Hadron spectroscopy @ LHCb

清华大学高能物理研究中心
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第一届强子与重味物理理论实验联合研讨会
3.31-4.1 兰州大学

Outline

- Introduction to spectroscopy studies at LHCb
- Charmed mesons + baryons

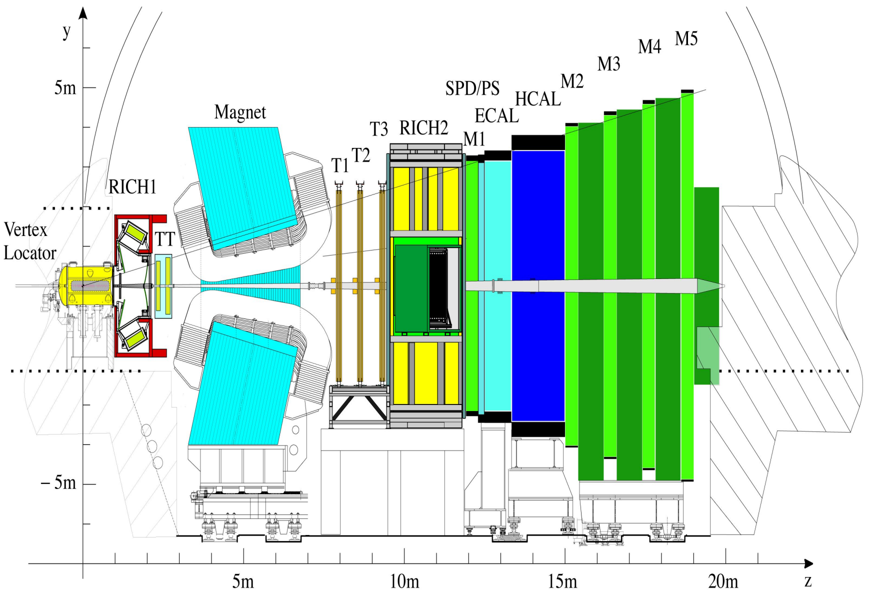
  ** Doubly charmed baryons -> Yuehong 's talk*
- Search for $\boldsymbol{B_c^*}$
- Tetraquark states
- Pentaquark states
- Future prospects

  ** LHCb prospects → Wenbin's talk*

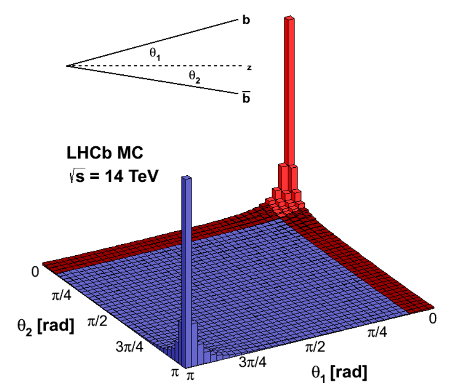
LHCb Detector

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:

- $\sigma(\mathrm{IP}) \approx 20\ \mu\mathrm{m}$ 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

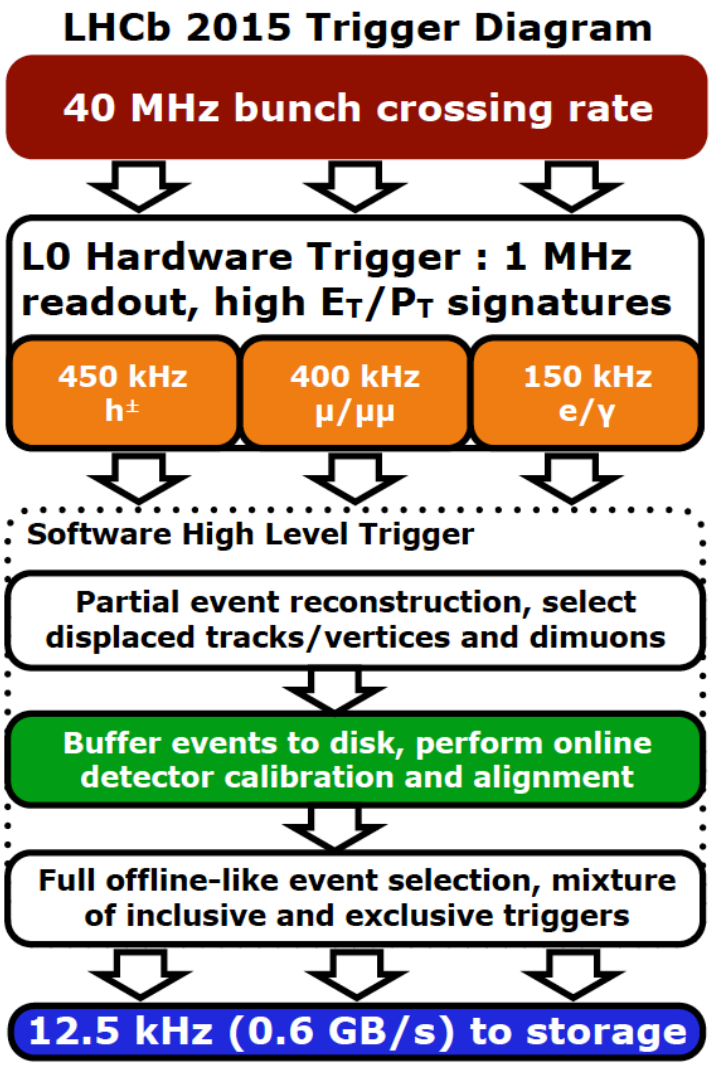
- $> 99\%$

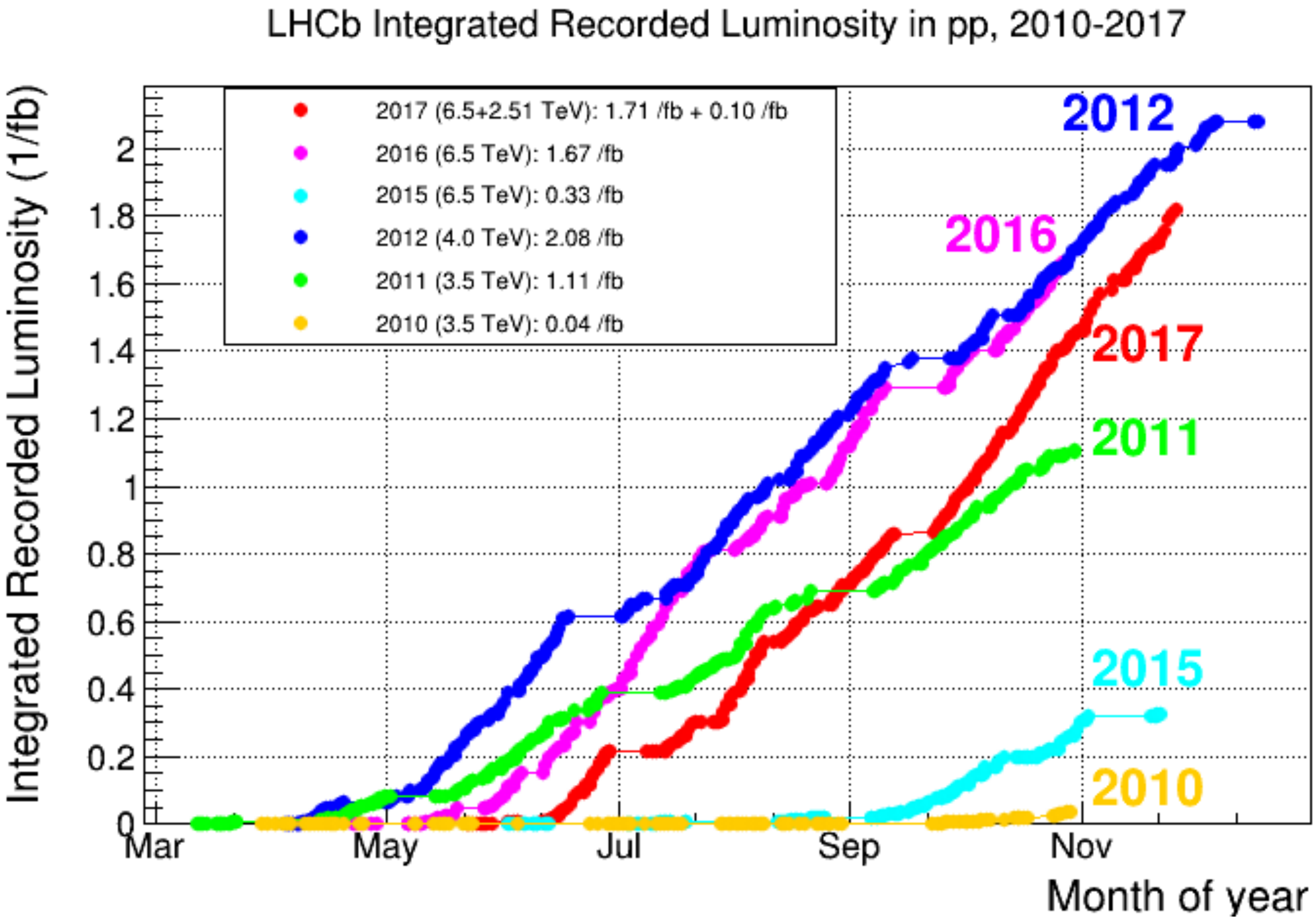
LHCb Trigger in RUN II

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: $J/\psi, D^0, D^+$, ...



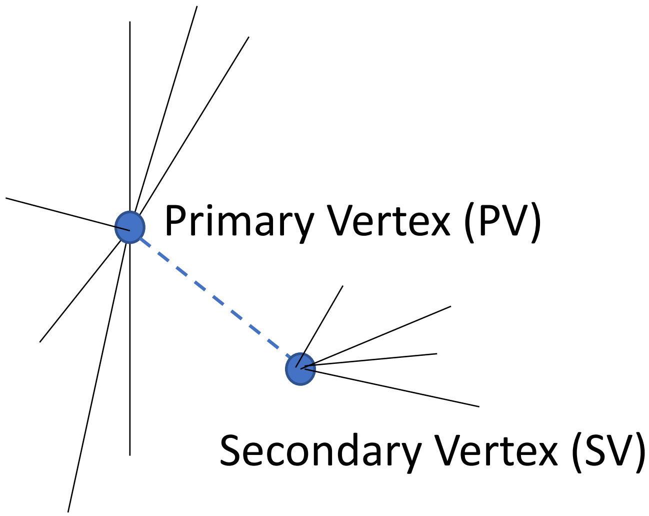

LHCb Integrated Recorded Luminosity in pp, 2010-2017
2017 (6.5+2.51 TeV): 1.71 /fb + 0.10 /fb
2016 (6.5 TeV): 1.67 /fb
2015 (6.5 TeV): 0.33 /fb
2012 (4.0 TeV): 2.08 /fb
2011 (3.5 TeV): 1.11 /fb
2010 (3.5 TeV): 0.04 /fb
2012
2016
2017
2011
2015
2010
Integrated Recorded Luminosity (1/fb)
0
0.2
0.4
0.6
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

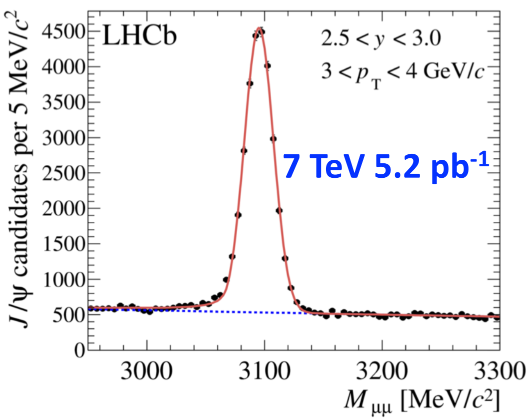
→ weakly decayed particles

→ particles from b/c decays

Study of charmonia as an example

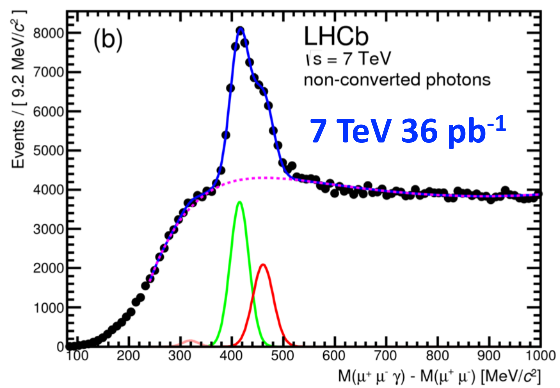
EPJC 71 (2011)1645

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



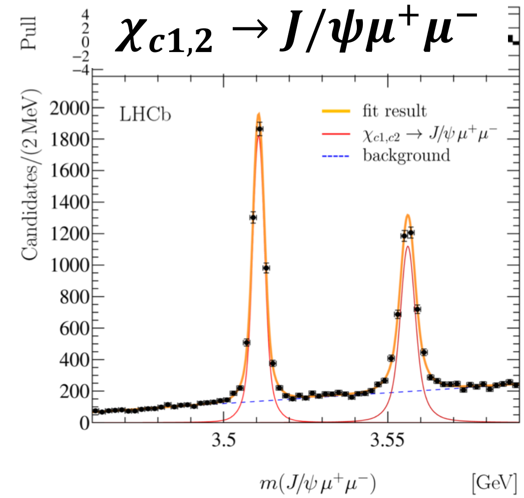
PLB 714 (2012) 215

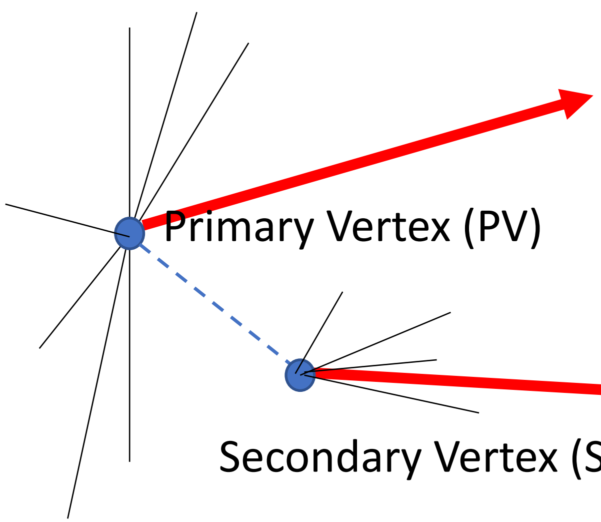
$\chi_{c1,2} \to J/\psi + \gamma$

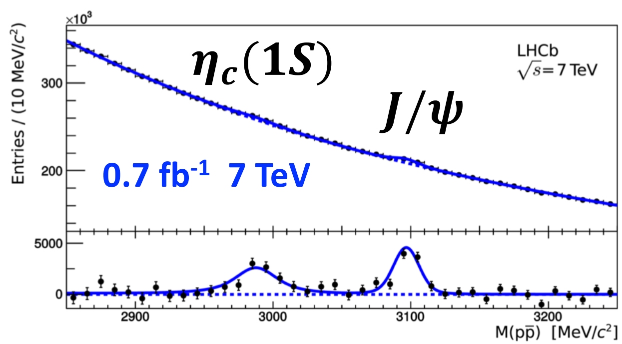


PRL 119 (2017) 221801

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

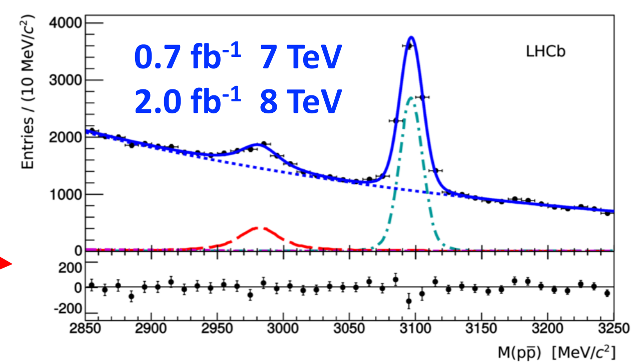






EPJC 75 (2015) 311

$J/\psi, \eta_c(1S) \to p\bar{p}$



Charmed mesons + baryons

- $\boldsymbol{D_{sJ}^{(**)}}$ **excited strange-charm mesons**
- $D_J^{0(**)}$ excited charm mesons → backup slides
- **Excited charmed baryons $\boldsymbol{\Lambda_c^*}$ and $\boldsymbol{\Omega_c^*}$**

