LHCb’s Prospect for Hadron Physics

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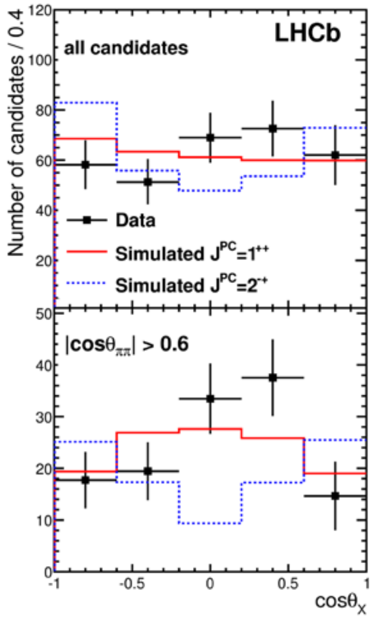
Spectroscopy Highlights at LHCb Run I/II

$X(3872)$ Quantum Numbers

[PRL110(2013)222001][PRD92(2015)011102]



$J^{PC} = 1^{++}$ established

Full angular analysis of $B^+ \to J/\psi \rho^0 K$ sets limit on D-wave decay fraction 4% @ 95% C.L.

Compatible with DD^* molecular interpretation

$\chi_{c1}(2^3P_1)$ closest allowed charmonium state

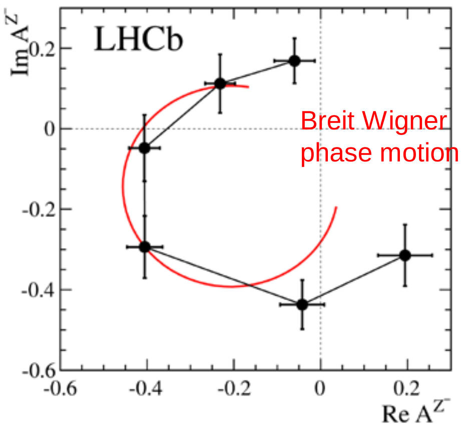
$B^+ \to X(3872)K^+$ w/ $X(3872) \to \pi\pi J/\psi$

Resonant nature of $Z^-(4430)$

[PRL112(2014)222002]

Amplitude analysis of $B^- \to \psi' K \pi$

Argand plot



$J^P = 1^+$

$m = 4475 \pm 7^{+15}_{-25}$ MeV

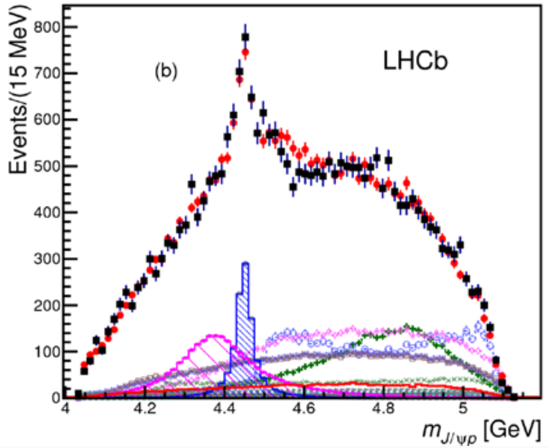
$\Gamma = 172 \pm 13^{+37}_{-34}$ MeV

Established the resonance character of the Z(4430)

Spectroscopy Highlights at LHCb Run I/II

Pentaquark-like structures in $J/\psi p$

[PRL115(2015)072001] using $\Lambda_b^0 \to J/\psi K^- p$



State	Mass [MeV]	Width [MeV]	J^P
$P_c(4380)^+$	$4380 \pm 8 \pm 29$	$205 \pm 18 \pm 86$	$3/2^-$
$P_c(4450)^+$	$4449.8 \pm 1.7 \pm 2.5$	$39 \pm 5 \pm 19$	$5/2^+$

