Heavy hadron spectroscopy at LHCb

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(on behalf of the LHCb collaboration)

DPF 2017, Fermilab
1 August 2017

Outlook

- LHCb detector

- Charmonia in b-hadron decays
  - $b \to (c\bar{c})X$, $c\bar{c}=\eta, J/\psi, \chi_c$
  - $B_s \to \eta_c \phi$, $B_s \to \eta_c \pi^+\pi^-$, $B_s \to \phi\phi\phi$
  - $\Lambda_b^0 \to \chi_{c1,2} pK$

- Charmed baryons
  - $\Lambda_c^* \to Dp$ in $\Lambda_b \to Dp\pi$ amplitude analysis
  - 5 new Ω_c^* states
  - observation of Ξ_{cc}^{++}

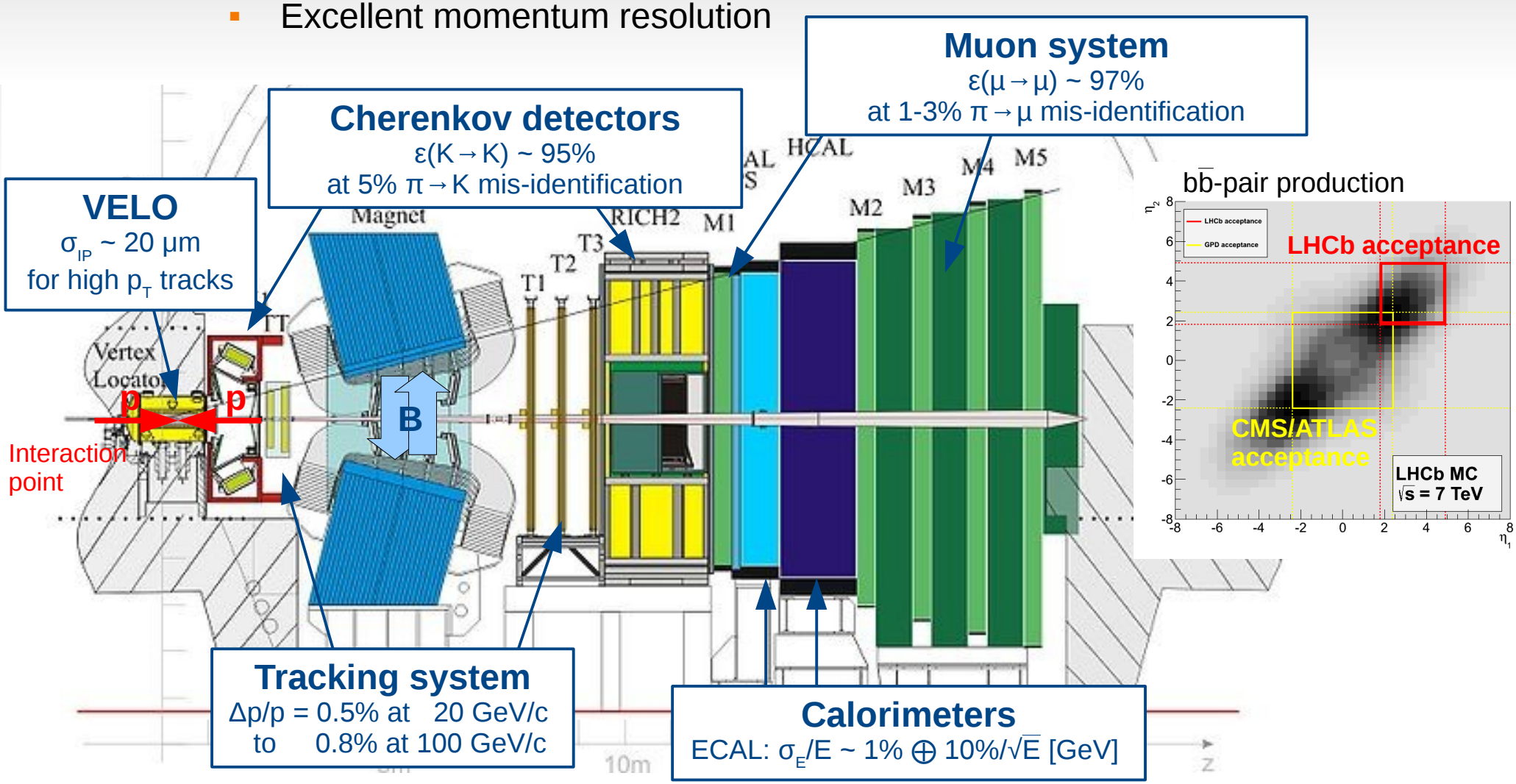
see also talks on
- HF production (Philip Ilten)
- Exotic QCD states (Liming Zhang)

LHCb detector

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

- High cross-section of heavy-quark production
- Excellent decay time resolution
- Excellent particle identification
- Excellent momentum resolution

Data collected in Run1:
1 fb^{-1} at 7 TeV
2 fb^{-1} at 8 TeV
in Run2:
2 fb^{-1} at 13 TeV (so far)

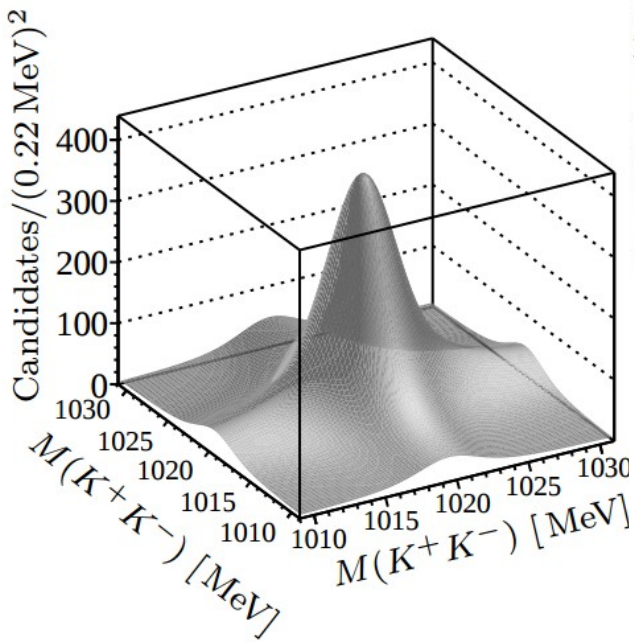


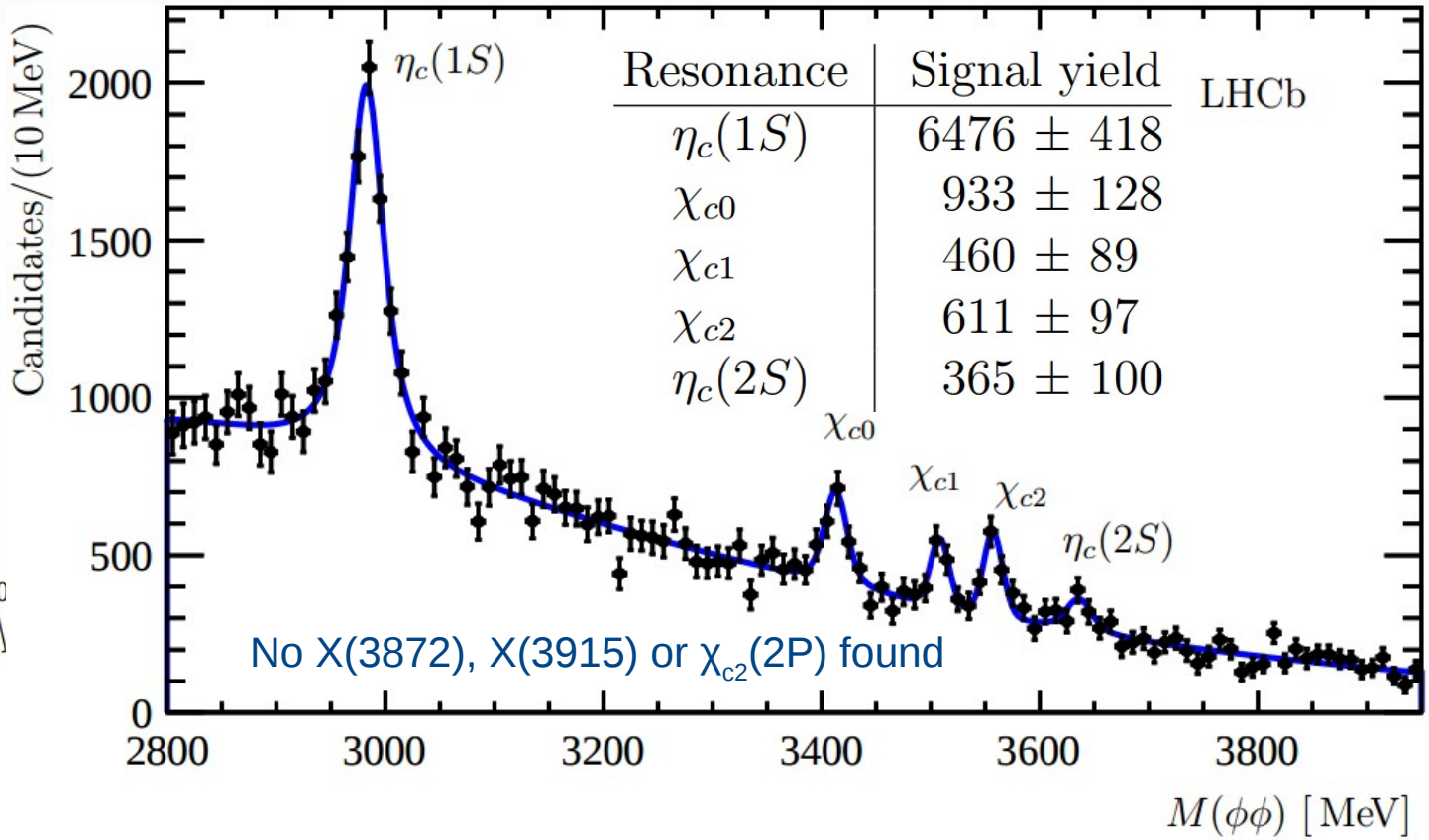
Charmonia in b-hadron decays

$b \to c\bar{c}(\to \phi\phi)+X$

arXiv:1706.07013

- Relative production of χ_c states in b-decays is an open question
- Inclusive production of J/ψ, ψ(2S), η_c(1S) in b-hadron decays have been already studied at LHCb EPJC 72 (2012) 2100 EPJC 75 (2015) 311
- No measurements for other charmonium states, probe them via decays to ϕϕ:
  select $K^+K^-K^+K^-$ candidates forming good vertex, separated from PV;
  require hadrons to have high pT and not originate from PV
- Separate ϕϕ from non-resonant and background with 2D fit to $M(K^+K^-)$





