LHCb results on (ordinary) charmonia and bottomonia

Marco Pappagallo

INFN and University of Bari

On behalf of the LHCb collaboration

Experimental and theoretical status of and perspectives for XYZ states

12-16 April 2021

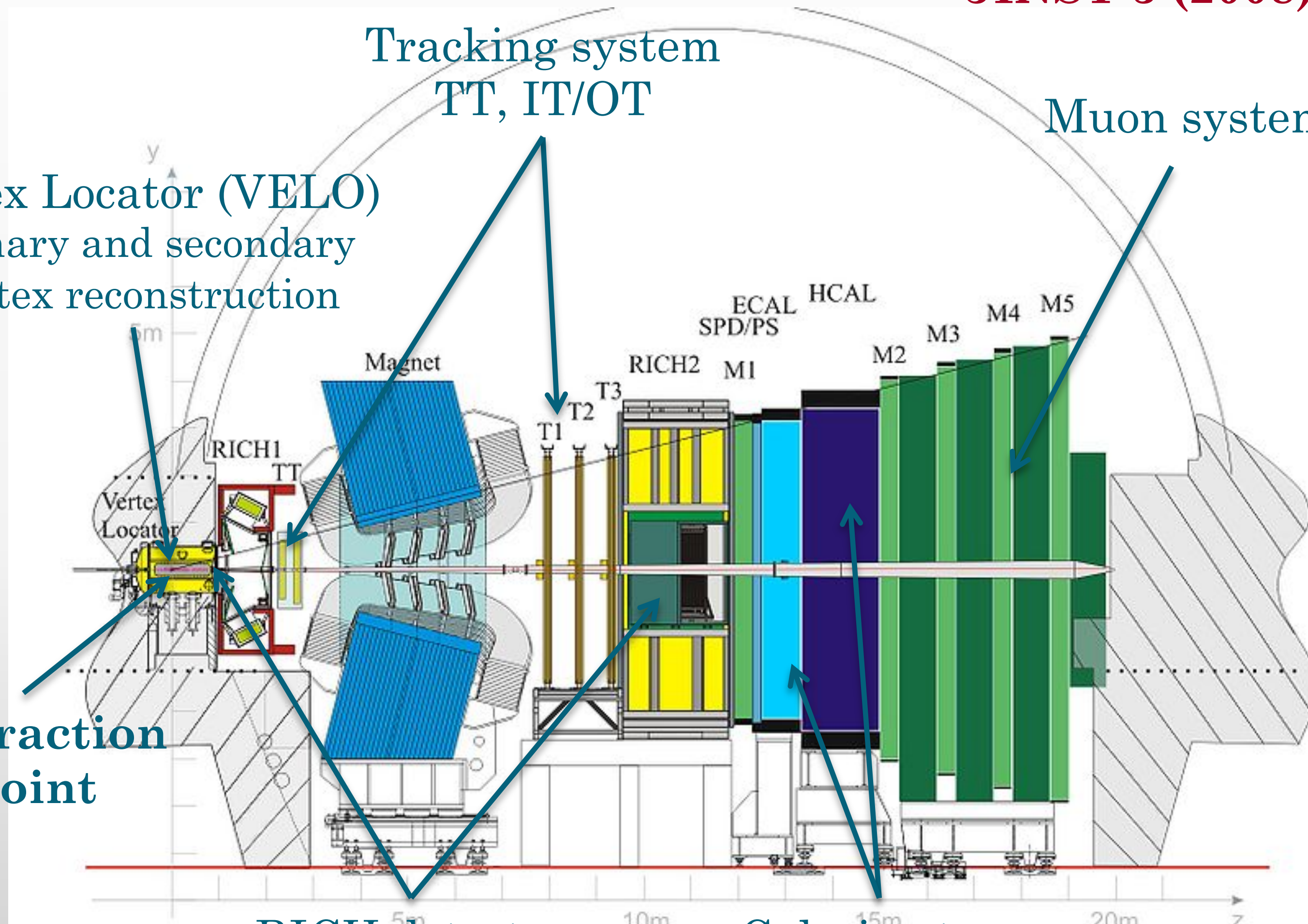
Outline

- Near-threshold $D\bar{D}$ spectroscopy and observation of a new charmonium state [JHEP 07 (2019) 035]
- Study of the $\psi_2(3823)$ and $\chi_{c1}(3872)$ states in $B^+ \to (J/\psi\pi^+\pi^-)K^+$ decays [JHEP 08 (2020) 123]
- Amplitude analysis of the $B^+ \to D^+D^-K^+$ decay

[PRL 125 (2020) 242001, PRD 102 (2020) 112003]

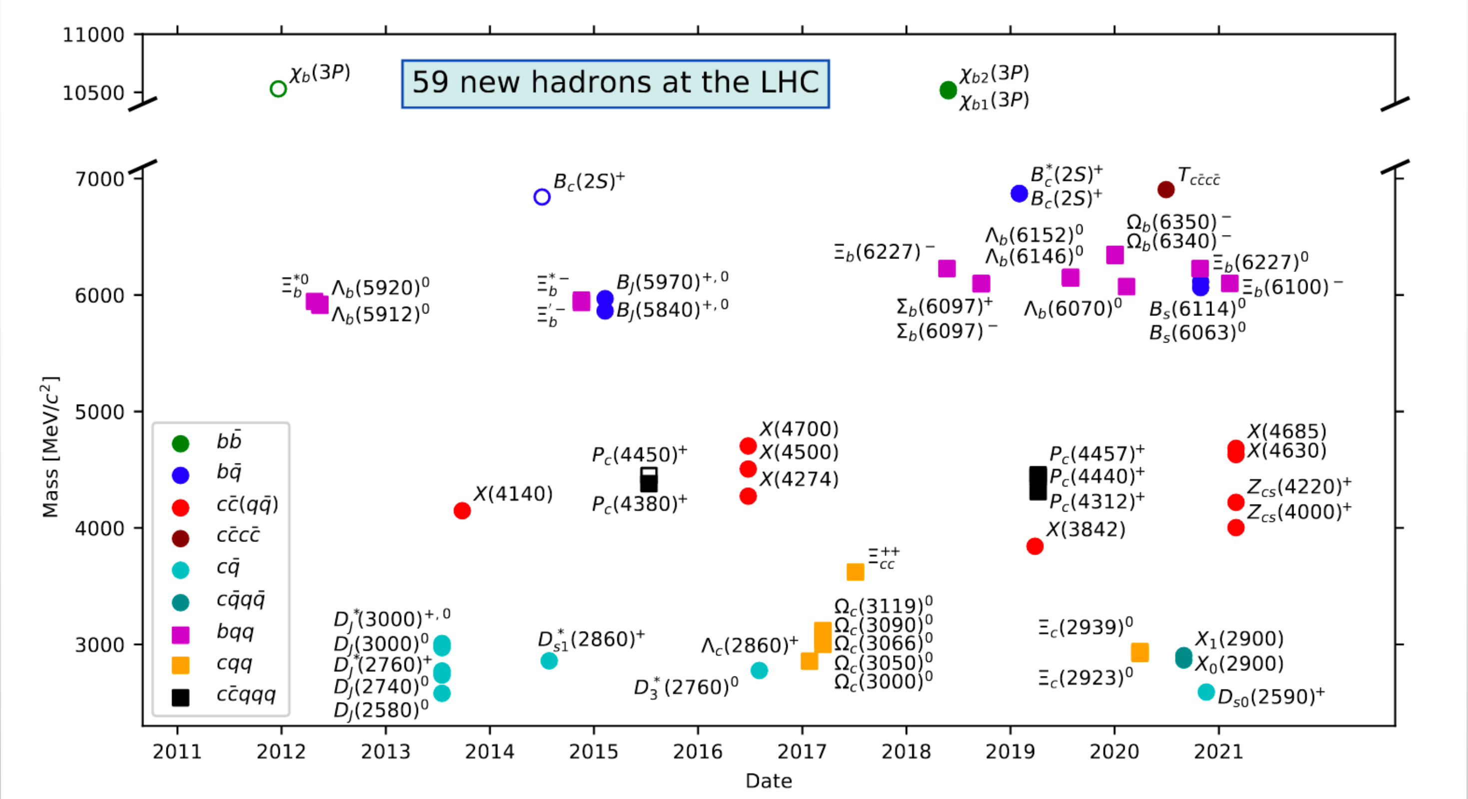
The LHCb Detector

JINST 3 (2008) S08005



50+ New Hadrons at LHC!

