Exotic hadrons with heavy quarks
Part 1: Introduction

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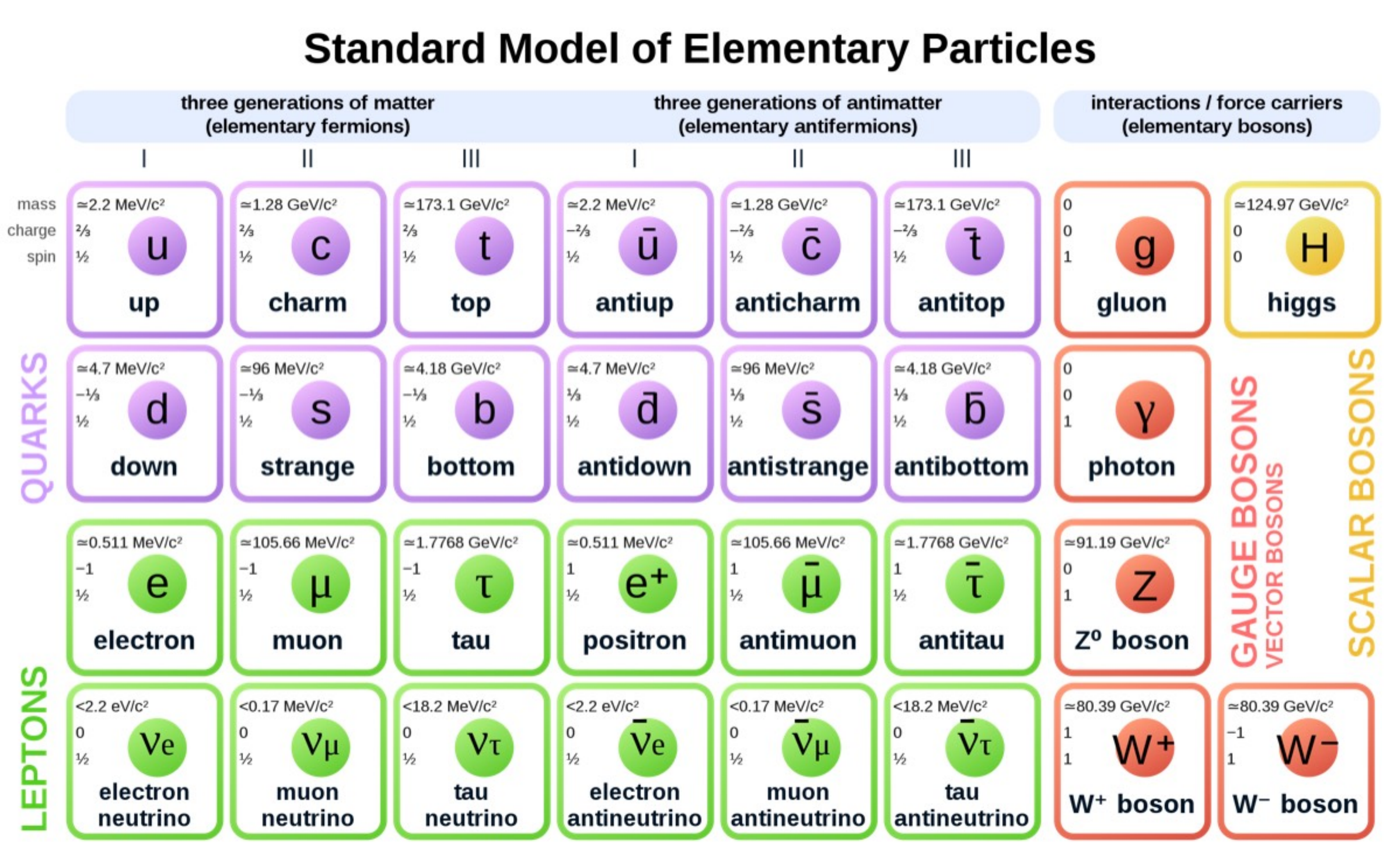
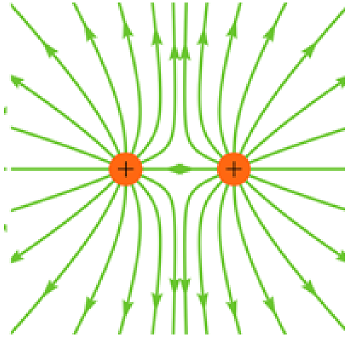
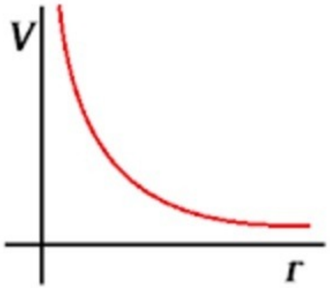
Standard Model of fundamental interactions

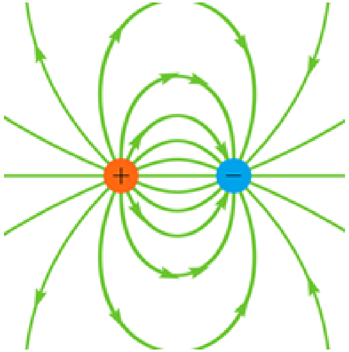


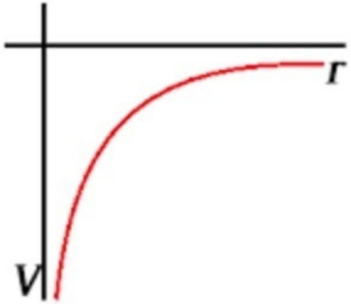
Quantum Electrodynamics

$$L_{\text{QED}} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \bar{\psi}(i\gamma_\mu \partial^\mu - m - e\gamma_\mu A^\mu)\psi$$

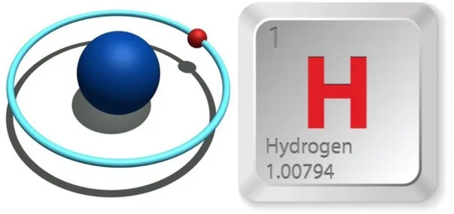


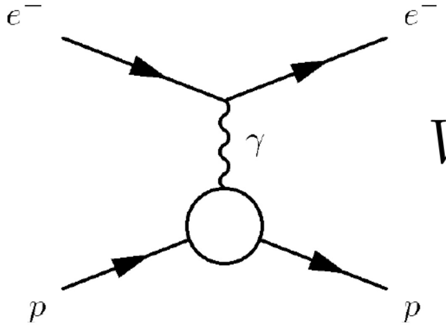






Bound states in QED

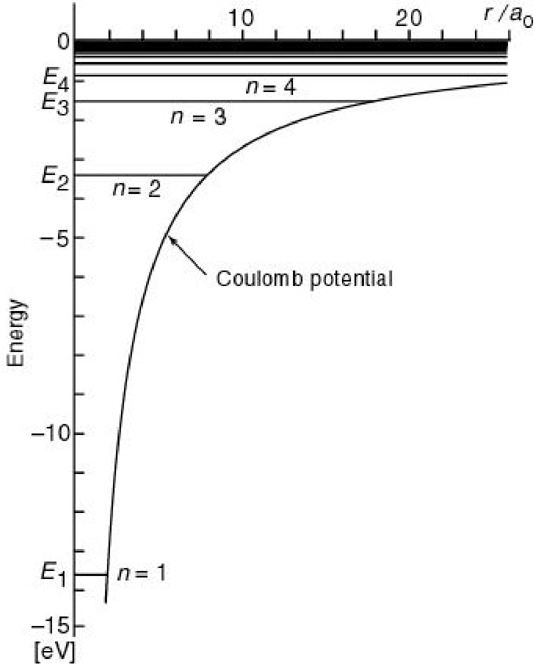




$$V(r) = -\frac{\alpha}{r} \qquad \alpha = \frac{e^2}{4\pi\hbar c} \approx \frac{1}{137} \ll 1$$

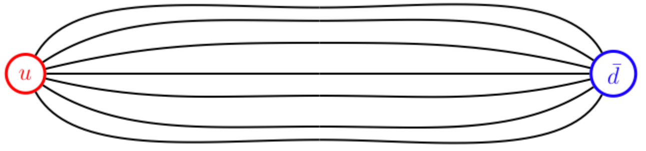
$$E = \frac{m}{\sqrt{1 + \frac{\alpha^2}{\left(n_r + \sqrt{(j+\frac{1}{2})^2 - \alpha^2}\right)^2}}}$$

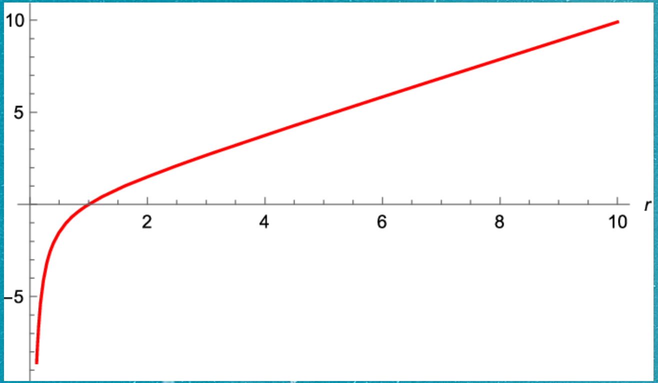
$$E = m - \frac{m\alpha^2}{2(n_r + j + \frac{1}{2})^2} = m - \frac{m\alpha^2}{2n^2}$$