Resonance	Signal yield
$\eta_c(1S)$	6476 ± 418
χ_{c0}	933 ± 128
χ_{c1}	460 ± 89
χ_{c2}	611 ± 97
$\eta_c(2S)$	365 ± 100

$b \to c\bar{c}(\to \phi\phi)+X$

arXiv:1706.07013

- Measure relative production cross-sections using known $\mathcal{B}(c\bar{c} \to \phi\phi)$

$$\frac{\mathcal{B}(b \to \chi_{c1}X)}{\mathcal{B}(b \to \chi_{c0}X)} = 0.92 \pm 0.20 \pm 0.02 \pm 0.14_{\mathcal{B}}$$

$$\frac{\mathcal{B}(b \to \chi_{c2}X)}{\mathcal{B}(b \to \chi_{c0}X)} = 0.38 \pm 0.07 \pm 0.01 \pm 0.05_{\mathcal{B}}$$

$$\frac{\mathcal{B}(b \to \chi_{c0}X)}{\mathcal{B}(b \to \eta_c(1S)X)} = 0.62 \pm 0.10 \pm 0.05 \pm 0.15_{\mathcal{B}}$$

$$\frac{\mathcal{B}(b \to \chi_{c1}X)}{\mathcal{B}(b \to \eta_c(1S)X)} = 0.56 \pm 0.12 \pm 0.05 \pm 0.13_{\mathcal{B}}$$

$$\frac{\mathcal{B}(b \to \chi_{c2}X)}{\mathcal{B}(b \to \eta_c(1S)X)} = 0.23 \pm 0.04 \pm 0.02 \pm 0.06_{\mathcal{B}}$$

- Absolute BF determined using $\mathcal{B}(b \to \eta_c(1S)X)$ previously measured with $p\bar{p}$ mode
  Also measured differential cross-sections in bins of p_T

EPJC 75 (2015) 311

- χ_{c1} production measured to be in agreement with predictions,
  χ_{co} and χ_{c2} production was measured for the first time,
  in case of χ_{co} found to be larger than expected

Beneke, Maltoni, Rothstein.
PRD 59 (1999) 054003

- First evidence of $\eta_c(2S)$ inclusive production in b decays and of $\eta_c(2S) \to \phi\phi$

$$\mathcal{B}(b \to \eta_c(2S)X) \times \mathcal{B}(\eta_c(2S) \to \phi\phi) = (6.34 \pm 1.81 \pm 0.57 \pm 1.89) \times 10^{-7}$$

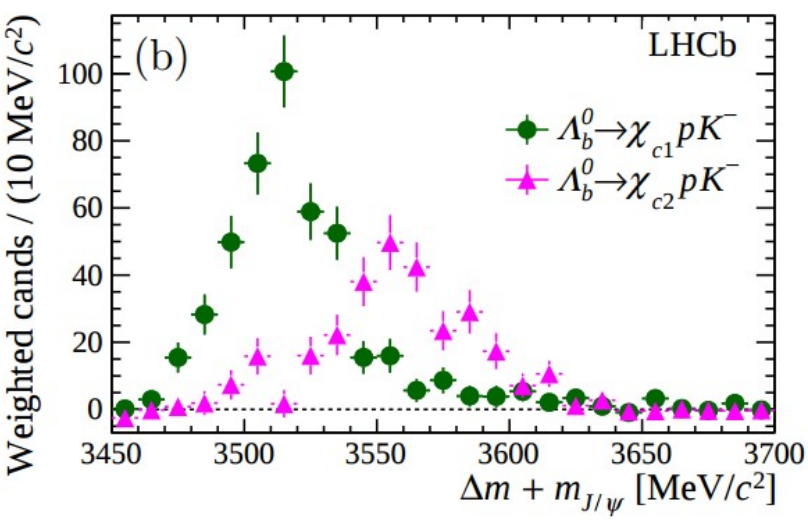
- Measured masses and $\eta_c(1S)$ width are consistent with the world averages

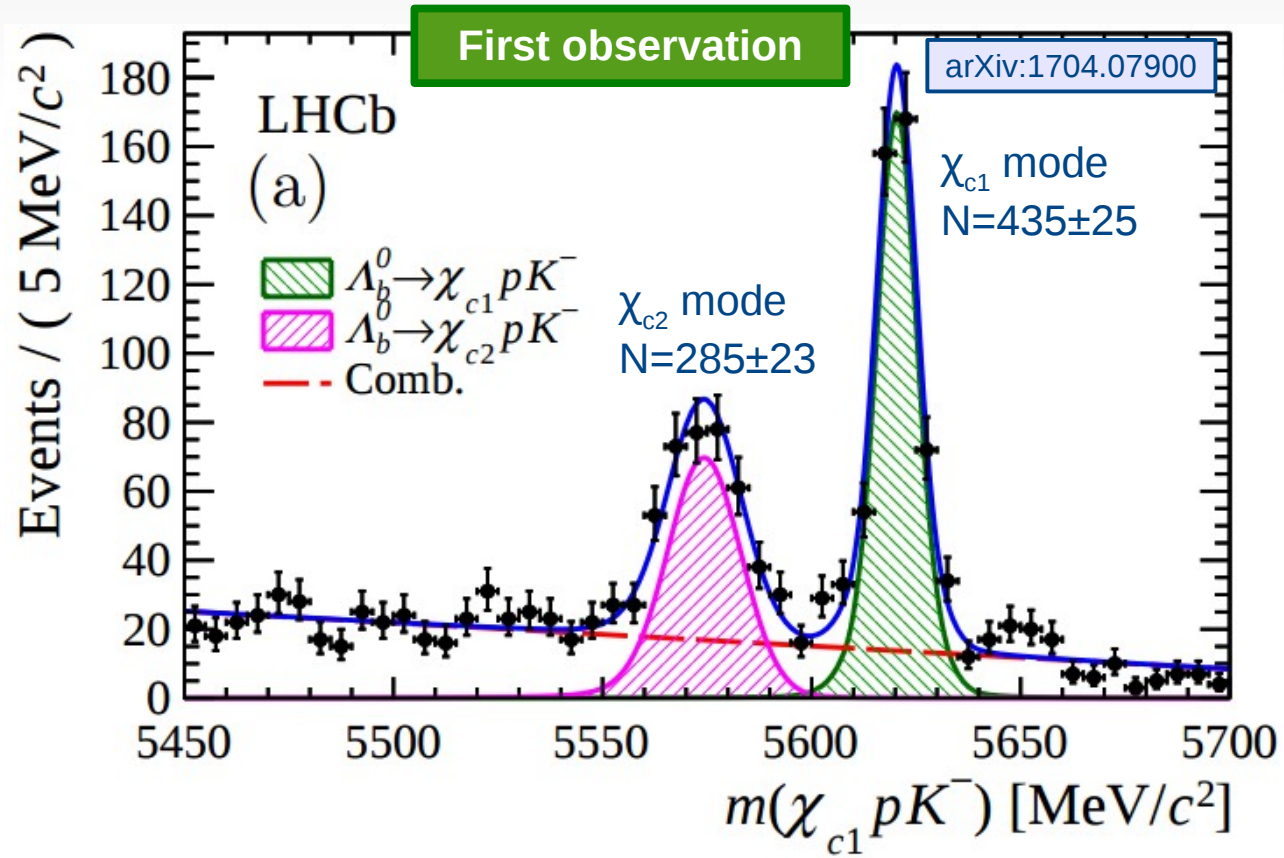
$\Lambda_b \to \chi_{c1,2} pK$

- Motivation:
  - test QCD factorization prediction for relative $\chi_{c1,2}$ rates
    (continuation of previous analysis of $B^0 \to \chi_{c1,2} K^{*0}$ and $B_s^0 \to \chi_{c1} \phi$ decays where χ_{c2} mode is ~20% suppressed) NPB 874 (2013) 663
  - a channel for $P_c^+ \to \chi_{c1} p$ studies

- Reconstruct $\chi_{c1,2}$ using decay to $J/\psi\gamma$, γ from calorimeter

- Constraint $J/\psi\gamma$ mass to $\chi_{c1,2}$ nominal mass to improve resolution





$\Lambda_b \to \chi_{c1,2} pK$

- Branching fractions relative to $\Lambda_b \to J/\psi pK$ mode and to each other are measured

arXiv:1704.07900

$$\frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c1} pK^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi pK^-)} = 0.242 \pm 0.014 \pm 0.013 \pm 0.009\,,$$

$$\frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c2} pK^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi pK^-)} = 0.248 \pm 0.020 \pm 0.014 \pm 0.009\,,$$

$$\frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c2} pK^-)}{\mathcal{B}(\Lambda_b^0 \to \chi_{c1} pK^-)} = 1.02 \pm 0.10 \pm 0.02 \pm 0.05\,,$$

- No suppression for χ_{c2} in contrast to $B \to \chi_{c1,2} K$ decays

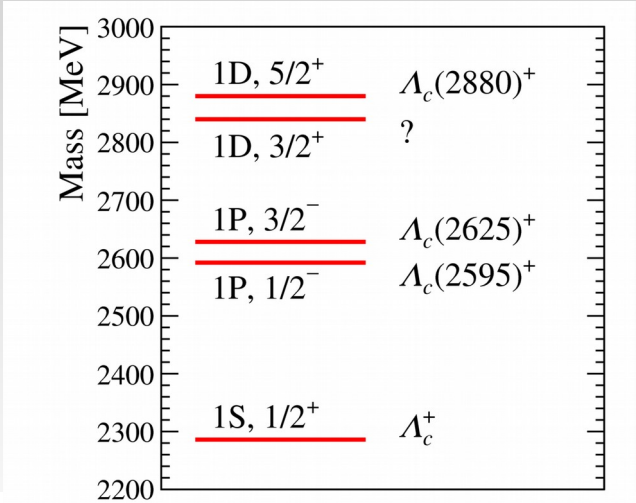
- In addition the Λ_b mass was measured
  the updated LHCb average: $5619.62 \pm 0.16 \pm 0.13\ \mathrm{MeV}/c^2$

