Status and prospects for spectroscopy studies at LHCb

Yuanning Gao (Tsinghua University)

On Behalf of the LHCb Collaboration

Joint BESIII-LHCb workshop **Feb. 8-9, 2018**

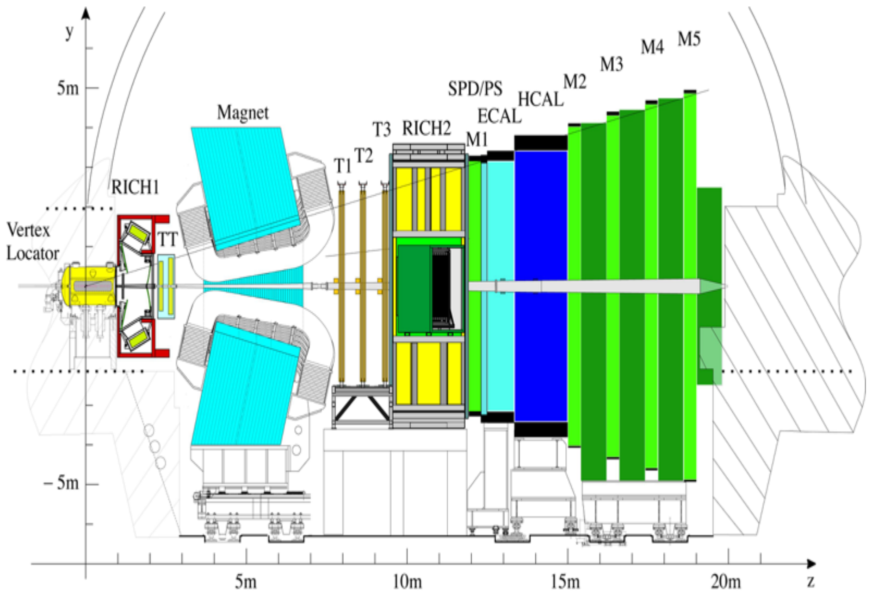
Outline

- Introduction to spectroscopy studies at LHCb
- Studies of charmonium states
- Excited charmed mesons
- Charmed and doubly charmed baryons
- Charmonium-like states
- Pentaquarks
- Selected topics on b-flavored hadrons
- Future prospects

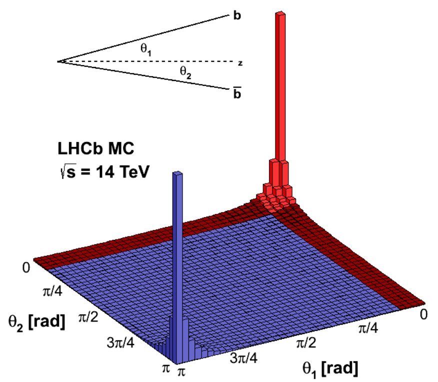
LHCb Detector

LHCb, Int. J. Mod. Phys. A30 (2015) 1530022

Forward spectrometer running in pp collider



- $2 < \eta < 5$ range: $\sim 25\%$ of $b\bar{b}$ pairs inside LHCb acceptance



Excellent vertex and IP, decay time resolution:

- $\sigma(\text{IP}) \approx 20$ μm for high-p_T tracks
- $\sigma(\tau) \approx 45$ fs for $B_s^0 \to J/\psi\phi$ and $B_s^0 \to D_s^-\pi^+$ decays

Very good momentum resolution:

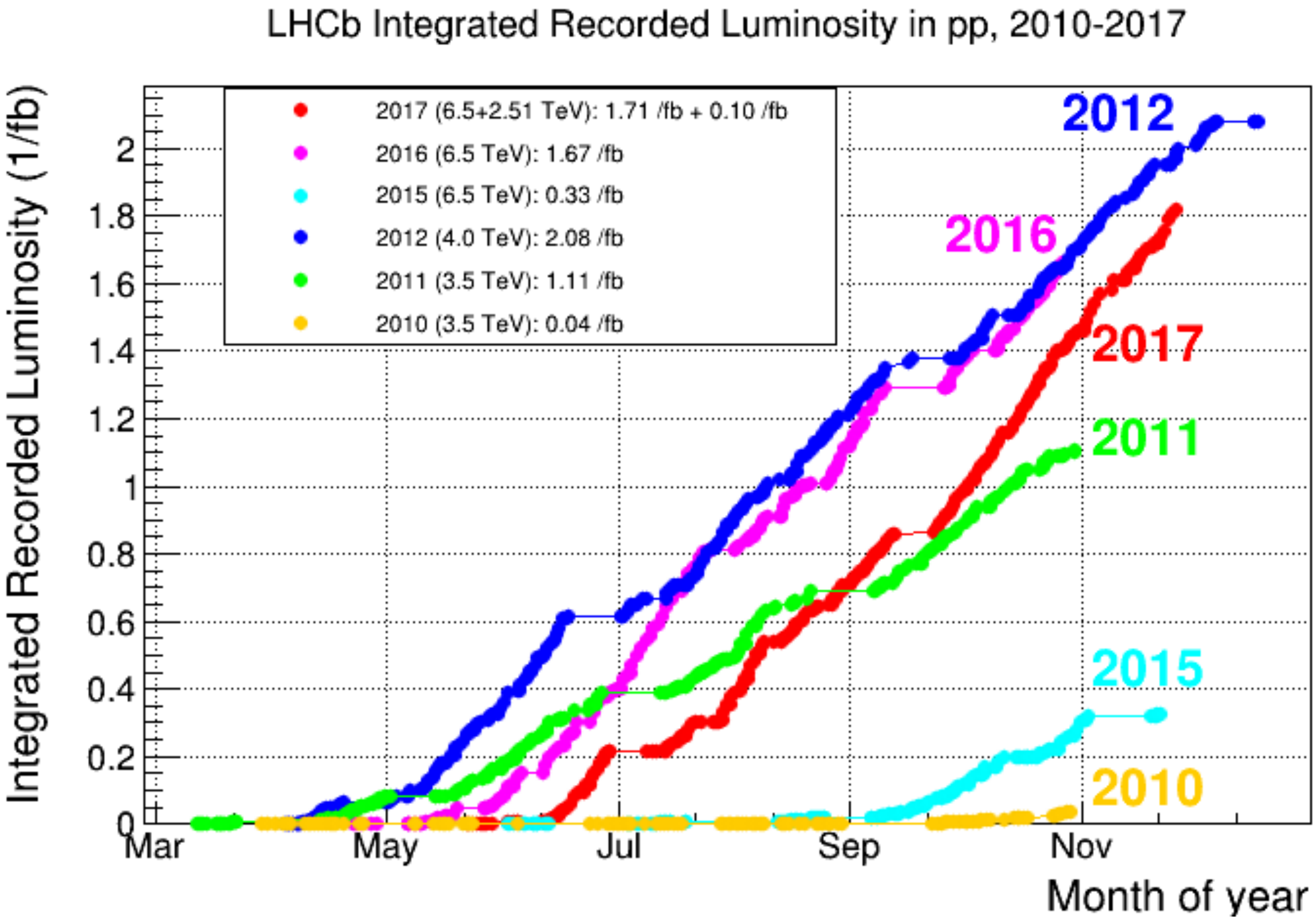
- $\delta p/p \approx 0.5\% - 1\%$ for $p \in (0,200)$ GeV
- $\sigma(m_B) \approx 24$ MeV for two-body decays

Hadron and Muon identification

- $\epsilon_{K\to K} \approx 95\%$ for $\epsilon_{\pi\to K} \approx 5\%$ up to 100 GeV
- $\epsilon_{\mu\to\mu} \approx 97\%$ for $\epsilon_{\pi\to\mu} \approx 1-3\%$

Data good for analyses

- $> 99\%$

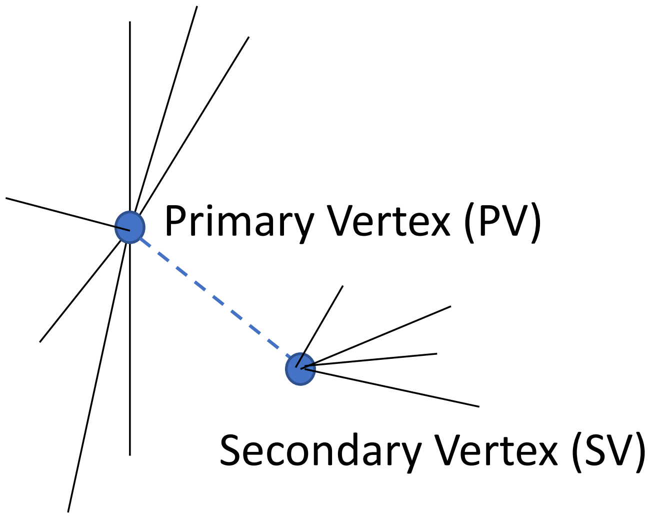

LHCb Integrated Recorded Luminosity in pp, 2010-2017
2017 (6.5+2.51 TeV): 1.71 /fb + 0.10 /fb
2016 (6.5 TeV): 1.67 /fb
2015 (6.5 TeV): 0.33 /fb
2012 (4.0 TeV): 2.08 /fb
2011 (3.5 TeV): 1.11 /fb
2010 (3.5 TeV): 0.04 /fb
2012
2016
2017
2011
2015
2010
Integrated Recorded Luminosity (1/fb)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Mar
May
Jul
Sep
Nov
Month of year

Physics program at LHCb

- Not only precision measurements in *b, c* sectors
  - CKM and CP-violation parameters
  - rare decays
  - testing lepton universality
  - ...
- But also a general purpose detector
  - electroweak measurements: $\sin\theta_W$, W/Z, top quark, ..
  - spectroscopy, exotic hadrons
  - soft QCD
  - heavy ions
  - ...

Experiment strategies

- Advantage: high production rates
- Challenge: reconstruct an unstable particle from O(10^2) tracks



√ tracking

→ excellent mass resolution

√ particle identification

→ no. of combinations reduced

√ Vertexing

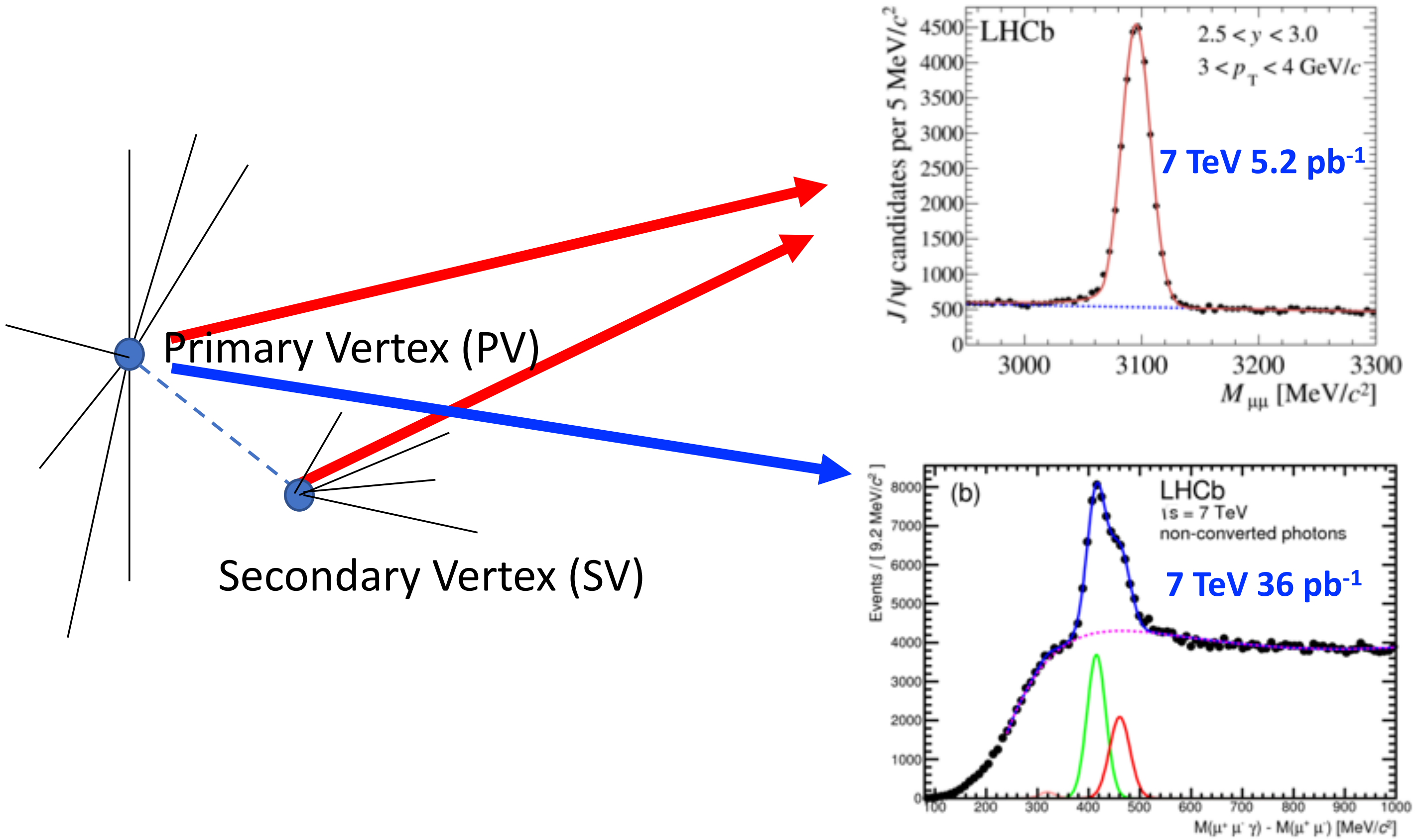
→ weakly decayed particles

→ particles from b/c decays

Charmonia studies at LHCb

- At LHCb charmonia $[c\bar{c}]$ may be accessed by

  - $[c\bar{c}] \rightarrow J/\psi(\rightarrow \mu^+\mu^-) + X$



$J/\psi \rightarrow \mu^+\mu^-$

LHCb-PAPER-2011-003
EPJC 71 (2011)1645

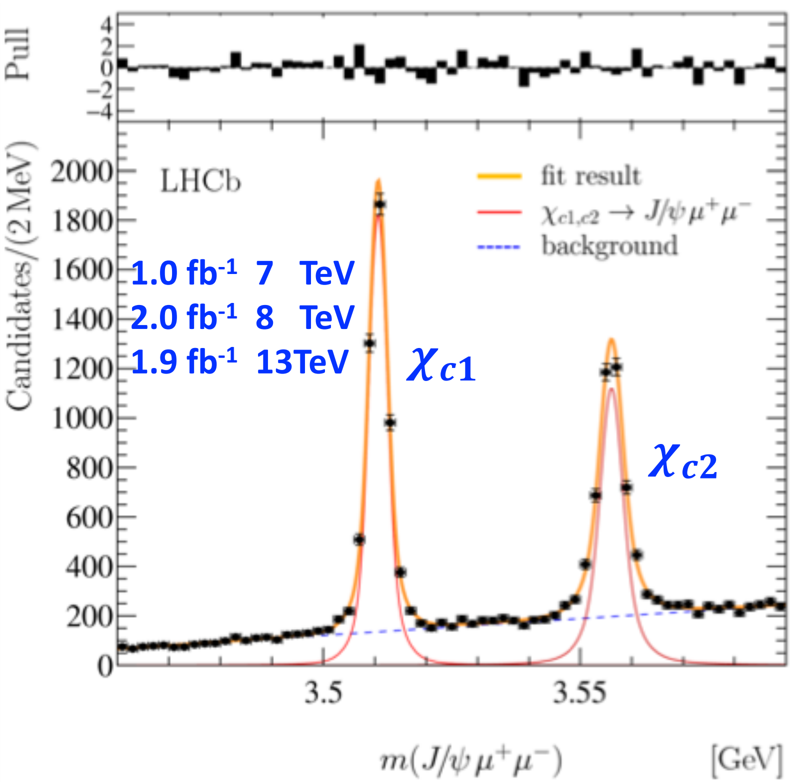
$\chi_{c1,2} \rightarrow J/\psi + \gamma$

LHCb-PAPER-2011-019
PLB 714 (2012) 215

Muonic decays of χ_{c1} and χ_{c2}

LHCb-PAPER-2017-036
PRL 119 (2017) 221801

- 1st observation of $\chi_{c1,2} \to J/\psi\mu^+\mu^-$
- Competitive mass and width measurements

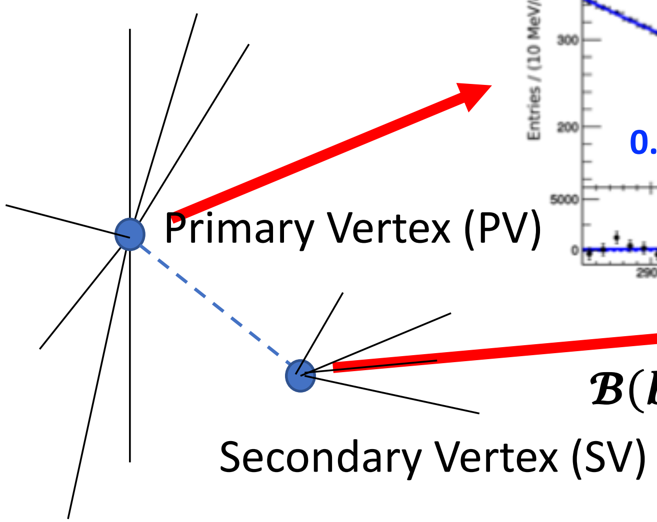


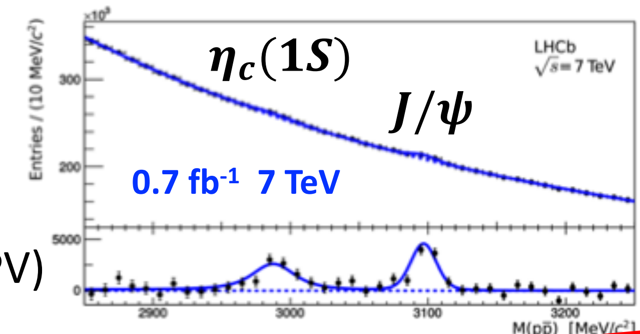
Fit parameter		Fitted value
$N(\chi_{c1})$		$4\,755 \pm 81$
$N(\chi_{c2})$		$3\,969 \pm 96$
$m(\chi_{c1})$	[MeV]	$3\,510.66 \pm 0.04$
$m(\chi_{c2})$	[MeV]	$3\,556.07 \pm 0.06$
$\Gamma(\chi_{c2})$	[MeV]	2.10 ± 0.20

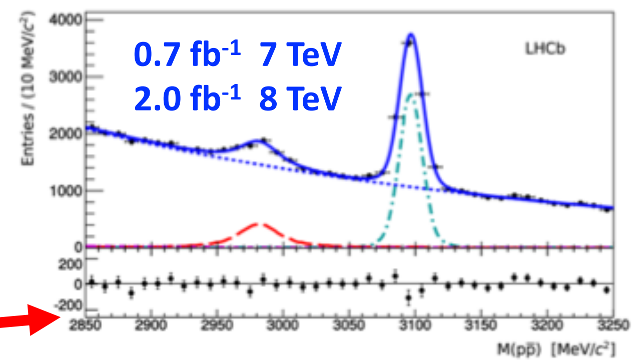
Charmonia studies at LHCb

- At LHCb charmonia $[c\bar{c}]$ may be accessed by
  - $[c\bar{c}] \to J/\psi(\to \mu^+\mu^-) + X$
  - $[c\bar{c}] \to p\bar{p}$

LHCb-PAPER-2014-029
EPJC 75 (2015) 311







$$\mathcal{B}(b \to \eta_c(1S)X) = (4.88 \pm 0.64 \pm 0.29 \pm 0.67_{\mathcal{B}})\times 10^{-3}$$

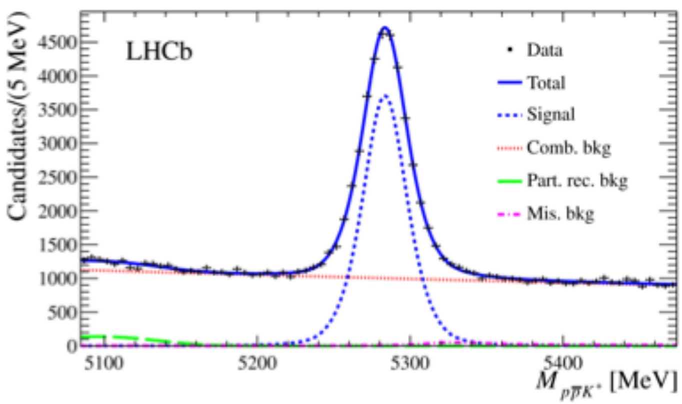
1st Observation

$$\sigma_{\eta_c(1s)} = 0.52 \pm 0.09 \pm 0.08 \pm 0.06_{\sigma_{J/\psi},\mathcal{B}}\,\mu\text{b} \quad \sqrt{s} = 7\text{ TeV}$$
$$= 0.59 \pm 0.11 \pm 0.09 \pm 0.08_{\sigma_{J/\psi},\mathcal{B}}\,\mu\text{b} \quad \sqrt{s} = 8\text{ TeV}$$

Charmonia from $B^+ \to p\bar{p}K^+$

- Exclusive reconstruction: clean sample, better control of background and resolution effects

LHCb-PAPER-2016-016
PLB 769 (2017) 305



$$m_{J/\psi} - m_{\eta_c(1S)} = 110.2 \pm 0.5 \pm 0.9\ \text{MeV}$$

$$m_{\psi(2S)} - m_{\eta_c(2S)} = 52.2 \pm 1.7 \pm 0.6\ \text{MeV}$$

$$\Gamma_{\eta_c(1S)} = 34.0 \pm 1.9 \pm 1.3\ \text{MeV}$$

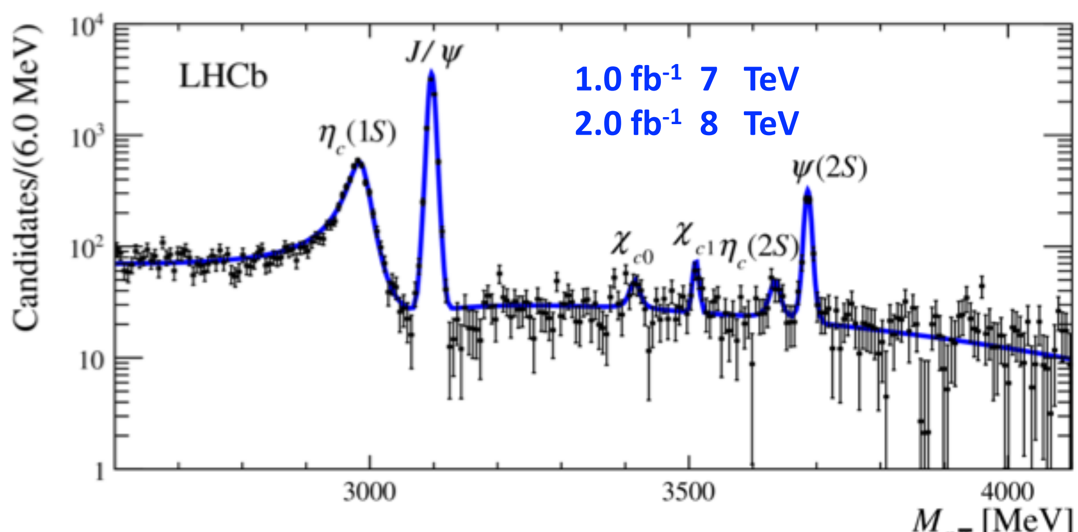
$$\mathcal{R}_{[c\bar{c}]} = \frac{\mathcal{B}(B^+ \to [c\bar{c}]K^+)\times\mathcal{B}([c\bar{c}] \to p\bar{p})}{\mathcal{B}(B^+ \to J/\psi K^+)\times\mathcal{B}(J/\psi \to p\bar{p})}$$

$$\mathcal{R}_{\eta_c(2S)} = (1.58 \pm 0.33 \pm 0.09)\times 10^{-2}$$

1 st Observation

$$\mathcal{R}_{\psi(3770)} < 10\times 10^{-2}$$

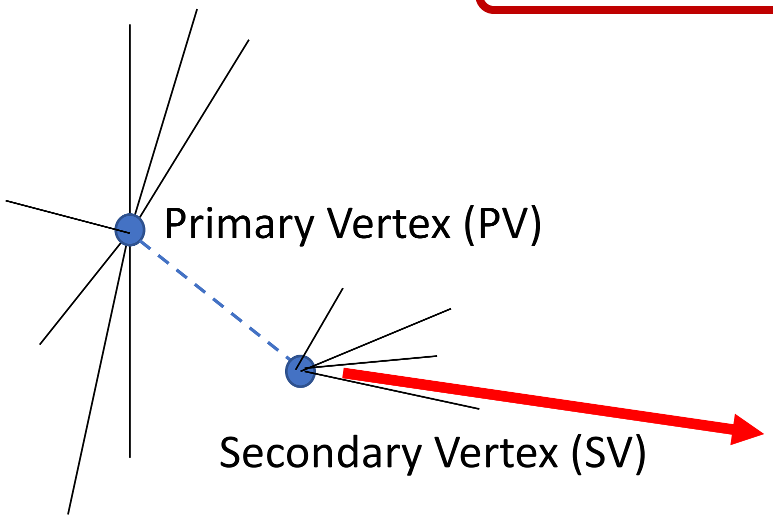
$$\mathcal{R}_{X(3872)} < 0.25\times 10^{-2}$$



