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Heavy flavour spectroscopy at LHCb

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on behalf of the LHCb collaboration

Tsinghua University

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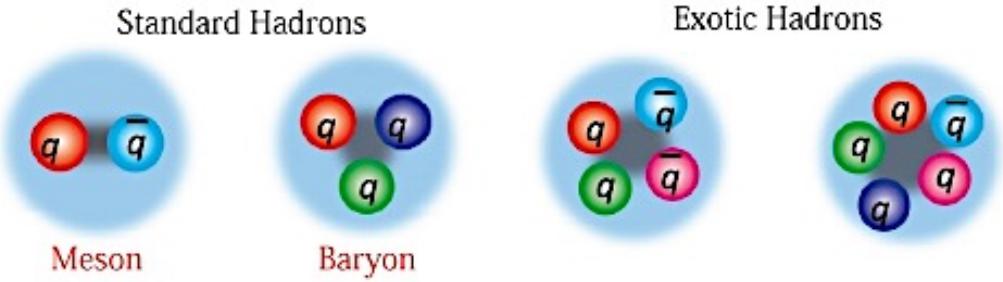
Outline

- Introduction
- Exotic hadrons (selected results)
  - Pentaquarks
  - Tetraquarks
- Conventional hadrons (selected results)
  - Five new narrow Ω_c^0 states
  - Doubly charmed baryon Ξ_{cc}^{++}
- Summary and outlook

Heavy flavour spectroscopy

- Spectroscopy benefits better understanding of QCD
  - Test phenomenological models and lattice QCD methods
  - Heavy hadrons (containing b or c quarks) of great interest
- LHCb experiment: a unique and important lab. in the study of spectroscopy for both conventional and exotic hadrons
  - $X(3872), Z(4430), P_c(4380)^+, P_c(4450)^+$ ...
  - B^{**}, Ξ_b', Ξ_b^* ...



LHCb detector

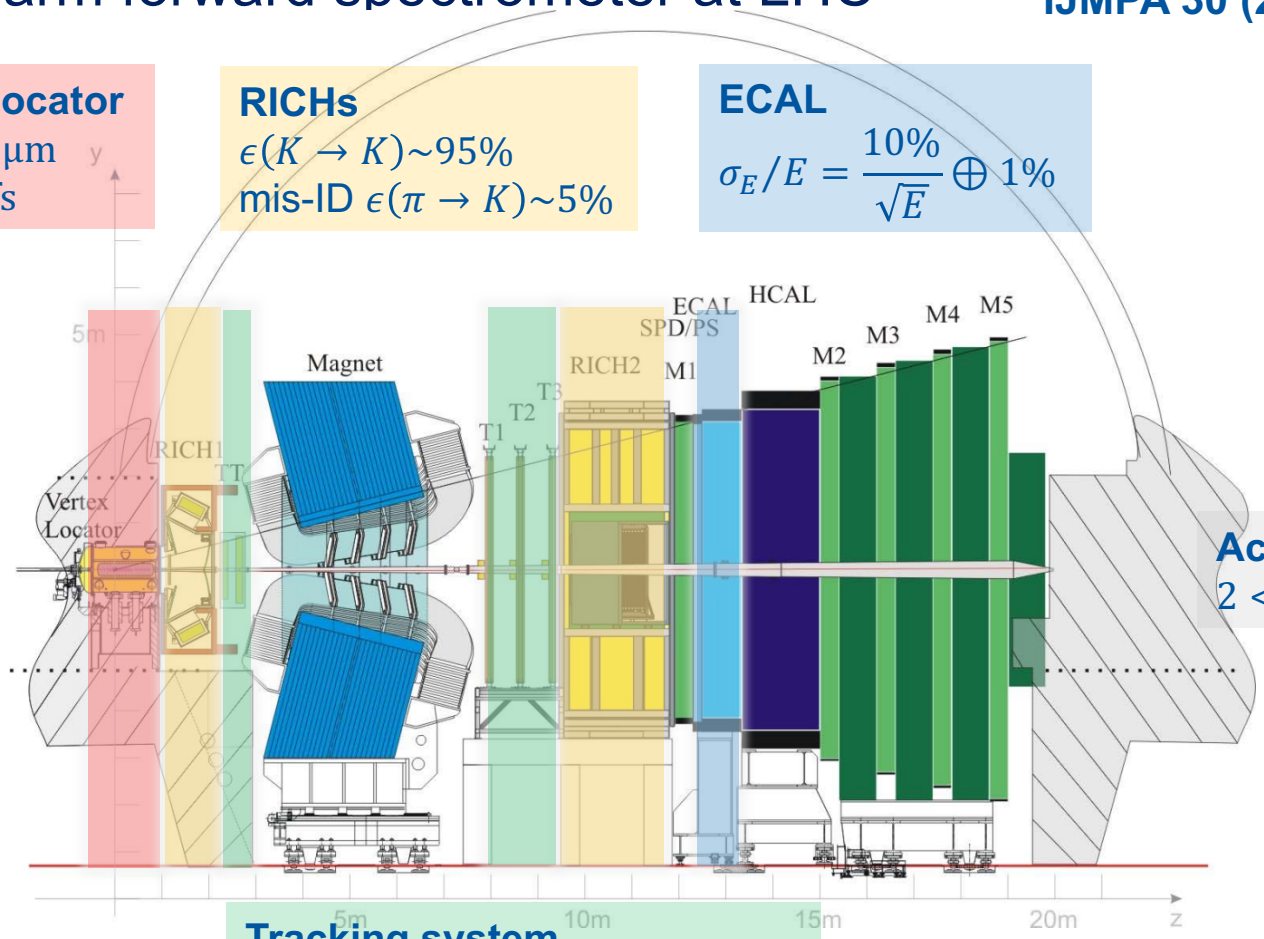
- A single-arm forward spectrometer at LHC

JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022

Vertex Locator
$\sigma_{\mathrm{IP}} = 20\ \mu\mathrm{m}$
$\sigma_\tau = 45$ fs

RICHs
$\epsilon(K \to K) \sim 95\%$
mis-ID $\epsilon(\pi \to K) \sim 5\%$

ECAL
$\sigma_E/E = \frac{10\%}{\sqrt{E}} \oplus 1\%$



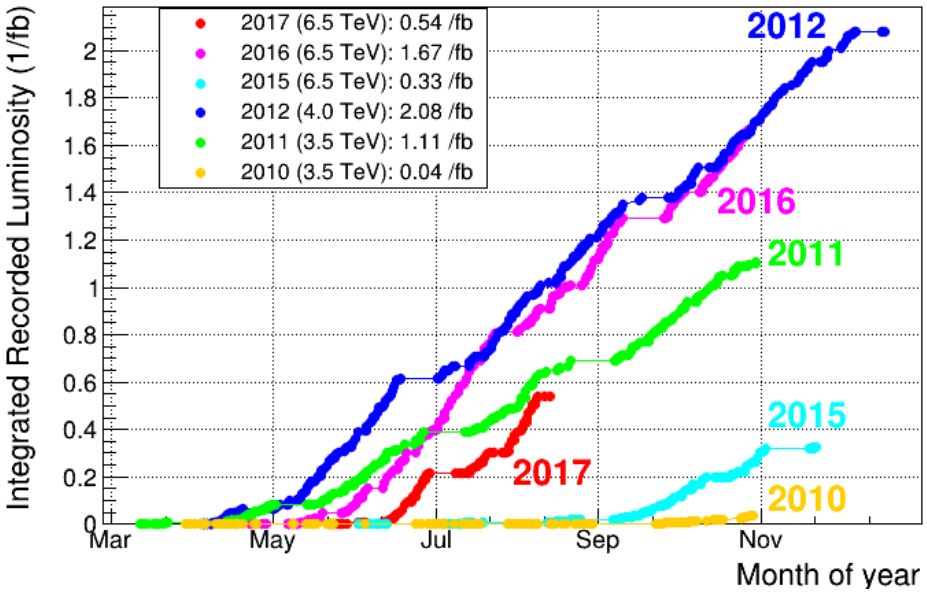
Acceptance
$2 < \eta < 5$

Tracking system
$\epsilon_{\mathrm{tracking}} \sim 96\%$
$\sigma_p/p \sim 0.5\% - 1\%(5 - 200\ \mathrm{GeV})$

