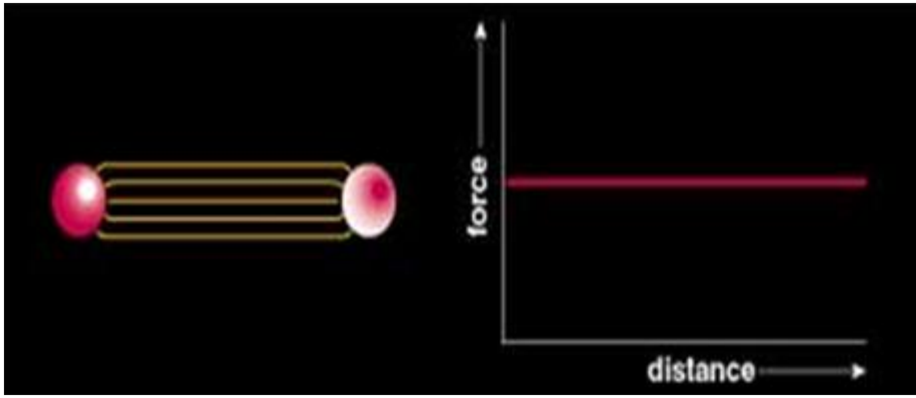
- For centre-of-mass energies $E_{\text{cm}} \geq 10$ GeV, one is above the threshold for the production of pairs of c and b quarks, and so

$$R = 3\left[2 \times \left(\frac{2}{3}\right)^2 + 3 \times \left(-\frac{1}{3}\right)^2\right] = \frac{11}{3}\,.$$

Electric Field and Colour (Chromo) Fields.

- The electric field spreads.
- The colour field glues and hence forms *flux tubes*.
- Each term in the Fourier Series for the electric field is a *photon.*
- Similarly, the colour field is composed of gluons.
- Both photons and gluons have zero rest mass, but gluons carry colour charge and self-interact (glue).
- Confinement: Free quarks can not be detected.





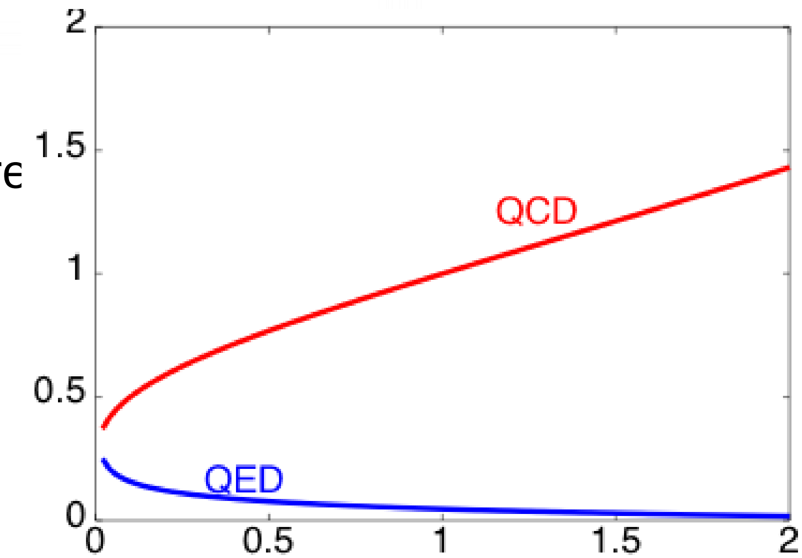
QCD; problems with Lagrangian and Perturbative expansion

$$\mathcal{L}_{QCD} = -\frac{1}{4} F^B_{\alpha\beta} F^{B,\alpha\beta} + \sum_f \bar{q}_{f,a} \left(i D_\mu \gamma^\mu - m_f \right)_{ab} q_{f,b}$$

$$F^B_{\alpha\beta} = \left[\partial_\alpha G^B_\beta - \partial_\beta G^B_\alpha - g f^{BCD} G^C_\alpha G^D_\beta \right].$$

Leads to Feynman diagrams.

But for our number of flavours, g and its square increases for lower momentum transfers eventually making theory unsolvable for the usual hadronic physics of spectroscopy and decays.



$$\alpha_s(|q^2|) = \frac{\alpha_s(\mu^2)}{1 + (\alpha_s(\mu^2)/12\pi)(11n - 2f)\ln(|q^2|/\mu^2)}$$

How can you calculate with large coupling….