$D_{sJ}^{(**)}$ 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 $pp \to (D^+K^0, D^0K^+) + X$ **JHEP 10 (2012) 151**

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

$D_{sJ}^*(3040)$

$D_{sJ}^*(2860)$

$D_{s1}^*(2700)$

$D_{s2}^*(2573)$

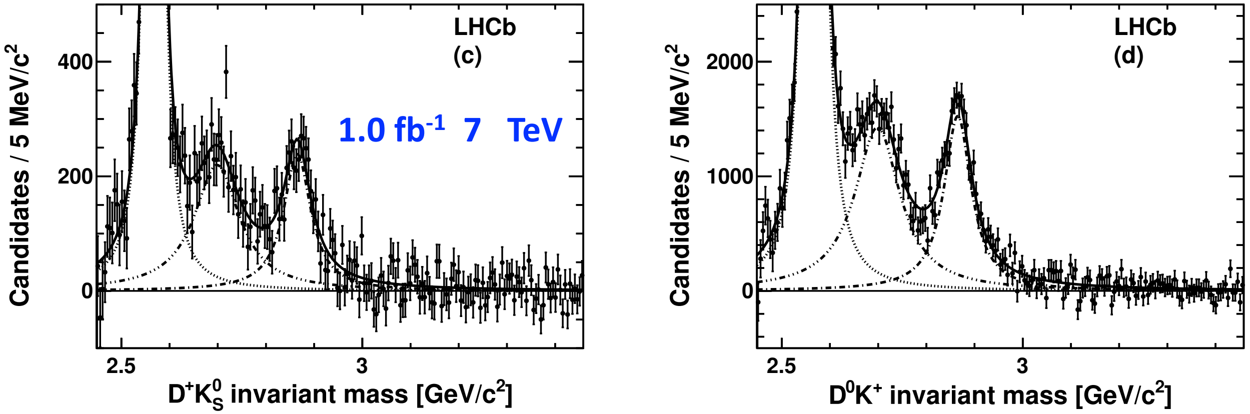
$D_{s1}(2536)$

$D_{s1}(2460)$

$D_{s0}^*(2317)$

D_s^*

D_s



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D_s^*

D_s

- Inclusive $pp \to (D^+K^0, D^0K^+) + X$
  $D_{s2}^*(2573), D_{s1}^*(2700), D_{sJ}^*(2860)$

LHCb-PAPER-2012-016
JHEP 10 (2012) 151

- Dalitz plot analysis $B_s^0 \to \overline{D}^0 K^- \pi^+$ reveals two states $D_{s1}^*(2860), D_{s3}^*(2860)$

PRL 113 (2014) 162001 PRD 90 (2014) 072003

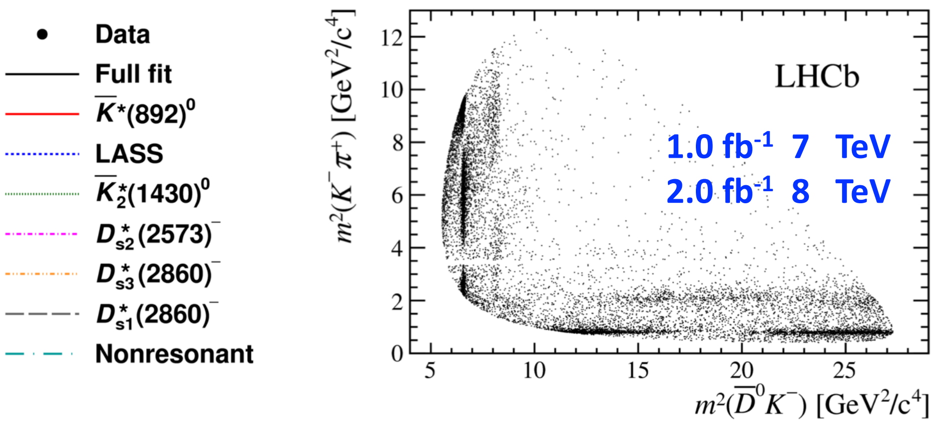
States observed from B-factories and other experiments
- $D_s^*, D_{s0}^*(2317)$ below *DK* threshold
- States with unnatural spin-parity ($J^P = 0^-, 1^+, 2^-, \ldots$)

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

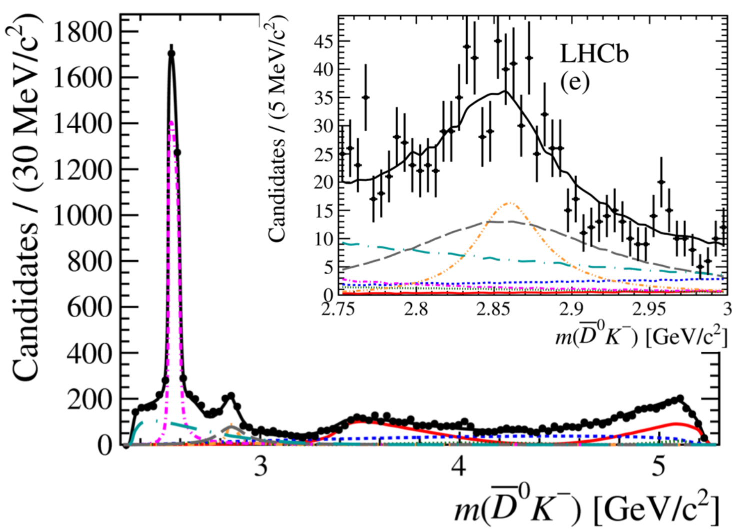
- ~11K signal events with purity 87%

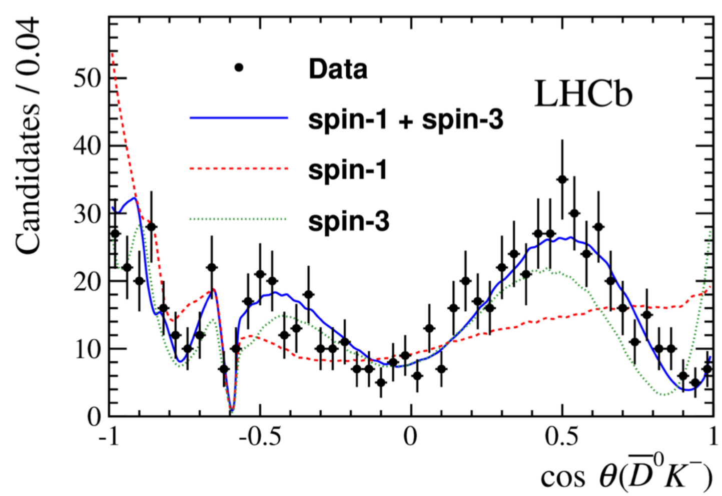
PRL 113 (2014) 162001

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 $pp \to (D^+K^0, D^0K^+) + X$ 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 $D_{s1}^{*}(2860), D_{s3}^{*}(2860)$
  PRL 113 (2014) 162001 PRD 90 (2014) 072003
- Inclusive $pp \to (D^{*+}K^0, D^{*0}K^+) + X$
  $D_{s2}^{*}(2536), D_{s2}^{*}(2573), D_{s1}^{*}(2700), D_{s3}^{*}(2860), D_{sJ}^{*}(3040)$
  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 ($J^P = 0^-, 1^+, 2^-, \ldots$)

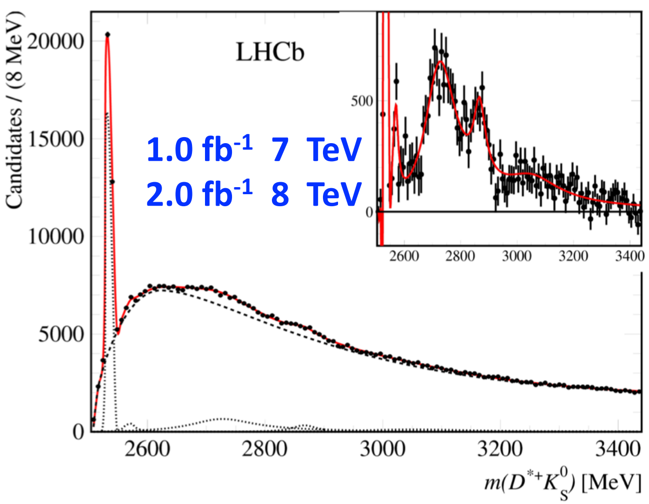
Inclusive analysis $pp \to (D^{*+}K^0, D^{*0}K^+) + X$

- Resonant contribution seen due to $D_{s2}^*(2536), D_{s2}^*(2573), D_{s1}^*(2700)$ and $D_{s3}^*(2860)$, weak evidence of $D_{sJ}^*(3040)$ JHEP 02 (2016) 133
- Angular distribution reflects the spin-parity assignment

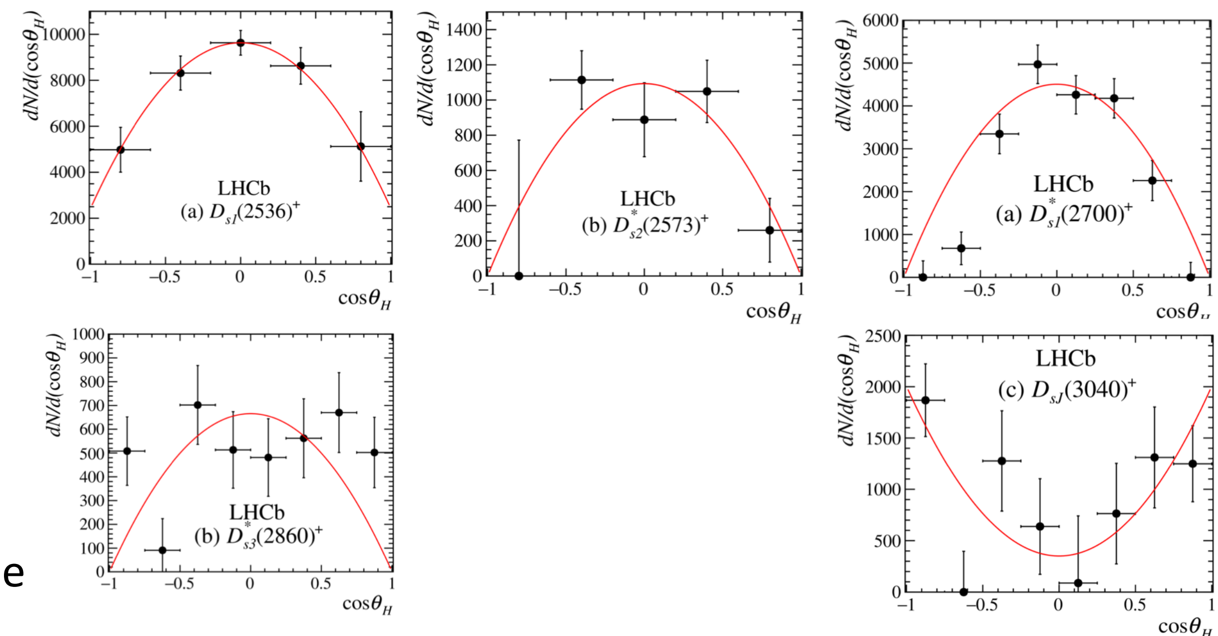
$\sin^2\theta_H$ Natural Spin-Parity

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

$D_{sJ}^{(**)} \to D\pi K$ rest frame
θ_H: angle between πK



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



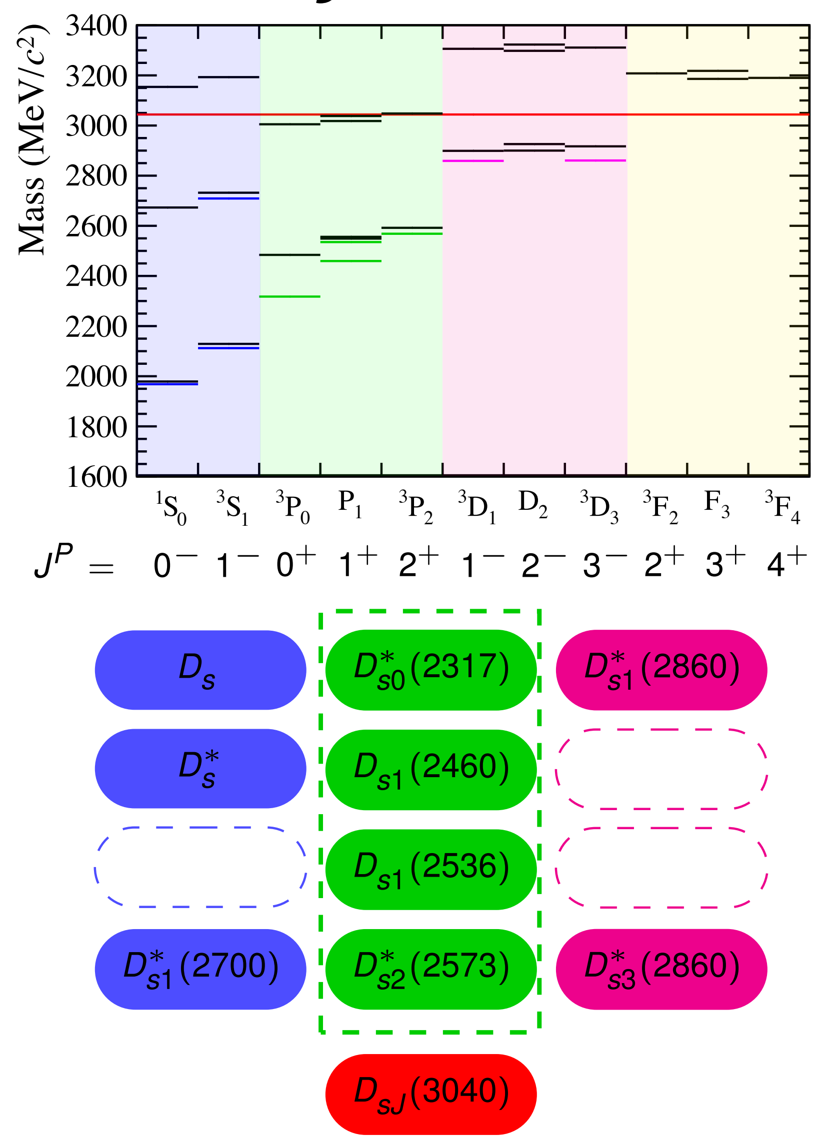
Possible assignment of $D_{sJ}^{(**)}$ states