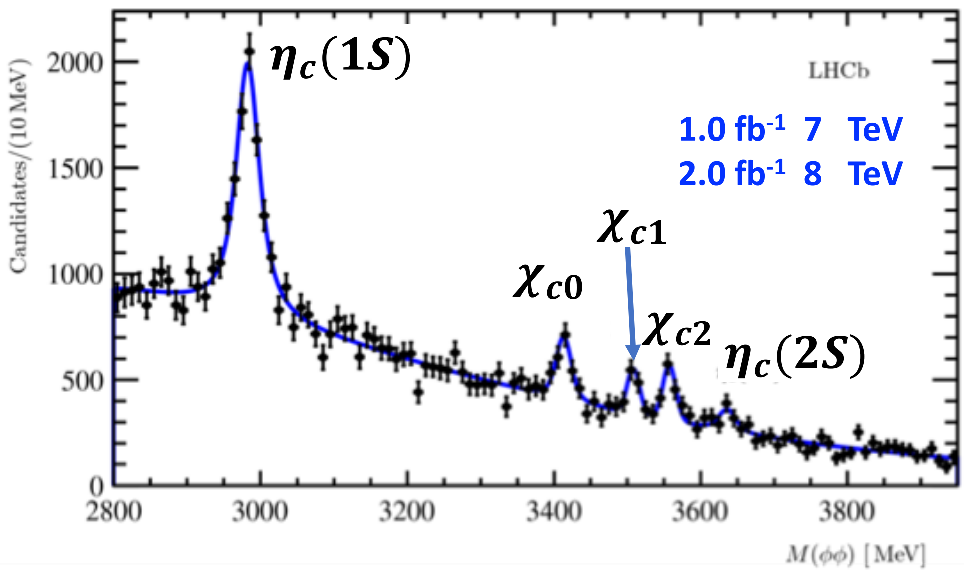
Charmonia studies at LHCb

- At LHCb charmonia $[c\bar{c}]$ may be accessed by
  - $[c\bar{c}] \to J/\psi(\to \mu^+\mu^-) + X$
  - $[c\bar{c}] \to p\bar{p}$
  - $[c\bar{c}] \to \phi\phi$

LHCb-PAPER-2017-007
EPJC 77 (2017) 609



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



Charmonia from $b \to \phi\phi + X$

- Allow to measure production ratios

LHCb-PAPER-2017-007
EPJC 77 (2017) 609

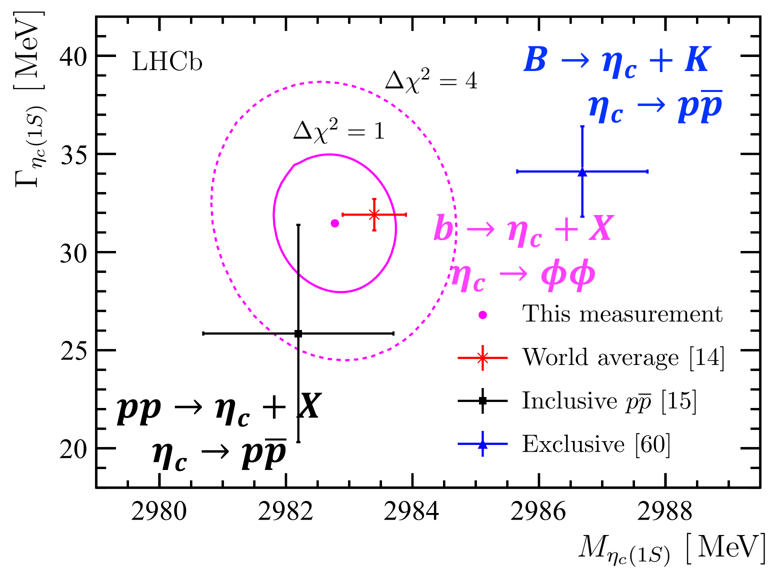
$$R^{C_1}_{C_2} \equiv \frac{\mathcal{B}(b \to C_1\, X) \times \mathcal{B}(C_1 \to \phi\,\phi)}{\mathcal{B}(b \to C_2\, X) \times \mathcal{B}(C_2 \to \phi\,\phi)}$$

$$R^{\chi_{c0}}_{\eta_c(1S)} = 0.147 \pm 0.023 \pm 0.011,$$
$$R^{\chi_{c1}}_{\eta_c(1S)} = 0.073 \pm 0.016 \pm 0.006,$$
$$R^{\chi_{c2}}_{\eta_c(1S)} = 0.081 \pm 0.013 \pm 0.005,$$
$$R^{\chi_{c1}}_{\chi_{c0}} = 0.50 \pm 0.11 \pm 0.01,$$
$$R^{\chi_{c2}}_{\chi_{c0}} = 0.56 \pm 0.10 \pm 0.01,$$
$$R^{\eta_c(2S)}_{\eta_c(1S)} = 0.040 \pm 0.011 \pm 0.004,$$

1st Observation of $\eta_c(2S) \to \phi\phi$

- Competitive measurements of masses of widths

	Measured value	World average [14]
$M_{\eta_c(1S)}$	$2982.8 \pm 1.0 \pm 0.5$	2983.4 ± 0.5
$M_{\chi_{c0}}$	$3413.0 \pm 1.9 \pm 0.6$	3414.75 ± 0.31
$M_{\chi_{c1}}$	$3508.4 \pm 1.9 \pm 0.7$	3510.66 ± 0.07
$M_{\chi_{c2}}$	$3557.3 \pm 1.7 \pm 0.7$	3556.20 ± 0.09
$M_{\eta_c(2S)}$	$3636.4 \pm 4.1 \pm 0.7$	3639.2 ± 1.2
$\Gamma_{\eta_c(1S)}$	$31.4 \pm 3.5 \pm 2.0$	31.8 ± 0.8
$\Gamma_{\eta_c(2S)}$	–	$11.3\,^{+\,3.2}_{-\,2.9}$



$D_{sJ}^{(**)}$ spectroscopy

- Strange-charm states studied widely to test QCD models

$D_{sJ}^{*}(3040)$

$D_{sJ}^{*}(2860)$

$D_{s1}^{*}(2700)$

$D_{s2}^{*}(2573)$

$D_{s1}(2536)$

$D_{s1}(2460)$

$D_{s0}^{*}(2317)$

D_{s}^{*}

D_{s}

States observed from B-factories and other experiments

- $D_s^*, D_{s0}^*(2317)$ below DK threshold
- States with unnatural spin-parity ($J^P = 0^-, 1^+, 2^-, \ldots$)

$D_{sJ}^{(**)}$ spectroscopy

- Strange-charm states studied widely to test QCD models
  - Inclusive $pp \to (D^+K^0, D^0K^+) + X$ LHCb-PAPER-2012-016 JHEP 10 (2012) 151

    $D_{s2}^*(2573), D_{s1}^*(2700), D_{sJ}^*(2860)$

$D_{sJ}^*(3040)$

$D_{sJ}^*(2860)$

$D_{s1}^*(2700)$

$D_{s2}^*(2573)$

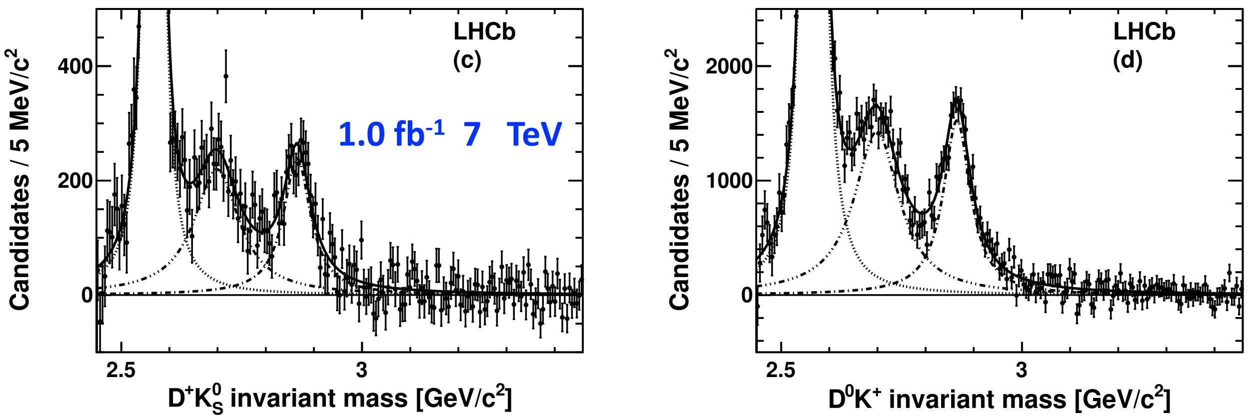
$D_{s1}(2536)$

$D_{s1}(2460)$

$D_{s0}^*(2317)$

D_s^*

D_s



States observed from B-factories and other experiments
- $D_s^*, D_{s0}^*(2317)$ below *DK* threshold
- States with unnatural spin-parity ($J^P = 0^-, 1^+, 2^-, \ldots$)

$D_{sJ}^{(**)}$ spectroscopy

- Strange-charm states studied widely to test QCD models

$D_{sJ}^*(3040)$

$D_{sJ}^*(2860)$

$D_{s1}^*(2700)$

$D_{s2}^*(2573)$

$D_{s1}(2536)$

$D_{s1}(2460)$

$D_{s0}^*(2317)$

D_s^*

D_s

- Inclusive $pp \to (D^+K^0, D^0K^+) + X$ LHCb-PAPER-2012-016 JHEP 10 (2012) 151
  $D_{s2}^*(2573), D_{s1}^*(2700), D_{sJ}^*(2860)$
- Dalitz plot analysis $B_s^0 \to \overline{D}^0 K^- \pi^+$ reveals two states $D_{s1}^*(2860), D_{s3}^*(2860)$

LHCb-PAPER-2014-035 PRL 113 (2014) 162001

LHCb-PAPER-2014-036 PRD 90 (2014) 072003

States observed from B-factories and other experiments

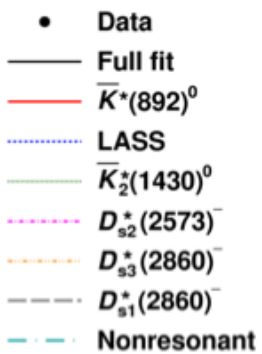
- $D_s^*, D_{s0}^*(2317)$ below *DK* threshold
- States with unnatural spin-parity ($J^P = 0^-, 1^+, 2^-, \ldots$)

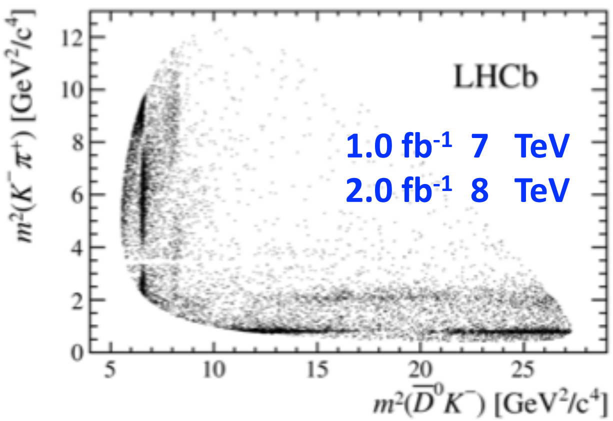
Dalitz plot analysis $B_s \to \bar{D}^0 K^- \pi^+$

- ~11K signal events with purity 87%

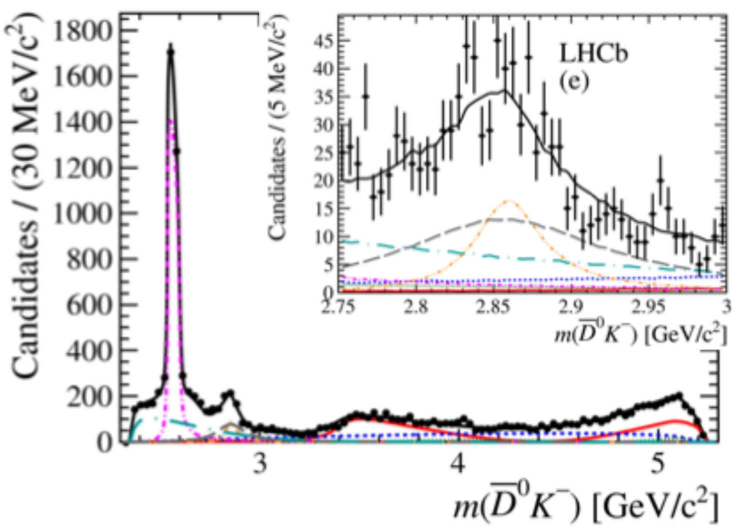
LHCb-PAPER-2014-035
PRL 113 (2014) 162001

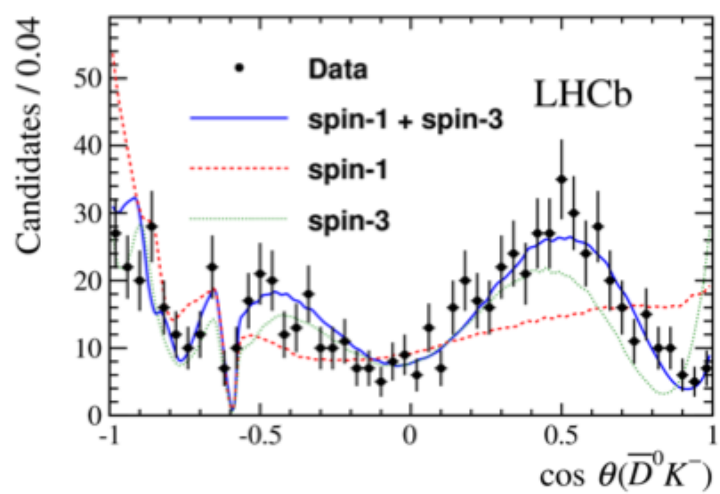
LHCb-PAPER-2014-036
PRD 90 (2014) 072003





1st Observation of of a heavy flavored spin-3 resonance





$D_{sJ}^{(**)}$ spectroscopy

- Strange-charm states studied widely to test QCD models

$D_{sJ}^*(3040)$

$D_{sJ}^*(2860)$

$D_{s1}^*(2700)$

$D_{s2}^*(2573)$

$D_{s1}(2536)$

$D_{s1}(2460)$

$D_{s0}^*(2317)$

D_s^*

D_s

- Inclusive $pp \to (D^+K^0, D^0K^+) + X$ LHCb-PAPER-2012-016 JHEP 10 (2012) 151
  $D_{s2}^*(2573), D_{s1}^*(2700), D_{sJ}^*(2860)$
- Dalitz plot analysis $B_s^0 \to \overline{D}^0K^-\pi^+$ reveals two states $D_{s1}^*(2860), D_{s3}^*(2860)$
  LHCb-PAPER-2014-035 PRL 113 (2014) 162001
  LHCb-PAPER-2014-036 PRD 90 (2014) 072003
- Inclusive $pp \to (D^{*+}K^0, D^{*0}K^+) + X$
  $D_{s1}^*(2536), D_{s2}^*(2573), D_{s1}^*(2700), D_{s3}^*(2860), D_{sJ}^*(3040)$
  LHCb-PAPER-2015-052 JHEP 02 (2016) 133

States observed from B-factories and other experiments
- $D_s^*, D_{s0}^*(2317)$ below *DK* threshold
- States with unnatural spin-parity ($J^P = 0^-, 1^+, 2^-, \ldots$)

Inclusive analysis $pp \rightarrow (D^{*+}K^0, D^{*0}K^+) + X$

- Resonant contribution seen due to $D_{s1}^*(2536), D_{s2}^*(2573), D_{s1}^*(2700)$ and $D_{s3}^*(2860)$, weak evidence of $D_{sJ}^*(3040)$

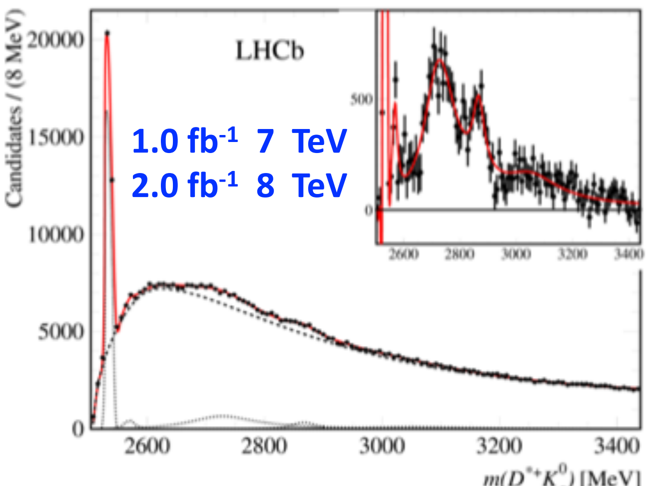
LHCb-PAPER-2015-052
JHEP 02 (2016) 133

- Angular distribution reflects the spin-parity assignment

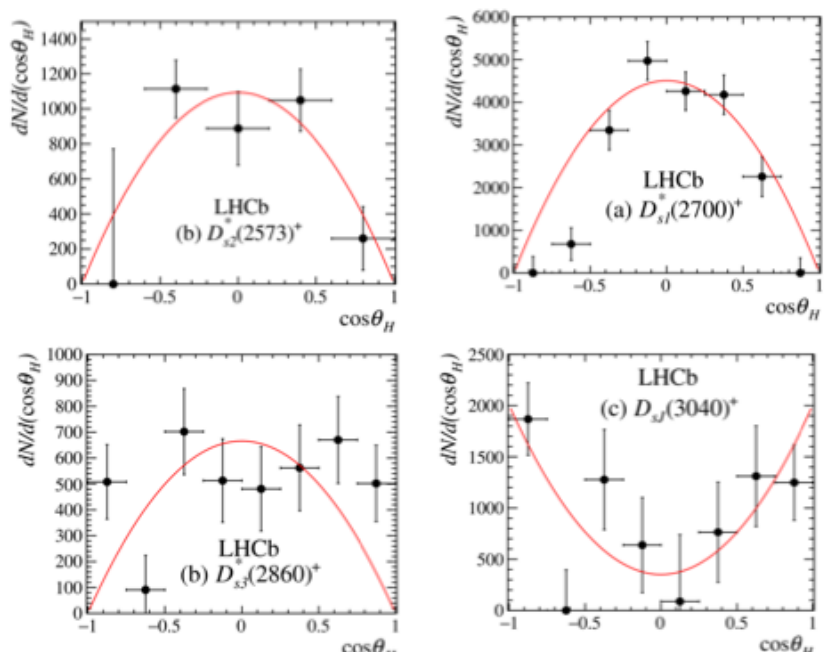
$\sin^2\theta_H$	Natural Spin-Parity
$1 + h\cos^2\theta_H$	Unnatural Spin-Parity

$D_{sJ}^{(**)} \rightarrow D\pi K$ rest frame

θ_H: angle between πK



$D^{*+} \rightarrow D^0\pi^+, D^0 \rightarrow K^-\pi^+$ sample



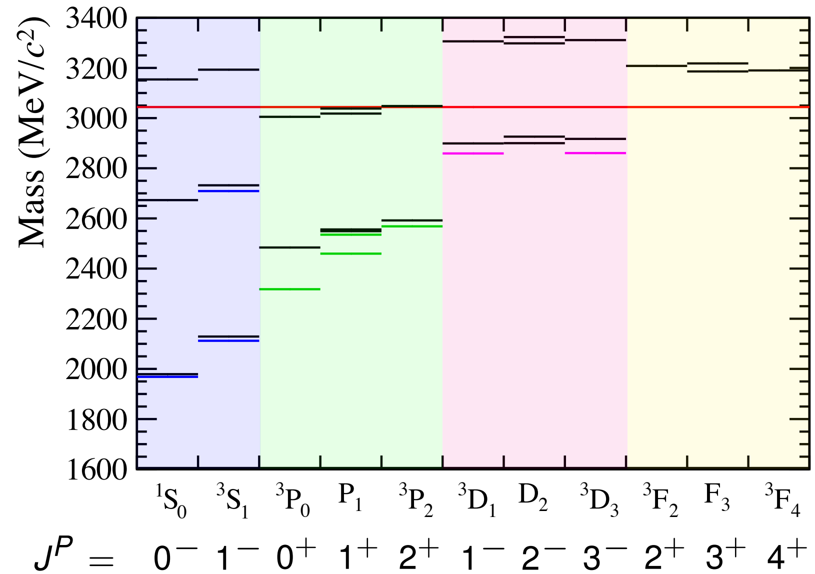
Possible assignment of $D_{sJ}^{(**)}$ states