The *S*-matrix expansion in powers of coupling or H_I

$$S = \sum_{n=0}^{\infty} \frac{(-i)^n}{n!} \int \dots \int d^4x_1\, d^4x_2 \dots d^4x_n\, T\{\mathscr{H}_1(x_1)\mathscr{H}_1(x_2)\dots\mathscr{H}_1(x_n)\}, \quad (6.23)$$

can be written as

$$S = T \exp\left[-i \int d^4x\, \mathcal{H}_I(x)\right]$$

Path Integrals..

$$< f|i > = \int [dx(t)] e^{iS/\hbar} = \int \left(\prod dx_i\right) e^{iS/\hbar}$$

In scalar field theory

$$\langle 0 | \, T\phi(x_1)\phi(x_2)\ldots\phi(x_n) \, |0\rangle = \frac{1}{Z}\int \mathcal{D}\phi \, e^{iS[\phi]}\phi(x_1)\phi(x_2)\ldots\phi(x_n)$$

In QCD, scalar field $\phi(x)$ is replaced by colour *i'*d field $\psi_i(x)$ and the gluonic field $A^a_\mu(x)$.

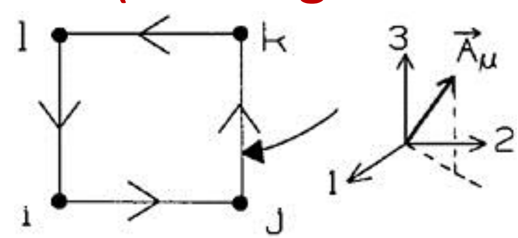
$$\langle 0|T\{\psi(x_1),\bar{\psi}(x_2)\}|0\rangle = \left(\frac{1}{Z}\right)\int d[\bar{\Psi}\Psi A_\mu]\psi(x_1)\bar{\psi}(x_2)e^{iS_0} \; ,$$

In lattice QCD, a pure gluonic Euclidean (imaginary time) path integral (using *adiabatic approximation*) with $U(x, x+\epsilon n) = \exp\left[ie\epsilon n^\mu A_\mu(x)\right]$

is an expectation value. Imaginary time; Wick's rotation (of integration limits.

$$S_{QCD} = S_G[U] + S_F^{(W)}[U,\psi,\bar{\psi}],$$

$$\langle O\rangle = \frac{\int DU O(U) e^{-S(U)}}{\int DU e^{-S(U)}} \qquad S_G = \frac{6}{g_0^2}\sum_P [1 - \frac{Tr}{6}(U_P + U_P^\dagger)],$$



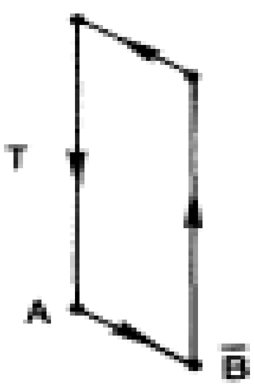
$$S = \frac{\beta}{N_c}\sum_{x,\mu>\nu}\left(N_c - \mathrm{Tr}\,\Box_{\mu\nu}(x)\right) \quad \Rightarrow \quad \beta = \frac{2N_c}{g_0^2}.$$

to get an agreement with an integral of $\frac{1}{2}F_{\mu\nu}F_{\mu\nu}$.

The strong coupling expansion
in inverse coupling
β, though bare.

Confinement "derived" in the strong coupling limit.

Quantum Mechanics ("Quarks, Gluons and Lattices" by Creutz)
$Z=\int[dx]e^{-S}=Tr(..e^{-\text{Time Hamiltonian}})$



In the expectation value $\sum_n O_n P_n$ an operator $O(U)$ for $Q\overline{Q}$ time evolution.

$$\langle O\rangle = \frac{\int DU\, O(U) e^{-S(U)}}{\int DU\, e^{-S(U)}}$$

The expectation value itself is called a Wilson loop.

For the simplest Wilson loop
$W(R,T)=e^{-\text{Energy(R)Time}}$ for time→∞.
In the strong coupling limit,
Energy is proportional to the $Q\overline{Q}$ separation; QCD (Bosonic) Strings

But in the continuum limit of zero lattice spacing , bare inverse coupling β is not small;
we need a calculational procedure valid for all β.

- Lattice numerical evaluation of the path integral

$$\langle O \rangle = \frac{\int DU O(U) e^{-S(U)}}{\int DU e^{-S(U)}}$$

with *importance sampling* of this sharply peaked integrand, can be performed for all values of g and energies.