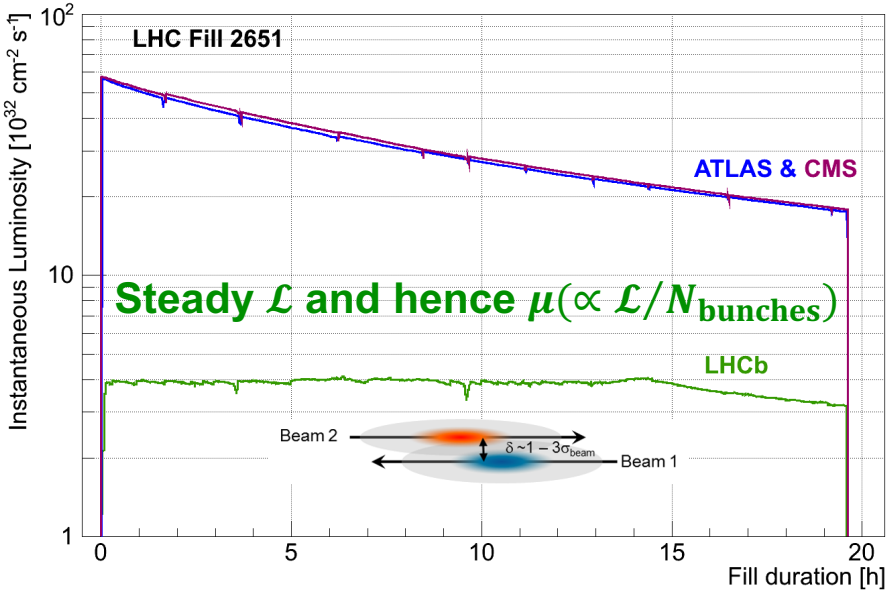
Data acquisition at LHCb

- Run1: $1.1\ \mathrm{fb}^{-1}$ @ $7\ \mathrm{TeV}(2011)$, $2.1\mathrm{fb}^{-1}$ @ $8\ \mathrm{TeV}(2012)$
- Run2: $0.3\ \mathrm{fb}^{-1}$ @ $13\ \mathrm{TeV}(2015)$, $1.7\ \mathrm{fb}^{-1}$ @ $13\ \mathrm{TeV}(2016)$

LHCb integrated luminosity in pp



Development of the instantaneous luminosity

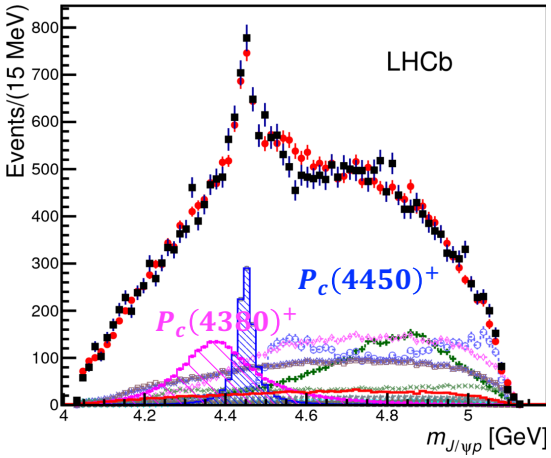


Exotic hadrons

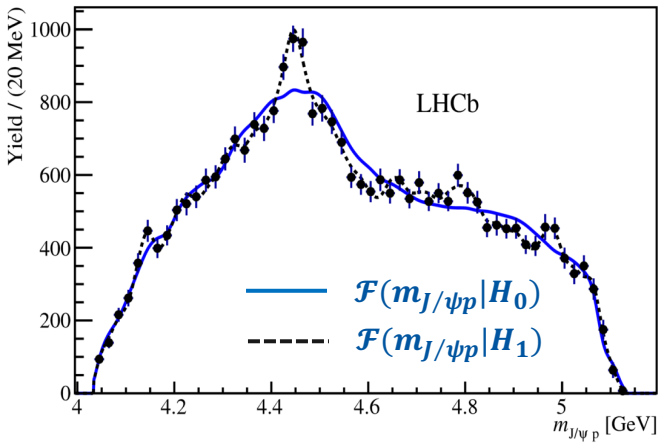
Pentaquarks at LHCb

- $P_c(4380)^+$ and $P_c(4450)^+$ observed in $\Lambda_b^0 \to J/\psi p K^-$ decays with 6-d amplitude analysis, and confirmed by model-independent analysis
- Evidence (3.1σ) of the two pentaquarks candidates in $\Lambda_b^0 \to J/\psi p \pi^-$

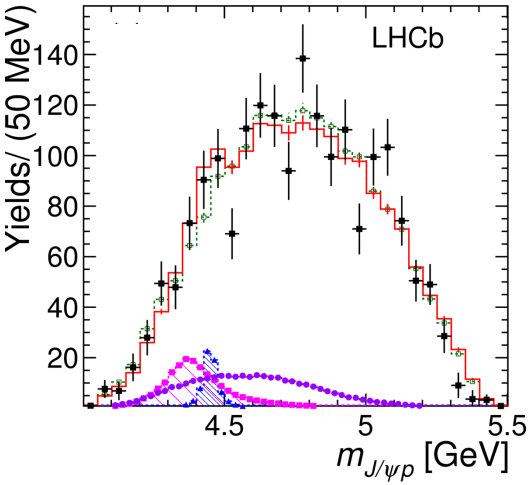
PRL115 (2015) 072001



PRL 117 (2016) 082002



PRL 117 (2016) 082003

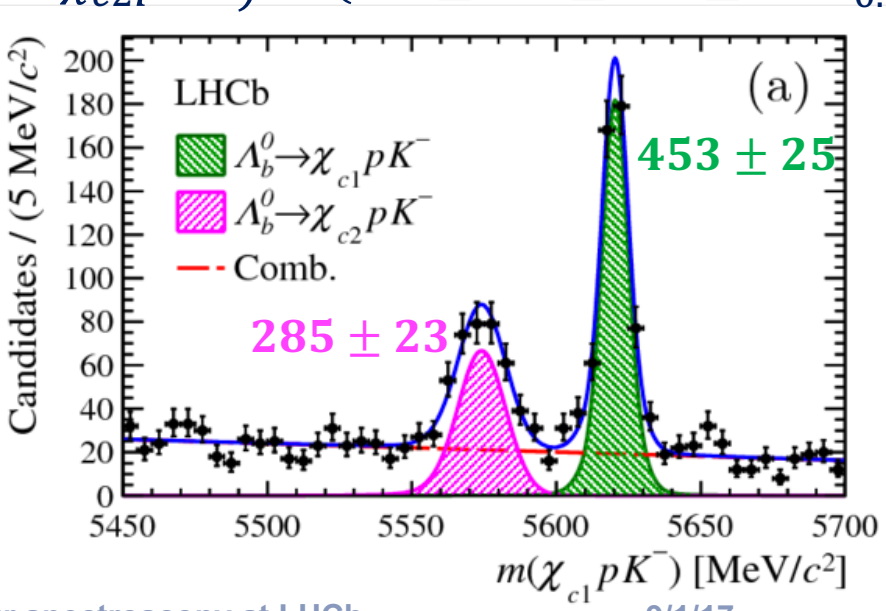


- Other channels
  - Observation of $\Xi_b^- \to J/\psi \Lambda K^-$: pentaquarks with open strangeness
  - Observation of $\Lambda_b^0 \to \chi_{c1,2} p K^-$ (in details)

PLB 772 (2017) 265-273

Observation of $\Lambda_b^0 \to \chi_{c1,2} p K^-$

- $P_c(4450)^+$ near the $\chi_{c1} p$ threshold **PRL 119 062001 (2017)**
  - Test phenomenological models of pentaquarks
- Data sample: 3.0 fb^{-1} pp collision data at 7 and 8 TeV
- Search for $\Lambda_b^0 \to \chi_{cJ} p K^-$, where χ_{cJ} reconstructed with $J/\psi\gamma$
  - $m(J/\psi\gamma)$ is constrained to $m_{\chi_{c1}}$
- $\mathcal{B}\left(\Lambda_b^0 \to \chi_{c1} p K^-\right) = (7.3 \pm 0.4 \pm 0.4 \pm 0.6^{+1.0}_{-0.6}) \times 10^{-5}$
- $\mathcal{B}\left(\Lambda_b^0 \to \chi_{c2} p K^-\right) = (7.5 \pm 0.4 \pm 0.4 \pm 0.6^{+1.0}_{-0.6}) \times 10^{-5}$

