Exotic Hadrons at LHCb

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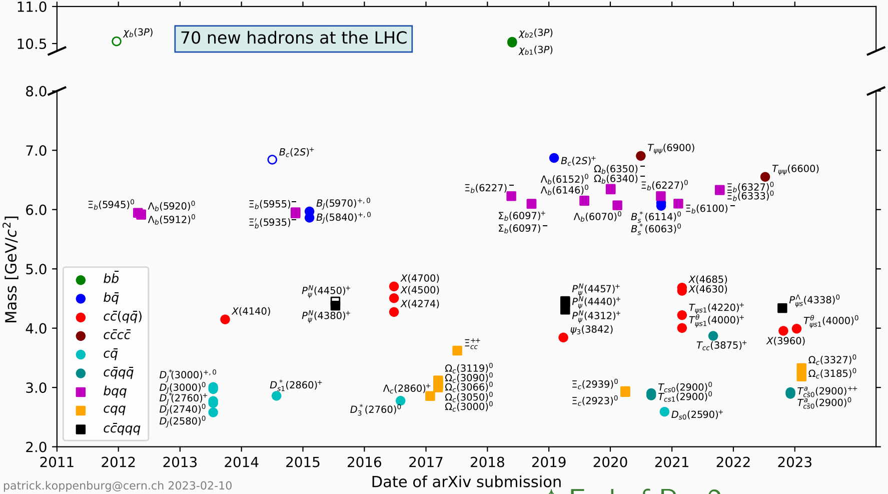
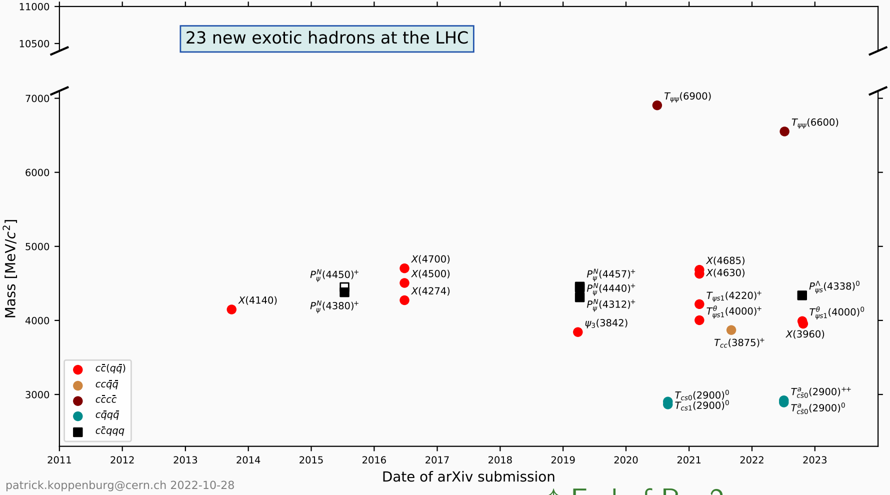
Hadron spectroscopy at the LHC



↑ End of Run2

Hadron spectroscopy at the LHC



↑ End of Run2

Experimental signatures beyond the quark model

- **Shifted masses and/or widths wrt. (naive?) model expectation**

$\chi_{c1}(3872)$
Very narrow charmonium-like state above the open charm threshold, far from predicted $c\bar{c}$ mass

$\Lambda(1405)$
Strangeness $S = -1$ baryon, but lighter than nucleon counterpart $N^*(1535)$

$_{s0}(2317)$
Narrow state 160 MeV below quark model prediction for $c\bar{s}$

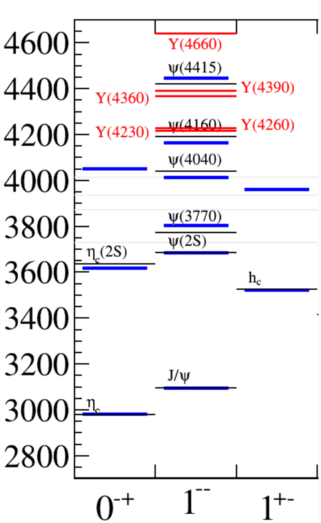
Typically associated with 2-body thresholds

Experimental signatures beyond the quark model

- **Shifted masses and/or widths**
  wrt. (naive?) model expectation

- **Supernumerous states**

Too many charmonium vector states



Experimental signatures beyond the quark model

- **Shifted masses and/or widths**
  wrt. (naive?) model expectation
- **Supernumerous states**
- **Spin-exotic mesons**

Forbidden quantum numbers for $q\bar{q}$

In the light meson sector:
$_1(1600)$ with $J^{PC} = 1^{-+}$
in , $'\pi$ and 3 decays

Experimental signatures beyond the quark model

- **Shifted masses and/or widths wrt. (naive?) model expectation**
- **Supernumerous states**
- **Spin-exotic mesons**
- **Charged states with hidden charm**

Examples of **charged exotic mesons**

$Z_c^+(4430)$ $(2S)$
$Z_c^+(3900)$ $J/\psi,^*$

Minimal quark content: $c\bar{c}u\bar{d}$

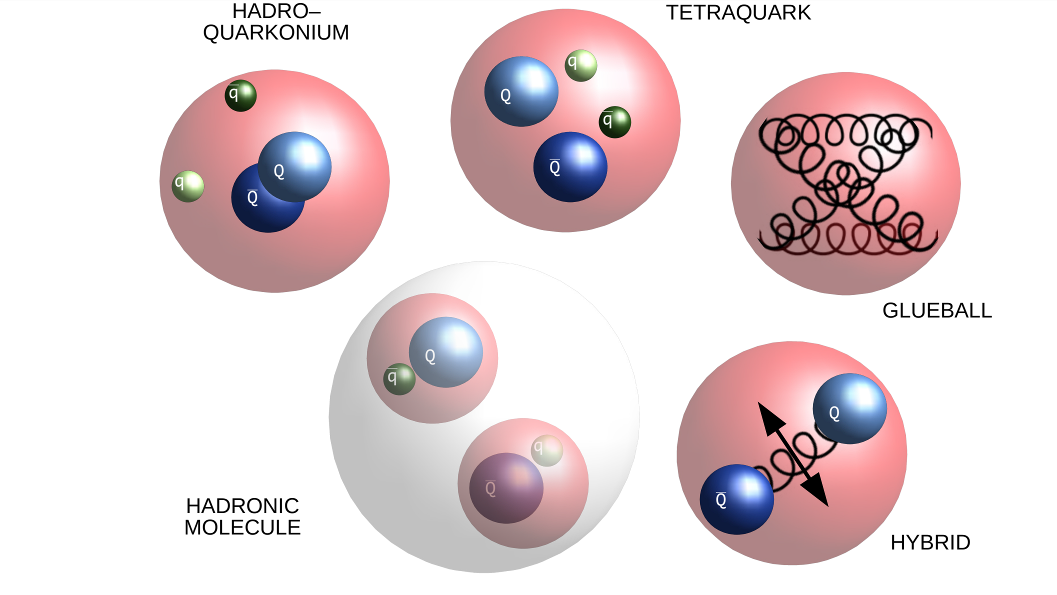
Baryons with hidden charm

$P_c^+(4380)$ J/ψ
$P_c^+(4450)$ J/ψ

Minimal quark content: $c\bar{c}uud$

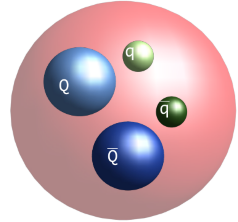
Unambiguously states beyond the quark model multiplets.

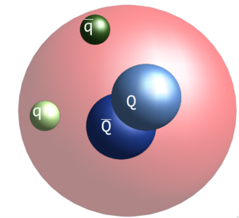
Preview: Models of Hadrons beyond the quark model

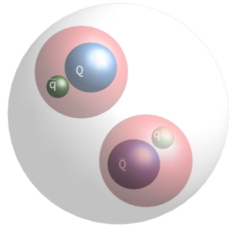


Graphics: C. Hanhart

Multiquark states







Tetraquarks

- **Compact** object made from $|\,Qq\rangle$ and $|\,\bar{Q}\bar{q}\rangle$ diquarks

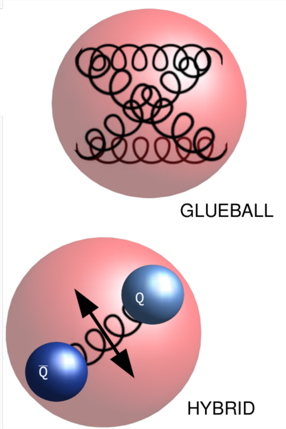
Hadro-Quarkonium

- **Compact** $|\,Q\bar{Q}\rangle$ color singlet surrounded by a light-quark / pion cloud.

