

Exotic hadrons with heavy quarks

Part 1: Introduction

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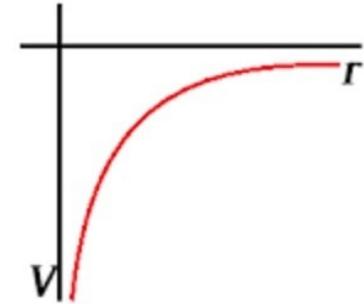
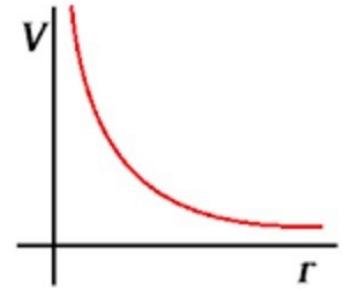
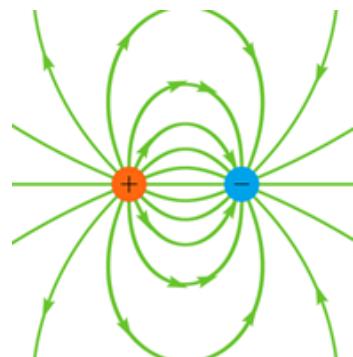
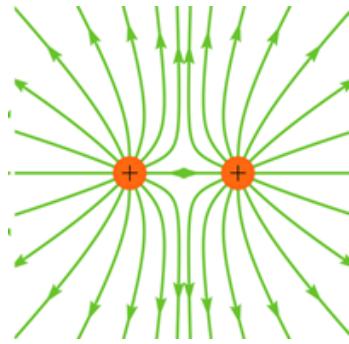


Standard Model of fundamental interactions

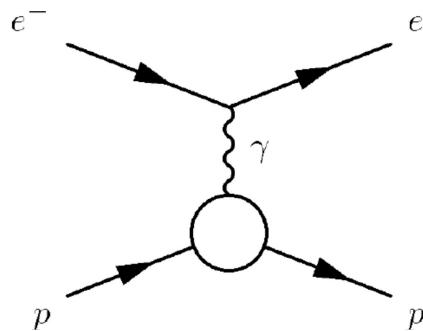
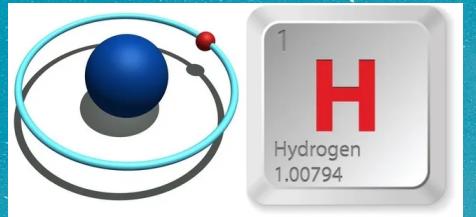
Standard Model of Elementary Particles											
three generations of matter (elementary fermions)				three generations of antimatter (elementary antifermions)				interactions / force carriers (elementary bosons)			
	I	II	III		I	II	III		0	0	0
mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$		$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$		0	0	0
charge	$2/3$	$2/3$	$2/3$		$-2/3$	$-2/3$	$-2/3$		1	1	1
spin	$1/2$	$1/2$	$1/2$		$1/2$	$1/2$	$1/2$		1	0	0
QUARKS											
mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$		$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$		0	0	0
charge	$2/3$	$2/3$	$2/3$		$-2/3$	$-2/3$	$-2/3$		1	1	1
spin	$1/2$	$1/2$	$1/2$		$1/2$	$1/2$	$1/2$		1	0	0
mass	$\approx 4.7 \text{ MeV}/c^2$	$\approx 96 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$		$\approx 4.7 \text{ MeV}/c^2$	$\approx 96 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$		0	0	0
charge	$-1/3$	$-1/3$	$-1/3$		$1/3$	$1/3$	$1/3$		1	1	1
spin	$1/2$	$1/2$	$1/2$		$1/2$	$1/2$	$1/2$		1	0	0
mass	$\approx 1.7768 \text{ GeV}/c^2$	$\approx 105.66 \text{ MeV}/c^2$	$\approx 0.511 \text{ MeV}/c^2$		$\approx 1.7768 \text{ GeV}/c^2$	$\approx 105.66 \text{ MeV}/c^2$	$\approx 91.19 \text{ GeV}/c^2$		0	0	0
charge	-1	-1	-1		1	1	1		1	1	1
spin	$1/2$	$1/2$	$1/2$		$1/2$	$1/2$	$1/2$		1	1	1
LEPTONS											
mass	$\approx 0.511 \text{ MeV}/c^2$	$\approx 105.66 \text{ MeV}/c^2$	$\approx 1.7768 \text{ GeV}/c^2$		$\approx 0.511 \text{ MeV}/c^2$	$\approx 105.66 \text{ MeV}/c^2$	$\approx 91.19 \text{ GeV}/c^2$		0	0	0
charge	-1	-1	-1		1	1	1		1	1	1
spin	$1/2$	$1/2$	$1/2$		$1/2$	$1/2$	$1/2$		1	1	1
mass	$\approx 0.000511 \text{ MeV}/c^2$	$\approx 0.00010566 \text{ GeV}/c^2$	$\approx 0.0017768 \text{ GeV}/c^2$		$\approx 0.000511 \text{ MeV}/c^2$	$\approx 0.00010566 \text{ GeV}/c^2$	$\approx 0.009119 \text{ GeV}/c^2$		0	0	0
charge	-1	-1	-1		1	1	1		1	1	1
spin	$1/2$	$1/2$	$1/2$		$1/2$	$1/2$	$1/2$		1	1	1
GAUGE BOSONS VECTOR BOSONS											
mass	$<2.2 \text{ eV}/c^2$	$<0.17 \text{ MeV}/c^2$	$<18.2 \text{ MeV}/c^2$		$<2.2 \text{ eV}/c^2$	$<0.17 \text{ MeV}/c^2$	$<80.39 \text{ GeV}/c^2$		0	0	0
charge	0	0	0		0	0	1		1	1	1
spin	$1/2$	$1/2$	$1/2$		$1/2$	$1/2$	1		1	1	1
mass	$\approx 0.0000007 \text{ eV}/c^2$	$\approx 0.000000017 \text{ MeV}/c^2$	$\approx 0.000000182 \text{ GeV}/c^2$		$\approx 0.0000007 \text{ eV}/c^2$	$\approx 0.000000017 \text{ MeV}/c^2$	$\approx 0.0000008039 \text{ GeV}/c^2$		0	0	0
charge	0	0	0		0	0	1		1	1	1
spin	$1/2$	$1/2$	$1/2$		$1/2$	$1/2$	1		1	1	1
SCALAR BOSONS											
mass	$\approx 124.97 \text{ GeV}/c^2$								0	0	0
charge	0								1	1	1
spin	0								1	1	1