Quantum number assignment not unique

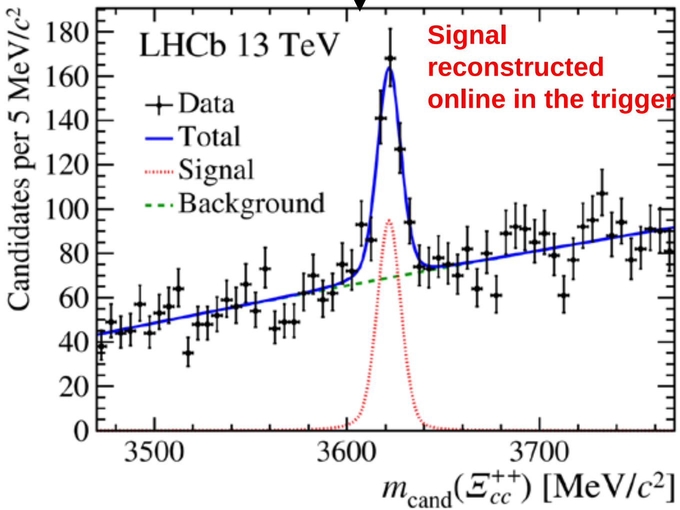
First observation of doubly charmed Baryon

[PR L119(2017)112001][PRL121(2018)162002][PRL121(2018)052002]

Ξ_{cc}^{++} Observed in decay to $\Lambda_c^+ K^- \pi^+ \pi^+$ and $\Xi_c^+ \pi^+$

$\Lambda_c^+ \to pK^-\pi^+$

confirmation



$$m = 3621.40 \pm 0.72(stat) \pm 0.27(syst) \pm 0.14(\Lambda_c)\ \text{MeV}/c^2$$

$$\tau = 0.256^{+0.024}_{-0.022}(stat) \pm 0.014(syst)\ \text{ps}$$

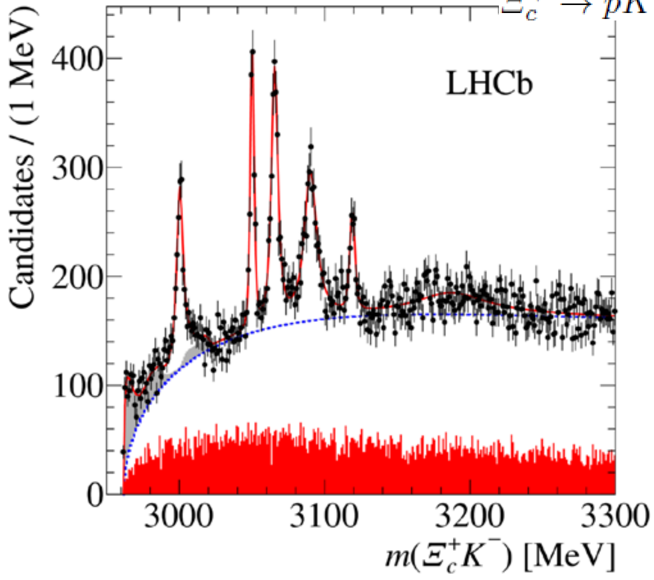
Spectroscopy Highlights at LHCb Run I/II

Excited Ω_c states

[PRL118(2017)182001]

5 narrow resonances in $\Xi_c^+ K^-$

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



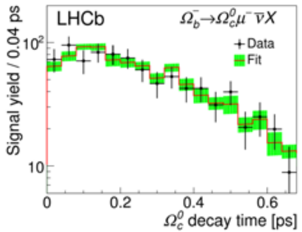
Quantum numbers still unknown

Beauty Spectroscopy

Ω_b lifetime [PRL121(2018)092003]

$$\tau = 268 \pm 24 \pm 10 \pm 2\ \mathrm{fs}$$

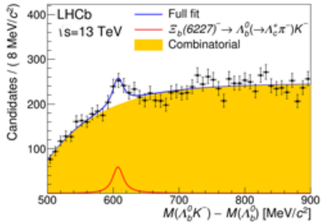
4 times larger than world average



A new Ξ_b excited state

[PRL121(2018)072002]