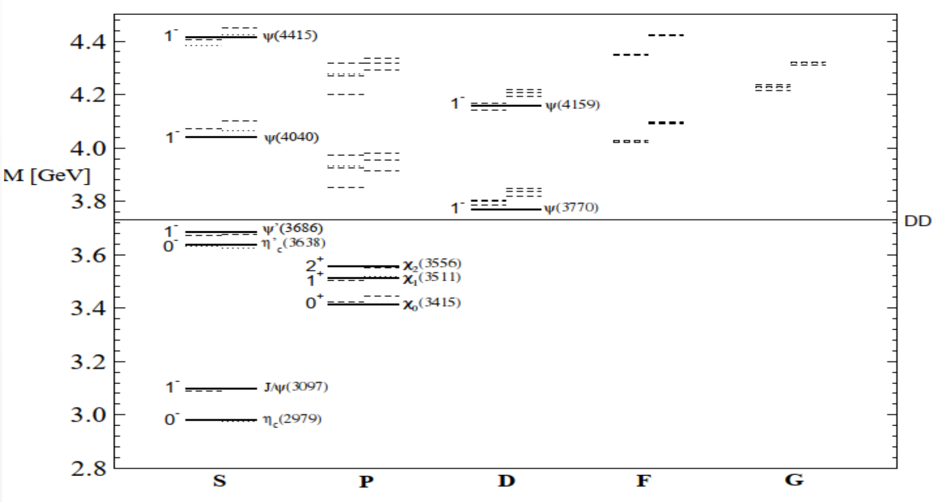
- Over the past 10 years the LHC has discovered 59 new hadrons, mainly from LHCb.
- The discovery of new particles provides valuable information on probing the limits of the quark model.



Near-threshold $D\bar{D}$ spectroscopy and observation of a new charmonium state

[JHEP 07 (2019) 035]

Charmonium



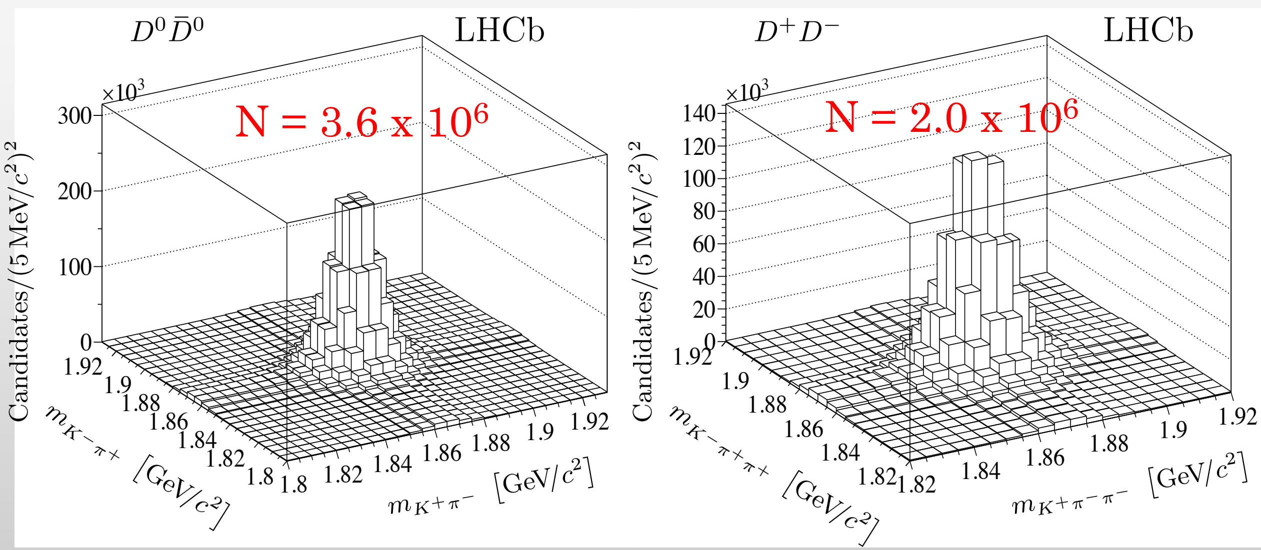
Multiplet	State	Expt.	Input (NR)	Theor. NR	Theor. GI
1S	$J/\psi(1^3S_1)$	3096.87 ± 0.04	3097	3090	3098
	$\eta_c(1^1S_0)$	2979.2 ± 1.3	2979	2982	2975
2S	$\psi'(2^3S_1)$	3685.96 ± 0.09	3686	3672	3676
	$\eta_c'(2^1S_0)$	3637.7 ± 4.4	3638	3630	3623
3S	$\psi(3^3S_1)$	4040 ± 10	4040	4072	4100
	$\eta_c(3^1S_0)$			4043	4064
4S	$\psi(4^3S_1)$	4415 ± 6	4415	4406	4450
	$\eta_c(4^1S_0)$			4384	4425
1P	$\chi_2(1^3P_2)$	3556.18 ± 0.13	3556	3556	3550
	$\chi_1(1^3P_1)$	3510.51 ± 0.12	3511	3505	3510
	$\chi_0(1^3P_0)$	3415.3 ± 0.4	3415	3424	3445
	$h_c(1^1P_1)$	see text		3516	3517
2P	$\chi_2(2^3P_2)$			3972	3979
	$\chi_1(2^3P_1)$			3925	3953
	$\chi_0(2^3P_0)$			3852	3916
	$h_c(2^1P_1)$			3934	3956
3P	$\chi_2(3^3P_2)$			4317	4337
	$\chi_1(3^3P_1)$			4271	4317
	$\chi_0(3^3P_0)$			4202	4292
	$h_c(3^1P_1)$			4279	4318
1D	$\psi_3(1^3D_3)$			3806	3849
	$\psi_2(1^3D_2)$			3800	3838
	$\psi(1^3D_1)$	3769.9 ± 2.5	3770	3785	3819
	$\eta_{c2}(1^1D_2)$			3799	3837
2D	$\psi_3(2^3D_3)$			4167	4217
	$\psi_2(2^3D_2)$			4158	4208
	$\psi(2^3D_1)$	4159 ± 20	4159	4142	4194
	$\eta_{c2}(2^1D_2)$			4158	4208
1F	$\chi_4(1^3F_4)$			4021	4095
	$\chi_3(1^3F_3)$			4029	4097
	$\chi_2(1^3F_2)$			4029	4092
	$h_{c3}(1^1F_3)$			4026	4094
2F	$\chi_4(2^3F_4)$			4348	4425
	$\chi_3(2^3F_3)$			4352	4426
	$\chi_2(2^3F_2)$			4351	4422
	$h_{c3}(2^1F_3)$			4350	4424
1G	$\psi_5(1^3G_5)$			4214	4312
	$\psi_4(1^3G_4)$			4228	4320
	$\psi_3(1^3G_3)$			4237	4323
	$\eta_{c4}(1^1G_4)$			4225	4317

- Many states above $D\bar{D}$ threshold not yet observed
- Two $J^{PC} = 1^{--}$ D-wave states but no states with spin J>2

Near threshold $D\bar{D}$ spectroscopy

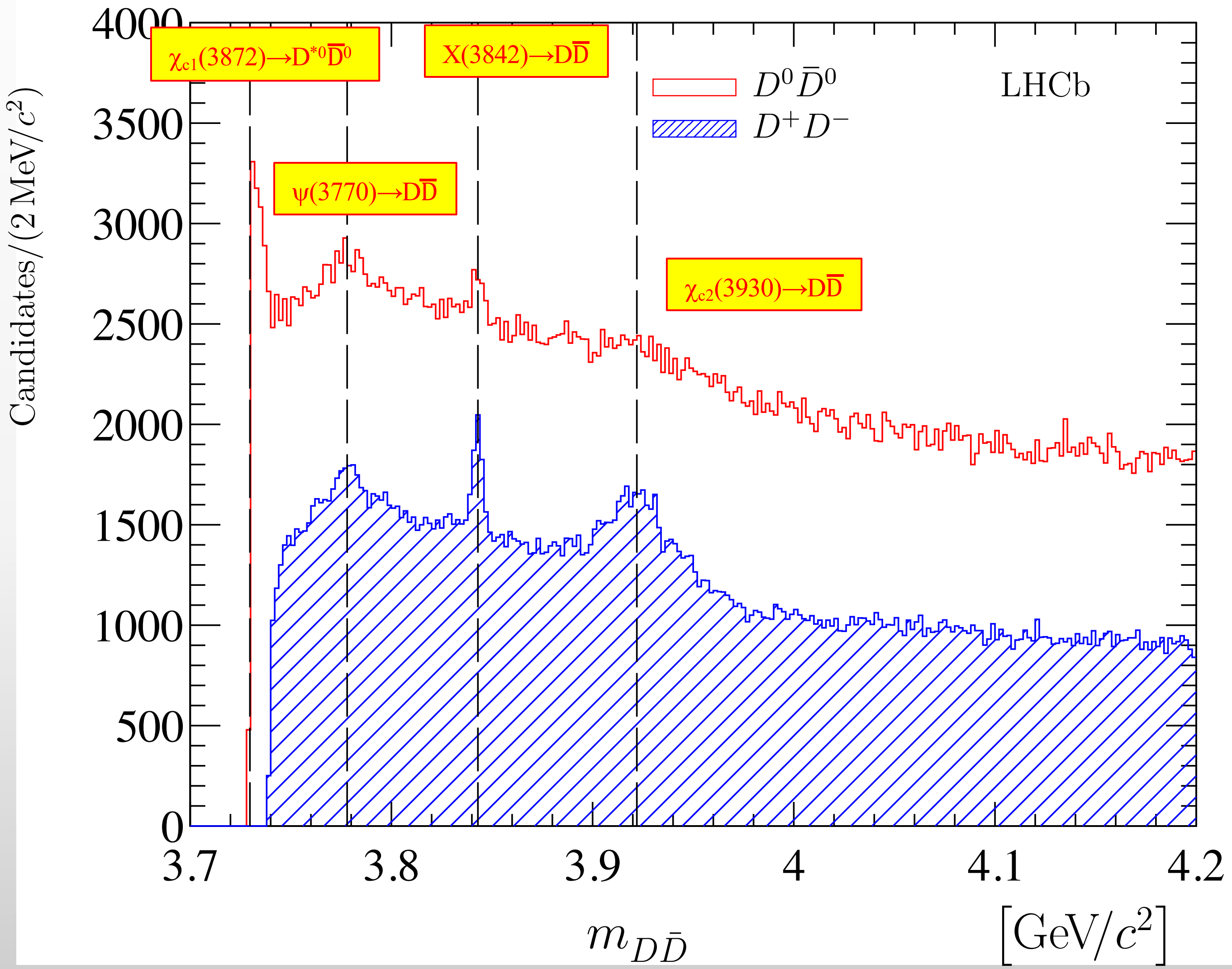
[JHEP 07 (2019) 035]

