Exotic hadrons at LHCb

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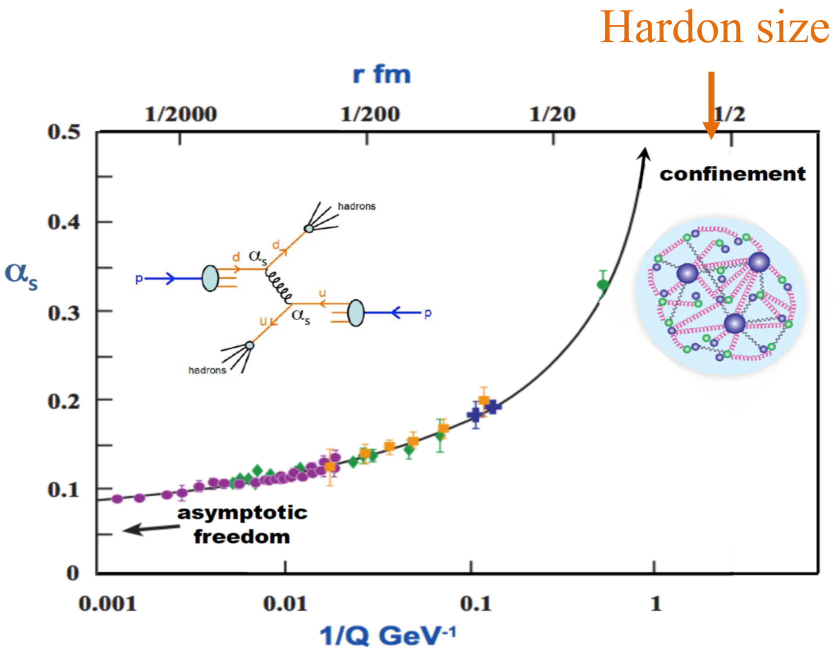
Outline

- Introduction
- Exotic baryons at LHCb
  - 1st evidence of $J/\psi\Lambda$ resonance in $\Xi_b^- \to J/\psi\Lambda K^-$ decays
  - Search for pentaquarks in $\eta_c p$ system
  - Search for open-charm pentaquarks in $\Lambda_c^+ K^+$ system
- Exotic mesons at LHCb
  - 1st observation of open-charm tetraquark candidates in $D^- K^+$ system
  - 1st observation of full charmed tetraquark candidate in di-J/ψ system
  - $X(3872)$ lineshape
- Summary and prospects

Introduction

- Hadron spectroscopy provides opportunities to study QCD in the non-perturbative region
  - Extensive and precise spectroscopy combined with a thorough theoretical analysis, will add substantially to our knowledge
- Complex exotic hadrons can reveal new or hidden aspects of the dynamics of strong interactions
  - Predicted in quark model
  - Recent results show strong evidence for their existence



【1】H.-X. Chen, W. Chen, X. Liu and S.-L. Zhu, Phys. Rept. 639 (2016) 1-121.
【2】A. Ali, J. Lange, S. Stone, Prog. Part. Nucl. Phys. 97 (2017) 123-198.
【3】F.-K. Guo, C. Hanhart, U.-G. Meißner, Q. Wang, Q. Zhao and B.-S. Zou, Rev. Mod. Phys. 90 (2018) 015004.
【4】S. Olsen, T. Skwarnicki, D. Zieminska, Rev. Mod. Phys. 90 (2018) 15003.
【5】Y.-R. Liu, H.-X. Chen, W. Chen, X. Liu and S.-L. Zhu, Prog. Part. Nucl. Phys. 107 (2019) 237-320.
【6】F.-K. Guo, X.-H. Liu and S. Sakai, Prog. Part. Nucl. Phys. 112 (2020) 103757

tetraquark ?

pentaquark ?

hybrid ?

… EXOTIC

Tetra and pentaquark candidates

- Confirmation of $Z(4430)^-$

  [PRL 112 (2014) 222002]

- Observation of four $J/\psi\phi$ structures

  [PRL 118 (2017) 022003]

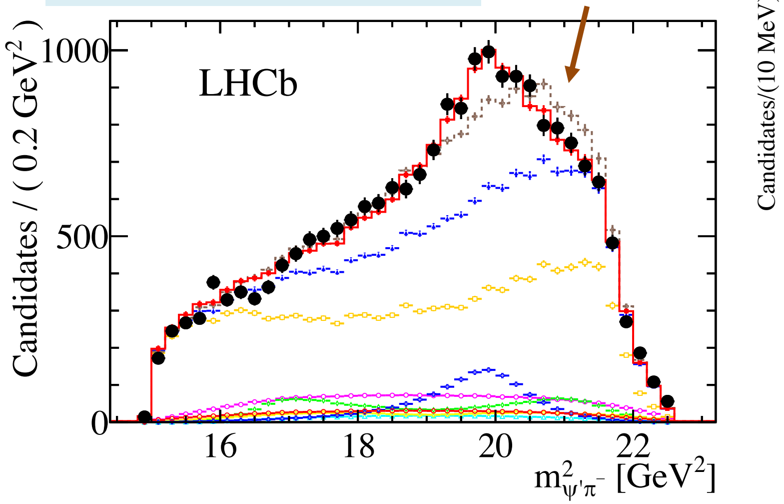
- Observation of narrow charmonium pentaquarks

  [PRL 115 (2015) 072001, PRL 122 (2019) 222001]

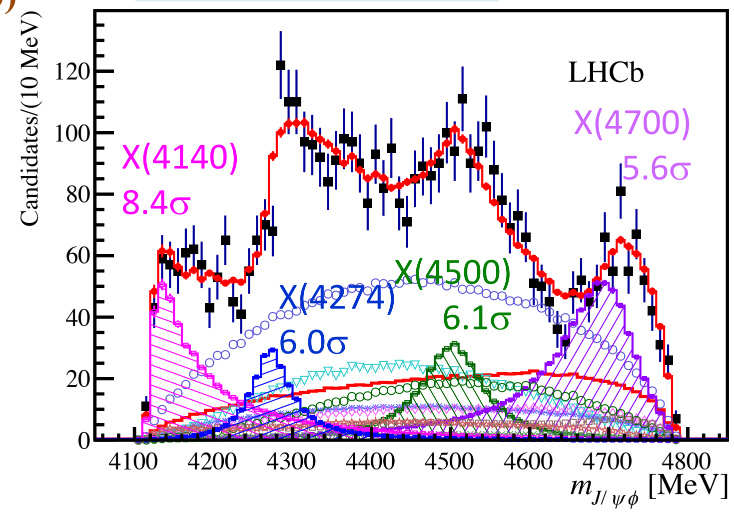
- Evidence of exotic contribution in Cabibbo-suppressed decays

  [PRL 117 (2016) 082003]