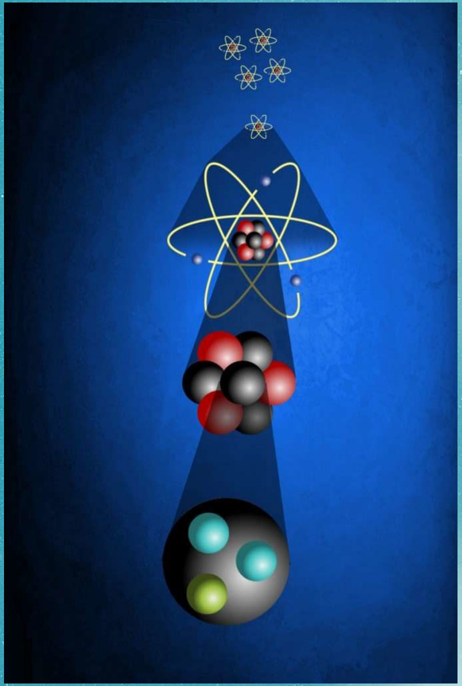


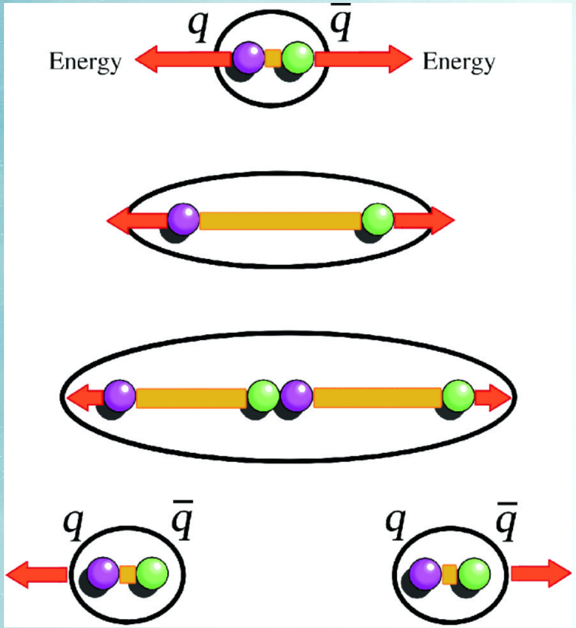
Quantum Chromodynamics

$$L_{\text{QCD}} = -\frac{1}{4} F^a_{\mu\nu} F^{\mu\nu}_a + \bar{\psi}_\alpha (i\gamma_\mu \partial^\mu - m - g\gamma_\mu A^\mu_a t^a)^\alpha_\beta \psi^\beta$$







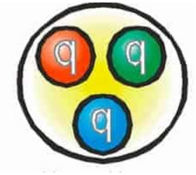


Bound states in QCD - Hadrons

1964 – Invention of constituent Quark Model

Murray Gell-Mann and George Zweig

Quark-antiquark meson



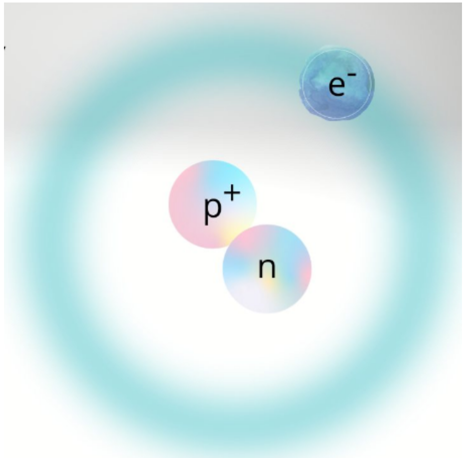
Three-quark baryon

Ordinary hadrons

Exotic hadrons:

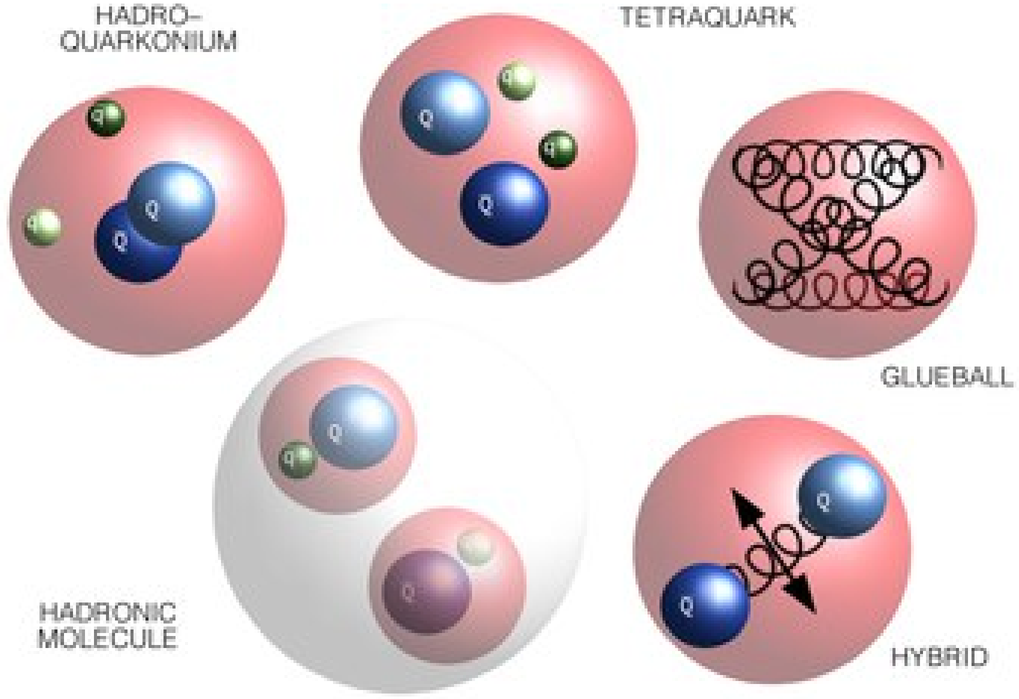
Hadronic Exotica

Deuterium

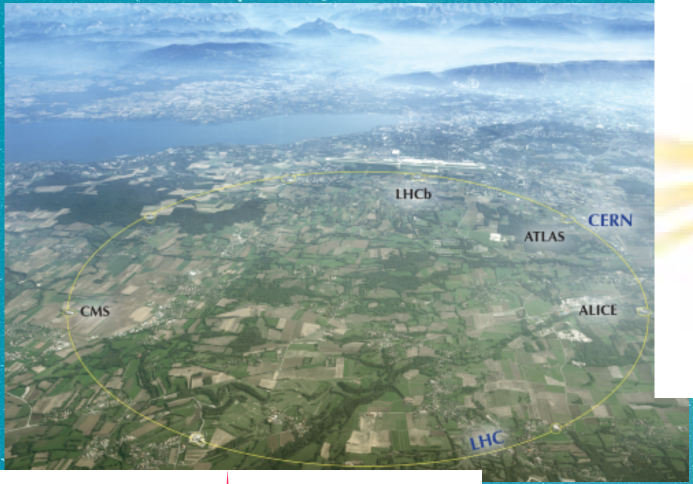


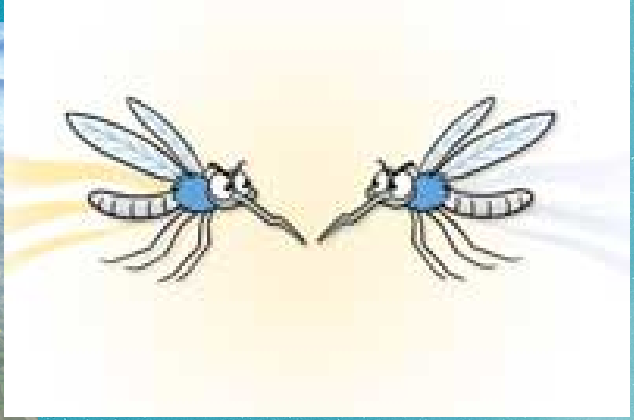
Nucleus is deuteron:
bound state of
proton & neutron

