Exotic hadrons at LHCb

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Colliders and $b\bar{b}$ rates

- Tremendous rate potential at hadron colliders
  - physics reach determined by the detector capabilities not by the machine
- Collect all $b$-hadron species at the same time:
  - additional gain by a factor of $\sim 10$-100 in integrated $B_s$ rates at hadronic colliders vs $e^+e^-$ machines
  - time dependent CPV studies of $B_s$ possible
  - also get $\Lambda_b$, $B_c$ which are out of reach of the 10 GeV $e^+e^-$ factories
  - Clean source of $c$-hadrons via $b \rightarrow c W^{++}$
- Prompt charm rates factor of 10 higher than beauty rates:
  - nuisance and great physics opportunity at the same time

\[
N = \sigma_{b\bar{b}} \int L \, dt \times \varepsilon_{\text{geometrical}} \times \varepsilon_{\text{trigger}} \times \varepsilon_{\text{rest}}
\]

large

major challenge for $b$, $c$ physics at hadron colliders

<table>
<thead>
<tr>
<th>Year</th>
<th>Colliders</th>
<th>LHCb</th>
<th>ATLAS</th>
<th>CMS</th>
<th>Detectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>LHCb</td>
<td>10 fb$^{-1}$, ATLAS, CMS 25 fb$^{-1}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2005</td>
<td>LHCb</td>
<td>5 fb$^{-1}$</td>
<td>ATLAS, CMS 450 fb$^{-1}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2010</td>
<td>Run I</td>
<td>3 fb$^{-1}$</td>
<td>ATLAS, CMS 300 fb$^{-1}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2015</td>
<td>Run II</td>
<td>5 fb$^{-1}$</td>
<td>ATLAS, CMS 300 fb$^{-1}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2020</td>
<td>Run III</td>
<td>50 fb$^{-1}$</td>
<td>ATLAS, CMS 300 fb$^{-1}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2025</td>
<td>Run IV</td>
<td>300 fb$^{-1}$</td>
<td>ATLAS, CMS 300 fb$^{-1}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2030</td>
<td>Run V+VI</td>
<td>450 fb$^{-1}$</td>
<td>ATLAS, CMS 3000 fb$^{-1}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2035</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

$\int L \, dt$

- CDF 10 fb$^{-1}$, D0 8 fb$^{-1}$
- LHCb 3 fb$^{-1}$, 5 fb$^{-1}$
- ATLAS, CMS 450 fb$^{-1}$, 300 fb$^{-1}$

$\frac{\sigma_{b\bar{b}}}{L \, dt}$

- $\sqrt{s_{pp}}$
  - 7-8 TeV, 13 TeV, 14 TeV

$\sigma_{b\bar{b}} \times \varepsilon_{\text{geometrical}} \times \varepsilon_{\text{trigger}} \times \varepsilon_{\text{rest}}$

large

major challenge for $b$, $c$ physics at hadron colliders
LHCb vs central detectors

- Advantages of LHCb (forward spectrometer):
  - comparable b cross-section in much smaller solid angle; smaller number of electronic channels; smaller event size; much larger trigger bandwidth to tape (Run I ~5 kHz, Run II ~12 kHz)
  - b and c physics dominate the trigger bandwidth (e.g. CMS b-trigger rate ~25 Hz; almost 3 orders of magnitude less than LHCb)
  - large $p_T$ for small $p_T$ (in central region $p_T \sim 0$); can identify muons to lower $p_T$ values
  - large bandwidth important for triggering on purely hadronic final states (central detectors limited to dimuon trigger)
  - large bandwidth important for collecting very large charm samples
  - space for RICH detectors: $p/K/\pi$ separation; crucial for background suppression in many channels; increased flavor tagging

- Limitation of present LHCb detector:
  - luminosity limited by the detector readout capabilities (upgrades of the detector will allow increasing the luminosity)
  - compared to Belle: poor $\gamma$ (i.e. $\pi^0$) and $K_s$ detection (will be improved in Phase II upgrade)
Reconstruction of $X(3872)$ in exclusive $B$ decays

$B^+ \rightarrow X(3872)K^+$, $X(3872) \rightarrow J/\psi \pi^+\pi^-$, $J/\psi \rightarrow \mu^+\mu^-$

vs. Belle

$\sigma_M \sim 2.3$ MeV $\quad$ PRD84 (2011) 052004

$bkg \pm 2\sigma$ $\quad 18%$

Belle set $\Gamma < 1.2$ MeV at 90% C.L.

