Experimental review of multiquark states

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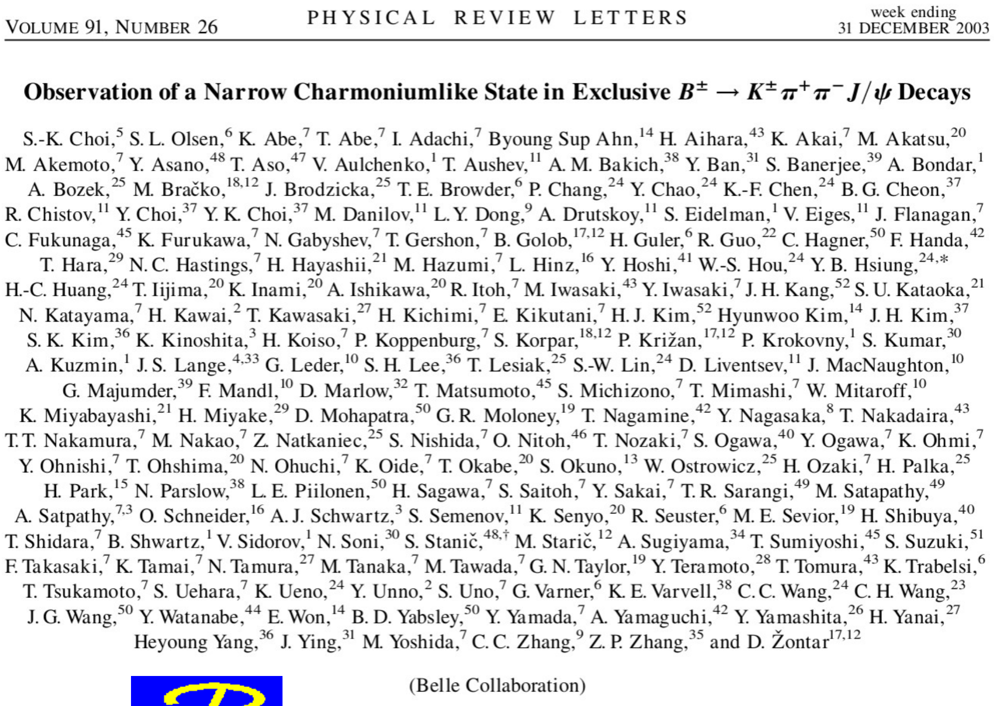
University of Warwick

5th International Workshop on Heavy Quark Physics
Islamabad, Pakistan

12 December 2023

How it started

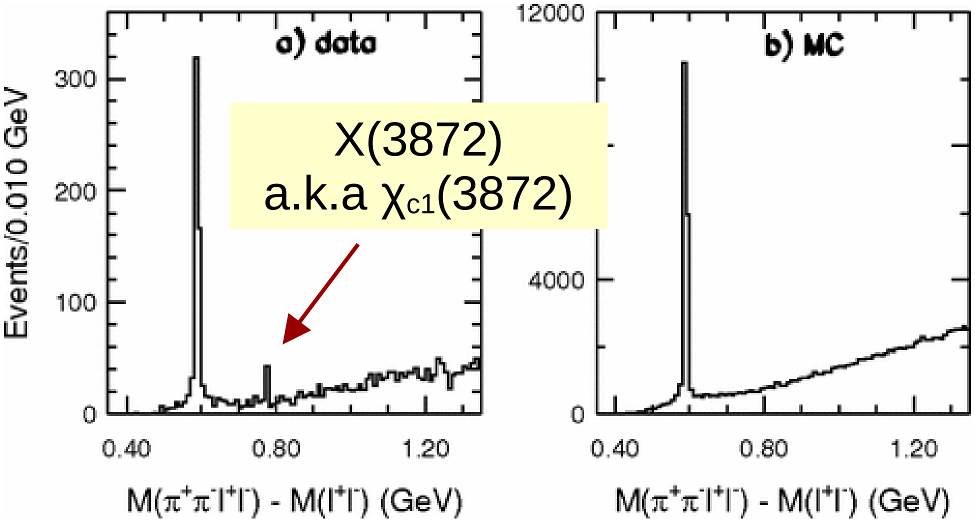


VOLUME 91, NUMBER 26 PHYSICAL REVIEW LETTERS week ending 31 DECEMBER 2003

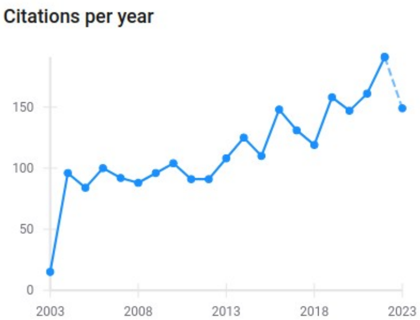
Observation of a Narrow Charmoniumlike State in Exclusive $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}J/\psi$ Decays

