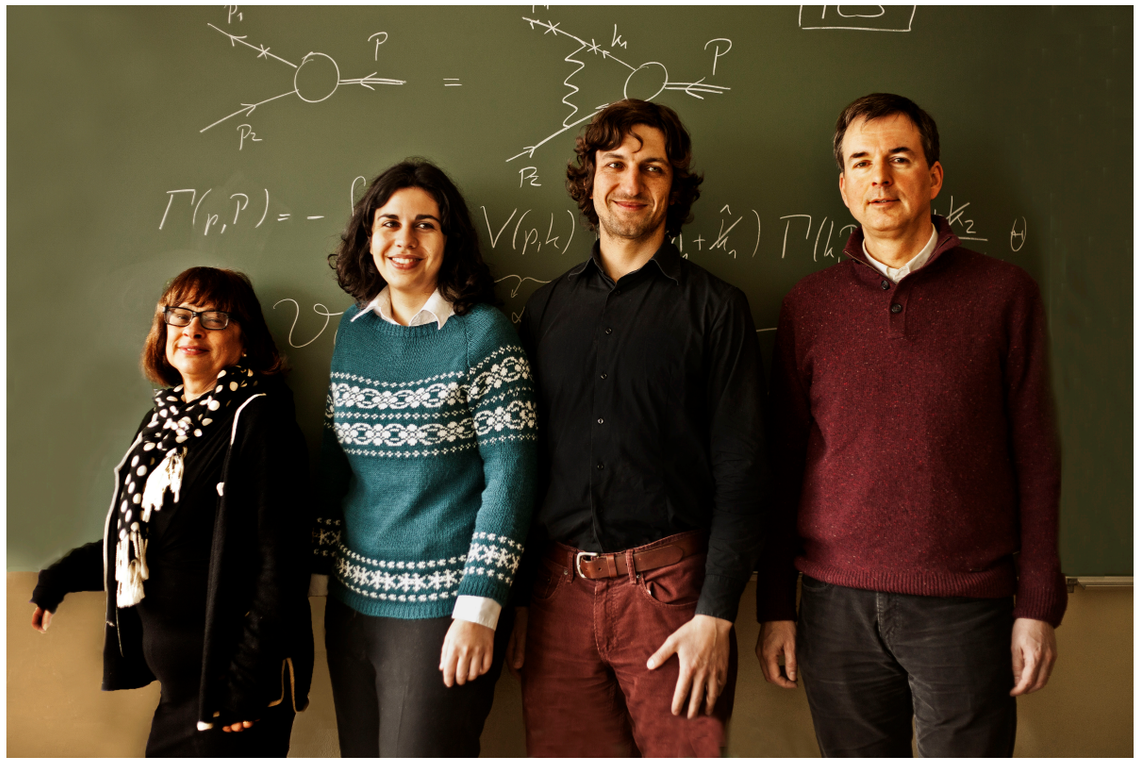
The structure of hadrons

Research opportunities

Alfred Stadler
LIP Lisbon and University of Évora

Fifth Lisbon mini-school on Particle and Astroparticle Physics, Feb 7, 2020

Team members



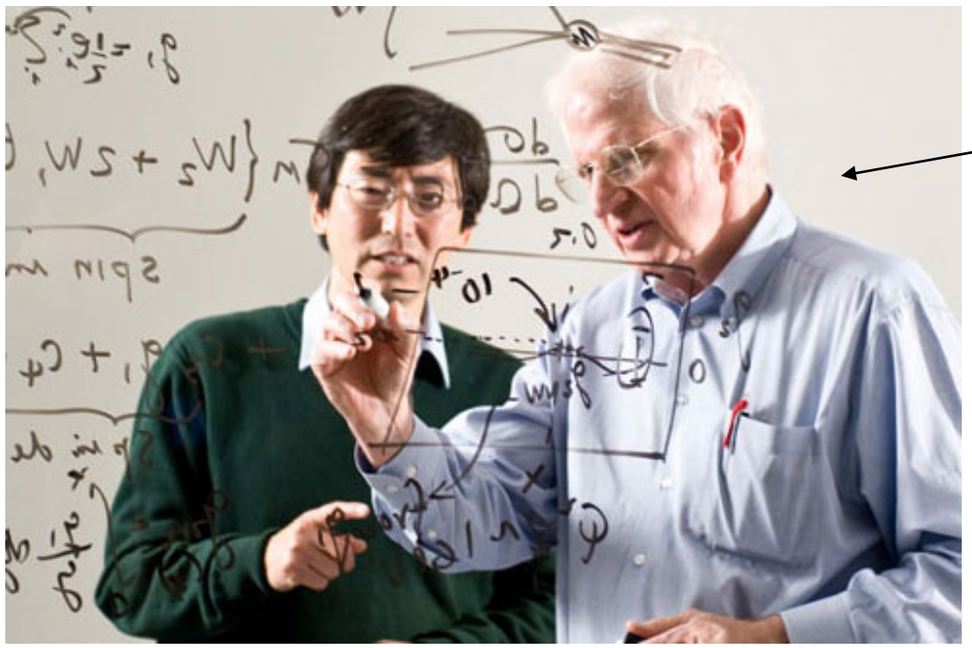
Madalena Lourenço
(just started)

Teresa Peña

Sofia Leitão
(finished PhD)

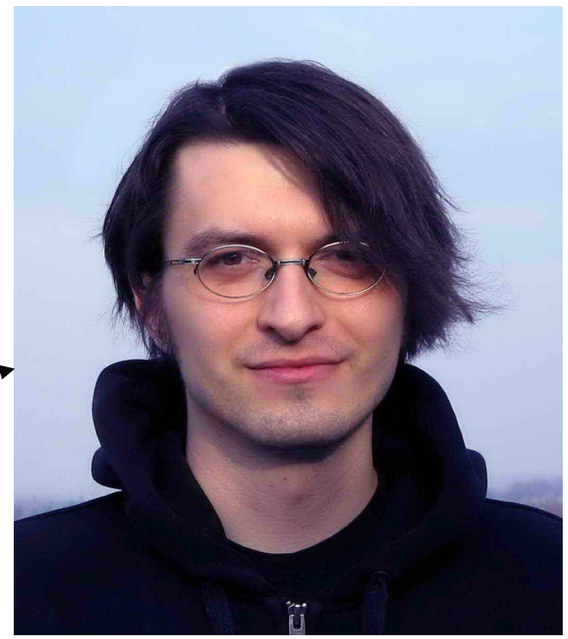
Elmar Biernat

Alfred Stadler



Franz Gross
JLab (USA)