Quantum Electrodynamics

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



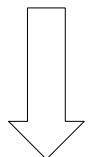
Bound states in QED



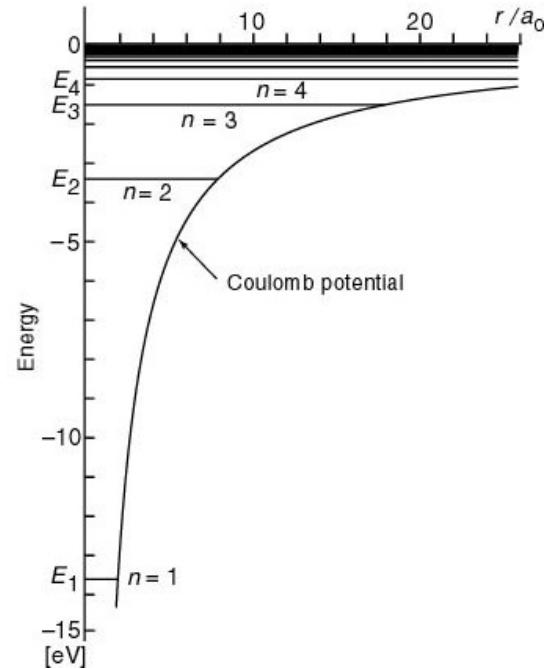
$$V(r) = -\frac{\alpha}{r}$$

$$\alpha = \frac{e^2}{4\pi\hbar c} \approx \frac{1}{137} \ll 1$$

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

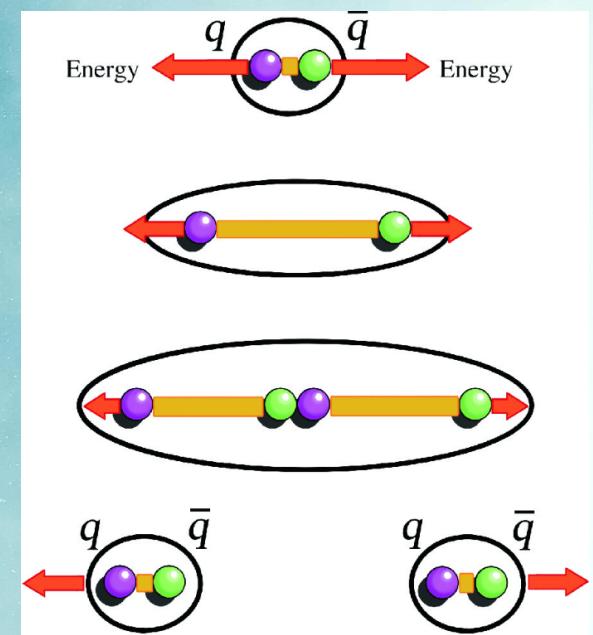
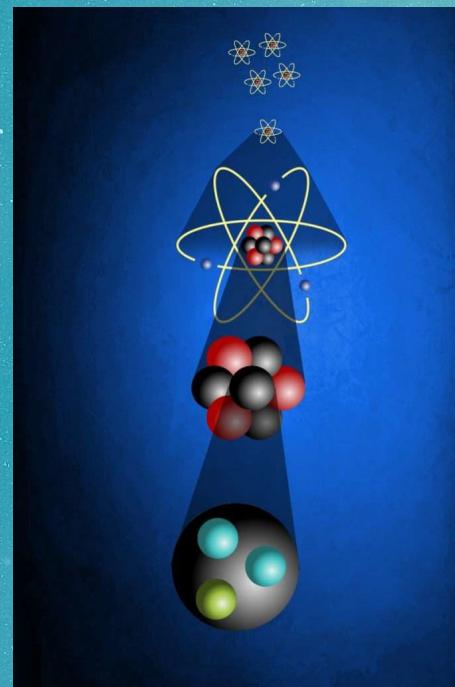
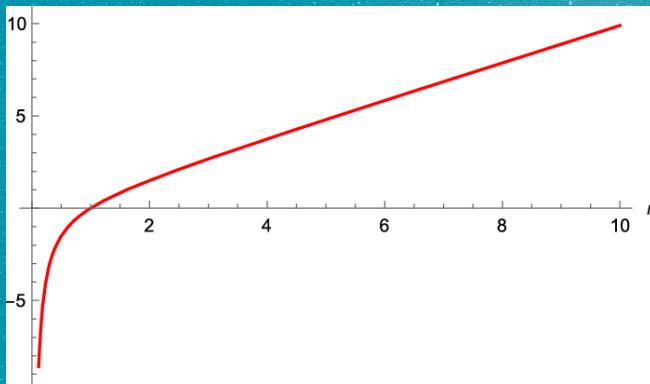
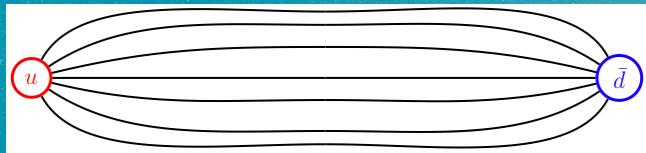


$$E = m - \frac{m\alpha^2}{2(n_r + j + \frac{1}{2})^2} = m - \frac{m\alpha^2}{2n^2}$$



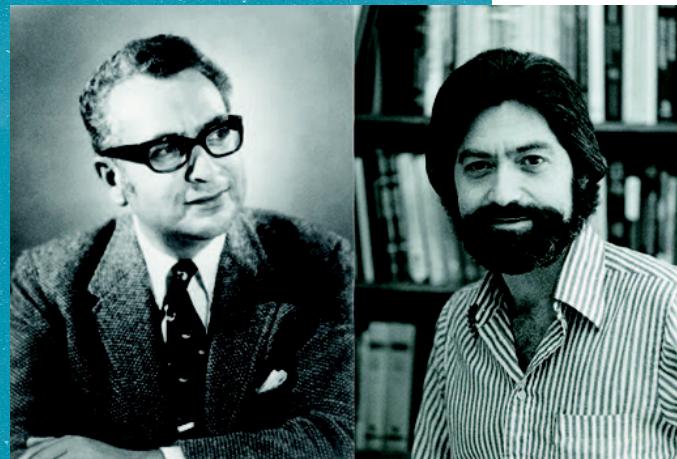
Quantum Chromodynamics

$$L_{\text{QCD}} = -\frac{1}{4} F_{\mu\nu}^a F_a^{\mu\nu} + \bar{\psi}_\alpha (i\gamma_\mu \partial^\mu - m - g\gamma_\mu A_a^\mu t^a)^\alpha_\beta \psi^\beta$$



Bound states in QCD - Hadrons

1964 – Invention of constituent Quark Model



Murray Gell-Mann and George Zweig



Quark-antiquark meson



Three-quark baryon



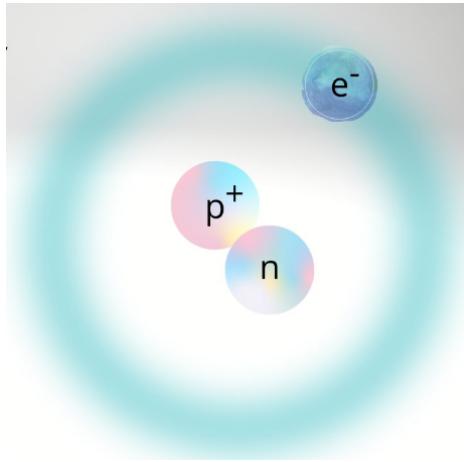
Ordinary
hadrons

Exotic hadrons:



Hadronic Exotica

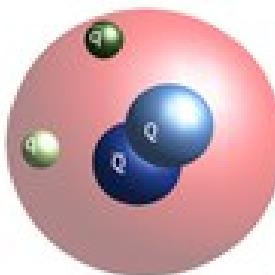
Deuterium



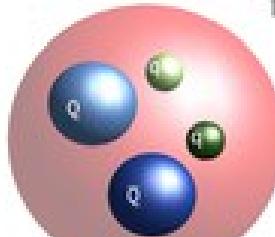
Nucleus is deuteron:
bound state of
proton & neutron

Known for nearly 100 years

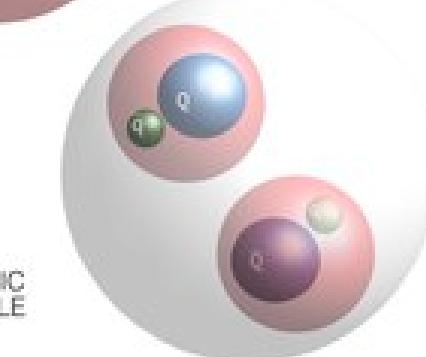
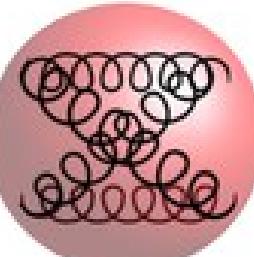
HADRO-
QUARKONIUM



TETRAQUARK

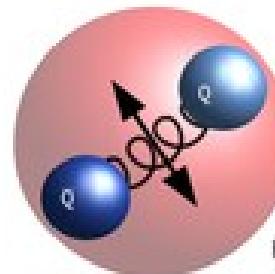


GLUEBALL

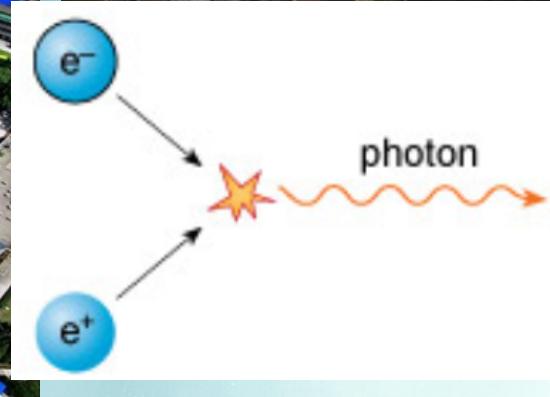
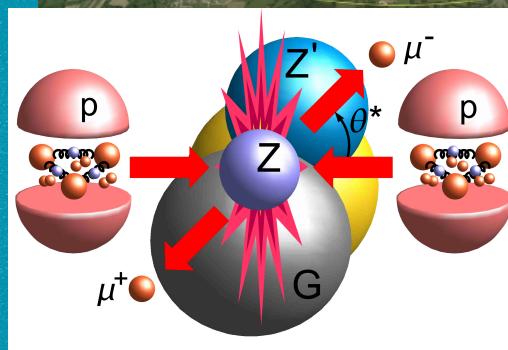
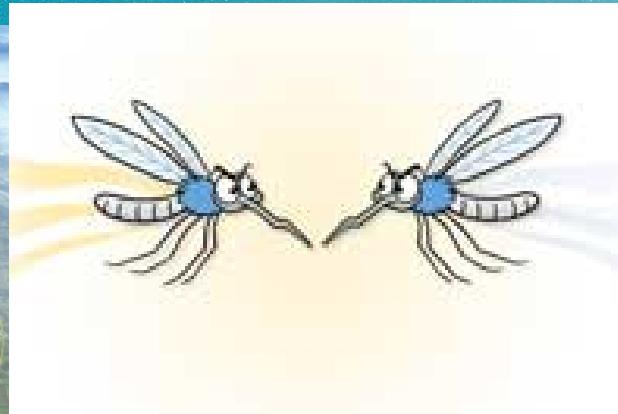
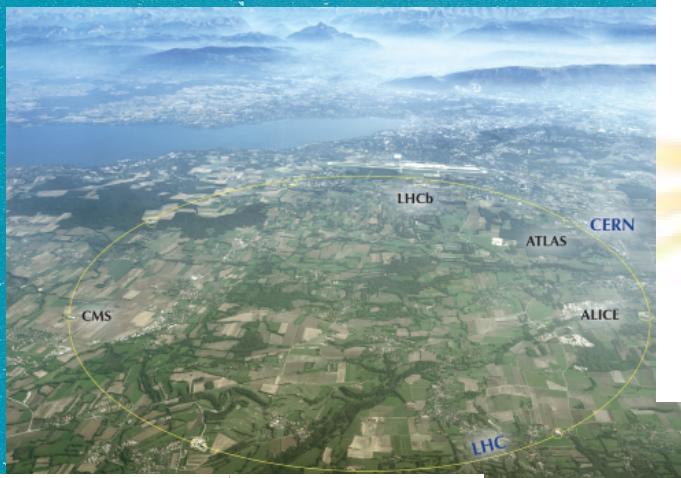


