Spectroscopy of Exotic Hadrons

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Belle II Academy, March 25th, 2021

HISKP Bonn
• What do we mean with "Exotic Hadrons" and why are they interesting?

• Measuring properties of excited hadronic states – challenges:
  • Thresholds, coupled channels, hadronic loops
  • How can we define universal observables?

• Selected examples and current hot topics
The fermion-antifermion system

Positronium

- **Radius**: $\sim 2a_0 \approx 10^{-10}\text{m}$
- **Energy scale**: $E_B \sim 7\text{eV}$
- **Electric force**: $\sim 2 \cdot 10^{-8}\text{N}$
The fermion-antifermion system

Charmonium

- **Radius**: $\sim 10^{-16}$ m
- **Energy scale**: $E_B \sim 0.7$ GeV
- **Strong force**: $\sim 125$ kN
**Simplest Model: Potentials**

**Ansatz:** Follow the inspiration from positronium, devise a potential for the quark-quark interaction and solve a Schrödinger type equation.

**As an exercise:** Make all quarks heavy $\Rightarrow$ static $q\bar{q}$ potential.

Cornell potential:

$$V^{q\bar{q}}(r) = -\frac{4\alpha_s}{3r} + kr + C$$

Slope $k \approx 0.16 \text{ GeV}^2 \approx 0.8 \text{ GeV/fm} \approx 13 \text{ t g}$
Spin interactions

For practical applications the potential model has to include spin-spin, spin-orbit and tensor interaction terms:

\[ V^{q\bar{q}}(r) = -\frac{4\alpha_s}{3r} + kr + \frac{1}{m_q m_{\bar{q}}} \left[ \frac{32\pi \alpha_s}{9} \delta_\sigma(r) \vec{s}_q \vec{s}_{\bar{q}} + \left( \frac{2\alpha_s}{r^3} - \frac{k}{2r} \right) \vec{\ell} \cdot \vec{s} + \frac{4\alpha_s}{r^3} T \right] \]

with

\[ T = (\vec{s}_q \cdot \hat{r})(\vec{s}_{\bar{q}} \cdot \hat{r}) - \frac{1}{3} \vec{s}_q \vec{s}_{\bar{q}} \]

The spin-spin interaction is modeled as a contact interaction with gaussian smearing and hyperfine coupling \( \sigma \):

\[ \delta_\sigma(r) = \left( \frac{\sigma}{\pi} \right)^3 e^{-\sigma^2 r^2} \]

Caveats: \( \alpha_s \) is a running coupling, quark masses are not observable (renormalisation scheme dependent), etc ...
Charmonium: The $c\bar{c}$ vs the positronium spectrum

Mass [MeV/$c^2$]

<table>
<thead>
<tr>
<th>$J^{PC}$</th>
<th>$S = 0$</th>
<th>$S = 1$</th>
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<td>$0^{-+}$</td>
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<tr>
<td>$2^{++}$</td>
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</table>

Potential model

$\eta_{(2S)}$, $\psi_{(2S)}$, $h_\ell$, $\chi_{c0}$, $\chi_{c1}$, $\chi_{c2}$

[PRD75(2007)074031]


$D^0\bar{D}^0$

E=0 eV $\Rightarrow$ [PRA93(2016)012506] dissociation

$\eta$, $\psi$, $J/\psi$

$\ell = 0$ ($S$), $\ell = 1$ ($P$)

$\eta_{(2S)}$, $\psi_{(2S)}$

$\ell = 0$ ($S$), $\ell = 1$ ($P$)

$J/\psi$

$\eta$

$J^{PC}$

$S = 0$ $S = 1$ $S = 0$ $S = 1$
Charmonium: The $c\bar{c}$ vs the positronium spectrum

**Important differences**

- Positronium dissociates into fundamental fermions
- Quarkonium dissociates into hadrons (not quarks)
- The connection between the spectrum and the fundamental degrees of freedom is highly nontrivial (and in fact not fully understood)
- Exotic hadrons are a key showcase for emergent structures

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Potential model

- Mass [MeV/c$^2$]
- $J^{PC} = 0^{-+}$, $S = 0$
- $J^{PC} = 1^{+-}$, $S = 0$
- $J^{PC} = 0^{++}$, $S = 1$
- $J^{PC} = 1^{++}$, $S = 1$
- $J^{PC} = 2^{++}$, $S = 1$

---

Potential model

- E=0 eV $\Rightarrow$ [PRA93(2016)012506]
- Dissociation
- [PRD75(2007)074031]

---

- $\eta (2S)$
- $\psi (2S)$
- $\psi J/c$
The Charmonium Spectrum in Radiative Transitions with Crystal Ball at SPEAR

\[ e^- e^+ \rightarrow \psi(2S) \rightarrow \gamma + X \]

The $c\bar{c}$ Spectrum in decays to hadrons (modern data)

$B^{\pm} \rightarrow p\bar{p}K^{\pm}$

Charmonia in $p\bar{p}$

[PLB769(2017)10]

Inclusive, detached $\phi\phi$

Charmonia in $\phi\phi$

Vector states cannot couple:

$V \rightarrow V + V$ forbidden

First evidence for $B^0_s \rightarrow \phi\phi\phi$

[EPJ C77(2017)609]
Charmonium: The highlying $c\bar{c}$ spectrum

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

Cornell potential vs lattice QCD

$V(\sigma^{1/2})$
Breakdown of the potential model above open flavour threshold

Consider the strong decay

$$|Q\bar{Q}\rangle \rightarrow |Qq\rangle + |q\bar{Q}\rangle$$

which is kinematically allowed if $m(|Q\bar{Q}\rangle) > m(|Qq\rangle) + m(|q\bar{Q}\rangle)$

- States above the threshold become broad resonances
- Shifts their masses

String breaking as seen on the Lattice:

[PLB793(2019)493]
Discovery of a narrow resonance above open charm threshold in 2003

- Discovered in $J/\psi \pi \pi$
- $m = 3871 \pm 0.17$ MeV
- above the open charm threshold
- right at $D^0 \bar{D}^*$ threshold
- very narrow $\Gamma < 1.2$ MeV
- $BR(D^0 \bar{D}^*) > 30$

Renaissance in hadron spectroscopy
The $\chi_{c1}(3872)$ aka $X(3872)$
If it’s not Charmonium - what then? 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 $\sim \frac{1}{\sqrt{2\mu E_b}} \gg 1\text{ fm}$
  - near two-body threshold
How to distinguish these scenarios?

