Quarkonia

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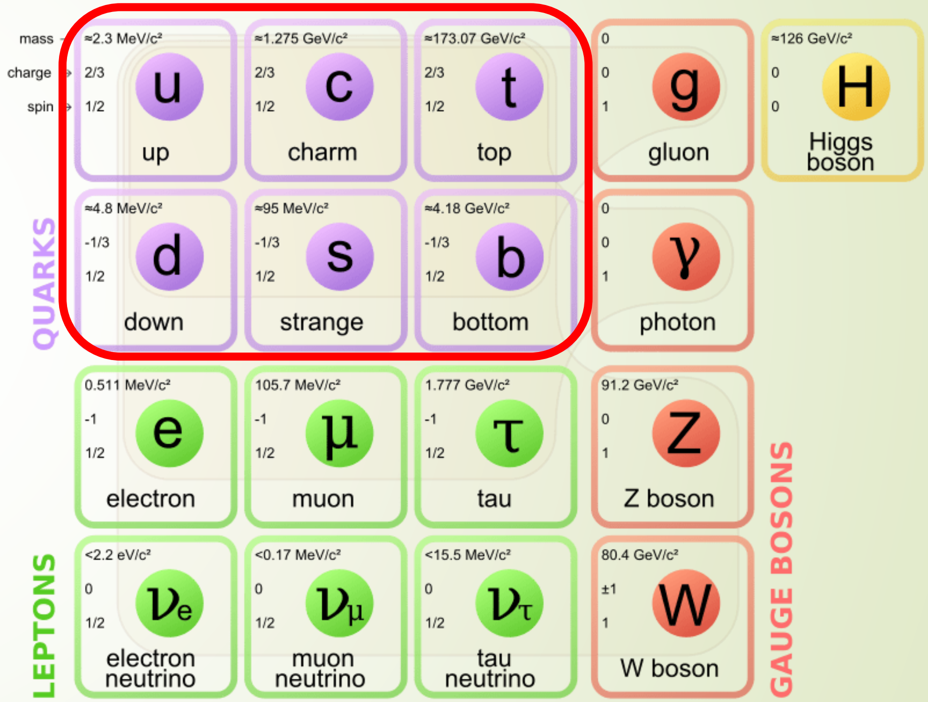
Hadrons

- Almost all visible matter is made up of **hadrons**: bound states of quarks
- But we still don't fully understand the dynamics of hadron formation



Hadron formation

The **simplest bound state** we could study would be two quarks of the same flavor (and mass): $q\bar{q}$

↓

The **up, down and strange** quarks are too light: we cannot distinguish the time of production of the quark-antiquark pair from that of the bound state

