Spectroscopy at LHCb - exotic states

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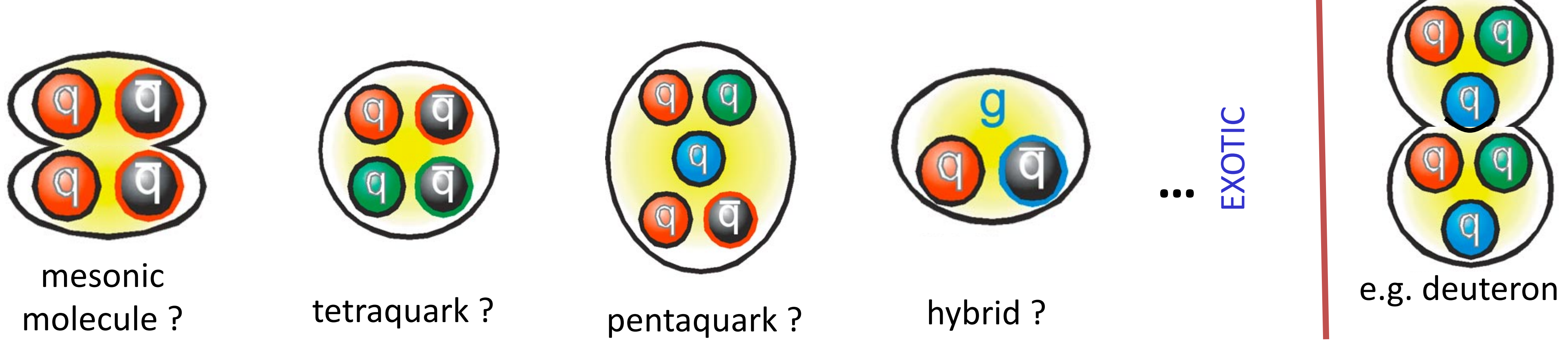
Outline

- Introduction
- Exotic baryons at LHCb
  - Observation of a narrow pentaquark state, $P_c(4312)^+$, and of two-peak structure of the $P_c(4450)^+$ **[PRL 122 (2019) 222001]**
  - Observation of $B^0_{(s)} \to J/\psi p\bar{p}$ decays and precision measurements of the $B^0_{(s)}$ masses **[PRL 122 (2019) 191804]**
- Exotic mesons at LHCb
  - Evidence of $\eta_c(1S)\pi^-$ resonance in $B^0 \to \eta_c(1S)K^+\pi^-$ **[EPJ C78 (2018) 1019]**
  - Model-independent observation of exotic contributions to $B^0 \to J/\psi K^+\pi^-$ decays **[PRL 122 (2019) 152002]**
- Summary and prospects

Introduction

- QCD describing strong interaction between quarks and gluons is not well understood due to its non-perturbative nature at low energy scale
- Hadron spectroscopy provides opportunities to test QCD and its effective models
  - e.g. lattice QCD, diquark model, potential model …
- Exotic hadrons provide unique probe to QCD
  - Predicted in quark model
  - Recent results show strong evidence for their existence



Tetra and pentaquark candidates ($3fb^{-1}$)

- Confirmation of $Z(4430)$

  [PRL 112 (2014) 222002]

- Observation of four $J/\psi\phi$ structures

  [PRL 118 (2017) 022003]

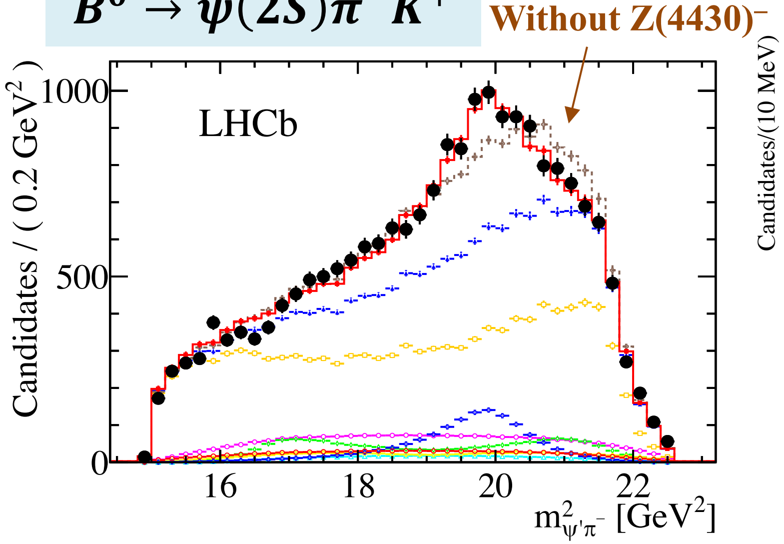
- Observation of two charmonium pentaquarks

  [PRL 115 (2015) 072001]

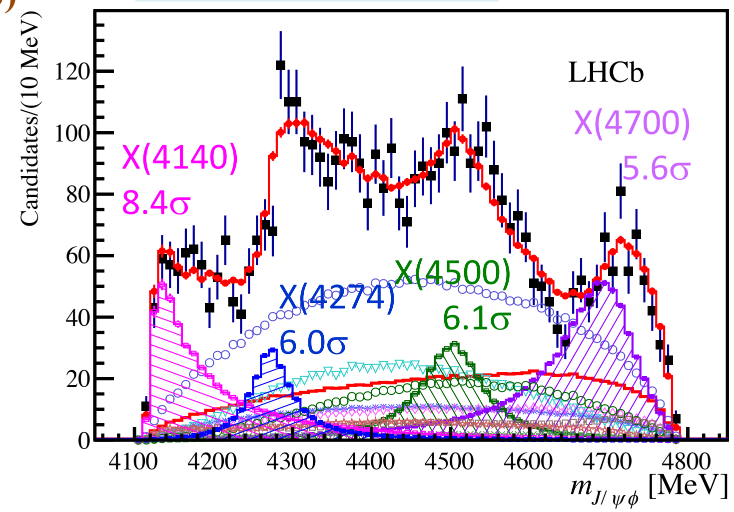
- Evidence of exotic contribution in Cabibbo-suppressed decays

  [PRL 117 (2016) 082003]

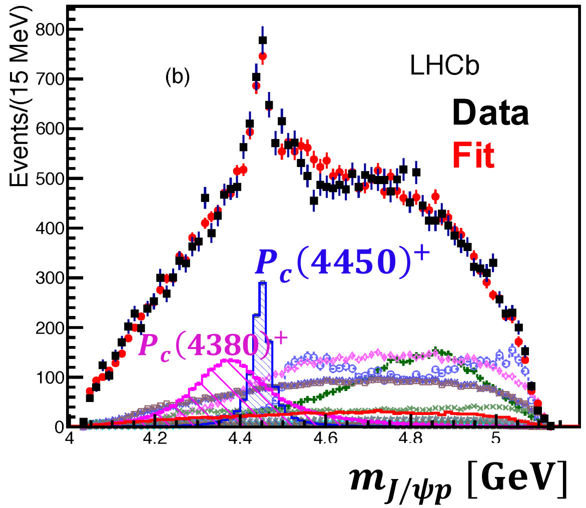
$B^0 \to \psi(2S)\pi^- K^+$



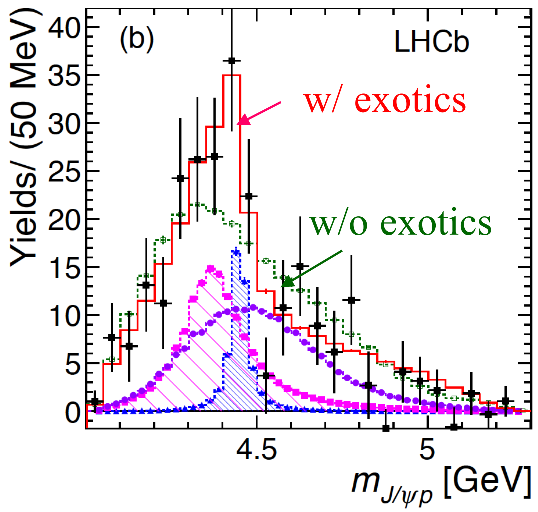
$B^+ \to J/\psi\phi K^+$



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

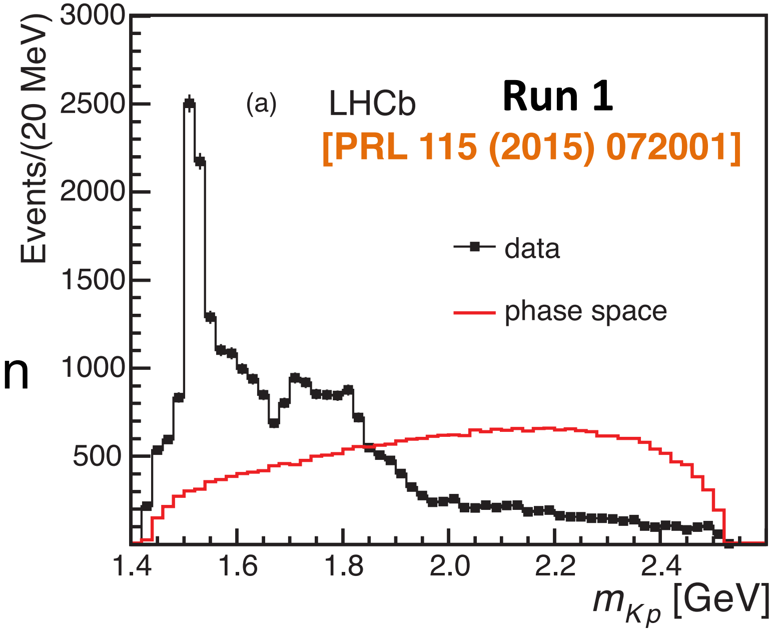


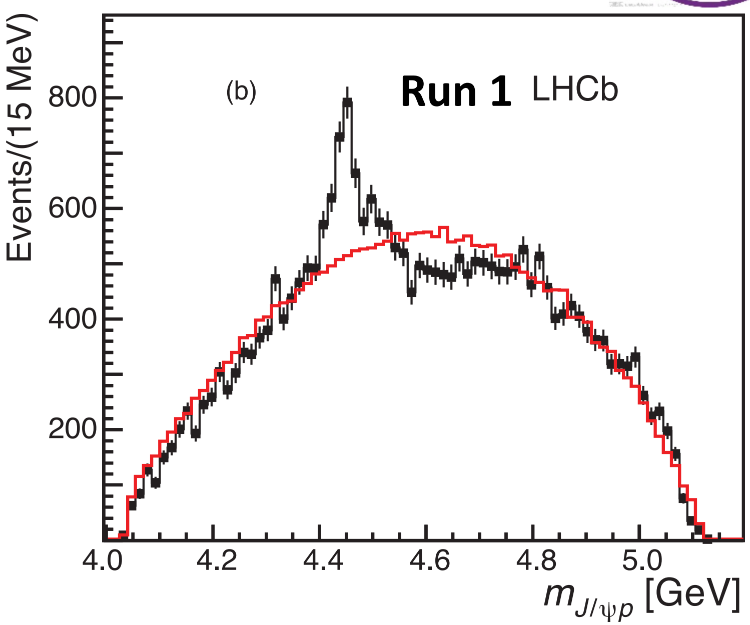
$\Lambda_b^0 \to J/\psi p \pi^-$

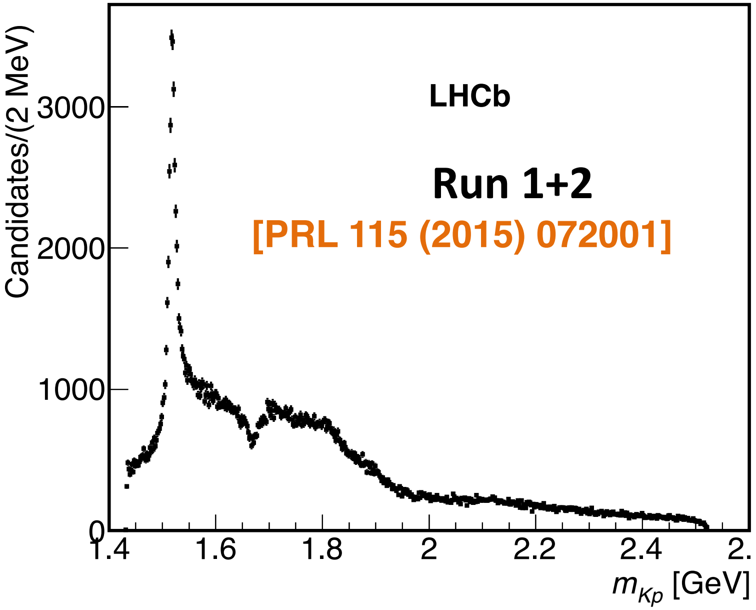


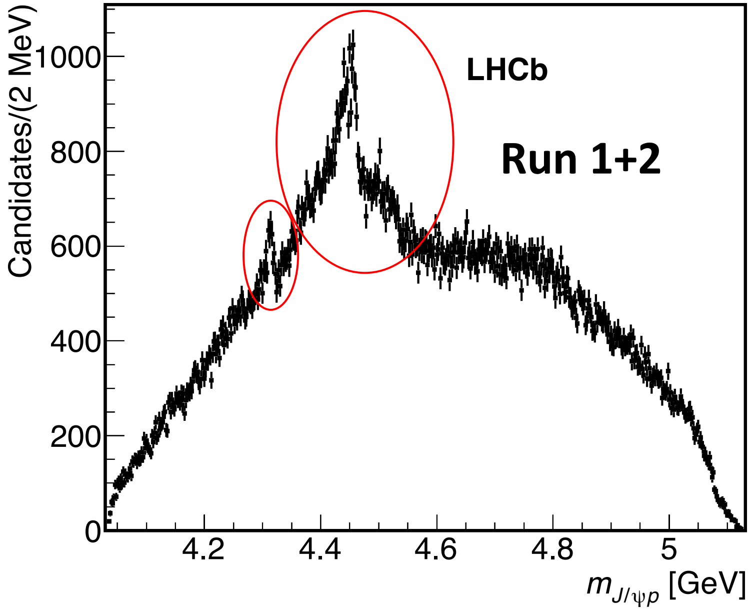
Update $\Lambda_b^0 \to J/\psi p K^-$ (3+6 fb[-1])

