The structure of hadrons

Research opportunities

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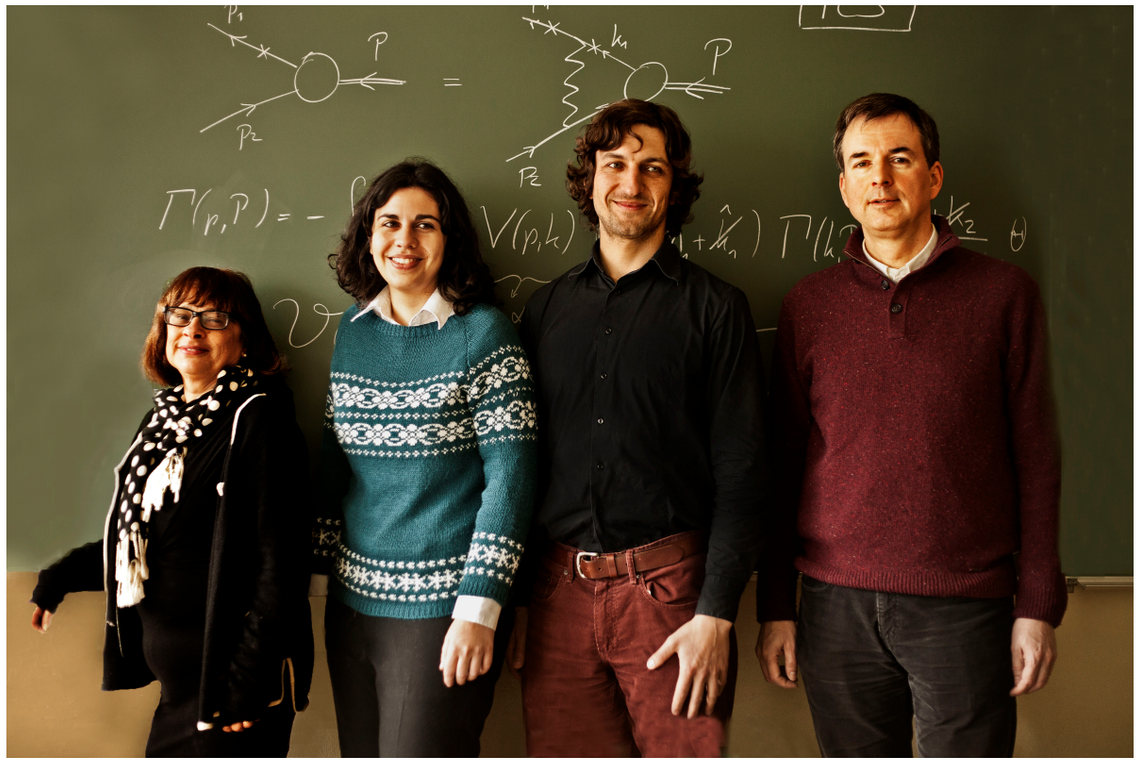
Team members



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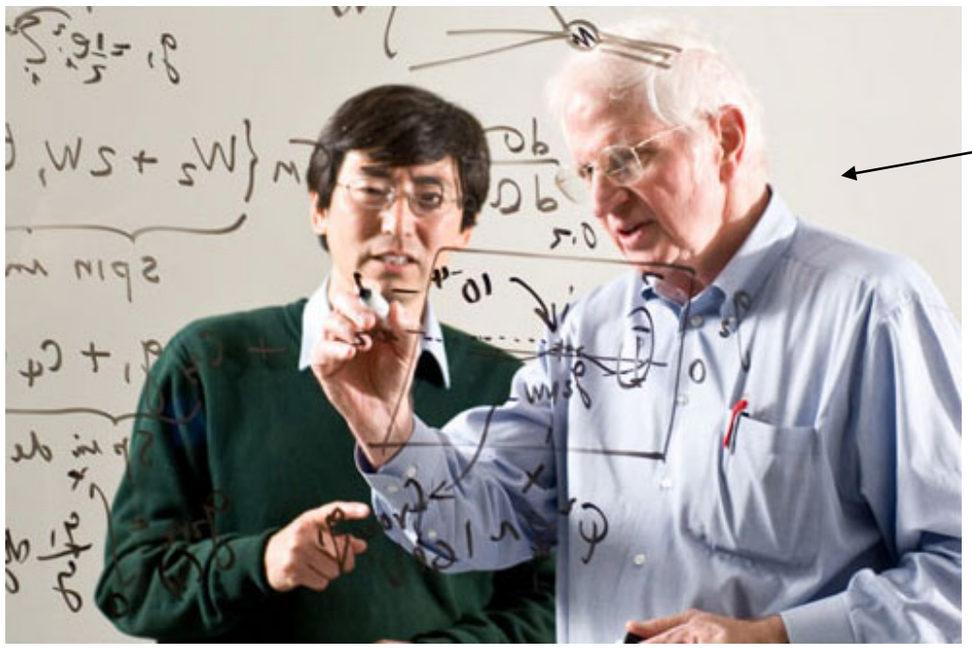