observed in $\Lambda_b^0 K^-$ and $\Xi_b^0 \pi^-$



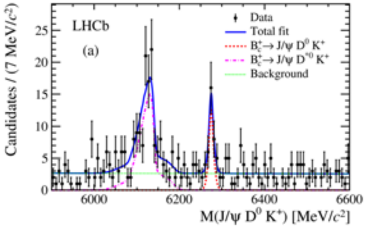
First observation of

$B_c \to J/\psi D^{0(*)} K$

[PRD95(2017)032005]

most precise single measurm. of B_c mass:

$$m = 6274.28 \pm 1.40(stat) \pm 0.32(syst)\ \mathrm{MeV}/c^2$$

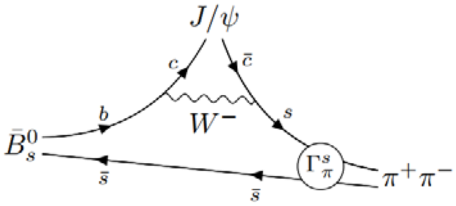


Spectroscopy Highlights at LHCb Run I/II

Light hadron physics

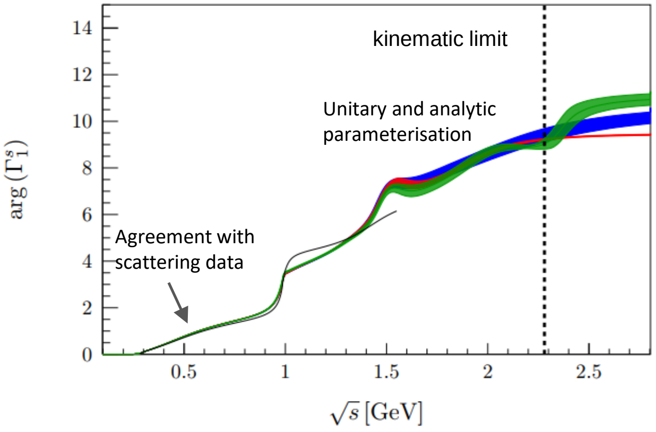
S.Ropertz, C.Hanhart, B.Kubis [1809.06867]

Extracting the pion
scalar formfactor
using dispersion analysis



K^+K^-

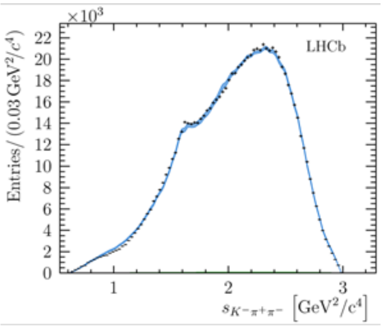
Formfactor phase:

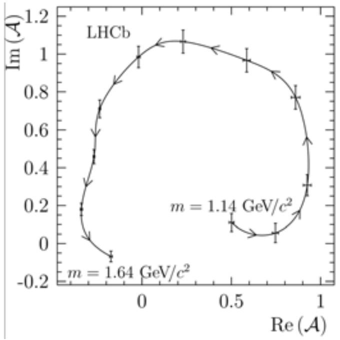


Strangeness spectroscopy

[EPJC78(2018)443]