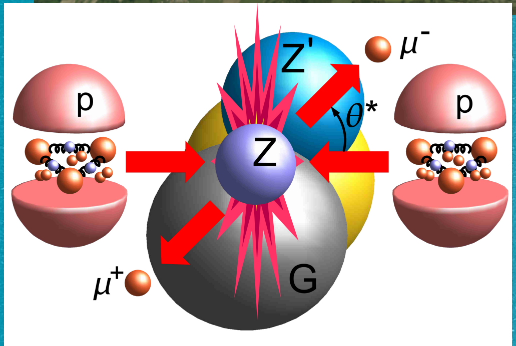
Known for nearly 100 years

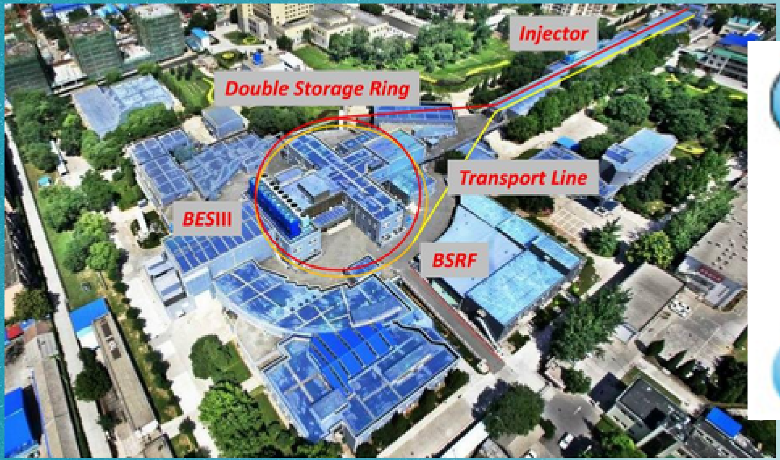


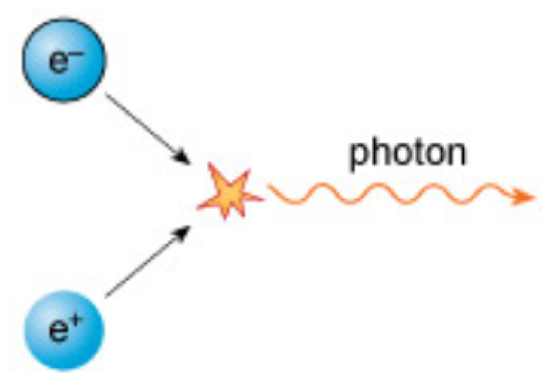
Contemporary collider experiments



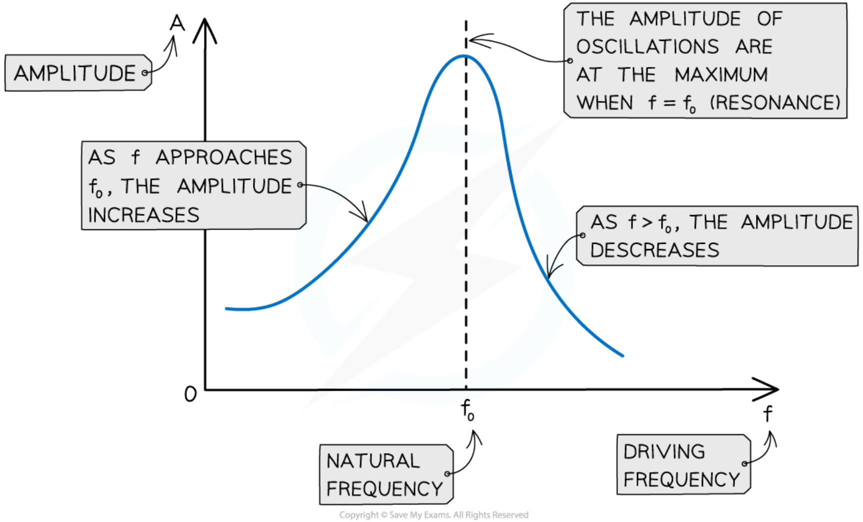


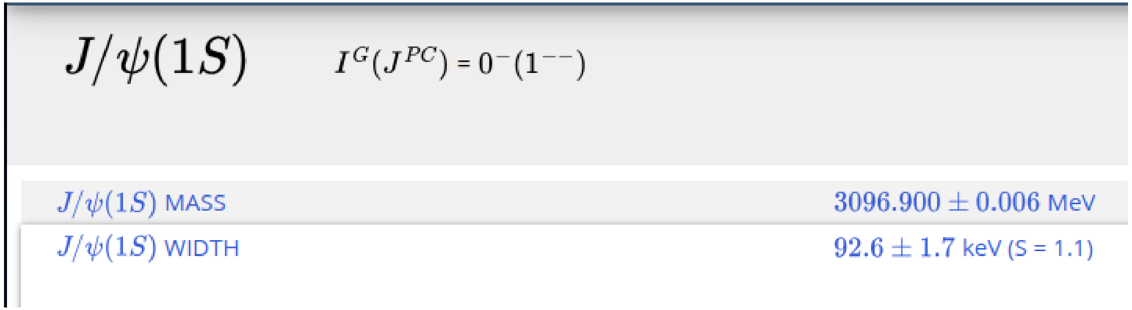






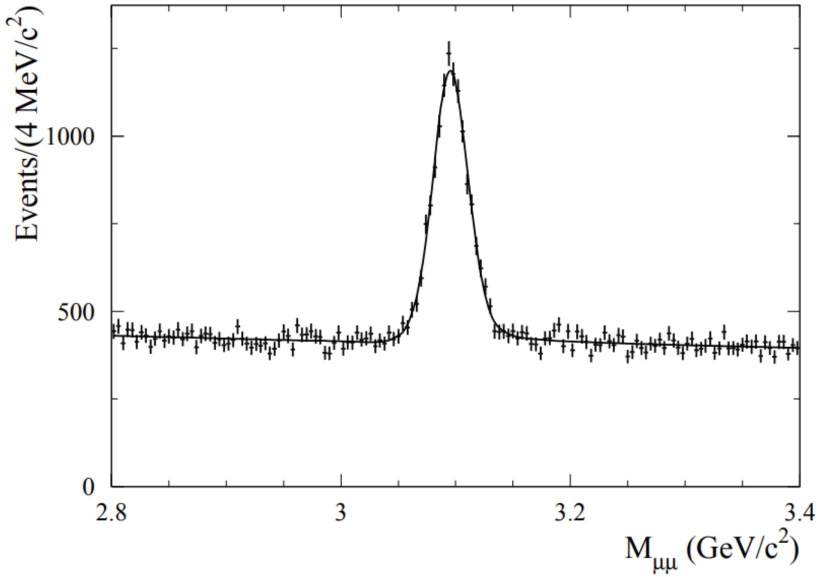
Resonance

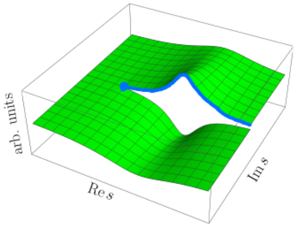




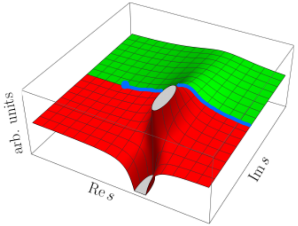
$J/\psi(1S)$ $I^G(J^{PC}) = 0^-(1^{--})$

$J/\psi(1S)$ MASS	3096.900 ± 0.006 MeV
$J/\psi(1S)$ WIDTH	92.6 ± 1.7 keV (S = 1.1)

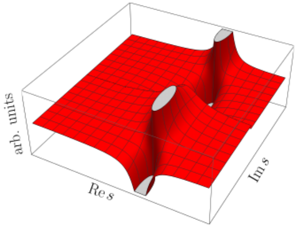




first Riemann sheet



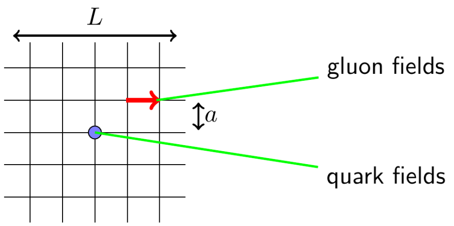
transition from first to second Riemann sheet



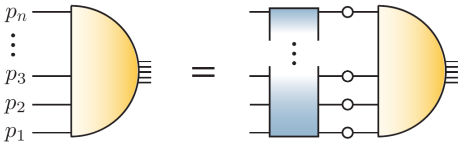
second Riemann sheet

Theoretical Approaches

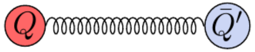
QCD on lattice



Functional Methods



Quark Models



$$H_0 = \sqrt{p^2 + m_1^2} + \sqrt{p^2 + m_2^2} + V_0(r) + V_{\mathrm{SD}}(r)$$

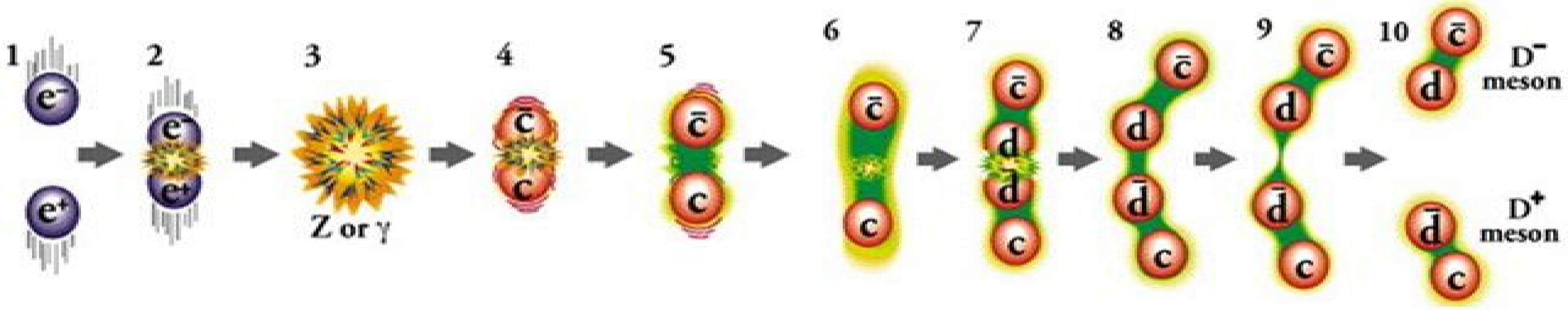
$$V_0(r) = \sigma r - \frac{\frac{4}{3}\alpha_s}{r} + C_0$$

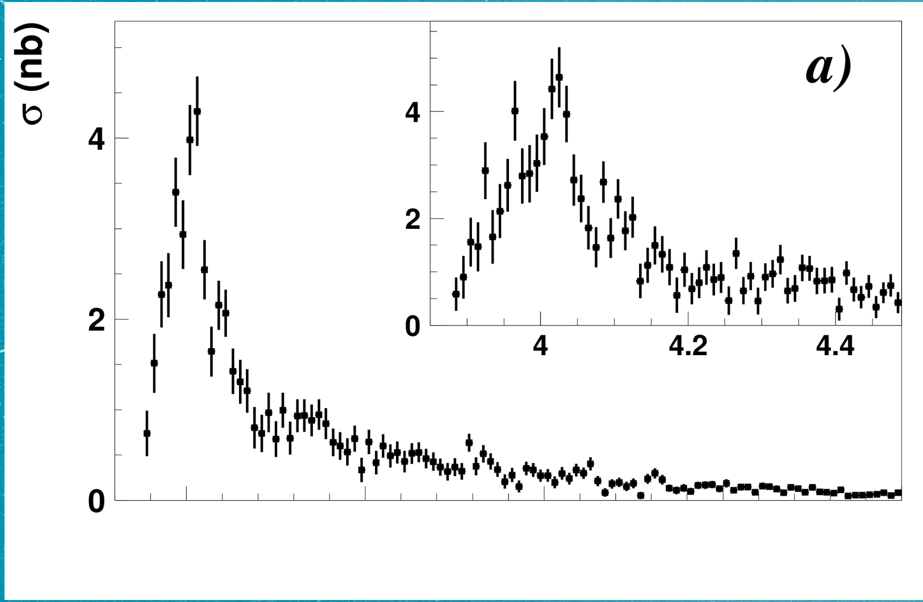
XYZ states

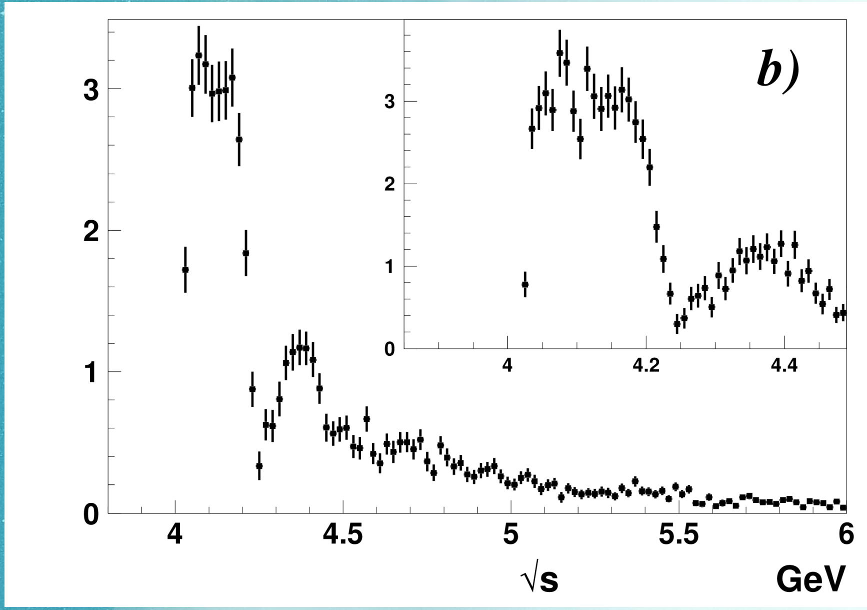
In particle physics, XYZ particles (also referred to as XYZ states) are recently-discovered heavy mesons whose properties do not appear to fit the standard picture of charmonium and bottomonium states. They are therefore types of exotic mesons. The term arises from the names given to some of the first such particles discovered: X(3872), Y(4260) and Zc(3900), although the symbols X and Y have since been deprecated by the Particle Data Group.