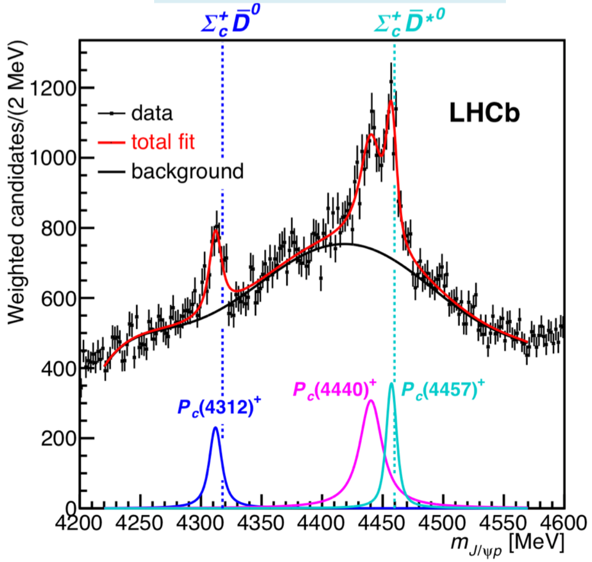
$B^0 \to \psi(2S)\pi^- K^+$



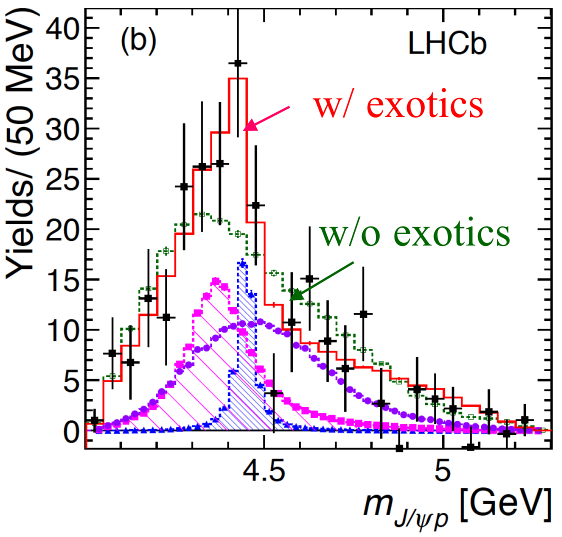
$B^+ \to J/\psi\phi K^+$



$\Lambda_b^0 \to J/\psi p K^-$



$\Lambda_b^0 \to J/\psi p \pi^-$



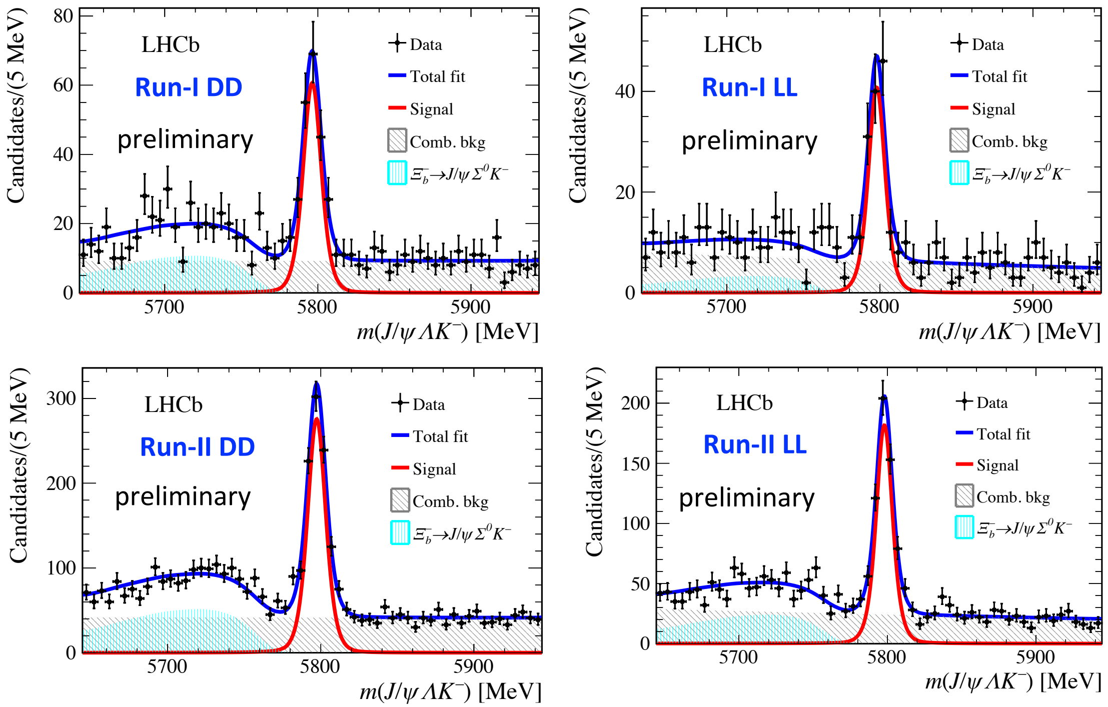
Evidence of $J/\psi\Lambda$ resonance: data sample

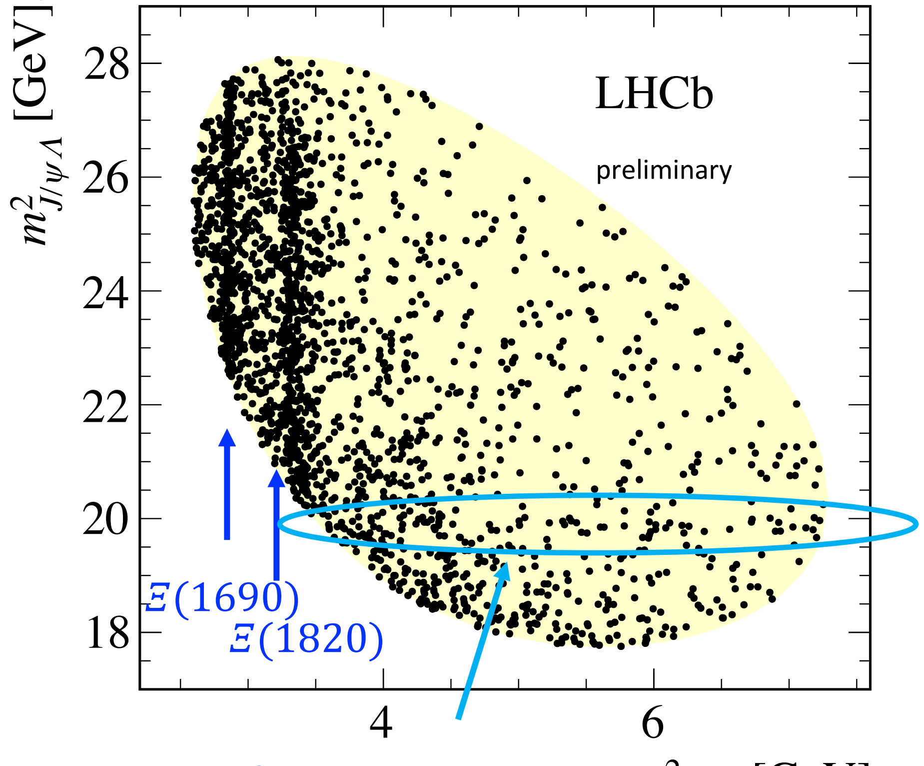
- Hidden-charm pentaquark with strangeness P_{cs} is predicted, and suggested to search for in $\Xi_b^- \to J/\psi\Lambda K^-$
  [JJ Wu PRL 105 (2010) 232001; HX Chen PRC 93(2016) 064203]

[LHCb-PAPER-2020-039] in preparation

$\Lambda \to p\pi^-$ reconstructed by Long-Long, or Downstream-Downstream tracks

~1750 $\Xi_b^- \to J/\psi\Lambda K^-$ signals (purity ~80%)

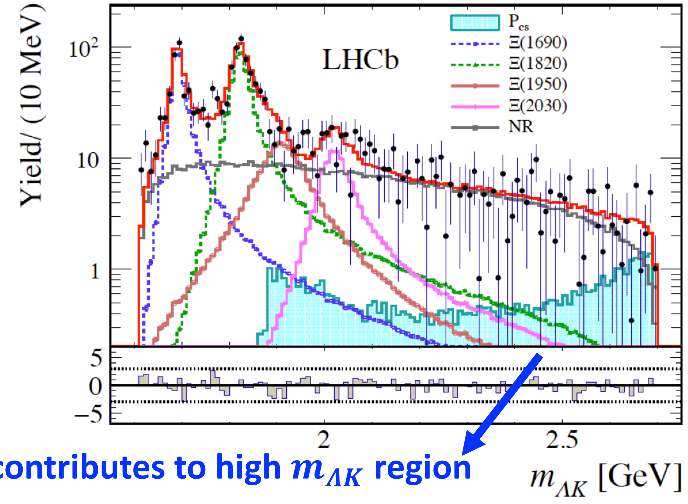


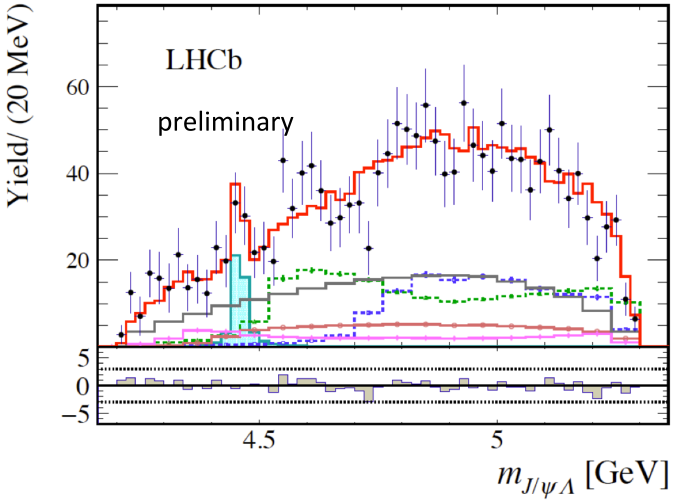


Potential P_{cs}^0 structure?
Full amplitude analysis is required

Evidence of $J/\psi\Lambda$ resonance: amplitude fit

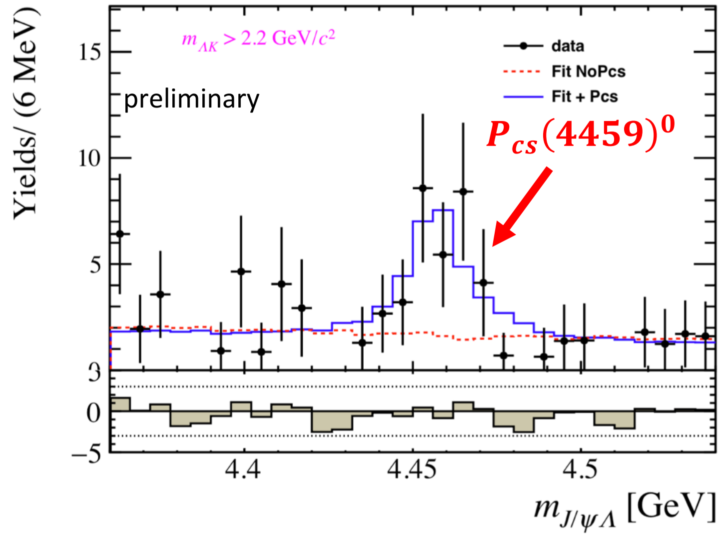
- Modelled by one P_{cs}
  - Adding a P_{cs} improves $2\ln\mathcal{L}$ by 43 units, statistical significance of **4.3σ** evaluated by toy experiments
  - Including various syst. uncertainty, the smallest significance is 3.1σ
  - Look-elsewhere effect is included in both cases
- Statistics not enough for J^P determination

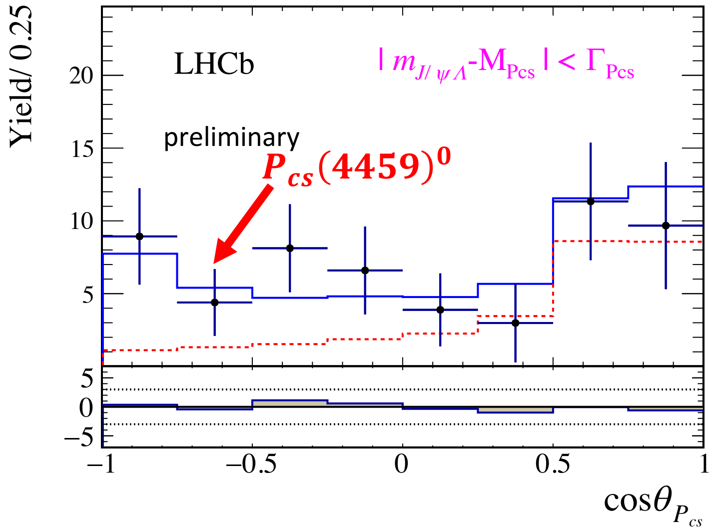




P_{cs} contributes to high $m_{\Lambda K}$ region

Zooms in to P_{cs} signal region. Visible improvement.