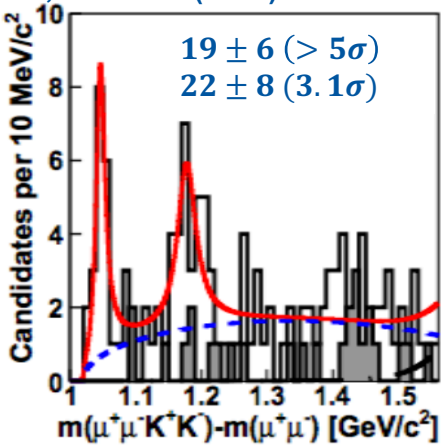


Useful for future investigation of the two observed pentaquark candidates: $P_c(4380)^+$ and $P_c(4450)^+$

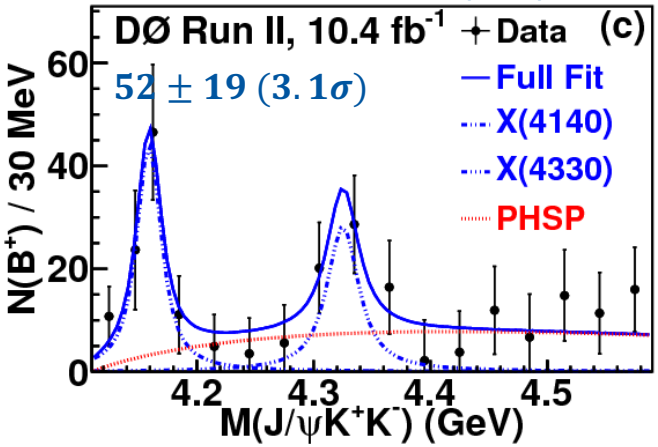
Confusing $J/\psi\phi$ structures in $B^+ \to J/\psi\phi K^-$

- Evidence or observations of $X(4140)$ from CDF, D0 and CMS

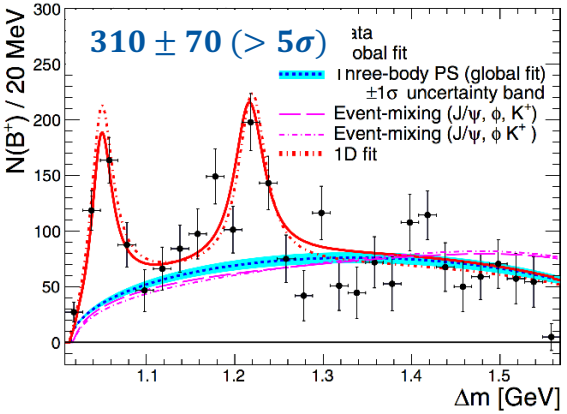
CDF, MPL A32 (2017) no.26 1750139



D0, PRD89 (2014) 012004



CMS, PLB734 (2014) 261



	Mass [MeV]	Width [MeV]
CDF	$4143.4^{+2.9}_{-3.0} \pm 0.6$	$15.3^{+10.4}_{-6.1} \pm 2.5$
D0	$4159.0 \pm 4.3 \pm 6.6$	$19.9 \pm 12.6^{+3.0}_{-8.1}$
CMS	$4148.0 \pm 2.4 \pm 6.3$	$28^{+15}_{-11} \pm 19$

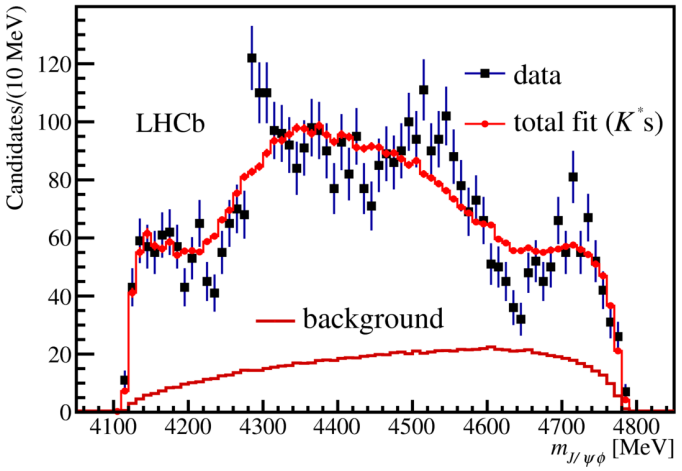
Narrow peaks with large uncertainties

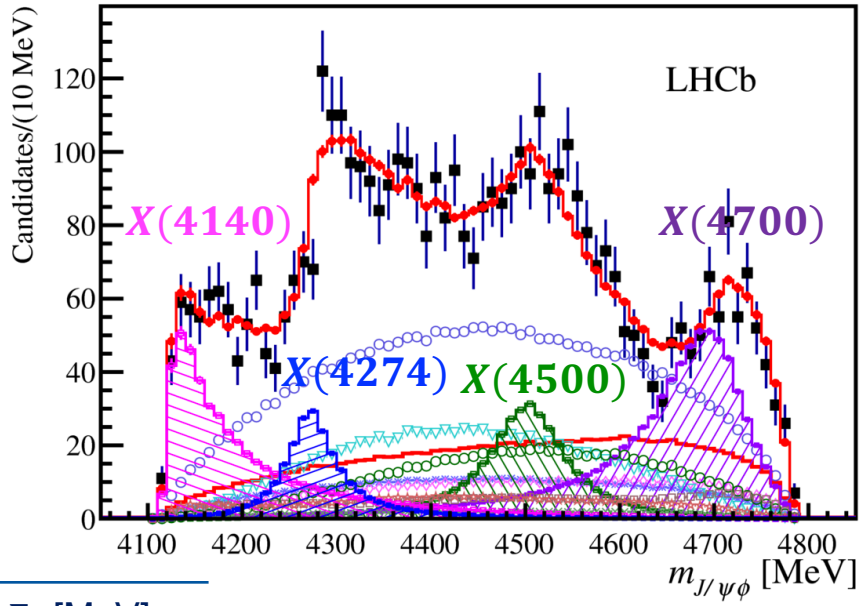
- Negative results from Belle, LHCb ($0.37\ \text{fb}^{-1}$) and BABAR
- No amplitude analysis conducted in the above results

Observation of $J/\psi\phi$ structures

- Data sample: $3.0\ \mathrm{fb}^{-1}$ pp collision data at 7 and 8 TeV
- First full amplitude analysis of $B^+ \to J/\psi\phi K^-$
- Kaon excitations alone insufficient to describe data
- Four resonant X states needed

PRL118 (2017) 022003
PRD 95 (2017) 012002





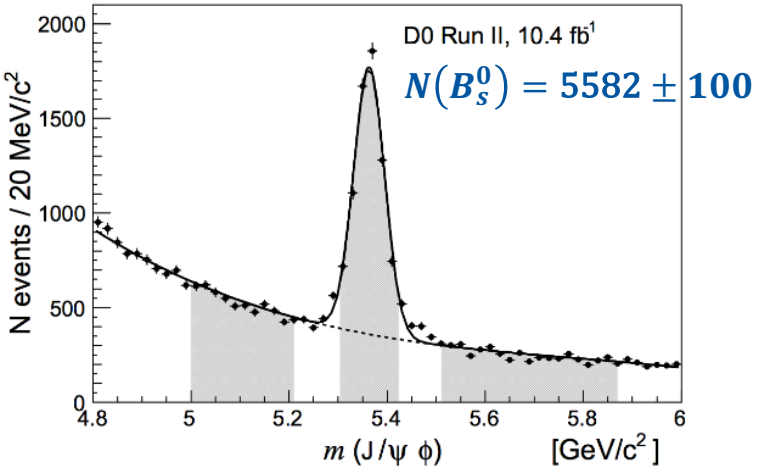
	Signif.	M_0 [MeV]	Γ_0 [MeV]
$X(4140)$	8.4σ	$4146.5 \pm 4.5^{+4.6}_{-2.8}$	$83 \pm 21^{+21}_{-14}$
$X(4274)$	6.0σ	$4273.3 \pm 8.3^{+17.2}_{-3.6}$	$56 \pm 11^{+8}_{-11}$
$X(4500)$	6.1σ	$4506 \pm 11^{+12}_{-15}$	$92 \pm 21^{+21}_{-20}$
$X(4700)$	5.6σ	$4704 \pm 10^{+14}_{-24}$	$120 \pm 31^{+42}_{-33}$