Gernot Eichmann



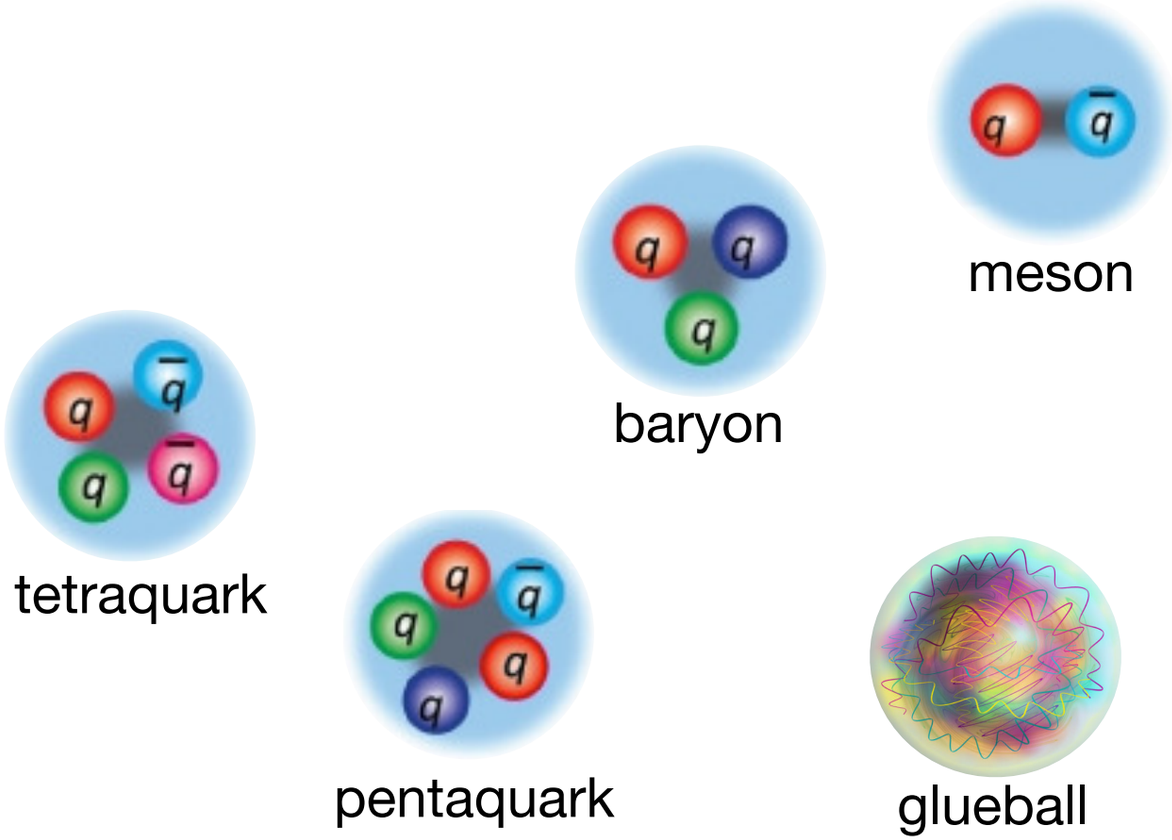
Hadrons

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

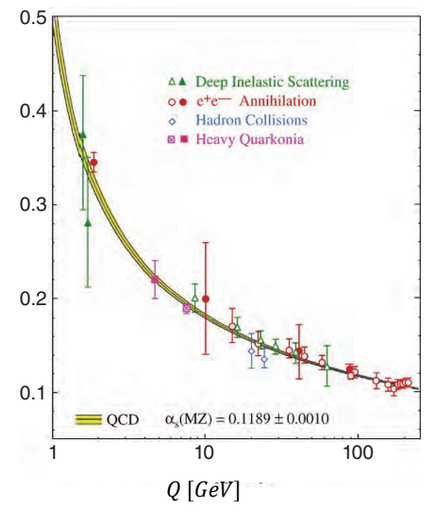
- Intense activity at accelerators around the world
  (Europe, USA, Japan, China, …)
- Measure properties of known hadrons with high precision
- Discovery of new particles
- Search for exotic hadrons



Hadrons

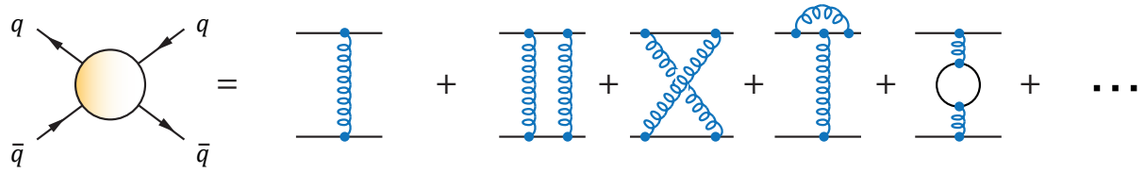
Theory

$$\alpha = \frac{g^2}{4\pi}$$



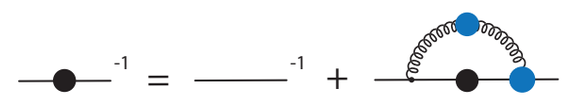
- QCD is very hard to solve (non-perturbative at low energies)

- Bound states cannot be obtained in perturbation theory, need an infinite number of Feynman diagrams

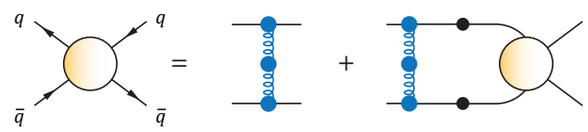


Which tools are available? Lattice QCD, Effective Field Theories, …

Our framework:



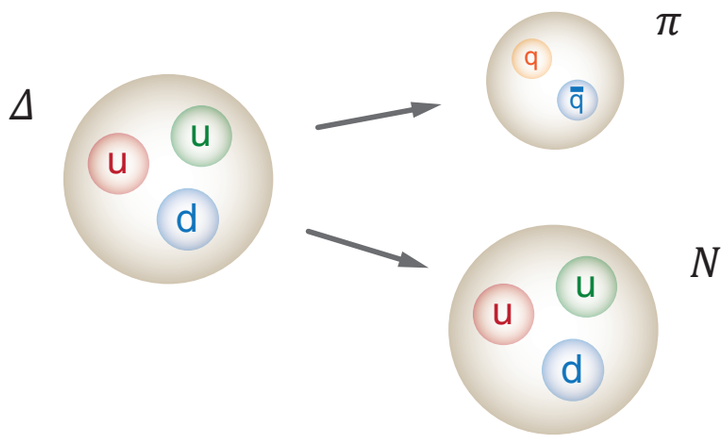
- Dyson-Schwinger/Bethe-Salpeter type equations (DSE/BSE)
- Covariant Spectator Theory (CST)
  Reorganization of DSE/BSE + phenomenology