Hadronic Molecules

- **Extended** object made from two hadrons $|\,Q\bar{q}\rangle$ and $|\,q\bar{Q}\rangle$
- Typical size $\sim \dfrac{1}{\sqrt{2\mu E_b}} \gg 1\,\text{fm}$
- near two-body threshold

Gluonic excitations



Glueball

- Bound state without valence quarks.

Hybrid

- Gluonic field configuration contributes to properties of hadron

But hold on: what about the (naive) quark model?

SU(3) Color - Constructing color singlets

Quarks are color triplets

$$q^i \quad \text{with} \quad i = 1, 2, 3 \quad \text{or} \quad R, G, B$$

Baryon color wave function:

$$\epsilon_{ijk} q^i q^j q^k$$

totally anitsymmetric under color exchange
$\Rightarrow$ symmetric under exchange of flavour, spin and position.

Meson color wave function:

$$q^i \bar{q}_i$$

But what binds the quarks together?

SU(3) Color - What binds quarks together?

QCD is similar to QED:

	QED	QCD
Symmetry	$U(1)$	$SU(3)$
Charges (generators)	Q	$T_a = \frac{1}{2}\lambda_a$ 8 Gell-Mann matrices λ_a
Gauge bosons	Photon	8 Gluons

Electromagnetic force between two charges Q_A and Q_B is proportional to their product and **attractive if**

$$Q_A Q_B < 0$$

What is the corresponding rule in QCD?

Gell-Mann matrices

$$\lambda_1 = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \lambda_2 = \begin{pmatrix} 0 & -i & 0 \\ i & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$\lambda_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \lambda_4 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix}$$

$$\lambda_5 = \begin{pmatrix} 0 & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & 0 \end{pmatrix} \quad \lambda_6 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}$$

$$\lambda_7 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -i \\ 0 & i & 0 \end{pmatrix} \quad \lambda_8 = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix}$$

SU(3) Color - "Colorfulness" - the Casimir operator

Color interaction is again proportional to the (tensor) product of charges

$$\sum_a T_a^A T_a^B$$

which can be written as

$$\sum_a T_a^A T_a^B = \frac{1}{2} \sum_a \left(T_a^2 - T_a^{A^2} - T_a^{B^2} \right)$$

with the $SU(3)$ *(quadratic) Casimir operator* $C_2 = \sum_a T_a^2$

- C_2 depends on how the two components A and B are combined,
  i. e . on the $SU(3)$ representation the two-particle state corresponds to

- C_2 is analoge to angular momentum magnitude $\vec{J}^2$ in $SU(2)$.
- Measures the total "colorfulness"
- $\Rightarrow$ **strongest attraction in least "colorful" states when $C_2 = 0$**

SU(3) Color - Two-Body representations

Most simple system is $q\bar{q}$, which is a product of a triplet and an antitriplet

$$3 \otimes \overline{3} = 1 \oplus 8$$

Building representations from the irreducible $q = 3$ and $\bar{q} = \overline{3}$ we have for the representation (u, v) (u(v) counts steps across top(bottom) of multiplet)

$$C_2(u, v) = (3u + 3v + u^2 + uv + v^2)/3$$

In this labeling we have

$$1 = (0, 0) \quad 3 = (1, 0) \quad \overline{3} = (0, 1) \quad 8 = (1, 1) \quad 10 = (3, 0)$$

where the color singlet has a vanishing Casimir operator

$$C_2(1) = 0$$

and is therefore the most bound state.

Note: $C_2(1, 0) = C_2(0, 1) = 4/3$ and $C_2(1, 1) = 3 > C_2(1, 0) \cdot C_2(0, 1)$!

SU(3) Color - Diquarks

How should we think about a baryon $|qqq\rangle$?

$\Rightarrow$ look at quarks pair-wise :

$$3 \otimes 3 = \overline{3} \oplus 6$$

A pair of quarks behaves as an antitriplet! And the tensorproduct of the charges in the $3 \otimes 3 \rightarrow \overline{3}$ configuration is

$$\sum_a T_a^A T_a^B = \frac{1}{2}\left(\frac{4}{3} - \frac{4}{3} - \frac{4}{3}\right) = -\frac{2}{3}$$

attractive!

We can expect correlations between quark-pairs to exist within hadrons.

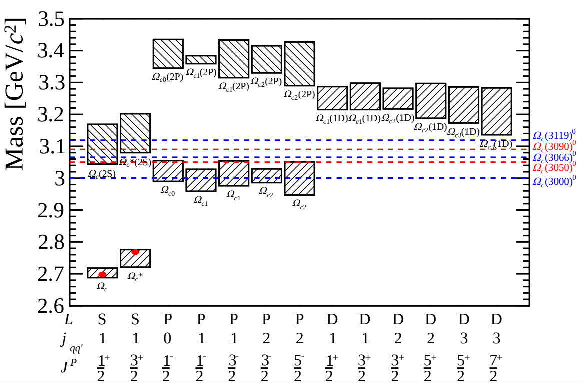
These “Diquarks“ are a useful tool to discuss multiquark objects.

Depending on the symmetry of the spin-flavour part of the wave function one talks about "good" (spin singlet, flavour triplet) and "bad" (spin and flavour triplet) diquarks.

Strangely charming baryons: The Ω_c [PRL118(2017)182001]

- The $|css>$ system is a proving ground for HQET
- Scale separation between heavy charm and light quarks
- Heacy quark acts as static source of color
- Popular model: heavy quark + light diquark
- Two S-wave ground states Ω_c^0 and $\Omega_c^0(2770)$ observed
- 5 P-wave states predicted

Summary of theoretical predictions



Five Ω_c exitations in λ-mode predicted

- Negative parity states $\Rightarrow$ one unit of orbital angular momentum
- light diquark $| ss\rangle$ in S-Wave $\Rightarrow \psi(x)$ symmetric under $s \leftrightarrow s$
- P-Wave: $\ell = 1$ between heavy quark and diquark (λ-mode)
- Total wavefunction needs to be antisymmetric (Pauli) under $s \leftrightarrow s$

$$\psi(c, s, s) = \psi^{\text{sym}}(x)\psi^{\text{asym}}_{\text{color}}\psi^{\text{sym}}_{\text{flavor}}\psi^{?}_{\text{spin}}$$

$\Rightarrow \psi_{\text{spin}}$ must be symmetric $|\uparrow\uparrow\rangle \quad \Rightarrow \quad s = 1$

- Possible angular momentum combinations:

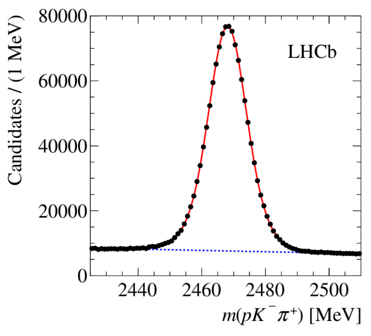
$S = s_c \oplus s$	$S = 1/2$	$S = 2/3$
$J = S \oplus \ell$	$\frac{1}{2}, \frac{3}{2}$	$\frac{1}{2}, \frac{3}{2}, \frac{5}{2}$

$\Rightarrow$ **5 states predicted**

predicted mass ordering:
$\frac{1}{2}, \frac{1}{2}, \frac{3}{2}, \frac{3}{2}, \frac{5}{2}$

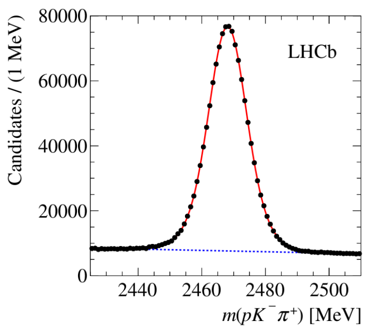
Five new Ω_c states in the decay $\Xi_c^+ K^-$ [PRL118(2017)182001]

Reconstruct $\Xi_c \to pK^-\pi^+$



- Ξ_c detached from primary vertex
- PID of daughter tracks
- pointing to primary vertex
  $\Rightarrow$ looking for prompt Ω_c

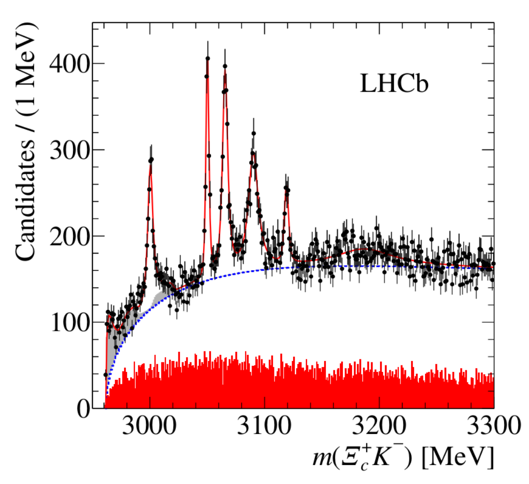
Reconstruct $\Xi_c \to pK^-\pi^+$



- Ξ_c detached from primary vertex
- PID of daughter tracks
- pointing to primary vertex

