Flavours - Classical spectroscopy

V. Mariani for the ALICE, ATLAS, CMS, LHCb Collaborations
Measurements and observations of heavy flavour production provide important tests of QCD and give insight into particle production at colliders.

- **Hadronization challenging** to understand -> measurements needed

- Form **baseline or background** for other physics studies at the LHC

- LHC provides access to **wide kinematic range** with a **very high production cross section** if compared to $e^+e^-$ colliders.
Experiments at the LHC
I’ll show the main / latest results from the four Collaborations on the Heavy Flavour spectroscopy.
The $B_c$ mesons ($b\bar{c}$) family is predicted to be very populated but the spectroscopy and property studies are still scarce.

Less explored compared to quarkonia because of the small production rate: dominant mechanism requires the production of both $cc\bar{c}\bar{c}$ and $bb\bar{b}\bar{b}$.

The $b\bar{c}$ exited states decay to the ground states via the cascade emission of $\gamma$ and $\pi$ pairs -> total width of $O(100\text{KeV})$ -> hard to detect
The existence of two separate states, $B_c^+(2S)$ and $B_c^{*+}(2S)$, was announced by CMS in [1], using data from Run2.

Significance of 2 peaks instead of 1 is 6.5 $\sigma$

$\Rightarrow$ First observation of two exited states

Consistent with ATLAS observation of one unresolved $B^*(2S)$ state [PRL 113 (2014) 212004]

$\Rightarrow$ backup

$M(B_c^+(2S)) = 6871.0 \pm 1.2$ (stat) $\pm 0.8$ (syst) $\pm 0.8$ (B$_c^+$) MeV

$\Delta M = \Delta M_1 - \Delta M_2 = 29.1 \pm 1.5$ (stat) $\pm 0.7$ (syst) MeV
$B_c^*(2S)$

LHCb could confirm the result using the statistics of Run1+Run2 (8.5 fb$^{-1}$) [2]

The second state is seen with a global (local) significance of 2.2$\sigma$ (3.2$\sigma$).

$M(B_c^+(2s)) = 6872.1 \pm 1.3$ (stat) $\pm 0.1$ (syst) $\pm 0.8$ ($B_c^+$) MeV

$\Delta M = \Delta M_1 - \Delta M_2 = 31.1 \pm 1.4$ (stat) MeV

Consistent with CMS and with the theoretical predictions

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[2] PRL 122 232001
Barions with heavy-flavor quark

- Spectroscopy of baryons that contain a heavy-flavor quark can test predictions of heavy-quark effective theory.

- Several theoretical calculations exist for various excitations of the ground state baryons containing a b quark.

- The widths and the production cross sections of various excited states are generally unknown.

This situation makes experimental searches for excited heavy-quark baryons both challenging and important for testing various theoretical models.
LHCb already measured two narrow states [3] denoted as \( \Lambda_b(5912)^0 \) and \( \Lambda_b(5920)^0 \)

- Using data collected at 7, 8 and 13 TeV (L=9/fb) a search in the \( \Lambda_b^0 \pi^+\pi^- \) spectrum in the range 6.10-6.25 GeV has been performed [4].

Two \( \Lambda_b^0 \) decays: \( \Lambda_b^0 \to \Lambda_c^+\pi^- \) and \( \Lambda_b^0 \to J/\psi pK^- \)

A clear excess of \( \Lambda_b^0 \pi^+\pi^- \) candidates around 6.15 GeV for both \( \Lambda_b^0 \) decay modes

Mass above the \( \Sigma_b^{*\pm}\pi^\mp \) threshold => three regions investigated:

- \( \Lambda_b^0 \pi^\pm \) mass within the width of \( \Sigma_b^\pm \)
- \( \Lambda_b^0 \pi^\pm \) mass within the width of \( \Sigma_b^{*\pm} \)
- Nonresonant region

[3] PRL 109, 172003
[4] PRL 123, 152001
$\Lambda_b^0$ excited states

The shapes suggest two different narrow peaks => states are called $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$ and masses and widths are measured:

$$m_{\Lambda_b(6146)^0} = 6146.17 \pm 0.33 \pm 0.22 \pm 0.16 \text{ MeV},$$
$$m_{\Lambda_b(6152)^0} = 6152.51 \pm 0.26 \pm 0.22 \pm 0.16 \text{ MeV},$$
$$\Gamma_{\Lambda_b(6146)^0} = 2.9 \pm 1.3 \pm 0.3 \text{ MeV},$$
$$\Gamma_{\Lambda_b(6152)^0} = 2.1 \pm 0.8 \pm 0.3 \text{ MeV},$$

The mass difference between the two states is $6.34 \pm 0.32 \pm 0.02 \text{ MeV}$.