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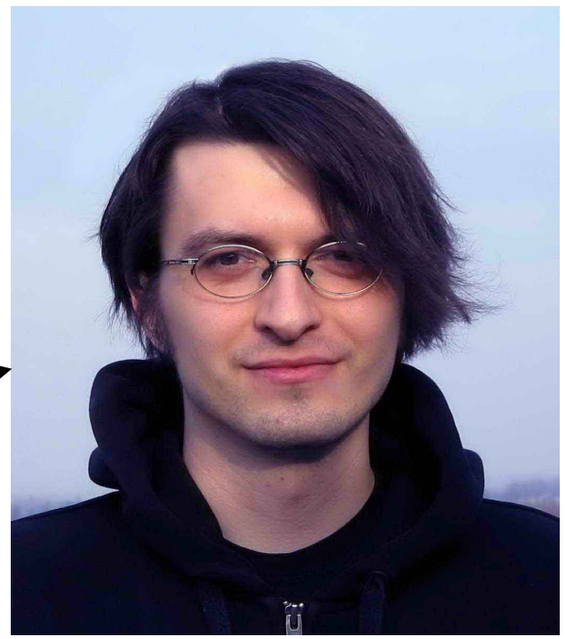


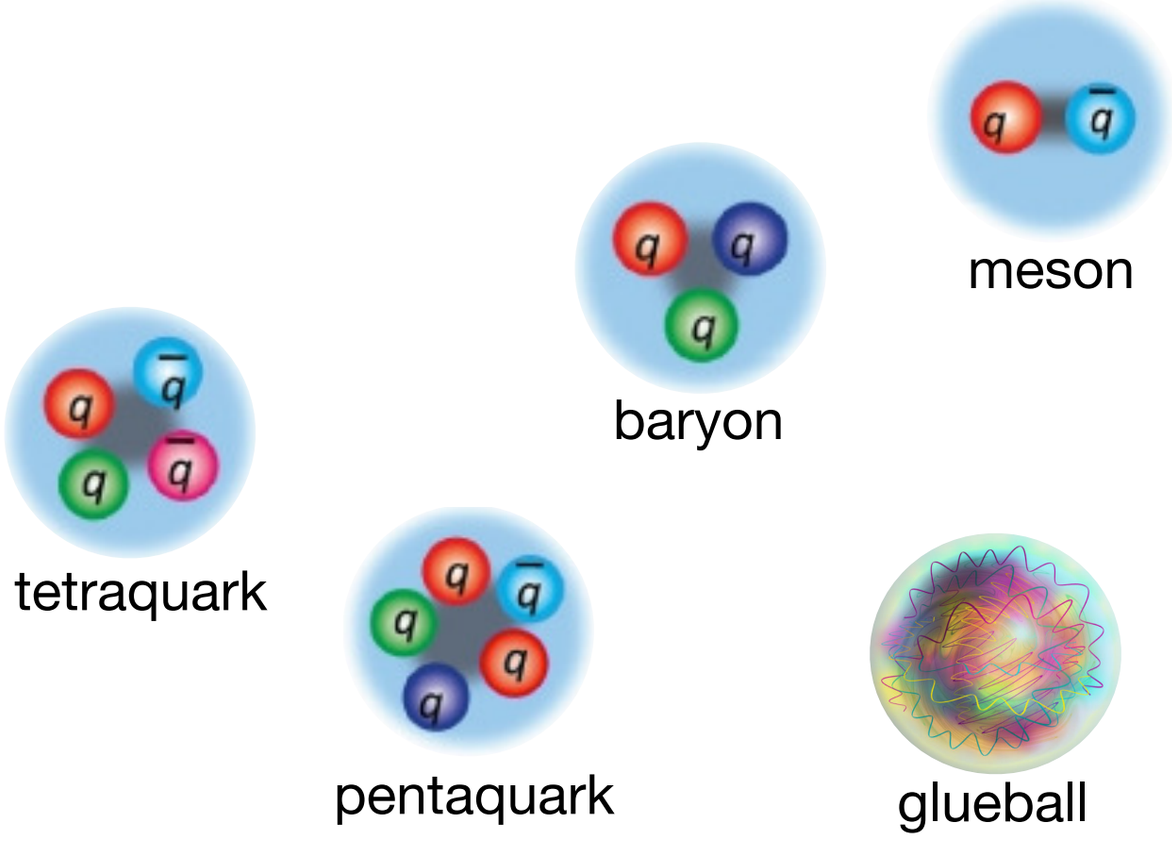
Hadrons

Hadrons are strongly interacting particles.