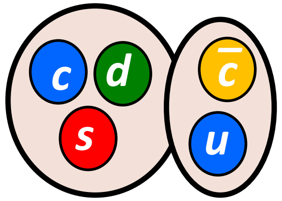




[LHCb-PAPER-2020-039] in preparation

Evidence of $J/\psi\Lambda$ resonance: discussion

- The peak position is consistent with $\Xi_c^0\bar{D}^{*0}$ molecule model prediction



Predicts **two states** with J^P 1/2(3/2)$^-$

System	$[\Xi_c\bar{D}^*]_{\frac{1}{2}}$	$[\Xi_c\bar{D}^*]_{\frac{3}{2}}$
ΔE	$-17.8^{+3.2}_{-3.3}$	$-11.8^{+2.8}_{-3.0}$
M	$4456.9^{+3.2}_{-3.3}$	$4463.0^{+2.8}_{-3.0}$

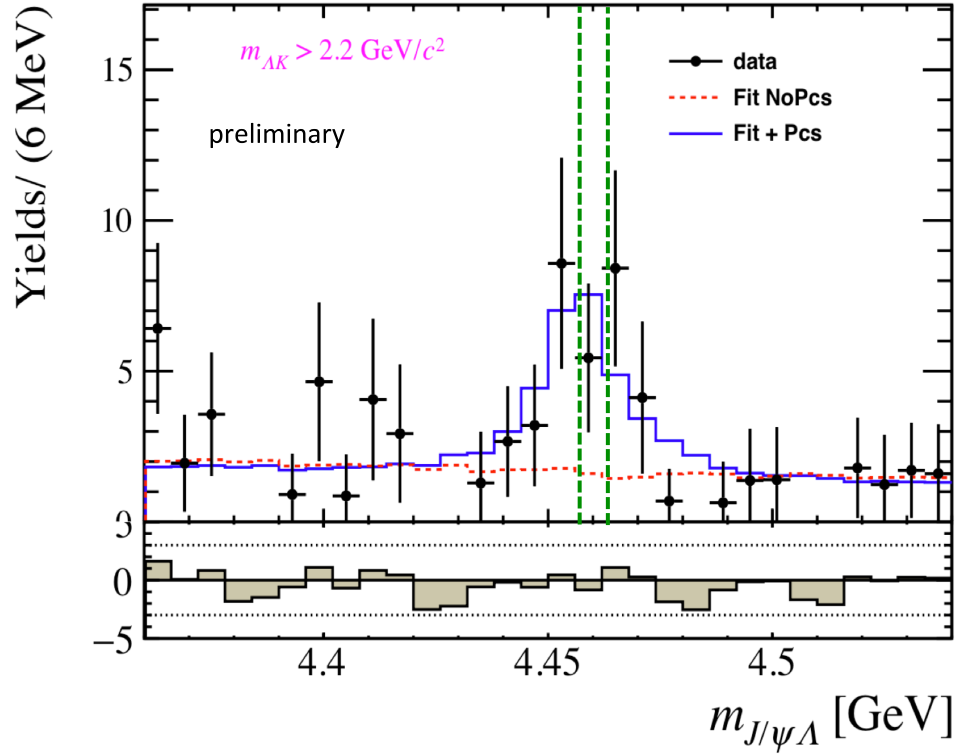
- Two-peak hypothesis is allowed
  - More data is required to distinguish one-peak vs two-peak
- $\Xi_c^0\bar{D}^{*0}$ SU(3) partner is $\Lambda_c^+\bar{D}^{*0}$, not $\Sigma_c\bar{D}^*$ for observed $P_c(4440)^+$ and $P_c(4457)^+$
  - Indicit $\Lambda_c^+\bar{D}^{*0}$ molecule exist?
  - The theory paper disfavors it, but should be examined by experiments

Mass is about 19 MeV below $\Xi_c^0\bar{D}^{*0}$ threshold

State	M_0 [MeV]	Γ[MeV]	FF (%)
$P_{cs}(4459)^0$	$4458.8 \pm 2.9\,^{+4.7}_{-1.1}$	$17.3 \pm 6.5\,^{+8.0}_{-5.7}$	$2.7\,^{+1.9}_{-0.6}\,^{+0.7}_{-1.3}$

[Bo Wang, Lu Meng, Shi-Lin Zhu，PRD 101 (2020) 034018, arXiv:1912.12592]

Predict two states

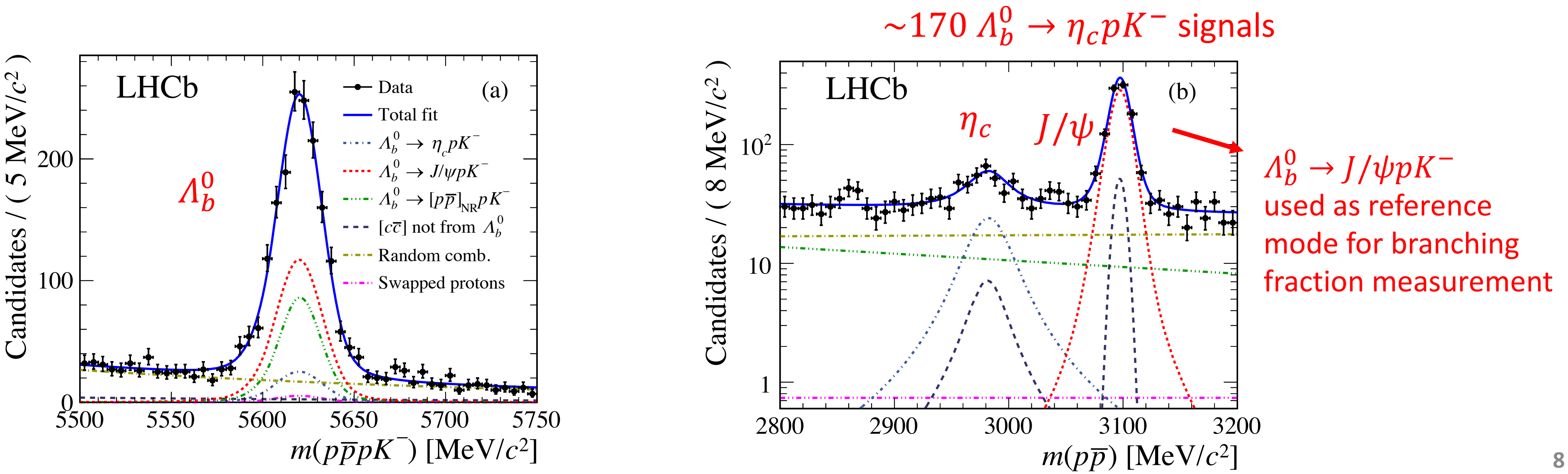


[LHCb-PAPER-2020-039] in preparation

1st observation of $\Lambda_b^0 \to \eta_c p K^-$

[arXiv:2007.11292]
Accepted by PRD

- Same quark contents as $\Lambda_b^0 \to J/\psi p K^-$. Provide unique environment for P_c studies
- If $P_c(4312)^+$ is $\Sigma_c \bar{D}$ molecule, predicted $\frac{\mathcal{B}(P_c(4312)^+ \to \eta_c p)}{\mathcal{B}(P_c(4312)^+ \to J/\psi p)} \sim 3$
  [PRD 100 (2019) 034020, 100 (2019) 074007, 102 (2020) 036012]
- LHCb run2 data (5.5 fb^{-1})
  - η_c reconstructed using $\eta_c \to p\bar{p}$
- Fit 2D mass spectrum to confirm the existence

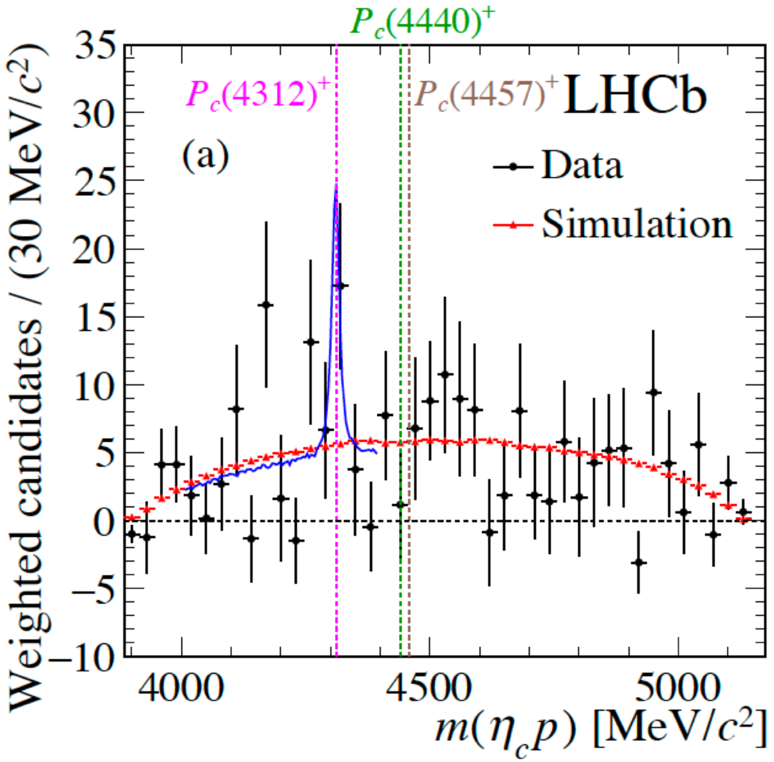


Search for P_c^+ in $\eta_c p$ system

[arXiv:2007.11292]
Accepted by PRD

- Check background-subtracted $\eta_c p$ mass spectrum
  - sPlot technique. 2D mass as discriminating variable.