States measured are consistent with the predictions for the doublet of $\Lambda_b(1D)^0$ states with quantum numbers $J^P = 3/2^+$ and $5/2^+$.

However, the interpretation of these states as excited $\Sigma_b^0$ states cannot be excluded.
CMS recently measured [5] exited states of the $\Lambda_b^0$ using Run2 data 16-18 with $L=140/fb$

- Two $\Lambda_b^0$ decays: $\Lambda_b^0 \to \psi(2S)\Lambda \to \psi(2S)p\pi^-$ and $\Lambda_b^0 \to J/\psi\Lambda \to J/\psi p\pi^-$
- $\Lambda_b(5912)^0$ and $\Lambda_b(5920)^0$ states have been confirmed (backup)

In the higher mass the $\Lambda_b^0\pi^+\pi^-$ spectrum show some structures

Broad excess (4$\sigma$ significance) maybe related to intermediate states of $\Sigma_b^{*\pm}$ and $\Sigma_b^{\pm}$.

$m=6073\pm5$ (stat) MeV
width=$55\pm11$ (stat) MeV.

More data to better elucidate

=> LHCb also confirmed a similar structure (backup)

Narrow peak around 6150 MeV (more that 5$\sigma$ significance) consistent with $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$, but also with a single peak hypothesis.

$m_{\Lambda_b(6146)^0}=6146.5\pm1.9\pm0.8\pm0.2$ MeV
$m_{\Lambda_b(6152)^0}=6152.7\pm1.1\pm0.4\pm0.2$ MeV

In agreement with the LHCb measurement

[5] PRL 803, 135345
**$\Xi_c$ and $\Xi_{cc}$ states**

Results from ALICE [6] in the $\Xi_c^0 \rightarrow \Xi^+ \pi^\pm$ at 13 TeV

First measurement of $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ critical towards understanding the dynamics of weak decays of doubly heavy baryons [7]

$\Xi_c^0 \rightarrow \Xi^+ \pi^\pm$ and charge conjugation in $3 < p_T < 4$ GeV in pp collisions

Average of the $\Xi_{cc}^{++}$ mass: $3621.24 \pm 0.65 \pm 0.31$ MeV

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[7] PRL 121, 162002
New $\Xi_b^{0,-}$ states

- New exited $\Xi_b^0$ state $\Xi_b(6227)^0$ observed in the $\Xi^-\pi^+$ using Run1 and Run2 data ($L=8.5/fb$) [8]

- Two $\Xi_b^-$ decays: $\Xi_b^- \rightarrow \Xi_c^0\pi^-$ and $\Xi_b^- \rightarrow \Xi_c^0\pi^-\pi^+\pi^-$

\[ \delta M_\pi = M(\Xi_b^-\pi^+) - M(\Xi_b^-) \]

⇒ Clear peak shown in the two decays with 10σ significance

Identified as $\Xi_b(6227)^0$ with:

$\delta m_{\pi}^{\text{peak}} = 429.8^{+1.4}_{-1.5}\text{MeV}$

$m(\Xi_b(6227)^0) = 6227.1^{+1.5}_{-1.3}\text{MeV}$

$\Gamma(\Xi_b(6227)^0) = 18.6^{+5.0}_{-4.1}\text{MeV}$

- New exited $\Xi_b^-$ state $\Xi_b(6100)^-\Xi_b^-\pi^-\pi^+$ using Run2 data ($L=140/fb$) [9]