Wikipedia

Open-flavour thresholds

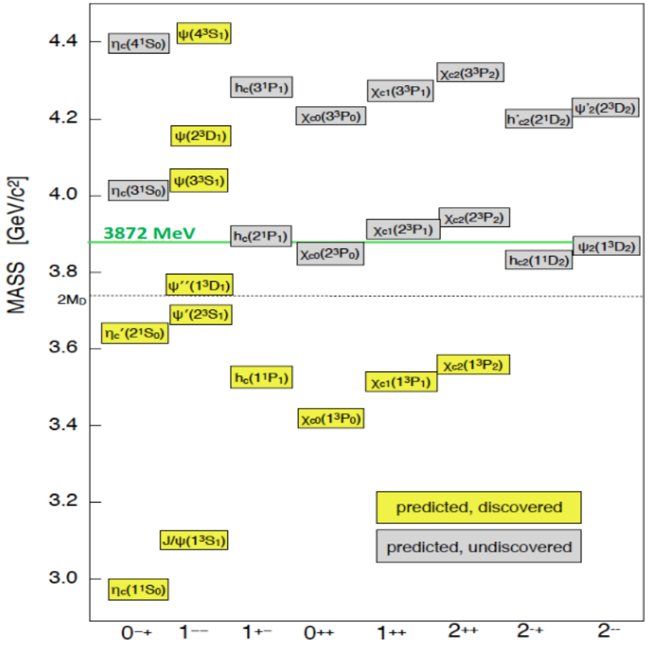


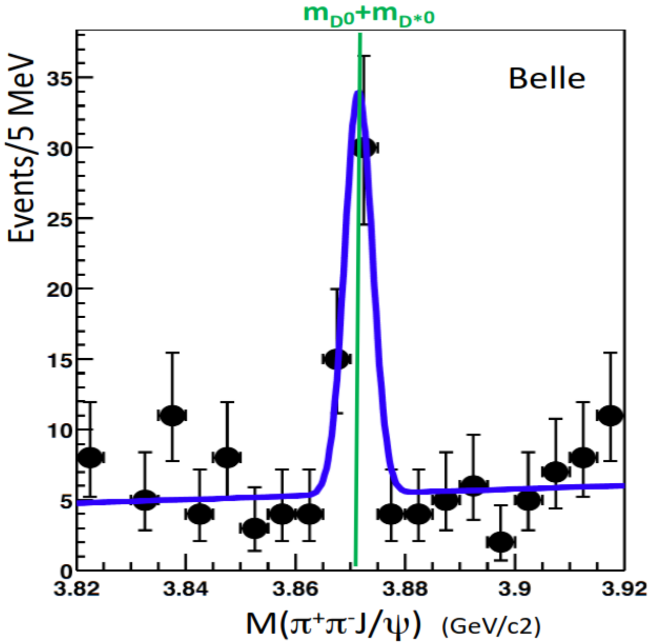




X(3872)

$$M_{X(3872)} = 3871.65 \pm 0.06 \text{ MeV}$$
$$\Gamma_{X(3872)} = 1.19 \pm 0.21 \text{ MeV}$$

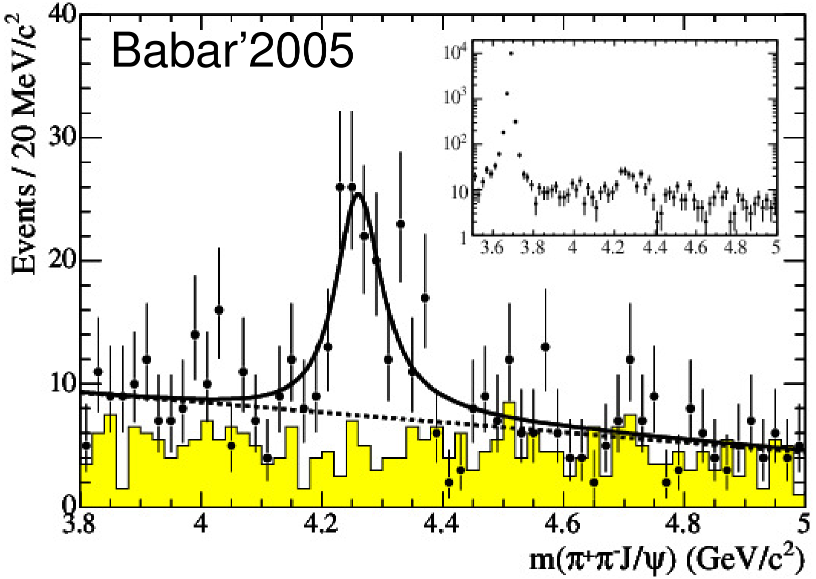




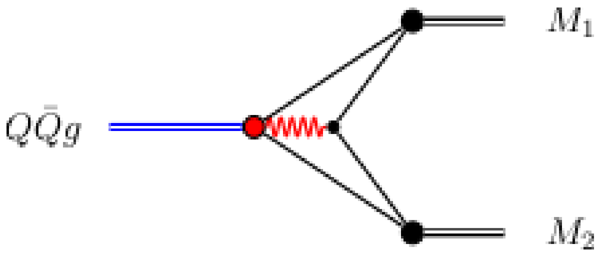
$$|X\rangle = \lambda|\bar{c}c\rangle + \chi(p)|D\bar{D}^*\rangle + \dots$$

$$\psi_{D\bar{D}^*} \underset{r\to\infty}{\sim} e^{-\kappa_B r} \qquad \kappa_B = \sqrt{2\mu E_B}$$

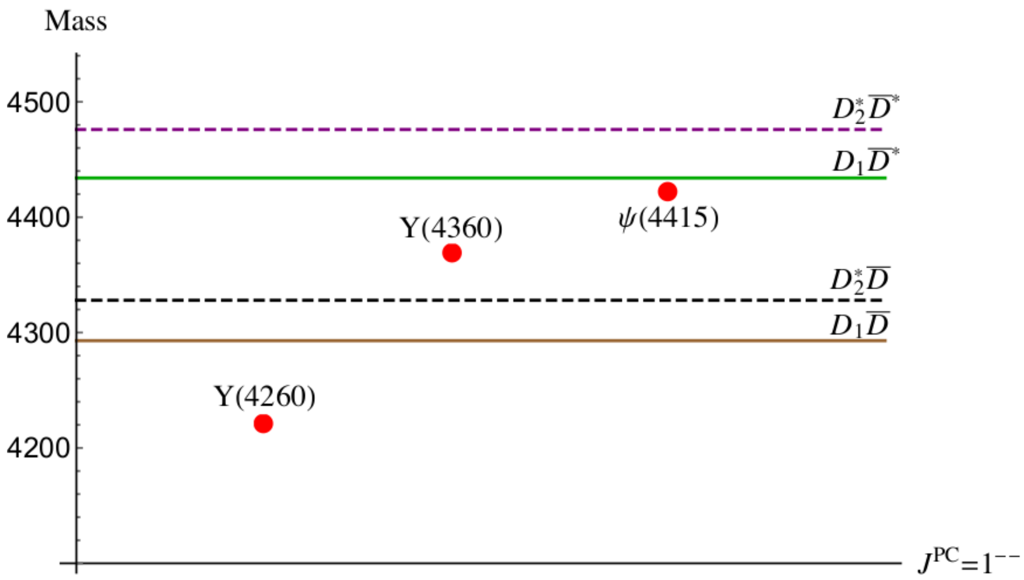
Y(4260)/Y(4230)



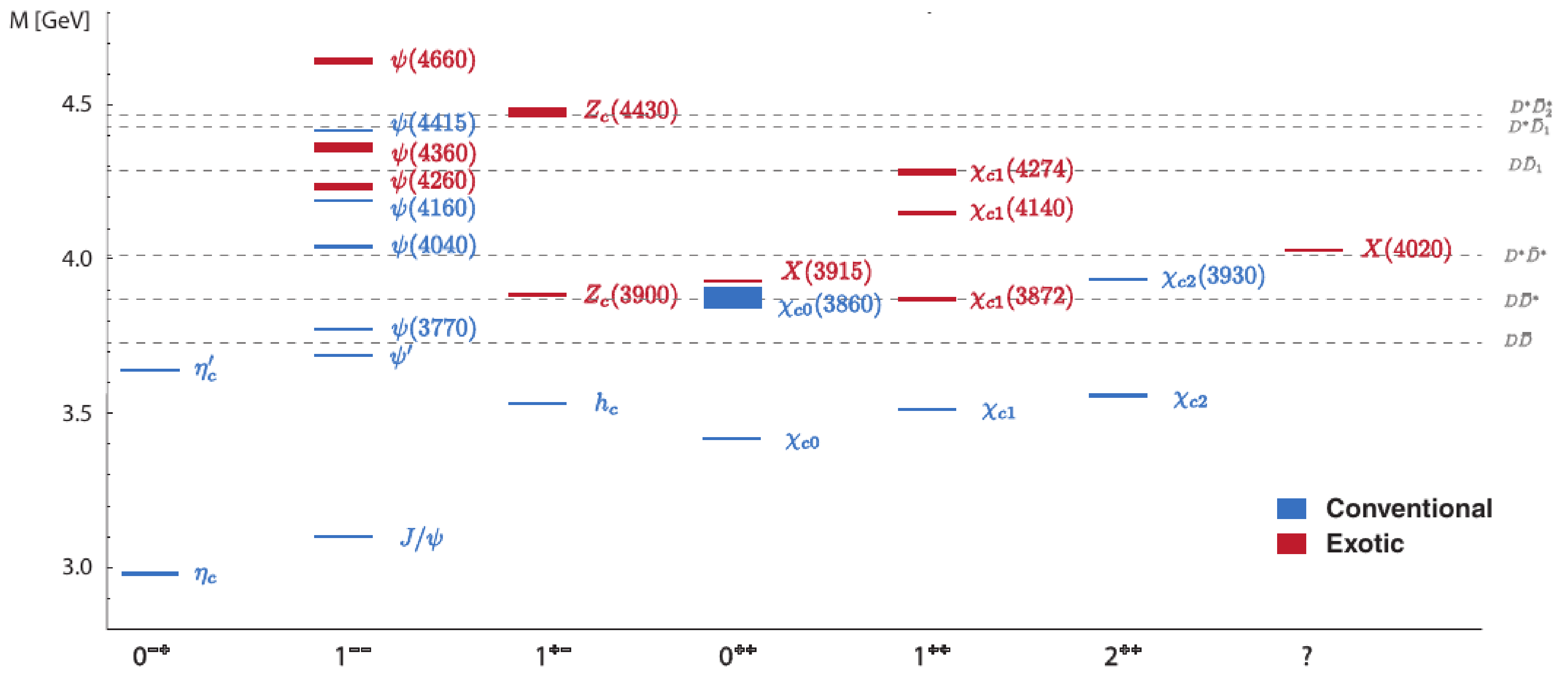
Hybrid?