LHCb already has a better sensitivity to the natural width than in the Belle analysis.

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>LHCb $fb^{-1}$</th>
<th>U. Phase I $fb^{-1}$</th>
<th>U. Phase II $fb^{-1}$</th>
<th>Belle $ab^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \rightarrow X(3872)\pi^+K^-$, $B^+ \rightarrow X(3872)\pi^+$, $B_s^0 \rightarrow X(3872)K^+K^-$, $B_c^+ \rightarrow X(3872)\pi^+$, $\Lambda_b^0 \rightarrow X(3872)pK^-$, …</td>
<td>3 $fb^{-1}$</td>
<td>8 $fb^{-1}$</td>
<td>50 $fb^{-1}$</td>
<td>300 $fb^{-1}$</td>
</tr>
<tr>
<td>$B^+ \rightarrow K^+X(3872)$ ($\rightarrow J/\psi\pi^+\pi^-$)</td>
<td>1k</td>
<td>5k</td>
<td>33k</td>
<td>200k</td>
</tr>
</tbody>
</table>
Determination of $X(3872)$ $J^{PC}$

Analysis of 5D angular correlations in the decay:
$B^+ \rightarrow X(3872)K^+$, $X(3872) \rightarrow J/\psi \, \rho \, J/\psi \rightarrow \mu^+ \mu^-$, $\rho \rightarrow \pi^+ \pi^-$

$X(3872) \rightarrow J/\psi \rho$, $J/\psi \rightarrow \mu^+ \mu^-$, $\rho \rightarrow \pi^+ \pi^-$

PRL 110, 222001 (2013),
Bin Gui Ph.D. Syracuse 2014
https://surface.syr.edu/etd/189/

$J^{PC} = 1^{++}$ at 16\sigma

Remaining options: $\psi (23 \, P_1)$ or exotic hadron

This measurement ruled out $\eta_c (1^{1D}_2)$. D-wave contribution <4% at 95% CL
Probing $X(3872) \rightarrow J/\psi \omega$

Isospin violating decay

$B^+ \rightarrow X(3872)K^+$, $X(3872) \rightarrow J/\psi \pi^+\pi^-, J/\psi \rightarrow \mu^+\mu^-$

The amplitude analysis for $J^{PC}$ determination averaged over $M(\pi^+\pi^-)$

The most precise determination of $M(\pi^+\pi^-)$.

LHCb has recorded more data since then!

On-going projects: include $M(\pi^+\pi^-)$ in the amplitude fit and determine $\omega(782)$ contribution interfering with $\rho(770)^0$.

<table>
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<tr>
<th>Decay mode</th>
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<th>U. Phase</th>
<th>Belle</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \rightarrow K^+X(3872)(\rightarrow J/\psi \pi^+\pi^-)$</td>
<td>$3 \text{ fb}^{-1}$</td>
<td>8 $\text{ fb}^{-1}$</td>
<td>50 $\text{ fb}^{-1}$</td>
</tr>
<tr>
<td>$B^+ \rightarrow K^+J/\psi\omega(782)(\rightarrow \pi^+\pi^-\pi^0)$</td>
<td>1k</td>
<td>5k</td>
<td>33k</td>
</tr>
</tbody>
</table>


Radiative decays of $X(3872)$

$$\frac{BR(X(3872)\rightarrow \psi(2S)\gamma)}{BR(X(3872)\rightarrow J/\psi(1S)\gamma)} = 2.48\pm0.64\pm0.29 \quad (>0 \text{ at } 4.4\sigma)$$

by a factor of $\sim 100!$

Hard to find mechanism to favor $\psi(2S)\gamma$ over $J/\psi(1S)\gamma$ other than $2P\rightarrow 2S$

$\nabla$ Does not rule out $D\bar{D}^*$ component at large distances

(F.-K. Guo et al., PL B742, 394 (2015); arXiv:1410.6712)
Prompt production of \(X(3872)\) at LHCb

(inclusive \(X(3872)\); dominated by prompt production)