- 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

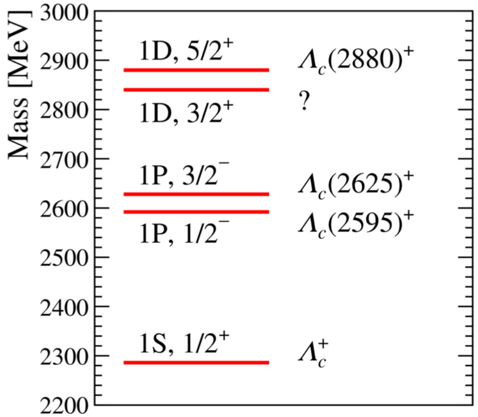


$\Lambda_c^{(*)}$ spectroscopy

- Status

B.Chen, K.-W. Wei and A. Zhang, EPJA 51 (2015) 82

– experimental observations / nonrelativistic *heavy quark-light diquark* model



states seen with confirmed properties

$\Lambda_c(2765)$ or Σ_c

threshold structure near 2840 MeV

$\Lambda_c(2940)$ ***D^*N molecule?***

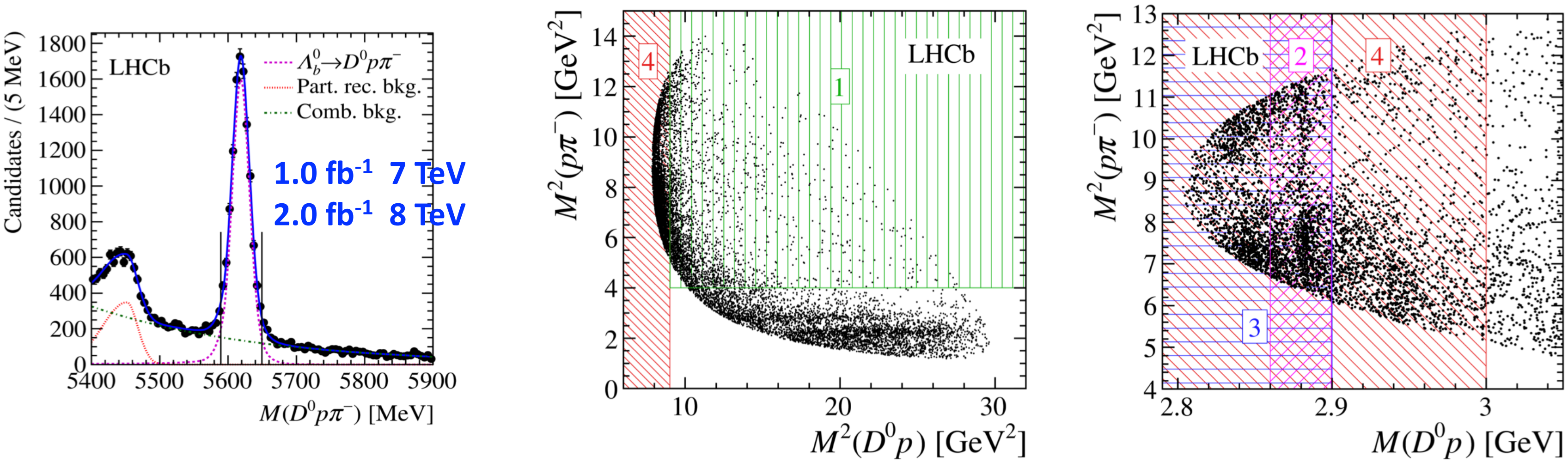
- $\mathcal{B}(\Lambda_b \to D^0 p\pi^-)$ measured with 1fb^{-1} **PRD 89 (2014) 032001**

  Amplitude analysis with 3 fb-1 **JHEP 05 (2017) 030**

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

LHCb-PAPER-2016-061
JHEP 05 (2017) 030

- Clean sample with ~11K signal events



fit in different phase space regions to reduce complexities

Yield	Phase space region				
	Full	1	2	3	4
$\Lambda_b^0 \to D^0 p\pi^-$	$11\,212 \pm 126$	$2\,250 \pm 61$	$1\,674 \pm 46$	$3\,141 \pm 63$	$4\,750 \pm 79$
Combinatorial	$14\,024 \pm 224$	$4\,924 \pm 132$	968 ± 78	$2\,095 \pm 96$	$4\,188 \pm 127$
Partially rec.	$4\,106 \pm 167$	$1\,344 \pm 96$	321 ± 64	691 ± 75	$1\,204 \pm 96$
Signal in box	10 233	2 061	1 500	2 803	4 261
Background in box	1 616	598	89	192	427

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

LHCb-PAPER-2016-061
JHEP 05 (2017) 030

- $\Lambda_c(2880)$ $J^P = \frac{5}{2}^+$ confirmed

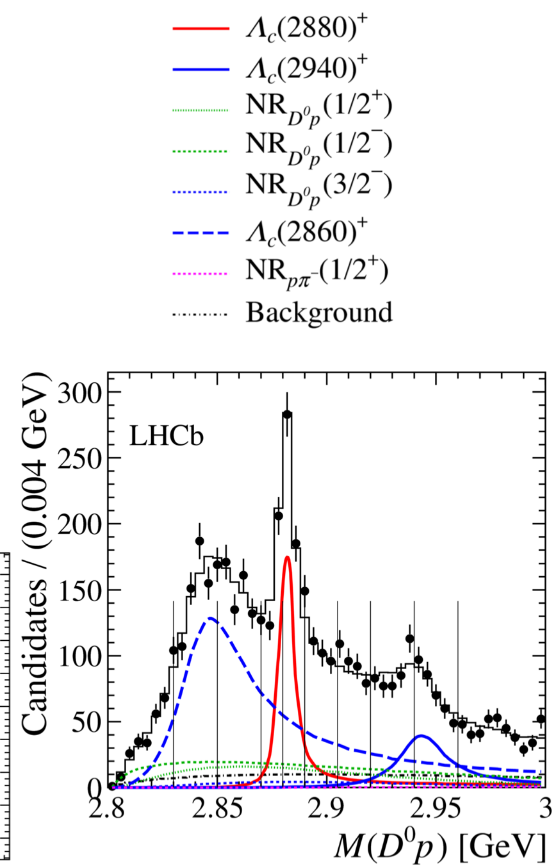
$$m(\Lambda_c(2880)^+) = 2881.75 \pm 0.29(\text{stat}) \pm 0.07(\text{syst})^{+0.14}_{-0.20}(\text{model})\ \text{MeV},$$
$$\Gamma(\Lambda_c(2880)^+) = 5.43^{+0.77}_{-0.71}(\text{stat}) \pm 0.29(\text{syst})^{+0.75}_{-0.00}(\text{model})\ \text{MeV}.$$

- $\Lambda_c(2860)$ $J^P = \frac{3}{2}^+$ confirmed

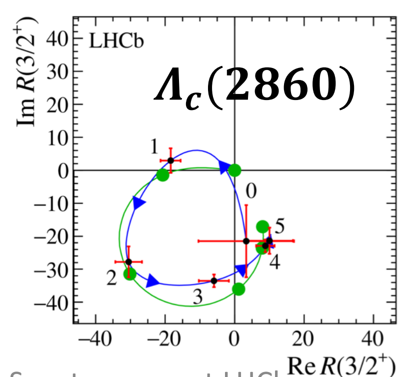
$$m(\Lambda_c(2860)^+) = 2856.1^{+2.0}_{-1.7}(\text{stat}) \pm 0.5(\text{syst})^{+1.1}_{-5.6}(\text{model})\ \text{MeV},$$
$$\Gamma(\Lambda_c(2860)^+) = 67.6^{+10.1}_{-8.1}(\text{stat}) \pm 1.4(\text{syst})^{+5.9}_{-20.0}(\text{model})\ \text{MeV}.$$

- $\Lambda_c(2940)$ $J^P = \frac{3}{2}^-$ favored , ($\frac{3}{2}^+$, $\frac{5}{2}^-$, $\frac{5}{2}^+$ ~3σ)

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



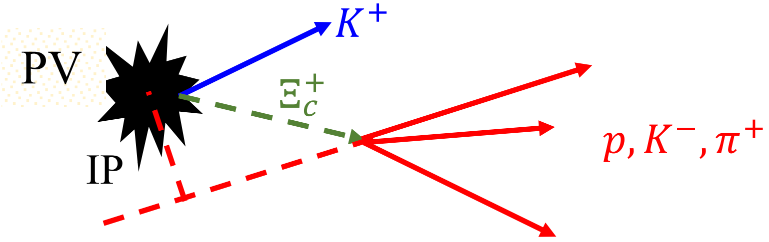
Argand plot
Breit-Wigner



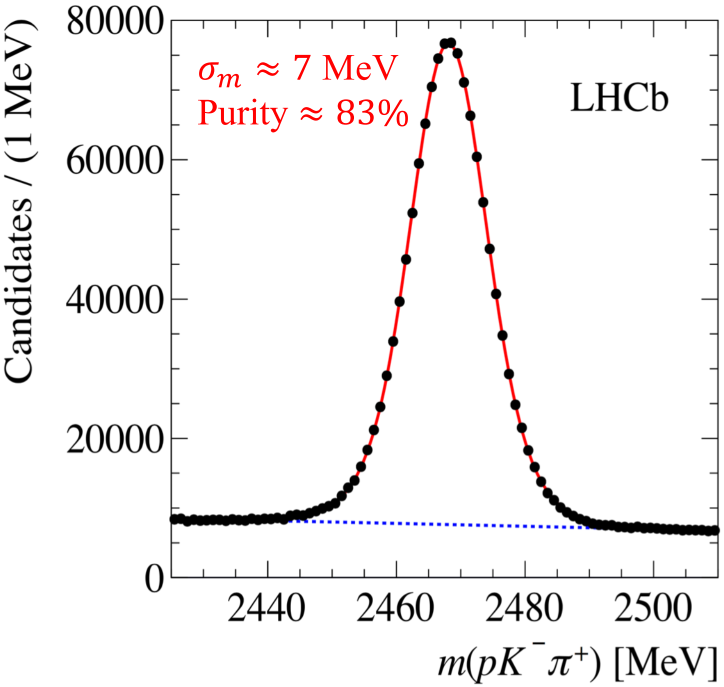
Observation of exited Ω_c states

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: $\Omega_c^{**0} \rightarrow \Xi_c^+ K^-,\ \Xi_c^+ \rightarrow pK^-\pi^+$**



Cabibbo suppressed decay, but much higher reconstruction efficiency

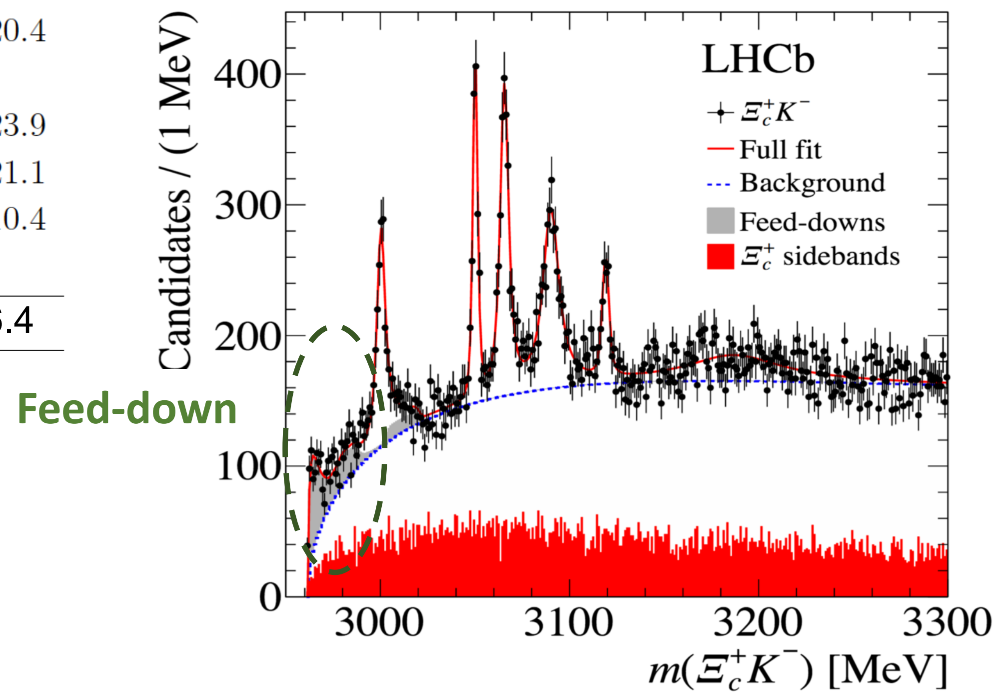


Observation of exited Ω_c states

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
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$	20.4
		< 1.2 MeV, 95% CL	
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$	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
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$	10.4
		< 2.6 MeV, 95% CL	
$\Omega_c(3188)^0$	$3188 \pm 5 \pm 13$	$60 \pm 15 \pm 11$	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*

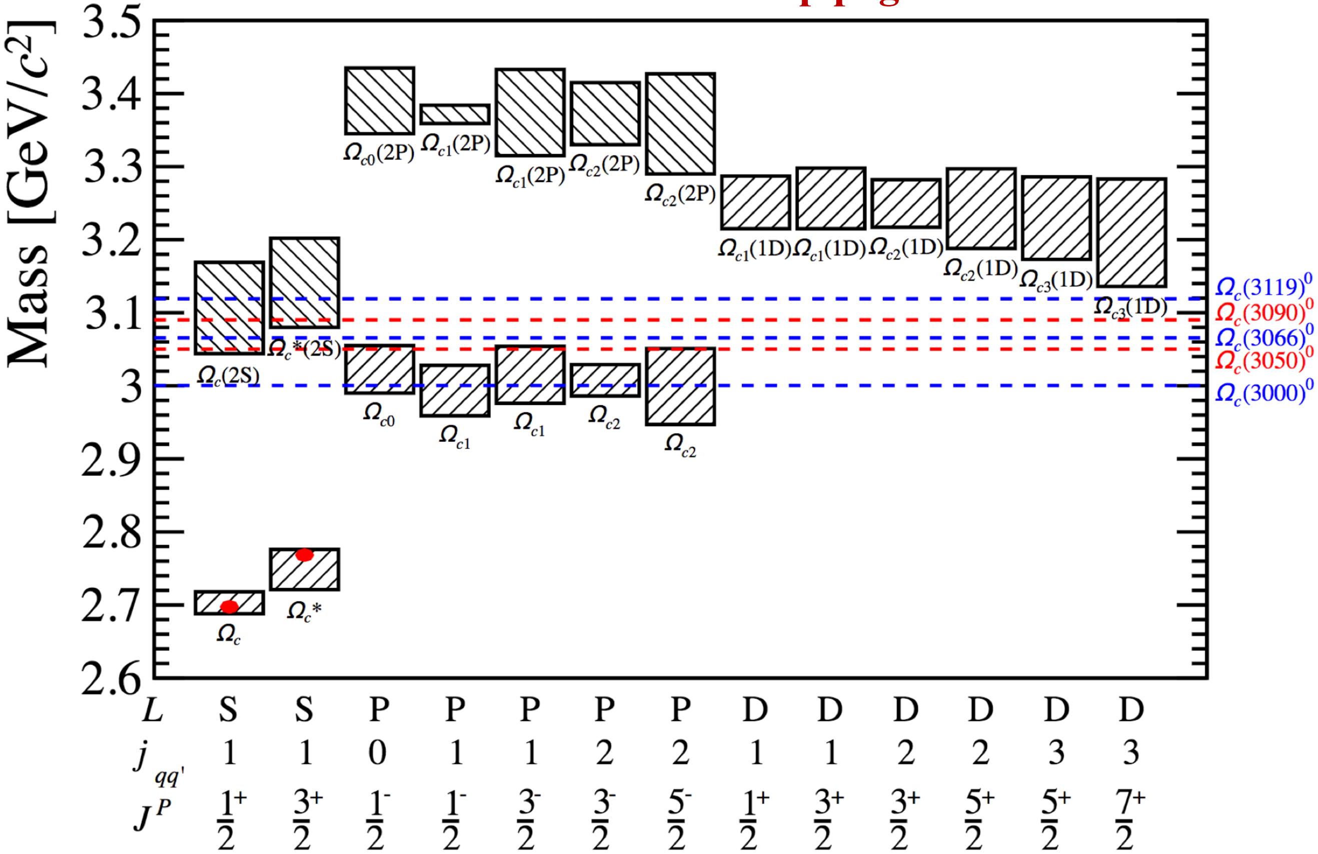
Feed-down: $\Omega_c^{**0} \to K^- \Xi_c^{\prime +}, \Xi_c^{\prime +} \to \gamma \Xi_c^+$, $m(\Xi_c^+ K^-)$ mass peaks shifted