↓

Top quarks are too heavy: they decay before they can interact and combine

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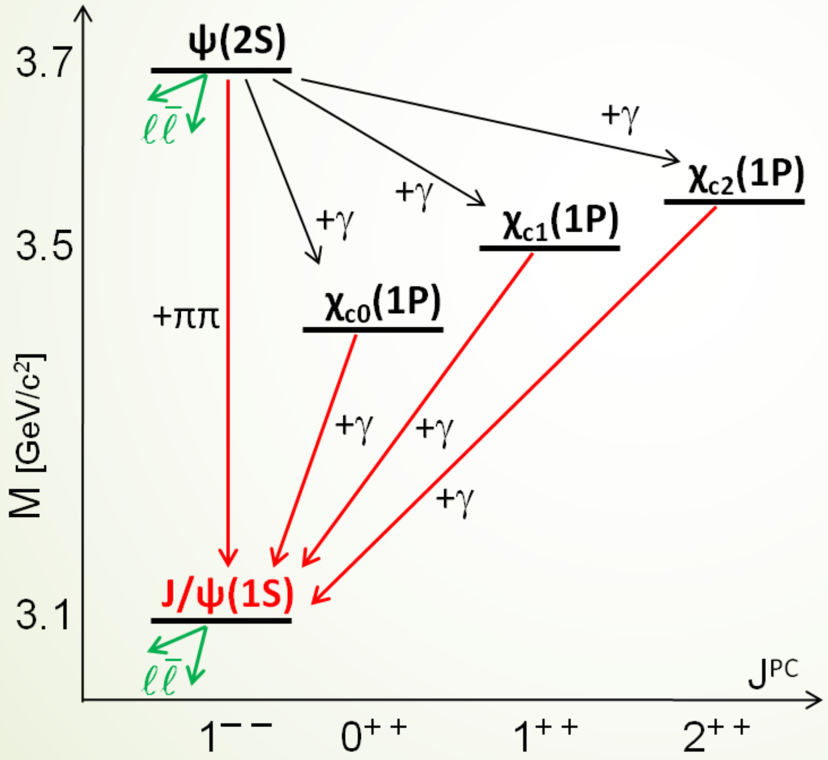
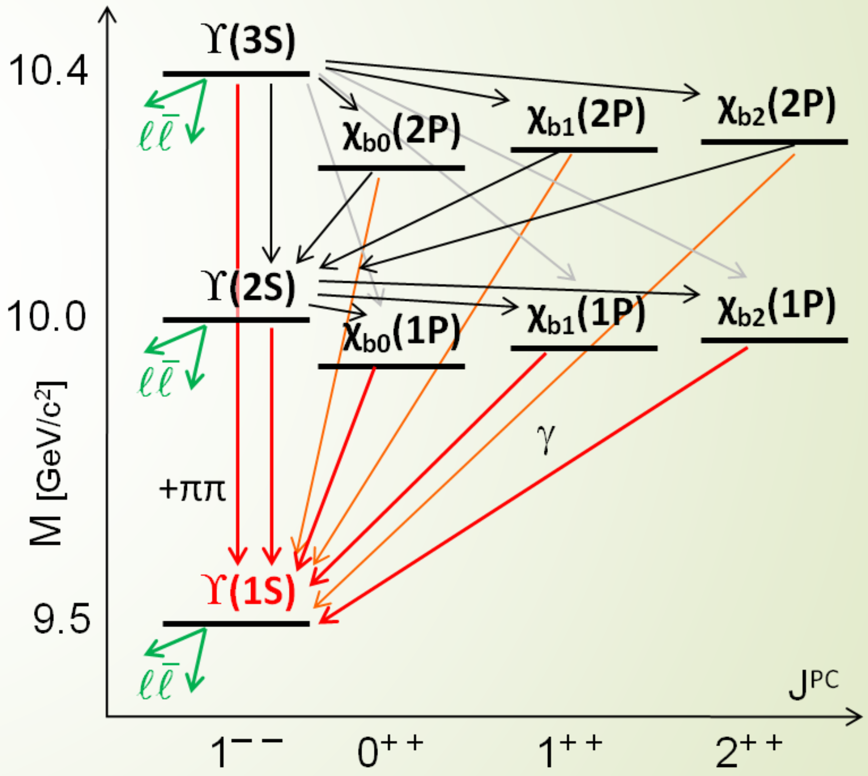
We can study **heavy quarkonium:** bound states of $c\bar{c}$ (charmonium) or $b\bar{b}$ (bottomonium)

Heavy quarkonia

Charmonium



Bottomonium



NRQCD

- We want to study quarkonium formation: what happens between the production of the **initial quark-antiquark pair** and the detection of the **final bound state**
- The process includes **gluon emission**, ensuring that the bound state is colour neutral: this means that the initial pair and the final bound state are free to have **different L, S, J quantum numbers**
- **NRQCD** (nonrelativistic quantum chromodynamics) considers the hypothesis of **factorization** between the production of the $Q\bar{Q}$ pair and the formation of the bound state:

$$\sigma(A + B \to \mathcal{Q} + X) = \sum_{S,\,L,\,C} \overbrace{\mathcal{S}\{A + B \to (Q\bar{Q})_C\,[^{2S+1}L_J] + X\}} \times \overbrace{\mathcal{L}\{(Q\bar{Q})_C\,[^{2S+1}L_J] \to \mathcal{Q}\}}$$

Polarization

$$\sigma(A + B \rightarrow \mathcal{Q} + X) = \sum_{S,\,L,\,C} \mathcal{S}\{A + B \rightarrow (Q\bar{Q})_C\,[^{2S+1}L_J] + X\} \times \mathcal{L}\{(Q\bar{Q})_C\,[^{2S+1}L_J] \rightarrow \mathcal{Q}\}$$

- This raises the question: which colour and angular-momentum transitions are favoured for each of the bound states?
- And associated questions: Is there a **common pattern** in the hierarchy of transitions? Can we explain the results based on **fundamental** quark-antiquark interactions? …
- Because the transitions are characterized by how S, L and J change, **angular momentum measurements** can discriminate among them
- $\vec{J}$ vs $\vec{p}$ alignment = "Polarization"
- Right now, the **measurement of the polarization** of different quarkonium states is essential to advance in our knowledge of QCD bound-state formation

Questions?