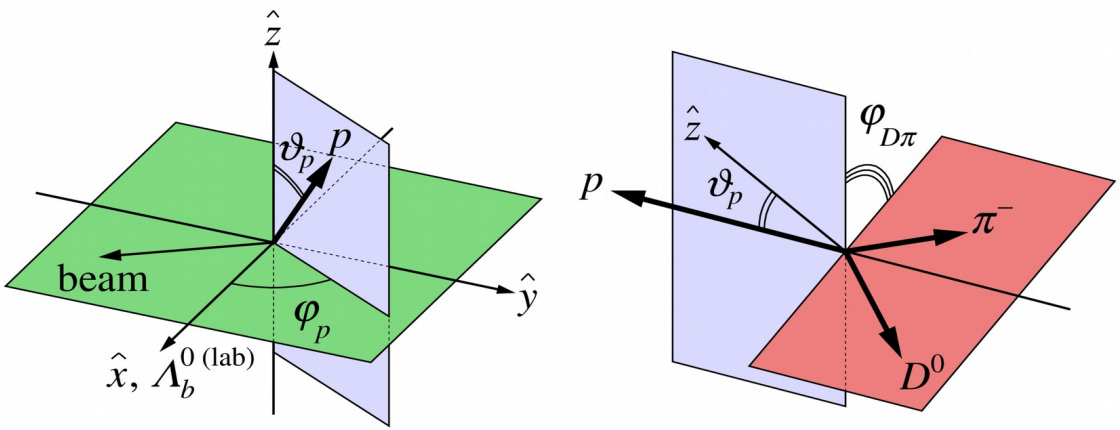
Charmed baryons

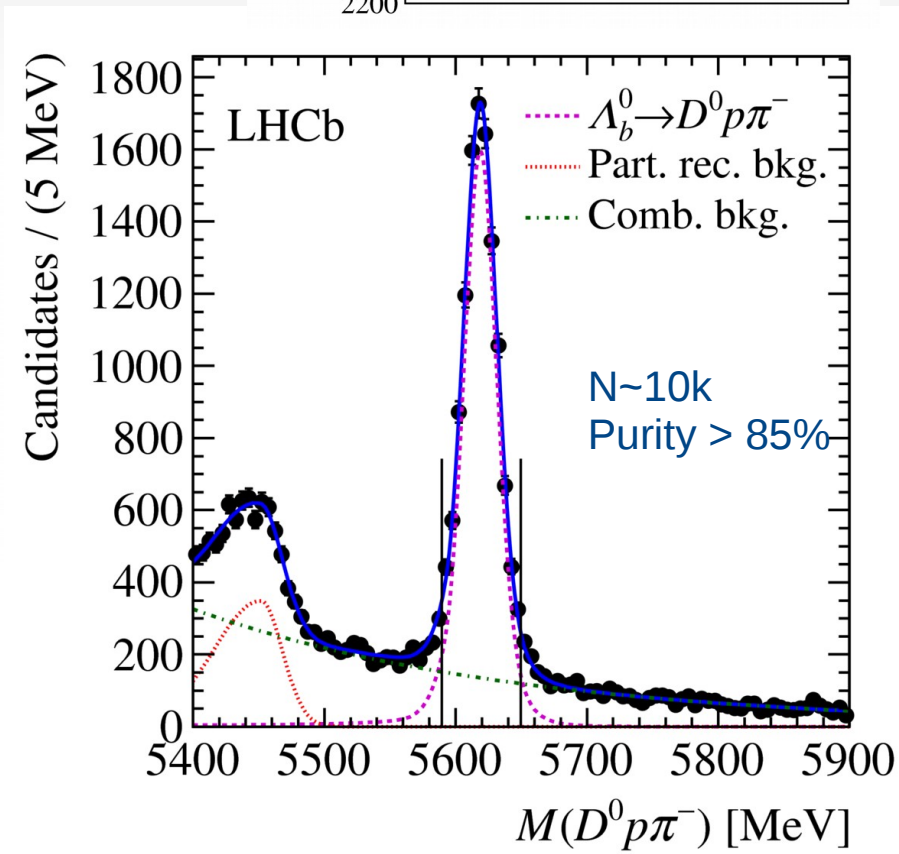
Amplitude analysis of $\Lambda_b \to D^0 p \pi^-$

- Explore $\Lambda_c^{*+} \to D^0 p$ states (Λ_c^{*+}=udc) in particular probe J^P of $\Lambda_c(2940)^+$ state which has possible interpretation as D*N molecule

- Follow helicity formalism to describe 5D amplitude of $D^0 p$ and $p\pi^-$ masses and 3 angles







JHEP 05 (2017) 30

Amplitude analysis of $\Lambda_b \to D^0 p \pi^-$

JHEP 05 (2017) 30

- $\Lambda_c(2880)^+$: $5/2^+$ preferred over 7/2(4σ) and 1/2,3/2(>5σ)

$$m(\Lambda_c(2880)^+) = 2881.75 \pm 0.29(\text{stat}) \pm 0.07(\text{syst})^{+0.14}_{-0.20}(\text{model})\ \text{MeV},$$
$$\Gamma(\Lambda_c(2880)^+) = 5.43^{+0.77}_{-0.71}(\text{stat}) \pm 0.29(\text{syst})^{+0.75}_{-0.00}(\text{model})\ \text{MeV}.$$

consistent with world average and has similar precision

- $\Lambda_c(2860)^+$: $3/2^+$ preferred over all others (6σ)

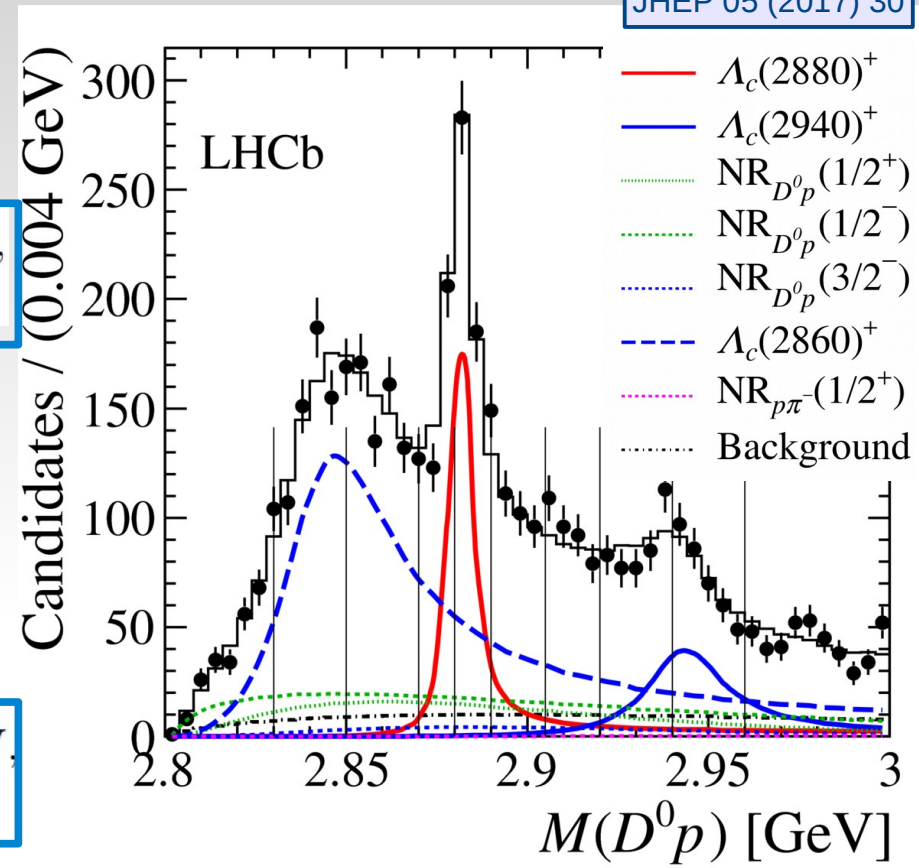
First observation

$$m(\Lambda_c(2860)^+) = 2856.1^{+2.0}_{-1.7}(\text{stat}) \pm 0.5(\text{syst})^{+1.1}_{-5.6}(\text{model})\ \text{MeV},$$
$$\Gamma(\Lambda_c(2860)^+) = 67.6^{+10.1}_{-8.1}(\text{stat}) \pm 1.4(\text{syst})^{+5.9}_{-20.0}(\text{model})\ \text{MeV}$$

consistent with predictions for D-wave excitation

Chen, Wei, Liu, Matsuki; arXiv:1609.07967

Chen et al.; arXiv:1611.02677



- $\Lambda_c(2940)^+$: $3/2^-$ preferred, though 1/2 and 7/2 not excluded

First measurement of spin-parity

$$m(\Lambda_c(2940)^+) = 2944.8^{+3.5}_{-2.5}(\text{stat}) \pm 0.4(\text{syst})^{+0.1}_{-4.6}(\text{model})\ \text{MeV},$$
$$\Gamma(\Lambda_c(2940)^+) = 27.7^{+8.2}_{-6.0}(\text{stat}) \pm 0.9(\text{syst})^{+5.2}_{-10.4}(\text{model})\ \text{MeV}.$$