- Two $\Xi_b^-$ decays: $\Xi_b^- \rightarrow \Xi^-/\psi$ and $\Xi_b^- \rightarrow J/\psi\Lambda K^-$

\[ \Delta M = M(\Xi_b^-\pi^+\pi^-) - M(\Xi_b^-) + 2m_{\pi}^{PDG} \]

⇒ Clear peak shown in the two decays with > 6σ significance

Identified as $\Xi_b(6100)^-$ with:

$\Delta M = 24.14 \pm 0.22 \pm 0.05\text{MeV}$

$m(\Xi_b(6100)^-) = 6100.3 \pm 0.2 \pm 0.1 \pm 0.6\text{MeV}$

Natural width consistent with 0

Consistent with $J^P=3/2^-$

[8] PHYSICAL REVIEW D 103, 012004

[9] CMS-BPH-20-004 accepted by PRL
The bottomonium family ($b\bar{b}$) plays a special role in understanding how the QCD binds quarks into hadrons.

The $\chi_b(3P)$ state is especially interesting since its properties could be affected by the proximity of the open-beauty threshold.

The $\chi_b(3P)$ state is reconstructed though the decay: $\chi_b \rightarrow Y(nS)\gamma \rightarrow 2\mu\gamma$ where $n = 1,2,3$. 

![Diagram of bottomonium family](image-url)
\( \chi_b(3P) \)

- **Firstly observed** by ATLAS in [10] at 7 TeV through the radiative decays \( \chi_b(nP) \to \Upsilon(1S)\gamma \) and \( \chi_b(nP) \to \Upsilon(2S)\gamma \)

\( \chi_b(3P) \) identified as third peak around 10.5 GeV

Significance of about 6\( \sigma \)

Mass of the \( \chi_b(3P) \) baricenter

\[ m = 10.530 \pm 0.005 \text{ (stat)} \pm 0.009 \text{ (syst)} \text{ MeV} \]

[10] PRL 108, 152001
The first observation of the $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$ resolved states performed with 13 TeV data from 2015 to 2017 (L=80/fb) [11]

**Photons energy scale** calibrated in a control sample and applied event by event

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$\chi_b(3P)$

The **first observation of the $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$ resolved states** performed with 13 TeV data from 2015 to 2017 (L=80/fb) [11]

Photons energy scale calibrated in a control sample and applied event by event

\[ M(\chi_{b1}(3P)) = 10513.42 \pm 0.41 \text{ (stat)} \pm 0.18 \text{ (syst)} \pm 0.5 \text{ (Y(3S)) MeV} \]
\[ M(\chi_{b2}(3P)) = 10524.02 \pm 0.57 \text{ (stat)} \pm 0.18 \text{ (syst)} \pm 0.5 \text{ (Y(3S)) MeV} \]
\[ \Delta M = 10.60 \pm 0.64 \text{ (stat)} \pm 0.17 \text{ (syst) MeV} \]

compatible with the theoretical expectations

Conclusion

- I showed the latest results on heavy flavor classical spectroscopy from the four LHC collaborations: ALICE, ATLAS, CMS and LHCb
- Hadron spectroscopy and help to shed light on the mechanisms responsible for dynamics of quarks and baryon formation.

- Very important results have been produced, mainly from Run2 data, with an impressive precision and sensitivity

- Heavy flavor spectroscopy is a very active field: much more results has to come!
I showed the latest results on heavy flavor classical spectroscopy from the four LHC collaborations: ALICE, ATLAS, CMS and LHCb.

Hadron spectroscopy and help to shed light on the mechanisms responsible for dynamics of quarks and baryon formation.

Very important results have been produced, mainly from Run2 data, with an impressive precision and sensitivity.

Heavy flavor spectroscopy is a very active field: much more results has to come!