- An order of magnitude increases in signal yield
  - Inclusion of Run 2 data (x 5)
  - Improved data selection (x 2) by putting PID in MVA selection
- Consistent distributions between old and new samples
- More structures appear
- Fit 1D $m_{J/\psi p}$ distribution
  - Several fits with different selection/weighting for systematic evaluation







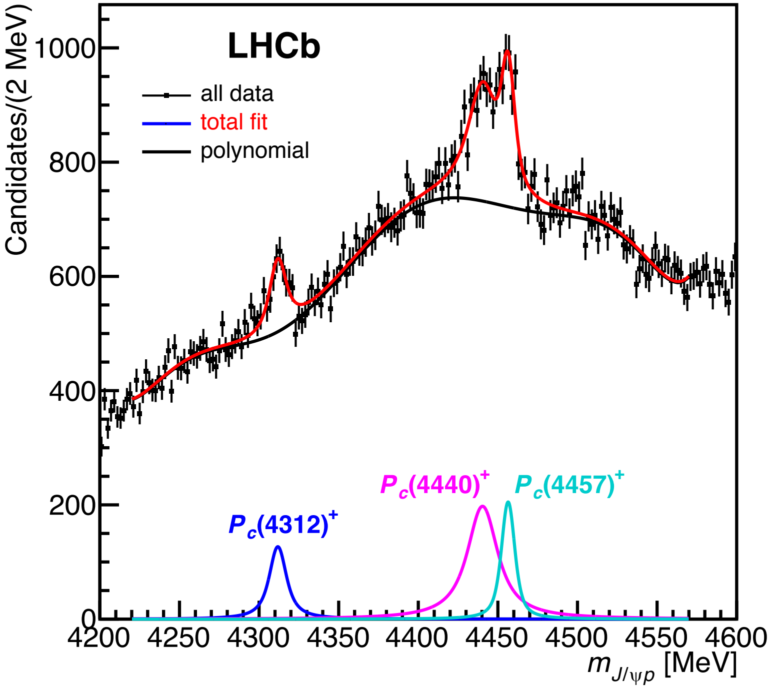


Fit-1: all candidates

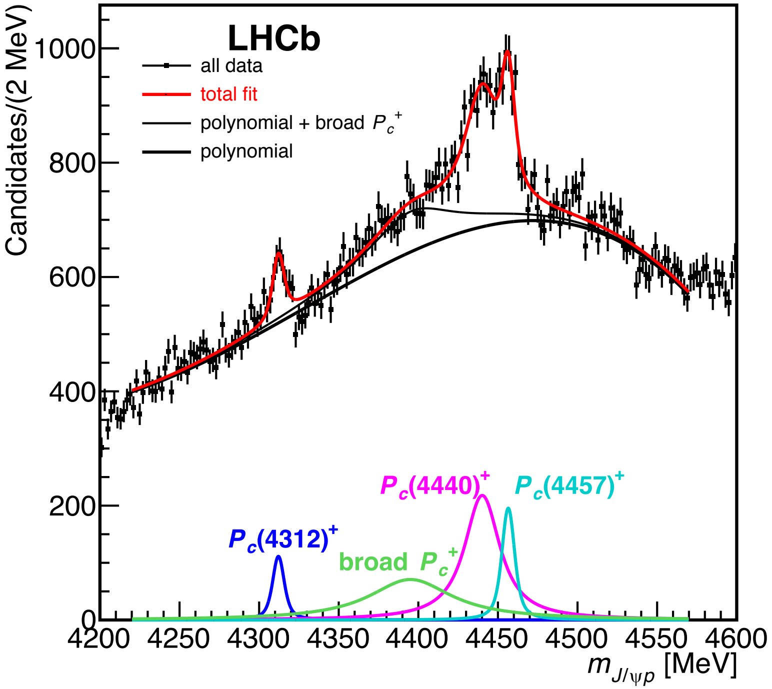
[PRL 122 (2019) 222001]

- Fit inclusive $m_{J/\psi p}$ distribution
- Clear narrow structures, but background is high

high-order polynomial



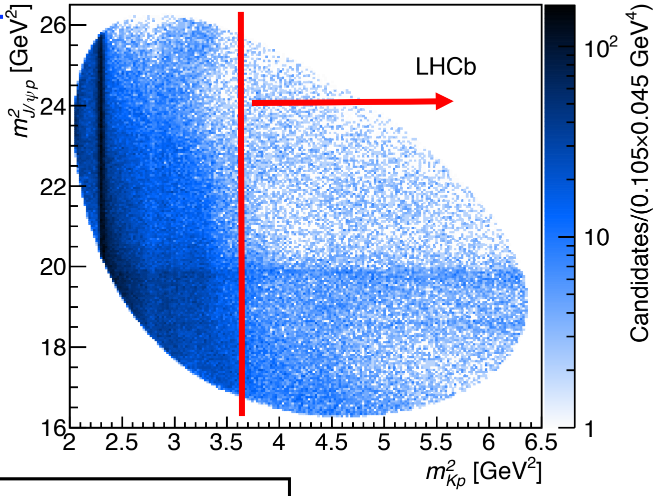
low-order polynomial + broad P_c^+ as bkg.

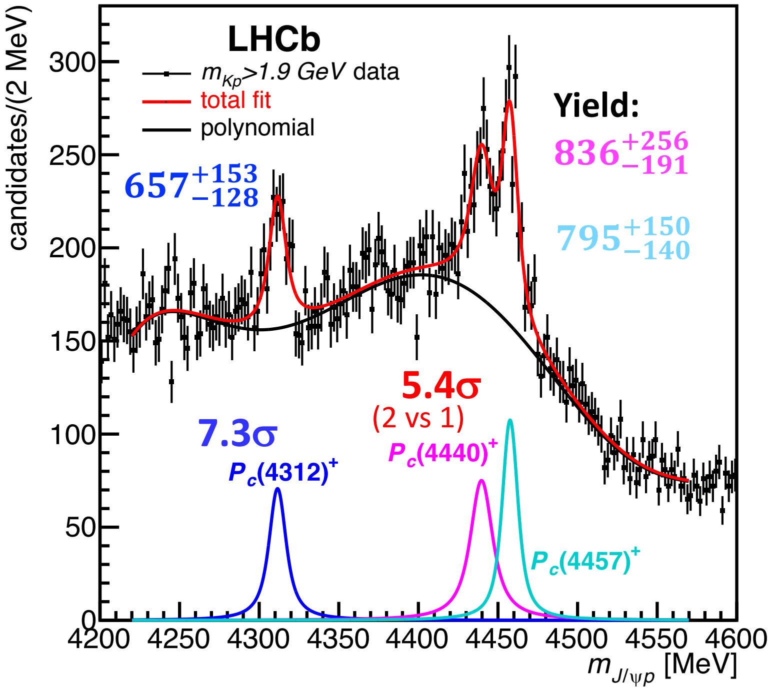


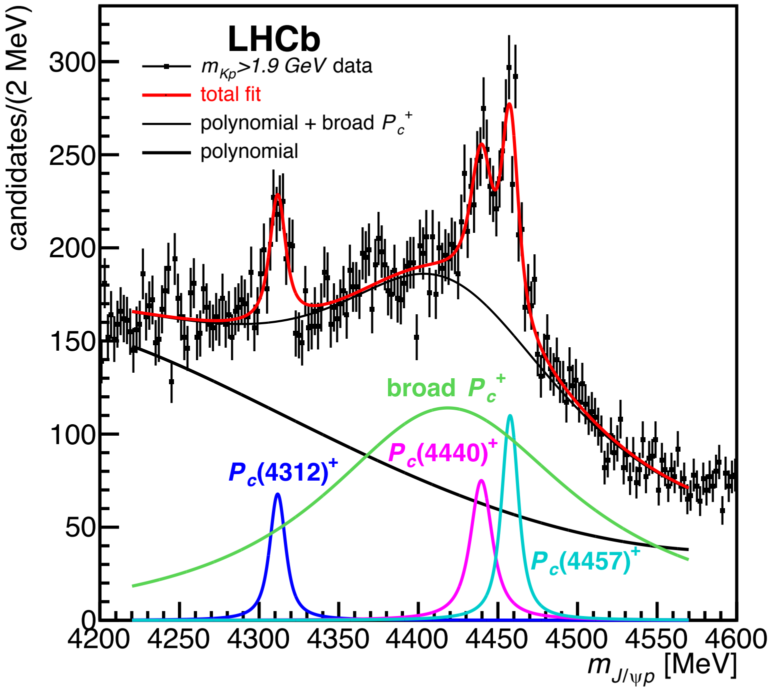
Fit-2: P_c^+ dominated region

- Fit $m_{Kp} > 1.9$ GeV events, ~80% Λ^* background removed
- Significances: $P_c(4312)^+$, **7.3σ**;
  2 peaks over 1 around 4450 MeV, **5.4σ**
  - Evaluated with toy simulations from 6D amplitude model
  - Have taken account of look elsewhere effect

[PRL 122 (2019) 222001]



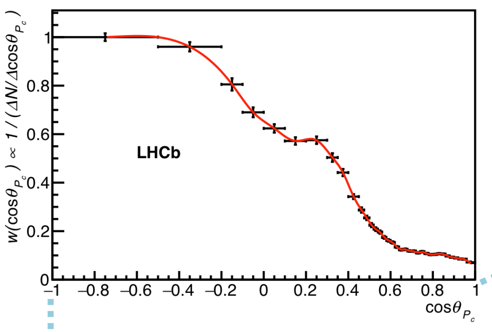


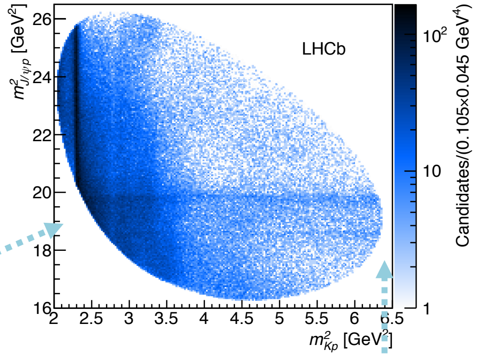


Fit-3: Novel method

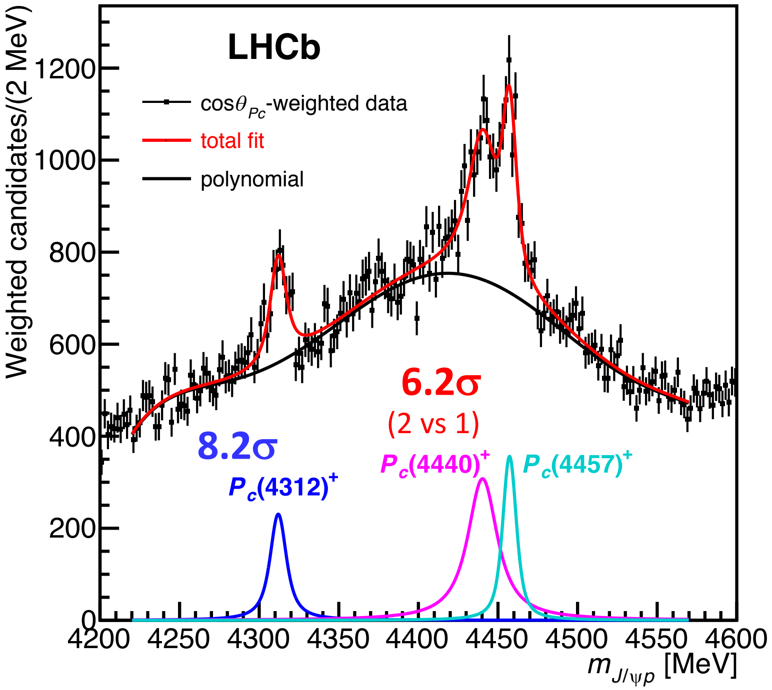
[PRL 122 (2019) 222001]

