Hadron spectroscopy and exotic states at LHCb

Results and prospects

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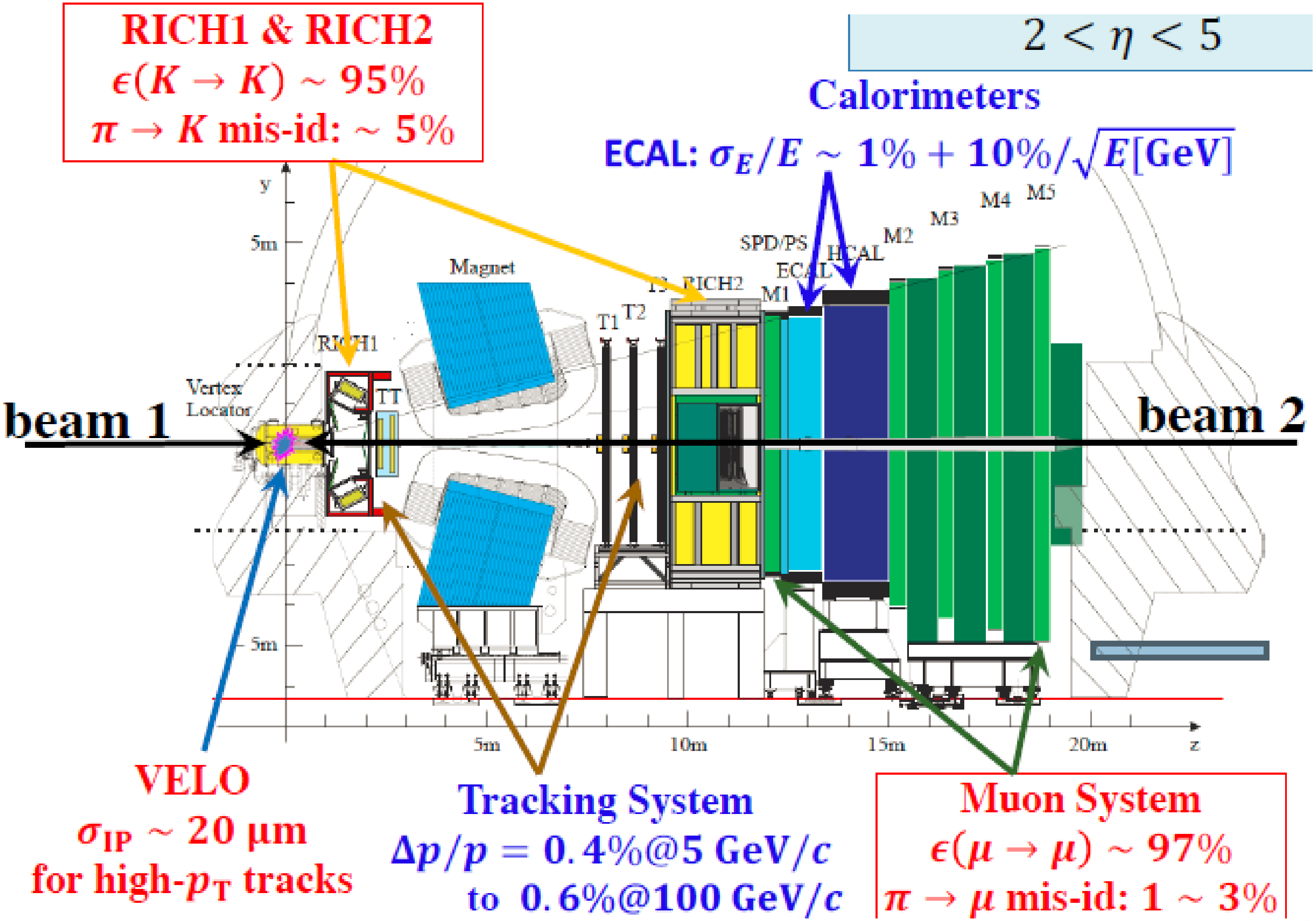
Outline

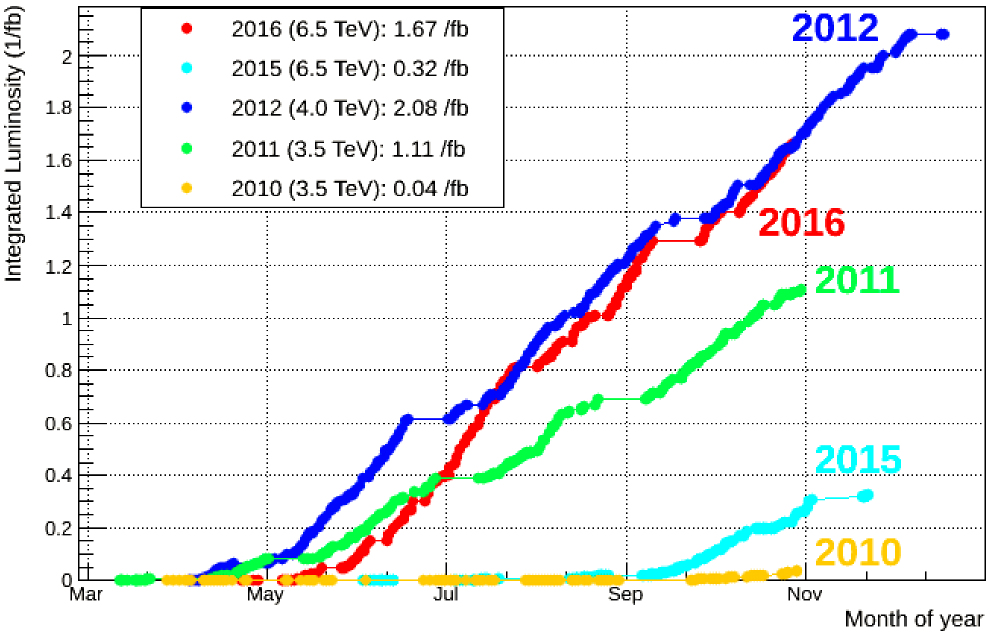
- **The LHCb detector and data**
- **Exotic states**
  - $J/\psi\phi$ **exotic states in** $B^+ \to J/\psi\phi K^+$
  - **Non-confirmation of the X(5568) tetraquark**
  - **Confirmation of the pentaquarks**
  - $\Lambda_b^0 \to \chi_{cj} p K^- (j = 1, 2)$
- **Five new** Ω_c **states**
- **Conclusion and outlook**