STAY TUNED
backup
Recently also the relative cross sections of the $B_c^*(2S)$ and $B_c^{*+}(2S)$ states with respect to the $B_c^+$ have been measured

\[
R^+ = \frac{\sigma(B_c^+(2S))}{\sigma(B_c^0)} \cdot \frac{B(B_c^+(2S) \to B_c^+ \pi^+ \pi^-)}{B(B_c^0 \to B_c \pi^+ \pi^-)} = \frac{N(B_c^+(2S))}{N(B_c^0)} \frac{\epsilon(B_c^+)}{\epsilon(B_c^0)},
\]

\[
R^{*+} = \frac{\sigma(B_c^{*+}(2S))}{\sigma(B_c^0)} \cdot \frac{B(B_c^{*+}(2S) \to B_c^{*+} \pi^+ \pi^-)}{B(B_c^0 \to B_c \pi^+ \pi^-)} = \frac{N(B_c^{*+}(2S))}{N(B_c^0)} \frac{\epsilon(B_c^{*+})}{\epsilon(B_c^0)},
\]

\[
\frac{R^{*+}}{R^+} = \frac{\sigma(B_c^{*+}(2S))}{\sigma(B_c^0)} \cdot \frac{B(B_c^{*+}(2S) \to B_c^{*+} \pi^+ \pi^-)}{B(B_c^0 \to B_c \pi^+ \pi^-)} = \frac{N(B_c^{*+}(2S))}{N(B_c^0)} \frac{\epsilon(B_c^{*+})}{\epsilon(B_c^0)}.
\]

\[
R^+ = 3.57 \pm 0.69 \text{ (stat)} \pm 0.32 \text{ (syst)} \%,
\]

\[
R^{*+} = 4.91 \pm 0.69 \text{ (stat)} \pm 0.57 \text{ (syst)} \%,
\]

\[
\frac{R^{*+}}{R^+} = 1.39 \pm 0.35 \text{ (stat)} \pm 0.09 \text{ (syst)}.
\]
Observed for the first time by ATLAS in 2014 using Run1 data (7 + 8 TeV) \[*\].

The $B_c^{\pm}$ selection criteria for the events are optimized separately for 7 and 8 TeV.

\[ \text{mass difference distribution:} \quad m(B_c^{\pm} \pi \pi) - m(B_c^{\pm}) - 2m(\pi) \]

Significance of the observation: 3.7$\sigma$ @7 TeV and 4.5$\sigma$ @8 TeV data.
Combined 7 + 8 TeV significance 5.2$\sigma$

Consistent with the predicted mass of the $B_c^{\pm}$ (2S) state.
Structure observed in the $B^+K^-$ mass spectrum using data from Run1+Run2 (9 fb$^{-1}$) [*]

K $p_T \in [0.5;1]$ GeV

K $p_T \in [1;2]$ GeV

K $p_T > 2$ GeV

Significance of single peak wrt null hypothesis > 20 sigma, double peak wrt single 7.7 sigma

$m_1 = 6063.5 \pm 1.2 \text{ (stat)} \pm 0.8 \text{ (syst) MeV}$,

$\Gamma_1 = 26 \pm 4 \text{ (stat)} \pm 4 \text{ (syst) MeV}$,

$m_2 = 6114 \pm 3 \text{ (stat)} \pm 5 \text{ (syst) MeV}$,

$\Gamma_2 = 66 \pm 18 \text{ (stat)} \pm 21 \text{ (syst) MeV}$.

$\Delta m = m_{BK} - m_B - m_K$
Selection:

- Two muons: $|\eta| < 2.5$, $p_T > 4$ GeV, distance of closest approach between the two muons < 0.5 cm, dimuon vertex fit $\chi^2 > 10\%$, dimuon invariant mass in the range 2.9–3.3 GeV, distance between the dimuon vertex and the beam axis larger than three times its uncertainty, dimuon $p_T$ aligned with the transverse displacement vector $\cos \theta > 0.98$

- third track produced at the dimuon vertex with: $|\eta| < 2.4$, $p_T > 3.5$ GeV, $\geq 1$ hit in the pixel layers, $\geq 5$ hits in the tracker, transverse IP > two times its uncertainty

- $B_c^\pm$ candidate obtained from a kinematic fit between the 2 muons and the track: $p_T > 15$ GeV, $|y| < 2.4$, $l > 100 \, \mu$m, and a kinematic fit $\chi^2$ probability > 10%

- $B_c^{\pm}(2S)$ and $B_c^{\pm*}(2S)$ candidates reconstructed from kinematic fit between $B_c^\pm$ candidate with two opposite-sign tracks with a common vertex. Only $B_c^\pm$ candidates with invariant mass in the range 6.2–6.355 GeV are selected. One of the pion candidates must have $p_T > 0.8$ GeV and the other $p_T > 0.6$ GeV.