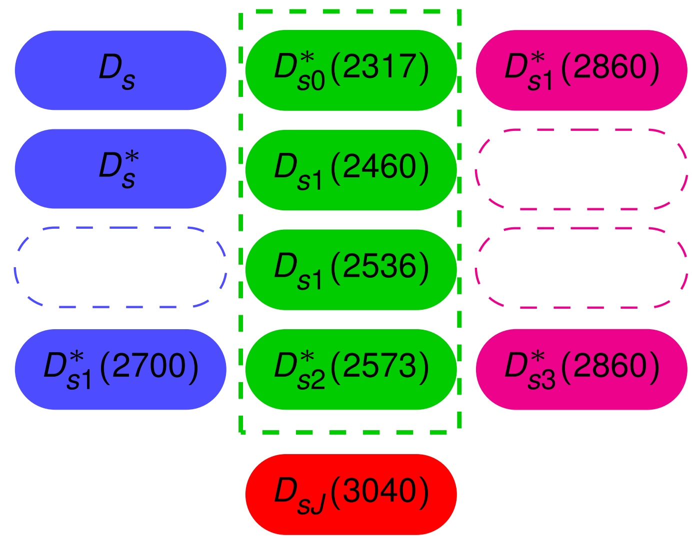
- Recent theory predictions

  S. Godfrey, I. T. Jardine, PRD 89 (2014) 072043

- Two states observed by LHCb could fit into the 1D states

- At least three more states expected up to 3 GeV/c^2





$D_J^{0(**)}$ spectroscopy

- Similar for $D_J^{0(**)}$ spectroscopy
- Recent theory predictions

  S. Godfrey, K. Moats, PRD 93 (2016) 034035

- Inclusive studies

  $e^+e^-, pp \to D^{(*)+}\pi^- X$

  BaBar, PRD 82(2011) 111101 LHCb-PAPER-2013-026 JHEP 09 (2013) 145

  Dalitz plot analyses

  LHCb-PAPER-2014-070 PRD 92 (2015) 032002

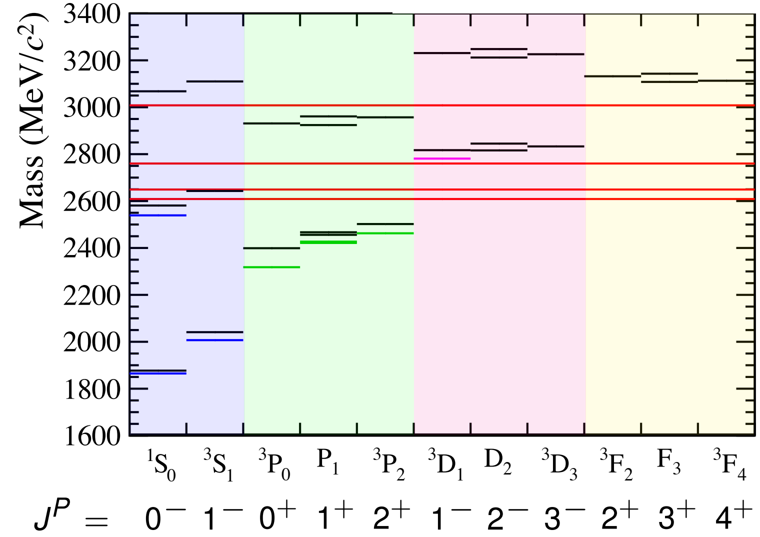
  $B^0 \to \overline{D}^0\pi^+\pi^-$

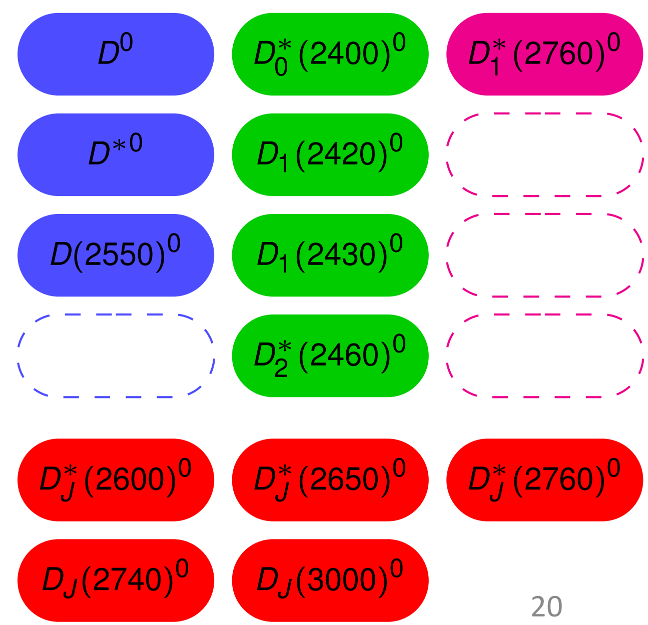
  $B^0 \to \overline{D}^0 K^+\pi^-$

  LHCb-PAPER-2015-017 PRD 92 (2015) 012012

- New states

  some have unknown J^P

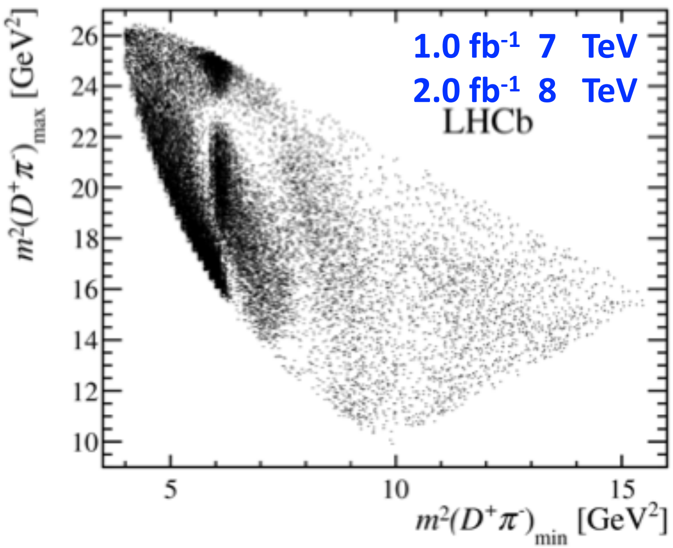


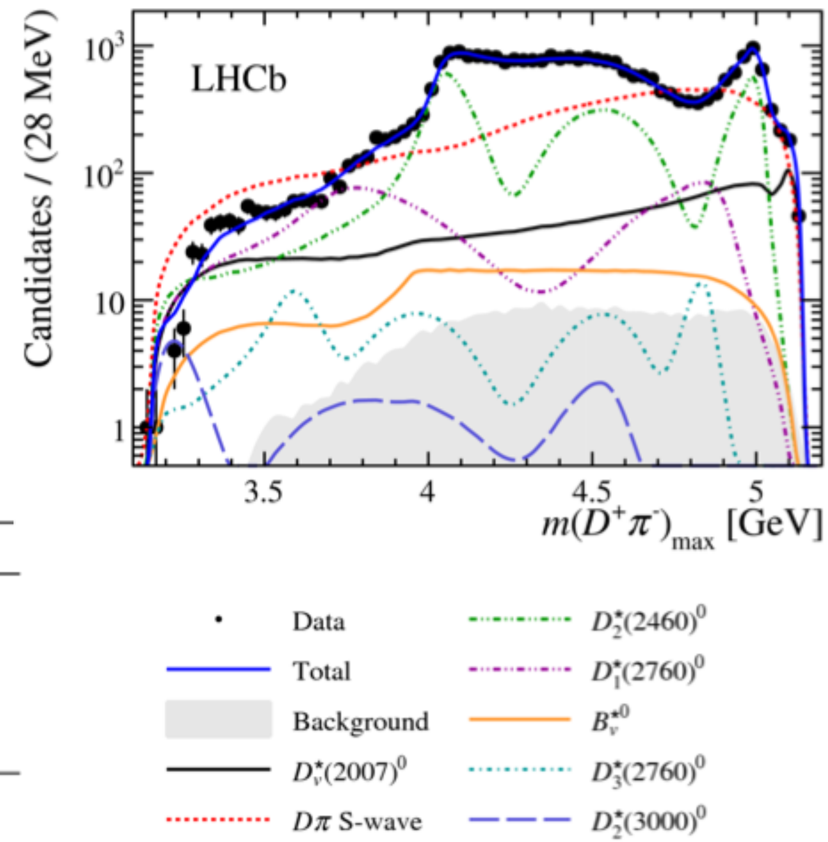


Dalitz plot analysis $B^- \to D^+\pi^-\pi^-$

- ~28000 events with 1% background

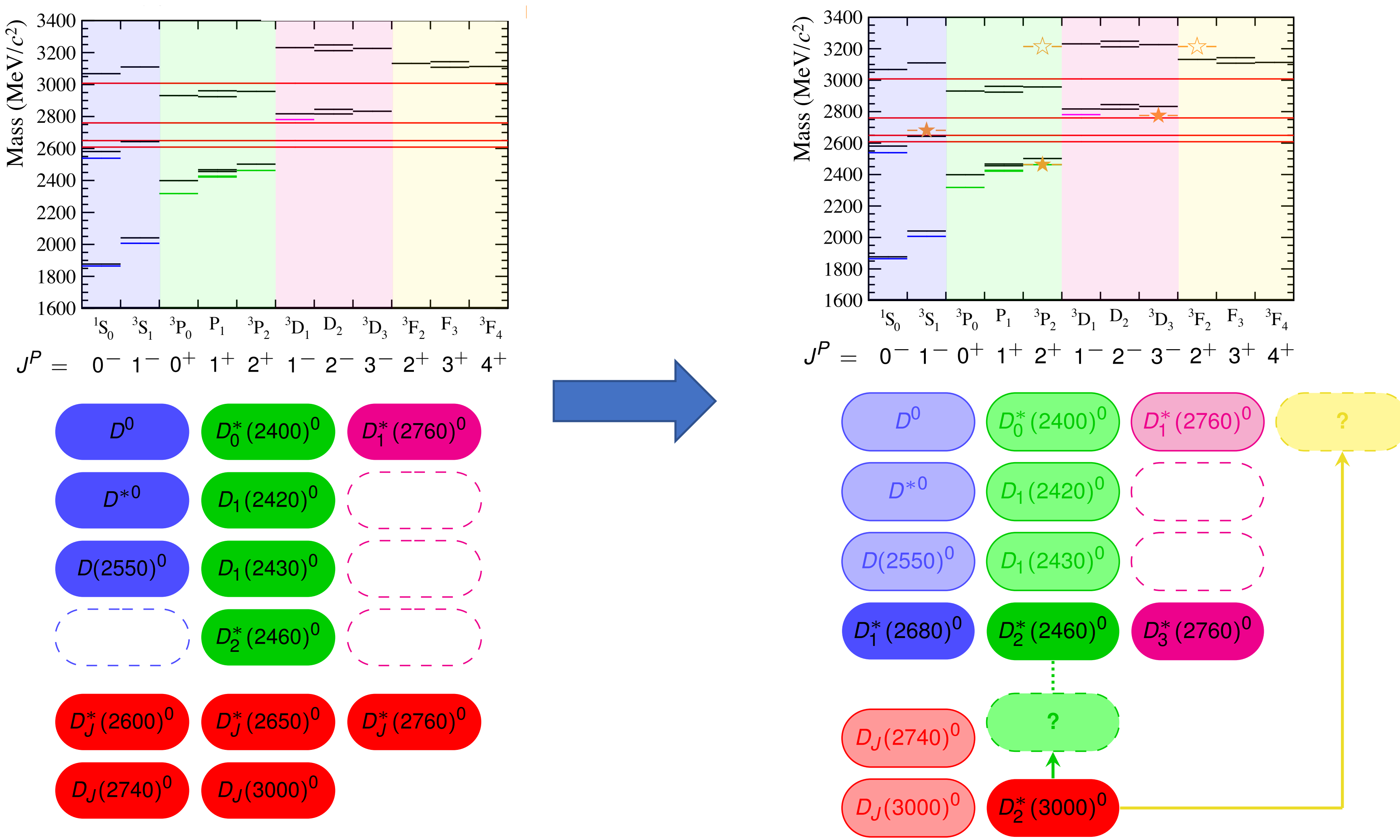
LHCb-PAPER-2016-026
PRD 94 (2016) 072001





Resonance	Branching fraction (10^{-4})
$D_2^*(2460)^0$	$3.62 \pm 0.06 \pm 0.14 \pm 0.09 \pm 0.25$
$D_1^*(2680)^0$	$0.84 \pm 0.06 \pm 0.07 \pm 0.18 \pm 0.06$
$D_3^*(2760)^0$	$0.10 \pm 0.01 \pm 0.01 \pm 0.02 \pm 0.01$
$D_2^*(3000)^0$	$0.02 \pm 0.01 \pm 0.01 \pm 0.01 \pm 0.00$
$D_v^*(2007)^0$	$1.09 \pm 0.07 \pm 0.07 \pm 0.24 \pm 0.07$
B_v^*	$0.27 \pm 0.10 \pm 0.14 \pm 0.16 \pm 0.02$
Total S-wave	$5.78 \pm 0.08 \pm 0.06 \pm 0.09 \pm 0.39$

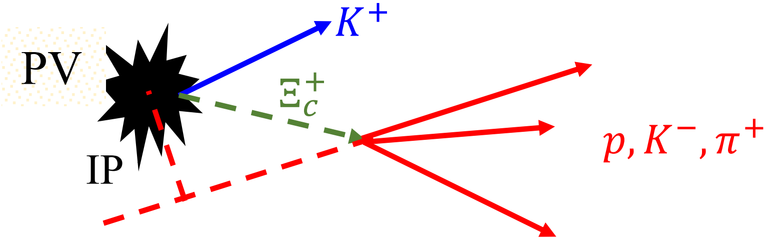
Possible assignment of $D_J^{0(**)}$ states



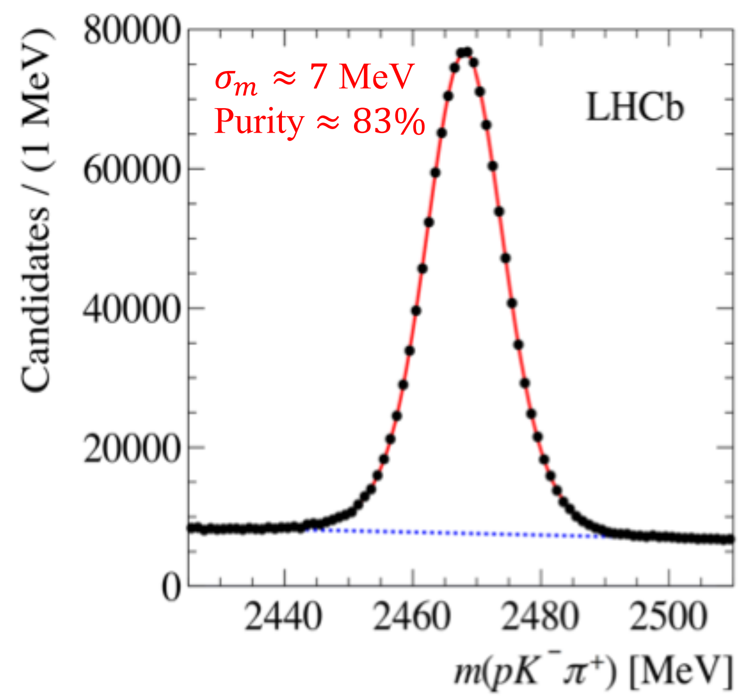
Observation of exited Ω_c states

LHCb, PRL 118 (2017) 182001

- **Excited $\Lambda_c^+, \Sigma_c, \Xi_c$ states have been reported but no excited Ω_c^0 states were observed before LHCb**
- **3 fb^{-1} Run I + 0.3 fb^{-1} Run II pp collisions data**
- **Decay: $\Omega_c^{**0} \to \Xi_c^+ K^-,\ \Xi_c^+ \to pK^-\pi^+$**



Cabibbo suppressed decay, but much higher reconstruction efficiency

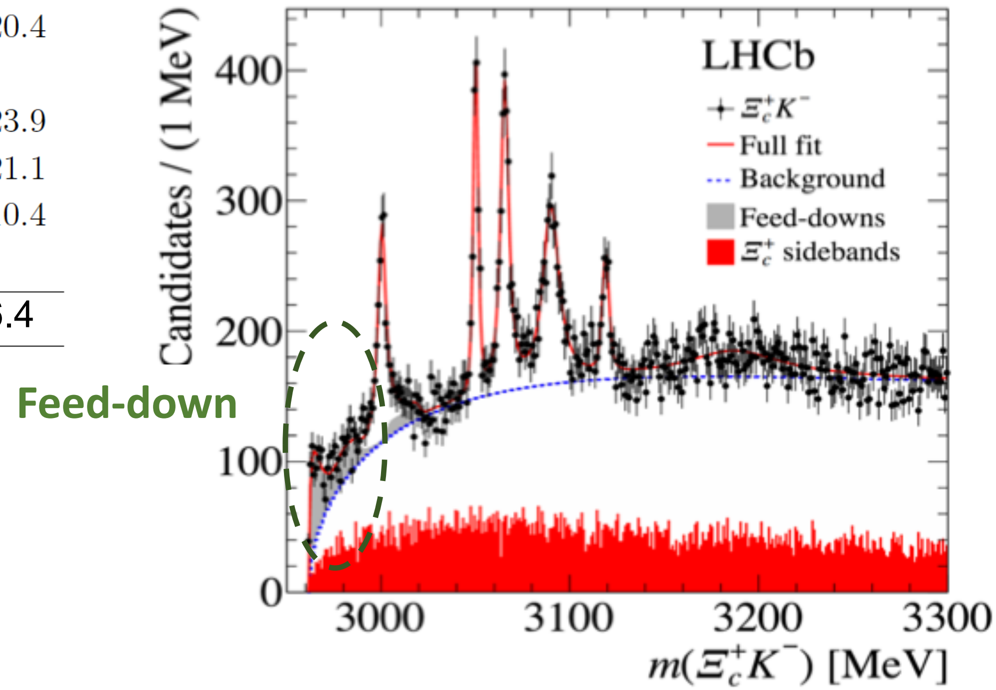


Observation of exited Ω_c states

LHCb, PRL 118 (2017) 182001

- **5 narrow states & evidence for 6th broader state at high mass**

Resonance	Mass (MeV)	Γ (MeV)	$N_\sigma = \sqrt{\Delta\chi^2}$
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$	20.4
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$ $< 1.2\,\text{MeV}, 95\%$ CL	20.4
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$	23.9
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$	21.1
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$ $< 2.6\,\text{MeV}, 95\%$ CL	10.4
$\Omega_c(3188)^0$	$3188 \pm 5 \pm 13$	$60 \pm 15 \pm 11$	6.4



Even at the most powerful particle accelerator on Earth, the discovery of a new particle is a big deal. Finding five new baryons in one go, as the Large Hadron Collider beauty experiment (LHCb) has done, is truly historical.

- Matteo Rini *Physics*

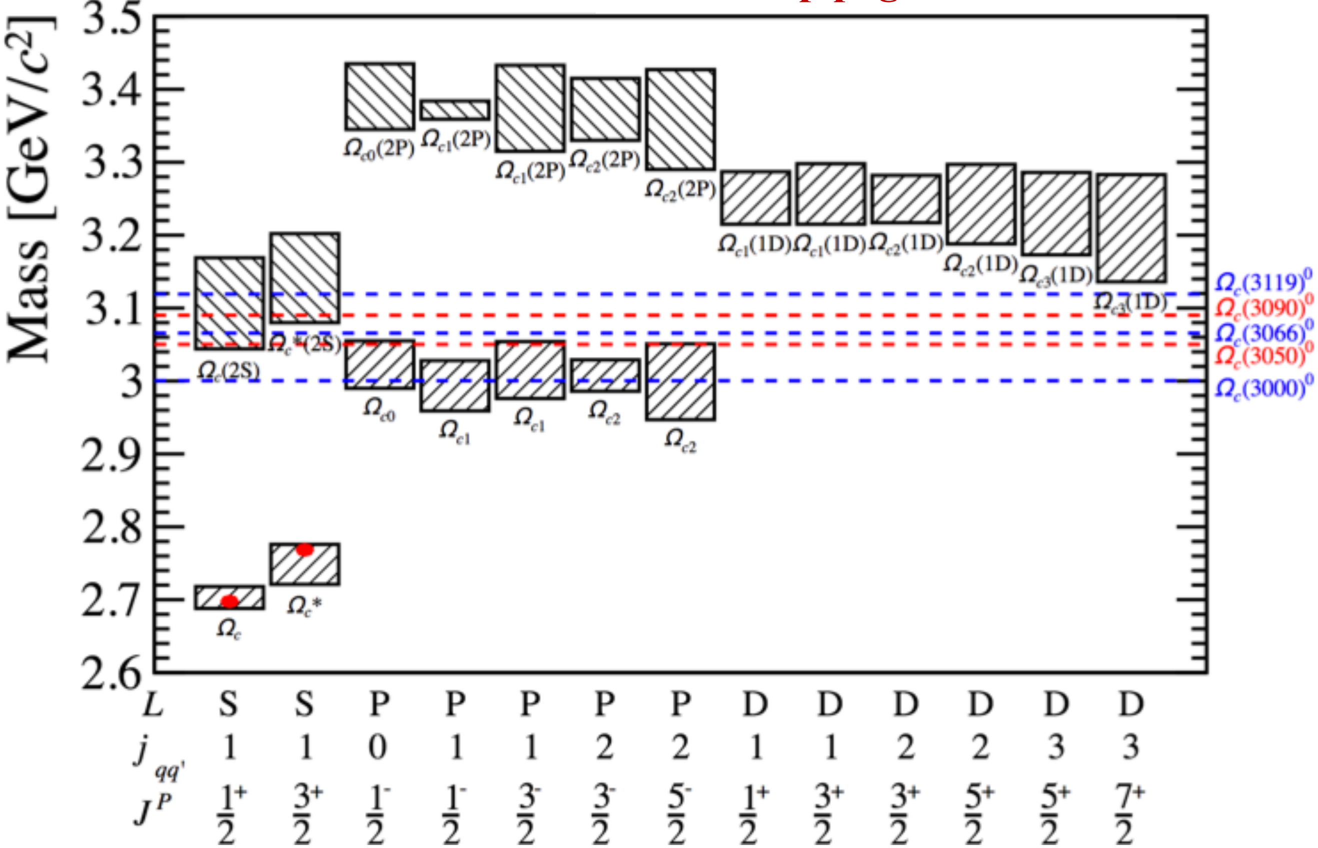
Feed-down: $\Omega_c^{**0} \to K^- \Xi_c'^+, \Xi_c'^+ \to \gamma \Xi_c^+$,
$m(\Xi_c^+ K^-)$ mass peaks shifted

Observation of exited Ω_c states

LHCb, PRL 118 (2017) 182001

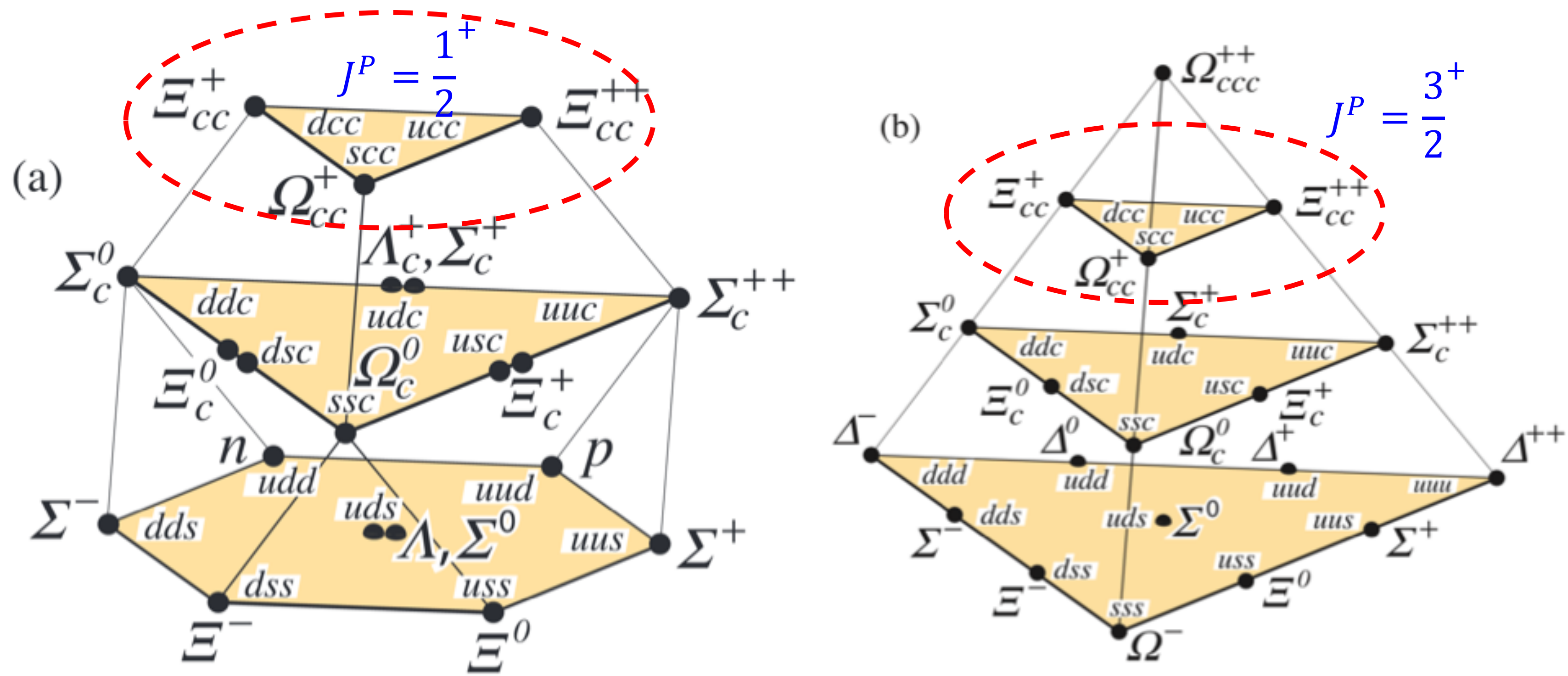
- Matching between observed peaks and predictions requires spin-parity information: studied with three-body decays or in decays of heavier baryons

See backup pages for the references



Doubly charmed baryons

- **Predicted to form two SU(4) baryon 20-plets with $J^P = \frac{1}{2}^+$ and $J^P = \frac{3}{2}^+$, each contains a SU(3) triplet with two *c* quarks: $\Xi_{cc}^{+}(ccd)$, $\Xi_{cc}^{++}(ccu)$, $\Omega_{cc}^{+}(ccs)$**
- **$J^P = \frac{3}{2}^+$ expected to decay to $\frac{1}{2}^+$ states via strong/electromagnetic interaction**
- **$J^P = \frac{1}{2}^+$ states decay weakly with a *c* quark transformed to lighter quarks**

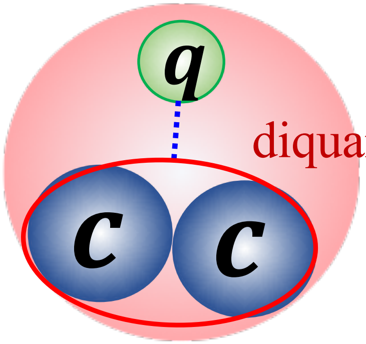


Masses and lifetimes

- **Masses of ground state and excitations by many theoretical models**
  - **Predicted $\Xi_{cc}^{+,++}$ masses $3.5-3.7$ GeV, $M(\Omega_{cc}^{+}) \approx M(\Xi_{cc}) + 0.1$ GeV**
  - **Mass splitting between Ξ_{cc}^{+} and Ξ_{cc}^{++} only a few MeV due to u, d symmetry**

Lattice QCD computations: $M(\Xi_{cc}) \approx 3.6\ \mathrm{GeV}, \quad M(\Omega_{cc}^{+}) \approx 3.7\ \mathrm{GeV}$

HQET: two charm quarks considered as a heavy diquark, doubly heavy baryon similar to a heavy meson Qq



- **Lifetime known to be affected by**

spectator + non-spectator + Pauli interference

$$\tau(\Xi_{cc}^{++}(ccu)) \gg \tau(\Xi_{cc}^{+}(ccd))$$

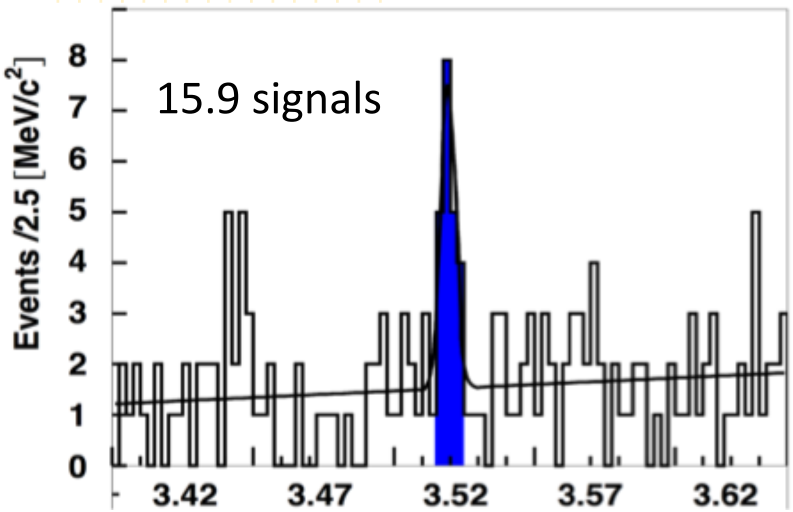
$$\tau(\Xi_{cc}^{++}) \in [\,200-700]\ \mathrm{fs}$$

See backup pages for the references

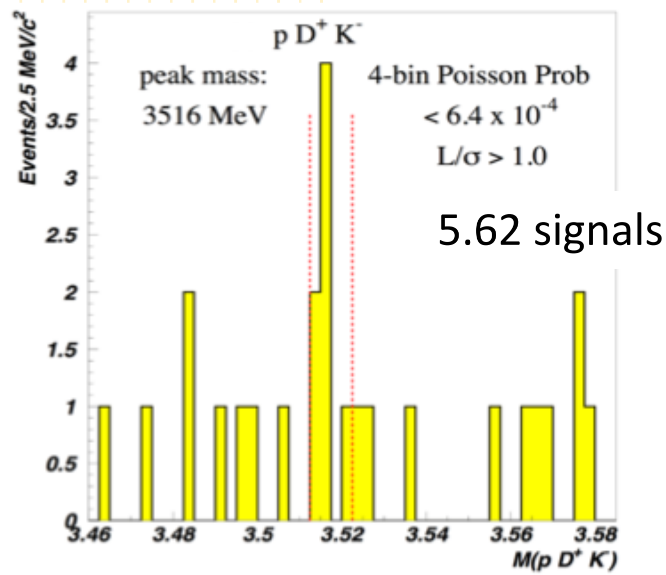
Results from SELEX

- **SELEX (Fermilab E781) collides high energy hyperon beams (Σ^-, p) with nuclear targets, dedicated to study charm baryons**
- **Observed $\Xi_{cc}^+(ccd)$ in $\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+$ and $\Xi_{cc}^+ \to p D^+ K^-$ decays**
  - **Short lifetime**: $\tau(\Xi_{cc}^+) < 33$ fs @90% CL, but not zero
  - **Large production:** $R = \frac{\sigma(\Xi_{cc}^+) \times \mathrm{BF}(\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+)}{\sigma(\Lambda_c^+)} \sim 20\%$
  - **Mass (combined):** 3518.7 ± 1.7 MeV

$\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+$ **PRL 89 (2002) 112001**



