# LHCb: New Results on Pentaquarks

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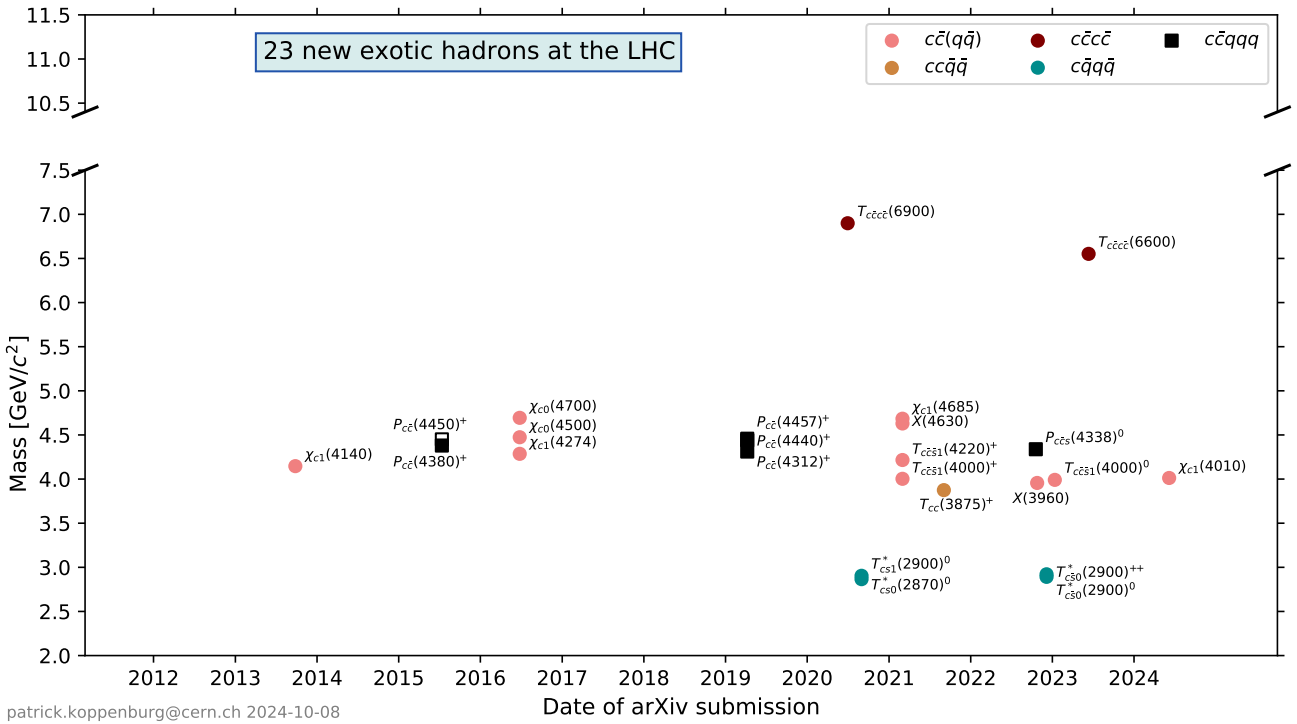
10th Chinese Large Hadron Collider Physics

# Introduction


# Introduction - Spectroscopy at LHCb

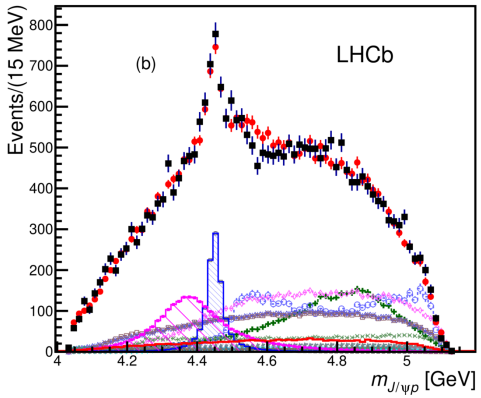
- The LHCb experiment is excellent for exotic spectroscopy.
  - High luminosity $p\bar{p}$ collision to produce $c$ and $b$ hadrons.
  - Detector optimized for $b$ and $c$ physics.
  - Many exotics are LHCb observations/evidence (red).