S.-K. Choi,[5] S. L. Olsen,[6] K. Abe,[7] T. Abe,[7] I. Adachi,[7] Byoung Sup Ahn,[14] H. Aihara,[43] K. Akai,[7] M. Akatsu,[20] M. Akemoto,[7] Y. Asano,[48] T. Aso,[47] V. Aulchenko,[1] T. Aushev,[11] A. M. Bakich,[38] Y. Ban,[31] S. Banerjee,[39] A. Bondar,[1] A. Bozek,[25] M. Bračko,[18,12] J. Brodzicka,[25] T. E. Browder,[6] P. Chang,[24] Y. Chao,[24] K.-F. Chen,[24] B. G. Cheon,[37] R. Chistov,[11] Y. Choi,[37] Y. K. Choi,[37] M. Danilov,[11] L. Y. Dong,[9] A. Drutskoy,[11] S. Eidelman,[1] V. Eiges,[11] J. Flanagan,[7] C. Fukunaga,[45] K. Furukawa,[7] N. Gabyshev,[7] T. Gershon,[7] B. Golob,[17,12] H. Guler,[6] R. Guo,[22] C. Hagner,[50] F. Handa,[42] T. Hara,[29] N. C. Hastings,[7] H. Hayashii,[21] M. Hazumi,[7] L. Hinz,[16] Y. Hoshi,[41] W.-S. Hou,[24] Y. B. Hsiung,[24,*] H.-C. Huang,[24] T. Iijima,[20] K. Inami,[20] A. Ishikawa,[20] R. Itoh,[7] M. Iwasaki,[43] Y. Iwasaki,[7] J. H. Kang,[52] S. U. Kataoka,[21] N. Katayama,[7] H. Kawai,[2] T. Kawasaki,[27] H. Kichimi,[7] E. Kikutani,[7] H. J. Kim,[52] Hyunwoo Kim,[14] J. H. Kim,[37] S. K. Kim,[36] K. Kinoshita,[3] H. Koiso,[7] P. Koppenburg,[7] S. Korpar,[18,12] P. Križan,[17,12] P. Krokovny,[1] S. Kumar,[30] A. Kuzmin,[1] J. S. Lange,[4,33] G. Leder,[10] S. H. Lee,[36] T. Lesiak,[25] S.-W. Lin,[24] D. Liventsev,[11] J. MacNaughton,[10] G. Majumder,[39] F. Mandl,[10] D. Marlow,[32] T. Matsumoto,[45] S. Michizono,[7] T. Mimashi,[7] W. Mitaroff,[10] K. Miyabayashi,[21] H. Miyake,[29] D. Mohapatra,[50] G. R. Moloney,[19] T. Nagamine,[42] Y. Nagasaka,[8] T. Nakadaira,[43] T. T. Nakamura,[7] M. Nakao,[7] Z. Natkaniec,[25] S. Nishida,[7] O. Nitoh,[46] T. Nozaki,[7] S. Ogawa,[40] Y. Ogawa,[7] K. Ohmi,[7] Y. Ohnishi,[7] T. Ohshima,[20] N. Ohuchi,[7] K. Oide,[7] T. Okabe,[20] S. Okuno,[13] W. Ostrowicz,[25] H. Ozaki,[7] H. Palka,[25] H. Park,[15] N. Parslow,[38] L. E. Piilonen,[50] H. Sagawa,[7] S. Saitoh,[7] Y. Sakai,[7] T. R. Sarangi,[49] M. Satapathy,[49] A. Satpathy,[7,3] O. Schneider,[16] A. J. Schwartz,[3] S. Semenov,[11] K. Senyo,[20] R. Seuster,[6] M. E. Sevior,[19] H. Shibuya,[40] T. Shidara,[7] B. Shwartz,[1] V. Sidorov,[1] N. Soni,[30] S. Stanič,[48,†] M. Starič,[12] A. Sugiyama,[34] T. Sumiyoshi,[45] S. Suzuki,[51] F. Takasaki,[7] K. Tamai,[7] N. Tamura,[27] M. Tanaka,[7] M. Tawada,[7] G. N. Taylor,[19] Y. Teramoto,[28] T. Tomura,[43] K. Trabelsi,[6] T. Tsukamoto,[7] S. Uehara,[7] K. Ueno,[24] Y. Unno,[2] S. Uno,[7] G. Varner,[6] K. E. Varvell,[38] C. C. Wang,[24] C. H. Wang,[23] J. G. Wang,[50] Y. Watanabe,[44] E. Won,[14] B. D. Yabsley,[50] Y. Yamada,[7] A. Yamaguchi,[42] Y. Yamashita,[26] H. Yanai,[27] Heyoung Yang,[36] J. Ying,[31] M. Yoshida,[7] C. C. Zhang,[9] Z. P. Zhang,[35] and D. Žontar[17,12]

(Belle Collaboration)