- Large doubly charm production in the LHCb acceptance:
  - $6230 \pm 120 \pm 630$ nb ($D^0\bar{D}^0$) @ sqrt s = 7 TeV **[JHEP 06 (2012) 141]**
  - $780 \pm 40 \pm 130$ nb (D^+D^-) @ sqrt s = 7 TeV
- Search for prompt resonances decaying into $D^0\bar{D}^0$ and D^+D^-
- Run 1 and Run 2 data (9 fb^{-1}) from 2011-2018
- Not necessarily produced in pp interaction
- $D^0 \rightarrow K^- \pi^+$, $D^+ \rightarrow K^- \pi^+ \pi^+$, pointing to primary vertex
- Purity ~88% for D^0D^0, ~90% for D^+D^-



Near threshold $D\bar{D}$ spectroscopy

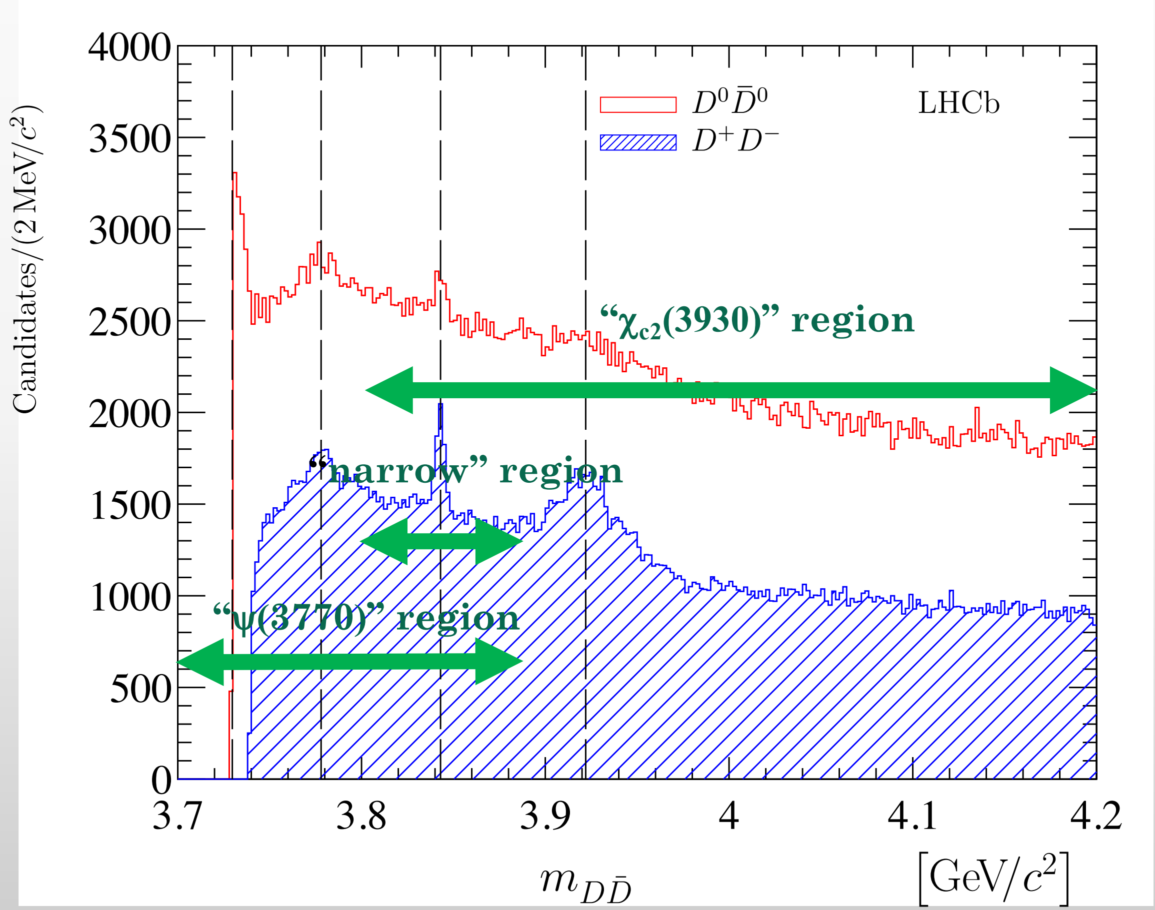
[JHEP 07 (2019) 035]



Near threshold $D\bar{D}$ spectroscopy

[JHEP 07 (2019) 035]

- To improve $D\bar{D}$ resolution: D mass constrained to the known values
- Challenging to fit the whole spectrum. Not trivial background shape
- Splitting the spectrum into three regions

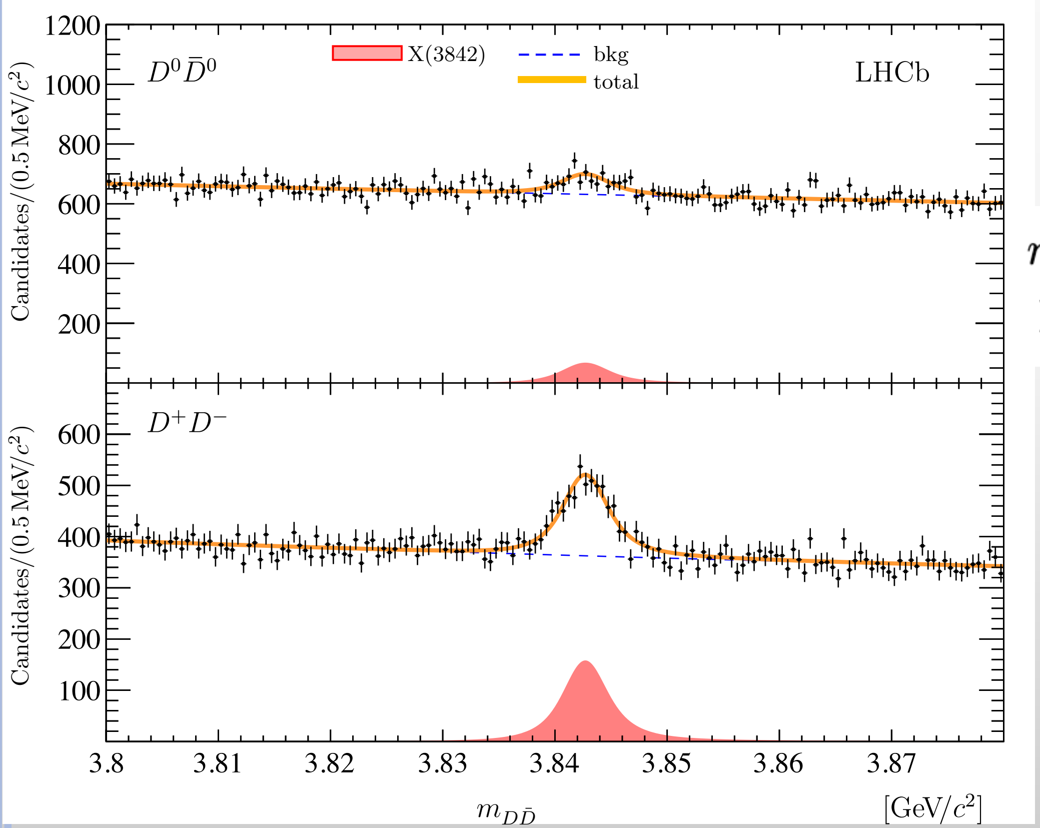


Near threshold $D\bar{D}$ spectroscopy

[JHEP 07 (2019) 035]