$\Xi_{cc}^+ \to p D^+ K^-$ **PLB 628 (2005) 18**



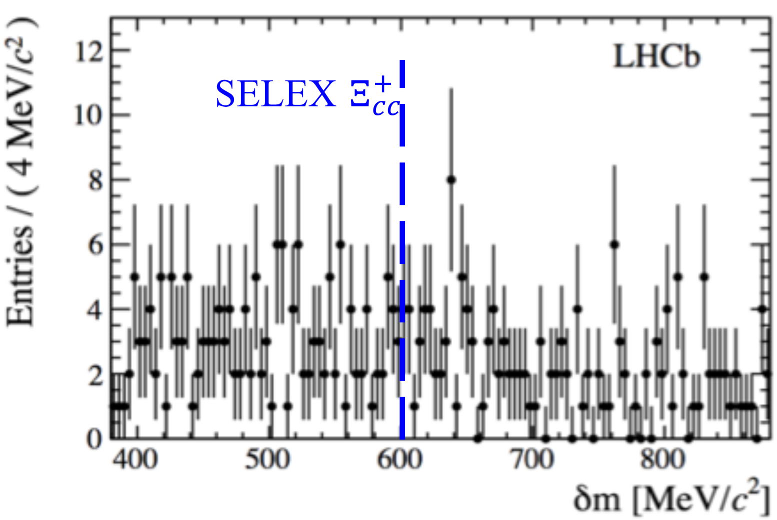
Previous studies from LHCb

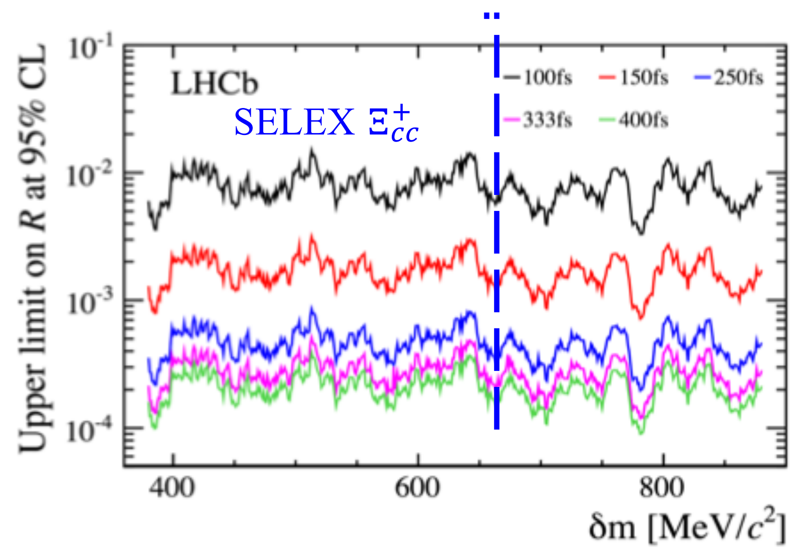
LHCb-PAPER-2013-049
JHEP 12 (2013) 090

- **SELEX results not confirmed by FOCUS, BaBar & Belle**
- **LHCb searched for $\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+}$ decay with 0.65 fb^{-1} of 7 TeV data**
  - $N(\Lambda_c^{+}) \approx 0.8$ M, requiring high-p_T
  - No significant peaking structure observed with $m \in [3.3, 3.8]$ GeV
  - Experiment sensitivity strongly depends on Ξ_{cc}^{+} lifetime

$$R = \frac{\sigma(\Xi_{cc}^{+}) \times \mathrm{BF}(\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+})}{\sigma(\Lambda_c^{+})} < 0.013 \text{ for } \tau = 100 \text{ fs},$$

$$< 3.3 \times 10^{-4} \text{ for } \tau = 400 \text{ fs} \quad @\ 95\% \text{ CL}$$





$$\delta m = m([pK^{-}\pi^{+}]_{\Lambda_c^{+}} K^{-}\pi^{+}) - m([pK^{-}\pi^{+}]_{\Lambda_c^{+}}) - m(K^{-}) - m(\pi^{+})$$

$\Xi_{cc}^{++}(ccu)$ at LHCb

LHCb-PAPER-2017-018
PRL 119 (2017) 112001

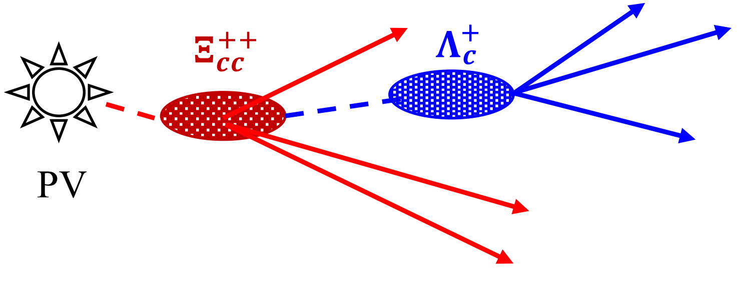
- **Expected to have longer lifetime than Ξ_{cc}^{+}, higher sensitivity at LHCb**
- **Decay: $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$, branching fraction up to 10%**

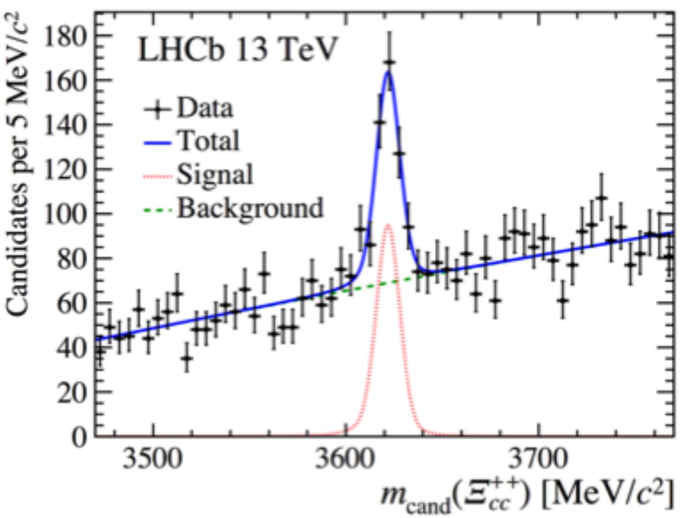
Yu et al., arXiv:1703.09086

- **LHCb run II at $\sqrt{s} = 13$ TeV, ~ 1.7 fb^{-1}**
  - 313 ± 33 **events**, 12σ
  - **8TeV data analyzed for cross-check,** 7σ
  - **Consistent with weakly decays**
  - $m(\Xi_{cc}^{++}) = 3621.40 \pm 0.72(\text{stat}) \pm 0.27(\text{syst}) \pm 0.14(\Lambda_c^+)$ MeV

    ~ 100 MeV above SELEX Ξ_{cc}^{+} peaks

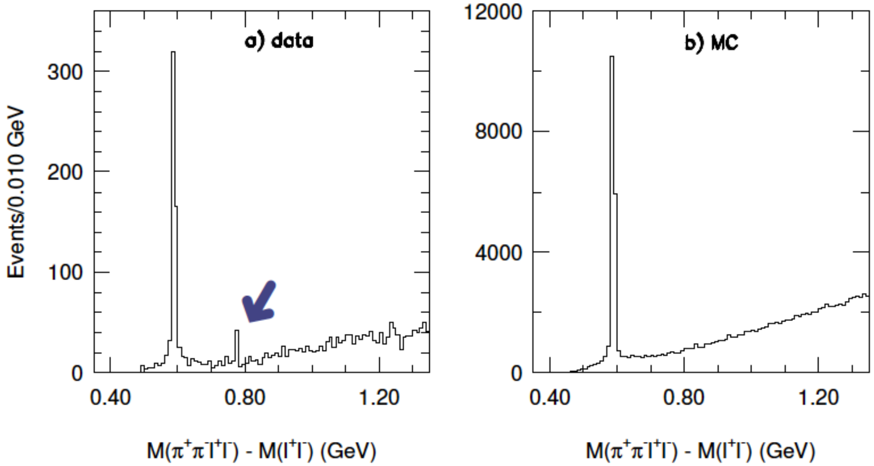
$\Xi_{cc}^{++} \to K^-\pi^+\pi^+\Lambda_c^+(\to pK^-\pi^+)$





$X(3872)$

- Observed by Belle in 2003 Belle, PRL 91 (2003) 262001



$B^{\pm} \to XK^{\pm}, X \to J/\psi\pi^{+}\pi^{-}$

$M_X = 3872.0 \pm 0.6 \pm 0.5\ \mathrm{MeV}/c^2$

$\Gamma < 2.3\ \mathrm{MeV}$

$\pi^+\pi^-$ spectrum consistent with ρ^0

- CDF determined the quantum numbers to be $J^{PC} = 1^{++}$ or 2^{-+}

CDF, PRL 98 (2007) 132002

- LHCb determined $J^{PC} = 1^{++}$ with $1\ \mathrm{fb}^{-1}$ of data

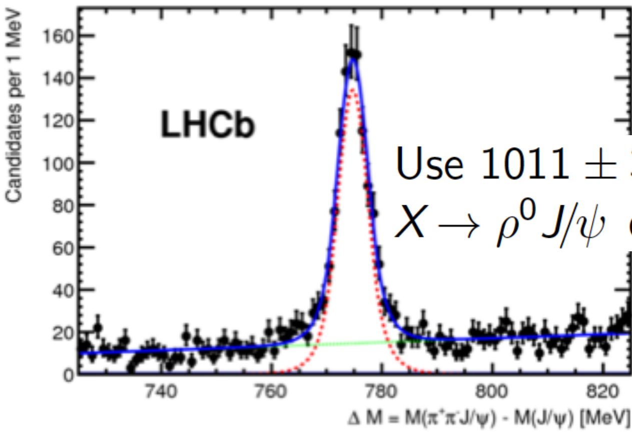
LHCb-PAPER-2013-001, PRL 110 (2013) 222001

Both CDF and LHCb assumed the decay dominated by the lowest angular momentum $L_{\min}$

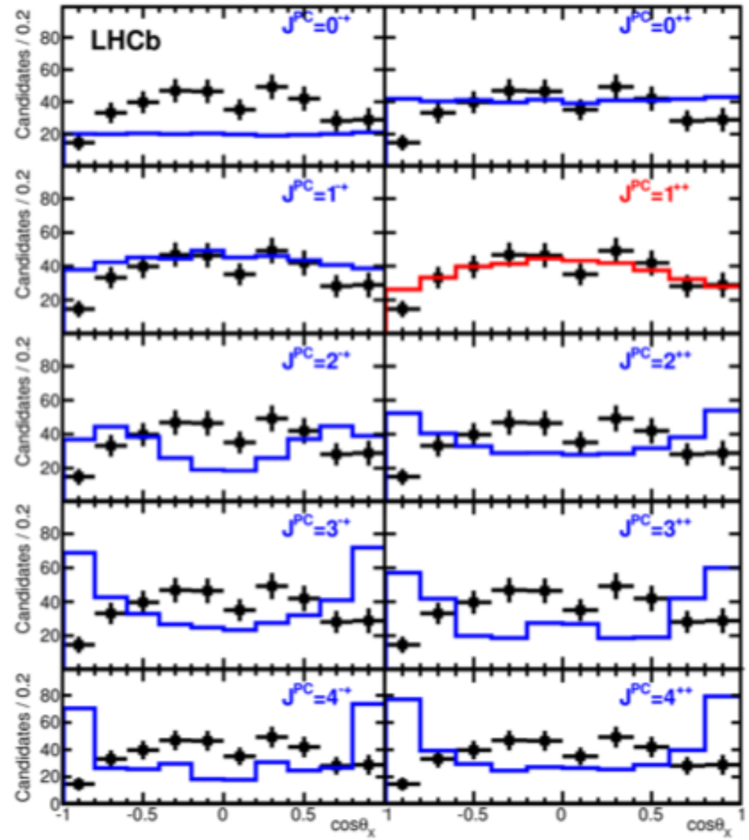
$X(3872)$ quantum number determination

- Re-analysis using 3 $\mathbf{fb}^{-1}$ of data without $L_{\mathbf{min}}$ assumption

LHCb-PAPER-2015-015
PRD 92 (2015) 011102 (R)



Use 1011 ± 38 $B^+ \to X K^+$,
$X \to \rho^0 J/\psi$ decays



	B_{LS}	
J^{PC}	Any L value	Minimal L value
0^{-+}	B_{11}	B_{11}
0^{++}	B_{00}, B_{22}	B_{00}
1^{-+}	$B_{10}, B_{11}, B_{12}, B_{32}$	B_{10}, B_{11}, B_{12}
1^{++}	B_{01}, B_{21}, B_{22}	B_{01}
2^{-+}	$B_{11}, B_{12}, B_{31}, B_{32}$	B_{11}, B_{12}
2^{++}	$B_{02}, B_{20}, B_{21}, B_{22}, B_{42}$	B_{02}
3^{-+}	$B_{12}, B_{30}, B_{31}, B_{32}, B_{52}$	B_{12}
3^{++}	$B_{21}, B_{22}, B_{41}, B_{42}$	B_{21}, B_{22}
4^{-+}	$B_{31}, B_{32}, B_{51}, B_{52}$	B_{31}, B_{32}
4^{++}	$B_{22}, B_{40}, B_{41}, B_{42}, B_{62}$	B_{22}

Parity-allowed LS couplings in
$X \to \rho^0 J/\psi$

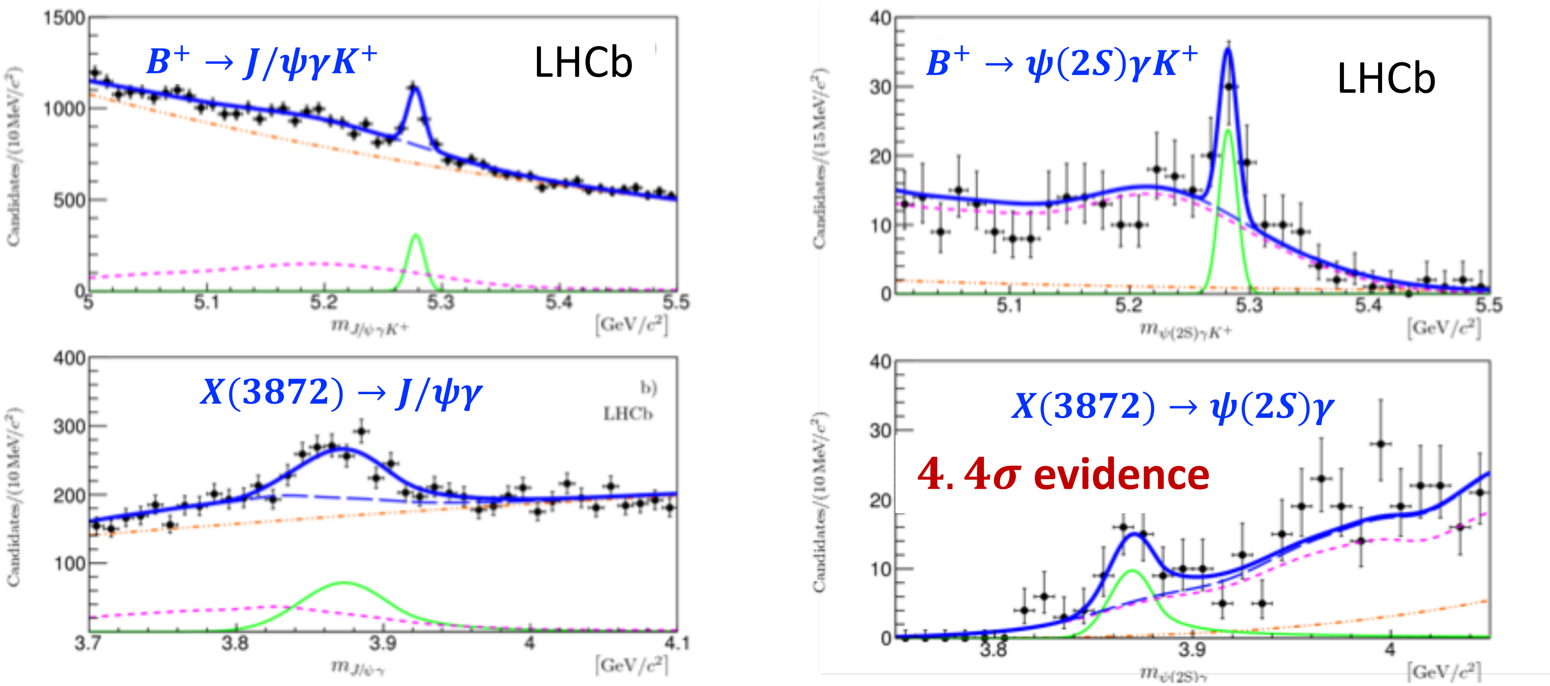
$J^{PC} = 1^{++}$ confirmed

D-wave fraction $< 4\%$

$X(3872) \to J/\psi\gamma, \psi(2S)\gamma$

LHCb-PAPER-2014-008
NPB 886 (2014) 665

- Analyses using 3 fb^{-1} of data



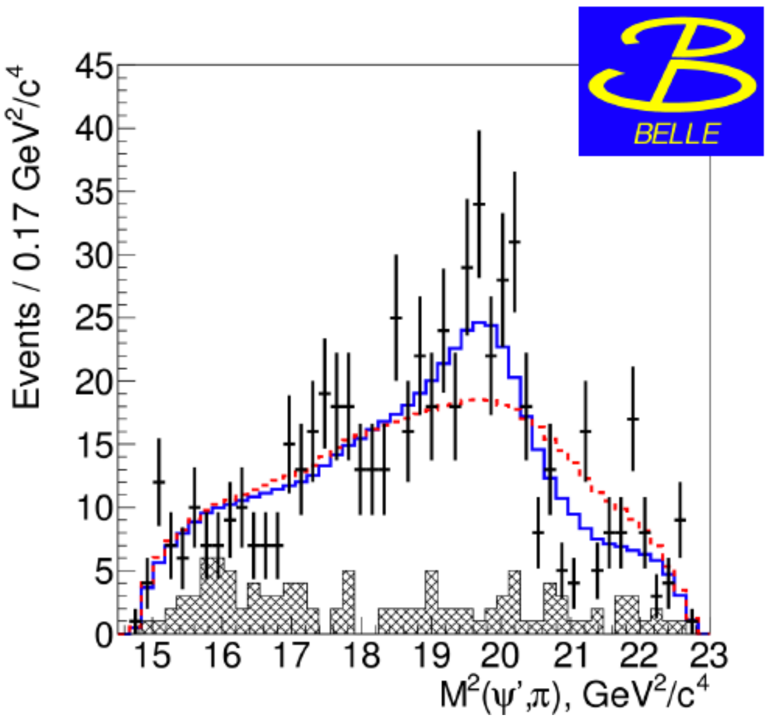
- An important ingredient to reveal the nature of $X(3872)$

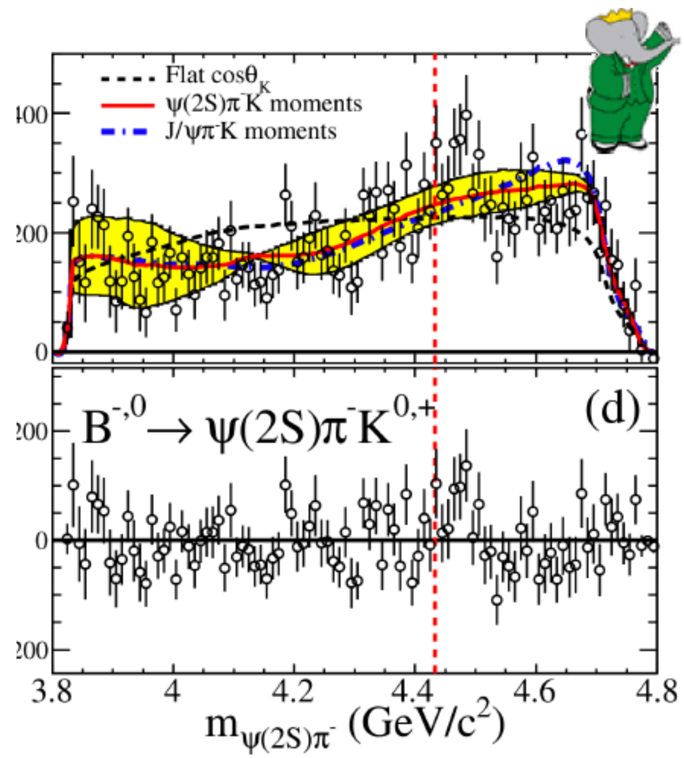
$$\frac{\mathcal{B}(\mathrm{X(3872)} \to \psi(2\mathrm{S})\gamma)}{\mathcal{B}(\mathrm{X(3872)} \to \mathrm{J}/\psi\gamma)} = 2.46 \pm 0.64 \pm 0.29$$

$Z(4430)^{-}$

Belle, PRL 100 (2008) 142001
Belle, PR D80 (2009) 031104
Belle, PR D88 (2013) 074026

- Originally found by Belle in $B^0 \to \psi(2S)\pi^- K^+$
- BaBar could not confirm BaBar, PR D79 (2009) 112001





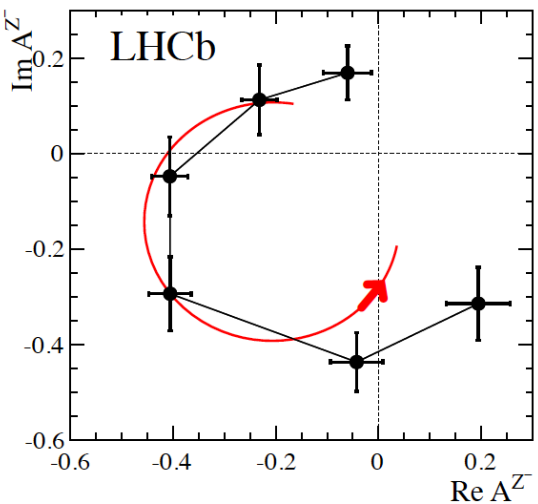
$Z(4430)^-$

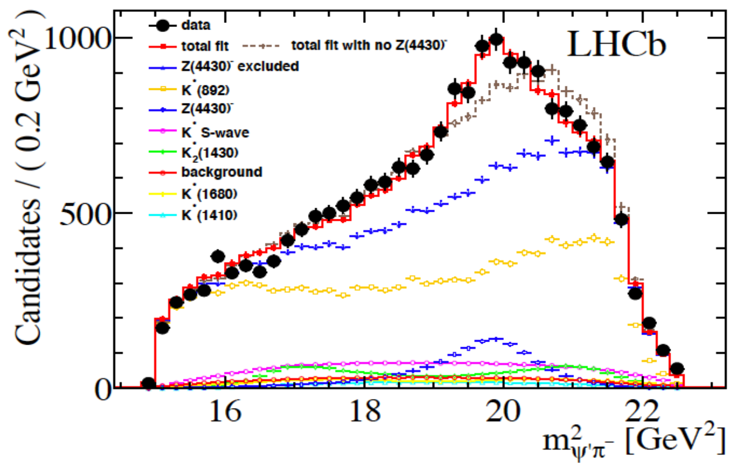
LHCb-PAPER-2014-014
PRL 112 (2014) 222002

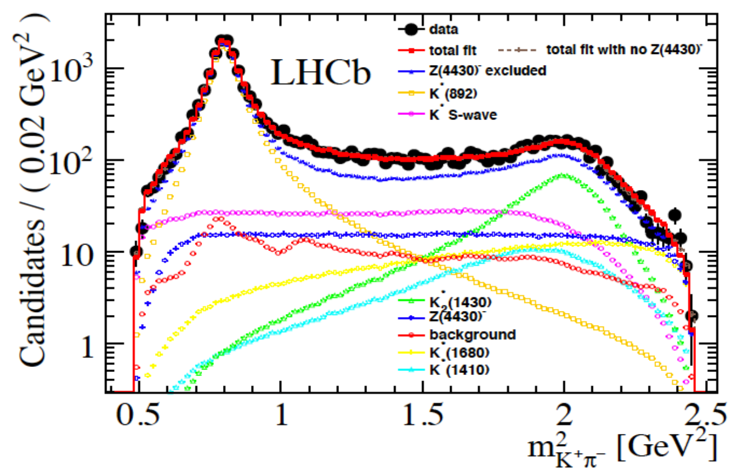
- LHCb full amplitude analysis using $3\ \mathbf{fb}^{-1}$

$$m = 4475 \pm 7\,^{+15}_{-25}\ \mathrm{MeV}/c^2$$
$$\Gamma = 172 \pm 13\,^{+37}_{-34}\ \mathrm{MeV}/c^2.$$

- $J^P = 1^+$ is confirmed
- *Argand plot* shows a clear resonance feature



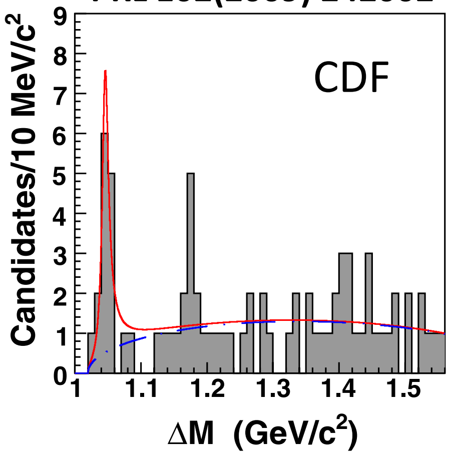




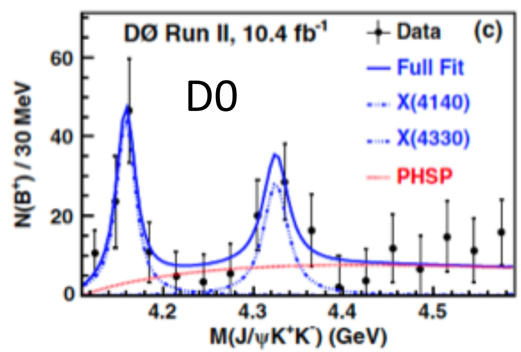
$X \to J/\psi\phi$

- Narrow structure in $J/\psi\phi$ discovered by CDF, confirmed by D0 and CMS. No evidence by BaBar/Belle/LHCb(0.37 fb^{-1})

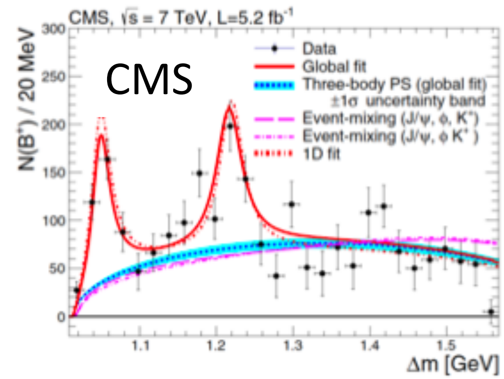
PRL 102(2009) 242002



PRD 89(2014) 242002



PLB 734(2014) 261

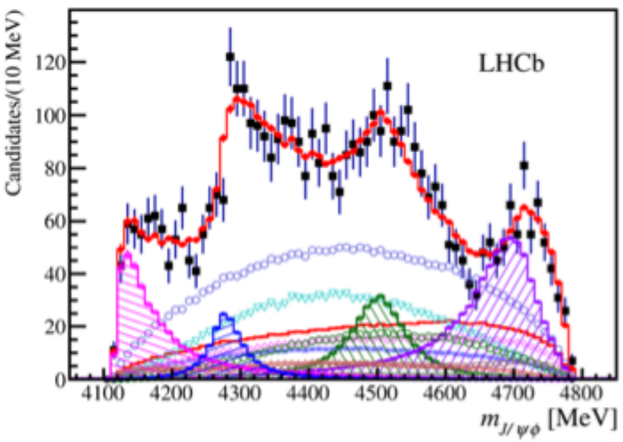


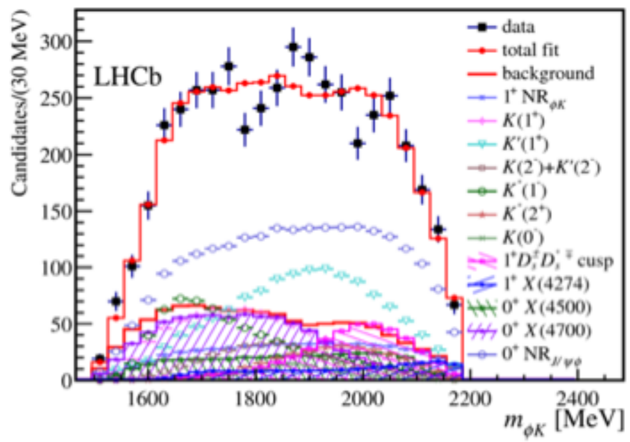
	Mass [MeV]	Width [MeV]	Sig.
CDF	$4143.4^{+2.9}_{-3.0} \pm 0.6$	$15.3^{+10.4}_{-6.1} \pm 2.5$	$> 5\sigma$
D0	$4159 \pm 4.3 \pm 6.6$	$19.9 \pm 12.6^{+3.0}_{-8.1}$	3σ
CMS	$4148.0 \pm 2.4 \pm 6.3$	$28^{+15}_{-11} \pm 19$	5σ