Molecule?



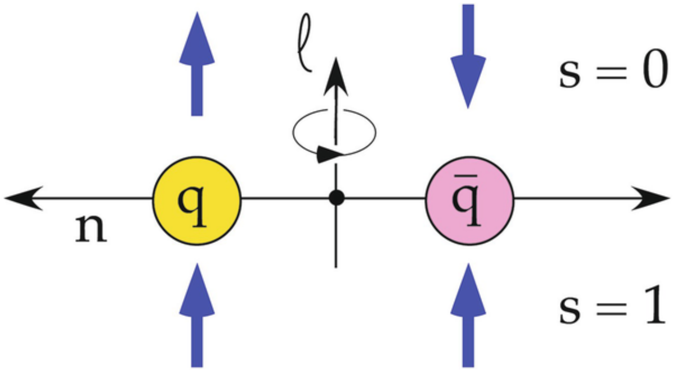
Charmonium



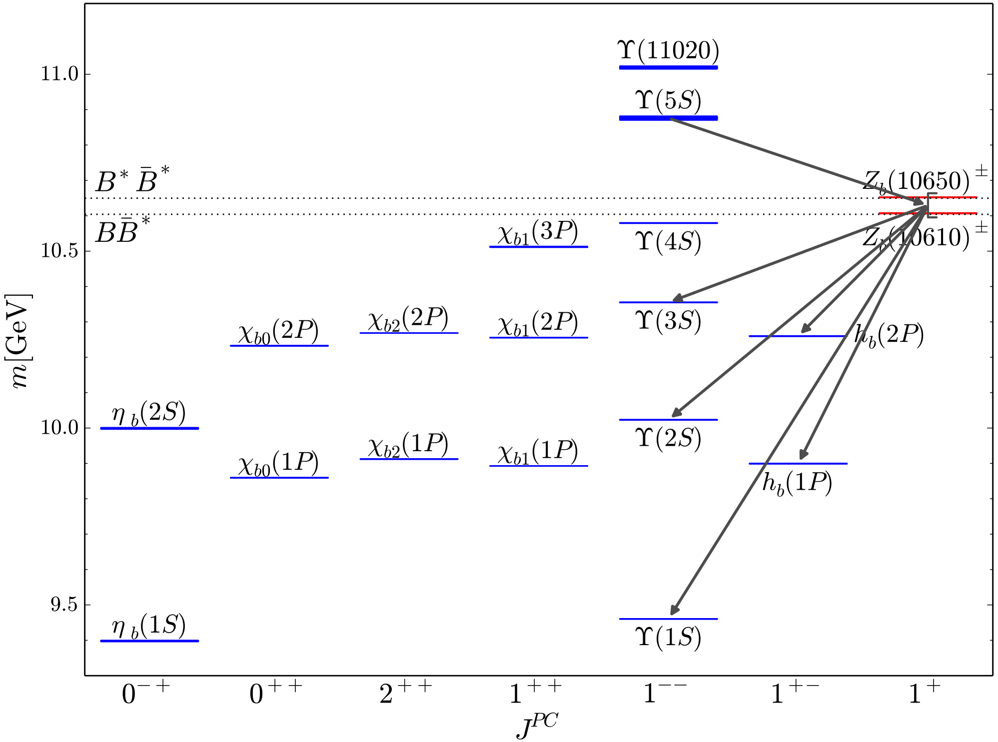
M [GeV]
4.5
4.0
3.5
3.0
$\psi(4660)$
$\psi(4415)$
$\psi(4360)$
$\psi(4260)$
$\psi(4160)$
$\psi(4040)$
$\psi(3770)$
ψ'
J/ψ
η_c'
η_c
$Z_c(4430)$
$Z_c(3900)$
h_c
$X(3915)$
$\chi_{c0}(3860)$
χ_{c0}
$\chi_{c1}(4274)$
$\chi_{c1}(4140)$
$\chi_{c1}(3872)$
χ_{c1}
$\chi_{c2}(3930)$
χ_{c2}
$X(4020)$
$D^*\bar{D}_2^*$
$D^*\bar{D}_1$
$D\bar{D}_1$
$D^*\bar{D}^*$
$D\bar{D}^*$
$D\bar{D}$
Conventional
Exotic
0^{-+}
1^{--}
1^{+-}
0^{++}
1^{++}
2^{++}
?

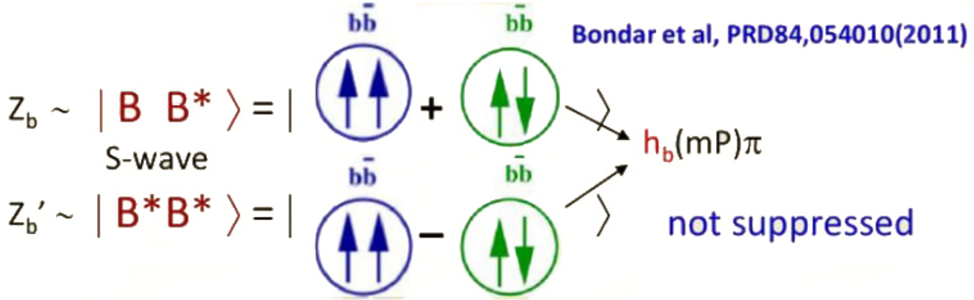
Charged Z states

To flip or not to flip?