Narrow region around the new peak

Fit model: F-wave RBW convolved with a resolution function (Signal)
2nd order polynomial (Background)



$$m_{X(3842)} = 3842.71 \pm 0.16 \pm 0.12\,\text{MeV}/c^2\,,$$
$$\Gamma_{X(3842)} = 2.79 \pm 0.51 \pm 0.35\,\text{MeV}\,,$$

The narrow natural width and the mass of the X(3842) state suggest the interpretation of the X(3842) state as the $\psi_3(1^3D_3)$ charmonium state with $J^{PC} = 3^{--}$

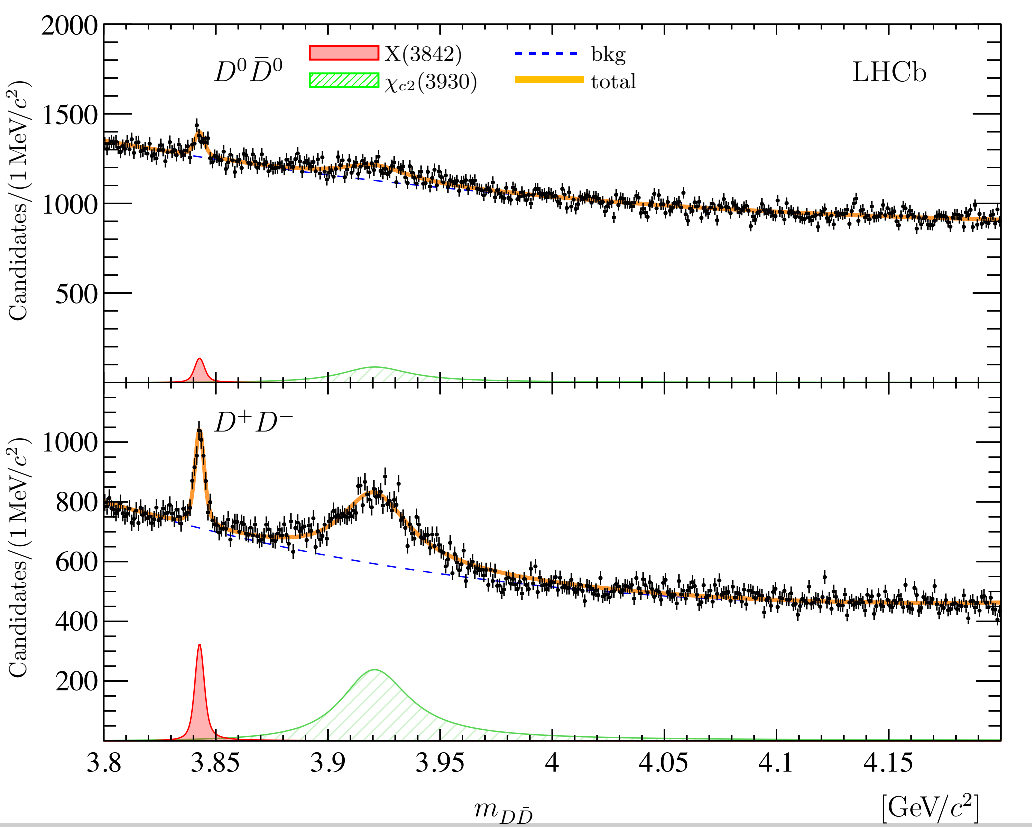
Near threshold $D\bar{D}$ spectroscopy

[JHEP 07 (2019) 035]

The $\chi_{c2}(3930)$ region

X(3842): Parameters fixed to the previous fit values

$\chi_{c2}(3930)$: D-wave RBW convolved to the detector resolution



$$m_{\chi_{c2}(3930)} = 3921.9 \pm 0.6 \pm 0.2\,\text{MeV}/c^2\,,$$
$$\Gamma_{\chi_{c2}(3930)} = 36.6 \pm 1.9 \pm 0.9\,\text{MeV}\,.$$

Near threshold $D\bar{D}$ spectroscopy

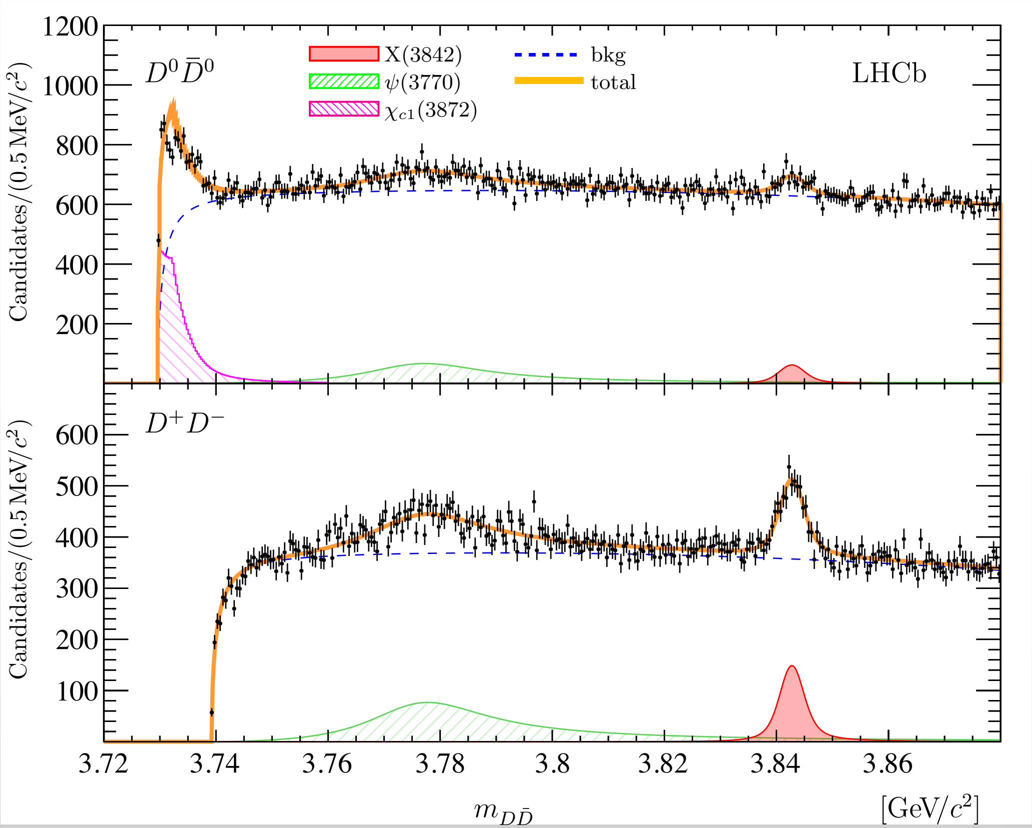
[JHEP 07 (2019) 035]

The $\psi(3770)$ region

X(3842): Parameters fixed to the previous fit values

$\chi_{c1}(3872)$: $D^0\bar{D}^{*0}$ and $D^0\bar{D}^0\pi^0$ from simulation events (according to phase space)

$\psi(3770)$: P-wave Breit Wigner (the natural width is Gaussian constrained)

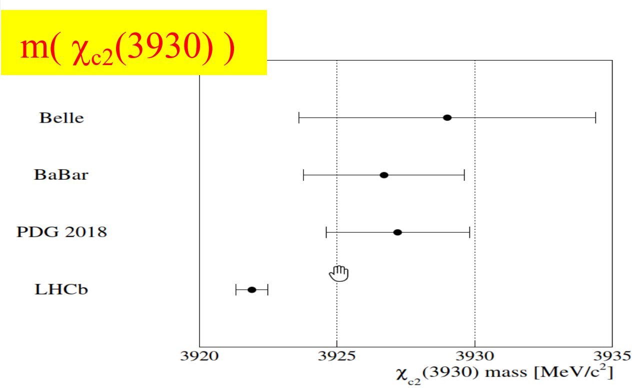


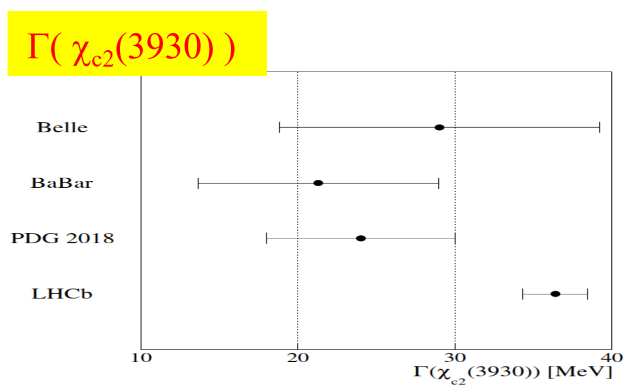
$$m_{\psi(3770)} = 3778.1 \pm 0.7 \pm 0.6\,\mathrm{MeV}/c^2$$