Exotic states in $B^+ \to J/\psi\phi K^+$

- LHCb perform full 6D amplitude analysis

LHCb-PAPER-2016-018
PRL 118 (2017)022003
LHCb-PAPER-2016-019
PRD 95 (2017) 012002





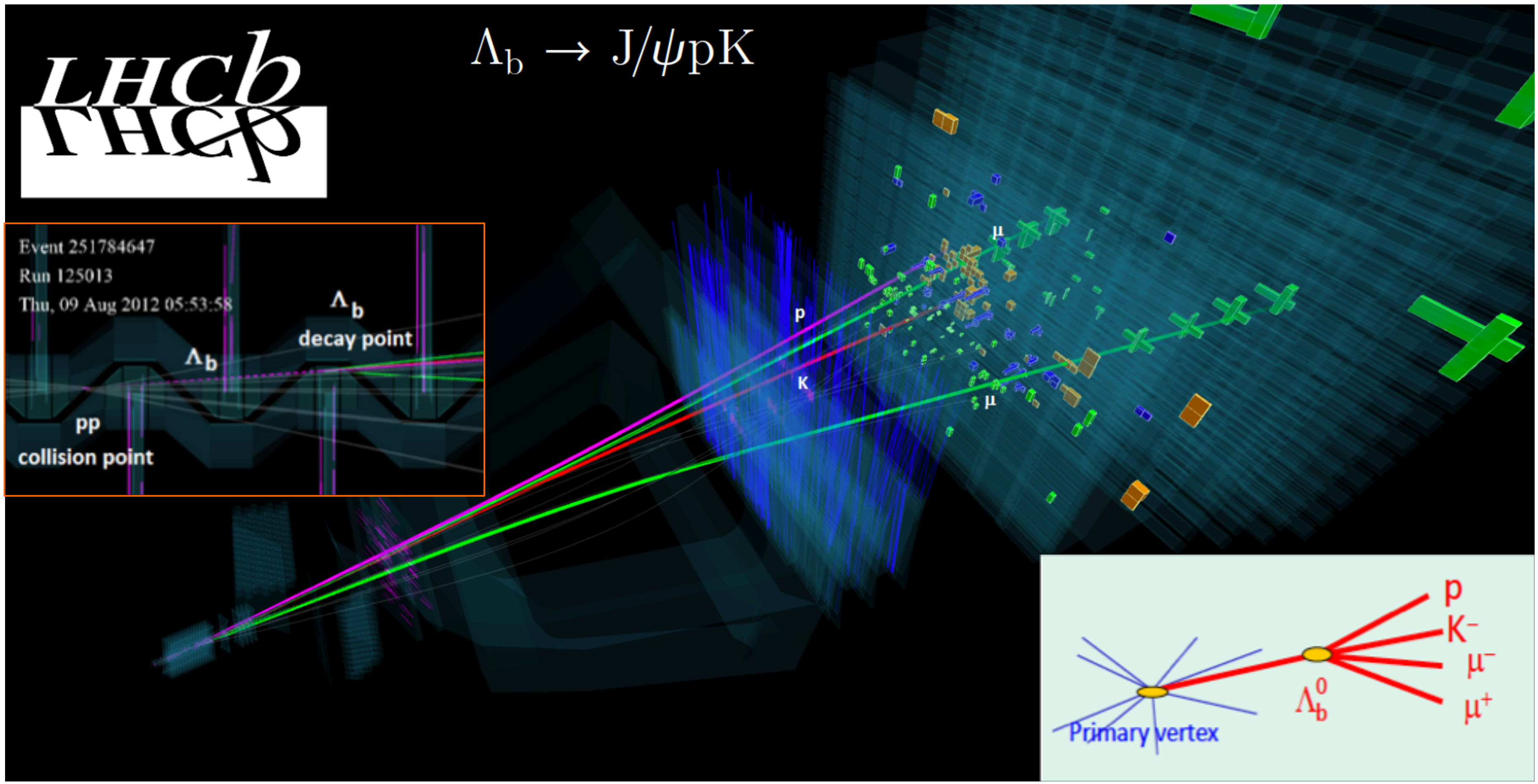
- 4 peaks are observed with X(4140) wider than CDF/DO/CMS

State	Signif	J^{PC}	M [MeV]	Γ [MeV]
X(4140)	8.4σ	1^{++}	$4160 \pm 4^{+5}_{-3}$	$83 \pm 21^{+21}_{-14}$
X(4274)	5.8σ	1^{++}	$4273 \pm 8^{+17}_{-4}$	$56 \pm 11^{+8}_{-11}$
X(4500)	6.1σ	0^{++}	$4506 \pm 11^{+12}_{-15}$	$92 \pm 21^{+21}_{-20}$
X(4700)	5.6σ	0^{++}	$4704 \pm 10^{+14}_{-24}$	$120 \pm 31^{+42}_{-33}$

Significant larger at LHCb

$\Gamma_{\text{avg}}^{\text{CDF/D0/CMS}} = 15.7 \pm 6.3$ MeV

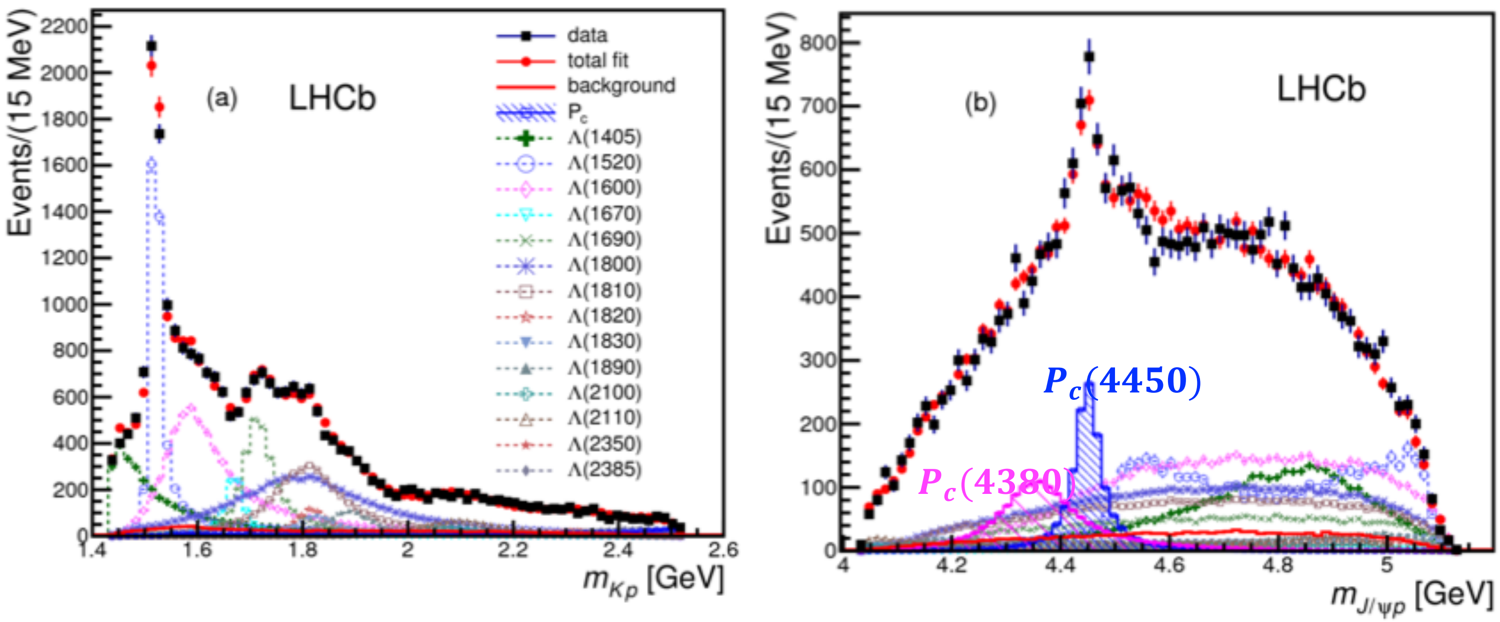
Pentaquark studies

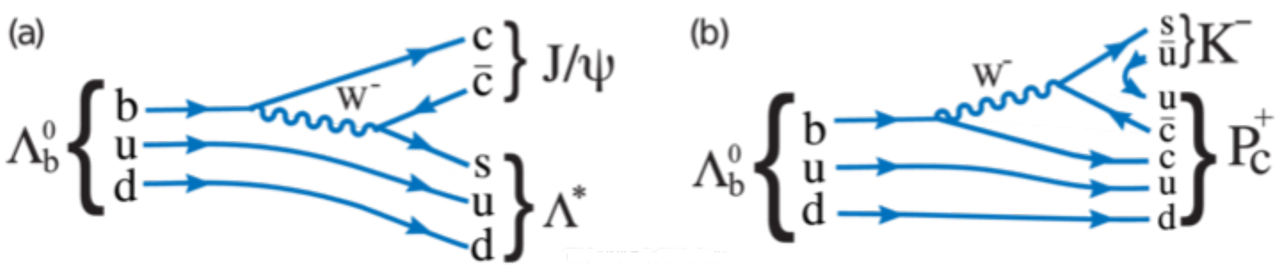


Discovery of pentaquark states

LHCb, PRL 115(2015) 072001

- Two pentaquark states observed in $\Lambda_b^0 \to J/\psi p K^-$



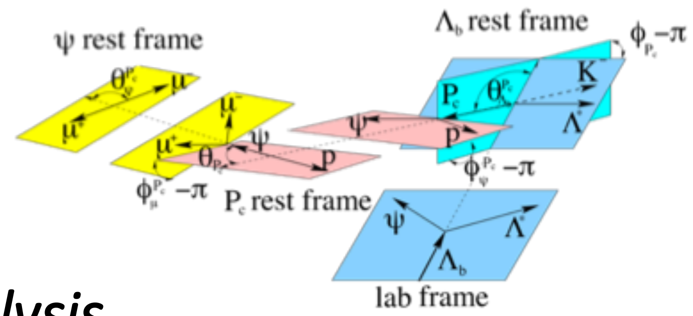


Discovery of pentaquark states

- Amplitude analysis reveals the properties

LHCb, PRL 115(2015) 072001

	$P_c(4380)^+$	$P_c(4450)^+$
J^P	$\frac{3}{2}^-$	$\frac{5}{2}^+$
Mass [MeV/c^2]	$4380 \pm 8 \pm 29$	$4449.8 \pm 1.7 \pm 2.5$
Width [MeV]	$205 \pm 18 \pm 86$	$39 \pm 5 \pm 19$
Significance	9σ	12σ



- Confirmed by *a model independent analysis*

LHCb-PAPER-2016-009
PRL 117 (2016) 082002

- Production & decay

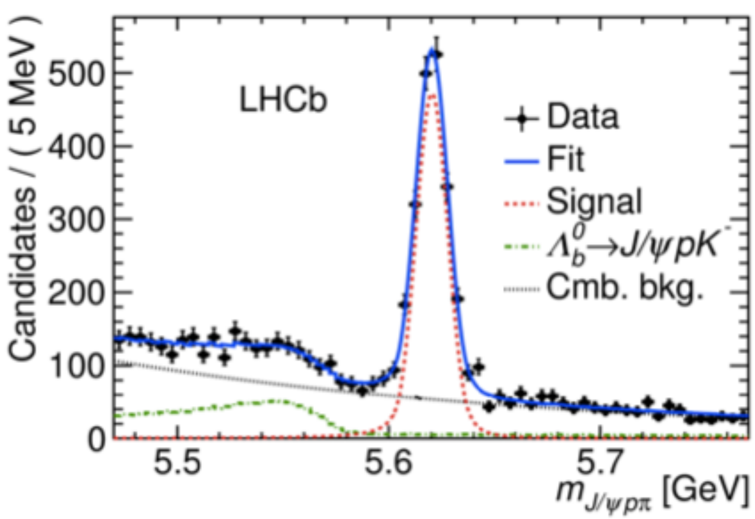
LHCb-PAPER-2015-032
Chin. Phys. C 40 (2016) 011001

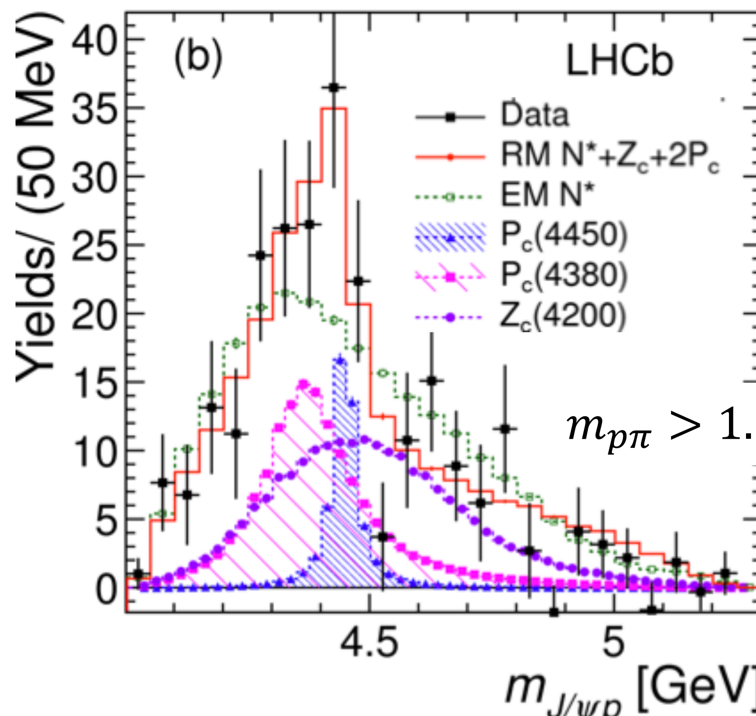
$$\mathcal{B}(\Lambda_b^0 \to P_c^+(4380)K^-)\mathcal{B}(P_c^+ \to J/\psi\, p) = \left(2.56 \pm 0.22 \pm 1.28\,^{+\,0.46}_{-\,0.36}\right) \times 10^{-5}$$
$$\mathcal{B}(\Lambda_b^0 \to P_c^+(4450)K^-)\mathcal{B}(P_c^+ \to J/\psi\, p) = \left(1.25 \pm 0.15 \pm 0.33\,^{+\,0.22}_{-\,0.18}\right) \times 10^{-5}$$

Study of $\Lambda_b^0 \to J/\psi p\pi^-$

LHCb-PAPER-2016-015
PRL 117(2016) 082003

- Cabbibo suppressed mode with less statistics
- Exotic Z contributions in $J/\psi\pi$
- Fit with 2 pentaquarks + $Z_c(4200)$ favored by 3σ compared to no exotic contributions





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

LHCb-PAPER-2017-011,
PRL 119 (2017) 062001

- $Pc(4450)$ close to $\chi_{c1}p$ threshold, triangle singularity ?

Guo et al., PR D92(2015) 071502

- Study with radiative $\chi_{cJ} \to J/\psi\gamma$ decays

Mass constraint on χ_{c1} to improve resolution, forces χ_{c2} to lower mass

- First observation of this mode,

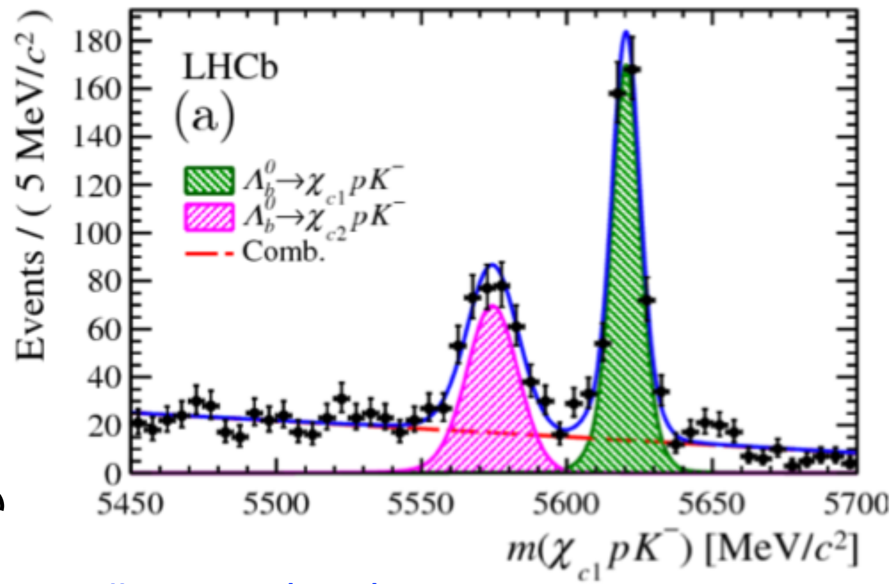
full amplitude analysis foreseen

with RUNII data added in

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

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

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



Suppressed in $B \to \chi_{cJ} K$ decays

Belle, PRD 78 (2008) 072004
BaBar, PRL 102 (2009) 132001
LHCb, NPB 874 (2013) 663

Observation of $\Xi_b^- \to J/\psi \Lambda K^-$

LHCb-PAPER-2016-053
PLB 772 (2017) 265

- Look for $udsc\bar{c}$ pentaquark in this mode

Wu et al., PRL 105 (2010) 232001
Chen et al., PRC 93 (2016) 065203

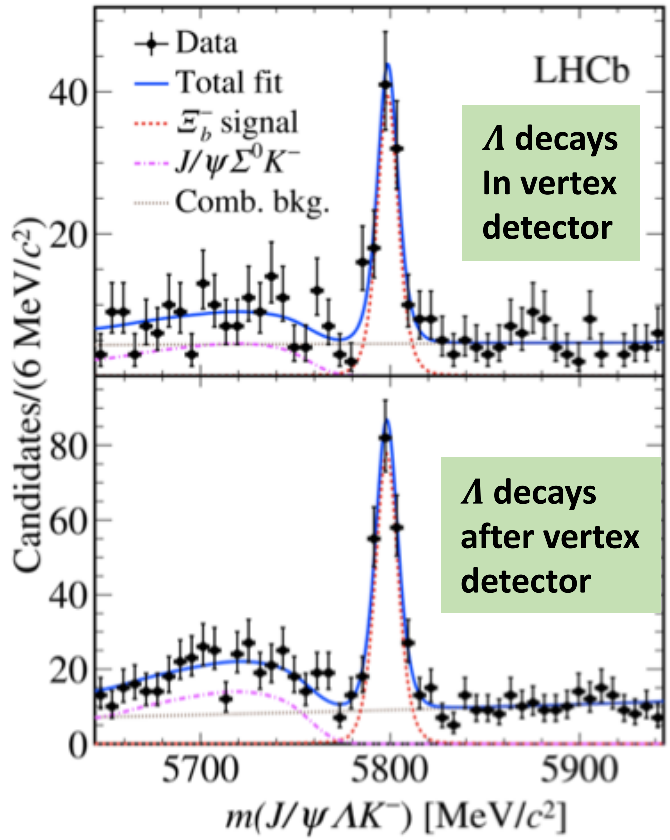
- First observation with RUNI data
- ~300 candidates seen

$$\frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} \frac{\mathcal{B}(\Xi_b^- \to J/\psi \Lambda K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi \Lambda)} = (4.19 \pm 0.29 \pm 0.15) \times 10^{-2}$$

$$m(\Xi_b^-) - m(\Lambda_b) = 177.08 \pm 0.47 \pm 0.16 \,\mathrm{MeV}/c^2$$

(one of the two world best measurements)

- Full amplitude analysis foreseen with RUNII data added in



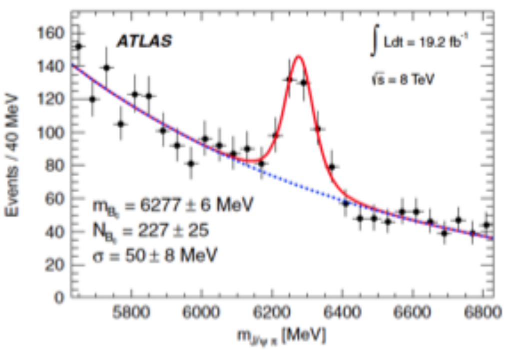
$B_c^{(*)}(2S) \to B_c^{(*)}\pi^+\pi^-$

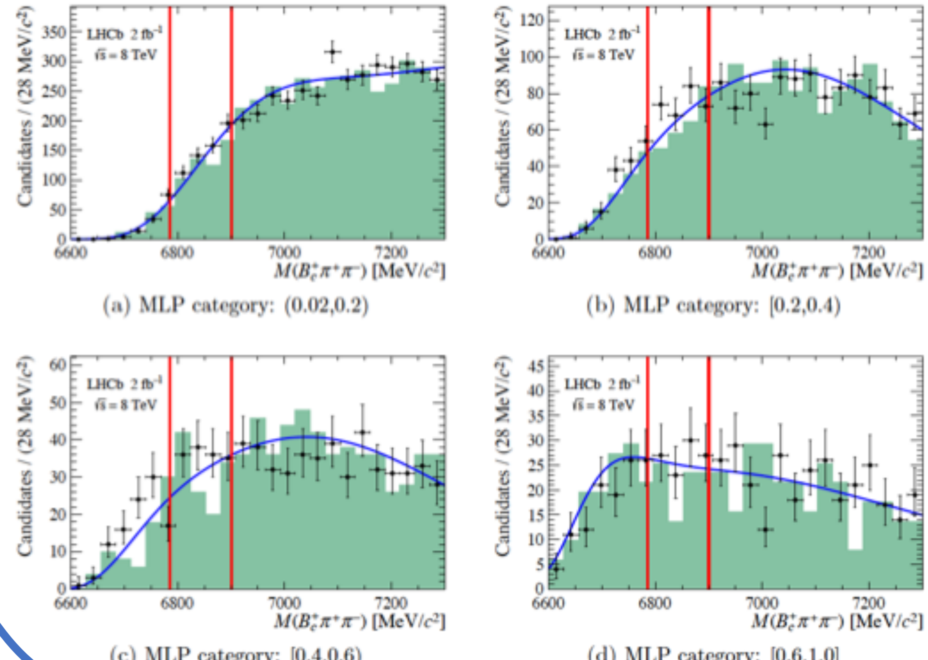
LHCb-PAPER-2017-042
arXiv:1712.04094

ATLAS, PRL 113 (2014) 212004

Data	Signal events
7 TeV	100 ± 23
8 TeV	227 ± 25

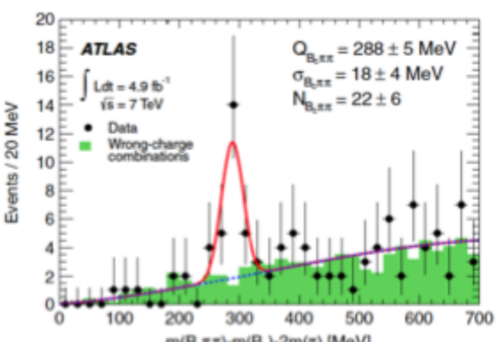
$N_{B_c}^{\text{ATLAS}}$

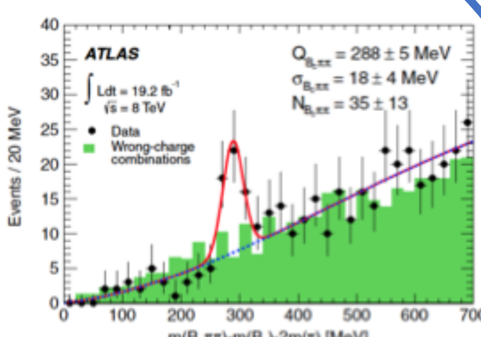




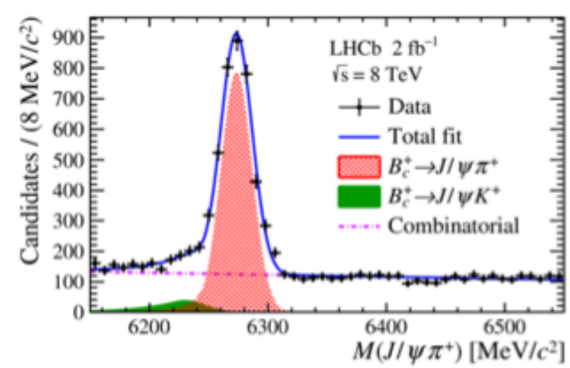
$$m_{B_c(2S)} = 6842 \pm 4 \pm 5\ \text{MeV}$$

5.2σ





$$N_{B_c}^{\text{LHCb 8TeV}} = 3325 \pm 73$$



LHCb-PAPER-2017-042
arXiv:1712.04094

$$\mathcal{R} = \frac{\sigma_{B_c^{(*)}(2S)^+}}{\sigma_{B_c^+}} \cdot \mathcal{B}(B_c^{(*)}(2S)^+ \to B_c^{(*)+}\pi^+\pi^-)$$
$$= \frac{N_{B_c^{(*)}(2S)^+}}{N_{B_c^+}} \cdot \frac{\varepsilon_{B_c^+}}{\varepsilon_{B_c^{(*)}(2S)^+}},$$

	$\sqrt{s} = 7\,\text{TeV}$	$\sqrt{s} = 8\,\text{TeV}$
ATLAS	$(0.22 \pm 0.08\,(\text{stat}))/\varepsilon_7$	$(0.15 \pm 0.06\,(\text{stat}))/\varepsilon_8$
LHCb	$-$	$< [0.04, 0.09]$

$\varepsilon_7, \varepsilon_8$: **relative efficiencies of reconstructing $B_c^{(*)}(2S)^+$ wrt B_c^+**

- **ATLAS did not publish $\varepsilon_7, \varepsilon_8$**
- **More studies needed to resolve the large tension between ATLAS and LHCb.**