**Molecules:**

- Note: Molecules are a special case of dynamically generated states
- Associated to thresholds → lineshape
- S-wave between constituents → implies parity of state

**Compact states:**

- large multiplets
- typically large widths
- different models predict different relative branching fractions

Comparison of spectra with EFTs and Lattice need well defined observables (poles, residues).

[Rev. Mod. Phys. 90(2018)015004]
| 
| --- | --- | --- |
| J/ψ π⁺ π⁻ | X(3872) | Y(4260) region | p$ar{p}$ incl. |
| | | Y(4008) | |
| ψ (2S) π⁺ π⁻ | Y(4360) | Y(4660) | pp incl. |
| Λ_cΛ_c | | Y(4630) | |
| ψγ | X(3872) | | |
| $\chi_{c1}(1P)\gamma$ | X(3832) | | |
| $\chi_{c1}(1P)\omega$ | | | |
| J/ψω | X(3872) | Y(3940) | X(3915) |
| J/ψφ | X(4140) | X(4274) | X(4700) | |
| J/ψπ | Z(4430) | Z(4200) | Z(4240) | X(4350) | X(3872) |
| ψ (2S)π | Z(4430) | | |
| $\chi_{c1}(1P)\pi$ | Z(4051) | Z(4248) | | |
| $h_{c}(1P)\pi$ | | | | |
| DD | | | Z(4020) |
| DD⁺ | X(3872) | X(3940) | Z(3885) |
| D⁺D⁺ | X(4160) | | Z(4025) |
| J/ψp | $P_c(4380)$ | $P_c(4312)$ | |
| | $P_c(4440)$ | $P_p(4457)$ | |
Measuring Properties of (exotic) Hadrons
Observables and potential difficulties

- **Resonance parameters**: pole position $M = m_0 - i\frac{\Gamma}{2}$
  - $\leftrightarrow$ Mass $m_0$
  - $\leftrightarrow$ Width $\Gamma$
  - Challenge: precise determination needs knowledge of all decay channels

- Coupling to all possible **decay channels**

- **Spin parity quantum numbers** $J^{PC}$
  - Can sometimes be inferred from production mechanism
    - Typical example: $e^+e^- \rightarrow X$ then $J^{PC}(X) = 1^{--}$ (photon)
  - Determine $J^P$ from angular distributions of decay products

In many cases these steps are not independent of each other.
Spin parity quantum numbers
Exploiting narrow signals

- $X(3872)$ is extremely narrow
- Main physics background: $K_1(1270) \rightarrow K\pi\pi$
- Background subtracted in angles using sidebands in $J/\psi\pi\pi$ mass
- Not a full 4-body analysis
- Justified by narrow signal

Dalitz plot for $B^+ \rightarrow J/\psi\rho K^+$
Measuring the Spin-Parity of the $\chi_{c1}(3872)$ in $B^+ \rightarrow X(3872)K^+ \rightarrow J/\psi \pi \pi K^+$

Modelling of decay matrix element in helicity formalism. \textbf{Note interference!}

\[
|\mathcal{M}(\Omega|J_X)|^2 = \sum_{\Delta \lambda_\mu=-1,+1} \sum_{\lambda_{J/\psi}, \lambda_{\rho}=-1,0,+1} A_{\lambda_{J/\psi}, \lambda_{\rho}} D^{J_X}_{0, \lambda_{J/\psi} - \lambda_{\rho}}(0, \theta_X, 0)^* D^{1}_{\lambda_{\rho}, 0}(\Delta \phi_{X, \rho}, \theta_{\rho}, 0)^* D^{1}_{\lambda_{J/\psi}, \Delta \lambda_\mu}(\Delta \phi_{X, J/\psi}, \theta_{J/\psi}, 0)^* \]

(1)
Amplitude analysis $X(3872) \rightarrow J/\psi \rho$ (3 fb$^{-1}$)

- 1011 ± 38 Candidates
- incl. D-Wave-contributions L=2

$J^{PC} = 1^{++}$ best fit
- D-wave small < 4%@95%CL
Amplitude analysis $X(3872) \rightarrow J/\psi \rho \ (3 \text{ fb}^{-1})$

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$\cos \theta_{\rho} > 0.6$
Mass and Width
Mass dependence of observed lineshapes parameterized by

- Relativistic, single-channel Breit-Wigner amplitudes $BW(m_{D^0 p})$

$$BW(m|M_0, \Gamma_0) = \frac{1}{M_0^2 - m^2 - iM_0 \Gamma(m)},$$

where

$$\Gamma(m) = \Gamma_0 \left( \frac{q}{q_0} \right)^{2\ell+1} \frac{M_0}{m} B'_\ell(q, q_0, d)^2.$$

- with Blatt-Weiskopf barrier factors $B'_\ell(p, p_0, d)$, implementing the correct momentum dependence of the phase space
Precision measurements of mass and width of the $\chi_{c1}(3872)$ at LHCb

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

[PRD102(2020)092005]

**Exclusive $B^\pm \rightarrow J/\psi \pi^+ \pi^- K^\pm$**

[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:
  \[ m_{\chi_c(3872)}^{\text{LHCb}} = 3871.64 \pm 0.06 \pm 0.01 \text{MeV}/c \]

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

- Distance to \(D^0D^{0*}\) threshold \(\delta E = m_{D^0} + m_{D^{0*}} - m_{\chi_c(3872)}\)
  \[ \delta E|_{\text{LHCb}} = 0.07 \pm 0.12 \text{MeV} \]

- First non-zero value for Breit-Wigner width
  \[ \Gamma|_{\text{LHCb}} = 1.13 \]

- Threshold is within the natural width
  \(\Rightarrow\) Breit-Wigner is not the correct line-shape
Lesson for aspiring exotics hunters: one channel is never enough
Taking into account the $DD^*$ threshold: Flatté

Adding external information from Belle and BaBar that the $\chi_{c1}(3872)$ predominantly decays to $DD^*$ distorts the lineshape [PRD80(2009)074004].

Shape parameters:

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<td>3871.69</td>
<td>+0.00 +0.05</td>
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<td>-0.04 -0.13</td>
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Systematic uncertainties of equal importance:
- Resolution+Bkg model
- Momentum scale
- Threshold mass

Small effect: $D^{0*}$ width

- $J/\psi\pi\pi$ data alone cannot distinguish line shapes
- Flatté narrower than BW by factor 5
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Resolve lineshape

The PANDA project at FAIR
Why does this happen? Competing decay channels

Lineshape in $J/\psi \pi \pi$

Breakdown of intensity in $J/\psi \pi \pi$ as the $D^0 \bar{D}^{*0}$ channel sets in. (Unitarity!)

Neglecting $D^*$ width

Treatment of width [PRD81(2010)094028]
What is a resonance?