Numerical Simulations of QCD

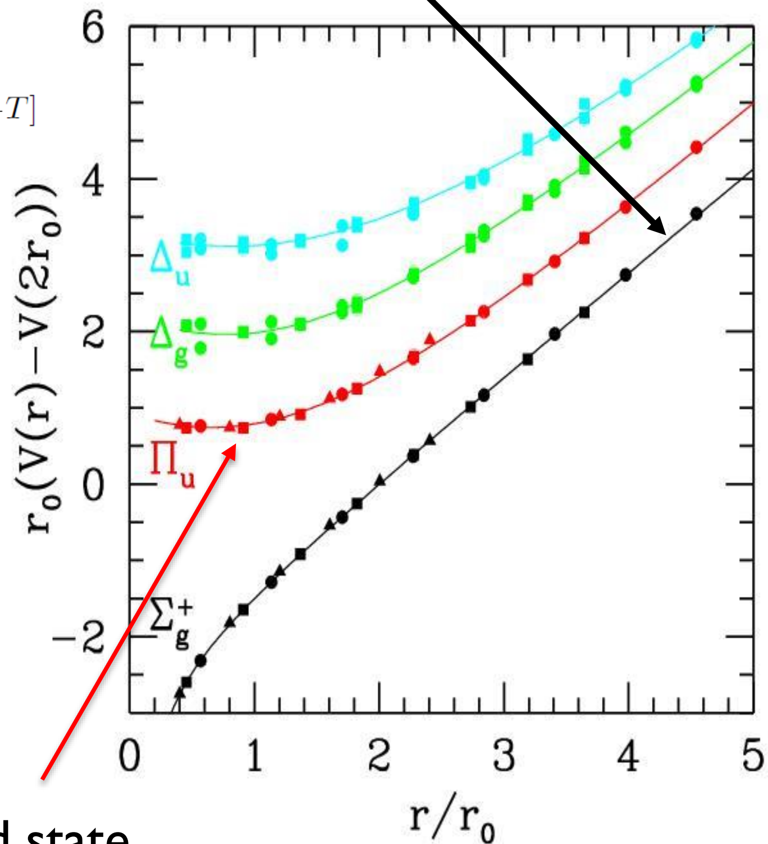
Gluonic ground state energy (black curve) fitted by optimum values of the *quark potential model parameters* α_s , *b*, σ and m_c .

$$V_{q\overline{q}}(r) = \frac{-4\alpha_s}{3r} + br + \frac{32\pi\alpha_s}{9m_c^2}(\frac{\sigma}{\sqrt{\pi}})^3 e^{-\sigma^2 r^2}\overrightarrow{S}_c.\overrightarrow{S}_{\overline{c}} + \frac{1}{m_c^2}[(\frac{2\alpha_s}{r^3} - \frac{b}{2r})\overrightarrow{L}.\overrightarrow{S} + \frac{4\alpha_s}{r^3}T]$$

Quark potential model extension to hybrids (mesons with excited gluonic field).

$$V^h_{q\overline{q}}(r) = V_{q\overline{q}}(r) + V_g(r)$$

Energy of the ground state color field vs q qbar separation



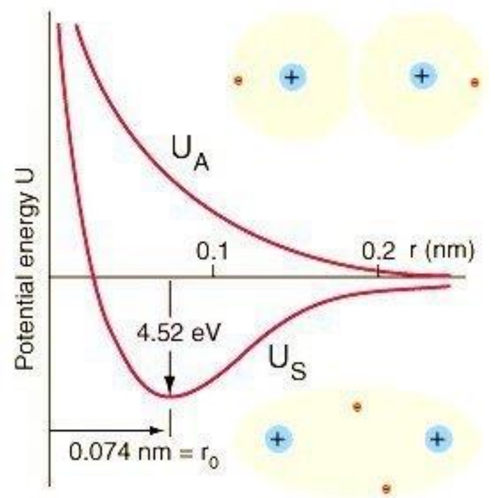
Energy of the excited state color field vs q qbar separation

Quark Model as an approximation to QCD

- In retrospect, quark model is an approximation to QCD in which all the properties of the hadrons are understood in terms of only quark properties; one potential for one $Q\overline{Q}$ separation is in quark model.