Observation of exited Ω_c states

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



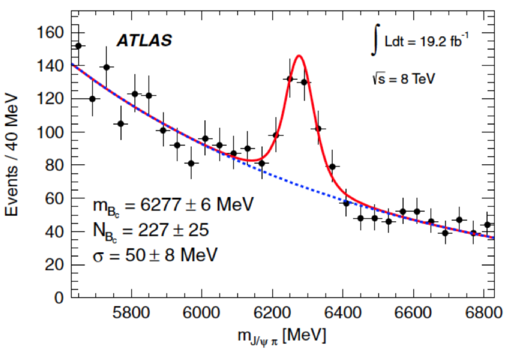
$B_c^{(*)}(2S) \to B_c^{(*)}\pi^+\pi^-$

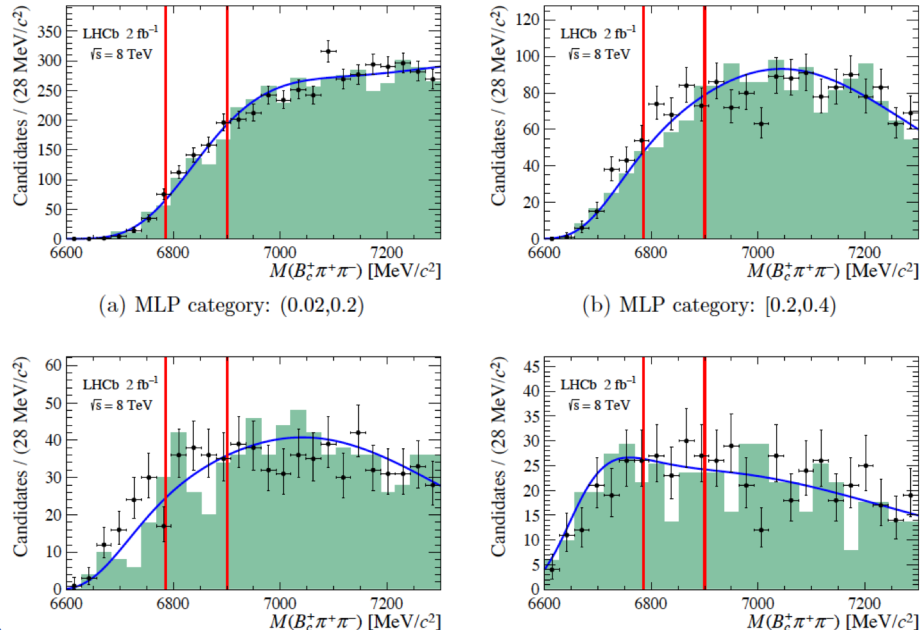
LHCb-PAPER-2017-042
JHEP 01 (2018) 138

ATLAS, PRL 113 (2014) 212004

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

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



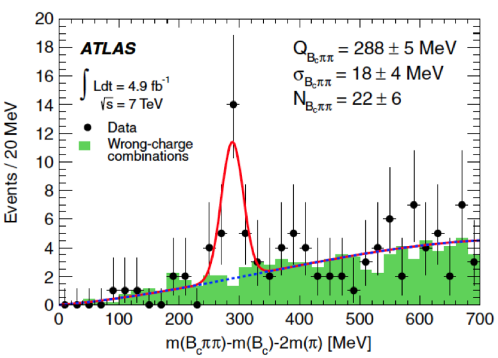


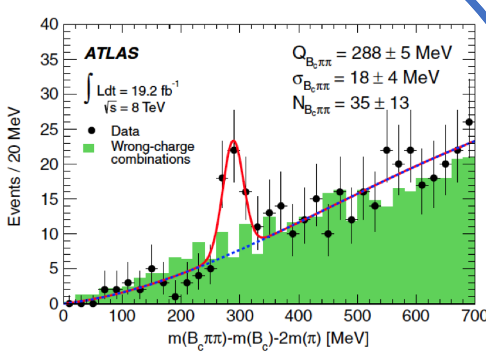
(a) MLP category: (0.02,0.2)
(b) MLP category: [0.2,0.4)
(c) MLP category: [0.4,0.6)
(d) MLP category: [0.6,1.0]

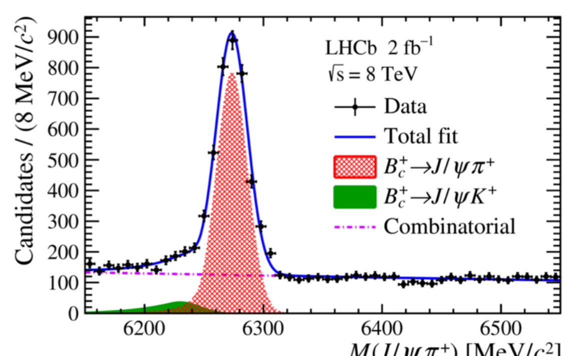
$$m_{B_c(2S)} = 6842 \pm 4 \pm 5\ \text{MeV}$$

5.2σ

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







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

	$\sqrt{s} = 7\,\text{TeV}$	$\sqrt{s} = 8\,\text{TeV}$
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.**

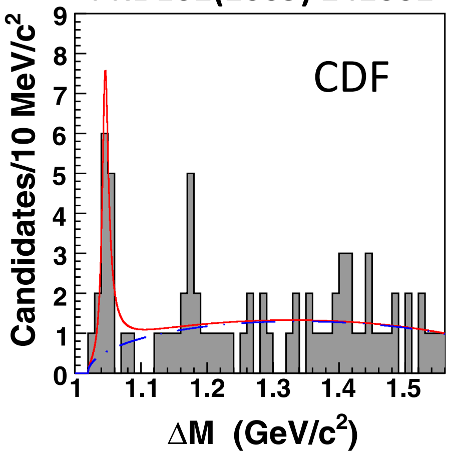
Tetraquark States

- $X(3872)$ → backup slides
- $Z(4430)$ → backup slides
- $\boldsymbol{X \to J/\psi\phi}$
- $\boldsymbol{X(5568)}$**?**

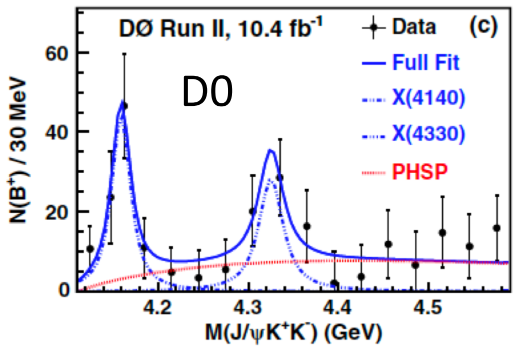
$X \to J/\psi\phi$

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

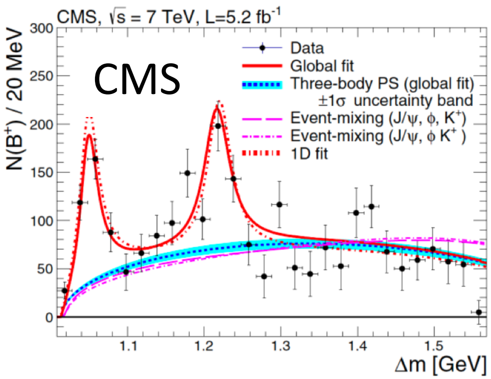
PRL 102(2009) 242002



PRD 89(2014) 242002



PLB 734(2014) 261

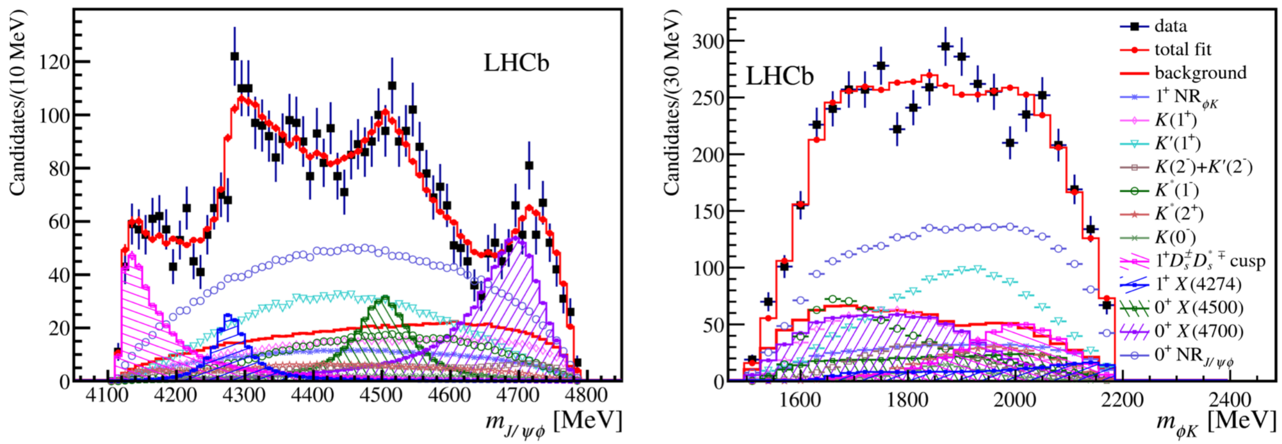


	Mass [MeV]	Width [MeV]	Sig.
CDF	$4143.4^{+2.9}_{-3.0} \pm 0.6$	$15.3^{+10.4}_{-6.1} \pm 2.5$	$> 5\sigma$
D0	$4159 \pm 4.3 \pm 6.6$	$19.9 \pm 12.6^{+3.0}_{-8.1}$	3σ
CMS	$4148.0 \pm 2.4 \pm 6.3$	$28^{+15}_{-11} \pm 19$	5σ

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

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

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

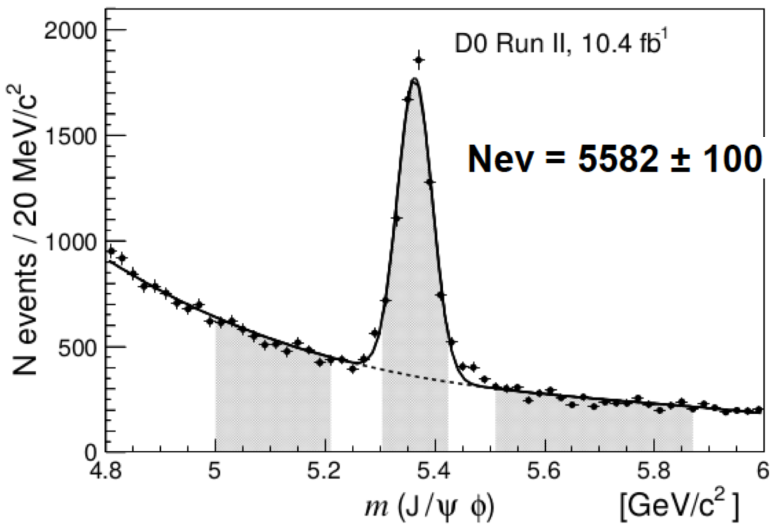
- mass and width

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

- high production rate

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

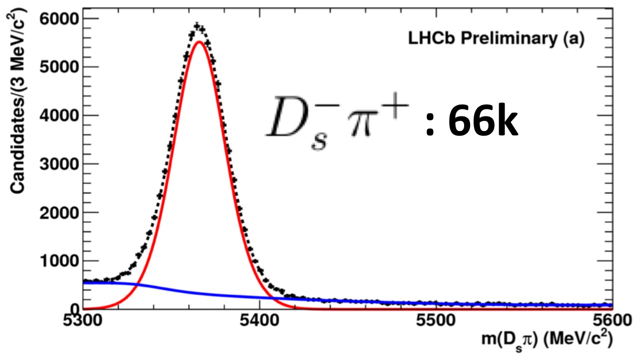
$$(8.6 \pm 1.9 \pm 1.4)\%$$

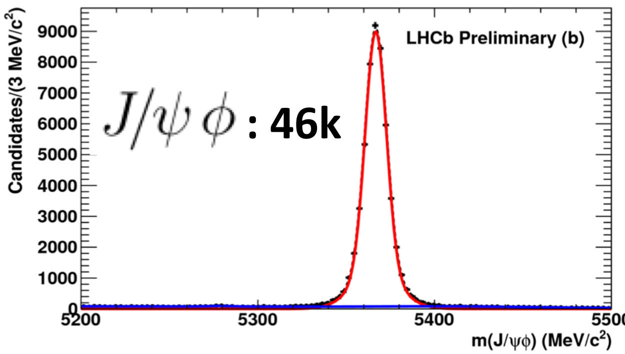


Tetraquark searches in $B_s\pi^{\pm}$

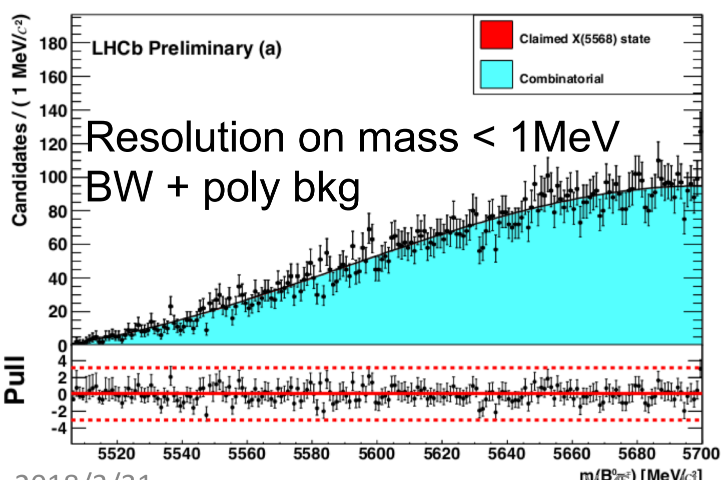
LHCb-PAPER-2016-029
PRL 117 (2016) 152003

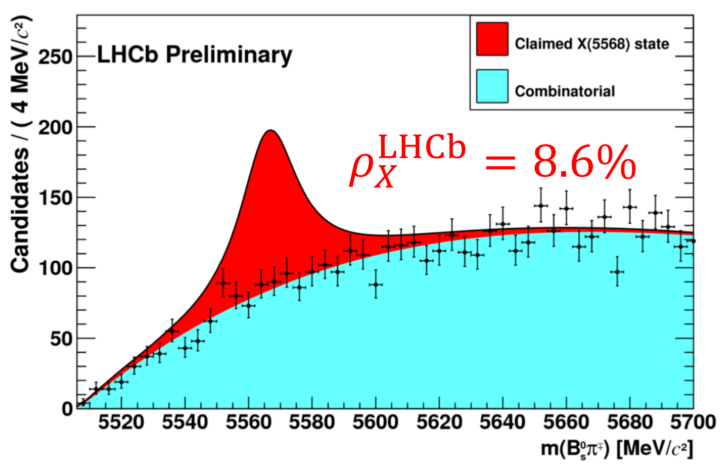
- Very large and clean B_s sample at LHCb





- Add a pion, no peak observed at 5568 MeV





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

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

- Upper limits

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

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

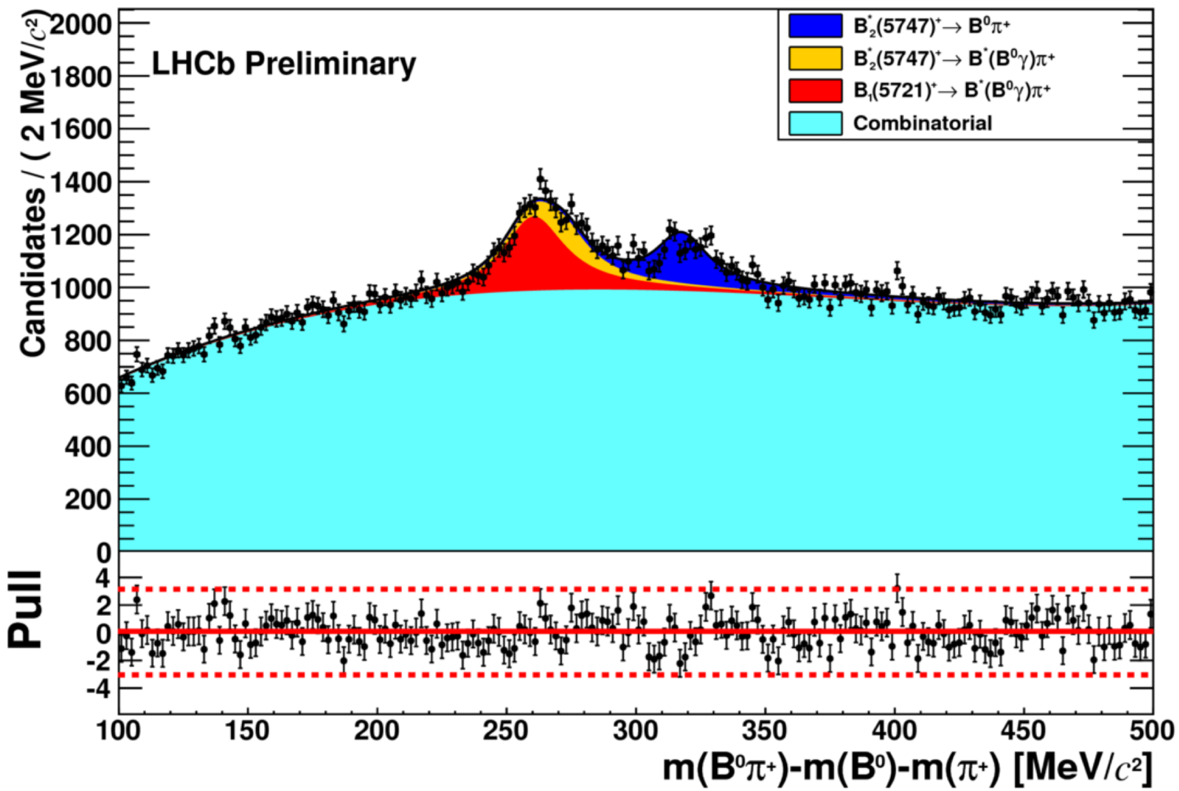
		$B_s^0 \to D_s^- \pi^+$	$B_s^0 \to J/\psi\,\phi$	Sum
$N(B_s^0)$	$B_s^0\ p_{\mathrm{T}} > 5\,\mathrm{GeV}/c\ (10^3)$	66.3 ± 0.3	46.3 ± 0.2	112.6 ± 0.4
$N(B_s^0)$	$B_s^0\ p_{\mathrm{T}} > 10\,\mathrm{GeV}/c\ (10^3)$	30.1 ± 0.2	14.1 ± 0.1	44.2 ± 0.2
$N(X)$	$B_s^0\ p_{\mathrm{T}} > 5\,\mathrm{GeV}/c$	23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