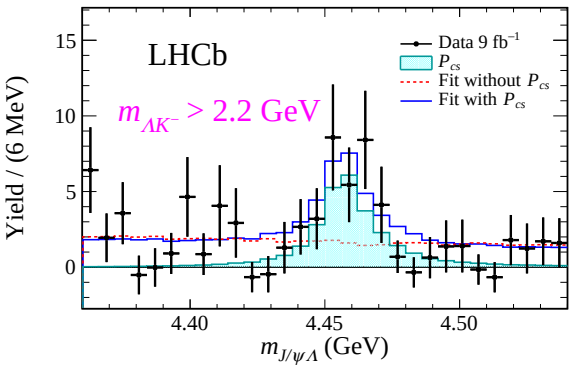

Link to Patrick Koppenburg's plots.

# Introduction - Pentaquarks at LHCb

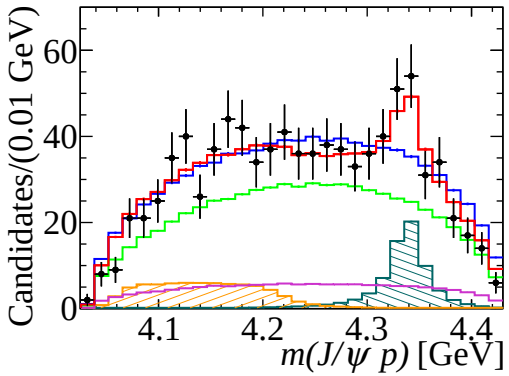
- Pentaquark candidates first observed at LHCb in $\Lambda_b \to J/\psi p K$: PRL 115 (2015) 072001.
- More evidence or observations
  - $\Xi_b \to J/\psi \Lambda K$: Sci.Bull. 66 (2021) 1278-1287
  - $B_s \to J/\psi p \bar{p}$: PRL 128 (2022) 062001
  - $B \to J/\psi \Lambda \bar{p}$: PRL 131 (2023) 031901



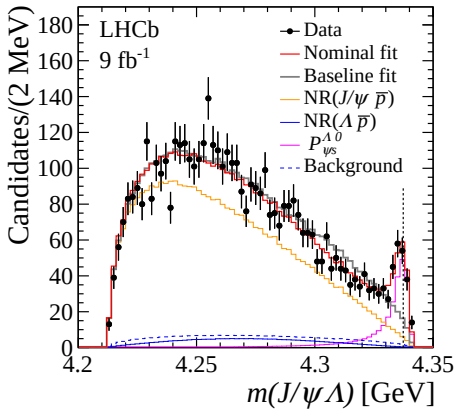

$\Lambda_b \to J/\psi p K$




$\Xi_b \to J/\psi \Lambda K$



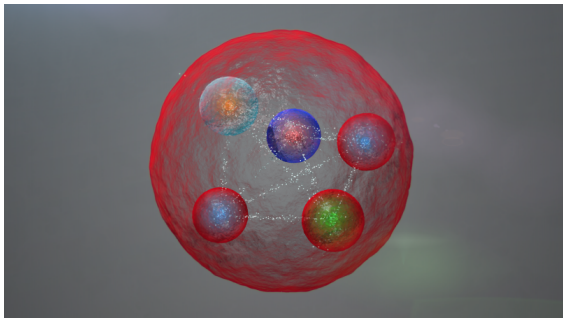

$B_s \to J/\psi p \bar{p}$




$B \to J/\psi \Lambda \bar{p}$

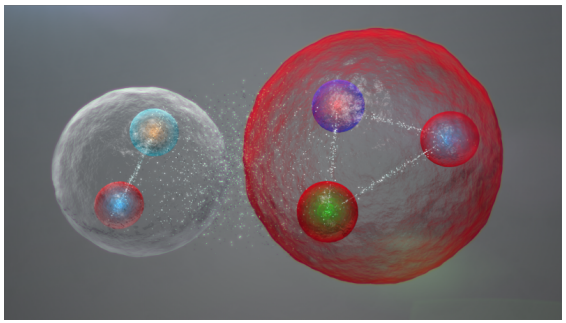
# Introduction - Motivation

- Real nature of pentaquarks still unknown.
- Several interpretations:



