Observation of a resonant structure near the $D_s^+ D_s^-$ threshold at LHCb

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First measurement of $B^+ \to D_s^+ D_s^- K^+$ decay

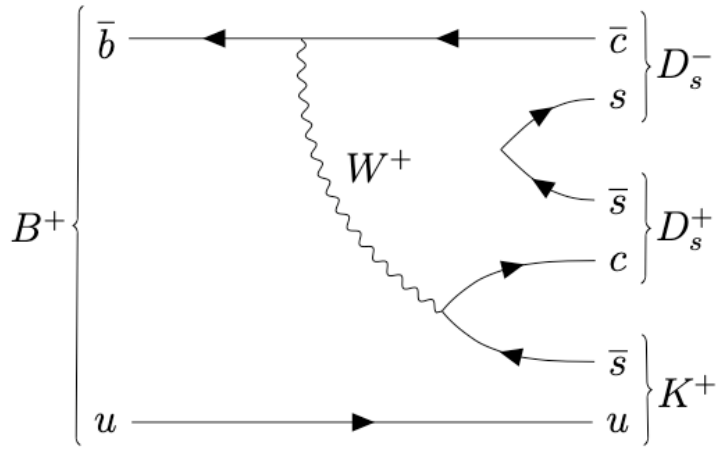
$\bar{b} \to \bar{c}c\bar{s}$

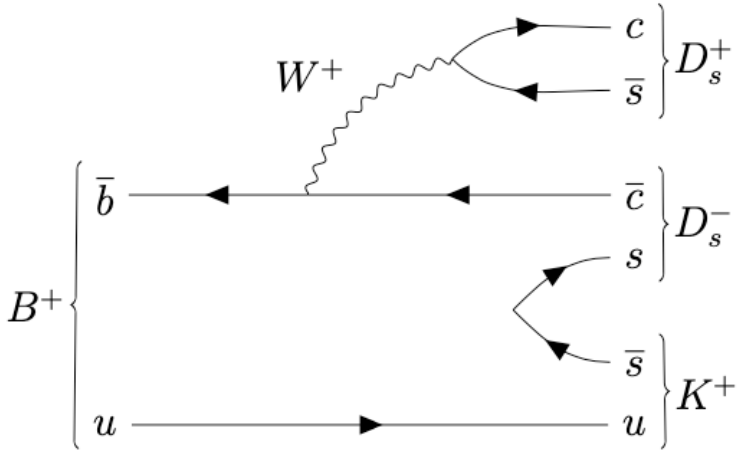
Useful links

- CERN seminar
- IHCEP2022
- Quark confinement 2022

Based on:

LHCb-PAPER-2022-018 [Amplitude analysis, in preparation]
LHCb-PAPER-2022-019 [Branching fraction, in preparation]





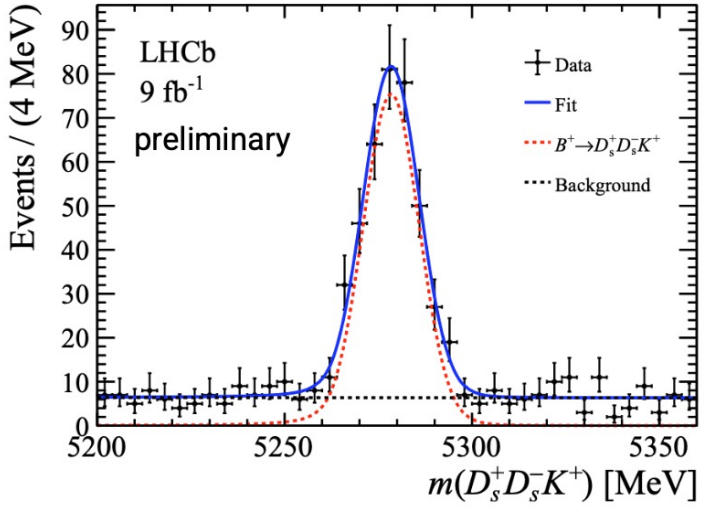
- Cabibbo favoured $\bar{b} \to \bar{c}c\bar{s}$ transition only focus on $D^{(*)}\overline{D}^{(*)}$ to date.
- Those involving $D_s^{(*)+} D_s^{(*)-}$ pairs have never been explored.
- Such decays provide an excellent groundwork for investigations of open-charm and charmonium spectroscopy

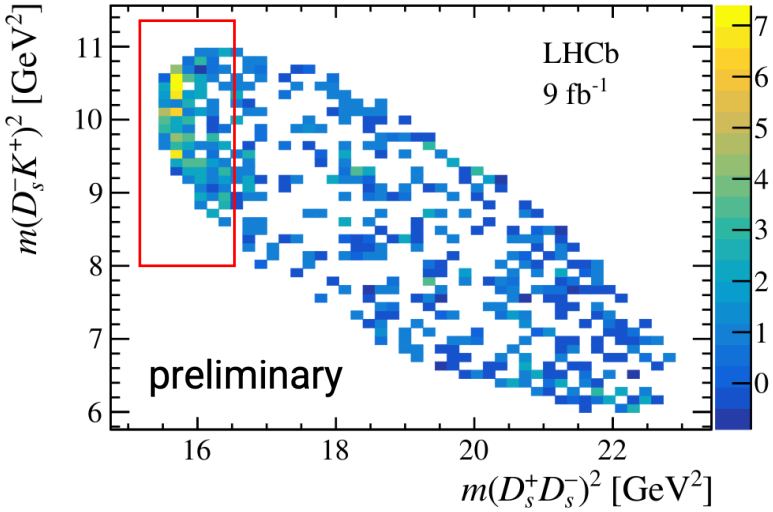
Note: charge-conjugate processes are always included.