$3/2^-$ consistent with interpretations of D*N or 2P excitation

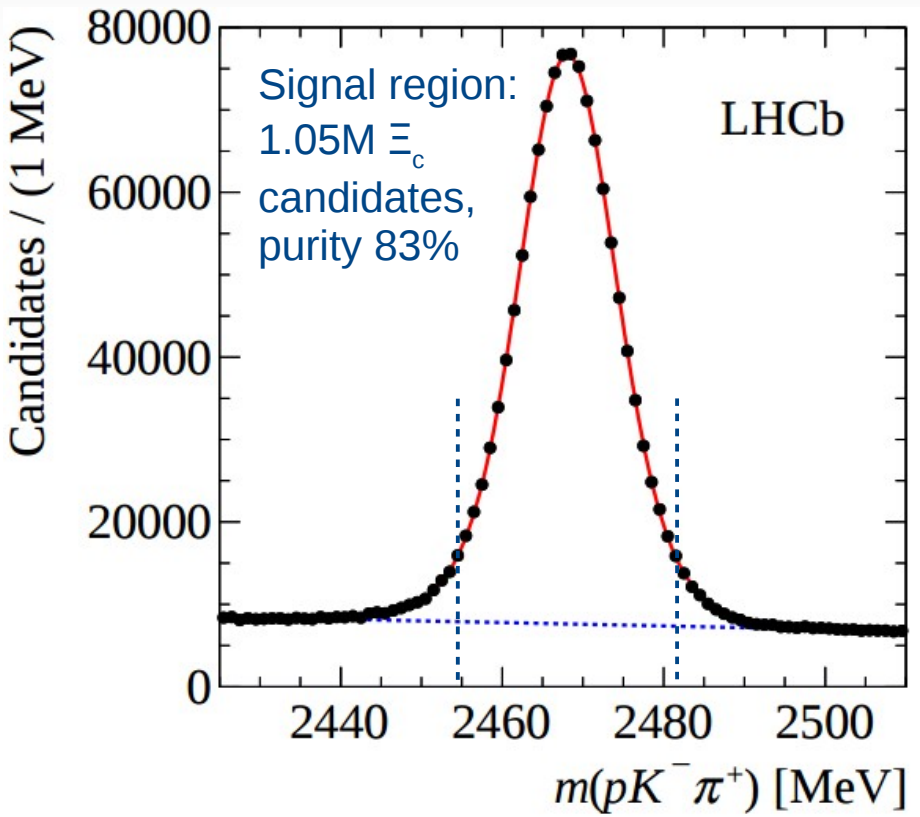
Zhang; PRD 89 (2014) 096006

Ortega, Entem, Fernandez; PLB 718 (2013) 1381

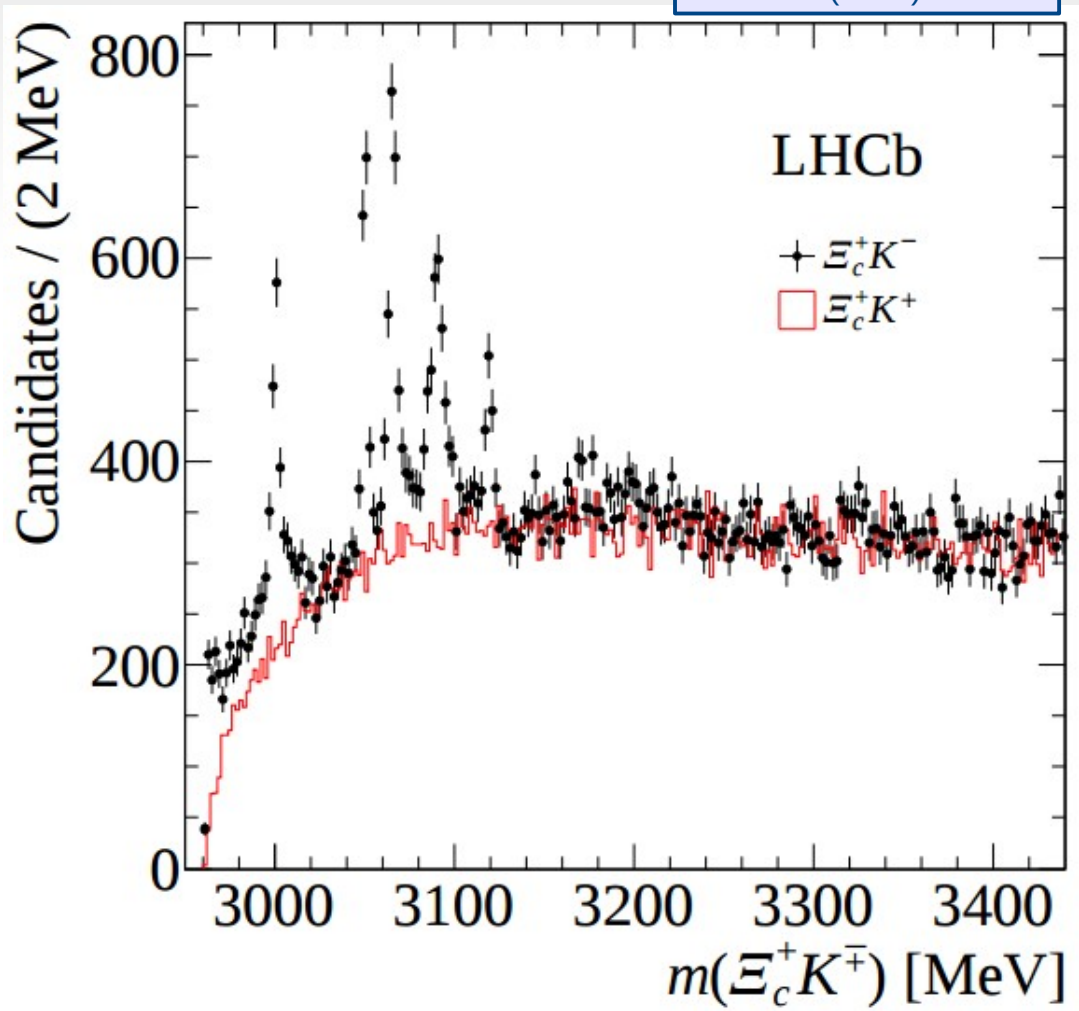
Dong, Faessler, Gutsche, Lyubovitskij; PRD 90 (2014) 094001

New states in $\Omega_c \to \Xi_c^+ K^-$

- Ω_c quark content: ssc
  only $1/2^+$ and $3/2^+$ ground states were observed
- Explore excited Ω_c states in their strong decay to $\Xi_c^+ K^-$
  using $\Xi_c^+ \to pK^-\pi^+$
- 5 narrow peaks seen

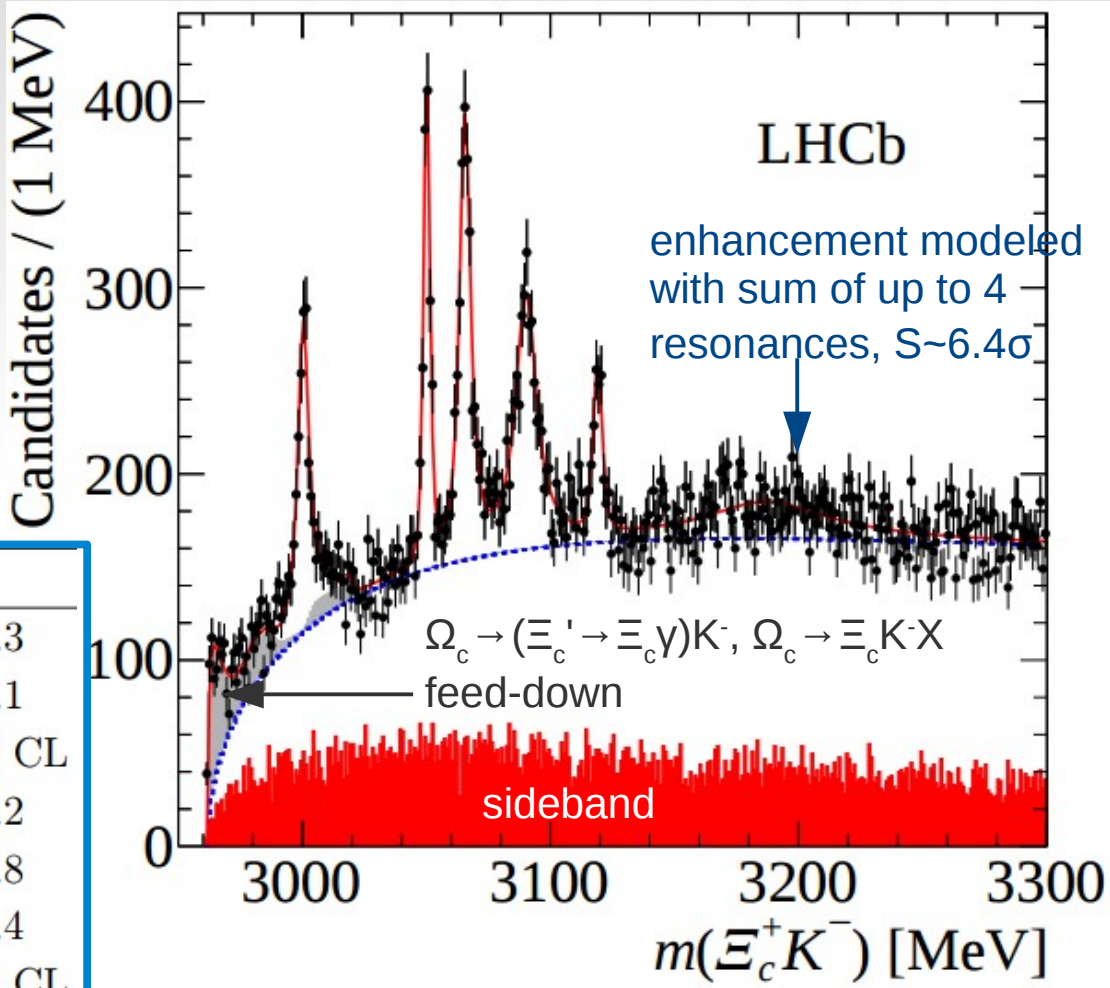


PRL 118 (2017) 182001



New states in $\Omega_c \to \Xi_c^+ K^-$

- Describe peaks with relativistic Breit-Wigner convoluted with Gaussian with σ from 0.7 to 1.7 MeV
- Account for feed-down from $\Omega_c \to (\Xi_c^{+\prime} \to \Xi_c^+ \gamma) K^-$ and $\Omega_c \to \Xi_c^+ K^- X$
- Model enhancement at ~3200 with either one Breit-Wigner or sum of 4
- Measured masses and widths



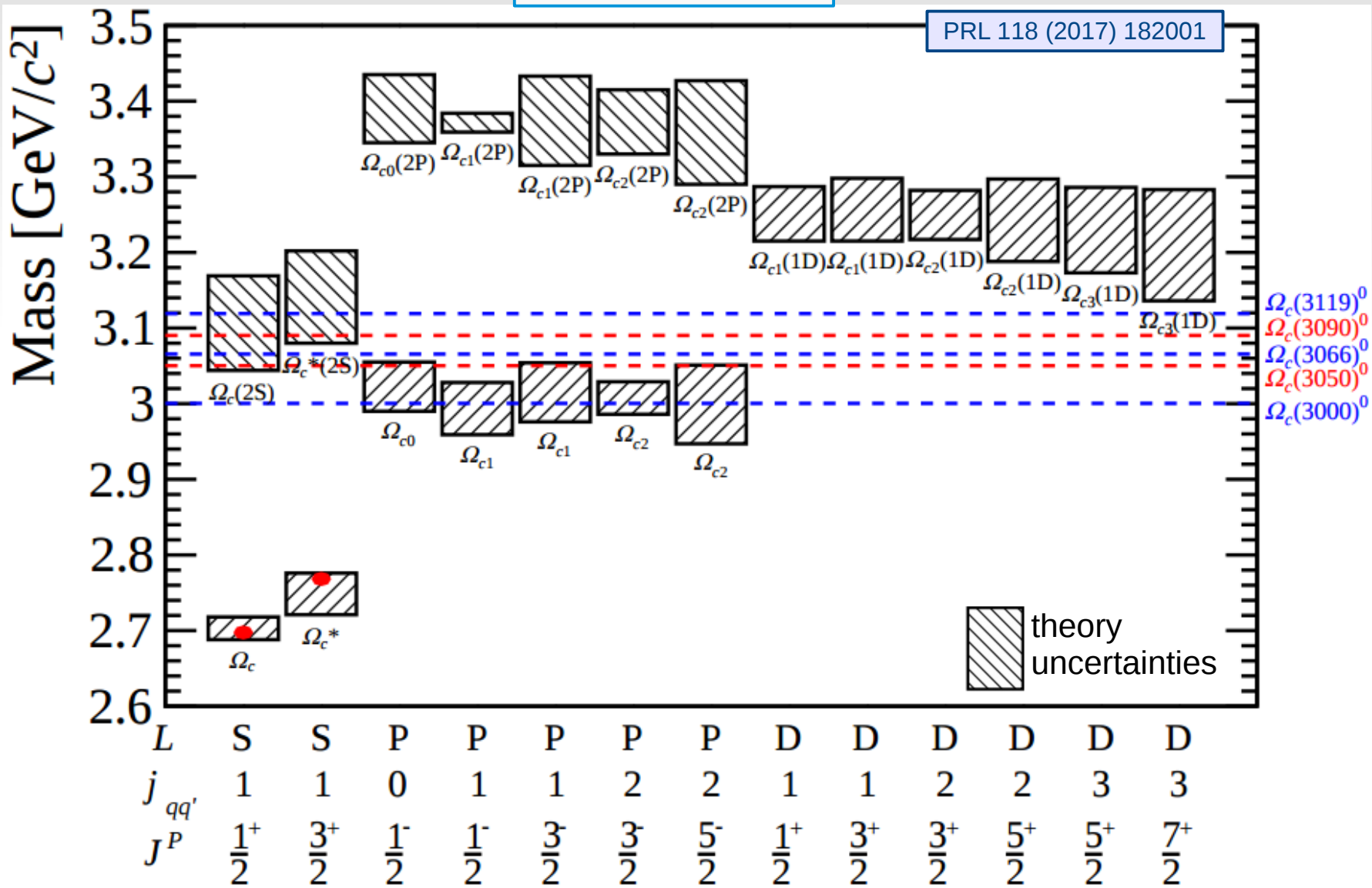
Resonance	Mass (MeV)	Γ (MeV)
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$
		< 1.2 MeV, 95% CL
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$
$\Omega_c(3090)^0$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