Searches for weakly decaying b-flavored pentaquarks

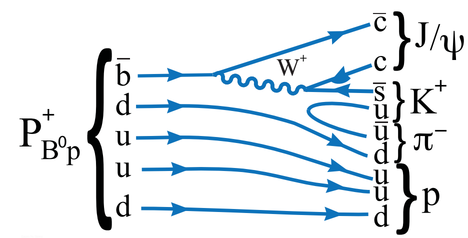
LHCb-PAPER-2017-043
arXiv:1712.08086

- Skyrme model prediction on pentaquark state: the heavier the constitute quarks, the more tightly bound the pentaquark state

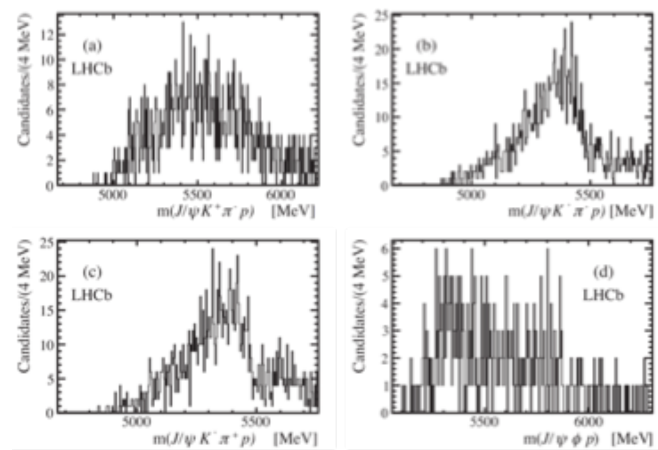
PLB 590(2004) 185; PLB 586(2004)337; PLB 331(1994)362

- Search for masses below strong decay threshold

Mode	Quark content	Decay mode	Search window
I	$\bar{b}duud$	$P^+_{B^0p} \to J/\psi K^+\pi^- p$	4668–6220 MeV
II	$b\bar{u}udd$	$P^-_{\Lambda^0_b\pi^-} \to J/\psi K^-\pi^- p$	4668–5760 MeV
III	$b\bar{d}uud$	$P^+_{\Lambda^0_b\pi^+} \to J/\psi K^-\pi^+ p$	4668–5760 MeV
IV	$\bar{b}suud$	$P^+_{B^0_s p} \to J/\psi \phi p$	5055–6305 MeV



- No evidence observed (yet)



Upper limit set on relative $\sigma\times\mathcal{B}$ as a function of P masses

Prospect: RUNI+RUNII

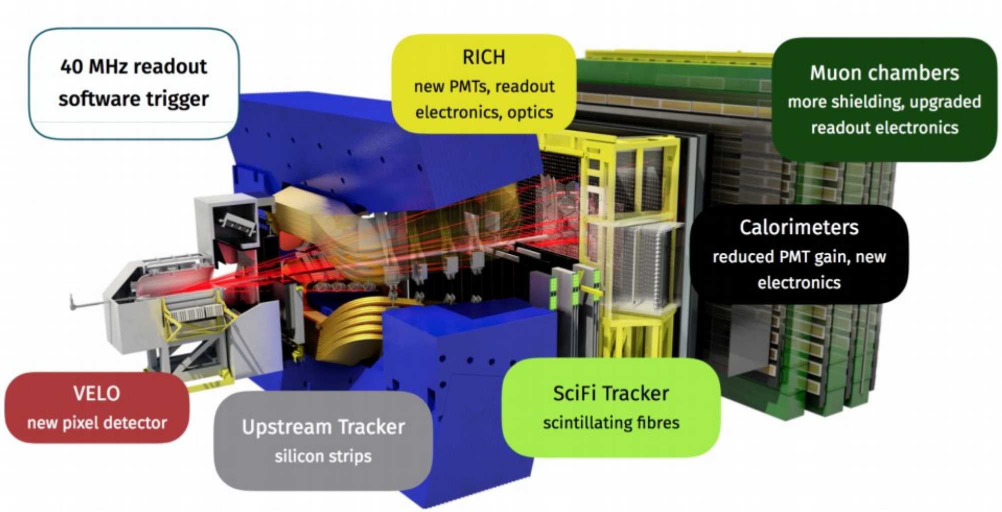
- Data samples
  - 1 fb^{-1} (7 TeV)+ 2 fb^{-1} (8 TeV)
  - ~6 fb^{-1} at 13 TeV with $\sigma_{b\bar{b}}(13\text{TeV})/\sigma_{b\bar{b}}(7\text{TeV}) \approx 2$

- A far from completed list benifited from full RUNI+RUNII data
  - search for excited B_c states
  - precise $m_{X(3872)} - m_{\psi(2S)}$, new decay modes
  - properties of Ξ_{cc}^{++}: lifetime, production cross-sections, new decay modes, ...
  - searches for $\Xi_{cc}^{+}, \Omega_{cc}^{+}, \Xi_{bc}^{+}, \Xi_{bc}^{0}$ ...
  - J^P of $P_c(4380)$ & $P_c(4450)$, new decay modes
  - amplitude analysis $\Lambda_b^0 \to \chi_{c1,2} p K^-$, cusp?
  - amplitude analysis $\Xi_b^- \to J/\psi \Lambda K^-$, new pentaquarks?

  ....

Spectroscopy with the upgraded LHCb

- LHCb will be upgraded in 2019, software trigger with 40MHz



- Allow PID at the trigger level – great increase (~2x) of trigger efficiency on full hadronic final states

- A new computing approach to data-analysis is needed

Summary

- LHCb has made important contributions to the knowledge of hadron spectroscopy
  - Observation/study of excited $\boldsymbol{B}(\boldsymbol{D})$mesons & $\boldsymbol{b}(\boldsymbol{c})$ baryons
  - Observation/study of exotic states
  - Discovery of doubly charmed baryons
  - …
- Stay tuned with new results from RUNI+RUNII
- Spectroscopy at the upgraded LHCb is challenging and promising

Backup slides

References: Ω^{**} mass

D. Ebert, R. N. Faustov, and V. O. Galkin, *Masses of excited heavy baryons in the relativistic quark-diquark picture*, Phys. Lett. **B659** (2008) 612, arXiv:0705.2957.

W. Roberts and M. Pervin, *Heavy baryons in a quark model*, Int. J. Mod. Phys. **A23** (2008) 2817, arXiv:0711.2492.

H. Garcilazo, J. Vijande, and A. Valcarce, *Faddeev study of heavy-baryon spectroscopy*, J. Phys. **G34** (2007) 961, arXiv:hep-ph/0703257.

S. Migura, D. Merten, B. Metsch, and H.-R. Petry, *Charmed baryons in a relativistic quark model*, Eur. Phys. J. **A28** (2006) 41, arXiv:hep-ph/0602153.

D. Ebert, R. N. Faustov, and V. O. Galkin, *Spectroscopy and Regge trajectories of heavy baryons in the relativistic quark-diquark picture*, Phys. Rev. **D84** (2011) 014025, arXiv:1105.0583.

A. Valcarce, H. Garcilazo, and J. Vijande, *Towards an understanding of heavy baryon spectroscopy*, Eur. Phys. J. **A37** (2008) 217, arXiv:0807.2973.

Z. Shah, K. Thakkar, A. K. Rai, and P. C. Vinodkumar, *Mass spectra and Regge trajectories of Λ_c^+, Σ_c^0, Ξ_c^0 and Ω_c^0 baryons*, Chin. Phys. **C40** (2016) 123102, arXiv:1609.08464.

J. Vijande, A. Valcarce, T. F. Carames, and H. Garcilazo, *Heavy hadron spectroscopy: A quark model perspective*, Int. J. Mod. Phys. **E22** (2013) 1330011, arXiv:1212.4383.

References: Ω_c^* masses (cont'd)

T. Yoshida *et al.*, *Spectrum of heavy baryons in the quark model*, Phys. Rev. **D92** (2015) 114029, `arXiv:1510.01067`.

H.-X. Chen *et al.*, *P-wave charmed baryons from QCD sum rules*, Phys. Rev. **D91** (2015) 054034, `arXiv:1502.01103`.

H.-X. Chen *et al.*, *D-wave charmed and bottomed baryons from QCD sum rules*, Phys. Rev. **D94** (2016) 114016, `arXiv:1611.02677`.

G. Chiladze and A. F. Falk, *Phenomenology of new baryons with charm and strangeness*, Phys. Rev. **D56** (1997) R6738, `arXiv:hep-ph/9707507`.

M. Padmanath, R. G. Edwards, N. Mathur, and M. Peardon, *Excited-state spectroscopy of singly, doubly and triply-charmed baryons from lattice QCD*, `arXiv:1311.4806`.

References: Ξ_{cc} masses

S. S. Gershtein, V. V. Kiselev, A. K. Likhoded, and A. I. Onishchenko, Phys. Atom. Nucl. **63**, 274 (2000), [Yad. Fiz. 63, 334 (2000)], arXiv:hep-ph/9811212 [hep-ph].

S. S. Gershtein, V. V. Kiselev, A. K. Likhoded, and A. I. Onishchenko, Mod. Phys. Lett. **A14**, 135 (1999), arXiv:hep-ph/9807375 [hep-ph].

C. Itoh, T. Minamikawa, K. Miura, and T. Watanabe, Phys. Rev. **D61**, 057502 (2000).

S. S. Gershtein, V. V. Kiselev, A. K. Likhoded, and A. I. Onishchenko, Phys.Rev. **D62**, 054021 (2000).

K. Anikeev *et al.*, in *Workshop on B physics at the Tevatron: Run II and beyond, Batavia, Illinois, September 23-25, 1999* (2001) arXiv:hep-ph/0201071 [hep-ph].

V. Kiselev and A. Likhoded, Phys.Usp. **45**, 455 (2002), arXiv:hep-ph/0103169 [hep-ph].

D. Ebert, R. Faustov, V. Galkin, and A. Martynenko, Phys.Rev. **D66**, 014008 (2002), arXiv:hep-ph/0201217 [hep-ph].

D.-H. He, K. Qian, Y.-B. Ding, X.-Q. Li, and P.-N. Shen, Phys.Rev. **D70**, 094004 (2004), arXiv:hep-ph/0403301 [hep-ph].

C.-H. Chang, C.-F. Qiao, J.-X. Wang, and X.-G. Wu, Phys.Rev. **D73**, 094022 (2006), arXiv:hep-ph/0601032 [hep-ph].

W. Roberts and M. Pervin, Int.J.Mod.Phys. **A23**, 2817 (2008), arXiv:0711.2492 [nucl-th].

A. Valcarce, H. Garcilazo, and J. Vijande, Eur.Phys.J. **A37**, 217 (2008), arXiv:0807.2973 [hep-ph].

J.-R. Zhang and M.-Q. Huang, Phys.Rev. **D78**, 094007 (2008), arXiv:0810.5396 [hep-ph].

Z.-G. Wang, Eur.Phys.J. **A45**, 267 (2010), arXiv:1001.4693 [hep-ph].

M. Karliner and J. L. Rosner, Phys. Rev. **D90**, 094007 (2014), arXiv:1408.5877 [hep-ph].

K.-W. Wei, B. Chen, and X.-H. Guo, Phys. Rev. **D92**, 076008 (2015), arXiv:1503.05184 [hep-ph].

Z.-F. Sun and M. J. Vicente Vacas, Phys. Rev. **D93**, 094002 (2016), arXiv:1602.04714 [hep-ph].

C. Alexandrou and C. Kallidonis, (2017), arXiv:1704.02647 [hep-lat].

B. O. Kerbikov, M. I. Polikarpov, and L. V. Shevchenko, Nucl. Phys. **B331**, 19 (1990).

S. Fleck and J.-M. Richard, Prog. Theor. Phys. **82**, 760 (1989).

S. Chernyshev, M. A. Nowak, and I. Zahed, Phys. Rev. **D53**, 5176 (1996), arXiv:hep-ph/9510326 [hep-ph].

T. M. Aliev, K. Azizi, and M. Savcı, Nucl. Phys. **A895**, 59 (2012), arXiv:1205.2873 [hep-ph].

Z.-F. Sun, Z.-W. Liu, X. Liu, and S.-L. Zhu, Phys. Rev. **D91**, 094030 (2015), arXiv:1411.2117 [hep-ph].

N. Mathur, R. Lewis, and R. M. Woloshyn, Phys. Rev. **D66**, 014502 (2002), arXiv:hep-ph/0203253 [hep-ph].

Y. Namekawa *et al.* (PACS-CS collaboration), Phys. Rev. **D87**, 094512 (2013), arXiv:1301.4743 [hep-lat].

Z. S. Brown, W. Detmold, S. Meinel, and K. Orginos, Phys. Rev. **D90**, 094507 (2014), arXiv:1409.0497 [hep-lat].

M. Padmanath, R. G. Edwards, N. Mathur, and M. Peardon, Phys. Rev. **D91**, 094502 (2015), arXiv:1502.01845 [hep-lat].

P. Pérez-Rubio, S. Collins, and G. S. Bali, Phys. Rev. **D92**, 034504 (2015), arXiv:1503.08440 [hep-lat].

Y. Liu and I. Zahed, Phys. Rev. **D95**, 116012 (2017), arXiv:1704.03412 [hep-ph]; (2017), arXiv:1705.01397

References: Ξ_{cc} lifetimes

K. Anikeev *et al.*, in *Workshop on B physics at the Tevatron: Run II and beyond, Batavia, Illinois, September 23-25, 1999* (2001) arXiv:hep-ph/0201071 [hep-ph].

V. Kiselev and A. Likhoded, Phys.Usp. **45**, 455 (2002), arXiv:hep-ph/0103169 [hep-ph].

M. Karliner and J. L. Rosner, Phys. Rev. **D90**, 094007 (2014), arXiv:1408.5877 [hep-ph].

S. Fleck and J.-M. Richard, Prog. Theor. Phys. **82**, 760 (1989).

B. Guberina, B. Melić, and H. Štefančić, Eur.Phys.J. **C9**, 213 (1999), arXiv:hep-ph/9901323 [hep-ph].

V. Kiselev, A. Likhoded, and A. Onishchenko, Phys.Rev. **D60**, 014007 (1999), arXiv:hep-ph/9807354 [hep-ph].

C.-H. Chang, T. Li, X.-Q. Li, and Y.-M. Wang, Commun.Theor.Phys. **49**, 993 (2008), arXiv:0704.0016 [hep-ph].

A. V. Berezhnoy and A. K. Likhoded, Phys. Atom. Nucl. **79**, 260 (2016), [Yad. Fiz. 79, 151 (2016)].

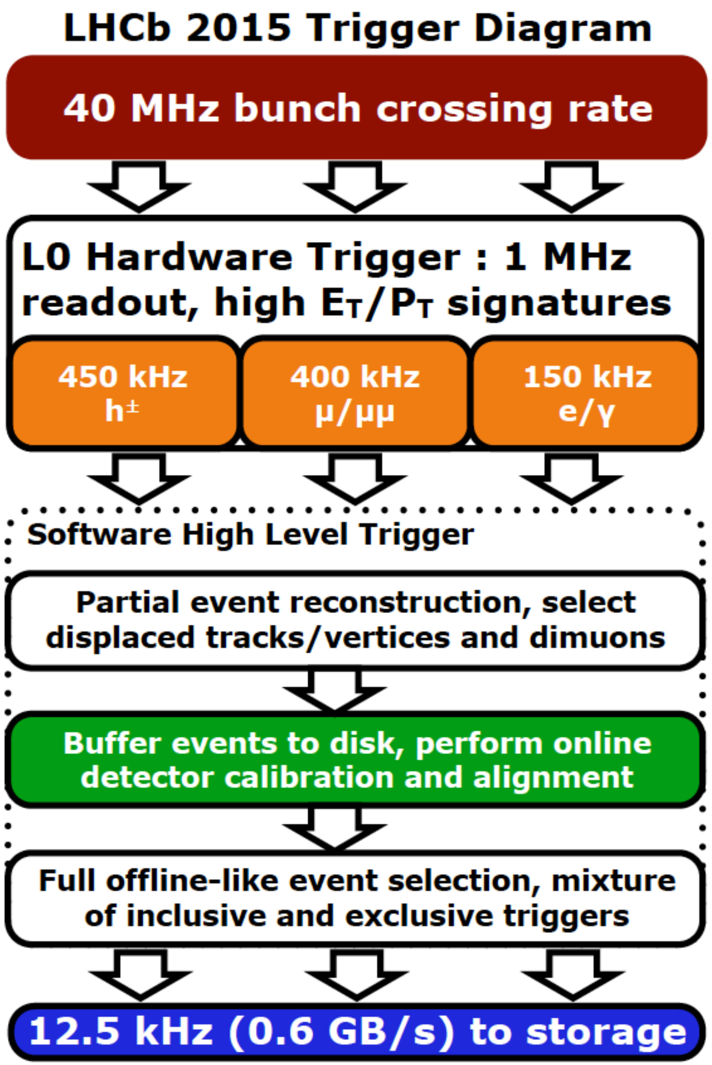
LHCb Trigger in RUN II

TURBO stream introduced in 2015

- 5 kHz of 12 kHz go to TURBO
- Only trigger information saved

  → smaller event, faster analysis

- Used for high yield exclusive trigger lines: $J/\psi, D^0, D^+$, ...

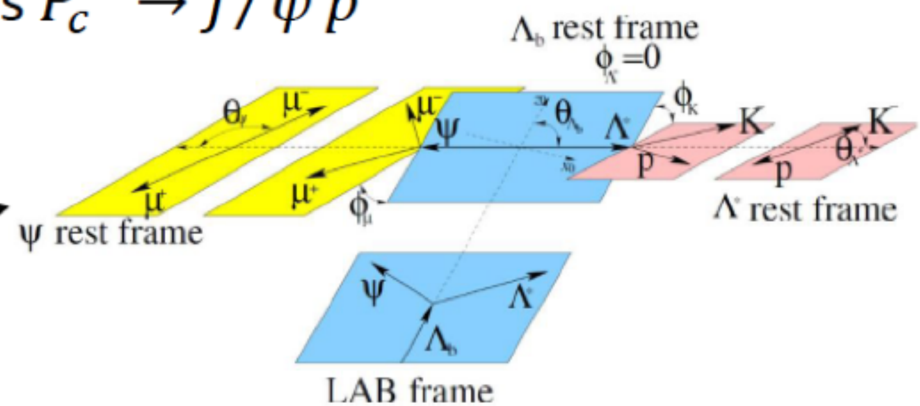


Amplitude analysis of $\Lambda_b^0 \to J/\psi p K$

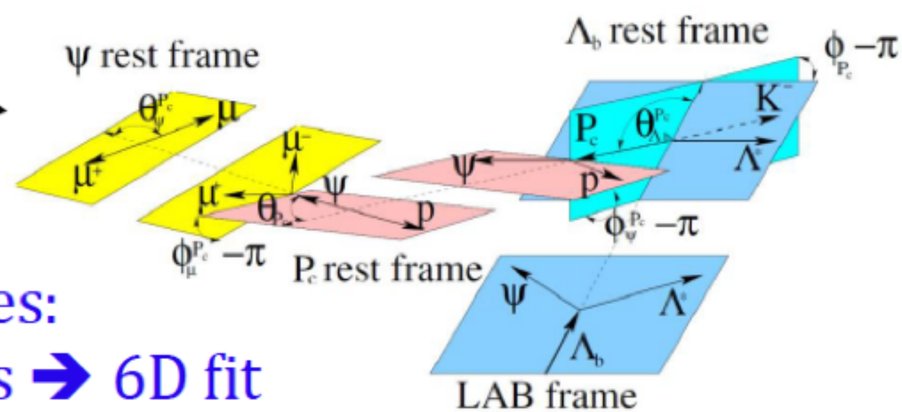
LHCb, PRL 115(2015) 072001

- Allows for $\Lambda^* \to pK^-$ resonances to interfere with pentaquark states $P_c^+ \to J/\psi\, p$

$\Lambda_b^0 \to J/\psi \Lambda^*,$
$\Lambda^* \to pK^-$



$\Lambda_b^0 \to P_c^+ K^-,$
$P_c^+ \to J/\psi p$



- Independent variables: $m(pK^-)$ and 5 angles ➔ 6D fit

Amplitude analysis of $\Lambda_b^0 \to J/\psi p K$

LHCb, PRL 115(2015) 072001

- Two models to deal with $\Lambda^* \to pK$ contributions

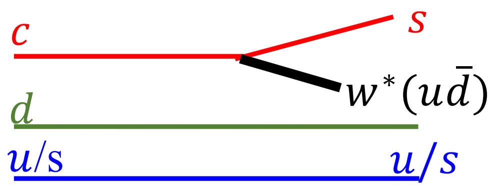
State	J^P	M_0 (MeV)	Γ_0 (MeV)	Red.	Ext.
$\Lambda(1405)$	$1/2^-$	$1405.1^{+1.3}_{-1.0}$	50.5 ± 2.0	3	4
$\Lambda(1520)$	$3/2^-$	1519.5 ± 1.0	15.6 ± 1.0	5	6
$\Lambda(1600)$	$1/2^+$	1600	150	3	4
$\Lambda(1670)$	$1/2^-$	1670	35	3	4
$\Lambda(1690)$	$3/2^-$	1690	60	5	6
$\Lambda(1800)$	$1/2^-$	1800	300	4	4
$\Lambda(1810)$	$1/2^+$	1810	150	3	4
$\Lambda(1820)$	$5/2^+$	1820	80	1	6
$\Lambda(1830)$	$5/2^-$	1830	95	1	6
$\Lambda(1890)$	$3/2^+$	1890	100	3	6
$\Lambda(2100)$	$7/2^-$	2100	200	1	6
$\Lambda(2110)$	$5/2^+$	2110	200	1	6
$\Lambda(2350)$	$9/2^+$	2350	150		6
$\Lambda(2585)$	?	$\approx$2585	200		6
				64	146

Last columns show number of parameters are left free. Masses and Width are fixed.
Red.: Reduced model (fast). Ext.: Allows for more helicity (LS) couplings.

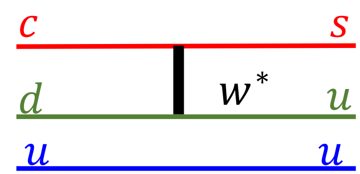
Doubly charmed baryons

- Lifetimes known to be affected by spectator decays + non-spectator decays and Pauli interference, qualitatively

Spectator (Γ_s)



W-exchange (W)



- Expectation: $\tau(\Xi_{cc}^{++}(ccu)) \gg \tau(\Xi_{cc}^{+}(ccd))$

- Calculations give $\tau(\Xi_{cc}^{++}) \in [\,200 - 700]$ fs

See backup pages for references

Particle	τ (ps)
D^0	0.410 ± 0.002
D_s^+	0.500 ± 0.007
D^+	1.040 ± 0.007
$D_b^+(B_c^+)$	0.507 ± 0.009
$\Lambda_c^+(cud)$	0.200 ± 0.006
$\Xi_c^0\,(csd)$	0.112 ± 0.012
$\Xi_c^+(csu)$	0.442 ± 0.026
$\Omega_c^0\,(css)$	0.069 ± 0.012

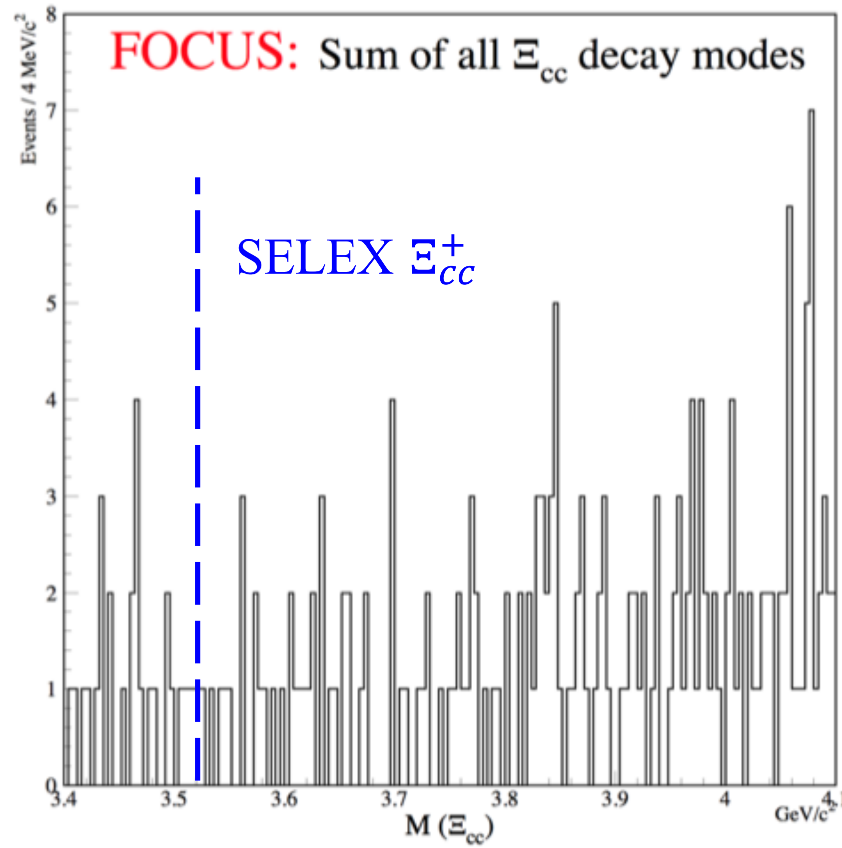
Results from FOCUS

- FOCUS (Fermilab E831) studies charm hadrons produced in photon-nuclear fixed target collisions
- FOCUS didn't confirm Ξ_{cc}^{+} observed by SELEX in $\Lambda_c^+ K^- \pi^+$ decay

Decay Mode	$\Xi_{cc}^{+} \to \Lambda_c^+ K^- \pi^+$	
Experiment	FOCUS	SELEX
Ξ_{cc} Events	<2.21 @ 90%	15.8
Reconstructed Λ_c	$19,444 \pm 262$	1650
Relative Efficiency	5%	10%
Ξ_{cc}/Λ_c^+	$<0.23\%$ @ 90%	9.6%
$\frac{\text{SELEX}}{\text{FOCUS}}$ Rel $\frac{\Xi_{cc}}{\Lambda_c}$ Prod	>42 @ 90%	

- Other modes also studied: $\Xi_{cc}^{+} \to \Lambda_c^+ X, D^0 X$ $D^+ X$, no SELEX-like signal peak observed