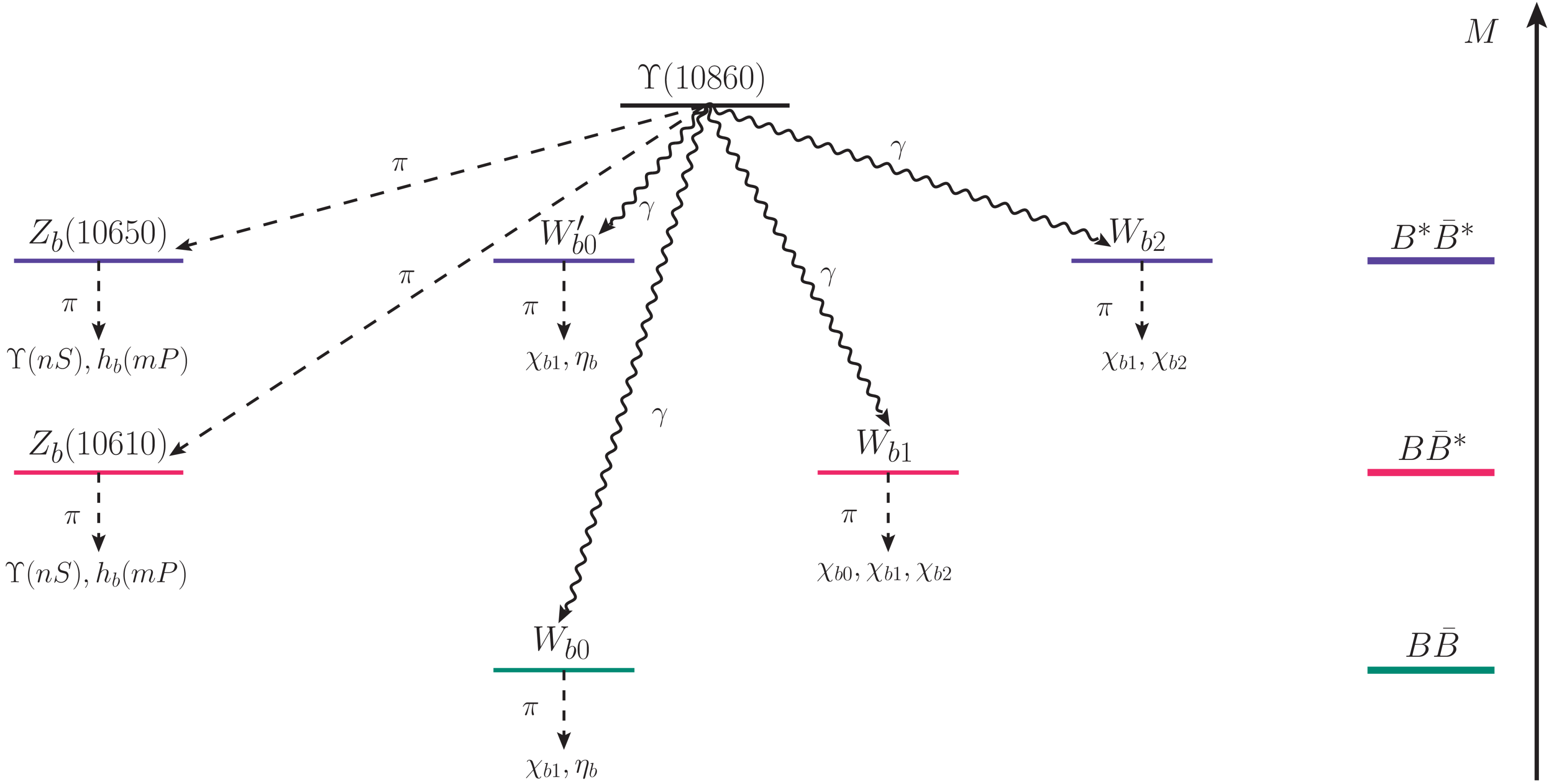


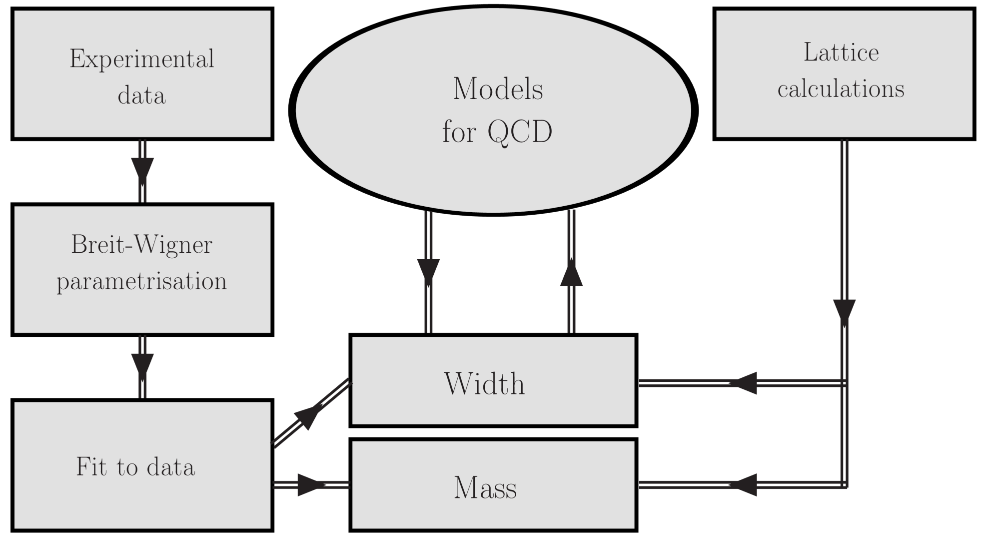
$$\delta H_{\text{flip}} \propto \frac{\Lambda_{\text{QCD}}}{m_b} \simeq \frac{0.25 \text{ GeV}}{4.5 \text{ GeV}} \ll 1$$