Extraction of K* amplitudes from $D^0 \to K\pi\pi\pi$

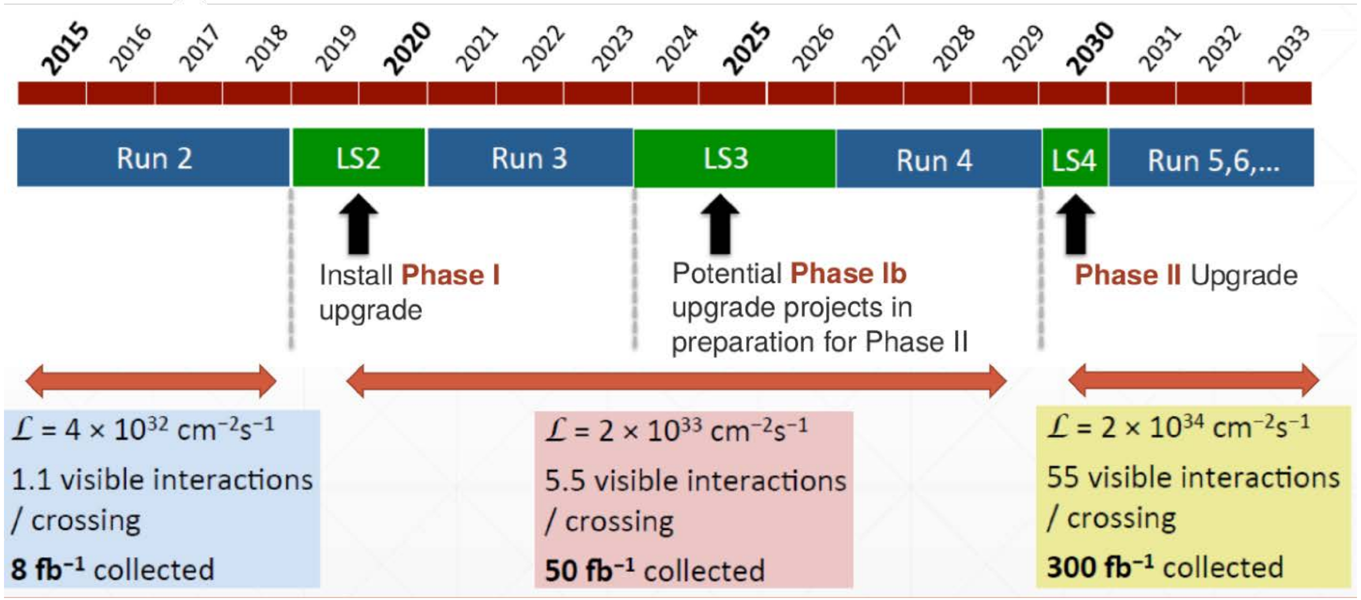




$$K(1460) : m = 1482.40 \pm 3.58 \pm 15.22\,\mathrm{MeV}/c^2$$

$$\Gamma_0 = 335.60 \pm 6.20 \pm 8.65\,\mathrm{MeV}/c^2$$

Prospects with the LHCb Upgrades



- Large samples of Jpsi hh modes
- First observations of many interesting channels, but amplitude analyses stat. limited

- Amplitude analyses with complex final states
- Search for suppressed decays

- Amplitude analyses with suppressed decays
- Decays with challenging final states
- Rare initial states

Tetraquark and Pentaquark properties

Multichannel analysis of exotic hadrons
and search for suppressed decays.
Examples:

- $X(3872) \rightarrow \chi_{c1}\pi\pi, J/\psi\omega, J\psi\rho, D\bar{D}^*$ (investigate nature of X(3872))
- $P_c \rightarrow J/\psi p, \chi_{c1}p, \Lambda_c\bar{D}^{0(*)}$
- $Z^+ \rightarrow J/\psi\pi, \psi(2S)\pi, \chi_c\pi, \eta_c\pi$
- Radiative decays, such as
  $X(3872) \rightarrow \psi\gamma$ (see [NUCL.PHYS. B886(2014)665] for Run I measurement)

Amplitude analysis: $\Lambda_b \to \Lambda_c \bar{D}^{0(*)} K$

- Search for pentaquark decays with two open charm daughters
- Predictions in molecular model