Nucl. Phys. Proc. Suppl. 115 (2003) 33

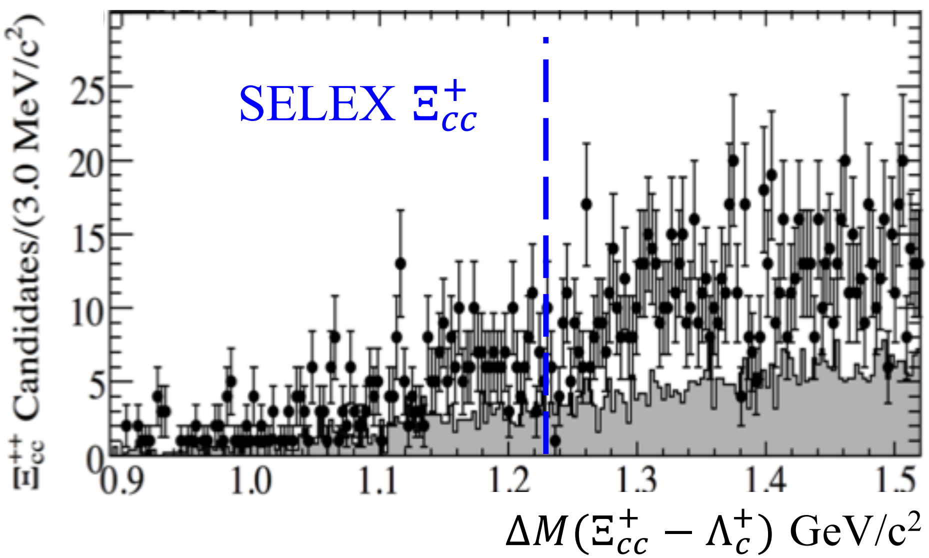


Results from Babar & Belle

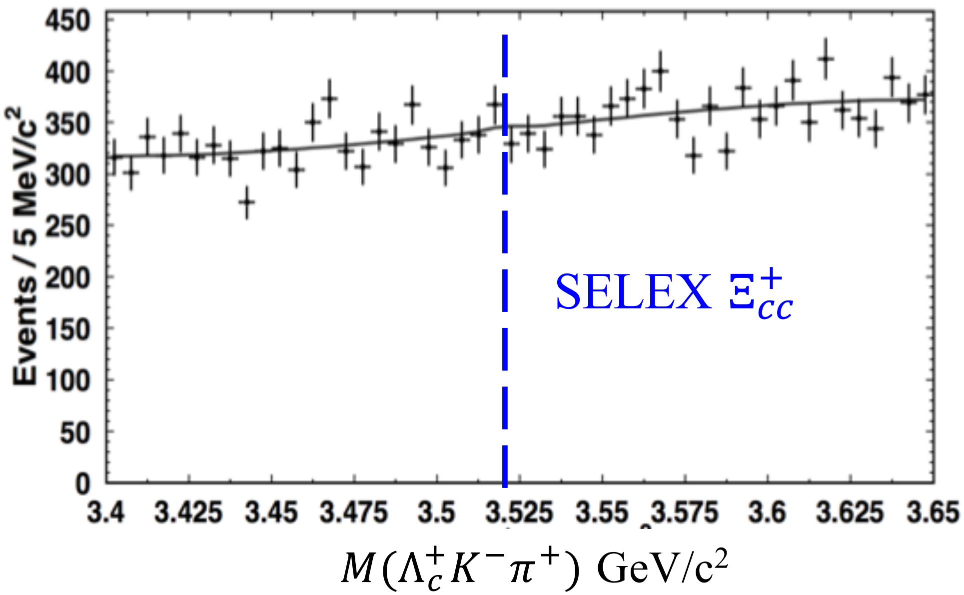
- e^+e^- colliders working at $\Upsilon(4S)$ mass $\sqrt{s} = 10.58$ GeV
- Large Λ_c^+ yields: $\approx$ 0.6 M at BaBar, $\approx$ 0.8 M at Belle
- SELEX-like Ξ_{cc}^+ signal not confirmed in $\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+$ decays

$$R = \frac{\sigma(\Xi_{cc}^+)\times \mathrm{BF}(\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+)}{\sigma(\Lambda_c^+)} < 2.7\times10^{-4}\ \text{(BaBar)} \quad 1.5\times10^{-4}\ \text{(Belle)} \quad @\ 95\%\ \text{CL}$$

BaBar: PRD 74 (2006) 011103



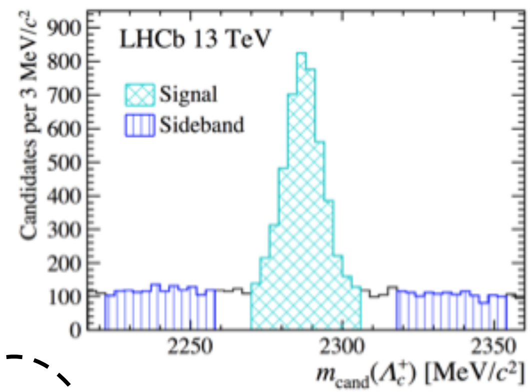
Belle: PRL 97 (2006) 162001



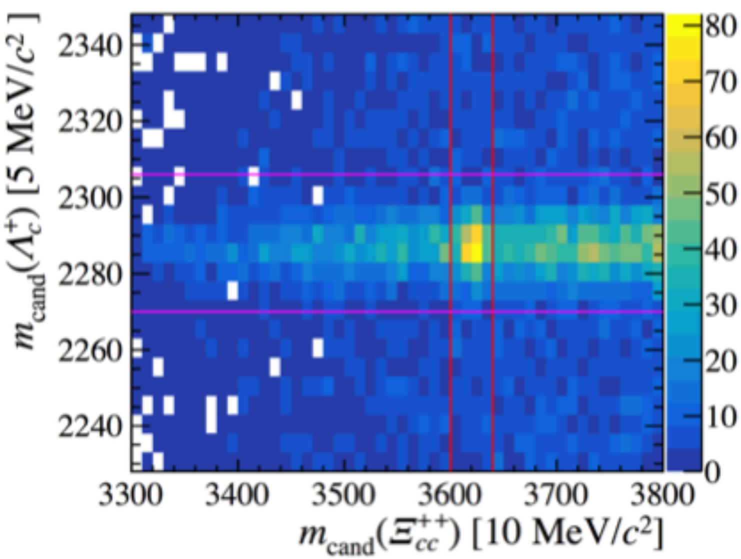
Mass spectrum

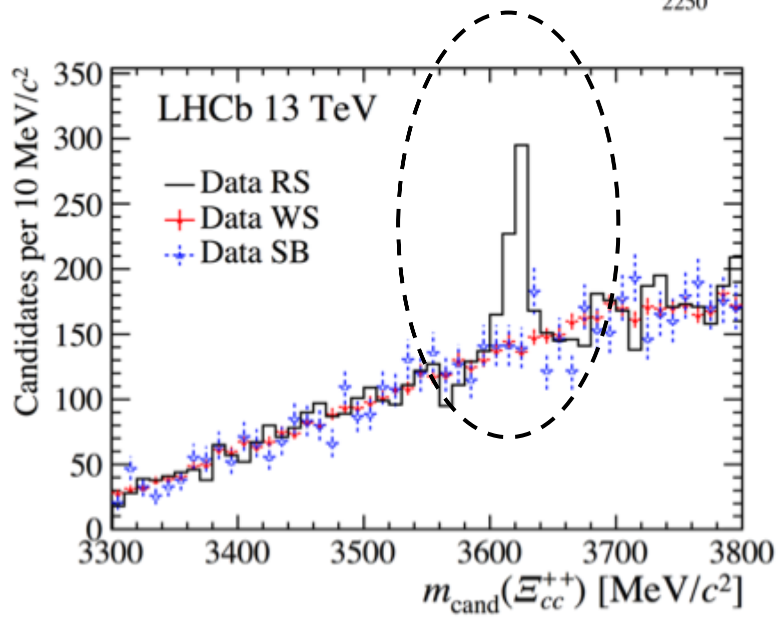
LHCb-PAPER-2017-018
PRL 119 (2017) 112001

- A significant structure in right sign (RS) combinations: $\Lambda_c^+ K^- \pi^+ \pi^+$
- Not present in wrong sign (WS) combinations: $\Lambda_c^+ K^- \pi^+ \pi^-$
- Not observed for Λ_c^+ background candidates
- Distributions similar except the peak in RS



A significant peak!



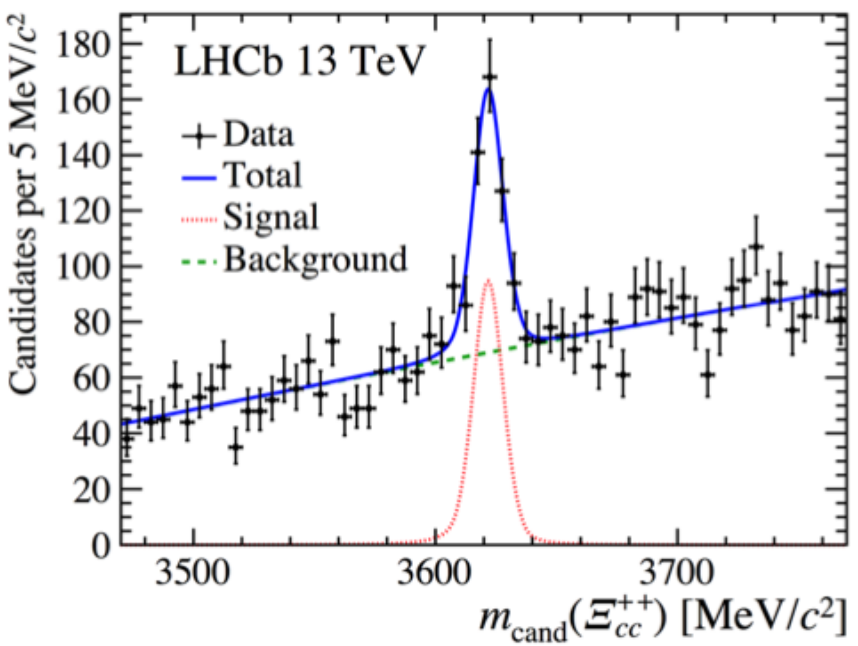


Fitting the mass peak

LHCb-PAPER-2017-018
PRL 119 (2017) 112001

- Studying Λ_c^+-mass corrected mass: $m_{\text{cand}}(\Xi_{cc}^{++}) = m(\Lambda_c^+ K^- \pi^+) - m(\Lambda_c^+) + m_{\text{PDG}}(\Lambda_c^+)$
  - Signal yield: 313 ± 33
  - Resolution: 6.6 ± 0.8 MeV, consistent with simulated value
  - Local significance $> 12\sigma$

$$m(\Xi_{cc}^{++}) = 3621.40 \pm 0.72(\text{stat}) \pm 0.27(\text{syst}) \pm 0.14(\Lambda_c^+)\ \text{MeV}$$
$$m(\Xi_{cc}^{++}) - m(\Lambda_c^+) = 1134.94 \pm 0.72(\text{stat}) \pm 0.27(\text{syst})\ \text{MeV}$$



Systematic uncertainties

Source	Value [MeV/c^2]
Momentum-scale calibration	0.22
Selection bias correction	0.14
Unknown Ξ_{cc}^{++} lifetime	0.06
Mass fit model	0.07
Sum of above in quadrature	0.27
Λ_c^+ mass uncertainty	0.14

Fitting the mass peak

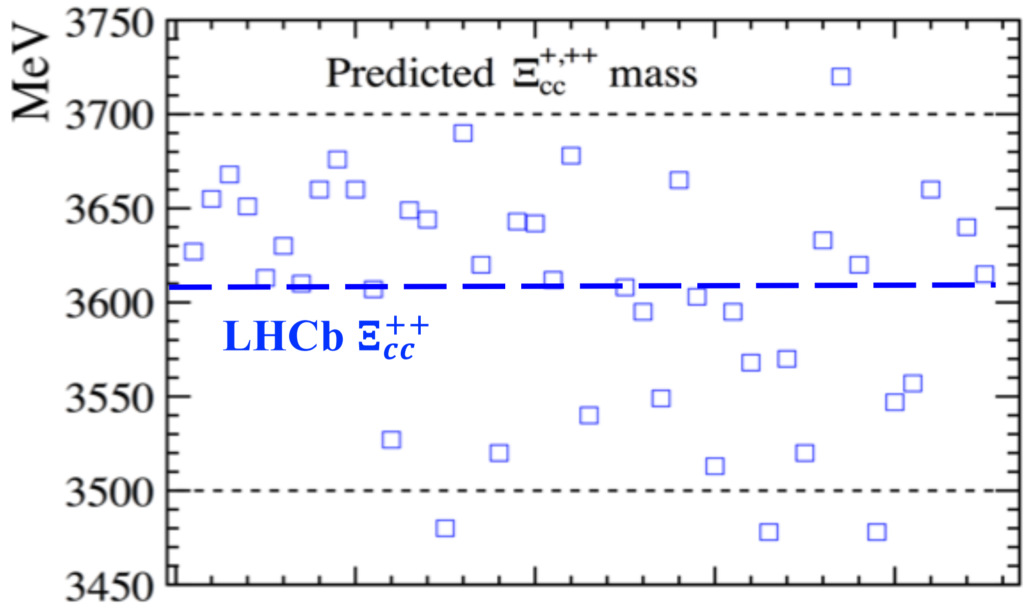
LHCb-PAPER-2017-018
PRL 119 (2017) 112001

- Studying Λ_c^+-mass corrected mass: $m_{\text{cand}}(\Xi_{cc}^{++}) = m(\Lambda_c^+ K^- \pi^+) - m(\Lambda_c^+) + m_{\text{PDG}}(\Lambda_c^+)$
  - ➢ Signal yield: 313 ± 33
  - ➢ Resolution: 6.6 ± 0.8 MeV, consistent with simulated value
  - ➢ Local significance $> 12\sigma$

$$m(\Xi_{cc}^{++}) = 3621.40 \pm 0.72(\text{stat}) \pm 0.27(\text{syst}) \pm 0.14(\Lambda_c^+)\ \text{MeV}$$

$$m(\Xi_{cc}^{++}) - m(\Lambda_c^+) = 1134.94 \pm 0.72(\text{stat}) \pm 0.27(\text{syst})\ \text{MeV}$$

Value consistent with many theoretical calculations, especially LQCD

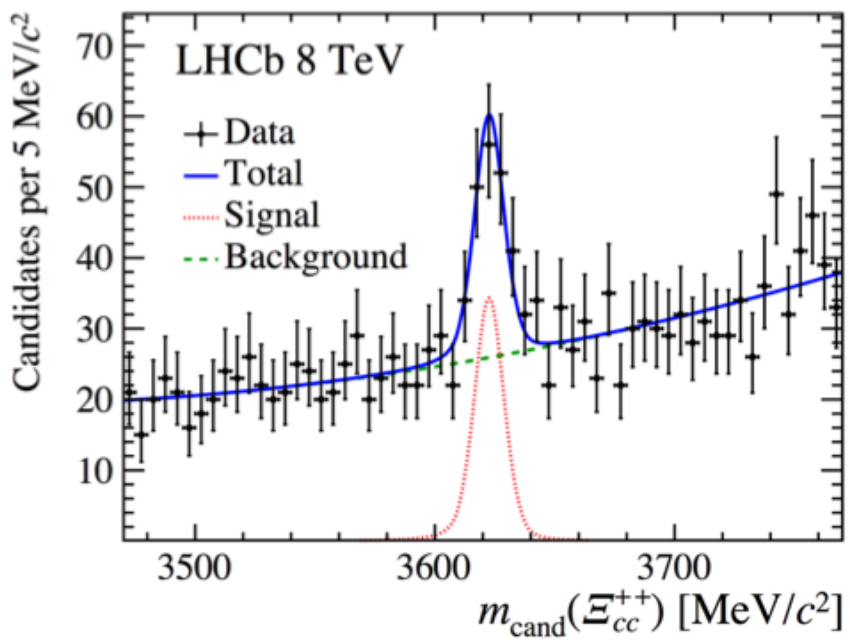


See backup pages for references

Test with RUNI data

LHCb-PAPER-2017-018
PRL 119 (2017) 112001

- Signal peak presents in RUNI data sample with significance $> 7\sigma$



$N(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+) = 113 \pm 21$

Resolution: 6.6 ± 1.4 MeV

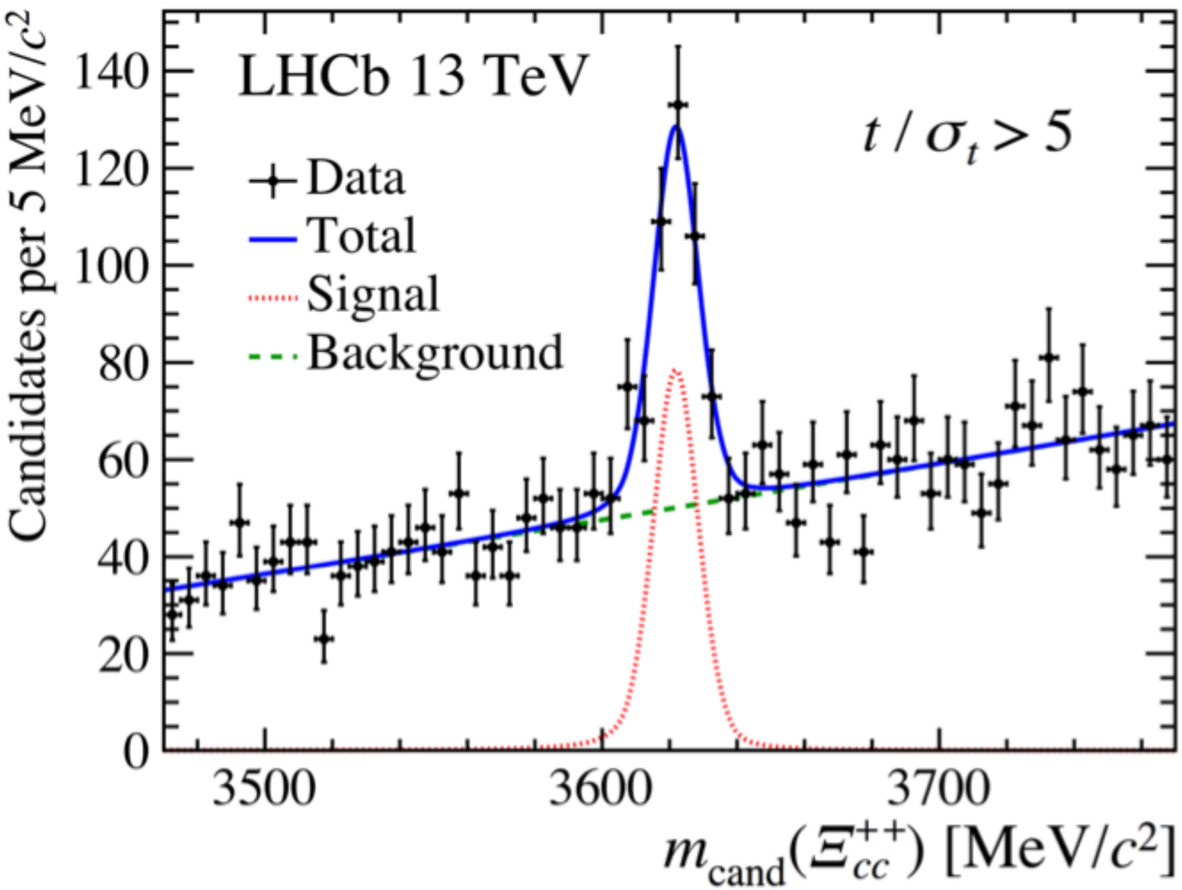
$\delta M(\text{run I, run II}) = 0.8 \pm 1.4$ MeV

Consistent between two samples

Signal properties

LHCb-PAPER-2017-018
PRL 119 (2017) 112001

- Peaking structure remains significant ($> 12\sigma$) after requiring minimum decay time, $t > 5\sigma_t$. It is indeed a weak decay.



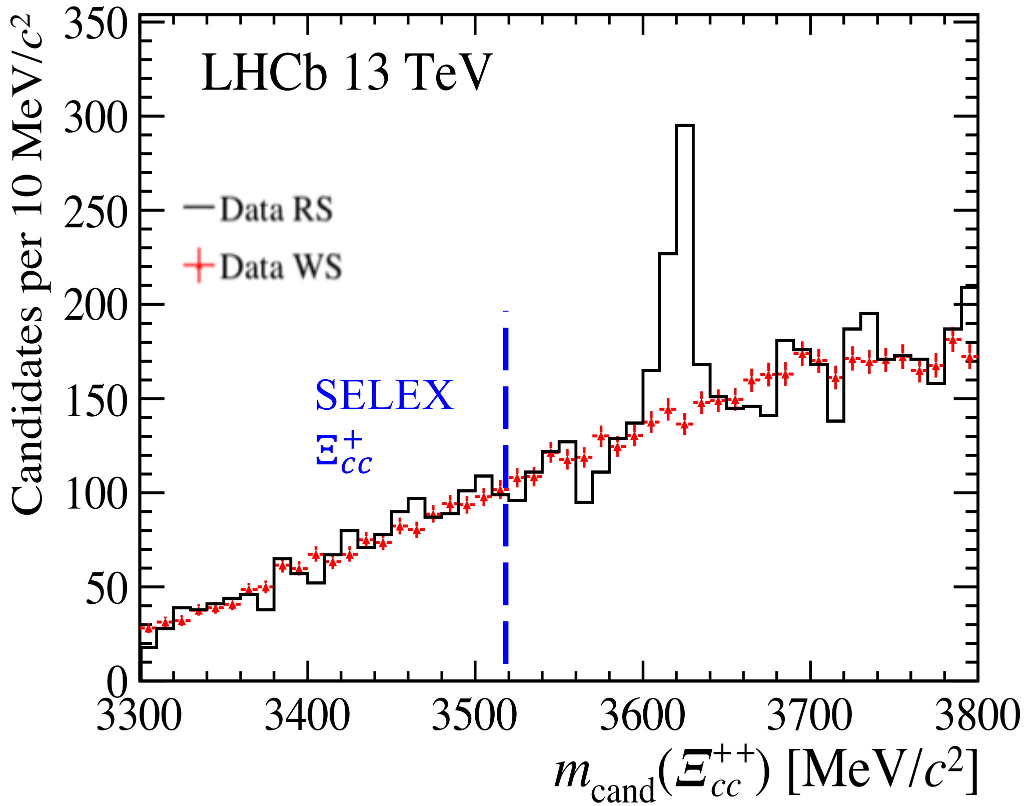
Comparison with SELEX

LHCb-PAPER-2017-018
PRL 119 (2017) 112001

- Large mass difference: $m(\Xi_{cc}^{++})_{\text{LHCb}} - m(\Xi_{cc}^{+})_{\text{SELEX}} = 103 \pm 2$ MeV
  - ➢ Inconsistent with being isospin partners

Hwang and Chung, PRD 78(2008) 073013;
Brodsky et al., PLB 698 (2011) 251;
Karliner and Rosener, arXiv: 1706.06961

- Production: $N(\Xi_{cc})/N(\Lambda_c^+)$ much smaller in LHCb result



Tetraquark searches in $B_s\pi^{\pm}$

- D0 announced a new state $X(5568)^{\pm} \to B_s\pi^{\pm}$ PRL 117 (2016) 022003

- significance of 5.1σ

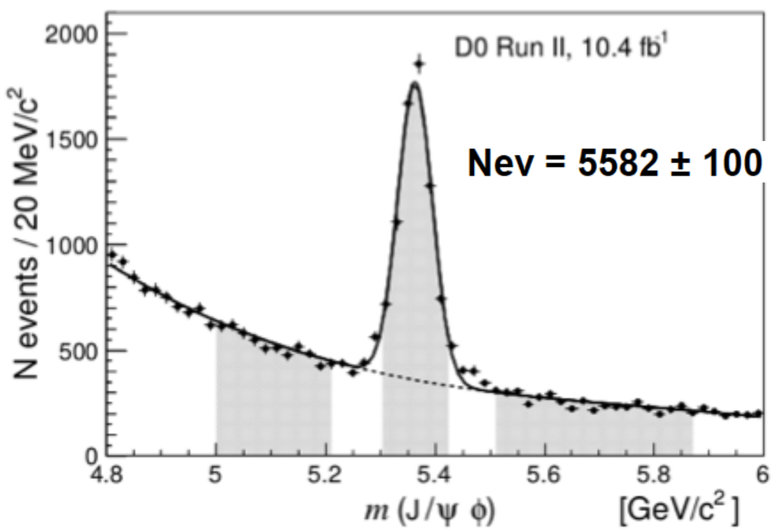
- mass and width

$$m = 5567.8 \pm 2.9\,(\text{stat})\,^{+0.9}_{-1.9}\,(\text{syst})\ \text{MeV}/c^2$$
$$\Gamma = 21.9 \pm 6.4\,(\text{stat})\,^{+5.0}_{-2.5}\,(\text{syst})\ \text{MeV}/c^2$$

- high production rate

$$\rho_X^{\text{D0}} \equiv \left.\frac{\sigma(p\bar{p}\to X+\text{anything})\times\mathcal{B}(X\to B_s^0\pi^{\pm})}{\sigma(p\bar{p}\to B_s^0+\text{anything})}\right|_{\text{D0 Acc.}}$$

$$(8.6 \pm 1.9 \pm 1.4)\%$$



Tetraquark searches in $B_s\pi^{\pm}$

LHCb-PAPER-2016-029
PRL 117 (2016) 152003

- Upper limits

$$\rho_X^{\mathrm{LHCb}} \equiv \left.\frac{\sigma(pp\to X+\mathrm{anything})\times\mathcal{B}(X\to B_s^0\pi^{\pm})}{\sigma(pp\to B_s^0+\mathrm{anything})}\right|_{\mathrm{LHCb\ Acc.}}$$

$$= \frac{N(X)}{N(B_s^0)}\times\frac{1}{\epsilon^{\mathrm{rel}}(X)} \qquad \epsilon^{\mathrm{rel}}(X)=\epsilon(X)/\epsilon(B_s^0)$$