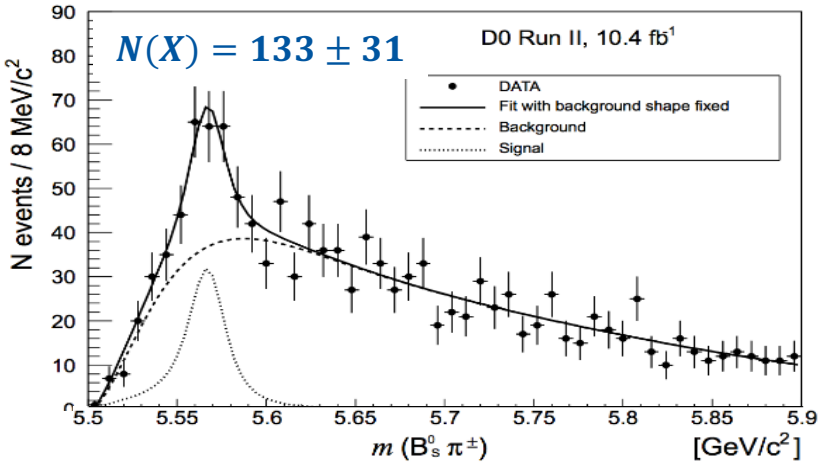
- **Width much larger**
- **Larger data samples required to resolve this issue**

$X(5568)$ reported by D0

- D0 reports a narrow structure at 5568 MeV in $B_s^0\pi^\pm$ spectrum with $B_s^0 \to J/\psi\phi$, using 10.4 fb^{-1} $p\bar{p}$ collision data

D0, PRL 117 022003 (2016)





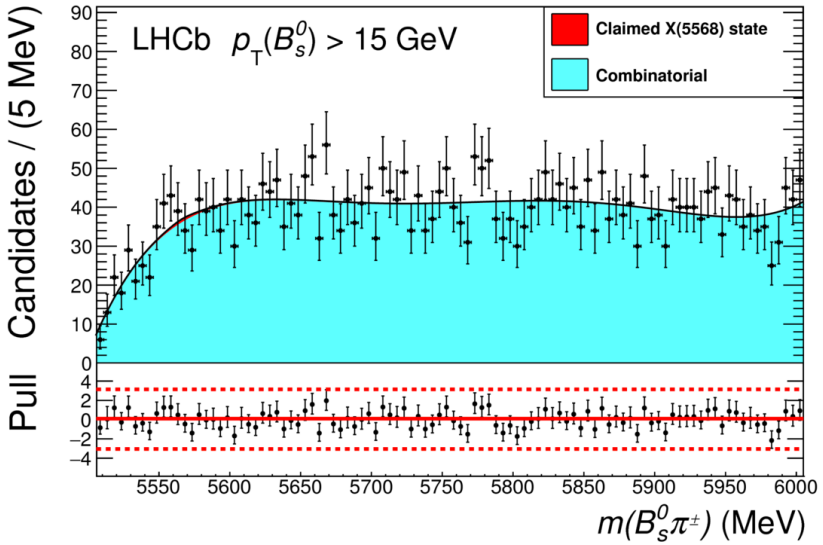
- Significance: local 4.8σ and global 3.9σ
- $M_X = 5567.8 \pm 2.9^{+0.9}_{-1.9}$ MeV
- $\Gamma_X = 21.9 \pm 6.4^{+5.0}_{-2.5}$ MeV
- $\rho^{\mathrm{D0}} = (8.6 \pm 1.9 \pm 1.4)\%$
- Significance varies a lot with or w/o the cone cut $\sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.3$

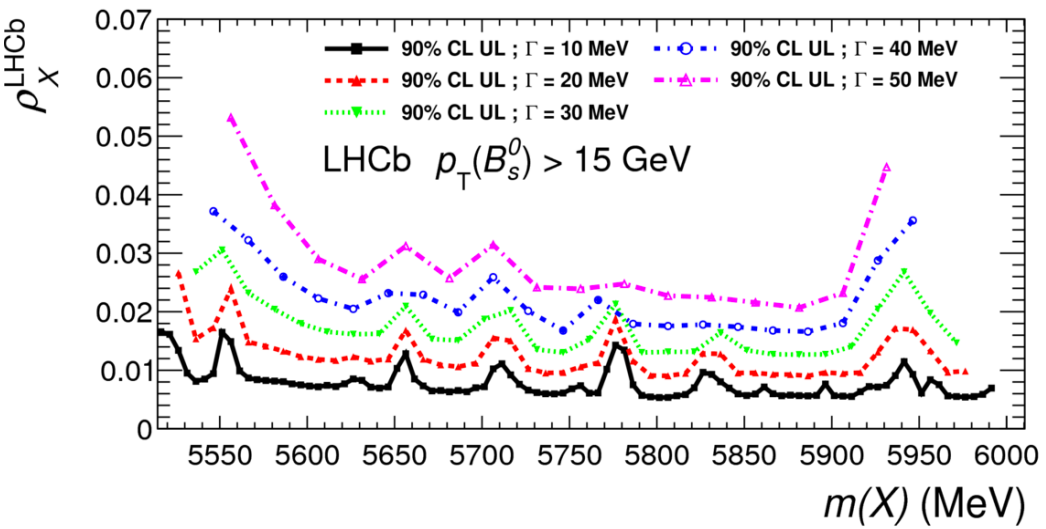
- D0 also reports consistent results in $B_s^0\pi^\pm$ spectrum with $B_s^0 \to \mu^+ D_s^- X$

$X(5568)$ search at LHCb

- LHCb searches with 105,800 B_s^0 combined with $\pi^{\pm}$
  - No signal is observed with 19 times more B_s^0 than D0
  - Upper limits on ρ^{LHCb} set as function of mass corresponding to different width hypothesis
  - $\rho^{\mathrm{LHCb}}[p_{\mathrm{T}}(B_s^0) > 15\ \mathrm{GeV}] < 0.02\ @\ 95\%\ \mathrm{C.L.}$