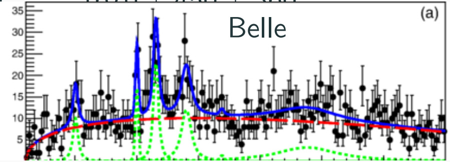
  $\Rightarrow$ looking for prompt Ω_c

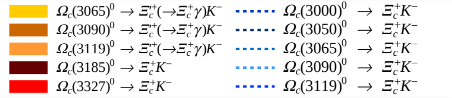
Adding another kaon:



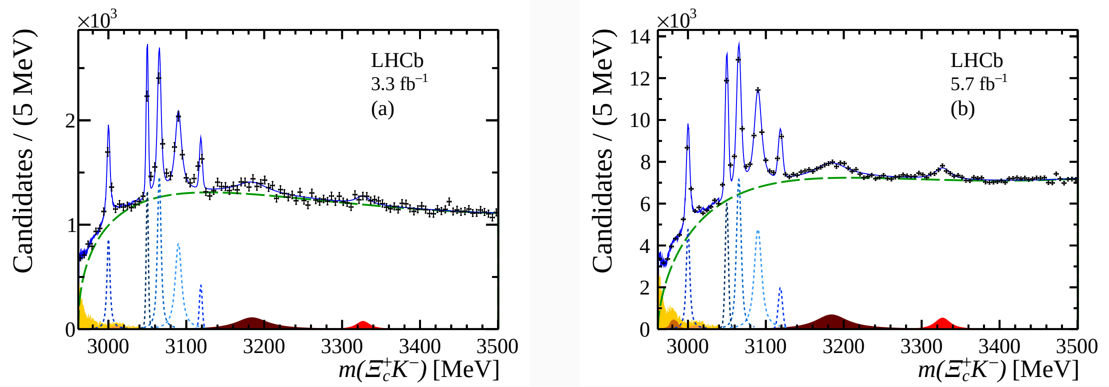
Resonance	Mass (MeV)	Γ (MeV)	Yield	N_σ
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$	$1300 \pm 100 \pm 80$	20.4
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$	$970 \pm 60 \pm 20$	20.4
		$< 1.2\,\mathrm{MeV}$, 95% CL		
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$	$1740 \pm 100 \pm 50$	23.9
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$	$2000 \pm 140 \pm 130$	21.1
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$	$480 \pm 70 \pm 30$	10.4
		$< 2.6\,\mathrm{MeV}$, 95% CL		
$\Omega_c(3188)^0$	$3188 \pm 5 \pm 13$	$60 \pm 15 \pm 11$	$1670 \pm 450 \pm 360$	

- Are these the 5 P-wave states? [PRD95(2017)114012]
- Why two very narrow states? [PRD96(2017)014009]
- **4 states confirmed by Belle [PRD97(2018)051102]**





Analysing the full LHCb dataset (Run I+II) $\sim 9\,\mathrm{fb}^{-1}$



Revised masses and widths [2302.04733]

Resonance	m (MeV)	Γ (MeV)
$\Omega_c(3000)^0$	$3000.44 \pm 0.07\ ^{+0.07}_{-0.13} \pm 0.23$	$3.83 \pm 0.23\ ^{+1.59}_{-0.29}$
$\Omega_c(3050)^0$	$3050.18 \pm 0.04\ ^{+0.06}_{-0.07} \pm 0.23$	$0.67 \pm 0.17\ ^{+0.64}_{-0.72}$
		$< 1.8\,\text{MeV}, 95\%$ C.L.
$\Omega_c(3065)^0$	$3065.63 \pm 0.06\ ^{+0.06}_{-0.06} \pm 0.23$	$3.79 \pm 0.20\ ^{+0.38}_{-0.47}$
$\Omega_c(3090)^0$	$3090.16 \pm 0.11\ ^{+0.06}_{-0.10} \pm 0.23$	$8.48 \pm 0.44\ ^{+0.61}_{-1.62}$
$\Omega_c(3119)^0$	$3118.98 \pm 0.12\ ^{+0.09}_{-0.23} \pm 0.23$	$0.60 \pm 0.63\ ^{+0.90}_{-1.05}$
		$< 2.5\,\text{MeV}, 95\%$ C.L.
$\Omega_c(3185)^0$	$3185.1 \pm 1.7\ ^{+7.4}_{-0.9} \pm 0.2$	$50 \pm 7\ ^{+10}_{-20}$
$\Omega_c(3327)^0$	$3327.1 \pm 1.2\ ^{+0.1}_{-1.3} \pm 0.2$	$20 \pm 5\ ^{+13}_{-1}$

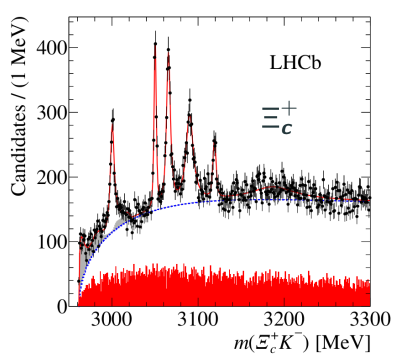
Two new states compatible with predicted $S - Wave$ states?

Lattice calculations [PRL119(2017)042001] put the $\Omega_c(3185)$ in the mass range of P-Wave states, while at higher masses many states can contribute.

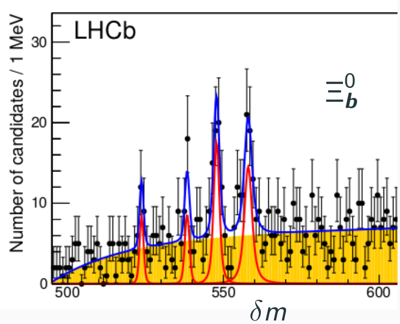
Nearby thresholds: ΞD at $\sim 3180\,\text{MeV}$ and ΞD^* at $\sim 3325\,\text{MeV}$

Double strange heavy baryons - looking at beauty sector

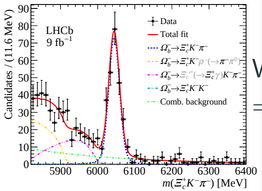
[PRL118(2017)182001]



[PRL124(2020)082002]

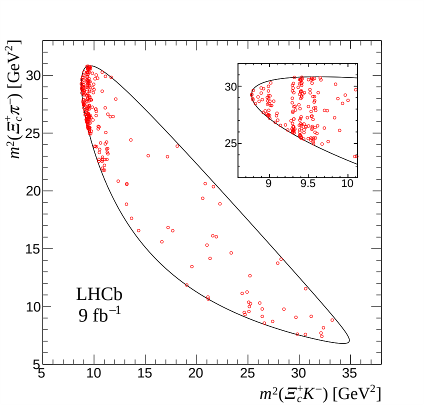


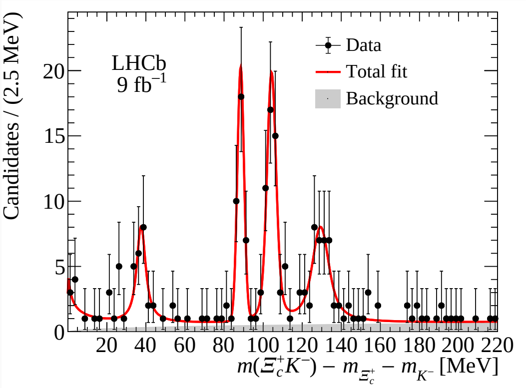
- Most natural J^P assignment would be $1/2^-, 1/2^-, 3/2^-, 3/2^-, 5/2^-$
- Quark di-quark model predicts 5 P-wave excitations, $5/2$ Ω_b state not seen? [PRD102(2020)014027]
- Molecular model can explain 3 Ω_c and 4 Ω_b states $\Xi'_Q \bar{K}, \Xi^*_Q \bar{K}, \Xi \bar{B}/\bar{D}, \Xi \bar{B}^*$ [PRD101(2020)054033] J^P assignment would be $1/2^-, 3/2^-, 1/2^-, 3/2^-$ for Ω_b



Well defined source

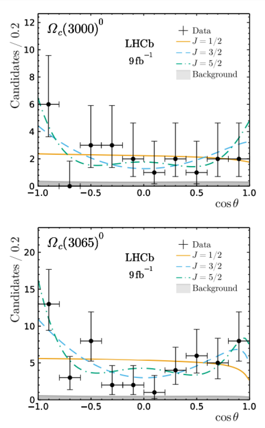
$\Rightarrow$ measure spins

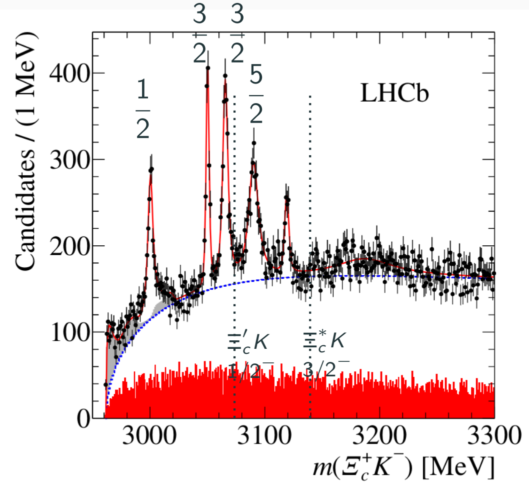


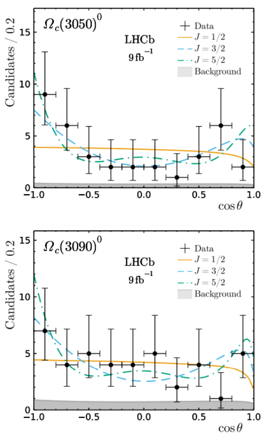


- statistically limited
- Only four states seen (as in Belle)
- $J = \frac{1}{2}, \frac{1}{2}, \frac{3}{2}, \frac{3}{2}$ assignment rejected at $3.5\,\sigma$

Ω_c Speculations







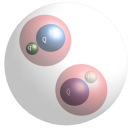
Quark model states: unobserved $1/2^-$ state?