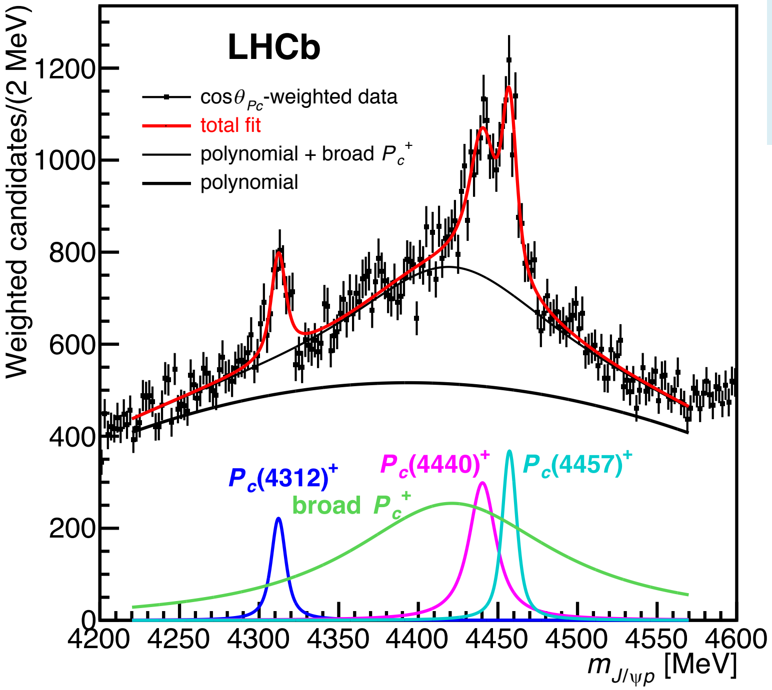
- Candidates weighted by $w(\cos\theta_{P_c}) = \frac{1}{\sigma^2_{\text{stat.}}} \approx \frac{1}{S+B}$
  - w is inverse of $\cos\theta_{P_c}$ distribution of Λ_b^0 candidates with $m_{J/\psi p} \in [4.2, 4.6]$ GeV
- Most statistically sensitive method





Nominal fit for M&Γ measurements



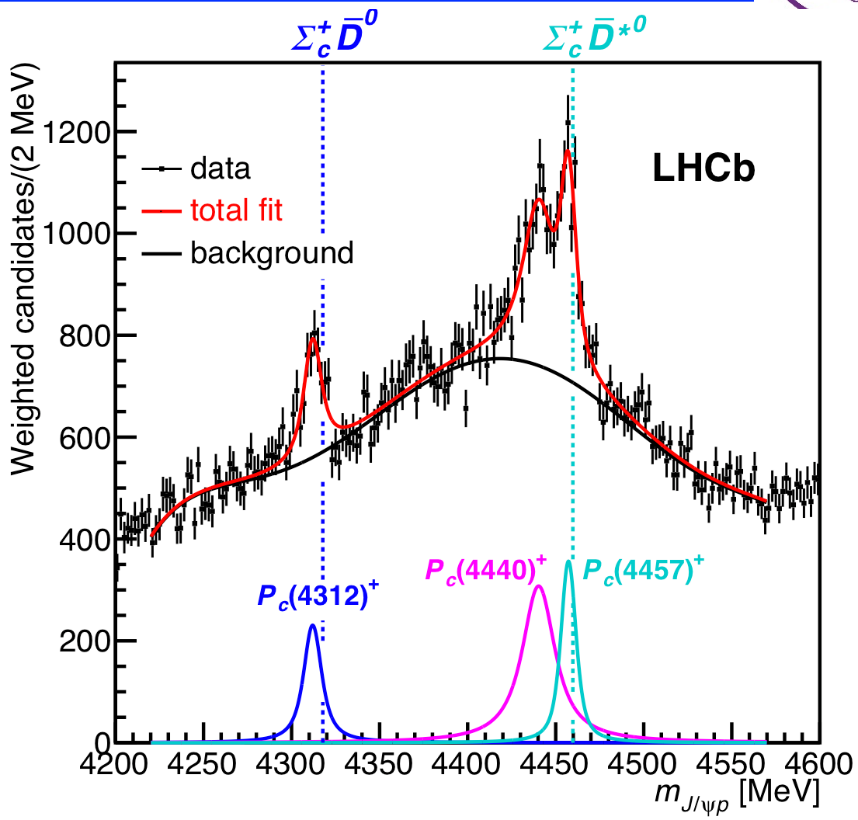


θ_{P_c} is P_c helicity angle, correlated with m_{Kp}

Observation of three narrow structures

- The masses of $P_c(4312)^+$, $P(4440)^+$, $P_c(4457)^+$ **just below mass thresholds of $\Sigma_c^+\bar{D}^{(*)0}$**

- Broad $P_c(4380)^+$ is neither be confirmed nor excluded
- J^P measures and information of $P_c(4380)^+$ require detailed amplitude analysis



State	M [MeV]	Γ [MeV]	(95% CL)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$	(< 27)	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$	(< 49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$	(< 20)	$0.53 \pm 0.16^{+0.15}_{-0.13}$

[PRL 122 (2019) 222001]

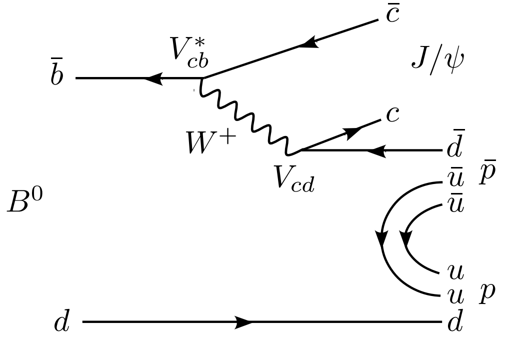
Largest systematic uncertainty: unknown interference terms

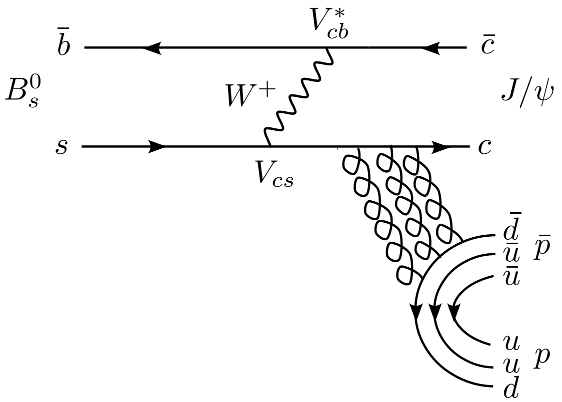
Observation of $B^0_{(s)} \to J/\psi p\bar{p}$

[PRL 122 (2019) 191804]

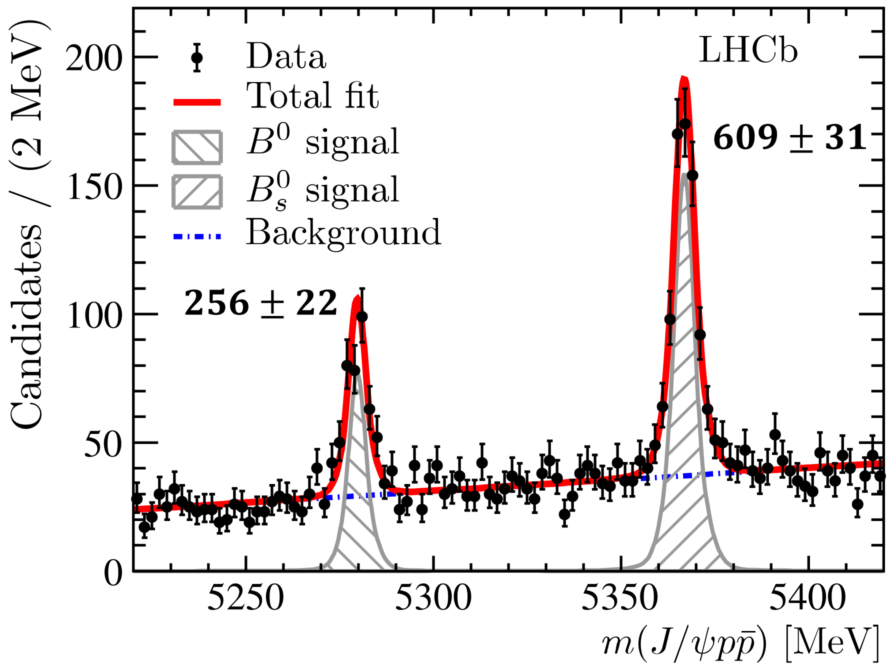
Decay modes are suppressed

B^0: Cabibbo suppressed **B_s^0: "OZI" suppressed**



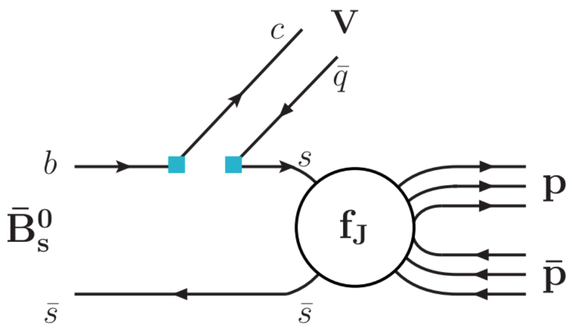


$\mathcal{L} = 4.7\text{fb}^{-1}$, 2011-2016 data



Can be enhanced through

- **Exotic states** in $J/\psi p$ system
- **Glueballs in $p\bar{p}$ system**
  [Y. K. Hsiao and C. Q. Geng, EPJ C75 (2015) 101, arXiv:1412.4900]



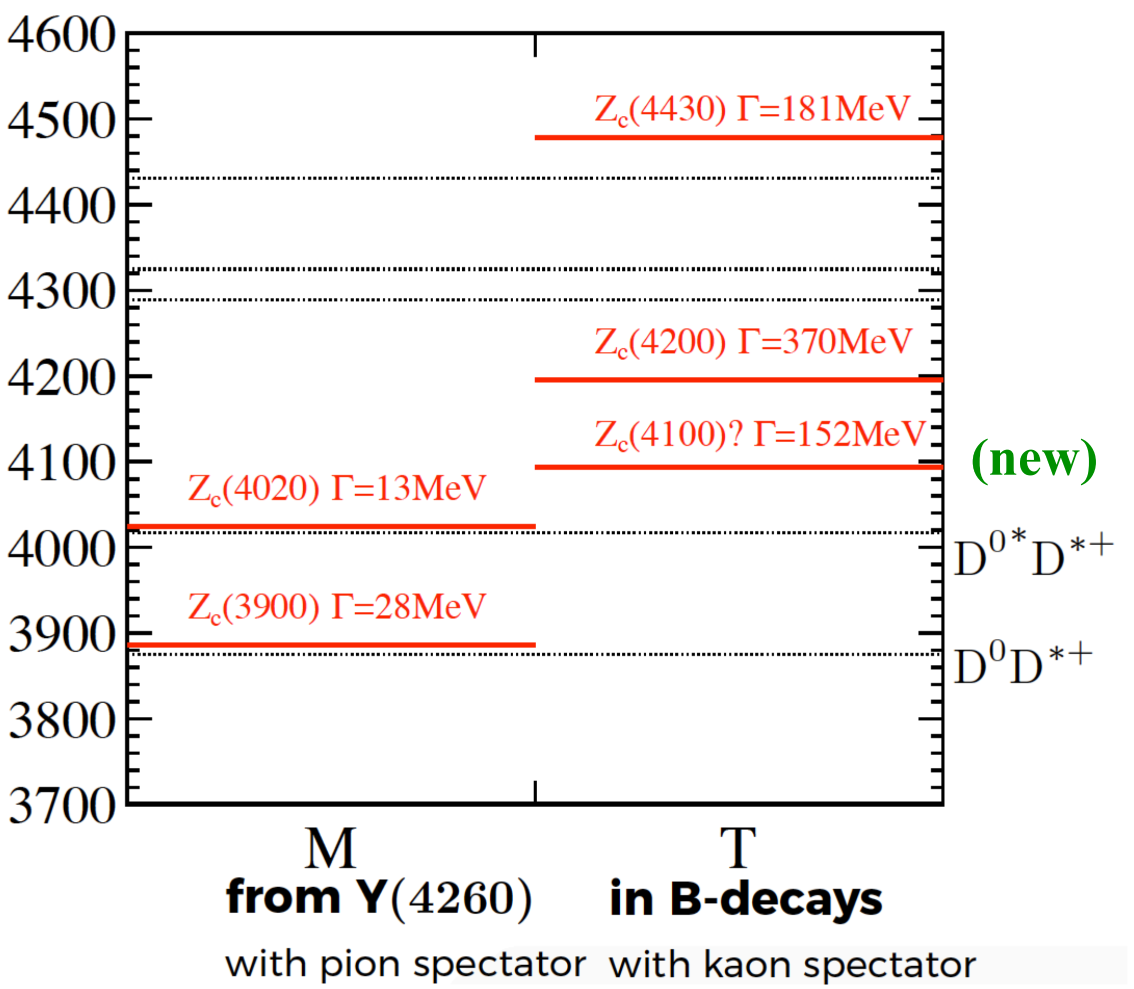
$\mathcal{B}(B_s^0 \to J/\psi p\bar{p}) = (3.58 \pm 0.19 \pm 0.31)\times 10^{-6}$

larger than predicted value ~10^{-9}

$\mathcal{B}(B^0 \to J/\psi p\bar{p}) = (4.51 \pm 0.40 \pm 0.43)\times 10^{-7}$

Charged exotic mesons with hidden charm

All Z_c states have at least $c\bar{c}q\bar{q}$ quark content



All Z_c observed so far have $J^P=1^+$

LHCb has an evidence of $Z_c(4100) \to \eta_c \pi$ that cannot be 1^+

Tightly bound tetraquarks?

