Heavy Quarkonium

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The Standard Model is the fundamental theory that describes, up to now completely successfully, all the phenomena occurring in particle physics. The sector of the theory that describes the strong interaction, i.e. the interaction of quarks and gluons, is called QCD. Differently from the other parts of the theory the low energy region of QCD cannot be studied by expanding in a small coupling constant, i.e. in perturbation theory. The non-perturbative nature of the QCD vacuum is a major difficulty that affects the determination of several observables in particle physics and some of the parameters of the Standard Model.

Heavy quarkonia (bound states of two heavy quarks: $b\bar{b}$, $c\bar{c}$, ...) are an ideal tool to study the non-perturbative dynamics of QCD. This because they are non-relativistic (NR) bound states and, therefore, characterized by at least three hierarchically ordered energy scales: m, mv and mv^2. We can say that these scales probe the QCD vacuum at different depths. The quantity m is the heavy-quark mass and $v \ll 1$ the heavy-quark relative velocity. The mass m of the heavy quark is large enough to be treated perturbatively; the other scales may and may not lie in the perturbative regime in dependence of the specific system and process under examination. In any case non-perturbative contributions can be factorized in well defined operator matrix elements [1]. They may be fixed phenomenologically on some data set, used to make predictions on some other data set or calculated on the lattice.

In the following I will list three different type of observables of the heavy quarkonia, where our understanding has dramatically improved over the last years.

A) The bottomonium spectrum. Fig. 1 shows a recent determination of the bottomonium spectrum from lattice NRQCD. The determination is accurate up to $\mathcal{O}(v^4, \alpha_s^0)$ in the velocity and $\alpha_s(m_b)$ expansion and is done with two dynamical fermions at the strange quark mass [2]. Very recent calculations with $2+1$ dynamical fermions (one fermion at the strange quark mass and two at one fifth of it) show an improved agreement with the data [3]. These are the first, fully realistic (i.e. unquenched), lattice determinations of the bottomonium spectrum.

B) Quarkonium decays. By disentangling degrees of freedom associated with the scale mv from those associated with the scale mv^2, significant simplifications in the number of the non-perturbative matrix elements have been recently achieved [4]. These have led, among others, to new predictions for the bottomonium P-wave inclusive decay widths into light hadrons (derived by using the non-perturbative parameters fitted on the charmonium

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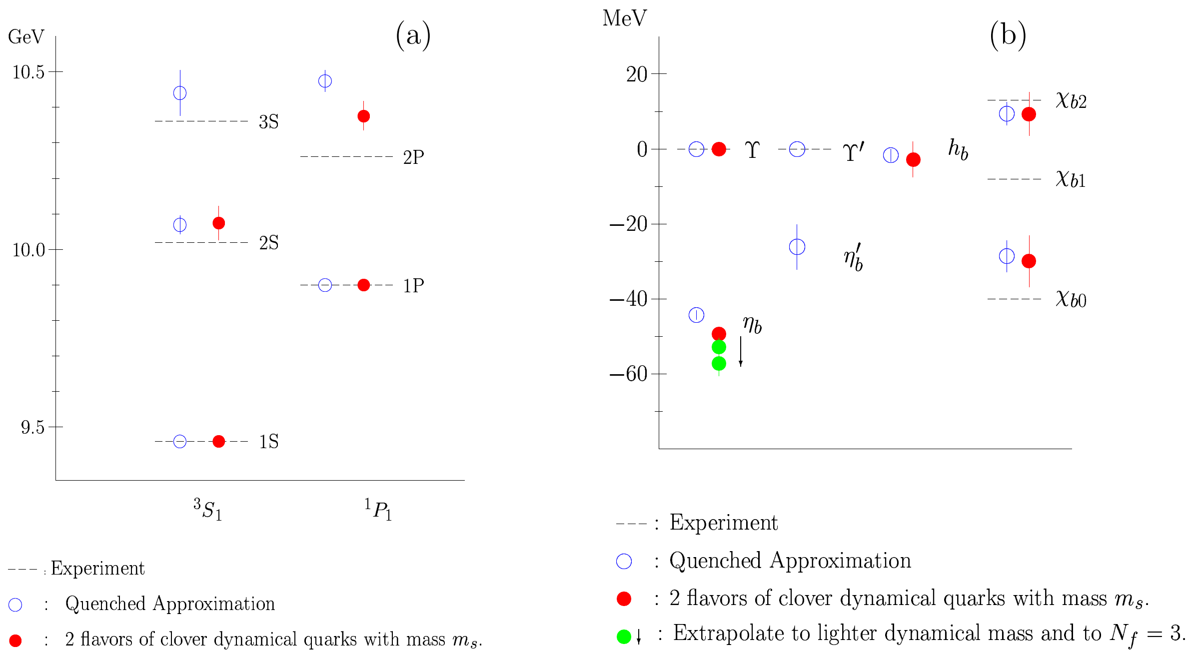