Role of thresholds? Could there be molecular contributions?

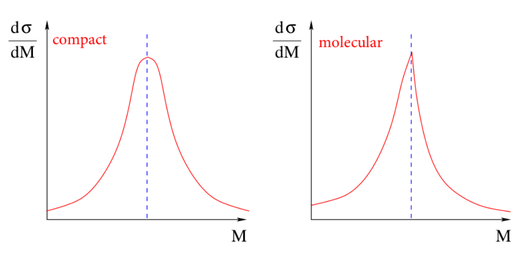
$\Xi_c' K$ disfavoured by spin analysis.

Molecules:

- Arising from **interaction in a Hadron-Hadron system**



- **Small binding energy**
  $\Rightarrow$ signals close to 2-body threshold
- **Composite nature dominates** over compact component
  [PR137(1965)B672][PLB586(2004)53]
- Close to threshold **only S-Wave** important



$$T(E) = \frac{g^2/2}{E - E_r + g^2/2(i\sqrt{2\mu E} + \gamma) + i\Gamma_0/2}$$

- Sizeable coupling g to the 2-body system (reduced mass μ)
  $\Rightarrow$ energy dependence dominated by $\sqrt{2\mu E}$ $\Rightarrow$ asymmetric in E
- Compact system: energy dependence driven by E

We speak of a shallow bound state of two hadrons if

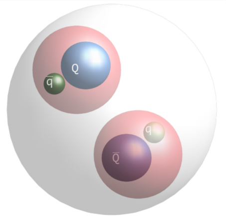
$$R > R_{\text{conf}} \qquad \Rightarrow \qquad E_b < \frac{1}{2\mu R_{\text{conf}}^2}$$

for example at DD^* threshold, with $R_{\text{conf}} \approx 1\,\text{fm} \approx (200 MeV)^{-1}$ and $\mu_{DD^*} \approx 966\,\text{MeV}$

$$E_b < 20\,\text{MeV}$$

We know they exist:

- Deuteron $E_b = 2.22\,\text{MeV}$
- Hypertriton $E_b = 0.13 \pm 0.05\,\text{MeV}$ from Λd threshold
- Not a molecule but important hadronic interaction: virtual state in nn scattering



do Mesonic or Baryon-Meson molecules exist?

Hadronic Molecules as a useful paradigm

- Relatively high predictive power - only need to know 2-body thresholds
- Limited number of predicted states (S-Wave at threshold)
- Universal paradigm: Properties fully defined by scattering length in 2-body channel
- $\Rightarrow$ hadrons relevant degrees of freedom
- At threshold: small relative momentum scale k
- Potential scattering useful model.
- Approaches available to incorporate low-energy effective theories of QCD

- **The majority of the discovered exotic hadrons lies close to two-body thresholds.**

Cross section for Hard-Sphere scattering at low energy

Cross section at low energy is given by S-Wave phase shift only:

$$\frac{d\sigma}{d\Omega} = |f(\theta)|^2 = \frac{\sin^2 \delta_0}{k^2} \approx \frac{(kR)^2}{k^2} = R^2 \quad \text{since} \quad kR \ll 1 \tag{1}$$

Note that indeed there remains no angular dependence for the S-wave cross section.

The total cross section for scattering off a hard sphere at low energy is simply obtained by integrating this constant over the full solid angle, which gives

$$\boxed{\sigma_{tot} = 4\pi R^2 \qquad \text{valid at low energies, i.e.} \quad kR \ll 1} \tag{2}$$

At low energy the scattering cross section is 4 times the geometric cross section of the object.

Inside

$$u(r) \equiv rA_{\ell=0}(r) \propto \sin k'r$$

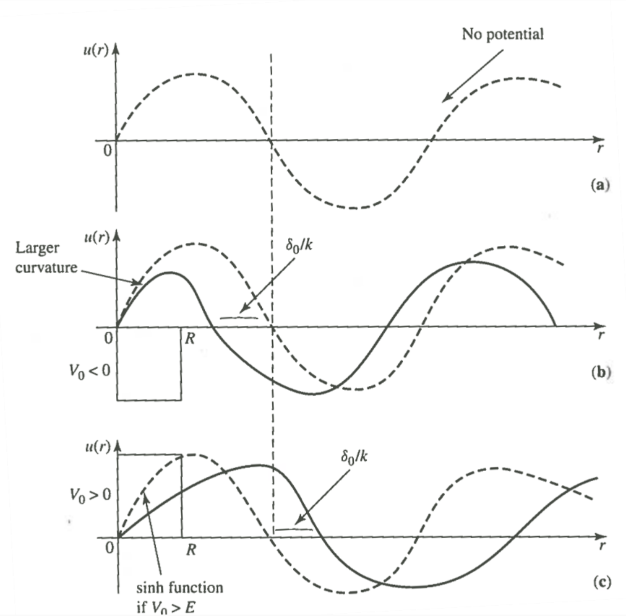
$$E - V_0 = \frac{\hbar^2 k'^2}{2m}$$

attractive potential:

wave function pulled in

repulsive potential:

wave function pushed out

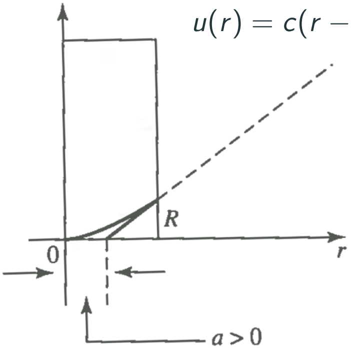


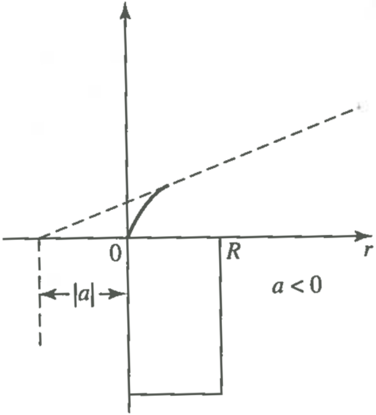
reproduced from Sakurai/Napolitano 2nd Edition

Scattering at very low energies: the scattering length

Low energies ⇒ long wavelengths ⇒ linear outside wavefunction

$u(r) = c(r - a)$





$$\lim_{k \to 0} \sin(kr + \delta_0) = c(r - a)$$

$$\frac{u'}{u} = k \cot(kr + \delta_0) \xrightarrow{k \to 0} \frac{1}{r - a}$$

setting r=0 $\boxed{\lim_{k \to 0} k \cot \delta_0 = -\frac{1}{a}}$

plots reproduced from Sakurai/Napolitano 2nd Edition

Interpretation of the scattering length

The scattering length a is the intercept of the outside wave function extrapolated to $u(r) = 0$.

Scattering amplitude at low energy written in terms of scattering length

$$f_{\ell=0}(k \to 0) = \frac{1}{k \cot \delta_0(k) - ik} = \frac{1}{-\frac{1}{a} - ik}$$

Total cross section at low energy:

$$\boxed{\sigma_{tot} = 4\pi \lim_{k\to 0} |f_{\ell=0}(k)|^2 = 4\pi a^2}$$

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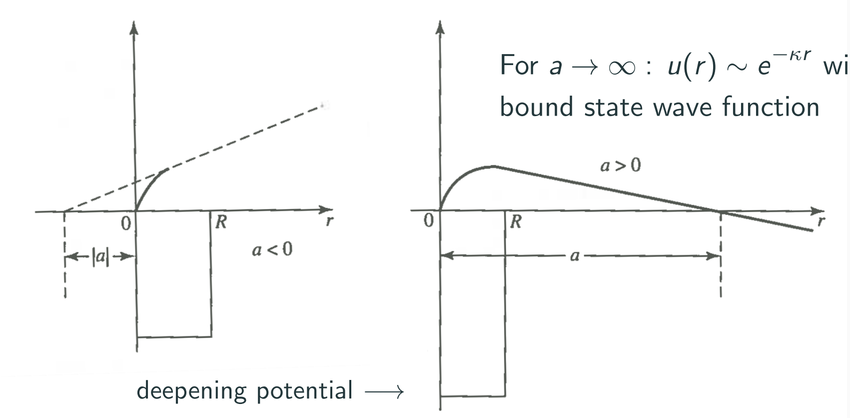
At low energies the scattering cross section for arbitrary potentials is given by the hard-sphere cross section with the radius replaced by the scattering length!