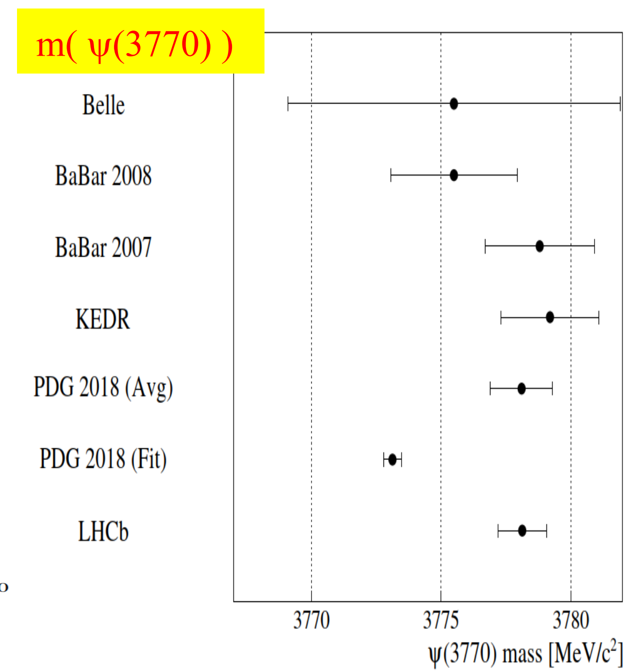
Near threshold $D\bar{D}$ spectroscopy

[JHEP 07 (2019) 035]

- Observation of a new charmonium X(3842)!
- Prompt hadroproduction of the $\chi_{c2}(3930)$ state is observed for the first time
  - Precise measurements of its mass and width. The measured mass is not far from the X(3915) meson (which is only known to decay to J/ψ ω). Are they the same meson?
- Prompt hadroproduction of the ψ(3770) state is observed for the first time







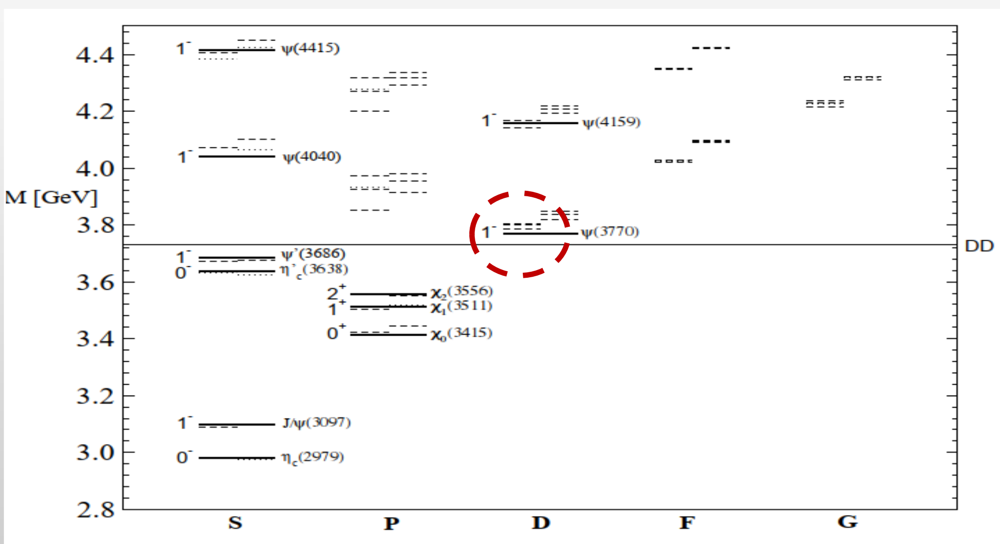
Study of the $\psi_2(3823)$ and $\chi_{c1}(3872)$ states in $B^+ \to (J/\psi\pi^+\pi^-)K^+$ decays

[JHEP 08 (2020) 123]

$B^+ \to (J/\psi\pi^+\pi^-)K^+$

JHEP 08 (2020) 123

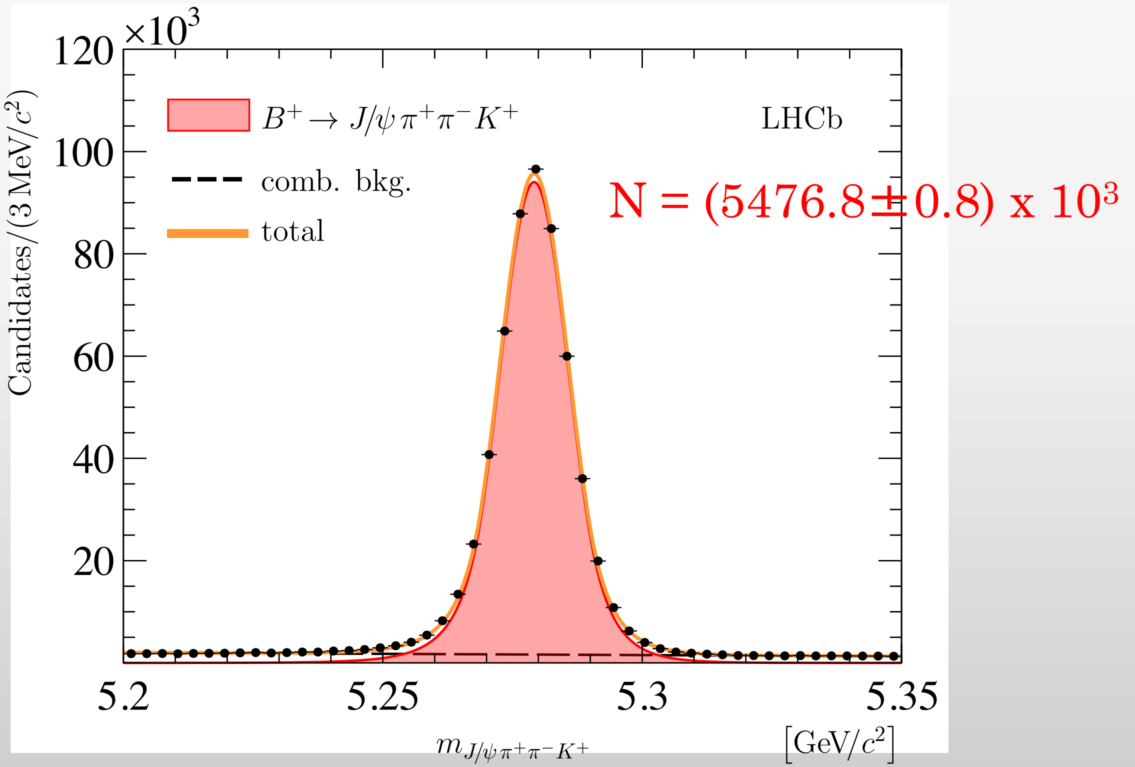
- A recent analysis of $D^0\bar{D}^0$ and D^+D^- mass spectra led to the observation of a new narrow state, interpreted as a spin-3 component of the D-wave charmonium triplet, $\psi_3(1^3D_3)$ state, and a precise measurement of the mass of the vector component of this triplet, the $\psi(3770)$ state
- Evidence for the third, tensor component of the triplet, the $\psi_2(3823)$ state, was reported by the Belle collaboration in the $B\to(\psi_2(3823)\to\chi_{c1}\gamma)$ K . This was confirmed by the BES III collaboration with a significance > 5**σ** .



$B^+ \rightarrow (J/\psi \pi^+ \pi^-) K^+$

JHEP 08 (2020) 123

- Using LHCb data corresponding to 9 fb^{-1} at 7, 8 and 13 TeV
- J/ψ mass constraint is applied
- Boosted Decision Tree (BDT) algorithm used
- BDT output optimised by using a Punzi figure of merit $\varepsilon/(5/2+\sqrt{B})$