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

Tetraquark searches in $\boldsymbol{B_s\pi}$

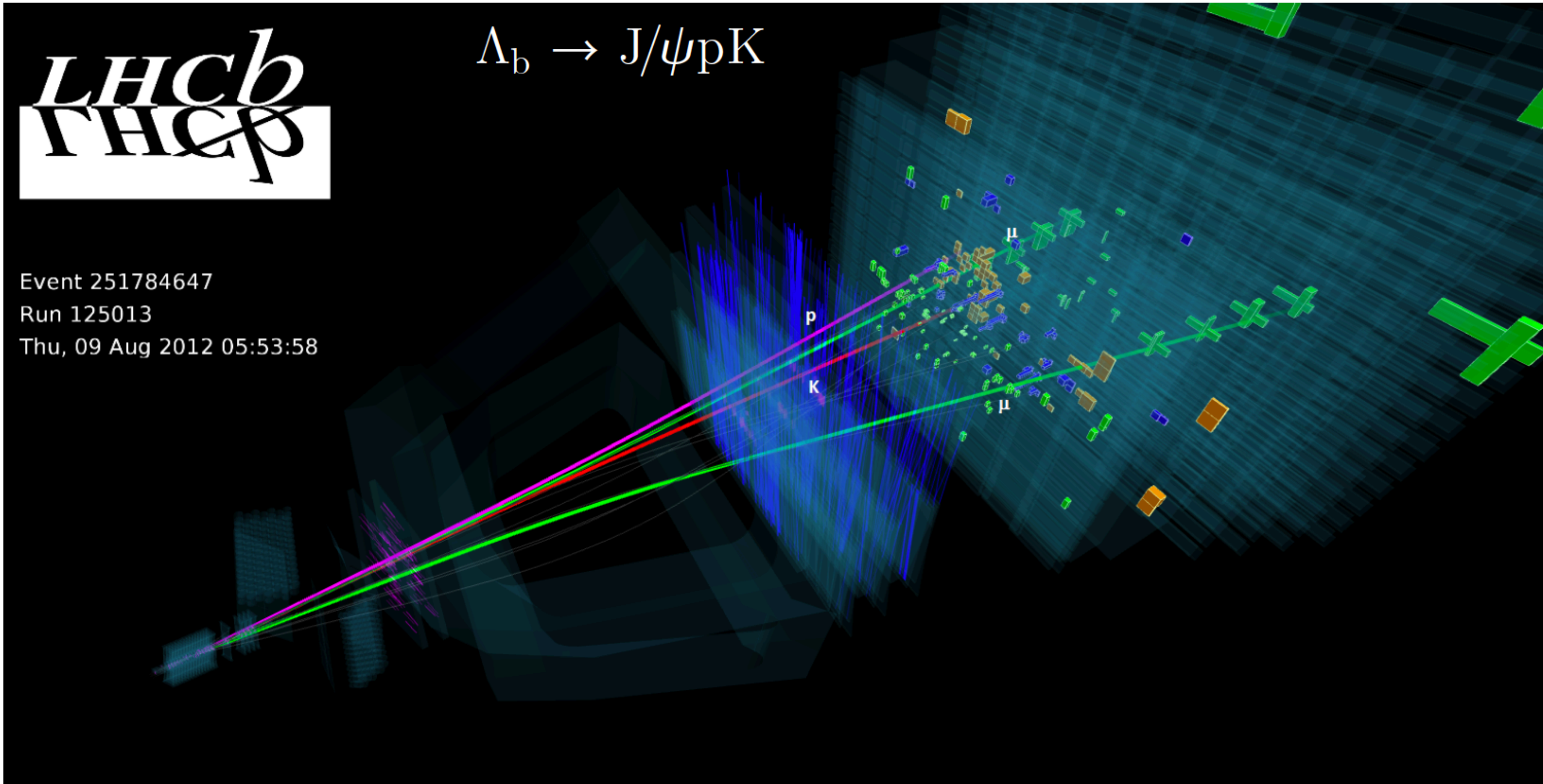
LHCb-PAPER-2016-029
PRL 117 (2016) 152003

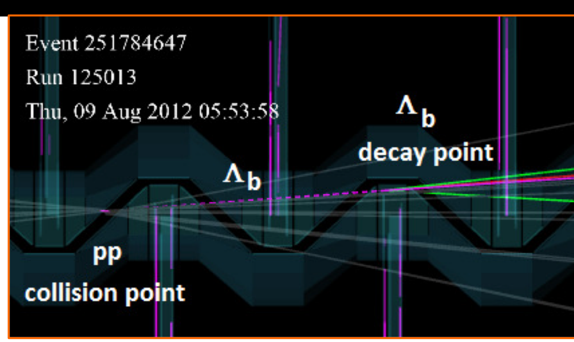
- Use similar selection criteria as $B_c \to B_s\pi$, consistent result
- Similar selection on $B^0\pi$

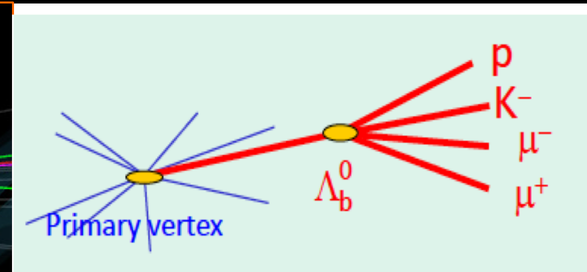


Pentaquark States

- Observation of $P_c(4450)$ and $P_c(4380)$
- Model independent confirmation
- P_c's in $\Lambda_b^0 \to J/\psi p \pi^-$
- Observation of $\Lambda_b^0 \to \chi_{c1,2} p K^-$
- Observation of $\Xi_b^- \to J/\psi \Lambda K^-$
- Search for weakly decayed pentaquarks


$\Lambda_b \to J/\psi pK$
LHCb
Event 251784647
Run 125013
Thu, 09 Aug 2012 05:53:58
p
K
μ
μ

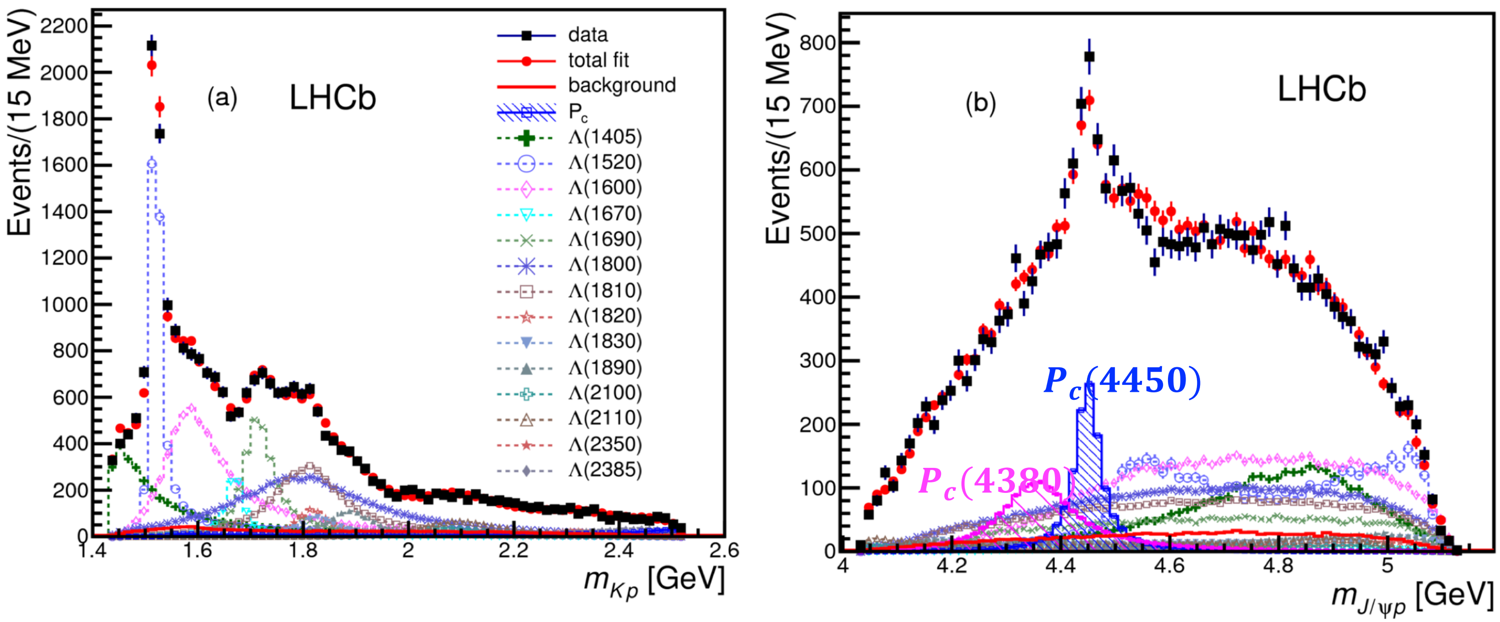

Event 251784647
Run 125013
Thu, 09 Aug 2012 05:53:58
Λ_b
decay point
Λ_b
pp
collision point

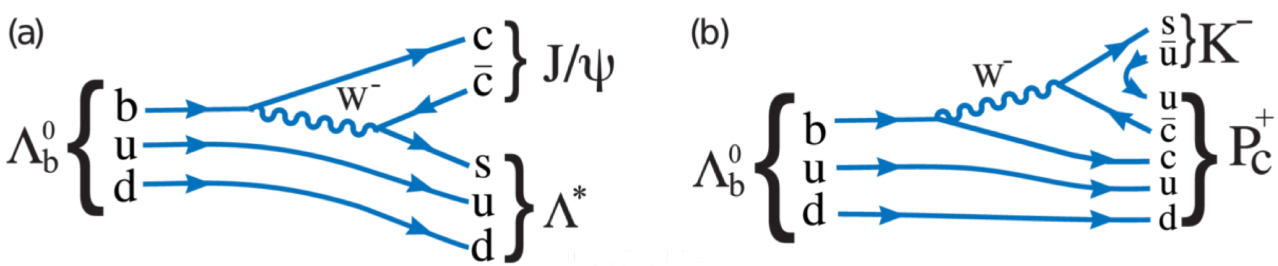

p
K^-
μ^-
μ^+
Λ_b^0
Primary vertex

Observation of pentaquark states

LHCb, PRL 115(2015) 072001

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



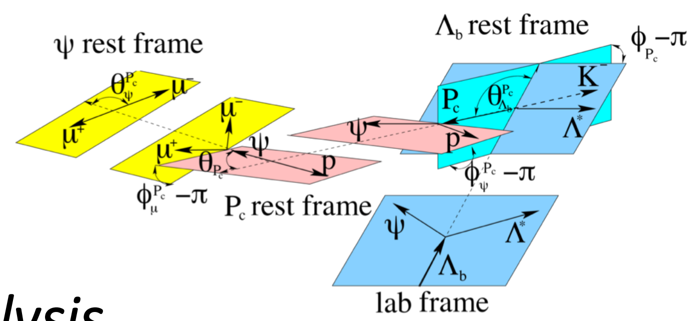


Discovery of pentaquark states

LHCb, PRL 115(2015) 072001

- Amplitude analysis reveals the properties

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

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

Λ^* 's in $\Lambda_b^0 \to J/\psi p K^-$

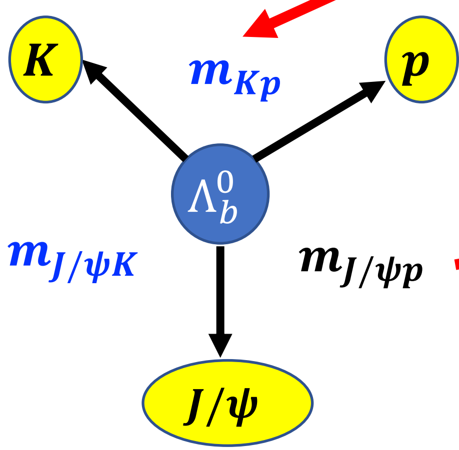
- 2 models for $\Lambda^* \to pK^-$ contributions based on PDG
  - *Extended model* allows all LS couplings of each resonance, and include poorly motivated states → 146 parameters
  - *Reduced model* uses only well motivated states → 64 parameters
  - *Other possibilities* checked, including isospin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

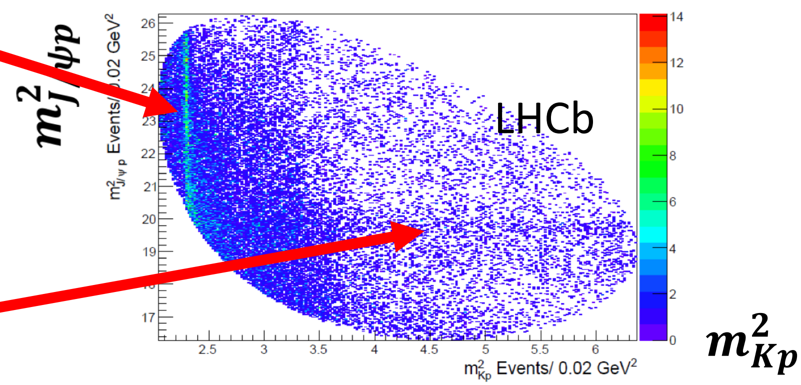
→ Confirm that conventional pK^- contributions cannot describe the data, with minimal assumptions on their spin, and no assumptions on their number, shapes, masses, widths, and interference patterns.

Model independent analysis

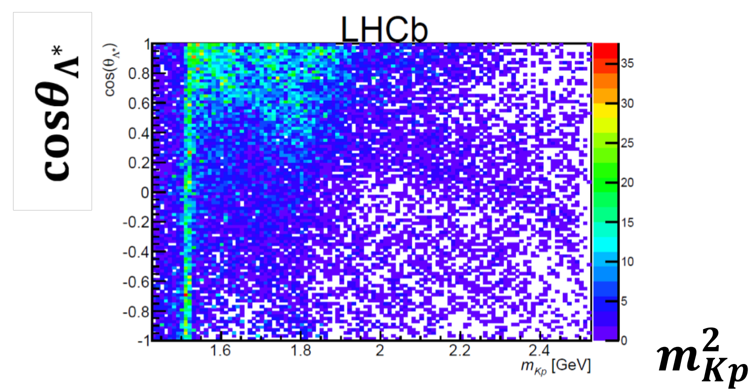
- **Can P_c's be explained by the reflections of $\Lambda^{*\prime}s$?**

Resonances in this channel only?