- $\Omega_c(3050)$ and $\Omega_c(3119)$ are exceptionally narrow

New states in $\Omega_c \to \Xi_c^+ K^-$

- Matching the observed states with the predictions

Chin. Phys. C40 (2016) 123102; arXiv:1609.08464



Doubly Charmed Baryon

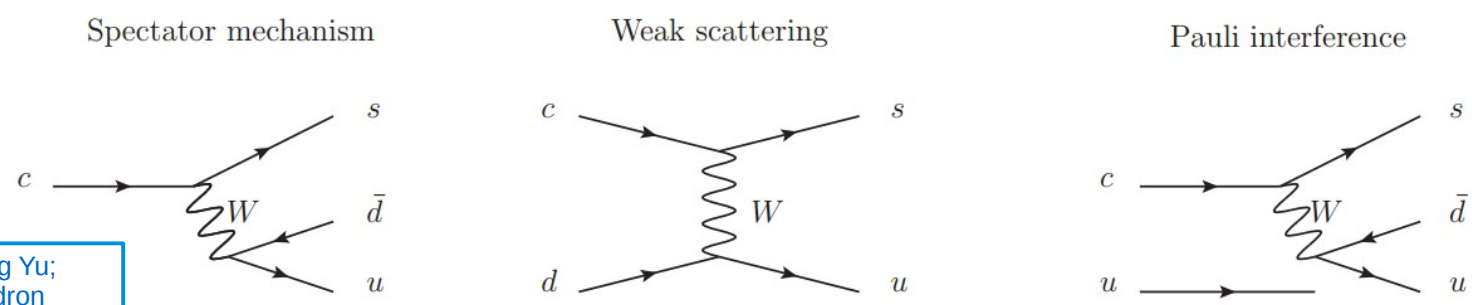
- Predictions for ground Ξ_{cc} state mass: 3.5-3.7 GeV
  $\Xi_{cc}^{+}/\Xi_{cc}^{++}$ mass splitting only few MeV due to u/d symmetry
  diquark(cc) – quark(q) model: 3620 MeV
  3615±55 MeV
  3627±12 MeV
  Solve 3-body problem: 3632.8±2.4 MeV
  Lattice QCD: ~3600 MeV

  Comparison by Karliner and Rosner; PRD 90 (2014) 094007
  Ebert, Faustov, Galkin, Martynenko; PRD 66 (2002) 014008
  Kiselev, Berezhnoy, Likhoded; arXiv:1706.09181
  Karliner and Rosner; PRD 90 (2014) 094007
  Kerbikov, Polikarpov, Shevchenko; NPB 331 (1990) 19
  Comparison by Y. Zhang; CERN Seminar, July 2017

- Lifetime highly depends on spectator quark
  $\tau(\Xi_{cc}^{++}) \sim 200\text{-}700$ fs
  $\tau(\Xi_{cc}^{+}) \sim 50\text{-}250$ fs

$$\frac{\tau_{\Xi_{cc}^{+}}}{\tau_{\Xi_{cc}^{++}}} = 0.25 \sim 0.37$$

Comparison by Fu-Sheng Yu; Workshop on heavy hadron spectroscopy, CERN, July 2017



- Production

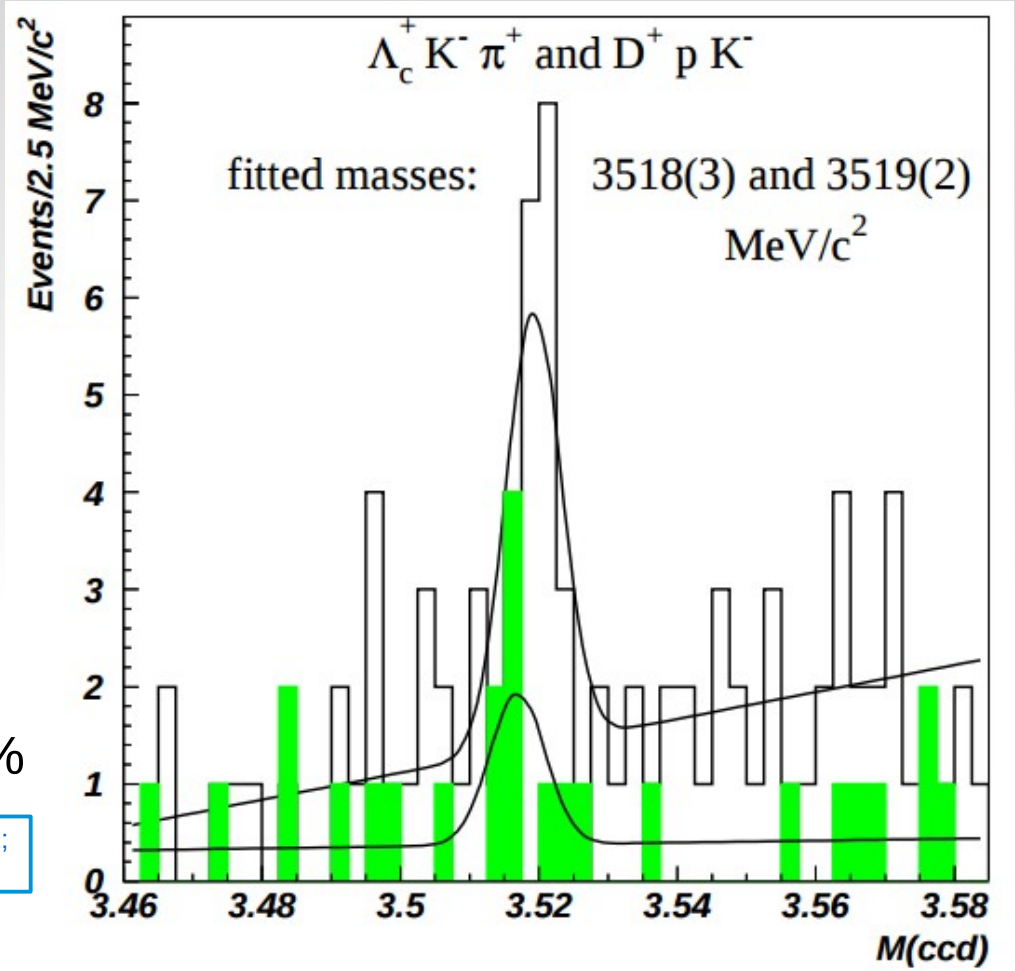
$$\sigma(\Xi_{QQ}) \lesssim 0.3 \cdot \sigma^{\mathrm{SPS}}((Q\bar{Q}) + Q)$$

Likhoded; Workshop on heavy hadron spectroscopy, CERN, July 2017

Claim of Ξ_{cc}^{+} observation by SELEX

- SELEX (Fermilab E781): collisions of hyperon beams (Σ,p) with nuclear fix target
- Observed a peak in two modes: $\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+}$ (6.3σ), $\Xi_{cc}^{+} \to D^{+} p K^{-}$ (4.8σ)
- Mass consistent with lower predictions: 3518.7±1.7 MeV
- Short lifetime: τ < 33fs
- Large production rate: $N(\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+})/N(\Lambda_c^{+}) \sim 20\%$

PRL 89 (2002) 112001; PLB 628 (2005) 18



- Consequent searches by FOCUS (Fermilab 831), BaBar, Belle, LHCb → no confirmation

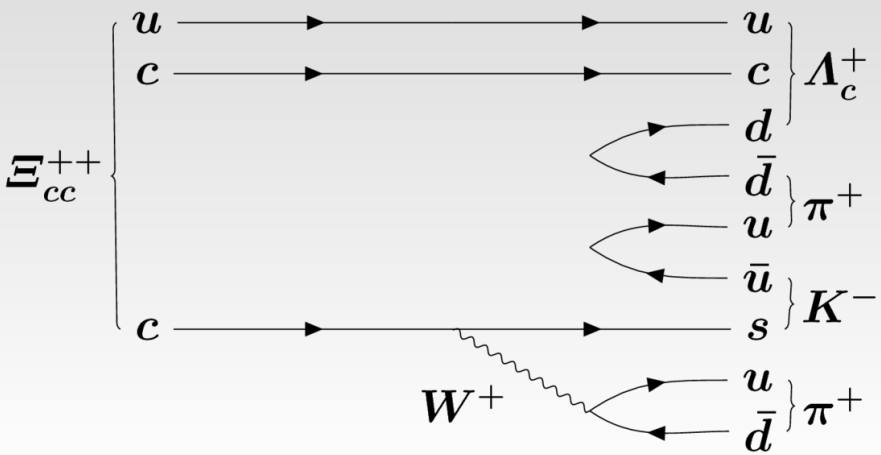
FOCUS, NPPS 115 (2003) 33; BaBar, PRD 74 (2006) 011103; Belle, PRL 97 (2006) 162001; LHCb, JHEP 12 (2013) 090