- **A pole of the transition amplitude in the complex s-plane**
  - The real part of the pole position is the mass of the particle
  - The imaginary part is related to the width

- All data is measured on the real s-axis. We need to extrapolate to the complex plane to find the pole position

- Only pole positions and residues of the poles are unique! Observed shape on the real axis depends on process!

Pole residues are related to partial widths in channel $i$ with phasespace $\sigma_i$:

$$\Gamma_i = BR_i \Gamma_{pole} = \frac{|res_i|^2 \sigma_i}{|m_{pole}|}$$
Isolated Resonances: Relativistic Breit-Wigner

Mass dependence of observed lineshapes parameterized by

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- with Blatt-Weiskopf barrier factors $B'_\ell(p, p_0, d)$, implementing the correct momentum dependence of the phase space

Note: For B-decays the amplitude will also contain a Blatt-Weiskopf from the decay of the mother particle (even though the resonance shape itself is not resolved)

$p$ and $q$ are momenta of the daughter particles in the rest-frame of the decaying particle.

$p_0$ and $q_0$ calculated on the nominal resonance mass
Extrapolating into the complex s-plane

\[ s_P = s_R - i\gamma \]

need analytic continuation below threshold

Expand amplitude \( T(s) \) around the pole:

\[
g(s) = (s - s_p)T(s)
\]

\[
g(s) = g(s_p) + (s - s_p)g'(s_p) + \cdots
\]

For small \( \gamma \):

\[
g(s) \approx g(s_p)
\]

\[
T(s) \approx \frac{-g(s_p)}{s_R - s - i\gamma}
\]

Fixed width BW is just the most simplistic extrapolation into the complex plane
Typical Problems

We need to understand the full analytic structure of the amplitude.

Branch cut singularities $\Rightarrow$ coupled channels

"Sum of two BW"

Resonance close to 2nd channel threshold

Lefthand cut
Analytic structure in vicinity of $D^0\bar{D}^{*0}$ threshold

Extrapolated to $DD^*$ bound state with $E_b = 24$ keV

Pole at: $E_\Pi = (0.06 - 0.13 i)$ MeV

[PRD102(2020)092005]
$E_b < 100\,\text{keV at 90\%CL}$

Best estimate: $E_{II} = (0.06 - 0.13\ i)\,\text{MeV}$

Best estimate: $E_{III} = (-3.58 - 1.22\ i)\,\text{MeV}$
Pole asymmetry: mixture of molecule and compact state

- It was shown in [PLB586(2004)53] that in the quasi-bound state scenario the asymmetry of the pole locations wrt to branch point contains information on nature of state
  - Pure molecule (deuteron-like): second pole is far from threshold
  - Pure compact state: both poles close to threshold
- For single channel [Rev. Mod. Phys. 90(2018)015004]:
  \[
  \frac{|k_2| - |k_1|}{|k_1| + |k_2|} = 1 - Z.
  \]
  - \(Z\) is the probability to find a compact component in the \(\chi_{c1}(3872)\).
  - \(k = \sqrt{-2\mu E_b}\) is purely imaginary here
- Best fit: \(Z = 15\%\)
- Smallest asymmetry compatible with data \(\Rightarrow Z < 33\%\)
We speak of a shallow bound state of two hadrons if

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

at \( D^0 \bar{D}^{0*} \) threshold, with \( R_{\text{conf}} \approx 1 \text{ fm} \approx (200 \text{ MeV})^{-1} \) 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 \( \Lambda d \) threshold
- Not a molecule but important hadronic interaction: virtual state in \( nn \) scattering

\( \chi_{c1}(3872) \) good candidate for a \( D \bar{D}^* \) molecule!

- \( E_b = 24 \text{ keV} \Rightarrow R \approx 30 \text{ fm} \)
Is such a huge object plausible?  

Classically one would assume a large object to be strongly affected by its production environment.  

Hint for compact nature?  

Molecule would be disintegrated at high multiplicity?  

No rigorous theoretical treatment.  

Model intriguing but hotly debated.
Further Molecule Candidates with Hidden Charm

Constituent need to be narrow in order to produce narrow signals
$Z$ states in $e^+e^-(\sqrt{s} \approx 4260 \text{ MeV}) \rightarrow Z^\pm \pi^{\mp}$ decays

$Z_c(3900)$

$J/\psi \pi^\pm$

- Data
- Total fit
- Background fit
- PHSP MC
- Sideband

$Z_c(4020)$

$h_c \pi^\pm$

$D^0 D^{*-}$

$M(D^0 D^{*-}) (\text{GeV}/c^2)$

$D^{*0} D^{*-}$

$M(D^{*0} D^{*-}) (\text{GeV}/c^2)$

BESIII data
Coupled channel analysis of $J/\psi \pi^\pm$ and $D^0D^{*-}$ to infer the type of pole from lineshape [PLB755(2016)337]

Both a resonance or a virtual state describe the data. Experimental accuracy does not yet allow to establish the type of pole.
Meson-Baryon Molecules?
Narrow structures in J/ψp

Full Run I+II dataset reveals

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

investigated in J/ψp projection alone (no angular analysis)
Triangle Singularities


\[ A \rightarrow BCD \] tree amplitude

\[ A \rightarrow BCD \] triangle amplitude

The triangle diagram has a **singularity close to the physical region** when

- All particles in the loop are on shell
- In the A-restframe particle 3 is moving in the same direction as particle 1

\[ S. \text{Coleman and R. E. Norton, Nuovo Cim. } 38, 438 (1965) \]

⇒ **sharp structure at two-body threshold 13**

- Scattering 13 \( \rightarrow \) BC is subject to usual orbital angular momentum supression
Kinematics of Triangle Singularities

When can a triangle singularity happen close to the physical region?

For fixed $m_A$, $m_1$, $m_3$ and $m_{BC}$ singularity in physical region only when

$$m_2^2 \in \left[ \frac{m_A^2 m_3 + m_C^2 m_1}{m_1 + m_3} - m_1 m_3, (m_A - m_1)^2 \right]$$

Singularity in physical region when

$$m_A^2 \in \left[ (m_1 + m_2)^2, (m_1 + m_2)^2 + \frac{m_1}{m_3} [(m_2 - m_3)^2 - m_D^2] \right]$$

$$m_{BC}^2 \in \left[ (m_1 + m_3)^2, (m_1 + m_3)^2 + \frac{m_1}{m_2} [(m_2 - m_3)^2 - m_D^2] \right]$$
We have seen that triangle singularities can create broad as well as narrow structures depending on the exact kinematics.

Triangle singularities can describe data!