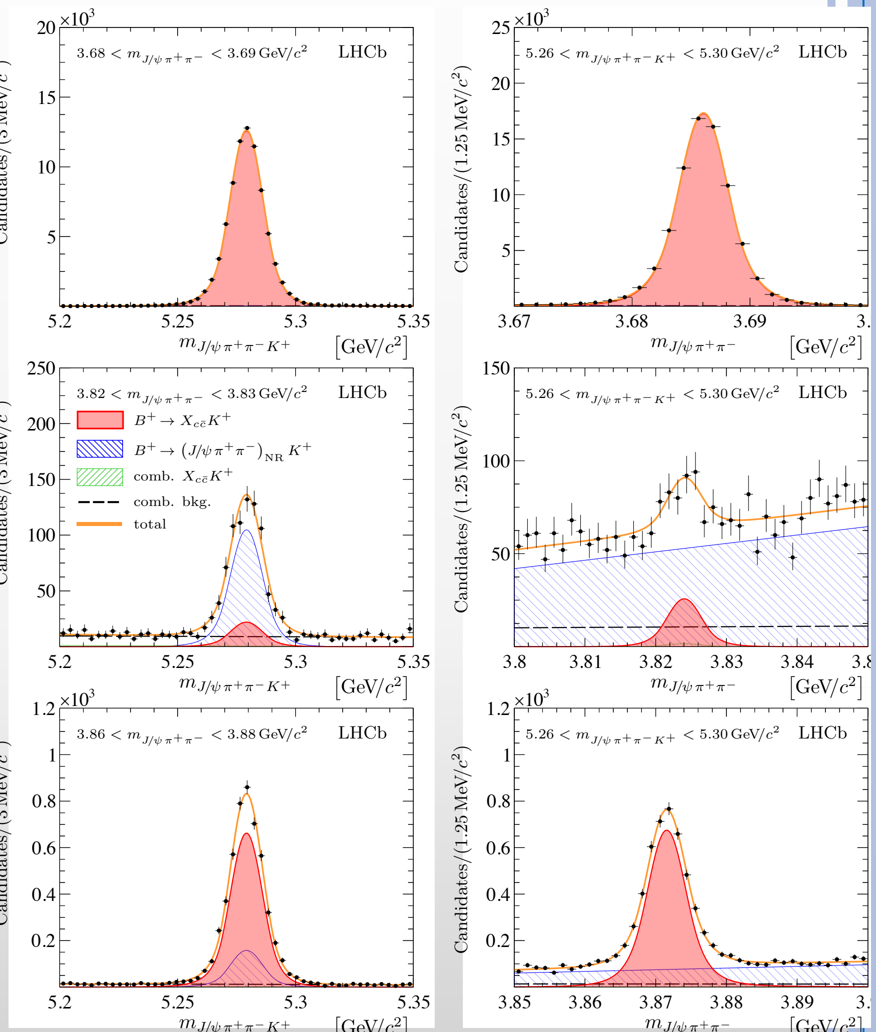
$B^+ \to (J/\psi\pi^+\pi^-)K^+$

JHEP 08 (2020) 123

- 2D unbinned maximum likelihood fit ($m(J/\psi\pi^+\pi^- K)$ vs $m(J/\psi\pi^+\pi^-)$) to determine the yields of $B^+ \to X_{cc} K^+$
- A B^+ mass constraint applied to further improve the mass resolution
- $\psi(2S)$, $\chi_{c1}(3872)$ and $\psi_2(3823)$ observed

$$m_{\psi_2(3823)} = 3824.08 \pm 0.53 \pm 0.14 \pm 0.01\,\mathrm{MeV}/c^2,$$

$$\Gamma_{\psi_2(3823)} < 5.2\,(6.6)\,\mathrm{MeV\ at\ }90\,(95)\%\ \mathrm{CL}.$$



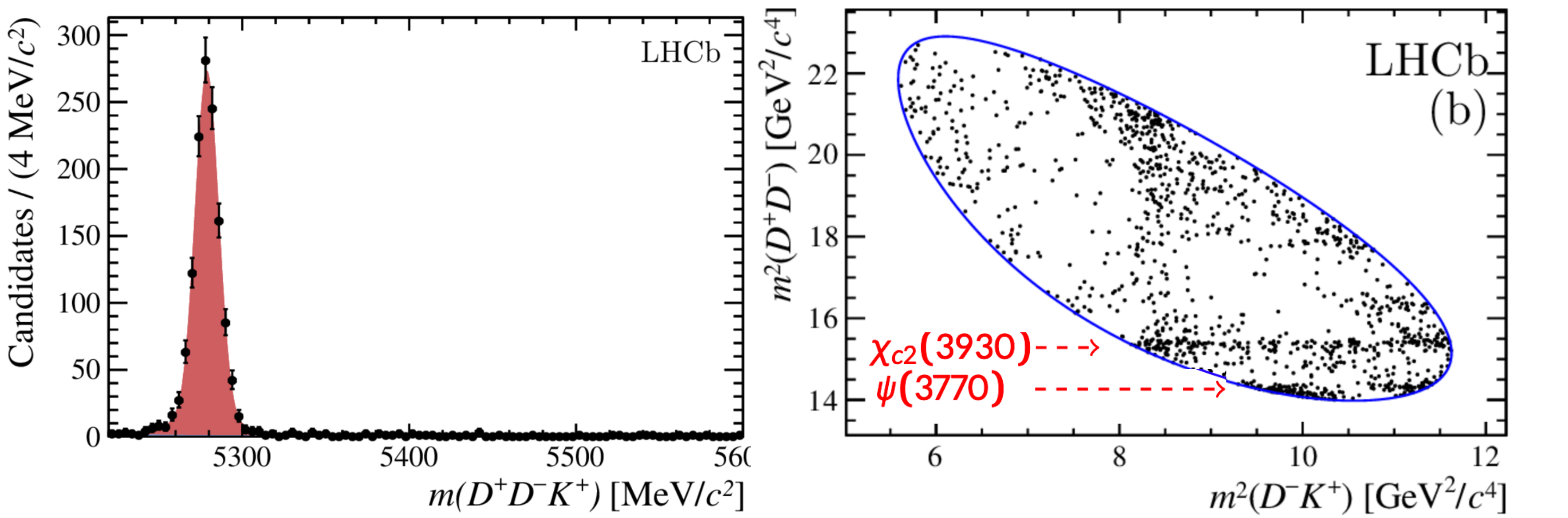
Amplitude analysis of the $B^+ \to D^+ D^- K^+$ decay

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

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

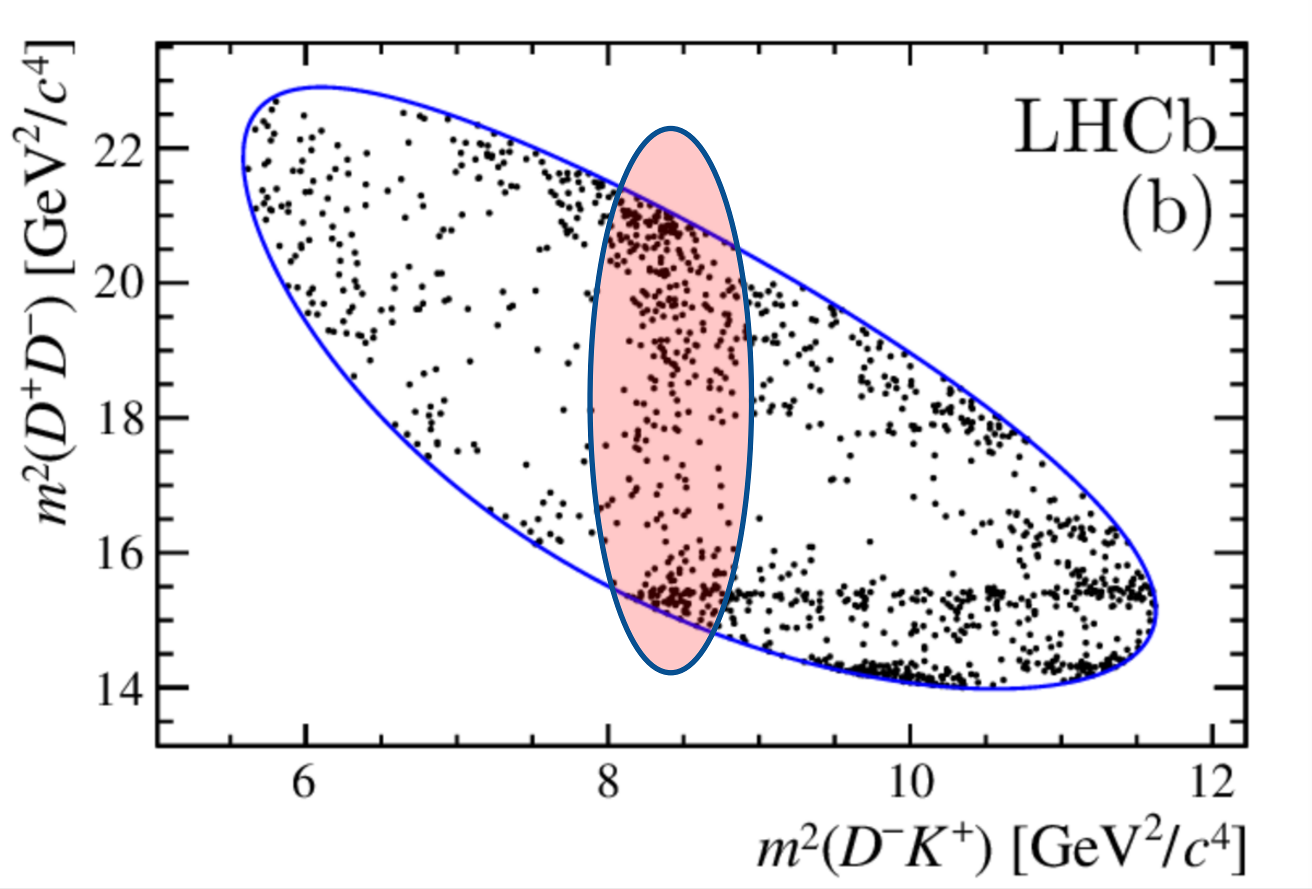
PRL 125 (2020) 242001
PRD 102 (2020) 112003

- $B^+ \to D^+ D^- K^+$ interesting for charmonia; conventional resonances only expected in the D^+D^- channel
- States decaying to D^-K^+ would have quark content $[cu\bar{d}\bar{s}]$
- Full Run 1 + Run 2 pp datasets (9 fb^{-1})
- Reconstruct $B^+ \to [K^-\pi^+\pi^+]_{D+}\ [K^+\pi^-\pi^-]_{D-}\ K^+$



Surprising structure in D⁻K⁺

PRL 125 (2020) 242001
PRD 102 (2020) 112003



Model Independent Approach

PRL 125 (2020) 242001
PRD 102 (2020) 112003

Can the reflections of the structures in $m(D^+D^-)$ and $\cos\vartheta_{D+D-}$ reproduce the m(DK) distributions?