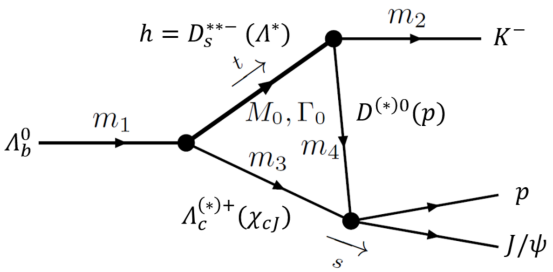
Compact pentaquark

JHEP 12 (2015) 128
PLB 749 (2015) 289-291
PRD 95, 054027
PLB 793 (2019) 365-371



Baryon-Meson Molecule

PRL 115 (2015) 122001
PLB 753 (2016) 547-551
PRC 85 (2012) 044002




Triangle Diagram

PRD 92 (2015) 071502

# New Results from the LHCb Experiment


# LHCb experiment - New Results

- Did LHCb find a new pentaquark?

# LHCb experiment - New Results

- Did LHCb find a new pentaquark? **No**

# LHCb experiment - New Results

- Did LHCb find a new pentaquark? **No**
- Thank you for listening!

# LHCb experiment - New Results

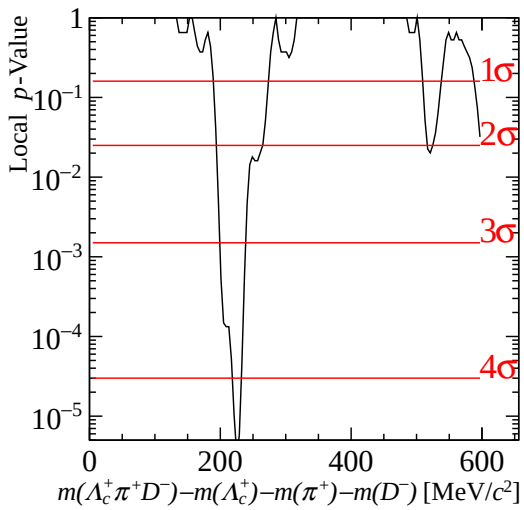
- Just joking

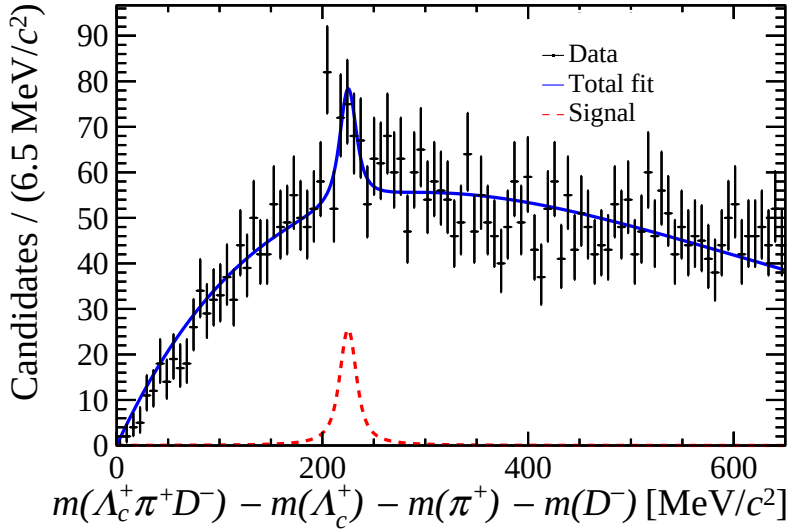
# LHCb experiment - New Results

- Just joking, LHCb performed an inclusive search for prompt pentaquarks:
  - Prompt meaning the $P^+_{c\bar{c}}$ is directly produced from $pp$ collisions, as opposed to $P^+_{c\bar{c}}$ have been observed in $b$ decays.
  - PRD 110 (2024) 032001
- And observed a few decay modes with prospects for future pentaquark searches.
  - $\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{(*)0} K^-$: EPJC 84 (2024) 575.
  - $\Lambda_b^0 \to D^+ D^- \Lambda$: JHEP 07 (2024) 140.
  - $\Lambda_b^0 \to \Sigma_c^{(*)++} D^{(*)-} K^-$: PRD 110 (2024) L031104.