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



Model independent analysis

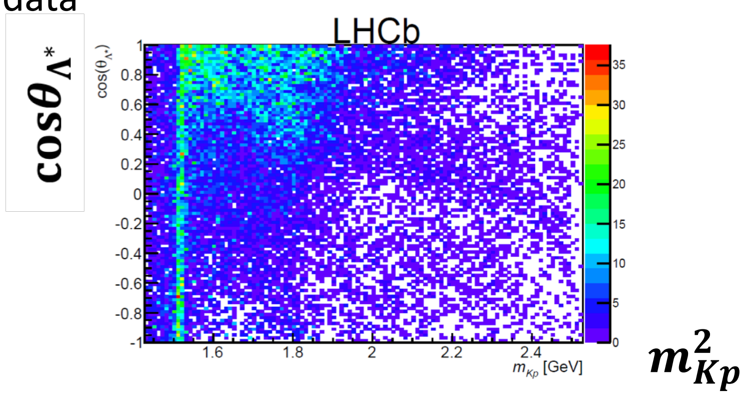
LHCb-PAPER-2016-009
PRL 117 (2016) 082002

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

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

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

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

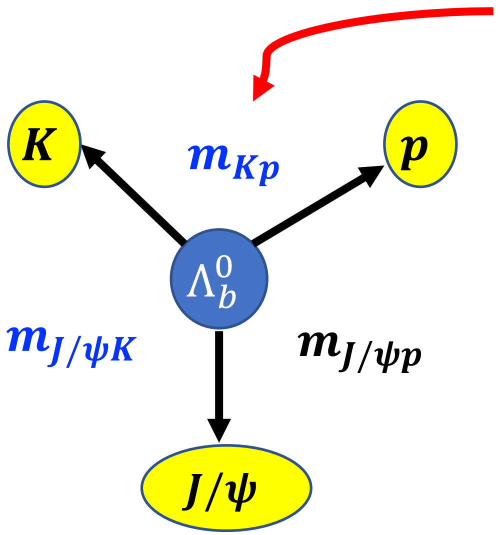


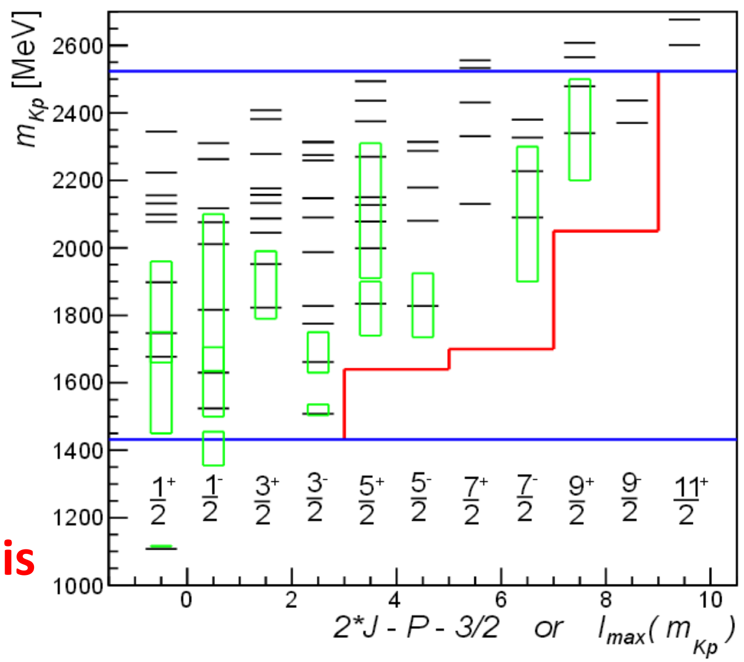
Model independent analysis

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

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

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





Determined by model & scattering data

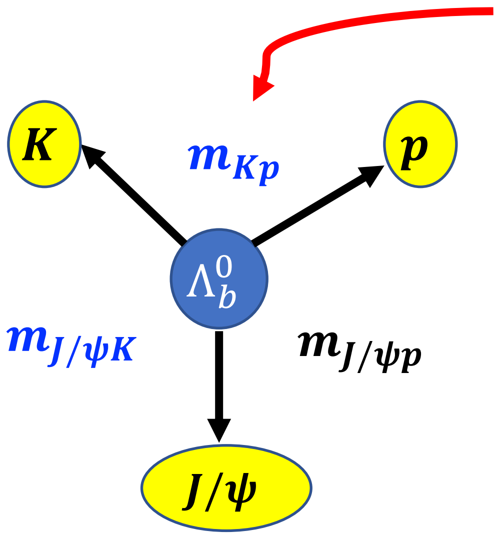
- the only model dependent part of the analysis

Model independent analysis

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

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

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



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

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

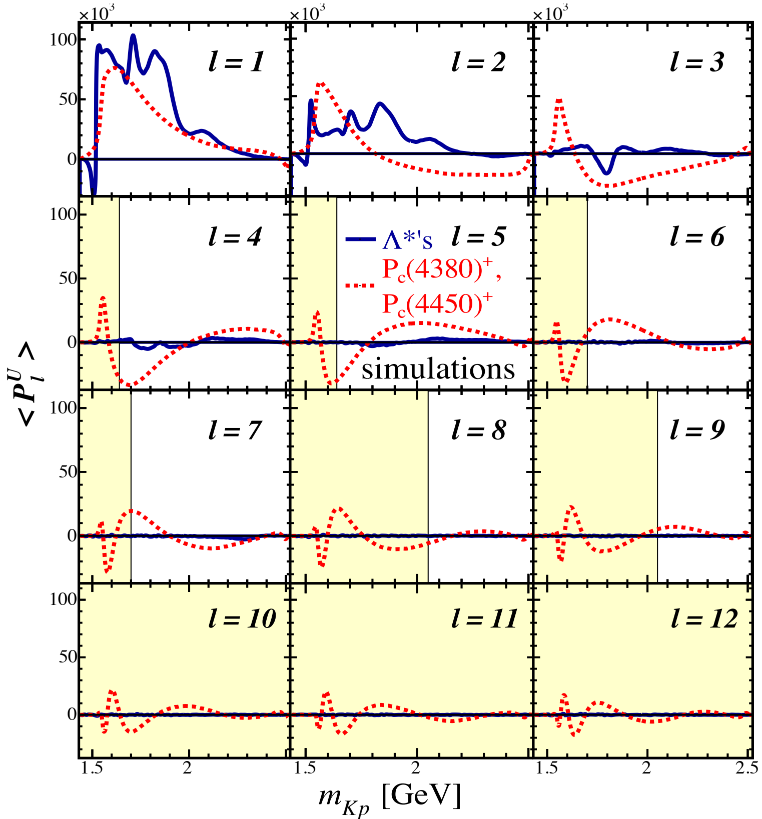
Model independent analysis

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

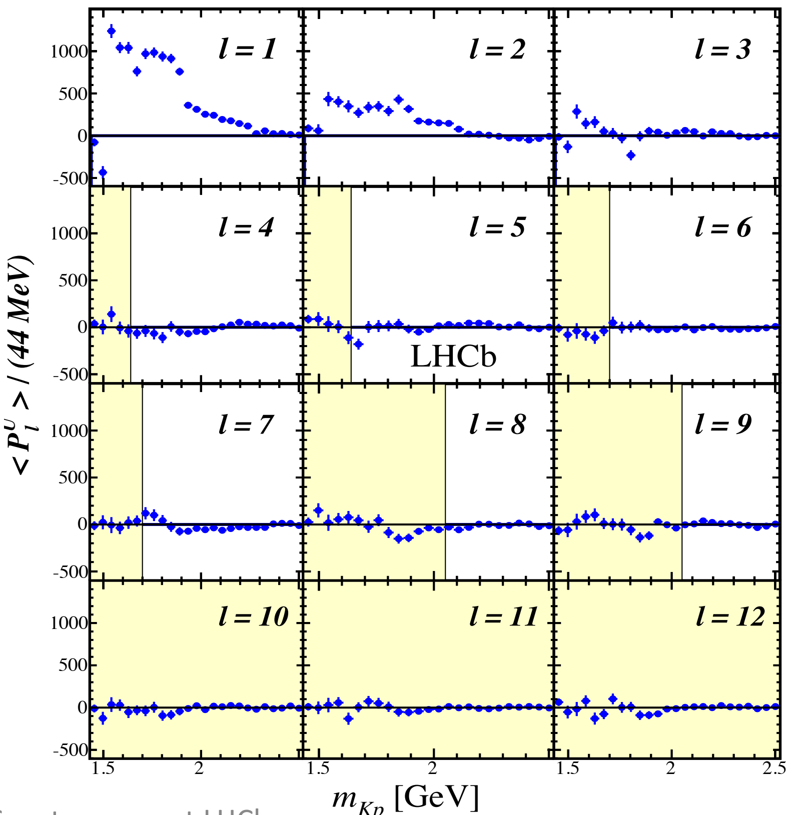
- **Legendre moments from simulation & data**

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

simulation



data

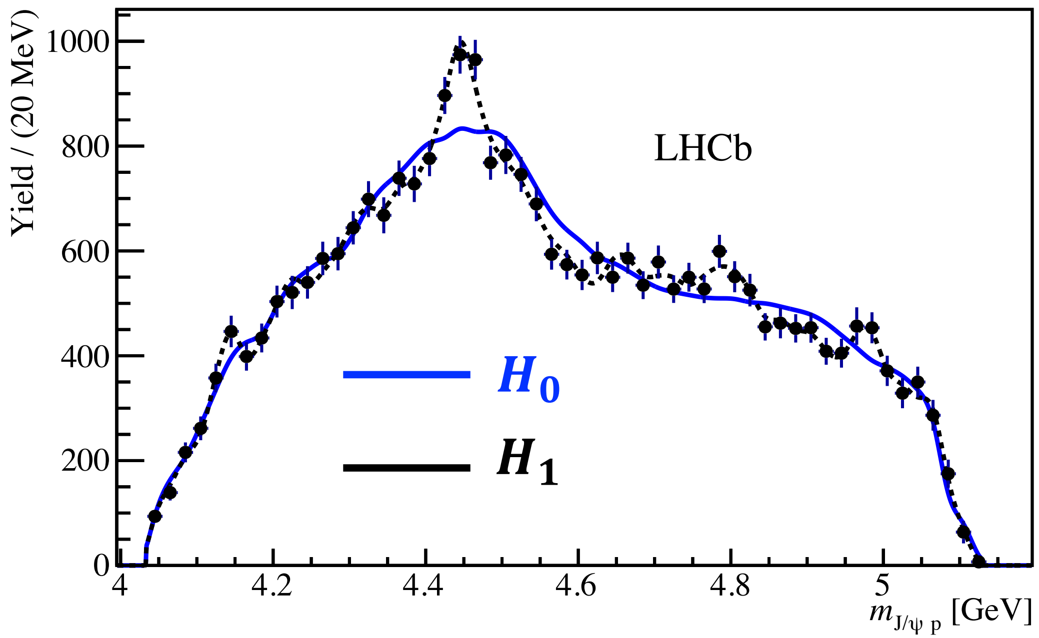


Model independent analysis

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

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

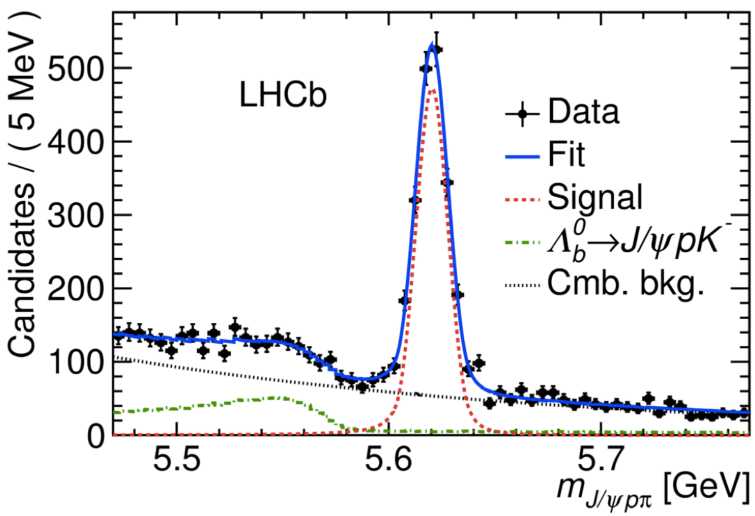
H_0 rejected at ~ 10 σ

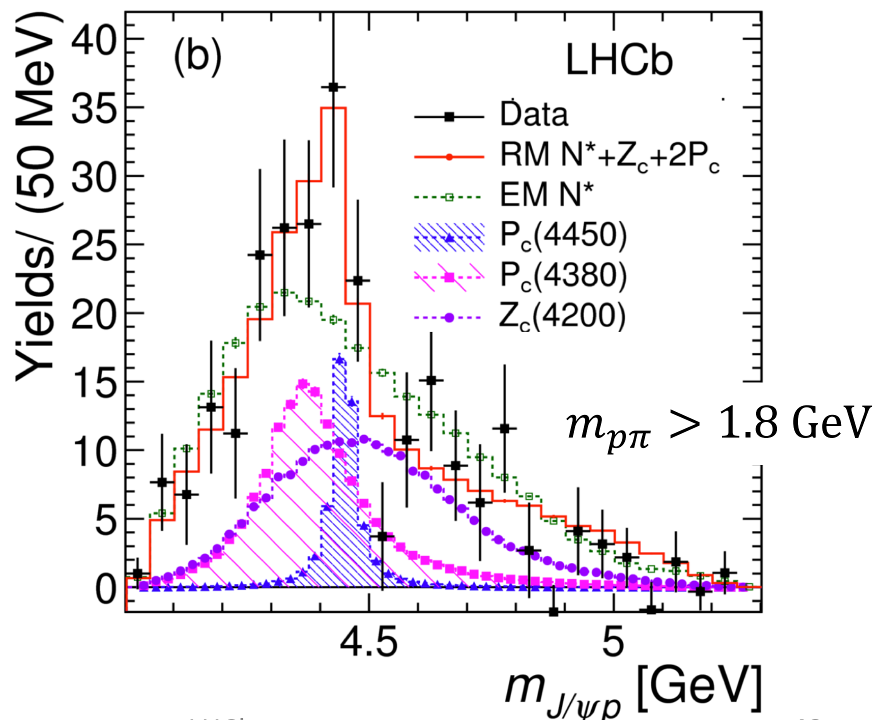


Study of $\Lambda_b^0 \to J/\psi p \pi^-$

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

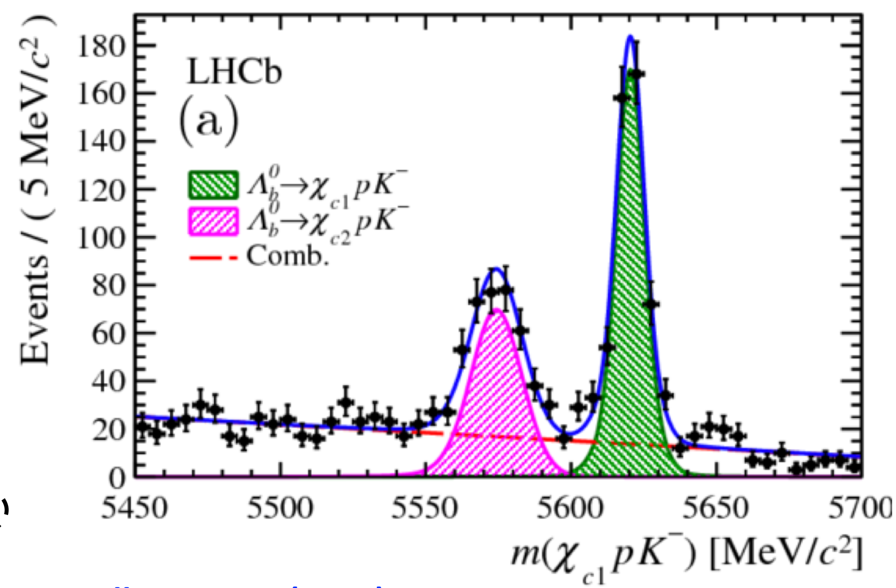
  with RUNII data added in

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

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

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

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 $uds\bar{c}c$ pentaquark in this mode