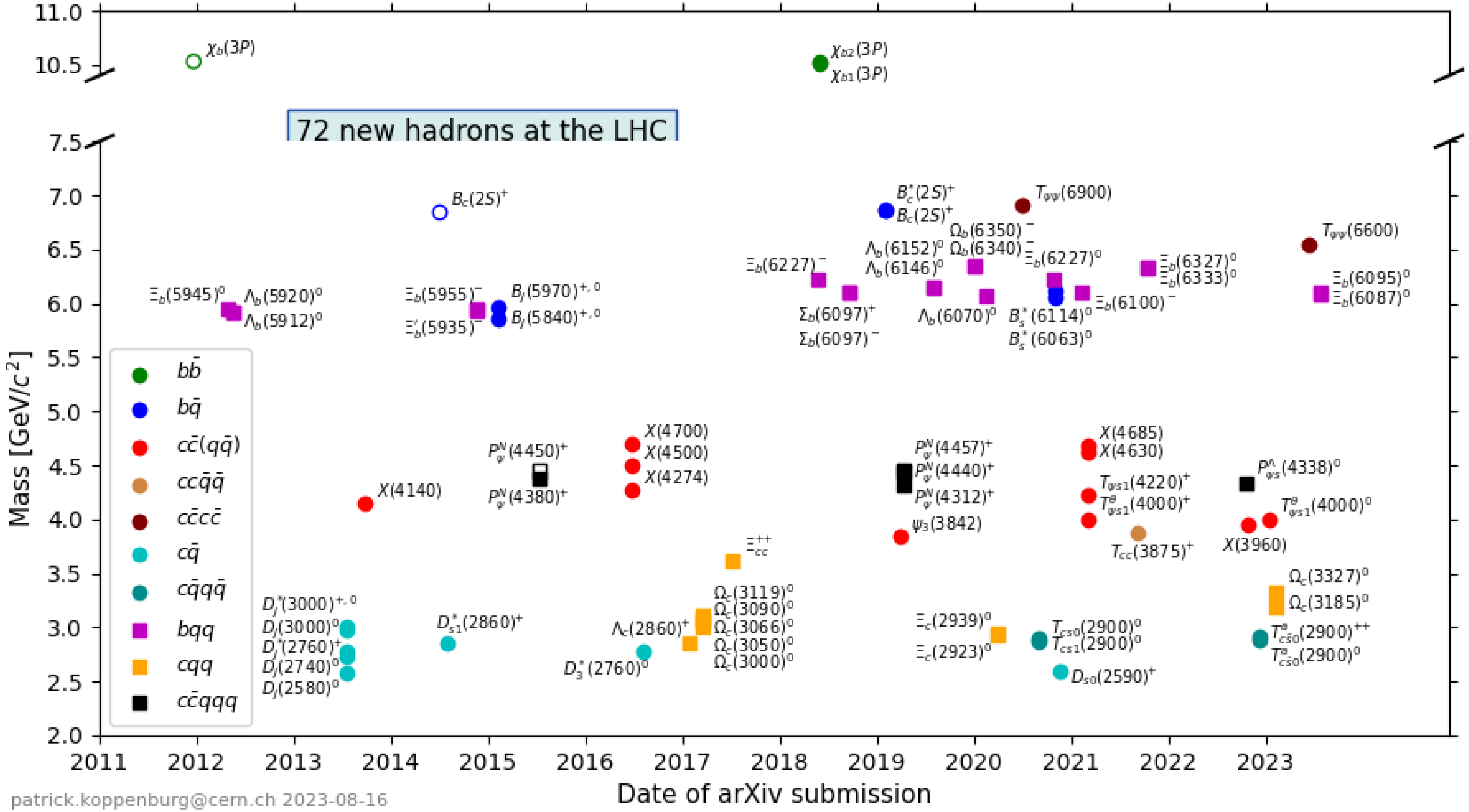


X(3872)
a.k.a $\chi_{c1}(3872)$



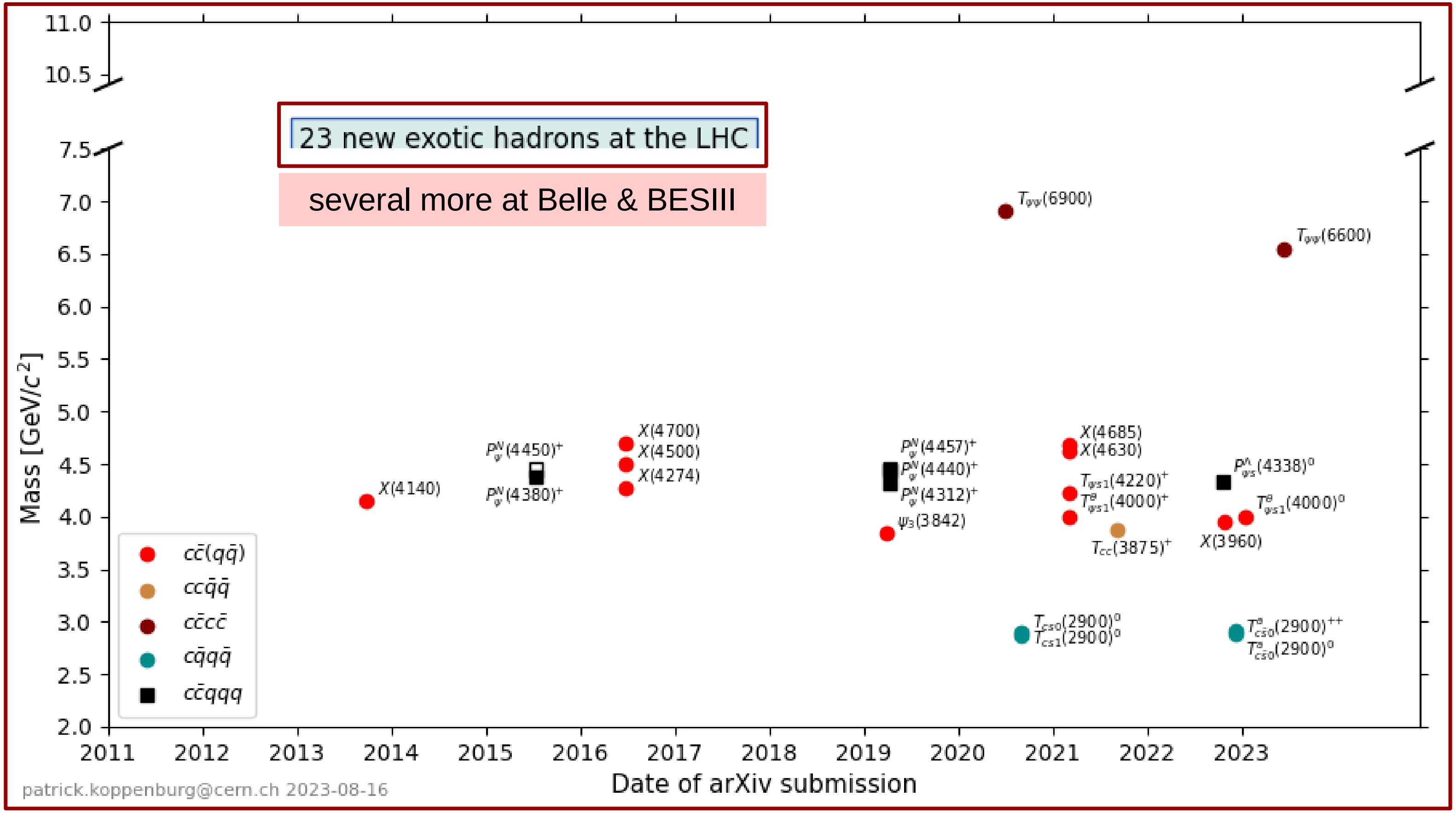
15th most cited paper on hep-ex

How it’s going



patrick.koppenburg@cern.ch 2023-08-16

How it’s going



23 new exotic hadrons at the LHC

several more at Belle & BESIII

patrick.koppenburg@cern.ch 2023-08-16

Content

- Huge progress in hadron spectroscopy in past decade
  - Mostly due to new states with heavy flavours discovered by LHCb
    - Important contributions also from BESIII, Belle, BaBar, CMS, ATLAS, ...
  - Manifestly exotic, potentially exotic and conventional states
- Selected highlights (impossible to cover everything!)
  - $\chi_{c1}(3872)$, $P_{c\bar{c}}$ states, Ξ_{cc}^{++} and partners, T_{cc}^{+}, T_{cs} & $T_{c\bar{s}}$
- Future outlook

Will follow PDG naming scheme as updated for 2023 RPP

https://pdg.lbl.gov/2023/reviews/rpp2023-rev-naming-scheme-hadrons.pdf

The LHCb experiment

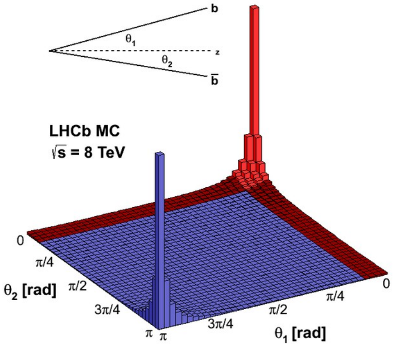
- Huge charm and beauty production cross-section in the forward direction in pp collisions at LHC energies
  - Essentially all hadrons produced
- Require superb detection capability to separate signal from potentially overwhelming background
  - LHCb strengths in vertexing, tracking and charged particle identification
  - Capability for online selection (trigger) also crucial
- Two main production mechanisms
  - prompt: highest cross-section, but high backgrounds; only for cleanest channels
  - via B decays: lower rates (cross-section + BF + acceptance), but very clean