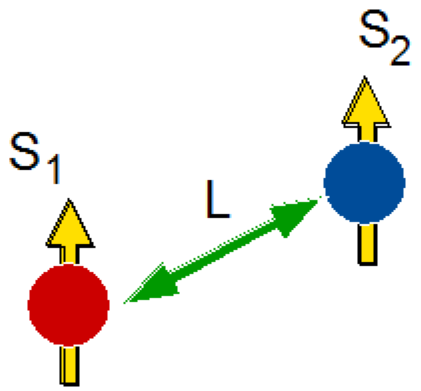
- This can be compared with Adiabatic approximation in molecular physics, where the all properties of a system of nuclei and electrons are understood in terms of properties of the nuclei only, with electron cloud giving an effective potential between nuclei, etc.

- But see the figures above and on the right.



Quark Model (understanding of) Mesons

and its failure.



Spin: $S=S_1+S_2=(0,1)$

Orbital Angular Momentum: L=0,1,2,…

Total Spin: J=L+S

L=0, S=0 : J=0   L=0, S=1 : J=1

L=1 , S=0 : J=1   L=1, S=1 : J=0,1,2

…   …

$P = (-1)^{L+1}$

$C = (-1)^{L+S}$

allowed combinations

$\Rightarrow J^{PC} = 0^{-+}\ 0^{++}\ 1^{--}\ 1^{+-}\ 2^{++} \ldots$

not-allowed combinations

$\Rightarrow J^{PC} = 0^{--}\ 0^{+-}\ 1^{-+}\ 2^{+-} \ldots$

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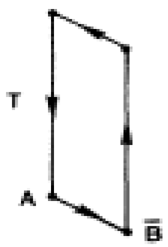
Four-quark flux distribution and binding in lattice SU(2)

antiquark at separation R. When the plaquette is located at $t=T/2$ in the μ-ν plane, the following expression isolates, in the limit $T\rightarrow\infty$, the contribution of the color field at position $\mathbf{r}$:

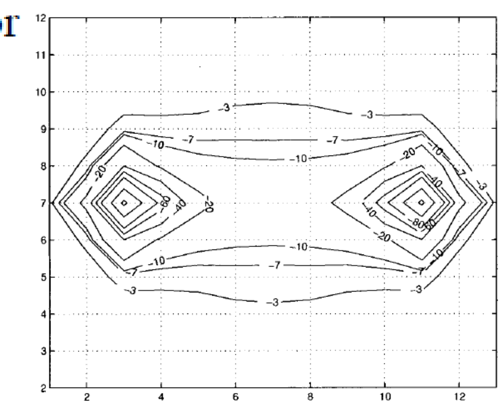


$$f_R^{\mu\nu}(\mathbf{r})=\left[\frac{\langle W(R,T)\square_{\mathbf{r}}^{\mu\nu}\rangle-\langle W(R,T)\rangle\langle\square^{\mu\nu}\rangle}{\langle W(R,T)\rangle}\right]. \quad (2.1)$$

$$\langle O\rangle = \frac{\int DU\, O(U) e^{-S(U)}}{\int DU\, e^{-S(U)}}$$

Here $\langle\square\rangle$ is taken in the gauge vacuum. Like all the other expectation values, it is averaged over all lattice sites.

In the naive continuum limit these contributions are related to the mean squared fluctuation of the Minkowski color fields by



$$f_R^{ij}(\mathbf{r})\rightarrow -\frac{a^4}{\beta}B_k^2(\mathbf{r})$$

$$\text{with } i,\ j,\ k \text{ cyclic} \quad \text{and} \quad f_R^{i4}(\mathbf{r})\rightarrow\frac{a^4}{\beta}E_i^2(\mathbf{r}). \quad (2.2)$$

3. Y-type Flux-Tube Formation in Lattice QCD

Recently, as a clear evidence for Y-Ansatz, Y-type flux-tube formation is actually observed in the maximally-Abelian projected QCD from the direct measurement for the action density of the gluon field in the spatially-fixed 3Q system.[20,21,22] (See Fig.5)