FIG. 1. (a) The radial and orbital excitations in the $b\bar{b}$ system, as calculated in lattice QCD using NRQCD for the b quarks. (b) The fine structure of low-lying $b\bar{b}$ states.

data). They read:

$$\frac{\Gamma(\chi_{b0}(1P) \to \mathrm{LH})}{\Gamma(\chi_{b1}(1P) \to \mathrm{LH})} = \frac{\Gamma(\chi_{b0}(2P) \to \mathrm{LH})}{\Gamma(\chi_{b1}(2P) \to \mathrm{LH})} = 8.0 \pm 1.3,$$

$$\frac{\Gamma(\chi_{b1}(1P) \to \mathrm{LH})}{\Gamma(\chi_{b2}(1P) \to \mathrm{LH})} = \frac{\Gamma(\chi_{b1}(2P) \to \mathrm{LH})}{\Gamma(\chi_{b2}(2P) \to \mathrm{LH})} = 0.50^{+0.06}_{-0.04}.$$

The first CLEOIII data appeared just afterwards and read [5]:

$$\frac{\Gamma(\chi_{b0}(2P) \to \mathrm{LH})}{\Gamma(\chi_{b1}(2P) \to \mathrm{LH})} = 19.3 \pm 9.8, \qquad \frac{\Gamma(\chi_{b1}(2P) \to \mathrm{LH})}{\Gamma(\chi_{b2}(2P) \to \mathrm{LH})} = 0.29 \pm 0.06.$$

C) Quarkonium production. One of the big successes of the NRQCD factorization introduced in [1] has been the correct description of the Tevatron production data [6], see Fig. 2 (a) taken from [7].

In order to test the theory fully it is, however, necessary to prove that the non-perturbative matrix elements are universal, i.e. that the same fitting for the production data describes, for instance, the polarisation data. The first data [8] seem to indicate a potential problem, see Fig. 2 (b) taken from [7]. Before claiming a possible (and challenging) discrepancy, however, more precise data are needed.

Finally, I mention that the theoretical developments of the last years in heavy quarkonium physics and the intense ongoing experimental activity (at CLEO, Tevatron, BES, BaBar, Belle, ...) has recently led to the creation of a dedicated working group [9].

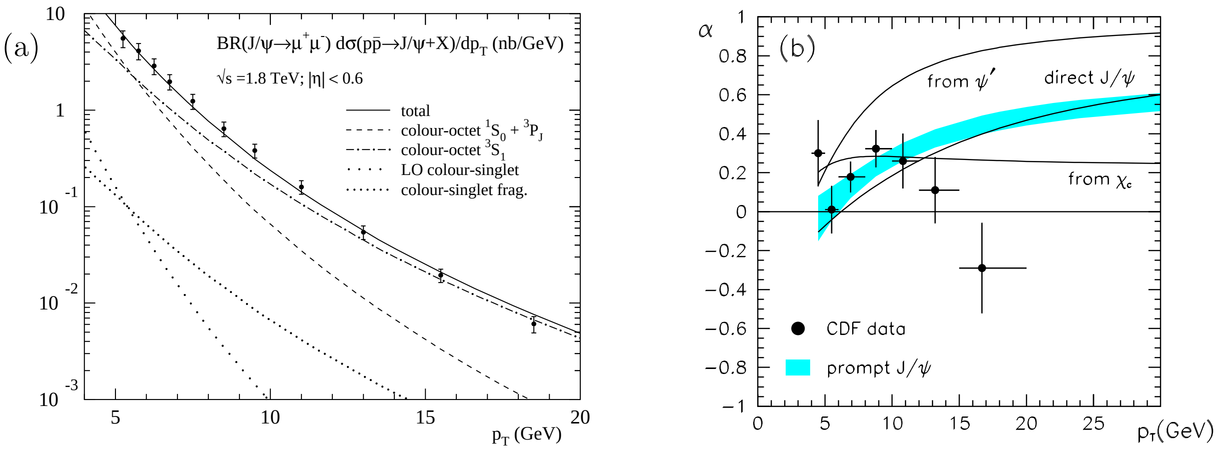

FIG. 2. (a) Colour-singlet and colour-octet contributions to direct J/ψ production at the Tevatron compared to experimental data. (b) Polar angle asymmetry α for prompt J/ψ production at the Tevatron compared to experimental data.

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