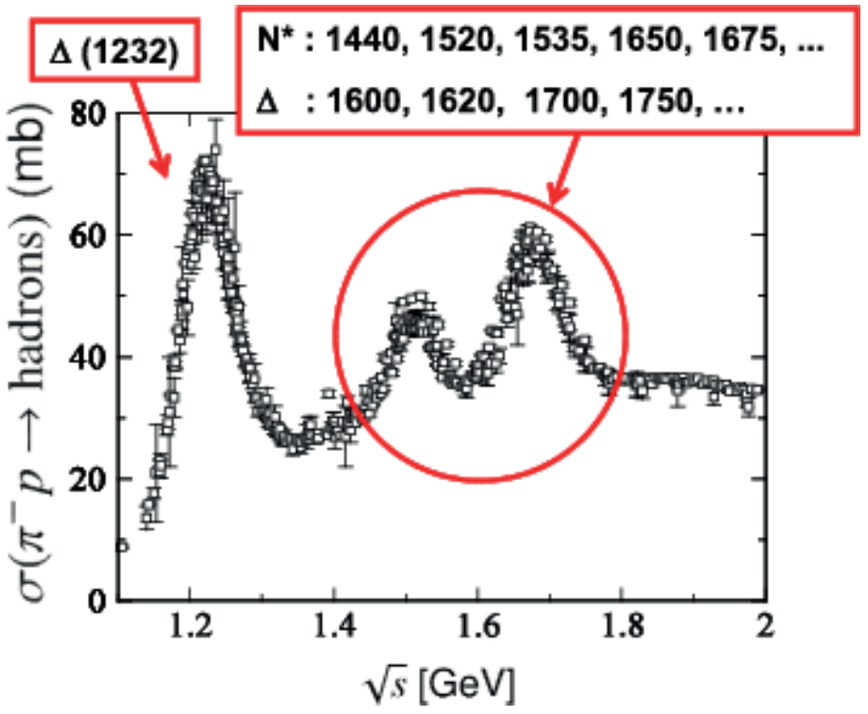
Integral equations: sum an infinite series of a selected class of Feynman diagrams

Topic: Resonances

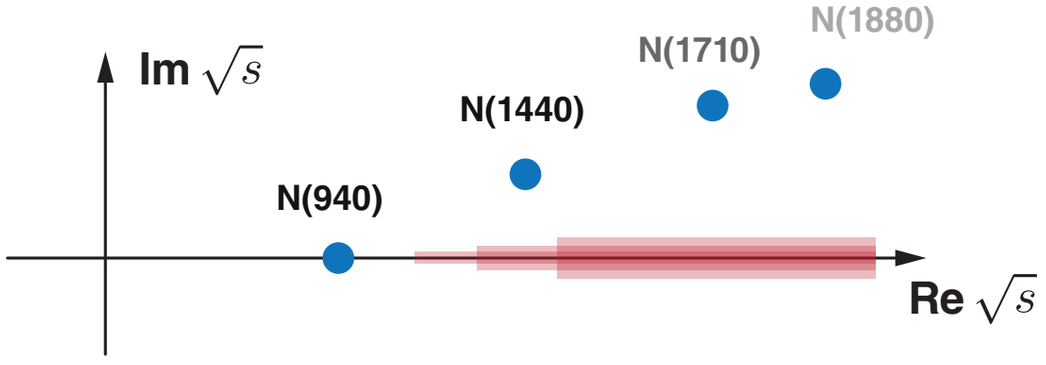
Most hadrons are short-lived resonances and decay into other hadrons



Mathematically: poles in complex momentum plane

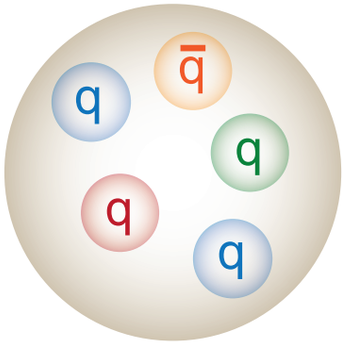


Task: solve BSE numerically and find poles in the complex momentum plane

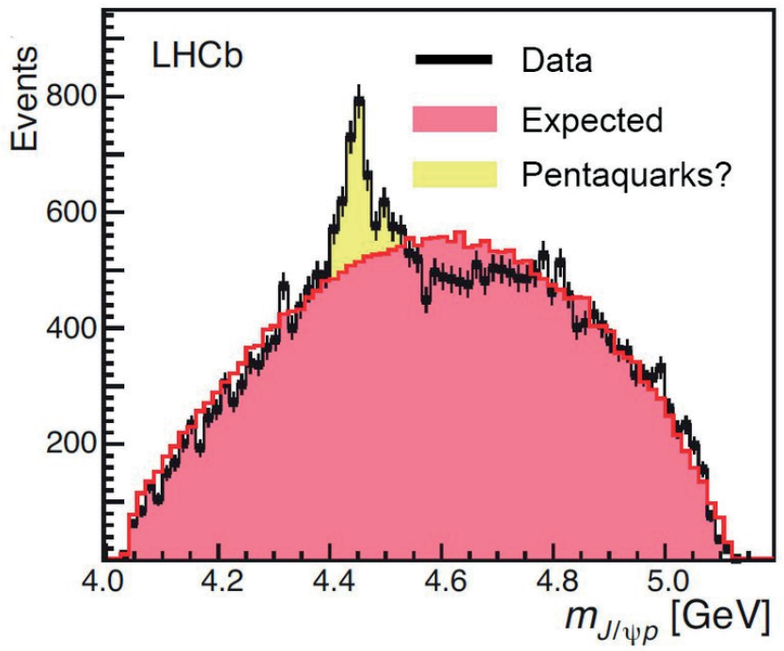


Topic: Exotic hadrons and multiquarks

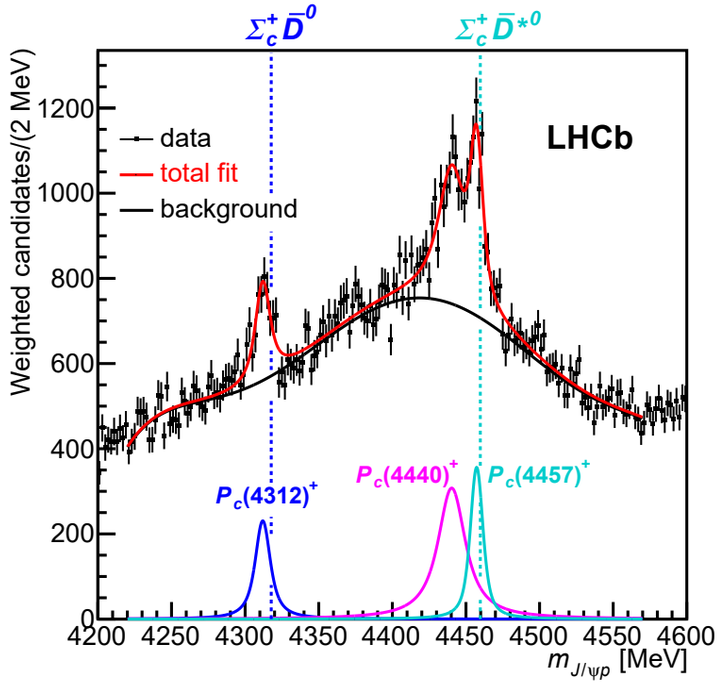
What are pentaquarks?