\( \psi(4260) \) and \( K^*(892) \) widths fixed to PDG values.

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<td>190</td>
<td>172</td>
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**Figure captions**

- \( Z_c(4430) \) and \( Z_c(4200) \) as Triangle Singularities?
- Triangle singularities can describe data!
- \( \psi(4260) \) and \( K^*(892) \) widths fixed to PDG values.
Pentaquarks: Triangle singularities?

- For realistic width, only one peak can be generated by triangle.
For realistic width only one peak can be generated by triangle.

Double triangle can explain 2 of the three peaks [2103.06817]
8 coupled channels $\Sigma_c^{(*)}\bar{D}^0(\ast)(1/2^-, 3/2^-)$, $J/\psi\, p$

with contact interaction and one-pion exchange (OPE)

Fit with heavy quark spin symmetry necessarily gives a narrow $P_c(4380)$
• $\gamma p \rightarrow J/\psi p$
• No signal found
• Upper limits on branching fractions into $J/\psi p$

<table>
<thead>
<tr>
<th>State</th>
<th>Limit</th>
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<tr>
<td>$P_c(4312)$</td>
<td>4.6%</td>
</tr>
<tr>
<td>$P_c(4440)$</td>
<td>2.3%</td>
</tr>
<tr>
<td>$P_c(4457)$</td>
<td>3.8%</td>
</tr>
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</table>

• disfavours Hadrocharmonium

What are the additional decay channels?
⇒ coupling to open charm channels crucial

$\Lambda_c^+ \bar{D}^{(*)}, \Sigma_c^* \bar{D}^{(*)}$
Strange and Charming News in 2020/21
A first Tetraquark with four different flavours!

\[ |D^-\rangle = |\bar{c}d\rangle \quad |K^+\rangle = |\bar{s}u\rangle \quad |\bar{c}d\bar{s}u\rangle \]

Amplitude analysis of \( B^+ \rightarrow D^+D^-K^+ \)

Two states with spin-parities: \( 0^+ \) and \( 1^- \)

**X_0(2900)**: \( M = 2.866 \pm 0.007 \pm 0.002 \text{ GeV}/c^2 \), \( \Gamma = 57 \pm 12 \pm 4 \text{ MeV} \),

**X_1(2900)**: \( M = 2.904 \pm 0.005 \pm 0.001 \text{ GeV}/c^2 \), \( \Gamma = 110 \pm 11 \pm 4 \text{ MeV} \),
Evidence for two states

$m(D^+D^-) > 4 \text{ GeV}$

Two body thresholds:

- $D^*K^*: 1^- \otimes 1^- \text{ in S-wave}$
  - $\Rightarrow J^P = 0^+, 1^+, 2^+$

- $D_1K: 1^+ \otimes 0^- \text{ in S-wave}$
  - $\Rightarrow J^P = 1^-$

![Graphs showing asymmetric peak and LHCb data](image-url)
The first charged exotic candidate with strangeness!  

\[ e^+e^- \rightarrow K^+(D_s^-D^{*0} + D_s^{*-}D^0) \] at BES III

**Trick:** use precise knowledge of beam momentum to improve resolution

Recoil mass from 4-momenta

\[ RM(X) = |p_{e^+e^-} - p_X| \]

Breit-Wigner:

\[ m_0(Z_{cs}(3985)^-) = 3985.2^{+2.1}_{-2.0} \text{ MeV}/c^2, \]
\[ \Gamma_0(Z_{cs}(3985)^-) = 13.8^{+8.1}_{-5.2} \text{ MeV}. \]

Threshold enhancement \( Z_{cs} \) with \( 5.3\sigma \) significance, consistent with \( |c\bar{c}s\bar{u}\rangle \) state.

Should be visible in \( J/\psi K^- \). Search ongoing.
Update of amplitude analysis

\[ B \to J/\psi \phi K \]

[PR118(2017)022003][PRD95(2017)012002]

Now: Run I+II statistics

24 220 ± 170 candidates

(6x improvement)

Possible contributions:

Highlylying \( K^* \to \phi K \), exotic \( X \to J/\psi \phi \), exotic \( Z_{cs} \to J/\psi K \)
**Z_{cs} candidates at LHCb** 

Full model: seven Breit-Wigner resonances in $J/\psi \phi + two \ Z_{cs} + five \ K^*$

2017 model: four Breit-Wigner resonances in $J/\psi \phi + five \ K^*$
Full model: seven Breit-Wigner resonances in $J/\psi \phi + \text{two } Z_{cs} + \text{five } K^*$
<table>
<thead>
<tr>
<th>Contribution</th>
<th>Significance ( \times \sigma )</th>
<th>( M_0 ) [MeV]</th>
<th>( \Gamma_0 ) [MeV]</th>
<th>FF [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( X(2^-) )</td>
<td>4.8 (8.7)</td>
<td>4146 ± 18 ± 33</td>
<td>135 ± 28 +59 -30</td>
<td>2.0 ± 0.5 +0.8 -1.0</td>
</tr>
<tr>
<td>( X(4150) )</td>
<td>4146 ± 18 ± 33</td>
<td>135 ± 28 +59 -30</td>
<td>2.0 ± 0.5 +0.8 -1.0</td>
<td></td>
</tr>
<tr>
<td>( X(1^-) )</td>
<td>5.5 (5.7)</td>
<td>4626 ± 16 +18 -110</td>
<td>174 ± 27 +134 -73</td>
<td>2.6 ± 0.5 +2.9 -1.5</td>
</tr>
<tr>
<td>( X(4630) )</td>
<td>4626 ± 16 +18 -110</td>
<td>174 ± 27 +134 -73</td>
<td>2.6 ± 0.5 +2.9 -1.5</td>
<td></td>
</tr>
<tr>
<td>All ( X(0^+) )</td>
<td></td>
<td>20 ± 5 +14 -7</td>
<td></td>
<td>20 ± 5 +14 -7</td>
</tr>
<tr>
<td>( X(4500) )</td>
<td>20 (20)</td>
<td>4474 ± 3 ± 3</td>
<td>77 ± 6 +10 -8</td>
<td>5.6 ± 0.7 +2.4 -0.6</td>
</tr>
<tr>
<td>( X(4700) )</td>
<td>17 (18)</td>
<td>4694 ± 4 +16 -3</td>
<td>87 ± 8 +16 -6</td>
<td>8.9 ± 1.2 +4.9 -1.4</td>
</tr>
<tr>
<td>NR( J/\psi )</td>
<td>4.8 (5.7)</td>
<td></td>
<td></td>
<td>28 ± 8 +19 -11</td>
</tr>
<tr>
<td>All ( X(1^+) )</td>
<td></td>
<td>26 ± 3 +8 -10</td>
<td></td>
<td>26 ± 3 +8 -10</td>
</tr>
<tr>
<td>( X(4140) )</td>
<td>13 (16)</td>
<td>4118 ± 11 +19 -36</td>
<td>162 ± 21 +24 -49</td>
<td>17 ± 3 +19 -6</td>
</tr>
<tr>
<td>( X(4274) )</td>
<td>18 (18)</td>
<td>4294 ± 4 +3 -6</td>
<td>53 ± 5 +5</td>
<td>2.8 ± 0.5 +0.8 -0.4</td>
</tr>
<tr>
<td>( X(4685) )</td>
<td>15 (15)</td>
<td>4684 ± 7 +13 -16</td>
<td>126 ± 15 +37 -41</td>
<td>7.2 ± 1.0 +4.0 -2.0</td>
</tr>
<tr>
<td>All ( Z_{cs}(1^+) )</td>
<td></td>
<td></td>
<td></td>
<td>25 ± 5 +11 -12</td>
</tr>
<tr>
<td>( Z_{cs}(4000))</td>
<td>15 (16)</td>
<td>4003 ± 6 +4 -14</td>
<td>131 ± 15 +26</td>
<td>9.4 ± 2.1 ±3.4</td>
</tr>
<tr>
<td>( Z_{cs}(4220))</td>
<td>5.9 (8.4)</td>
<td>4216 ± 24 +43 -30</td>
<td>233 ± 52 +97 -73</td>
<td>10 ± 4 +10 -7</td>
</tr>
</tbody>
</table>