LHCb detector

2008 JINST 3 S08005



LHCb data



RUN-I

1 fb^{-1} of pp collisions at 7 TeV

2 fb^{-1} of pp collisions at 8 TeV

RUN-II (2015~2018 13 TeV)

LHCb: $\boldsymbol{\sigma(pp \rightarrow b\bar{b}) \approx 0.3\ \mathrm{mb}\ @7\ \mathrm{TeV}}$

$\boldsymbol{\sigma(pp \rightarrow b\bar{b}) \approx 0.5\ \mathrm{mb}\ @13\ \mathrm{TeV}}$

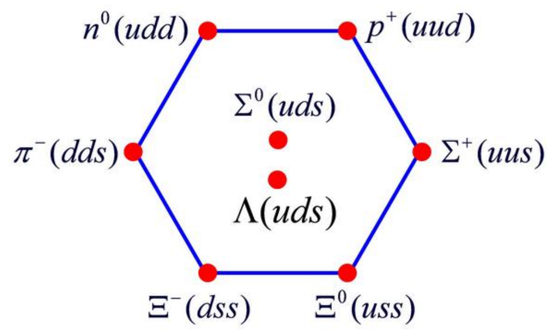
- Huge data sample of b-hadron decays provides great opportunities for study of spectroscopy and exotic states

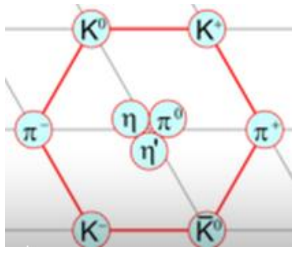
	$\boldsymbol{B^0}$	$\boldsymbol{B^+}$	$\boldsymbol{B_s^0}$	***b* baryons ($\boldsymbol{\Lambda_b}$ ...)**	$\boldsymbol{B_c^+}$
Fraction(%)	40	40	10	10	0.1
Component	$\bar{b}d$	$\bar{b}u$	$\bar{b}s$	bqq	$\bar{b}c$

LHCb-PAPER-2011-018

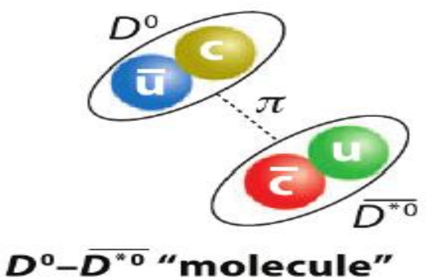
QCD theory

- According to the traditional quark model, a meson is composed of $q\bar{q}$ and a baryon is composed of qqq. Both mesons and baryons are color singlets.



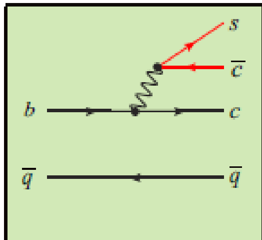
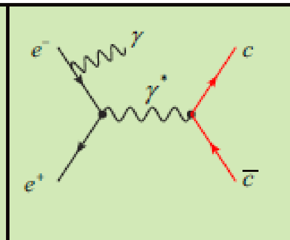
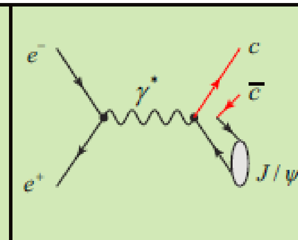
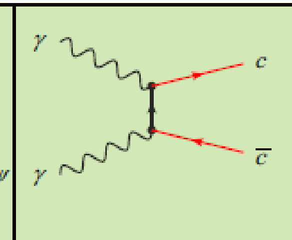
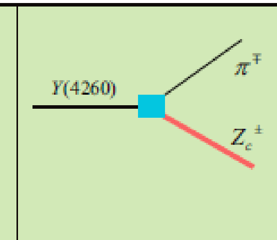


- QCD allows many other possible color singlets such as dibaryons, pentaquarks, glueballs, tetraquarks, hadronic molecules, hybrid hadrons etc



XYZ states

- Many observed states do not fit to quarkonium picture

				
$X(3872)$	$Y(4260)$	$X(3940)$	$X(3915)$	$Z_c(3900)$
$Y(3940)$	$Y(4008)$	$X(4160)$	$X(4350)$	$Z_c(4025)$
$Z^+(4430)$	$Y(4360)$		$Z(3930)$	$Z_c(4020)$
$Z^+(4051)$	$Y(4630)$			$Z_c(3885)$
$Z^+(4248)$	$Y(4660)$			
$Y(4140)$				
$Y(4274)$				
$Z_c^+(4200)$				
$Z^+(4240)$				
$X(3823)$				

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- More new exotic states were studied
  - X(4500), X(4700) …

X(4140) state

- The $X(4140)$ state is first claimed by the CDF collaboration in 2008.