- Observed hadrons are mesons (π, η, ρ, ω, K, …) and baryons (p, n, Δ, Λ, Σ, …)
- QCD: fundamental degrees of freedom are quarks and gluons (not directly observed)
- Hadrons are interpreted as bound states: mesons as $q\bar{q}$, baryons as qqq
- Can we understand the measured hadron properties in terms of quarks and gluons?

Experiment

- Intense activity at accelerators around the world
  (Europe, USA, Japan, China, …)
- Measure properties of known hadrons with high precision
- Discovery of new particles
- Search for exotic hadrons



Hadrons

Theory

- QCD is very hard to solve
  (non-perturbative at low energies)
- Bound states cannot be obtained in perturbation theory, need an infinite number of Feynman diagrams

Which tools are available?

- Lattice QCD (on discretized space-time)
- Dyson-Schwinger/Bethe-Salpeter type equations
  (integral equations: sum an infinite series of a selected class of diagrams)
  Our framework: Covariant Spectator Theory (CST)
- …

Quark-antiquark interaction

Heavy quark systems ~ nonrelativistic

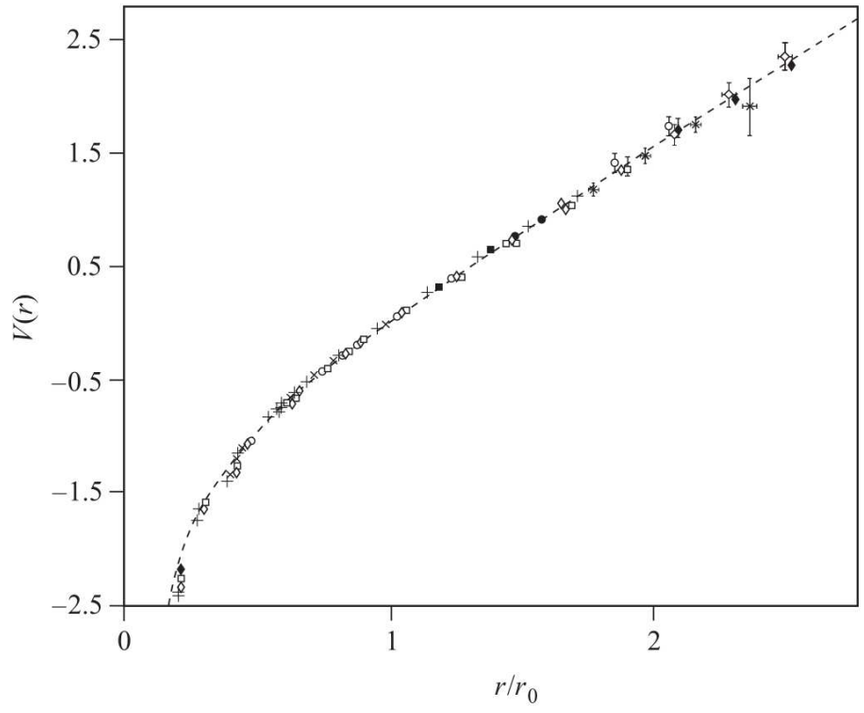
Charmonium $c\bar{c}$ quite well described with the Cornell potential in the Schrödinger equation:

$$V(r) = \sigma r - \frac{\alpha_s}{r} - C$$

Confinement
(long distance)

One-gluon-exchange
(short distance)

Static QCD potential from the lattice



Allton et al, UKQCD Collab., PRD **65**, 054502 (2002)

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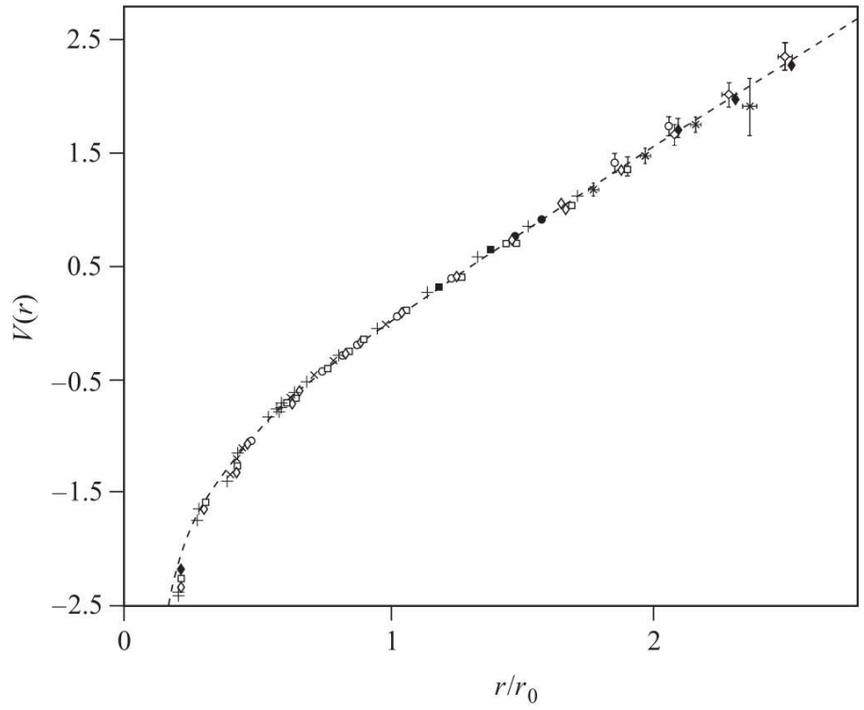