PRL 117 (2016) 152003

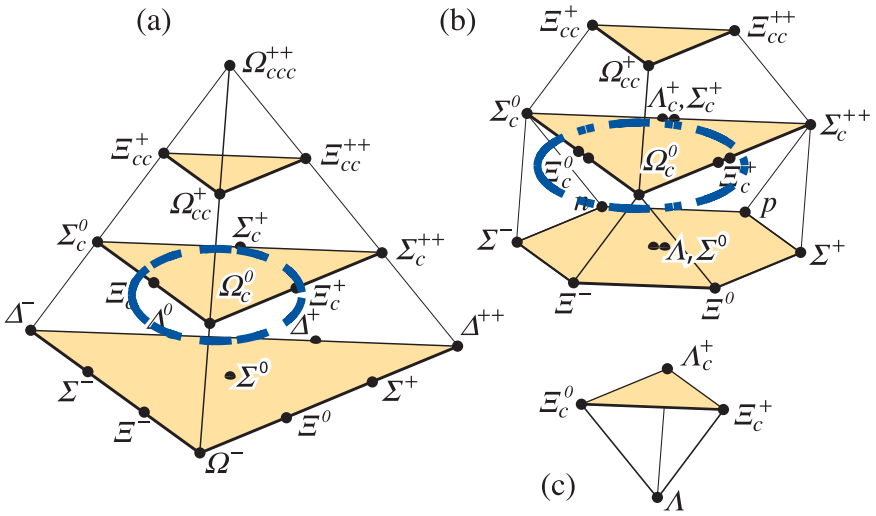




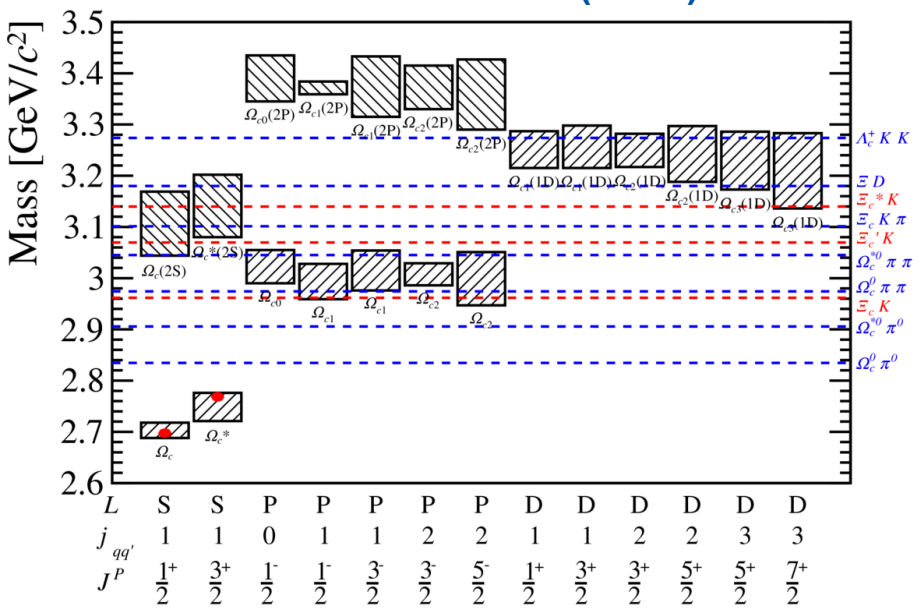
Conventional hadrons

Ω_c^0 baryons

- Limited knowledge of charmed baryons
- No excited Ω_c^0 states were observed before LHCb
- Mass of resonances above the $\Xi_c K$ threshold 2.96 GeV



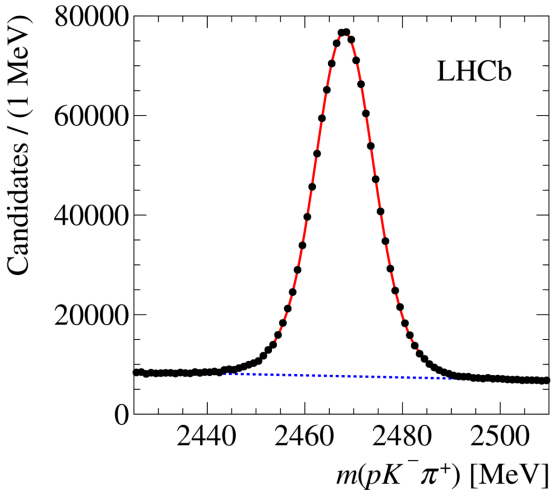
PRL118 (2017) 182001

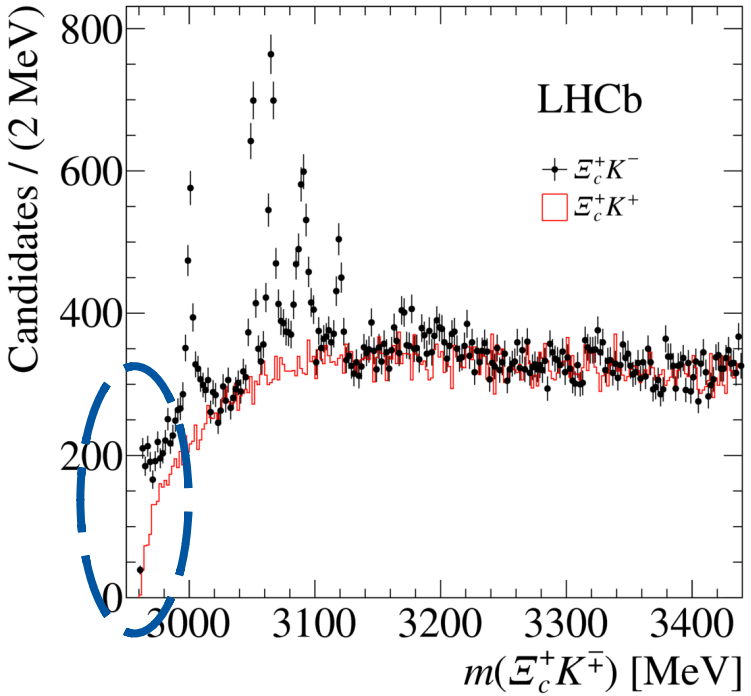


Five new narrow Ω_c^0 states decaying to $\Xi_c^+ K^-$

- Data sample: $3.3\ \mathrm{fb}^{-1}$ pp collision data at 7, 8 and 13 TeV
- Ξ_c^+ combined with a K^- from primary vertex
  - Ξ_c^+ reconstructed with $pK^-\pi^+$
  - Ξ_c^+ also combined with K^+ to form wrong-sign(WS) candidates
- Five narrow structures observed
  - No peak in WS sample
  - Steep rise near the threshold

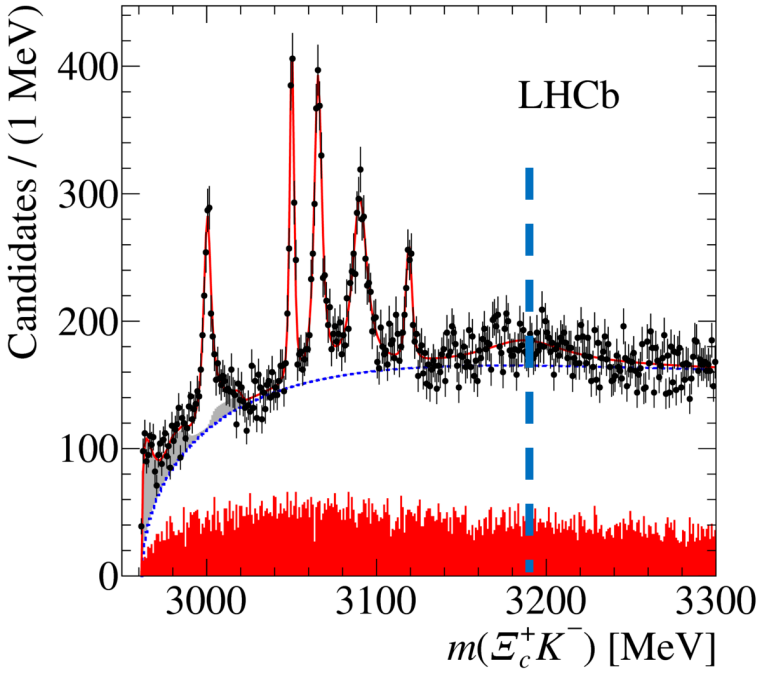
PRL118 (2017) 182001





Five new narrow Ω_c^0 states decaying to $\Xi_c^+ K^-$

- A binned χ^2 fit to $m(\Xi_c^+ K^-)$ spectrum
  - Signal: relativistic Breit-Wigner functions convolved with experimental resolution
  - Background: empirical function from WS sample
  - Feed-down contributions $\Omega_c(X)^0 \to K^- \Xi_c'^+$, $\Xi_c'^+ \to \Xi_c^+ \gamma$



PRL118 (2017) 182001

Resonance	Mass (MeV)	Γ (MeV)
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$
		< 1.2 MeV, 95% CL
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$
		< 2.6 MeV, 95% CL
$\Omega_c(3188)^0$	$3188 \pm 5 \pm 13$	$60 \pm 15 \pm 11$
$\Omega_c(3066)^0_{\rm fd}$		
$\Omega_c(3090)^0_{\rm fd}$		
$\Omega_c(3119)^0_{\rm fd}$		

Fit improves by including a broad structure in the 3188 MeV mass region

Five new narrow Ω_c^0 states decaying to $\Xi_c^+ K^-$

- Quantum numbers to be determined through
  - Possible three-body decays or decays of heavy baryons