Flatté and K-matrix parameterisation have been tested where applicable
A fully charmed $c\bar{c}\bar{c}\bar{c}$ Tetraquark candidate [SciB65(2020)1983]

Several $J/\psi$-Charmonium thresholds

LHCb

Single parton scattering (SPS)

Double parton scatterings (DPS)
Stable molecules of Positronium $Ps_2$ can be created by impinging an intense positron beam on a porous silica substrate [Nature449(2007)195].

Decays via annihilation $\tau(Ps_2) < \tau(Ps)$. Detection through density/temperature dependent annihilation rates.

Radiative transition observed

Positron Accumulator

Sub ns pulses of $3 \times 10^{10} \text{cm}^2 \text{s}^{-1}$ positrons (> 10mA)
Summary – Exotic Hadrons

• Entering era of precision measurements: coupled channels and pole extractions must become standard.

• Still finding new candidates
  • Pentaquarks, Flavorfull Tetraquarks, Tetraquarks with Strangeness, fully charmed Tetraquarks

• Changes our view on the nature of hadrons
  ⇒ they start to look a lot like nuclei!

• Big next questions: why do those structures emerge and not others?
Backup
Remark: Why does the sum of two Breit-Wigners violate unitarity?

Consider a single channel. Then from unitarity: \( \text{Im}(T) = \sigma |T|^2 \) with phasespace \( \sigma \)

Sum of two Breit-Wigners:

\[
T = -\frac{\text{res}_1}{s - M_1^2 + iM_1\Gamma_1} - \frac{\text{res}_2}{s - M_2^2 + iM_2\Gamma_2}
\]

Using \( \sigma_i|\text{res}_i|^2 = M_i\Gamma_i \) (with real residues)

\[
\text{Im}T = \frac{\text{res}_1^2\Gamma_1M_1}{(s - M_1^2)^2 + M_1^2\Gamma_1^2} + \frac{\text{res}_2^2\Gamma_2M_2}{(s - M_2^2)^2 + M_2^2\Gamma_2^2}
\]

\[
\sigma |T|^2 = \frac{\text{res}_1^2\Gamma_1M_1}{(s - M_1^2)^2 + M_1^2\Gamma_1^2} + \frac{\text{res}_2^2\Gamma_2M_2}{(s - M_2^2)^2 + M_2^2\Gamma_2^2} + 2\sigma \text{Re} \left[ \frac{\text{res}_1}{s - M_1^2 + iM_1\Gamma_1} \frac{\text{res}_2}{s - M_2^2 + iM_2\Gamma_2} \right]
\]

Gluonic excitations

**Glueball**
- Bound state without valence quarks.

**Hybrid**
- Gluonic field configuration contributes to properties of hadron
$M_\pi = 400$ MeV

significant overlap with gluonic operators
The $\psi(4230)$ formerly known as $Y(4260)$

Detailed scan of the energy region between 4 and 4.6 GeV in $e^+e^- \rightarrow J/\psi\pi\pi$ reveals substructure of what was previously called $Y(4260)$.

Possibly a mixture of Hybrid, $D_1\bar{D}$ molecule and $c\bar{c}$ state.

To make progress: Identify more members of hybrid multiplet.
Spin exotic mesons and light hybrids

Fermion-Antifermion pair $q\bar{q}$ cannot couple to

$$J^{PC} = 0^{--}, 0^{+-}, 1^{--}, 2^{+-}, ...$$

Resonances with such forbidden quantum numbers would be manifestly non-$q\bar{q}$

Model: **Hybrid Mesons** – Gluonic excitations contribute to quantum numbers

Lightest spin exotic in lattice QCD

Dominant overlap with chromomagnetic operators (orange) $\Rightarrow$ **Hybrid mesons**

One isovector expected at $m < 2$ GeV
Coupled channel analysis of $\eta\pi^-$ and $\eta'\pi^-$

JPAC analysis of COMPASS data: Diffractively produced $\eta\pi^-$ and $\eta'\pi^-$

2 exotic resonances?

$J^{PC} = 1^{--}$

$J^{PC} = 2^{++}$
Data can be described with a single $J^{PC} = 1^{-+}$ resonance.

Result is consistent with lattice QCD expectations for a single isovector hybrid state.