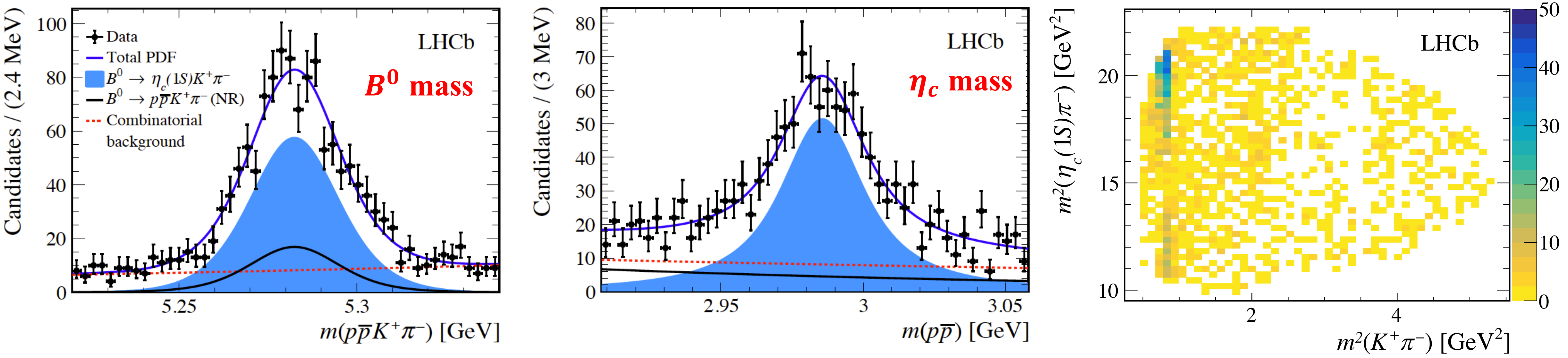
- Far from thresholds
- Large width

Hadronic molecules

- At 2-body thresholds
- Narrow

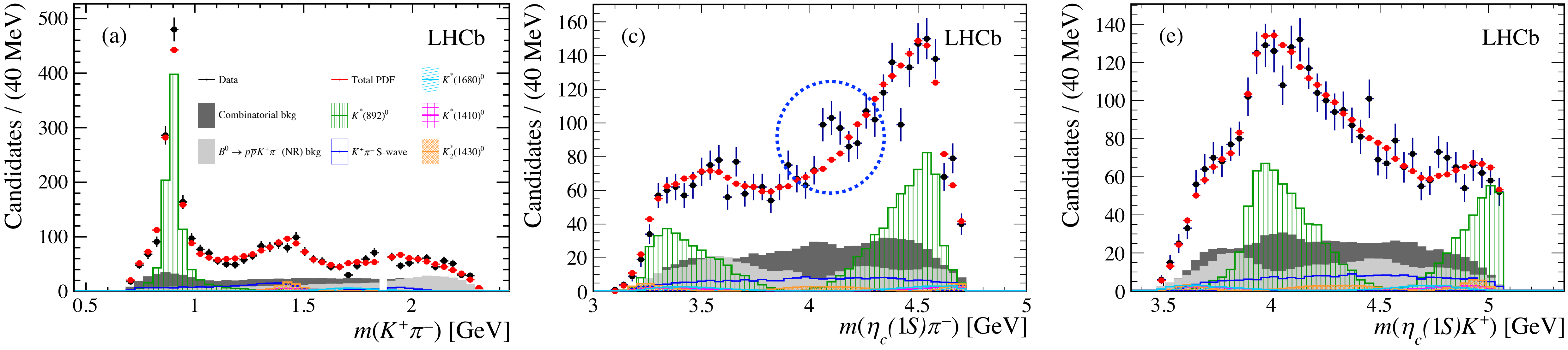
Evidence of $Z_c(4100)^-$ in $B^0 \to \eta_c \pi^- K^+$ [EPJ C78 (2018) 1019]

- $\mathcal{L} = 4.7\text{fb}^{-1}$, 2011-2016 data
- 2D fit to $m(p\bar{p}K^+\pi^-)$ and $m(p\bar{p})$ distribution $N_{\text{sig}} = 1870 \pm 74$

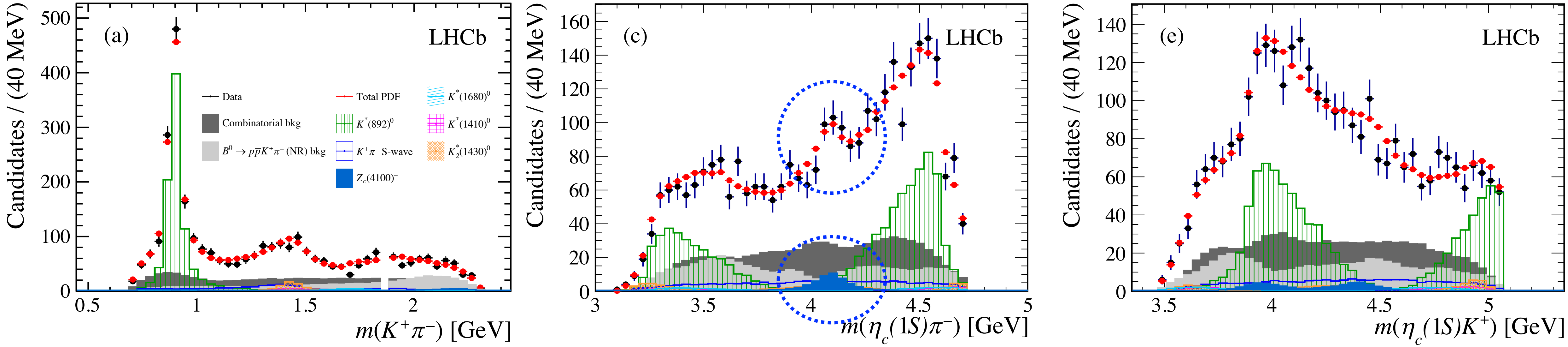


- Dalitz plot dominated by $K^*(892)$ signal

Evidence of $Z_c(4100)^-$ in $B^0 \to \eta_c\pi^-K^+$ [EPJ C78 (2018) 1019]



Evidence of $Z_c(4100)^-$ in $B^0 \to \eta_c \pi^- K^+$ [EPJ C78 (2018) 1019]



Adding a $J^P = 1^-$ resonance in $\eta_c\pi$ with

$m_Z = 4096 \pm 20^{+18}_{-22}$ MeV $\Gamma_Z = 152 \pm 58^{+60}_{-35}$ MeV

improves fit by $\Delta(-2\ln\mathcal{L}) = 41.4$ (4.8σ)

$J^P = 0^+$ is also allowed by the data

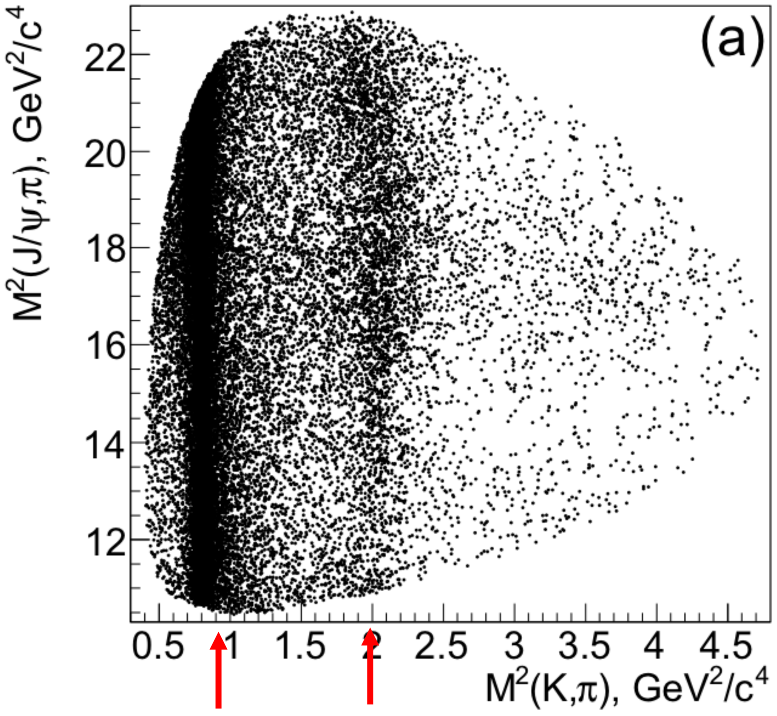
Systematic effects on significance

Source	$\Delta(-2\ln\mathcal{L})$	Significance
Nominal fit	41.4	4.8σ
Fixed yields	45.8	5.2σ
Phase-space border veto	44.6	5.1σ
η_c width	36.6	4.3σ
$K^+\pi^-$ S-wave	31.8	3.9σ
Background	27.4	3.4σ

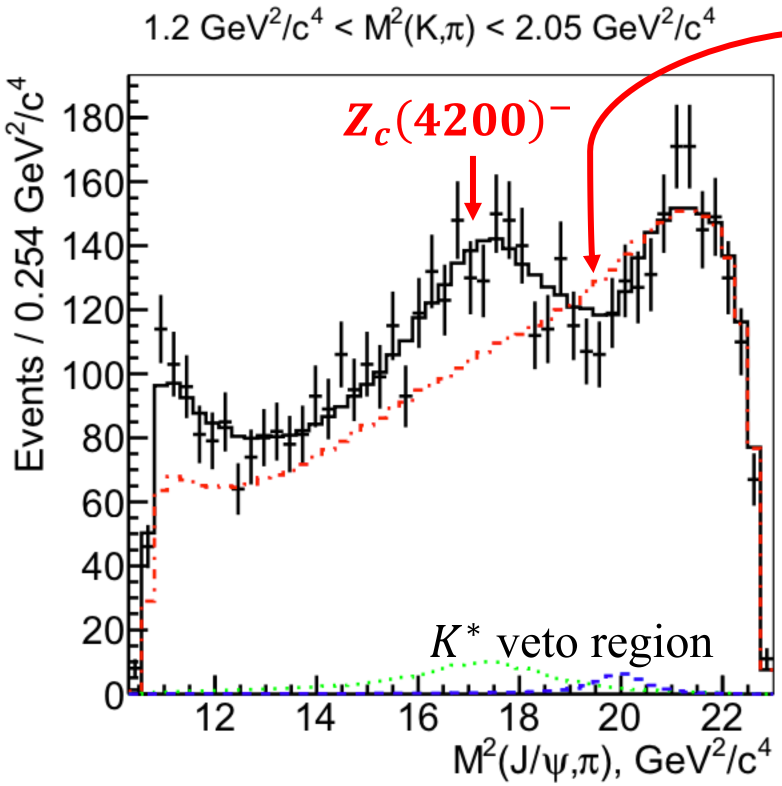
Z_c^- in $B^0 \to J/\psi K^+\pi^-$ from Belle

[PRD 90 (2014) 112009]

- With ~30k signal, Belle observed a new $Z_c(4200)^-$ and evidence for $Z_c(4430)^-$ in $B^0 \to J/\psi K^+\pi^-$ decays
- Exotic fit fractions are small, $(1.9^{+0.7}_{-0.5})\%$ $Z_c(4200)^-$ & $(0.5^{+0.4}_{-0.1})\%$ $Z_c(4430)^-$



