Recent results on exotic hadrons at LHCb

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(On behalf of the LHCb collaboration)

Implications of LHCb measurements and future prospects

28 Oct. – 30 Oct. 2020

Outline

- Overview of recent LHCb publications for exotic hadrons

- Selected topics

  arXiv:2009.00025, arXiv:2009.00026

  - Exotic D^-K^+ structure in $B^+ \to D^+D^-K^+$

  LHCb-PAPER-2020-035 In preparation

  - Observation of $X(4740)$ in $B_s^0 \to J/\psi K^+K^-\pi^+\pi^-$

  LHCb-PAPER-2020-039 In preparation

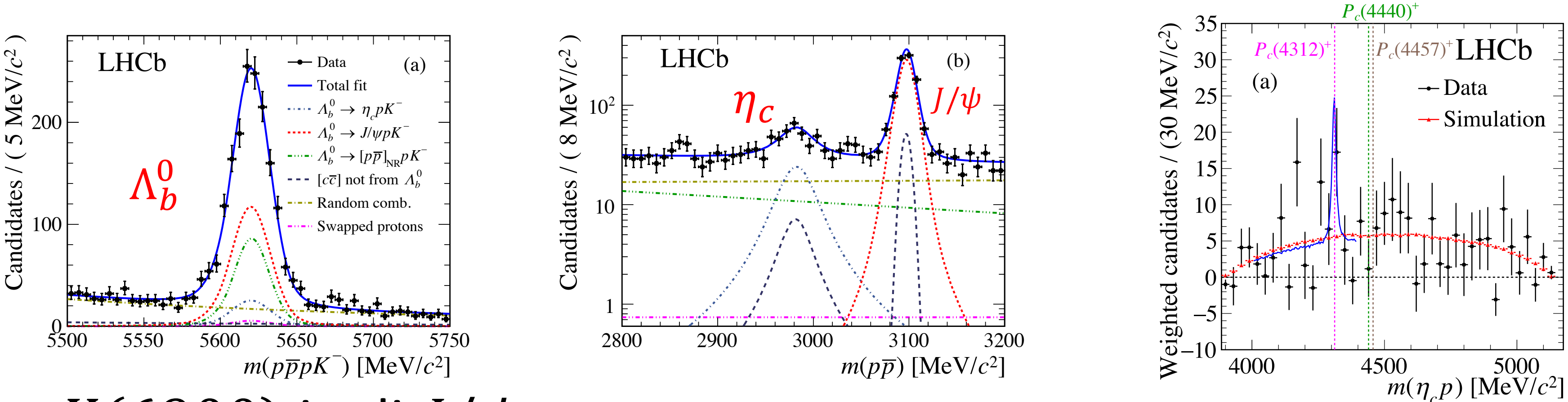
  - Evidence of P_{cs} candidate in $\Xi_b^- \to J/\psi K^-\Lambda$

- Summary and prospects

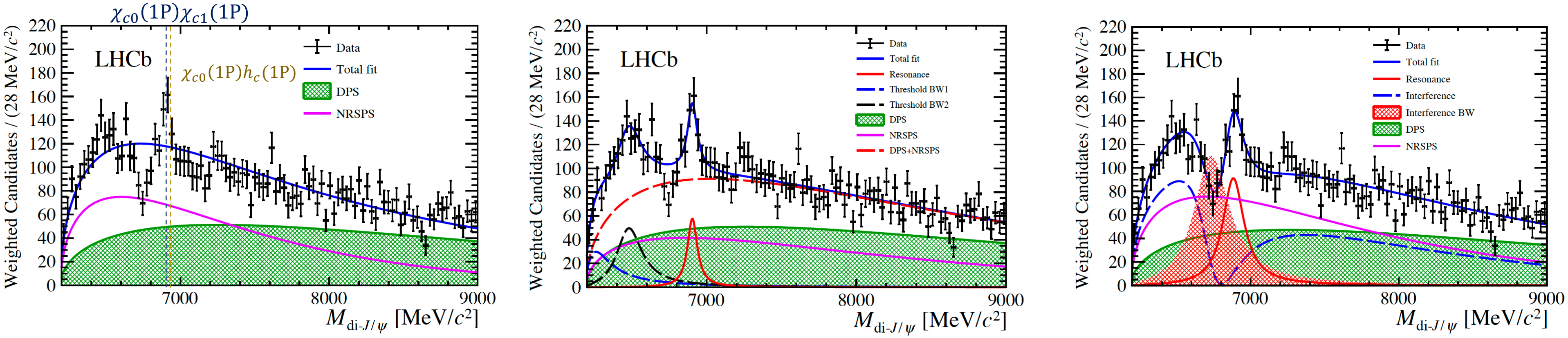
Overview of recent LHCb publications for exotic hadrons

arXiv:2007.11292

- $\Lambda_b^0 \to \eta_c p K^-$ observation and search for P_c contribution



- $X(6900)$ in di-J/ψ system arXiv:2006.16957. Science Bulletin



- $\chi_{c1}(3872)$
  - Mass measurement JHEP 08 (2020) 123 $m_{\chi_{c1}(3872)} - m_{\psi(2S)} = 185.49 \pm 0.06 \pm 0.03\,\text{MeV}/c^2$
  - Line shape study arXiv:2005.13419 $\Gamma_{BW} = 1.39 \pm 0.24 \pm 0.10\,\text{MeV}$
  - Multiplicity-dependent production arXiv:2009.06619

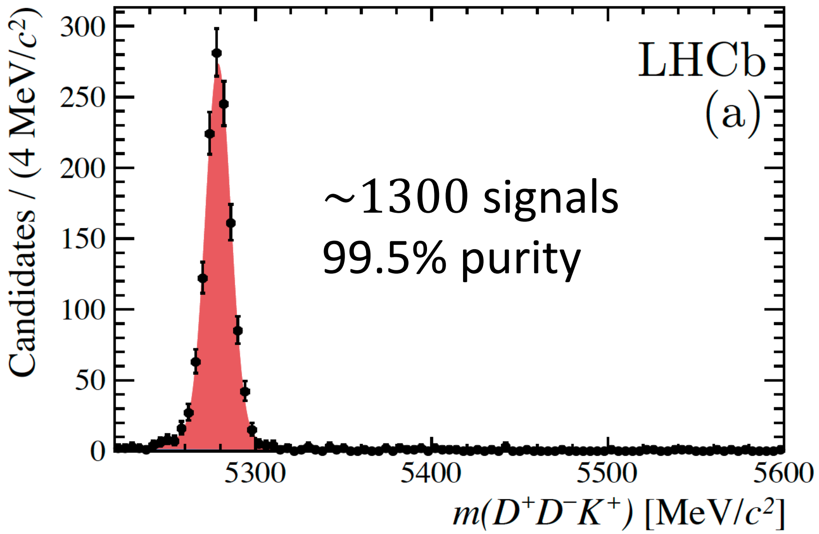
    (See Jana's slides on Wednesday)

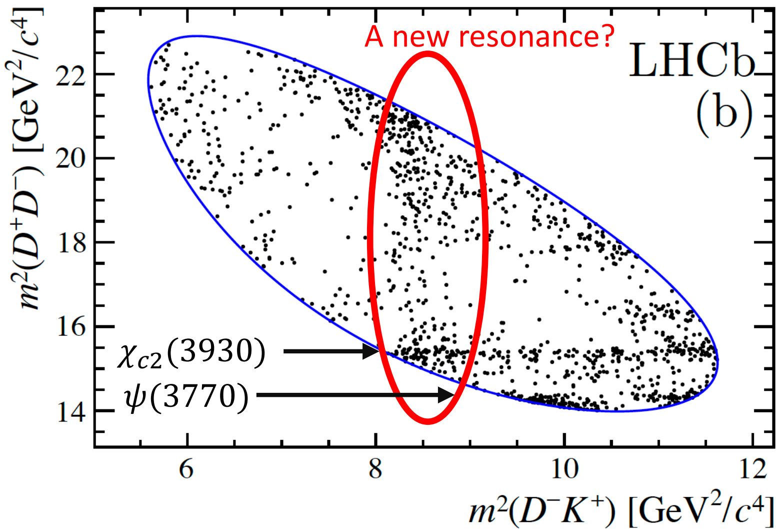
Exotic D^-K^+ structure in the $B^+ \to D^+D^-K^+$ decays

Link to CERN seminar:
https://indico.cern.ch/event/900975/

The $B^+ \to D^+D^-K^+$ data sample

- Run-I + Run-II, lumi~$9fb^{-1}$

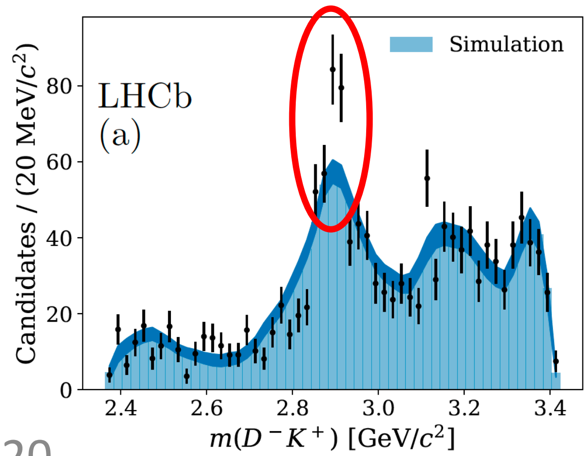




- Model-independent study

arXiv:2009.00025
Accepted by PRL

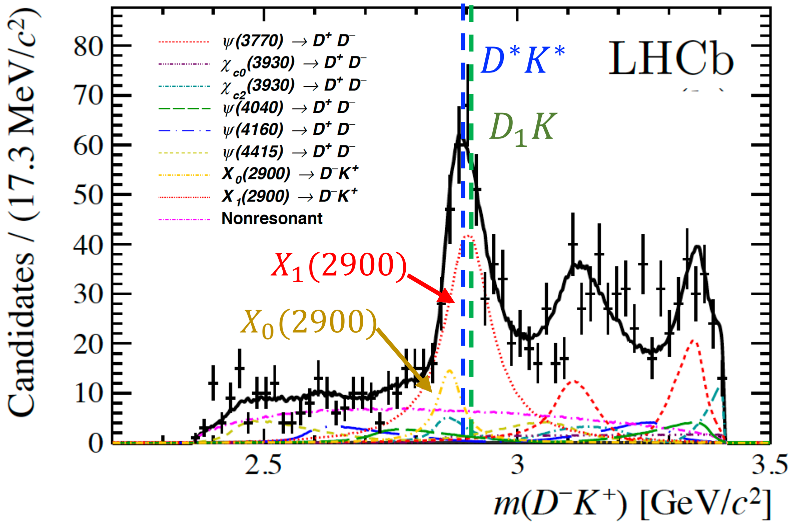
  - Hypothesis with only D^+D^- resonances ($J_{\max} = 2$) is rejected by 3.9σ
  - Indicate the existence of exotic contributions

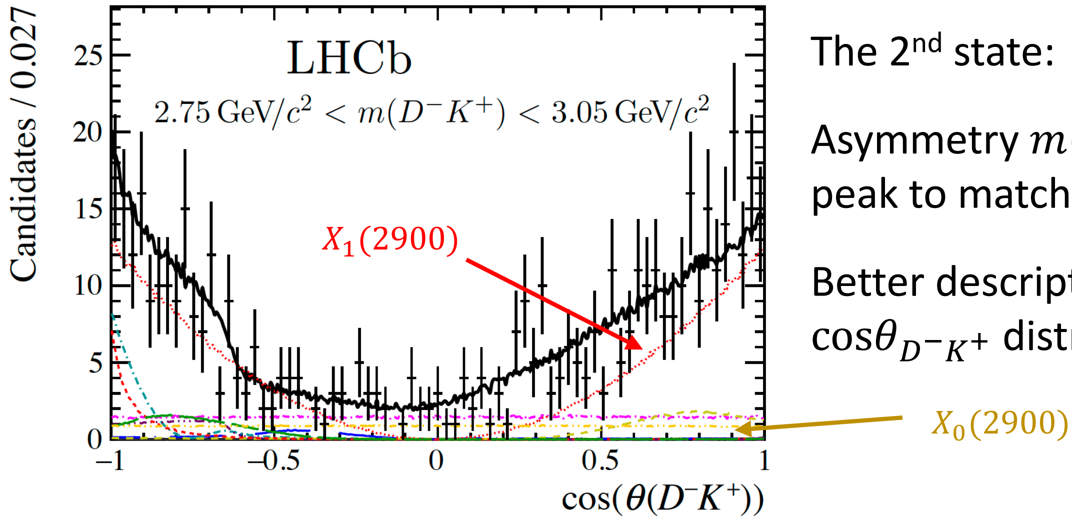


arXiv:2009.00026
Accepted by PRD

Amplitude analysis

- Add two D^-K^+ states (BW) at $\sim$2.9GeV





The 2nd state:

Asymmetry $m(D^-K^+)$ peak to match data

Better description on $\cos\theta_{D^-K^+}$ distribution

- Need more intricate theoretical studies
  - Very close to D^*K^*, D_1K thresholds. Rescattering ?

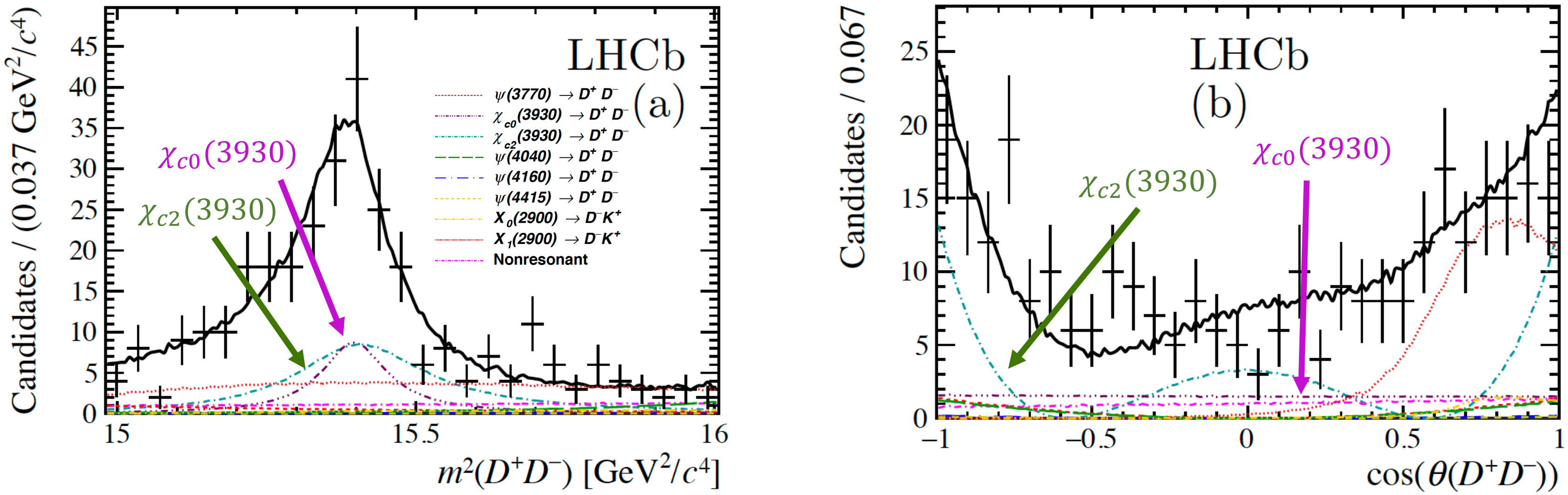
Candidates for the 1st open-charm tetraquarks (four different flavors)!

$$X_0(2900): \quad M = 2.866 \pm 0.007 \pm 0.002\,\text{GeV}/c^2, \quad \Gamma = 57 \pm 12 \pm 4\,\text{MeV}$$
$$X_1(2900): \quad M = 2.904 \pm 0.005 \pm 0.001\,\text{GeV}/c^2, \quad \Gamma = 110 \pm 11 \pm 4\,\text{MeV}$$

arXiv:2009.00026
Accepted by PRD

Amplitude analysis

- Require two χ_c states with $m(D^+D^-)$~3.93GeV



	Resonance	Mass (GeV/c^2)	Width (MeV)
new	$\chi_{c0}(3930)$	$3.9238 \pm 0.0015 \pm 0.0004$	$17.4 \pm 5.1 \pm 0.8$
	$\chi_{c2}(3930)$	$3.9268 \pm 0.0024 \pm 0.0008$	$34.2 \pm 6.6 \pm 1.1$

The same as the $X(3915)$ state?

$X(3915)$ MASS	3918.4 ± 1.9 MeV
$X(3915)$ WIDTH	20 ± 5 MeV (S = 1.1)

Observation of $X(4740)$ in the $B_s^0 \to J/\psi K^+K^-\pi^+\pi^-$(new)

The $B_s^0 \to J/\psi K^+K^-\pi^+\pi^-$ sample

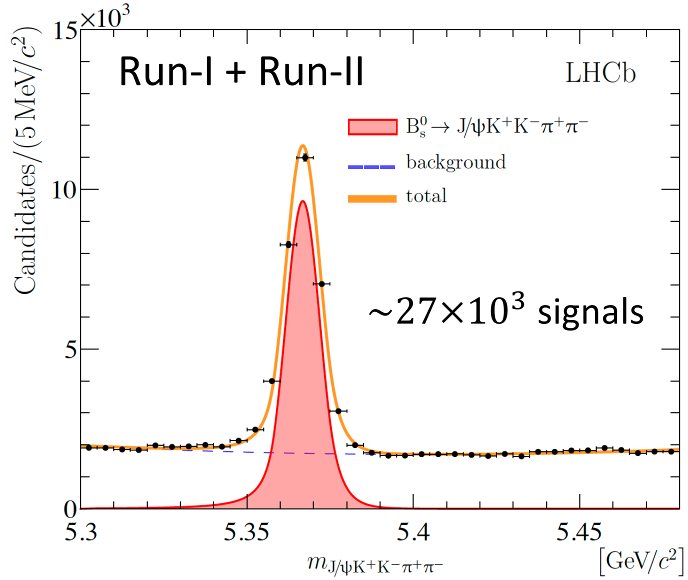
- Study the contribution of $\chi_{c1}(3872)$ and conventional resonances

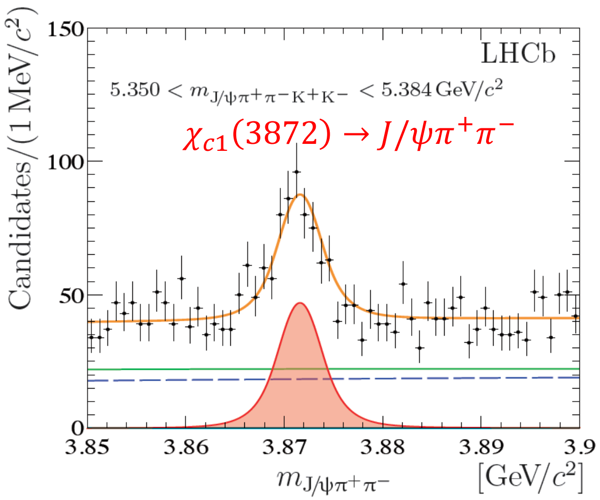
$B_s^0 \to \chi_{c1}(3871)\phi$ $B_s^0 \to \psi(2S)\phi$ $B_s^0 \to J/\psi K^* K^*$

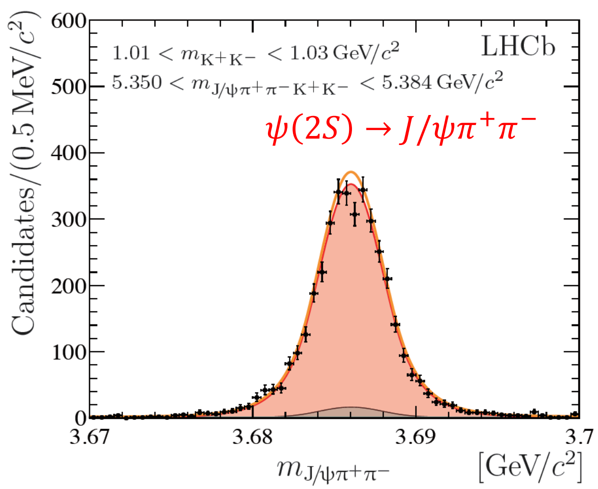
Branching fraction ratio measurement:

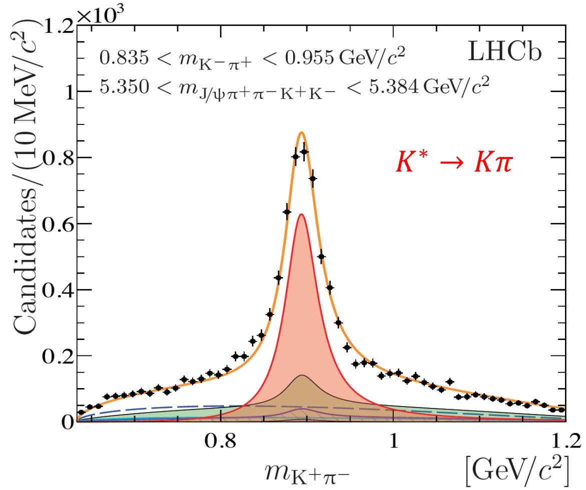
$$\mathcal{R}^{\chi_{c1}(3872)\phi}_{\psi(2S)\phi} = (2.39 \pm 0.23 \pm 0.07) \times 10^{-2}$$

$$\mathcal{R}^{J/\psi K^{*0}\overline{K}^{*0}}_{\psi(2S)\phi} = 1.21 \pm 0.04 \pm 0.04$$





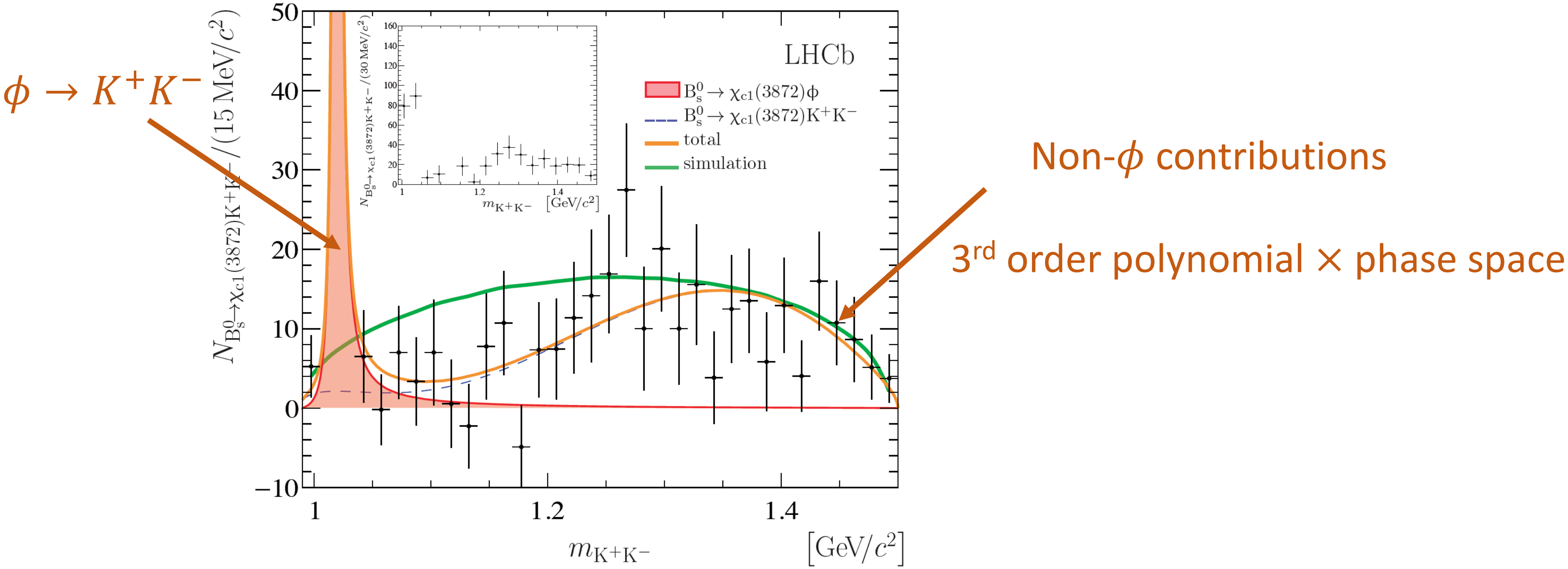




The $B_s^0 \to J/\psi K^+K^-\pi^+\pi^-$ sample

- 1st observation of non$-\phi$ $B_s^0 \to \chi_{c1}(3872)K^+K^-$ decays

$m(K^+K^-)$ for bkg-subtracted $B_s^0 \to \chi_{c1}(3872)K^+K^-$ sample

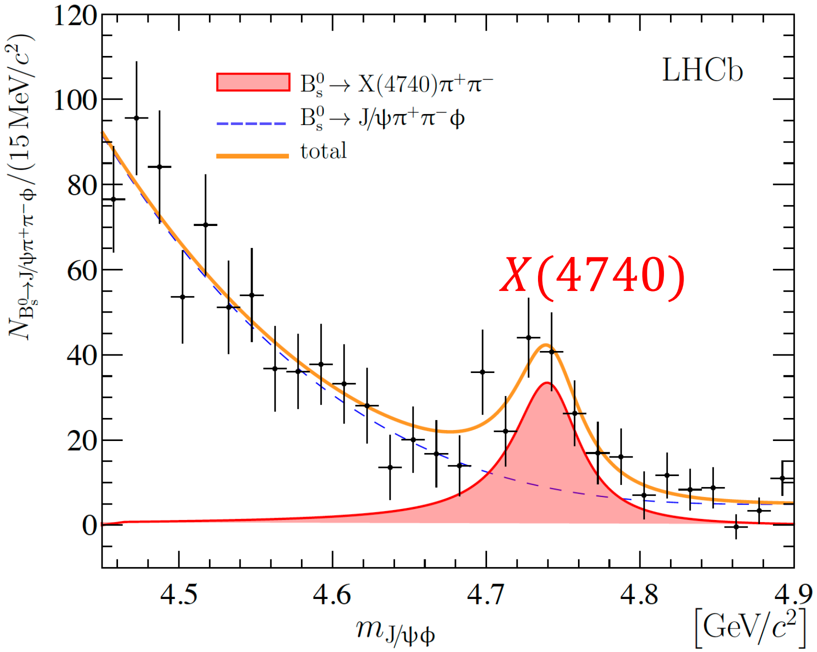


Amplitude analysis at above ϕ region:

Very challenging, but an interesting topic after LHCb upgrade !

$X(4740)$ in $J/\psi\phi$ structure

- An excess observed in background-subtracted $m(J/\psi\phi)$ spectrum of $B_s^0 \to J/\psi\phi\pi^+\pi^-$ decays



$$m_{X(4740)} = 4741 \pm 6 \pm 6\ \mathrm{MeV}/c^2\,,$$
$$\Gamma_{X(4740)} = 53 \pm 15 \pm 11\ \mathrm{MeV}\,.$$

Signal significance $\sim 5.2\sigma$

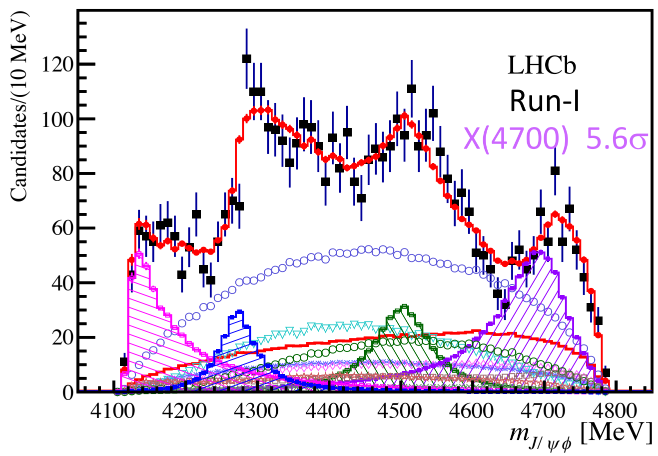
$\psi(2S), \chi_{c1}(3872)$ vetoed by cutting $m(J/\psi\pi^+\pi^-)$

No similar structure in simulated $B_s^0 \to J/\psi\phi^*$ decays

Need a full amplitude analysis to study interference

Coherent sum of signal and background components as alternative fit model at this stage

PRL118(2017)022003



Close to $X(4700)$ observed in $B^+ \to J/\psi\phi K^+$?

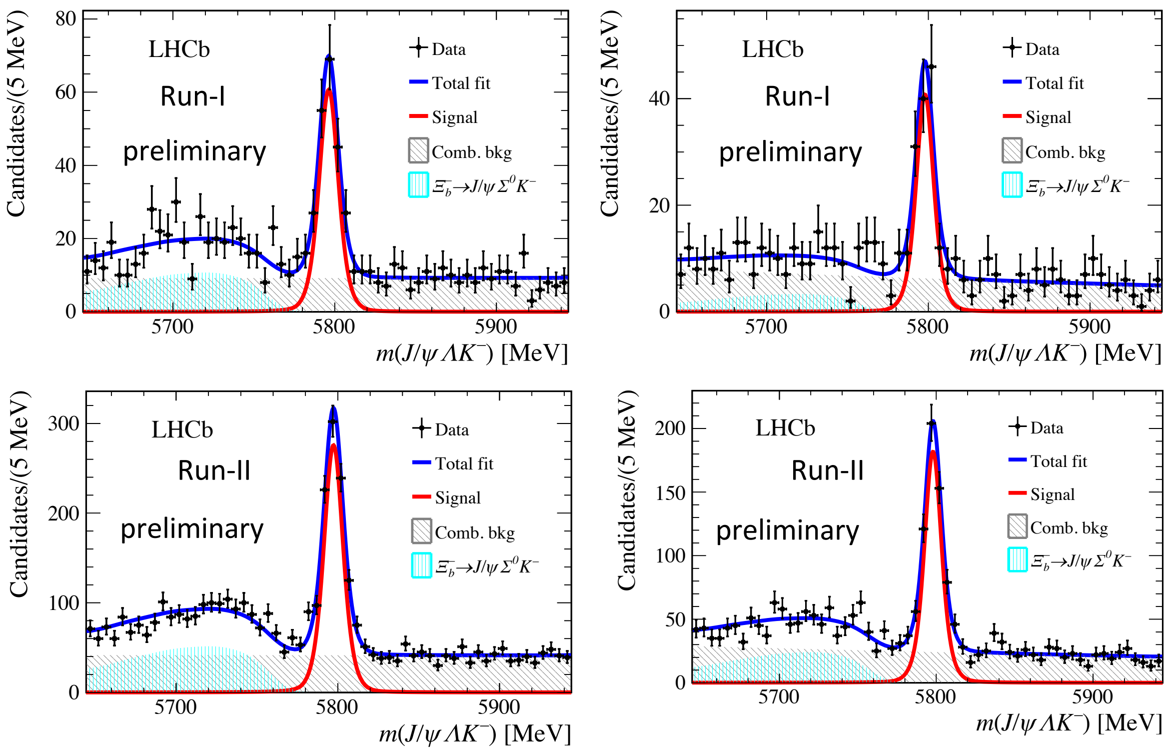
The $B^+ \to J/\psi\phi K^+$ analysis with Run-I + Run-II data is on going. Stay tuned for improved precisions !

Evidence of a $J/\psi\Lambda$ resonance in $\Xi_b^- \to J/\psi K^- \Lambda$ decay (new)

The $\Xi_b^- \to J/\psi K^- \Lambda$ data sample

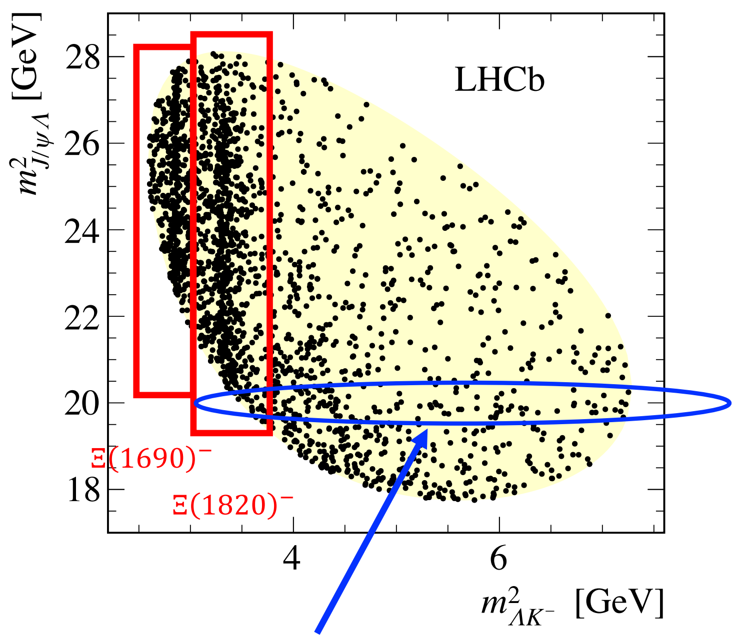
PRC93(2016)065203

- Used to search for predicted $[uds c\bar{c}]$ pentaquark P_{cs}
- Run-I + Run-II data: ~1750 signals, purity ~80%



Long Long

Downstream Downstream



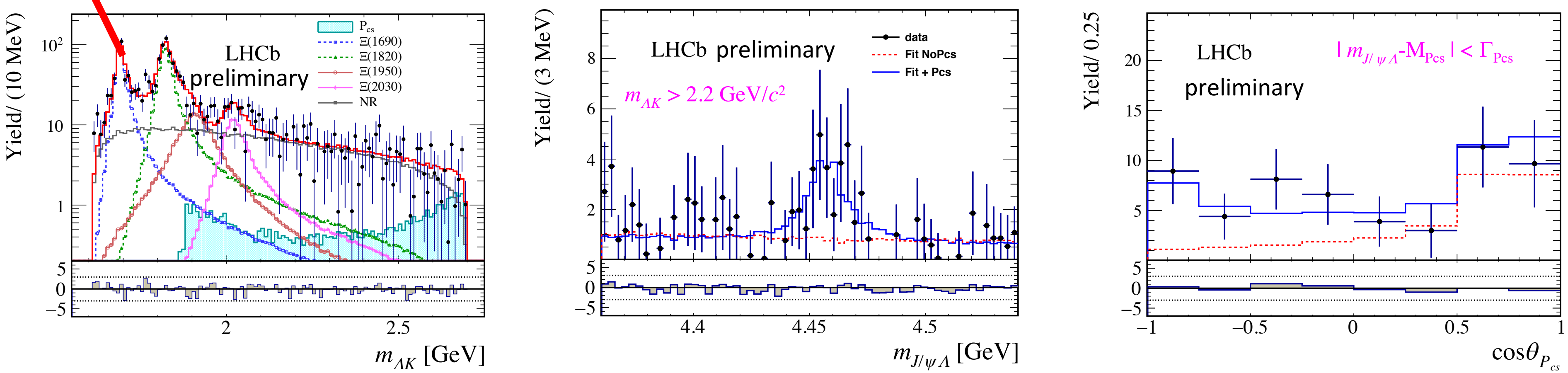
Potential P_{cs} contribution?
Amplitude analysis required.
(next slide)

Full 6D amplitude analysis

- Adding a P_{cs} improves $-2\ln L$ by 43 units, $\sim 4.3\sigma$ significance
  - $\mathbf{3.1\sigma}$ **significance** when syst. uncertainty considered

Two Ξ^{*-} states

Zooms in to P_{cs} signal region for better visibility



P_{cs} mass 19MeV below the $\Xi_c^0\overline{D}^{*0}$ threshold. Statistic not enough for J^P determination.

State	M_0 [MeV]	Γ[MeV]
$P_{cs}(4459)^0$	$4458.8 \pm 2.9\,^{+4.7}_{-1.1}$	$17.3 \pm 6.5\,^{+8.0}_{-5.7}$
$\Xi(1690)^-$	$1692.0 \pm 1.3\,^{+1.2}_{-0.4}$	$25.9 \pm 9.5\,^{+14.0}_{-13.5}$
$\Xi(1820)^-$	$1822.7 \pm 1.5\,^{+1.0}_{-0.6}$	$36.0 \pm 4.4\,^{+7.8}_{-8.2}$

Consistent with PDG, with improved precision

Conclusions & open questions

- Fruitful results about exotic hadrons from LHCb
  - Observation of $\Lambda_b^0 \to \eta_c p K^-$ for pentaquark search
  - Evidence of a strangeness pentaquark in $\Xi_b^- \to J/\psi K^- \Lambda$

    Theoritical predictions of P_{cs} J^P ?

    Inspirations to search for other P_{cs} states / search for P_{cs} in other channels ?

  - $X(6900)$ in di$-J/\psi$ spetrum

    What's the nature of those near-threshold states ?

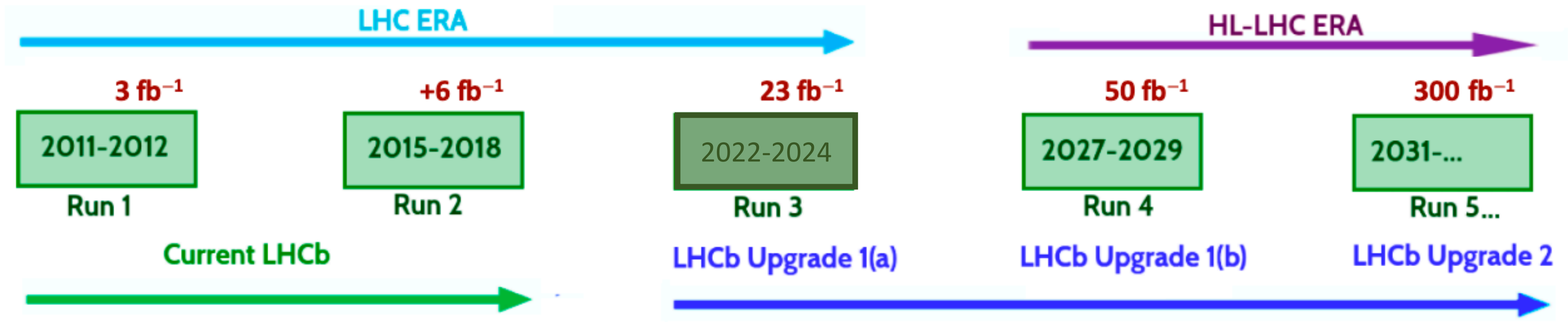
    Resonance? Rescattering effect ?
  - $X_0(2900), X_1(2900)$ in the $B^+ \to D^+ D^- K^+$ decay
    - Candidates of 1st open-charm tetraquark states
  - $X(4740)$ in the $B_s^0 \to J/\psi K^+ K^- \pi^+ \pi^-$ decays

    Close to $X(4700)$ in $B^+ \to J/\psi \phi K^+$

    Same state ? Other connections ?
  - More results about $\chi_{c1}(3872)$:
    - The mass measurement, line shape study
    - The multiplicity-dependent production (See Jana's talk on Wednesday)

arXiv:1808.08865

Prospects



- LHCb is boosting the data to a new level
  - 7x data by 2029 than current (14x) for hadronic decays
  - Half of these by 2024
  - Another 6x increase from Upgrade II

Decay mode	LHCb $23\,\text{fb}^{-1}$	LHCb $50\,\text{fb}^{-1}$	LHCb $300\,\text{fb}^{-1}$
$B^+ \to X(3872)(\to J/\psi\pi^+\pi^-)K^+$	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

Thank you for your attention !

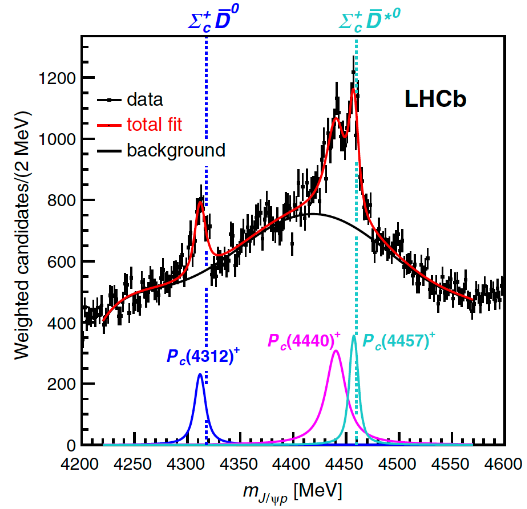
Any questions or comments ?

Back up

arXiv:2007.11292

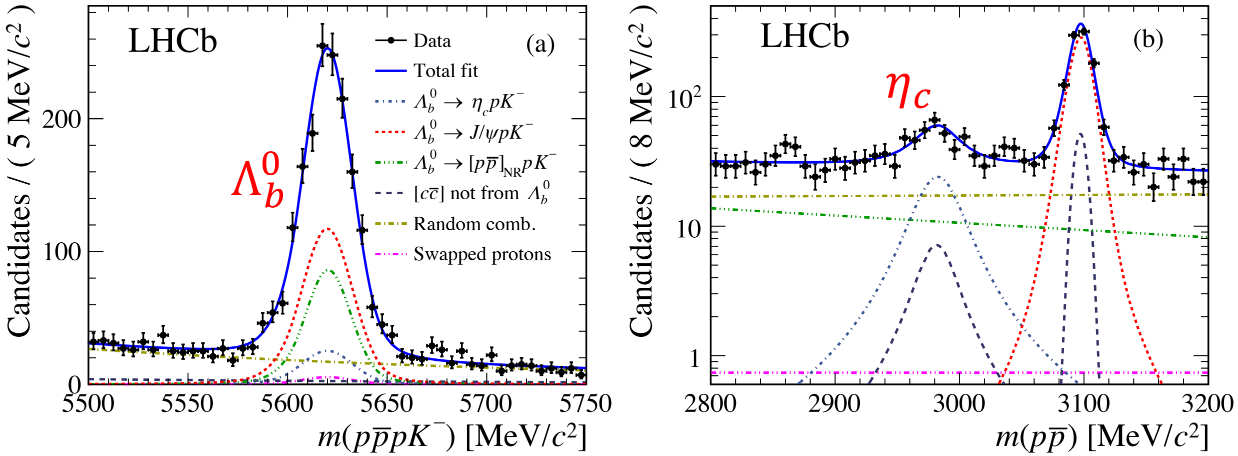
Pentaquark search in $\Lambda_b^0 \to \eta_c p K^-$

PRL122(2019)222001

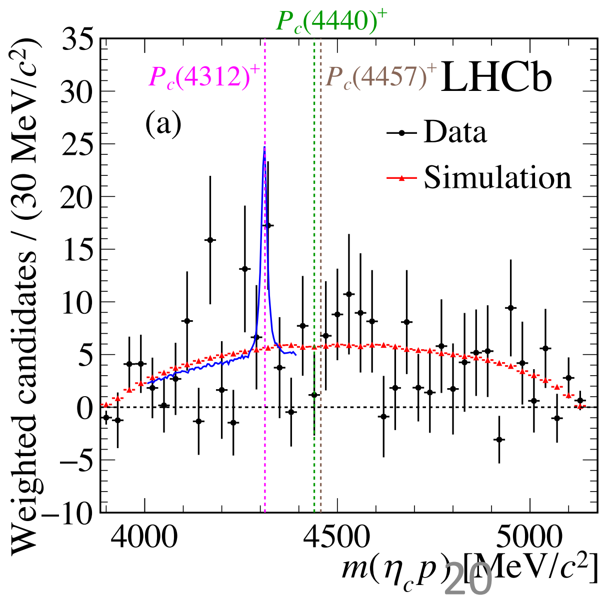


- Pentaquarks P_c observed in $\Lambda_b^0 \to J/\psi p K^-$
- $\Lambda_b^0 \to \eta_c p K^-$ for P_c search
    - Run-II data, $\eta_c \to p\bar{p}$, observe this decay

2D mass fit for $\Lambda_b^0 \to \eta_c p K^-$ signal extraction



Bkg-subtracted $m(\eta_c p)$ spectrum



$\sim$170 $\Lambda_b^0 \to \eta_c p K^-$ signals; $R(P_c(4312)^+) < 0.24$ @ 95% C.L.

No significant P_c contribution seen in $m(\eta_c p)$ spectrum.

Stay tuned with LHCb upgrade data !

Significance test of D^+K^- structure

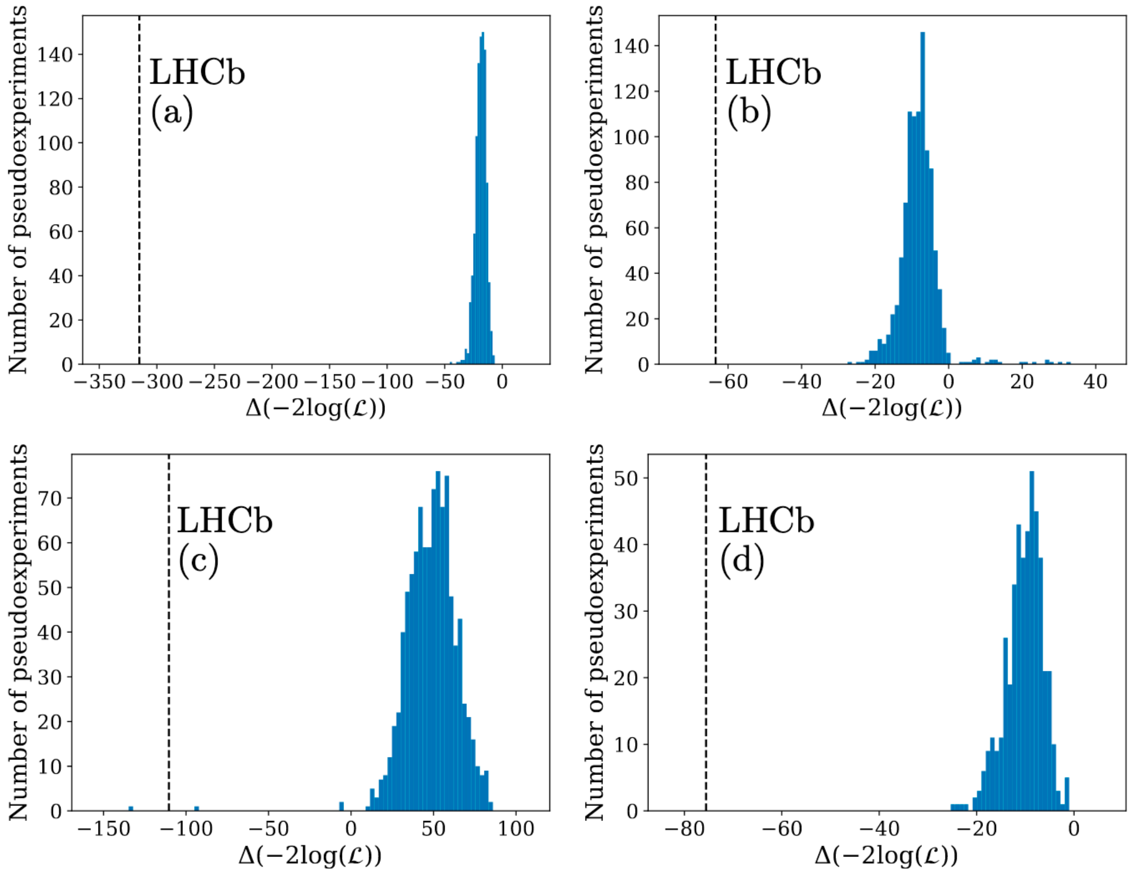


Figure 15: Distributions of the test-statistic t in ensembles of pseudoexperiments generated according to various hypotheses and compared to values found in data (indicated by dashed vertical lines). In (a), the H_0 hypothesis is a model fit to data without D^-K^+ resonances. In (b), (c) and (d) plots, the H_0 hypothesis assumes a single $\chi_{cJ}(3930)$ state, which has spin-0, spin-1 and spin-2, respectively.

$B_s^0 \to J/\psi K^+ K^- \pi^+ \pi^-$ analysis

- $J/\psi\phi$ and $\phi\pi^+\pi^-$ mass spectra

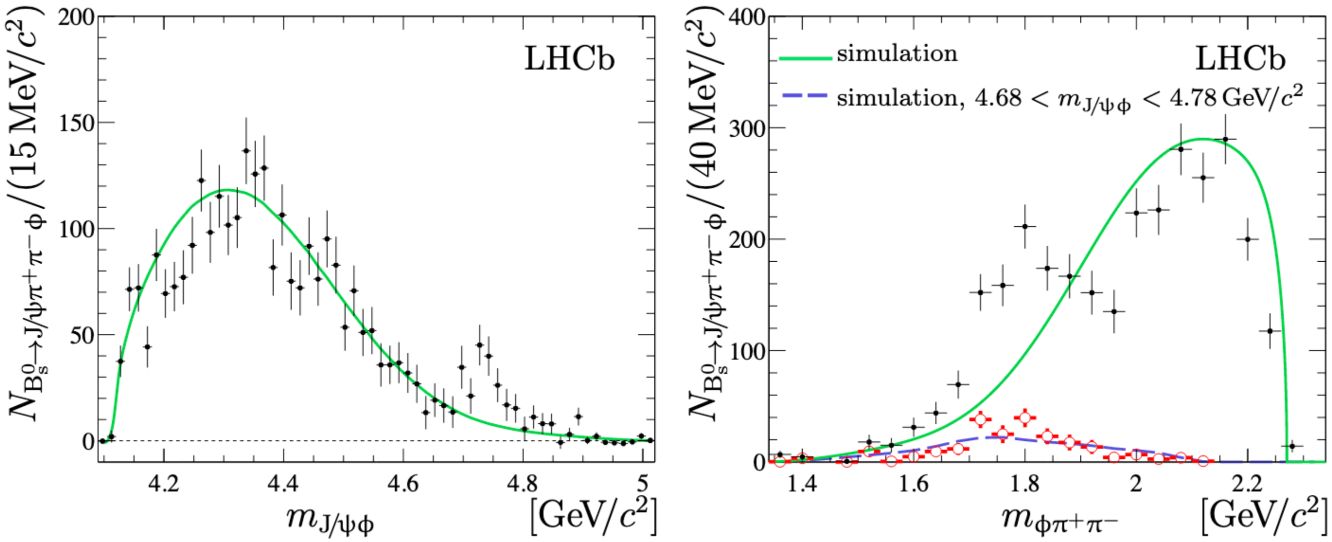


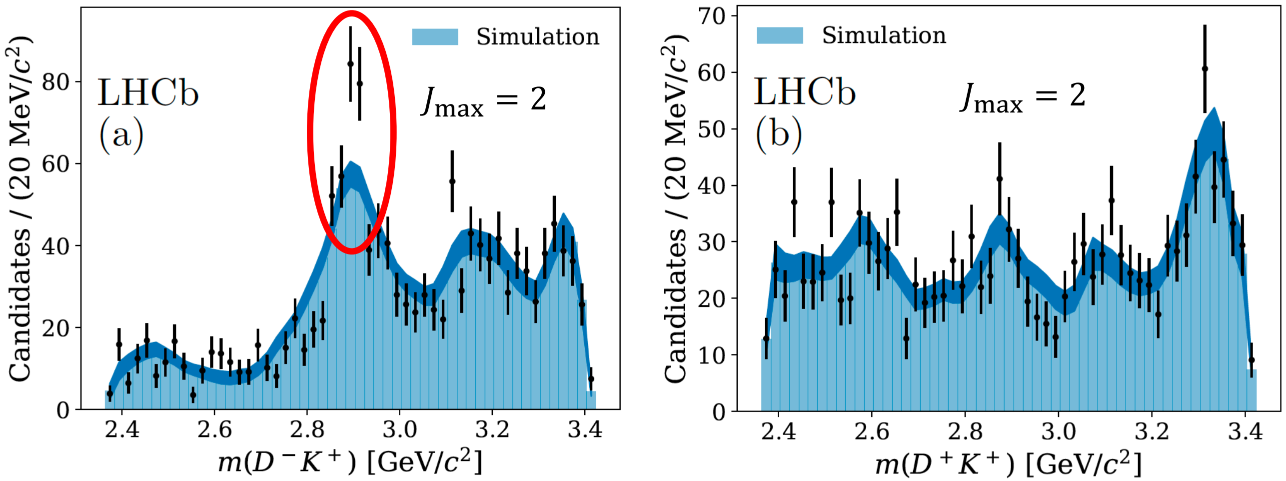
Figure 9: Background-subtracted (left) $J/\psi\phi$ and (right) $\phi\pi^+\pi^-$ mass distributions from $B_s^0 \to J/\psi\pi^+\pi^-\phi$ decays (points with error bars). The expectation from simulated $B_s^0 \to J/\psi\pi^+\pi^-\phi$ decays is overlaid (green solid line). In the right figure, the background-subtracted $\phi\pi^+\pi^-$ mass distribution in the region $4.68 < m_{J/\psi\phi} < 4.78\ \mathrm{GeV}/c^2$ is shown (red open circles with error bars) together with corresponding expectation for simulated $B_s^0 \to J/\psi\pi^+\pi^-\phi$ decays (blue dashed line).

arXiv:2009.00025

The model-independent study

- Moments analysis:
  - In $m(D^+D^-)$ slice, expend $\cos(\theta_{D^+D^-})$ distribution in terms of P_L
  - D^+D^- resonances contribute only to $L \leq 2J_{\max}$

$J_{\max} = 2$ cannot well describe $m(D^-K^+)$ spetrum



Hypothesis with only D^+D^- resonances ($J_{\max} = 2$) is rejected by 3.9σ

Amplitude analysis for further investigations