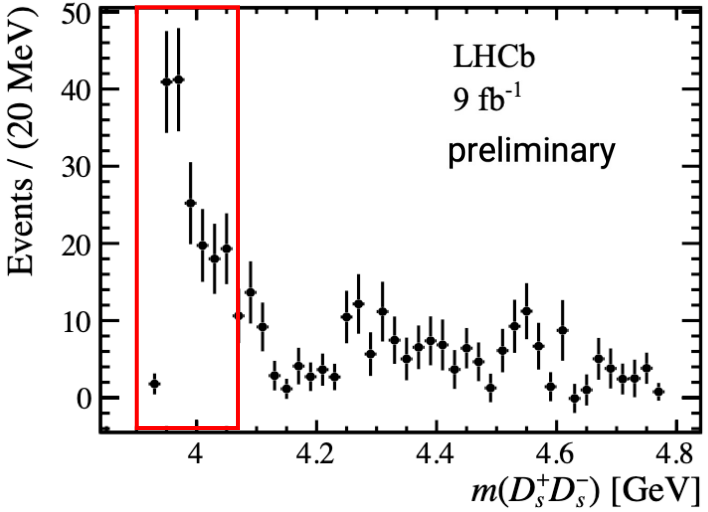
Yields and distributions

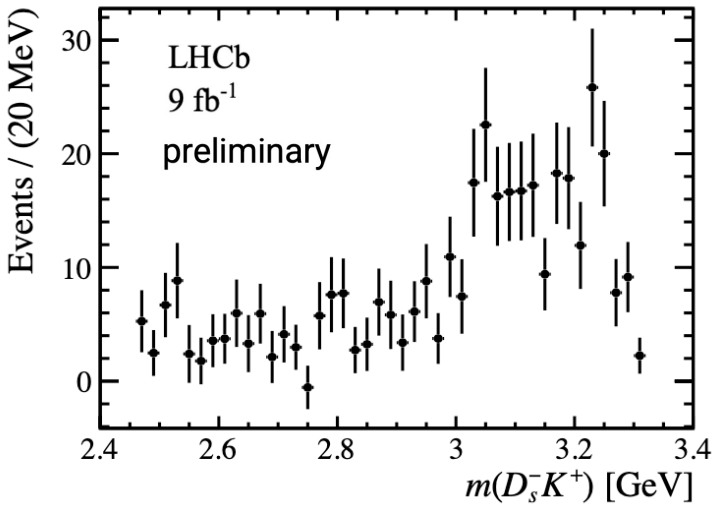
- Full data set, 9 fb^{-1}
- $D_s^+ \to K^+K^-\pi^+$
- 360 B^+ signal candidates
- Purity of 84.4% within ± 20 MeV