- The $B_c^{\pm} \pi^+ \pi^-$ candidates must have $|y| < 2.4$ and a vertex $\chi^2$ probability larger than 10%
Selection:

- Two muons with $p_T > 550$ MeV and good track-fit quality. Required to form a common decay vertex with an invariant mass in the range 3040-3140 MeV.

- Pion with $p_T > 1000$ MeV, good track-fit quality, and be inconsistent with originating from any PV.

- The $J/\psi$ candidate is combined with a charged pion to form the $B_c^\pm$ candidate.

- The $B_c^\pm$ candidate is required to have a good-quality vertex, a trajectory consistent with coming from PV, and a decay time larger than 0.2 ps.

- A BDT is used to further suppress bkg ($p_T/\eta/\text{decay length}/\text{decay time}/\chi^2$).

- $B_c^\pm$ candidates with $M$ in 6200--6320 MeV are combined with a pair of oppositely charged particles identified as pions. These pion candidates are required to originate from the PV, and each have $p_T > 300$ MeV, $p > 1500$ MeV, and a good track-fit quality.

- The $B_c^{\pm*}(2S)$ candidate is required to have a good vertex-fit quality.
 Samples of $\Lambda_b^0$ candidates are formed from $\Lambda_c^+\pi^-$ combinations, where the $\Lambda_c^+$ baryon is reconstructed in the $pK^-\pi^+$ final state.

 The reconstructed $\Lambda_c^+$ vertex is required to have a good fit quality and to be significantly displaced from all PVs and to have a mass of $\pm 25\text{MeV}$ wrt known value

 BDT used to reduce bkg (inputs: kinematic variables of the $\Lambda_c^+$ and $\Lambda_b^0$, the lifetime of the $\Lambda_b^0$, kinematic variables and quality of particle identification for pions, kaons, and protons, and variables describing the consistency of the selected candidates)

 Selected $\Lambda_b^0$ candidates are combined with pairs of pions originating from the same PV as the $\Lambda_b^0$. Only pion pairs with $p_T^{\pi^+\pi^-} > 500\text{ MeV}$ are used, to suppress the otherwise large combinatorial
$\Lambda_b^0 \to \psi \Lambda$ ($\mu^+\mu^- + \Lambda \to p\pi^-$ from V0 collection)

- $\Lambda$ vtx fit probability $> 1\%$, $p_T(\Lambda) > 1$ GeV,
- $\cos(3D \text{ $\Lambda$ pointing angle to $\Lambda_b^0$ vertex}) > 0.99$,
- $L_{xy}/\sigma_{L_{xy}}(\Lambda \text{ vtx} \to \Lambda_b^0 \text{ vtx}) > 5$,
- $\Lambda$ mass within 10 MeV from PDG

$\Lambda_b^0$ vtx fit probability $> 1\%$

- $p_T(\Lambda_b^0) > 5$ GeV,
- $\cos(2D \text{ $\Lambda_b^0$ pointing angle to PV}) > 0.99$,
- $L_{xy}/\sigma_{L_{xy}}(\Lambda_b^0 \text{ vtx} \to \text{PV}) > 3$

Additional channel $\Lambda_b^0 \to \psi(2S)\Lambda$, $\psi(2S) \to J/\psi \pi^+\pi^-$, $J/\psi \to \mu^+\mu^-$: as above, additional 2 pions – high-purity tracks, $p_T > 0.35$ GeV; $\Lambda_b^0$ obtained by vertexing $\mu^+\mu^-\pi^+\pi^-\Lambda$ with $J/\psi$ and $\Lambda$ mass constraints; $3672 < M(J/\psi\pi^+\pi^-) < 3700$ MeV
$\Lambda_b^0 - \text{CMS}$

$M(\Lambda_b(5912)^0) = 5912.32 \pm 0.12 \pm 0.01 \pm 0.17 \text{ MeV}$,

$M(\Lambda_b(5920)^0) = 5920.16 \pm 0.07 \pm 0.01 \pm 0.17 \text{ MeV}$,
Table 1: Quark-model predictions for the masses of the lightest \( \Lambda_b \) and \( \Sigma_b^{(*)} \) states (in MeV).