PRL 102 242002

- Many experiments results

CDF	Belle	LHCb	CMS	D0	BaBar
3.8σ	**3.2σ**	**>5.0σ**	**>5.0σ**	**3.1σ**	**<2.0σ**
2.7 fb^{-1} @ 1.96 TeV	825 fb^{-1} @$\Upsilon(nS)$	3 fb^{-1} @7&8 TeV	5.2 fb^{-1} @7 TeV	10.4 fb^{-1} @1.96 TeV	422.5 fb^{-1} @$\Upsilon(4S)$
PRL 102 242002	**PRL 104 112004**	**PRL 102 242002**	**PLB 734 261-281**	**PRD 89 012004**	**PRD 91 012003**

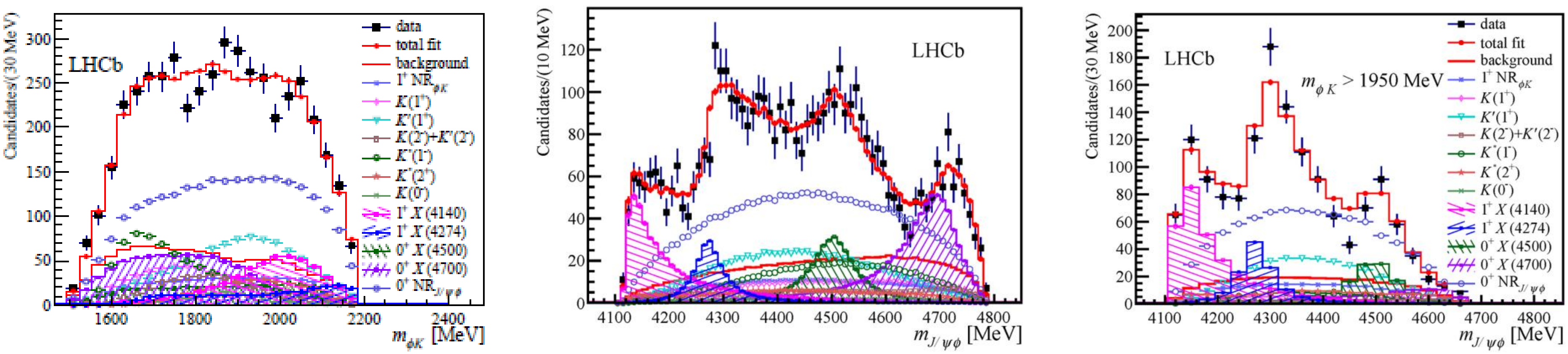
- Theoretical interpretations
  - Tetraquark
  - Molecular
  - Dynamically generated resonances
  - Coupled channel effect

New result of X states in $B^+ \to J/\psi\phi K^+$ from LHCb

- Update the results with full run-I data

PRL 102 242002

- Use amplitude analysis
  - $B^+ \to J/\psi K^{*+}(\to \phi K^+)$, $B^+ \to X\,(\to J/\psi\phi)K^+$, $B^+ \to Z_c^+\,(\to J/\psi K^+)\,\phi$
  - Four new X states decaying to $J/\psi\phi$ are needed in addition to $Z_c^+ \to J/\psi K^+$

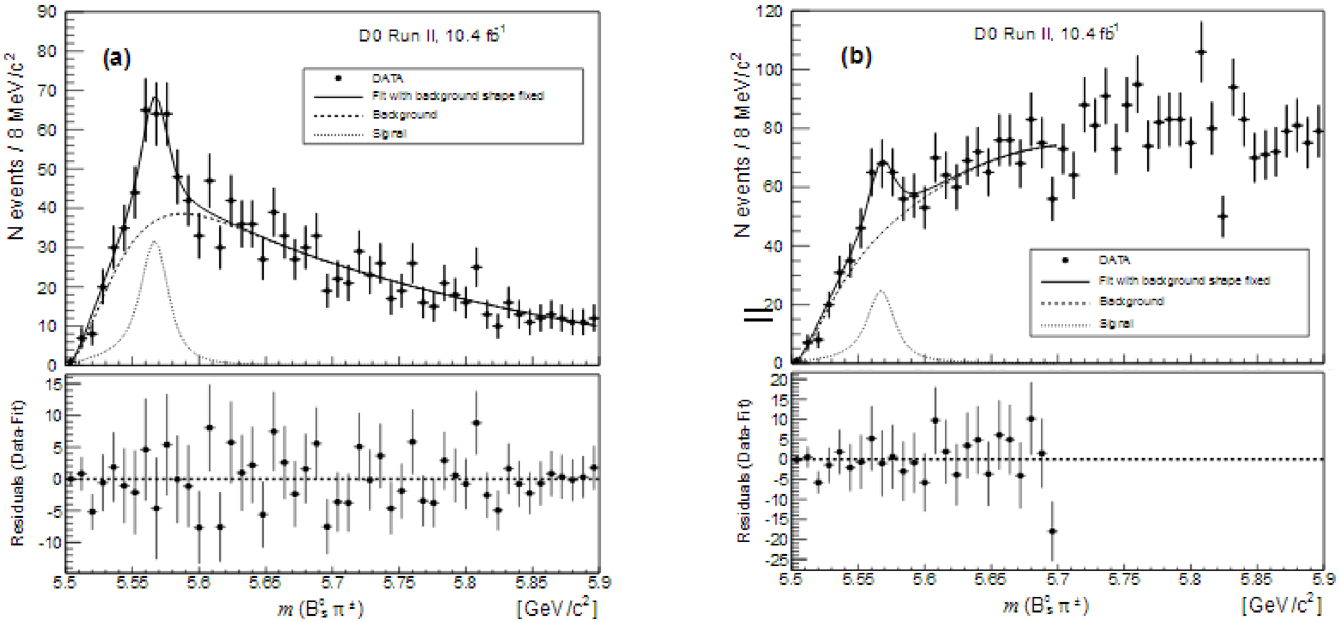


Fit results (the significances of all four exotic states **>5.0σ**)