Bound states

Note: deepening the potential well will lead to very long scattering lengths, much longer than the range R of the potential!



For $a \to \infty$: $u(r) \sim e^{-\kappa r}$ with $\kappa \approx 0$
bound state wave function

Flip of the sign of a is associated with the formation of a bound state.

plots reproduced from Sakurai/Napolitano 2nd Edition

Relation between binding energy and scattering length

Outside

$$u(r) \sim e^{-\kappa r} \qquad r > R$$

Inside with very small energy $E = 0 \pm \epsilon$

$$u(r) \propto \sin k' r \quad \text{with} \quad \frac{\hbar^2 k'^2}{2m} = E - V_0 \approx |V_0| \quad \text{and} \quad k' \approx \kappa$$

In terms of how the wave functions are connected at $r = R$ there is no difference between bound state or zero-energy scattering.

Map the wave functions:

$$-\left.\frac{\kappa e^{-\kappa r}}{e^{-\kappa r}}\right|_{r=R} = \left.\left(\frac{1}{r-a}\right)\right|_{r=R}$$

for $R \ll a$ the binding energy

$$\kappa \approx \frac{1}{a} \quad \Rightarrow \boxed{E_b = \frac{\hbar^2 \kappa^2}{2m} \approx \frac{\hbar^2}{2ma^2}}$$

Example: the deuteron

Bound state $^3S_1$ in neutron-proton system

$$E_b = 2.22\,\text{MeV} \qquad \text{or} \quad k = \sqrt{2mE_b}/\hbar = 45.7\,\text{MeV}$$

Scattering length measured to be:

$$a_{triplet} = 5.42 \times 10^{-13} cm$$

Inserting numbers, noting that the mass appearing is the reduced mass $\mu = \dfrac{m_1 m_2}{m_1 + m_2}$

$$\frac{\hbar^2}{2\mu a^2} = \frac{\hbar^2}{m_N a^2} = 1.4\,\text{MeV}$$

Result can be improved by allowing more terms in the expansion

$$k \cot \delta_0 = -\frac{1}{a} + \frac{1}{2} r_0 k^2$$

with effective range $r_0 = 1.76 \times 10^{-13} cm$ for the deuteron $\Rightarrow k = 46.4\,\text{MeV}$

Weinberg's Composition Criterion I

Composite object with compact $| \psi_0 \rangle$ component and molecular component $| h_1 h_2 \rangle$

$$| \Psi \rangle = \begin{pmatrix} \lambda \, | \psi_0 \rangle \\ \chi(k) \, | h_1 h_2 \rangle \end{pmatrix}$$

Hamiltonian:

$$H \, | \Psi \rangle = E \, | \Psi \rangle, \quad H = \begin{pmatrix} H_c & V \\ V & H^0_{hh} \end{pmatrix}$$

Trick: absorb all hadron-hadron interactions into $| \psi_0 \rangle$.

Keep only kinetic term in Hamiltonian $H^0_{hh} = k^2/2\mu$.

$\Rightarrow$ for the wavefunction

$$\chi(k) = \lambda \frac{f(k)}{E - k/2\mu}$$

with transition formfactor

$$\langle \psi_0 \, | \, V \, | \, h_1 h_2 \rangle = f(k)$$

Weinberg's Composition Criterion II

Wavefunction Normalisation:

$$1 = \langle \Psi \mid \Psi \rangle = \lambda^2 \langle \psi_0 \mid \psi_0 \rangle + \int \frac{d^3k}{(2\pi)^3} |\chi(k)|^2 \langle h_1 h_2 \mid h_1 h_2 \rangle =$$

$$= \lambda^2 \left[1 + \int \frac{d^3k}{(2\pi)^3} \frac{f(k)^2}{(E_b - k/2\mu)^2} \right]$$

allows probabilistic interpretation of λ^2 as fraction of compact component.

Integral converges for $f(k) = f(0) = g_0 = const$. If the inverse range of the forces $\beta \gg \gamma = 1/R$ one gets

$$1 = \lambda^2 \left[1 + \frac{\mu^2 g_0^2}{2\pi\sqrt{2\mu E_b}} + \mathcal{O}\left(\frac{\gamma}{\beta}\right) \right] \quad \Rightarrow \quad \boxed{g_0^2 = \frac{2\pi\gamma}{\mu^2}\left(\frac{1}{\lambda^2} - 1\right)}$$

Relation between probability to find compact component in wavefunction and the coupling to the continuum channel.

Weinberg's Composition Criterion II

The coupling g_0 also appears in the one-channel Flatté (more generally in the self-energy)

Flatté:

$$T(E) = \frac{g_0^2}{E + E_B + g_0^2 \frac{\mu}{2\pi}(ik + \gamma)}$$

Effective range expansion:

$$T(E) = -\frac{2\pi}{\mu} \frac{1}{1/a + (r/2)k^2 - ik}$$

with effective range r and scattering length a. Finally

$$\boxed{a = -2\frac{1-\lambda^2}{2-\lambda^2}\left(\frac{1}{\gamma}\right) + \mathcal{O}\left(\frac{1}{\beta}\right)} \qquad \boxed{r = -\frac{\lambda^2}{1-\lambda^2}\left(\frac{1}{\gamma}\right) + \mathcal{O}\left(\frac{1}{\beta}\right)}$$

For a fully molecular state $\lambda = 0$ the negative scattering length get's maximal $a = -\frac{1}{\gamma}$ and $r \sim \mathcal{O}\left(\frac{1}{\beta}\right)$

For a compact state $a = -\mathcal{O}\left(\frac{1}{\beta}\right)$ and $r \to -\infty$.

Application to Deuteron

pn scattering length and effective range [JPG10(1984)165] and binding energy [Nucl. Phys. A380(1982)261.]

$$a = -5.419 \pm 0.007\,\mathrm{fm} \qquad r = 1.764 \pm 0.008\,\mathrm{fm} \qquad E_b = 2.22\,\mathrm{MeV}$$

therefore

$$\gamma = \sqrt{2\mu E_b} = 45.7\,\mathrm{MeV} = 0.23\,\mathrm{fm}^{-1}$$

Let's take pion mass to calculate the range of forces

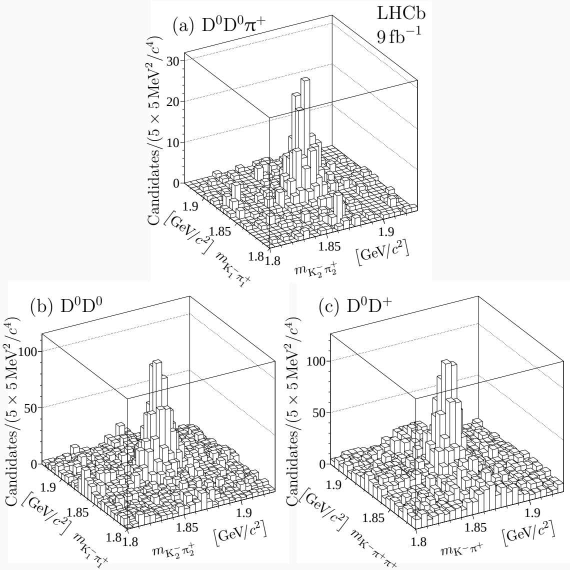
$$\frac{1}{\beta} \approx \frac{1}{m_\pi} \approx 1.4\,\mathrm{fm} \quad \approx r$$

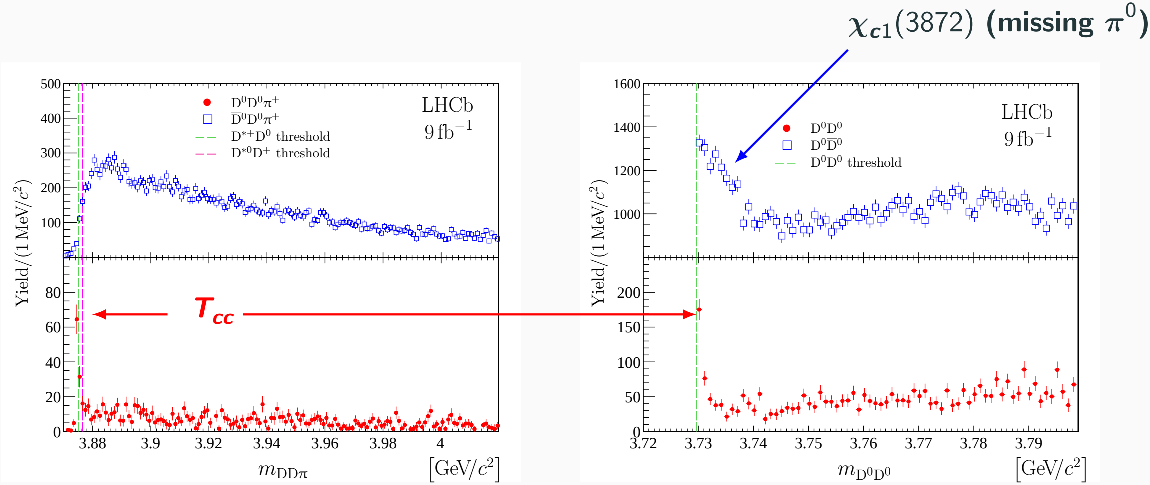
On the order of the effective range. Together with the large negative (in this convention) scattering length Weinberg concluded:

The Deuteron is a composite object.