Most results shown today exploit production via B decays

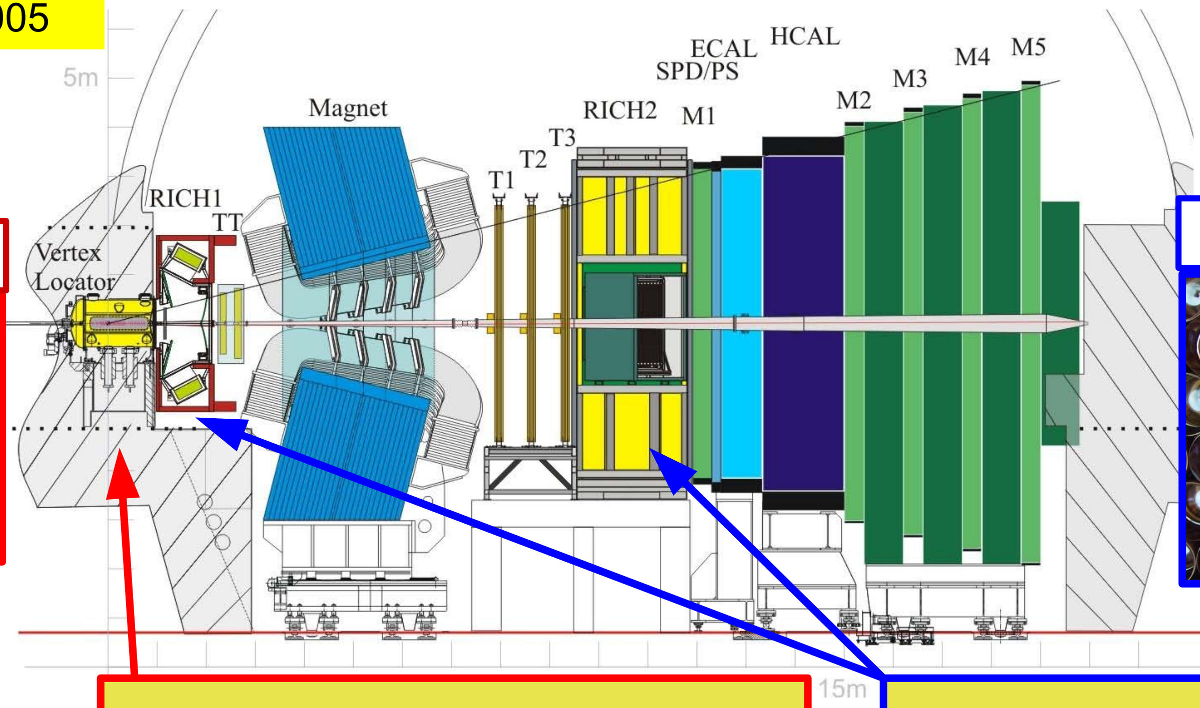
The LHCb detector

(2011-18 edition)