- Mass of X(4140) agrees with world average, width larger
- $J^P = 1^+$ prefer for X(4140) and X(4272), $J^P = 0^+$ for X(4500) and X(4700)

A puzzle of tetraquark from D0

- The D0 collaboration has recently claimed a 5.1σ evidence for a exotic tetraquark state $X(5568)^{\pm} \rightarrow B_s^0 \pi^{\pm}$ **PRL 117 022003**



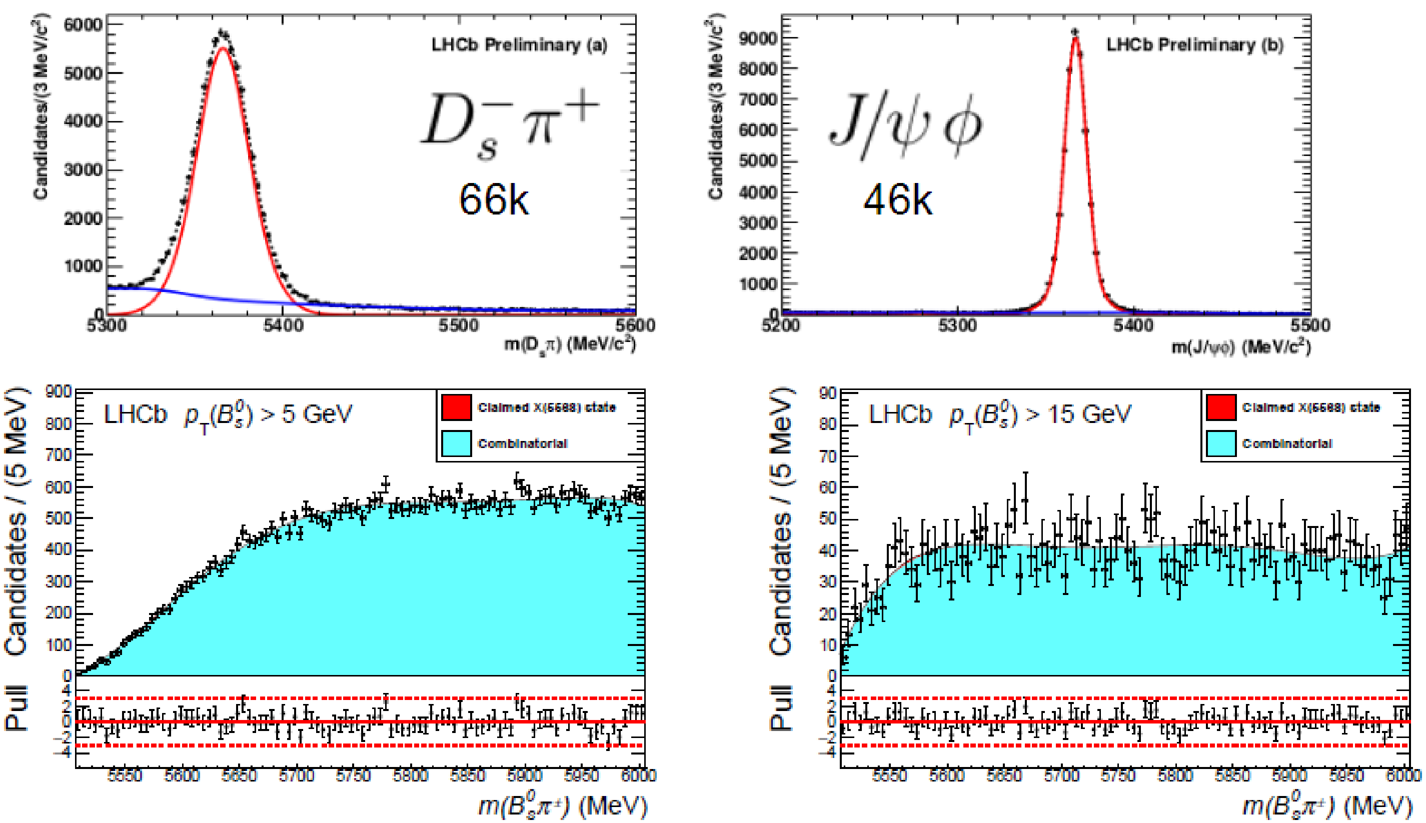
(a) cone cut $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.3$ (b) without the cone cut

$\boldsymbol{m = 5567.8 \pm 2.9(stat)^{+0.9}_{-1.9}(sys)}$ **MeV** $\boldsymbol{\Gamma = 21.9 \pm 6.4(stat)^{+5.0}_{-12.5}(sys)}$ **MeV**

Non-confirmation of the X(5568) in LHCb

- Searched for $X(5568)^{\pm} \to B_s^0 \pi^{\pm}$ at LHCb using Run-I data
  - Very large and clean B_s^0 signal

PRL 117 152003

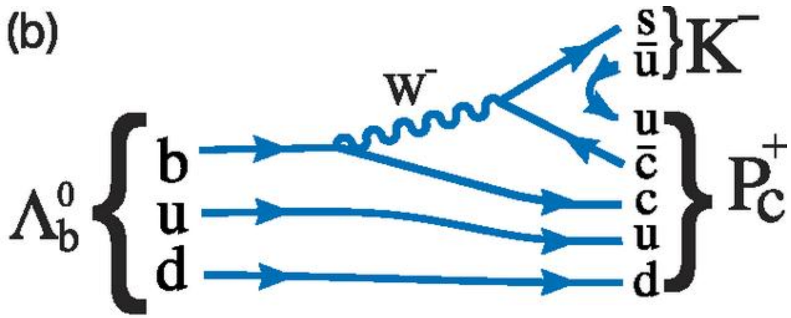


(a) $P_t(B_s^0) > 5$ GeV (b) $P_t(B_s^0) > 15$ GeV

- No observation of any X(5568)-like signal at LHCb, similar result from CMS.