The T_{cc}

- $D^0 \to K^-\pi^+$
- $D^+ \to K^-\pi^+\pi^+$
- **Double mis-ID $\leftrightarrow$ is a potential problem**
  cross-checked with D^+D^+, $D^+D^0\pi^+$,D^0D^0,D^0D^- and $D^0D^0\pi^+$
- Decay times are required to be $> 100\,\mu m/c$
- After initial selection D^0 and D^+ decay product momenta (and additional π^+) are reoptimized under mass and vertex pointing constraints (kinematic fit)





No structures found in neither $D^+D^0\pi^+$ nor D^+D^+

$\Rightarrow$ Isosinglet

Pole on the second Riemann sheet

$$\delta m = -360 \pm 40^{+4}_{-0}\ \text{keV}/c^2$$

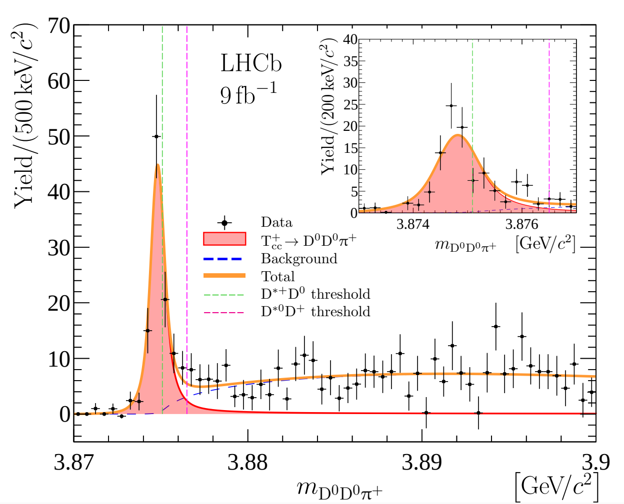
$$\Gamma = 48 \pm 2^{+0}_{-14}\ \text{keV}$$

$D^* D$ scattering length

$$a = [-(7.16 \pm 0.51) + i(1.85 \pm 0.28)]\ fm$$

Effective range

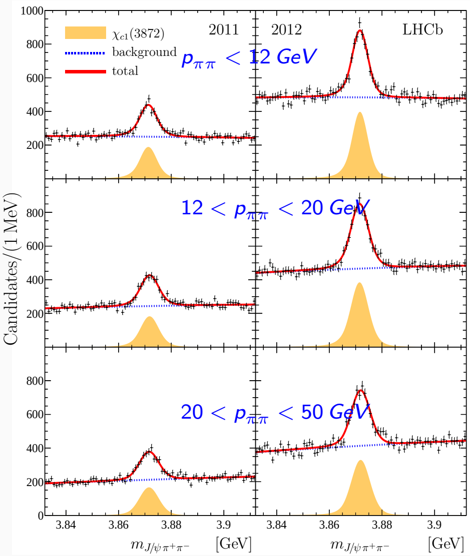
$$-r < 11.9(16.9)\ fm \quad @ \quad 90(95)\% CL$$



Precision measurements of mass and width of the $\chi_{c1}(3872)$ at LHCb

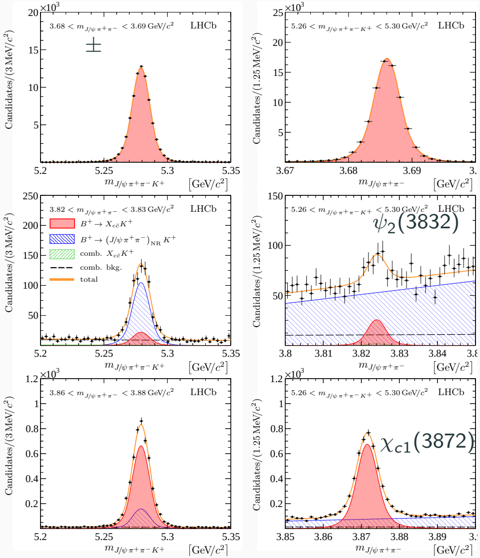
Inclusive $\chi_{c1}(3872) \to J/\psi\pi^+\pi^-$

[PRD102(2020)092005]

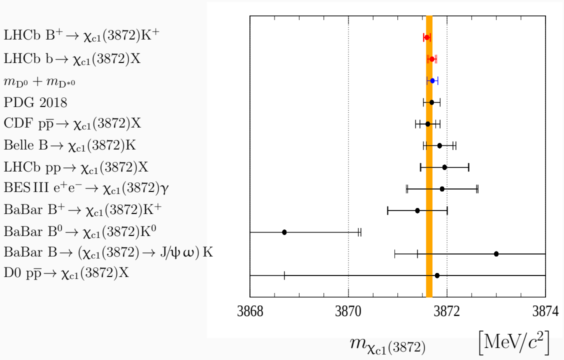


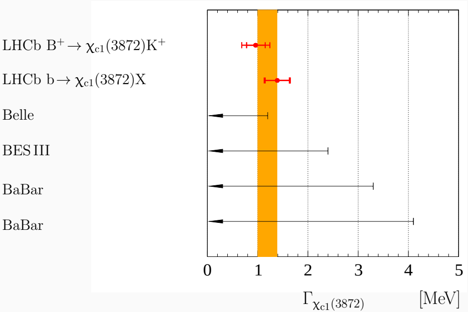
Exclusive $^{\pm} \to J/\psi\pi^+\pi^-K^\pm$

[JHEP08(2020)123]



Comparison between inclusive and exclusive analysis and previous measurements





First time a width was established for this state.

Preliminary conclusion from Breit-Wigner fits

- Most precise measurements of the Breit-Wigner mass. LHCb average:

$$m_{\chi_{c1}(3872)}\big|_{\text{LHCb}} = 3871.64 \pm 0.06 \pm 0.01\,\text{MeV}/c$$

- Uncertainty now smaller than uncertainty of threshold location
  $m_{D^0} + m_{D^{0*}} = 3871.70 \pm 0.11\, MeV$

[PDG2019][JHEP08(2020)123]

- Distance to $D^0 D^{0*}$ threshold $\delta E = m_{D^0} + m_{D^{0*}} - m_{\chi_{c1}(3872)}$

$$\delta E\big|_{\text{LHCb}} = 0.07 \pm 0.12\, MeV$$

- **First non-zero value for Breit-Wigner width**

$$\Gamma\big|_{\text{LHCb}} = 1.13$$

- Threshold is within the natural width
  $\Rightarrow$ Breit-Wigner is not the correct line-shape

Flatté parameters and comparison to Breit-Wigner [PRD102(2020)092005]

g	$f_\rho \times 10^3$	Γ_0 [MeV]
$0.108 \pm 0.003\,^{+0.005}_{-0.006}$	$1.8 \pm 0.6\,^{+0.7}_{-0.6}$	$1.4 \pm 0.4 \pm 0.6$

Shape parameters:

Mode [MeV]	Mean [MeV]	FWHM [MeV]
$3871.69\,^{+0.00}_{-0.04}\,^{+0.05}_{-0.13}$	$3871.66\,^{+0.07}_{-0.06}\,^{+0.11}_{-0.13}$	$0.22\,^{+0.06}_{-0.08}\,^{+0.25}_{-0.17}$

