Exotic Hadrons at LHCb

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on behalf of the LHCb collaboration

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Outline

1. Exotic hadrons
2. LHCb experiment
3. Selected LHCb results
   - Evidence of a $J/\psi K_s^0$ structure in $B^0 \to J/\psi \phi K_s^0$
   - Observation of a $D_s^+ D_s^-$ resonance in $B^+ \to D_s^+ D_s^- K^+$
   - Observation of a doubly charged tetraquark and its neutral partner
   - Observation of a $J/\psi \Lambda$ resonance in $B^- \to J/\psi \Lambda \bar{p}$
   - Prompt pentaquarks in charm states
4. Prospects and summary

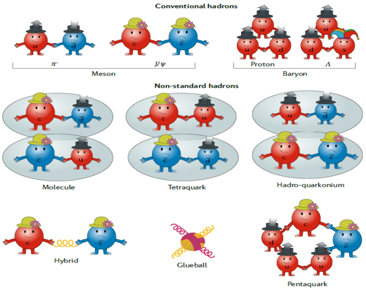
Exotic hadrons

The quark model was proposed to classify and describe hadrons in 1964

- **Conventional hadrons**: hadrons with minimal quark content $q\bar{q}$ and qqq
- **Exotic hadrons**: everything beyond $q\bar{q}$−meson and qqq−baryon scheme
- Exotic hadrons can provide unique probe to QCD

Different properties expected depending on proposed binding mechanism

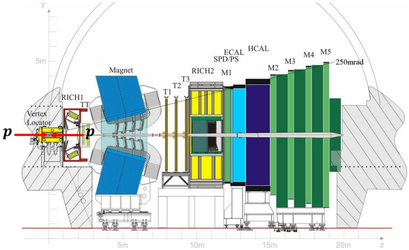
- Phenomenological approaches:
  - compact multiquark states
  - hadronic molecule states
  - hybrid
  - glueball
  - ...

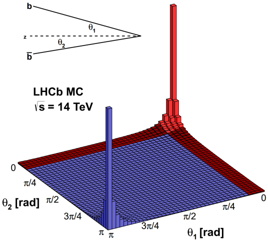


Nat Rev Phys 1, 480-494 (2019)

LHCb detector and performance

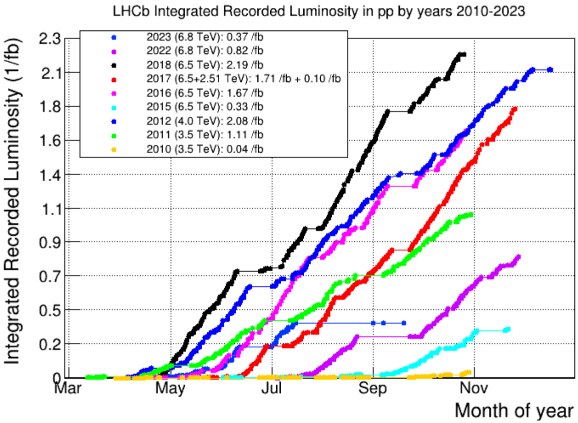
LHCb detector before end of 2018 (Int. J. Mod. Phys. A30 (2015) 1530022)





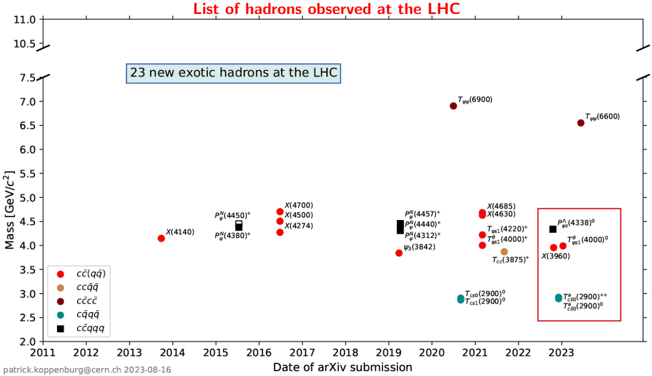
- A single-arm forward spectrometer covering the pesudorapidity range $2 < \eta < 5$
- **Particle identification**: $\epsilon(K \to K) \sim 95\%$ with $\epsilon(\pi \to K) \sim 5\%$
  $\epsilon(\mu \to \mu) \sim 97\%$ with $\epsilon(\pi \to \mu) \sim 1 - 3\%$
- **Momentum resolution**: $\Delta p/p = 0.5\%$ at low momentum to 1.0% at 200 GeV/c
- **Spatial resolution**: $\sigma_{\text{IP}} \sim 20\mu$m, $\sigma_{\text{PV, x/y}} \sim 10\mu$m, $\sigma_{\text{PV, z}} \sim 60\mu$m
- **LHCb detector designed for decays of hadrons with a b or c quarks**