The LHCb Detector
JINST 3 (2008) S08005



VELO silicon strips



RICH PMTs

Precision primary and secondary vertex measurements

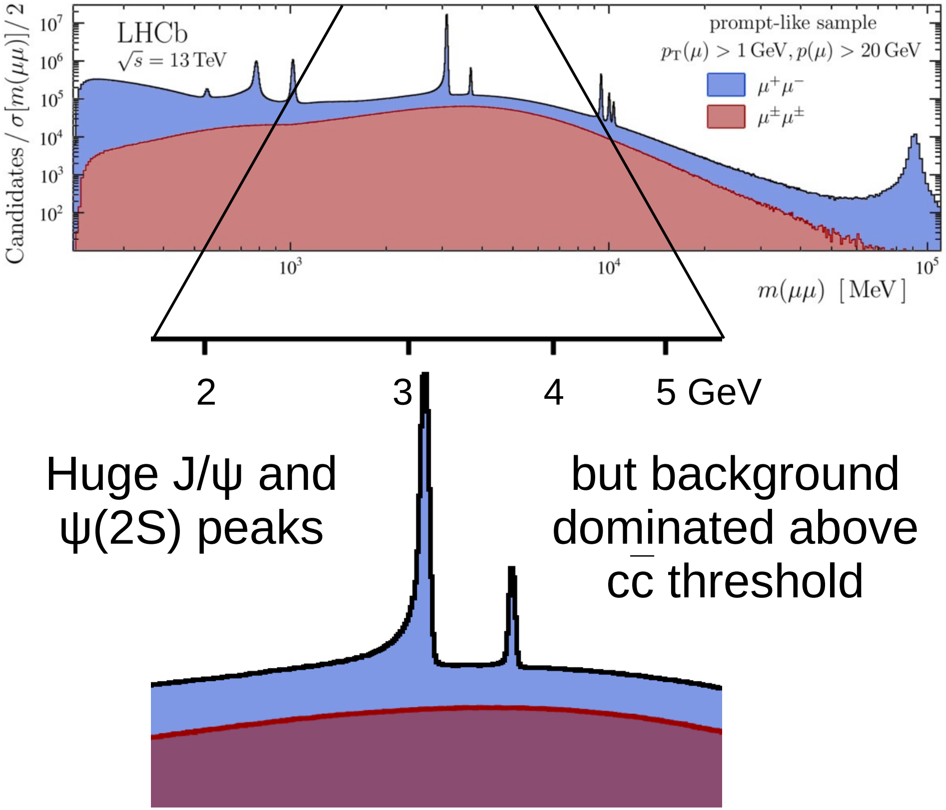
Excellent K/π separation capability

Prompt vs. B decays

example with $\mu^+\mu^-$

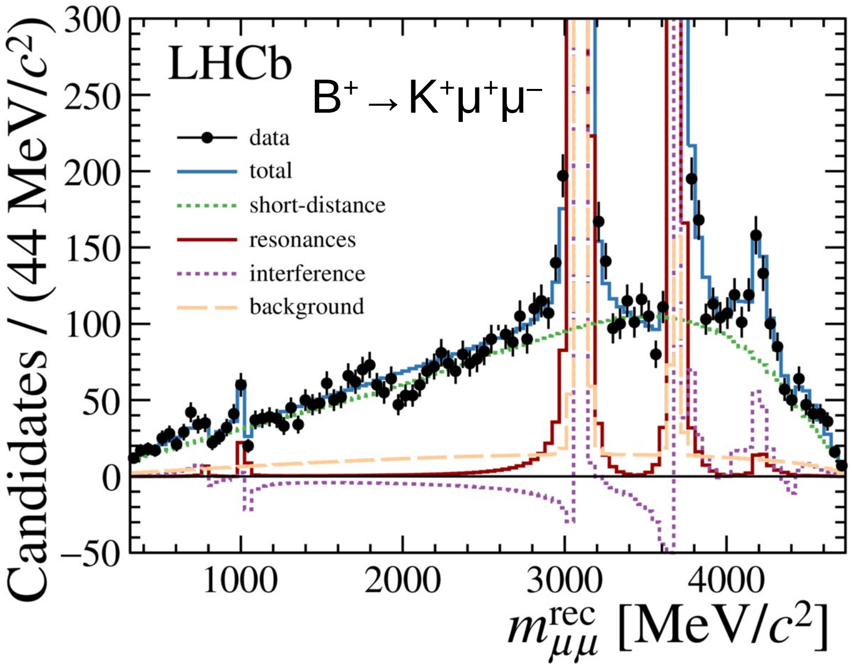
PRL 120 (2018) 061801

EPJ C77 (2017) 161



Huge J/ψ and ψ(2S) peaks

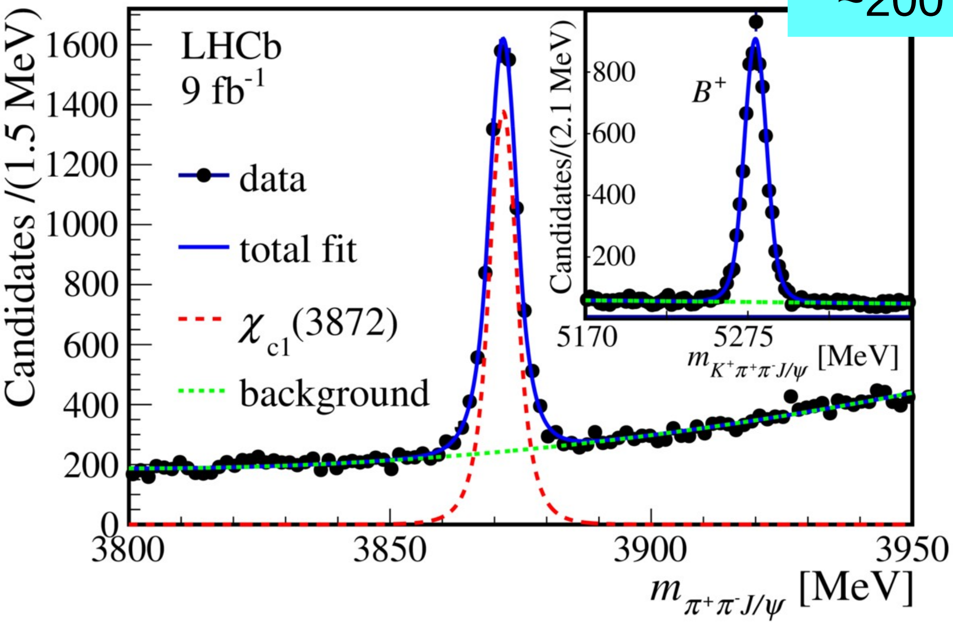
but background dominated above $c\bar{c}$ threshold



Clear contribution from ψ(4160);
relative phases can be measured

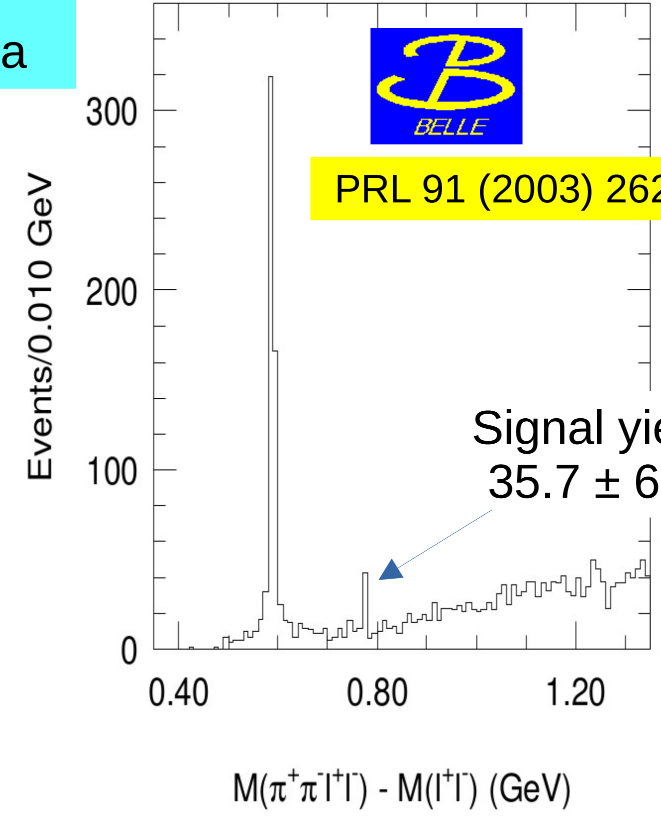
$\chi_{c1}(3872)$ in $B^+ \to J/\psi \pi^+ \pi^- K^+$ decays