# Inclusive Search for Prompt $P_{c\bar{c}}$

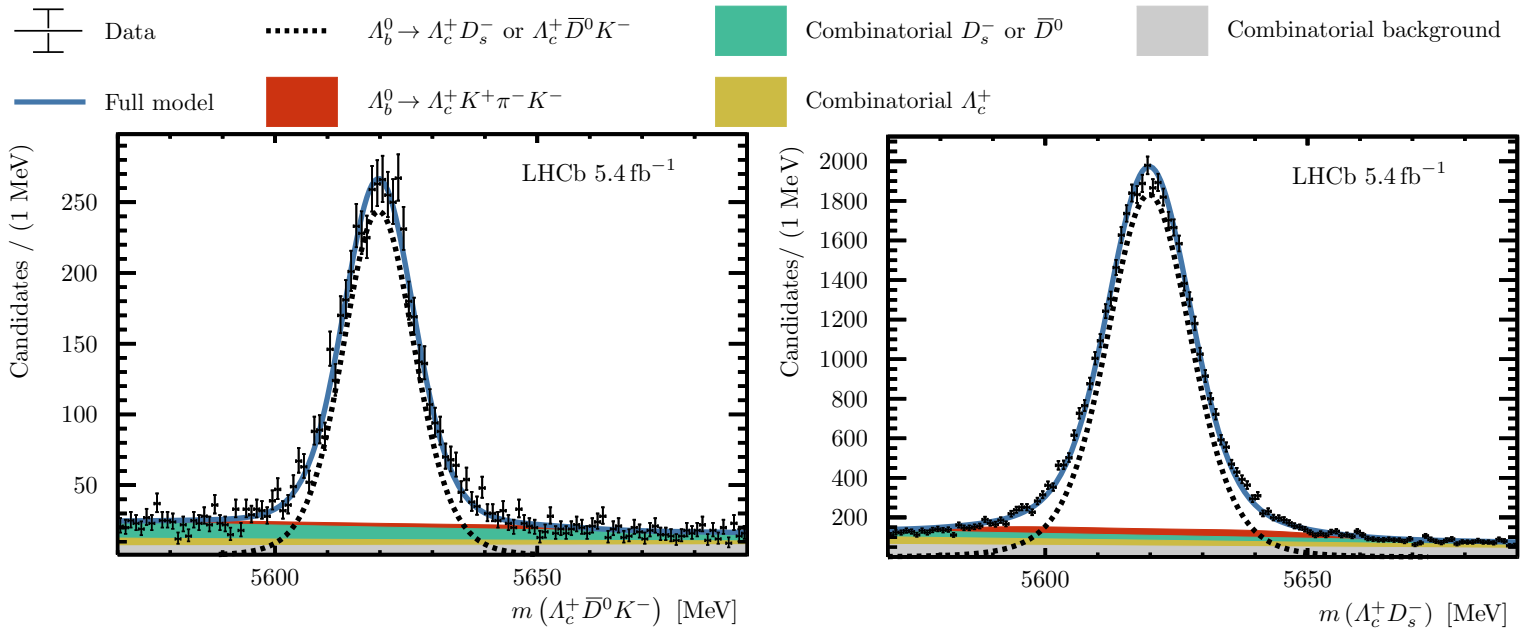
- Search for $P_{cc}$ and $P_{c\bar{c}}$ by combining:
  - 5 different charmed baryons: $\Lambda_c^+$, $\Sigma_c^{++}$, $\Sigma_c^0$, $\Sigma_c^{*++}$, $\Sigma_c^{*0}$.
  - 6 different charmed meson: $D^0$, $\bar{D}^0$, $D^+$, $D^-$, $D^{*+}$, $D^{*-}$.
  - Total of 30 possible combinations!
- Scanned for pentaquarks up to 600 MeV away from threshold.
- Even with $4.5\sigma$ local significance, pseudoexperiments that account for look elsewhere effect shows result is consistent with background only hypothesis - no new pentaquarks.