<table>
<thead>
<tr>
<th></th>
<th>LHCb (p_T &gt; 5) GeV 7 TeV</th>
<th>CMS (p_T &gt; 10) GeV 7 TeV</th>
<th>ATLAS (p_T &gt; 10) GeV 8 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution ((\sigma))</td>
<td>(\sim 3.3) MeV</td>
<td>(\sim 6) MeV</td>
<td>(\sim 6) MeV</td>
</tr>
<tr>
<td>signal yield</td>
<td>(\sim 16.1) k/fb(^{-1})</td>
<td>(\sim 2.5) k/fb(^{-1})</td>
<td>(\sim 2.6) k/fb(^{-1})</td>
</tr>
<tr>
<td>bkg/signal in (\pm 2\sigma)</td>
<td>5.8</td>
<td>8.6</td>
<td>11.1</td>
</tr>
</tbody>
</table>

Lower trigger thresholds lead to higher production cross-sections at LHCb, which offset lower luminosities.

Better mass resolution provides for smaller backgrounds.

LHCb is also in position to improve \(X(3872)\) mass measurement.

Since systematics will dominate, exclusive modes may be more suitable for mass and width determination. (work in progress)

Prompt production cross-section in forward region will also be re-measured.
**B^0 \rightarrow \psi(2S)\pi^+K^-**

\[ \rightarrow \psi(2S)\pi^+ \]

**LHCb**

**Kaon excitations**

**Molecule or cusp?**

**Tetraquark?**

**The results improved on the earlier characterization of Z(4430)^- by Belle.**

4 expected and well experimentally established kaon resonances in the amplitude fit include tail of K^*3(1780) in model variations
Amplitude analysis of $B^0 \rightarrow \psi(2S)\pi^+K^-$

4D maximum likelihood fit

$$(m_{K\pi}^2, m_{\psi\pi}^2, \theta_\psi, \varphi_\psi)$$

- Use of all decay angles in the fit, in addition to the Dalitz plane, improves sensitivity of the analysis, especially to $J^P$ of various contributions.
Charged charmonium-like states in $B$ decays

Amplitude analyses used to distinguish $\bar{K}^{*0} \to \pi^+K^-$ and $(c\bar{c})\pi^+$ contributions

$Z_c(4200)^+, Z_c(4050)^+, Z_c(4250)^+$ await confirmation (LHCb has enough data to do it already)

$Z_c(3900)^+$ and $Z_c(4020)^+$ observed in $e^+e^- \to \pi^-Z_c^+$, not observed in $B \to K Z_c^+$, (and vice versa).

Sensitivity to production mechanism, points to hadron-level interactions.

No clear explanations.

- Too broad to be molecular bound states?
- No tetraquark model can accommodate all of them.
- Rescattering effects?
- Artifacts of complicated amplitude analyses?
Resonant structure of \( Z(4430)^- \)?

- Detailed studies of “exotic” amplitudes desired to shed light onto their nature: example Argand diagram of \( Z(4430)^- \rightarrow \psi(2S)\pi^- \).

\[ D^0\bar{D}^*(2S)^- \text{ cusp would be smeared by } \Gamma_{D^*(2600)} = 139 \text{ MeV,} \]

and more round if produced via a triangle diagram.

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>LHCb</th>
<th>U.Phase I</th>
<th>II</th>
<th>Belle</th>
<th>II</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B^0 \rightarrow \psi(2S)\pi^-K^+ )</td>
<td>3 fb(^{-1})</td>
<td>8 fb(^{-1})</td>
<td>50 fb(^{-1})</td>
<td>300 fb(^{-1})</td>
<td>0.7 ab(^{-1})</td>
</tr>
<tr>
<td>( B^0 \rightarrow J/\psi(1S)\pi^-K^+ )</td>
<td>25k</td>
<td>0.13M</td>
<td>0.8M</td>
<td>5M</td>
<td>2k</td>
</tr>
<tr>
<td>( B^0 \rightarrow \chi_c1\pi^-K^+ )</td>
<td>0.4M</td>
<td>1.3M</td>
<td>10M</td>
<td>62M</td>
<td>30k</td>
</tr>
</tbody>
</table>

Statistical accuracy will be sufficient to distinguish between resonant poles and cusps/triangles.

Systematic errors hard to predict.

Need to scrutinize dependence on:

- formalism (work with JPAC; see Mikhasenko et al EPJ, C78, 229 (2018), arXiv:1712.02815)
- \( K^* \) model

Huge statistics already for detailed studies of \( J/\psi(1S)\pi^- \) exotics. Phase-space in \( K\pi \) reaches to \( K^*_2(2045) \) pole.
Exotic hadrons at LHCb, T. Skwarnicki, SCGP Stony Brook, May 2018

**B^+ → J/ψ φ K^+**

- PRL118, 022003 (2017)
- PR, D95, 012002 (2017)

LHCb

1. **X(4700)**
2. **X(4500)**
3. **X(4274)**
4. **X(4140)**

→ J/ψφ

Tetraquarks? Charmonium? Molecules or cusps?