LHCb data taking



- **Run1 (2011 - 2012)**: 3 fb^{-1} *pp* collision @ 7, 8 TeV
- **Run2 (2015 - 2018)**: 6 fb^{-1} *pp* collision @ 13 TeV
- **Run3**: Physics quality data starting 2023 @ 13.6 TeV

Exotic hadrons at the LHC



Exotic hadrons observed by LHCb in 2023 [new naming convention (arXiv:2205.15233)]

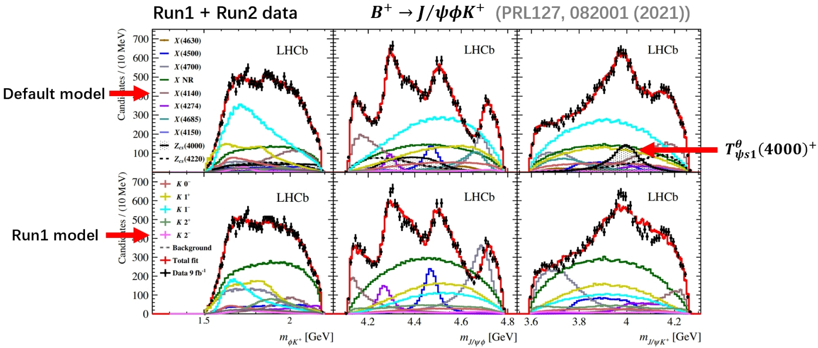
- $T^{\theta}_{\psi s1}(4000)^0$: $J/\psi K^0_S$ structure in $B^0 \to J/\psi \phi K^0_S$ (PRL131, 131901(2023))
- $T^{f}_{\psi\phi}(3960)^0$: $D^+_s D^-_s$ resonance in $B^+ \to D^+_s D^-_s K^+$ (PRL131, 071901(2023))
- $T^{a}_{c\bar{s}0}(2900)^{++(0)}$: $D^+_s \pi^+$ and $D^+_s \pi^-$ resonances in $B \to \overline{D} D_s \pi$ (PRL131, 041902(2023))
- $P^{\Lambda}_{\psi s}(4338)^0$: $J/\psi \Lambda$ resonance in $B^- \to J/\psi \Lambda \bar{p}$ (PRL131, 031901(2023))

Evidence of a $J/\psi K_s^0$ structure in $B^0 \to J/\psi \phi K_s^0$

- $T_{\psi s1}^{\theta}(4000)^+$ $[c\bar{c}u\bar{s}]$ are observed in $B^+ \to J/\psi \phi K^+$ with a significance of 15σ (PRL127, 082001 (2021))

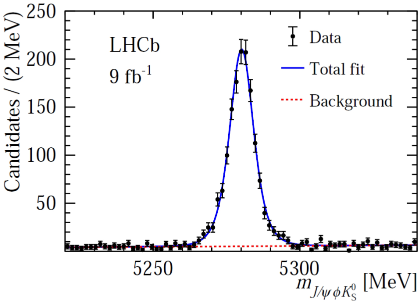
- $T_{\psi s1}^{\theta}(4000)^0$ $[c\bar{c}d\bar{s}]$, the isospin partner of $T_{\psi s1}^{\theta}(4000)^+$, is expected to exist based on isospin symmetry of the strong interaction

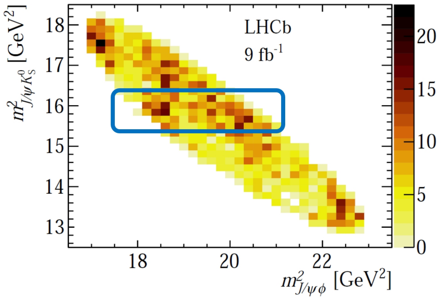
- Search for $T_{\psi s1}^{\theta}(4000)^0$ in $B^0 \to J/\psi \phi K_S^0$



