Recent results on charmonium (-like) spectroscopy at LHCb

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(On behalf of the LHCb collaboration)

QWG 2022

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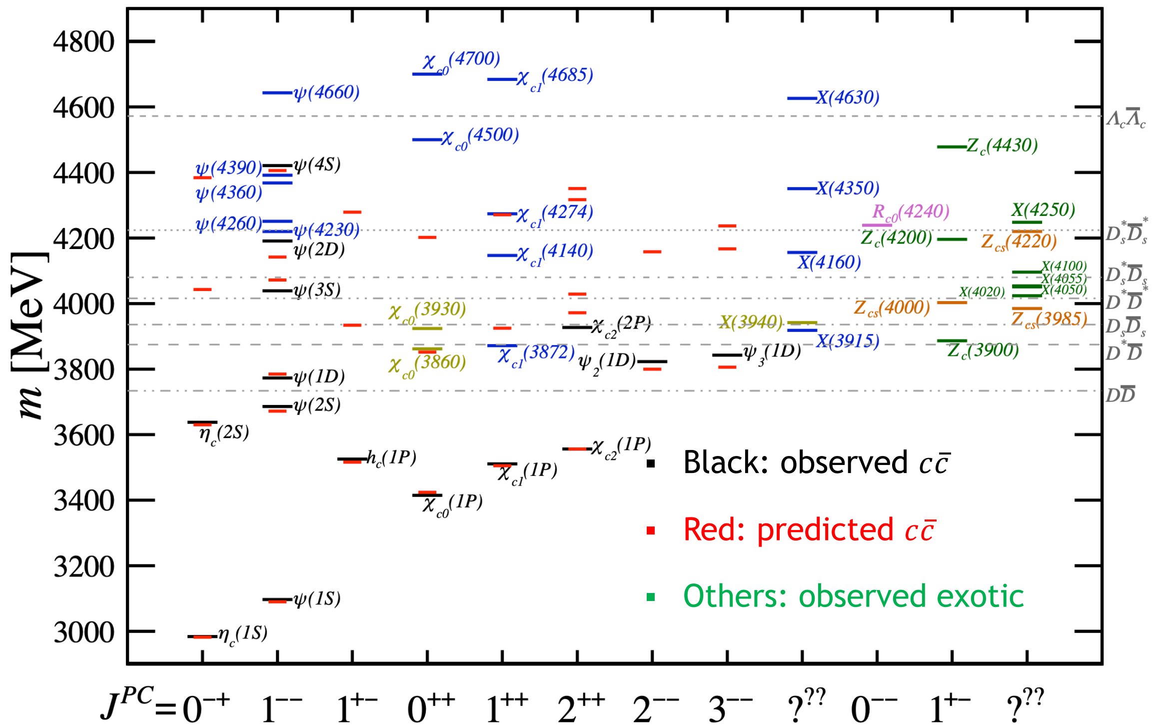
Charmonium(-like) spectroscopy

- Rich structures
  - Conventional $c\bar{c}$ states
    - Predominantly decay into $D^{(*)}\bar{D}^{(*)}$ if mass above threshold
      - OZI allowed
  - Exotic candidates
    - May have large fraction for $c\bar{c}+h/\gamma$ decay process
      - OZI suppressed for conventional states



Prog. Theor. Exp. Phys. 2020 (2020) 083C01   Phys. Rev. D, 2005, 72: 054026

- Puzzles to resolve by theorists and experimentists
  - Identification of conventional/exotic nature of some states
  - Inner structure of exotic candidates
- More new particles may rise in experiment
  - Open charm: $D^{(*)}\bar{D}^{(*)}$, $D_s^{(*)}\bar{D}_s^{(*)}$, ⋯
  - Hidden charm: $c\bar{c}+h/\gamma$

Topics in this talk

- Charmonium(-like) states in B decays
  - A near-threshold $D_s^+ D_s^-$ structure in $B^+ \to D_s^+ D_s^- K^+$

    LHCb-PAPER-2022-018
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    In preparation

  - Study of $J/\psi\eta$ resonances in $B^+ \to J/\psi\eta K^+$

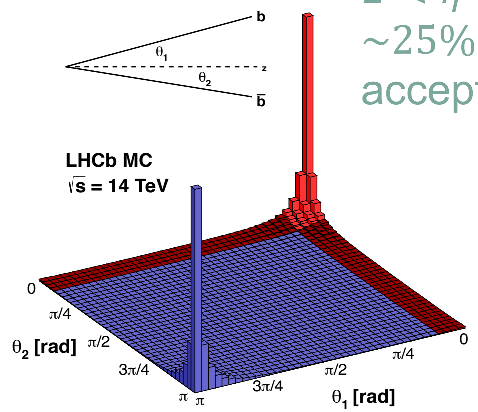
    J. High Energ. Phys. **2022**, 46 (2022)

LHCb experiment

JINST 3 (2008) S08005, Int.J.Mod.Phys. A30 (2015) 1530022

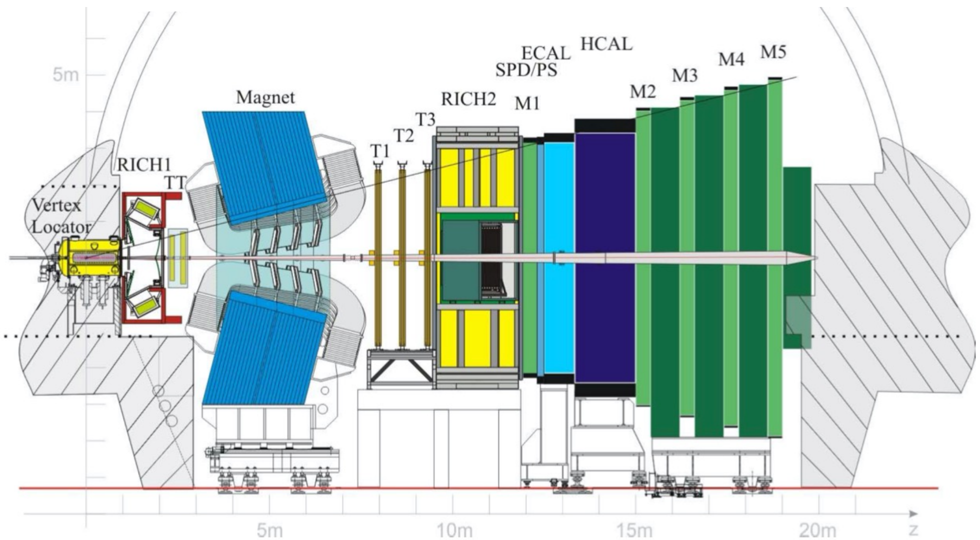
- Dedicated for precise and efficient heavy-hadron reconstruction
  - Single-arm and forward design
  - Powerful particle identification
    - $\epsilon(K \to K) \sim 95\%$ with $\epsilon(\pi \to K) \sim 5\%$
    - $\epsilon(\mu \to \mu) \sim 97\%$ with $\epsilon(\pi \to \mu) \sim 1-3\%$
  - High momentum resolution
    - $\Delta p/p = 0.4 \sim 0.6\%\ (5-100\mathrm{GeV}/c)$
    - $\sigma_{m_B} \sim 10\mathrm{MeV}$ for $B \to D\bar{D}K$ (m_D constrained)
  - High spatial resolution
    - $\sigma_{\mathrm{IP}} \sim 20\mu\mathrm{m}$; $\sigma_{\mathrm{PV},x/y} \sim 10\mu\mathrm{m}$; $\sigma_{\mathrm{PV},z} \sim 60\mu\mathrm{m}$