No significant $P_c(4312)^+$ contribution (~2σ)



Relative P_c^+ production rates

$$R(P_c(4312)^+) < 0.24 \text{ @ } 95\% \text{ C. L.}$$

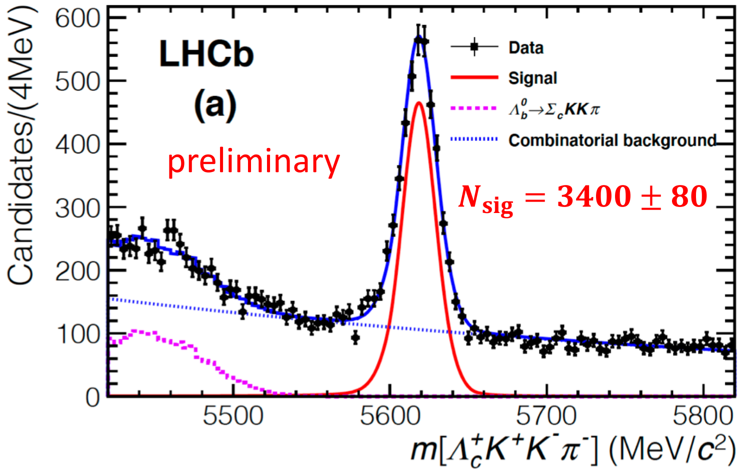
(Uncertainty is too large to give any conclusion yet)

- The $\Lambda_b^0 \to \eta_c p K^-$ branching fraction measured

$$\frac{\mathcal{B}(\Lambda_b^0 \to \eta_c p K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi\, p K^-)} = 0.333 \pm 0.050\ (\text{stat.}) \pm 0.019\ (\text{syst.}) \pm 0.032\ (\mathcal{B})$$

Search for pentaquark in $\Lambda_c^+ K^+$ system

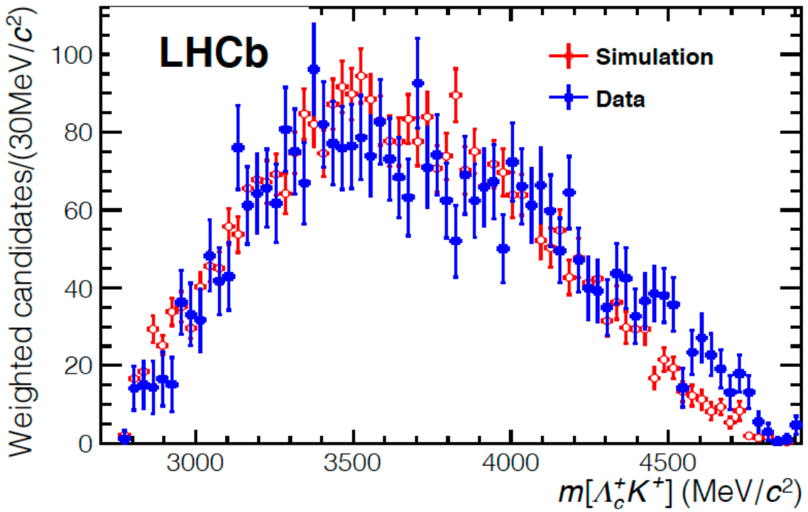
- Potential open-charm pentaquark $[c\bar{s}uud]$ decay to $\Lambda_c^+ K^+$
- Run1 data (3 fb^{-1})
  - Λ_c^+ reconstructed using $\Lambda_c^+ \to pK^-\pi^+$
  - $\Lambda_b^0 \to \Lambda_c^+ D_s^-$ used for normalization channel
- **1st observation of $\Lambda_b^0 \to \Lambda_c^+ K^+ K^- \pi^-$**



$$\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ K^+ K^- \pi^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-)} = (9.26 \pm 0.29 \pm 0.46 \pm 0.26) \times 10^{-2},$$

$$\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ K^+ K^- \pi^-) = (1.02 \pm 0.03 \pm 0.05 \pm 0.10) \times 10^{-3}$$

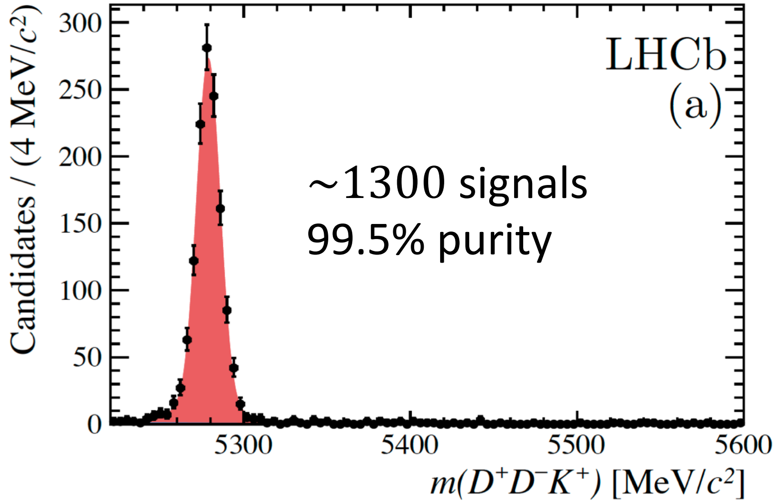
- No excess observed in $m(\Lambda_c^+ K^+)$ spectrum
- Will search with more data and can also look for pentaquark $[c\bar{s}udd]$ in $\Lambda_c^+ K^+ \pi^-$ system

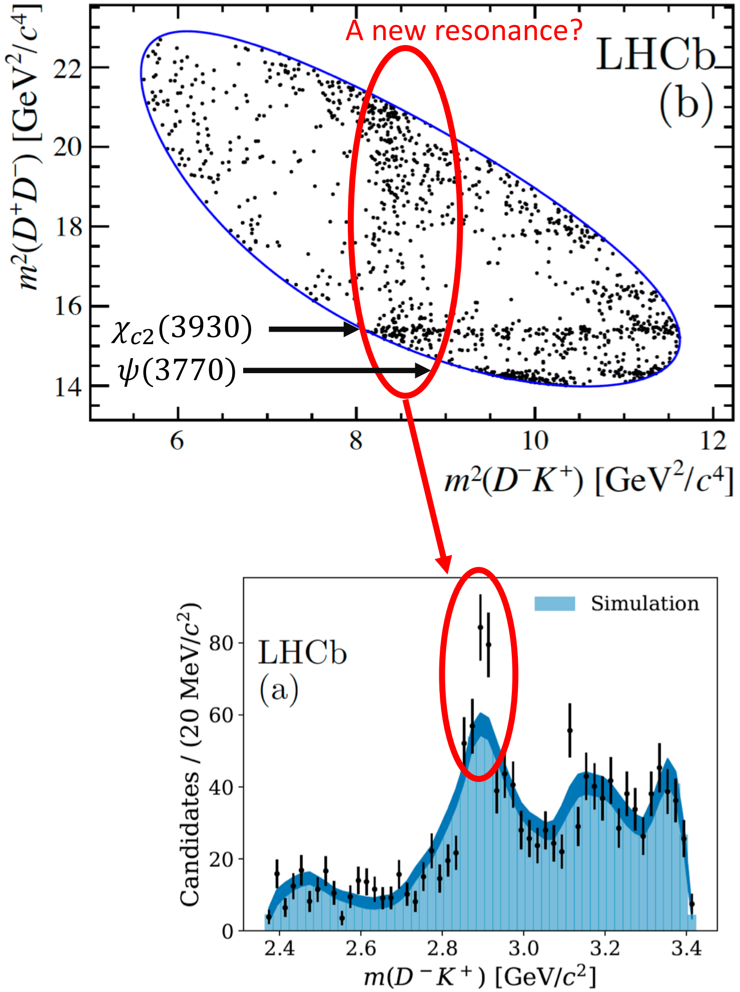


[LHCb-PAPER-2020-028] in preparation

Observation of $D^- K^+$ structure: data sample

- $B^+ \to D^+ D^- K^+$ decays (9 fb^{-1})





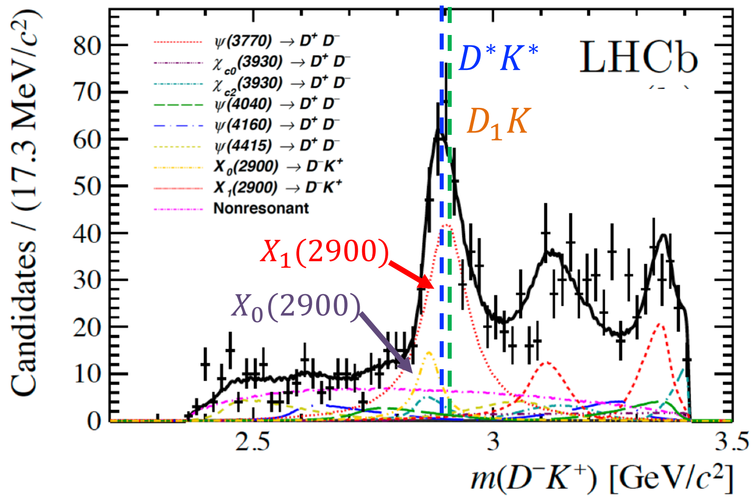
- Model-independent study
  - Hypothesis with only D^+D^- resonances ($J_{\max} = 2$) is rejected by 3.9σ
  - Indicate the existence of exotic contributions

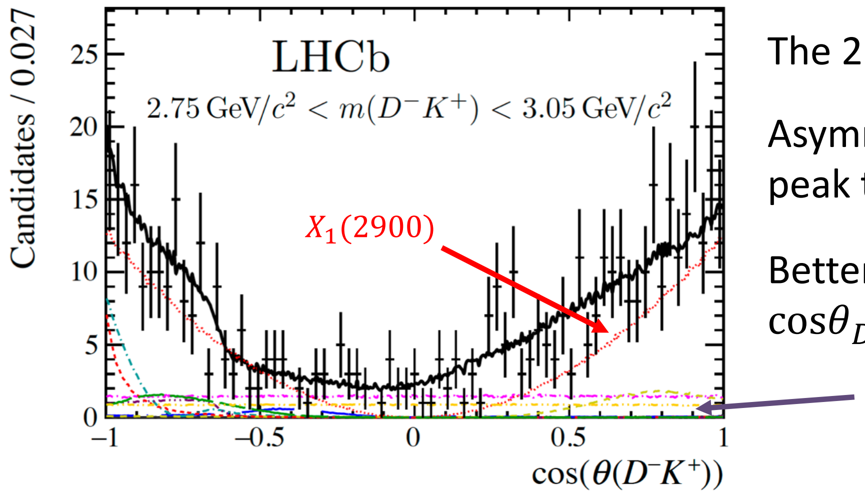
[arXiv:2009.00025]
Accepted by PRL

Amplitude analysis

[arXiv:2009.00026]
Accepted by PRD

- Add two D^-K^+ states (BW) at $\sim 2.9\ \mathrm{GeV}$, $J^P=0^+, 1^-$
  - Improve $2\ln\mathcal{L}$ by >300 units



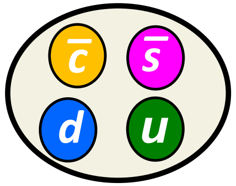


The 2nd state:

Asymmetry $m(D^-K^+)$ peak to match data

Better description on $\cos\theta_{D^-K^+}$ distribution

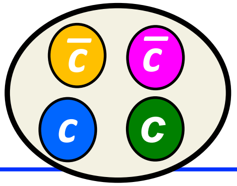
- Need more intricate theoretical studies
  - Very close to D^*K^*, D_1K thresholds. Rescattering ?