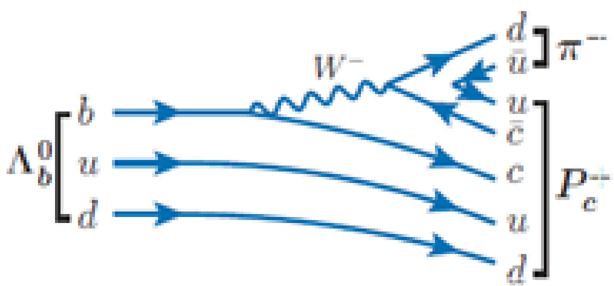
$\Lambda_b^0 \to J/\psi p K^-$ VS $\Lambda_b^0 \to J/\psi p \pi^-$

- First time discovery of two pentaquark states $P_c(4380)^+$ and $P_c(4450)^+$ in the mode $\Lambda_b^0 \to J/\psi p K^-$ by the LHCb collaboration

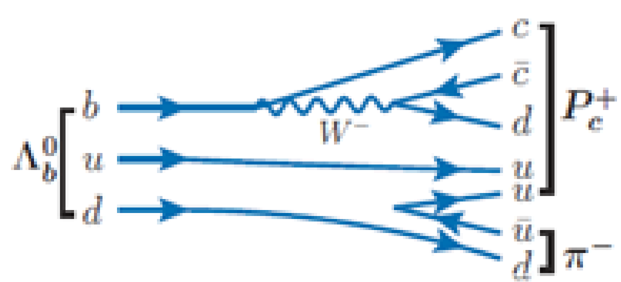


PRL 115 072001

- Now look for pentaquarks in doubly cabibbo suppressed Λ_b^0 decays to further rule out the possibility of threshold enhancement



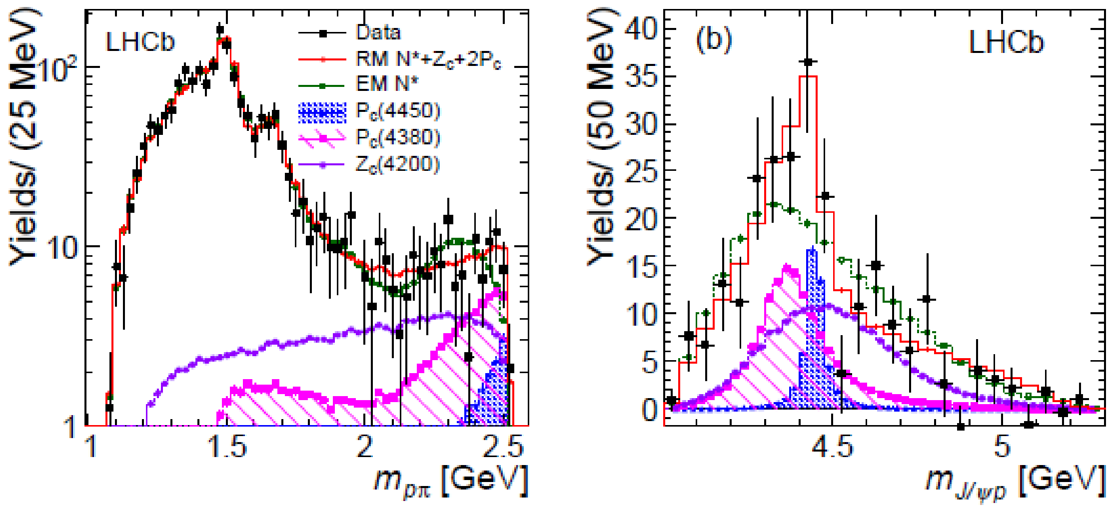
"external" W^{*-} exchange



"internal" W^{*-} exchange

Pentaquarks in $\Lambda_b^0 \to J/\psi p \pi^-$

- Analysing the same Run I dataset with $\Lambda_b^0 \to J/\psi p K^-$
  - The statistics is around 15 times lesser
- Incorporate an amplitude analysis
  - $\Lambda_b^0 \to J/\psi N^*(\to p\pi^-)$, $\Lambda_b^0 \to P_c^+ (\to J/\psi p)\pi^-$, $\Lambda_b^0 \to Z_c^- (\to J/\psi \pi^-)\, p$



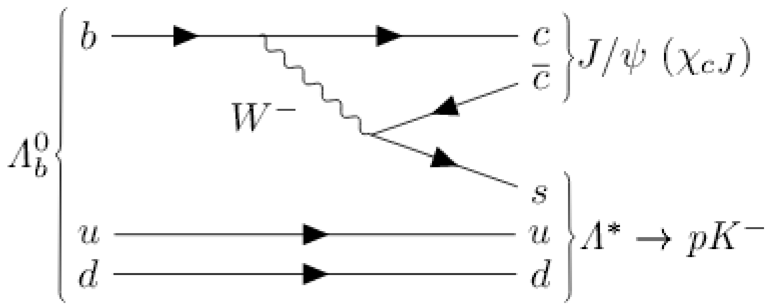
PRL 117 082003

- Fit results
  - Exotic contribution significance (either P_c^+ or Z_c^-): 3.3σ
  - P_c^+ significance assuming null Z_c^- contribution: 3.1σ
  - P_c^+ component is not significant as long as a Z_c^- component is present, and viceversa.