How are the five quarks distributed?

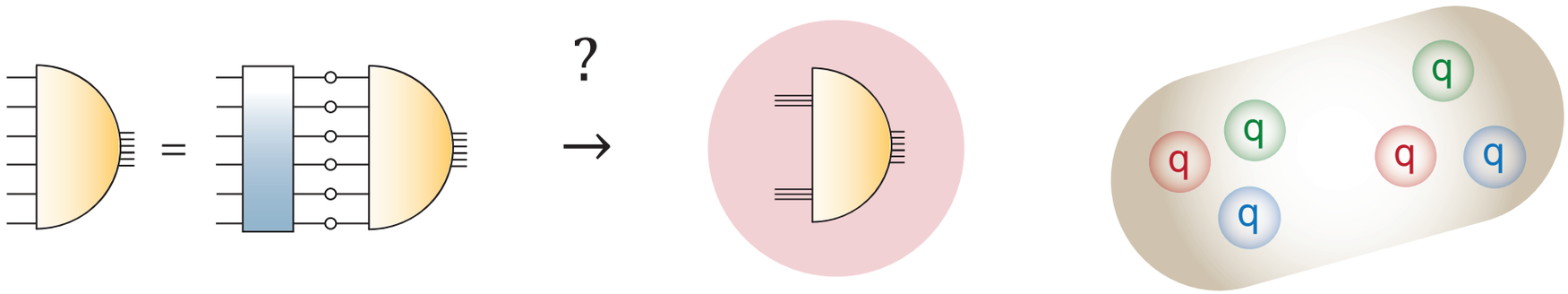


Aaij et al. (LHCb), Phys. Rev. Lett. 115 (2015)

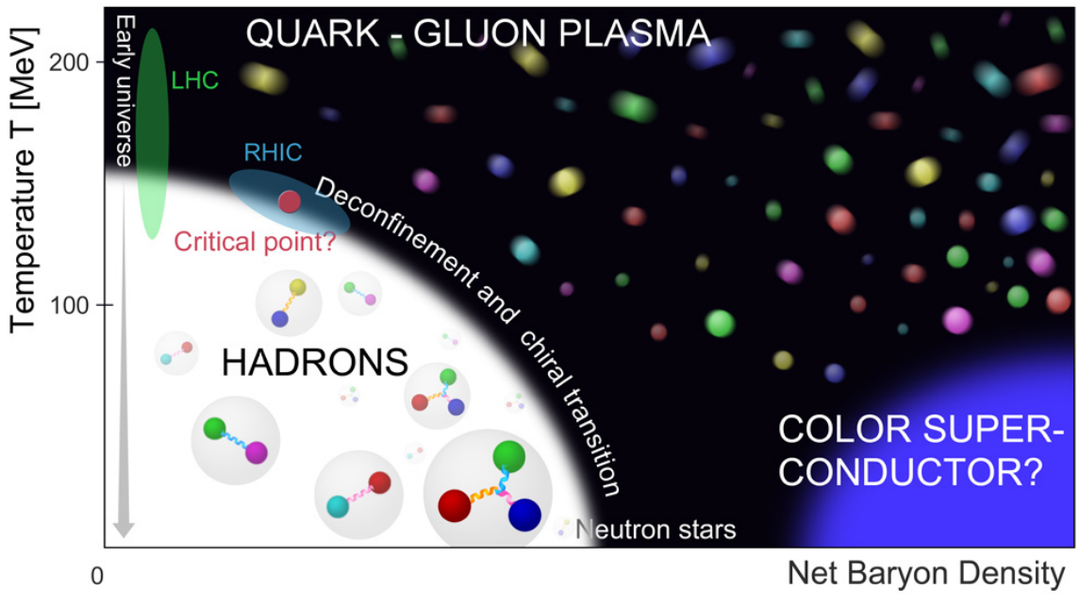


Aaij et al., Phys. Rev. Lett. 112 (2019) 222001

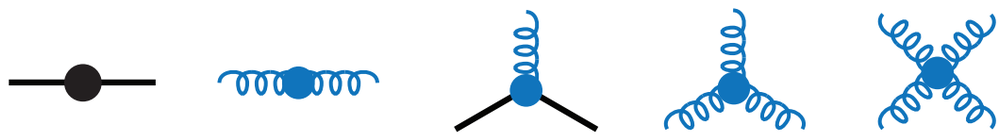
Can we understand the nuclear force from first principles?



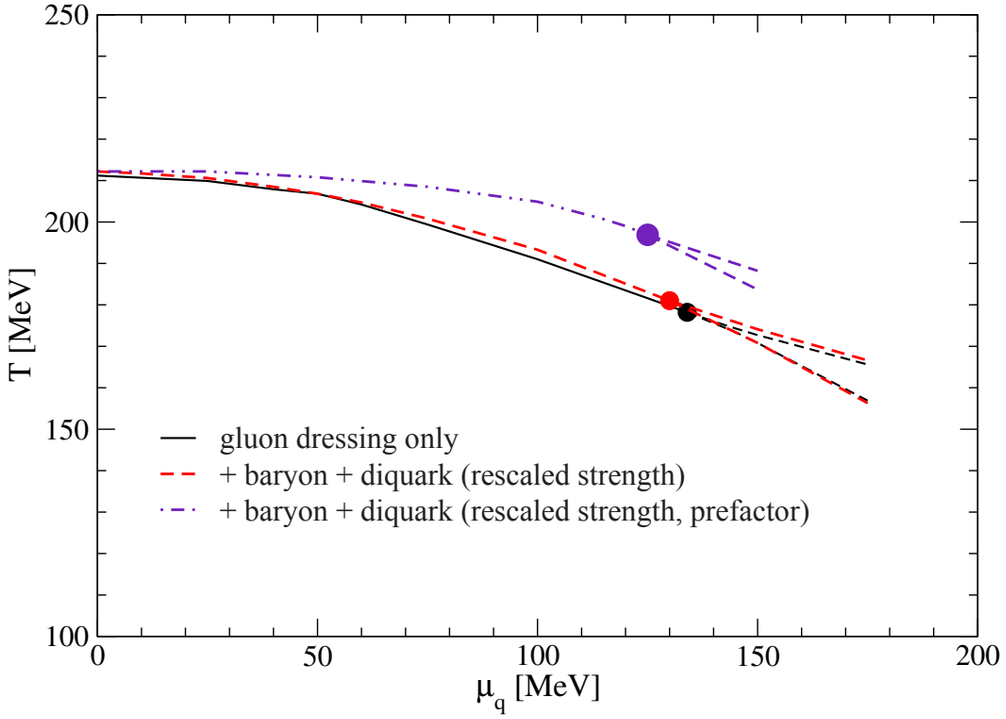
Topic: QCD under extreme conditions



- How do correlation functions change with temperature and density?