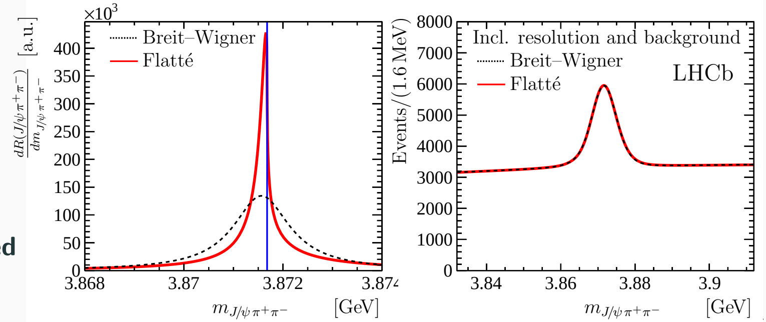
- J/ψ data alone cannot distinguish line shapes
- Flatté narrower than BW by factor 5

Systematic uncertainties on g

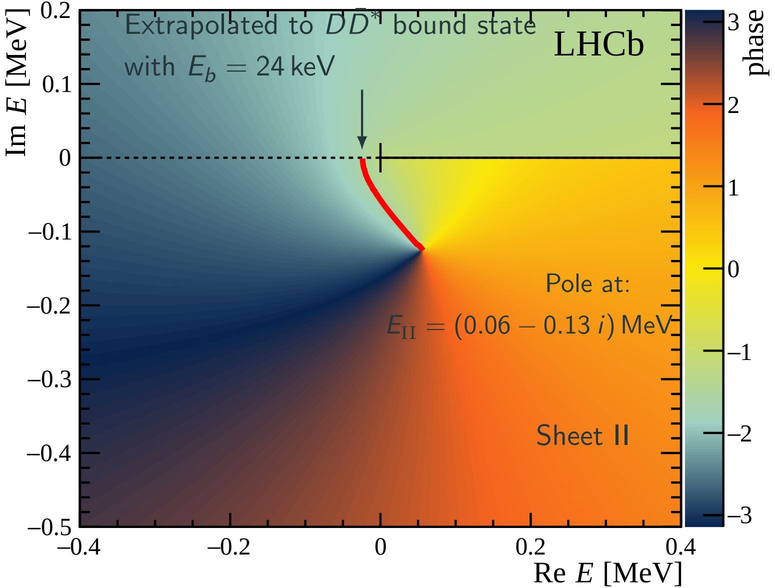
- Momentum scale
- Threshold mass

Small effect:
Resolution+Bkg model and D^{0*} width

Systematic uncertainties quoted do not include scaling!



Analytic structure of the Flatté model at $D^0\bar{D}^{*0}$ threshold [PRD102(2020)092005]



Fitting Coupled Channels is not always easy

As you have shown in [arXiv:2110.07484] the relation between g and $E_f = m_0 - m_{\text{threshold}}$ is given by

$$g(E_f) = \frac{2(E_p - E_f)}{\sqrt{2\mu_1|E_p|} + \sqrt{2\mu_2(\delta + |E_p|)}}$$

Where E_p is the real part of the pole location.

For small E_p compared to δ this becomes

$$g(E_f) = -\frac{2E_f}{\sqrt{2\mu_2\delta}}$$

and it is clear that the slope of this function is driven by the isospin splitting δ.

Uncertainty on isospin splitting smaller than threshold location uncertainty:

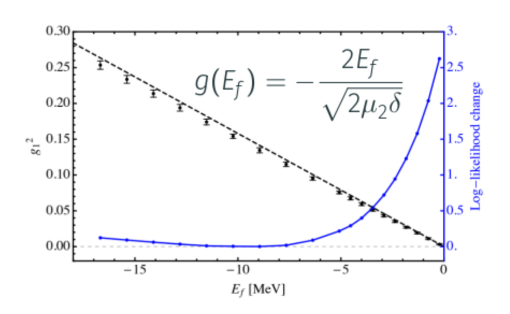
$$m_{D^*(2007)^0} - m_{D^0} = 142.014 \pm 0.030\,\text{MeV} \qquad m_{\mathrm{D}^0} + m_{\mathrm{D}^{0*}} = 3871.70 \pm 0.11\,MeV$$

Fitting Coupled Channels is not always easy

Nonvanishing offset

$$g(0) = \frac{2(E_p)}{\sqrt{2\mu_1|E_p|} + \sqrt{2\mu_2(\delta + |E_p|)}}$$

From which the pole position can in principle be extracted. Problem: all the uncertainties in the $g(E_f)$-plot are highly correlated.



Better alternative: remove correlation by subtraction:

$$D(E) = E - E_p + \frac{i}{2}\left[g\left(k_1 - i\gamma_1 + k_2 - i\gamma_2\right) + \Gamma_\rho(E) + \Gamma_\omega(E) + \Gamma_0\right].$$

directly fitting for real part of the pole position E_p with

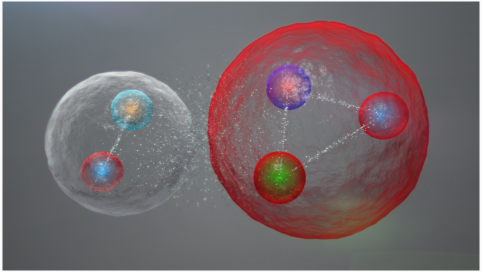
$$\gamma_a = \sqrt{2\mu_a(\delta_a - E_p)}$$

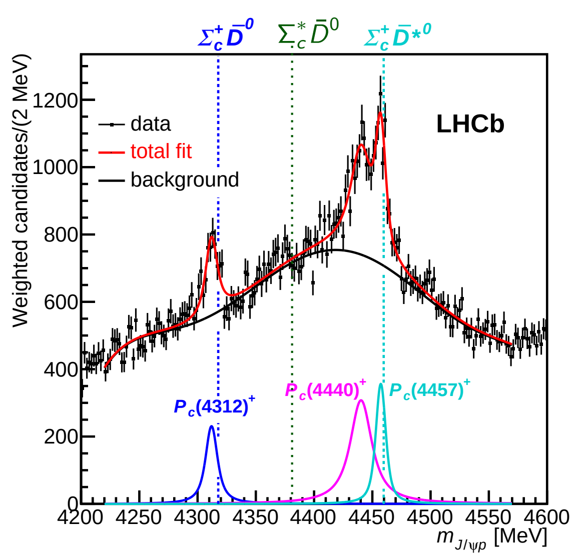
Pentaquarks

Full Run I+II dataset reveals

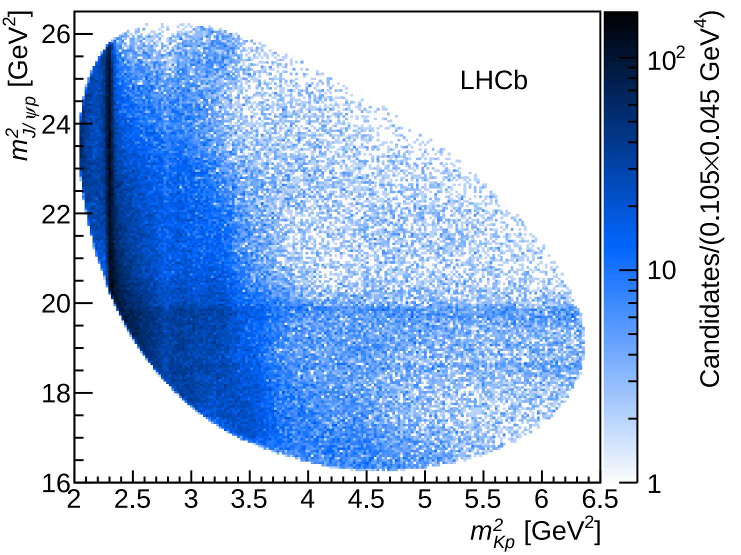
- **New narrow structure at $m = 4312$ MeV**
- **Peak at 4450 MeV split into two peaks**

investigated in J/ψ projection alone (no angular analysis)





$\cos\theta_{P_c}$ weighted

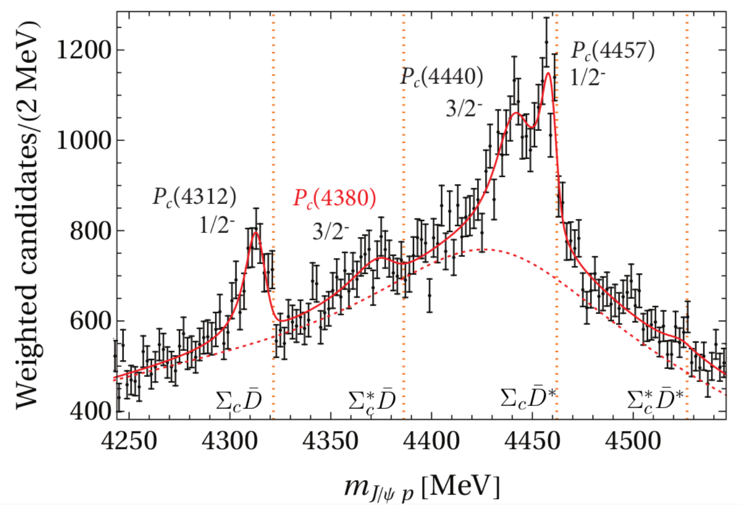


Status update: a measurement of the quantum numbers of the $P_c(4312)$ is about to be published. Stay tuned but don't expect big surprises.