Candidates for the 1st open-charm tetraquarks (four different flavors)!

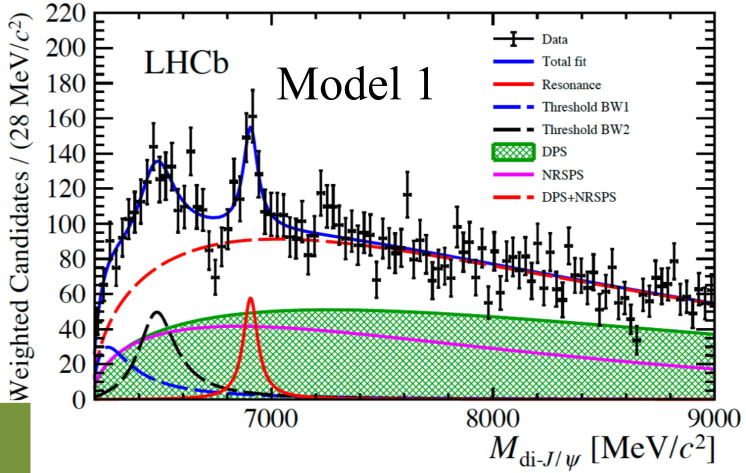
$$X_0(2900): \quad M = 2.866 \pm 0.007 \pm 0.002\ \mathrm{GeV}/c^2, \quad \Gamma = 57 \pm 12 \pm 4\ \mathrm{MeV}$$
$$X_1(2900): \quad M = 2.904 \pm 0.005 \pm 0.001\ \mathrm{GeV}/c^2, \quad \Gamma = 110 \pm 11 \pm 4\ \mathrm{MeV}$$

$X(6900)$ in di-J/ψ system

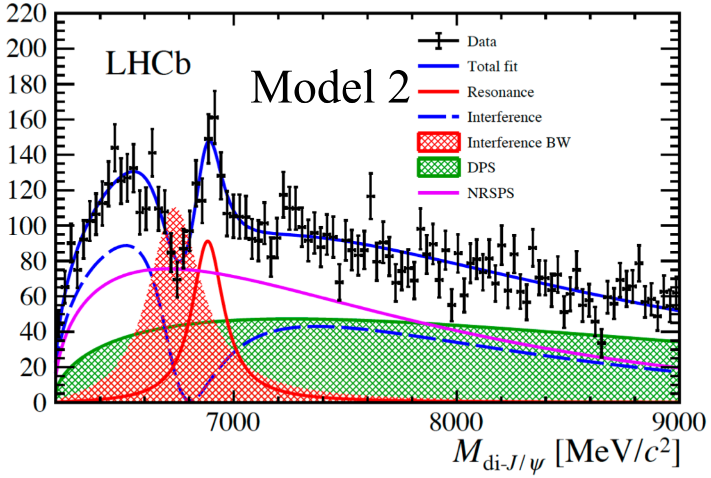


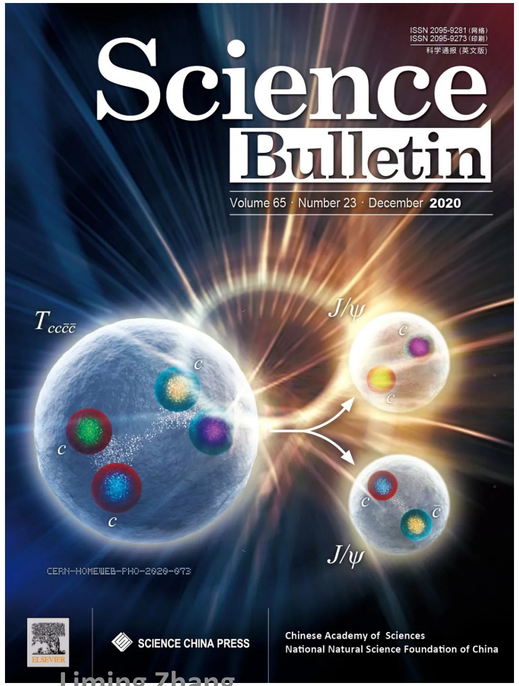
[arXiv:2006.16957]
To appear in Science Bulletin

- Search for di-J/ψ structure using full data
  - DPS + NRSPS cannot well describe data
  - A di-J/ψ resonance $X(6900)$ significantly improves the fit
  - Two fit models: both has $> 5\sigma$ significance of $X(6900)$
  - A first candidate for the $T_{c\bar{c}c\bar{c}}$ tetraquark state



Model 1: No interference between NRSPS and BW
$M(6900) = 6905 \pm 11 \pm 7$ MeV
$\Gamma(6900) = 80 \pm 19 \pm 33$ MeV
Model 2: Interference between NRSPS and a broad BW
$M(6900) = 6886 \pm 11 \pm 11$ MeV
$\Gamma(6900) = 168 \pm 33 \pm 69$ MeV





$X(3872)$ lineshape

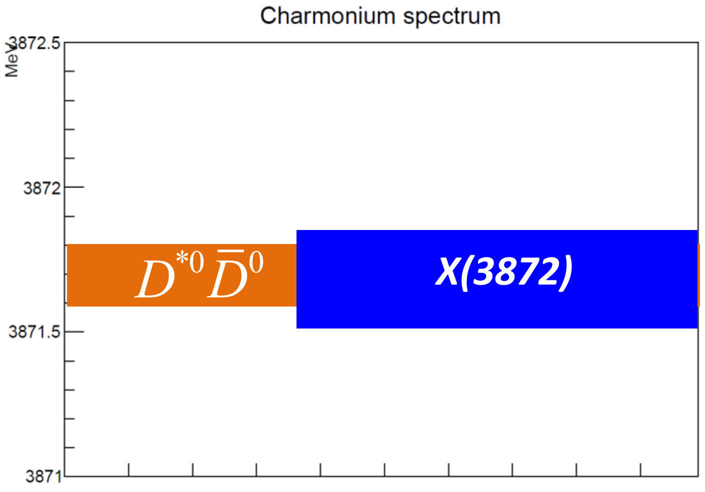
- $X(3872)$ nature is still uncertain, although many studies are performed since 2003
  - $J^{PC} = 1^{++}$ [Phys. Rev. D92 (2015) 011102(R)]
  - **Mass = 3871.69 ± 0.17 MeV**
  - **Width < 1.2 MeV** @90% CL

$$\boldsymbol{\delta E = (m_{D^{*0}} + m_{D^0}) - m_{X(3872)} = 0.01 \pm 0.20\ \mathrm{MeV}}$$

[PDG 2020]

- Molecular interpretation requires $\delta E > 0$, the knowledge is limited by the mass precision of $X(3872)$

- Current precision is dominated by CDF results 10 years ago

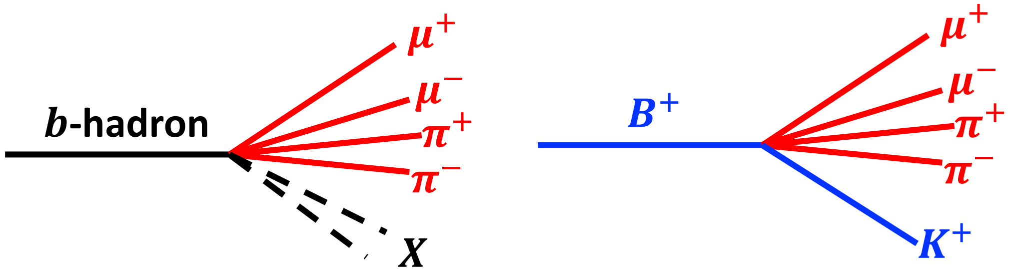


$\chi_{c1}(3872)$ MASS FROM $J/\psi X$ MODE

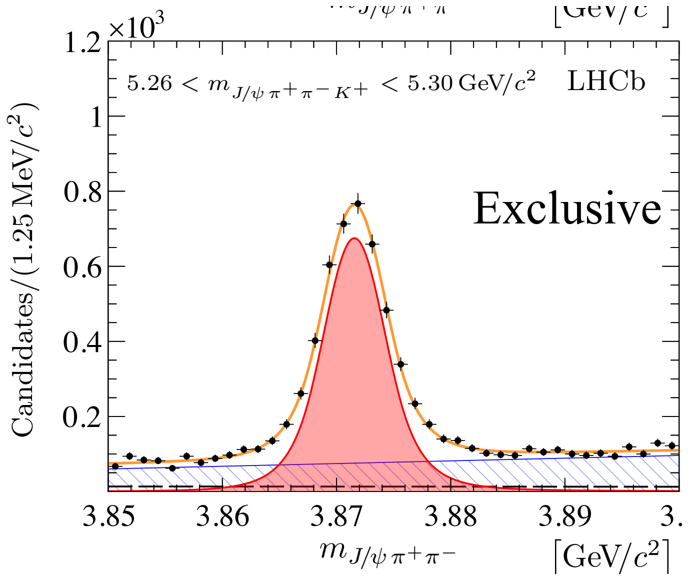
VALUE (MeV)	EVTS	DOCUMENT ID		TECN
3871.69 ± 0.17	**OUR AVERAGE**			
3871.9 ±0.7 ±0.2	20 ±5	ABLIKIM	2014	BES3
3871.95 ±0.48 ±0.12	0.6k	AAIJ	2012H	LHCB
3871.85 ±0.27 ±0.19	~ 170	[1] CHOI	2011	BELL
$3873\ ^{+1.8}_{-1.6} \pm 1.3$	27 ±8	[2] DEL-AMO-SANCH..	2010B	BABR
3871.61 ±0.16 ±0.19	6k	[3, 2] AALTONEN	2009AU	CDF2
3871.4 ±0.6 ±0.1	93.4	AUBERT	2008Y	BABR
3868.7 ±1.5 ±0.4	9.4	AUBERT	2008Y	BABR
3871.8 ±3.1 ±3.0	522	[4, 2] ABAZOV	2004F	D0