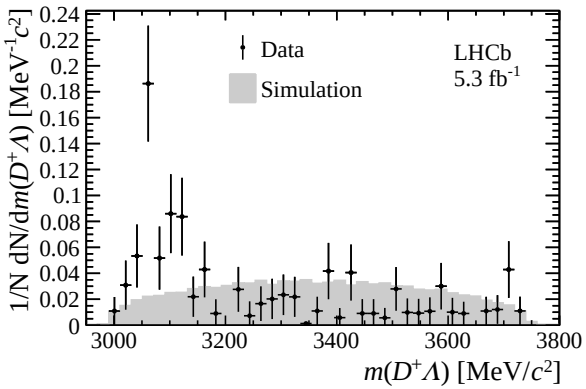
# Branching Fraction of $\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{(*)0} K^-$

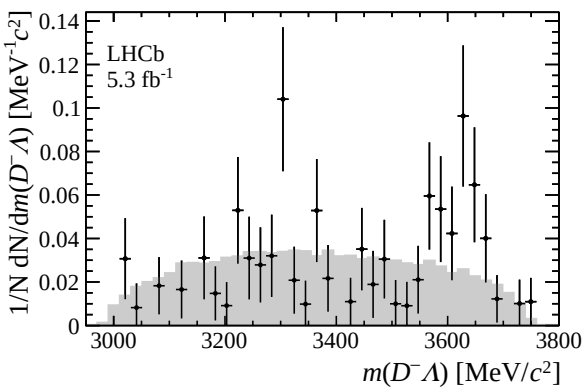
- Measured branching fractions normalized to $\Lambda_b^0 \to \Lambda_c^+ \bar{D}_s^+$.
- Compared to $\mathcal{B}(\Lambda_b \to J/\psi p K)$ Chinese Phys. C 40 011001:
  - $\mathcal{B}(\Lambda_b \to J/\psi p K)/\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{*0} K^-) = 0.152^{+0.032}_{-0.028}$
  - $\mathcal{B}(\Lambda_b \to J/\psi p K)/\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{0} K^-) = 0.049^{0.011}_{-0.009}$
- Important for future pentaquark searches:
  - Extract $P_{c\bar{c}}^+$ fit fraction in $\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{(*)0} K^-$ and $\Lambda_b \to J/\psi p K$.
  - Test theory predictions of $\mathcal{B}(P_{c\bar{c}}^+ \to J/\psi p)/\mathcal{B}(P_{c\bar{c}}^+ \to \Lambda_c^+ \bar{D}^{(*)0})$.

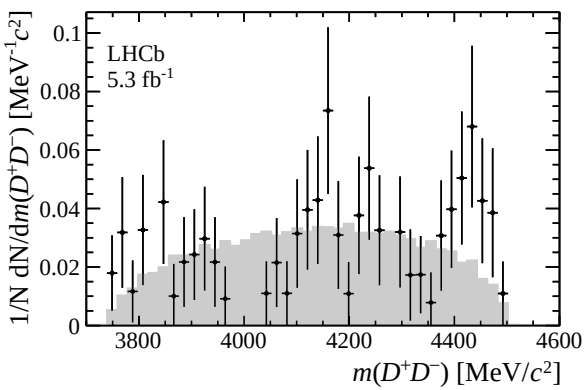


# First observation of $\Lambda_b^0 \to D^+ D^- \Lambda$

- Yanxi Wu and Yanxi Zhang. Motivation: JHEP 07 (2024) 140.
  - Charmonium and exotics known to decay into $D^+ D^-$.
  - Possibility of $P_{\bar{c}s}$ in $m(D\Lambda)$ spectrum, analogous to $X(2900)$ in $B^+ \to D^+ D^- K^+$: PRD 102, 112003.
- Observed $\sim 90$ $\Lambda_b^0 \to D^+ D^- \Lambda$ candidates but rich structure in invariant mass spectrums compared to nonresonant phase space:

