MEASURING CHARM AND BOTTOM QUARK MASSES
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ABSTRACT

The meaning and the extraction of heavy quark masses are discussed. A simple
production model is presented which incorporates the running of the heavy quark
mass into perturbative calculations. The model offers the possibilities of (i) under-
standing the differing charmed mass values extracted from different experiments,
(ii) determining the short–distance mass relevent to quark mass matrix and mixing
angle studies, and (iii) determining the long–distance charm mass, which determines
the charm quark threshold and sensitively affects the extraction of \( \sin^2 \theta_w \). Threshold
old and forward angle production offer the best possibilities to test the model and
extract meaningful charm/bottom masses.

1. Quark Masses and QCD

This year, the Particle Data Group (PDG) introduced into the Review of
Particle Properties a “Quark Table,” in which they list values for the quark masses\(^1\). The d–, u–, and s–quark mass values are “current–quark masses” extracted from
pion and kaon masses using chiral symmetry. The c– and b–quark mass values
are potential model masses estimated from charmonium, bottomonium, D, and
B masses; they are not the running masses derivable from the QCD Lagrangian.
Moreover, the masses are poorly determined: \( m_c \) is given a range of 1.3 to 1.7 GeV,
and \( m_b \) is given a range of 4.7 to 5.3 GeV. The PDG say that “since the subject of
quark masses is controversial, the purpose of the table is to provoke discussion.”

Experiments on quark scattering and production can provide the PDG with
running QCD masses, with the running scale provided by the subprocess invariants
\( \hat{s}, \hat{t}, \) and \( \hat{u} \). Because of the running of QCD, one expects to find (i) scattering quark
masses smaller than the potential model masses listed above, and (ii) extracted mass
values that change with scale and with reaction channel. Point (i) expresses the
fact tha QCD is asymptotically free. At large scale one expects a measured mass to
be the bare current mass in the electroweak Lagrangian; this mass originates from
the Higgs mechanism and has nothing to do with QCD. Point (ii) reflects running, but also the fact that different reaction channels have different intrinsic scales. For example, in Drell–Yan or $e^+e^-$ production, the quark lines are external and the quarks are constituent–like; while in heavy quark production via boson–boson fusion there is an internal quark line and the associated quark is a short–distance, off–shell (by $i - m_Q$) current quark. Reactions with t– or u–channel quark exchange will yield lighter quark mass values than reactions without.

Unfortunately, the extraction of scattering masses is necessarily model–dependent, for “hadronization” or “fragmentation” of the final state quarks is inherently nonperturbative (hadrons and jets do not appear in the QCD Lagrangian), and nonperturbative QCD must be modelled rather than calculated.

2. Models for Heavy Hadron Production

One way to view the model dependence of the perturbative/nonperturbative QCD interface is to ask, at what stage in the calculation do nonperturbative effects enter? In conventional QCD phenomenology, a common mass parameter is used everywhere in the Feynman diagrams and hadronization is added on in a classical fashion. The charmed mass value that emerges from fits to hadroproduction data (where gluon–gluon fusion is dominant) appears to us to be too large. Fits with lowest order QCD give $m_c = 1.2 \text{ GeV}$, which is fine, but fits with loop–corrected QCD give $m_c = 1.5 \text{ GeV}$, which is as large as the mass determined from potential models! Furthermore, in a one–mass model there is no possibility to understand the different mass values that seem to emerge from different reaction channels. And finally, there is no possibility for running the mass into the nonperturbative region where the running is greatest.