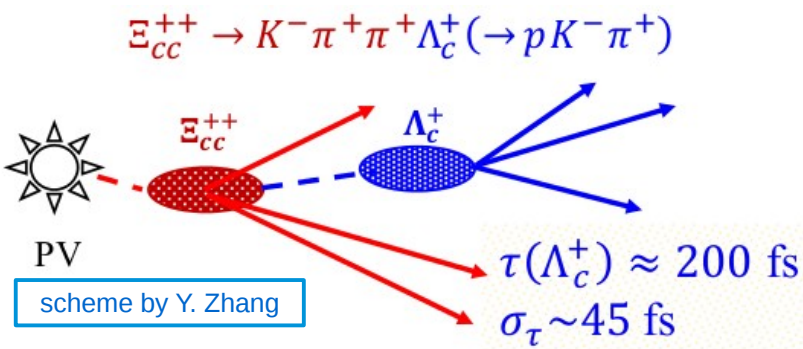
Search for Ξ_{cc}^{++} at LHCb

arXiv:1707.01621

- Choose the $\Xi_{cc}^{++}(ccu)$ with a higher lifetime → higher sensitivity
- $\Xi_{cc}^{++}(ccu) \to \Lambda_c^+ K^- \pi^+ \pi^+$, $Br(\Lambda_c^+ \to pK^-\pi^+) \sim 10\%$
- Analyze 1.7fb^{-1} of Run2
  Dedicated trigger ensuring high efficiency
- Select Λ_c^+ with
  - high-PT daughters not originating from PV
  - good decay vertex displaced from PV
  - → purity of 72%
- Ensure no clone tracks
- Apply MVA selection for the Ξ_{cc}^{++} candidate at the final step
  - kinematics of daughter particles
  - decay tree fit quality
  - separation from PV

  optimized with wrong-sign $\Lambda_c^+ K^- \pi^+ \pi^-$ sample



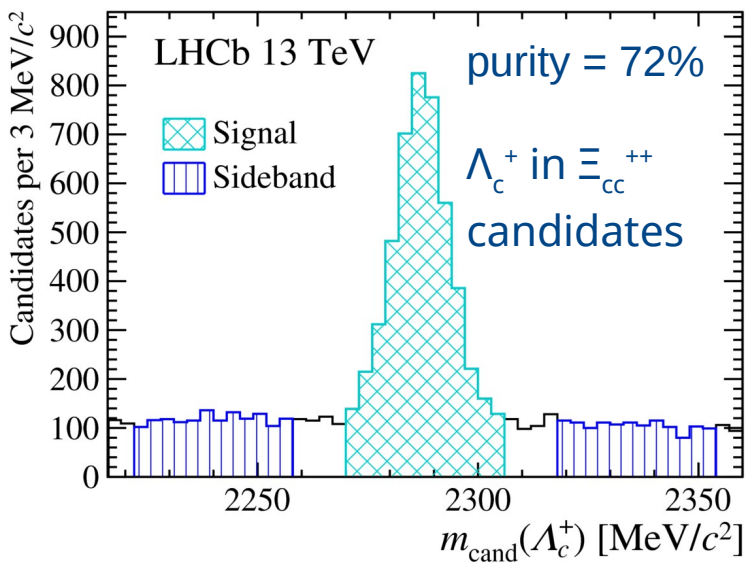


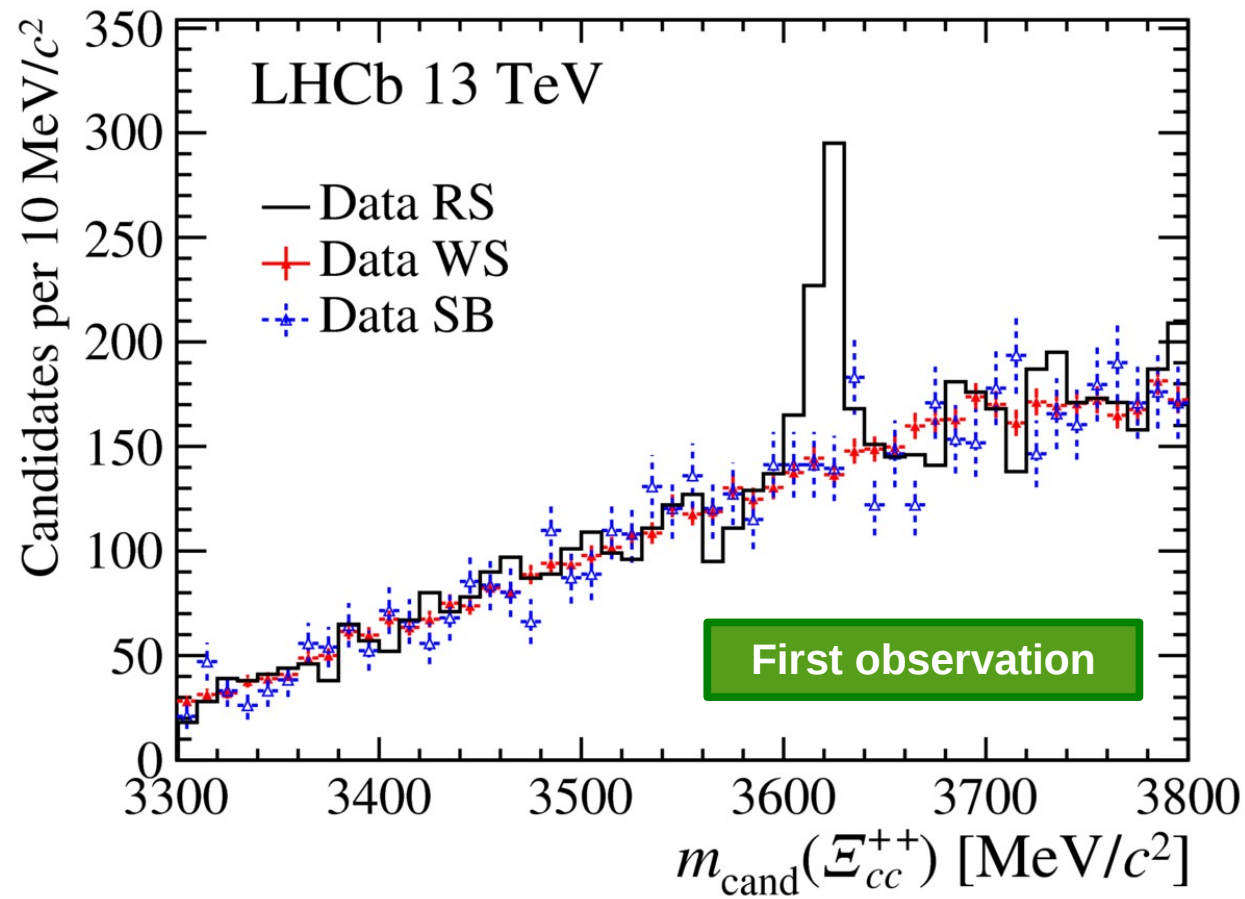
scheme by Y. Zhang

Observation of Ξ_{cc}^{++} at LHCb

arXiv:1707.01621

- A significant peak is observed
- No sign in both wrong-sign $\Lambda_c^+ K^- \pi^+ \pi^-$ and Λ_c^+ sideband samples
- Background distributions are well consistent between 3 samples





- Further checks:
  - MVA efficiency across mass
  - variation of MVA selection
  - variations of PID selections
  - check with cut-based selection
  - 2012 data collected at 8 TeV
  - require lifetime to be larger than $5\sigma_\tau$
  - multiple candidates & combinations from Λ_c and Ξ_c daughters

Observation of Ξ_{cc}^{++} at LHCb

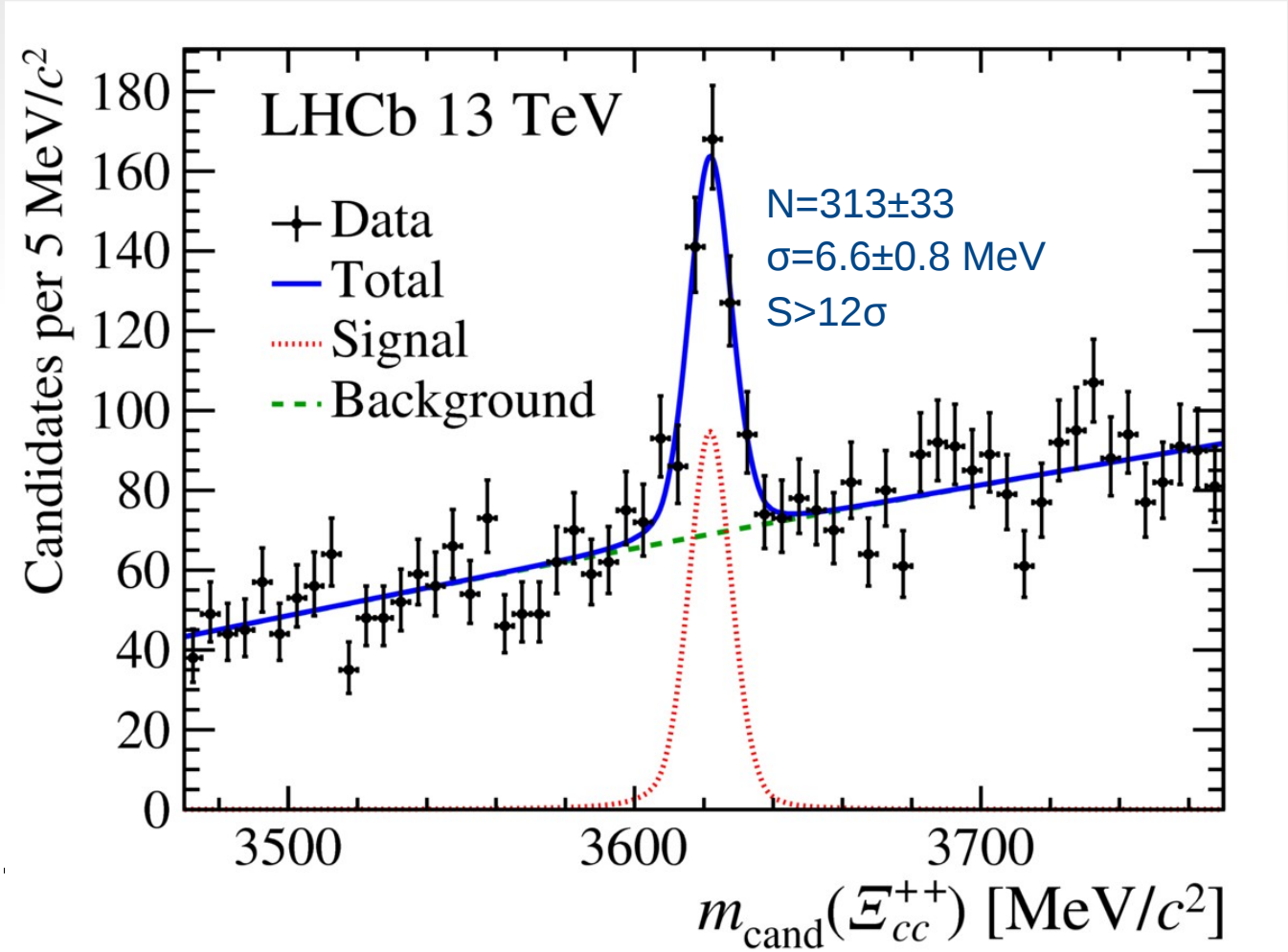
arXiv:1707.01621

- Fitting the peak gives significance >12σ and mass

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

systematics dominated by momentum scale uncertainty and selection bias correction

- Consistent with the predictions: 3.5-3.7 GeV
- Inconsistent with SELEX: 3518.7±1.7 MeV
- Further plans:
  - measure lifetime
  - search for Ξ_{cc}^{+} and more decay modes
  - prove spin-parity $1/2^+$
  - excited states, Ω_{cc}, Ξ_{bc}, ...