LHCb results with Breit-Wigner fit

- Two measurements using $X(3872) \to J/\psi\pi^+\pi^-$ related to $\psi(2S)$
  - Inclusive $b \to X(3872)$ + anything
  - Exclusive $B^+ \to X(3872)K^+$
- Mass resolution is 2-3 MeV



Meas.	Yield	M_{BW} (MeV)	Γ_{BW} (MeV)
Inclusive [arXiv:2005.13419]	~15.6k (more bkg)	$3871.695 \pm 0.067 \pm 0.068 \pm 0.010$	$1.39 \pm 0.24 \pm 0.10$
Exclusive [arXiv:2005.13422]	~4.2k (less bkg)	$3871.59 \pm 0.06 \pm 0.03 \pm 0.010$	$0.96^{+0.19}_{-0.18} \pm 0.21$



LHCb average

$$M_{BW} = 3871.64 \pm 0.06 \pm 0.01\ \mathrm{MeV};\ \Gamma_{BW} = 1.19 \pm 0.19\ \mathrm{MeV}$$

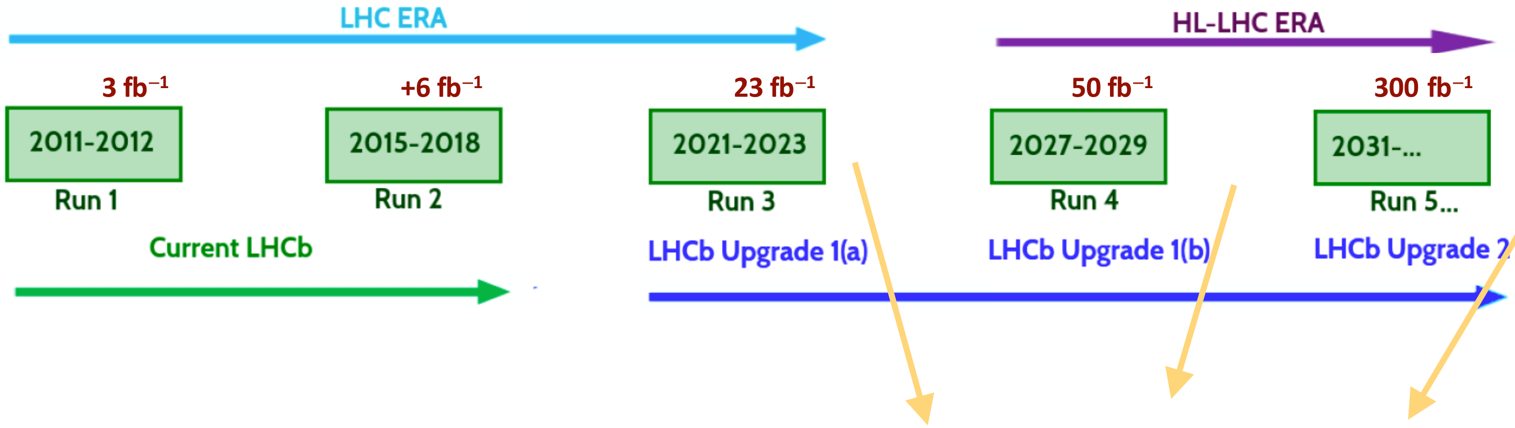
$$\delta E = M(D^0) + M(\bar{D}^{*0}) - M(\chi_{c1}(3872)) = 0.07 \pm 0.12\ \mathrm{MeV}$$

Uncertainty on δE is now dominated by knowledge of kaon masses

Flatté function also investigated, precision is limited by mass resolution

Prospects

[arXiv:1808.08865]



- **LHCb is now boosting the data to a new level**
  - **Expect to 7x more data (14x hadronic events) by 2029 than current, half of these by 2023**
  - **Could have another 6x increase from Upgrade II**

Decay mode	LHCb		
	$23\,\mathrm{fb}^{-1}$	$50\,\mathrm{fb}^{-1}$	$300\,\mathrm{fb}^{-1}$
$B^+ \to X(3872)(\to J/\psi\pi^+\pi^-)K^+$	14k	30k	180k
$B^+ \to X(3872)(\to \psi(2S)\gamma)K^+$	500	1k	7k
$B^0 \to \psi(2S)K^-\pi^+$	340k	700k	4M
$B_c^+ \to D_s^+ D^0 \overline{D}^0$	10	20	100
$\Lambda_b^0 \to J/\psi\, pK^-$ [*]	680k	1.4M	8M
$\Xi_b^- \to J/\psi\, \Lambda K^-$	4k	10k	55k
$\Xi_{cc}^{++} \to \Lambda_c^+ K^-\pi^+\pi^+$	7k	15k	90k
$\Xi_{bc}^+ \to J/\psi\, \Xi_c^+$	50	100	600

$\chi_{c1}(3872)$ lineshape from multi-channels

$Z_c(4430)$, also explore $B \to D_{(s)}^{(*)}\overline{D}_{(s)}K^-$?

Doubly-charmed tetraquark $\mathcal{T}_{cc}^+ \to D_s^+ D^0$

More information for pentaquarks

[*] updated according to the latest result

Summary

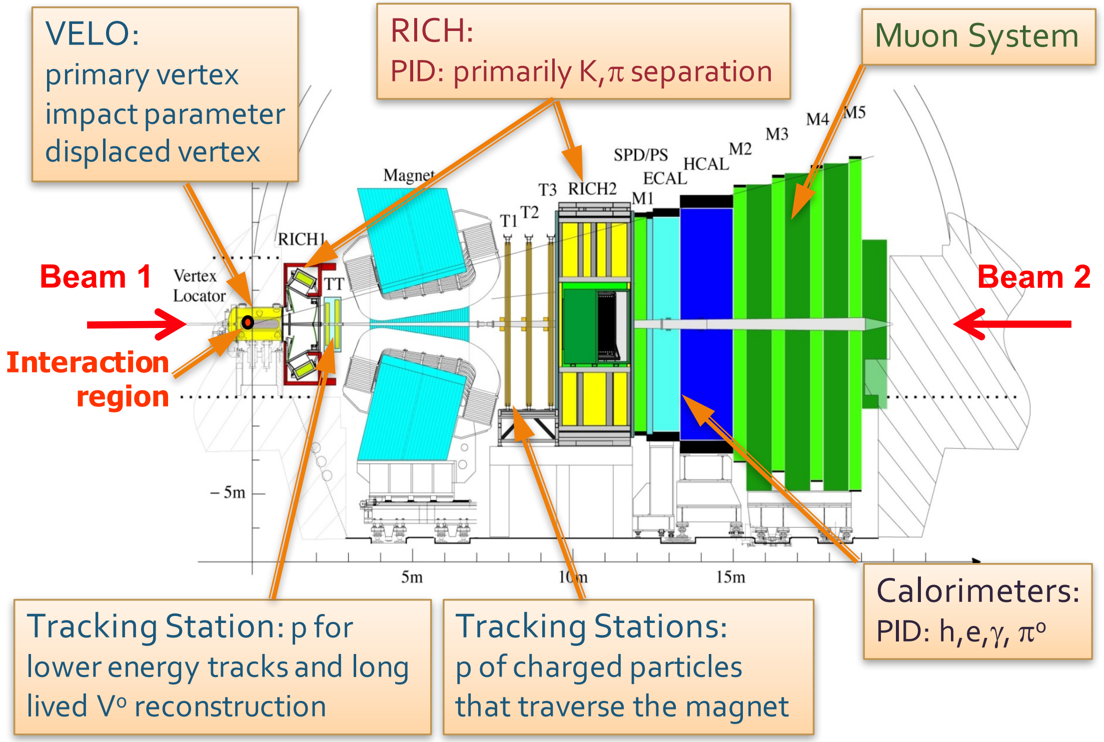
- LHC is a heavy-quark hadron factory, with LHCb detector dedicated for flavour physics, we can also
  - Explore meson and baryon excitation spectra
  - Study exotic hadron spectroscopy

- Many interesting results
  - Observations of first candidates for open-charm tetraquark $X_{0,1}(2900)$, full charmed tetraquark $X(6900)$
  - Evidence of first candidate for hidden-charm pentaquark with strangeness $P_{cs}(4459)^0$

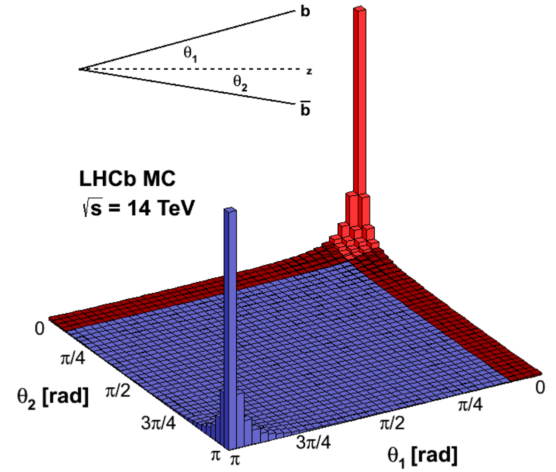
Backup

LHCb detector and performance

The LHCb detector described in [JINST 3 (2008) S08005]