- Continue to study other channels in run-II

Study of $\Lambda_b^0 \to \chi_{cj} p K^-$

- $\Lambda_b^0 \to \chi_{c1} p K^-$ can test the re-scattering effect hypothesis of $P_c(4450)^+$ because it close to the $\chi_{c1} p$ threshold

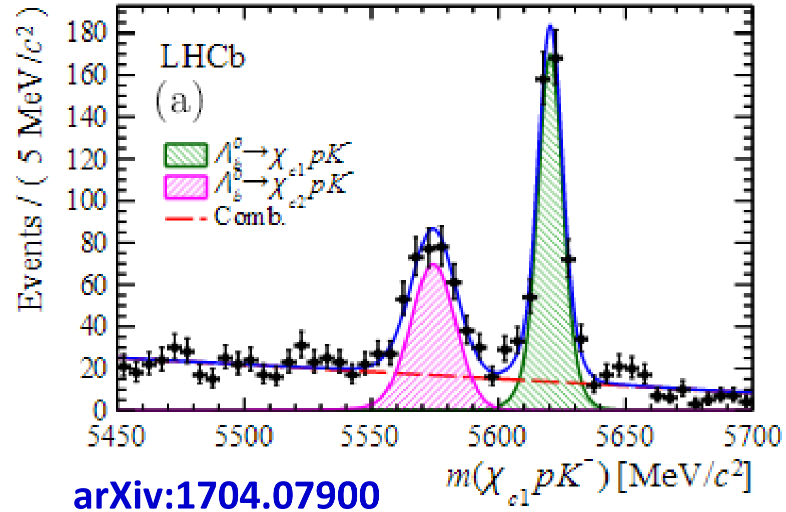


- Test the factorisation approach
  - χ_{c1} mode is suppressed relative to the χ_{c2} mode
  - The additional spectator quark in the baryon decay modify final-state interactions

Results of $\Lambda_b^0 \to \chi_{cj} p K^-$

- LHCb first observation of the decays $\Lambda_b^0 \to \chi_{c1} p K^-$ and $\Lambda_b^0 \to \chi_{c2} p K^-$ by using Run-I data
- These channels used to make a measurement of the Λ_b^0 mass

$$m(\Lambda_b^0) = 5619.44 \pm 0.28(stat) \pm 0.26(syst)\ MeV/c^2$$



arXiv:1704.07900

- Ratios of branching fractions:

$$\frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c1} p K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)} = \mathbf{0.242 \pm 0.014(stat) \pm 0.013(syst) \pm 0.009}$$

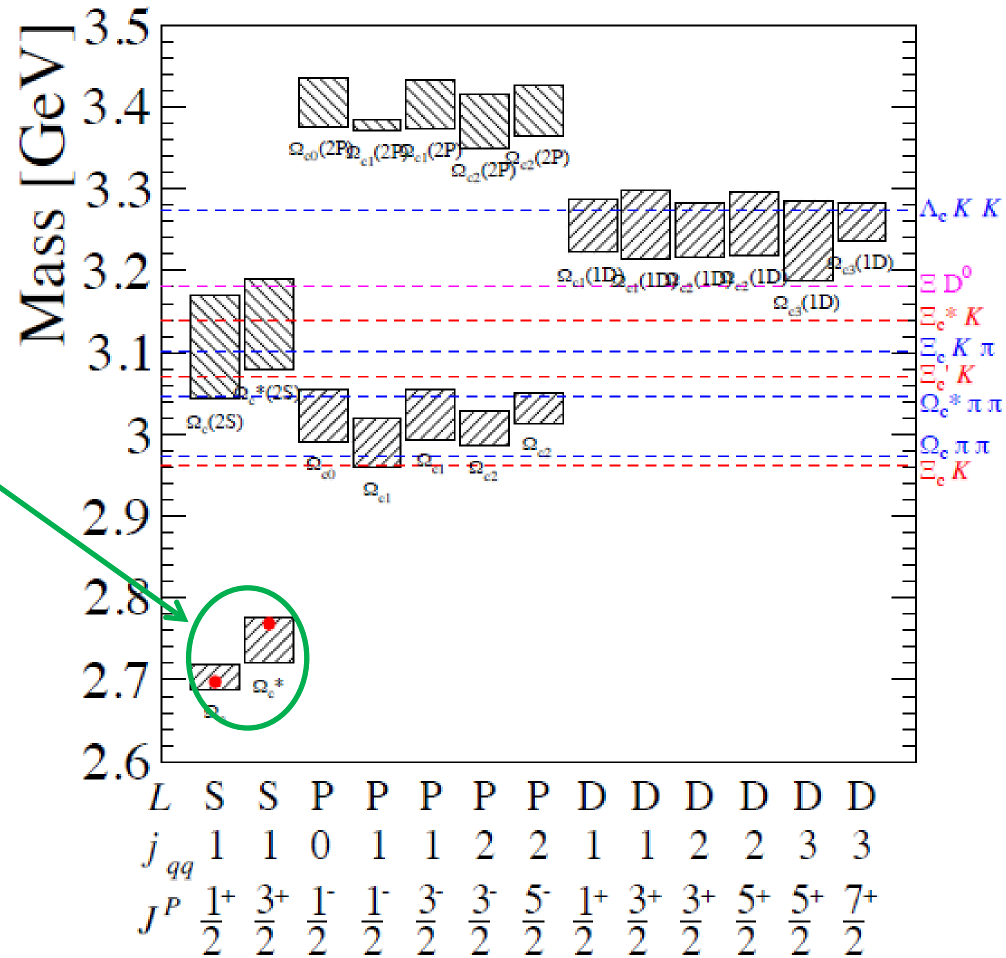
$$\frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c2} p K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)} = \mathbf{0.248 \pm 0.020(stat) \pm 0.014(syst) \pm 0.009}$$

$$\frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c2} p K^-)}{\mathcal{B}(\Lambda_b^0 \to \chi_{c1} p K^-)} = \mathbf{1.02 \pm 0.10(stat) \pm 0.02(syst) \pm 0.05}$$