Thus, there is motivation to look at other models for the perturbative/nonperturbative interface. One simple approach is to admit the heavier, dressed, constituent mass in the phase space limits. A more motivated two–mass model has recently been introduced by us$^2$. It models running of the heavy quark mass at the Feynman diagram level: the mass in quark propagators is identified with the short–distance mass arising from electroweak symmetry breakdown, and the mass in the “free” Dirac spinors and in the phase space limits is identified with the long-distance/constituent mass. Specifically, quark propagators are $(\not{p} - m_{SD})^{-1}$, while quark spinors satisfy the Dirac equations $(\not{p} - m_{LD})u(p, m_{LD}) = 0$ and $(\not{p} + m_{LD})v(p, m_{LD}) = 0$. SD and LD denote short and long distance, respectively. An immediate prediction is that charm-masses extracted from reaction channels dominated by graphs with (without) internal charm-quark lines will have smaller (larger) values.

The LD constituent mass in the Dirac spinor encompasses some of the nonperturbative physics of color bleaching, fragmentation, and hadronization. It may also be viewed as arising from a mass insertion on external quark legs due to interactions with QCD vacuum condensates. As such, it is a simple representation
of highly complicated physics. The successes of the nonrelativistic quark model in describing static hadron properties argue that constituent quarks do behave like Dirac particles, a result supported by current algebra. Assigning different masses to internal and external lines creates nonconserved currents, which break gauge invariance. This becomes an issue in higher order calculations where internal gauge boson lines are present. The breaking of gauge invariance can be avoided by retaining $(\not p - m_{SD})u(p, m_{LD}) = 0$ and $(\not p + m_{SD})v(p, m_{LD}) = 0$. Then the LD mass shows up only in the relations $u(p, m_{LD})\bar{u}(p, m_{LD}) = \not p + m_{LD}$ and $v(p, m_{LD})\bar{v}(p, m_{LD}) = \not p - m_{LD}$, and in the phase space limits. Alternatively, one may note that when nonperturbative effects turn on, the physics that results looks nothing like any known extrapolation from the QCD Lagrangian. Hence it may make sense to allow nonperturbative effects to break gauge invariance in any perturbative calculation, with the faith that an all orders calculation will produce the exact gauge invariant physics. (Just this philosophy is adopted in some versions of light–cone QCD.) This point of view motivates calculating in physical gauges, where unitarity is manifest. Further discussion on this issue is contained in ref.2.

3. Experimental Comparison of Heavy Hadron QCD Models

In ref.2 it is shown that $m_{SD}$ determines the peak magnitude and the asymptotic magnitude of the subprocess $gg \rightarrow c\bar{c}$ cross section, while $m_{LD}$ determines the threshold energy. Thus, in principle both masses are measureable. The running-mass model gets both the threshold and the rate correct with $m_{SD} \sim 1.2$ GeV and $m_{LD} \gtrsim 1.5$ GeV. To quantitatively distinguish between conventional perturbative QCD and this model, it may be necessary to compare across reaction channels; we have mentioned that this model predicts a lighter charm mass only for those reactions having a t- and/or u-channel charmed line. It may also be possible to distinguish between the two models by examining a single reaction cross section near threshold where the greatest differences in shapes occurs, or near the forward scattering angle, where $t$ most closely approaches the SD charmed-mass pole. It may be possible to experimentally determine $\hat{s}$ and $\hat{t}$ (or $\theta_{cm}$) on an event by event basis, through final state measurements. Eventually, photon-photon charm-production data will become available; in this reaction, $\hat{s}$ and $\hat{t}$ are measureable, and there is no dependence on an initial state gluon distribution. The forward scattering peak is quite sensitive to the charmed mass.

We encourage charm and bottom production experimenters to analyze data with the model discussed here. If it turns out that this model and the conventional QCD model both fit the data and yield differing charm masses, then available experiments are insufficient to quantitatively determine the short–distance charm mass. But if a detailed study should show a preference for one model over the other, then Nature will have spoken, and we will have listened.

4. References
1. Particle Data Group, *Phys. Rev.* D45 (1992) II.4.
2. K. Ghafoori–Tabrizi and T. J. Weiler, *Phys. Rev.* D, to appear Dec. 1, 1992.
3. S. Weinberg, *Phys. Rev. Lett.* 65 (1990) 1181.