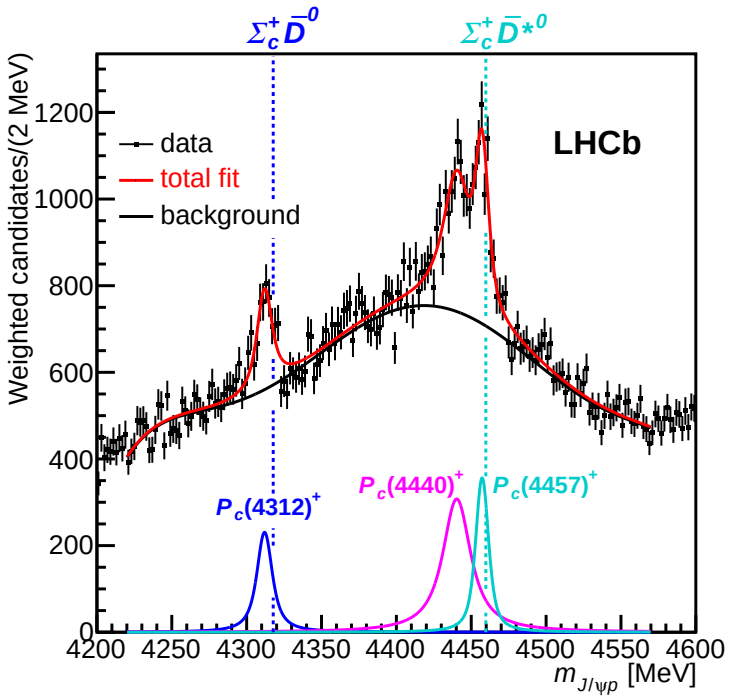


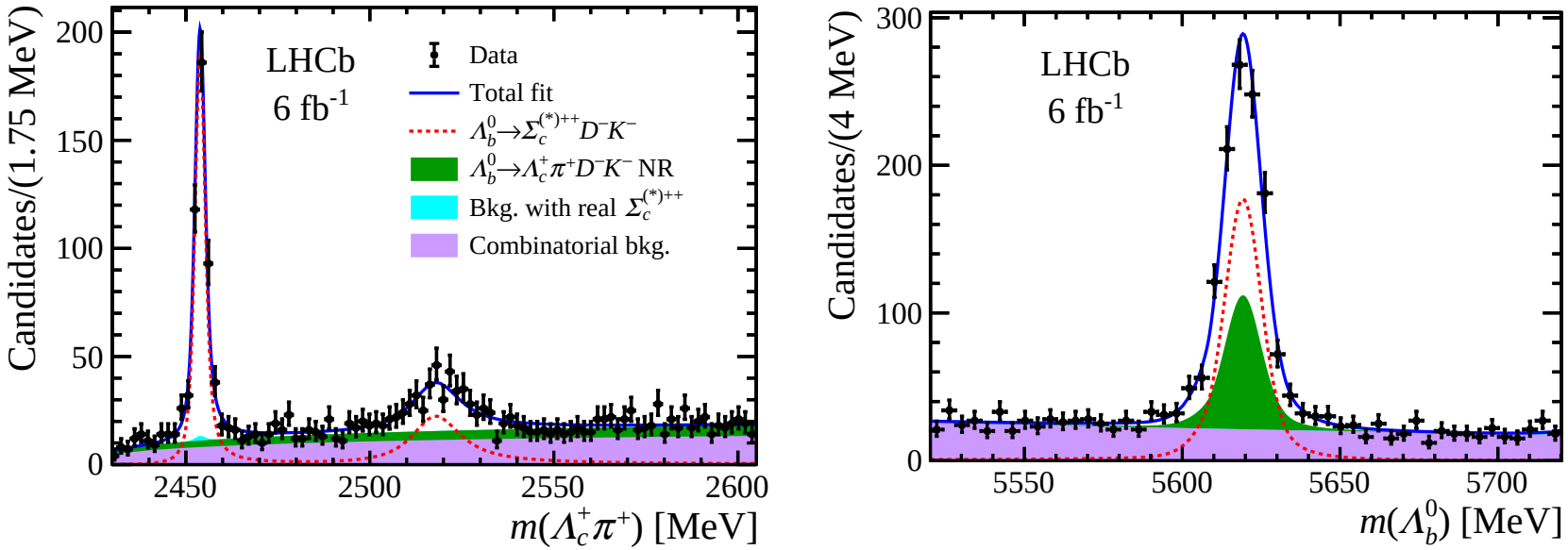
# First observation of $\Lambda_b^0 \to \Sigma_c^{(*)++} D^{(*)-} K^-$