Summary

- Charmonia in b-hadron decays
  - $b \to (c\bar{c})X$, $c\bar{c}=\eta, J/\psi, \chi_c$
  - $B_s \to \eta_c \phi$, $B_s \to \eta_c \pi^+\pi^-$, $B_s \to \phi\phi\phi$
  - $\Lambda_b^0 \to \chi_{c1,2} pK$

  → tests for factorization approach, refine masses and widths, opens new channels for exotica studies

arXiv:1706.07013
JHEP 07 (2017) 021
arXiv:1704.07900

- Charm baryons:
  - $\Lambda_c^* \to Dp$ in $\Lambda_b \to Dp\pi$ amplitude analysis
  - 5 new Ω_c^* states
  - observation of Ξ_{cc}^{++}

JHEP 05 (2017) 30
PRL 118 (2017) 182001
arXiv:1707.01621

- Observation of 5 new B_c^+ decay modes
  - $B_c^+ \to D^0K^+$
  - $B_c^+ \to J/\psi D^0K^+$, $J/\psi D^{*0}K^+$;
  - first evidence for $B_c^+ \to J/\psi D^+K^{*0}$, $J/\psi D^{*+}K^{*0}$

PRL 118 (2017) 111803
PRD 95 (2017) 032005

- Looking forward for even more important results and discoveries

Backup

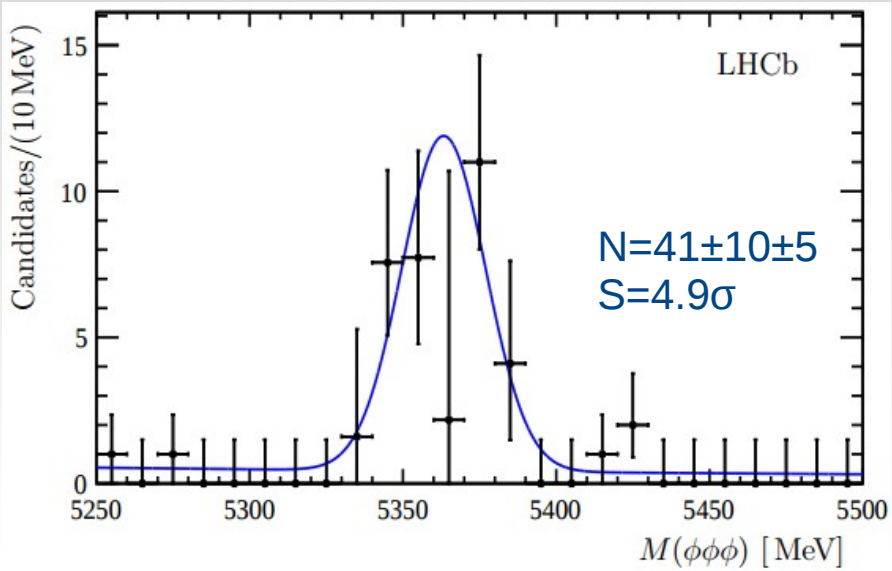
$B_s \to \phi\phi\phi$, $B_s \to \eta_c\phi$, $B_s \to \eta_c\pi^+\pi^-$

- In the same analysis an evidence for the $B_s \to \phi\phi\phi$ decay has been found

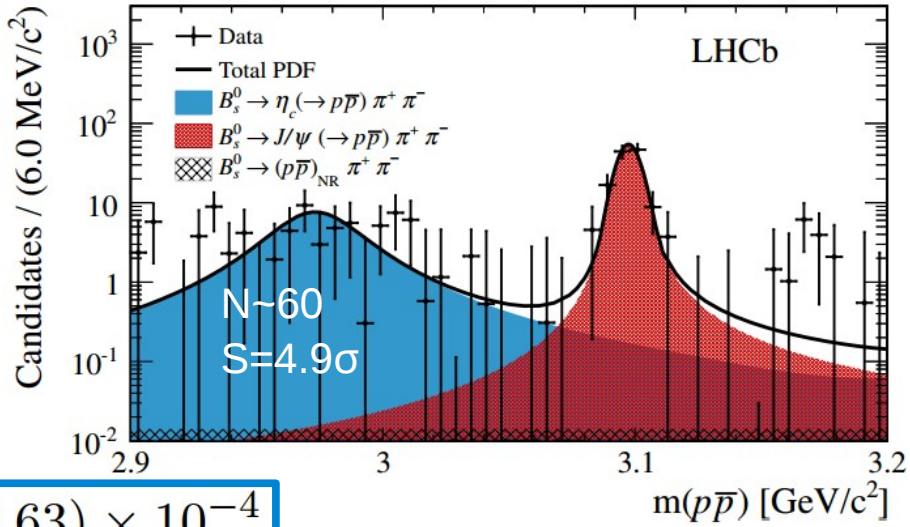
arXiv:1706.07013

$$\mathcal{B}(B_s^0 \to \phi\phi\phi) = (2.15 \pm 0.54 \pm 0.28 \pm 0.21_{\mathcal{B}}) \times 10^{-6}$$

- No strong indication of intermediate resonances (η_c,χ_c)



- By using combination of η_c decays to $p\bar{p}$, $K^+K^-\pi^+\pi^-$, $\pi^+\pi^-\pi^+\pi^-$ and $K^+K^-K^+K^-$ an observation and first evidence for $B_s \to \eta_c\phi$ and $B_s \to \eta_c\pi^+\pi^-$ decays have been obtained



$$\mathcal{B}(B_s^0 \to \eta_c\phi) = (5.01 \pm 0.53 \pm 0.27 \pm 0.63) \times 10^{-4}$$
$$\mathcal{B}(B_s^0 \to \eta_c\pi^+\pi^-) = (1.76 \pm 0.59 \pm 0.12 \pm 0.29) \times 10^{-4}$$

JHEP07 (2017) 021

Amplitude analysis of $\Lambda_b \to D^0 p \pi^-$

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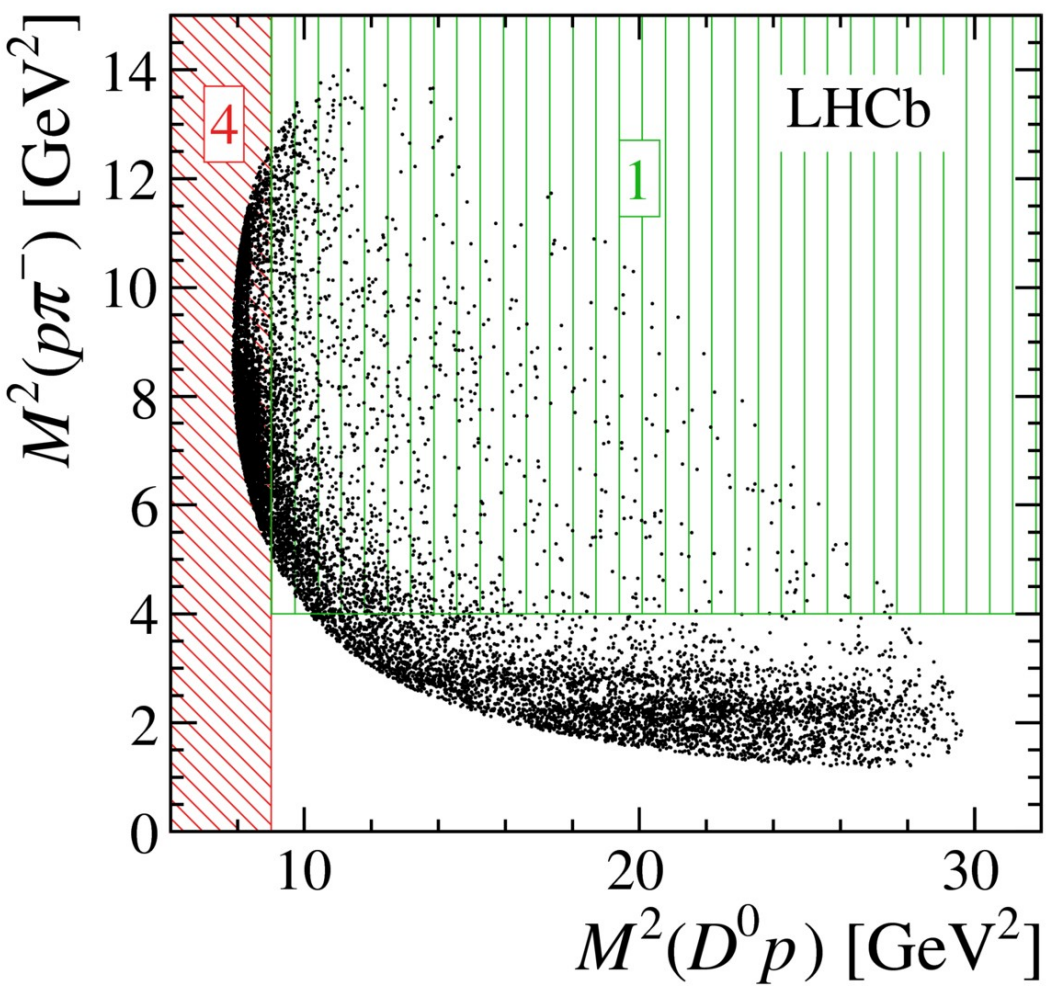
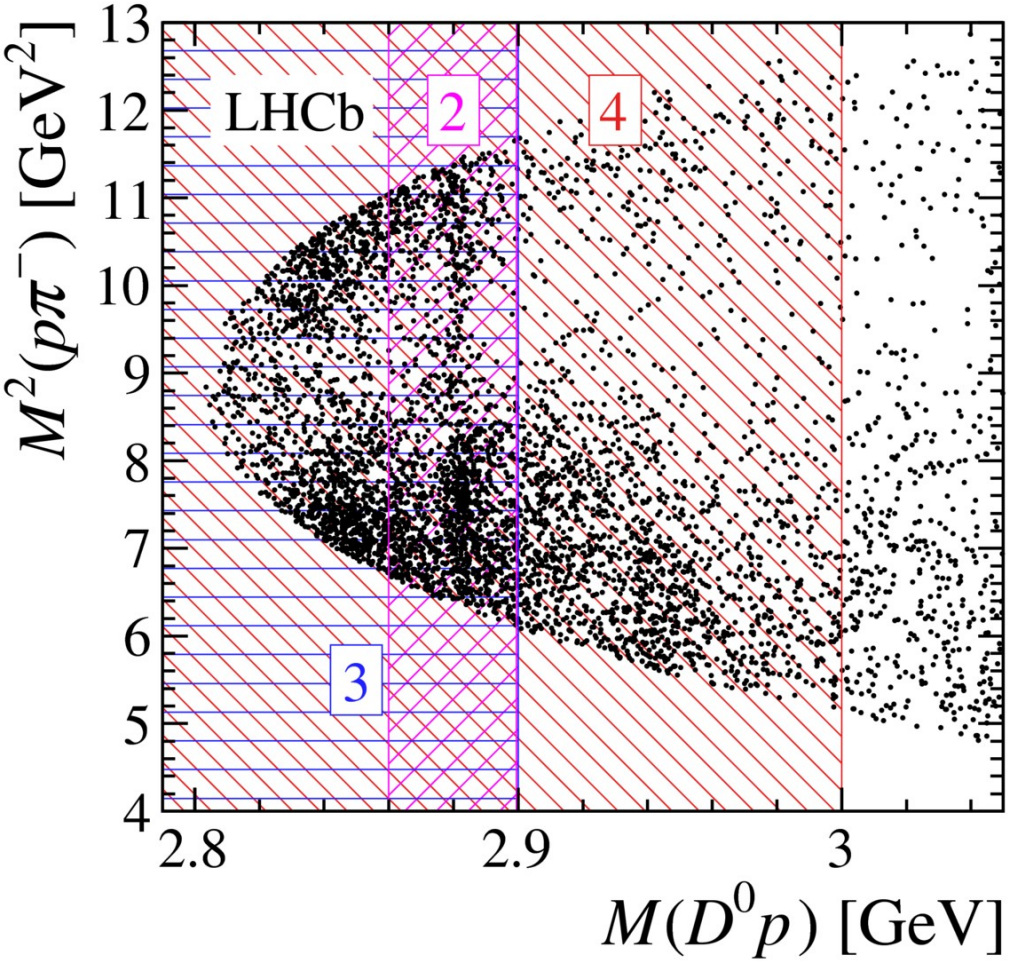
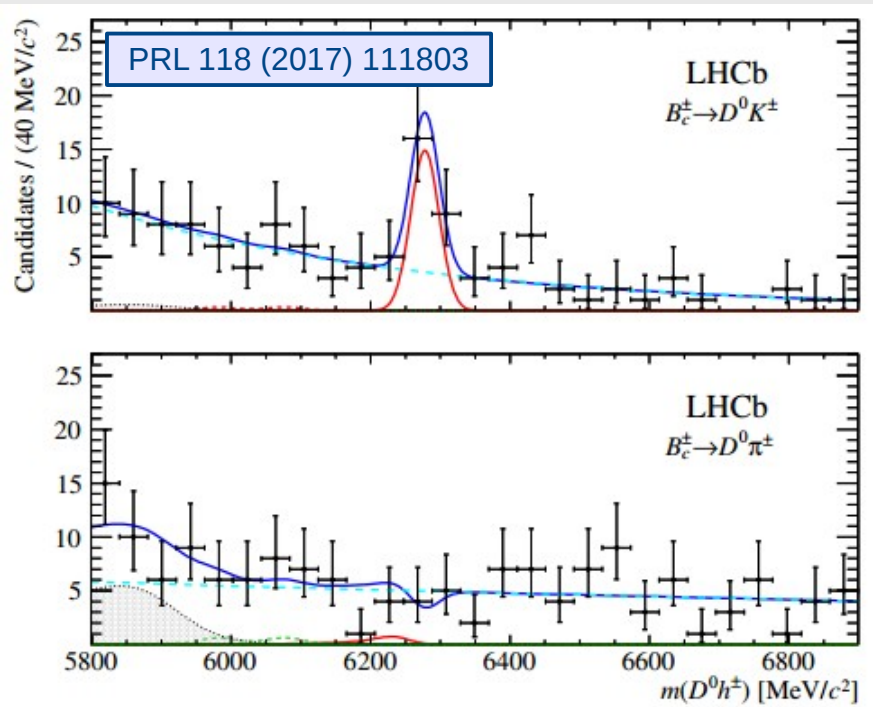
- Perform fit in 4 phase-space regions