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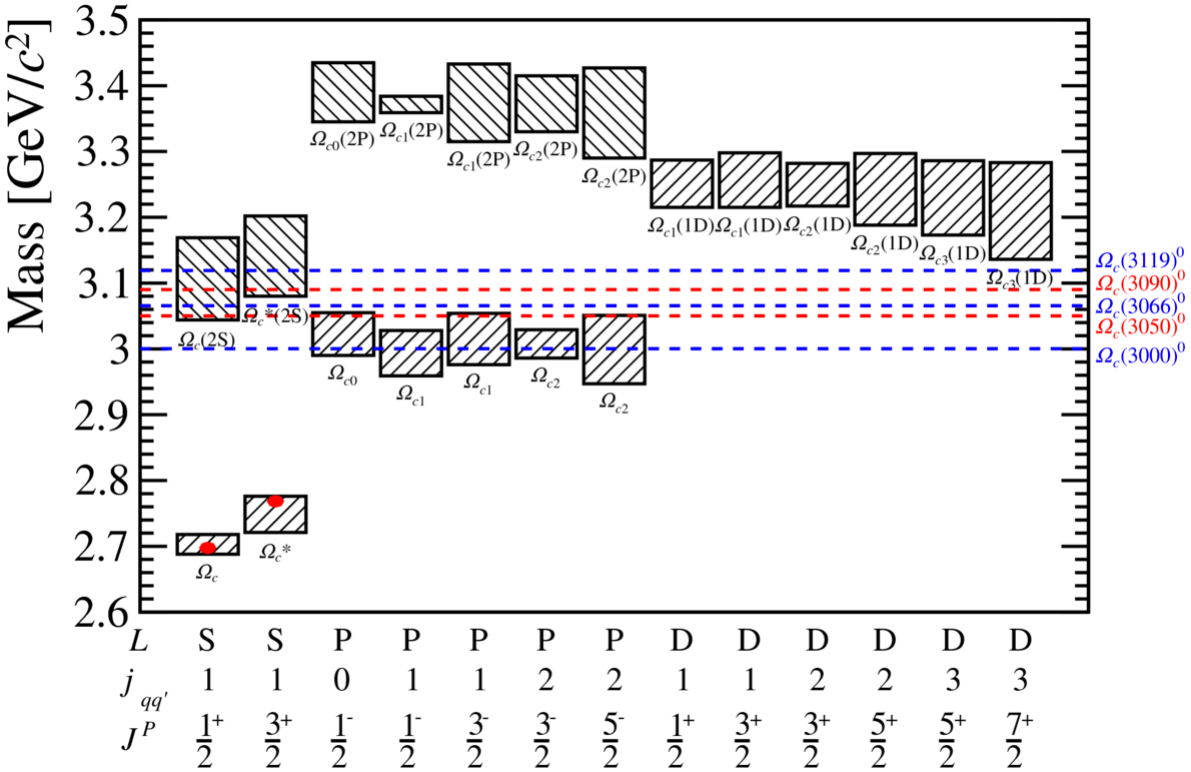
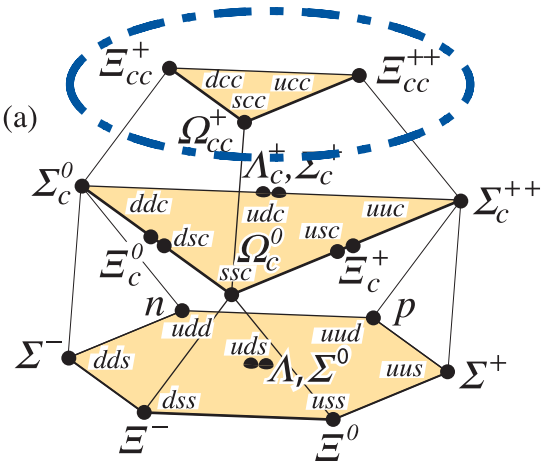
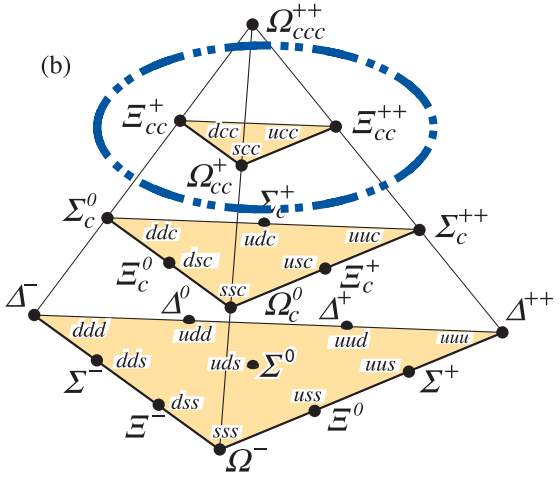


The doubly charmed baryons

- Two SU(4) 20-plets containing SU(3) triplets
  - $\Xi_{cc}^{+}(ccd)$, $\Xi_{cc}^{++}(ccu)$, $\Omega_{cc}^{+}(ccs)$

$J^P = \frac{1}{2}^+$





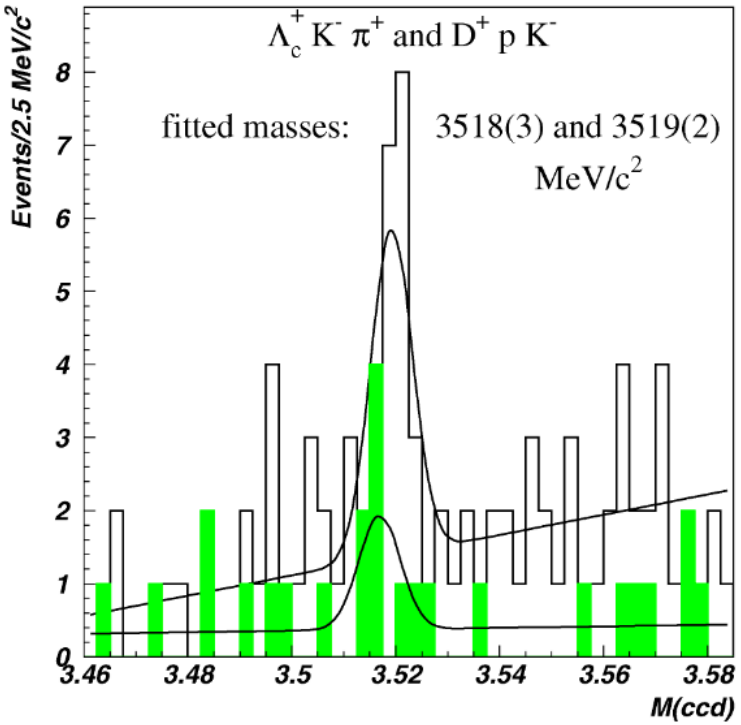
$J^P = \frac{3}{2}^+$

- Mass predictions (see backup for ref.)
  - $m_{\Xi_{cc}^+} \simeq m_{\Xi_{cc}^{++}} \approx 3600 \pm 100\ \mathrm{MeV}/c^2$
  - Mass difference only a few MeV/c^2
- Lifetime predictions (see backup for ref.)
  - $\tau_{\Xi_{cc}^{++}}(\sim 200 - 700\ \mathrm{fs}) > \tau_{\Xi_{cc}^{+}}(\sim 50 - 250\ \mathrm{fs})$

Previous experimental searches for Ξ_{cc}

- SELEX experiment observed 15.9 and 5.6 Ξ_{cc}^{+} candidates in $\Lambda_c^+ K^- \pi^+$ and pD^+K^- spectrum, respectively
  - Combined mass: 3518.7 ± 1.7 MeV
  - $\tau(\Xi_{cc}^{+}) < 33$ fs @ 90% C. L.
  - $R \equiv \frac{\sigma(\Xi_{cc}^{+}) \times \mathcal{B}(\Xi_{cc}^{+} \to \Lambda_c^+ K^- \pi^+)}{\sigma(\Lambda_c^+)} \sim 20\%$
- Negative results from FOCUS, BaBar, Belle and LHCb (0.65 fb^{-1}) experiments in different production environments