PR D108 (2023) L011103



20 years since discovery
~200 × more data

Signal yield of 6788 ± 117

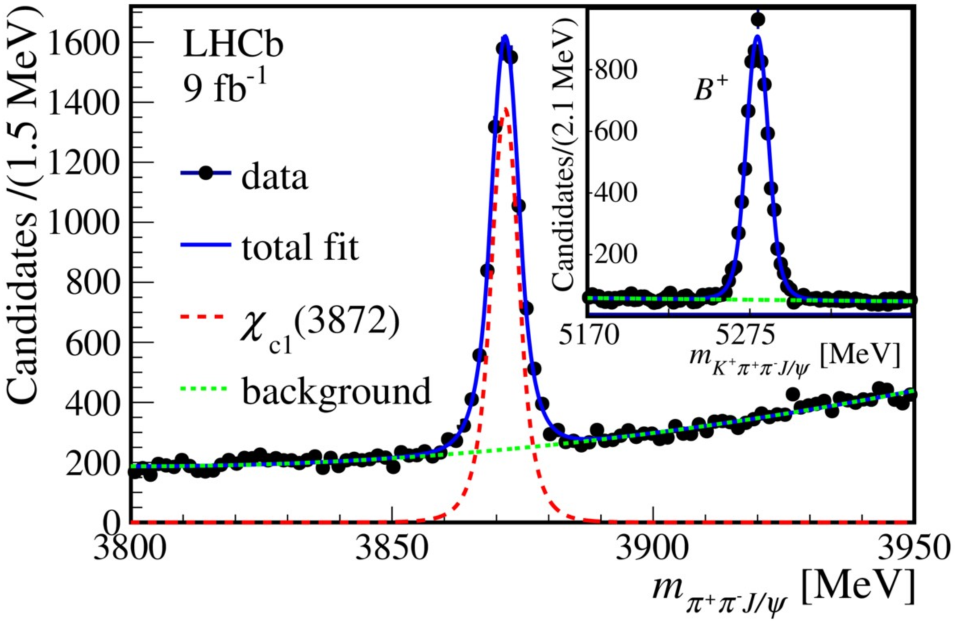


PRL 91 (2003) 262001

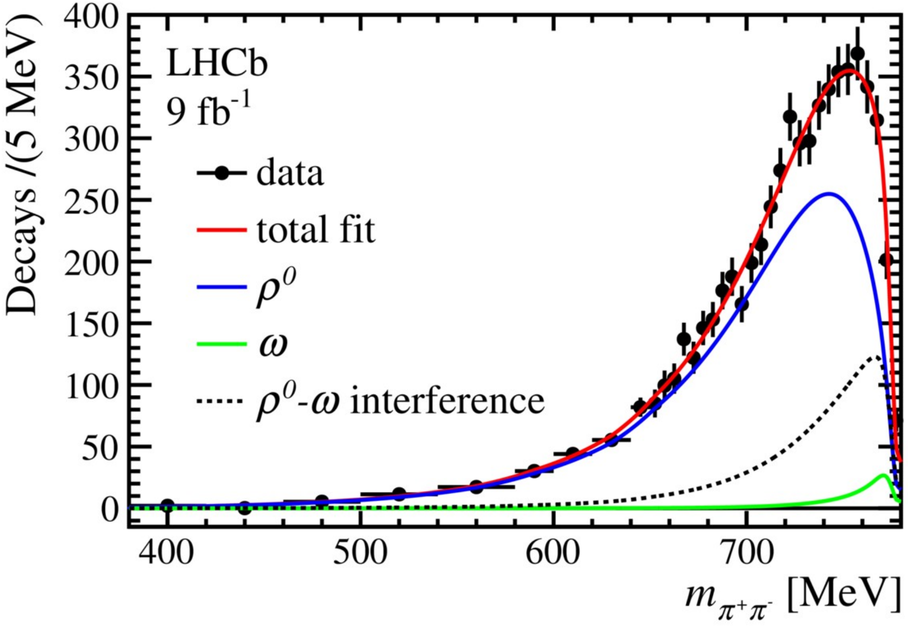
Signal yield
35.7 ± 6.8

$\chi_{c1}(3872)$ in $B^+ \to J/\psi\pi^+\pi^-K^+$ decays

PR D108 (2023) L011103



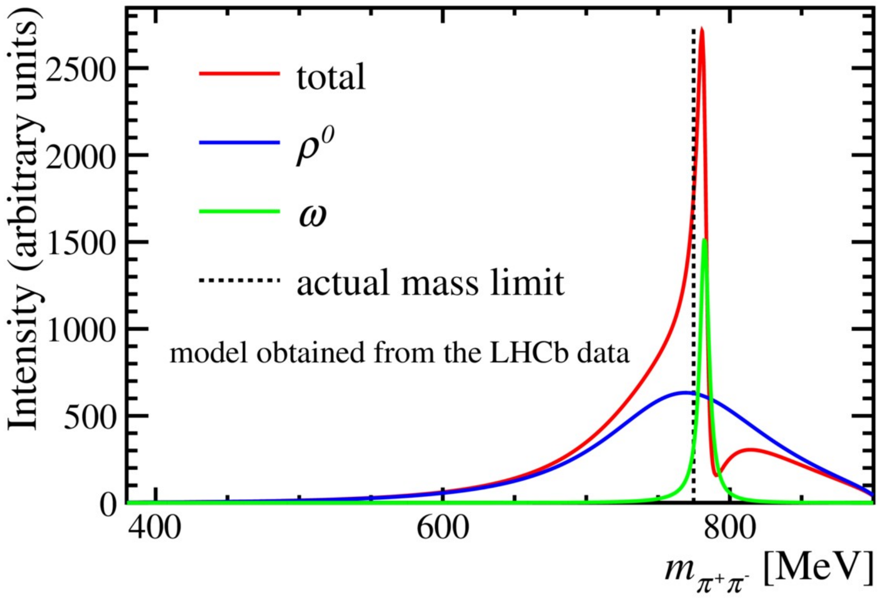
Signal yield of 6788 ± 117



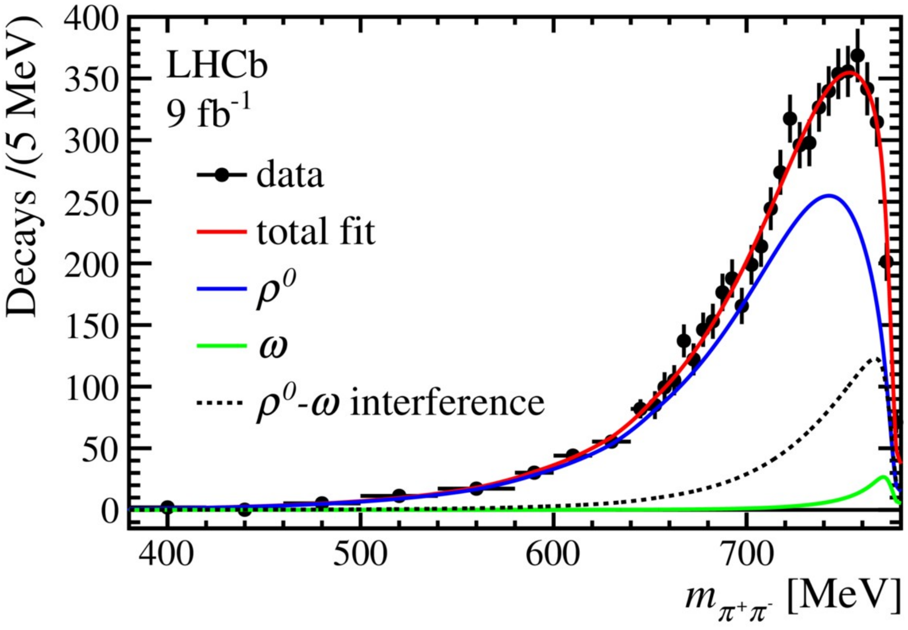
Clear need for ω contribution, and interference, to fit $m(\pi^+\pi^-)$ spectrum

$\chi_{c1}(3872)$ in $B^+ \rightarrow J/\psi\pi^+\pi^-K^+$ decays

PR D108 (2023) L011103



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

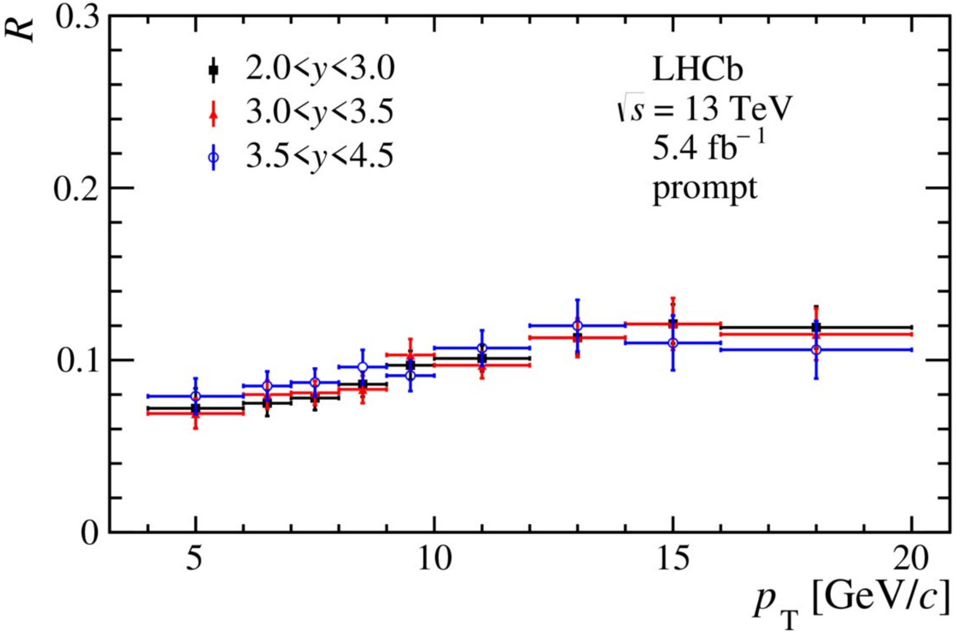


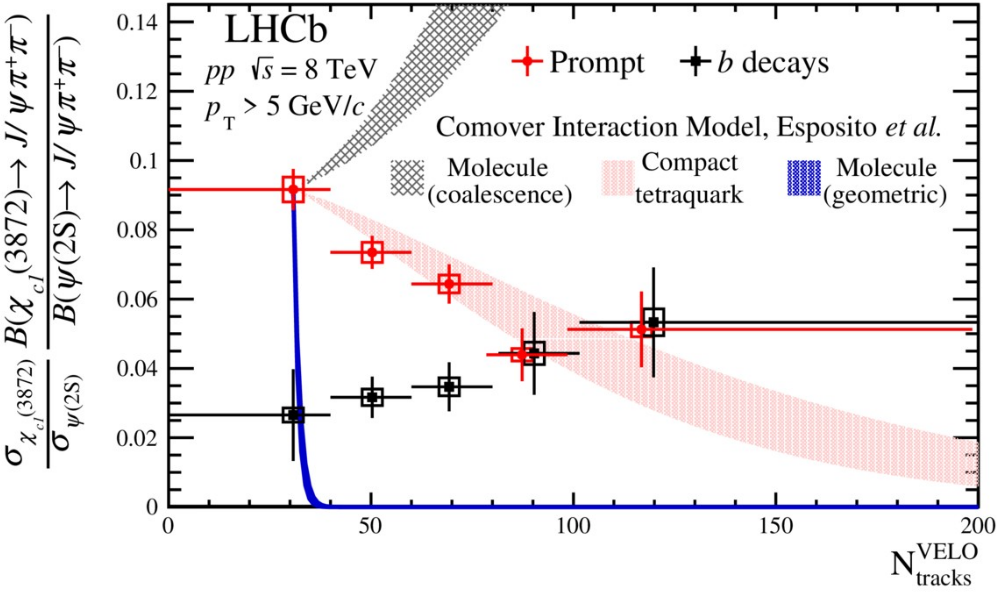
Clear need for ω contribution, and interference, to fit $m(\pi^+\pi^-)$ spectrum

$\chi_{c1}(3872)$ production in pp collisions

JHEP 01 (2022) 131

PRL 126 (2021) 092001

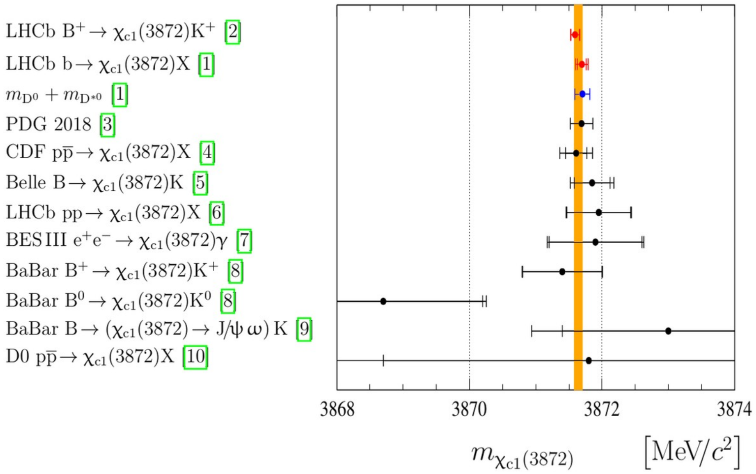




Production relative to $\psi(2S)$ studied as a function of p_T and occupancy
Studies of production in other environments (pPb, etc.) ongoing