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



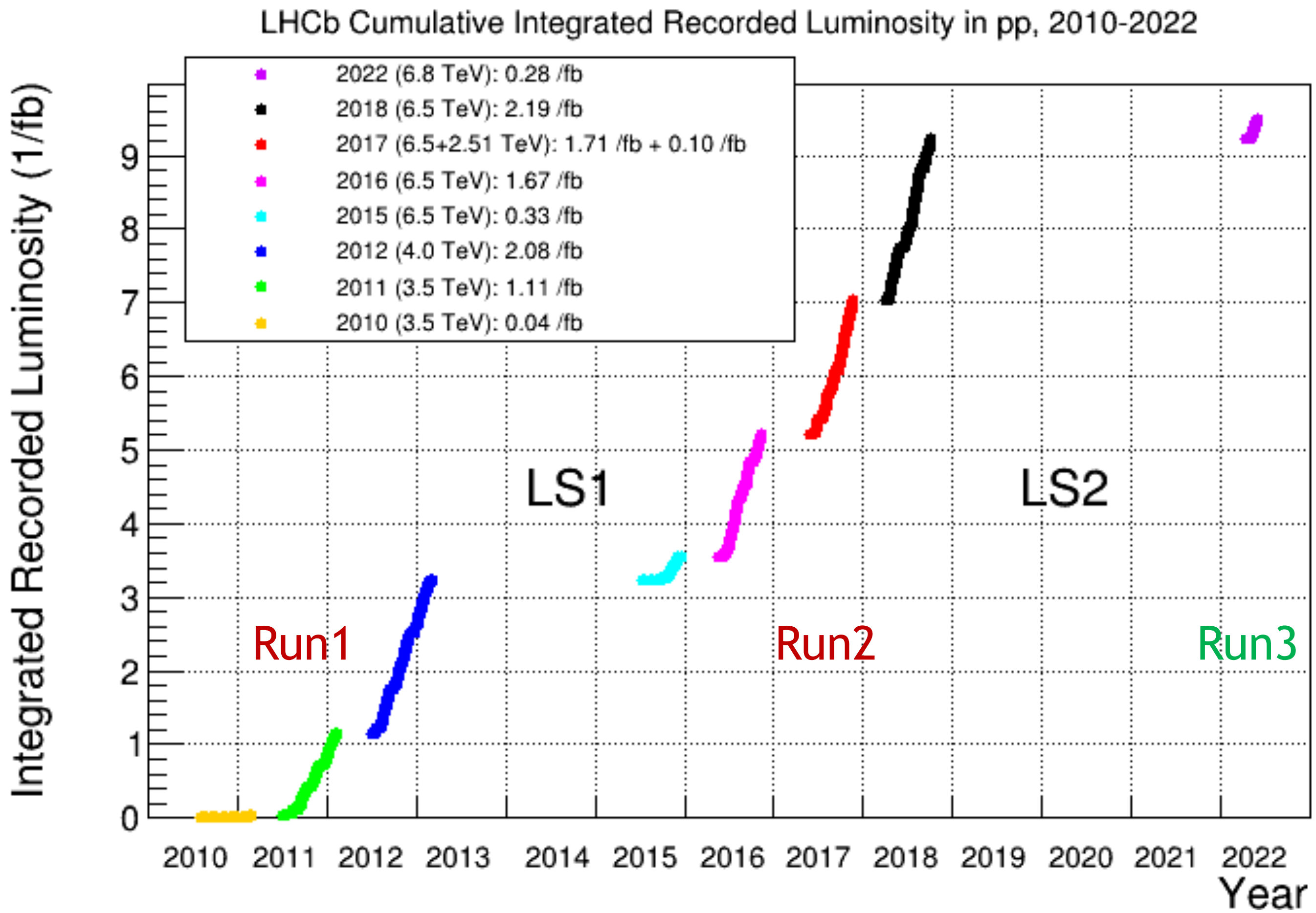
Ideal platform for studies of B decays presented in this talk

✓ High efficiency
✓ High resolution
✓ Low background



LHCb dataset

- Run1: 3 fb^{-1} pp collision @ 7, 8 TeV
- Run2: 6 fb^{-1} pp collision @ 13 TeV
- Run3: ongoing from 2022



A near-threshold $D_s^+ D_s^-$ structure in $B^+ \to D_s^+ D_s^- K^+$

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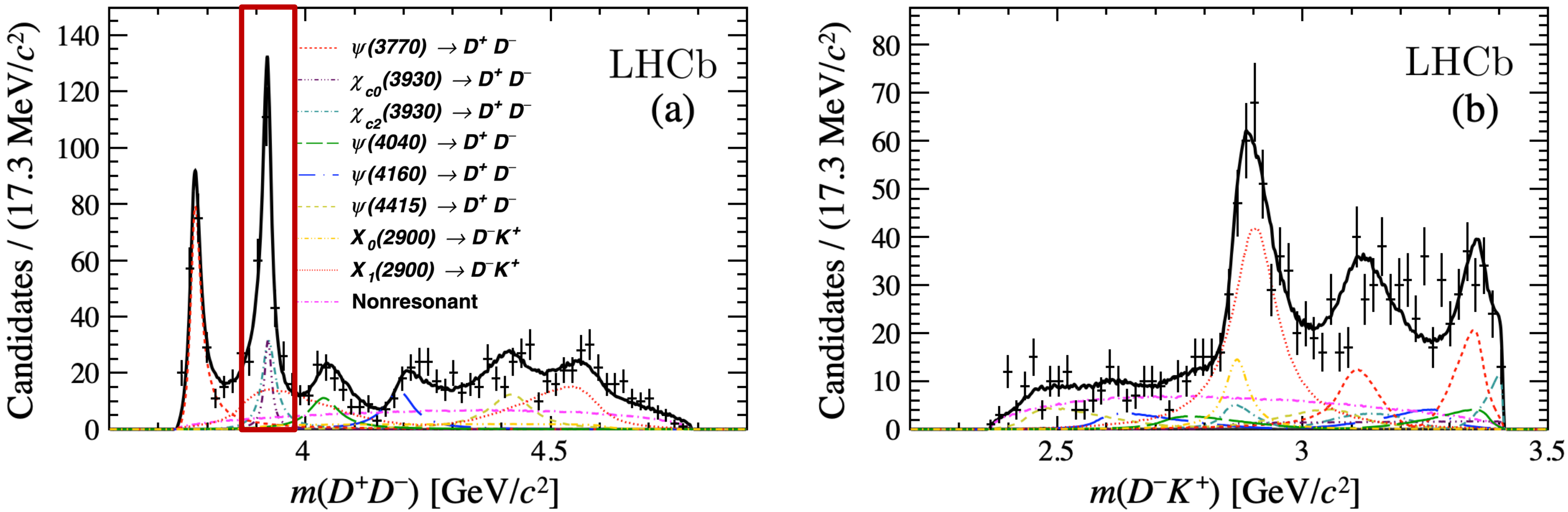
In preparation

What motivates this study?