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

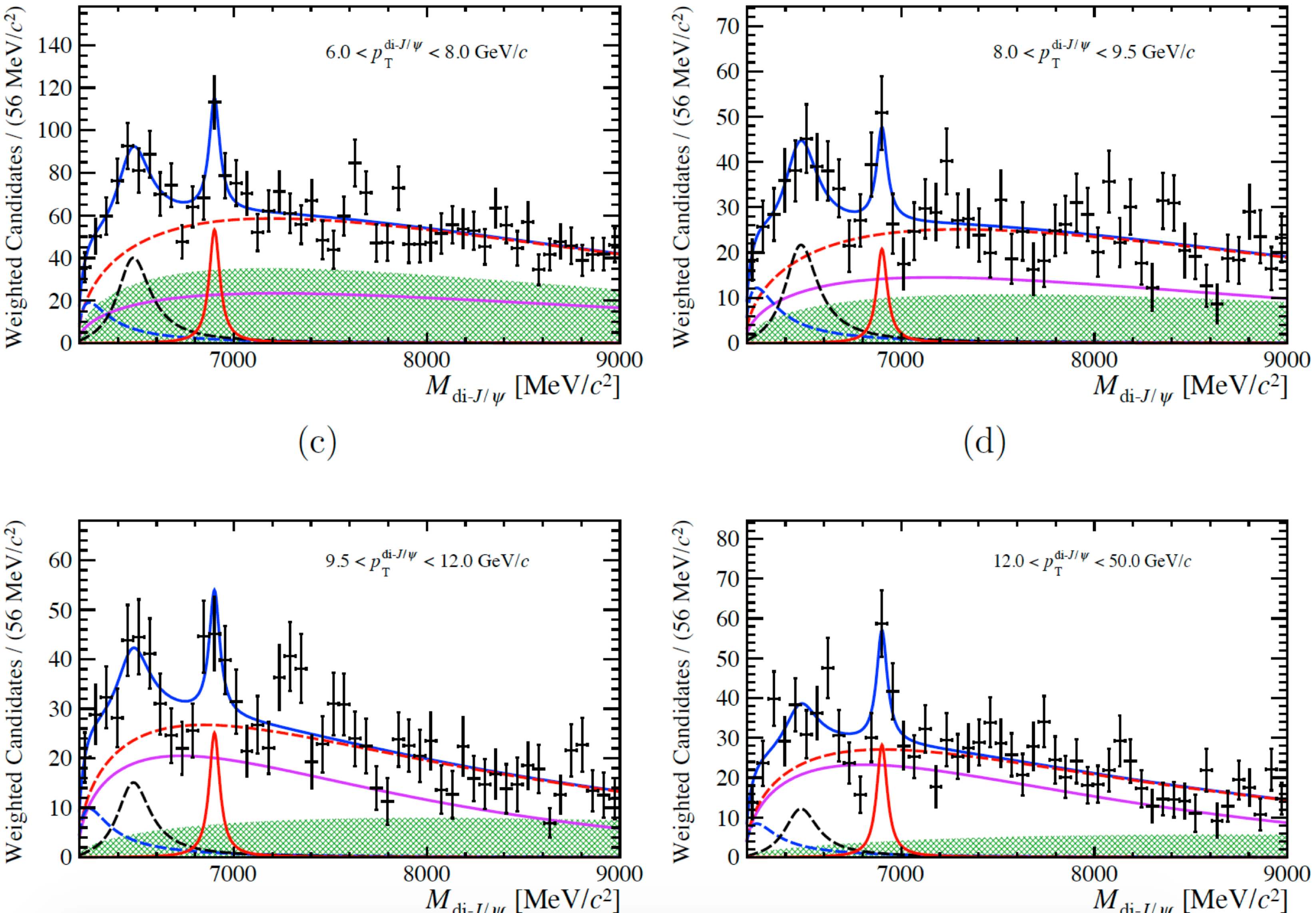


[Int. J. Mod. Phys. A 30 (2015) 1530022]

Impact parameter:	$\boldsymbol{\sigma_{IP} = 20\ \mu m}$
Proper time:	$\sigma_\tau = 45$ fs for $B_s^0 \to J/\psi\phi$ or $D_s^+\pi^-$
Momentum:	$\Delta p/p = 0.4 \sim 0.6\%$ (5 – 100 GeV/c)
Mass :	$\boldsymbol{\sigma_m = 8\ \mathrm{MeV}/c^2}$ **for** $\boldsymbol{B \to J/\psi X}$ **(constrained** $\boldsymbol{m_{J/\psi}}$**)**
RICH $K - \pi$ separation:	$\boldsymbol{\epsilon(K \to K) \sim 95\%}$ **mis-ID** $\boldsymbol{\epsilon(\pi \to K) \sim 5\%}$
Muon ID:	$\boldsymbol{\epsilon(\mu \to \mu) \sim 97\%}$ **mis-ID** $\boldsymbol{\epsilon(\pi \to \mu) \sim 1 - 3\%}$
ECAL:	$\Delta E/E = 1 \oplus 10\%/\sqrt{E(\mathrm{GeV})}$

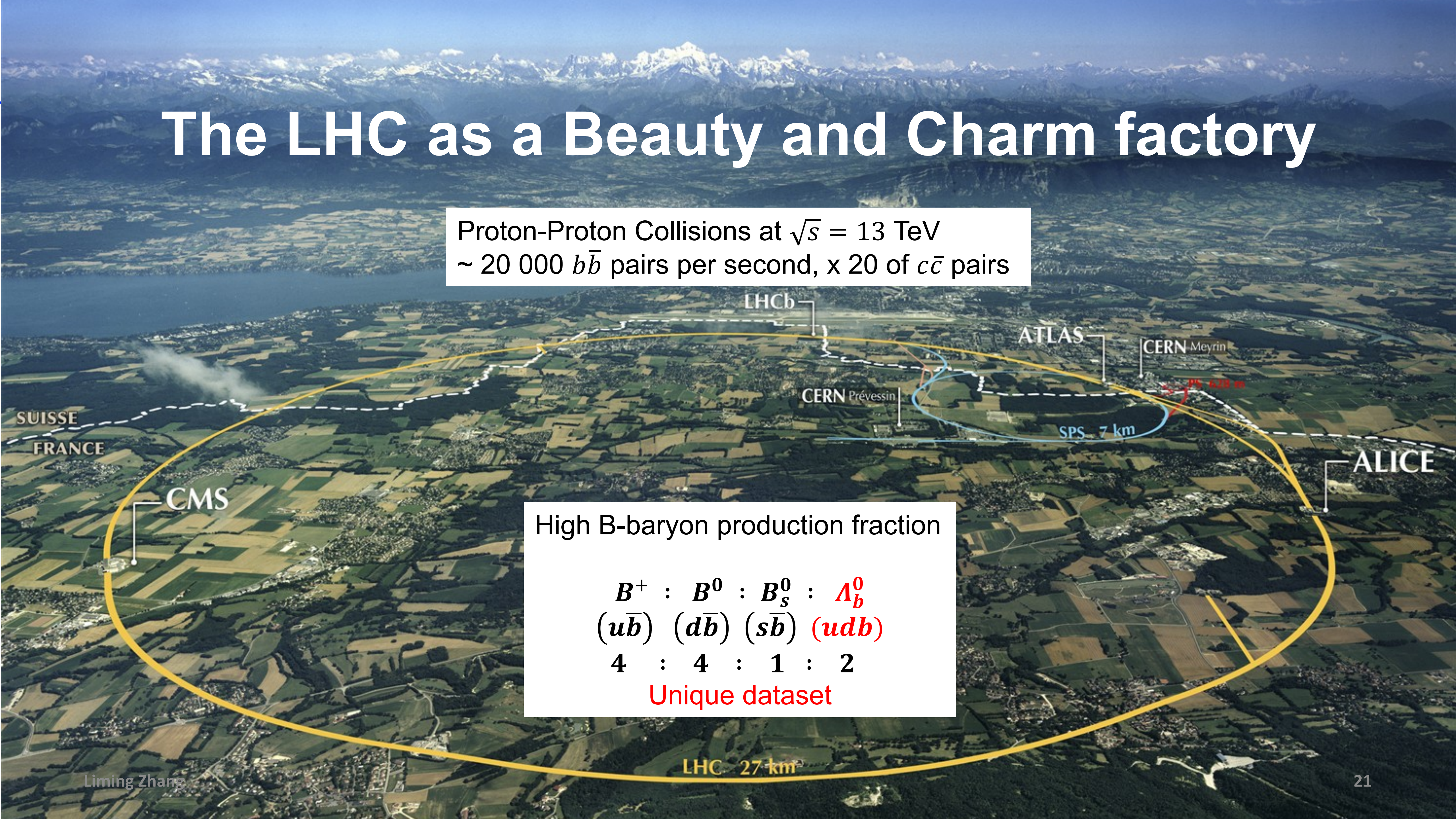
$X(6900)$ in di-J/ψ system

[arXiv:2006.16957]
To appear in Science Bulletin



The LHC as a Beauty and Charm factory

Proton-Proton Collisions at $\sqrt{s} = 13$ TeV
~ 20 000 $b\bar{b}$ pairs per second, x 20 of $c\bar{c}$ pairs

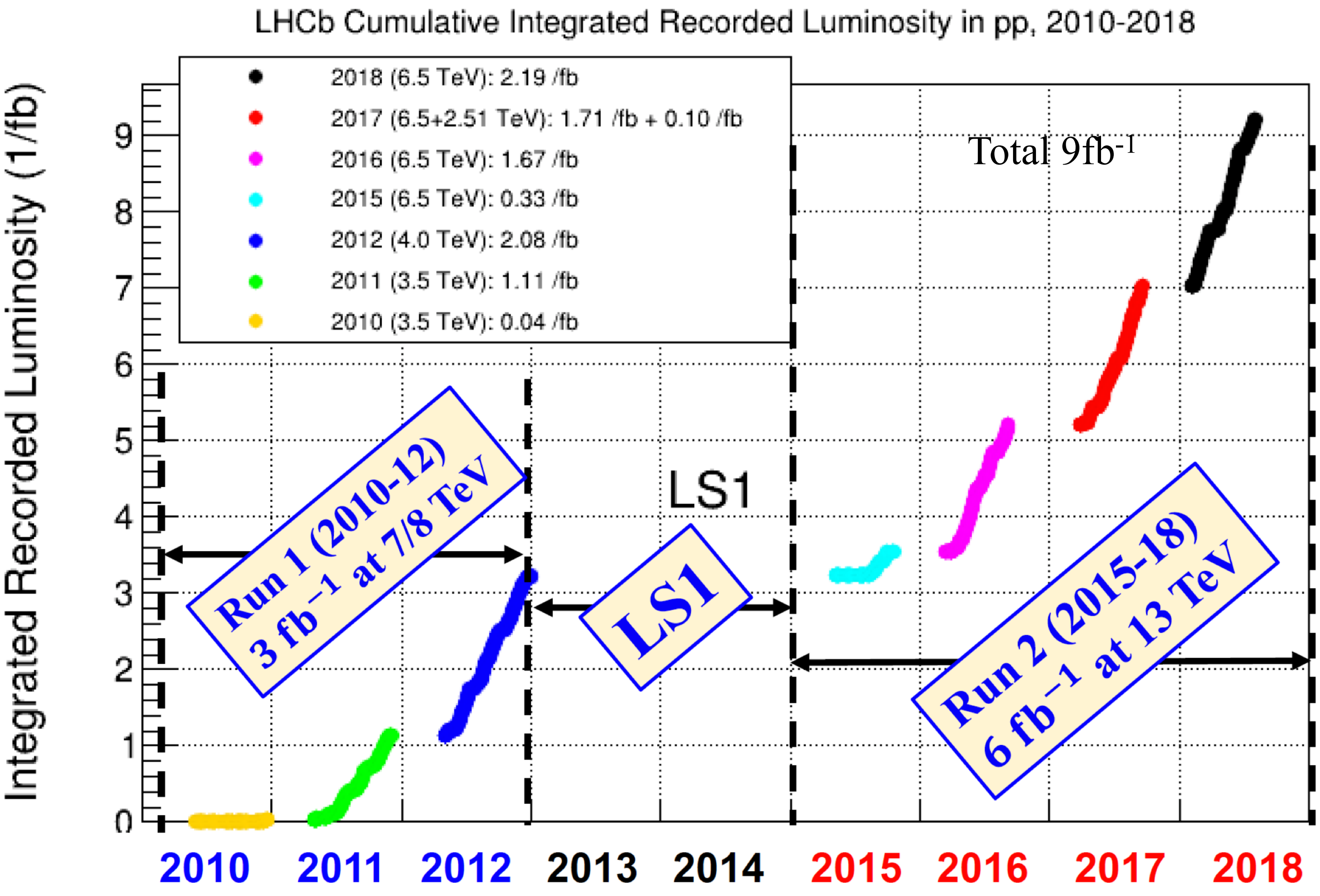


High B-baryon production fraction

$$\begin{array}{ccccccc} B^+ & : & B^0 & : & B_s^0 & : & \Lambda_b^0 \\ (u\bar{b}) & & (d\bar{b}) & & (s\bar{b}) & & (udb) \\ 4 & : & 4 & : & 1 & : & 2 \end{array}$$

Unique dataset

LHCb collected luminosity

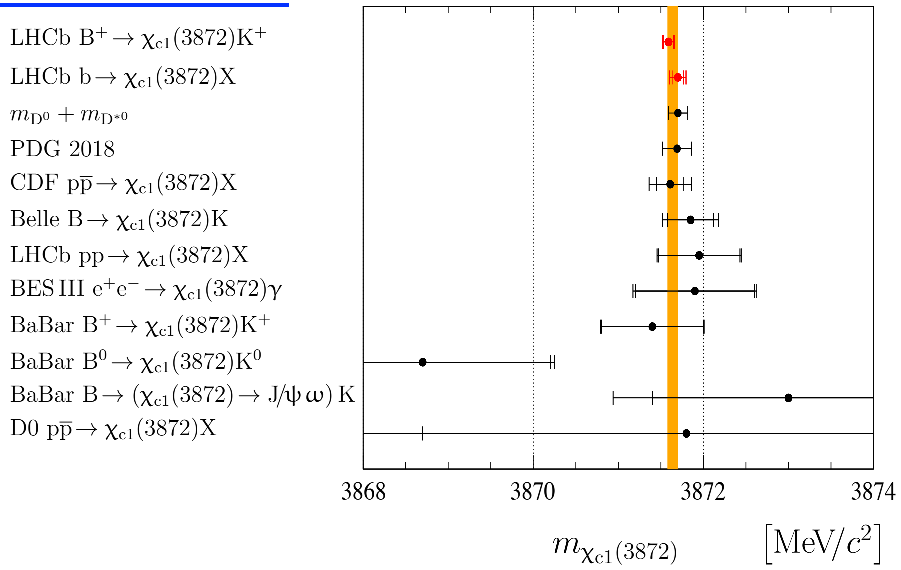


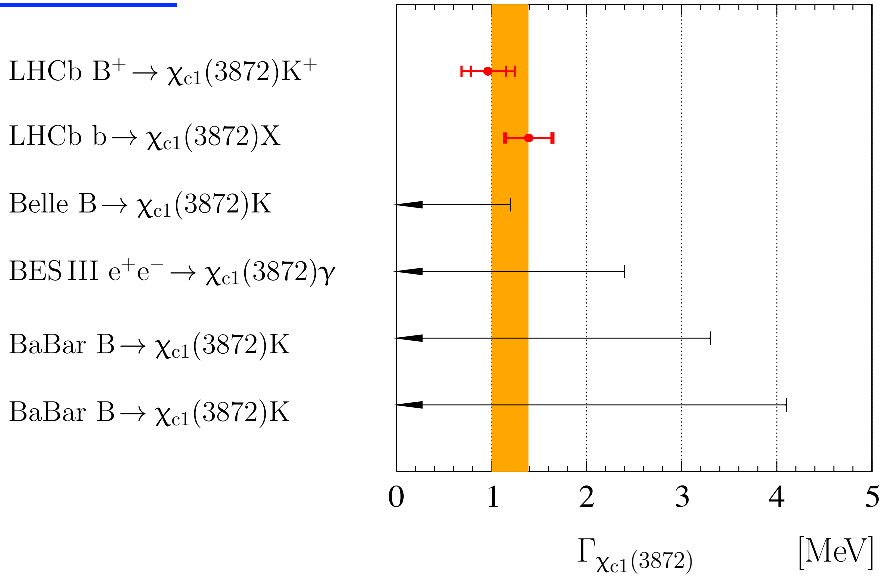
$\sigma(pp \to b\bar{b}X) \approx 300$ μb @7 TeV vs ≈ 500 μb @13 TeV

~25% can be collected in LHCb acceptance

Breit-Wigner mass and width

[arXiv: 2005.13422]





- World average
  - ✓Before: $M_{\rm BW} = 3871.68 \pm 0.17\ \mathrm{MeV}/c^2$; $\Gamma_{\rm BW} < 1.2\ \mathrm{MeV}/c^2$ at 90% C.L.
  - ✓After: $M_{\rm BW} = 3871.64 \pm 0.06\ \mathrm{MeV}/c^2$; $\Gamma_{\rm BW} = 1.19 \pm 0.19\ \mathrm{MeV}/c^2$
- LHCb average
  - ✓$M_{\rm BW} = 3871.64 \pm 0.06 \pm 0.01\ \mathrm{MeV}/c^2$; $\Gamma_{\rm BW} = 1.19 \pm 0.19\ \mathrm{MeV}/c^2$
  - ✓$\delta E = M(D^0) + M(\bar{D}^{*0}) - M\big(\chi_{c1}(3872)\big) = 0.07 \pm 0.12\ \mathrm{MeV}/c^2$

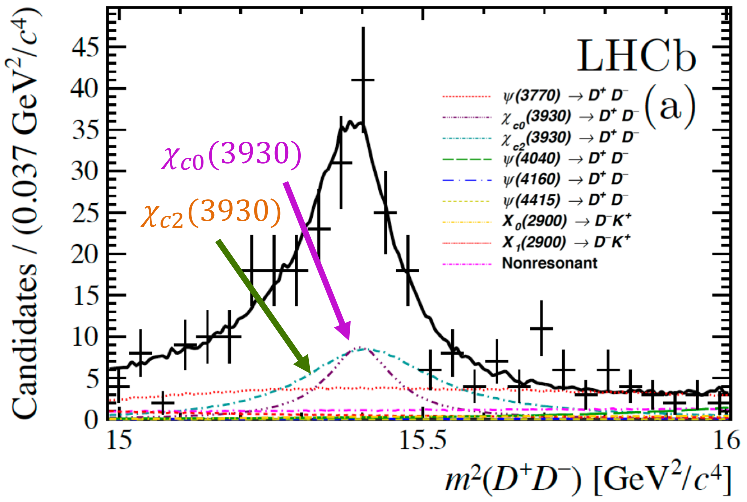
*Small statistical overlap between the two samples is considered

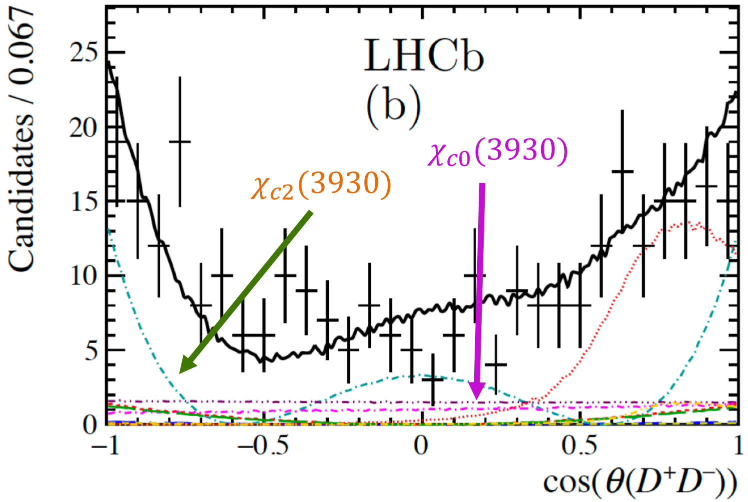
- Opening up of $D^0\bar{D}^{*0}$ threshold distorts the lineshape from Breit-Wigner ⇒

Amplitude analysis

[arXiv:2009.00026]
Accepted by PRD

Require two χ_c states with $m(D^+D^-) \sim 3.93\text{GeV}$





	Resonance	Mass (GeV/c^2)	Width (MeV)
new	$\chi_{c0}(3930)$	$3.9238 \pm 0.0015 \pm 0.0004$	$17.4 \pm 5.1 \pm 0.8$
	$\chi_{c2}(3930)$	$3.9268 \pm 0.0024 \pm 0.0008$	$34.2 \pm 6.6 \pm 1.1$

The same as the $X(3915)$ state?

$X(3915)$ MASS	3918.4 ± 1.9 MeV
$X(3915)$ WIDTH	20 ± 5 MeV (S = 1.1)