Coupled channel fit: Molecular Pentaquarks [PRL124(2020)072001]

8 coupled channels $\Sigma_c^{(*)}\bar{D}^{0(*)}(1/2^-, 3/2^-), J/\psi p$

with contact interaction and one-pion exchange (OPE)

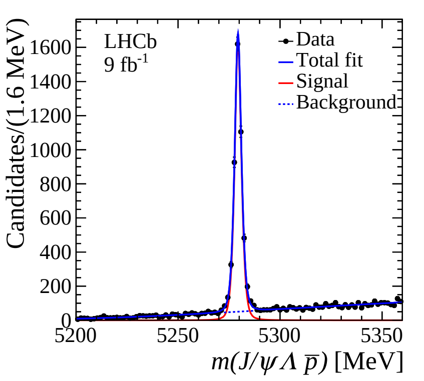


Fit with heavy quark spin symmetry necessarily gives a narrow $P_c(4380)$

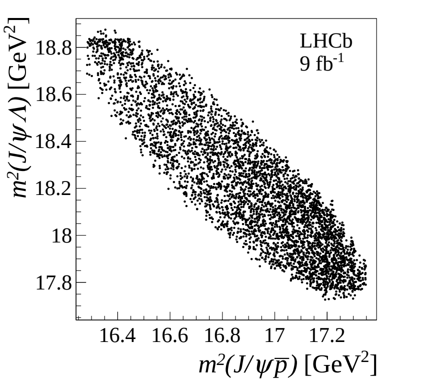
Pentaquark news: a strange candidate [2210.10346]

Decay $B^- \to J/\psi \Lambda \bar{p}$

$\sim$ 4400 candidates in Run I+II sample



Dalitz plot:



Best single B^- mass measurement

$$m(B) = 5279.44 \pm 0.05 \pm 0.07\,\text{MeV}$$

amplitude analysis performed

Observation of a narrow state decaying to $J/\psi\Lambda$

$$m = 4338.2 \pm 0.7 \pm 0.4\,\mathrm{MeV}$$

$$\Gamma = 7.01.21.3\mathrm{MeV}$$

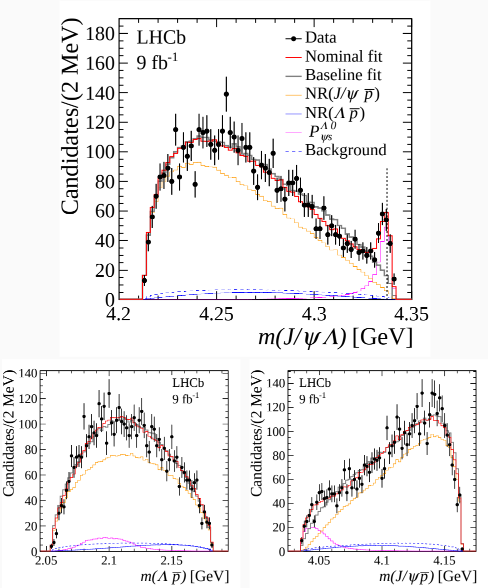
with preferred quantum numbers

$$J^P = 1/2^-$$

postive parity excluded at 90% CL.

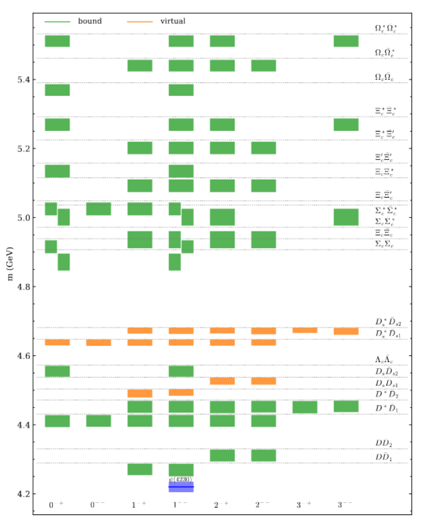
Right at the $\Xi_c D$ threshold at 4333 MeV!

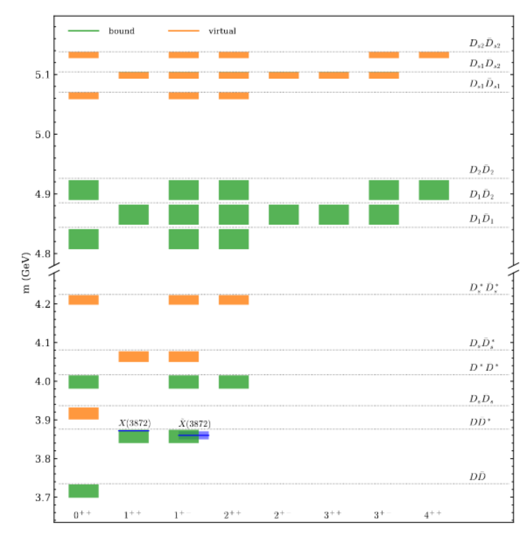
Good $\Xi_c D$ molecule candidate



A future program to explore the Hadronic Molecules

Nice survey by our theory colleaguse around Feng-Kung Guo [Prog Phys (2021)41:65]: Prediction of **227** heavy-antiheavy molecular states.





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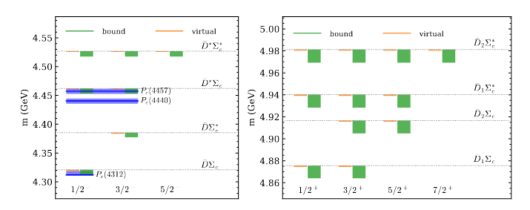
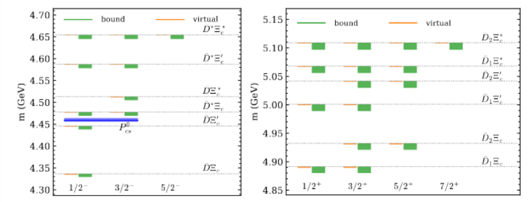




Experimental Challenges:

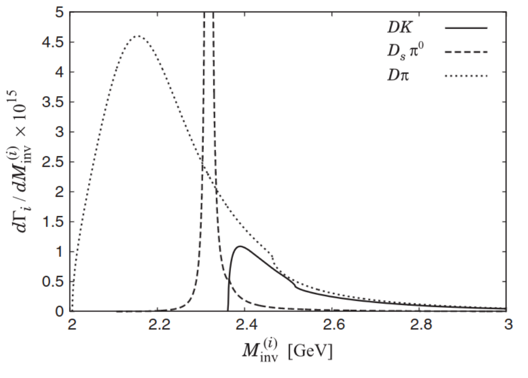
- Reconstructing multiparticle final states with open charm
- Access to high mass part of spectrum (limited by phase space in B-decays)

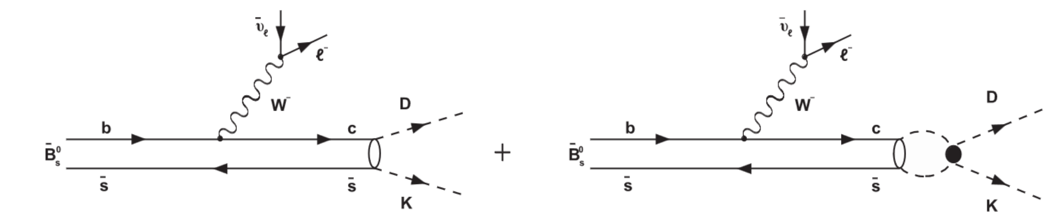
More ideas for the future: Exploiting Semileptonic decays ⇒ CmF

Proposed by Oset et Al in [PRD 92(2015)014031]

Production of exotic hadrons without crossed channel effects in semileptonic decays.

Interesting candidates: $D_s(2317)$ and $D^*(2400)$





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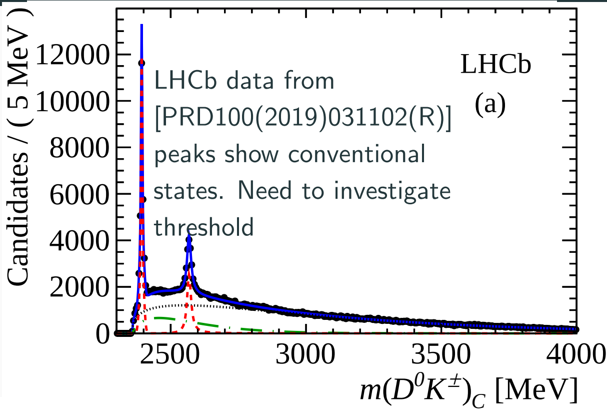

LHCb data from [PRD100(2019)031102(R)] peaks show conventional states. Need to investigate threshold