HADRONIC
MOLECULE

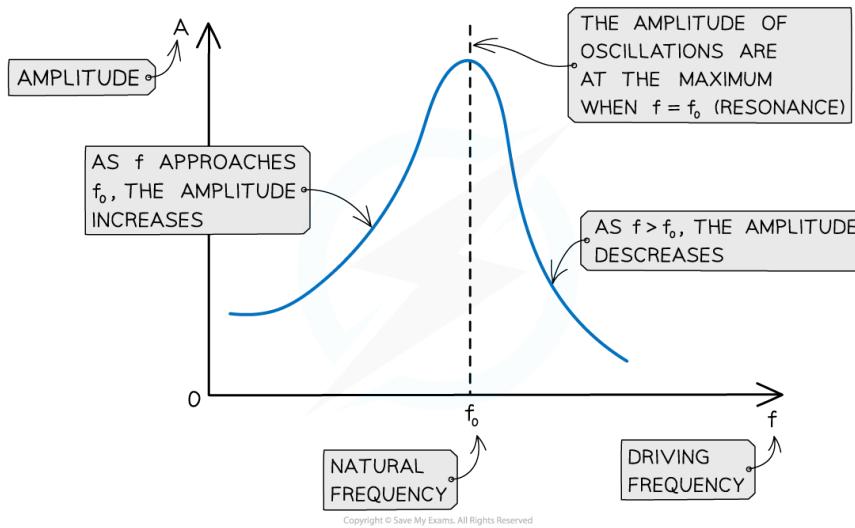
HYBRID



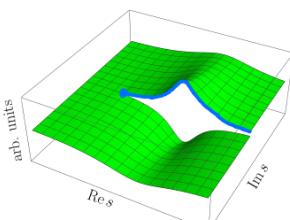
Contemporary collider experiments



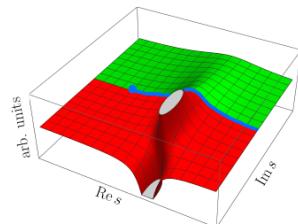
Resonance



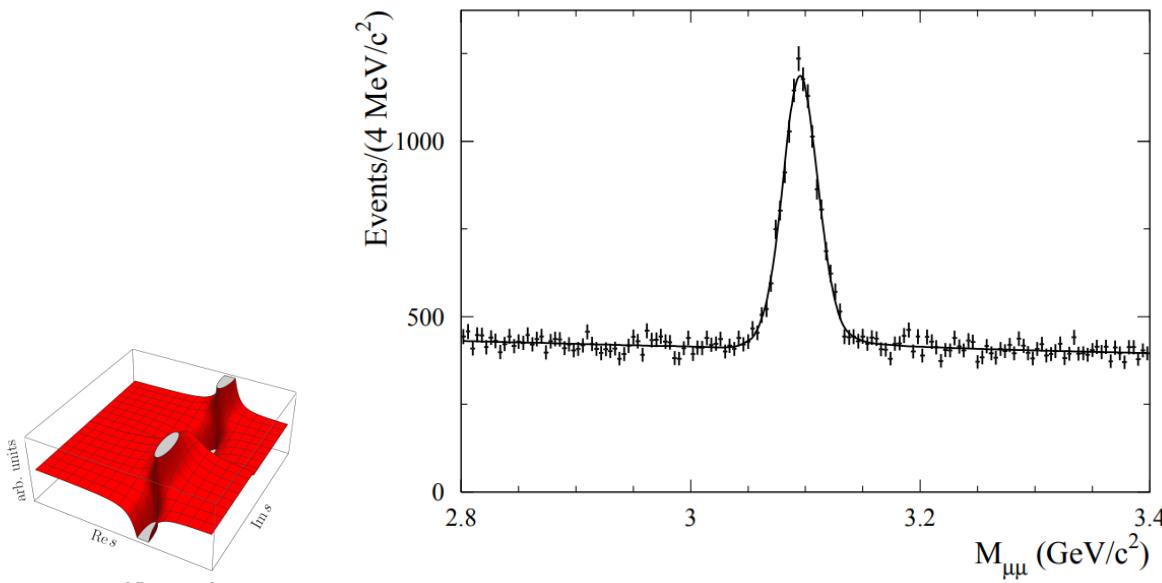
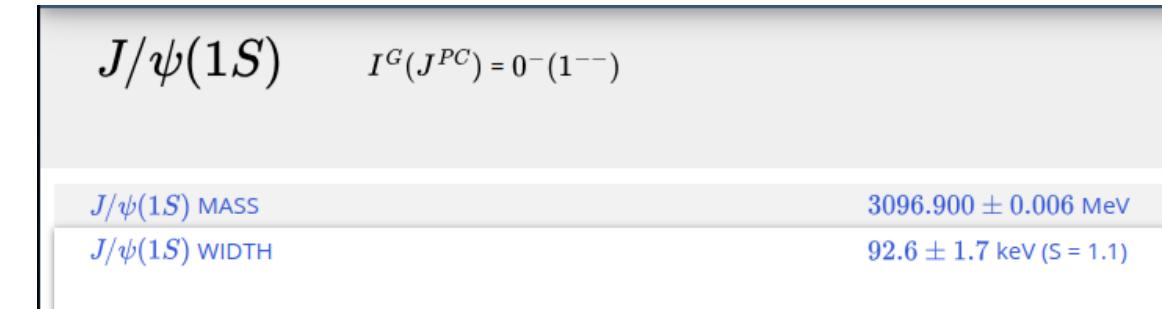
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first Riemann sheet

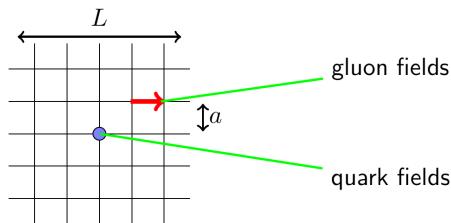


transition from first to second Riemann sheet

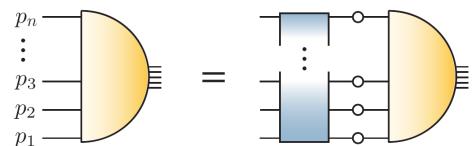


Theoretical Approaches

QCD on lattice



Functional Methods



Quark Models

A diagram illustrating Quark Models. It shows a quark Q (red circle) and an antiquark \bar{Q} (blue circle) connected by a spring-like line, representing a quark-antiquark pair.