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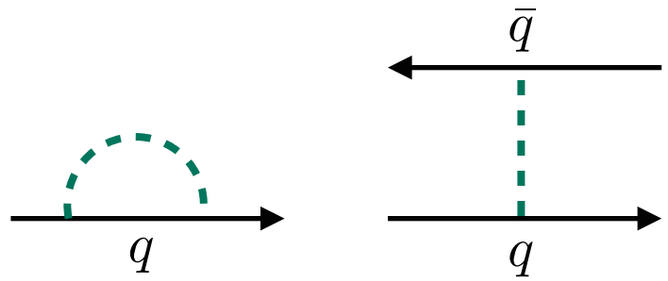
Objectives of our CST approach:

- Find $q\bar{q}$ interaction that can be used in all mesons (unified model)
- Must be relativistic (relativity necessary with light quarks), and reduce to linear+Coulomb in the nonrelativistic limit
- Manifest covariance: strongly constrains spin-dependence of interactions
- Quark masses are dynamic: self-interaction should be consistent with $q\bar{q}$ interaction

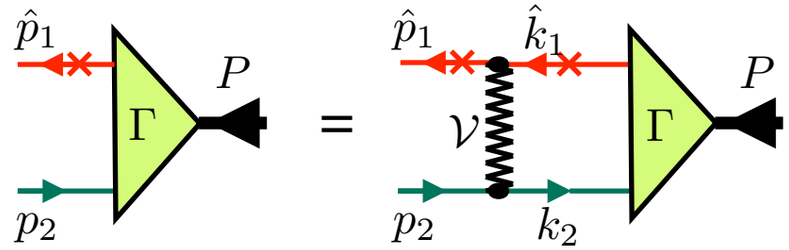
Huge mass variation:
from pions (~0.14 GeV)
to bottomonium (> 10 GeV)