<table>
<thead>
<tr>
<th>Poles</th>
<th>Mass (MeV)</th>
<th>Width (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_2(1320)$</td>
<td>$1306.0 \pm 0.8 \pm 1.3$</td>
<td>$114.4 \pm 1.6 \pm 0.0$</td>
</tr>
<tr>
<td>$a_2'(1700)$</td>
<td>$1722 \pm 15 \pm 67$</td>
<td>$247 \pm 17 \pm 63$</td>
</tr>
<tr>
<td>$\pi_1$</td>
<td>$1564 \pm 24 \pm 86$</td>
<td>$492 \pm 54 \pm 102$</td>
</tr>
</tbody>
</table>
B^{±} \rightarrow J/\psi \pi^{+} \pi^{-} K^{±} analysis results

Breit-Wigner masses:

\[ m_{\psi_{2}(3823)} = 3824.08 \pm 0.53 \pm 0.14 \pm 0.01 \text{MeV}/c \]
\[ m_{\chi_{c1}(3872)} = 3871.59 \pm 0.06 \pm 0.03 \pm 0.01 \text{MeV}/c \]

Breit-Wigner widths:

\[ \Gamma_{\psi_{2}(3823)} < 5.2(6.6) \text{MeV} \text{ at } 90(95)\% \text{CL.} \]
\[ \Gamma_{\chi_{c1}(3872)} = 0.96^{+0.19}_{-0.18} \pm 0.21 \text{MeV} \]

Dominant systematic uncertainty: signal and background shapes
(does not include the systematic of choosing a Breit-Wigner parameterization)
Factsheet $\chi_{c1}(3872)$

- $J^{PC} = 1^{++}$ established $\Rightarrow$ PDG nomenclature $\chi_{c1}(3872)$
  

- Mass $m = 3871.69 \pm 0.17$ MeV (in $X(3872) \rightarrow J/\psi X$ decays)
- $D\bar{D}^*$ threshold: $3871.70 \pm 0.11$ MeV
- Mass difference $m_X - m_{J/\psi} = 775 \pm 4$ MeV
- Width $\Gamma < 1.2$ MeV Belle [PRD84(2011)052004]

- Observed in Charmonium-like decay modes: $D^{*0}\bar{D}^0$, $J/\psi\pi\pi$, $J/\psi\omega$, $J/\psi\gamma$, $\psi(2S)\gamma$, $\chi_{c1}\pi^0$
- Mass and decay modes disfavour pure $c\bar{c}$ state. $\chi_{c1}(2P)$ predicted to be few 10 MeV higher in mass

- No charged partner, no $C = -1$ partner found
  
  $\chi_{c1}$
  
  - $X \rightarrow J/\psi\pi^+\pi^0$ Belle[PRL111(2013)032001],BaBar[PRD71(2005)031501]
  - $X \rightarrow J/\psi\eta$ Belle[PTEP(2014)043C01],Belle[PRL111(2013)032001]
Decays of the $\chi_{c1}(3872)$:

<table>
<thead>
<tr>
<th>Approx. product branching fractions</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{B}(B \rightarrow KX) \times \mathcal{B}(X \rightarrow D^0 \bar{D}^0)$</td>
<td>$\sim 1 \times 10^{-4}$</td>
</tr>
<tr>
<td>$\mathcal{B}(B \rightarrow KX) \times \mathcal{B}(X \rightarrow J/\psi \pi \pi)$</td>
<td>$\sim 1 \times 10^{-5}$</td>
</tr>
<tr>
<td>$\mathcal{B}(B \rightarrow KX) \times \mathcal{B}(X \rightarrow J/\psi \rho)$</td>
<td>$0.6 \times 10^{-5}$</td>
</tr>
<tr>
<td>$\mathcal{B}(X \rightarrow \chi_{c1}\pi^0)$</td>
<td>$0.88^{+0.33}_{-0.27} \pm 0.1$</td>
</tr>
<tr>
<td>$\mathcal{B}(X \rightarrow J/\psi \pi \pi)$</td>
<td></td>
</tr>
<tr>
<td>$\mathcal{B}(B \rightarrow KX) \times \mathcal{B}(X \rightarrow J/\psi \gamma)$</td>
<td>$\sim 2 \times 10^{-6}$</td>
</tr>
<tr>
<td>$\mathcal{B}(X \rightarrow \psi(2S)\gamma)$</td>
<td>$\sim 2 - 3$</td>
</tr>
</tbody>
</table>

Consider a $D^0 \bar{D}^{0*}$ molecule. What is the Isospin?

| $|\bar{u}c\rangle \otimes |u\bar{c}\rangle$ |

is a mixture of isospin singlet and triplet!

To build isospin eigenstates we need the charge conjugate mode $D^+D^{-*}$.

So $D^0 \bar{D}^{0*}$ would be 50% $I=0$ and 50% $I=1$.

Isospin violation?
Isospin of the $\chi_{c1}(3872)$ aka $X(3872)$

What Branching fractions would be expected for decays into $J/\psi \rho$ and $J/\psi \omega$ from a state with equal amounts of I=0 and I=1?

Take into account phase space:

- $J/\psi \pi\pi$ opens 500 MeV below X.
- $J/\psi \omega$ opens 8 MeV above X.

$\Rightarrow$ for 50/50 isospin mixture, the $J/\psi \omega$ would be completely suppressed by phasespace compared to $J/\psi \rho$

BUT $B(J/\psi\omega) \approx B(J/\psi\rho)$

$\Rightarrow X(3872)$ should be considered as Isospin singlet.

with no charged partners!
I=0 : Evidence from EFT and $X \rightarrow \chi_{cJ}\pi^0$ decays

For I=1 component the decay width into this channel would be larger than the total allowed width of the X(3872).

If both $D^0\overline{D}^0$ and $D^+D^-\star$ are included in the EFT, then the two corresponding loops enter with opposite sign and (almost) cancel each other.

The isospin violation is then driven by the $\sim 8$ MeV mass difference between those two channels.

New BESIII result on the $\chi_{cJ}\pi^0$ branching fraction [PRL122(2019)202001] will allow to constrain the couplings.
Analytic Structure of the Flatté Model: Example

Sheets II and IV analytically connected above threshold

Sheets I&II

$|F(m)|^2$

second sheet pole

$D^0 \bar{D}^{0*}$ threshold branch cut

Sheets III&IV

$|F(m)|^2$

third sheet pole
Impact of choice of $m_0 = 3864.5$ MeV

- Repeating the analysis with varying $m_0$
- As $m_0$ moves closer to threshold, pole moves into complex plane
- Combined confidence region (weighted with likelihood ratio)
Impact of choice of $m_0 = 3864.5$ MeV

- Repeating the analysis with varying $m_0$
- As $m_0$ moves closer to threshold, pole moves into complex plane
- Combined confidence region (weighted with likelihood ratio)
Impact of uncertainty of threshold location

- Threshold mass and mass scale uncertainty equal magnitude
- Repeat pole search with mass scale shifted by 0.066 MeV closer to threshold
- Pole still favored to lie on sheet II
- Systematically limited by knowledge of threshold mass
  ⇒ investigate $D^0\overline{D}^0\pi^0$ channel

Statistical uncertainties only
The assignment of $\psi(4230)$ (formerly known as $Y(4260)$ as a $DD_1$ molecule explains the decays into $Z_c(3900) + \pi$ and $\chi_{c1}(3872) + \gamma$ as seen by BESIII [PRL112(2014)092001].