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

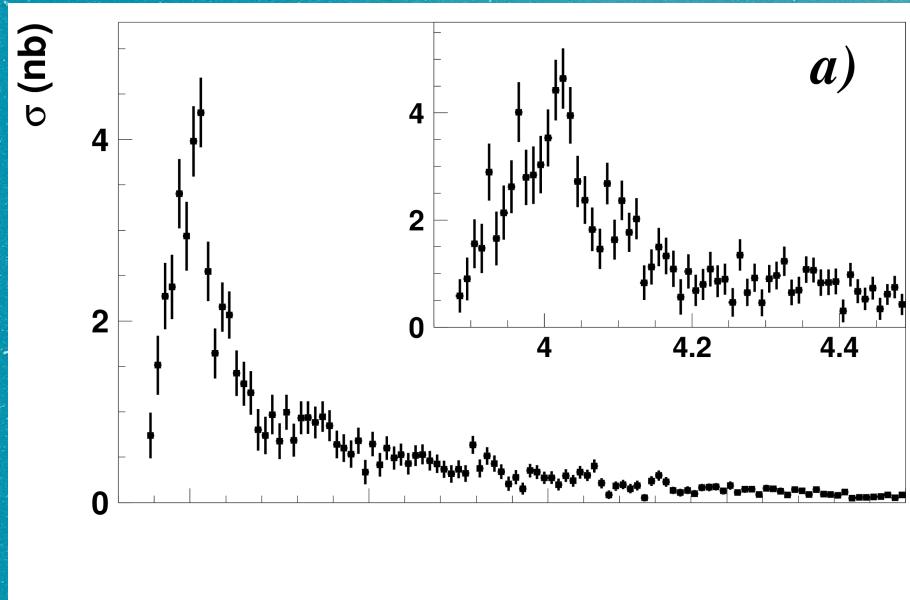
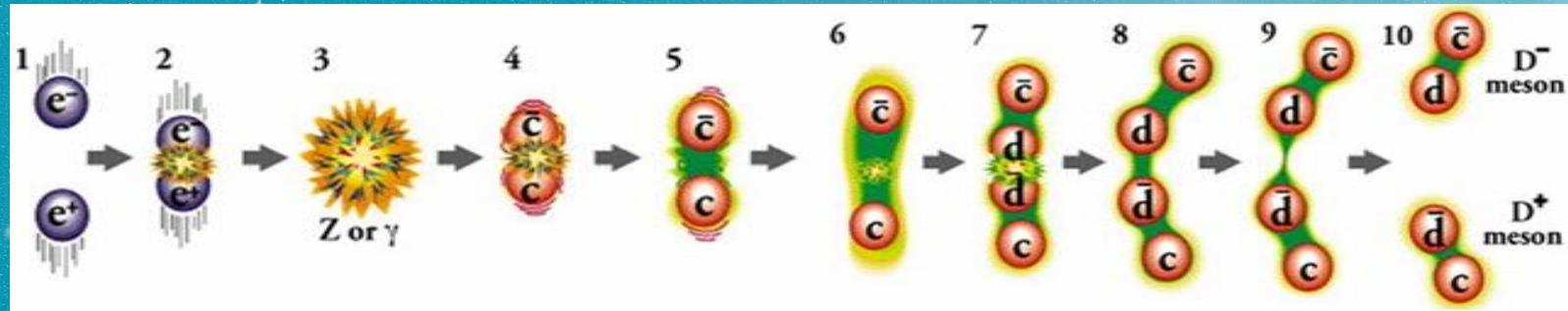
$$V_0(r) = \sigma r - \frac{\frac{4}{3}\alpha_s}{r} + C_0$$

XYZ states

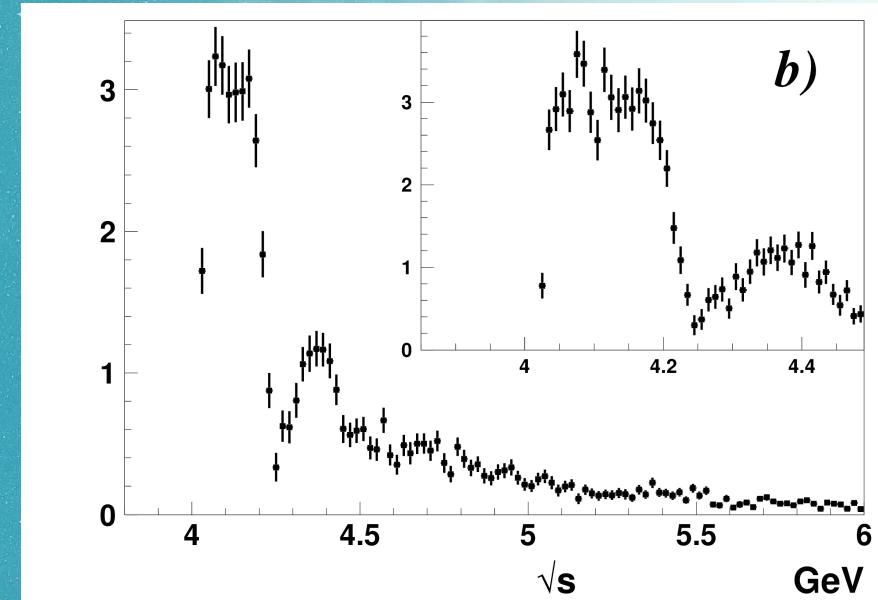
In particle physics, XYZ particles (also referred to as XYZ states) are recently-discovered heavy mesons whose properties do not appear to fit the standard picture of charmonium and bottomonium states. They are therefore types of exotic mesons. The term arises from the names given to some of the first 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



a)

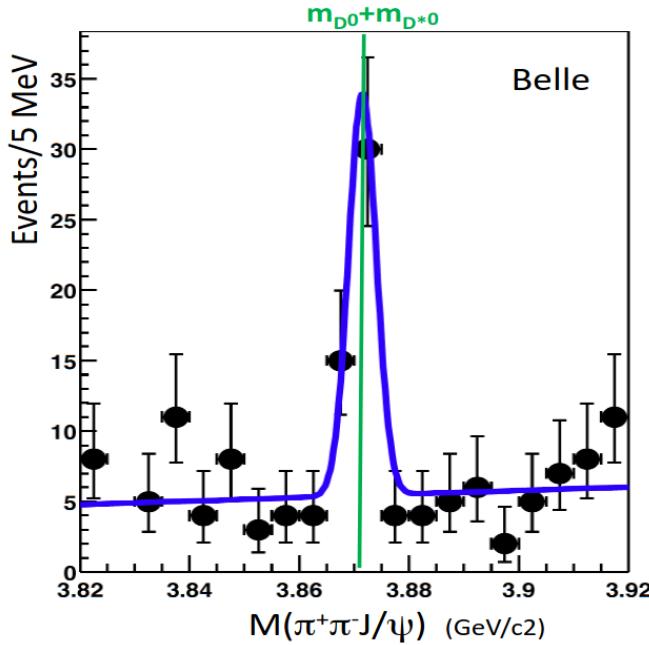
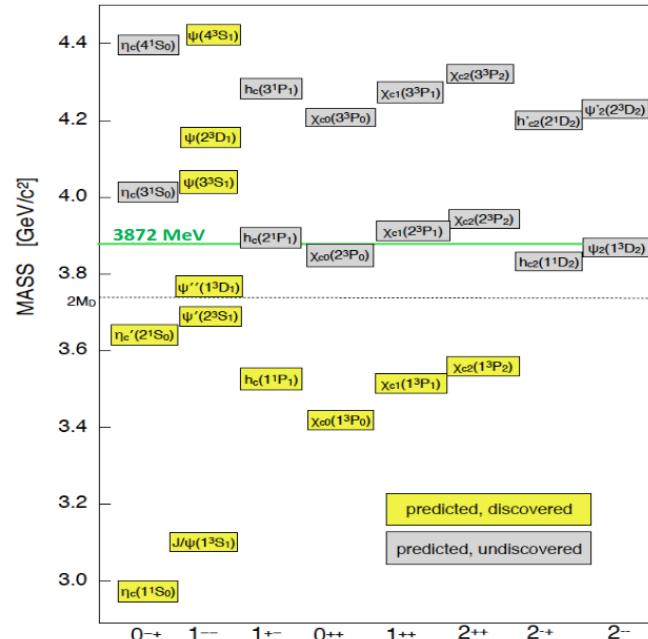


b)

X(3872)

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

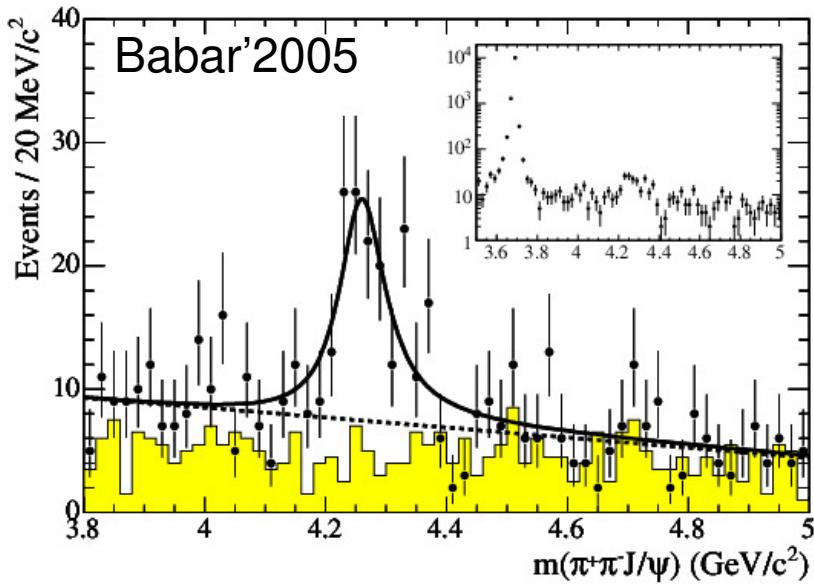
$$\Gamma_{X(3872)} = 1.19 \pm 0.21 \text{ MeV}$$