If no exotics in DK → Partial wave expansion in a given bin of $m^2(D^+D^-)$

Legendre Polynomials

$$\mathcal{M}(\theta_{D^+D^-}) = \underbrace{\mathcal{S}_{wave}}_{J(D^+D^-)=0} P_0 + \underbrace{\mathcal{P}_{wave}}_{J(D^+D^-)=1} P_1 + \underbrace{\mathcal{D}_{wave}}_{J(D^+D^-)=2} P_2 + \underbrace{\mathcal{F}_{wave}}_{J(D^+D^-)=3} P_3 + \underbrace{\mathcal{G}_{wave}}_{J(D^+D^-)=4} P_4 + \ldots$$

$$|\mathcal{M}(\theta_{D^+D^-})|^2 = \langle P_0\rangle P_0 + \langle P_1\rangle P_1 + \langle P_2\rangle P_2 + \langle P_3\rangle P_3 + \langle P_4\rangle P_4 + \langle P_5\rangle P_5 + \langle P_6\rangle P_6 + \ldots$$

where the moments $<P_N>$ determined from data: $\langle P_N\rangle = \sum_{i=1}^{N_{data}} \frac{1}{\epsilon_i} P_N(\cos\theta^i_{D^+D^-})$

Model Independent Approach

PRL 125 (2020) 242001
PRD 102 (2020) 112003

(e.g.) If only D^+D^- resonances up to J = 2

$$\mathcal{M}(\theta_{D^+D^-}) = \underbrace{\mathcal{S}_{wave}}_{J(D^+D^-)=0} P_0 + \underbrace{\mathcal{P}_{wave}}_{J(D^+D^-)=1} P_1 + \underbrace{\mathcal{D}_{wave}}_{J(D^+D^-)=2} P_2 + \underbrace{\mathcal{F}_{wave}}_{J(D^+D^-)=3} P_3 + \underbrace{\mathcal{G}_{wave}}_{J(D^+D^-)=4} P_4 + \ldots$$

$$|\mathcal{M}(\theta_{D^+D^-})|^2 = \langle P_0 \rangle P_0 + \langle P_1 \rangle P_1 + \langle P_2 \rangle P_2 + \langle P_3 \rangle P_3 + \langle P_4 \rangle P_4 + \langle P_5 \rangle P_5 + \langle P_6 \rangle P_6 + \ldots$$

Sum of the terms up to $P_{N_{max}}$, where $N_{max} = 2 * J(D^+D^-)$, has to describe the data projections

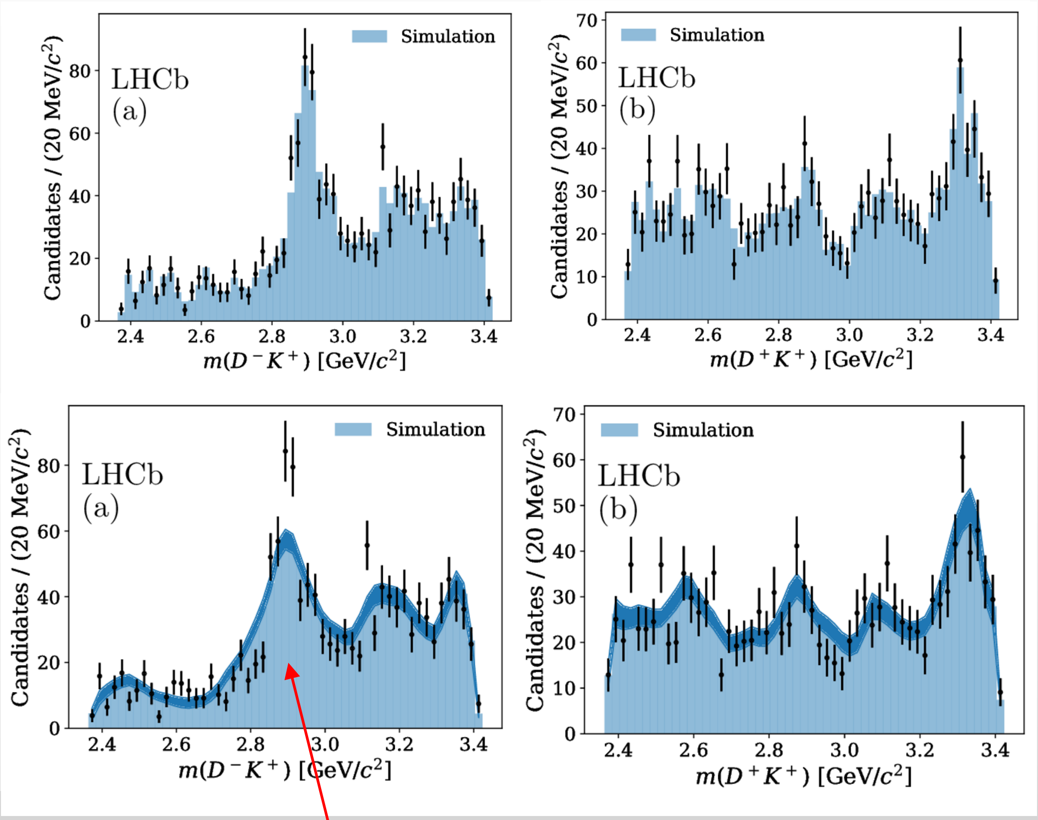
It should not happen →

There are D^+D^- resonances with J > 2
or
There are exotic(s) which make the high order terms non-zero!

MODEL-INDEPENDENT ANALYSIS APPROACH

PRL 125 (2020) 242001
PRD 102 (2020) 112003

Can D⁺D⁻K⁺ phase space be described by D⁺D⁻ partial-waves only?