K^* $K^*_{0,2}(1430)$

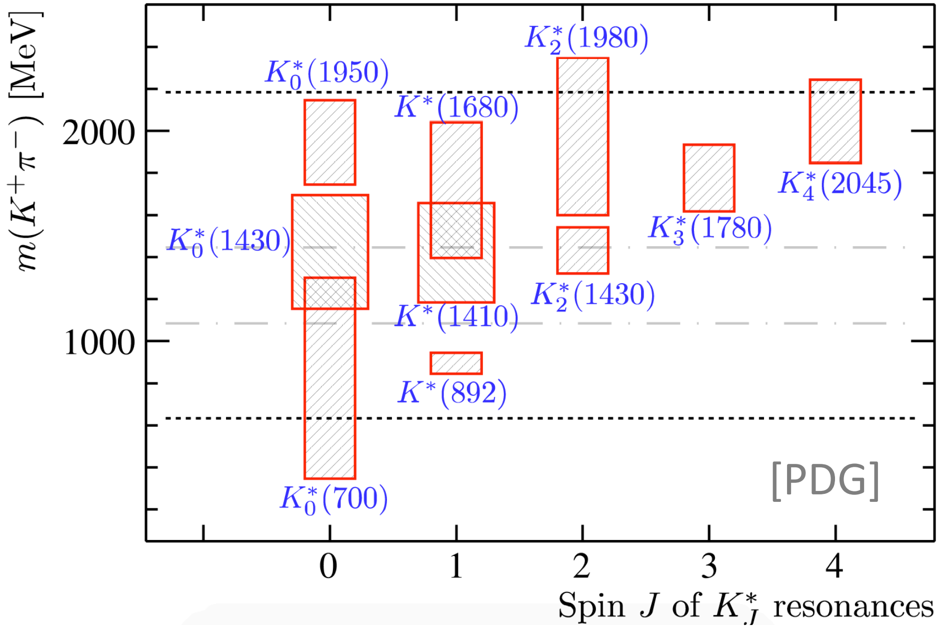


$Z_c(4430)^-$ **presented via destructive interference**

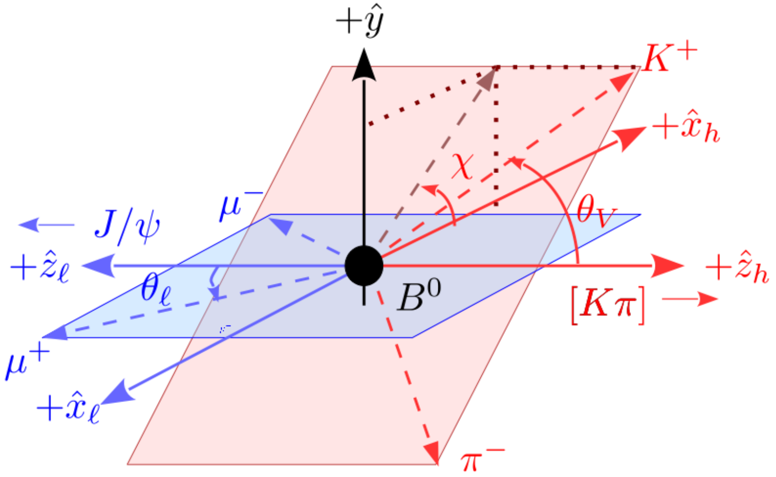
Model-independent confirmation from LHCb

- Run-1 data, x20 Belle signal yield $m(K^+\pi^-) \in [745, 1545]$ MeV, yield: $554{,}500 \pm 800$
- Reflect $K_J^* \to K^+\pi^-$ angular moments determined in function of $m(K^+\pi^-)$ onto $m(J/\psi\pi^-)$
- No assumption about resonant structures, only requires knowledge of highest spin ($J_{\max}^k$) of K_J^* for given $m(K^+\pi^-)$

$$J_{\max}^k = \begin{cases} 2 & \text{for } 1085 \le m(K^+\pi^-) < 1265 \text{ MeV} \\ 3 & \text{for } 1265 \le m(K^+\pi^-) < 1445 \text{ MeV} \end{cases}$$



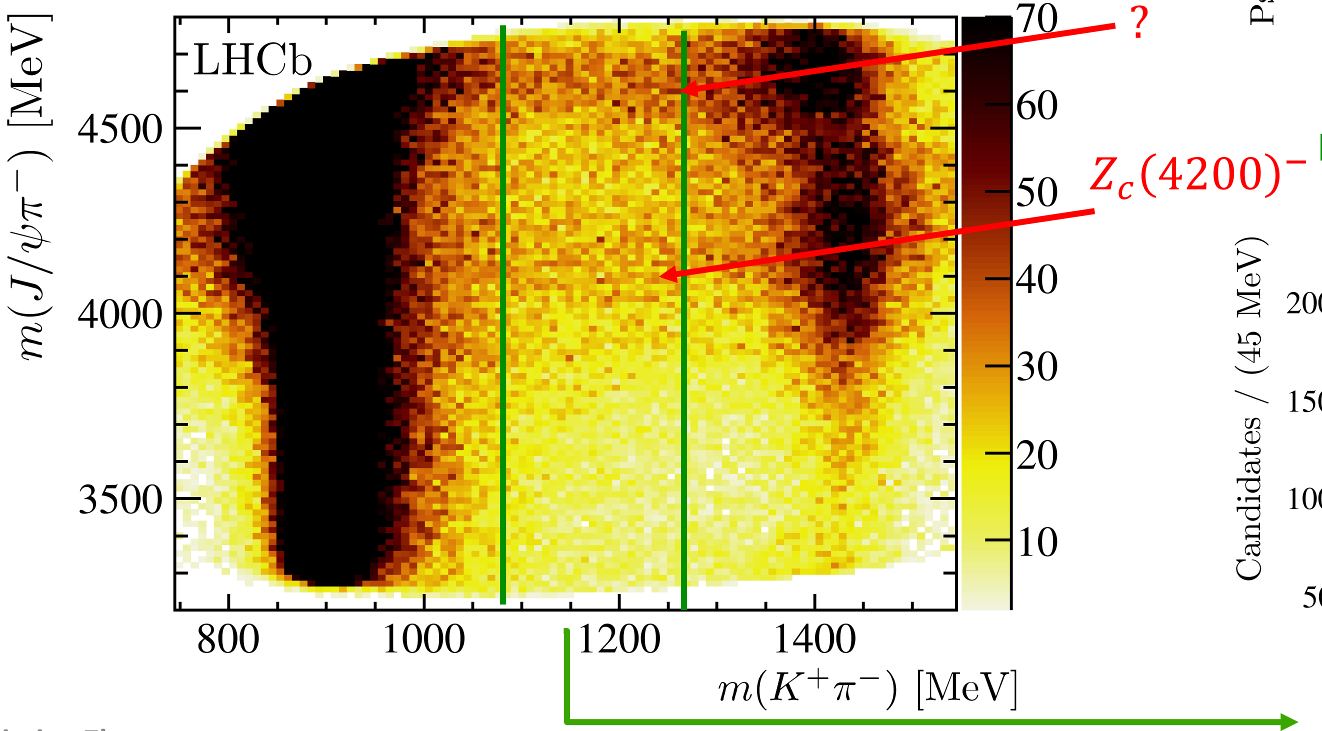
Used novel "3D" angular moments to boost sensitivity

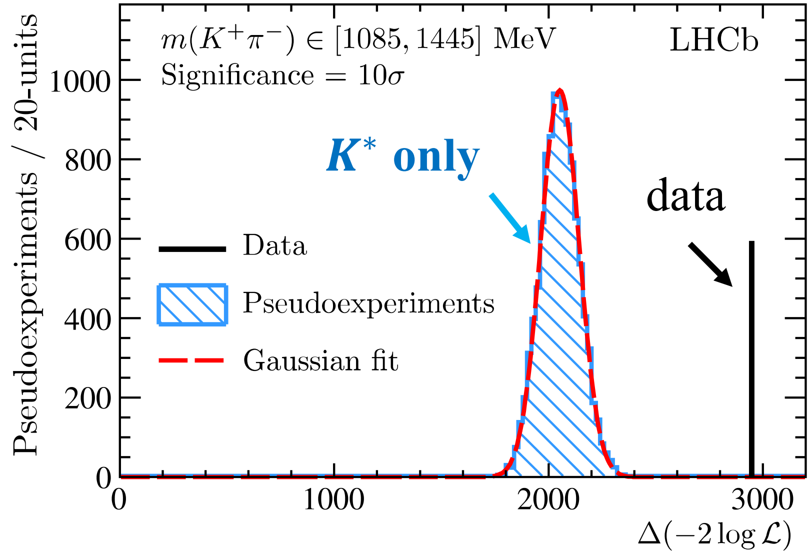


Model-independent confirmation from LHCb

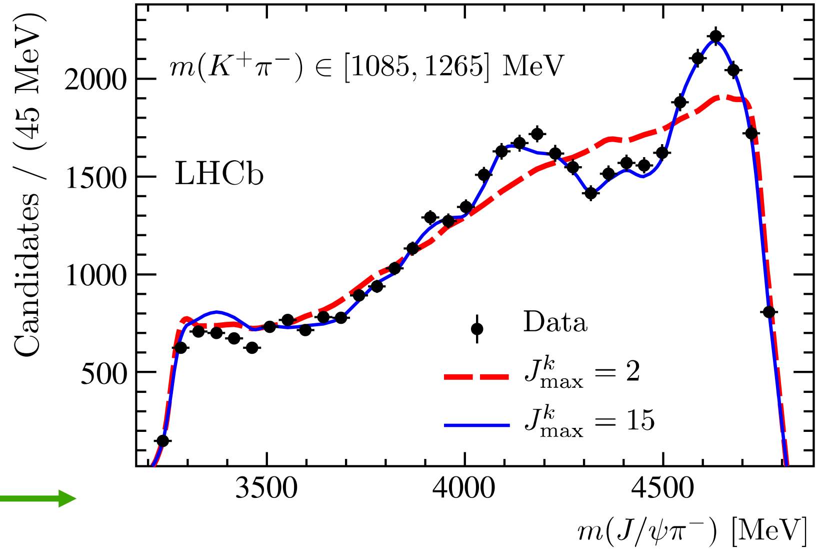
- Data inconsistent with K^*-only contributions by 10σ level
- Model dependent amplitude analysis needed to determine properties of these structures

[PRL 122 (2019) 152002]



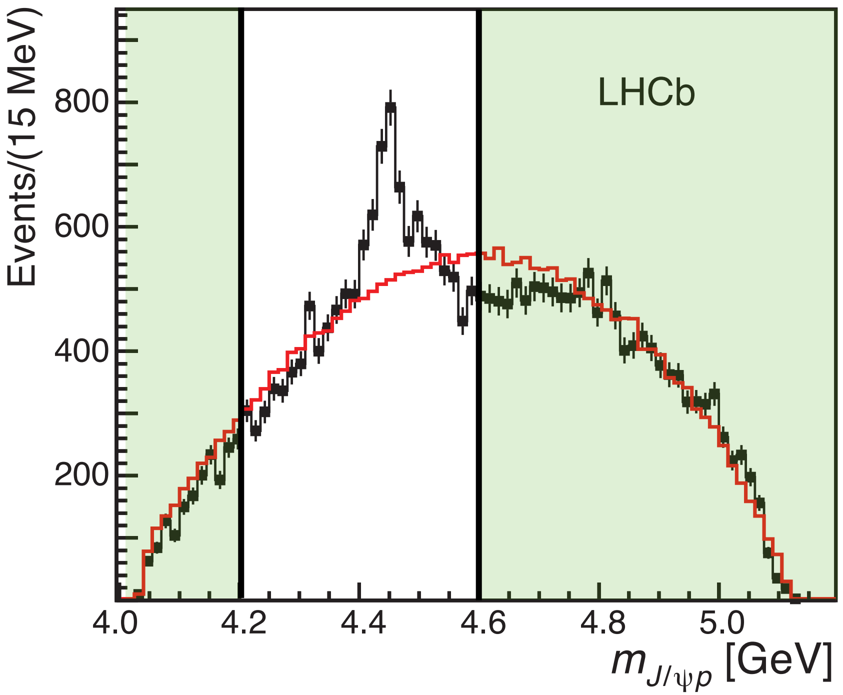


Example in narrow $m(K^+\pi^-)$ bin

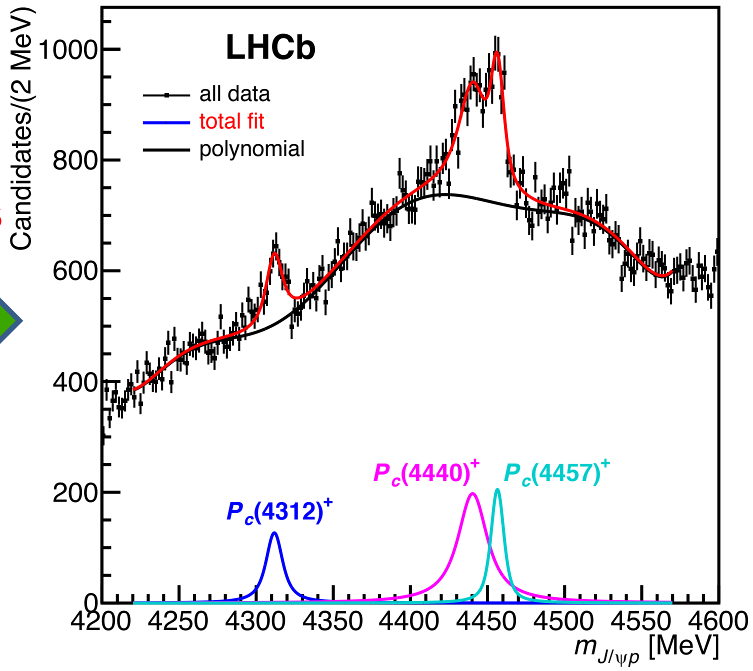


Summary

- Evidence of $Z_c(4100)^- \to \eta_c\pi^-$, $J^P \neq 1^+$
- Model-independent confirmation of exotic contribution to $B^0 \to J/\psi K^+\pi^-$
- Observation of $B^0_{(s)} \to J/\psi p\bar{p}$ decays
- With 10x signal yields, we observed three narrow pentaquark candidates