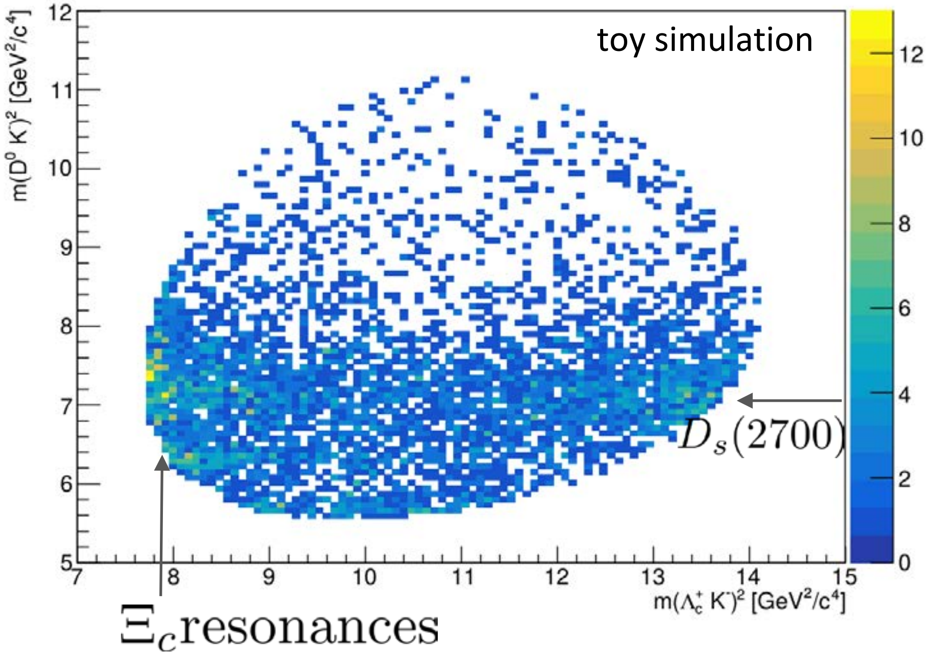
Mode	Widths (MeV)			
	$P_c(4380)$		$P_c(4450)$	
	$\bar{D}\Sigma_c^*(\frac{3}{2}^-)$	$\bar{D}^*\Sigma_c(\frac{3}{2}^-)$	$\bar{D}^*\Sigma_c(\frac{3}{2}^-)$	$\bar{D}^*\Sigma_c(\frac{5}{2}^+)$
$\bar{D}^*\Lambda_c$	131.3	41.6	80.5	22.6
$J/\psi p$	3.8	8.4	8.3	2.0
$\bar{D}\Lambda_c$	1.2	17.0	41.4	18.8

Final states

[PRD95(2017)114017],
[Nucl. Phys. A 954(2016)393]

- Challenging final state with 6 charged tracks

Toy simulation: Dalitz plot with 9fb^{-1}
(no pentaquarks in simulation)



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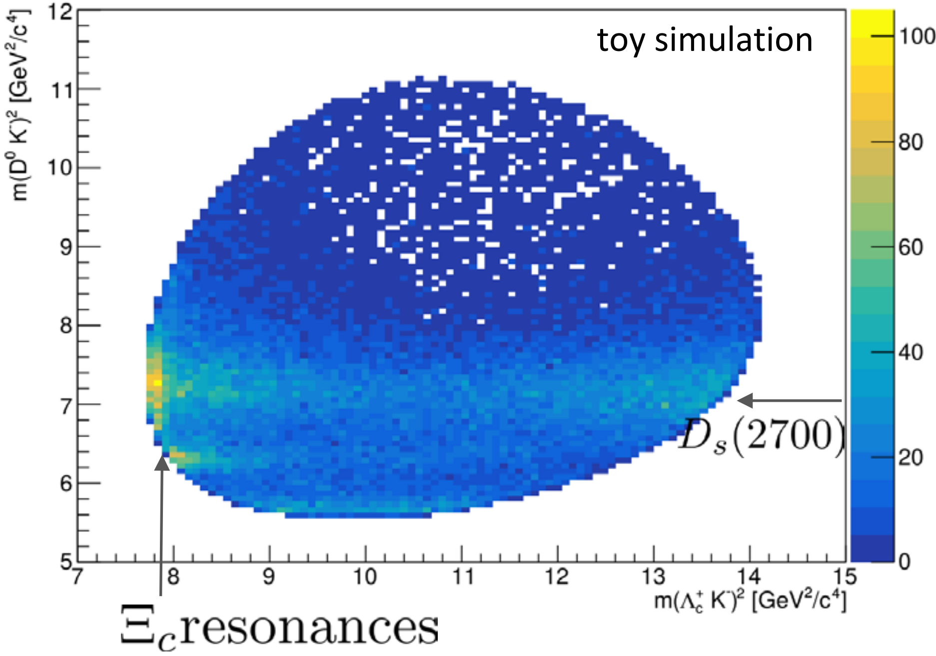
][PRD95(2017)114017]
[Nucl. Phys. A 954(2016)393