Since mostly not established states, we determined K^+ → φK^+ content entirely from our data (red points): 6 K^* resonances (of 4 different J^P) + 1 NR φK

Previously X(4140), X(4274) were observed by CDF, CMS and D0

Kaon excitations

Thomas Britton, PhD, Syracuse. 2016
https://surface.syr.edu/etd/510/
Amplitude analysis of $B^+ \rightarrow J/\psi \phi K^+$, $\phi \rightarrow K^+ K^-$

6D maximum likelihood fit

$$(m_{\phi K}^2, m_{\psi \phi}^2, \theta_\psi, \varphi_\psi, \theta_\phi, \varphi_\phi)$$

The inclusion of all decay angles in the amplitude fit, allowed resolution of various $K\phi$ partial waves, and led to a firm determination of $J^{PC}$ of $J/\psi \phi$ resonances:

- $X(4140): 1^{++}$ determined at $5.7\sigma$
- $X(4274): 1^{++}$ determined at $5.8\sigma$
- $X(4500): 0^{++}$ determined at $4.0\sigma$
- $X(4700): 0^{++}$ determined at $4.5\sigma$
Interpretation of $J/\psi\phi$ structures?

- **P-wave charmonia?**


- It appears unlikely that the $J/\psi\phi$ states are pure $c\bar{c}$ states.
- Interplay of $\chi_{cJ}(nP)$ states with ($c\bar{s})(\bar{c}s)$ or ($cs)(\bar{c}\bar{s})$?

\[
\begin{array}{c|c|c|c|c}
\text{J}\text{P} & \text{Mass (MeV)} & \text{Signal yield / } \rho_{J/\psi} & (20 \text{ MeV}) \\
\hline
5P & 4811 & 4795 & 4811 & 4825 \\
4P & 4553 & 4552 & 4553 & 4559 \\
3P & 4025 & 4022 & 4025 & 4031 \\
2P & 3502 & 3516 & 3531 & 3547 \\
1P & 3066 & 3080 & 3095 & 3110 \\
\end{array}
\]

Godfrey-Isgur model

$\chi_{cJ}(nP)$ states would couple to $J/\psi\phi$ and $J/\psi\omega$ the same way. The $J/\psi\phi$ structures do not show up in $J/\psi\omega$ spectrum.

It is possible to find matching $\chi_{cJ}(nP)$ states but the $J^P$-mass patterns are different.

- It appears unlikely that the $J/\psi\phi$ states are pure $c\bar{c}$ states.

from Olsen, Skwarnicki, Zieminska
Rev. Mod. Phys. 90, 015003 (2018); arXiv:1708.04012

(BaBar PRD82, 011101 (2010))

$B^\pm \rightarrow J/\psi\omega K^\pm$ BaBar

$B^\pm \rightarrow J/\psi\phi K^\pm$ LHCb

(normalized to the same area)
Interpretation of $J/\psi\phi$ structures?

- A molecule/threshold effect?

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>$0^+$</th>
<th>1+</th>
<th>$0^+,1^+,2^+,3^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>X(4700)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X(4500)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X(4274)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X(4140)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

No $\pi$-exchange forces ($I=0$)!


- Except for X(4140) being possibly affected by a $D_s^+D_s^*$ threshold, the observed $J/\psi\phi$ structures don’t fit the $D_{sJ}(*)$-pair mass thresholds or their quantum numbers.
Interpretation of $J/\psi\phi$ structures?

• Tetraquarks?

Predicted two 1++ states with correct mass splitting.

Includes a state with the right $X(4140)$ $J^{PC}$

<table>
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<tr>
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<th>LHCb</th>
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<th>U. Phase II</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \rightarrow J/\psi\phi K^+$</td>
<td>3 fb$^{-1}$</td>
<td>8 fb$^{-1}$</td>
<td>50 fb$^{-1}$</td>
</tr>
<tr>
<td>$B^+ \rightarrow J/\psi\phi K^+$</td>
<td>4.3k</td>
<td>15k</td>
<td>0.1M</td>
</tr>
</tbody>
</table>

MANY MORE RECENT PAPERS


Allow diquarks only in color triplet configuration; cuts # of states in half: only one 1++ state. Describe $X(4500),X(4700)$ 0++ states as the radial excitations (n=1).
$\Lambda_b^0 \rightarrow J/\psi p K^-$: unexpected $J/\psi p$ structures

$\Lambda(1520)$

$P_c^+(4450)$

$P_c^+(4380)$

$\rightarrow J/\psi p$

Over 60 expected from the quark model.