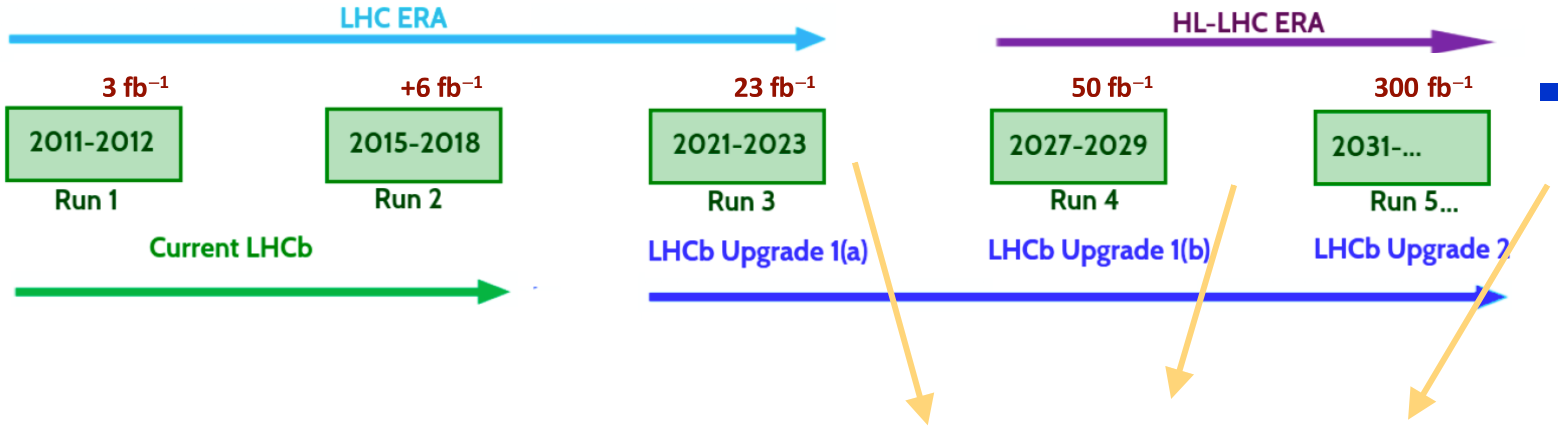


10x yields



Prospects

arXiv:1808.08865



Decay mode	LHCb 23 fb^{-1}	50 fb^{-1}	300 fb^{-1}
$B^+ \to X(3872)(\to J/\psi\pi^+\pi^-)K^+$	14k	30k	180k
$B^+ \to X(3872)(\to \psi(2S)\gamma)K^+$	500	1k	7k
$B^0 \to \psi(2S)K^-\pi^+$	340k	700k	4M
$B_c^+ \to D_s^+ D^0 \overline{D}^0$	10	20	100
$\Lambda_b^0 \to J/\psi\, pK^-$ [*]	680k	1.4M	8M
$\Xi_b^- \to J/\psi\, \Lambda K^-$	4k	10k	55k
$\Xi_{cc}^{++} \to \Lambda_c^+ K^-\pi^+\pi^+$	7k	15k	90k
$\Xi_{bc}^+ \to J/\psi\, \Xi_c^+$	50	100	600

- **LHCb is now boosting the data to a new level**
  - **Expect to 7x more data (14x hadronic events) by 2029 than current, half of these by 2023**
  - **Could have another 6x increase from Upgrade II**

$\chi_{c1}(3872)$ lineshape from multi-channels

$Z_c(4430)$, also explore $B \to D_{(s)}^{(*)}\overline{D}_{(s)}K^-$?

Doubly-charmed tetraquark $\mathcal{T}_{cc}^+ \to D_s^+ D^0$

More information for pentaquarks

[*] updated according to the latest result

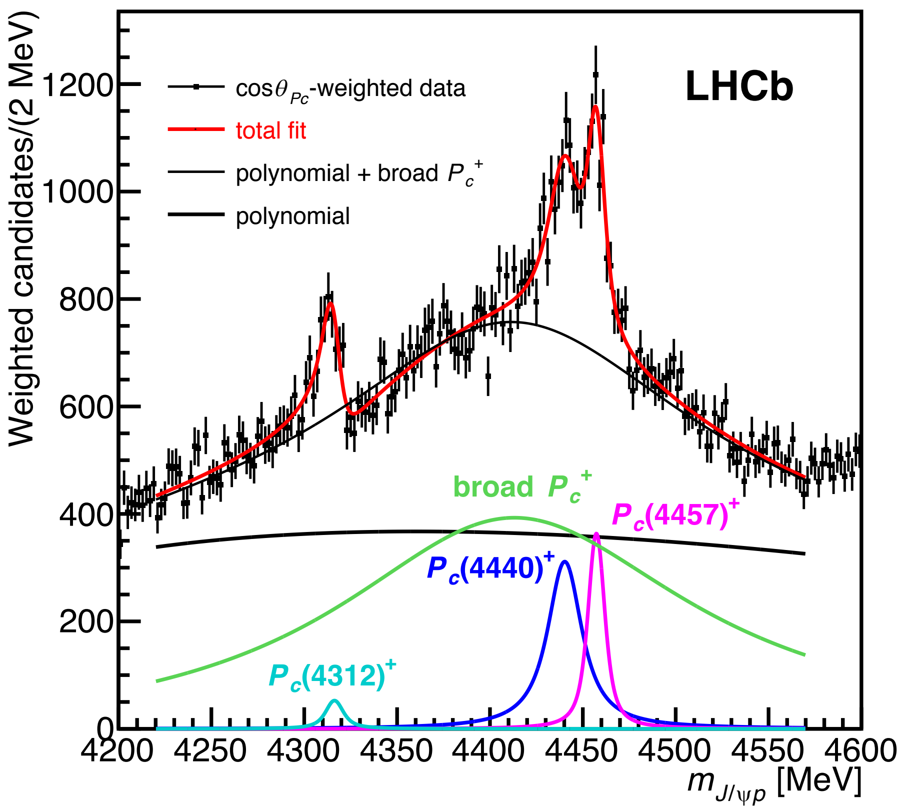
Backup

Fits with interferences

- Interference effect is important only if two overlying P_c^+ have same J^P
- Nominal fits use incoherent sum of BW amplitudes
- Systematic uncertainty considers fits with coherent sum, including broad P_c^+ state
  - No evidence for interferences
  - But this source gives the largest uncertainty on mass and width measurements, e.g. +6.8 MeV for $P_c(4312)^+$ mass

PRL 122, 222001 (2019)

Example of a fit with interference:
$P_c(4312)^+$ interfering with the broad P_c^+



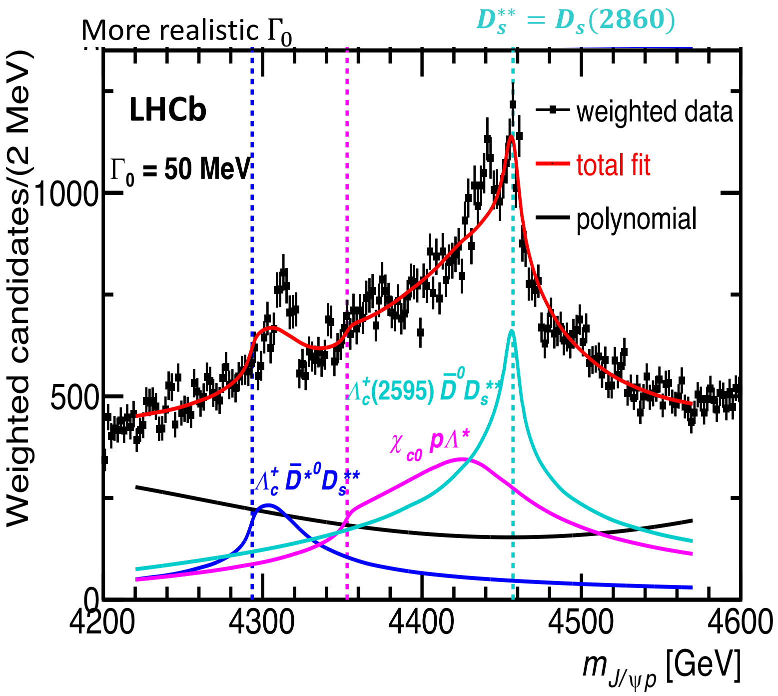
Triangle diagrams?

PRL 122 (2019) 222001

- Can produce peaking structure at or above mass threshold, but not below
- Cannot rule out $P_c(4457)^+$ as a triangle effect

$P_c(4312)^+$, $P_c(4440)^+$ are too far from any rescattering thresholds

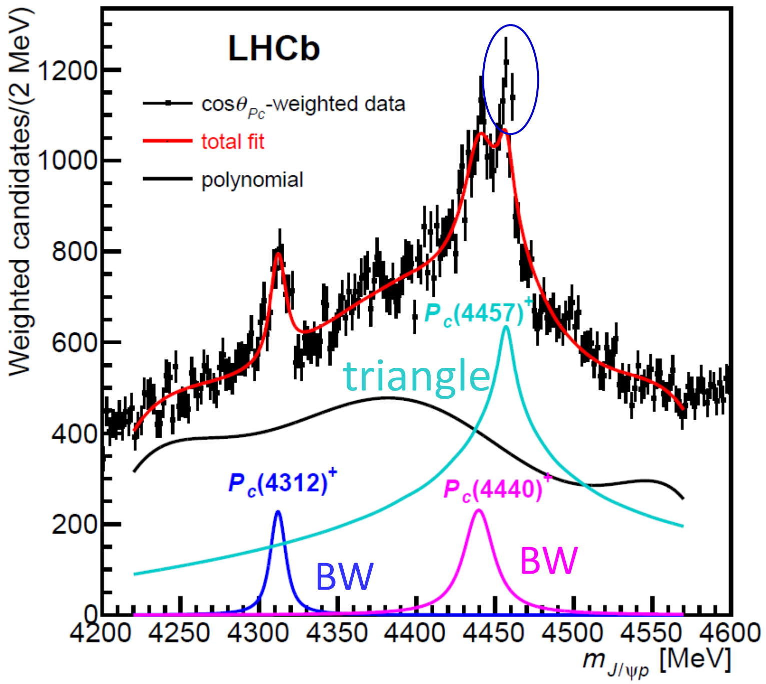
3 triangle-diagram amplitudes + polynomial

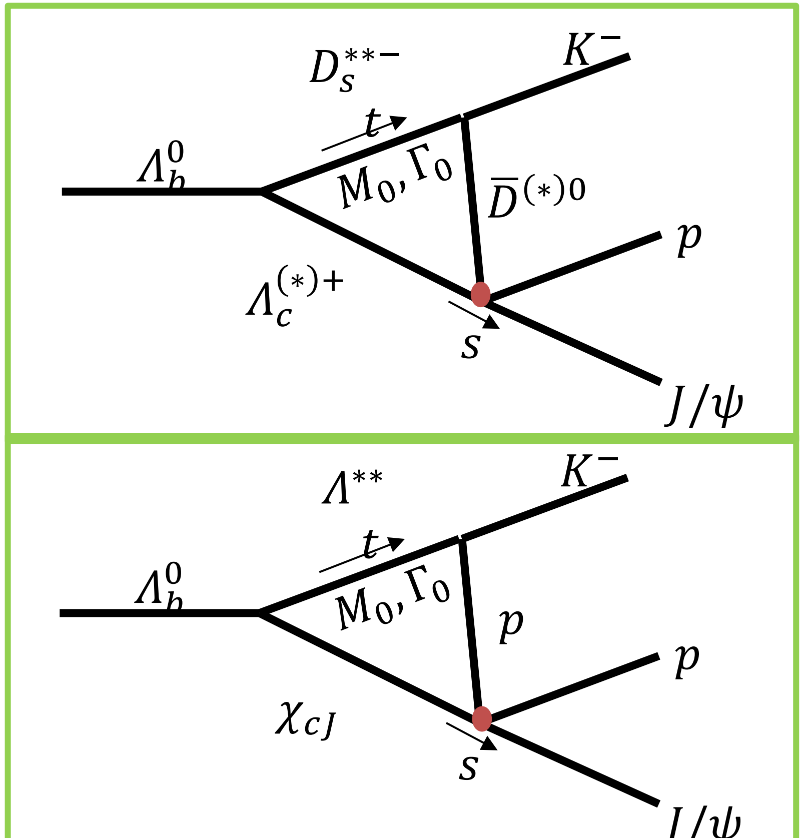


$P_c(4457)^+$ is right at the $\Lambda_c(2595)^+\bar{D}^0$ threshold

2BW + 1 triangle-diagram amplitudes + polynomial

Γ_0 = 159 MeV [PDG]





