Introduction / Overview

This course is basically an introduction to the SM of particle physics and its phenomenology. We'll start out today with an overview of the particles + forces, mentioning briefly some characteristics of each. We'll throw in some miscellaneous topics at a superficial level, including a summary of current and future HEP experiments. This is the "back-of-the envelope" section.

Following the intro. material we'll begin the serious stuff w/ a lightning review of relativistic kinematics and gauge invariance in classical electromagnetism. Then non-relativistic QM follows EM in as we work our way up to QED.

Standard Model of Particle Physics

SM of elementary particle interactions as we know them is described by the gauge theories

$$\underset{\substack{\nearrow \\ \text{Strong}}}{SU(3)_c} \times \underbrace{\underset{\substack{\uparrow \\ \text{Weak}}}{SU(2)_L} \times \underset{\substack{\uparrow \\ \text{EM}}}{U(1)}}_{\text{Electroweak}}$$

where SU(3) etc are the gauge groups that specify the interactions.

Particle Content:

① Matter particles : fundamental fermions (spin 1/2)

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L \quad e_R, \mu_R, \tau_R \; \Big\} \text{ leptons}$$

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \begin{pmatrix} c \\ s \end{pmatrix}_L \begin{pmatrix} t \\ b \end{pmatrix}_L \quad u_R, \dots t_R \; \Big\} \text{ quarks}$$

(The grouping in doublets refers to weak interactions; more on that later.)

The matter content is determined empirically.

(2) Force particles: Gauge bosons
(spin 1)

The beauty of gauge theory (actually one of the many beauties of gauge th.) is that

> Once the gauge group is specified, the mediators ("gauge bosons") and their interactions are completely determined.

The gauge bosons correspond to the members of the adjoint representation of the Lie algebra corresp. to the gauge group, + interactions (amongst themselves) are given by the commutation relations for the Lie algebra.

Interactions of the gauge bosons with the matter particles are determined by the requirement that the Lagrangian for the matter fields be unchanged under local gauge tranformations.

(So far, buzzwords. We'll see how it works later.)

N.B. Gauge invariance requires that the gauge bosons be massless. They're also vector fields, and hence spin 1.*

So, the gauge bosons are:

- EM force : γ
  $U(1)$: single generator $\Rightarrow$ 1 gauge boson

- Weak force : $W^{\pm}$, Z^0
  $SU(2)$: Three generators $\Rightarrow$ 3 gauge bosons
  N.B. $M_W \simeq 79$ GeV ?? see below
  $M_Z \simeq 90$ GeV

- Strong force : gluons (8 of them)
  $SU(3)$: 8 generators $\Rightarrow$ 8 colored gauge bosons

③ Leftover particle(s) from mass generation (spin 0)

Higgs boson

Not yet seen, but expect $\underset{\uparrow\ \text{expt.}}{\overset{\overset{\cancel{109}\ 114}{\cancel{64}}}{\cancel{98}}}\ \text{GeV} \le M_H \underset{\uparrow\ \text{theory}}{\lesssim} 1\ \text{TeV}$

as of 2002: Maybe hint at LEP near upper limit

* Gravitons are spin 2 but gravity is special (+ not well understood by me) + we'll ignore it.

SM parameters

6 quark masses

6 lepton masses

4 CKM param's λ A ρ η [illegible] running + Λ

3 gauge coupling constants g, g', g_s

(equivalently, α_{EM}, $\sin^2\theta_W$, α_s)

1 Higgs vacuum expectation value v

1 Higgs self-coupling (equivalently, m_H)

Electromagnetic Interaction

Quantum Electrodynamics (QED), which describes the EM interactions, is the best theory we have, and its predictions agree with exp'tal measurements to an amazing accuracy.

It works so well in part because (a) the coupling constant α is small, and a perturbation expansion in powers of α converges nicely, and (b) QED is an abelian theory, meaning the photons don't interact with each other and give rise to pesky behavior like confinement.