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

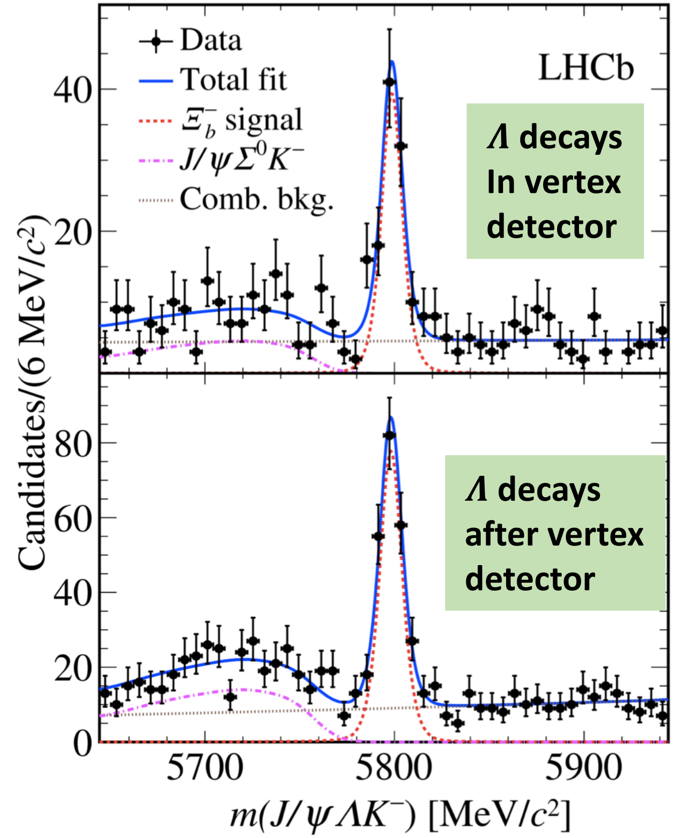
- First observation with RUNI data
- ~300 candidates seen

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

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

(one of the two world best measurements)

- Full amplitude analysis foreseen with RUNII data added in

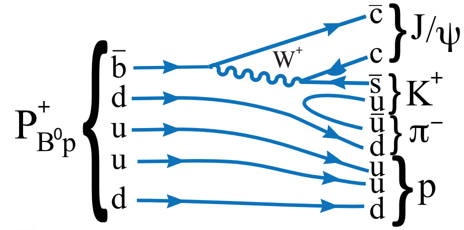


Searches for weakly decaying b-flavored pentaquarks

LHCb-PAPER-2017-043
arXiv:1712.08086

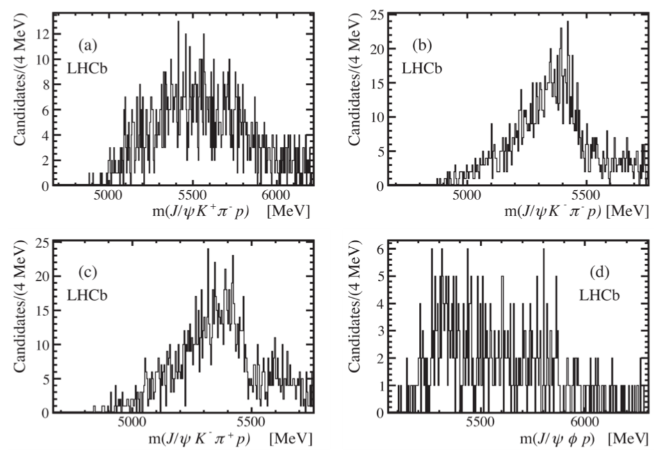
- Skyrme model prediction on pentaquark state: the heavier the constitute quarks, the more tightly bound the pentaquark state
  PLB 590(2004) 185; PLB 586(2004)337; PLB 331(1994)362
- Search for masses below strong decay threshold

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

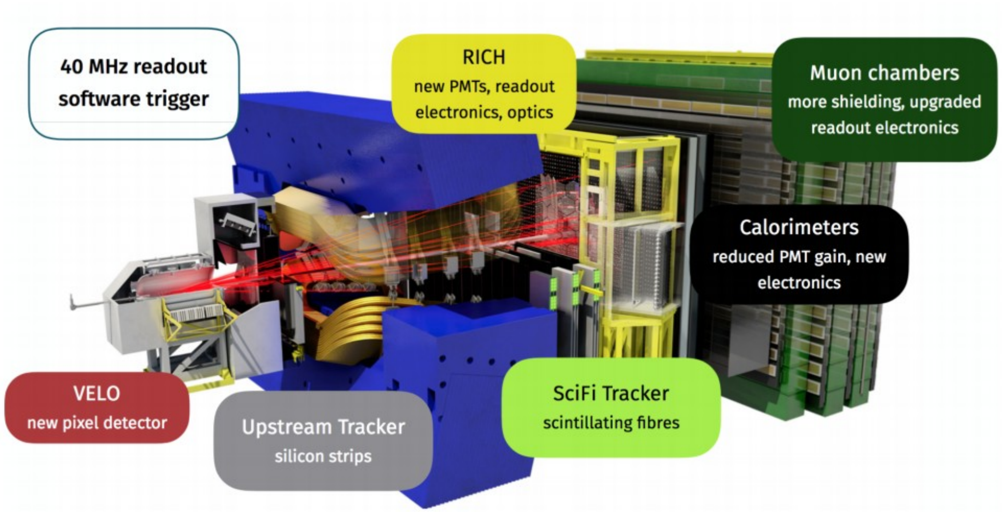
- Data samples
  - 1 fb^{-1} (7 TeV)+ 2 fb^{-1} (8 TeV)
  - ~6 fb^{-1} at 13 TeV with $\sigma_{b\bar{b}}(13\text{TeV})/\sigma_{b\bar{b}}(7\text{TeV}) \approx 2$

- 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

$D_J^{0(**)}$ 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

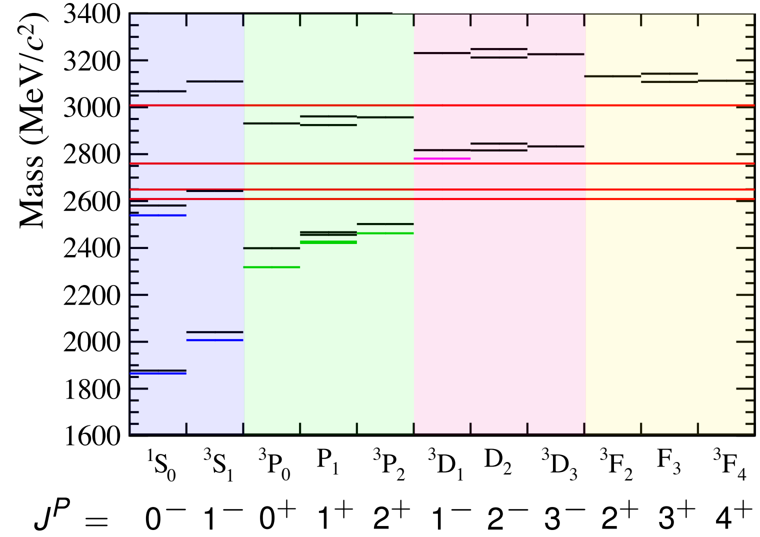
  Dalitz plot analyses

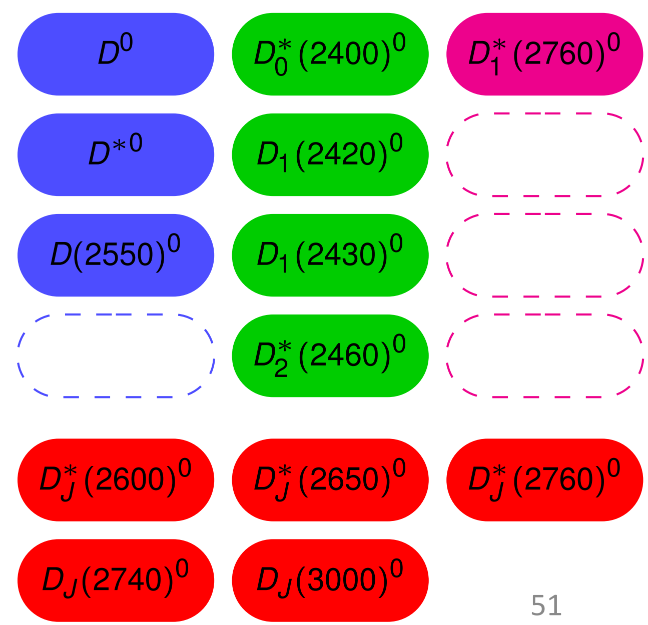
  $B^0 \to \overline{D}^0\pi^+\pi^-$ LHCb-PAPER-2014-070 PRD 92 (2015) 032002

  $B^0 \to \overline{D}^0 K^+\pi^-$ LHCb-PAPER-2015-017 PRD 92 (2015) 012012

- New states

  some have unknown J^P

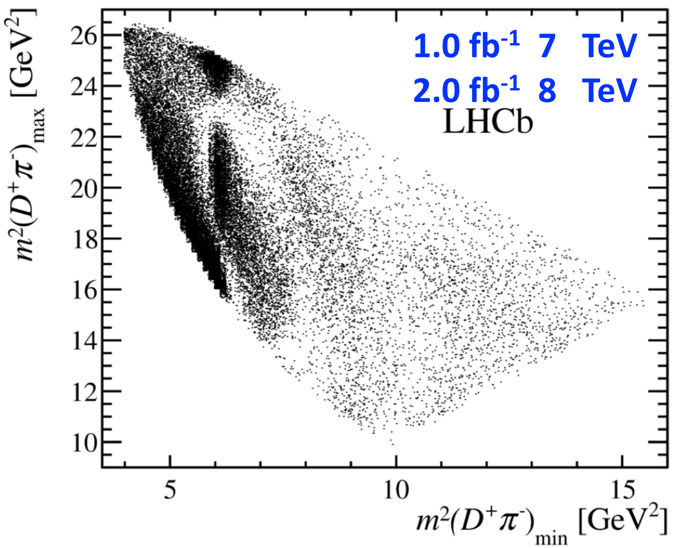


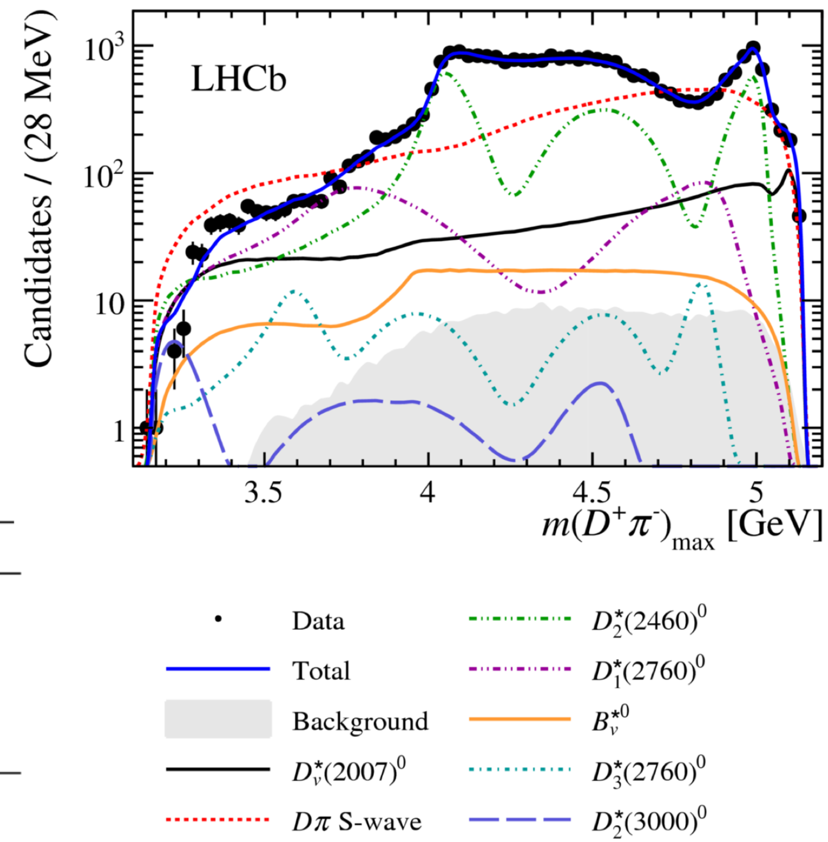


Dalitz plot analysis $B^- \to D^+\pi^-\pi^-$

- ~28000 events with 1% background

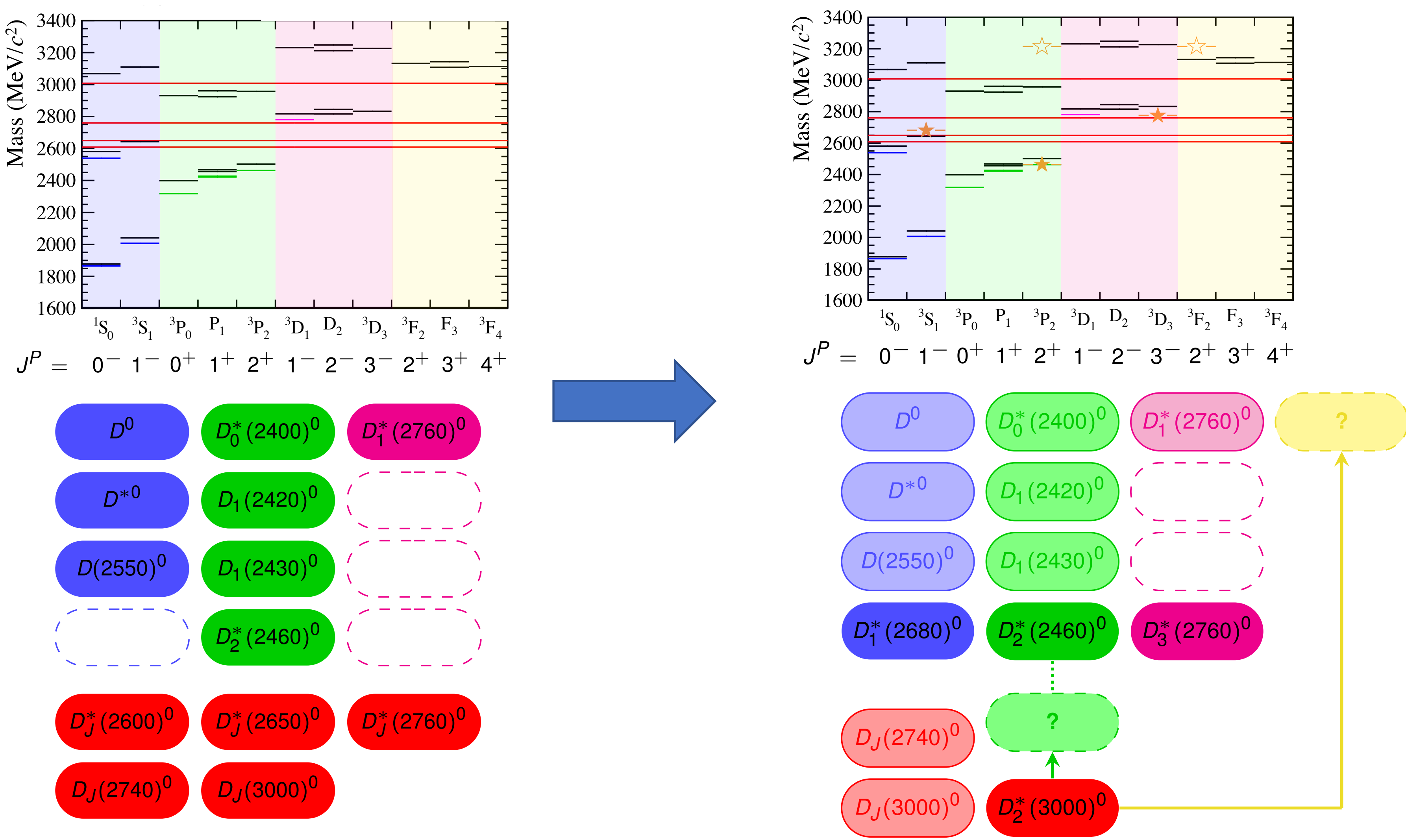
LHCb-PAPER-2016-026
PRD 94 (2016) 072001





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



References: $\Omega^{(**)}$ 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.

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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.