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

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

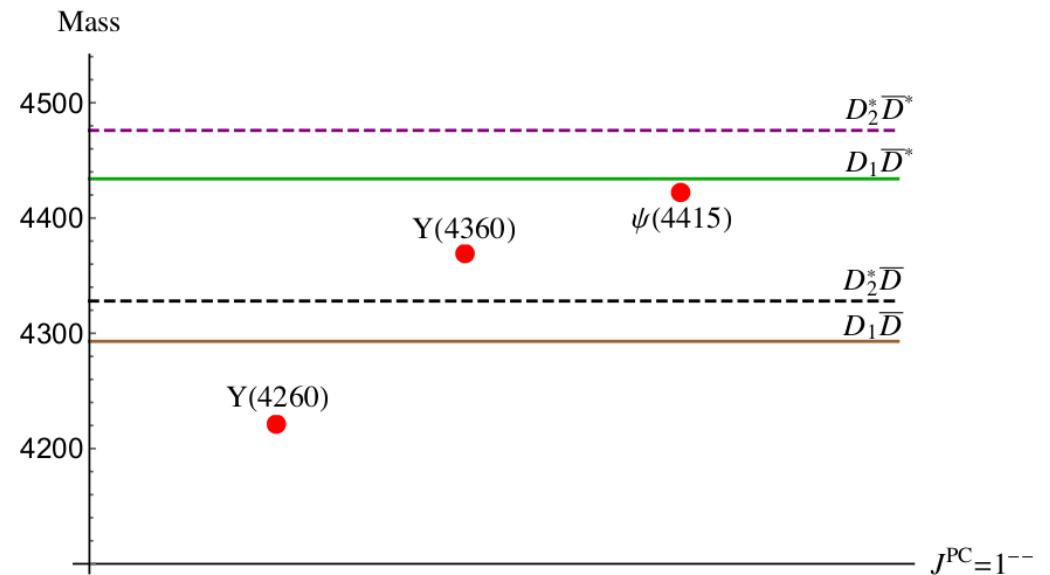
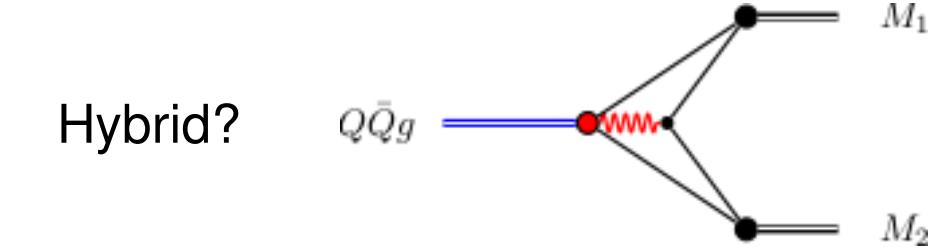
$\Upsilon(4260)/\Upsilon(4230)$



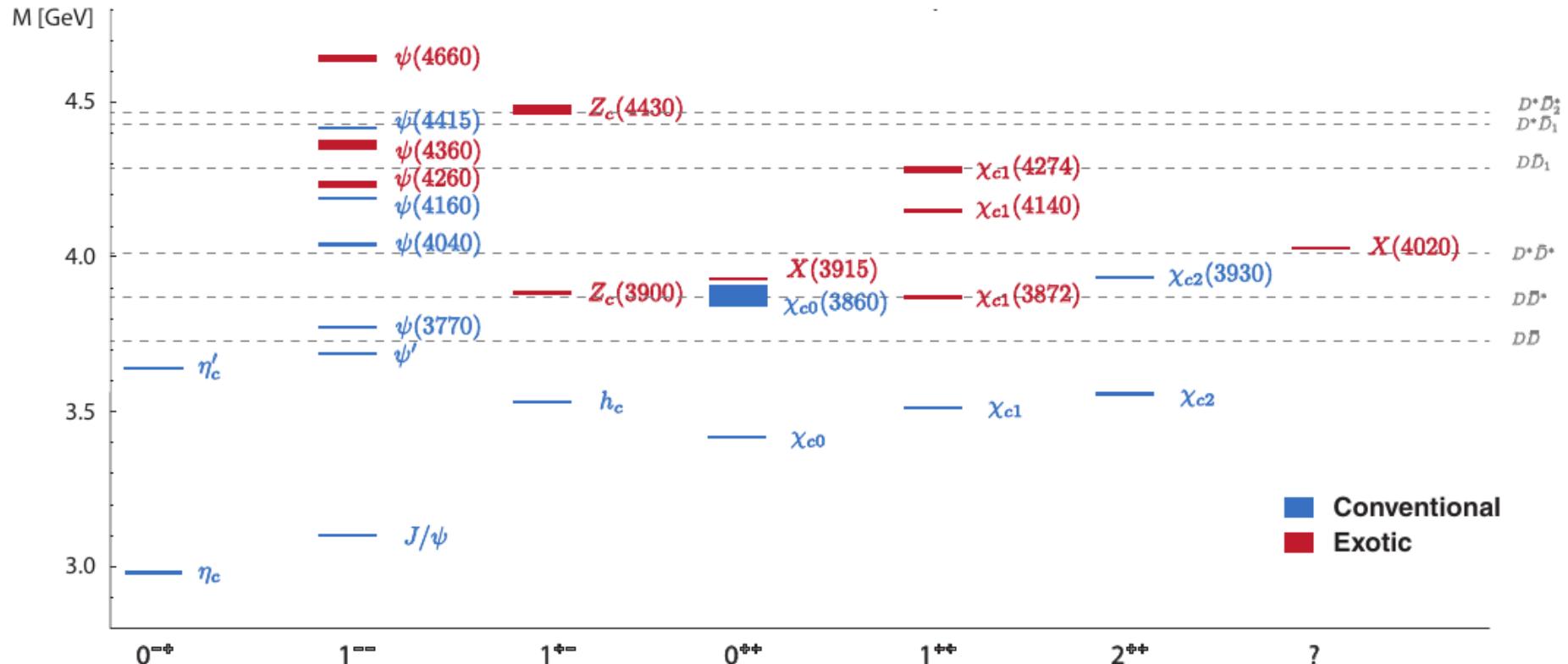
Molecule?



Hybrid?

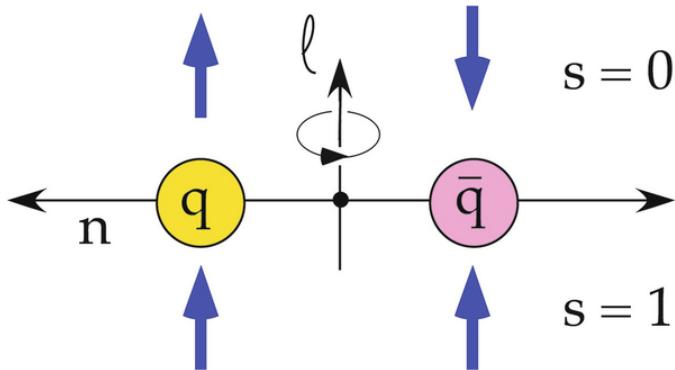


Charmonium

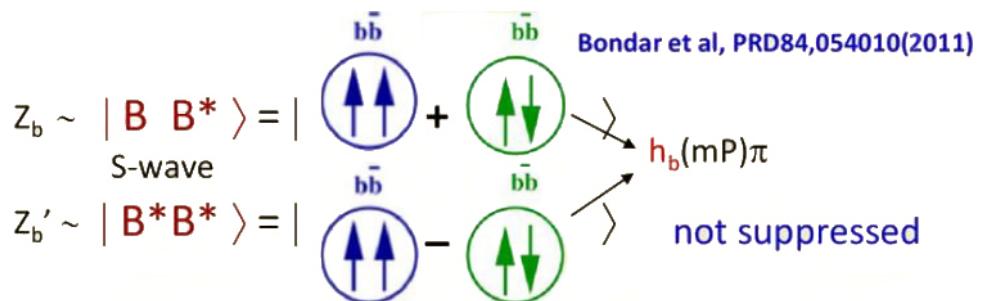
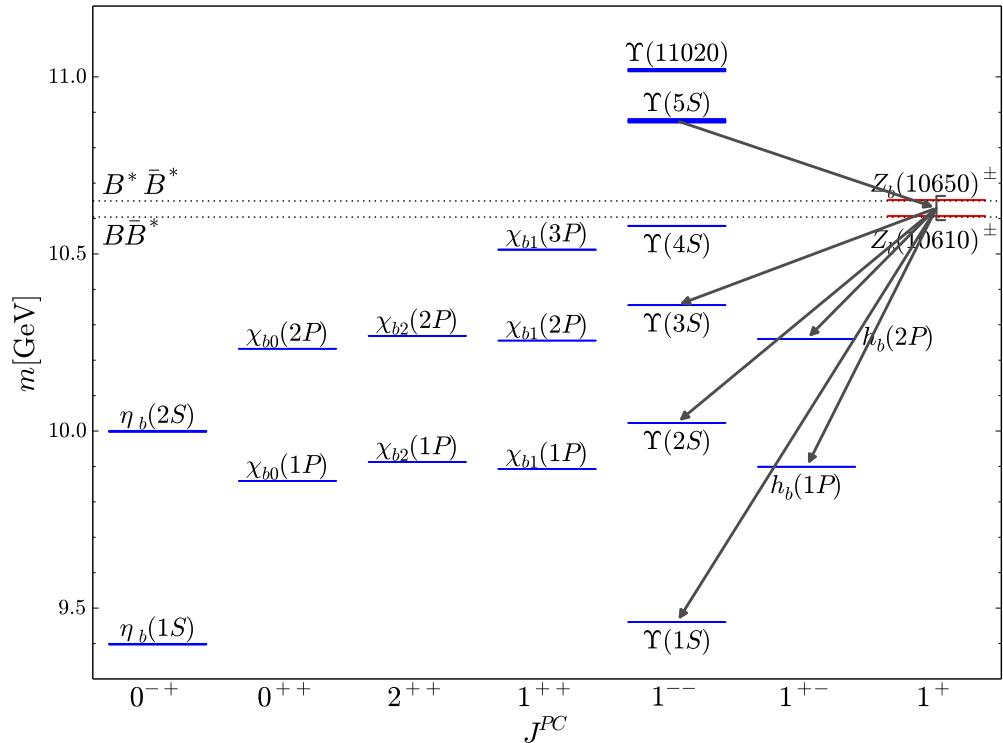