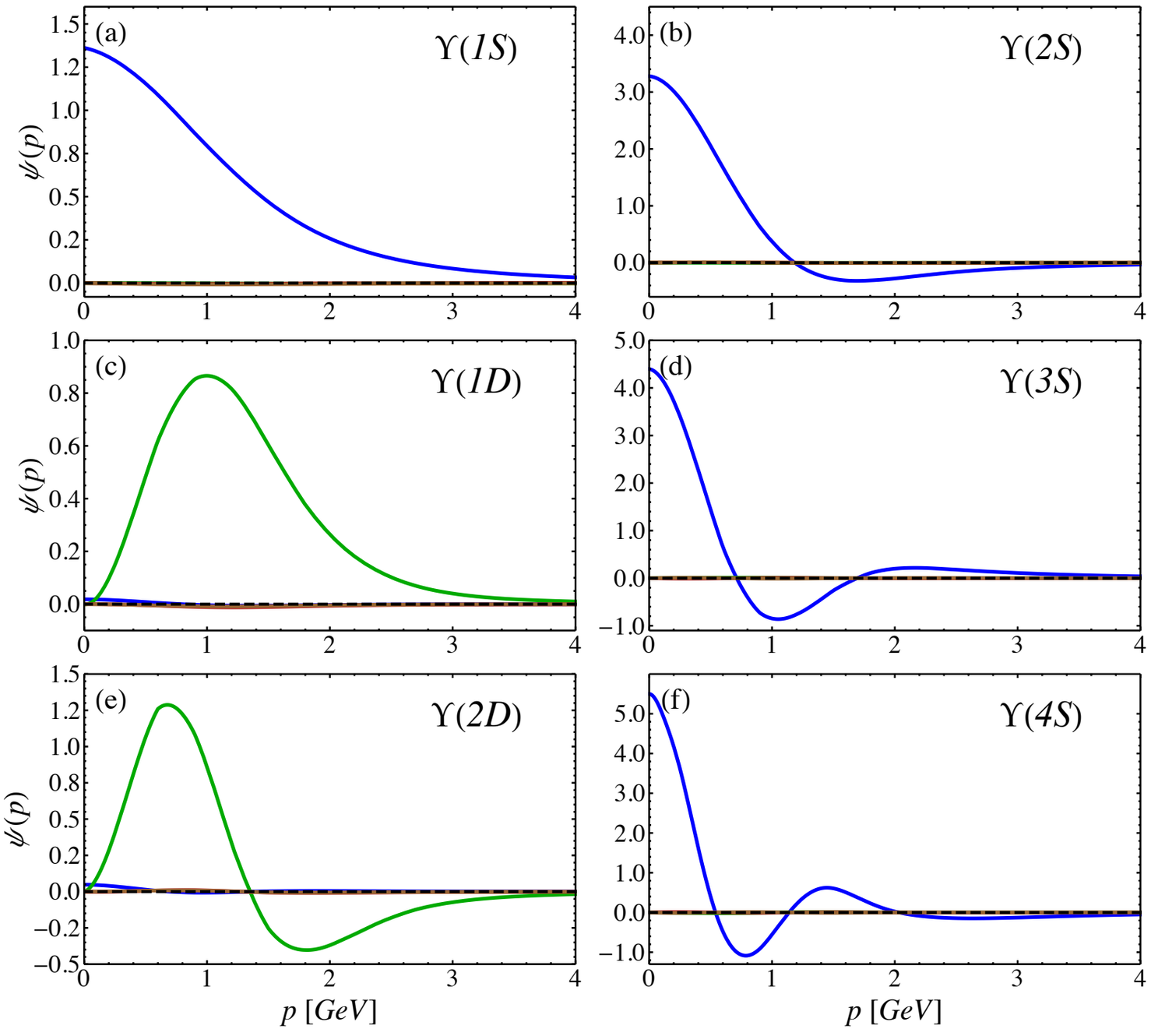


Meson masses and wave functions

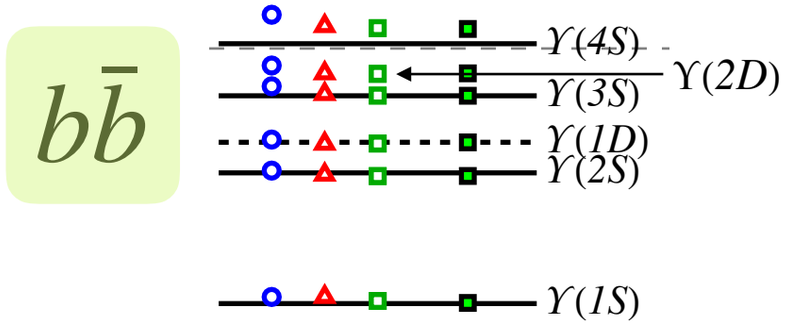
Solutions of the CST bound-state equations:

- meson masses
- vertex functions → relativistic wave functions





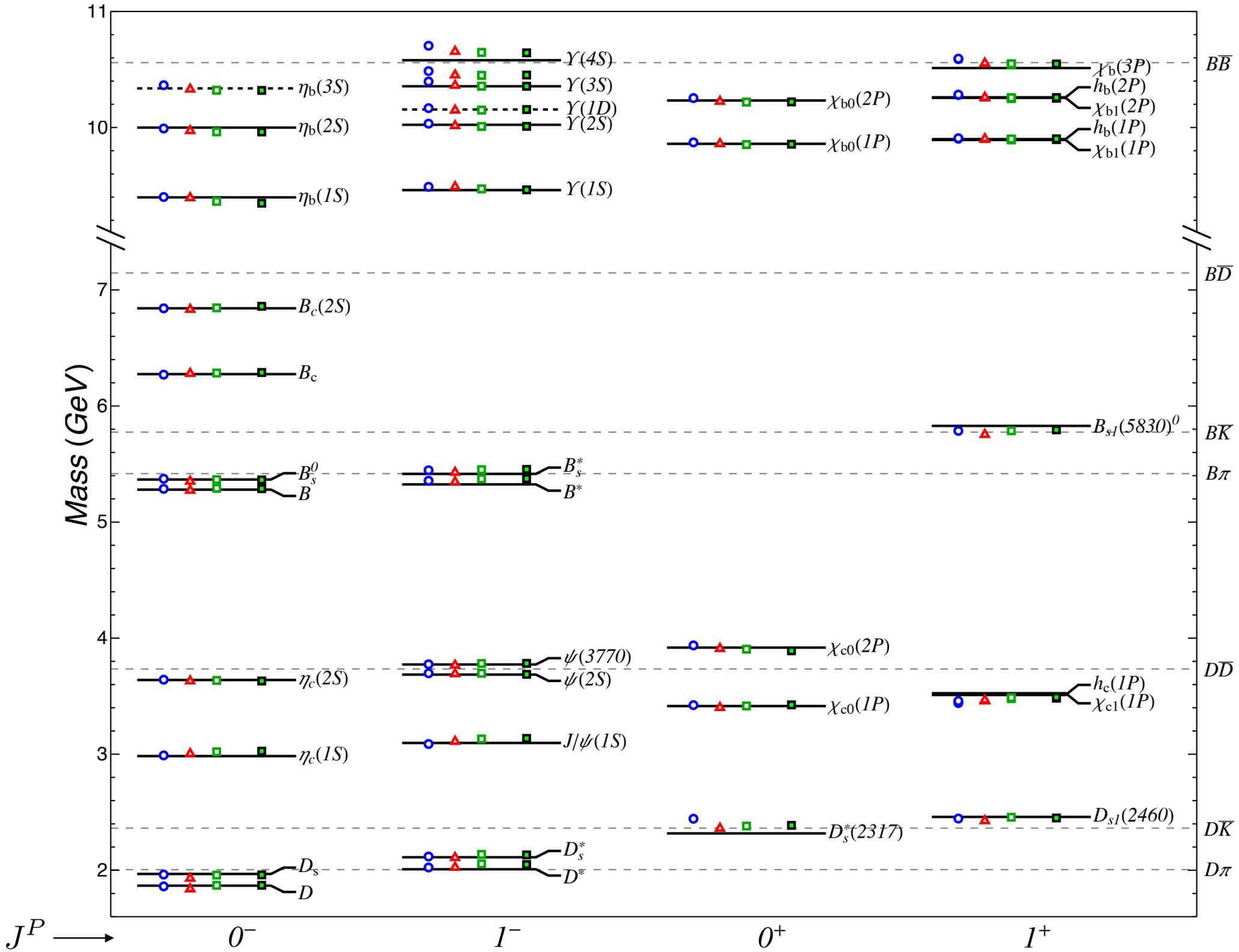
Model M1$_{S3}$



Partial waves

- S
- D
- P_t (spin triplet)
- P_s (spin singlet)