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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: $\Omega_c^{(**)}$ masses (cont'd)

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

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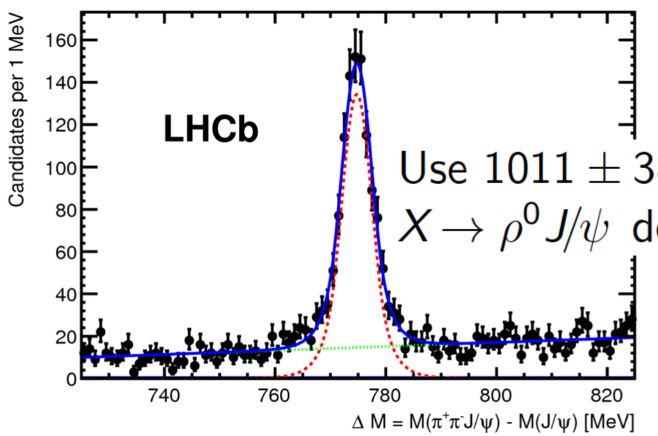
M. Padmanath, R. G. Edwards, N. Mathur, and M. Peardon, *Excited-state spectroscopy of singly, doubly and triply-charmed baryons from lattice QCD*, `arXiv:1311.4806`.

$X(3872)$ quantum number determination

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

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



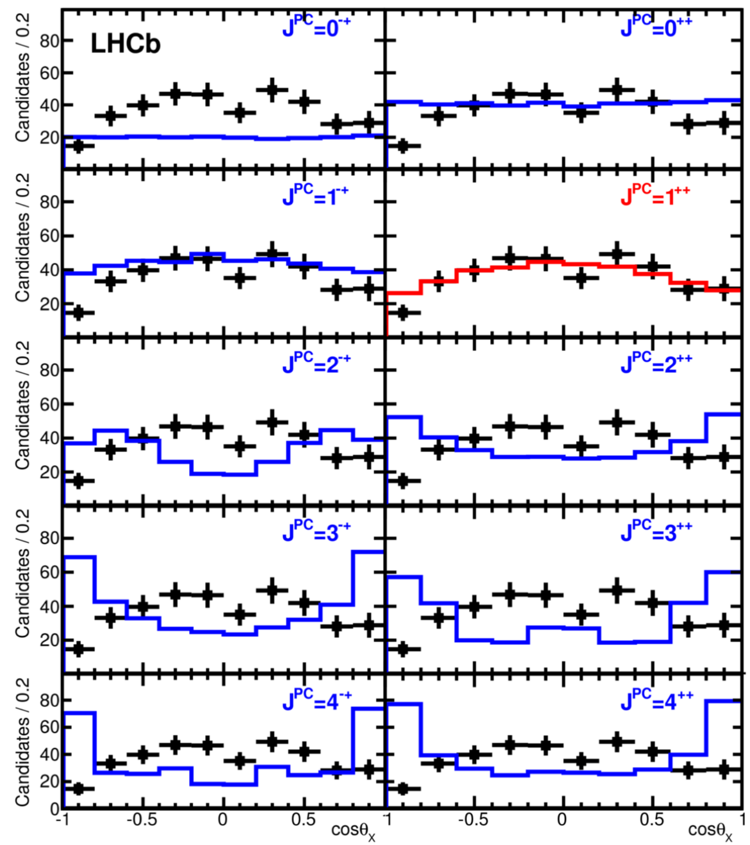
Use 1011 ± 38 $B^+ \to X K^+$, $X \to \rho^0 J/\psi$ decays

J^{PC}	B_{LS} Any L value	B_{LS} 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

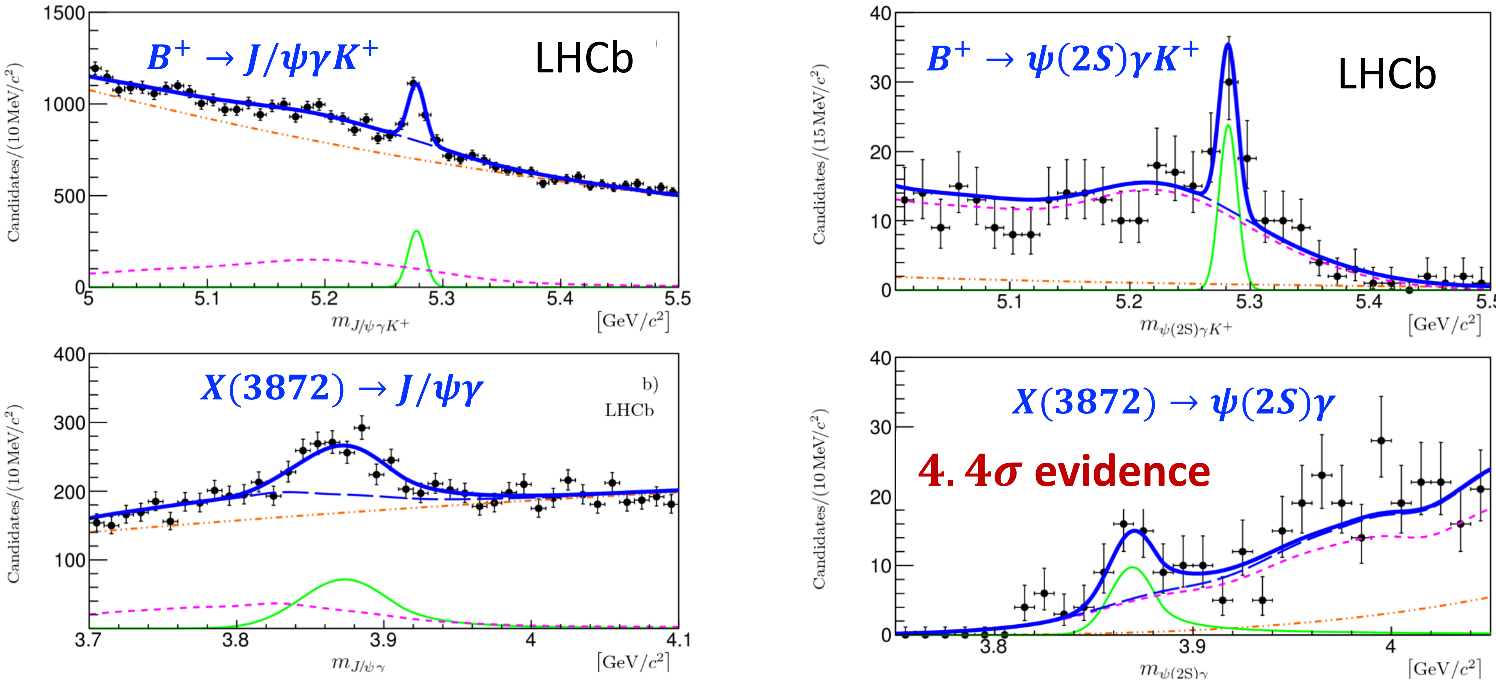
D-wave fraction $< 4\%$



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

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

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



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

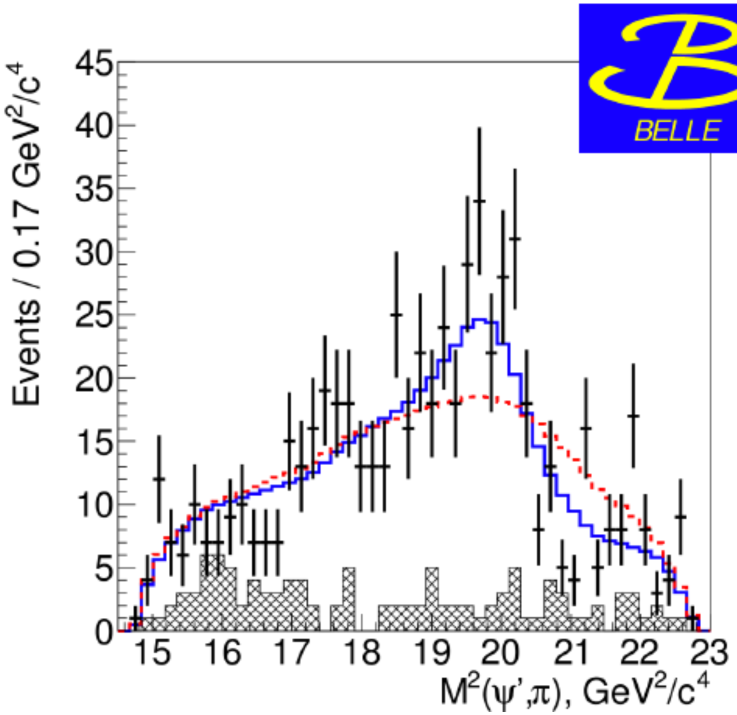
$$\frac{\mathcal{B}(X(3872) \to \psi(2S)\gamma)}{\mathcal{B}(X(3872) \to J/\psi\gamma)} = 2.46 \pm 0.64 \pm 0.29$$

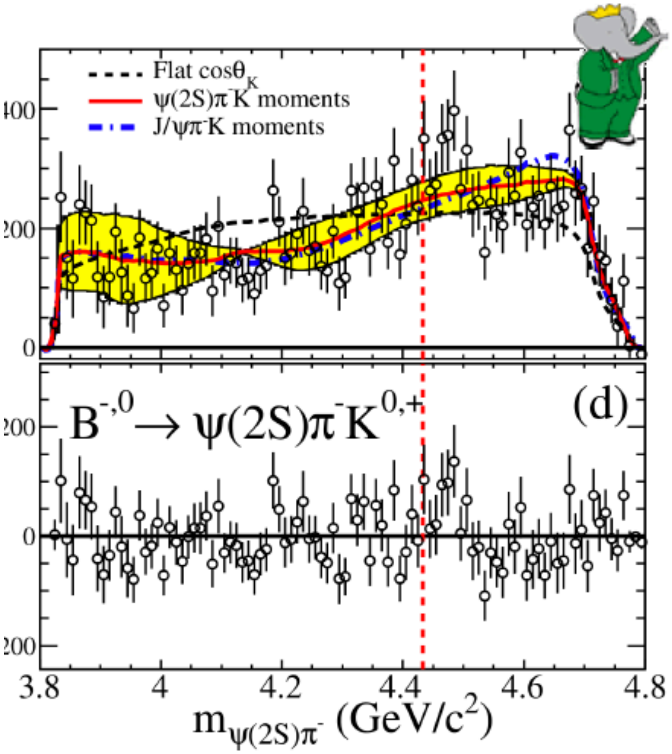
$Z(4430)^-$

- Originally found by Belle in $B^0 \to \psi(2S)\pi^- K^+$

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

- BaBar could not confirm BaBar, PR D79 (2009) 112001





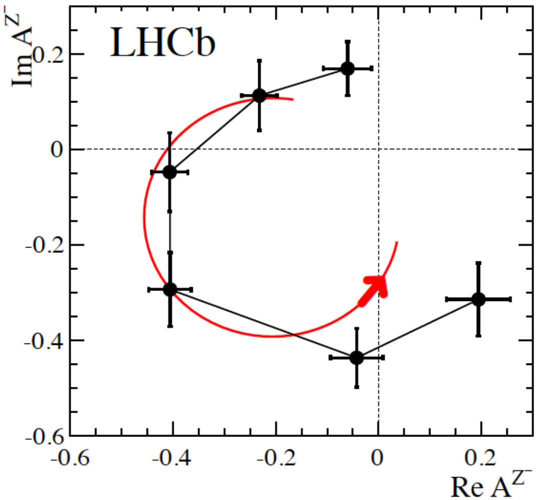
$Z(4430)^{-}$

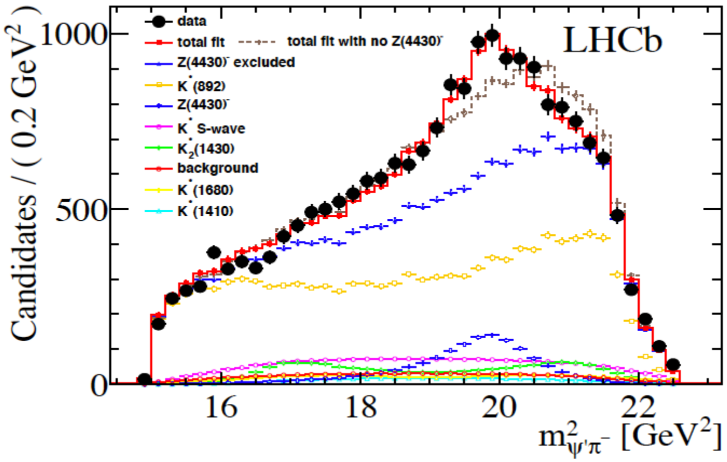
- LHCb full amplitude analysis using $\mathbf{3\ fb^{-1}}$

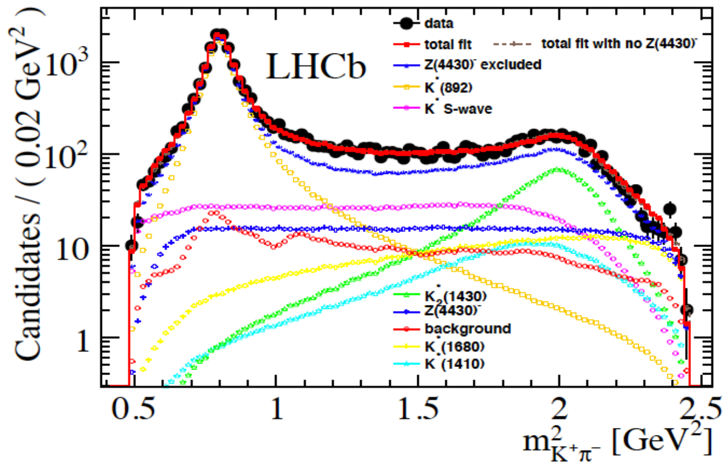
LHCb-PAPER-2014-014
PRL 112 (2014) 222002

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

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





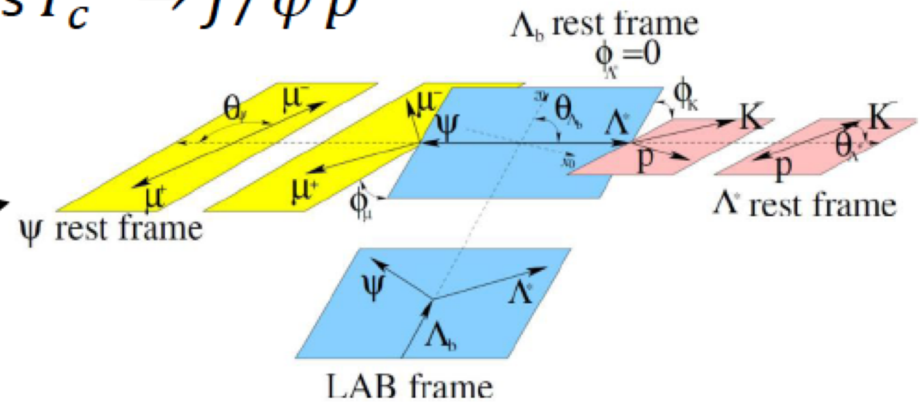


Amplitude analysis of $\Lambda_b^0 \to J/\psi p K$

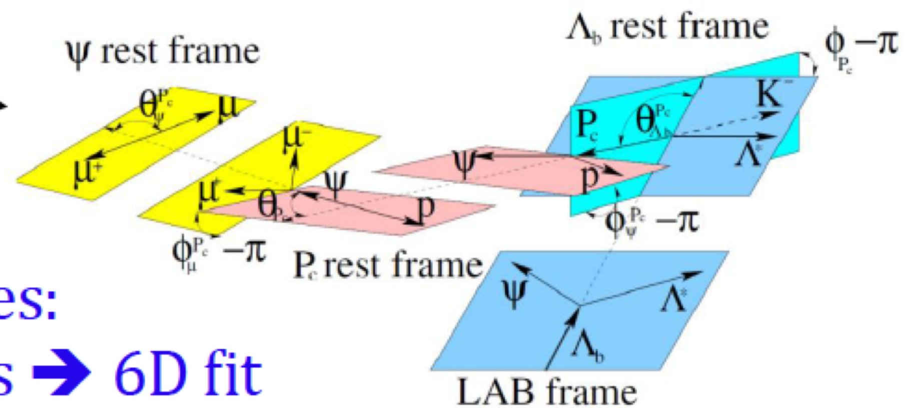
LHCb, PRL 115(2015) 072001

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

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



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



- 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.