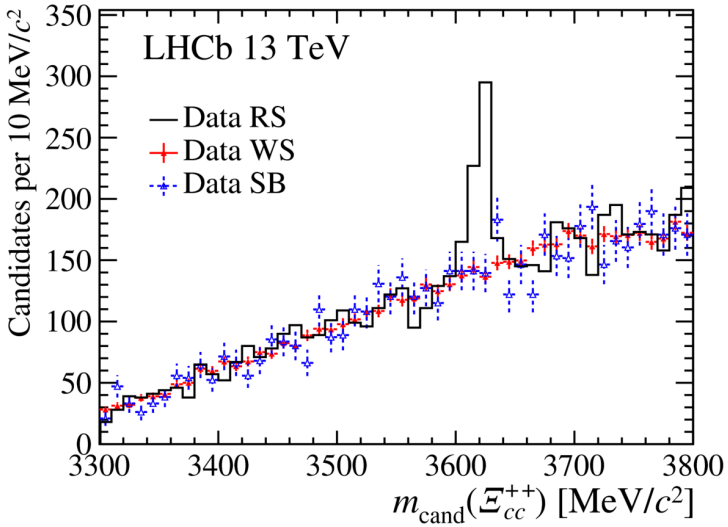
SELEX, PLB 628 (2005) 18

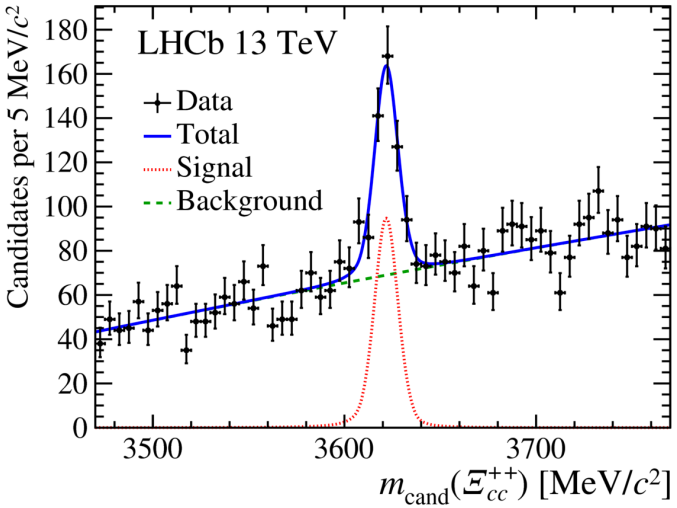


Observation of doubly charmed baryon Ξ_{cc}^{++}

- Data sample: $1.7\ \text{fb}^{-1}$ @ $\sqrt{s} = 13\ \text{TeV}$ (2016)
- $\Xi_{cc}^{++} \to \Lambda_c^+(\to pK^-\pi^+)K^-\pi^+\pi^+$
  - Multivariate selector
- Invariant mass spectrum
  - Significant structure at ~ 3620 MeV
  - No peak in wrong-sign and Λ_c^+ sideband samples
  - Confirmed in independent data sample

arXiv: 1707.01621

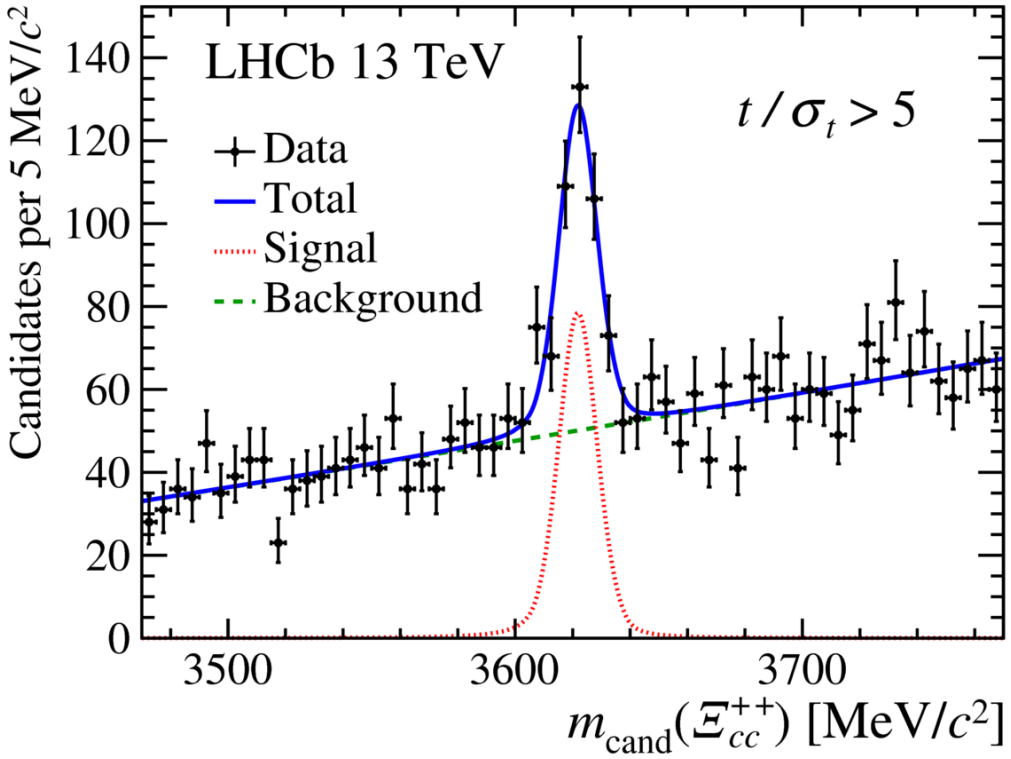




- Unbinned maximum-likelihood fit
- Yield: 313 ± 33
- Local significance $> 12\sigma$
- Resolution: $6.6 \pm 0.8\ \text{MeV}/c^2$
- $m(\Xi_{cc}^{++}) = 3621.40$
  $\pm 0.72(\text{stat.})$
  $\pm 0.27(\text{syst.})$
  $\pm 0.14(\Lambda_c^+)\ \text{MeV}/c^2$

Observation of doubly charmed baryon Ξ_{cc}^{++}

- Weakly decay signal
  - With minimum decay time requirement, the structure remains highly significant ($> 12\sigma$)



Observation of doubly charmed baryon Ξ_{cc}^{++}

- Comparison with SELEX experiment
  - $m(\Xi_{cc}^{++})_{\mathrm{LHCb}} - m(\Xi_{cc}^{+})_{\mathrm{SELEX}} = 103 \pm 2\ \mathrm{MeV}$
  - Inconsistent with being isospin partners
- Further studies
  - Searches in additional decay modes
  - Lifetime and production cross-section measurement
  - Search for isospin partner Ξ_{cc}^{+}

Summary and outlook

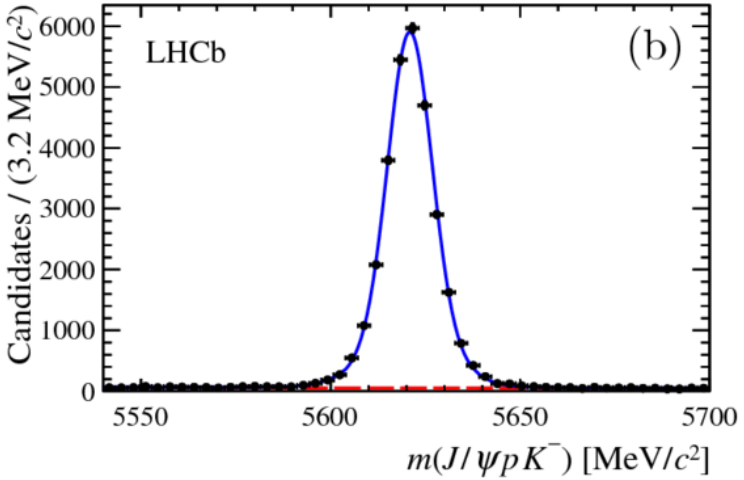
- LHCb has fruitful results in heavy flavour spectroscopy (unexhausted)
  - Observation of $\Lambda_b^0 \to \chi_{c1,2} p K^-$
  - Observation of $J/\psi\phi$ structures
  - Unconfirmed $X(5568)$
  - Observation of five new narrow Ω_c^0 states
  - Observation of doubly charmed baryon Ξ_{cc}^{++}
- More analyses with Run2 data ongoing
  - Stay tuned for the upcoming results

Thanks for your attention!