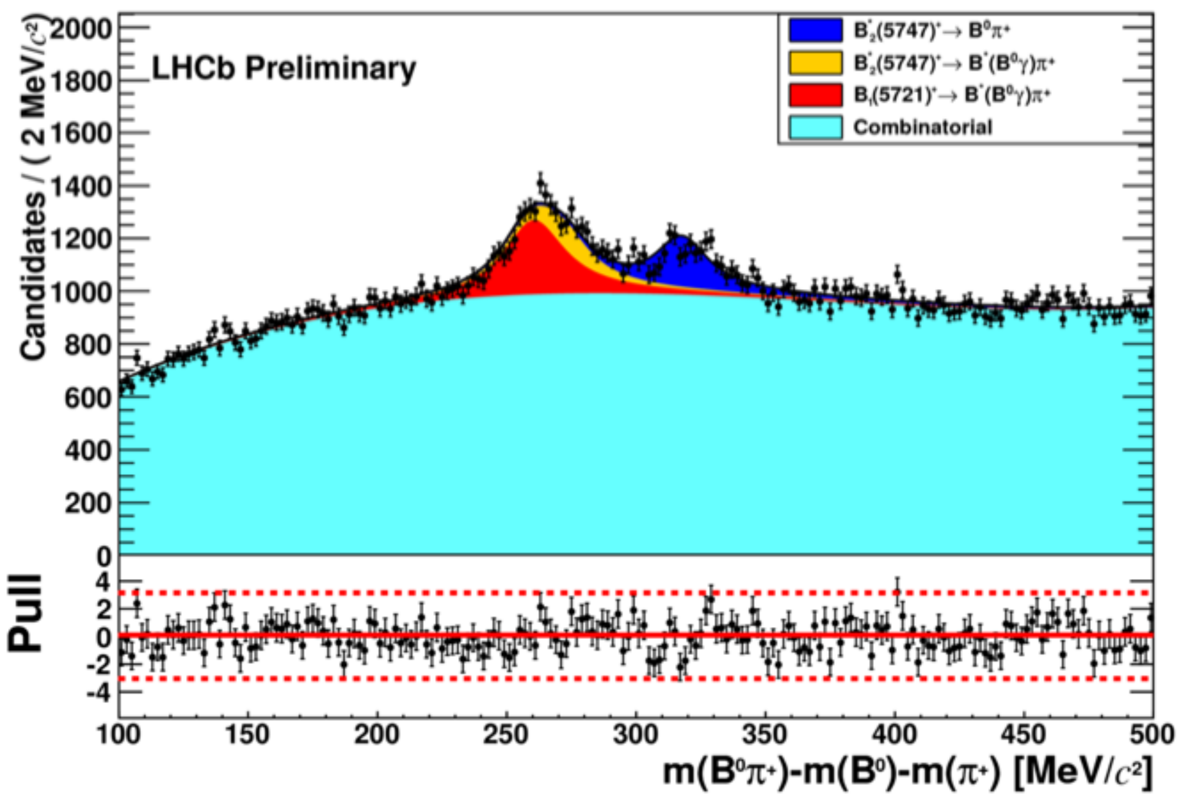
		$B_s^0\to D_s^-\pi^+$	$B_s^0\to J/\psi\phi$	Sum
$N(B_s^0)$	B_s^0 $p_T>5\,\mathrm{GeV}/c$ (10^3)	66.3 ± 0.3	46.3 ± 0.2	112.6 ± 0.4
$N(B_s^0)$	B_s^0 $p_T>10\,\mathrm{GeV}/c$ (10^3)	30.1 ± 0.2	14.1 ± 0.1	44.2 ± 0.2
$N(X)$	B_s^0 $p_T>5\,\mathrm{GeV}/c$	23 ± 55	-15 ± 37	8 ± 66
$N(X)$	B_s^0 $p_T>10\,\mathrm{GeV}/c$	70 ± 48	11 ± 30	81 ± 57
$\epsilon^{\mathrm{rel}}(X)$	B_s^0 $p_T>5\,\mathrm{GeV}/c$	0.141 ± 0.002	0.102 ± 0.001	—
$\epsilon^{\mathrm{rel}}(X)$	B_s^0 $p_T>10\,\mathrm{GeV}/c$	0.239 ± 0.003	0.230 ± 0.003	—

$$\rho_X^{\mathrm{LHCb}}(B_s^0\ p_T>5\,\mathrm{GeV}/c) < 0.009\,(0.010)\ @\ 90\,(95)\,\%\ \mathrm{CL}\,,$$
$$\rho_X^{\mathrm{LHCb}}(B_s^0\ p_T>10\,\mathrm{GeV}/c) < 0.016\,(0.018)\ @\ 90\,(95)\,\%\ \mathrm{CL}\,.$$

Tetraquark searches in $B_s\pi$

LHCb-PAPER-2016-029
PRL 117 (2016) 152003

- Use similar selection criteria as $B_c \to B_s\pi$, consistent result
- Similar selection on $B^0\pi$

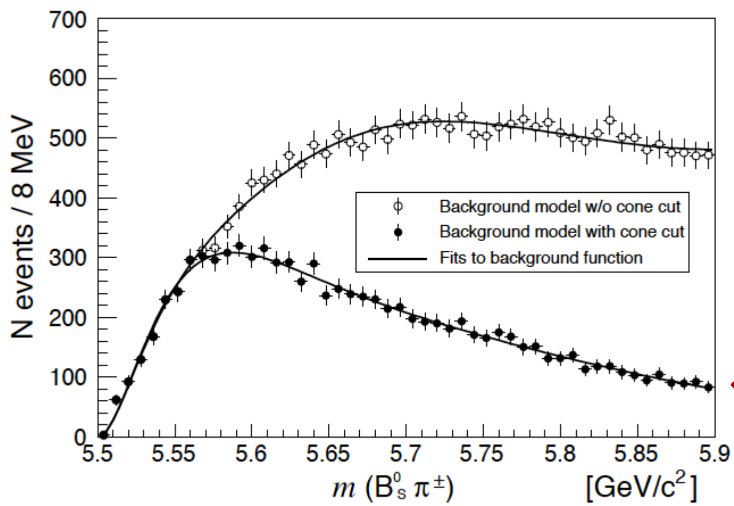


Tetraquark searches in $B_s\pi^{\pm}$

- A "cone cut" used in D0 analysis

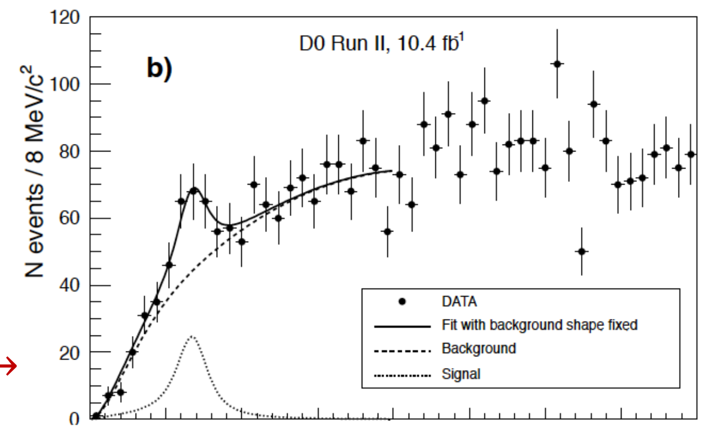
D0, arXiv:1602.07588

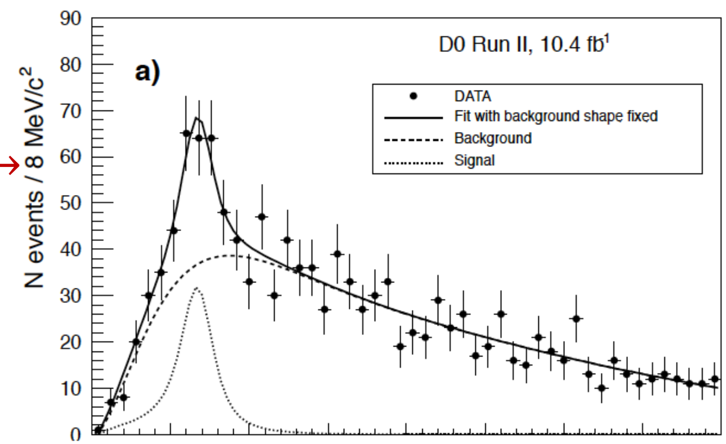
$$\Delta R = \sqrt{[\phi(B_s^0) - \phi(\pi)]^2 + [\eta(B_s^0) - \eta(\pi)]^2} < 0.3$$



← w/o cone cut →

← w/ cone cut →



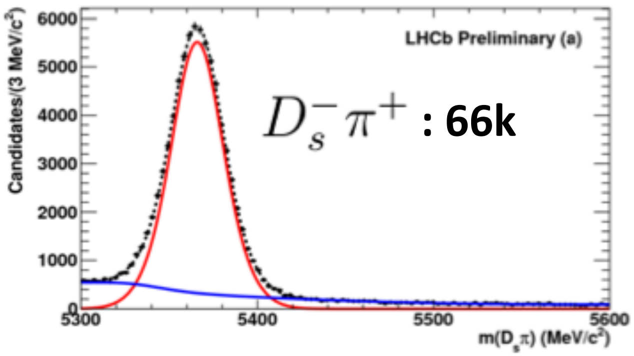


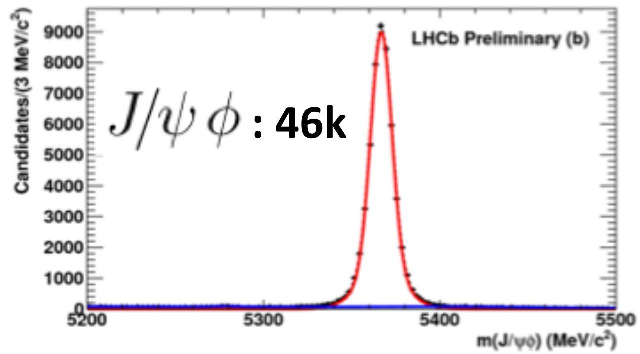
- *NOT* used in the LHCb analysis

Tetraquark searches in $B_s\pi^{\pm}$

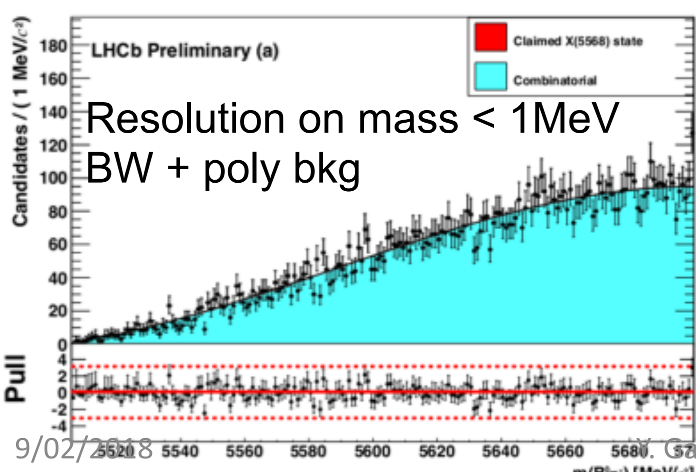
LHCb-PAPER-2016-029
PRL 117 (2016) 152003

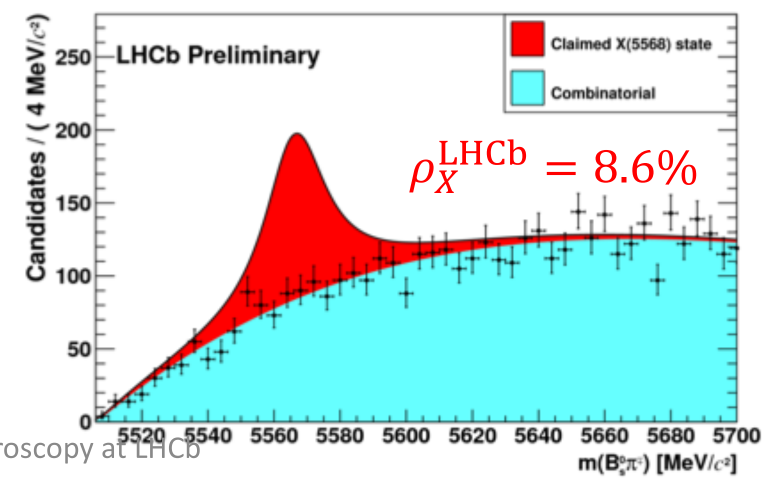
- Very large and clean B_s sample at LHCb





- Add a pion, no peak observed at 5568 MeV





Model independent analysis

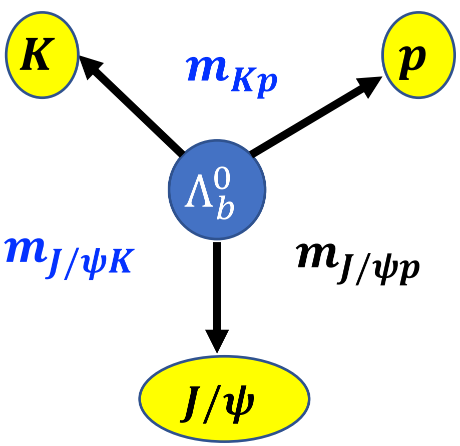
- 2 models for $\Lambda^* \to pK^-$ contributions based on PDG
  - *Extended model* allows all LS couplings of each resonance, and include poorly motivated states $\to$ 146 parameters
  - *Reduced model* uses only well motivated states $\to$ 64 parameters
  - *Other possibilities* checked, including isospin violating decays of Σ^{*0}'s, adding two new Λ^* states with free mass & width, non-resonance contributions, …, would not change the conclusion

→ Confirm that conventional pK^- contributions cannot describe the data, with minimal assumptions on their spin, and no assumptions on their number, shapes, masses, widths, and interference patterns.

Model independent analysis

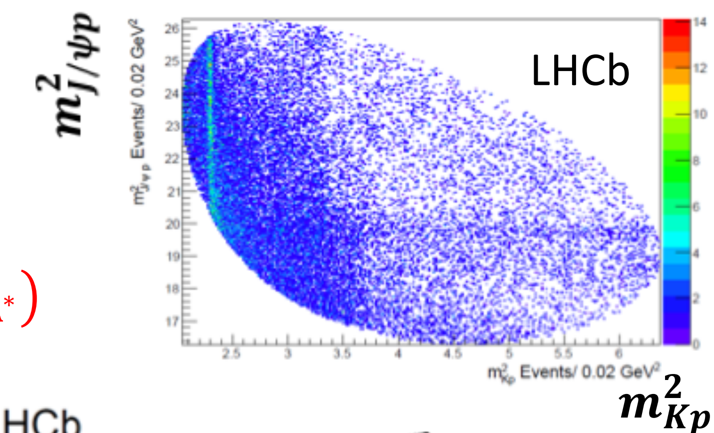
LHCb-PAPER-2016-009
PRL 117 (2016) 082002

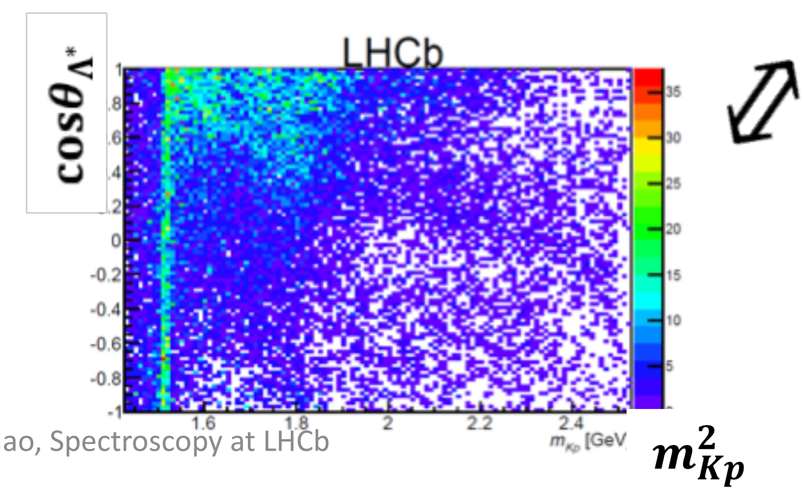
- The method introduced by Babar, improved by LHCb in $Z(4430)^-$ analysis → essentially a 2D Dalitz analysis
- Same data set as amplitude analysis



$$m_{Kp}^2 + m_{J/\psi p}^2 + m_{J/\psi K}^2 = m_{\Lambda_b^0}^2 + m_K^2 + m_p^2 + m_{J/\psi}^2$$

$$(m_{J/\psi p}^2, m_{Kp}^2) \rightarrow (m_{Kp}, \cos\theta_{\Lambda^*})$$





Model independent analysis

LHCb-PAPER-2016-009
PRL 117 (2016) 082002

- The distribution of $\cos\theta_{\Lambda^*}$ as a function of m_{Kp} can be decomposed as

$$\frac{\mathrm{d}N}{\mathrm{d}\cos\theta_{\Lambda^*}}(m_{Kp}) = \sum_{l=0}^{l_{\max}} \langle P_l^U \rangle (m_{Kp}) P_l(\cos\theta_{\Lambda^*})$$

- The unnormalized Legendre moment of rank l given by

$$\langle P_l^U \rangle (m_{Kp}) = \int_{-1}^{1} \mathrm{d}\cos\theta_{\Lambda^*} \, \underbrace{P_l(\cos\theta_{\Lambda^*})}_{\text{Legendre fun.}} \, \underbrace{\frac{\mathrm{d}N}{\mathrm{d}\cos\theta_{\Lambda^*}}(m_{Kp})}_{\text{Eff. Corrected data}}$$

- Generally $l_{\max} \to \infty$

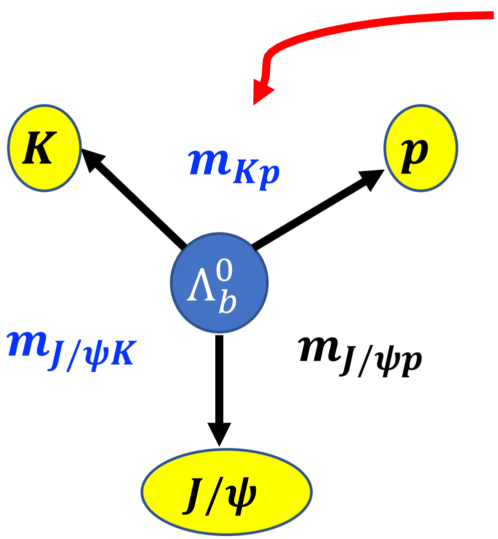
Model independent analysis

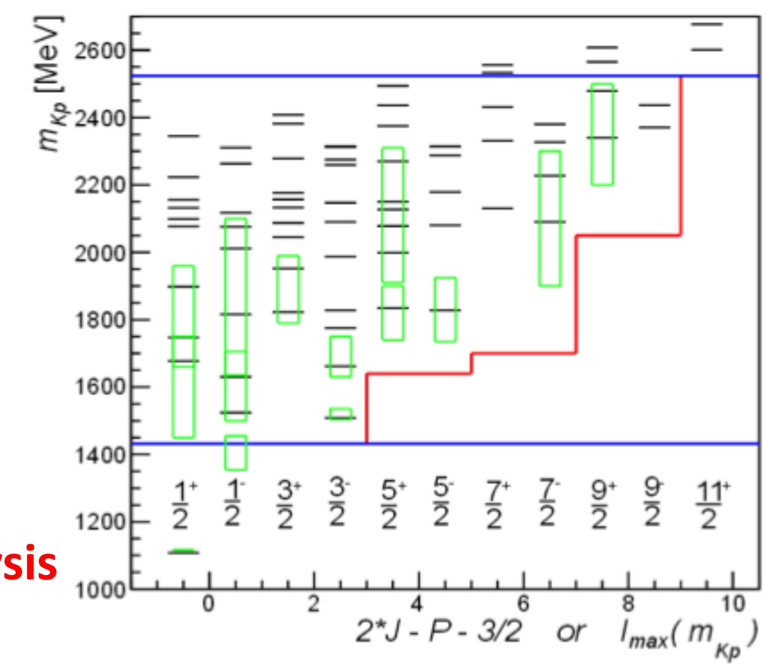
LHCb-PAPER-2016-009
PRL 117 (2016) 082002

$$\frac{\mathrm{d}N}{\mathrm{d}\cos\theta_{\Lambda^*}}(m_{Kp}) = \sum_{l=0}^{l_{\max}} \langle P_l^U \rangle (m_{Kp}) P_l(\cos\theta_{\Lambda^*})$$

- If only $\Lambda^* \to Kp$ contributions

$$l_{\max} \le 2J_{\max}$$





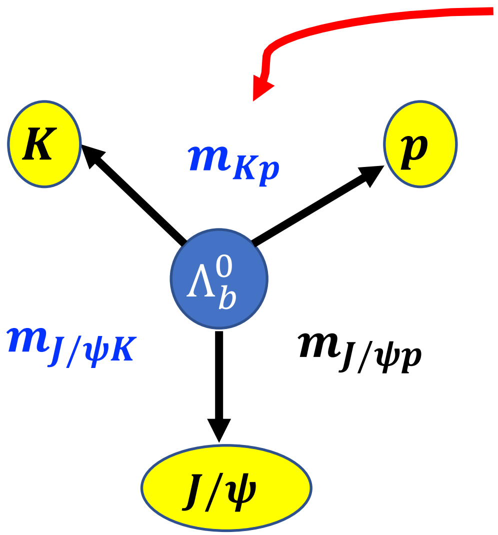
Determined by model & scattering data

- the only model dependent part of the analysis

Model independent analysis

LHCb-PAPER-2016-009
PRL 117 (2016) 082002

$$\frac{dN}{d\cos\theta_{\Lambda^*}}(m_{Kp}) = \sum_{l=0}^{l_{\max}} \langle P_l^U \rangle (m_{Kp}) P_l(\cos\theta_{\Lambda^*})$$



- If only $\Lambda^* \to Kp$ contributions
  $l_{\max} \le 2J_{\max}$

$$l_{\max} = \begin{cases} 3 & \text{if } m_{Kp} < 1.64\text{ GeV} \\ 5 & \text{if } 1.64 \le m_{Kp} < 1.7\text{ GeV} \\ 7 & \text{if } 1.7 \le m_{Kp} < 2.050\text{ GeV} \\ 9 & \text{if } m_{Kp} \ge 2.050\text{ GeV} \end{cases}$$

- Resonances from $J/\psi p, J/\psi K$ may have contributions to higher orders

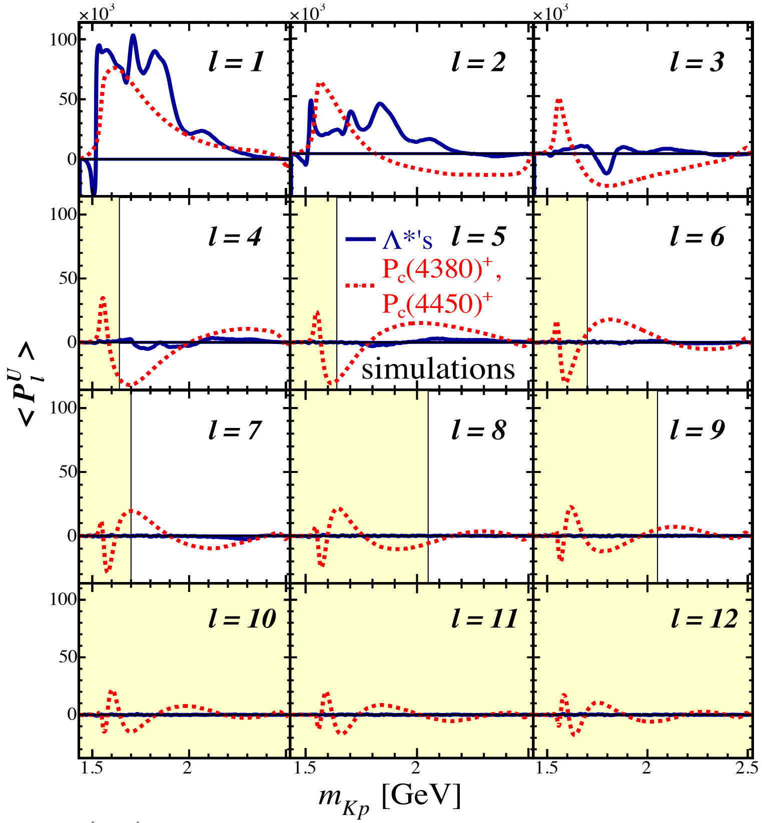
Model independent analysis

LHCb-PAPER-2016-009
PRL 117 (2016) 082002

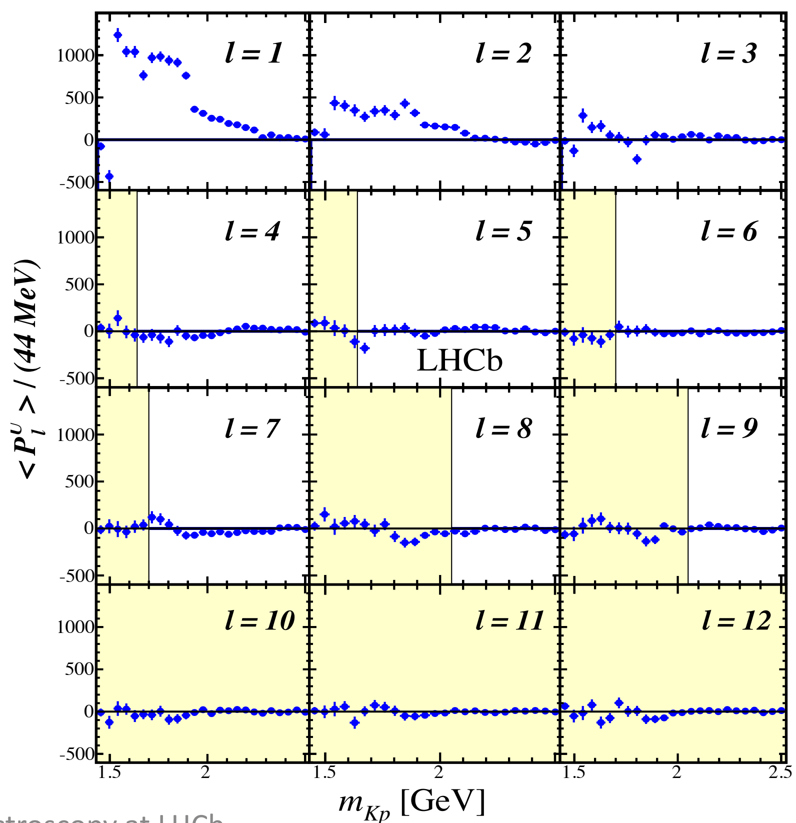
- **Legendre moments from simulation & data**

shaded region corresponding to $l_{\max}$ cutoff

simulation



data



Model independent analysis

LHCb-PAPER-2016-009
PRL 117 (2016) 082002

- Construct *Hypothesis* from measured Legendre moments
  - H_0 : $\Lambda^* \to pK^-$ only, $l \le l_{\max}$
  - H_1 : allow contributions from high order moments up to 31

H_0 rejected at ~ 10 σ