- No suppression in Λ_b^0 decays, it is different to B decays

Charm baryons

- Heavy quark effective theories (HQET) prediction

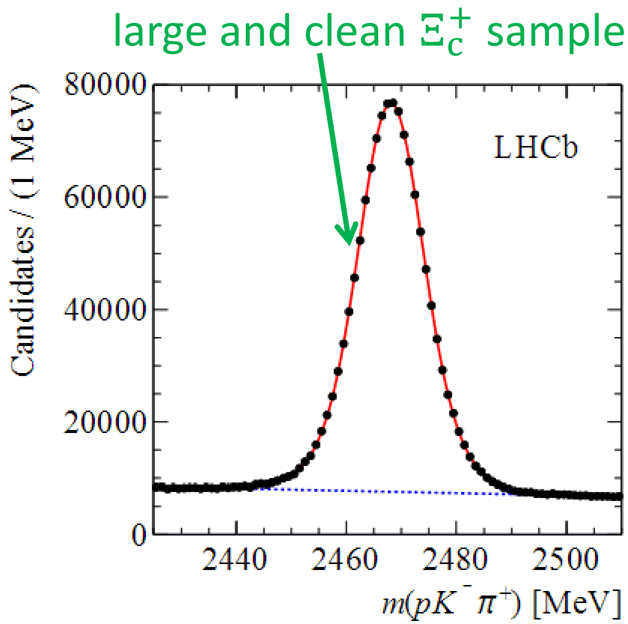


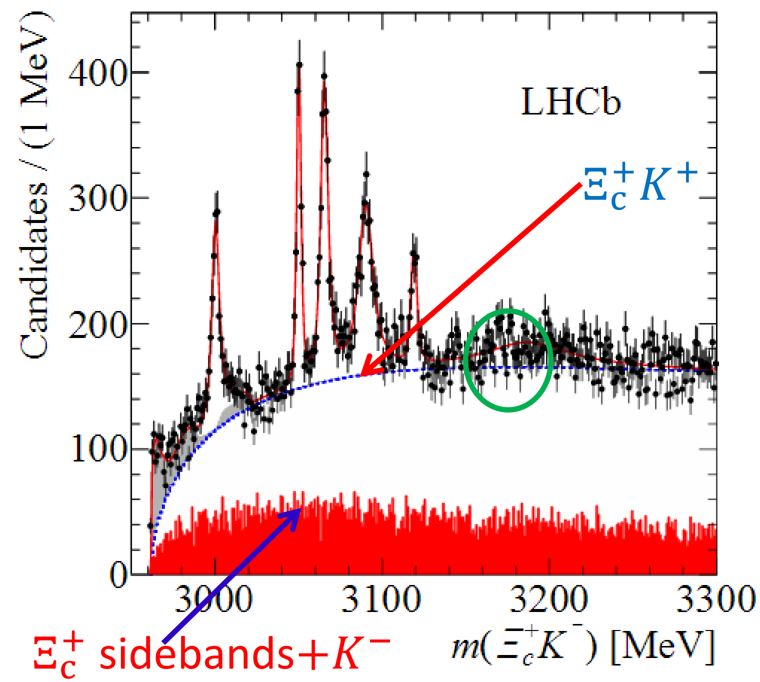
- Only the ground states
  Ω_c ($J^P = 1/2^+$) and
  Ω_c^* ($J^P = 3/2^+$) are
  known so far

- Precise measurements of the excited charm baryon properties can test HQET

Five new Ω_c states

- Study of the $\Xi_c^+ K^-$ mass spectrum $(3.3\ \mathrm{fb}^{-1})$ **PRL.118.182001**





$\Omega_c(3000)$	$\Omega_c(3050)$	$\Omega_c(3066)$	$\Omega_c(3090)$	$\Omega_c(3119)$
20.4σ	20.4σ	23.9σ	21.1σ	10.4σ

- Indicate a broad structure around 3188 MeV
- Some of them could be P-wave excited Ω_c and/or the radially excited $\Omega_c(2S)/\Omega_c^*(2S)$

Conclusion and outlook

- During the Run I, the LHCb has made several important study in hadron spectroscopy
  - Evidence for four X exotics have been seen in the $J/\psi\phi$ spectrum
  - The X(5568) tetraquark unconfirmed at the LHC
  - The original pentaquark discovery has been confirmed
  - $\Lambda_{\mathrm{b}}^{0} \rightarrow \chi_{cj} p K^{-}$will be useful for pentaquark studies in the future
  - New Ω_{c} states play an important role in test of HQET

- Further detailed studies of these states are expected with Run-II data

Thank you!