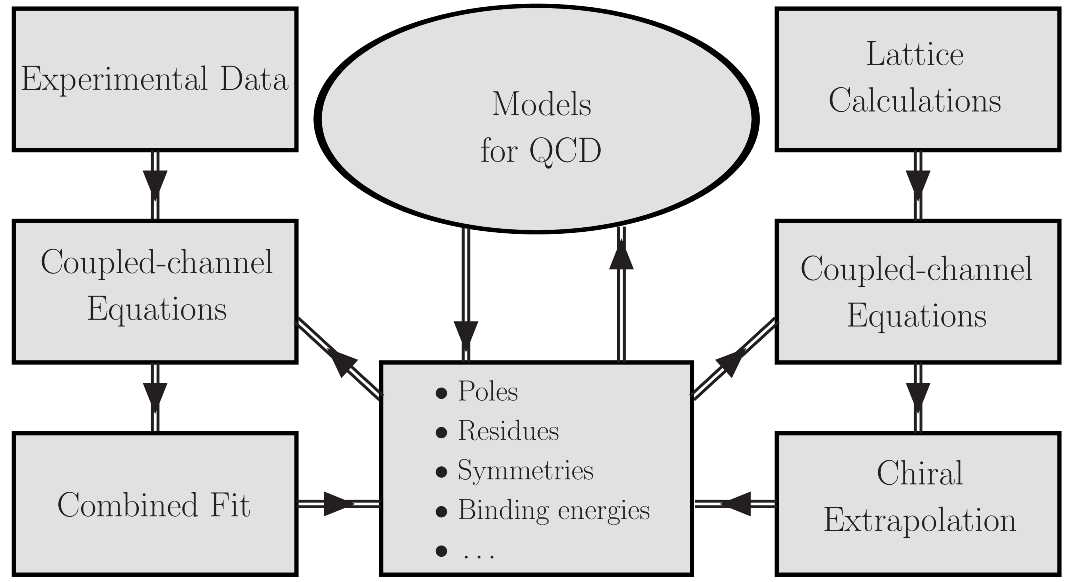
Spin partners



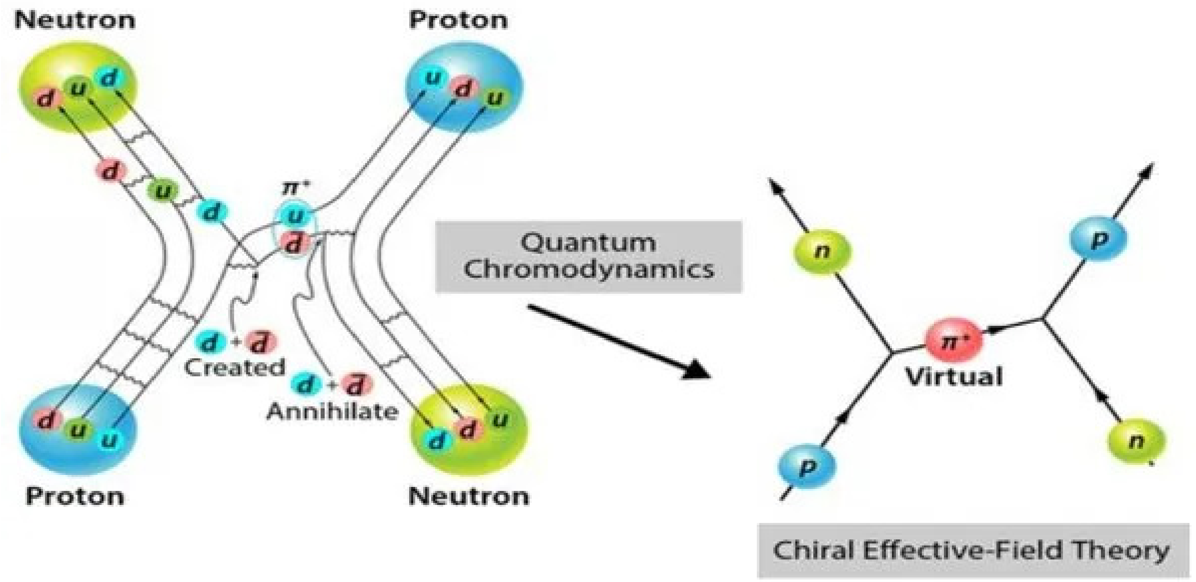


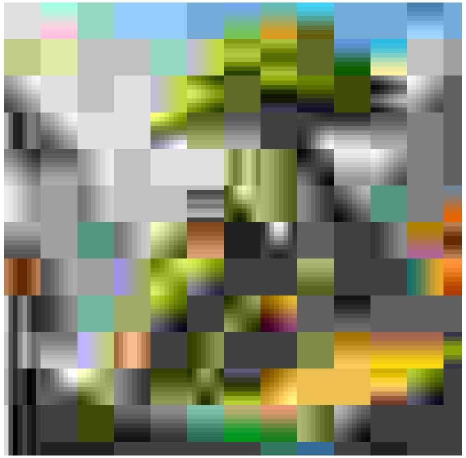
Below open-flavour threshold

Above open-flavour threshold

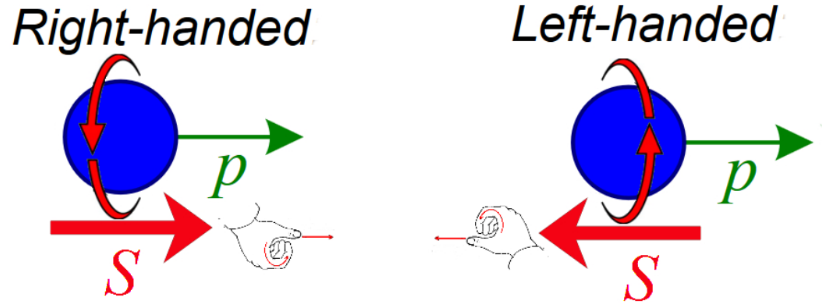


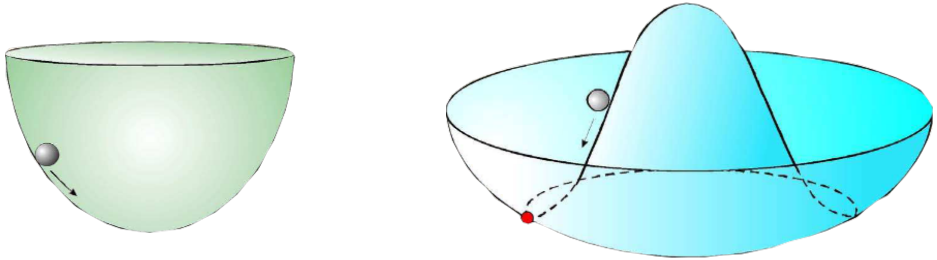
Effective Field Theory



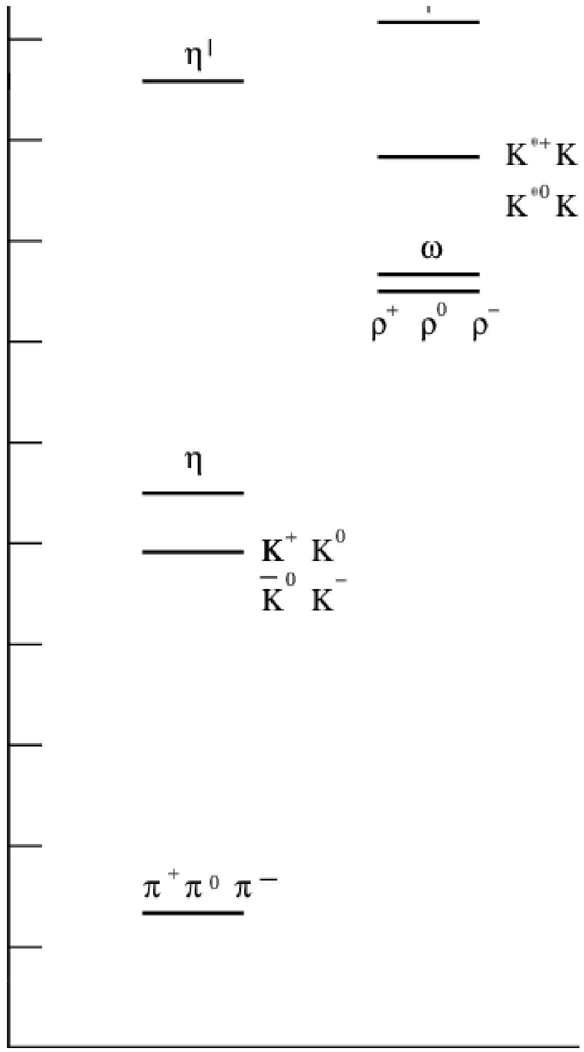


Chiral Perturbation Theory



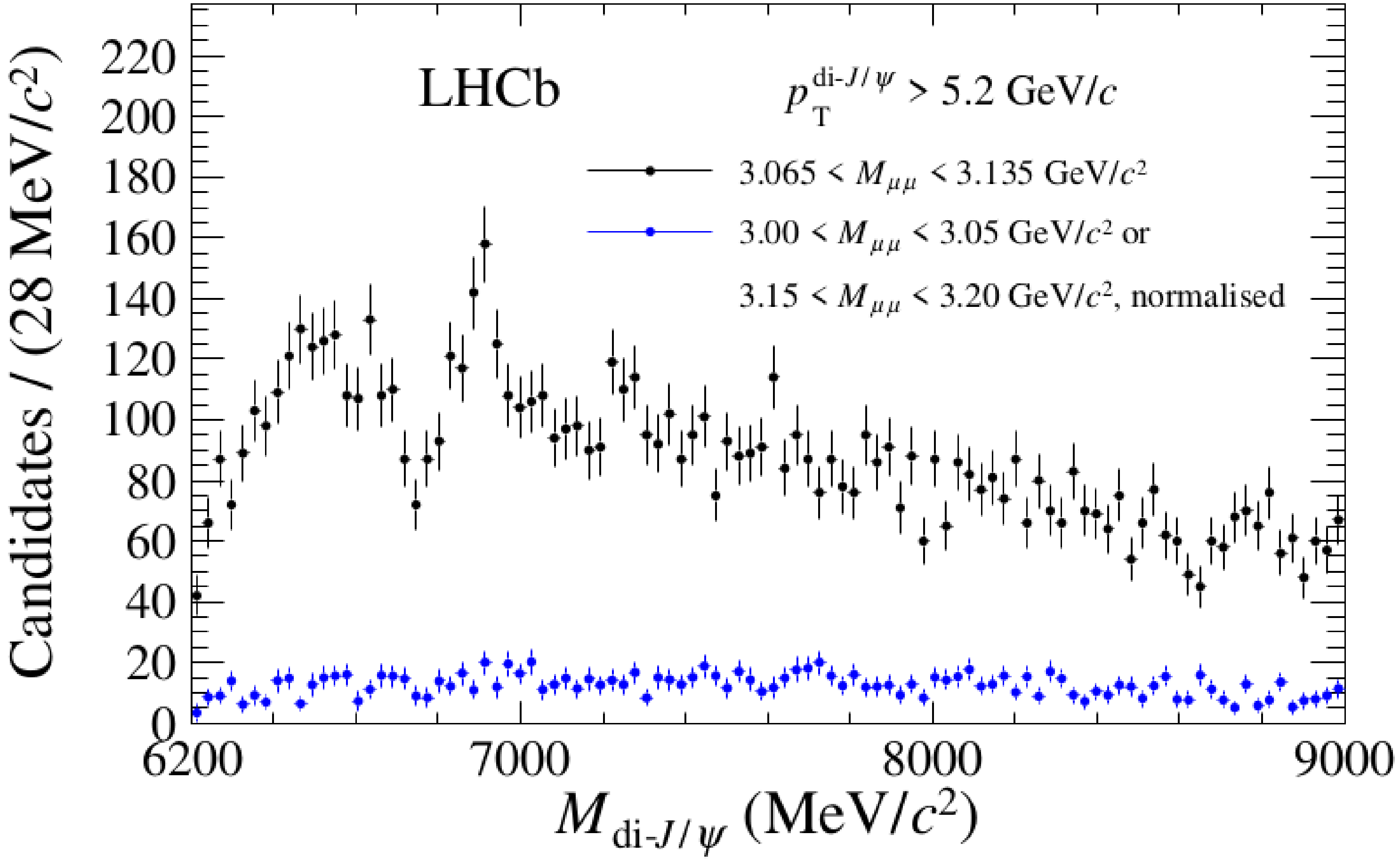


$$\mathcal{L}_{QCD} \xrightarrow[\text{low energy}]{} \mathcal{L}_{\pi\pi} + \dots$$

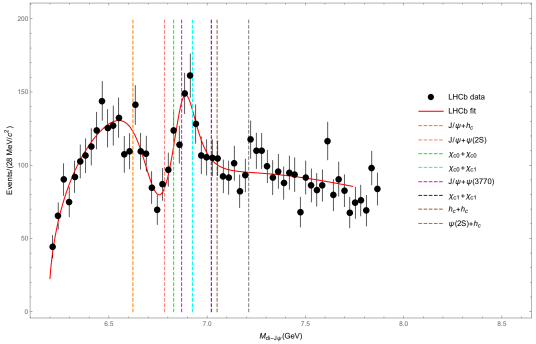


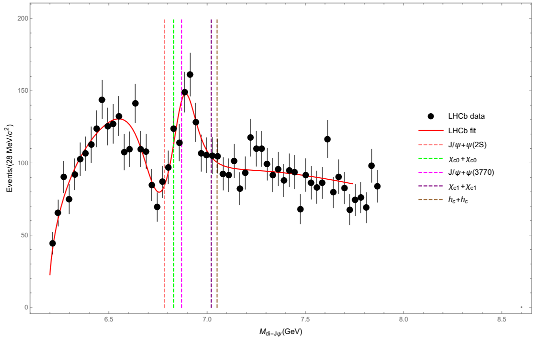
X(6200)/X(6900)

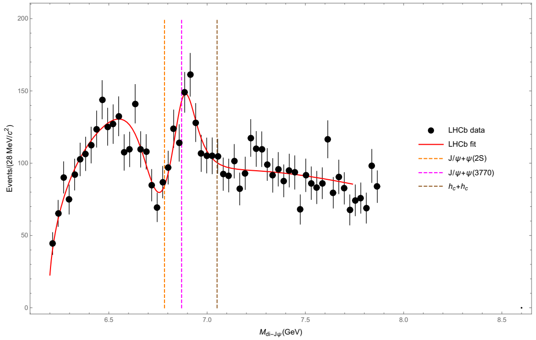
$$p + p \to J/\psi + J/\psi + \ldots$$

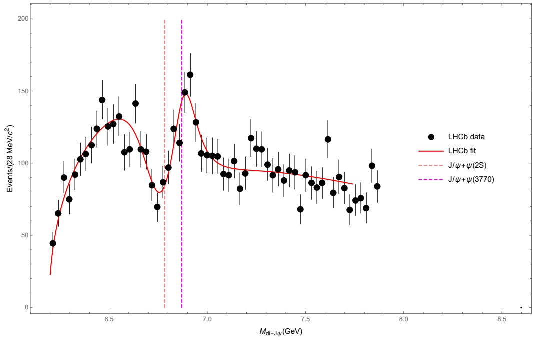


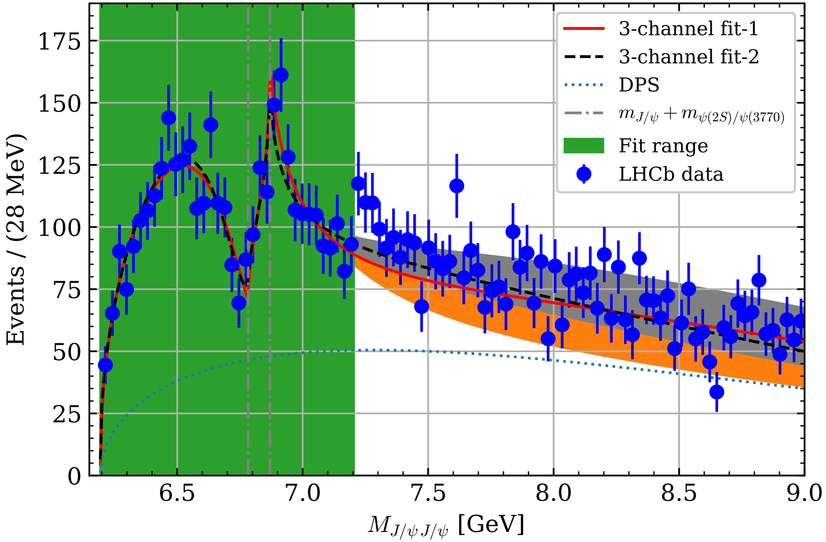
X(6200)/X(6900)

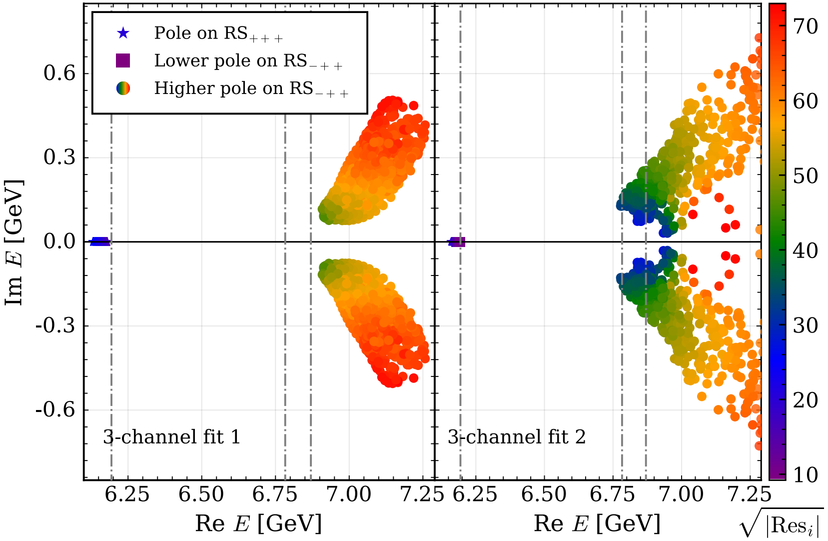

LHCb data
LHCb fit
$J/\psi+h_c$
$J/\psi+\psi(2S)$
$\chi_{c0}+\chi_{c0}$
$\chi_{c0}+\chi_{c1}$
$J/\psi+\psi(3770)$
$\chi_{c1}+\chi_{c1}$
h_c+h_c
$\psi(2S)+h_c$
Events/(28 MeV/c^2)
$M_{\text{di-}J/\psi}$(GeV)