$B^+ \to D^+ D^- K^+$

Phys.Rev.D102(2020) 112003, Phys. Rev. Lett. 125 (2020) 242001



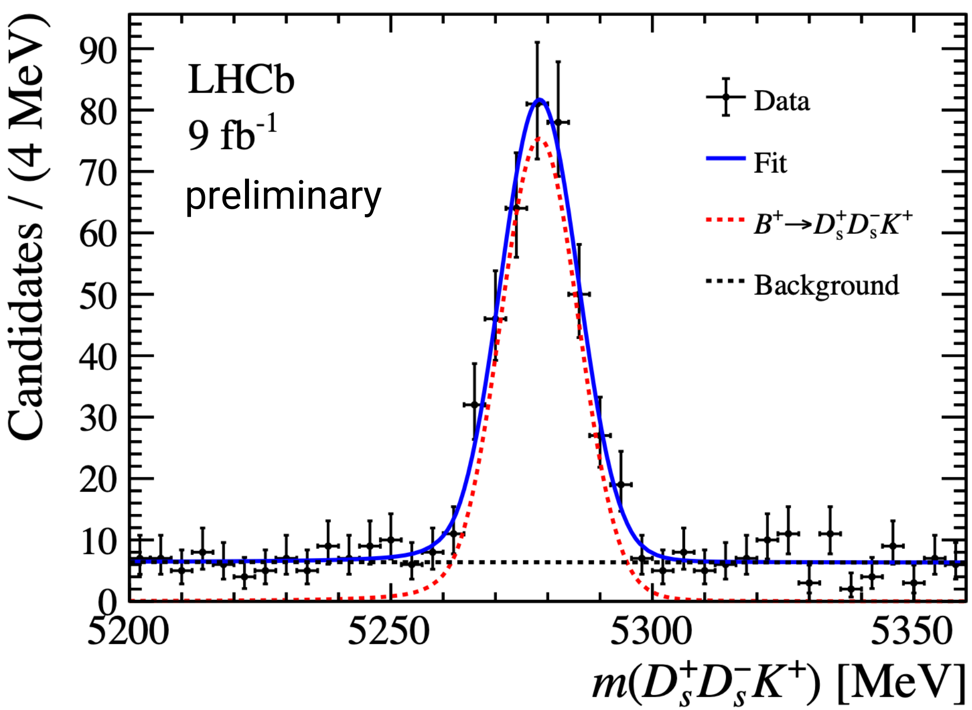
- $\chi_{c0}(3930) \to D^+ D^-$:
  - It is suggested to be the same particle as $\chi_{c0}(3915) \to J/\psi\omega$ PDG 2020
    - Exotic nature?
  - Some theories suggest $\chi_{c0}(3930)/\chi_{c0}(3915)$ to be a $c\bar{c}s\bar{s}$ tetraquark candidate

To search for $\chi_{c0}(3930) \to D_s^+ D_s^-$ in $B^+ \to D_s^+ D_s^- K^+$

JHEP 06 (2021) 035
Sci. Bull., 2021, 66: 1413

$B^+ \to D_s^+ D_s^- K^+$ dataset

- Dataset: full Run1 + Run2 data, $\mathcal{L} = 9\ \text{fb}^{-1}$
- Reconstruction: $B^+ \to D_s^+ D_s^- K^+,\ D_s^\pm \to K^\mp K^\pm \pi^\pm$



$N_{sig} = 360 \pm 22$

Purity: 84%

Near-threshold structure in $D_s^+ D_s^-$

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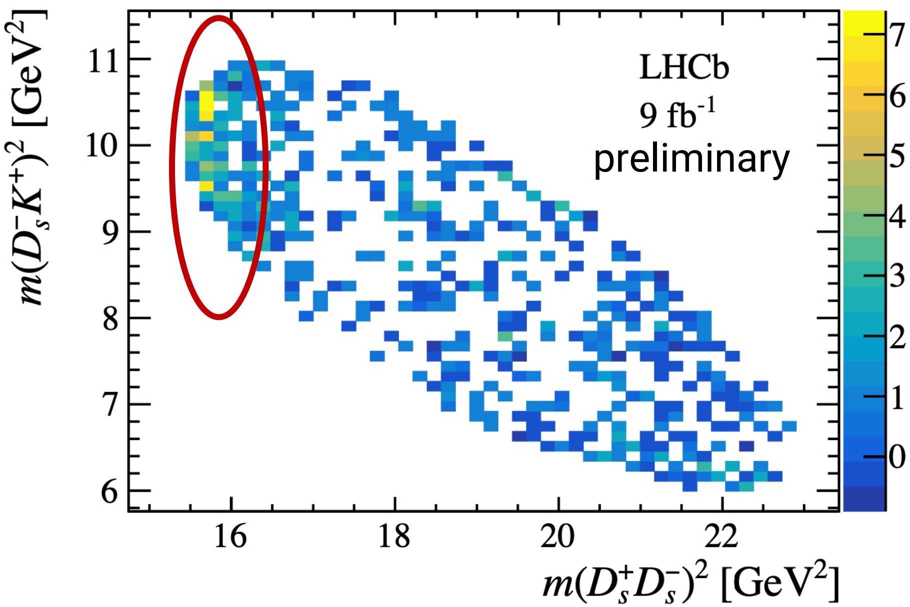

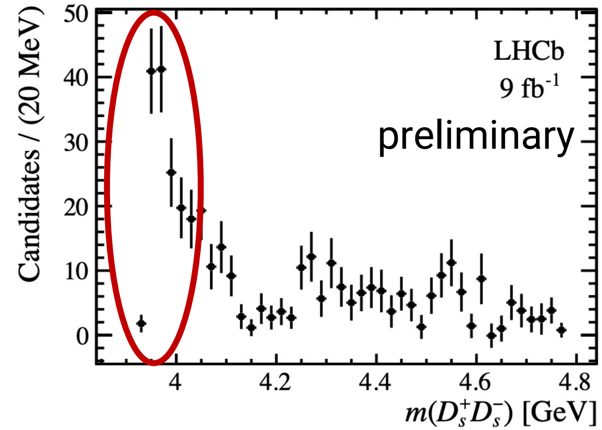

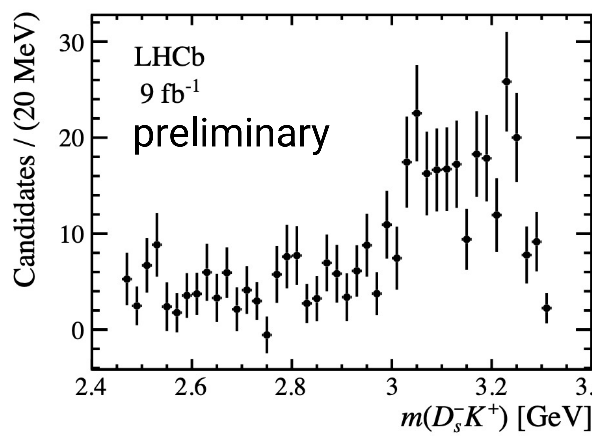

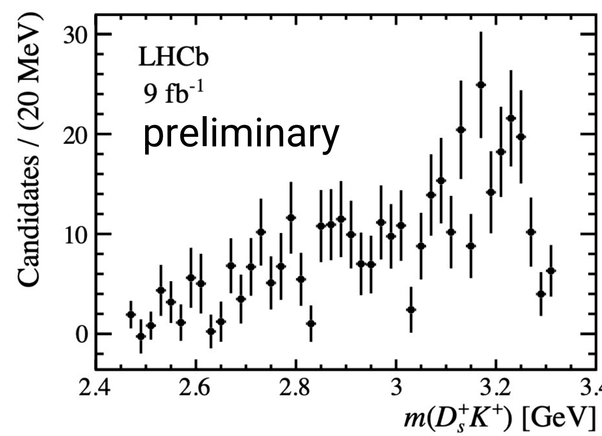

Background subtracted

Observation of $X(3960)$ in $D_s^+ D_s^-$

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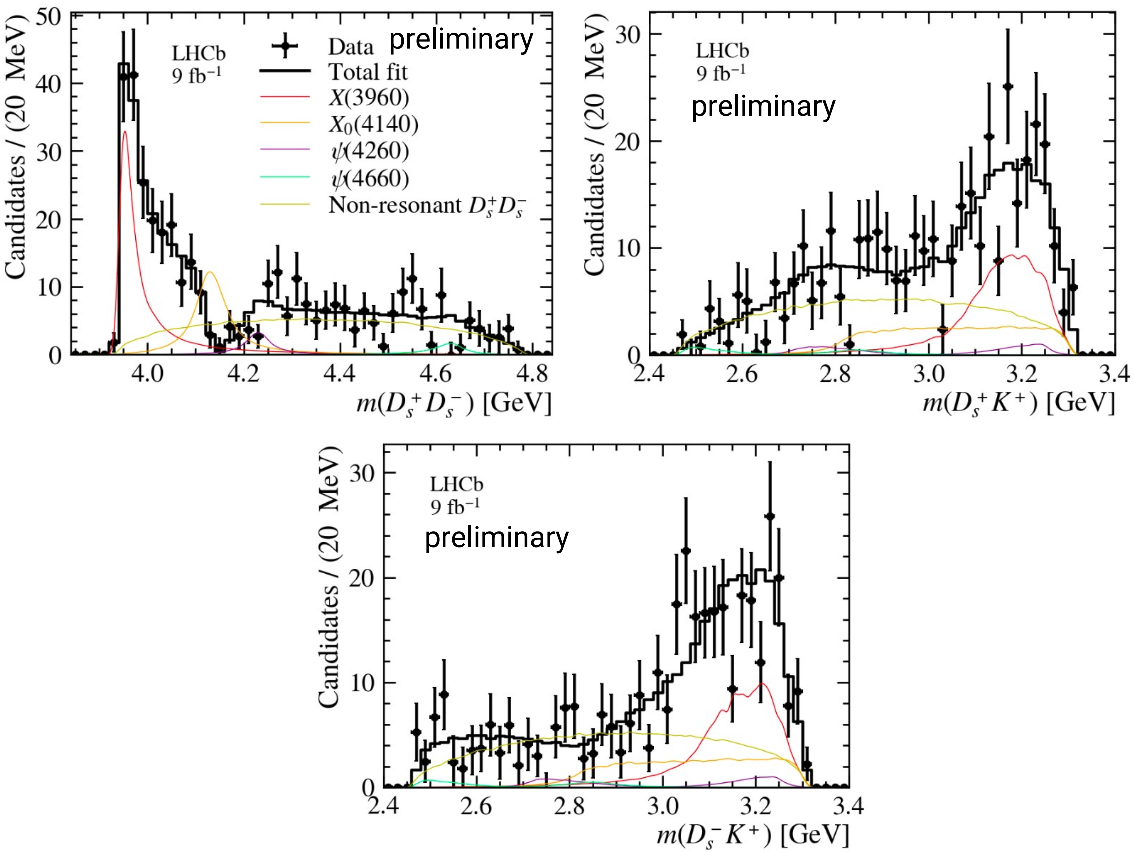
- Amplitude analysis
- Default model
  - 0^{++}: $X(3960)$, $X_0(4140)$, non-resonant (NR)
  - 1^{--}: $\psi(4260)$, $\psi(4660)$

$\psi(4260)$ is $\psi(4230)$ in PDG2022



✓ $X(3960)$ describes the near-threshold peak

✓ $X_0(4140)$ accounts for the dip at ~4.14 GeV via interference

Background subtracted

Amplitude fit result

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Component	J^{PC}	M_0 (MeV)	Γ_0 (MeV)	$\mathcal{F}$ (%)	$\mathcal{S}$ (σ)
$X(3960)$	0^{++}	$3956 \pm 5 \pm 10$	$43 \pm 13 \pm 8$	$25.4 \pm 7.7 \pm 5.0$	12.6 (14.6)
$X_0(4140)$	0^{++}	$4133 \pm 6 \pm 6$	$67 \pm 17 \pm 7$	$16.7 \pm 4.7 \pm 3.9$	3.8 (4.1)
$\psi(4260)$	1^{--}	4230 (fixed)	55 (fixed)	$3.6 \pm 0.4 \pm 3.2$	3.2 (3.6)
$\psi(4660)$	1^{--}	4633 (fixed)	64 (fixed)	$2.2 \pm 0.2 \pm 0.8$	3.0 (3.2)
NR	0^{++}	-	-	$46.1 \pm 13.2 \pm 11.3$	3.1 (3.4)

- First uncertainty statistical, and second systematic
- Fixed parameters taken from PDG 2018/2020 ($\psi(4260)$ is $\psi(4230)$ in PDG2022)

- $\mathcal{F}$: fit fraction
- $\mathcal{S}$: significance

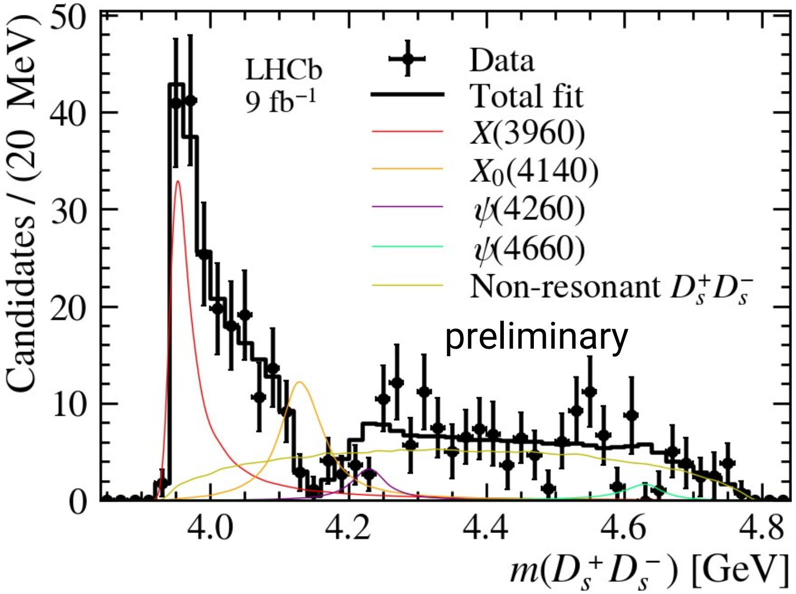
  (numbers in brackets don not include systematic effect)

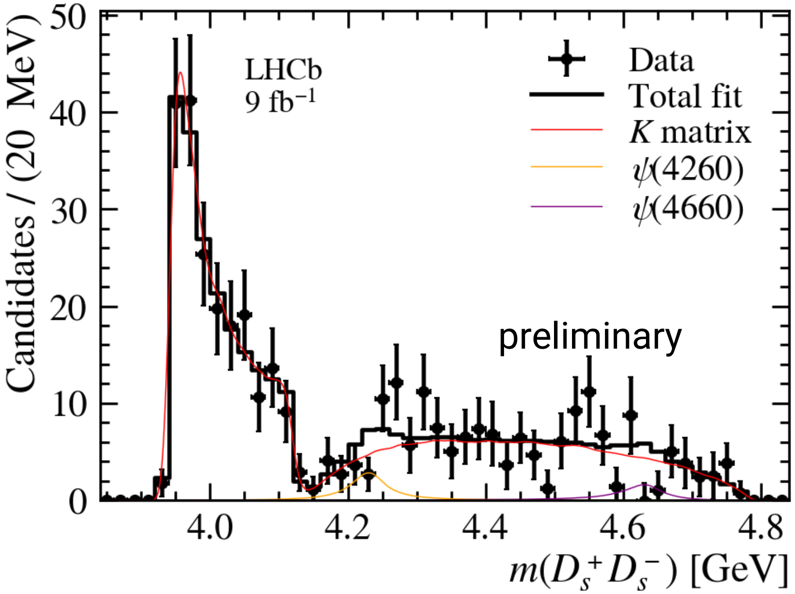
- Spin-parity tests:
  - $X(3960)$: 0^{++} favored; 1^{--} and 2^{++} rejected by at least 9σ
  - $X_0(4140)$: 0^{++} favored; 1^{--} and 2^{++} rejected by at least 3.5σ

Alternative K-matrix model

- Dip around $4.14\ \mathrm{GeV}$ near the $J/\psi\phi$ threshold

Background subtracted





The default model: modelled by a new resonance, $X_0(4140)$

Can also be described by considering $J/\psi\phi \to D_s^+D_s^-$ rescattering in the K-matrix formula

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

$X(3960)$ and $\chi_{c0}(3930)$

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- $X(3960)$: $M_0 = 3955 \pm 6 \pm 11$ MeV; $\Gamma_0 = 48 \pm 17 \pm 10$ MeV; $J^{PC} = 0^{++}$
- $\chi_{c0}(3930)$: $M_0 = 3924 \pm 2$ MeV; $\Gamma_0 = 17 \pm 5$ MeV; $J^{PC} = 0^{++}$

Phys.Rev.D102(2020) 112003, Phys. Rev. Lett. 125 (2020) 242001

- Are they the same particle? If yes

$\mathcal{FF}$: Fit fractions in the two B^+ decays

$$\frac{\Gamma(X \to D^+D^-)}{\Gamma(X \to D_s^+D_s^-)} = \frac{\mathcal{B}(B^+ \to D^+D^-K^+)\,\mathcal{FF}^X_{B^+ \to D^+D^-K^+}}{\mathcal{B}(B^+ \to D_s^+D_s^-K^+)\,\mathcal{FF}^X_{B^+ \to D_s^+D_s^-K^+}}$$

$$= 0.29 \pm 0.09\,(\text{stat}) \pm 0.10\,(\text{syst}) \pm 0.08\,(\text{ext})$$

$\mathcal{B}(B^+ \to D_s^+D_s^-K^+)$ also measured in this work

- $\Gamma(X \to D^+D^-) < \Gamma(X \to D_s^+D_s^-)$ implies the exotic nature of the state
  - Conventional charmonium predominantly decays into $D^{(*)}\overline{D}^{(*)}$
    - It is harder to excite an $s\bar{s}$ pair from vacuum compared with $u\bar{u}(d\bar{d})$

Summary on $X(3960) \to D_s^+ D_s^-$

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- Observation of near-threshold structure $X(3960)$ in $B^+ \to D_s^+ D_s^- K^+$ $> 12\sigma$

  $M_0 = 3955 \pm 6 \pm 11$ MeV; $\Gamma_0 = 48 \pm 17 \pm 10$ MeV; $J^{PC} = 0^{++}$

- Assuming $X(3960)$ and $\chi_{c0}(3930)$ to be the same particle

$$\frac{\Gamma(X \to D^+ D^-)}{\Gamma(X \to D_s^+ D_s^-)} = 0.29 \pm 0.09 \pm 0.10 \pm 0.08$$

  Indicating the exotic nature

  Then it should be called $T^f_{\psi\phi 0}(39xx)$ following the new exotic naming scheme

  arXiv:2206.15233 & Tim's talk

- Future studies

  - Precision measurements of $X(3960)$ and $\chi_{c0}(3930)$ properties -> to see if they are really the same particle
  - $X(3960)/\chi_{c0}(3930)/\chi_{c0}(3915) \to J/\psi\omega$ -> more input to help reveal the nature of this state

Study of $J/\psi\eta$ resonances in $B^+ \to J/\psi\eta K^+$

J. High Energ. Phys. **2022**, 46 (2022)

What motivates this study?

- Study charmonium(-like) states in $J/\psi\eta$
  - X_C': C-odd partner of $\chi_{c1}(3872)$
    - Predicted by many theoretical works

      [JPS Conf. Proc. 13 (2017) 020023, EPJ Web Conf. 137 (2017) 06002, ...]

    - Searched for by Belle and BaBar

BaBar	$\mathcal{B}(B^+ \to X_C' K^+) \times \mathcal{B}(X_C' \to J/\psi\eta)$	$< 7.7 \times 10^{-6}$	Phys. Rev. Lett. 93 (2004) 041801
Belle	$\mathcal{B}(B^+ \to X_C' K^+) \times \mathcal{B}(X_C' \to J/\psi\eta)$	$< 3.8 \times 10^{-6}$	PTEP 2014 (2014) 043C01

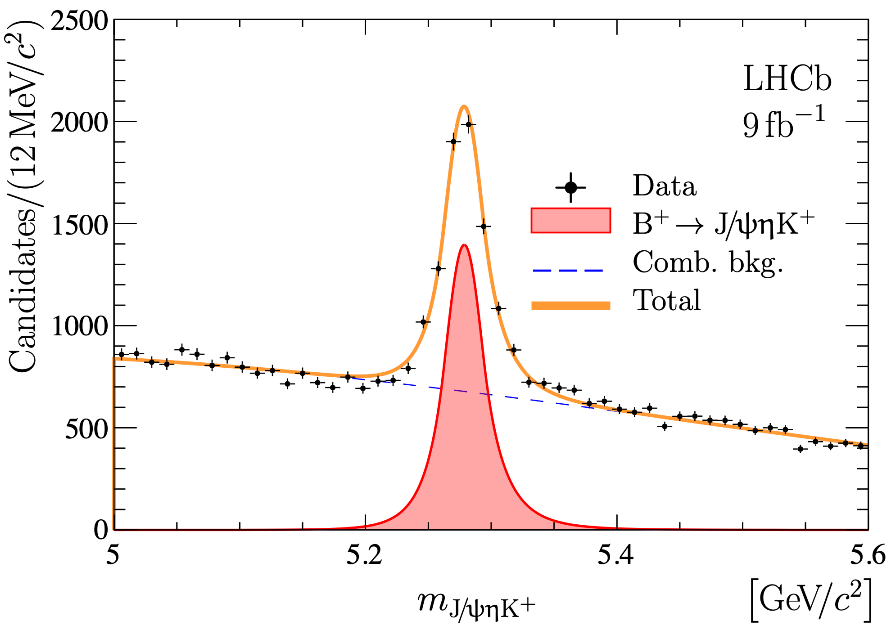
  - Other charmonium(-like) states
    - $\psi_2(3823)$, $\psi(4040)$, etc

$B^+ \to J/\psi\eta K^+$ dataset

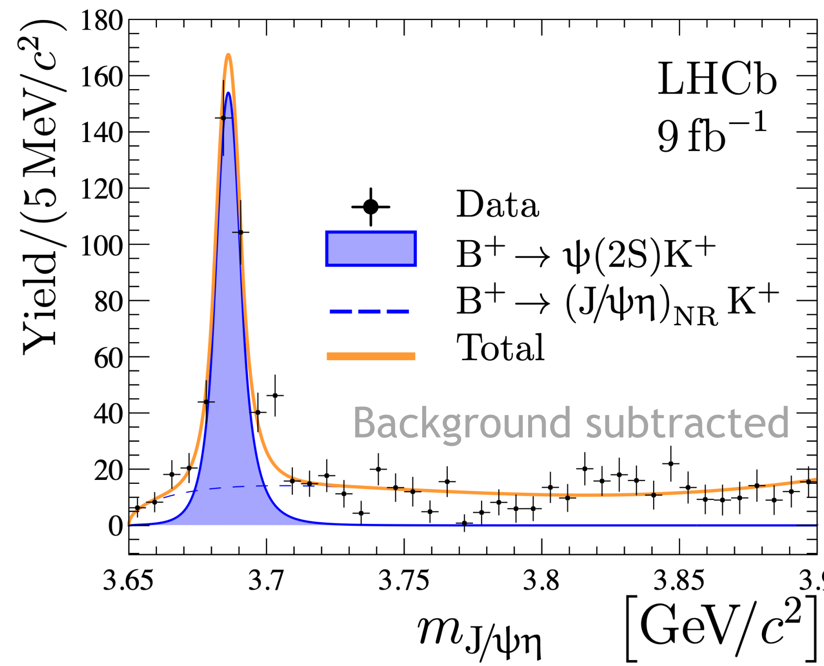
J. High Energ. Phys. 2022, 46 (2022)

- Full Run1 + Run2 data, $\mathcal{L} = 9\ \text{fb}^{-1}$
- $B^+ \to J/\psi\eta K^+, J/\psi \to \mu^+\mu^-, \eta \to \gamma\gamma$

N_{B^+}: $(5.39 \pm 0.16)\times 10^3$



Clear signature of $\psi(2S) \to J/\psi\eta$



Normalization for the fractions of other $J/\psi\eta$ states in the next slide

Resonances in the $J/\psi\eta$ system

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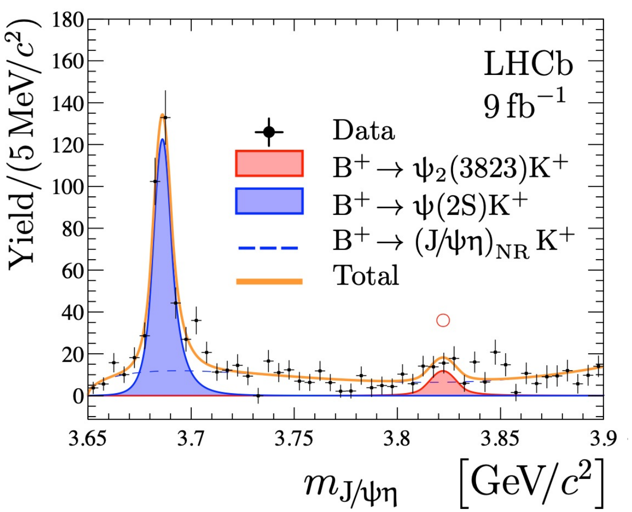
$$F_X \equiv \frac{\mathcal{B}(B^+ \to XK^+) \times \mathcal{B}(X \to J/\psi\eta)}{\mathcal{B}(B^+ \to \psi(2S)K^+) \times \mathcal{B}(\psi(2S) \to J/\psi\eta)}$$

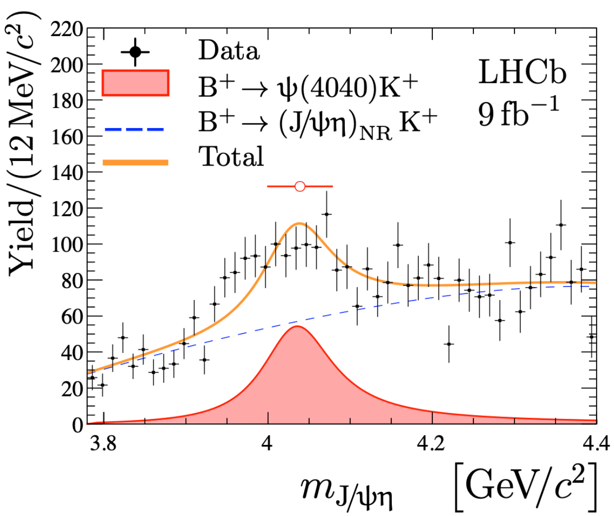
- Evidence for $\psi_2(3823)$, $\psi(4040) \to J/\psi\eta$

First evidence $F_{\psi_2(3823)} = (5.95^{+3.38}_{-2.55})\times 10^{-2}$ 3.4σ

$F_{\psi(4040)} = (40.6 \pm 11.2)\times 10^{-2}$ 4.7σ

Systematic uncertainty included





Background subtracted

- Upper limit for other states

	Upper limit on 90% CL F_X $[10^{-2}]$	B_X $[10^{-7}]$
$\psi(3770)$	2.2	4.6
$\psi_3(3842)$	2.9	6.1
$\psi(4160)$	4.2	8.7
$\psi(4415)$	4.6	9.6
$R(3760)$	2.0	4.1
$R(3790)$	3.2	6.7
$Z_c(3900)^0$	2.1	4.3
$\psi(4230)$	1.9	3.9
$\psi(4360)$	6.0	12.4
$\psi(4390)$	11.6	24.1
$Z_c(4430)^0$	6.1	12.7
X'_C	1.9	3.9

Upper limit is an order of magnitude smaller than the Belle and BaBar results

Phys. Rev. Lett. 93 (2004) 041801
PTEP 2014 (2014) 043C01

Discussions on $\psi_2(3823)$ and $\psi(4040)$

J. High Energ. Phys. 2022, 46 (2022)

- $\psi_2(3823)$:

$$\frac{\mathcal{B}(\psi_2(3823) \to J/\psi\eta)}{\mathcal{B}(\psi_2(3823) \to J/\psi\pi^+\pi^-)} = 4.4\,^{+2.5}_{-1.9} \pm 0.9$$

  - Inconsistent with the theoretical study — Phys. Rev. D94 (2016) 034005

- $\psi(4040)$:

$$\mathcal{B}(B^+ \to \psi(4040)K^+) = (1.64 \pm 0.45 \pm 0.23) \times 10^{-3}$$

This work

  - Inconsistent with the upper limit set using $\psi(4040) \to \mu^+\mu^-$ — Phys. Rev. Lett. 111 (2013) 112003
  - $\psi(4040)$ and $\psi(4160)$ production rates are different in several modes
    - $\psi(4040) \sim \psi(4160)$ in $B^+ \to D^+D^-K^+$ — Phys. Rev. D102 (2020) 112003
    - $\psi(4040) < \psi(4160)$ in $B^+ \to \mu^+\mu^-K^+$ — Phys. Rev. Lett. 111 (2013) 112003
    - $\psi(4040) > \psi(4160)$ in $B^+ \to J/\psi\eta K^+$ (this work)

Future studies to resolve these puzzles

Summary

- Recent results on charmonium(-like) spectroscopy at LHCb
  - Observation of near-threshold structure $X(3960)$ in $B^+ \to D_s^+ D_s^- K^+$
    - An interesting exotic candidate

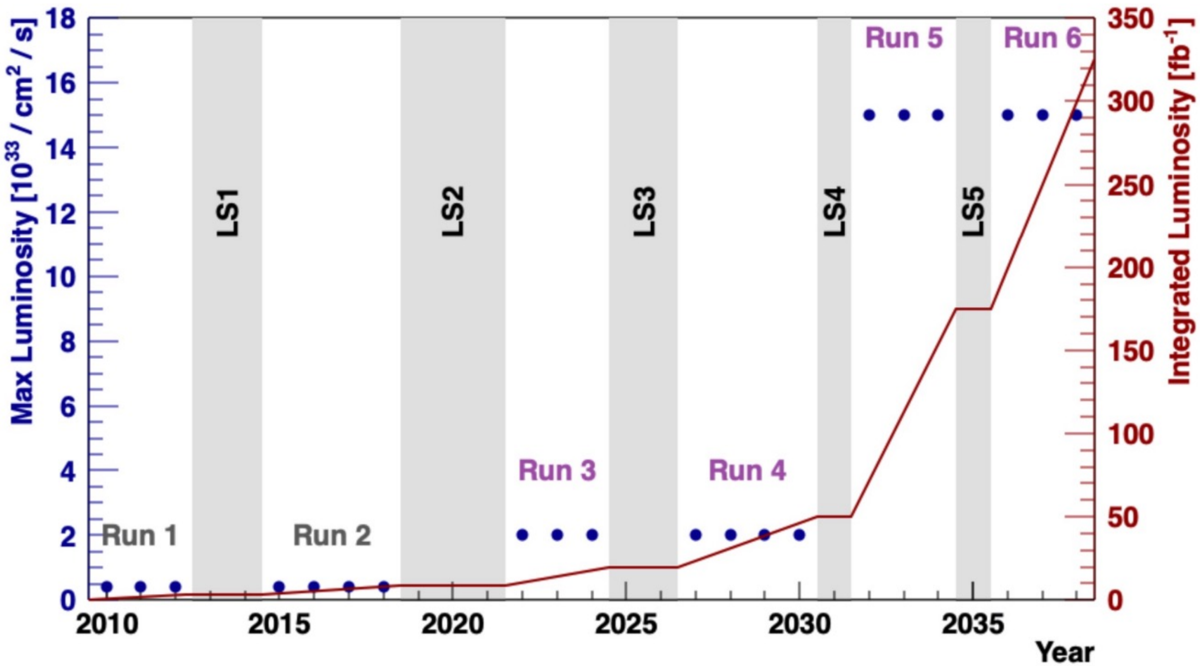
      Same state as $\chi_{c0}(3930)/\chi_{c0}(3915)$?

  - Investigation of $J/\psi\eta$ system in $B^+ \to J/\psi\eta K^+$
    - Evidence for $\psi_2(3823), \psi(4040) \to J/\psi\eta$
    - Upper limits on branching fractions of some other charmonium(-like) states

      e.g. C-odd partner of $\chi_{c1}(3872)$

Prospects

- We are now boosting our data to a new level



- Precision measurements on $X(3960)/\chi_{c0}(3930)$ properties
- More states in $B^+ \to J/\psi\eta K^+$ may rise
- Opportunities to investigate more $c\bar{c} + h$ and open charm final states
  - e.g. $J/\psi\omega$, $\Lambda_c^+\overline{\Lambda}_c^-$

Thank you for your attention!

Backup slides

Systematic uncertainties in $B^+ \to D_s^+ D_s^- K^+$ AmAn

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LHCb-PAPER-2022-019

	$X(3960)$			$X_0(4140)$			$\psi(4260)$	$\psi(4660)$	NR
Source	M_0	Γ_0	$\mathcal{F}$	M_0	Γ_0	$\mathcal{F}$	$\mathcal{F}$	$\mathcal{F}$	$\mathcal{F}$
Trigger	0	0	0.6	0	0	0.1	0.0	0.0	0.7
Simulation statistics	2	1	0.7	1	1	0.5	0.0	0.0	1.7
Particle identification	0	0	0.5	0	2	0.0	0.0	0.0	0.7
Additional components	1	3	3.4	3	5	2.5	3.2	0.7	10.1
Hadron size	0	1	0.0	1	1	0.1	0.0	0.0	0.1
Fixed parameters	1	2	2.8	4	4	2.9	0.1	0.1	3.7
$X(3960)$ model	10	7	1.6	0	1	0.7	0.0	0.0	2.1
sFit bias	1.9	1.5	1.5	2.6	1.1	0.4	0.3	0.3	2.1
Total	10	8	5.0	6	7	3.9	3.2	0.8	11.3

K-matrix model for $X(3960)$

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$$\begin{pmatrix} \mathcal{M}_{D_s^+D_s^-\to D_s^+D_s^-} & \mathcal{M}_{D_s^+D_s^-\to J/\psi\phi} \\ \mathcal{M}_{J/\psi\phi\to D_s^+D_s^-} & \mathcal{M}_{J/\psi\phi\to J/\psi\phi} \end{pmatrix} \equiv \begin{pmatrix} \mathcal{K}_{11} & \mathcal{K}_{12} \\ \mathcal{K}_{21} & \mathcal{K}_{22} \end{pmatrix}$$

$$\mathcal{K}_{ab}(m) = \sum_R \frac{g_b^R g_a^R}{M_R^2 - m^2} + f_{ab}$$

$$\mathcal{P}_b(m) = \sum_R \frac{\beta_R g_b^R}{M_R^2 - m^2} + \beta_b$$

$$\mathcal{M}_a = \sum_b (I - i\rho\mathcal{K})^{-1}_{ab}\mathcal{P}_b$$

Contribution	J^{PC}	M_R (MeV)	g_1^R (MeV)	Γ_ψ (MeV)	$\mathcal{F}$ (%)
$\lvert\mathcal{M}_1\rvert^2$	0^{++}	3957 ± 14	1350 ± 344		94.7 ± 0.4
$\psi(4260)$	1^{--}	4230 [59]		55 [59]	3.2 ± 0.5
$\psi(4660)$	1^{--}	4633 [31]		64 [31]	2.1 ± 0.2

β_R	$(1, 0i)$	β_1	$(-1.2, 2.5i) \pm (4.5, 3.1i)$
β_2	$(-137.2, -1.5i) \pm (2.7, 218.6i)$	f_{11}	0.8 ± 1.2
$f_{12} = f_{21}$	0.1 ± 0.1	f_{22}	8.0 ± 5.1

Large uncertainties. Larger data sample is needed

K-matrix model for $X(3960)$

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$$\begin{pmatrix} \mathcal{M}_{D_s^+D_s^-\to D_s^+D_s^-} & \mathcal{M}_{D_s^+D_s^-\to J/\psi\phi} \\ \mathcal{M}_{J/\psi\phi\to D_s^+D_s^-} & \mathcal{M}_{J/\psi\phi\to J/\psi\phi} \end{pmatrix} \equiv \begin{pmatrix} \mathcal{K}_{11} & \mathcal{K}_{12} \\ \mathcal{K}_{21} & \mathcal{K}_{22} \end{pmatrix}$$

$$\mathcal{K}_{ab}(m) = \sum_R \frac{g_b^R g_a^R}{M_R^2 - m^2} + f_{ab}$$

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$f_{12} = f_{21}$		0.1 ± 0.1	f_{22}	8.0 ± 5.1	

Large uncertainties. Larger data sample is needed

$\mathcal{B}(B^+ \to D_s^+ D_s^- K^+)$

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LHCb-PAPER-2022-019

- Essential input to calculate the width fraction

$$\frac{\Gamma(X \to D^+ D^-)}{\Gamma(X \to D_s^+ D_s^-)} = \frac{\mathcal{B}(B^+ \to D^+ D^- K^+)\, \mathcal{FF}^X_{B^+ \to D^+ D^- K^+}}{\mathcal{B}(B^+ \to D_s^+ D_s^- K^+)\, \mathcal{FF}^X_{B^+ \to D_s^+ D_s^- K^+}}$$

FF: Fit fraction

- Relative measurement

$$\mathcal{R} \equiv \frac{\mathcal{B}(B^+ \to D_s^+ D_s^- K^+)}{\mathcal{B}(B^+ \to D^+ D^- K^+)} = \frac{N^{\text{corr}}_{\text{sig}}}{N^{\text{corr}}_{\text{con}}} \left[\frac{\mathcal{B}(D^+ \to K^- \pi^+ \pi^+)}{\mathcal{B}(D_s^+ \to K^- K^+ \pi^+)} \right]^2$$

Know quantities from PDG

- w_{sig}, w_{con}: sWeights determined from B^+ mass fits to extract the signal components
- ϵ_{sig}, ϵ_{con}: efficiency obtained from MC simulation

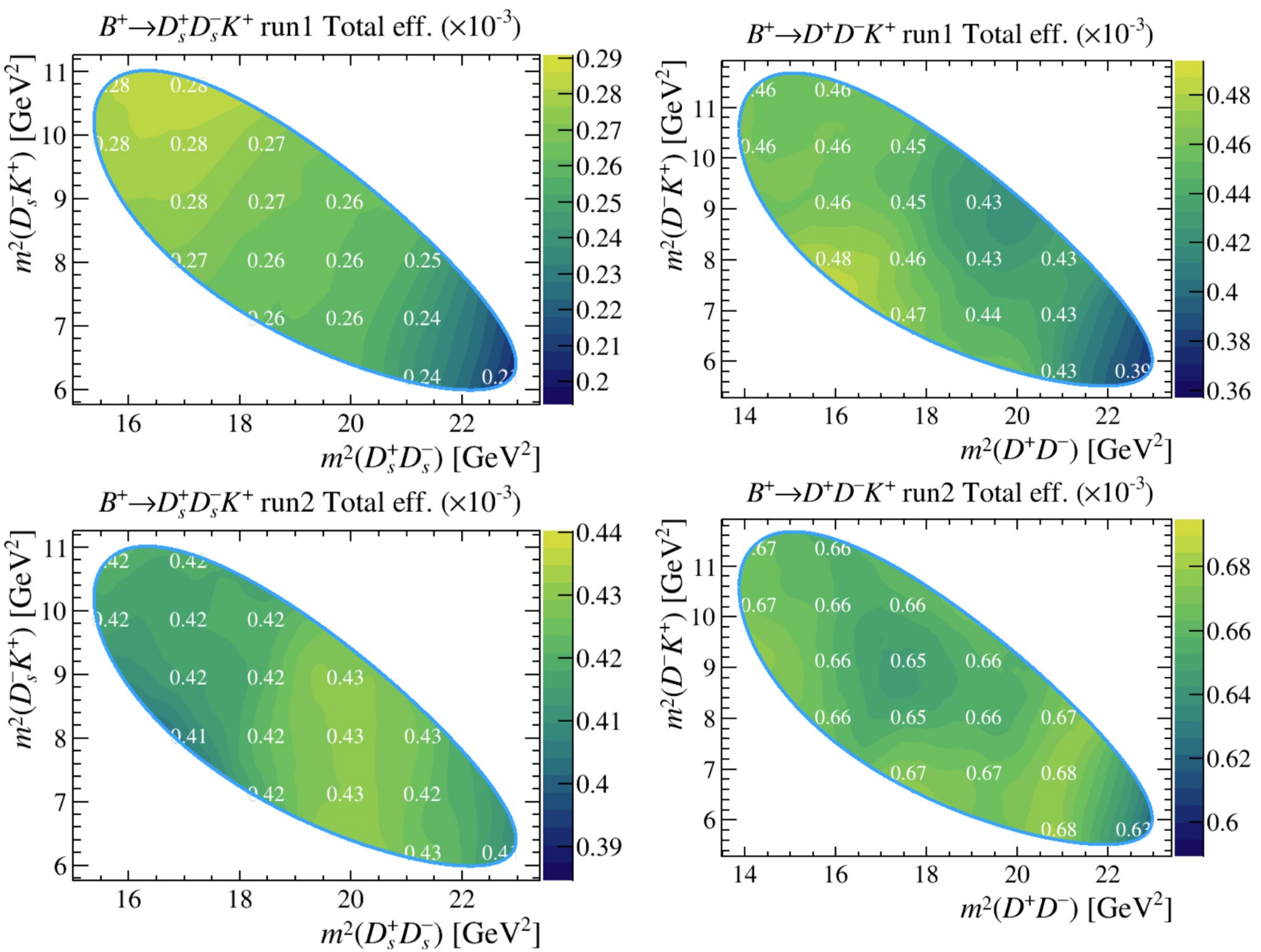
$$N^{\text{corr}}_{\text{sig}} = \sum_i \frac{w_{\text{sig},\, i}}{\epsilon_{\text{sig},\, i}(m^2(D_s^+ D_s^-), m^2(D_s^- K^+))}$$

$$N^{\text{corr}}_{\text{con}} = \sum_i \frac{w_{\text{con},\, i}}{\epsilon_{\text{con},\, i}(m^2(D^+ D^-), m^2(D^- K^+))}$$

Efficiency

LHCb-PAPER-2022-018
LHCb-PAPER-2022-019

- **Denominator:** Generator-level MC sample without any cut
- **Numerator:** Fully reconstructed MC sample after all the selection



Kernel density estimation is employed to obtain the smooth efficiency functions

Branching fraction result

LHCb-PAPER-2022-018
LHCb-PAPER-2022-019

$$\mathcal{R} = \frac{\mathcal{B}(B^+ \to D_s^+ D_s^- K^+)}{\mathcal{B}(B^+ \to D^+ D^- K^+)} = 0.525 \pm 0.033 \pm 0.027 \pm 0.034$$

1. Stat.
2. Syst.
3. External

Systematic source	Relative uncertainty (%)
L0 trigger correction	2.3
Signal model variation	0.3
Background model variation	0.1
B^+ mass fit bias	0.1
Limited size of MC samples	0.5
KDE parameters	0.4
Charmless and single-charm background	2.9
PID resampling	2.8
BDT working point	1.6
Tracking efficiency	1.0
Multiple candidate removal	0.7
MC truth match efficiency	0.6
Total syst. (stat.)	5.1 (6.3)

Full $J/\psi\eta$ mass range

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