$B^0 \to J/\psi \phi K_S^0$ dataset

- Decay channel: $B^0 \to J/\psi \phi K_S^0$, $J/\psi \to \mu^+\mu^-$, $\phi \to K^+K^-$, $K_S^0 \to \pi^+\pi^-$
- Dataset: LHCb Run1 and Run2 data (~ 9 fb^{-1})
- Fit to the $m_{J/\psi \phi K_S^0}$ distribution:
  - $N_{\rm sig} = 1866 \pm 47$, Purity: 94% (signal region: ± 15 MeV around B^0)

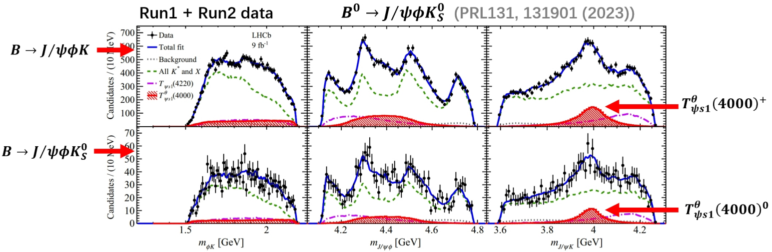




PRL131, 131901 (2023)

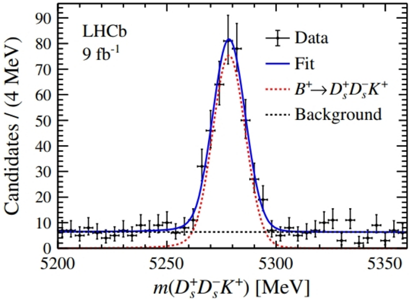
Amplitude analysis of $B^0 \to J/\psi\phi K_S^0$

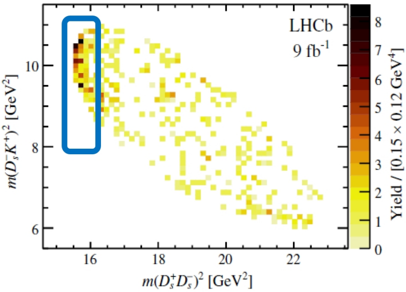
- A simultaneous fit is performed to $B^0 \to J/\psi\phi K_S^0$ and $B^+ \to J/\psi\phi K^+$ samples.
- The default model is taken from $B^+ \to J/\psi\phi K^+$ analysis (PRL127, 082001 (2021))
- Isospin symmetry: fit parameters for all the components except for the $T^{\theta}_{\psi s1}(4000)^{+(0)}$ are constrained by $B^+ \to J/\psi\phi K^+$
- Fit results from default model:
  - Line shape: BW function
  - $M(T^{\theta}_{\psi s1}(4000)^0) = (3999^{+12}_{-10}{}^{+9}_{-17})$ MeV, $\Gamma(T^{\theta}_{\psi s1}(4000)^0) = (105^{+29}_{-25}{}^{+17}_{-23})$ MeV
  - Significance: 4.0σ (5.4σ when isospin symmetry is assumed)
  - $\Delta M \equiv M_{T^{\theta}_{\psi s1}(4000)^0} - M_{T^{\theta}_{\psi s1}(4000)^+} = -12^{+11}_{-10}{}^{+6}_{-4}$ MeV (isospin partner)



Observation of a $D_s^+ D_s^-$ resonance in $B^+ \to D_s^+ D_s^- K^+$

- Decay channel: $B^+ \to D_s^+ D_s^- K^+$, $D_s^\pm \to K^+ K^- \pi^\pm$
- Dataset: LHCb Run1 and Run2 data ($\sim$ 9 fb^{-1})
- Fit to the $m_{D_s^+ D_s^- K^+}$ distribution:
  - $N_{\rm sig} = 360 \pm 22$, Purity: 84% (signal region: ± 20 MeV around B^+)



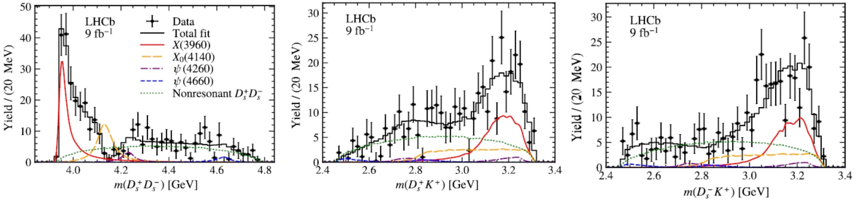


PRL131, 071901 (2023)