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<td>( \Lambda_b^0 )</td>
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\( \Lambda_b^0 - \text{LHCb} \)

- Data collected at 7, 8 and 13 TeV (L=9/fb) => new state observed in the \( \Lambda_b^0 \pi^+ \pi^- \) spectrum [*]
- Two \( \Lambda_b^0 \) decays: \( \Lambda_b^0 \to \Lambda_c^+ \pi^- \) and \( \Lambda_b^0 \to J/\psi pK^- \)

Broad excess referred as \( \Lambda_b^{**0} \)

- Mass difference wrt \( \Lambda_b^0 \)
  \( \Delta m = 452.7 \pm 2.9 \pm 0.5 \) MeV
- Width = 72\( \pm 11 \pm 2 \) MeV
- \( \Lambda_b^{**0} \) mass = 6072.3\( \pm 2.9 \pm 0.6 \pm 0.2 \) MeV

**Consistent with the CMS measurement**

Narrow peaks already measured as \( \Lambda_b(6146)^0 \) and \( \Lambda_b(6152)^0 \)

Can’t exclude that the broad structure corresponds to a superposition of more than one narrow states, but the interpretation of these states as excited \( \Sigma_b \) resonances is disfavoured.

[*] JHEP 06 (2020) 136
Measured for the first time by LHCb in [10] in the $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ decay with $m=3621.40 \pm 0.72 \pm 0.27 \pm 0.14$ MeV and its lifetime $0.256^{+0.024}_{-0.022}$ ps $\Rightarrow$ compatible with a weak interacting particle.

The first measurement of the decay $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$ is presented here [11], critical towards understanding the dynamics of weak decays of doubly heavy baryons.

Average of the $\Xi_{cc}^{++}$ mass: $3621.24 \pm 0.65 \pm 0.31$ MeV

Selection of $\Xi_{cc}^{++} \rightarrow \Xi_{c}^{+} (\rightarrow pK^{-}\pi^{+})\pi^{+}$ decay:
- three charged tracks with pT > 0.5GeV fitted to a common vertex
- $\Xi_{c}^{+}$ vertex displayed with lifetime > 0.15ps and invariant mass between 2450-2488 MeV
- Additional positive track with pT > 0.2 GeV combined to the $\Xi_{c}^{+}$
- $\Xi_{cc}^{++}$ candidate with pT > 2 GeV and originating from PV

BDT used to minimise combinatorial bkg with 3 sets of variables (particle kinematics, vertex fitting, lifetime)

Also the ratio between the two decays is measured as

\[
\mathcal{R}(\mathcal{B}) = \frac{\mathcal{B}(\Xi_{cc}^{++} \rightarrow \Xi_{c}^{+}\pi^{+}) \times \mathcal{B}(\Xi_{c}^{+} \rightarrow pK^{-}\pi^{+})}{\mathcal{B}(\Xi_{cc}^{++} \rightarrow \Lambda_{c}^{+} K^{-}\pi^{+}\pi^{+}) \times \mathcal{B}(\Lambda_{c}^{+} \rightarrow pK^{-}\pi^{+})}
\]

with $\mathcal{R}(\mathcal{B}) = 0.035 \pm 0.009$ (stat) $\pm 0.003$ (syst) in agreement with theory

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Selection:
- Two OS muons with pT > 4 GeV and |eta|<2.3 fitted to a common vertex
- Dimuon pT > 12 GeV and |y|<2
- 9.25 < m_{\mu\mu} < 9.65 GeV for the \(\Upsilon(1S)\) and 9.80 < m_{\mu\mu} < 10.10 GeV for the \(\Upsilon(2S)\)
- Photons are reconstructed as converted (in e+e-) or unconverted

Figure of merit \(\tilde{m}_k = \Delta m + m_{\Upsilon(kS)}\)