Challenging final state with 6 charged hadronic tracks
(detection efficiency ~×50 less than J/psi p K)

Toy simulation: **Dalitz plot with 50fb^{-1}**
(no pentaquarks in simulation)

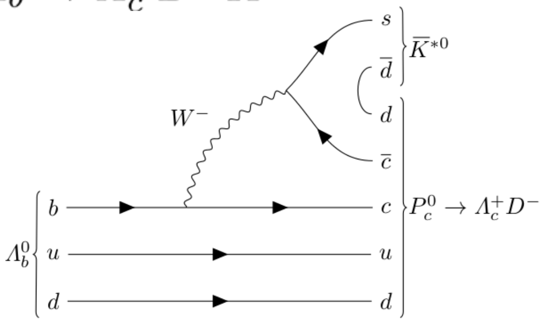


Search for Exotic Multiplets

- C-odd or charged partner to $\chi_{c1}(3872)$ has not been found yet
  - $J/\psi\eta, \chi_c\gamma; J/\psi\pi^{\pm}\pi^0$

- Isospin-partner of the pentaquarks can be searched for in decays to pairs of open charm hadrons

  $\Lambda_b \to \Lambda_c^+ D^- K^*$



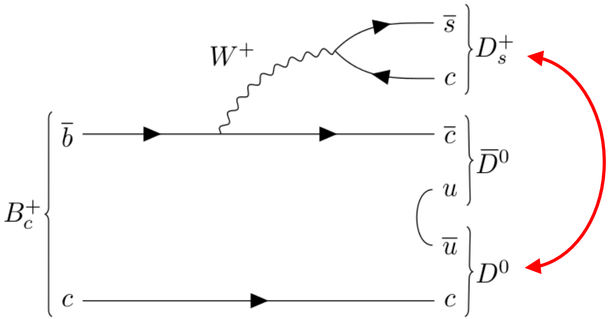
- Strange pentaquarks
  - $\Lambda_b \to J/\psi\Lambda\phi$

    $\Xi_b \to J/\psi\Lambda K$

    $\Xi_b \to \Lambda_c D_s K$
  - requires efficient Hyperon reconstruction
  - **LHCb is the only experiment where these heavy Baryon decays can be studied!**

Double Heavy Exotics

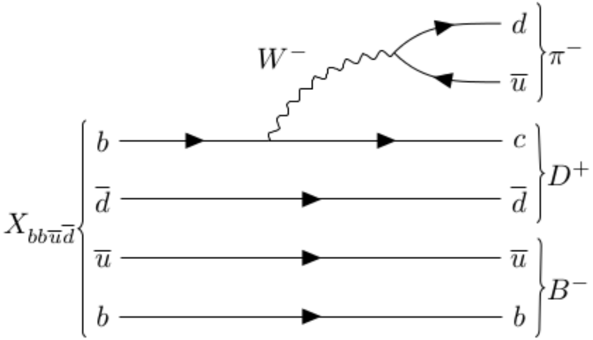
Doubly charmed tetraquarks $cc\bar{q}\bar{q}'$ would have unambiguously exotic signatures



Overcoming the B_c production cross section and detection efficiency (7 hadrons) requires Upgrade II samples.