13 better established $\Lambda^*$

states (***) and (****).

in the amplitude fit.

Molecules or cusps

Pentaquarks

$\Sigma_c^+$

$D^{*0}$

Nathan Jurik, Ph.D., Syracuse 2016

https://surface.syr.edu/etd/640/
Expected complexity of $\Lambda$ excitation spectrum within the mass range relevant to $\Lambda_b^0 \rightarrow J/\psi pK^-$ amplitude analysis

- Many overlapping states at high mass. Widths and couplings to $pK$ not well predicted.

$m_\pi = 391$ MeV

$\sim 57$ $sdud$ states

$\sim 7$ $sdug$-rich states (hybrids)
Amplitude analysis of $\Lambda_b^0 \rightarrow J/\psi pK^-$

6D maximum likelihood fit

$$m_{PK}^2, m_{\psi p}^2, \theta, \varphi, \theta_\Lambda, \varphi_\Lambda$$

All fit displays with

$$J^P = \frac{3}{2}^+ \text{ for } P_c(4380)^+$$
$$J^P = \frac{5}{2}^+ \text{ for } P_c(4450)^+$$


Subtraction of $L^*$ contributions peaking at large $\cos\theta_{Pc}$

Requires two $P_c$ states of opposite parity

Source of ambiguities in $J^P$ determination of $P_c$s.
Interpretations of $P_c(4450)^+ , P_c(4380)^+$?

Molecules

No $\frac{5\pm 2}{2}$ molecules in this mass range with reasonable values of binding energies

Karlinder, Rosner
PRL115, 122001 (2015)
and others

$P_c(4380)^+$ is too broad to be a molecule?

Tightly-bound penatquark

Can accommodate $\frac{5\pm 2}{2}$ when at least one diquark in $S=1$ state

Such mass difference and the opposite parity can be explained by $\Delta L=1$ and $\Delta S=1$.

It is crucial to determine $J^P$s!

Need more robust verifications of resonant hypothesis.

Realistic rescattering mechanisms (cusps, triangle anomalies) have the same $J^P$ selection rules as realistic molecular models (must happen in S-wave)

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<tbody>
<tr>
<td>$\Lambda_b \rightarrow J/\psi p K^-$</td>
<td>25k</td>
<td>0.13M</td>
<td>0.8M</td>
</tr>
</tbody>
</table>
Other channels related to $P_c(4450)^+, P_c(4380)^+$

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>LHCb</th>
<th>U. Phase</th>
<th>I</th>
<th>II</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda_b \to J/\psi p K^-$</td>
<td>3 fb$^{-1}$</td>
<td>8 fb$^{-1}$</td>
<td>50 fb$^{-1}$</td>
<td>300 fb$^{-1}$</td>
</tr>
<tr>
<td>$\Lambda_b \to J/\psi p\pi^-$</td>
<td>26k</td>
<td>0.13M</td>
<td>0.8M</td>
<td>5M</td>
</tr>
<tr>
<td>$\Lambda_b \to \chi_{c1}pK^-$</td>
<td>1.9k</td>
<td>10k</td>
<td>63k</td>
<td>0.4M</td>
</tr>
<tr>
<td>$\Lambda_b \to J/\psi p K^0\pi^-$</td>
<td>0.45k</td>
<td>2.2k</td>
<td>15k</td>
<td>0.1M</td>
</tr>
</tbody>
</table>

Hints of $J/\psi p$ structure; complicated by ambiguities with $Z^- \to J/\psi \pi^-$. A coupled-channel to $J/\psi p$. The $\chi_{c1}p$ mass threshold near $P_c(4450)^+$. Upgrade statistics will allow for amplitude analyses of sensitivity comparable (much better) than in the discovery paper.
Isospin partners of $P_c(4450)^+ , P_c(4380)^+$?