Back up

Theoretical references of $X(4140)$

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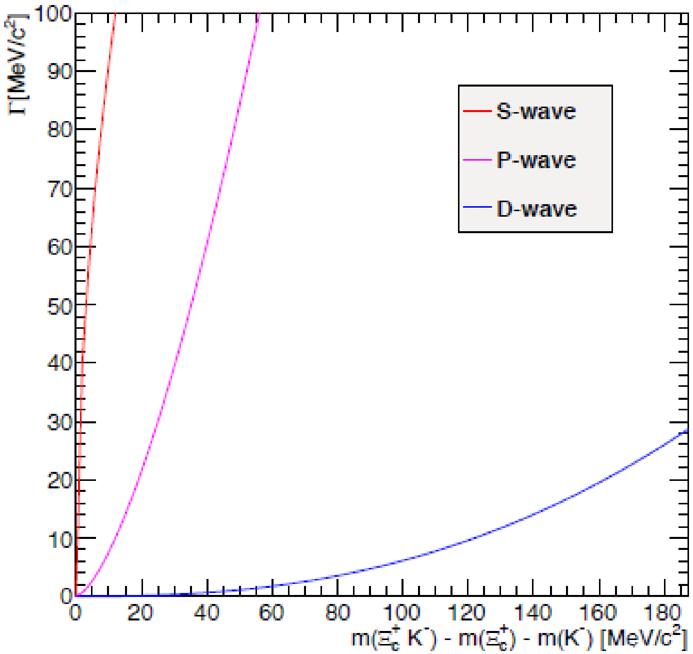
Results of the fit to $\Xi_c^+ K^-$

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

What are new Ω_c states ?

We have already seen the mass predictions but what about the widths?



$$S\text{-wave}: \quad \Gamma \sim 100\,\mathrm{MeV} \times \left[\frac{E_K - m_K}{10\,\mathrm{MeV}}\right]^{1/2},$$

$$P\text{-wave}: \quad \Gamma \sim 10\,\mathrm{MeV} \times \left[\frac{E_K - m_K}{10\,\mathrm{MeV}}\right]^{3/2},$$

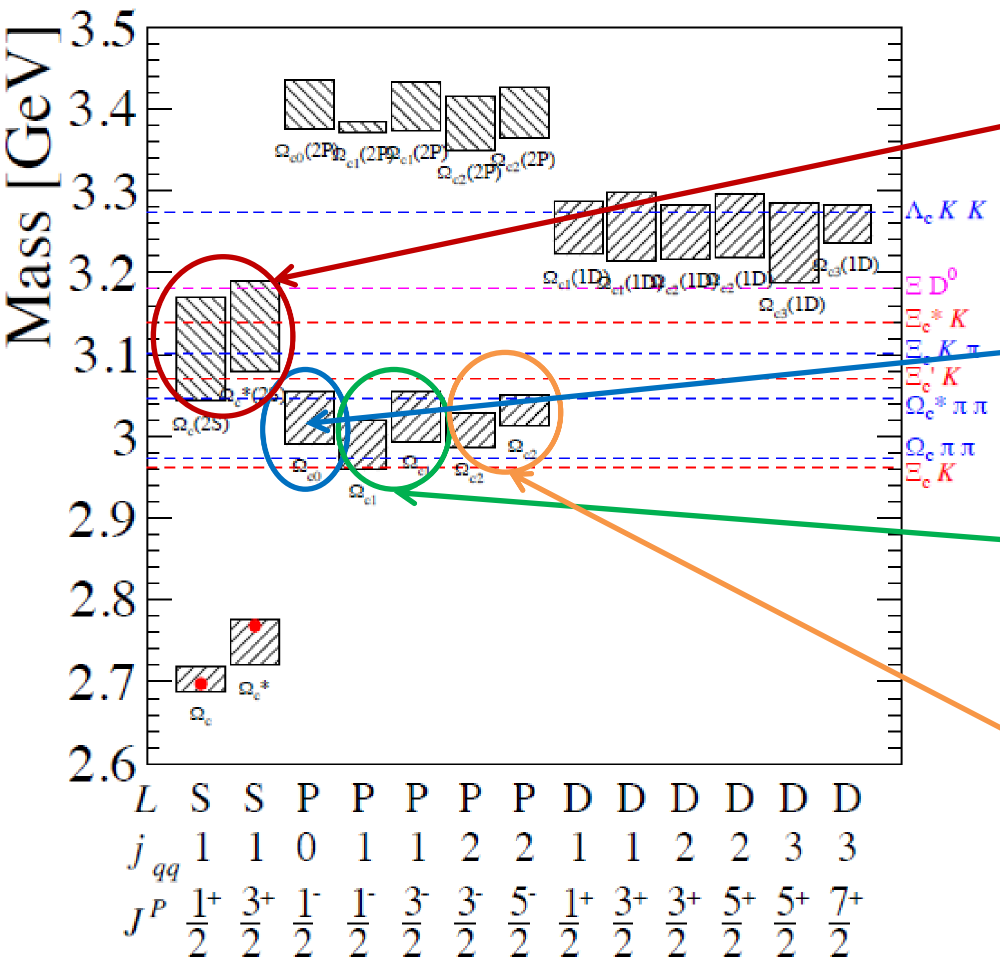
$$D\text{-wave}: \quad \Gamma \sim 10\,\mathrm{MeV} \times \left[\frac{E_K - m_K}{100\,\mathrm{MeV}}\right]^{5/2}.$$

[G. Chiladze, A. Falk arXiv: 9707507

D-wave transitions should return narrow states

P-wave transitions may return narrow states

What are new Ω_c states ?



$\Omega_c(2S)$ and $\Omega_c^*(2S)$ can decay to $\Xi_c^+ K^-$ by P-wave→broad

Ω_{c0} can decay to $\Xi_c^+ K^-$ by S-wave→broad

Ω_{c1}'s can't decay to $\Xi_c^+ K^-$

Ω_{c2}'s can decay to $\Xi_c^+ K^-$ by D-wave→narrow