Guo *et al*, PRD 92 (2015) 071502 and others

J^P of $Z_c(4100)^-$ and $\mathcal{B}$

arXiv:1809.07416

- The default fit has 4.3σ for $J^P = 1^-$ over 0^+
- Systematic uncertainty reduces to 1.2σ
  - Alternative $K^+\pi^-$ S-wave model (NR + κ + $K_0^*(1430)^0$)
- So $J^P = 1^-$ and 0^+ are both consistent with the data

Source	$\Delta(-2\ln\mathcal{L})$	Significance
Default	18.6	4.3σ
Fixed yields	23.8	4.9σ
Phase-space border veto	24.4	4.9σ
η_c width	4.2	2.0σ
Background	3.4	1.8σ
$K^+\pi^-$ S-wave	1.4	1.2σ

- Fit fraction of $Z_c(4100)^-$ is $(3.3 \pm 1.1^{+1.2}_{-1.1})\%$

$$\mathcal{B}(B^0 \to Z_c(4100)^- K^+, Z_c(4100)^- \to \eta_c(1S)\pi^-) = (1.89 \pm 0.64^{+0.73}_{-0.67})\times 10^{-5}$$

$$\mathcal{B}(B^0 \to \eta_c(1S) K^+\pi^-) = (5.73 \pm 0.24 \pm 0.13 \pm 0.66)\times 10^{-4}$$

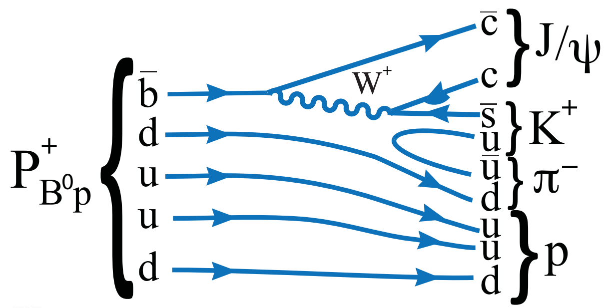
Weakly decaying *b*-flavoured pentaquarks

PRD 97 (2018) 032010

- Skyrme model: heavy quarks give tightly bound pentaquark

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

- Search for mass peaks 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	$\bar{b}suud$	$P^{+}_{B_s^0p} \to J/\psi \phi p$	5055–6305 MeV

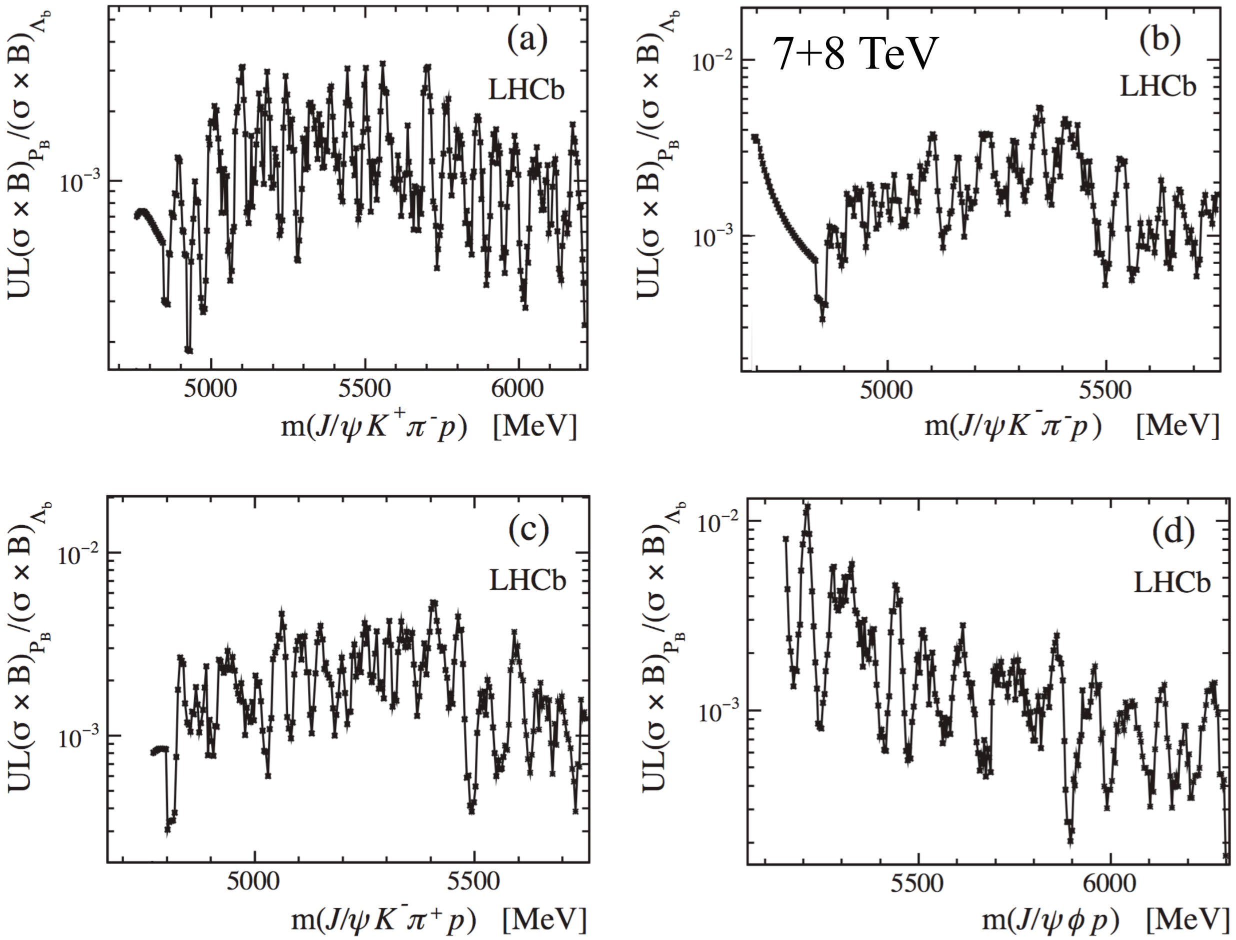
- Upper limit on production ratio $\sigma \cdot \mathcal{B}$ wrt $\Lambda_b^0 \to J/\psi K^- p$

$$R = \frac{\sigma(pp \to P_B X)\cdot \mathcal{B}(P_B \to J/\psi X)}{\sigma(pp \to \Lambda_b^0 X)\cdot \mathcal{B}(\Lambda_b^0 \to J/\psi K^- p)}$$

Weakly decaying *b*-flavoured pentaquarks

PRD 97 (2018) 032010

- No evidence for signal, 90% CL limits on $R < 10^{-2} - 10^{-3}$



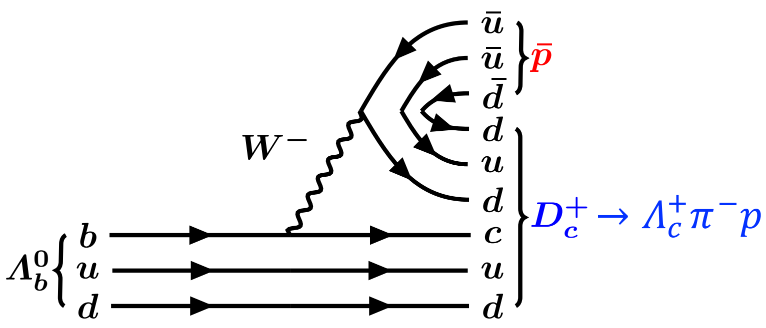
Search for dibaryon state

PLB 784 (2018) 101

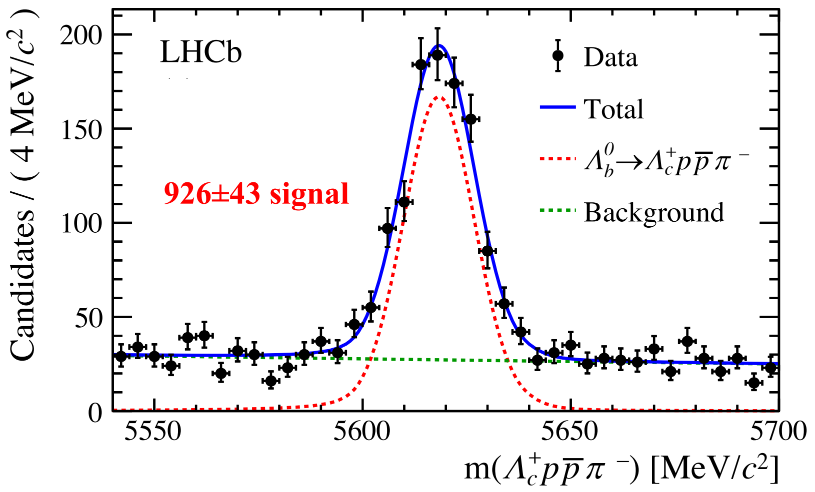
- A dibaryon state $[cd][ud][ud]$ could be produced in Λ_b^0 decays to final state $\Lambda_c^+\pi^-p\bar{p}$

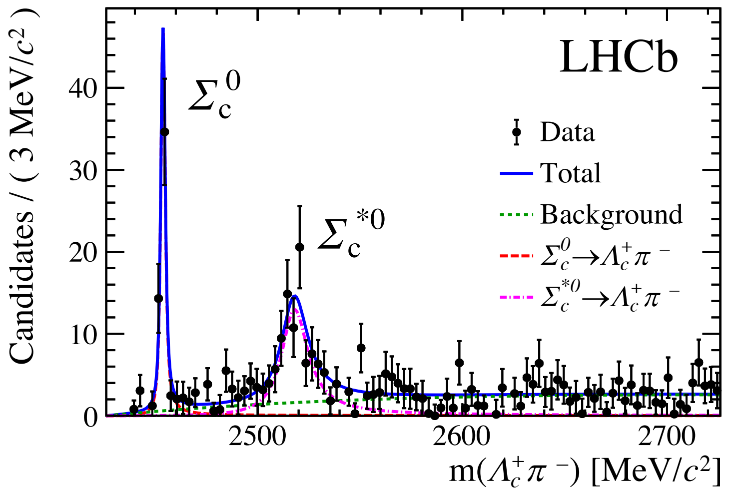
L. Maiani, et al. PLB 750 (2015) 37

- LHCb has discovered the decay $\Lambda_b^0 \to \Lambda_c^+\pi^-p\bar{p}$



Resonance contributions





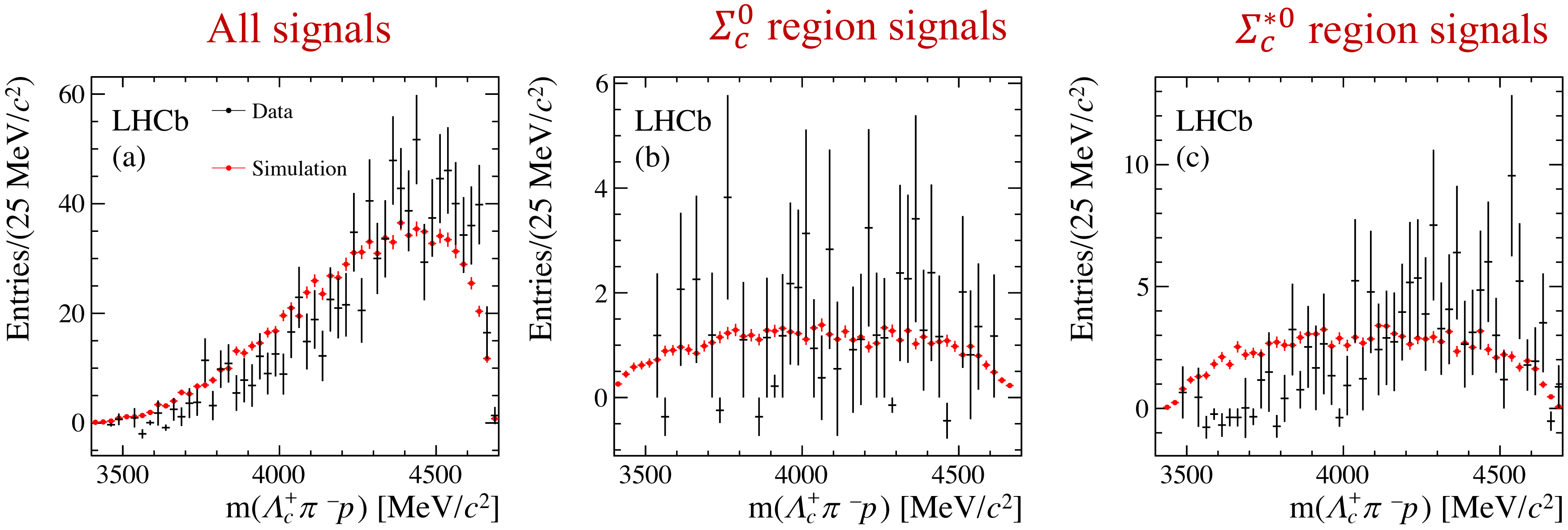
Search for dibaryon state

PLB 784 (2018) 101

- Ratio of branching fractions

$$\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ p\bar{p}\pi^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \pi^-)} = 0.0540 \pm 0.0023 \pm 0.0032$$