Charged Z states

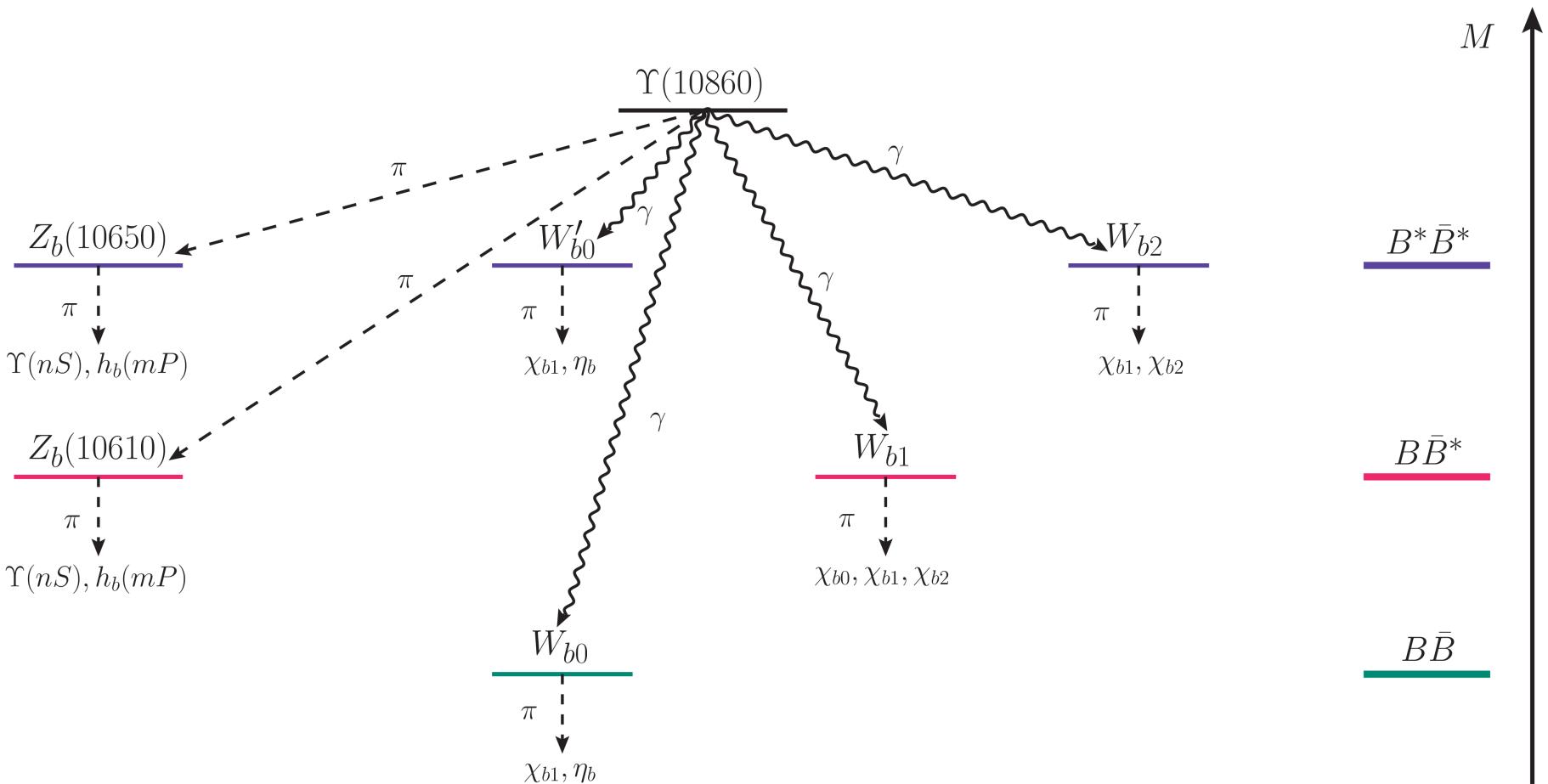
To flip or not to flip?



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



Spin partners



Experimental
data

Models
for QCD

Lattice
calculations

Breit-Wigner
parametrisation

Fit to data

Width

Mass

Above open-flavour
threshold

Below open-flavour
threshold

Experimental Data

Models
for QCD

Lattice
Calculations

Coupled-channel
Equations

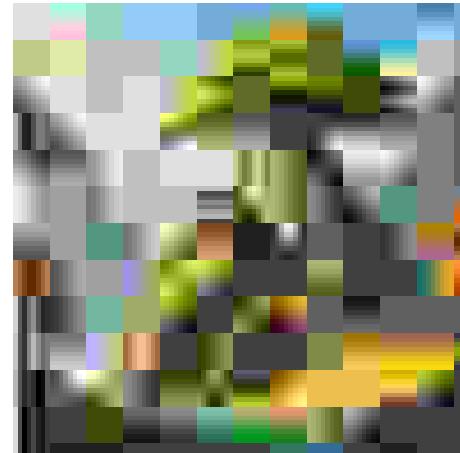
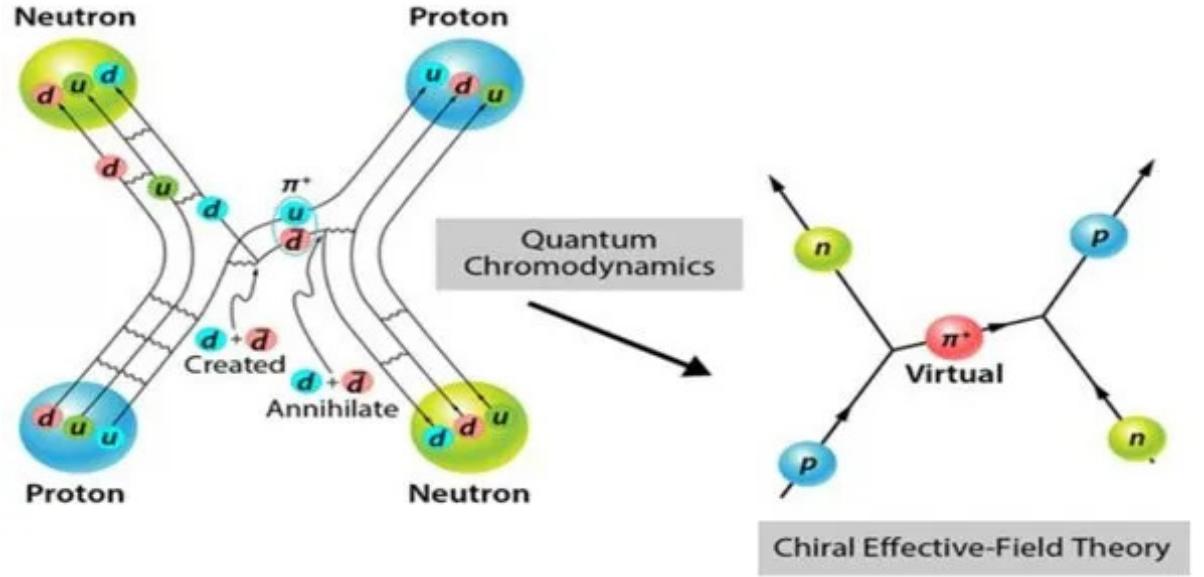
Combined Fit

- Poles
- Residues
- Symmetries
- Binding energies
- ...