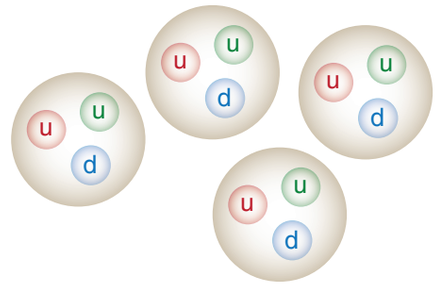


- Is there critical endpoint in the QCD phase diagram?



GE, Fischer, Welzbacher, Phys. Rev. D 93 (2016)

- How important are baryons for the phase transition?



- How does hadronization work?

CST with phenomenological quark-antiquark interaction

Heavy quark systems ~ nonrelativistic

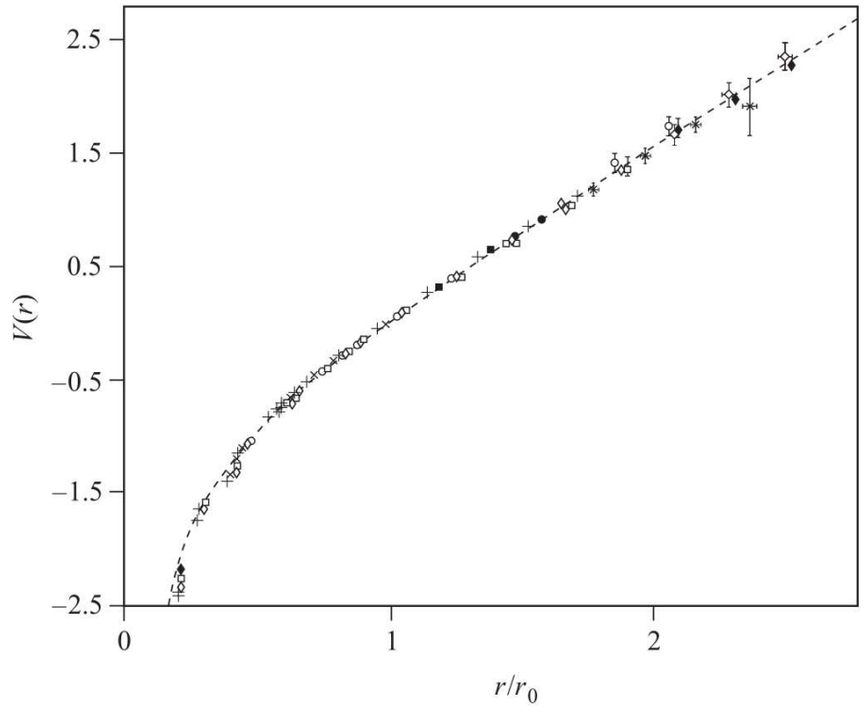
Charmonium $c\bar{c}$ quite well described with the Cornell potential in the Schrödinger equation:

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

Confinement
(long distance)

One-gluon-exchange
(short distance)

Static QCD potential from the lattice



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

CST with phenomenological quark-antiquark interaction

Heavy quark systems ~ nonrelativistic

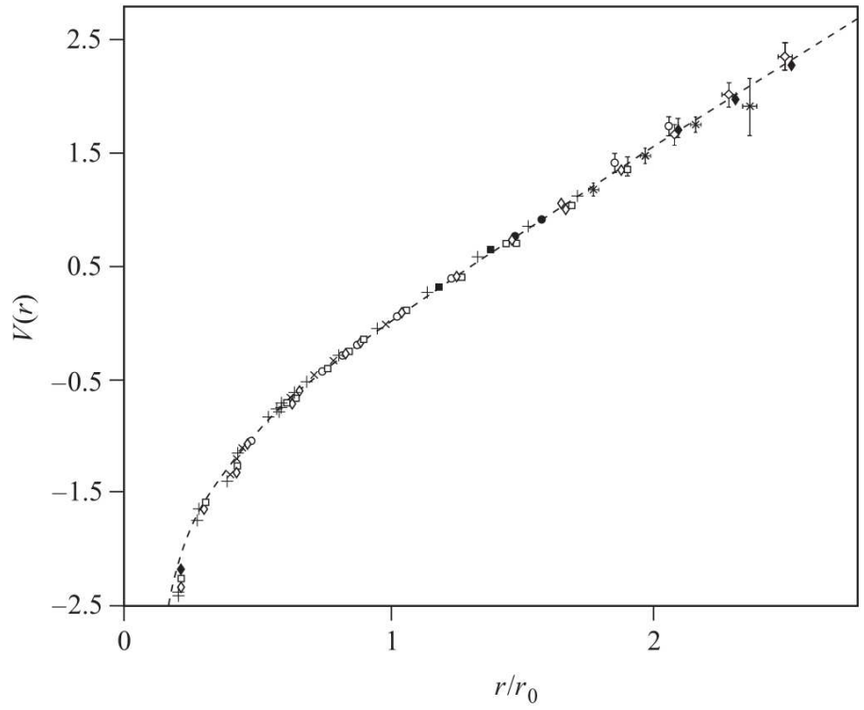
Charmonium $c\bar{c}$ quite well described with the Cornell potential in the Schrödinger equation:

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

Confinement (long distance)

One-gluon-exchange (short distance)

Static QCD potential from the lattice

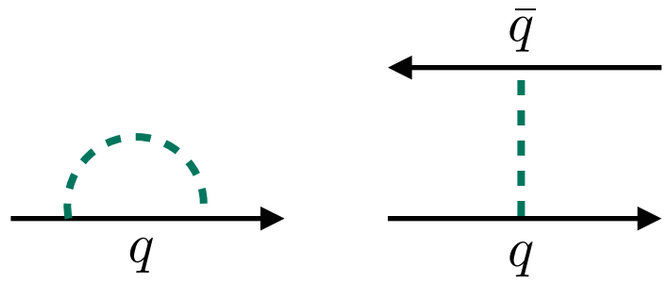


Allton et al, UKQCD Collab., PRD **65**, 054502 (2002)

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

Objectives of our CST approach:

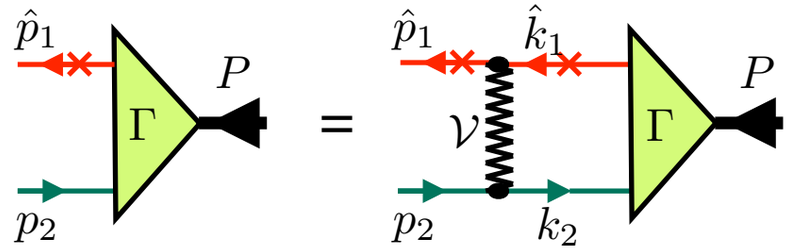
- Find $q\bar{q}$ interaction that can be used in all mesons (unified model)
- Must be relativistic (relativity necessary with light quarks), and reduce to linear+Coulomb in the nonrelativistic limit
- Manifest covariance: strongly constrains spin-dependence of interactions
- Quark masses are dynamic: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