- PhD thesis of Zan Ren. Motivation:
  - PRL 122 (2019) 222001: mass spectrum analysis of $\Lambda_b^0 \to J/\psi p K$ with Run $1+2$ data observed peaks in $m(J/\psi p)$ slightly below $\Sigma_c D^{(*)}$ thresholds.
  - Sizeable contribution from $P_{c\bar{c}}^+ \to \Sigma_c^{(*)} D^{(*)}$ decays can enhance the branching fraction of these decays.



# First observation of $\Lambda_b^0 \to \Sigma_c^{(*)++} D^{(*)-} K^-$

- Not much statistics (stat uncertainties only): PRD 110 (2024) L031104
  - $\Lambda_b^0 \to \Sigma_c^{++} D^- K^-$: $480 \pm 25$
  - $\Lambda_b^0 \to \Sigma_c^{++} D^{*-} K^-$: $279 \pm 26$
  - $\Lambda_b^0 \to \Sigma_c^{*++} D^- K^-$: $243 \pm 17$
  - $\Lambda_b^0 \to \Sigma_c^{*++} D^{*-} K^-$: $116 \pm 15$




Invariant mass distributions of signal $\Lambda_b^0 \to \Sigma_c^{(*)++} D^- K^-$.

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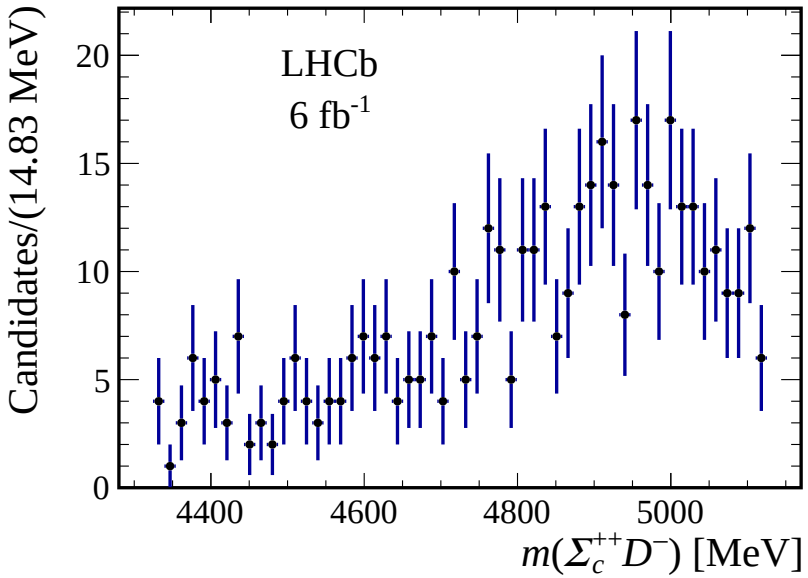
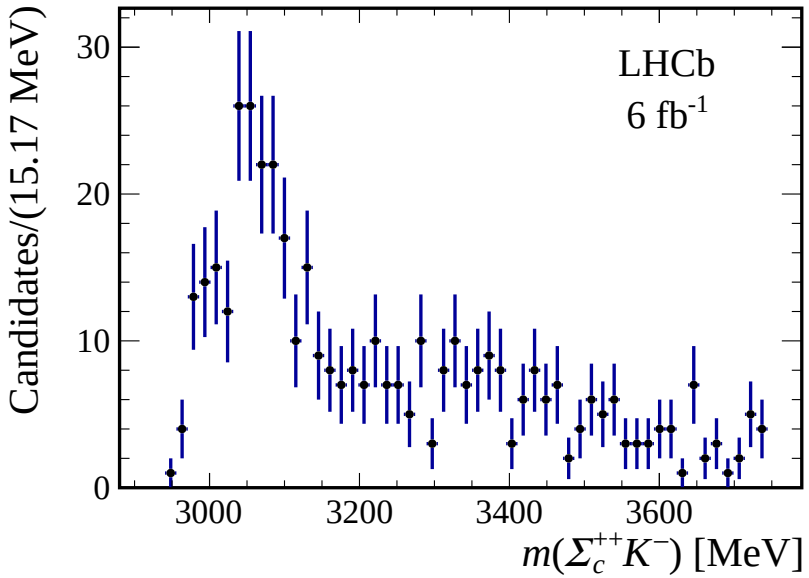
  - $\Lambda_b^0 \to \Sigma_c^{*++} D^- K^-$: $243 \pm 17$
  - $\Lambda_b^0 \to \Sigma_c^{*++} D^{*-} K^-$: $116 \pm 15$
- No obvious peaking structures in $\Lambda_b^0 \to \Sigma_c^{++} D^- K^-$ but statistics is low.