Mass spectra of heavy and heavy-light mesons



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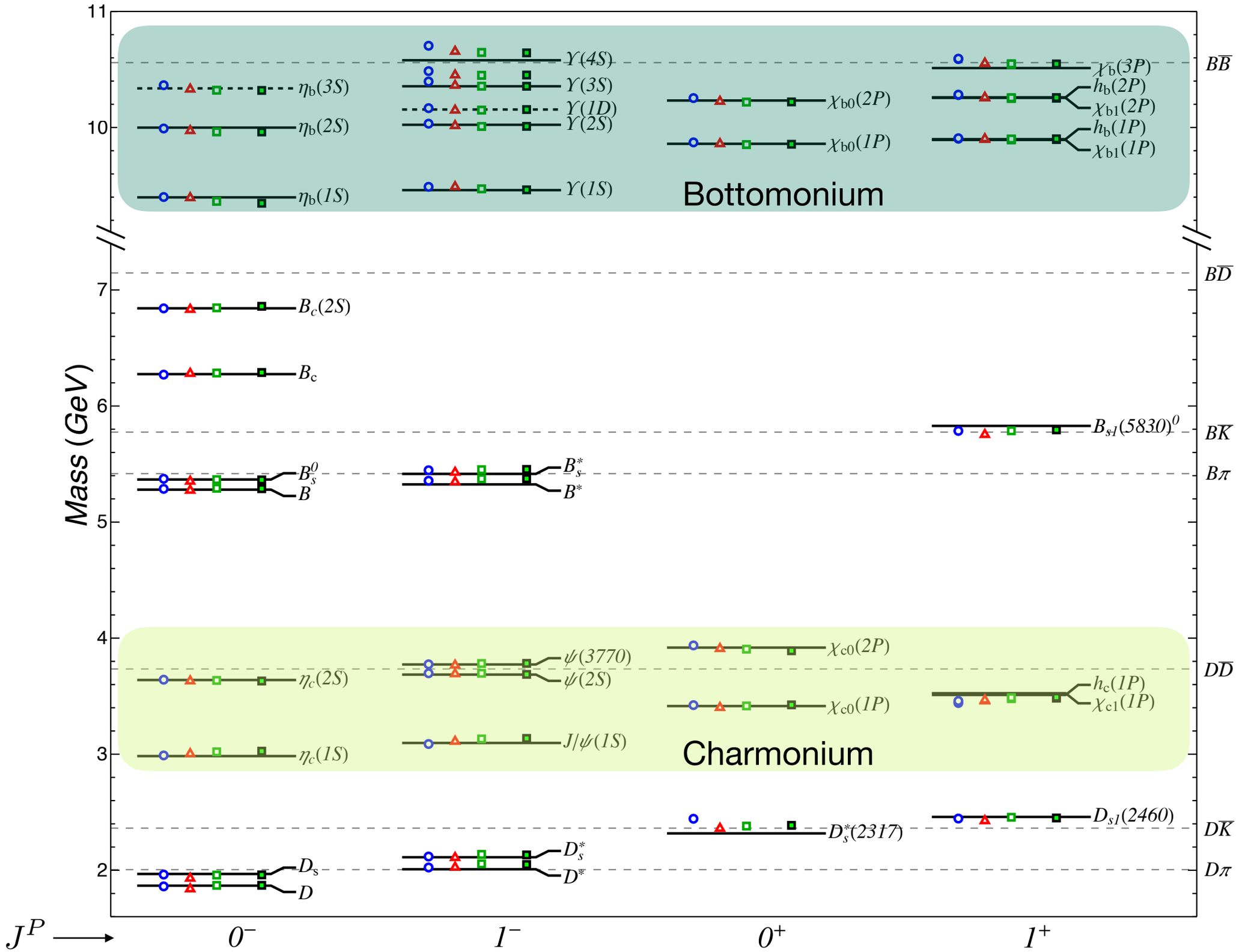
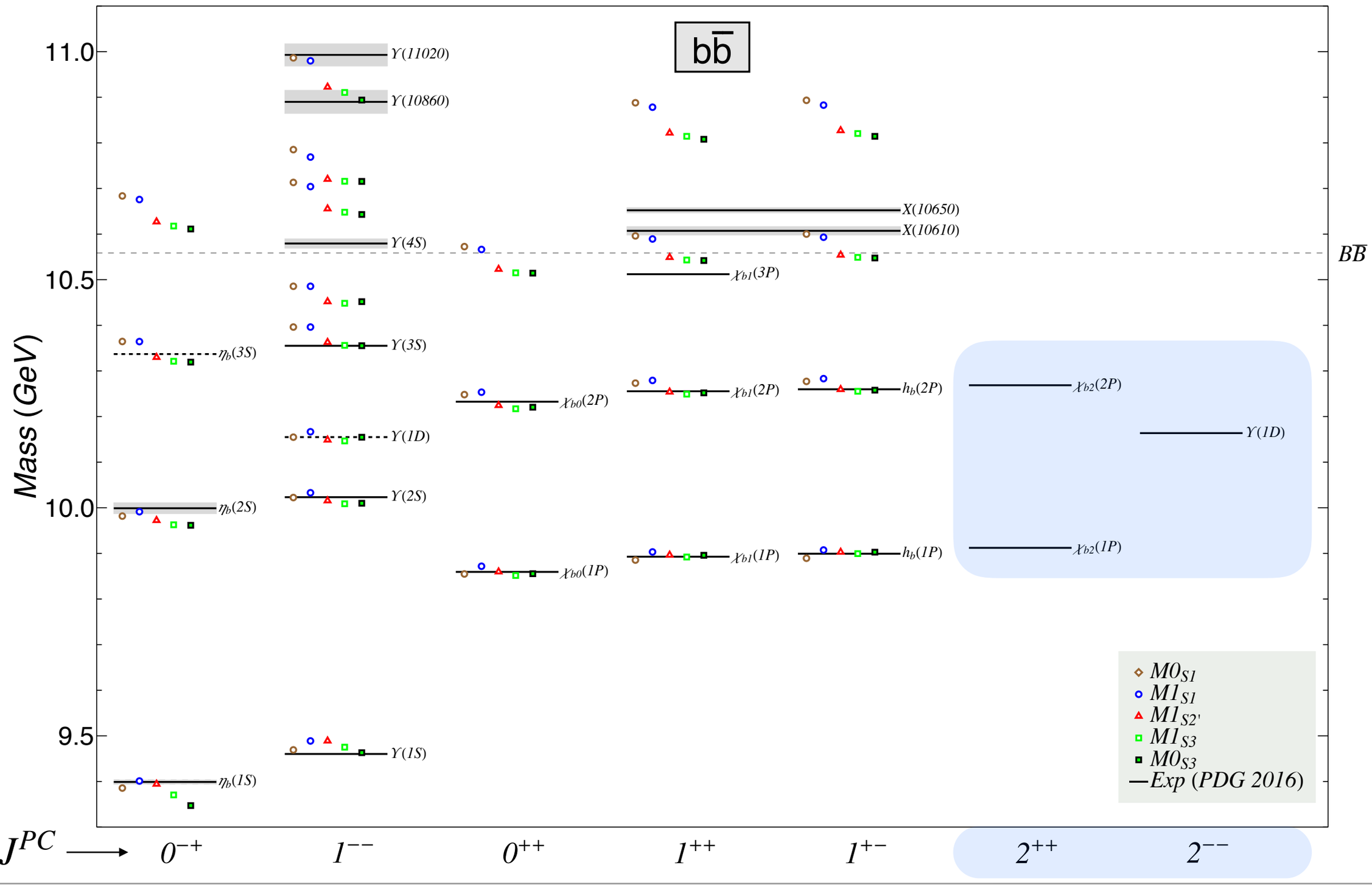


Topic 1: Tensor mesons

Calculation of tensor mesons (spin ≥ 2)



Topic 2: Role of relativity

Relativistically covariant quark-antiquark interaction kernel

$$\mathscr{V}(p,k) = \Big[(1-y)\big(\mathbf{1}_1 \otimes \mathbf{1}_2 + \gamma_1^5 \otimes \gamma_2^5\big) - y\,\gamma_1^\mu \otimes \gamma_{\mu 2}\Big]\, V_{\mathrm{L}}(p,k) - \gamma_1^\mu \otimes \gamma_{\mu 2}\,\big[V_{\mathrm{OGE}}(p,k) + V_{\mathrm{C}}(p,k)\big]$$