In the quark model $D_1$ is expected to undergo both decays, providing for the opposite C-parity.
Triangle Singularities


\[A \rightarrow BCD\] tree amplitude \[A \rightarrow BCD\] triangle amplitude

The triangle diagram has a **singularity close to the physical region** when

- All particles in the loop are on shell
- In the A-restframe particle 3 is moving in the same direction as particle 1


\[\Rightarrow\] **sharp structure at two-body threshold 13**

- Scattering \(13 \rightarrow BC\) is subject to usual orbital angular momentum supression
Kinematics of Triangle Singularities

When can a triangle singularity happen close to the physical region?

For fixed $m_A$, $m_1$, $m_3$ and $m_{BC}$ singularity in physical region only when

$$m_2^2 \in \left[ \frac{m_A^2 m_3 + m_C^2 m_1}{m_1 + m_3} - m_1 m_3, (m_A - m_1)^2 \right]$$

Singularity in physical region when

$$m_A^2 \in \left[ (m_1 + m_2)^2, (m_1 + m_2)^2 + \frac{m_1}{m_3} [(m_2 - m_3)^2 - m_D^2] \right]$$

$$m_{BC}^2 \in \left[ (m_1 + m_3)^2, (m_1 + m_3)^2 + \frac{m_1}{m_2} [(m_2 - m_3)^2 - m_D^2] \right]$$
The $a_1(1420)$ at COMPASS

Resonance-like structure observed at COMPASS in partial wave analysis of diffractive $3\pi$ production.

$[\text{PRL} 115(2015)082001]$

$$m = 1414_{-13}^{+15} \text{ MeV}/c^2 \quad \Gamma = 153_{-23}^{+8} \text{ MeV}/c^2$$
in the $J^{PC} = 1^{++} f_0(980)\pi$ partial wave.

Signal confirmed by VES experiment $[\text{IWHSS2016, unpublished}]$

Exotic features:

- only $\sim 200$ MeV above the $J^{PC} = 1^{++}$ groundstate $a_1(1260)$
  
  1st radial excitation expected above $\sim 1650$ MeV

- only seen in $f_0(980)\pi$ decay mode
$a_1(1420)$ as a triangle singularity

The signal appears very close to the $K^0 K^*$ threshold at $\sqrt{s} = 1.39$ GeV

- Natural width of the $K^*$ smoothes the physical line shape
- Model nicely explains $a_1(1420)$ signal, including relative production cross section
To fully fit data, intermediate particles need to be given unrealistically narrow width.

For realistic width, only one peak can be generated by triangle.

Need to take hadronic loops into account when building amplitude model.
Results with relativistic Breit-Wigner fits:

<table>
<thead>
<tr>
<th>State</th>
<th>( M ) [MeV]</th>
<th>( \Gamma ) [MeV]</th>
<th>(95% CL)</th>
<th>( \mathcal{R} ) [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_c(4312)^+ )</td>
<td>( 4311.9 \pm 0.7^{+6.8}_{-0.6} )</td>
<td>( 9.8 \pm 2.7^{+3.7}_{-4.5} )</td>
<td>(&lt; 27)</td>
<td>( 0.30 \pm 0.07^{+0.34}_{-0.09} )</td>
</tr>
<tr>
<td>( P_c(4440)^+ )</td>
<td>( 4440.3 \pm 1.3^{+4.1}_{-4.7} )</td>
<td>( 20.6 \pm 4.9^{+8.7}_{-10.1} )</td>
<td>(&lt; 49)</td>
<td>( 1.11 \pm 0.33^{+0.22}_{-0.10} )</td>
</tr>
<tr>
<td>( P_c(4457)^+ )</td>
<td>( 4457.3 \pm 0.6^{+4.1}_{-1.7} )</td>
<td>( 6.4 \pm 2.0^{+5.7}_{-1.9} )</td>
<td>(&lt; 20)</td>
<td>( 0.53 \pm 0.16^{+0.15}_{-0.13} )</td>
</tr>
</tbody>
</table>

- Mass and width central values measured with reweighted data
- Significance of two-peak structure (unweighted data): 5.4\( \sigma \)
- Largest systematic uncertainty: unknown interference terms
- Determination of spin and parity quantum numbers requires amplitude analysis.
Pentaquarks in the Di-Quark Picture

\[ P = \{ \bar{c}[cq]_s[qq]_s, \ell \} \]

**Diquark color configuration:**

\[ 3 \otimes 3 \rightarrow \bar{3} \]

- Opposite parity understood: additional orbital angular momentum \( \ell \)
- One unit \( \ell \) costs:
  \[ \delta m \approx m(\Lambda(1405)) - m(\Lambda(1116)) \approx 300 \text{ MeV} \]
- Coupling spins to \( s = 1 \) in the light-light di-quark:
  \[ \delta m \approx m(\Sigma_c(2455)) - m(\Lambda_c(2286)) \approx 200 \text{ MeV} \]

\[
\begin{align*}
P_c(4380) & \quad \frac{3}{2}^- \quad \{ \bar{c}[cq]_{s=1}[qq]_{s=1}, \ell = 0 \} \\
P_c(4450) & \quad \frac{5}{2}^+ \quad \{ \bar{c}[cq]_{s=1}[qq]_{s=0}, \ell = 1 \}
\end{align*}
\]

- Can explain the small mass gap!
Results for contact interaction + OPE ($\chi^2/d.o.f = 0.98$)