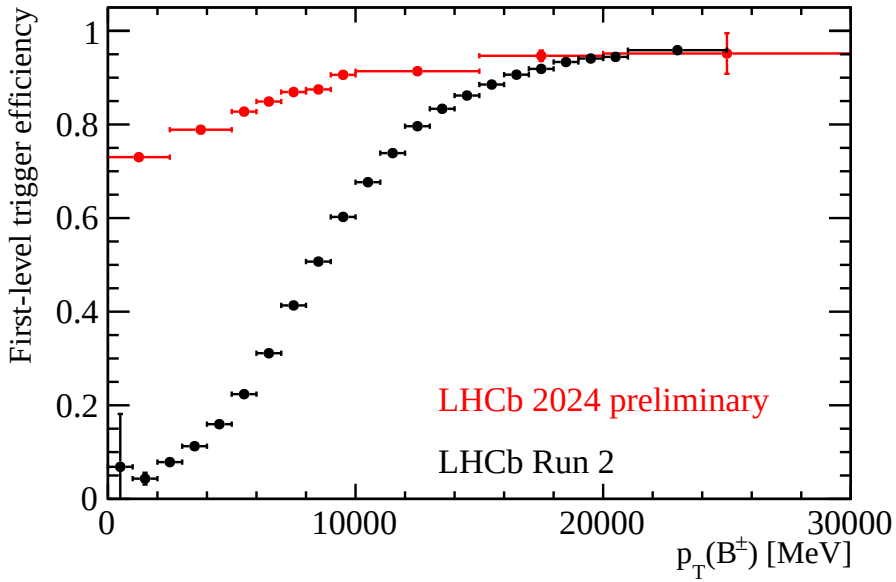




Supplementary material for LHCb-PAPER-2023-2 044

# Prospects and Summary

# LHCb Run 3 Prospects

- LHCb Run 3 on track to collect $2-3\times$ luminosity of Run $1+2$.
- New purely software trigger system significantly increases efficiencies of purely hadronic final states.
  - Improve statistics of open charm channels.
  - Open new possibilities of spectroscopy in Run $1+2$ channels that are statistically limited.




LHCb $B^+ \to D^0\pi^+$ efficiencies LHCB-FIGURE-2024-014.

# Summary

- LHCb experiment has published new results:
  - Search for prompt pentaquarks.
  - BF measurement of $\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{(*)0} K^-$
  - First observation of $\Lambda_b \to D^+ D^- \Lambda$.
  - First observation of $\Lambda_b \to \Sigma_c^{(*)++} D^{(*)-} K^-$.
- LHCb Run 3 will collect more data at a higher efficiency especially for open charm channels.
  - Expect results in new decay channels!