Coupled-channel
Equations

Chiral
Extrapolation

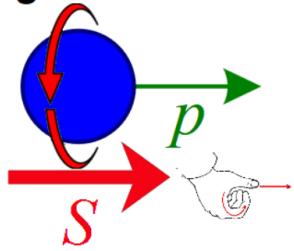
Effective Field Theory



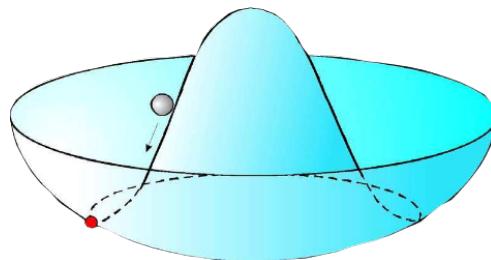
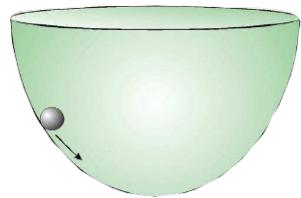
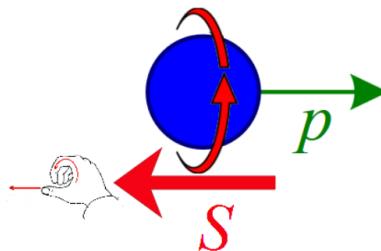
Chiral Perturbation Theory

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

Right-handed



Left-handed



η'

$\bar{\eta}$

$K^{*+} K$
 $K^{*0} K$

ω

$\rho^+ \rho^0 \rho^-$

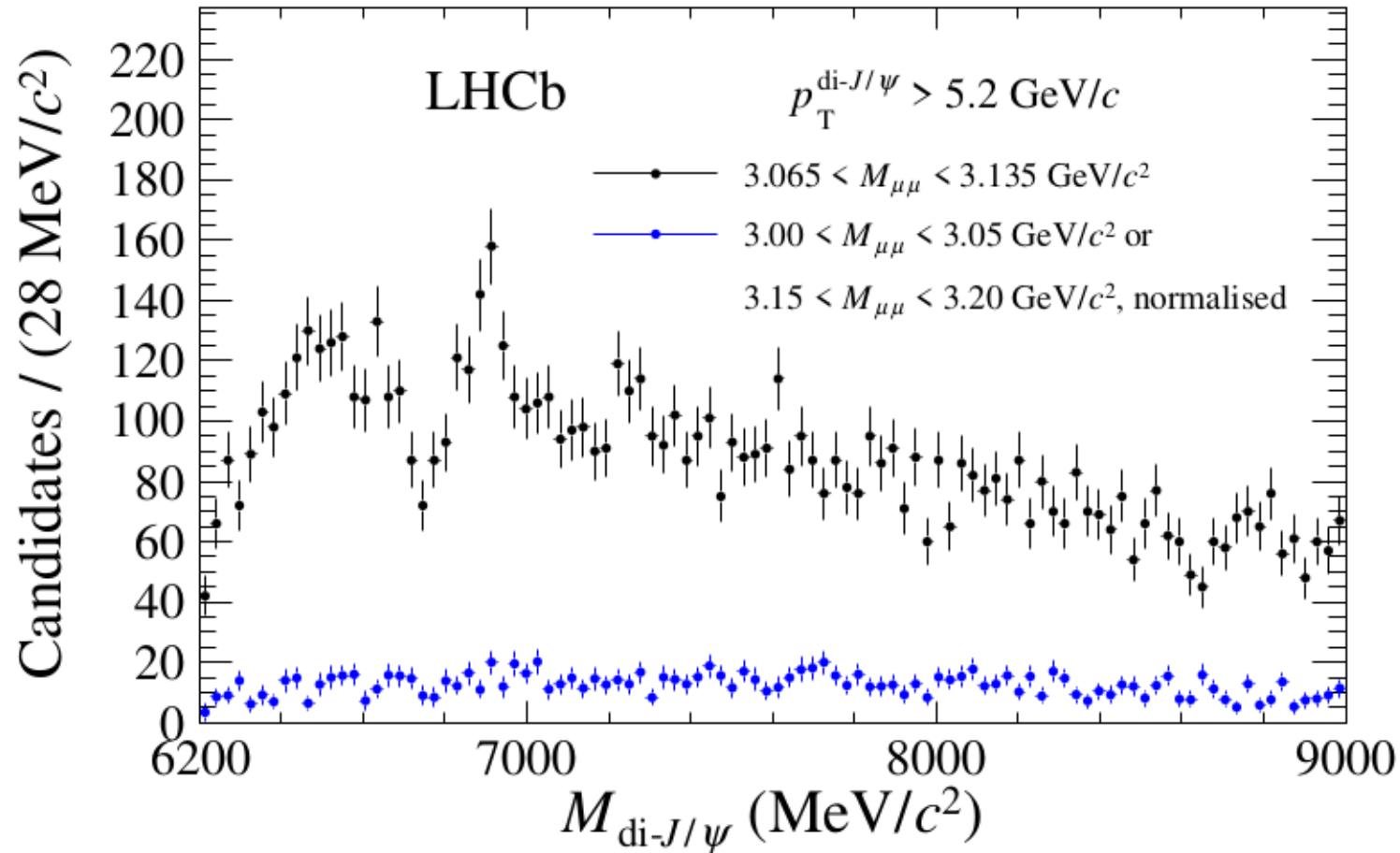
η

$K^+ K^0$
 $\bar{K}^0 K^-$

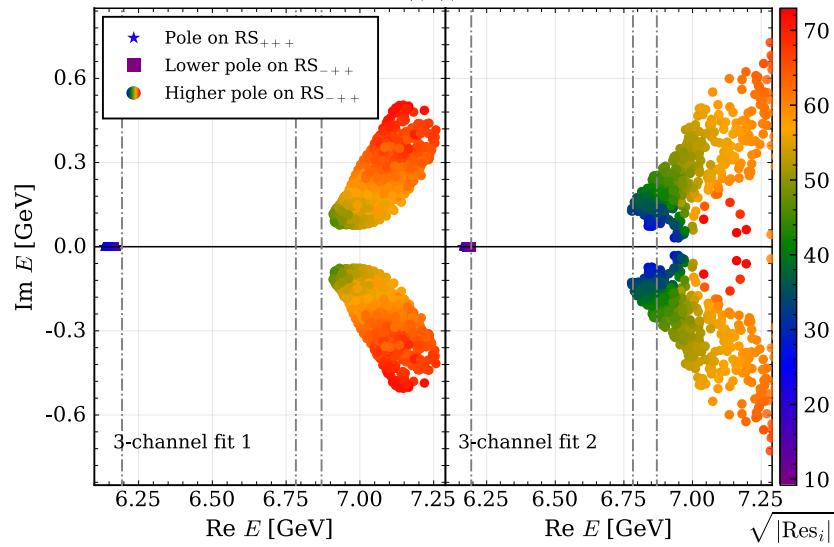
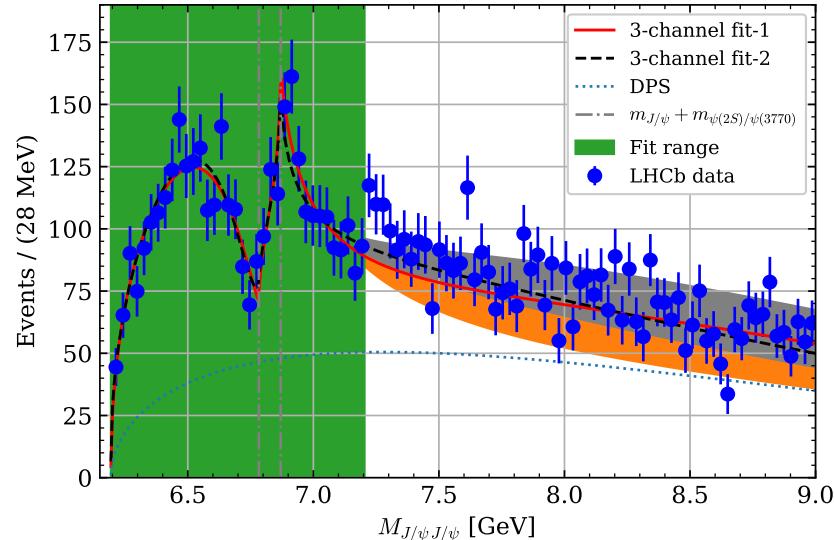
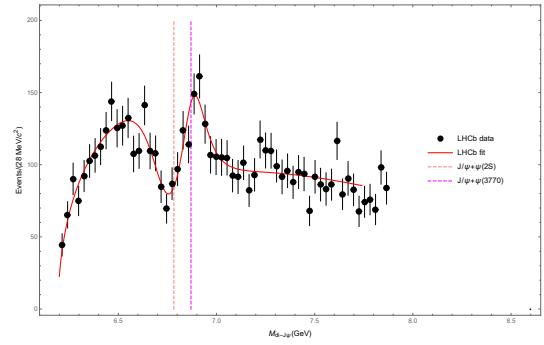
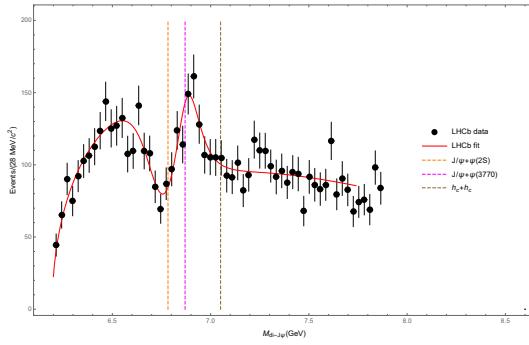
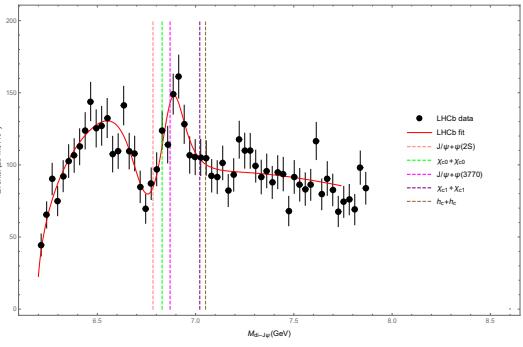
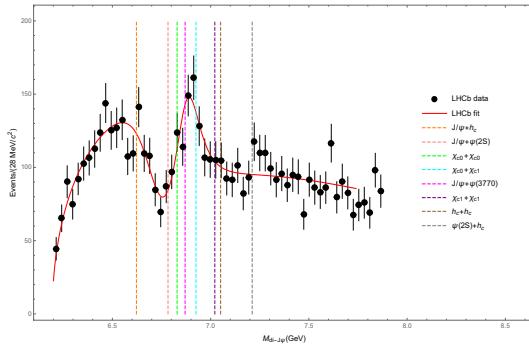
$\pi^+ \pi^0 \pi^-$