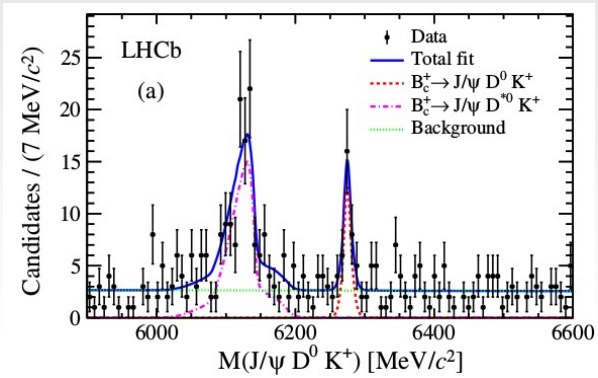


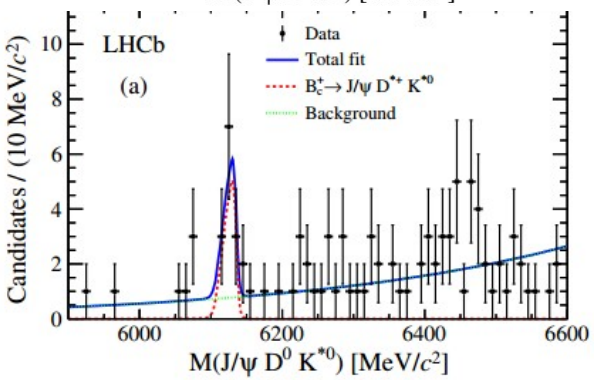


B_c^+ physics

- LHCb opened a door into B_c^+ physics: 2 → 10 new decay modes observed (only 2 before LHCb)
- Another 5 new modes this year







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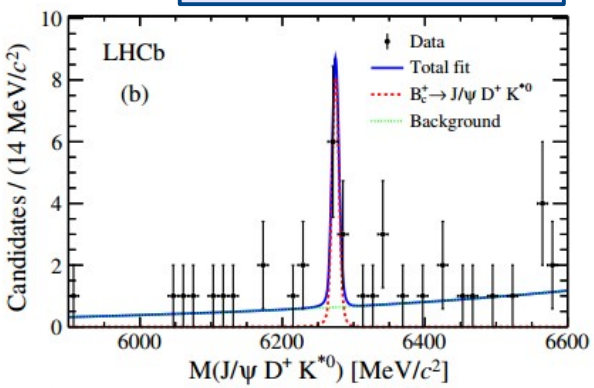

$$\mathcal{B}(B_c^+ \to D^0 K^+)/\mathcal{B}(B_c^+ \to J/\psi \pi^+) = \\ = 0.13 \pm 0.04 \pm 0.01 \pm 0.01$$

$$\frac{\mathcal{B}(B_c^+ \to J/\psi D^0 K^+)}{\mathcal{B}(B_c^+ \to J/\psi \pi^+)} = 0.432 \pm 0.136 \pm 0.028,$$

$$\frac{\mathcal{B}(B_c^+ \to J/\psi D^{*0} K^+)}{\mathcal{B}(B_c^+ \to J/\psi D^0 K^+)} = 5.1 \pm 1.8 \pm 0.4,$$

$$\frac{\mathcal{B}(B_c^+ \to J/\psi D^{*+} K^{*0})}{\mathcal{B}(B_c^+ \to J/\psi D^0 K^+)} = 2.10 \pm 1.08 \pm 0.34,$$

$$\frac{\mathcal{B}(B_c^+ \to J/\psi D^+ K^{*0})}{\mathcal{B}(B_c^+ \to J/\psi D^0 K^+)} = 0.63 \pm 0.39 \pm 0.08,$$

B_c^+ physics

- LHCb opened a door into B_c^+ physics: 2 → 10 new decay modes observed (only 2 before LHCb)
- Another 3 new modes this year

PDG 2010

$B_c^\pm$

$I(J^P) = 0(0^-)$
I, J, P need confirmation.

Quantum numbers shown are quark-model predicitions.

Mass $m = 6.277 \pm 0.006$ GeV (S = 1.6)
Mean life $\tau = (0.453 \pm 0.041) \times 10^{-12}$ s

B_c^- modes are charge conjugates of the modes below.

B_c^+ DECAY MODES × B($\bar{b} \to B_c$)	Fraction (Γ_i/Γ)		Confidence level	p (MeV/c)
The following quantities are not pure branching ratios; rather the fraction Γ_i/Γ × B($\bar{b} \to B_c$).				
$J/\psi(1S)\ell^+\nu_\ell$ anything	$(5.2^{+2.4}_{-2.1})$	$\times 10^{-5}$		–
$J/\psi(1S)\pi^+$	< 8.2	$\times 10^{-5}$	90%	2372
$J/\psi(1S)\pi^+\pi^+\pi^-$	< 5.7	$\times 10^{-4}$	90%	2352
$J/\psi(1S)a_1(1260)$	< 1.2	$\times 10^{-3}$	90%	2171
$D^*(2010)^+\overline{D}^0$	< 6.2	$\times 10^{-3}$	90%	2468

PDG 2017

Mass $m = 6274.9 \pm 0.8$ MeV
Mean life $\tau = (0.507 \pm 0.009) \times 10^{-12}$ s

$J/\psi(1S)\ell^+\nu_\ell$ anything	$(5.2^{+2.4}_{-2.1})$	$\times 10^{-5}$		–
$J/\psi(1S)\pi^+$	seen			2371
$J/\psi(1S)K^+$	seen			2341
$J/\psi(1S)\pi^+\pi^+\pi^-$	seen			2350
$J/\psi(1S)a_1(1260)$	< 1.2	$\times 10^{-3}$	90%	2169
$J/\psi(1S)K^+K^-\pi^+$	seen			2203
$J/\psi(1S)\pi^+\pi^+\pi^+\pi^-\pi^-$	seen			2309
$\psi(2S)\pi^+$	seen			2052
$J/\psi(1S)D_s^+$	seen			1822
$J/\psi(1S)D_s^{*+}$	seen			1728
$J/\psi(1S)p\overline{p}\pi^+$	seen			1792
$\chi_c^0\pi^+$	$(2.4^{+0.9}_{-0.8})$	$\times 10^{-5}$		2205
$p\overline{p}\pi^+$	not seen			2970
$D^*(2010)^+\overline{D}^0$	< 6.2	$\times 10^{-3}$	90%	2467
D^+K^{*0}	< 0.20	$\times 10^{-6}$	90%	2783
$D^+\overline{K}^{*0}$	< 0.16	$\times 10^{-6}$	90%	2783
$D_s^+K^{*0}$	< 0.28	$\times 10^{-6}$	90%	2751
$D_s^+\overline{K}^{*0}$	< 0.4	$\times 10^{-6}$	90%	2751
$D_s^+\phi$	< 0.32	$\times 10^{-6}$	90%	2727
K^+K^0	< 4.6	$\times 10^{-7}$	90%	3098
$B_s^0\pi^+$ / B($\bar{b} \to B_s$)	$(2.37^{+0.37}_{-0.35})$	$\times 10^{-3}$		–