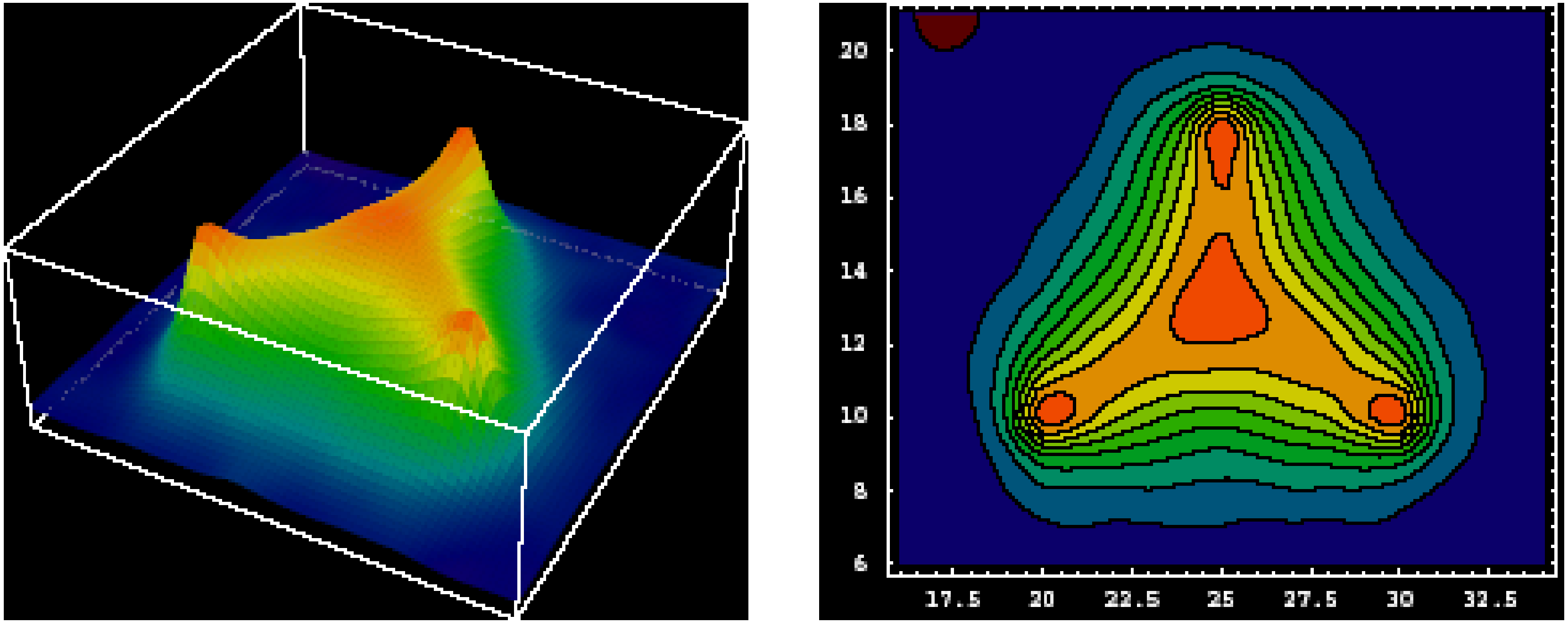
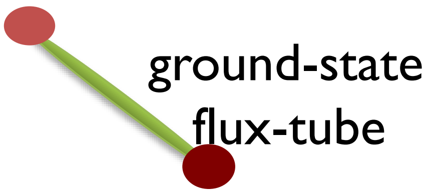
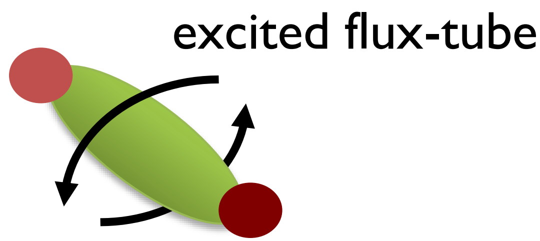


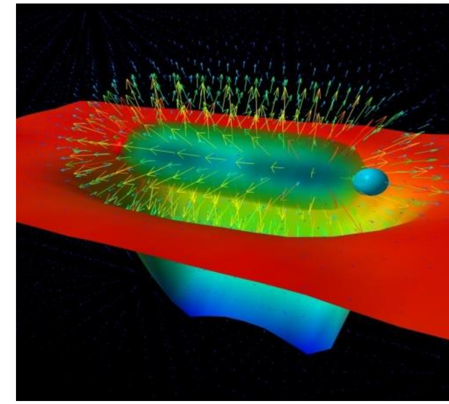
Figure 5. The lattice QCD result for Y-type flux-tube formation in the spatially-fixed 3Q system in maximally-Abelian projected QCD. The distance between the junction and each quark is about 0.5 fm.

Possible Physics
Beyond the Quark Model: “QCD effects”



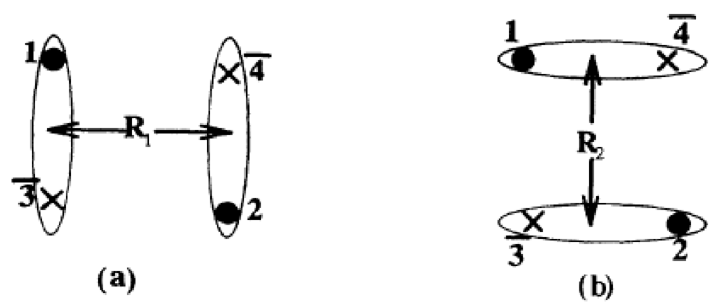
I-Hybrids (the gluonic field in an excited state)





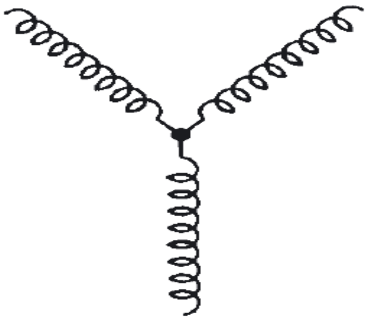
Only quark position is not sufficient
To specify the state

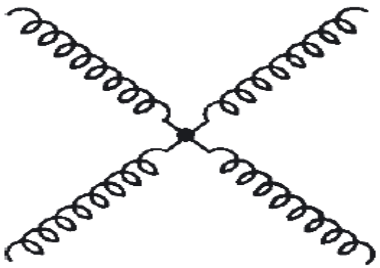
II-Multiquarks



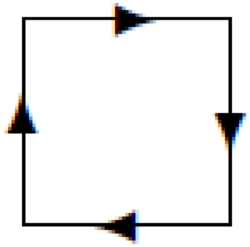
III-Glueballs (bound states of purely gluonic field)

Often understood as





But perturabative concept of gluons is not valid for the usual hadronic physics. Better understanding can be the lattice (gluonic *field)* plaquette with no quark

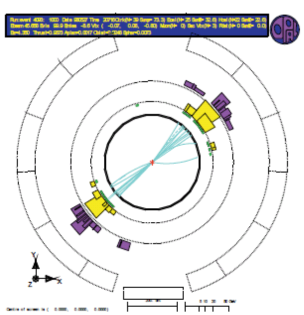


- In the Flux Tube (vibrating string with quantized modes) Model, these are modeled as closed strings.

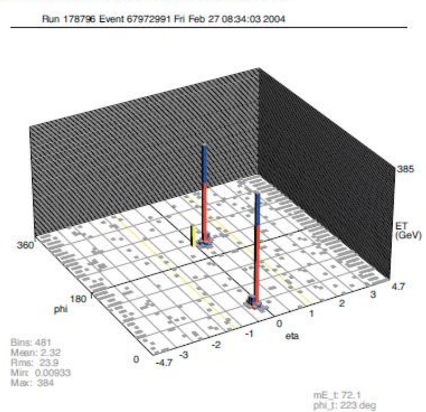
Continued: QCD effects ? (possibly not for two jets, if the description is in terms of quarks only….)

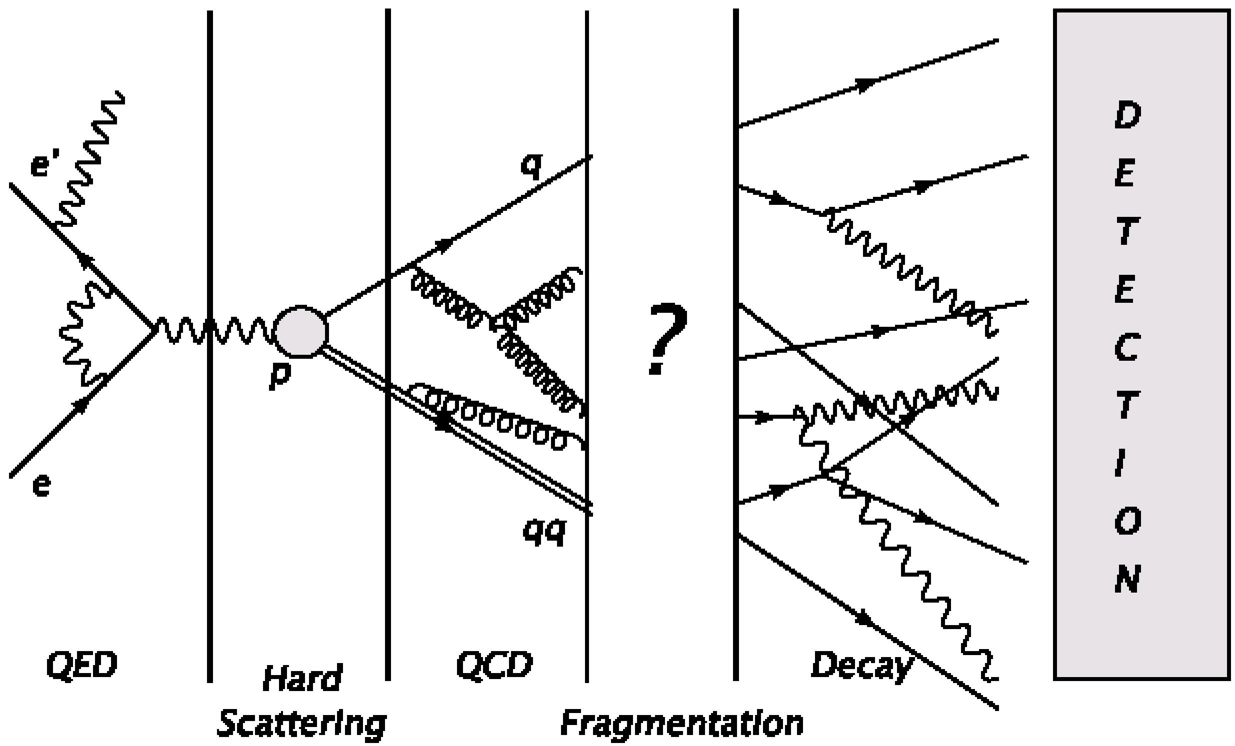
- Jets: Quarks and gluons do not reach detector but only hadrons….

For e^+e^-:



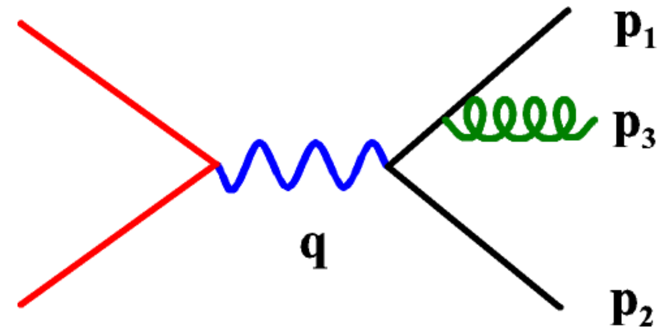
And in nucleon-nucleon collisions:

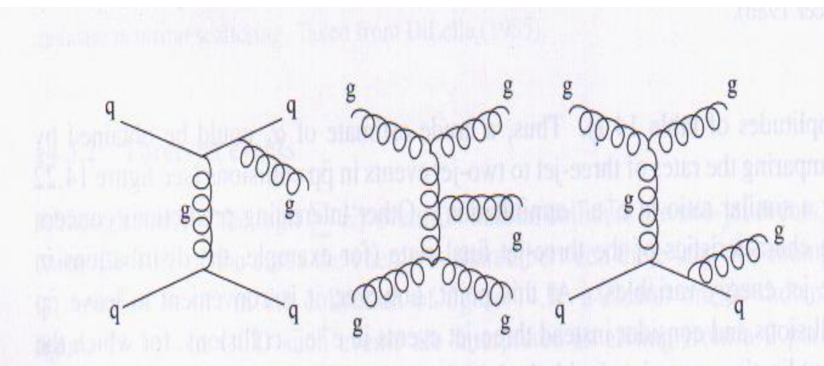


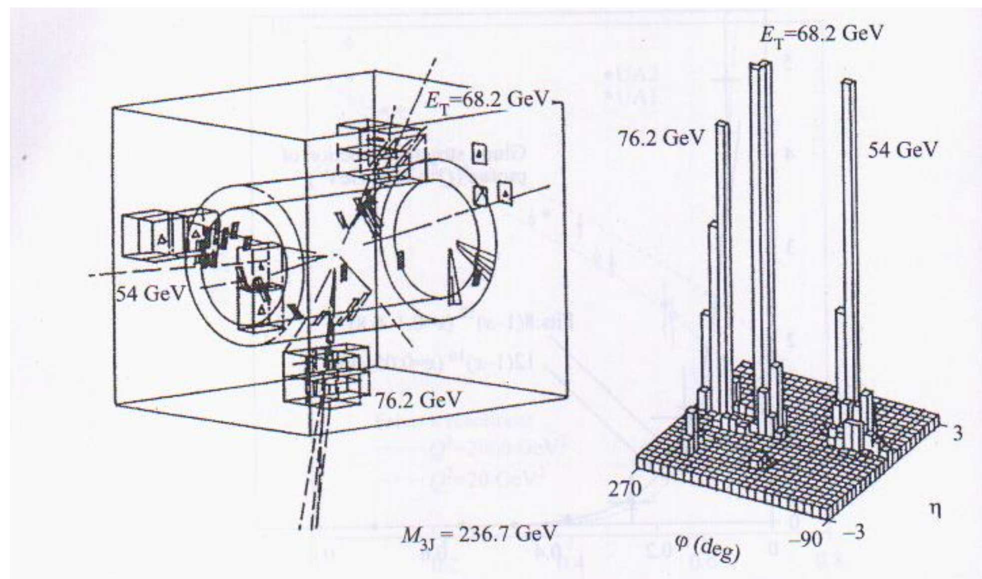


Clearly QCD Effects: Gluon vertices

Meaning three jet events in addition to the two-jet events expected (?) from the quark model



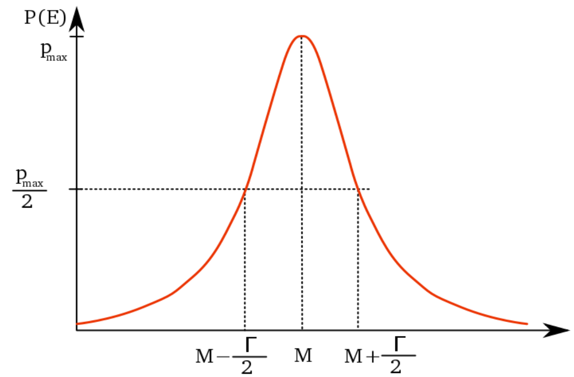


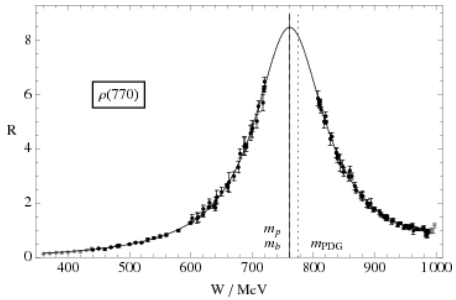


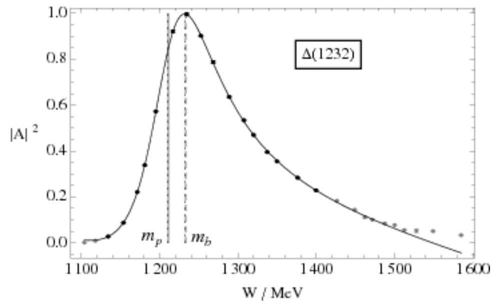
Defining mass and interaction time

- $M^2c^4 = E^2 - p^2c^2$

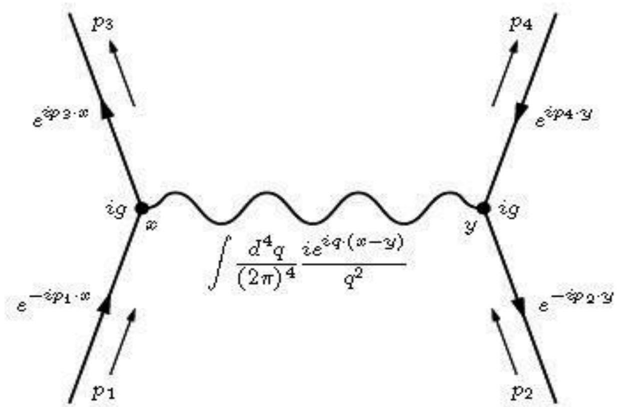
The Breit-Wigner Distribution: interaction or life time is inversely proportional to (energy) width Γ.







In theoretical physics, the masses *M* are predicted to be poles of the propagators:



$$\frac{Z\, f(q)}{q^2 - M^2}$$