Amplitude analysis of $B^+ \to D_s^+ D_s^- K^+$

- The default model: $T^f_{\psi\phi 0}(3960) + X_0(4140) + \psi(4260) + \psi(4660) + \mathrm{NR}$
- Only $R \to D_s^+ D_s^-$ chain is considered in default model
  - $T^f_{\psi\phi 0}(3960)$: **describe $D_s^+ D_s^-$ threshold enhancement**
  - $X_0(4140)$: **describe the dip around 4140 MeV**
- Fit results from default model: $(T(3960) = T^f_{\psi\phi 0}(3960))$
  - Line shape: Flatte model
  - $M_{T(3960)} = (3956 \pm 5 \pm 10)\ \mathrm{MeV}$, $\Gamma_{(T(3960)} = (43 \pm 13 \pm 8)\ \mathrm{MeV}$, $S(\sigma) : 12.6$
  - $M_{X_0(4140)} = (4133 \pm 6 \pm 6)\ \mathrm{MeV}$, $\Gamma_{(X_0(4140)} = (67 \pm 17 \pm 7)\ \mathrm{MeV}$, $S(\sigma) : 3.8$
  - $J^P = 0^+$ for $T(3960)$ and $X_0(4140)$

Run1+Run2 data **(PRL131, 071901 (2023))**



Discussion on $B^+ \to D_s^+ D_s^- K^+$ decay

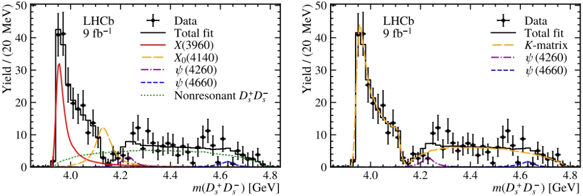
Are $T^f_{\psi\phi}(3960)$ and $\chi_{c0}(3930)$ the same state?

Resonance	J^P	M_0 (MeV)	Γ_0 (MeV)	Decay	Ref
$T^f_{\psi\phi 0}(3960)$	0^+	$3956 \pm 5 \pm 10$	$43 \pm 13 \pm 8$	$D_s^+ D_s^-$	PRL131, 071901 (2023)
$\chi_{c0}(3930)$	0^+	$3923.8 \pm 1.5 \pm 0.4$	$17.4 \pm 5.1 \pm 0.8$	$D^+ D^-$	PRD102, 112003 (2020)

- $\frac{\Gamma(X \to D^+ D^-)}{\Gamma(X \to D_s^+ D_s^-)} = \frac{\mathcal{B}(B^+ \to D^+ D^- K^+) \cdot FF(X \to D^+ D^-)}{\mathcal{B}(B^+ \to D_s^+ D_s^- K^+) \cdot FF(X \to D_s^+ D_s^-)} = 0.29 \pm 0.09 \pm 0.10 \pm 0.08$ (< 1.0)
  - **PHSP of $X \to D_s^+ D_s^-$ is much smaller than $X \to D^+ D^-$**
  - **It is harder to excite an $s\bar{s}$ pair from vacuum compared with $u\bar{u}(d\bar{d})$**
  - **This T state seems not to be a pure charmonium**

No definitive conclusion on existence of $X_0(4140)$

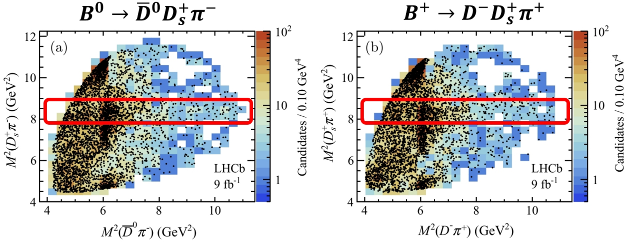
- Dip around 4140 MeV can also be described by $J/\psi\phi - D_s^+ D_s^-$ rescattering



PRL131, 071901 (2023)

First observation of a double charged tetraquark and its neutral partner in $B \to \bar{D}D_s\pi$

- Decay channel: $B^0 \to \bar{D}^0 D_s^+ \pi^-$ / $B^+ \to D^- D_s^+ \pi^+$, $\bar{D}^0 \to K^+\pi^-$ / $K^+\pi^-\pi^+\pi^-$
  $D^- \to K^+\pi^-\pi^-$
  $D_s^+ \to K^+K^-\pi^+$
- Dataset: LHCb Run1 and Run2 data (~ 9 fb^{-1})
- Fit to the $m_{\bar{D}^0 D_s^+ \pi^-}$ / $m_{D^- D_s^+ \pi^+}$ distributions:
  - $N_{\rm sig}^{B^0 \to \bar{D}D_s\pi} = 4009 \pm 70$, Purity: 90.7% (signal region: ± 20 MeV around B^0)
  - $N_{\rm sig}^{B^+ \to \bar{D}D_s\pi} = 3750 \pm 64$, Purity: 95.2% (signal region: ± 20 MeV around B^+)

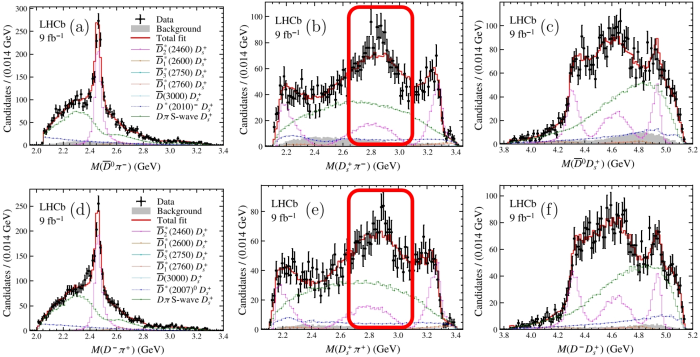


PRL131, 041902 (2023) / PRD108, 012017 (2023)

Amplitude analysis of $B^0 \to \bar{D}^0 D_s^+ \pi^- / B^+ \to D^- D_s^+ \pi^+$

- A combined amplitude analysis of the $B^0 \to \bar{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$ is performed.
- Isospin symmetry: all parameter are shared except for $\bar{D}^*(2007)^0$ and $D^*(2010)^-$
- Only the possible excited $\bar{D}^*$ resonances decaying to $\bar{D}^0\pi^-$ / $D^-\pi^+$ are considered before considering the possible existence of exotic states.

PRL131, 041902 (2023)



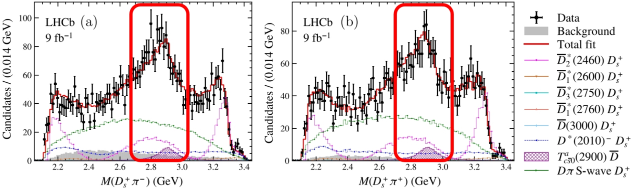
The model (only $\bar{D}^*$) cannot describe the peaking structure near 2900 MeV/ in $m_{D_s\pi}$?

Amplitude analysis of $B^0 \to \bar{D}^0 D_s^+ \pi^- / B^+ \to D^- D_s^+ \pi^+$

- To describe the peaking structures near 2900 MeV, two new $D_s\pi$ exotic resonances ($T^a_{c\bar{s}0}(2900)^0$ $[c\bar{s}\bar{u}d]$ and $T^a_{c\bar{s}0}(2900)^{++}$ $[c\bar{s}u\bar{d}]$) are included in the fit model (PRL131, 041902 (2023), PRD108, 012017 (2023))

- With isospin triplet assumption:
  - Line shape: BW function
  - $M(T^a_{c\bar{s}0}(2900)) = (2908 \pm 11 \pm 20)$ MeV
  - $\Gamma(T^a_{c\bar{s}0}(2900)) = (136 \pm 11 \pm 20)$ MeV / $J^P = 0^+$ / Significance: $> 9.0\sigma$

- Without isospin triplet assumption: ($T^0 = T^a_{c\bar{s}0}(2900)^0$ / $T^{++} = T^a_{c\bar{s}0}(2900)^{++}$)
  - Line shape: BW function
  - $M(T^0) = (2892 \pm 14 \pm 15)$ MeV / $\Gamma(T^0) = (119 \pm 26 \pm 13)$ MeV
  - $M(T^{++}) = (2921 \pm 17 \pm 20)$ MeV / $\Gamma(T^{++}) = (137 \pm 32 \pm 17)$ MeV
  - $\Delta M = (28 \pm 20 \pm 12)$ MeV / $\Delta\Gamma = (15 \pm 39 \pm 16)$ MeV (isospin triplet ✓)