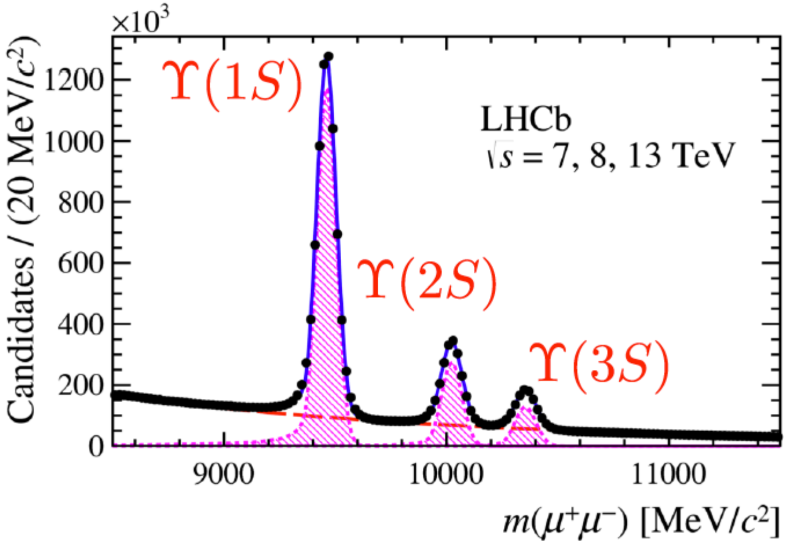
- No obvious dibaryon peak in $m(\Lambda_c^+\pi^- p)$ spectra

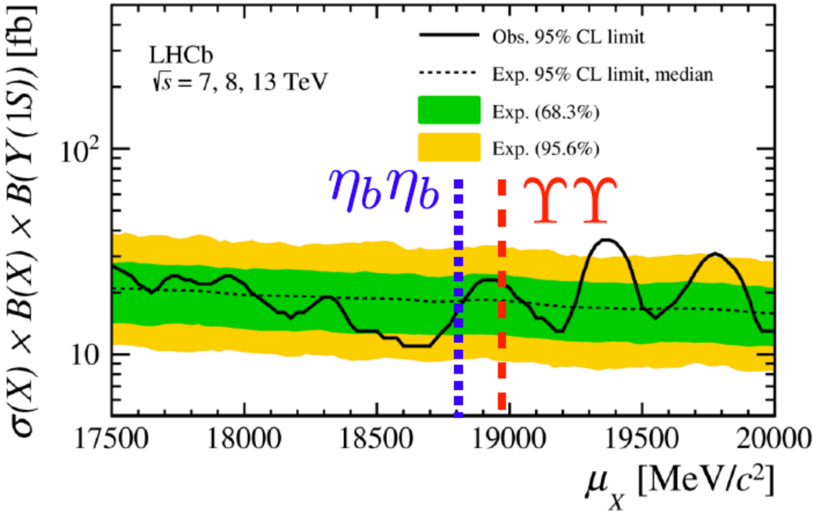


Search for $X_{bb\bar{b}\bar{b}} \to \Upsilon(1S)\mu^+\mu^-$

JHEP 10 (2018) 086

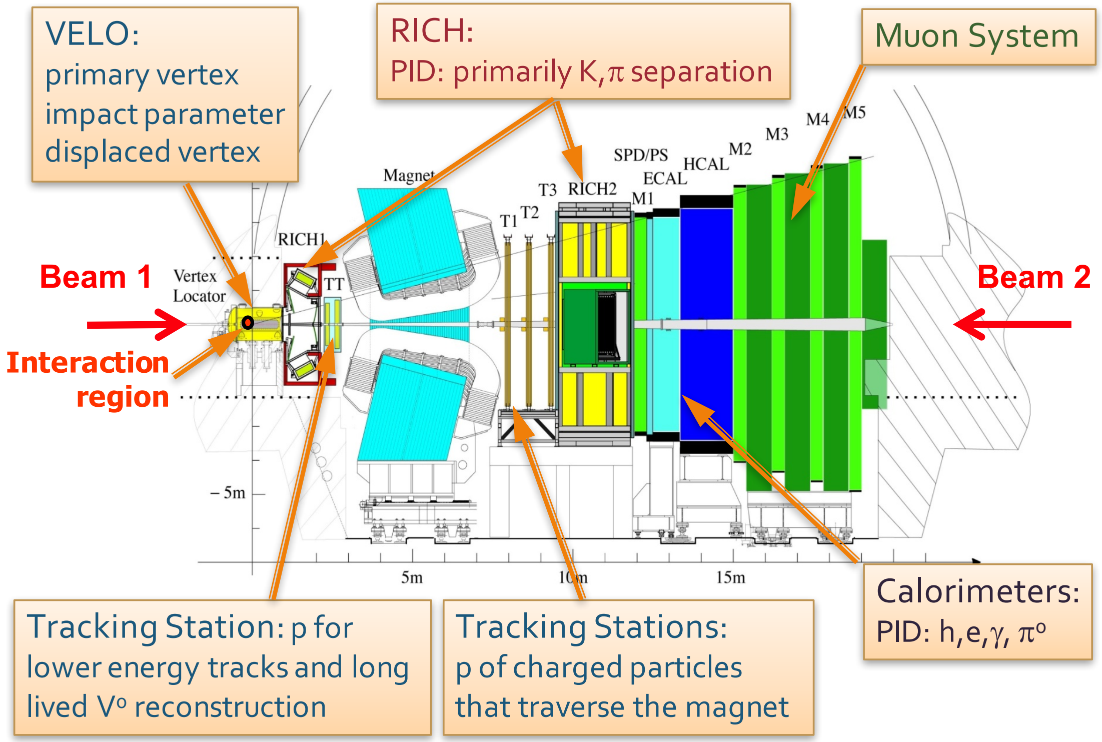
- Binding of double-heavy $b\bar{b}$ pairs quite different to $c\bar{c}$+light meson cloud
- Ground state bound $b\bar{b}b\bar{b}$ tetraquark $\sim 18 - 19$ GeV in many phenomenological models.
- Typically below $\eta_b\eta_b$ threshold. Can decay to $\Upsilon(1S)\mu^+\mu^-$
- No hint of a structure in LHCb search with 2011-2016 data. Upper limits placed.



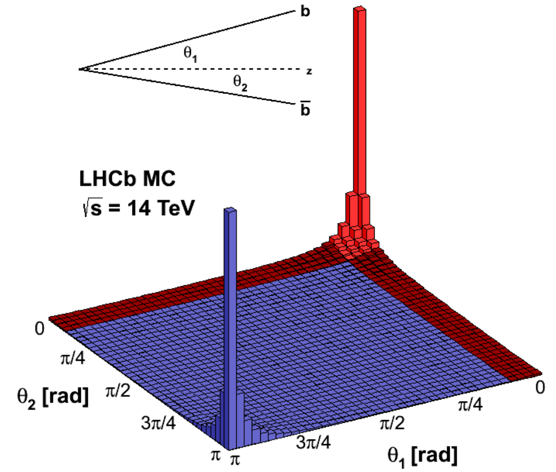


LHCb detector and performance

The LHCb detector described in [JINST 3 (2008) S08005]



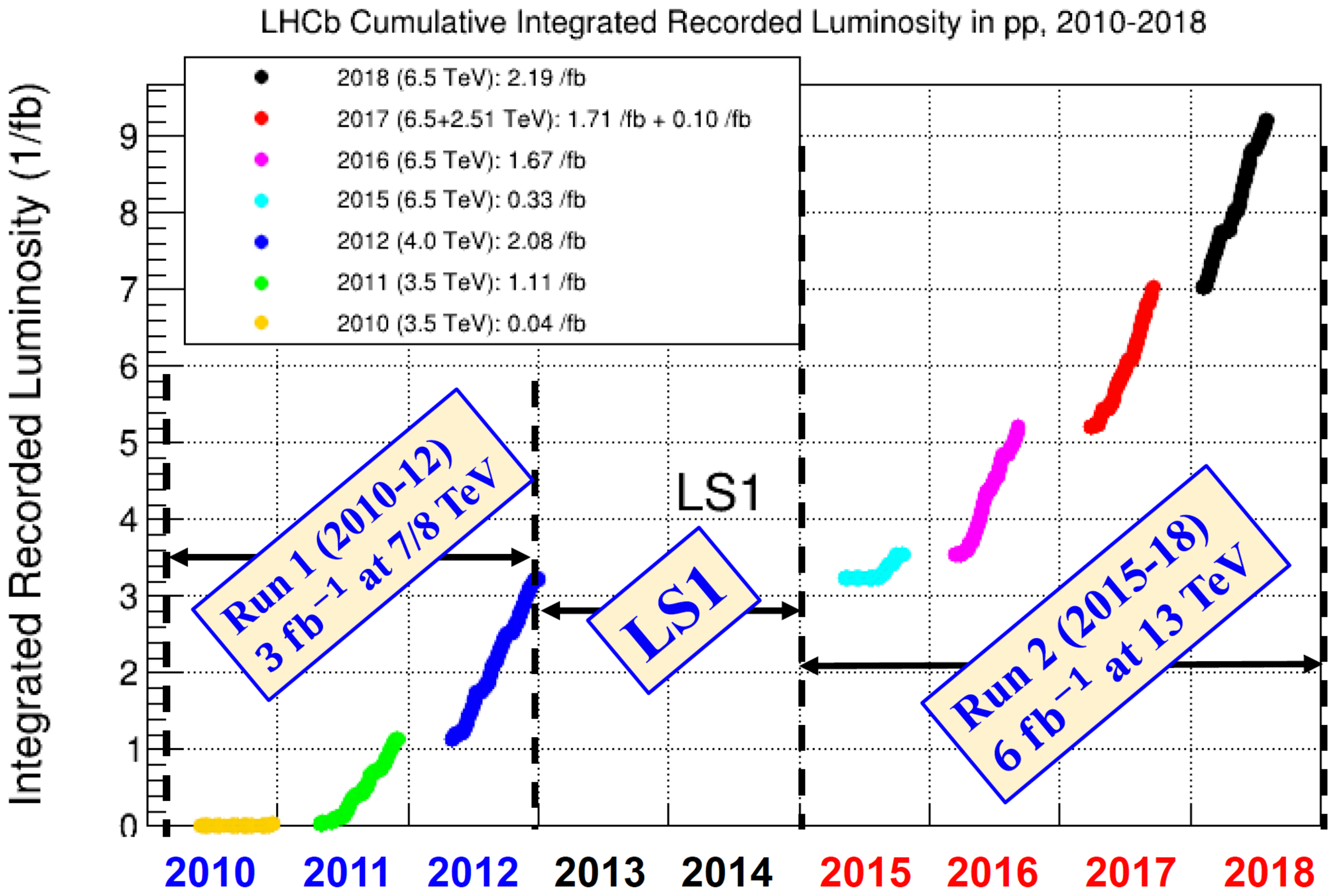
- $2 < \eta < 5$ range: $\sim 25\%$ of $b\bar{b}$ pairs inside LHCb acceptance



[Int. J. Mod. Phys. A 30 (2015) 1530022]

Impact parameter:	$\boldsymbol{\sigma_{IP} = 20\ \mu\mathrm{m}}$
Proper time:	$\sigma_\tau = 45$ fs for $B_s^0 \to J/\psi\phi$ or $D_s^+\pi^-$
Momentum:	$\Delta p/p = 0.4 \sim 0.6\%$ (5 – 100 GeV/c)
Mass :	$\boldsymbol{\sigma_m = 8\ \mathrm{MeV}/c^2}$ **for** $\boldsymbol{B \to J/\psi X}$ **(constrained** $\mathbf{m}_{J/\psi}$**)**
RICH $K - \pi$ separation:	$\boldsymbol{\epsilon(K \to K) \sim 95\%}$ **mis-ID** $\boldsymbol{\epsilon(\pi \to K) \sim 5\%}$
Muon ID:	$\boldsymbol{\epsilon(\mu \to \mu) \sim 97\%}$ **mis-ID** $\boldsymbol{\epsilon(\pi \to \mu) \sim 1 - 3\%}$
ECAL:	$\Delta E/E = 1 \oplus 10\%/\sqrt{E(\mathrm{GeV})}$

LHCb collected luminosity



$\sigma(pp \to b\bar{b}X) \approx 300$ μb @7 TeV vs ≈ 500 μb @13 TeV

~25% can be collected in LHCb acceptance