Expectation: O(100) candidates in 300 fb^{-1}

Double beauty exotics can be searched for in production:



Searches with beauty in the final state suffer from small branching fractions for exclusive reconstruction

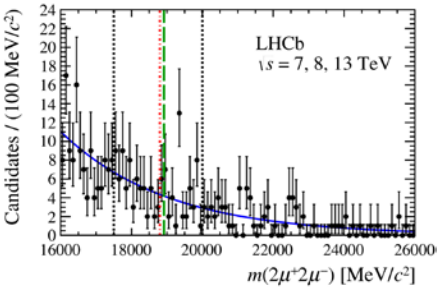
Beautiful exotics

Tetraquark and pentaquark model calculations tend to be more stable in the beauty sector

Tetraquarks with hidden beauty:

$\Upsilon(1S)\omega$ would profit from improved π^0 reconstruction in Upgrade II.

A first search $|b\bar{b}b\bar{b}\rangle \to \Upsilon\mu\mu$ yielded limits [JHEP10(2018)086] – will profit significantly from higher statistics



Pentaquarks with beauty:

Hidden beauty, double heavy:

$$|Q\bar{Q}qqq\rangle \to \Upsilon p, \Upsilon\Lambda, B_c p, B_c\Lambda$$

Open beauty:

A search [PRD97(2018)032010] for weakly decaying $|b\bar{q}qqq\rangle \to J\psi p h^+ h^-$ has set limits on production x branching fraction

Searches with beauty in the final state suffer from small branching fractions for exclusive reconstruction

Double Heavy Baryons

Expected yields for **doubly charmed baryons** after Run 5:

$$\Xi_{cc} : 25\,000$$

$$\Omega_{cc} : \ 4\,500$$

in each of several decay modes

Challenge: discriminate from prompt charm in the trigger (-> real time analysis)

Baryons with beauty and charm:

Predicted production cross section: 77nb

[PRD83(2011)034026]

Most promising decay modes for discovery:

$$J/\psi\Xi_c^+, J/\psi\Xi_c^0, J/\psi\Lambda_c^+, J/\psi\Lambda_c^+ K^-$$

$$\Xi_{cc}\pi^-, D^0\Lambda_c^+, D^0\Lambda_c^+\pi^-, D^0 D^0 p$$

Modes w/ beauty in FS: $\Xi_b\pi, \Lambda_b\pi, B^0 p$

Charmonium production

The kinematic distribution of the charmonium production cross section is well described in NRQCD

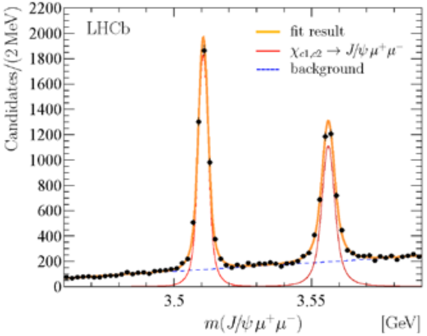
Polarisation observables are not understood in the same theory

Observation of

$$\chi_{c1,2} \to J/\psi \mu^+ \mu^-$$

will allow almost backgr. freestudy of polarisation

[PRL119(2017)221801]



Double charmonium production: Current data samples do not allow to distinguish between single parton and double parton scattering mechanism

Progress requires larger samples of prompt $J/\psi J/\psi, \Upsilon J/\psi, \Upsilon\Upsilon$

With Upgrade II polarisation observables in double charmonium production become feasible.

Hadron Physics with LHCb

- LHCb has demonstrated its ability to contribute to the understanding of hadrons much beyond the scope of flavor physics.

- Upgrade I will further improve LHCb's capability to reconstruct rare and complex final states (data-taking will start in 2021).

- The planned Upgrade II would boost the data-set drastically (a factor 100 w/r to what has been used so far in most analyses), allowing amplitude analyses even for suppressed decays and challenging final states.

- LHCb will further consolidate its role as one of the major players in the search for new exotic hadronic states and hadron spectroscopy.