X(6200)/X(6900)

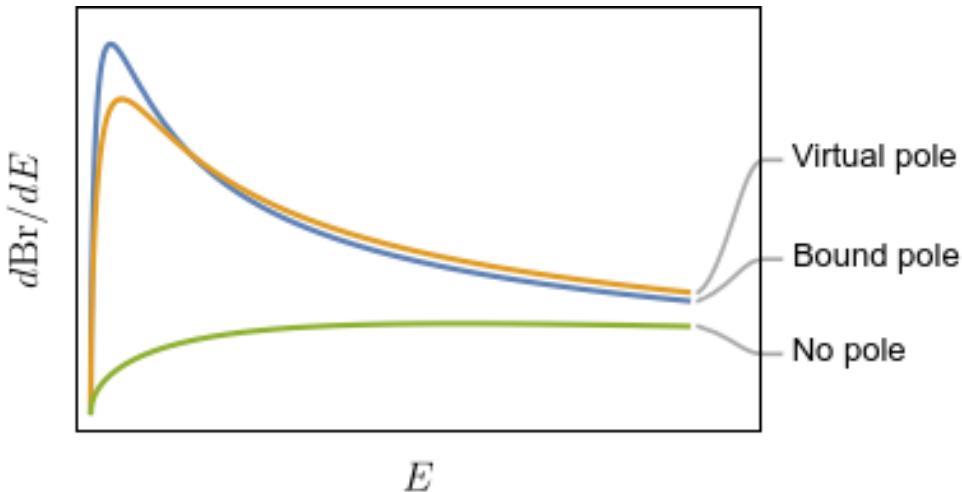
$p + p \rightarrow J/\psi + J/\psi + \dots$



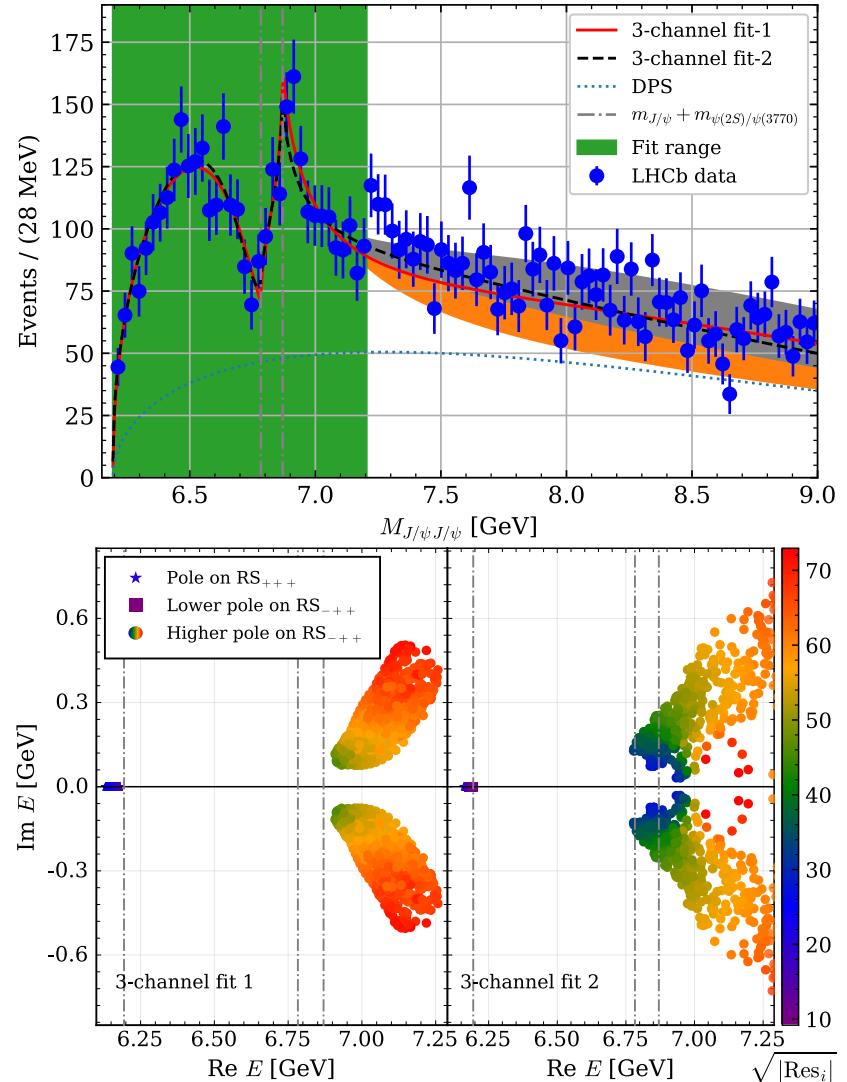
X(6200)/X(6900)



X(6200)/X(6900)

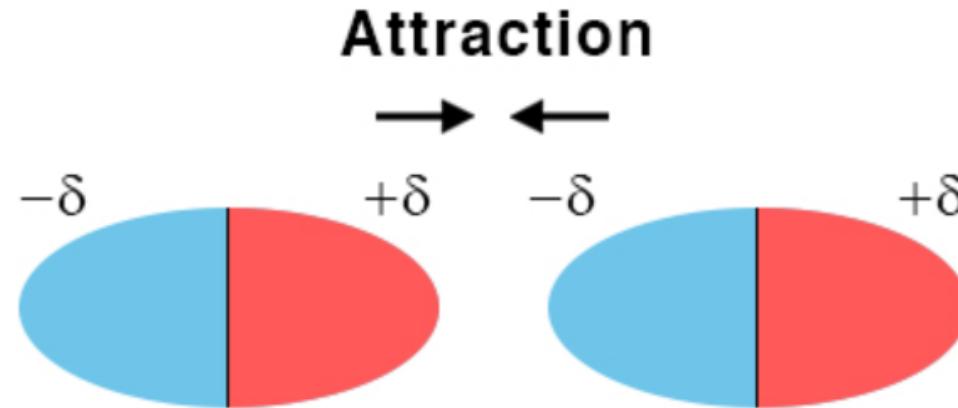
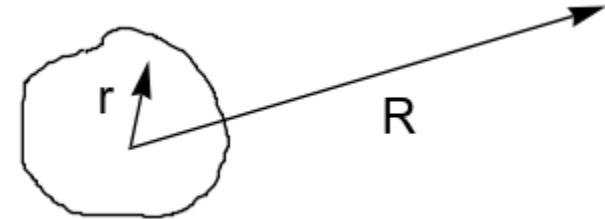


CMS & ATLAS Collaborations:
Additional BW structure near threshold
improves data description



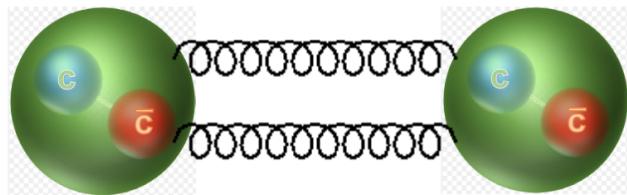
Polarisability in QED

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



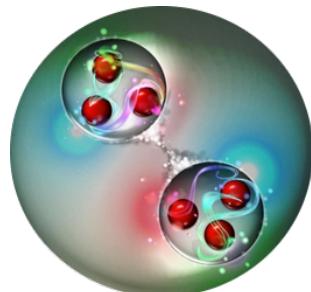
Strength of interaction of neutral objects at large distance depends on their *polarisability* that measures how easily they can be distorted by electric field

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 Miyamoto²

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