- $I_3(J/\psi p) = \frac{1}{2}$

- Whatever the nature of these states is, $I_3(J/\psi n) = -\frac{1}{2}$ partners should exist. Unfortunately neutrons are not detectable in LHCb.

- However such states can decay to open charm final states

- Relative to $J/\psi(\rightarrow \mu^+\mu^-)p$ extra 4 tracks to reconstruct and no dimuon to trigger on (efficiency loss by a factor of ~50).

- Upgrade luminosities are essential to reach sensitivity in these channels

- If $I(J/\psi p) = \frac{3}{2}$ then also

- Doubly-charged partner (prompt production?)
U-spin partners of $P_c(4450)^+, P_c(4380)^+$?

- Strange partners:

\[
\begin{align*}
\Xi_b^- & \rightarrow K^- + \ldots \\
\Lambda_b & \rightarrow \phi + \ldots \\
\phi & \rightarrow K^-K^+ \\
\Lambda_c^+ & \rightarrow pK^-\pi^+ \\
D_s^- & \rightarrow K^+K^-\pi^- \\
\end{align*}
\]

This will allow amplitude analyses

<table>
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<th>U. Phase II</th>
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</thead>
<tbody>
<tr>
<td>$\Lambda_b \rightarrow J/\psi\Lambda\phi$</td>
<td>3 fb$^{-1}$</td>
<td>8 fb$^{-1}$</td>
<td>50 fb$^{-1}$</td>
</tr>
<tr>
<td>$\Sigma_b^- \rightarrow J/\psi\Lambda K^-$</td>
<td>300</td>
<td>1.6k</td>
<td>10k</td>
</tr>
</tbody>
</table>

[PLB 772 (2017) 265]
Beautiful analogs of $P_c(4450)^+ , P_c(4380)^+$?

- Binding of hadrons with beauty quark(s) is “deeper” than with charm quark(s)
- If molecular structures, then masses must be very near relevant baryon-meson thresholds ($\Sigma_b B^*, \Sigma_b^* B, \Sigma_b^* B^*, \Lambda_b B^*, \Lambda_b^* B$)
- Beautiful analogs of the $P_c^+$ states ($\bar{b}budd$) would decay to easily detectable final state: $\Upsilon(\to \mu^+ \mu^-)p$ (if $\bar{b}busd$ exists in $\Upsilon(\to \mu^+ \mu^-)\Lambda$)
- Unfortunately, can only be searched for in prompt production:
  - Large backgrounds from protons produced in primary $pp$ collision (no secondary vertex formed)
  - If compact pentaquarks then prompt production can be sizeable, but prompt production of the $P_c^+$ states have not been observed so far
**Beautiful $\bar{b}qqqq$ pentaquarks with lifetime**

- If binding was large enough, the lightest ones might have masses below the relevant baryon-meson threshold and decay weakly.
- A secondary vertex eliminates combinatorial background from the particles produced at the primary vertex.
- LHCb has searched for stable $\bar{b}duud$, $\bar{b}suud$, $buudd$, $b\bar{d}uud$ in $J/\psi ph^+ h^-$ ($h = K$ or $\pi$) in Run I; found no evidence, and set upper limits on their production rate.
- Such searches will have a better sensitivity with larger integrated luminosity.
New particle zoo: charmonium above flavor threshold

Above the flavor threshold: More exotic states than $c\bar{c}$ states!

Old narrative (before 2003)

Mesons are $(q\bar{q})$ bound states.

All excited light hadrons are above “the open flavor threshold”!

Figures from Olsen, Skwarnicki, Zieminska
Rev. Mod. Phys. 90, 015003 (2018); arXiv:1708.04012

New narrative

Mesons are predominantly $(q\bar{q})$ bound states below the open flavor threshold. They are more complex structures above it, and we have not yet understood them.
Summary

• LHC offers enormous rates of heavy quarks via hadronic production cross-sections and large instantaneous luminosity

• Good place to study hadron spectroscopy with heavy quarks, including multi-quark exotics:

• Unique gateway to states produced in decays of b-baryons, $B_c$

• LHCb is well suited for such studies, thanks to hadron ID and large trigger bandwidth devoted to heavy flavors

• Near and farther future upgrades of the LHCb detector to take better advantage of the opportunity offered by the LHC:
  – Precision studies on already observed exotic hadron candidates
  – Hopes for detection of stable or narrow doubly-flavored tetraquarks (see Marco Pappagallo’s talk)
  – Judging from the recent history we should also expect unexpected!