So, here's a brief sketch

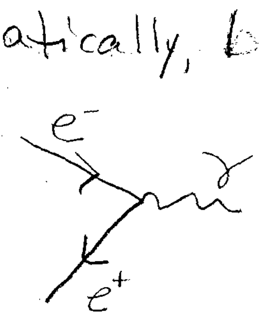
EM interactions: - are mediated by photons, γ.

- arise from requiring invariance of the theory under local $U(1)$ transformations. (These are phase transformations for ~~fermion~~ complex fields.) (fermions in SM)

- are characterized by coupling constant

$$\boxed{\alpha = \frac{1}{137}} \qquad \left(\text{Note } \alpha = \frac{e^2}{4\pi\hbar c} = \frac{e^2}{4\pi}\right)$$

Diagrammatically, basic interaction vertex is

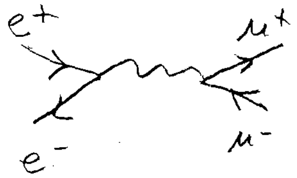


with strength e at vertex

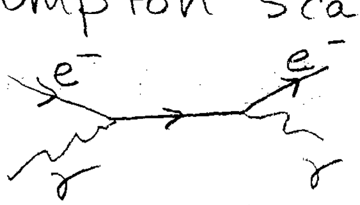
Any charged particle may be put in place of the electron, γ couples to charge.

EM interactions can be built up by combining γ^μ in various ways.

<u>Ex</u> $e^+e^- \to \mu^+\mu^-$



<u>Ex</u> Compton scattering $e\gamma \to e\gamma$



These are <u>tree</u> <u>diagrams</u>. The lines can also close on themselves to form <u>loops</u>, giving higher order corrections:

<u>Ex</u>  "self energy correction"

Two interesting loop effects in EM

① Running coupling / charge screening vacuum polarization

 + ...

Diagrams like this $\Rightarrow \alpha$ is not const, but depends logarithmically on the energy scale q^2!

$\Rightarrow \alpha$ increases with increasing energy

$\alpha \simeq \frac{1}{137}$ at atomic scales $\xleftarrow{eV's}$, where it was first measured, but

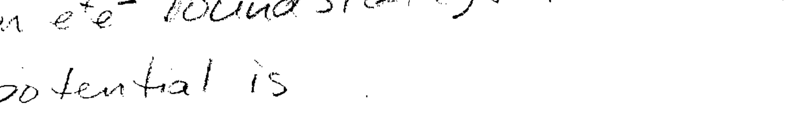
$\alpha(m_Z) \simeq \frac{1}{128}$. This effect is real, and measurable

② Coulomb potential + bound states

We know that the attractive EM force can give rise to bound states, (e.g. H atom or positronium, an e^+e^- bound state) + the corresponding potential is

$$V(r) = -\frac{\alpha}{r}$$

How is this related to the picture of a force arising from exchange of photons? One can obtain V(r) for, e.g., positronium by summing up diagrams for exchanges of all possible numbers of photons:



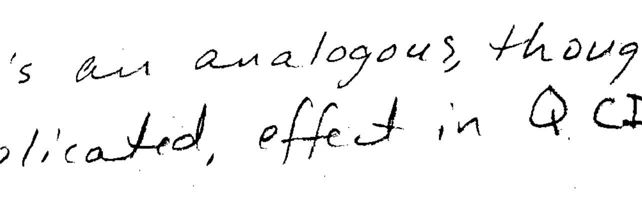
and transforming from momentum to position space, (We won't actually do the calculation, as it's beyond the scope of this course, but it's a nice result in any case) Two comments:

- Velocities in these bound states tend to be nonrelativistic, and so the energy levels can be calculated with the usual non-rel. QM methods

  (A different way of stating the same idea is that *binding energies* are *small* and so particles have to be *moving slowly* to form these bound states.)

- There's an analogous, though slightly more complicated, effect in QCD.

So consider, for example, *quarkonium* – a $q\bar{q}$ bound state – produced in e^+e^- annihilation. It can only happen if the q & $\bar{q}$ are produced w/ very small kinetic energy, i.e. near threshold. The cross section looks like characteristic resonance production, with a very narrow peak:



Note finally that the range of the EM interaction is infinite; this is related to the masslessness of the photon.

Weak Interaction

The weak interaction is responsible for nuclear β decay (and anything else that involves neutrinos). It's the only interaction in which all matter particles participate,
↖ i.e. all fundamental fermions

Brief sketch:

Weak interactions

- are mediated by the $W^\pm$, Z^0 gauge bosons
- arise from requiring invariance under local $SU(2)$ transformations
- involve both charge-changing ($W^\pm$) and neutral interactions. The charge changing interactions can change the identity of the particles involved
- are characterized by coupling constant

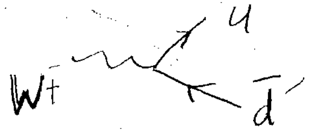
$$\boxed{G_F \simeq 10^{-5}\ m_P^{-2}}$$

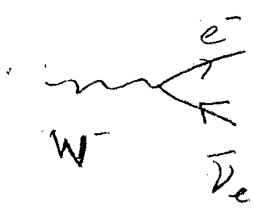
- have finite range because the W + Z are massive (more on masses below)
- couple to weak isospin*

*+ Z's to electric chg, when all's said + done

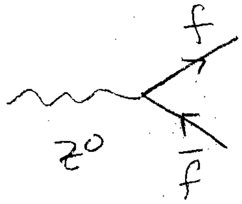
Diagrammatically, basic interaction vertices are

e.g.





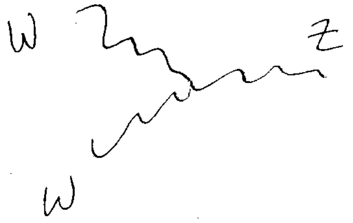
} strength ~ $\left(\frac{G_F M_W^2}{\sqrt{2}}\right)^{1/2}$

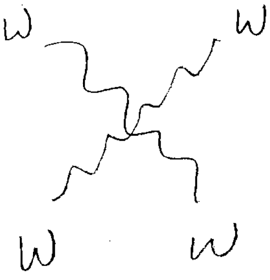


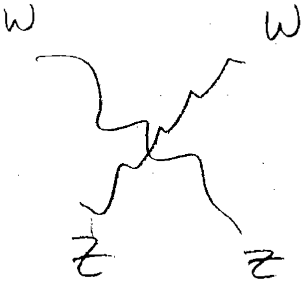
} strength ~ $\left(\frac{G_F M_W^2}{\sqrt{2}}\right)^{1/2}$ × stuff involving weak isospin + electric chg.

But wait, there's more!

The W's + Z's carry weak isospin themselves,
so they couple to each other!

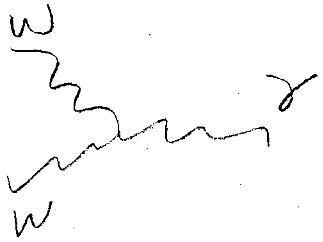


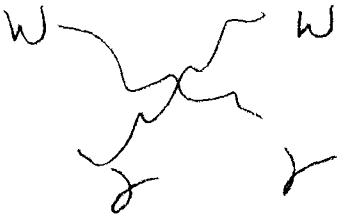




Mathematically, this corresponds to the fact that SU(2) is non-Abelian

Furthermore, the W's carry electric charge, and therefore must couple to photons:





not obvious
Comes fr/
EW unification

More comments on weak interactions:

- $\not{C}\not{P}$ here. It's built into the CKM matrix, which determines how quarks couple to the W's (hence the d' on p. 1.10)

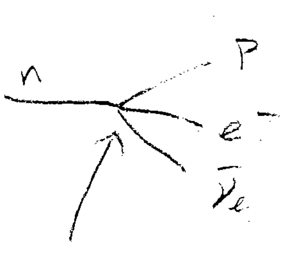
- Fermi theory vs. Electroweak

  Weak int's 1st observed in radioactive decay, e.g. β decay of neutron

$$n \to p + e^- + \overline{\nu}_e$$

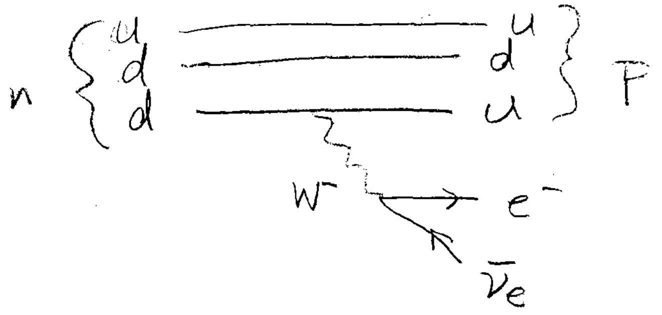
orig. called β-radiation

Described by Fermi as contact interaction among 4 fermions (4-Fermi theory)



strength $G_F/\sqrt{2}$

What we "really" think is going on, now that we have electroweak theory, is



strength $\left(\frac{G_F M_W^2}{\sqrt{2}}\right)^{1/2}$

at each vertex.

Now, we can identify these two theories

Fermi	EW
$\frac{G_F}{\sqrt{2}}$	$\frac{G_F M_W^2}{\sqrt{2}} \underbrace{\frac{1}{q^2 - M_W^2}}_{\text{W propagator}}$

In β decay, q^2 (= square of momentum transfer) is small compared to M_W^2 (MeV vs GeV). so $q^2 - M_W^2 \to M_W$

$$\Rightarrow \quad \frac{G_F}{\sqrt{2}} \longleftrightarrow \frac{G_F M_W^2}{\sqrt{2}} \frac{1}{M_W^2} = \frac{G_F}{\sqrt{2}}$$

Actually, there's more power here than it appears. In EW unification, the EW coupling is related to α_{EM}. Knowing α_{EM} and G_F $\Rightarrow$ predict $M_W \sim \mathcal{O}(90\text{ GeV})$

This is exactly what was done, and in the early 80's the W (+ the Z) were found in $p\bar{p}$ collider expt UA1 at CERN, as predicted.

Electroweak Unification

EM and weak interactions are intertwined, as implied above. So let's back up and sketch how it works.

$SU(2)_L \times U(1)_Y$:

These symmetries in the theory actually correspond to 4 <u>massless</u> gauge bosons

$$W^\pm, W^0, B^0$$

which are not the gauge bosons we know and love. They are related, though.

In fact, we have

$$\gamma = W^0 \sin\theta_W + B^0 \cos\theta_W$$

$$\text{"}Z^0\text{"} = W^0 \cos\theta_W - B^0 \sin\theta_W$$

$$\text{"}W^\pm\text{"} = W^\pm$$

<u>Comments:</u>

- θ_W is the weak, or Weinberg angle
  measuring $\sin^2\theta_W$ is big business in HEP.

- Quotes on "Z^0" + "$W^\pm$" because these things are massless, as they <u>must</u> be for gauge invariance.

- We know the W's + Z's are massive.

<u>Q</u>: What do we do? <u>A</u>: Invoke

= Spontaneous symmetry breaking =,

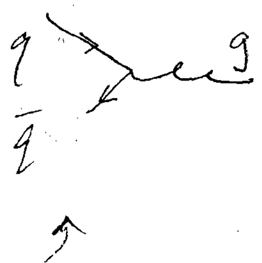
a clever way of generating mass while retaining gauge invariance in the theory. The symmetry is broken by the vacuum itself. A by-product is the Higgs boson.

Strong force

The strong force is also described by a gauge theory. This time the group is SU(3) and the mediators are 8 massless gluons.

The strong force couples to "color charge" and the theory is QCD (quantum chromodynamics). Only quarks (+ gluons) have color charge so the strong force acts only on them.

The basic interaction vertex is



w/ strength g_s; $\frac{g_s^2}{4\pi} = \boxed{\alpha_s \simeq 0.1}$

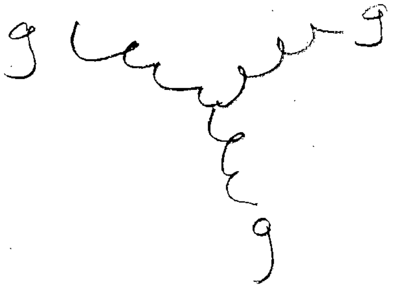
Looks a lot like QED, + in fact QCD has many similarities to QED. But there are big differences. Namely, the two things that make life easy in QED (cf p.1.5) are not true any more:

→

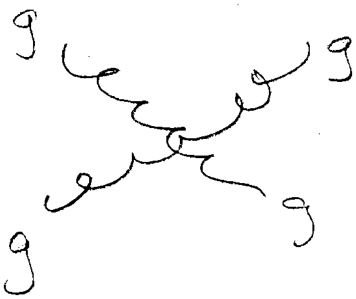
ⓐ $\alpha_s \simeq 0.1$ is big!
This means the interactions are strong (literally) and this leads to difficulties with convergence of perturbation series.

α_s^{n+1} isn't so much smaller than α_s^n, especially when you throw in extra factors.

ⓑ SU(3) is nonabelian: gluons carry color
The gluons interact w/ each other, as in



and



This has MAJOR CONSEQUENCES, like

Asymptotic Freedom!

and its relative (we believe)

Confinement!

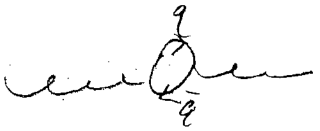
This colors (sorry...) the lives of theorists and experimentalists alike.

Asymptotic Freedom

As in QED, higher order corrections lead to

running of α_s with energy

As in QED, we have diagrams like



which make α_s increase with energy.

But we also have new diagrams like

which make α_s decrease with energy.

Bottom line: DECREASE WINS!*

So α_s gets small at high energies ("asymptotic freedom") and big at low energies (making pert. th. difficult).

*NB: Increase could win if we had enough quark flavors

Conversely, (+ equivalently)

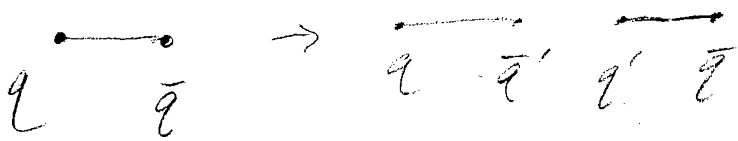
> α_s gets small at small length scales
> $\Rightarrow$ quarks inside protons are basically free
>
> and big at big ($\gtrsim 1$ fm) length scales
> $\Rightarrow$ quarks can't get out of protons easily

... which leads us to

Confinement

There may or may not be a free lunch, but there are definitely, as far as we know, no free quarks

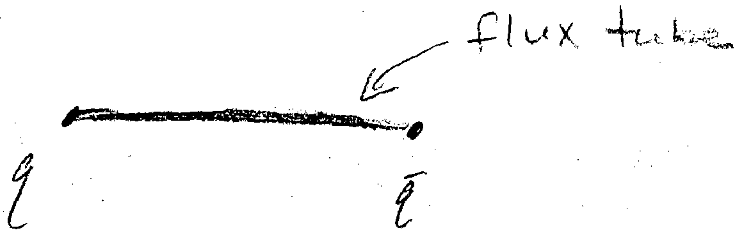
Try separating them, and the strong force gets so strong that it's energetically favorable to create a new quark-antiquark pair in between:



(Analogous to breaking magnet: can't get just north pole)

. . . . More on confinement + hadronization

How confinement works, as illustrated on the previous page, is described by a <u>string</u>, or <u>flux-tube</u> picture/model. As a q + $\bar{q}$ are pulled apart (but w/ separation smaller than 1 fm), the QCD field between them has very small transverse dimensions compared to the $q\bar{q}$ separation:



The field in between is referred to as a "chromo-electric flux tube" or "color string."
The quark-antiquark <u>potential</u> contains a Coulomb term as in QED (from see effects) plus a term that increases w/ separation r:

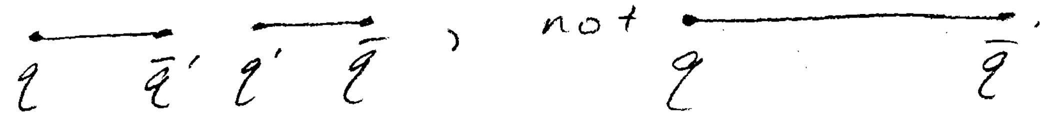
$$V(r) = \frac{-4\alpha_s}{3r} + \overset{\text{const.}}{K}r$$

At "large" r, ignoring the coulomb piece, this has the following <u>implications</u>:

- Force btwn quarks, fr/ $\frac{dV}{dr}$, is constant, indep. of separation
- Field w/in flux tube is constant, and so is energy density. Energy required to separate rises linearly with r

<u>NB</u> The Kr term in V(r) is phenomenological + is <u>not</u> obtained from QCD

⇒ At some separation — ~1 fm — it takes less energy to create a $q\bar{q}$ pair from the vacuum and have two shorter strings, than to continue the separation. Hence



(We often describe this process as the string between the q and $\bar{q}$ stretching and breaking.)

... and that's where hadrons come from.

Comments:

- Although what I described only seems to give mesons, baryons can also be produced.
- The whole string business is incorporated (in much more detail) into the Lund fragmentation model, which is used in Monte Carlo simulations
- Time/length/energy scale

The following scales are equivalent to 1 fm and characterize this hadronization process:

dist	1 fm
time	10^{-23} sec
energy	200 MeV

$(\hbar = c = 1)$

These are typical of strong interaction processes

What hadronization/confinement means for

① Experiment

- What comes out (of collisions, I mean)

Consider the time and distance scales on which hadronization occurs:

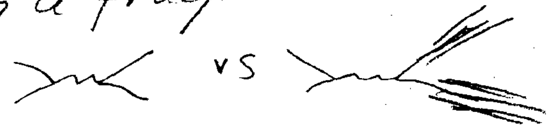
10^{-15} m ; 10^{-23} sec

⇒ quarks (and gluons) produced in high energy expts hadronize immediately, before they go anywhere. Each quark or gluon gives rise to a spray of hadrons, or "jet." The jet tracks the original quark or gluon, for the most part, but there are also low energy ("soft"*) hadrons that go pretty much everywhere.

⇒ The upshot is that

> Quarks and gluons are never seen in detectors. Instead, they show up as jets of hadrons.

So, unlike e's + μ's, the quarks + gluons that undergo the interactions described above aren't themselves observable. We have to work backwards using a fragmentation model of some sort.



* although QCD determines where they're more or less likely to go

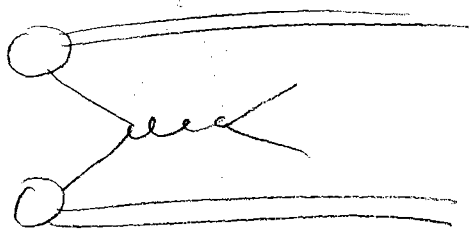
(1.22)

— What goes in

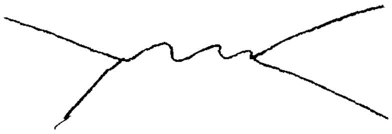
We can collide electrons + positrons "directly," but not quarks + antiquarks, or gluons. All we can do is throw bags of them at each other, i.e., collide hadrons. The "hard scattering" between the quarks takes place at less than the total energy of the collision. ⇒ lab and cm frame of interaction don't coincide.

e.g.

pp:



ee



<u>Bottom</u> <u>line</u> for confinement ⇒ experiment:

Any process that involves quarks or gluons involves hadrons in actual experiments, and, in particular, in detectors.

② Theory

Confinement has significance for theory in a couple of ways, one "deep" and one more prosaic (or practical, if you prefer).

— Deep

Confinement is, as of ~~Feb. 1995~~ ~~July 1996~~ Jan. 1999, still an experimental fact and not a theoretical one. We have argued that asymptotic freedom (which is relatively easily shown to follow from QCD) makes confinement plausible, but the truth is

We don't know if confinement follows from QCD!

Since we believe that QCD is the theory of the strong interactions, we would like to be able to

- show that QCD does imply confinement
- Calculate the hadron spectrum from 1st principles in QCD. (I.e, given QCD and the quarks, predict the masses & other properties of π's, K's ρ's, etc)

Why is this difficult ?!?

Because confinement is a nonperturbative effect. We know how to do perturbative calc's, but nonpert. ones are much less straightforward: expansions in powers of coupling constants don't usually suffice. Different, more clever methods must be brought to bear on this tough problem. Many theorists (incl. Rajeev + collaborators, including some of his students) are working hard on this.

(Aside: Lattice gauge theory is one of the nonpert. methods used to try to solve the problem of confinement + the hadronic mass spectrum.)

— Prosaic/practical

The SM as sketched above has quarks + gluons as fundamental particles, + our calculations of processes ($b\bar{b}$ production, for ex.) involve same. But what shows up in experiments are hadrons, so we have to relate the "partons" (quarks + gluons) in our calc's to the hadrons in the expts.

Generic $\boxed{\text{EX}}$ $gg \to q\bar{q}$ in $p\bar{p}$ collisions

— What goes in: The initial gluons are inside protons, so the cs. for $gg \to q\bar{q}$ has to be folded in w/ the distrib. of gluons in the protons. ("Parton distributions")

nomenclature

— What comes out: Quarks don't come out, jets of hadrons do. Phenomenological "fragmentation functions" describe how this happens (input: partons w/some mom; output: hadrons w/some momenta). Fortunately, for reasonably energetic outgoing partons, the resulting jets are pretty well collimated, w/ total momenta matching the parton momenta pretty well. Hence <u>jet distributions more or less follow parton distributions</u>, allowing phenomenologists like me to do calculations at the parton level, leaving fragmentation in the capable hands of experimentalists.

That is, unless you're interested in...

[EX] Heavy flavor decays, mixing, + $\not{C}\!\not{P}$ (e.g. B physics)

... in which case fragmentation cannot be swept under the rug, + must be dealt with, since it's hadrons that are doing the decaying, mixing, + violating.

We can still do calculations at the parton level but we must explicitly take into account the hadronic effects, usually in the form of "<u>hadronic</u> <u>matrix</u> <u>elements</u>" that multiply the parton-level stuff.

Things like potential models and the <u>H</u>eavy <u>Q</u>uark <u>E</u>ffective <u>T</u>heory (Isgur, Wise, et al) provide techniques for dealing with these problems. HQET, for example, exploits the symmetries of heavy quark systems (e.g. B mesons) in relating, e.g. various decay rates.

[<u>Interesting aside</u>: HQET is phenomenological but work of Rajeev + collaborators has shown that it may be obtainable fr/ 1st principles.]

So we need, e.g.,

We still think of the quark decay being responsible for the hadron decay, but hadronic effects must be incorporated. In real life it's the hadron that decays.* (Interesting exception: top.)

<u>Bottom</u> <u>line</u> for confinement ⇒ theory:

We would like to show, but have not yet, that QCD ⇒ confinement. In the meantime, we do practical calculations at the parton level and take hadronization into account (or not) as best we can with various models.

End of confinement (+ QCD) discussion

* Timescale argument: $\tau_{had} \sim 10^{-23}$ sec; $\tau_{\substack{weak\\decay}} \sim 10^{-8}$ sec $- 10^{-12}$ sec