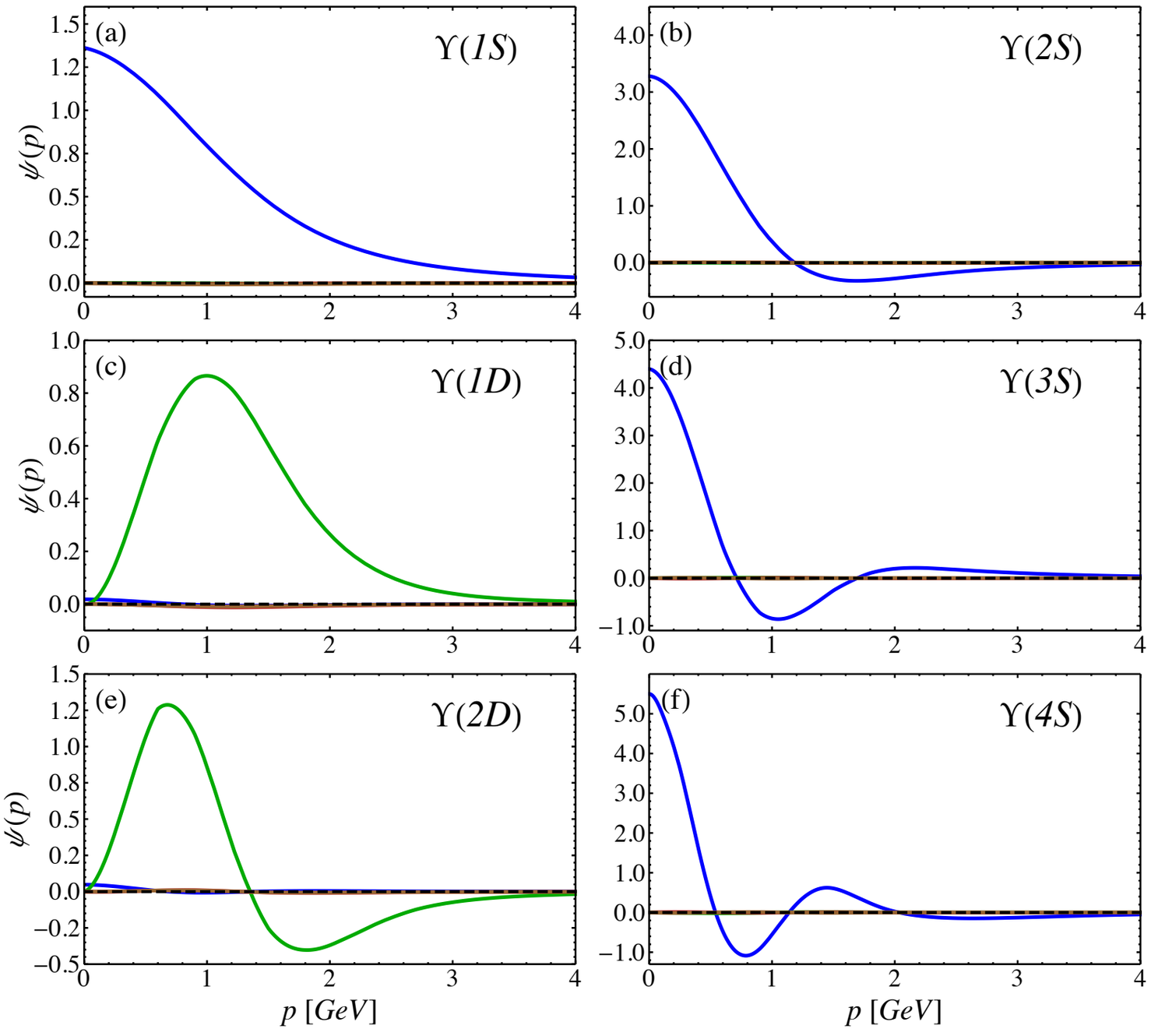


Meson masses and wave functions

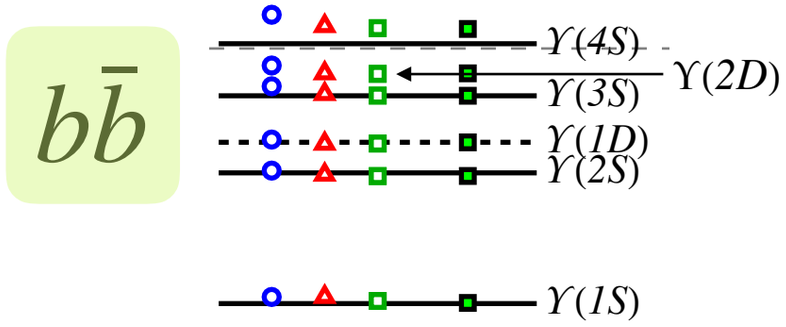
Solutions of the CST bound-state equations:

- meson masses
- vertex functions → relativistic wave functions





Model M1$_{S3}$

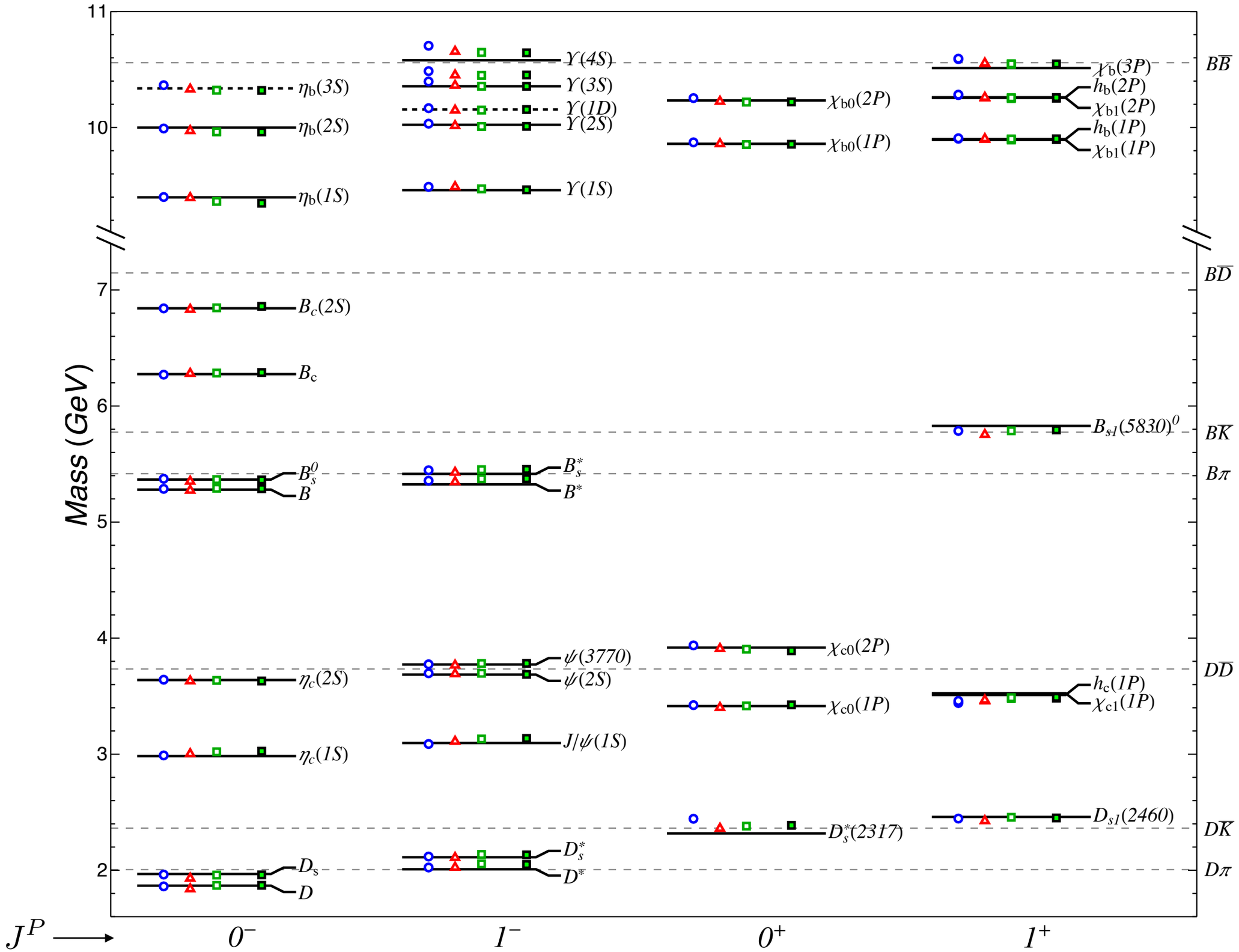


Angular momentum structure:

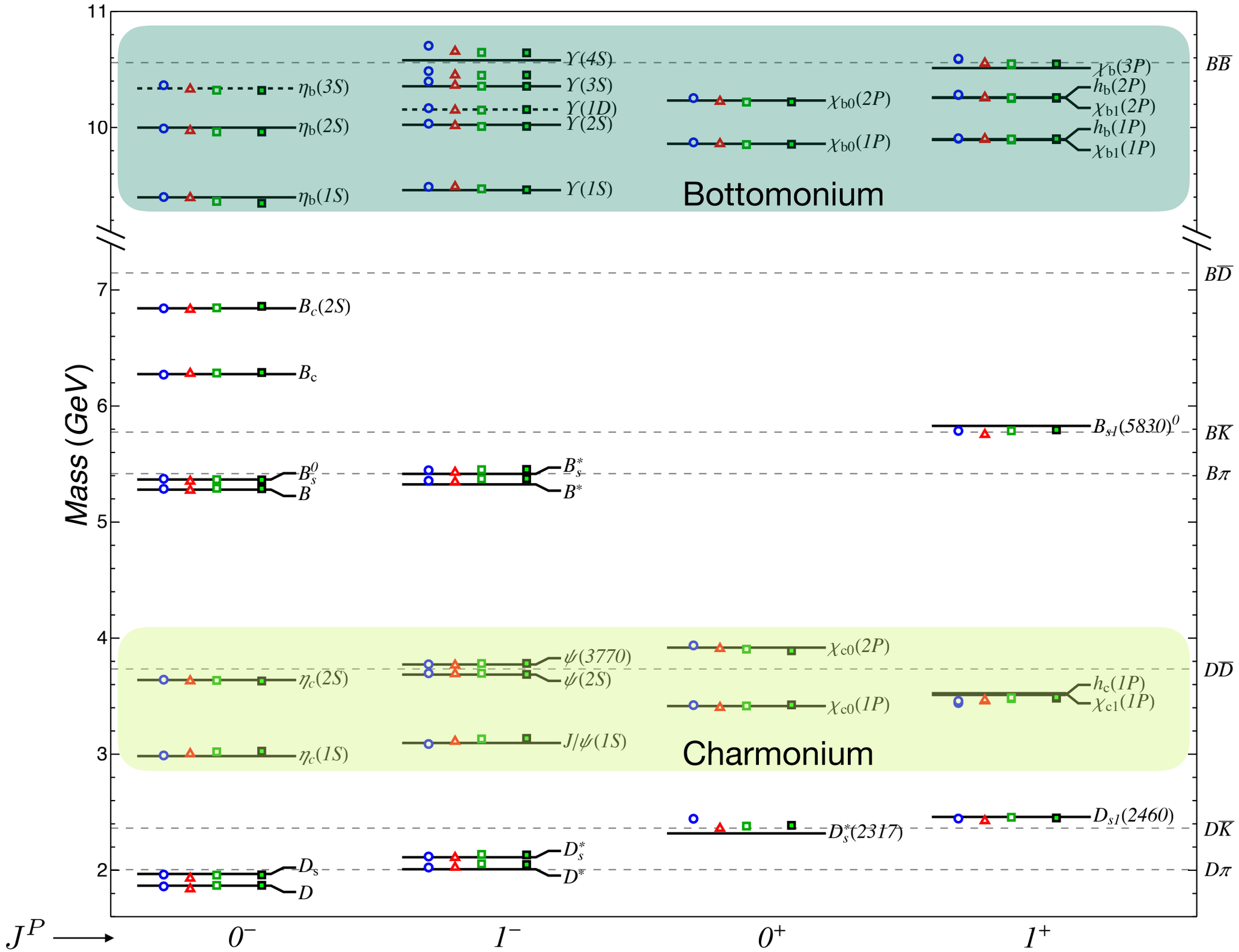
Partial waves

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

Mass spectra of heavy and heavy-light mesons

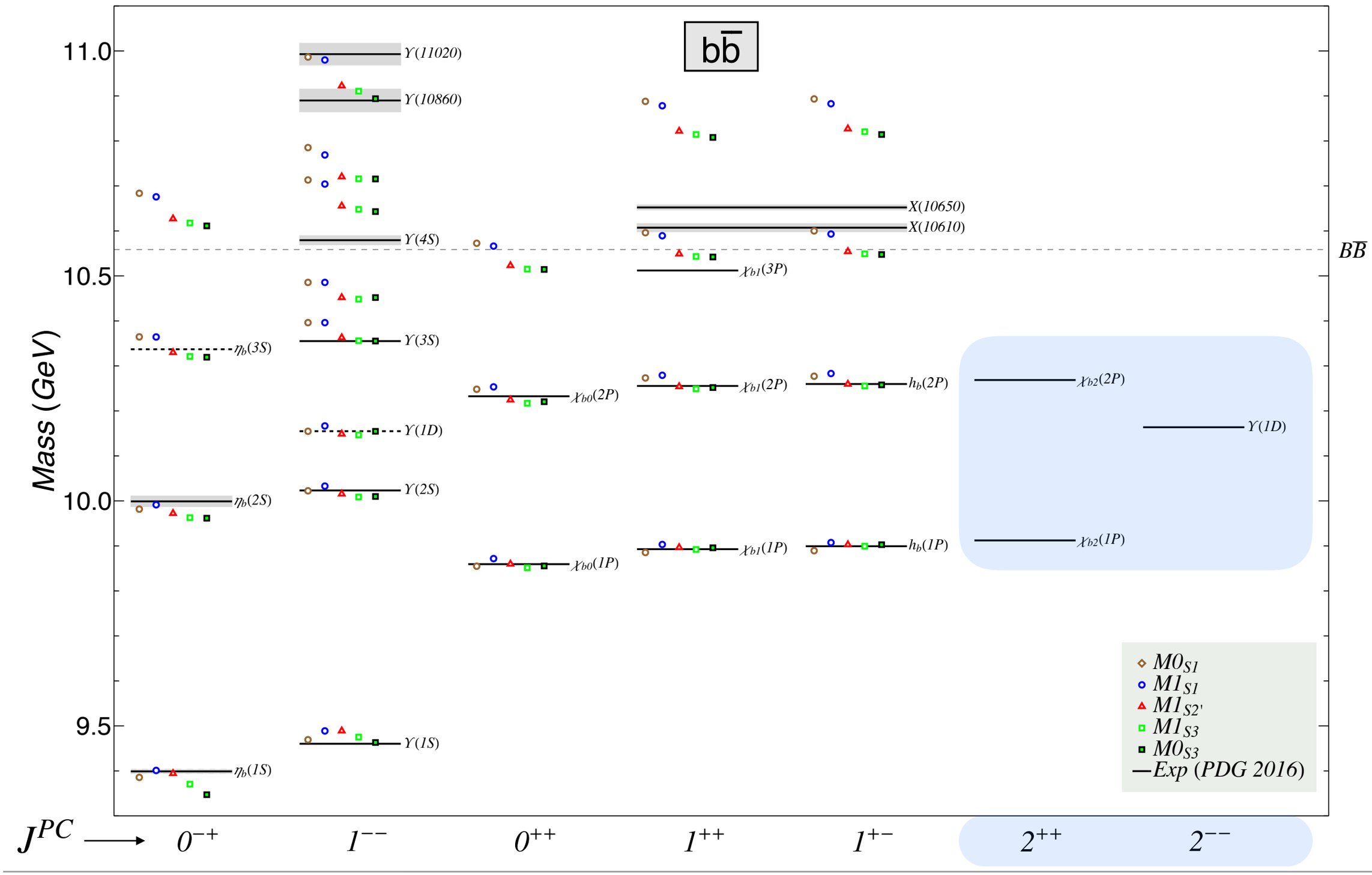


Mass spectra of heavy and heavy-light mesons



Topic: Tensor mesons

Calculation of tensor mesons (spin ≥ 2)



Topic: 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?

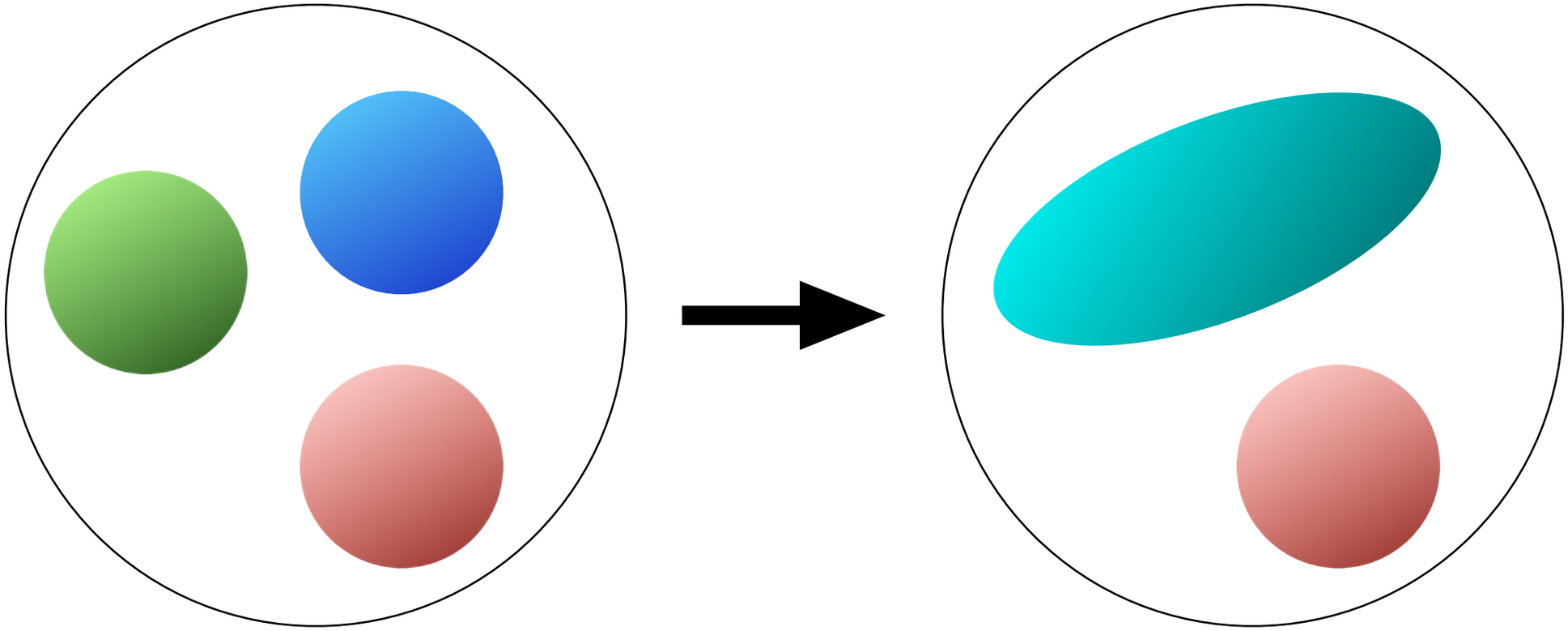
Topic: Quark mass function in CST

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: Baryons in a CST 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

Questions?

stadler@lip.pt

gernot.eichmann@tecnico.ulisboa.pt

teresa.pena@tecnico.ulisboa.pt

elmar.biernat@tecnico.ulisboa.pt