Backup

Observation of $\Lambda_b^0 \to \chi_{c1,2} p K^-$

- $\Lambda_b^0 \to J/\psi p K^-$ invariant mass distribution



PRL 119 062001 (2017)

- Relative branching fraction
  - $R_1 = 0.242 \pm 0.014 \pm 0.013 \pm 0.009$
  - $R_2 = 0.248 \pm 0.020 \pm 0.014 \pm 0.009$
  - where the uncertainties are statistical, systematic and due to uncertainty of $\chi_{c1,2} \to J/\psi\gamma$ branching fractions
- Absolute branching fractions can be acquired with
  - $\mathcal{B}\left(\Lambda_b^0 \to J/\psi p K^-\right)/\mathcal{B}(B^0 \to J/\psi K^*(892)^0)$
  - $\mathcal{B}(B^0 \to J/\psi K^*(892)^0)$

Observation of $J/\psi\phi$ structures

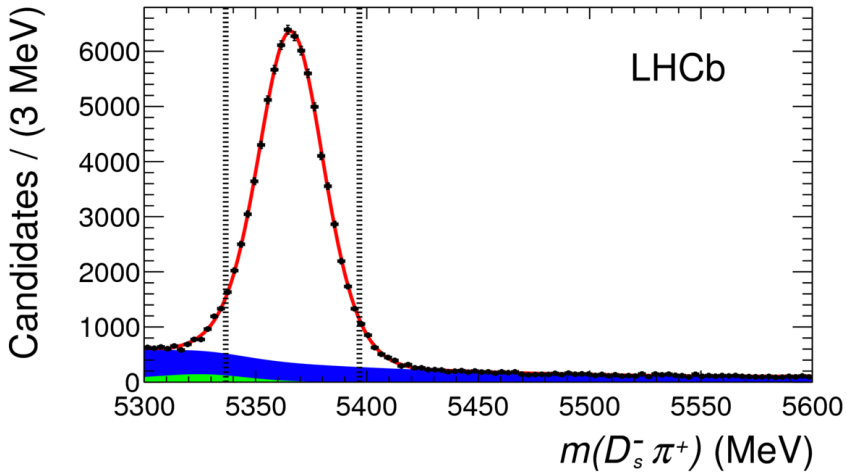
- Parameterization
  - $m_{J/\psi\phi}, \theta_X, \theta^X_{J/\psi}, \theta^X_\phi, \Delta\phi_{X,J/\psi}, \Delta\phi_{X,\phi}$
  - where θ denotes helicity angles and $\Delta\phi$ angles between decay planes
- Spin-parity

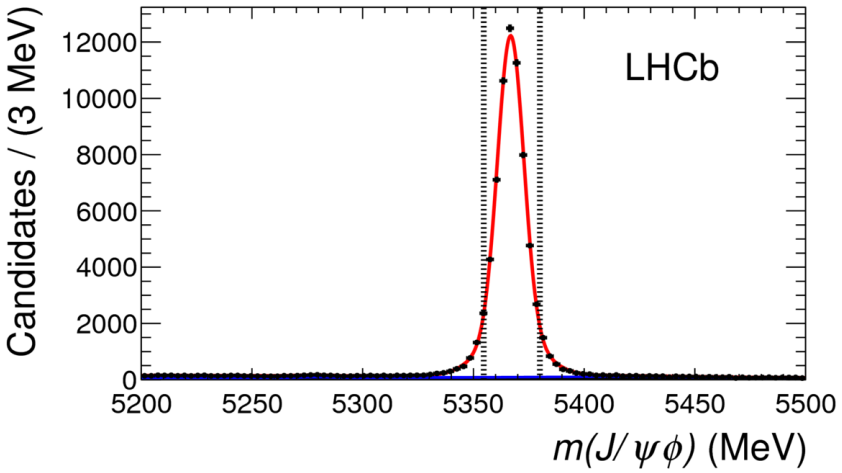
	J^{PC}	Signif. of J^{PC} assignments
$X(4140)$	1^{++}	5.7σ
$X(4274)$	1^{++}	5.8σ
$X(4500)$	0^{++}	4.0σ
$X(4700)$	0^{++}	4.5σ

$X(5568)$ search at LHCb

- $B_s^0 \to D_s^- \pi^+$ and $B_s^0 \to J/\psi\phi$ decays

PRL 117 (2016) 152003





- $\rho^{\mathrm{LHCb}}[p_{\mathrm{T}}(B_s^0) > 15\ \mathrm{GeV}] < 0.020$ @ 95% C. L.

  $\rho^{\mathrm{LHCb}}[p_{\mathrm{T}}(B_s^0) > 10\ \mathrm{GeV}] < 0.024$ @ 95% C. L.

  $\rho^{\mathrm{LHCb}}[p_{\mathrm{T}}(B_s^0) > 5\ \mathrm{GeV}] < 0.012$ @ 95% C. L.

Five new narrow Ω_c^0 states decaying to $\Xi_c^+ K^-$

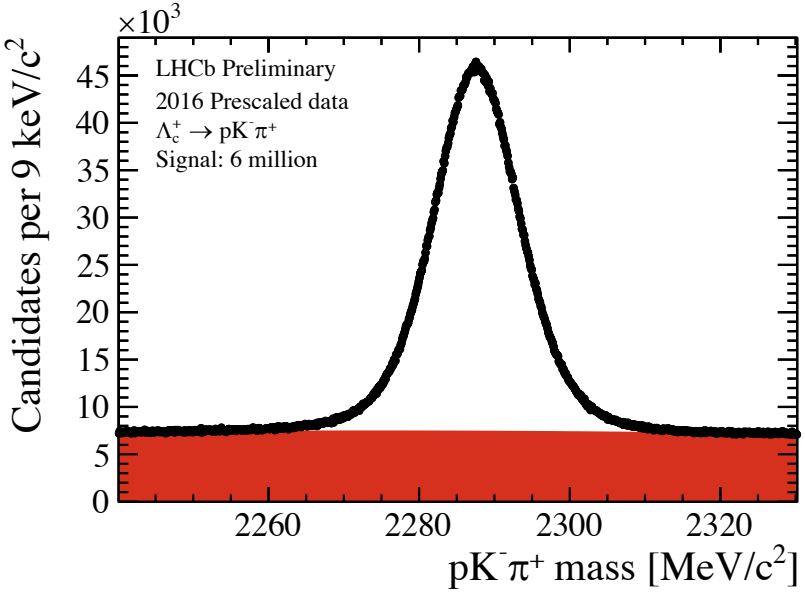
- Selections
  - Ξ_c^+ candidates
    - Proton PID requirement
    - Large Ξ_c^+ flight-distance significance
    - Ξ_c^+ candidates originating from the primary vertex
  - Likelihood ratio requirements
    - $\mathcal{L}(\mathbf{x}) = \sum_{i=1}^{11} \left| \ln\mathrm{PDF}_{sig}(x_i) - \ln\mathrm{PDF}_{back}(x_i) \right|$
  - $\Xi_c^+ K^-$ candidates
    - Originating from primary vertex
    - Good vertex fit quality
    - High Kaon PID probability
    - $p_{\mathrm{T}}(\Xi_c^+ K^-) > 4.5\ \mathrm{GeV}$

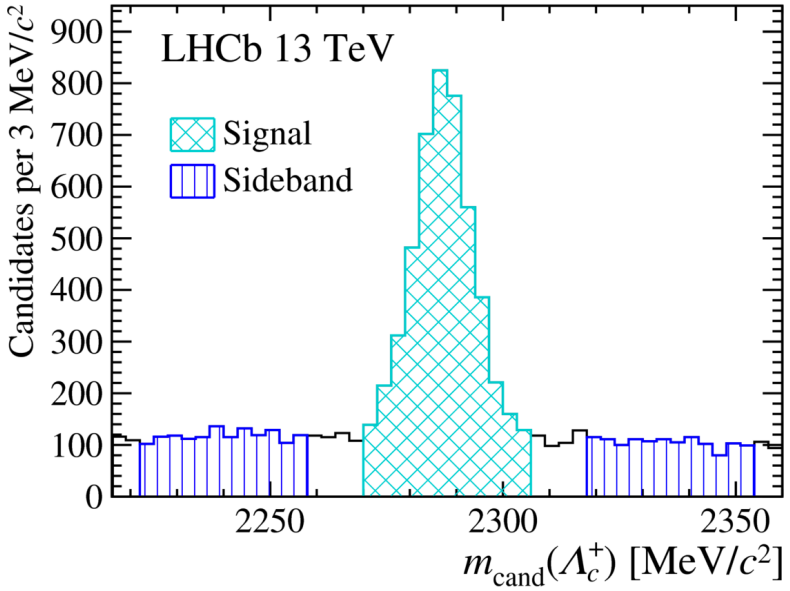
Observation of doubly charmed baryon Ξ_{cc}^{++}

- Selections
  - Final state tracks
    - Good track-quality
    - Appropriate PID probability
    - Minimum p_{T} requirments
  - Λ_c^+ candidates
    - Good vertex quality
    - Not originating from primary vertex
  - Ξ_{cc}^{++} candidates
    - $p_{\mathrm{T}} > 4\ \mathrm{GeV}$
  - Multivariate selector based on multilayer perceptron
    - Maximize $\epsilon/(\frac{5}{2}+\sqrt{B})$

Observation of doubly charmed baryon Ξ_{cc}^{++}

- 2016 inclusive Λ_c sample with 10% pre-scale
- Λ_c inviriant mass distribution of signal sample after selections





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