<table>
<thead>
<tr>
<th>Scheme II</th>
<th>$J^P$</th>
<th>Pole [MeV]</th>
<th>DC (threshold [MeV])</th>
<th>$G_{DC}$</th>
<th>Production</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_c(4312)$</td>
<td>$\frac{1}{2}^-$</td>
<td>4314(1) – 5(2)i</td>
<td>$\Sigma_c\bar{D}$ (4321.6)</td>
<td>2.94(3) – 0.44(14)i</td>
<td>541(202) – 70(29)i</td>
</tr>
<tr>
<td>$P_c(4380)$</td>
<td>$\frac{3}{2}^-$</td>
<td>4378(2) – 7(2)i</td>
<td>$\Sigma_c^*\bar{D}$ (4386.2)</td>
<td>3.05(4) – 0.56(16)i</td>
<td>267(166) – 155(64)i</td>
</tr>
<tr>
<td>$P_c(4440)$</td>
<td>$\frac{3}{2}^-$</td>
<td>4440(1) – 10(3)i</td>
<td>$\Sigma_c^<em>\bar{D}^</em>$ (4462.1)</td>
<td>4.05(3) – 0.65(13)i</td>
<td>955(236) – 25(6)i</td>
</tr>
<tr>
<td>$P_c(4457)$</td>
<td>$\frac{1}{2}^-$</td>
<td>4460(2) – 5(1)i</td>
<td>$\Sigma_c^<em>\bar{D}^</em>$ (4462.1)</td>
<td>2.31(12) – 0.63(16)i</td>
<td>$-872(144) + 180(31)i$</td>
</tr>
<tr>
<td>$P_c$</td>
<td>$\frac{1}{2}^-$</td>
<td>4525(1) – 3(2)i</td>
<td>$\Sigma_c^<em>\bar{D}^</em>$ (4526.7)</td>
<td>2.10(9) – 0.52(17)i</td>
<td>$-106(139) + 49(32)i$</td>
</tr>
<tr>
<td>$P_c$</td>
<td>$\frac{3}{2}^-$</td>
<td>4518(1) – 7(2)i</td>
<td>$\Sigma_c^<em>\bar{D}^</em>$ (4526.7)</td>
<td>2.99(5) – 0.66(20)i</td>
<td>82(67) – 89(23)i</td>
</tr>
<tr>
<td>$P_c$</td>
<td>$\frac{5}{2}^-$</td>
<td>4497(3) – 30(23)i</td>
<td>$\Sigma_c^<em>\bar{D}^</em>$ (4526.7)</td>
<td>4.92(48) – 1.04(48)i</td>
<td>$-85(202) + 0(66)i$</td>
</tr>
</tbody>
</table>

- Evidence for new narrow $P_c(4380)$:
  Source coupling to $\Sigma_c^*\bar{D}^0$ different from zero by $1.7\sigma$
- Data consistent with full set of 7 molecular states.
  Clear signals for four states
- Idea: four visible states enhanced by interference with nearby triangle singularities?
Overview further pentaquark models

- All molecular models predict $P_c(4413)$ to have $J^P = 1/2^-$.  
- Different multiplet structures possible

<table>
<thead>
<tr>
<th>Model</th>
<th>$P_c(4312)$</th>
<th>$P_c(4440)$</th>
<th>$P_c(4457)$</th>
<th>$P_c(4380)$</th>
<th>notes</th>
<th>references</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular</td>
<td>$\Sigma_c^{++} \bar{D}^-$</td>
<td>$\Sigma_c^{++} \bar{D}^-$</td>
<td>$\Sigma_c^+ \bar{D}^0$*</td>
<td>$\Sigma_c^+ \bar{D}^0$*</td>
<td>alt. for $P_c(4440/57)$</td>
<td>1903.11001</td>
</tr>
<tr>
<td></td>
<td>1/2$^-$</td>
<td>3/2$^-$</td>
<td>3/2$^-$</td>
<td>3/2$^-$</td>
<td>1/2$^-$, 3/2$^-$</td>
<td></td>
</tr>
<tr>
<td>Molecule OBE</td>
<td>$\Sigma_c^+ \bar{D}^0$</td>
<td>$\Sigma_c^+ \bar{D}^*$</td>
<td>$\Sigma_c^+ \bar{D}^*$</td>
<td>$\Sigma_c^+ \bar{D}^*$</td>
<td>no more states</td>
<td>1903.11013</td>
</tr>
<tr>
<td></td>
<td>1/2$^-$</td>
<td>1/2$^-$</td>
<td>3/2$^-$</td>
<td>3/2$^-$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Molecule</td>
<td>$\Sigma_c^+ \bar{D}^0$</td>
<td>$\Sigma_c^+ \bar{D}^*$</td>
<td>$\Sigma_c^+ \bar{D}^*$</td>
<td>$\Sigma_c^+ \bar{D}^*$</td>
<td></td>
<td>1904.00221</td>
</tr>
<tr>
<td>QDCS</td>
<td>1/2$^-$</td>
<td>3/2$^-$</td>
<td>1/2$^-$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Molecule + HQSS</td>
<td>$\Sigma_c^+ \bar{D}^0$</td>
<td>$\Sigma_c^+ \bar{D}^*$</td>
<td>$\Sigma_c^+ \bar{D}^*$</td>
<td>$\Sigma_c^+ \bar{D}^*$</td>
<td>septett</td>
<td>1903.11506</td>
</tr>
<tr>
<td></td>
<td>1/2$^-$</td>
<td>1/2$^-$</td>
<td>3/2$^-$</td>
<td>3/2$^-$</td>
<td>1/2$^-$, 3/2$^-$, $(5/2^-)$</td>
<td>1904.01296</td>
</tr>
<tr>
<td>alt. QPSS multiplet</td>
<td>1/2$^-$</td>
<td>3/2$^-$</td>
<td>3/2$^-$</td>
<td></td>
<td></td>
<td>1904.00587</td>
</tr>
<tr>
<td>$\bar{c}[cu]<em>{s=1}[ud]</em>{s=0}; \ell$</td>
<td>$\ell = 0$</td>
<td>$\ell = 1$</td>
<td>$\ell = 1$</td>
<td></td>
<td>difficult</td>
<td>1904.00446</td>
</tr>
<tr>
<td>compact</td>
<td>3/2$^-$</td>
<td>3/2$^+$</td>
<td>5/2$^+$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hadrocharmonium</td>
<td>1/2$^+$</td>
<td>1/2$^-$</td>
<td>3/2$^-$</td>
<td>several</td>
<td>large $\Gamma_{J/\psi P}$</td>
<td>1904.11616</td>
</tr>
</tbody>
</table>

- Clear distinction between compact and molecule $P_c(4312)$
- Determination of quantum numbers is crucial $\Leftrightarrow$ future amplitude analysis.
Hadronic molecule production in $\Lambda_b$ decays: Gateway states

Observation in [PRD92(2015)094003]:

- $P_c(4450)$ as $J^P = 3/2^-$ $\Xi^0 \Sigma_c^*(\ast)$ molecule
- $ud$ diquark in $\Lambda_b$: isospin singlet
- $ud$ diquark in $\Sigma_c^*$: isospin triplet

⇒ direct production suppressed
⇒ generation in final state interaction

Explains the relative production of $\Lambda(1405)$ and $P_c$ in $\Lambda_b \rightarrow J/\psi pK$. 
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Analogous scenario in the $\Lambda_b \rightarrow \Lambda_c \bar{D}^0 K$ channel?

Measure production ratio between $\Lambda_c^+ \bar{D}$ resonances and $D_{s0}(2317)$. 

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All exotic hadrons observed so far contain light quarks.

Predictions of all-heavy 4-quark states: