Exotic hadrons at LHCb

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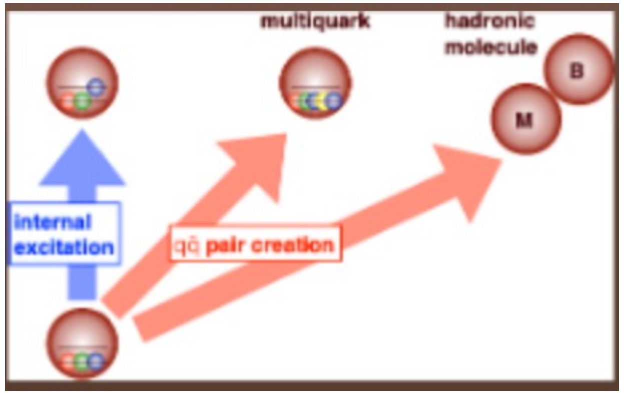
On behalf of the LHCb collaboration

2022.09.29



Exotics and Exotic Phenomena in
Heavy Ion Collisions (ExHIC)
29 September – 1 October 2022,
APCTP Headquarters, Korea

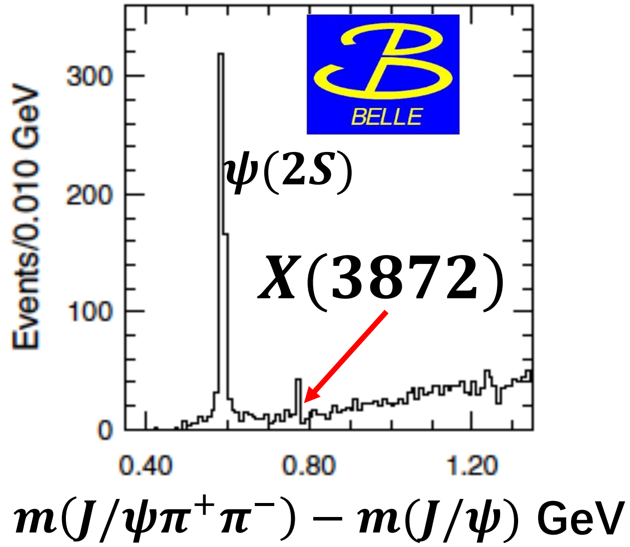
Outline

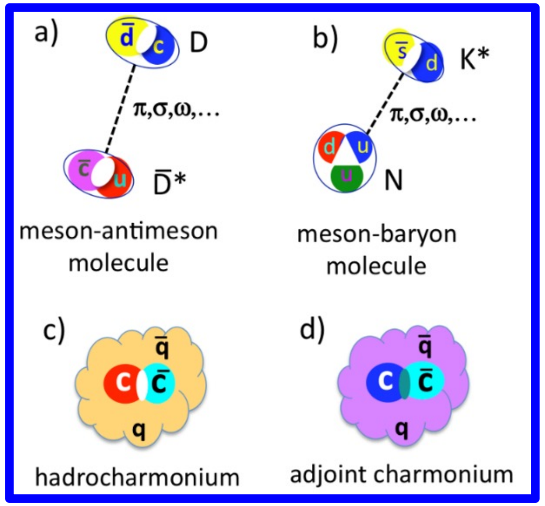
- Introduction and the LHCb experiment
- (Selected) results of exotic hadrons at LHCb
- Prospects and summary

Renaissance of spectroscopy in heavy flavour

- The $X(3872)$ [$\chi_{c1}(3872)$] state observed by Belle in 2003 in the $J/\psi\pi^+\pi^-$ spectrum
  - The harbinger of a new direction in hadron spectroscopy
- More exotic hadrons, mostly containing $c\bar{c}$ or $b\bar{b}$, have been observed soon later
  - Various models proposed for quark composition and binding mechanisms of these states
- Great progress achieved with combined efforts from both theory and experiments
  - LHCb has been providing propellant to boost our understanding since the start of the LHC

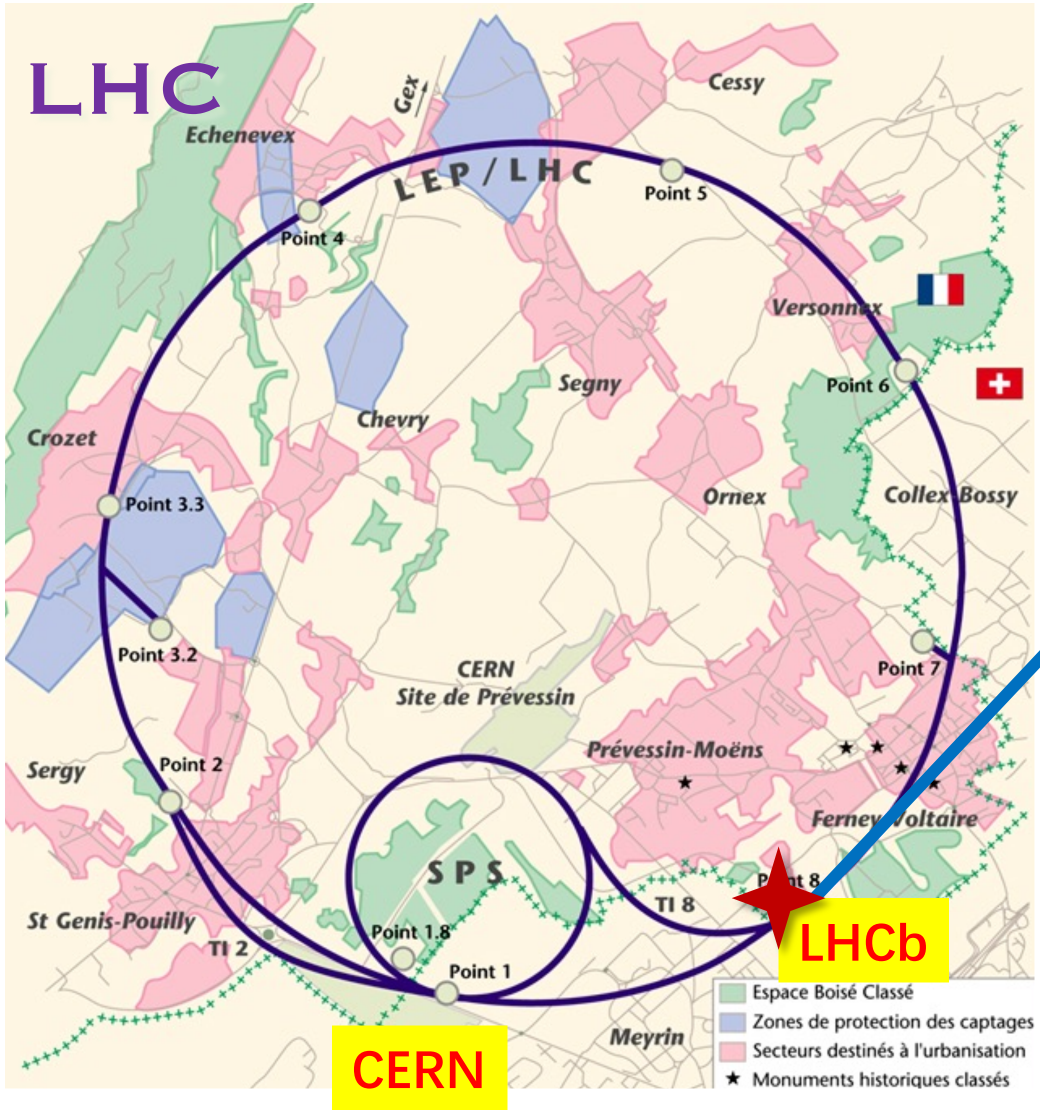
PRL91 (2003) 262001



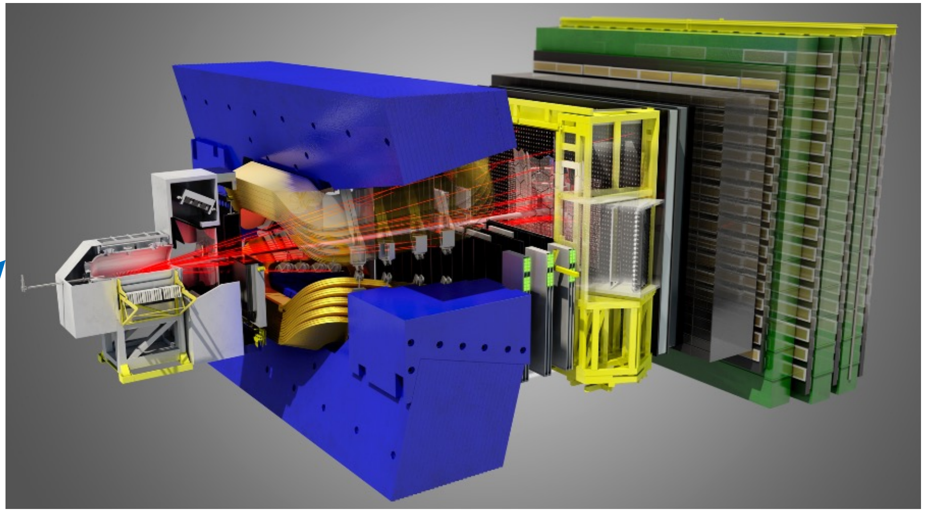


Rev. Mod. Phys. 90 (2018) 015003

The LHCb experiment



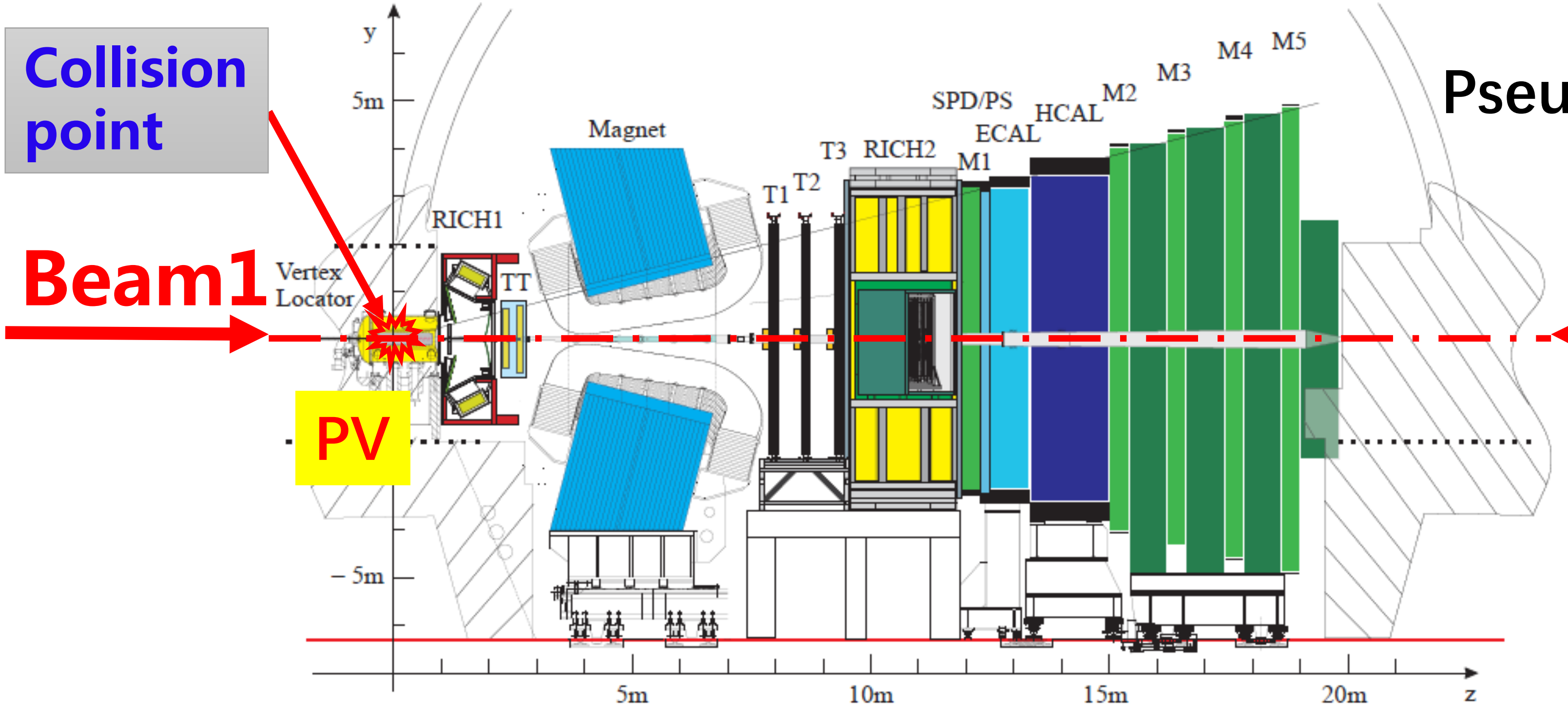
- A forward spectrometer at the LHC designed for the study of heavy flavour physics



- The LHCb collaboration
  - 1539 Members, from 95 institutes in 20 countries (by 29/09/2022)

The LHCb detector and physics

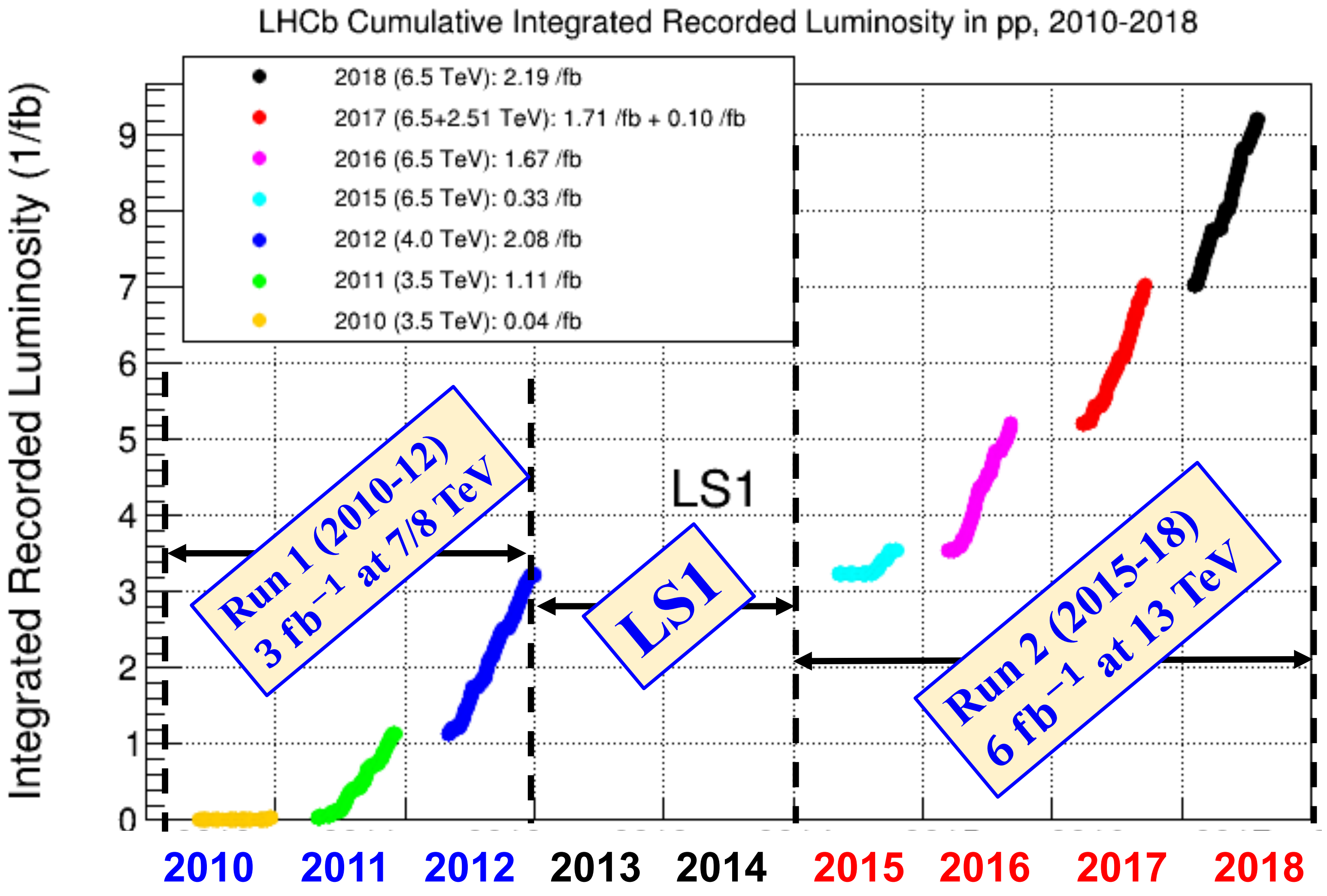
JINST 3 (2008) S08005
Int. J. Mod. Phys. A 30 (2015) 1530022



Pseudorapidity coverage
$2 < \eta < 5$

- Indirect search for New Physics via precision measurements of CKM, CPV and RD
- Direct search of new particles beyond SM
- QCD +EW precision measurements at large rapidity
- Hadron spectroscopy
- Heavy-ion and fixed target physics

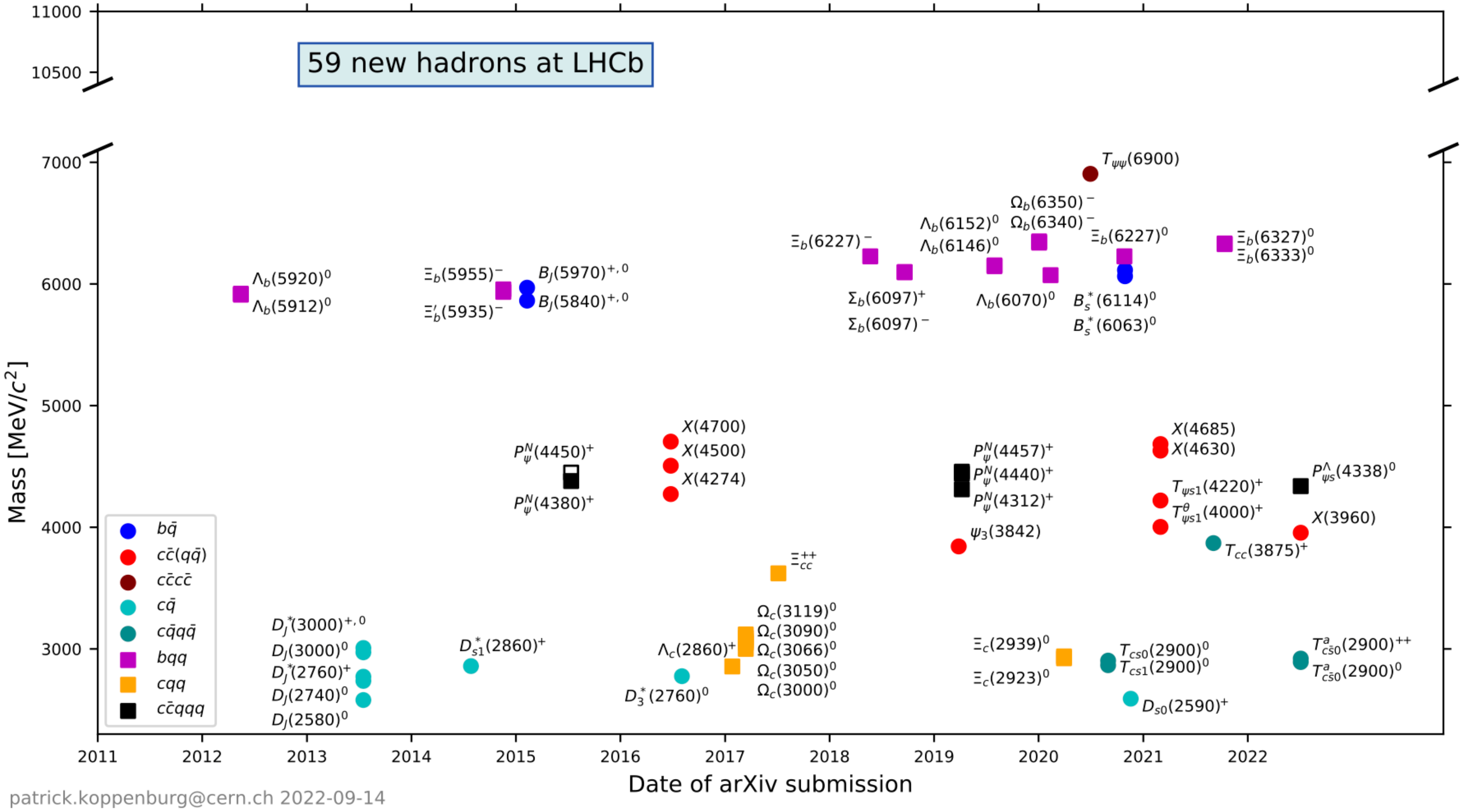
Data taking (run1+run2)



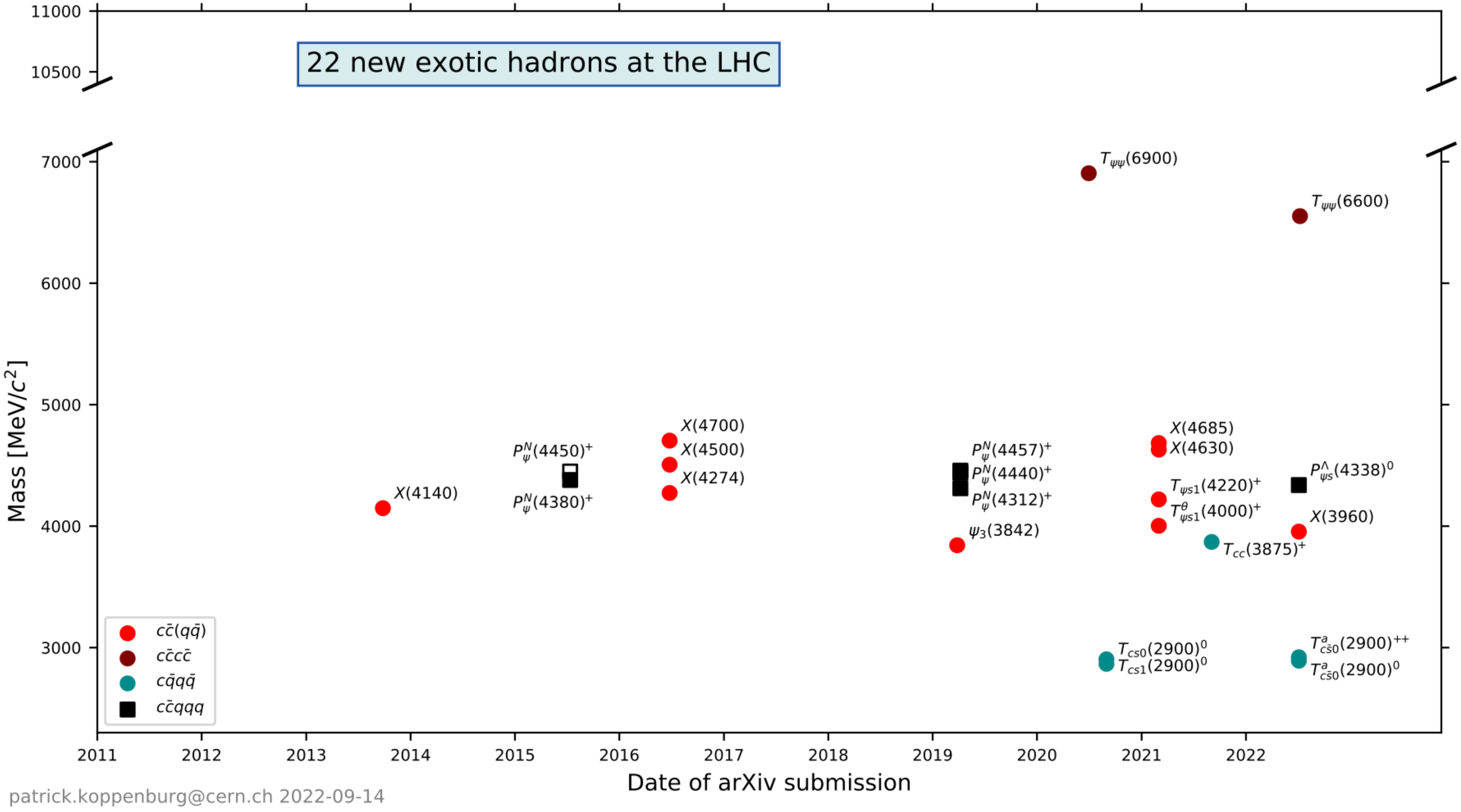
- A huge amount of $b\bar{b}$ and $c\bar{c}$ have been produced
  - $\sim 10^{12}\ b\bar{b}$
  - $\sim 10^{13}\ c\bar{c}$
- Many impressive results have been achieved

More than 9 fb^{-1} accumulated in Run1+Run2 (2011-2018)

Hadrons observed at LHCb (up to 2022-09-14)



Exotic hadrons discovered at LHCb (up to 2022-09-14)



Tetraquarks

Starting from $X(3872)$, *i.e.* $\chi_{c1}(3872)$, the first candidate

$\chi_{c1}(3872)$: B factory era

X(3872)

$I^G(J^P) = ?^?(?^?)$

PDG2004

OMITTED FROM SUMMARY TABLE

Seen by CHOI 03 in $B \to K\pi^+\pi^- J/\psi(1S)$ decays as a narrow peak in the invariant mass distribution of the $\pi^+\pi^- J/\psi(1S)$ final state, but not seen in the $\gamma\chi_{c1}$ final state of these decays. Possibly absent in the invariant mass spectrum of the final state $\pi^+\pi^- J/\psi(1S)$ in e^+e^- collisions. Interpretation as a 1^{--} charmonium state not favored.

Quantum numbers are not established.

X(3872) MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
3872.0±0.6±0.5	36	CHOI	03	BELL	$B \to K\pi^+\pi^- J/\psi$

X(3872) WIDTH

VALUE (MeV)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<2.3	90	36	CHOI	03	BELL	$B \to K\pi^+\pi^- J/\psi$

X(3872) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	e^+e^-	
Γ_2	$\pi^+\pi^- J/\psi(1S)$	seen
Γ_3	$\gamma\chi_{c1}$	

X(3872)

$I^G(J^{PC}) = 0^?(?^{?+})$

PDG2012

Seen by CHOI 03 in $B \to K\pi^+\pi^- J/\psi(1S)$ decays as a narrow peak in the invariant mass distribution of the $\pi^+\pi^- J/\psi(1S)$ final state, but not seen in the $\gamma\chi_{c1}$ final state of these decays. Possibly absent in the invariant mass spectrum of the final state $\pi^+\pi^- J/\psi(1S)$ in e^+e^- collisions. Interpretation as a 1^{--} charmonium state not favored. Isovector hypothesis excluded by AUBERT 05B and CHOI 11. A helicity amplitude analysis of the $X(3872) \to J/\psi\pi^+\pi^-$ decay gives two possible J^{PC} assignments: $J^{PC} = 1^{++}$ and 2^{-+} (ABULENCIA 07E and CHOI 11). A study of the 3π invariant mass distribution in $J/\psi\omega$ decays slightly favors $J^P = 2^-$ (DEL-AMO-SANCHEZ 10B).

See our note on "Developments in Heavy Quarkonium Spectroscopy".

X(3872) MASS FROM $J/\psi X$ MODE

LHCb measured its mass using 2010 data (34.7 pb^{-1})

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
3871.68± 0.17 OUR AVERAGE					
3871.95± 0.48±0.12	0.6k	AAIJ	12H	LHCB	$pp \to J/\psi\pi^+\pi^- X$
3871.85± 0.27±0.19	~ 170	[1] CHOI	11	BELL	$B \to K\pi^+\pi^- J/\psi$
3873 $^{+1.8}_{-1.6}$ ±1.3	27 ± 8	[2] DEL-AMO-SA.	10B	BABR	$B \to \omega J/\psi K$
3871.61± 0.16±0.19	6k	[2,3] AALTONEN	09AU	CDF2	$p\bar{p} \to J/\psi\pi^+\pi^- X$
3871.4 ± 0.6 ±0.1	93.4	AUBERT	08Y	BABR	$B^+ \to K^+ J/\psi\pi^+\pi^-$
3868.7 ± 1.5 ±0.4	9.4	AUBERT	08Y	BABR	$B^0 \to K^0_S J/\psi\pi^+\pi^-$
3871.8 ± 3.1 ±3.0	522	[2,4] ABAZOV	04F	D0	$p\bar{p} \to J/\psi\pi^+\pi^- X$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
3868.6					
3871.3					
3873.4					
3871.3					
3872.0					
3836					

Mass: close to the $\bar{D}^{*0}D^0$ threshold
Width: narrow
C parity: +
Isospin: 0

$\chi_{c1}(3872)$: the LHC era

PDG2014

$X(3872)$

$I^G(J^{PC}) = 0^+(1^{++})$

First observed by CHOI 03 in $B \to K\pi^+\pi^- J/\psi(1S)$ decays as a narrow peak in the invariant mass distribution of the $\pi^+\pi^- J/\psi(1S)$ final state. Isovector hypothesis excluded by AUBERT 05B and CHOI 11.

AAIJ 13Q perform a full five-dimensional amplitude analysis of the angular correlations between the decay products in $B^+ \to X(3872)K^+$ decays, where $X(3872) \to J/\psi\pi^+\pi^-$ and $J/\psi \to \mu^+\mu^-$, which unambiguously gives the $J^{PC} = 1^{++}$ assignment.

See our note on "Developments in Heavy Quarkonium Spectroscopy".

$X(3872)$ MASS FROM $J/\psi X$ MODE

Mass resolution: $0.17\ \mathrm{MeV}/c^2$

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
3871.69± 0.17 OUR AVERAGE					
3871.9 ± 0.7 ±0.2	20 ± 5	ABLIKIM	14	BES3	$e^+e^- \to J/\psi\pi^+\pi^-\gamma$
3871.95± 0.48±0.12	0.6k	AAIJ	12H	LHCB	$pp \to J/\psi\pi^+\pi^- X$
3871.85± 0.27±0.19	~ 170	[1] CHOI	11	BELL	$B \to K\pi^+\pi^- J/\psi$
3873 $^{+1.8}_{-1.6}$ ±1.3	27 ± 8	[2] DEL-AMO-SA...	10B	BABR	$B \to \omega J/\psi K$
3871.61± 0.16±0.19	6k	[2,3] AALTONEN	09AU	CDF2	$p\bar{p} \to J/\psi\pi^+\pi^- X$
3871.4 ± 0.6 ±0.1	93.4	AUBERT	08Y	BABR	$B^+ \to K^+ J/\psi\pi^+\pi^-$
3868.7 ± 1.5 ±0.4	9.4	AUBERT	08Y	BABR	$B^0 \to K^0_S J/\psi\pi^+\pi^-$
3871.8 ± 3.1 ±3.0	522	[2,4] ABAZOV	04F	D0	$p\bar{p} \to J/\psi\pi^+\pi^- X$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
3868.6 ± 1.2 ±0.2	8	[5] AUBERT	06	BABR	$B^0 \to K^0_S J/\psi\pi^+\pi^-$

$X(3872)$ WIDTH

VALUE (MeV)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<1.2	90		CHOI	11	BELL	$B \to K\pi^+\pi^- J/\psi$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<2.4	90		ABLIKIM	14	BES3	$e^+e^- \to J/\psi\pi^+\pi^-\gamma$
<3.3	90		AUBERT	08Y	BABR	$B^+ \to K^+ J/\psi\pi^+\pi^-$
<4.1	90	69	AUBERT	06	BABR	$B \to K\pi^+\pi^- J/\psi$
<2.3	90	36	[14] CHOI	03	BELL	$B \to K\pi^+\pi^- J/\psi$

[14] Superseded by CHOI 11.

PDG2022

$\chi_{c1}(3872)$

$I^G(J^{PC}) = 0^+(1^{++})$

also known as $X(3872)$

This state shows properties different from a conventional $q\bar{q}$ state. A candidate for an exotic structure. See the review on non-$q\bar{q}$ states.

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

Mass resolution: $0.06\ \mathrm{MeV}/c^2$

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
3871.65 ± 0.06 OUR AVERAGE					
3871.64 ± 0.06 ±0.01	19.8k	[1] AAIJ	20S	LHCB	$B^+ \to J/\psi\pi^+\pi^- K^+$
3871.9 ± 0.7 ±0.2	20	ABLIKIM	14	BES3	$e^+e^- \to J/\psi\pi^+\pi^-\gamma$
3871.95 ± 0.48 ±0.12	0.6k	AAIJ	12H	LHCB	$pp \to J/\psi\pi^+\pi^- X$
3871.85 ± 0.27 ±0.19	170	[2] CHOI	11	BELL	$B \to K\pi^+\pi^- J/\psi$
3873 $^{+1.8}_{-1.6}$ ±1.3	27	[3] DEL-AMO-SA...	10B	BABR	$B \to \omega J/\psi K$
3871.61 ± 0.16 ±0.19	6k	[3,4] AALTONEN	09AU	CDF2	$p\bar{p} \to J/\psi\pi^+\pi^- X$
3871.4 ± 0.6 ±0.1	93.4	AUBERT	08Y	BABR	$B^+ \to K^+ J/\psi\pi^+\pi^-$

$\chi_{c1}(3872)$ WIDTH

Width: $1.19 \pm 0.21\ \mathrm{MeV}/c^2$

VALUE (MeV)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
1.19±0.21 OUR AVERAGE Error includes scale factor of 1.1.						
1.39±0.24±0.10		15.6k	[1] AAIJ	20AD	LHCB	$pp \to J/\psi\pi^+\pi^- X$
$0.96^{+0.19}_{-0.18}$±0.21		4.2k	[2] AAIJ	20S	LHCB	$B^+ \to J/\psi\pi^+\pi^- K^+$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<2.4	90		ABLIKIM	14	BES3	$e^+e^- \to J/\psi\pi^+\pi^-\gamma$
<1.2	90		CHOI	11	BELL	$B \to K\pi^+\pi^- J/\psi$
<3.3	90		AUBERT	08Y	BABR	$B^+ \to K^+ J/\psi\pi^+\pi^-$
<4.1	90	69	AUBERT	06	BABR	$B \to K\pi^+\pi^- J/\psi$
<2.3	90	36	[3] CHOI	03	BELL	$B \to K\pi^+\pi^- J/\psi$

[1] Using $\chi_{c1}(3872)$ produced in inclusive b-hadron decays. Breit-Wigner parametrization.
[2] Using Breit-Wigner parametrization. Partially overlapping dataset with that of AAIJ 20AD.
[3] Superseded by CHOI 11.

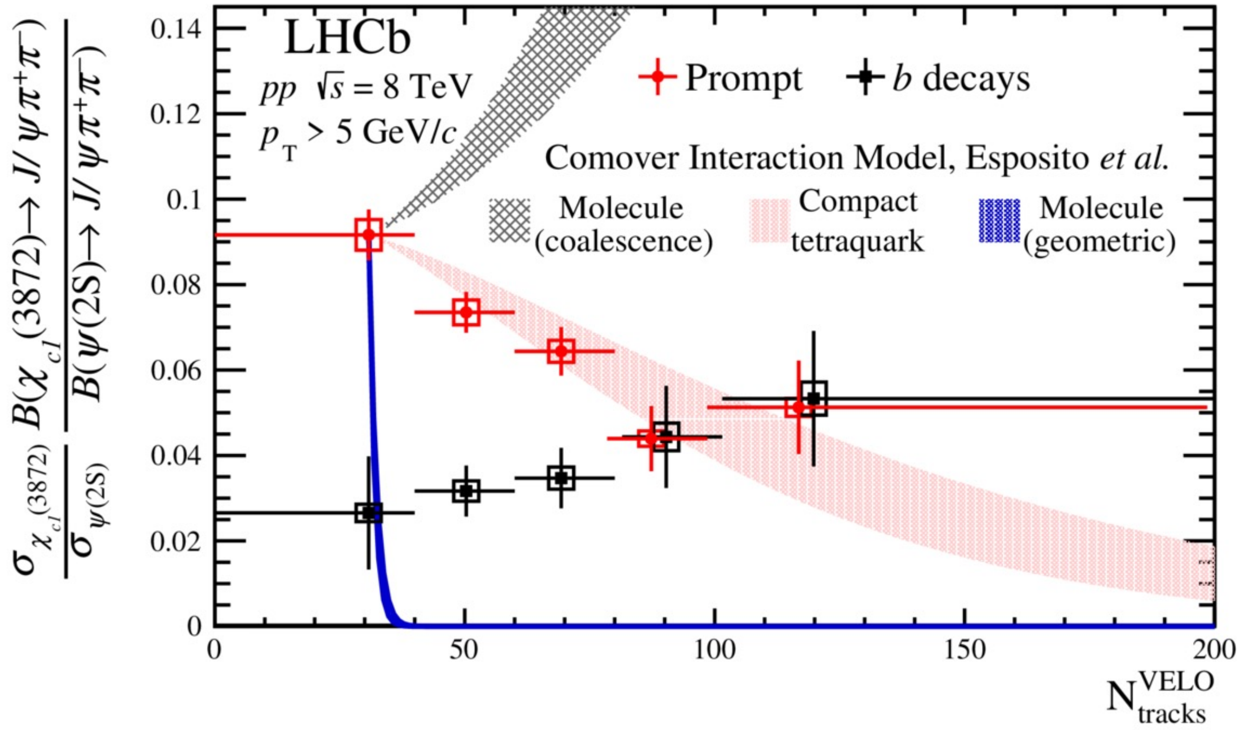
Studies of $\chi_{c1}(3872)$ at LHCb

- LHCb-PAPER-2011-034, Eur. Phys. J. C72 (2012) 1972
  - 2010 data, 34.7 pb^{-1}, mass and cross-section
- LHCb-PAPER-2013-001, Phys. Rev. Lett. 110 (2013) 222001
  - 2011 data, 1 fb^{-1}, determined $J^{PC} = 1^{++}$ (with assumptions of angular momentum)
- LHCb-PAPER-2015-015, Phys. Rev. D92 (2015) 011102(R)
  - 2011-2012 data, 3 fb^{-1}, determined $J^{PC} = 1^{++}$ (without assumptions of angular momentum)
- LHCb-PAPER-2016-016, Phys. Lett. B769 (2017) 305
  - 2011-2012 data, 3 fb^{-1}, Searched for $\chi_{c1}(3872) \to p\bar{p}$
- LHCb-PAPER-2019-023, JHEP 09 (2019) 028
  - 2011-2016 data, 4.9 fb^{-1}, discovered $\Lambda_b^0 \to \chi_{c1}(3872)pK^-$
- LHCb-PAPER-2020-008, Phys. Rev. D102 (2020) 092005
  - 2011-2012 data, 3 fb^{-1}, mass and width
- LHCb-PAPER-2020-009, JHEP 08 (2020) 123
  - 2011-2018 data, 9 fb^{-1}, mass and width
- LHCb-PAPER-2020-023, Phys. Rev. Lett. 126 (2021) 092001
  - 2012 data, 2 fb^{-1}, multiplicity-dependency of cross-sections
- LHCb-PAPER-2021-025, JHEP 01 (2022) 131
  - 2012 and 2016-2018 data, 2 fb^{-1} and 5.4 fb^{-1}, cross-section
- LHCb-PAPER-2021-045, arXiv:2204.12597
  - 2011-2018 data, 9 fb^{-1}, decays

$\chi_{c1}(3872)$ multiplicity-dependent cross-section

Phys. Rev. Lett. 126 (2021) 092001

- 2012 pp data (2 fb^{-1})
- Use $t_z \equiv \frac{(z_{\text{decay}} - z_{\text{PV}}) \times M}{p_z}$ to separate prompt $\chi_{c1}(3872)$ and those from b-hadron decays



$$\frac{\sigma_{\chi_{c1}(3872)} \mathcal{B}(\chi_{c1}(3872) \to J/\psi\pi^+\pi^-)}{\sigma_{\psi(2S)} \mathcal{B}(\psi(2S) \to J/\psi\pi^+\pi^-)}$$

Different multiplicity-dependence observed for $\chi_{c1}(3872)$ and $\psi(2S)$

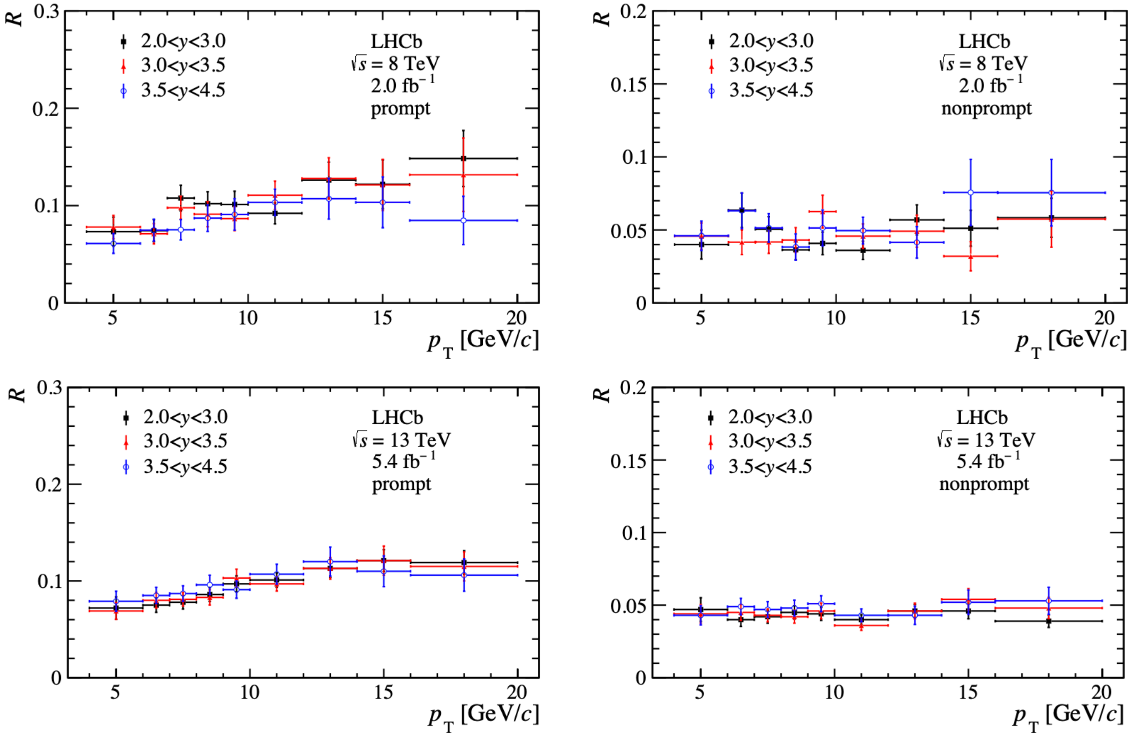
$\chi_{c1}(3872)$ cross-section

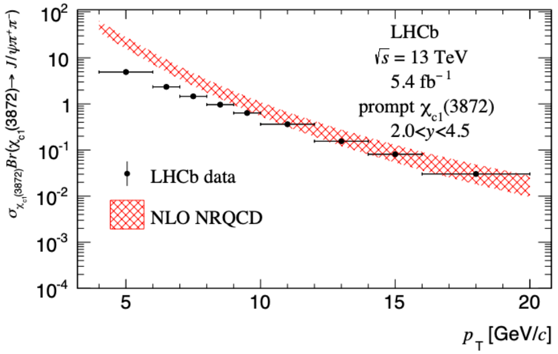
JHEP 01 (2022) 131

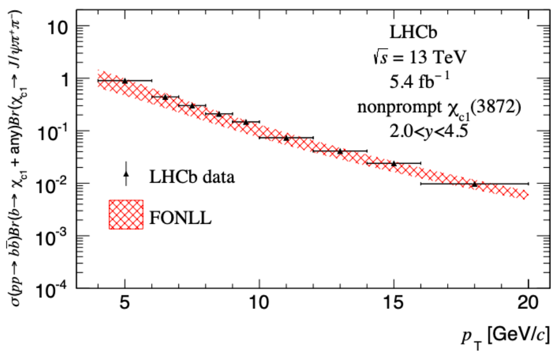
- 2012 data ($2\ \mathrm{fb}^{-1}$) and 2016-2018 ($5.7\ \mathrm{fb}^{-1}$) data
- Use $t_z \equiv \frac{(z_{\mathrm{decay}} - z_{\mathrm{PV}}) \times M}{p_z}$ to separate prompt $\chi_{c1}(3872)$ and those from b-hadron decays

$$R \equiv \frac{\sigma_{\chi_{c1}(3872)}}{\sigma_{\psi(2S)}} \times \frac{\mathcal{B}(\chi_{c1}(3872) \to J/\psi\pi^+\pi^-)}{\mathcal{B}(\psi(2S) \to J/\psi\pi^+\pi^-)}$$

$$R^{8\ \mathrm{TeV}}_{\mathrm{prompt}} = (7.6 \pm 0.5 \pm 0.9) \times 10^{-2}$$
$$R^{8\ \mathrm{TeV}}_{\mathrm{nonprompt}} = (4.6 \pm 0.4 \pm 0.5) \times 10^{-2}$$
$$R^{13\ \mathrm{TeV}}_{\mathrm{prompt}} = (7.6 \pm 0.3 \pm 0.6) \times 10^{-2}$$
$$R^{13\ \mathrm{TeV}}_{\mathrm{nonprompt}} = (4.4 \pm 0.2 \pm 0.4) \times 10^{-2}$$







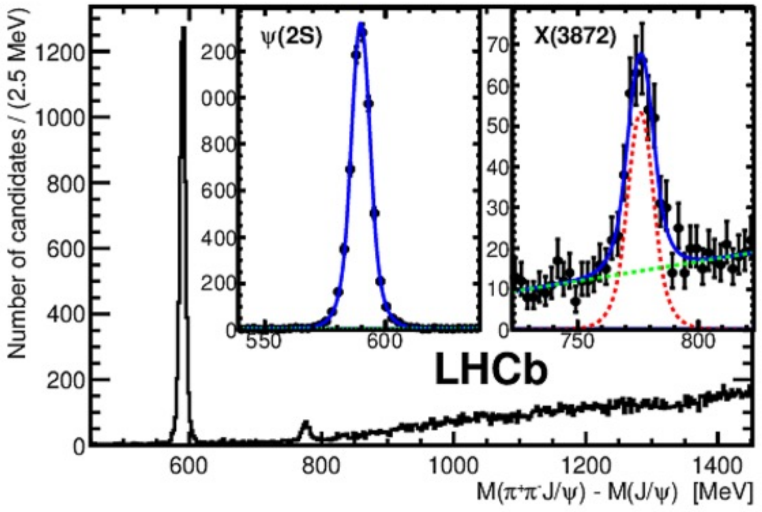
NLO NRQCD
K.T. Chao et al, PRD96 (2017) 074014

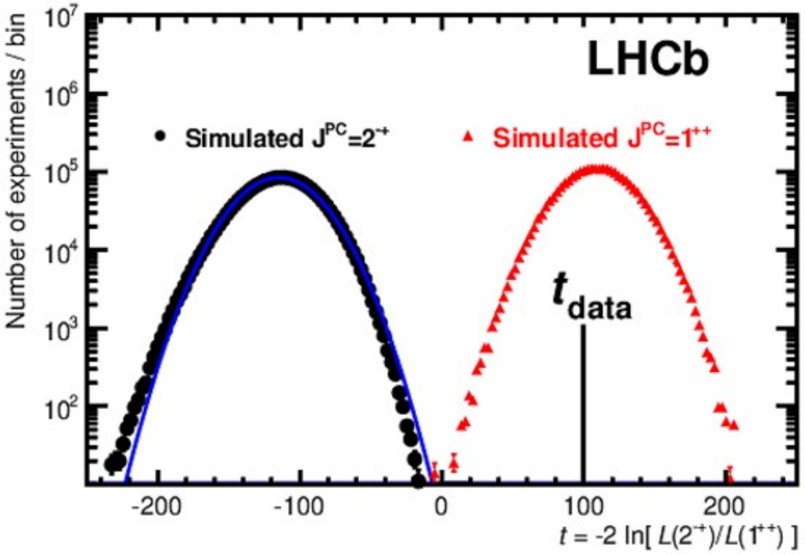
FONOLL, JHEP 05 (1998) 007
EPJC75 (2015) 610

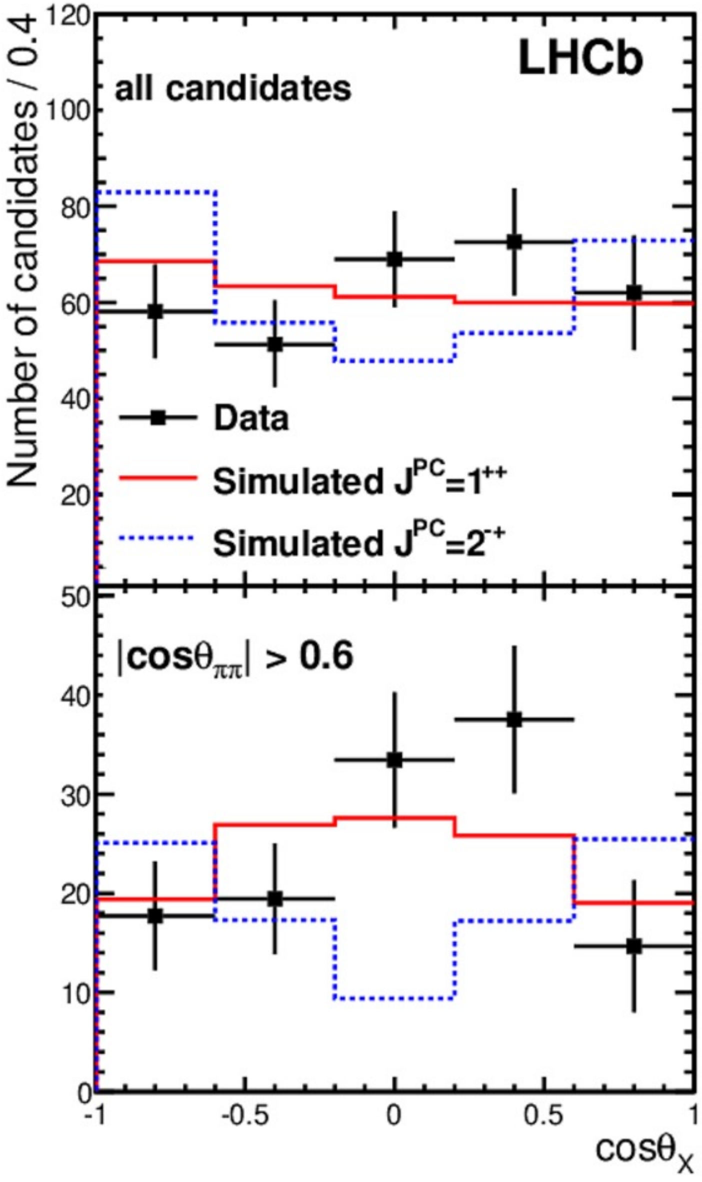
Phys. Rev. Lett. 110 (2013) 222001

$\chi_{c1}(3872)$ spin-parity determination

- 2011 data (1 fb^{-1}), $J^{PC} = 1^{++}$ determined
  - Assume that lowest angular momentum between the decay products has the largest contribution



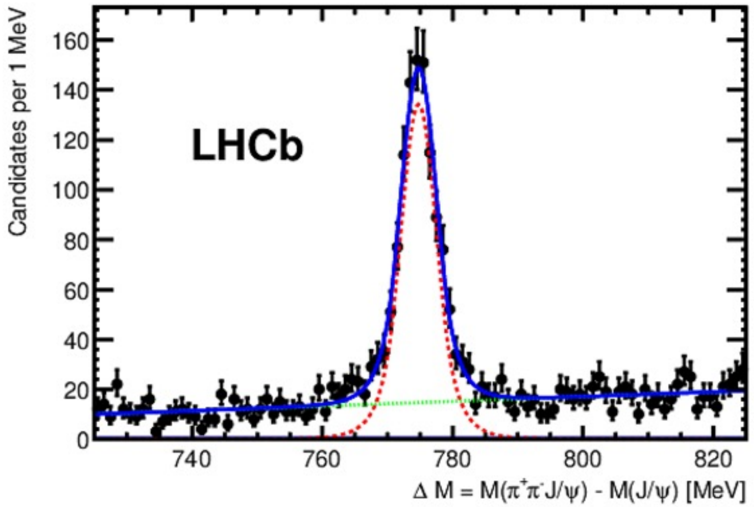


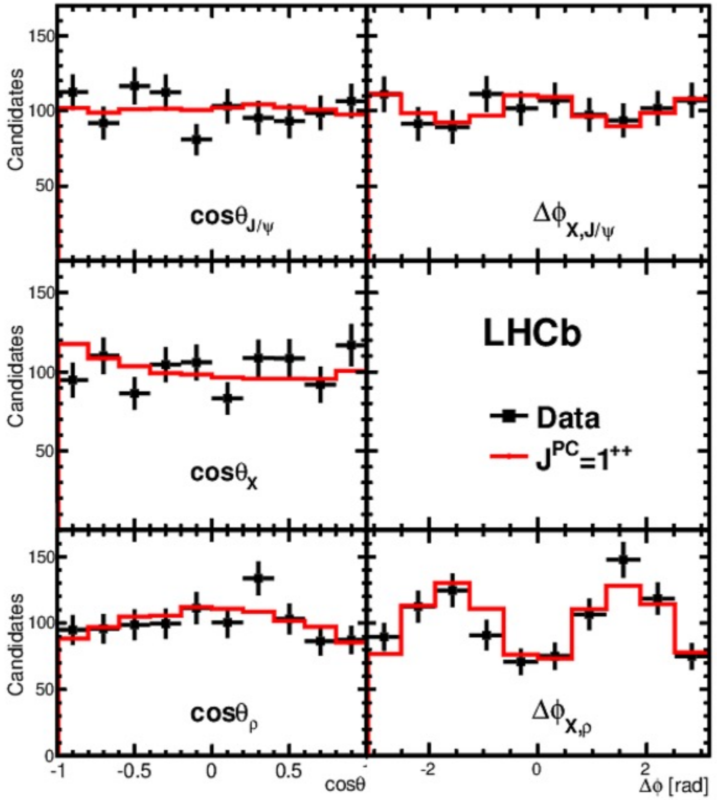


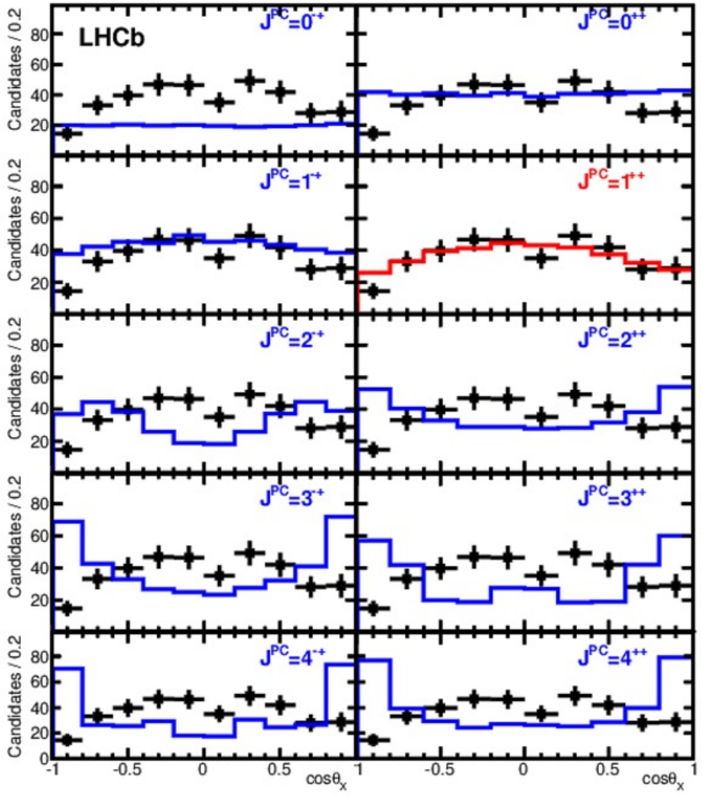
$\chi_{c1}(3872)$ spin-parity determination (cont.)

Phys. Rev. D92 (2015) 011102(R)

- 2011+2012 data ($3\ \mathrm{fb}^{-1}$), $J^{PC} = 1^{++}$ determined
  - No assumption for angular momentum



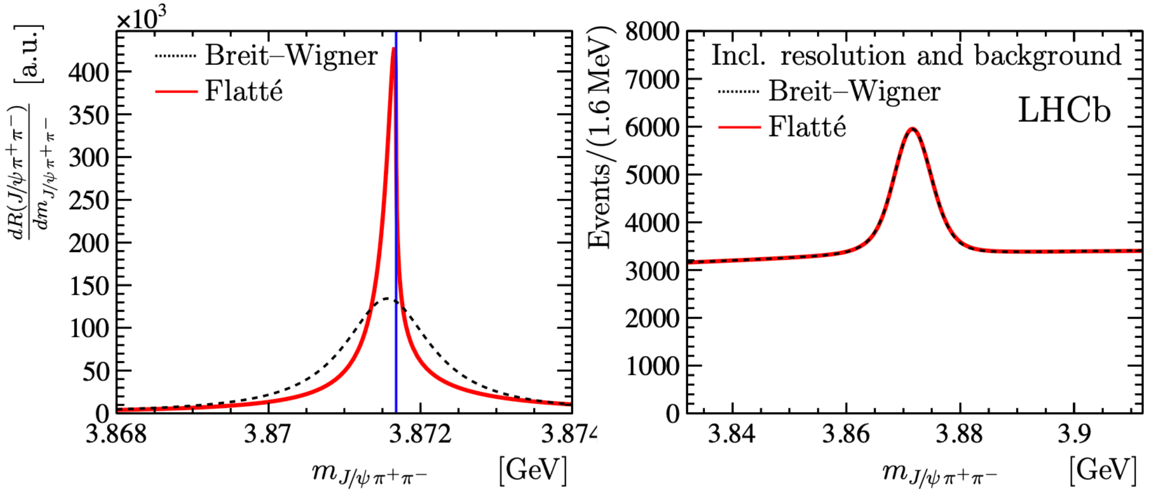




$\chi_{c1}(3872)$ mass and width: 2011-2012 data

[Phys. Rev. D102 (2020) 092005](#)

- $\chi_{c1}(3872)$ mass very close to the $\bar{D}^{*0}D^0$ threshold
  - $m_{\chi_{c1}(3872)} = 3871.68 \pm 0.17\ \mathrm{MeV}/c^2$, $\Gamma < 1.2\ \mathrm{MeV}$ [PDG2019]
  - $m_{D^0} + m_{D^{*0}} = 3871.70 \pm 0.11\ \mathrm{MeV}/c^2$
- Using the $b \to X(3872)$ sample
- Results with Breit-Wigner and Flatté are different



Breit-Wigner

$$m_{\chi_{c1}(3872)} = 3871.695 \pm 0.067 \pm 0.068 \pm 0.010\ \mathrm{MeV}$$

$$\Gamma_{\mathrm{BW}} = 1.39 \pm 0.24 \pm 0.10\ \mathrm{MeV}$$

Flatté

$$\mathrm{mode} = 3871.69^{+0.00+0.05}_{-0.04-0.13}\ \mathrm{MeV}$$

$$\mathrm{FWHM} = 0.22^{+0.07+0.11}_{-0.06-0.13}\ \mathrm{MeV}$$

$\chi_{c1}(3872)$ mass, width and BF: 2011-2018 data

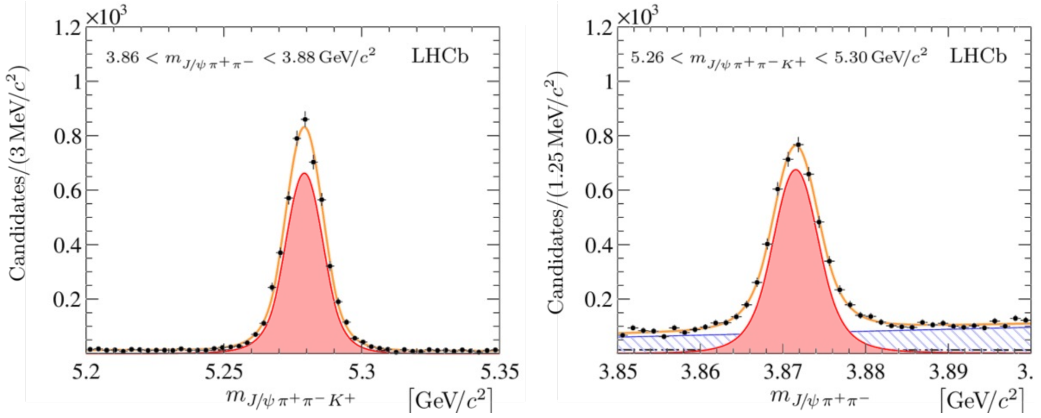
JHEP 08 (2020) 123

- Using the $B^+ \to J/\psi\pi^+\pi^- K^+$ sample

Breit-Wigner

$$m_{\chi_{c1}(3872)} = 3871.59 \pm 0.06 \pm 0.03 \pm 0.01\,\mathrm{MeV}/c^2$$

$$\Gamma_{\chi_{c1}(3872)} = 0.96^{+0.19}_{-0.18} \pm 0.21\,\mathrm{MeV}$$



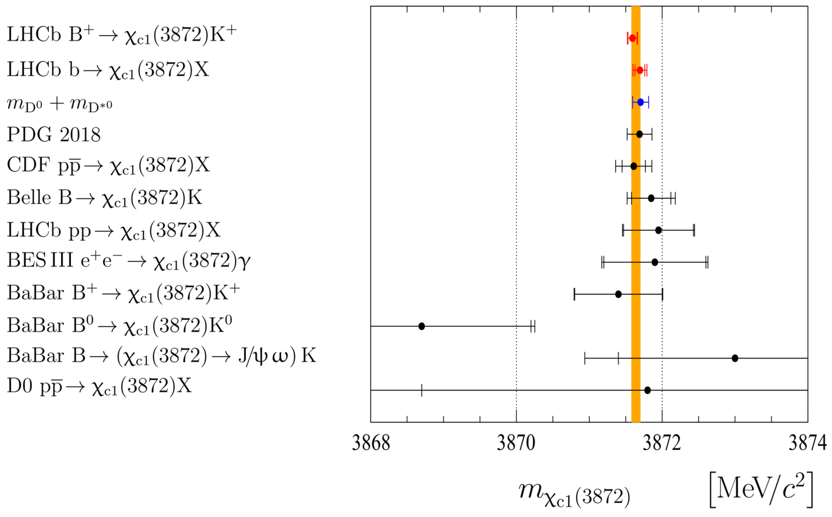
$$m_{\chi_{c1}(3872)}\big|_{\mathrm{LHCb}} = 3871.64 \pm 0.06 \pm 0.01\,\mathrm{MeV}/c^2$$

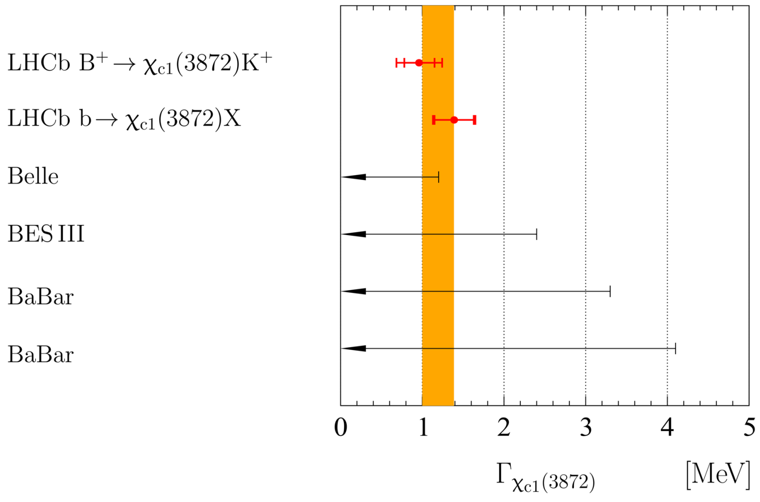
$$\delta E \equiv (\mathrm{m}_{\mathrm{D}^0} + m_{\mathrm{D}^{*0}})\,c^2 - m_{\chi_{c1}(3872)}c^2$$

Compare with D^0D^{*0} threshold

$$\delta E = 0.12 \pm 0.13\,\mathrm{MeV}$$

$$\delta E|_{\mathrm{LHCb}} = 0.07 \pm 0.12\,\mathrm{MeV}$$





$\chi_{c1}(3872) \to J/\psi\pi^+\pi^-$ decay: 2011-2018 data

arXiv:2204.12597

- Using $\chi_{c1}(3872)$ from the $B^+ \to \chi_{c1}(3872)K^+$ sample to study ω contributions in the $\chi_{c1}(3872) \to J/\psi\pi^+\pi^-$ decay
  - $\chi_{c1}(3872) \to J/\psi\rho^0$ is isospin violating decay

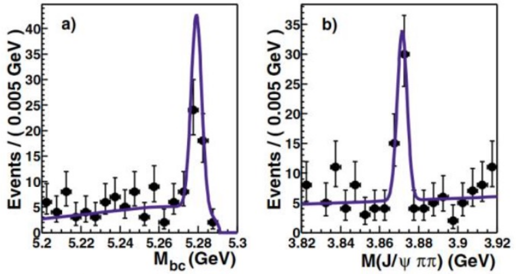
- Sizable ω contribution observed
  - $(21.4 \pm 2.3 \pm 2.0)\%$ of the total rate
  - $(1.9 \pm 0.4 \pm 0.3)\%$ when excluding interference

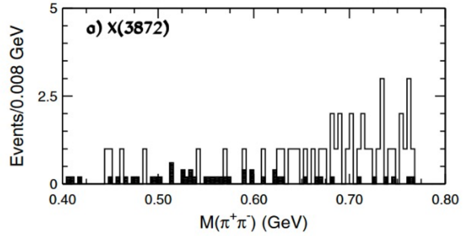
- Coupling constant ratio disfavours pure charmonium state

$$\frac{g_{\chi_{c1}(3872)} \to \rho^0 J/\psi}{g_{\chi_{c1}(3872)} \to \omega^0 J/\psi} = 0.29 \pm 0.04$$

Around 6 times larger than expected for pure charmonium state

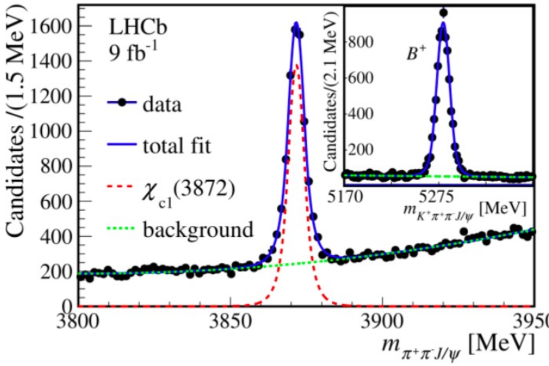
Belle:
PRL 91 (2003) 262001
$N_{\text{sig}} = 35.7 \pm 6.8$

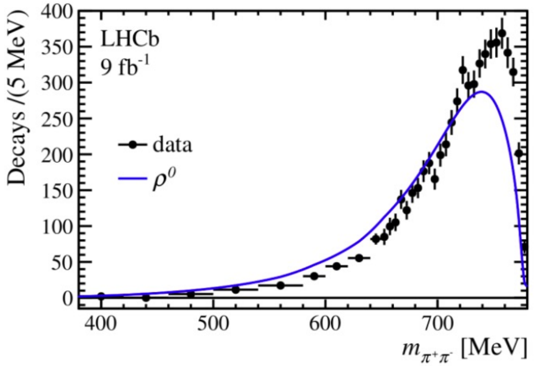




×190 larger

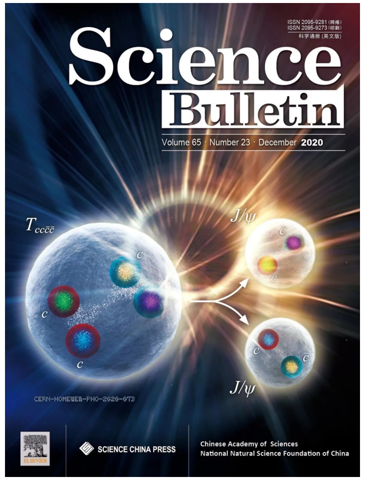
LHCb:
arXiv:2004.12597
$N_{\text{sig}} = 6788 \pm 117$





Observation of structure in the J/ψ-pair mass spectrum

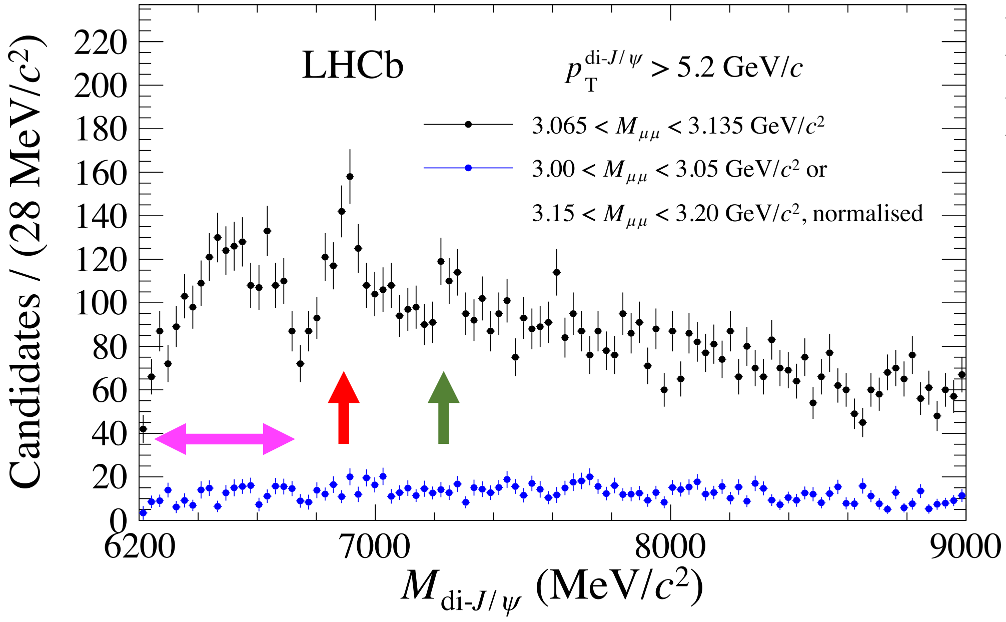
Science Bulletin 65 (2020) 1983



Exotic states with fully charm quarks: $T_{cc\bar{c}\bar{c}}$

Sci. Bull. 65 (2020) 1983

- States with fully heavy quarks are unique to study the strong interaction
- $T_{cc\bar{c}\bar{c}}$ states are predicted to have $m \in [5.8, 7.4]$ GeV, isolated from both quarkonia and quarkonium-like states
- LHCb observed structures in di-J/ψ mass spectrum using full Run1+2 data

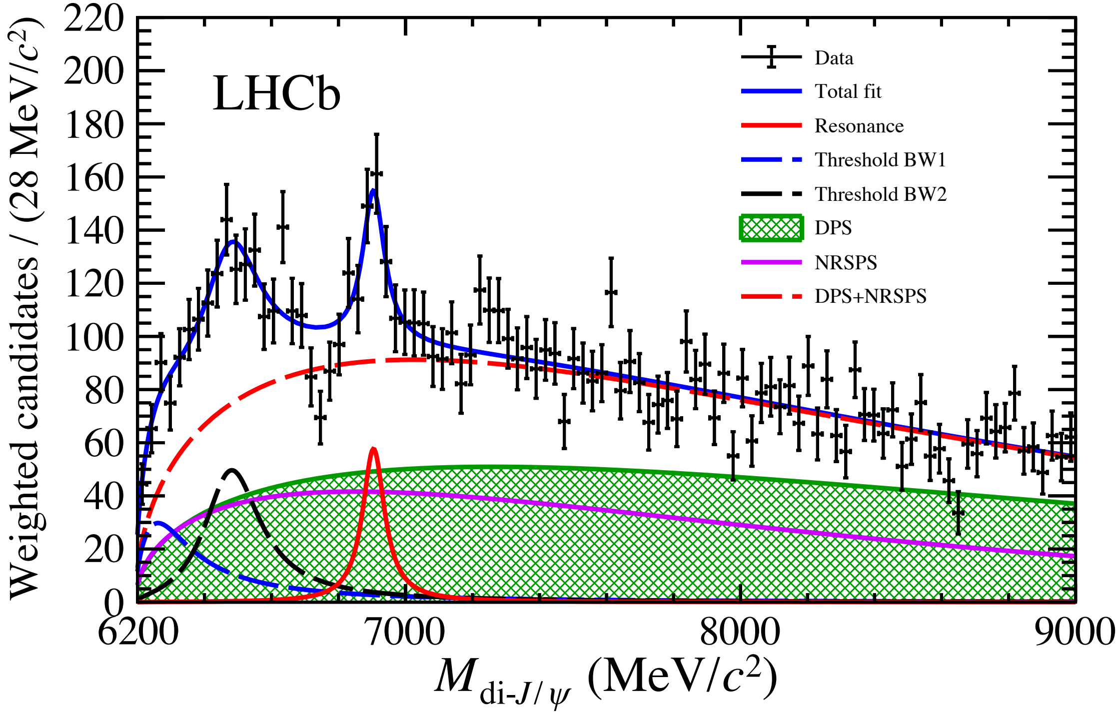


- J/ψ mass and pointing-to-PV constraints applied
- J/ψ-pair mass spectrum shows
  - ✓ a **broad structure next to threshold** ranging from 6.2 to 6.8 GeV $> 5\sigma$
  - ✓ a narrower **structure at about 6.9 GeV** $> 5\sigma$
  - ✓ hint for **another structure around 7.2 GeV** $< 1\sigma$
  - ✓ no evidence for further structures above 7.2 GeV

Possible interpretations

Sci. Bull. 65 (2020) 1983

- The presence of $T_{cc\bar{c}\bar{c}}$ states with no interference
  - One $T_{cc\bar{c}\bar{c}}$ state for $6.9\ \mathrm{GeV}/c^2$ peak + Two $T_{cc\bar{c}\bar{c}}$ states for threshold structure



No-interference fit:

✓Fit p-value: 4.6%

✓Parameters for $6.9\ \mathrm{GeV}/c^2$ peak

$M = 6905 \pm 11(\mathrm{stat})\ \mathrm{MeV}/c^2$

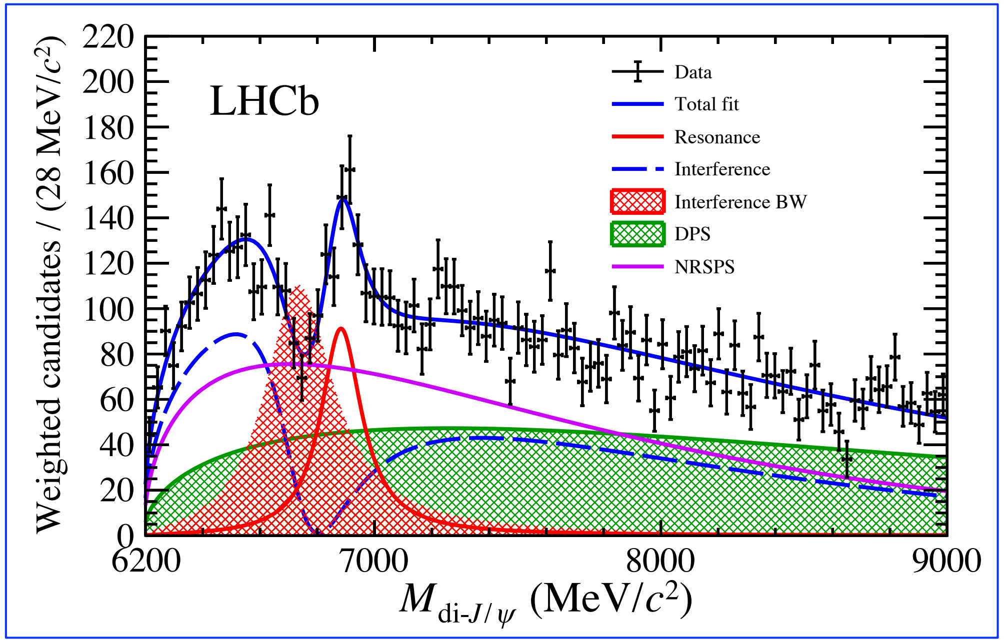
$\Gamma = 80 \pm 19(\mathrm{stat})\ \mathrm{MeV}/c^2$

$N_{\mathrm{signal}} = 252 \pm 63$

Possible interpretations (cont.)

Sci. Bull. 65 (2020) 1983

- Interference between $T_{cc\bar{c}\bar{c}}$ state and NR single-parton-scattering (NRSPS)
  - One $T_{cc\bar{c}\bar{c}}$ state for $6.9\ \mathrm{GeV}/c^2$ peak + one lower-mass state interfering with NRSPS



A simple model with interference:

✓ Fit p-value: 15.5%

✓ Parameters for $6.9\ \mathrm{GeV}$ peak

$M = 6886 \pm 11(\mathrm{stat})\ \mathrm{MeV}$

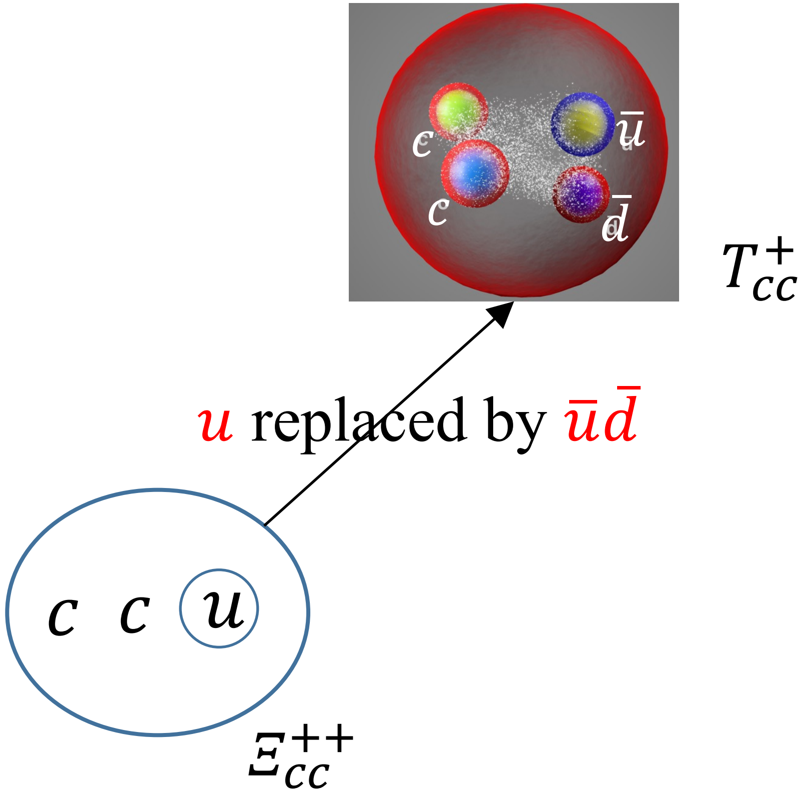
$\Gamma = 168 \pm 33(\mathrm{stat})\ \mathrm{MeV}$

$N_{\mathrm{signal}} = 784 \pm 148$

- Other possibilities
  - Feed-down from heavier quarkonia, e.g. $T_{cc\bar{c}\bar{c}} \to \chi_c(\to J/\psi\gamma) + J/\psi$
  - Near-threshold kinematic rescattering: $M(\chi_{c0}\chi_{c0}) = 6829.4\ \mathrm{MeV}$, $M(\chi_{c0}\chi_{c1}) = 6925.4\ \mathrm{MeV}$

Doubly charmed tetraquark T_{cc}^{+}

Nature Phys. 18 (2022) 7, 751
Nature Commun. 13 (2022) 1, 3351



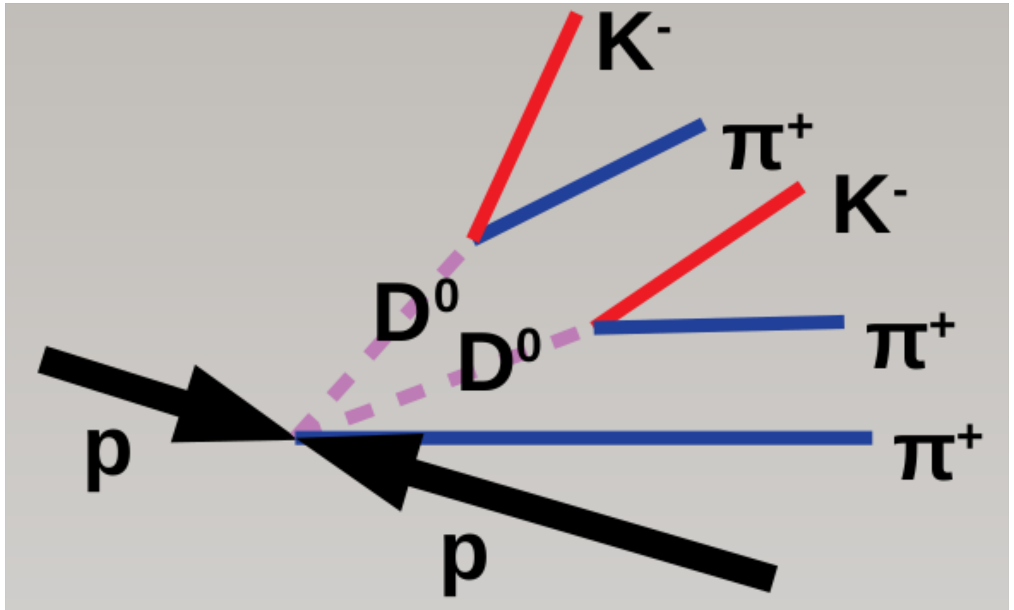
Similar to the doubly charmed baryon Ξ_{cc}^{++} observed by LHCb in 2017

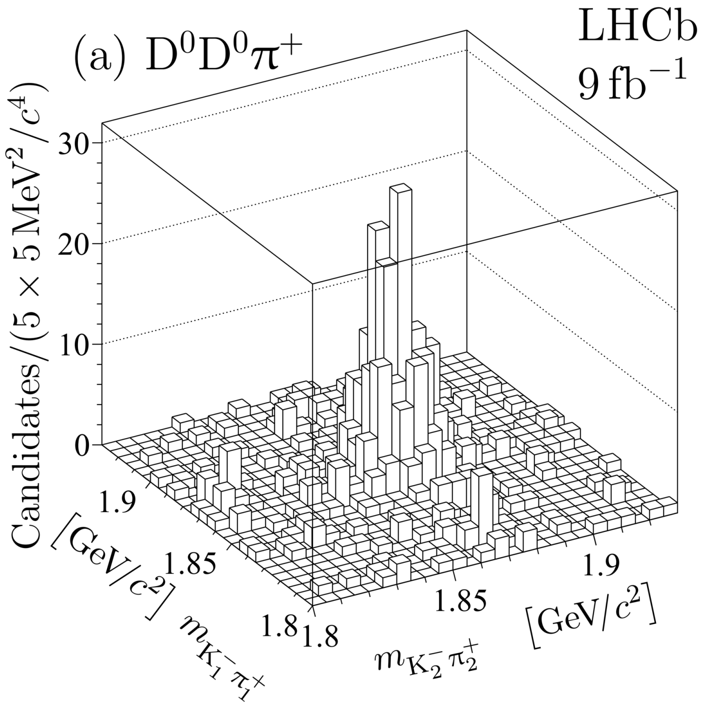
PRL 119 (2017) 112001

Doubly charmed tetraquark T_{cc}^{+}

Nature Phys. 18 (2022) 7, 751
Nature Commun. 13 (2022) 1, 3351

- 2011-2018 data (9 fb^{-1}) of pp collisions
- Search for tetraqaurks in the $D^0D^0\pi^+$ system (with $D^0 \to K^-\pi^+$)





Observation of $T_{cc}^{+} \to D^0 D^0 \pi^+$

Nature Phys. 18 (2022) 7, 751
Nature Commun. 13 (2022) 1, 3351

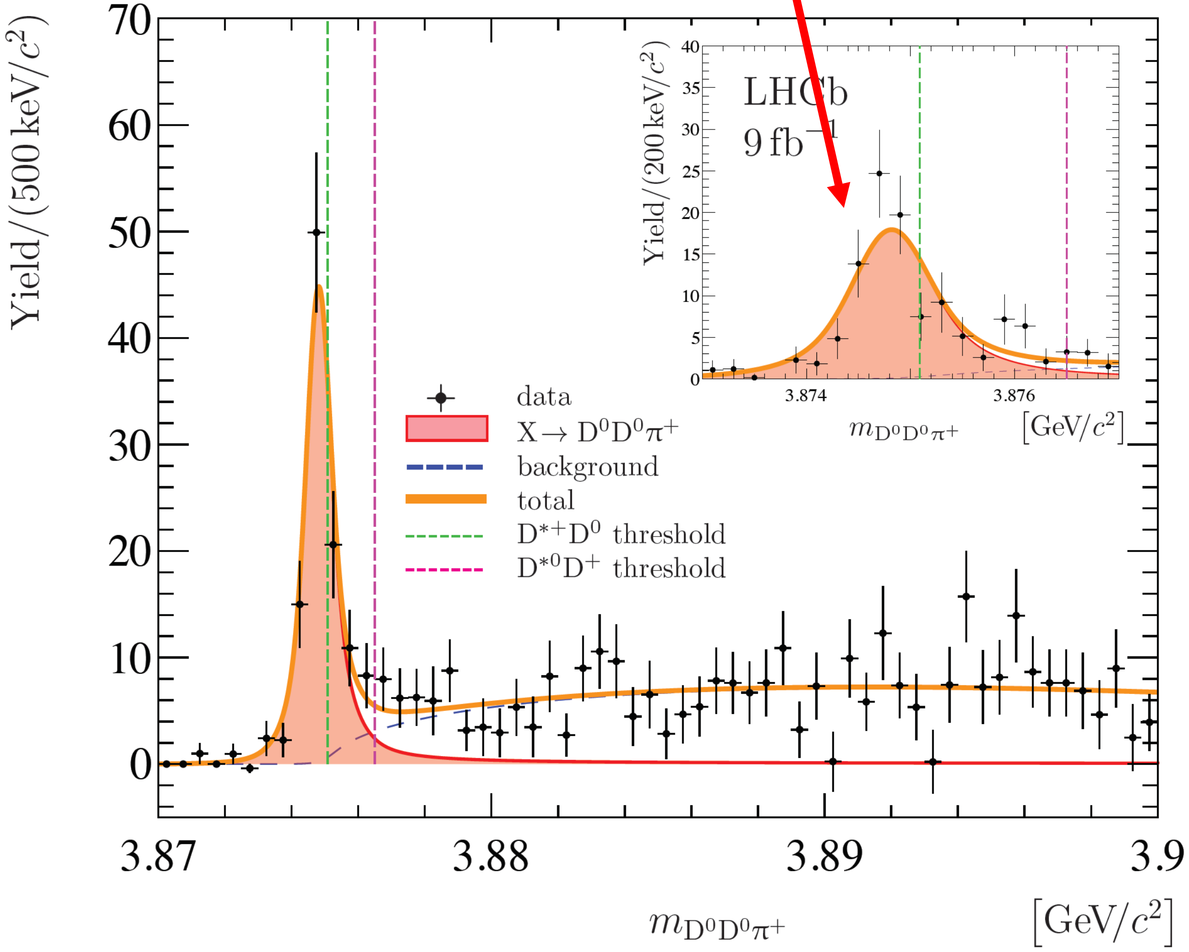
Parameter	value
N	117 ± 16
δm_{BW}	-273 ± 61 keV/c^2
Γ_{BW}	410 ± 165 keV
$\mathcal{S}$	$21.7\,\sigma$
$\mathcal{S}_{\delta m_{\mathrm{BW}}<0}$	$4.3\,\sigma$

$$\delta m_{\mathrm{BW}} \equiv m_{\mathrm{BW}} - (m_{D^{*+}} + m_{D^0})$$

Mass around 3875 MeV

Consistent with the ground isoscalar T_{cc}^{+} state $(cc\bar{u}\bar{d})$ with $J^P = 1^+$

Below $D^{*+}D^0$ threshold



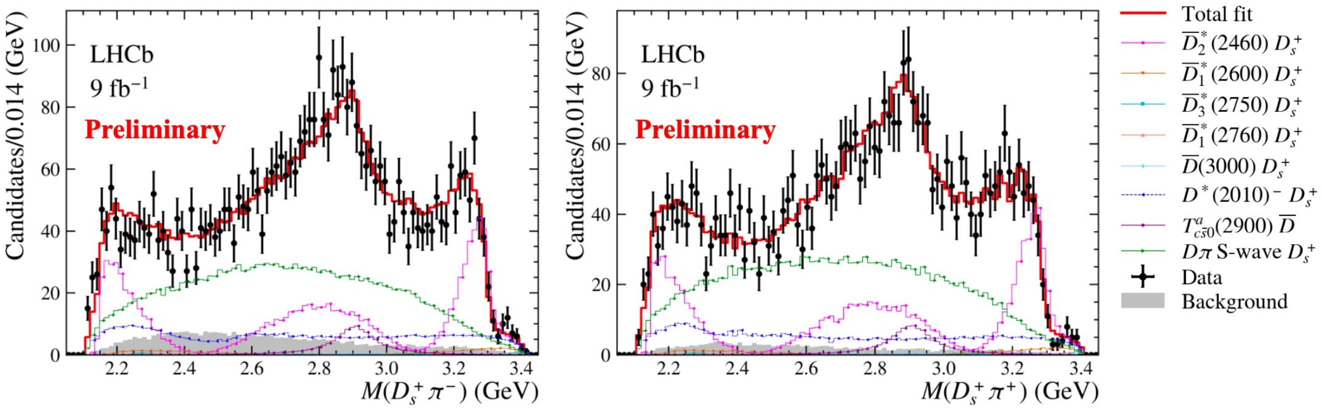
Observation of a double-charged tetraquark state and its isospin partner

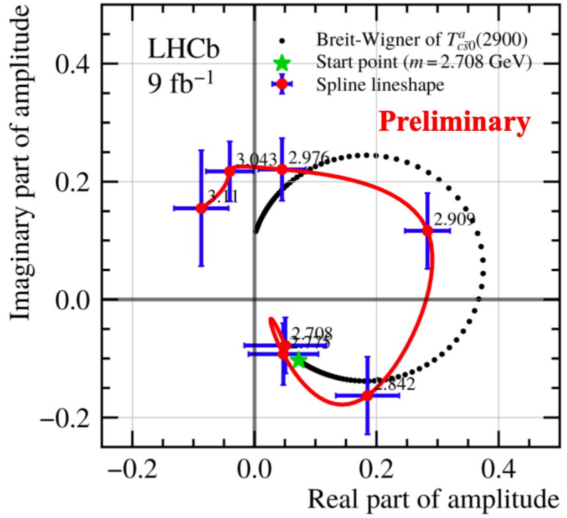
LHCb-PAPER-2022-026
LHCb-PAPER-2022-027
in preparation

Observation of $T^a_{c\bar{s}0}(2900)^{++}$ and $T^a_{c\bar{s}0}(2900)^0$

LHCb-PAPER-2022-026
LHCb-PAPER-2022-027
in preparation

- $X(2900) \to D^-K^+$ observed in $B^+ \to D^+D^-K^+$ decays
  - motivating searches for $D_s^+\pi^\pm$ states
- Amplitude analysis performed simultaneously for $B^0 \to \bar{D}^0 D_s^+\pi^-$ and $B^+ \to D^-D_s^+\pi^+$ decays



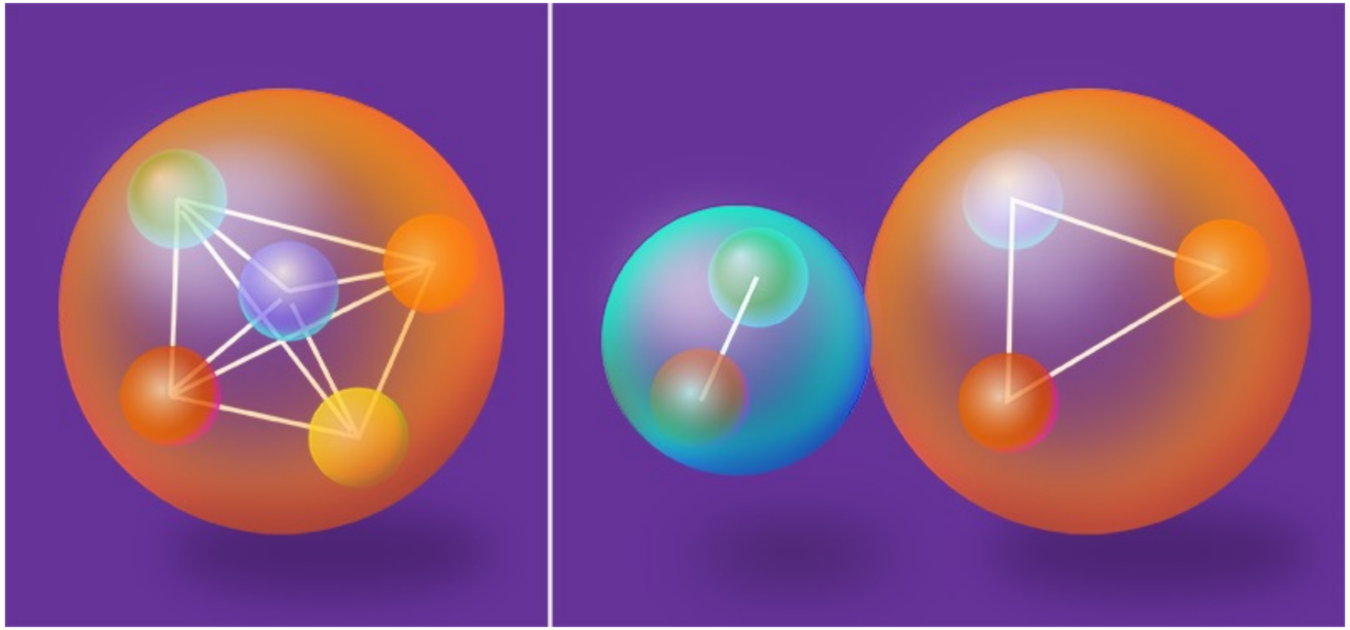


- **Two $D_s^+\pi$ exotic states with shared parameters are added.**
  - ✓ J^P up to 3^+ are tested, 0^+ produces the best likelihood.
  - ✓ Significance greater that 9σ.
  - ✓ Mass and width are measured:

$$M = 2.908 \pm 0.011 \pm 0.020\,\text{GeV}$$
$$\Gamma = 0.136 \pm 0.023 \pm 0.011\,\text{GeV},$$

$T^a_{c\bar{s}0}(2900)^{++} \to D_s^+\pi^+$
$T^a_{c\bar{s}0}(2900)^0 \to D_s^+\pi^-$
observed

Pentaquark states

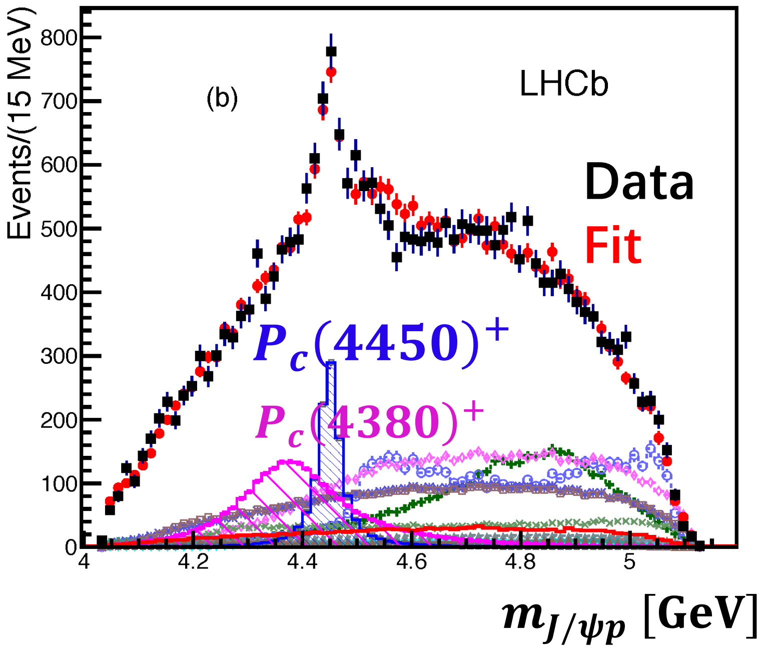


Recap: observation pentaquark states

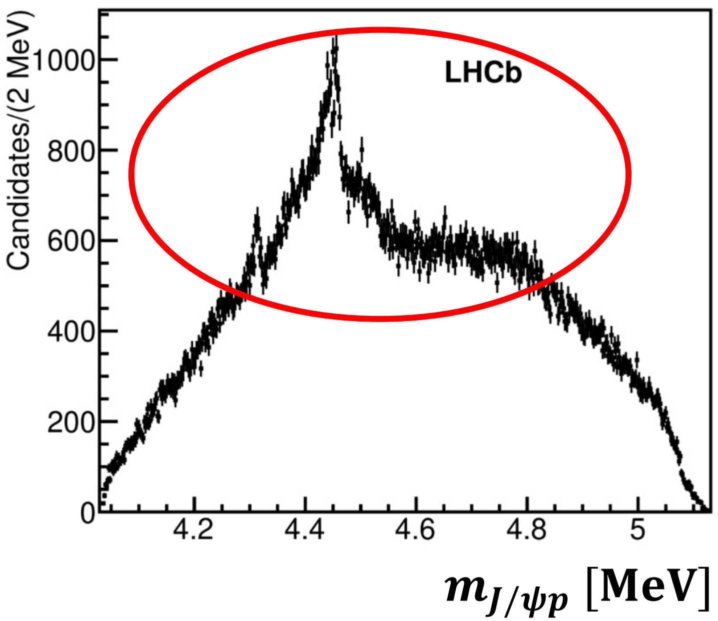
PRL 115 (2015) 072001

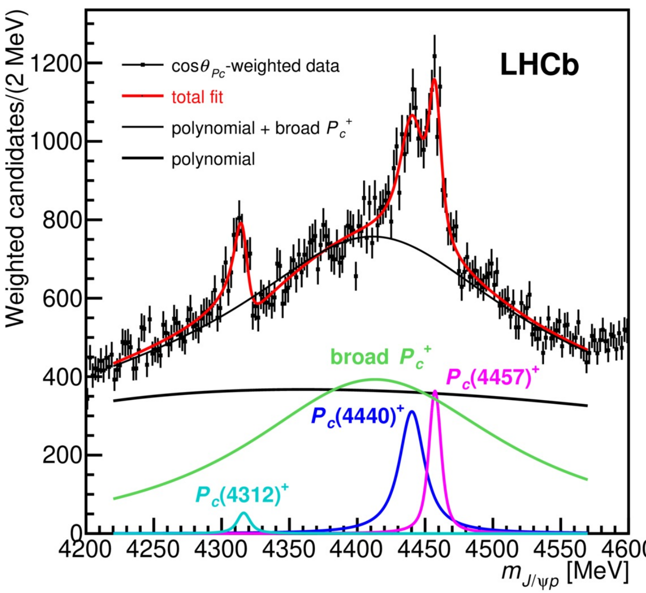
PRL 122 (2019) 222001

Dataset: $3\ \mathrm{fb}^{-1}$ (Run1, 2011-2012)



$9\ \mathrm{fb}^{-1}$ (Run1+2, 2011-2018)





$N(\Lambda_b^0 \to J/\psi p K^-)$ increases by a factor of 9 owing to re-optimized selections

➔ Fine structures observed thanks to the much larger sample size

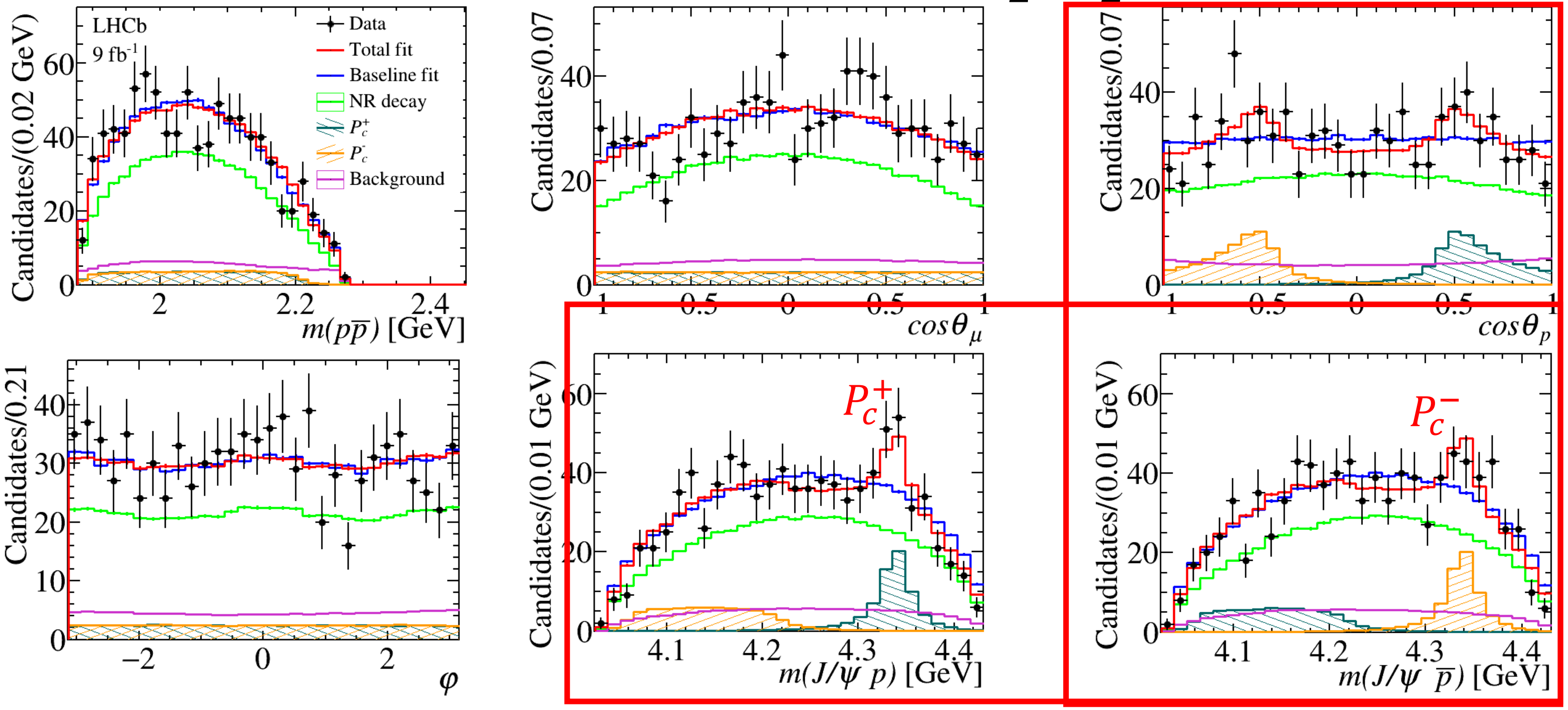
Phys.Rev.Lett. 128 (2022) 062001
LHCb-PAPER-2022-031 in preparation

Searching for pentaquarks in $B_s^0 \to J/\psi p\bar{p}$, $\Xi_b^- \to J/\psi K^- \Lambda$, and $B^- \to J/\psi \Lambda \bar{p}$ decays

Amplitude analysis of $B_s^0 \to J/\psi p\bar{p}$ decays

Phys.Rev.Lett. 128 (2022) 062001

- 2011-2018 data used (9 fb^{-1})
- Inclusion of $P_c^{\pm}$ contributions significantly improve descriptions of data
- Significance of 3.1σ~3.7σ for $J^P = (\frac{1}{2}^{\pm}, \frac{3}{2}^{\pm})$



No $P_c^{\pm}$ fit

W/ $P_c^{\pm}$ fit

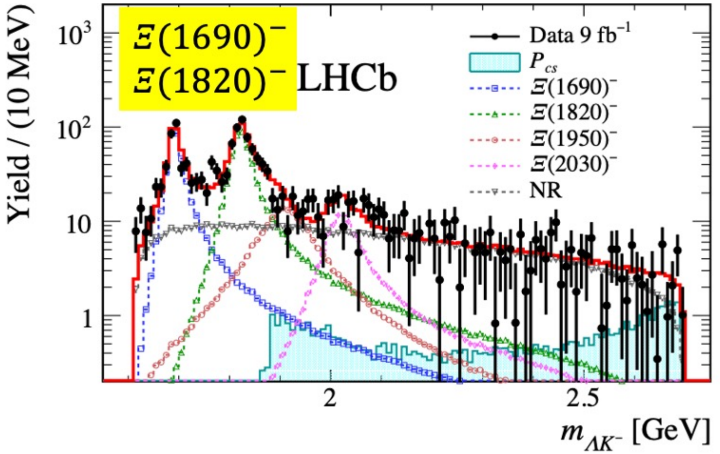
$$M_{P_c} = 4337^{+7}_{-4}(\text{stat})^{+2}_{-2}(\text{syst})\ \text{MeV},$$
$$\Gamma_{P_c} = 29^{+26}_{-12}(\text{stat})^{+14}_{-14}(\text{syst})\ \text{MeV},$$

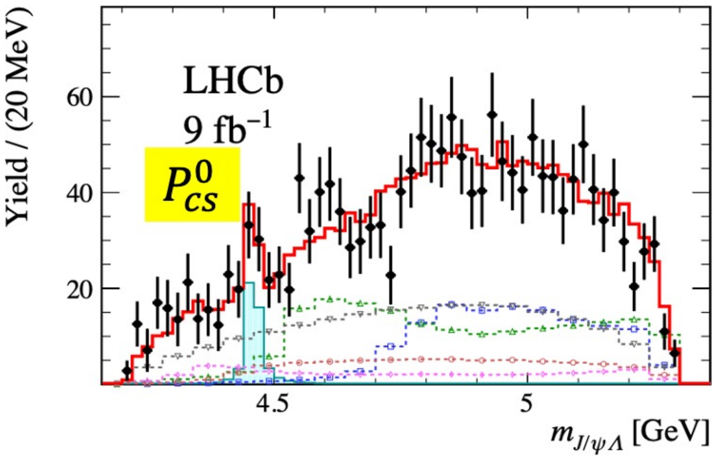
Amplitude analysis of $\Xi_b^- \to J/\psi K^- \Lambda$

Science Bulletin 66 (2021) 1278

- 2011-2018 data used ($9\ \mathrm{fb}^{-1}$)
- Significant contributions of $\Xi(1690)^-$ and $\Xi(1820)^-$ states
- Statistical significance of $P_{cs}^0(4459)^0 \to J/\psi\Lambda$ is 4.3σ
  - $\mathbf{3.1\sigma}$ when syst. uncertainty considered

State	M_0 [MeV]	Γ_0 [MeV]	FF (%)
$P_{cs}(4459)^0$	$4458.8 \pm 2.9\,^{+4.7}_{-1.1}$	$17.3 \pm 6.5\,^{+8.0}_{-5.7}$	$2.7\,^{+1.9}_{-0.6}\,^{+0.7}_{-1.3}$
$\Xi(1690)^-$	$1692.0 \pm 1.3\,^{+1.2}_{-0.4}$	$25.9 \pm 9.5\,^{+14.0}_{-13.5}$	$22.1\,^{+6.2}_{-2.6}\,^{+6.7}_{-8.9}$
$\Xi(1820)^-$	$1822.7 \pm 1.5\,^{+1.0}_{-0.6}$	$36.0 \pm 4.4\,^{+7.8}_{-8.2}$	$32.9\,^{+3.2}_{-6.2}\,^{+6.9}_{-4.1}$
$\Xi(1950)^-$	1910.6 ± 18.4	105.7 ± 23.2	$11.5\,^{+5.8}_{-3.5}\,^{+49.9}_{-9.4}$
$\Xi(2030)^-$	2022.8 ± 4.7	68.2 ± 8.5	$7.3\,^{+1.8}_{-1.8}\,^{+3.8}_{-4.1}$
NR	—	—	$35.8\,^{+4.6}_{-6.4}\,^{+10.3}_{-11.2}$





LHCb-PAPER-2022-031
in preparation

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

- 2011-2018 data used ($9\ \mathrm{fb}^{-1}$)

Q value: $128\ \mathrm{MeV}$

- Inclusion of $P_{\psi s}^{\Lambda} \to J/\psi \Lambda$ contribution significantly improve the fit
- Significance around 15σ, $J^P = \frac{1}{2}^-$ preferred

Preliminary

$$m(P_{\psi s}^{\Lambda}) = 4338.3 \pm 0.7 \pm 0.4\ \mathrm{MeV}$$
$$\Gamma(P_{\psi s}^{\Lambda}) = 7.0 \pm 1.2 \pm 1.3\ \mathrm{MeV}$$

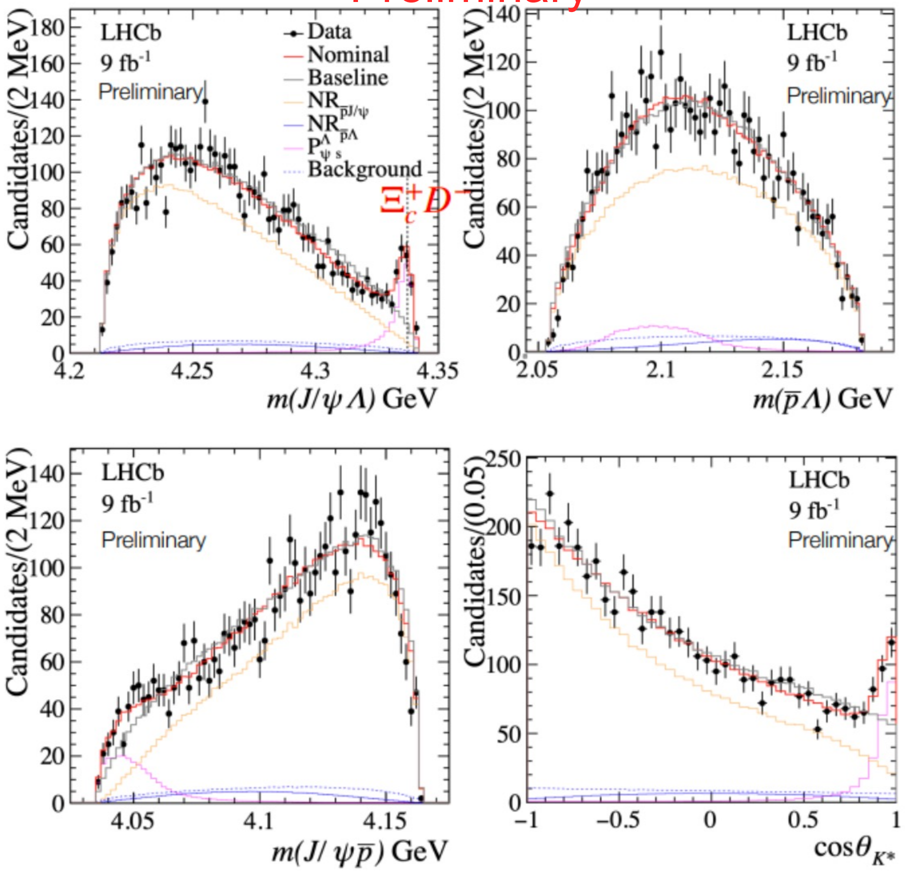
Spin ½ assigned

½- preferred

½+ excluded at 90% C.L.

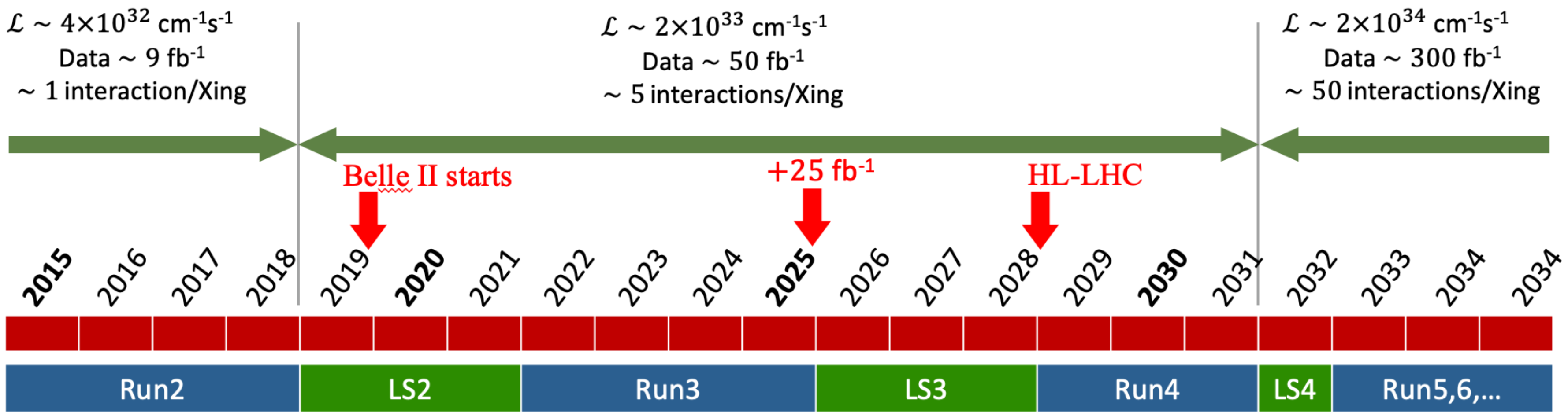
Other exotic contribution negligible

Preliminary



Prospects

The LHCb Upgrade: status and plan



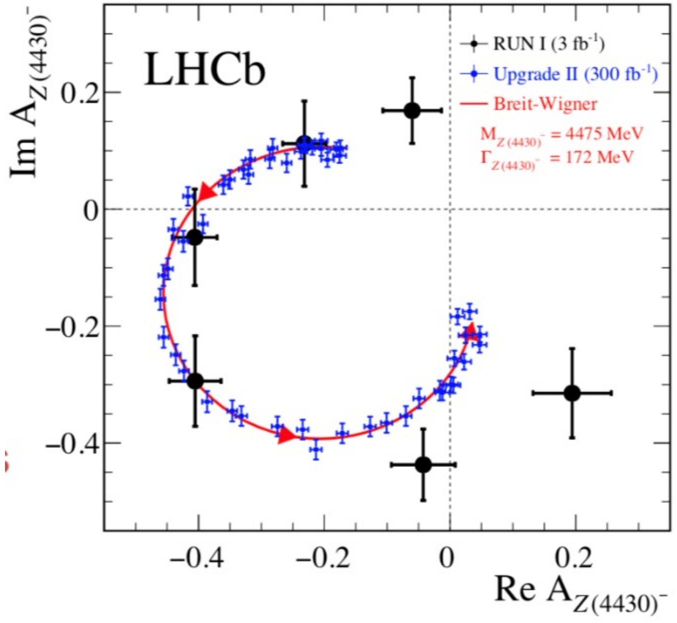
- 9 fb^{-1} accumulated in Run1+Run2 (2010-2018)
- Upgrade performed in LS2 (2019-2021)
  - 50 fb^{-1} expected after Run4
- Upgrade 1b and Upgrade 2 (LS3+LS4)
  - 300 fb^{-1} in total expected after Run5

Physics case: hadron spectroscopy

arXiv:1808.08865

- Much more b- and c-hadrons would be produced with the Upgrade
- A gold mine of exotic hadron studies
  - Observation of new states
  - Precision determination of the characteristics of observed hadrons
  - Understand the nature of these states and strong interactions

Decay mode	LHCb $23\,\mathrm{fb}^{-1}$	LHCb $50\,\mathrm{fb}^{-1}$	LHCb $300\,\mathrm{fb}^{-1}$	Belle II $50\,\mathrm{ab}^{-1}$
$B^+ \to X(3872)(\to J/\psi\pi^+\pi^-)K^+$	14k	30k	180k	11k
$B^+ \to X(3872)(\to \psi(2S)\gamma)K^+$	500	1k	7k	4k
$B^0 \to \psi(2S)K^-\pi^+$	340k	700k	4M	140k
$B_c^+ \to D_s^+ D^0 \overline{D}^0$	10	20	100	—
$\Lambda_b^0 \to J/\psi pK^-$	340k	700k	4M	—
$\Xi_b^- \to J/\psi \Lambda K^-$	4k	10k	55k	—
$\Xi_{cc}^{++} \to \Lambda_c^+ K^-\pi^+\pi^+$	7k	15k	90k	<6k
$\Xi_{bc}^+ \to J/\psi\,\Xi_c^+$	50	100	600	—



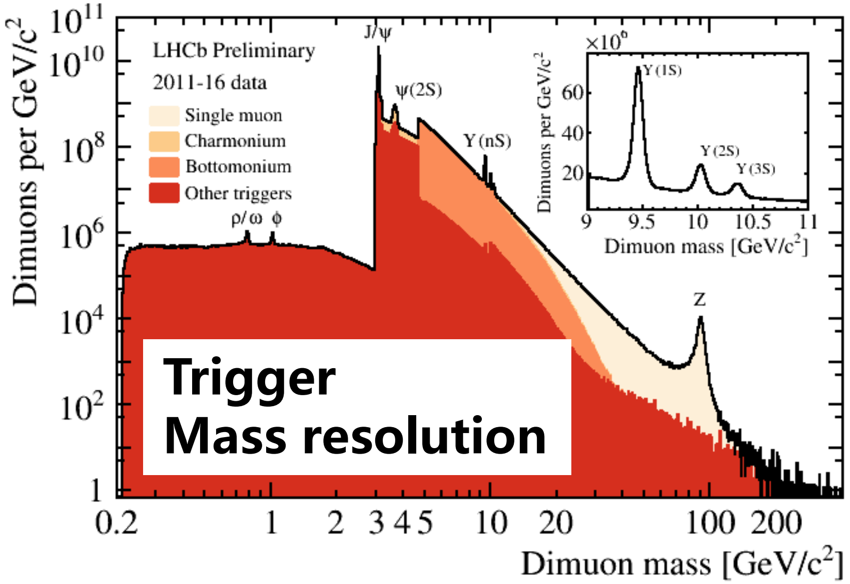
Summary

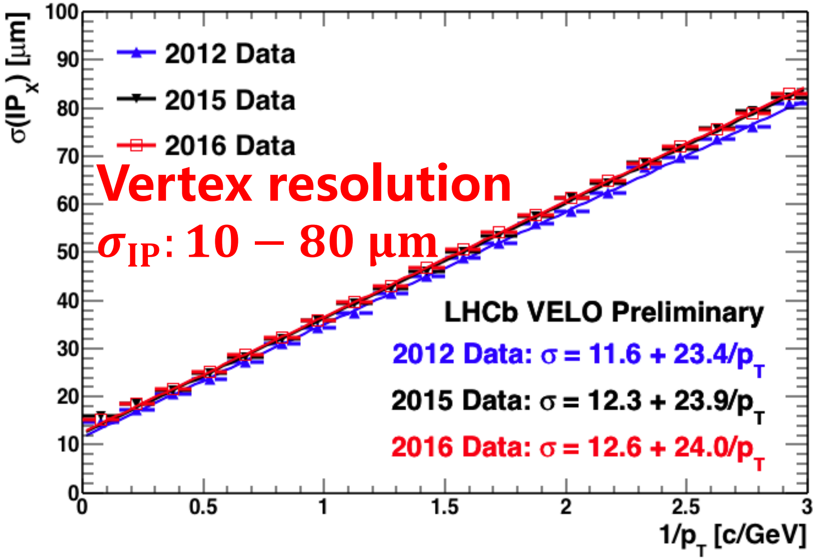
- LHCb has been continually producing interesting results in exotic states
  - Owing to the large production cross-sections provided by the LHC and the dedicated designed detector
- Discoveries of new states and precisely measured hadron properties provide important inputs to enhance our understanding
- The full Run1+Run2 data still not been fully exploited, and data of $50\ \mathrm{fb}^{-1}$ and $300\ \mathrm{fb}^{-1}$ expected to be collected after Run4 and Run5
- New data are coming, stay tuned for new results from LHCb

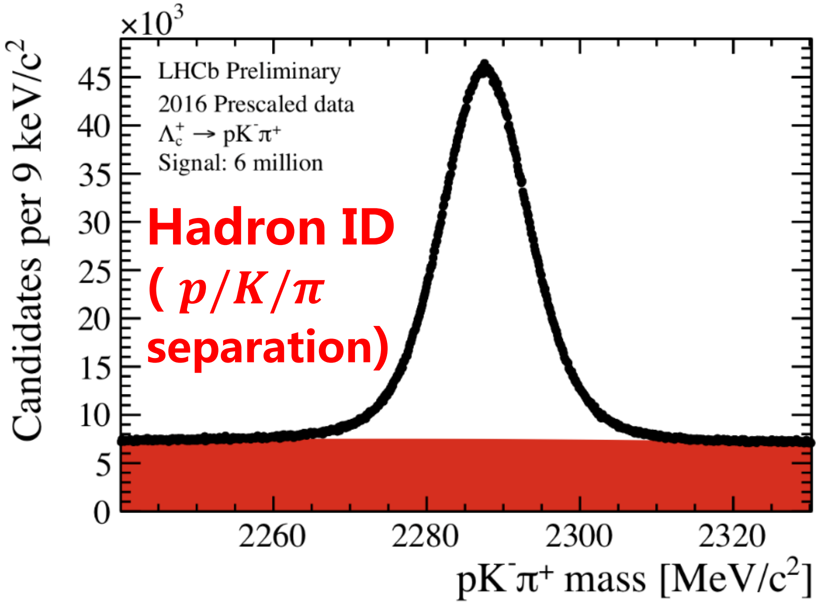
Thank you!

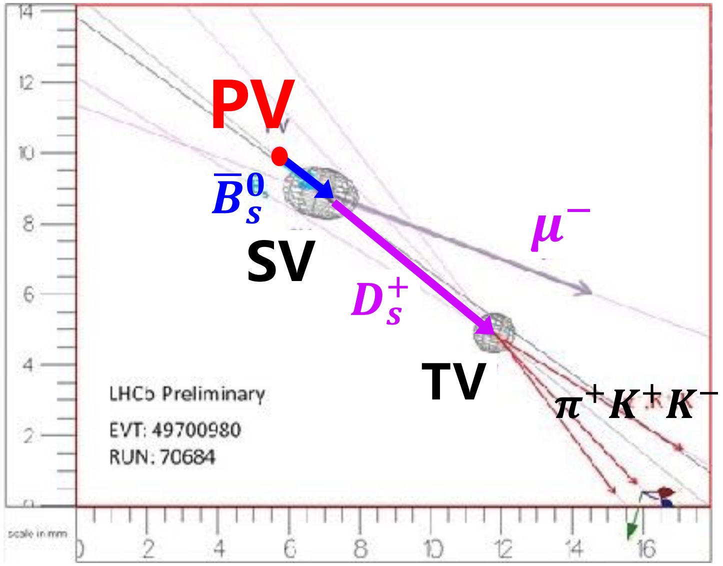
backup slides

Pros of heavy flavour measurement at LHCb









- Large production cross-section
- Efficient trigger
- Vertex locator with high precision
- High precision tracking system
- Powerful hadron identification
- Efficient muon system

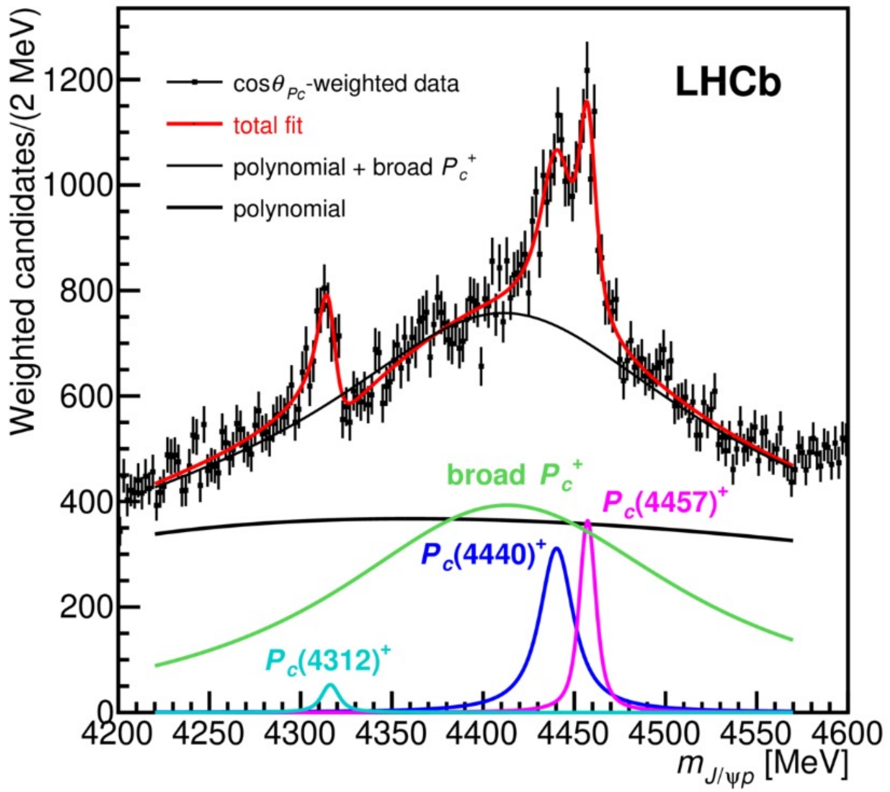
New pentaquark states in the full dataset (cont.)

PRL122 (2019) 222001

- Fit with Run1 model gives results **consistent** with those of Run1

- Fine structures
  - $P_c(4450)^+$ splits into two substructures
  - A new narrow peak at around 4312 MeV

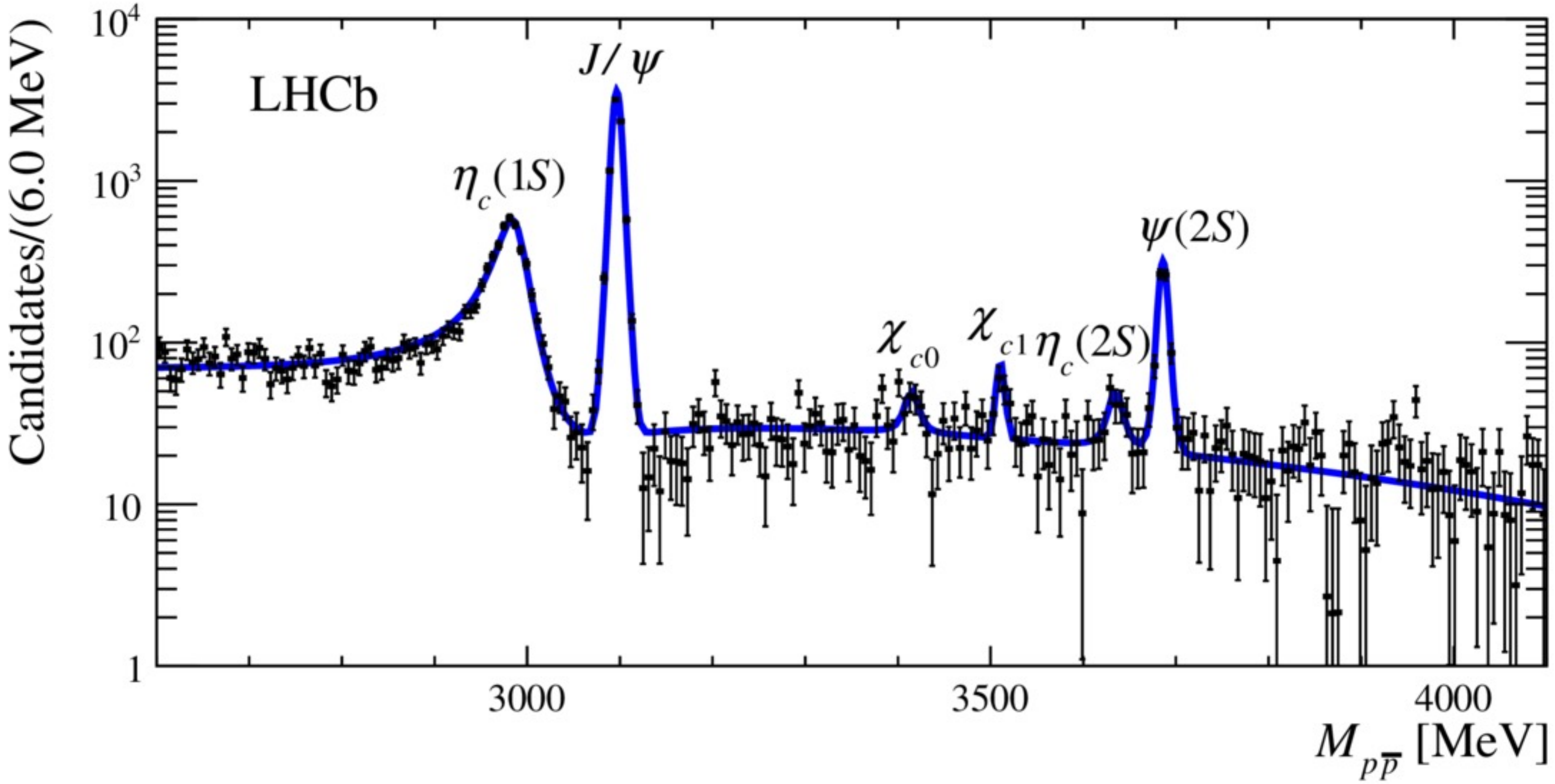
- One dimensional fit done
  - J^P and confirmation of $P_c(4380)^+$ need AmAn



State	M [MeV]	Γ [MeV]	(95% CL)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$	(< 27)	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$	(< 49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$	(< 20)	$0.53 \pm 0.16^{+0.15}_{-0.13}$

Search for $\chi_{c1}(3872) \to p\bar{p}$

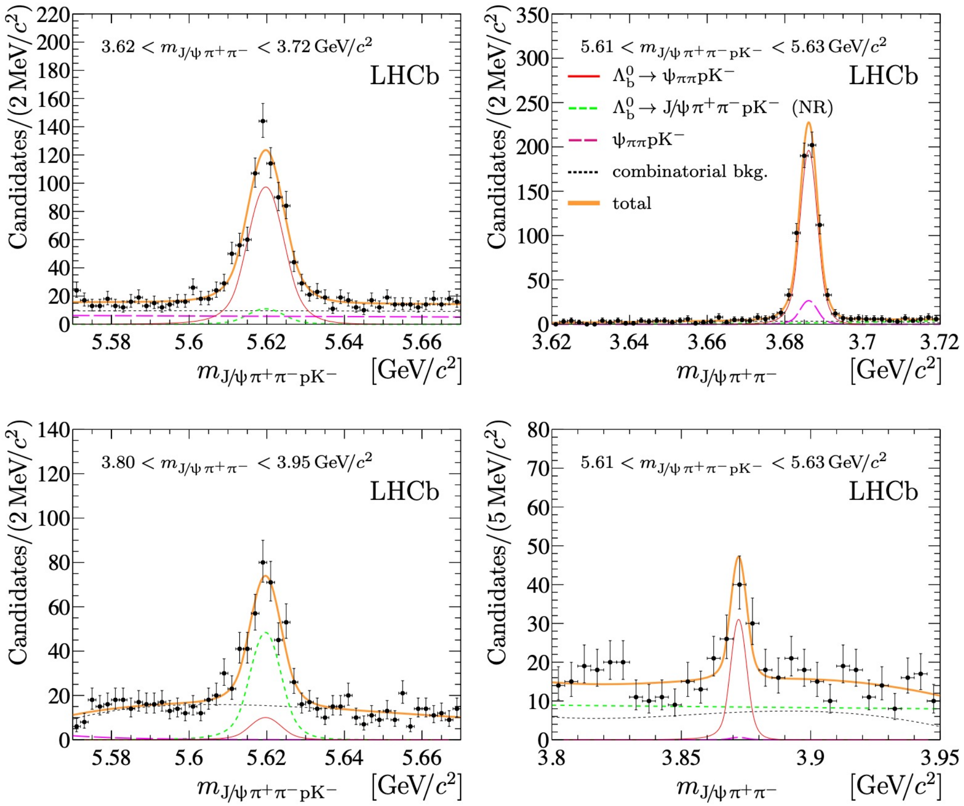
Phys. Lett. B769 (2017) 305



$$\frac{\mathcal{B}(B^+ \to X(3872)K^+) \times \mathcal{B}(X(3872) \to p\bar{p})}{\mathcal{B}(B^+ \to J/\psi K^+) \times \mathcal{B}(J/\psi \to p\bar{p})} < 0.20\,(0.25) \times 10^{-2}.$$

Observation of $\Lambda_b^0 \to \chi_{c1}(3872)pK^-$

JHEP 09 (2019) 028



$$\frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c1}(3872)pK^-)}{\mathcal{B}(\Lambda_b^0 \to \psi(2S)pK^-)} \times \frac{\mathcal{B}(\chi_{c1}(3872) \to J/\psi\,\pi^+\pi^-)}{\mathcal{B}(\psi(2S) \to J/\psi\,\pi^+\pi^-)} = (5.4 \pm 1.1 \pm 0.2) \times 10^{-2}$$

$$\mathcal{B}(\Lambda_b^0 \to \chi_{c1}(3872)pK^-) \times \mathcal{B}(\chi_{c1}(3872) \to J/\psi\,\pi^+\pi^-) = (1.2 \pm 0.3 \pm 0.2) \times 10^{-6}$$

Exotic D^-K^+ structure in $B^+ \to D^+D^-K^+$ decays

PR D102 (2020) 112003
PRL 125 (2020) 242001

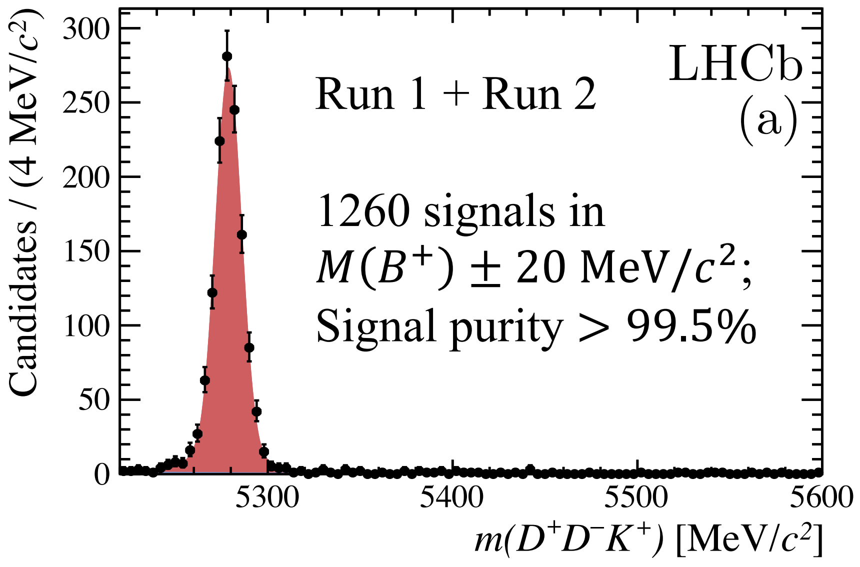
Observation of $X(4740)$ in $B_s^0 \to J/\psi K^+K^-\pi^+\pi^-$ decays

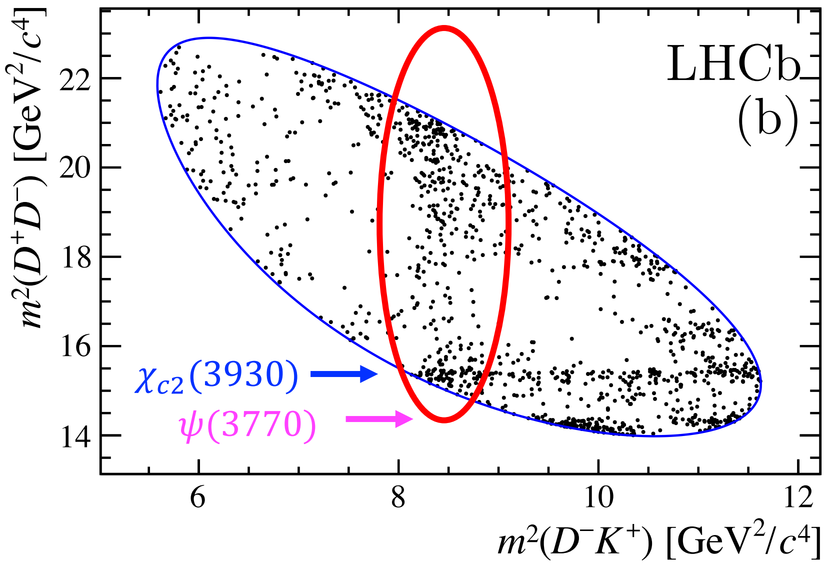
JHEP 02 (2021) 024

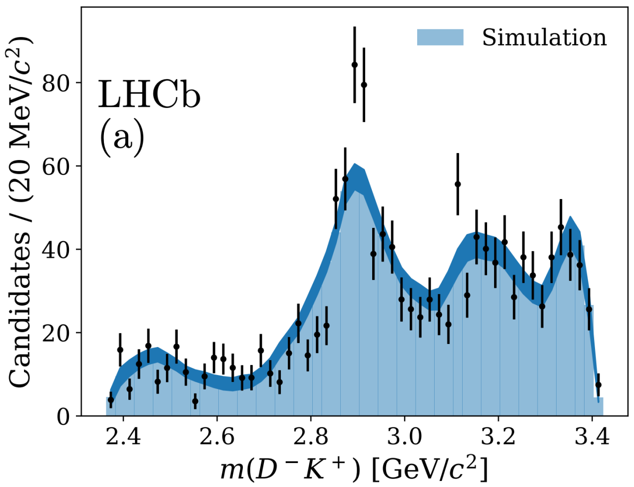
Exotic D^-K^+ structure in $B^+ \to D^+D^-K^+$ decays

PR D102 (2020) 112003
PRL 125 (2020) 242001

- Structure observed in $m(D^-K^+)$ spectrum in $B^+ \to D^+D^-K^+$ decays
- Model-independent study rejected hypothesis with only D^+D^- resonances ($J_{\max} = 2$) by 3.9σ
  - Evidence of exotic contribution of $\bar{c}\bar{s}ud$ states





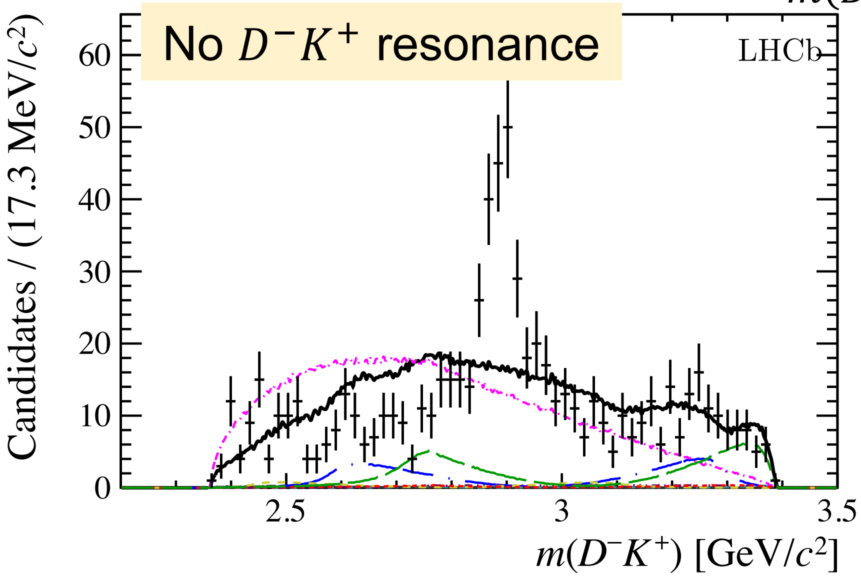


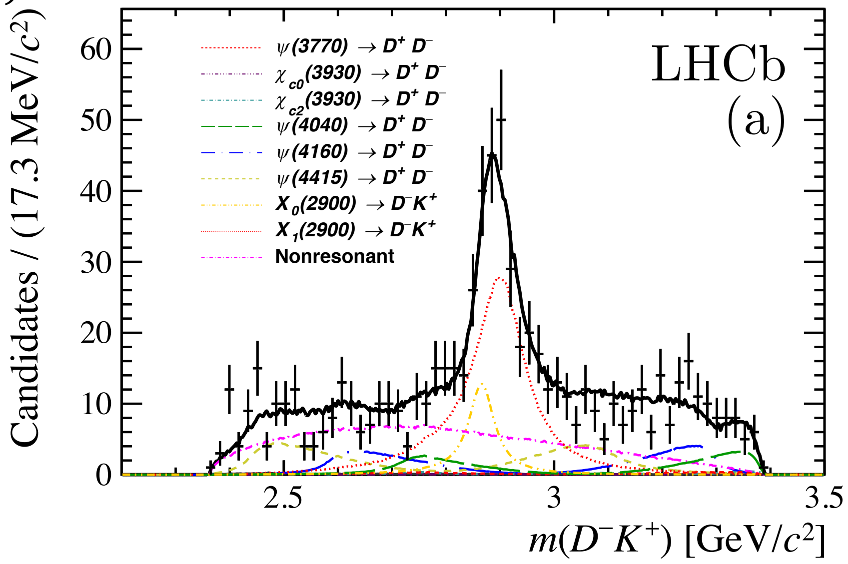
Amplitude analysis of $B^+ \to D^+ D^- K^+$ decays

PR D102 (2020) 112003
PRL 125 (2020) 242001

- Two resonances around 2.9 GeV with $J = 0$ and $J = 1$ needed in the $D^- K^+$ system

$m(D^+D^-) > 4$ GeV





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

- Close to $D^* K^*$ (2.902 GeV/c^2) and $D_1(2420)K$ (2.917 GeV/c^2) thresholds
  - kinematic rescattering effects? Molecule? Compact tetraquark?
- Could be first discovery of open-charm tetraquarks with four different flavors!

$X(4740)$ in $B_s^0 \to J/\psi K^+K^-\pi^+\pi^-$ decays

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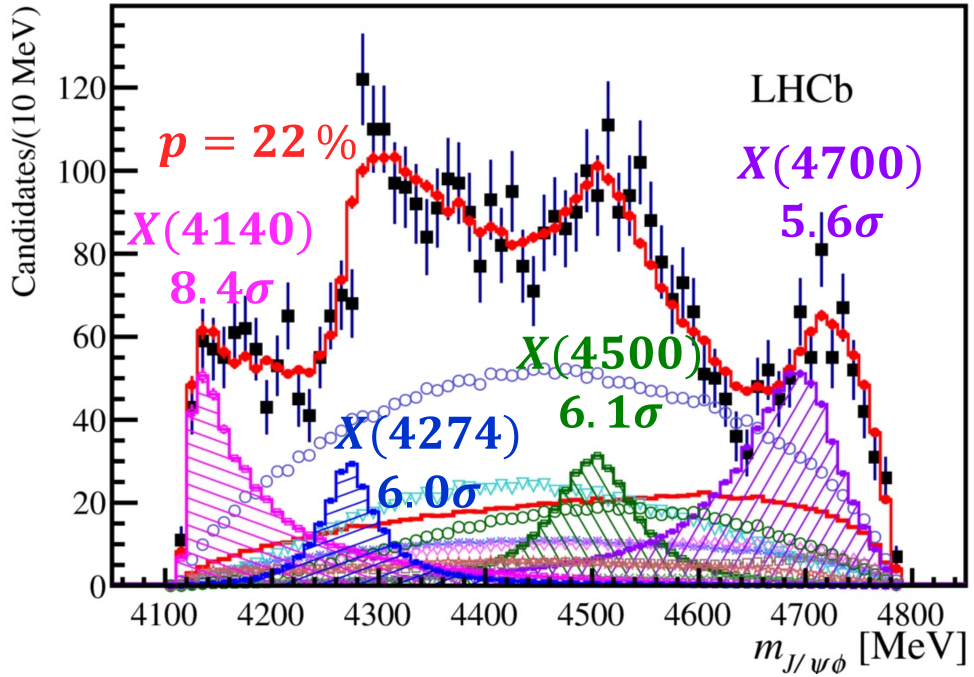
- Four X states observed with amplitude analysis of $B^+ \to J/\psi\phi K^+$ decays using Run1 data, update with full Run1+2 data is on going
- An excess around 4740 MeV observed in background-subtracted $m(J/\psi\phi)$ spectrum of $B_s^0 \to J/\psi\phi\pi^+\pi^-$ decays



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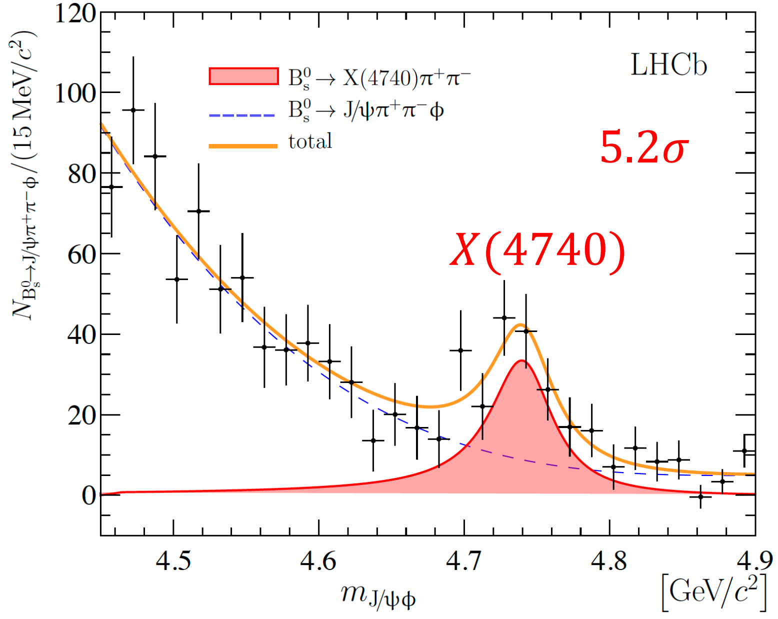

$$m_{X(4740)} = 4741 \pm 6 \pm 6\,\text{MeV}/c^2\,,$$
$$\Gamma_{X(4740)} = 53 \pm 15 \pm 11\,\text{MeV}\,.$$