LHCb data
LHCb fit
$J/\psi+\psi(2S)$
$\chi_{c0}+\chi_{c0}$
$J/\psi+\psi(3770)$
$\chi_{c1}+\chi_{c1}$
h_c+h_c
Events/(28 MeV/c^2)
$M_{\text{di-}J/\psi}$(GeV)

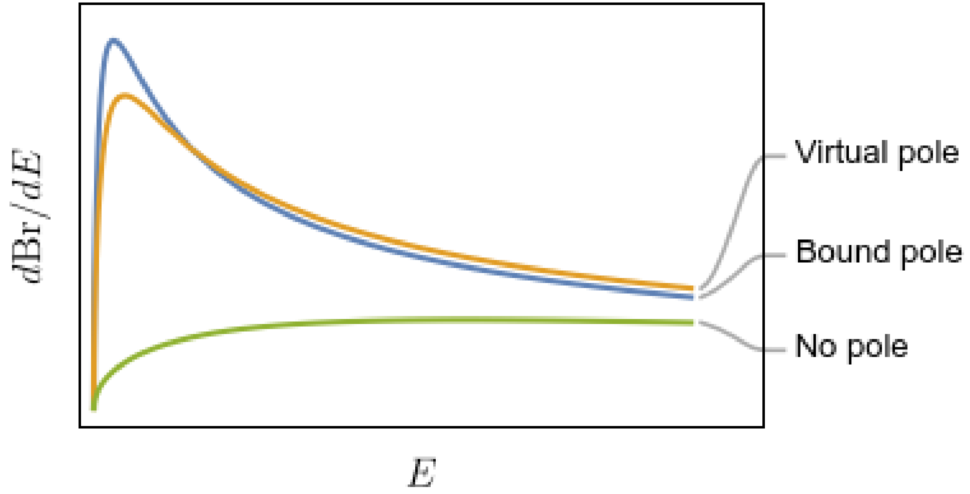

LHCb data
LHCb fit
$J/\psi+\psi(2S)$
$J/\psi+\psi(3770)$
h_c+h_c
Events/(28 MeV/c^2)
$M_{\text{di-}J/\psi}$(GeV)

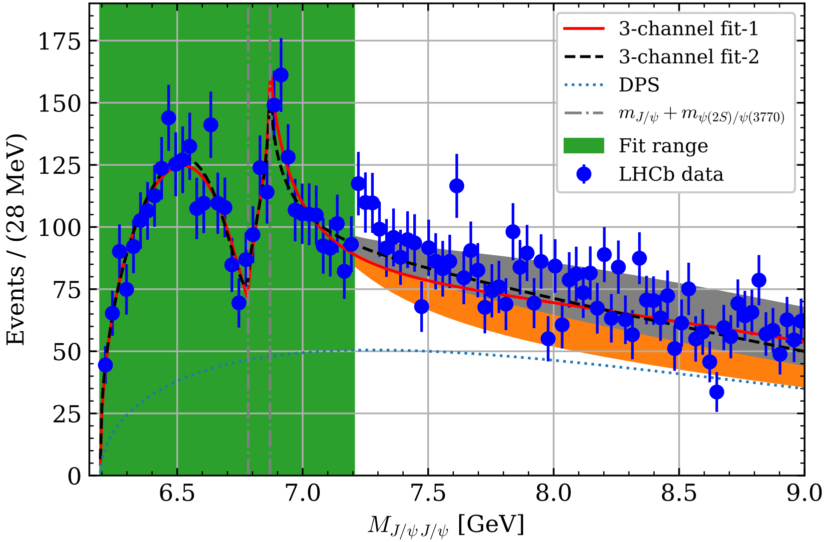

LHCb data
LHCb fit
$J/\psi+\psi(2S)$
$J/\psi+\psi(3770)$
Events/(28 MeV/c^2)
$M_{\text{di-}J/\psi}$(GeV)

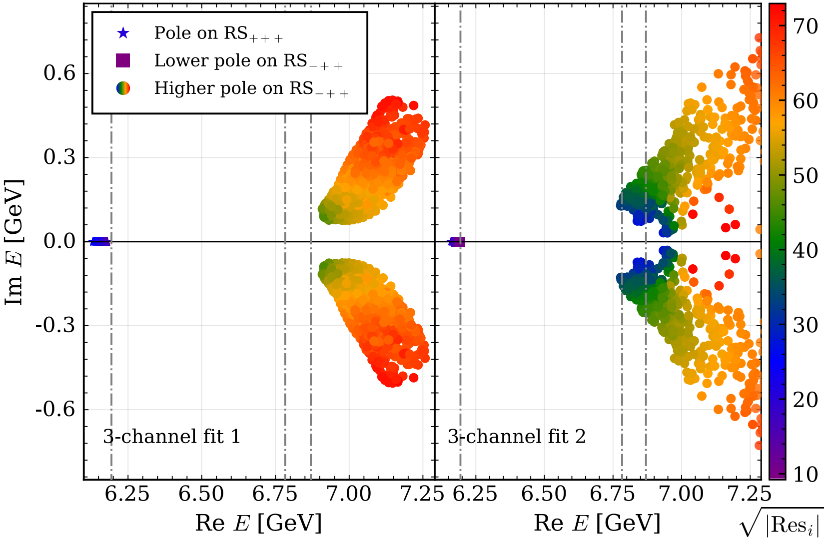

3-channel fit-1
3-channel fit-2
DPS
$m_{J/\psi}+m_{\psi(2S)/\psi(3770)}$
Fit range
LHCb data
Events / (28 MeV)
$M_{J/\psi\, J/\psi}$ [GeV]


Pole on RS_{+++}
Lower pole on RS_{-++}
Higher pole on RS_{-++}
3-channel fit 1
3-channel fit 2
Im E [GeV]
Re E [GeV]
Re E [GeV]
$\sqrt{|\text{Res}_i|}$

X(6200)/X(6900)

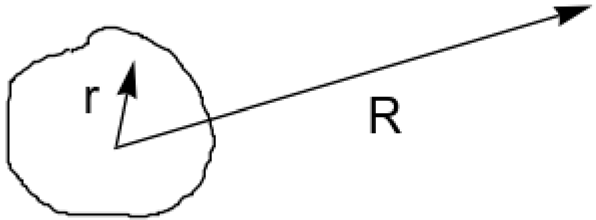




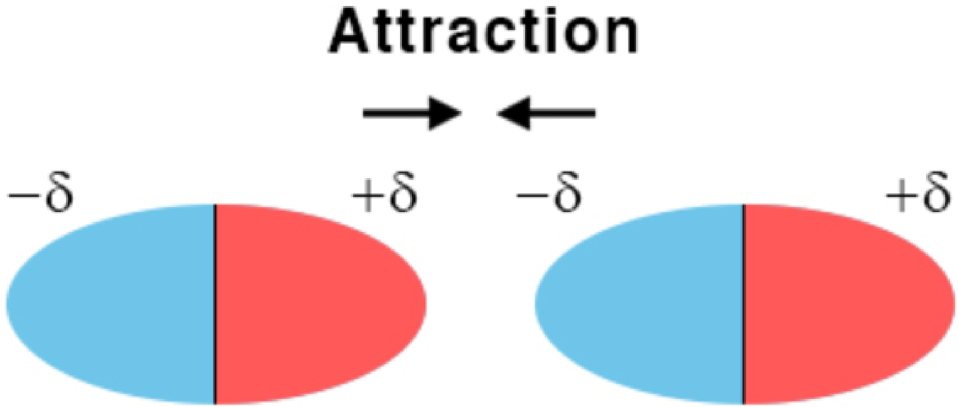


CMS & ATLAS Collaborations:
Additional BW structure near threshold improves data description

Polarisability in QED

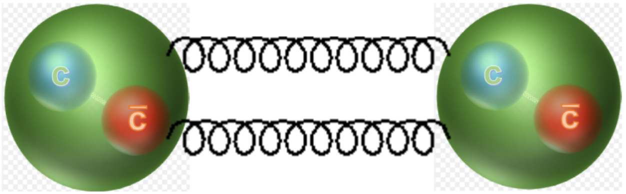


$$\Phi(R) = \frac{Q}{R} + \text{Dipole} + \text{Quadrupole} + \ldots$$



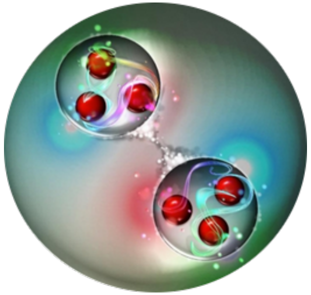
Strength of interaction of neutral objects at large distance depends on their *polarisability* that measures how easily they can be distorted by electric field

X(6200) as molecule



$$H_{\text{int}} \approx -\frac{1}{2}\zeta_a\, \vec{r}\cdot \vec{E}^a$$

$$\beta_{J/\psi} = \frac{1}{9}\langle J/\psi|\, \vec{r}\frac{1}{\hat{H}_O - M}\vec{r}\,|J/\psi\rangle = \frac{0.93}{\alpha_s^4 m_c^3}$$



$$\beta_{\Omega_{ccc}} \approx 2.6 \times \beta_{J/\psi}$$

PHYSICAL REVIEW LETTERS **127,** 072003 (2021)

Dibaryon with Highest Charm Number near Unitarity from Lattice QCD

Yan Lyu,[1,2,†] Hui Tong,[1,3,*] Takuya Sugiura,[3] Sinya Aoki,[4,2] Takumi Doi,[2,3]
Tetsuo Hatsuda,[3] Jie Meng,[1,5] and Takaya Miyamoto[2]

PHYSICAL REVIEW LETTERS **130,** 111901 (2023)

Strongly Bound Dibaryon with Maximal Beauty Flavor from Lattice QCD

Nilmani Mathur,[1,*] M. Padmanath,[2,†,§] and Debsubhra Chakraborty[1,‡]

- Considerable progress in hadronic physics in last years
- Many new states with heavy quarks qualify as exotic hadrons
- Complementary theoretical approaches to exotic hadrons
- New insights into physics of strong interactions

In the forthcomings lectures:

Lecture 2. Exotic hadrons with heavy quarks: Methods

Lecture 3. Exotic hadrons with heavy quarks: Applications