Nonrelativistic limit
+ 1st order relativistic corrections

$$V_C + \mathbf{S}_1 \cdot \mathbf{S}_2\, V_{SS} + \mathbf{L} \cdot \mathbf{S}\, V_{LS} + S_{12}\, V_T + \ldots$$

central spin-spin spin-orbit tensor

- Calculate nonrelativistic limit of $q\bar{q}$ interaction,
  but keep first order relativistic correction (→ hyperfine interaction)
- Solve nonrelativistic equation with relativistic corrections
- Compare with full relativistic results (masses and wave functions)
- As quark masses become smaller, where does the nonrelativistic description break down?

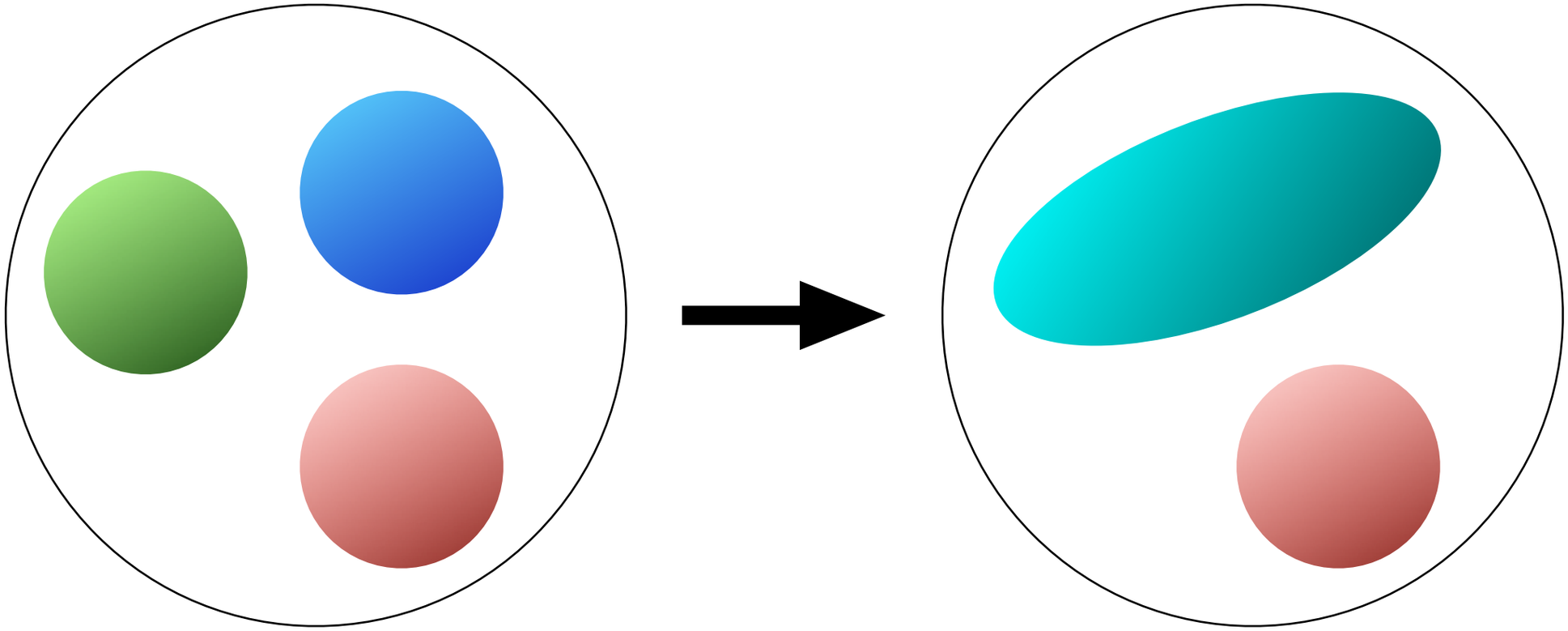
Topic 3: Quark mass function

Bare quark

Dressed quark

- A quark can interact with itself through the same mechanism as with another quark
- This quark self-interaction generates a momentum-dependent mass
- We have already calculated the gluon-contribution to the quark mass function in CST
- What still needs to be calculated is the contribution of the confining interaction

Topic 4: Baryons in a quark-diquark model



- Combine two quarks to a diquark (baryon → two-body problem)
- Quark-diquark interaction is related to quark-antiquark interaction
- Calculations are similar to mesons, but diquark spin is 0 or 1
- Calculate baryon spectrum, relativistic wave functions, form factors, …

More research topics

- There are other related research topics for masters theses
- And many other more advanced topics more suited for Ph. D. work

Ask me if you want to know more!