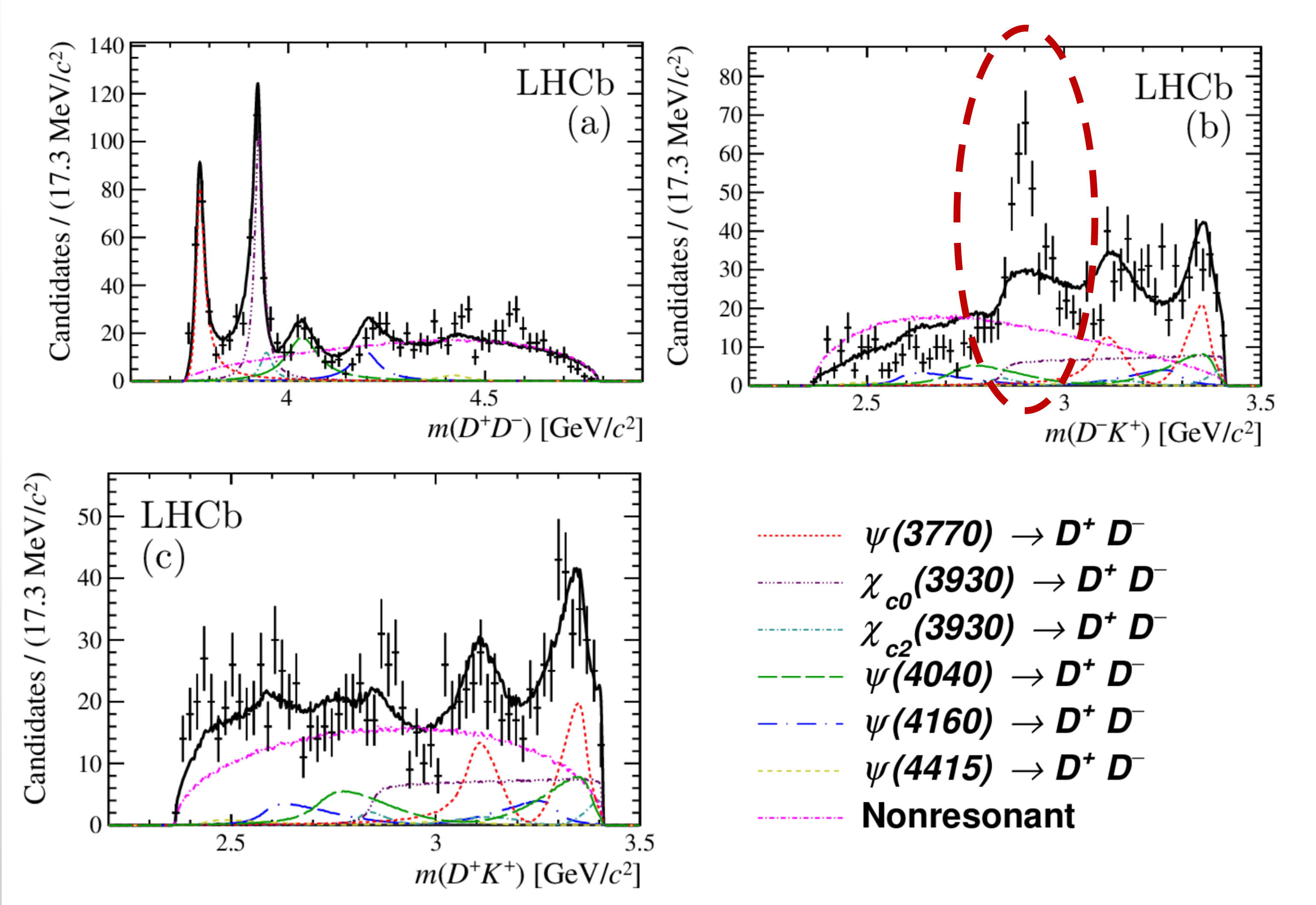
J = 15

J = 2

Clear discrepancy in describing the D⁻K⁺ spectrum

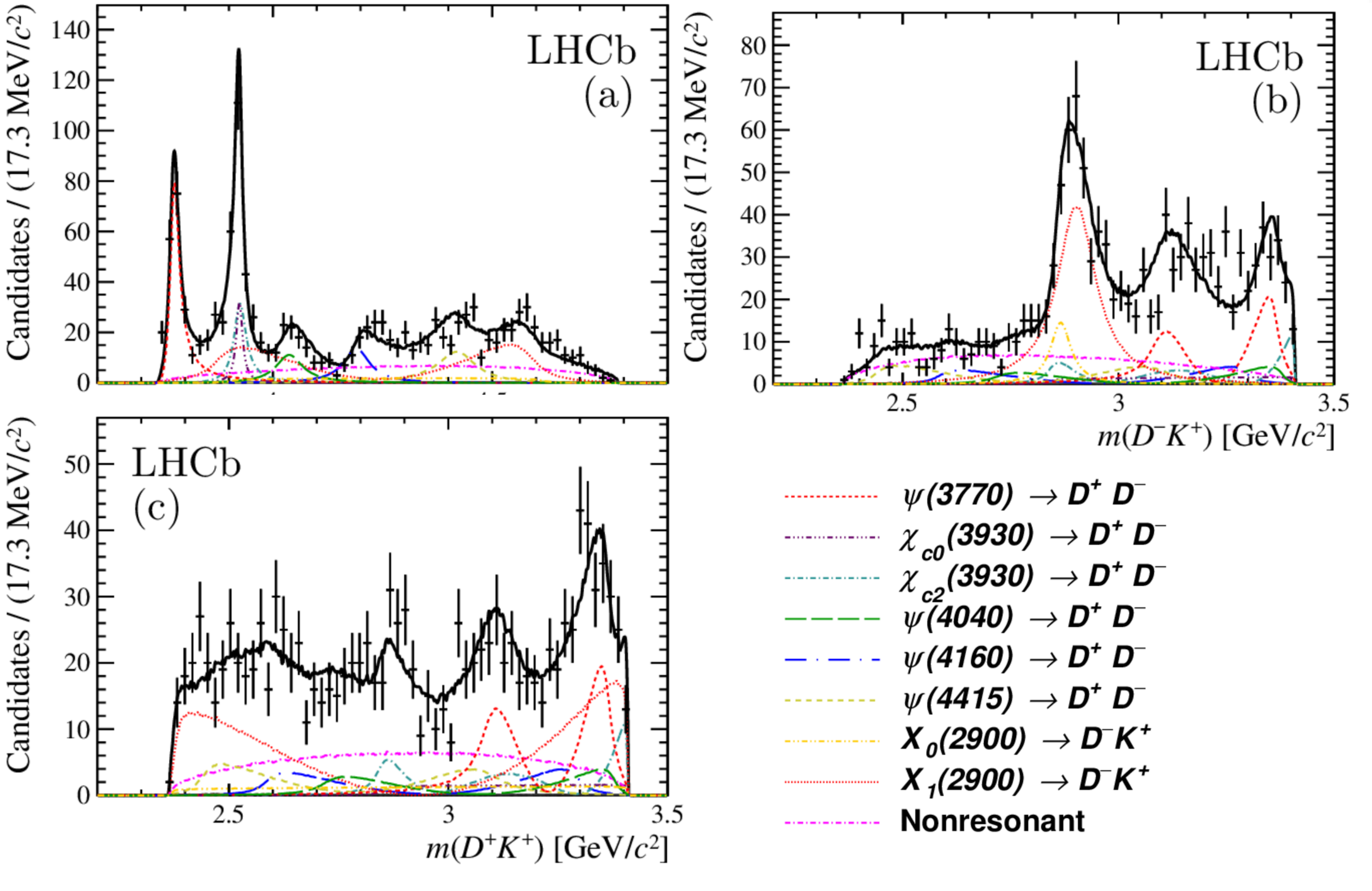
MODEL EXCLUDING D^-K^+ RESONANCES

PRL 125 (2020) 242001
PRD 102 (2020) 112003



Model including D^-K^+ resonances

PRL 125 (2020) 242001
PRD 102 (2020) 112003



Model including D^-K^+ resonances

PRL 125 (2020) 242001
PRD 102 (2020) 112003

Resonance	Mass (GeV/c^2)	Width (MeV/c^2)
$\chi_{c0}(3930)$	$3.9238 \pm 0.0015 \pm 0.0004$	$17.4 \pm 5.1 \pm 0.8$
$\chi_{c2}(3930)$	$3.9268 \pm 0.0024 \pm 0.0008$	$34.2 \pm 6.6 \pm 1.1$
$X_0(2900)$	$2.8663 \pm 0.0065 \pm 0.0020$	$57.2 \pm 12.2 \pm 4.1$
$X_1(2900)$	$2.9041 \pm 0.0048 \pm 0.0013$	$110.3 \pm 10.7 \pm 4.3$

- First exotic candidates with a single heavy quark
- Masses close to the D*K* threshold. Rescattering effects?
- Mass of $\chi_{c0}(3930)$ consistent to X(3915)

LHCb Going to Upgrade

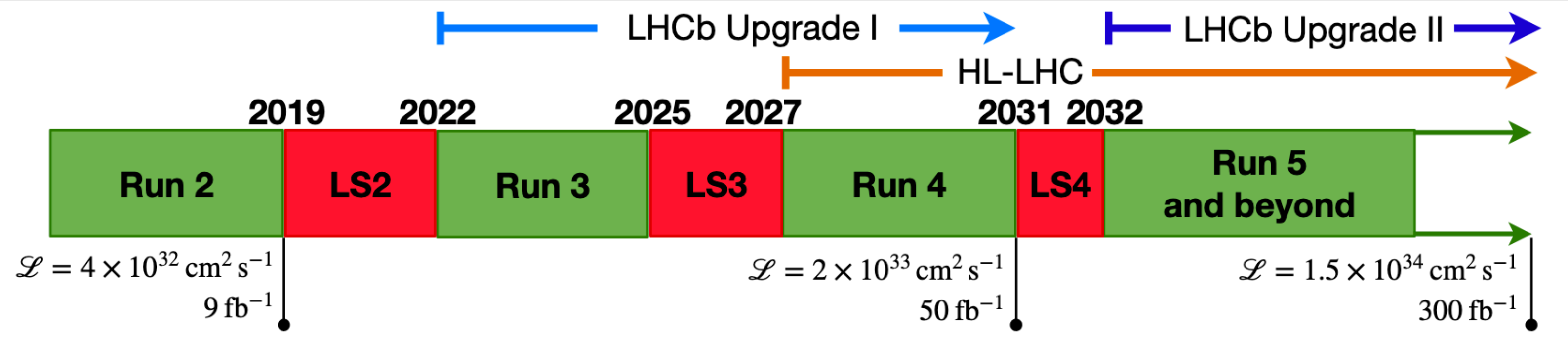
Upgrade I (Approved)

- Main limitation that prevents exploiting higher luminosity with the present detector is the Level-0 (hardware) trigger
  - ✓ Level-0 output rate < 1 MHz (readout rate) requires raising thresholds
- Hadron final states will benefit from removing L0
- Running at $2x10^{33}$ cm^{-2} s^{-1} with full software trigger, running at 40 MHz

Upgrade II (Under approval)

To be installed in Long Shutdown 4 of the LHC:

- Subsystems redesigned to operate at a luminosity of 1-2 x 10^{34} cm^{-2} s^{-1}
- Integrated luminosity of > 300 fb^{-1}
- Extension of the experiment's capabilities to select π^0, η and low-momentum tracks



Summary

- LHCb keeps discovering new states!
- Observation of new states challenges our current understanding of QCD
- Many b → $D^{(*)}D^{(*)}$ X analyses are ongoing featured by many tracks in the final states
- Such analyses will benefit from more efficient trigger algorithms in the upcoming Upgrade I and from large integrated luminosity in Upgrade II

Back-up slides