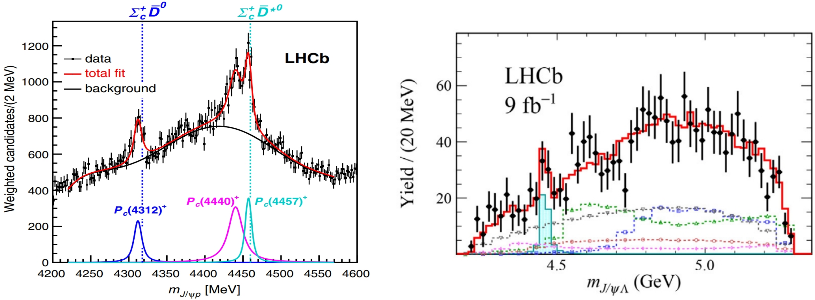


Observation of a $J/\psi\Lambda$ resonance in $B^- \to J/\psi\Lambda\bar{p}$

- First penptaquark candidate, P_{ψ}^{N+} $(c\bar{c}uud)$, was observed in the $J/\psi p$ system in the $\Lambda_b^0 \to J/\psi p K^-$ decay (PRL115, 072001 (2015), PRL122, 222001 (2019))

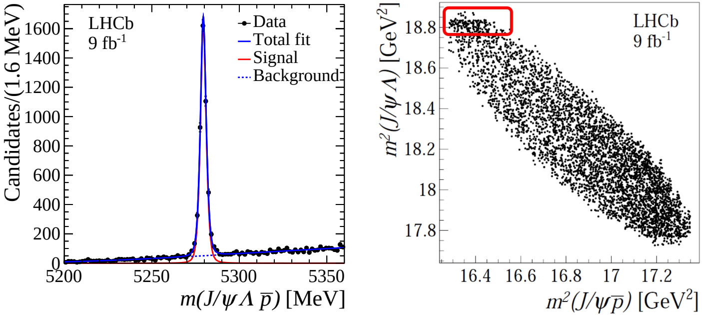
- Recently, evidence for a $P_{\psi s}^{\lambda 0}$ $(c\bar{c}uds)$ pentaquark candidate with s quark was found in the $J/\psi\Lambda$ system in the $\Xi_b^- \to J/\psi\Lambda K^-$ decay (Science Bulletin 66 (2021) 1278-1287)

- The $B^- \to J/\psi\Lambda\bar{p}$ decay offers a opportunity to simultaneously search for $\bar{P}_{\psi}^{N-}$ and $P_{\psi s}^{\Lambda 0}$ in the $J/\psi\bar{p}$ and $J/\psi\Lambda$ systems



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

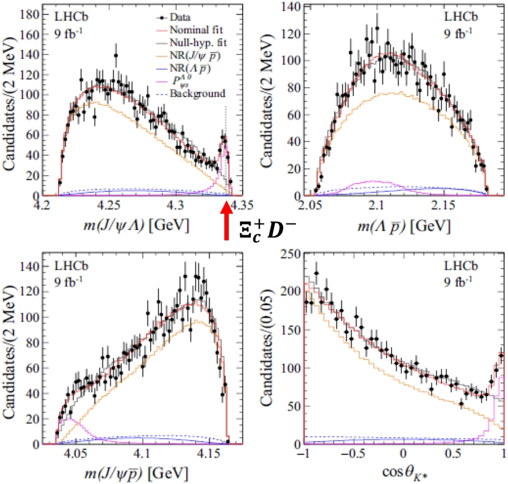
- Decay channel: $B^- \to J/\psi\Lambda\bar{p}$, $J/\psi \to \mu^+\mu^-$, $\Lambda \to p\pi^-$
- Dataset: LHCb Run1 and Run2 data ($\sim$ 9 fb^{-1})
- Fit to the $m(J/\psi\Lambda\bar{p})$ distribution:
  - $N_{\text{sig}} = 4620 \pm 70$
  - $N_{\text{sig}} \sim 4400$, Purity: 93.0% (signal region: $\pm$5 MeV around B^-)



PRL131, 031901 (2023)

Amplitude analysis of $B^- \to J/\psi \Lambda \bar{p}$

PRL131, 031901 (2023)



Fit results for $P_{\psi s}^{\Lambda 0}(4338)$:

- Line shape: BW function
- $M_0 = (4338.2 \pm 0.7 \pm 0.4)$ MeV
- $\Gamma_0 = (7.0 \pm 1.2 \pm 1.3)$ MeV
- $FF = (12.5 \pm 0.7 \pm 1.9)\%$
- High significance
- $J = \frac{1}{2}^-$ is preferred. $J^P = \frac{1}{2}^\pm / \frac{3}{2}^\pm$ are studied and $J^P = \frac{1}{2}^+$ is excluded at a 90% CL

Prompt pentaquarks in charm final states

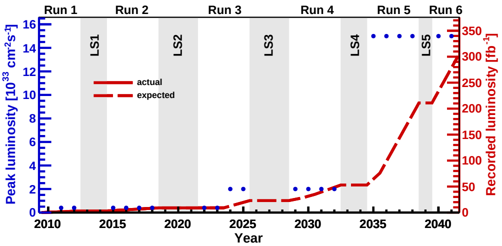
$\Sigma_c^{++}\bar{D}^0$	~~$\Sigma_c^{++}D^0$~~	$\Sigma_c^{++}D^-$	~~$\Sigma_c^{++}D^+$~~	~~$\Sigma_c^{++}D^{*-}$~~	~~$\Sigma_c^{++}D^{*+}$~~
$\Sigma_c^{0}\bar{D}^0$	~~$\Sigma_c^{0}D^0$~~	$\Sigma_c^{0}D^-$	~~$\Sigma_c^{0}D^+$~~	~~$\Sigma_c^{0}D^{*-}$~~	~~$\Sigma_c^{0}D^{*+}$~~
$\Sigma_c^{*++}\bar{D}^0$	$\Sigma_c^{*++}D^0$	$\Sigma_c^{*++}D^-$	$\Sigma_c^{*++}D^+$	$\Sigma_c^{*++}D^{*-}$	~~$\Sigma_c^{*++}D^{*+}$~~
$\Sigma_c^{*0}\bar{D}^0$	$\Sigma_c^{*0}D^0$	$\Sigma_c^{*0}D^-$	$\Sigma_c^{*0}D^+$	$\Sigma_c^{*0}D^{*-}$	~~$\Sigma_c^{*0}D^{*+}$~~
$\Lambda_c^+\bar{D}^0$	$\Lambda_c^+D^0$	$\Lambda_c^+D^-$	$\Lambda_c^+D^+$	$\Lambda_c^+D^{*-}$	$\Lambda_c^+D^{*+}$
$\Lambda_c^+\bar{D}^0\pi^+$	$\Lambda_c^+D^0\pi^+$	$\Lambda_c^+D^-\pi^+$	$\Lambda_c^+D^+\pi^+$	$\Lambda_c^+D^{*-}\pi^+$	$\Lambda_c^+D^{*+}\pi^+$
$\Lambda_c^+\bar{D}^0\pi^-$	$\Lambda_c^+D^0\pi^-$	$\Lambda_c^+D^-\pi^-$	$\Lambda_c^+D^+\pi^-$	$\Lambda_c^+D^{*-}\pi^-$	$\Lambda_c^+D^{*+}\pi^-$

[LHCb-PAPER-2023-018, in preparation]

- Search for pentaquark decays into a wide range of Σ_c, Λ_c and D combinations
- 42 different modes, 10 of which are too statistically limited, 32 modes tested
- Simultaneous fit to Σ_c/Λ_c and D^0 signal region and sideband region
- Scan of the mass in 4 MeV steps to search for peaks, calcualte $p-$value
- No clear signal observed, upper limits on all modes are set as function of mass

Summary and outlook

- **LHCb has been continually producing interesting results in exotic hadrons:**
  - Evidence of a $J/\psi K_s^0$ structure in $B^0 \to J/\psi \phi K_S^0$
  - Observation of a $D_s^+ D_s^-$ resonance in $B^+ \to D_s^+ D_s^- K^+$
  - Observation of a doubly charged tetraquark and its neutral partner
  - Observation of a $J/\psi\Lambda$ resonance in $B^- \to J/\psi\Lambda\bar{p}$
- **LHCb will continue to search for possible exotic hadrons in more decay channels and larger data samples**
  - 50 fb^{-1} by the end of Run4
  - 300 fb^{-1} by the end of Run6



Thanks for your listening!!!