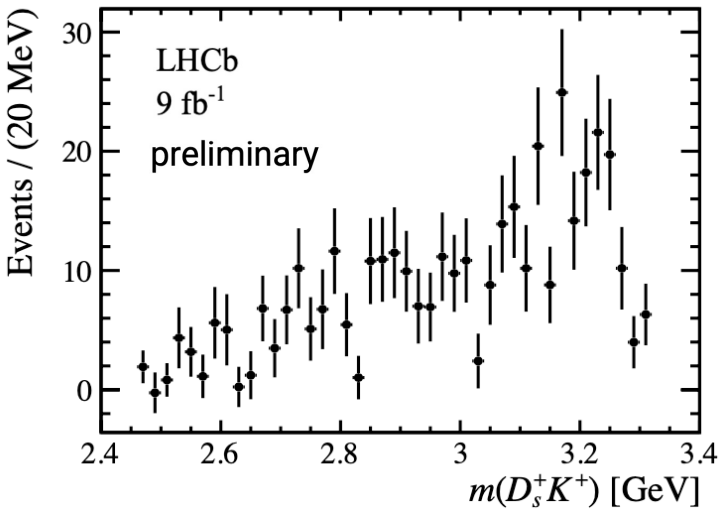
Threshold enhancement at $D_s^+ D_s^-$



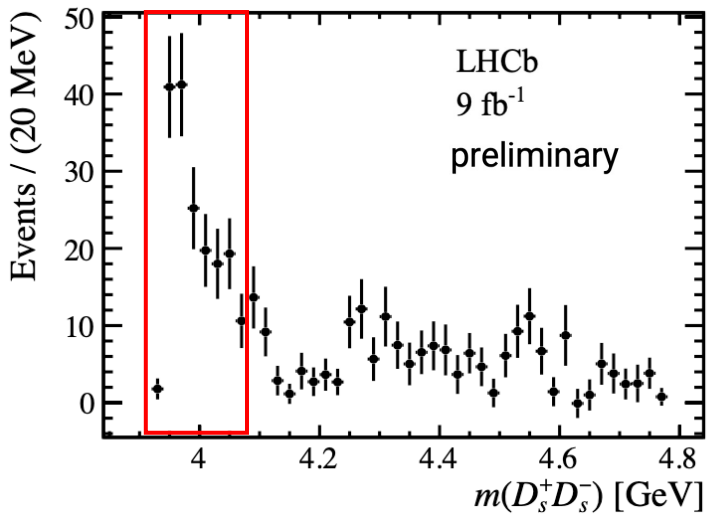


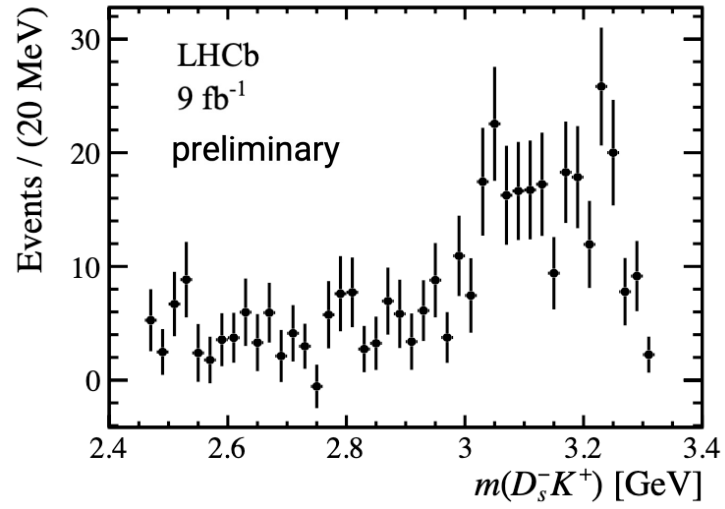






Considered components



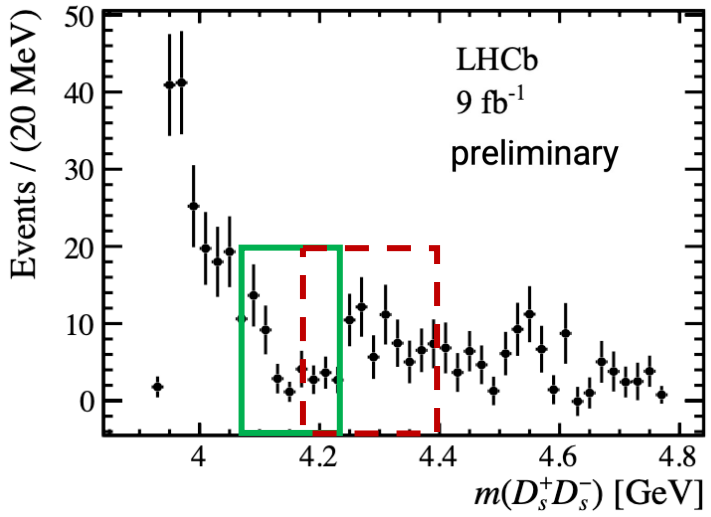


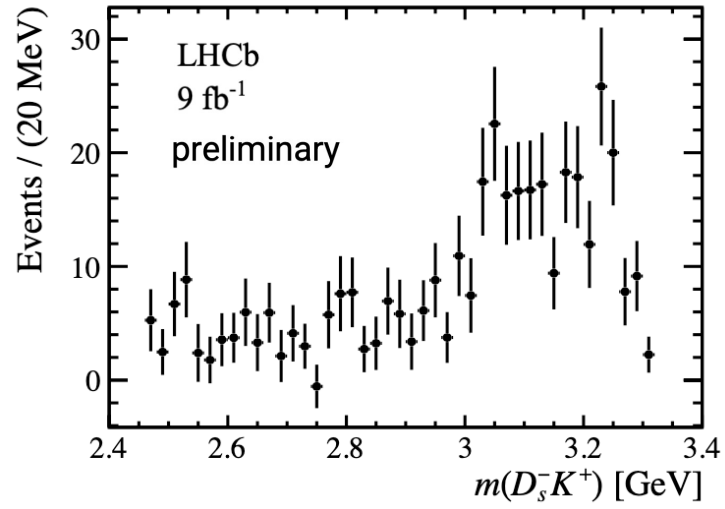
$D_s^+ D_s^-$	$X(3960)$	0^{++}
	$\chi_{c0}(4500)$	0^{++}
	$\chi_{c0}(4700)$	0^{++}
	$\psi(4040)$	1^{--}
	$\psi(4160)$	1^{--}
	$\psi(4260)$	1^{--}
	$\psi(4415)$	1^{--}
	$\chi_{c2}(3930)$	2^{++}
$D_s^- K^+$	$\overline{D}_0^*(2300)^0$	0^+
	$\overline{D}_1^*(2600)^0$	1^-
	$\overline{D}_1^*(2760)^0$	1^-
	$\overline{D}_2^*(2460)^0$	2^+
3-body PHSP	NR	S-wave

From $J/\psi\phi$

From PDG 2020

Considered components



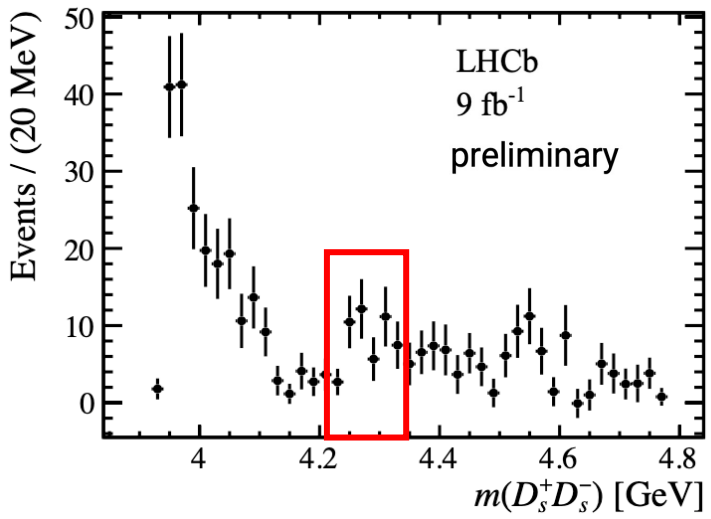


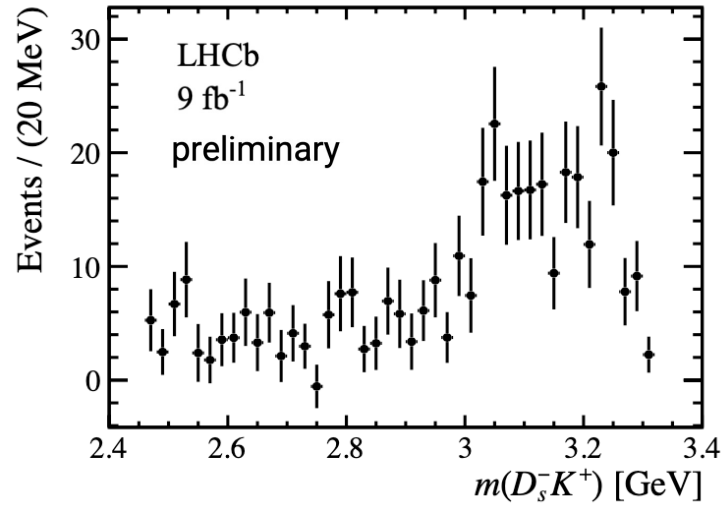
Need a state to describe the dip around 4140 MeV!

$X_0(4140) \neq \mathrm{X}(4140)$ in the $J/\psi\phi$ system

$D_s^+ D_s^-$	$X(3960)$	0^{++}	$> 14\sigma$
	$X_0(4140)$	0^{++}	$\sim 4\sigma$
	$\chi_{c0}(4500)$	0^{++}	
	$\chi_{c0}(4700)$	0^{++}	
	$\psi(4040)$	1^{--}	
	$\psi(4160)$	1^{--}	
	$\psi(4260)$	1^{--}	
	$\psi(4415)$	1^{--}	
	⋮	⋮	
	$\chi_{c2}(3930)$	2^{++}	
$D_s^- K^+$	$\overline{D}_0^*(2300)^0$	0^+	
	$\overline{D}_1^*(2600)^0$	1^-	
	$\overline{D}_1^*(2760)^0$	1^-	
	$\overline{D}_2^*(2460)^0$	2^+	
3-body PHSP	NR	S-wave	$> 3\sigma$

Considered components





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	$X_0(4140)$	0^{++}	$\sim 4\sigma$
	$\chi_{c0}(4500)$	0^{++}	
	$\chi_{c0}(4700)$	0^{++}	
	$\psi(4040)$	1^{--}	
	$\psi(4160)$	1^{--}	
	$\psi(4260)$	1^{--}	$> 3\sigma$
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$D_s^- K^+$	$\overline{D}_0^*(2300)^0$	0^+	
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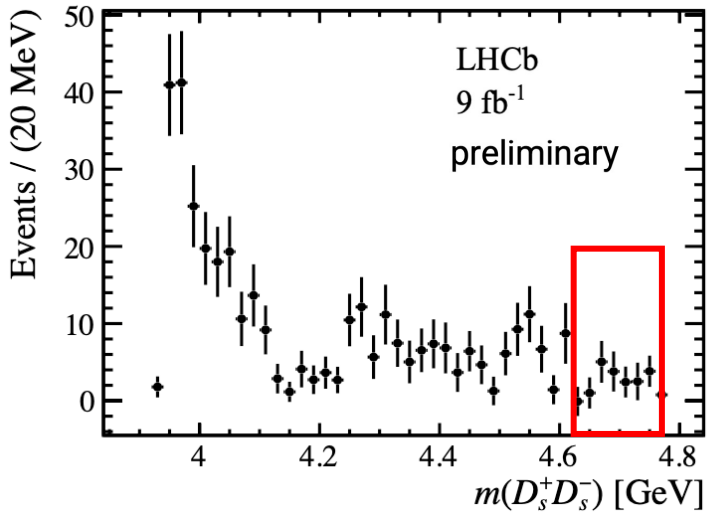
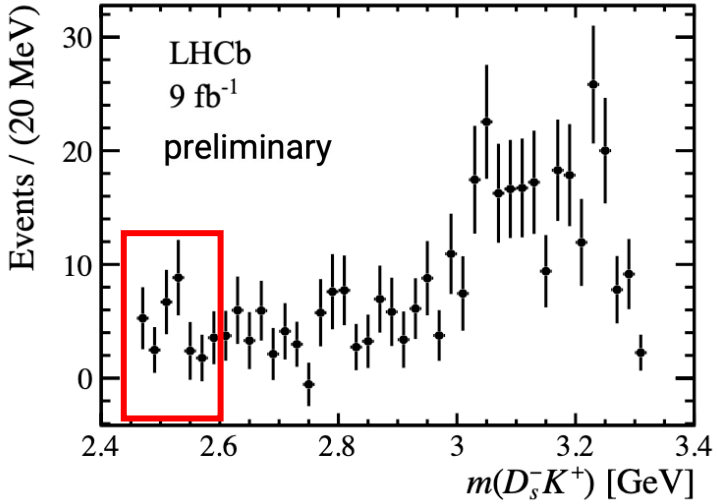
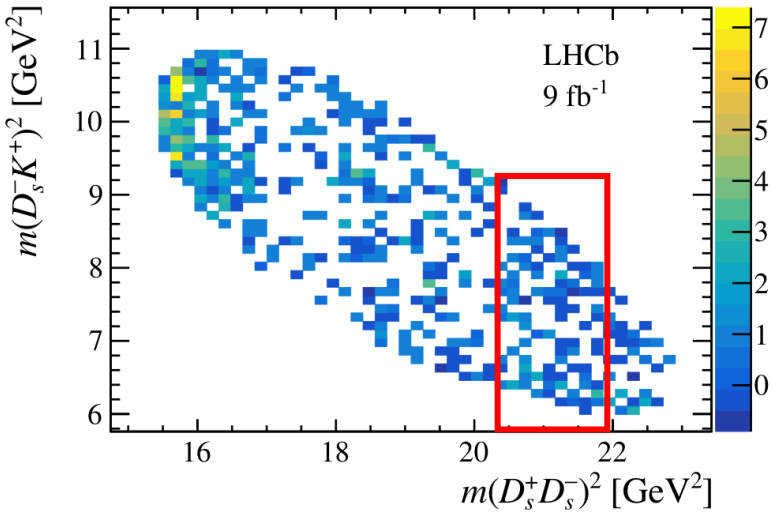
3-body PHSP	NR	S-wave	$> 3\sigma$

Considered components

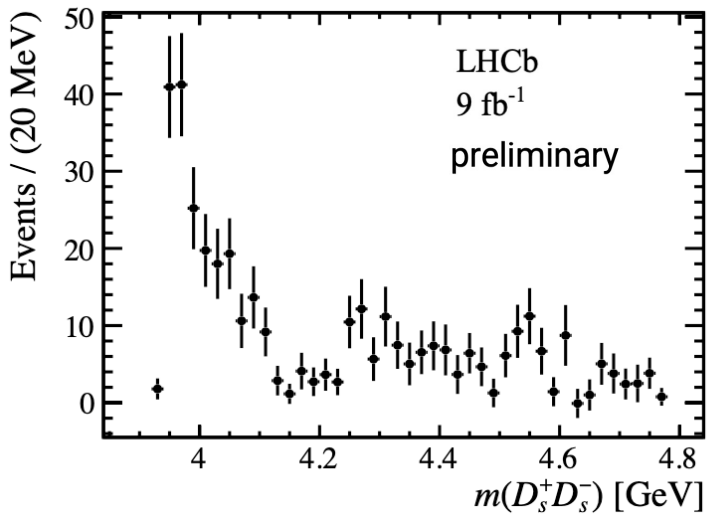


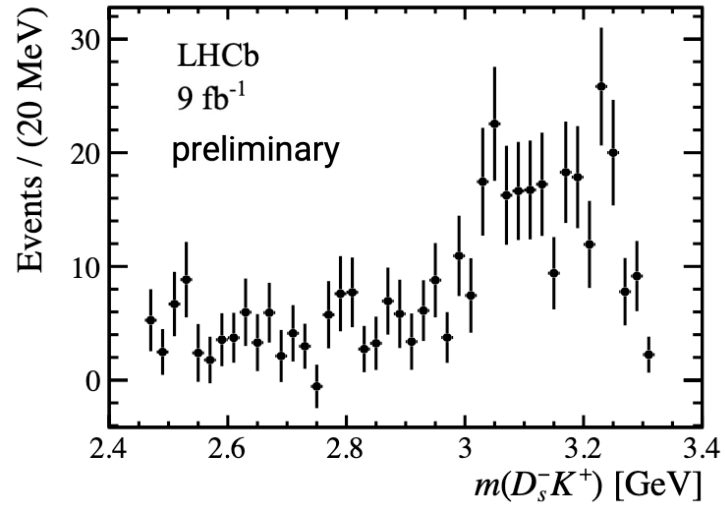


- Test $\overline{D}^*(2300)^0 \to D_s^- K^+$, failed
- From Dalitz and mass distributions, there may exist a $\psi(4660)$ satete.



Considered components



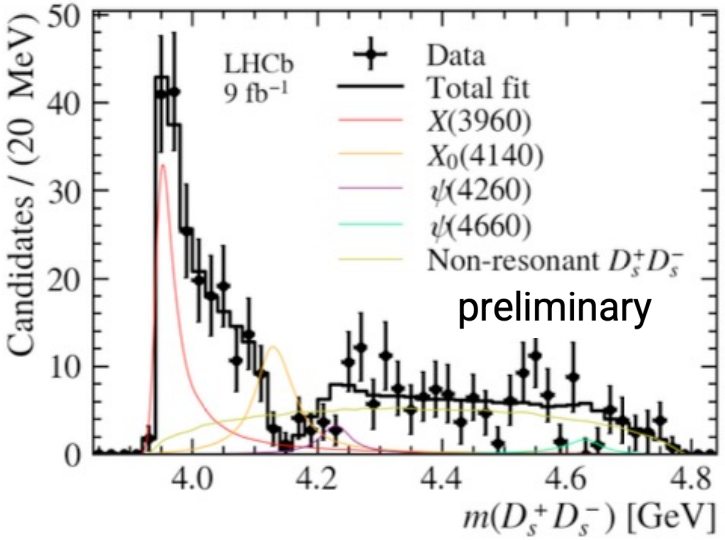


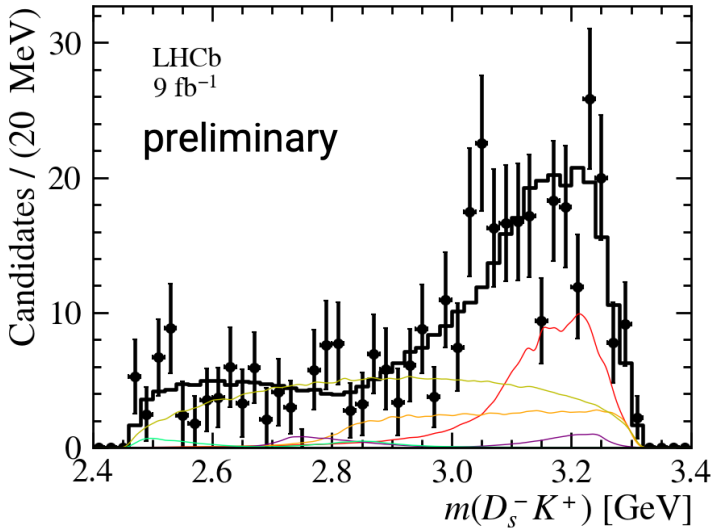
Adding $\psi(4600)$

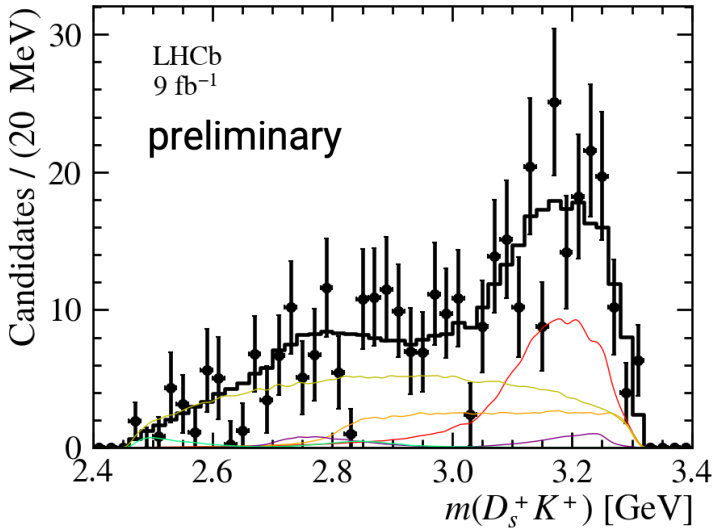
$\mathcal{S}(\text{others}) < 2\sigma$

$D_s^+ D_s^-$	$X(3960)$	0^{++}	$> 14\sigma$
	$X_0(4140)$	0^{++}	$\sim 4\sigma$
	$\chi_{c0}(4500)$	0^{++}	
	$\chi_{c0}(4700)$	0^{++}	
	$\psi(4040)$	1^{--}	
	$\psi(4160)$	1^{--}	
	$\psi(4260)$	1^{--}	$> 3\sigma$
	$\psi(4415)$	1^{--}	
	$\psi(4660)$	1^{--}	$> 3\sigma$
	$\chi_{c2}(3930)$	2^{++}	
$D_s^- K^+$	$\overline{D}_0^*(2300)^0$	0^+	
	$\overline{D}_1^*(2600)^0$	1^-	
	$\overline{D}_1^*(2760)^0$	1^-	
	$\overline{D}_2^*(2460)^0$	2^+	
3-body PHSP	NR	S-wave	$> 3\sigma$

Baseline amplitude fit



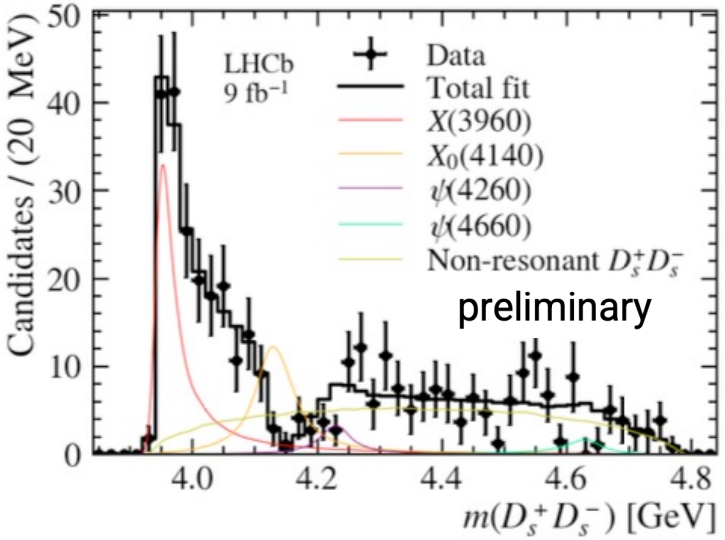




$X(3960)$: significant $X_0(4140)$ and ψ states: need to be confirmed in future

Component	J^{PC}	M_0 (MeV)	Γ_0 (MeV)	$\mathcal{F}$ (%)	$\mathcal{S}$ (σ)
$X(3960)$	0^{++}	$3956 \pm 5 \pm 11$	$43 \pm 13 \pm 8$	$25.4 \pm 7.7 \pm 8.0$	12.6 (14.3)
$X_0(4140)$	0^{++}	$4133 \pm 6 \pm 11$	$67 \pm 17 \pm 7$	$16.7 \pm 4.7 \pm 7.5$	3.7 (3.9)
$\psi(4260)$	1^{--}	4230	55	$3.6 \pm 0.4 \pm 3.0$	3.1 (3.3)
$\psi(4660)$	1^{--}	4633	64	$2.2 \pm 0.2 \pm 0.5$	2.9 (3.2)
NR	S-wave	-	-	$46.1 \pm 13.2 \pm 11.1$	3.1 (3.4)

Baseline amplitude fit



State	J^P preference	$\mathcal{S}(\sigma)$
$X(3960)$	0^+ over $1^-/2^+$	>9.3
$X_0(4140)$	0^+ over $1^-/2^+$	>3.5

$\mathcal{F}$: fit fraction

$\mathcal{S}$: significance (numbers in brackets don't include sys. effects)

Component	J^{PC}	M_0 (MeV)	Γ_0 (MeV)	$\mathcal{F}$ (%)	$\mathcal{S}$ (σ)
$X(3960)$	0^{++}	$3956 \pm 5 \pm 11$	$43 \pm 13 \pm 8$	$25.4 \pm 7.7 \pm 8.0$	12.6 (14.3)
$X_0(4140)$	0^{++}	$4133 \pm 6 \pm 11$	$67 \pm 17 \pm 7$	$16.7 \pm 4.7 \pm 7.5$	3.7 (3.9)
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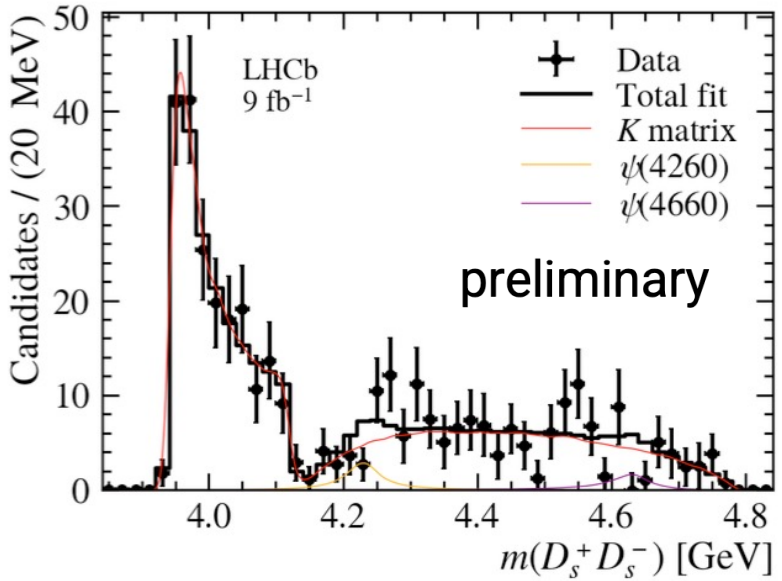
NR	S-wave	-	-	$46.1 \pm 13.2 \pm 11.1$	3.1 (3.4)

Alternative *K*-matrix model

- Dip around 4140 MeV near the $J/\psi\phi$ threshold
- A simple K-matrix with an explicit resonance and two coupled channels ($D_s^+D_s^-$ and $J/\psi\phi$)



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

$$\mathcal{K}_{ba}(m) = \sum_R \frac{g_b^R g_a^R}{M_R^2 - m^2} + f_{ba} \qquad \mathcal{P}_b(m) = \sum_R \frac{\beta_R g_b^R}{M_R^2 - m^2} + \beta_b$$

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

The dip can also be described by the $J/\psi\phi \leftrightarrow D_s^+D_s^-$ reaction.

Treat $X(3960)$ and $\chi_{c0}(3930)$ as same state | $T^f_{\psi\phi}$ or $\chi_{c0}(2P)$

$D_s^+D_s^-$ **threshold: 3936.7 MeV**

Resonance	J^{PC}	M_0 (MeV)	Γ_0 (MeV)	Decay	Reference
$X(3960)$	0^{++}	$3956 \pm 5 \pm 11$	$43 \pm 13 \pm 8$	$D_s^+D_s^-$	This work
$\chi_{c0}(3930)$	0^{++}	$3923.8 \pm 1.5 \pm 0.4$	$17.4 \pm 5.1 \pm 0.8$	D^+D^-	PRD102.112003(2020)
$\chi_{c0}(3915)$	$0^{++}/2^{++}$	3921.7 ± 1.8	18.8 ± 3.5	$D^+D^-, J/\psi\omega, \gamma\gamma$	PDG 2022

$$\frac{\Gamma(X \to D^+D^-)}{\Gamma(X \to D_s^+D_s^-)} = \frac{\mathcal{B}^{(1)}\,\mathcal{F}_X^{(1)}}{\mathcal{B}^{(2)}\,\mathcal{F}_X^{(2)}} = 0.29 \pm 0.09 \pm 0.10 \pm 0.08, \quad <1.0$$

- **It is harder to excite an $s\bar{s}$ pair from vacuum compared with $u\bar{u}(d\bar{d})$**
- **Phase space of $X \to D_s^+D_s^-$ is much smaller than $X \to D^+D^-$**

This X state seems not to be a pure charmonium!

Potential models for excited χ_{c0} states

$T^f_{\psi\phi}$ or $\chi_{c0}(2P)$

State		EXP	NRT	GI	PT	NPT	SP	GEM
1^3P_0	$\chi_{c0}(1P)$	3414.71 ± 0.30	3424	3445	3415.7	3415.2	3433	3430
1^3P_1	$\chi_{c1}(1P)$	3510.67 ± 0.05	3505	3510	3508.2	3510.6	3510	3491
1^3P_2	$\chi_{c2}(2P)$	3556.17 ± 0.07	3556	3550	3557.7	3556.2	3554	3523
2^3P_0	$\chi_{c0}(3860)$ $\chi_{c0}(3915)$	3862^{+48}_{-35} 3921.7 ± 1.8	3852	3916	3843.7	3864.3	3842	3868
2^3P_1	$\chi_{c1}(3872)$	3871.65 ± 0.06	3925	3953	3939.7	3950.0	3901	3911
2^3P_2	$\chi_{c2}(3930)$	3922.5 ± 1.0	3972	3979	3993.7	3992.3	3937	3935
3^3P_0			4202	4292			4131	4172
3^3P_1			4271	4317			4178	4204
3^3P_2			4317	4337			4208	4222

- Far away from the predicted $\chi_{c0}(3P)$ mass

Potential models for excited χ_{c0} states

$T^f_{\psi\phi}$ or $\chi_{c0}(2P)$

PRD95, 112003 (2017)

$\chi_{c0}(3860) \to D^+D^- + D^0\bar{D}^0$ in $e^+e^- \to J/\psi D\bar{D}$ decay

$M = 3862\,^{+26}_{-32}\,^{+40}_{-13}$ MeV

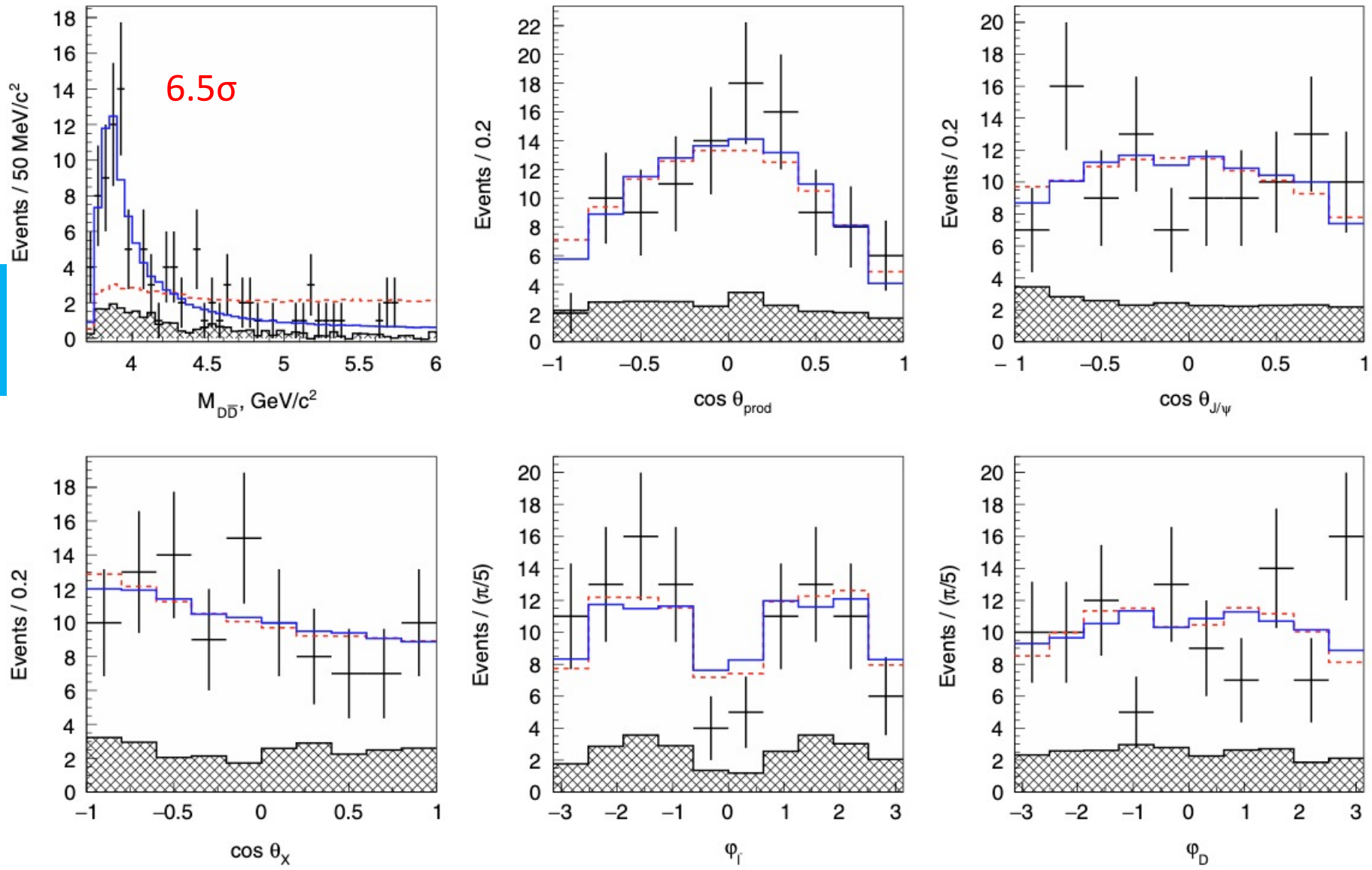
$\Gamma = 201\,^{+154}_{-67}\,^{+88}_{-82}$ MeV

0^{++} over 2^{++}, 2.5σ

Blue line: $\chi_{c0}(3860)$

Red dashed line: NR only

Need to be confirmed !



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1^3P_2	$\chi_{c2}(2P)$	3556.17 ± 0.07	3556	3550	3557.7	3556.2	3554	3523
2^3P_0	$\chi_{c0}(3860)$	3862^{+48}_{-35}	3852	3916	3843.7	3864.3	3842	3868
	$\chi_{c0}(3915)$	3921.7 ± 1.8						
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3^3P_0			4202	4292			4131	4172
3^3P_1			4271	4317			4178	4204
3^3P_2			4317	4337			4208	4222

$\rightarrow$ $X(3960) \neq \chi_{c0}(2P)/\chi_{c0}(3P)$

- Inappropriate mass
- Too small mass splitting, $M[\chi_{c2}(3930)] - M[X(3960)]$ <1 MeV, but theories > 60 MeV

What is nature of $X(3960)$?

$T^{f}_{\psi\phi}$ or $\chi_{c0}(2P)$

- Hybrid state can be ruled out, due to too low mass for a QCD-hybrid candidate (the lightest 0^{++} charmonium hybrid around 4450 MeV)[1]. ✗
- Lightest $c\bar{c}s\bar{s}$ tetraquark, ~3920 MeV, is proposed by Lebed et al.[2]. The QCD sum rule[3] also favors $\chi_{c0}(3915)$ as a 0^{++} $cq\bar{c}\bar{q}$ or $cs\bar{c}\bar{s}$ tetraquark. favour
- Molecular $D_s^+D_s^-$ (virtual) state, is calculated in the quark delocalization color screening model [4]. The recent lattice QCD results[5] found a narrow 0^{++} $D_s^+D_s^-$ bound state. Some phenomenological studies[6] regard it as the molecular (virtual) state. favour

→ $X(3960)$ is probably exotic $c\bar{c}s\bar{s}$ hadron.

[1] arXiv:1204.5425. [2] arXiv:1602.08421, 2005.07100. [3]arXiv:1706.09731.
[4] arXiv: 2103.12425. [5] arXiv:2011.02542, 2111.02934. [6]arXiv: 1503.04431, 2101.01021.

Summary

CERN 65th hadron

Branching fraction ratio

- First observation of the $B^+ \to D_s^+ D_s^- K^+$ decay
- Relative branching fraction is measured

LHCb Preliminary

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

Amplitude analysis

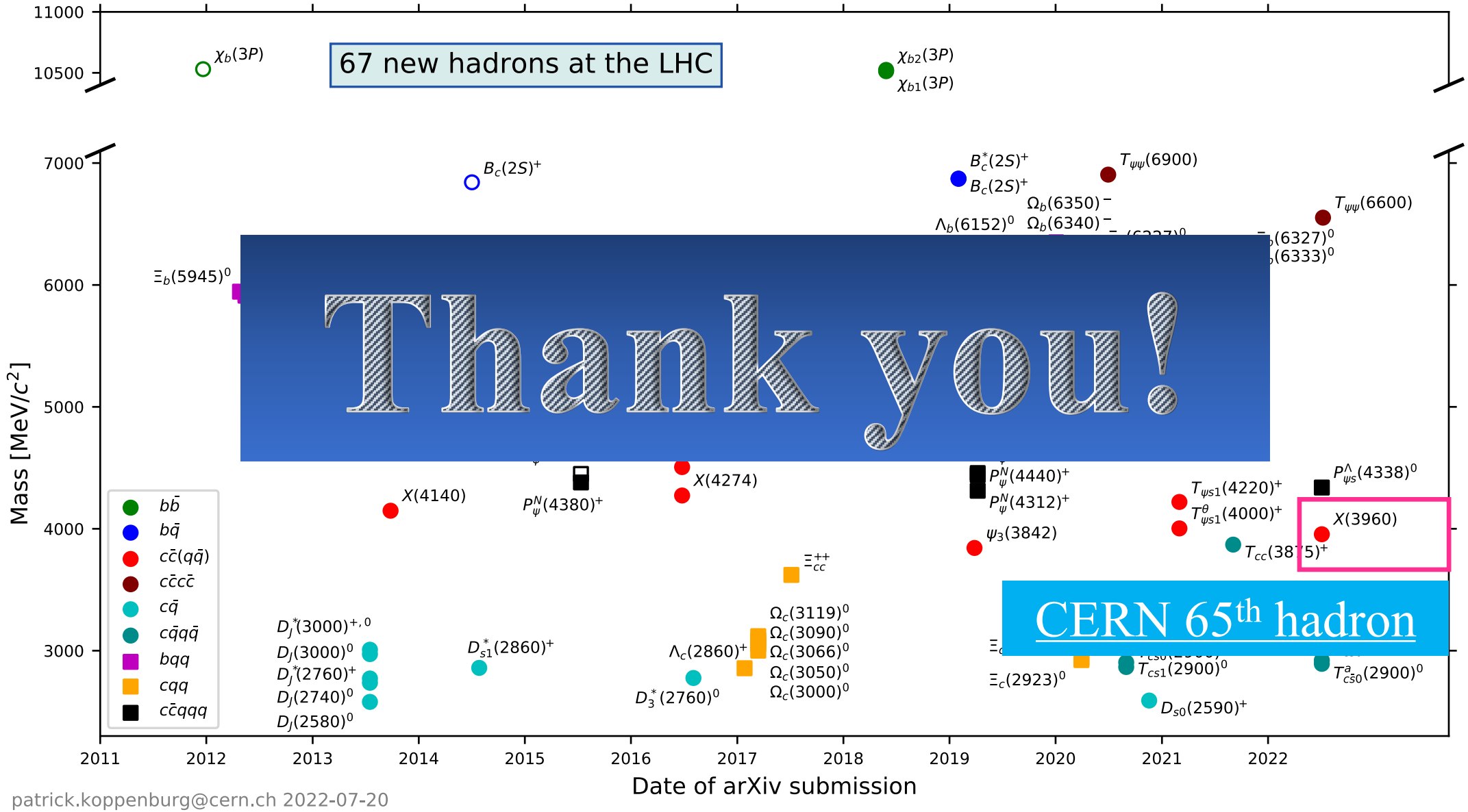
- First observation of the $D_s^+ D_s^-$ near-threshold structure, named $X(3960)$
- Favor exotic $c\bar{c}s\bar{s}$ state, disfavor $\chi_{c0}(2P)/\chi_{c0}(3P)$; if confirmed, should name $T^f_{\psi\phi}(3960)$
- New X(3960) : $M_0 = 3956 \pm 5 \pm 11$ MeV, $\Gamma_0 = 43 \pm 13 \pm 8$ MeV, $\mathcal{S} > 12\sigma$

  $J^{PC} = 0^{++}$ over $1^{--}/2^{++}$, $\mathcal{S} > 9\sigma$

CERN 65th hadron

- New $X_0(4140)$: only a hint ($<4\sigma$), need to more statistics to confirm

X(3960) is 65th new hadrons at CERN



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Back Up

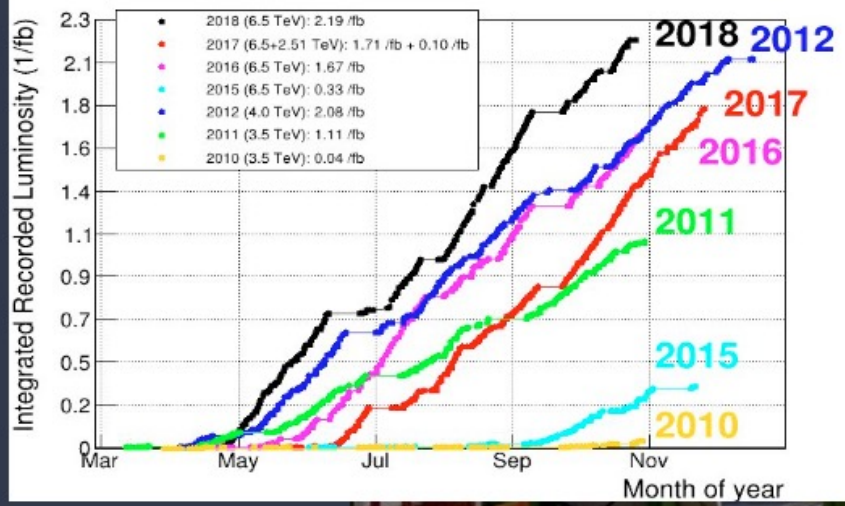
LHCb detector

JINST 3 (2008) S08005
IJMP A 30, 1530022 (2015)

The major player in spectroscopy thanks to its unique dedicated design

- high invariant mass resolution
- PID for separate *K*, *π*, *p*
- highly performant trigger

Luminosity:
Run 1 and Run 2: 9 fb^{-1}



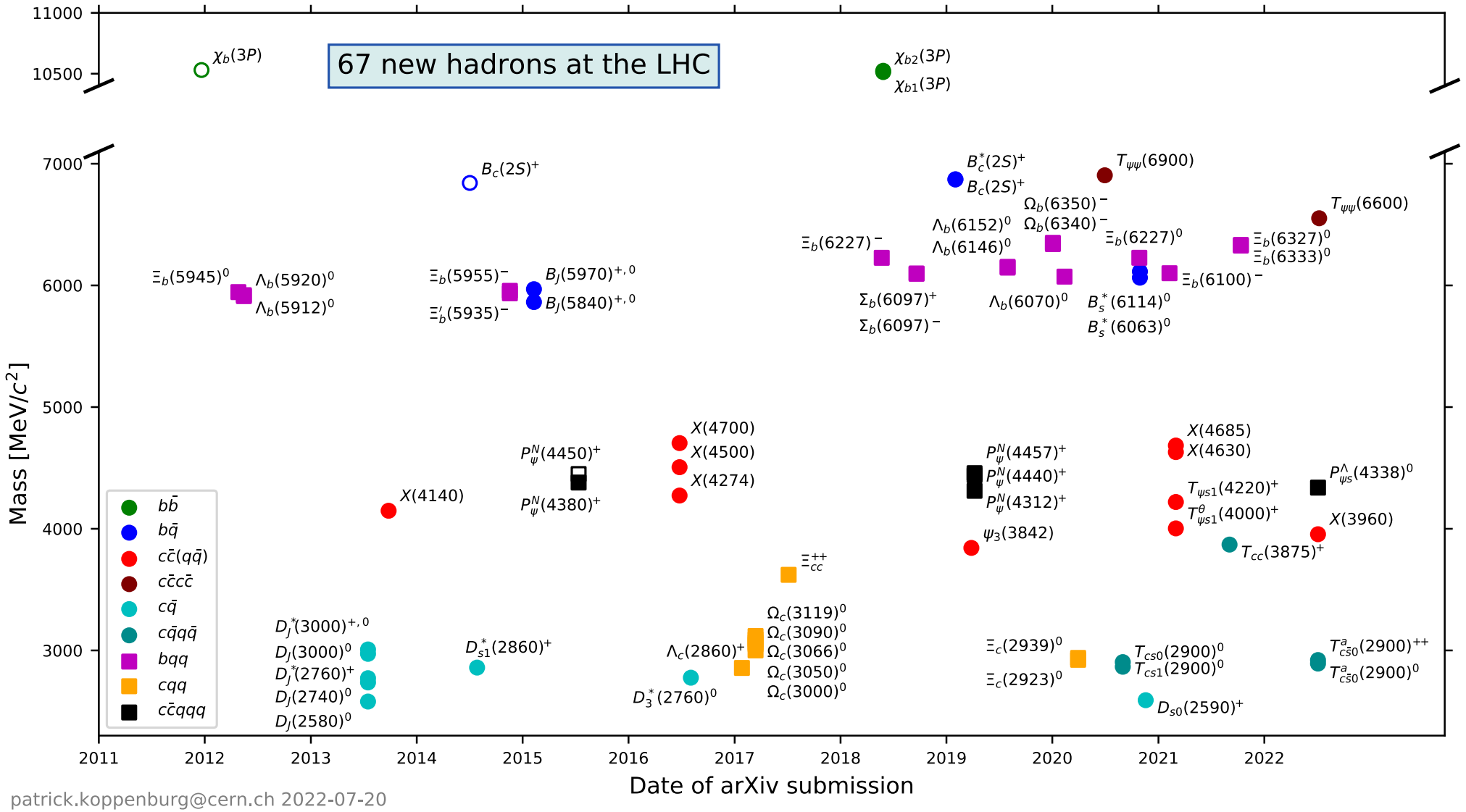
Tracking: momentum resolution of $\sigma_p / p \sim 0{,}5 - 1\%$

VELO: vertex detector
IP resolution: ~25 μm

Muon chambers, hardware trigger with ~90% efficiency

Calorimeters, hadron trigger with ~50% efficiency

RICH detectors for particle ID. pid(p - K)~95%



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