$\chi_{c1}(3872)$: other results and open questions

- Mass : 3871.64 ± 0.06 ± 0.01 MeV/c^2
  - obtained from Breit—Wigner fits
  - c.f. DD^* threshold 3871.70 ± 0.11 MeV/c^2
- Lineshape in $J/\psi\pi^+\pi^-$ studied in detail
  - Improved knowledge of $D\bar{D}\pi$ & $D\bar{D}\gamma$ couplings needed for further progress
- Disagreement on $B(\chi_{c1}(3872) \to \psi(2S)\gamma)$
  - Seen by BaBar & LHCb; not by Belle & BESIII

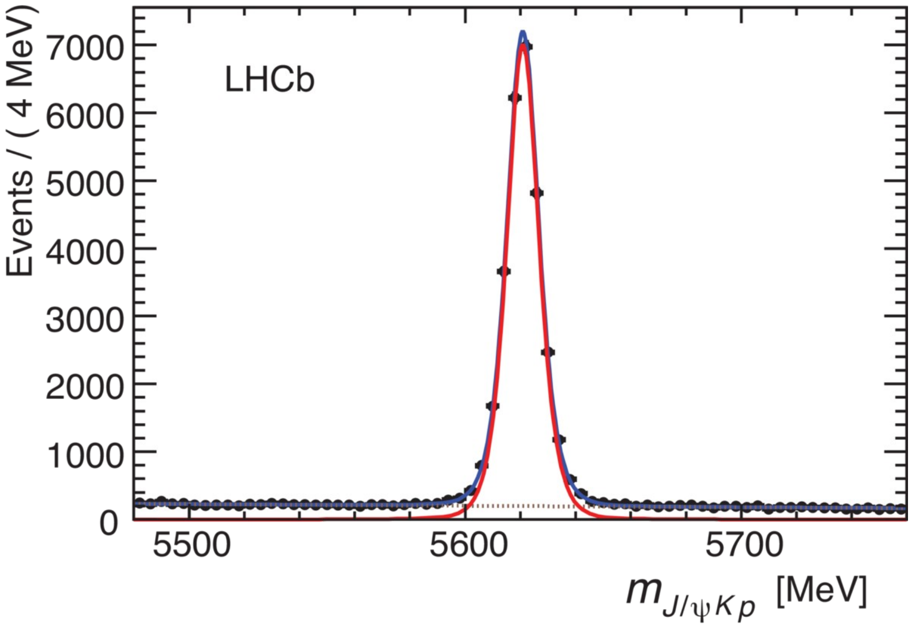


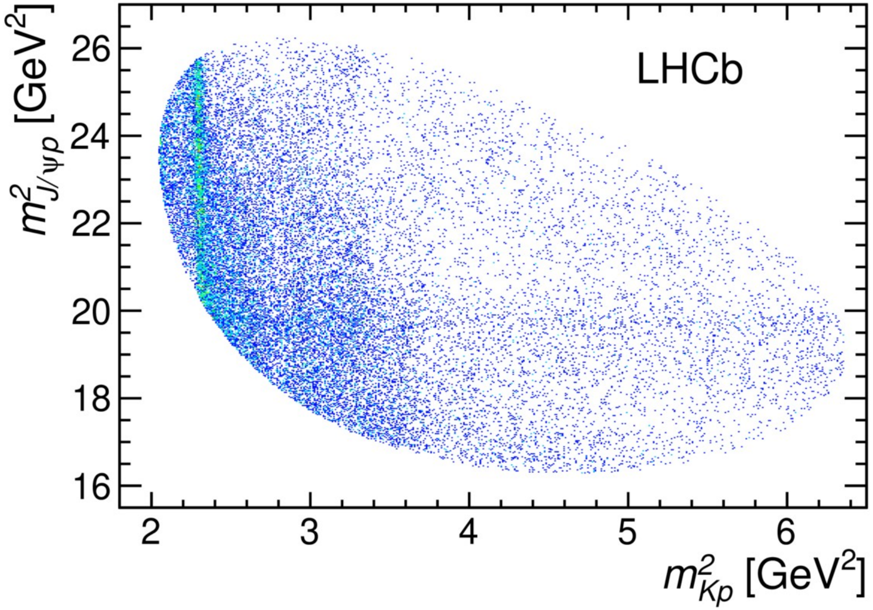
Studied in different experiments, different production environments, different decay channels

Unique in this respect among exotic hadrons (so far)

Charmonium pentaquark discovery

PRL 115 (2015) 072001





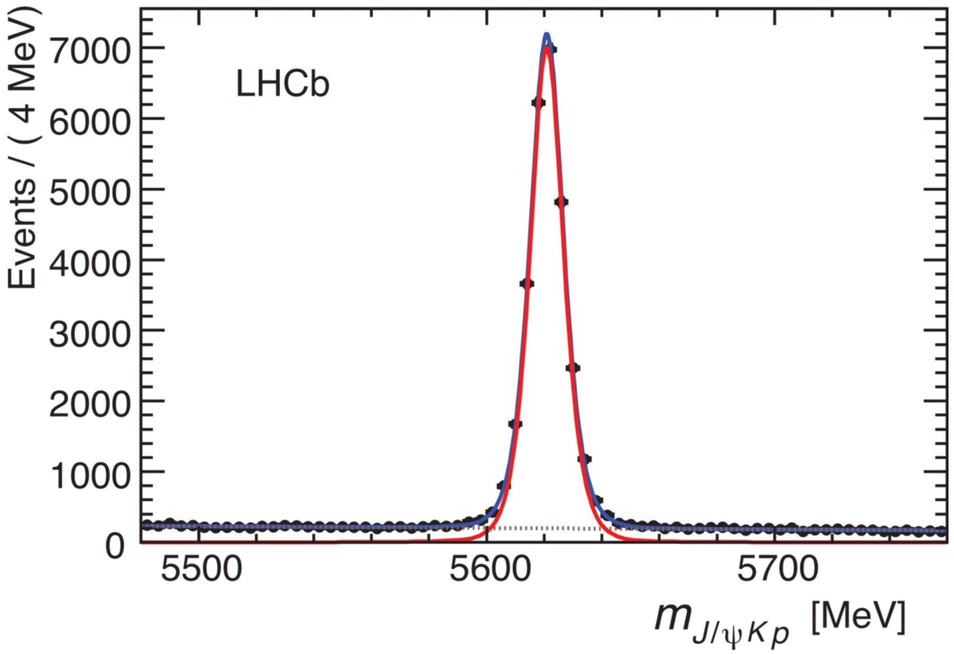
Almost background-free
$\Lambda_b^0 \rightarrow J/\psi p K^-$ sample

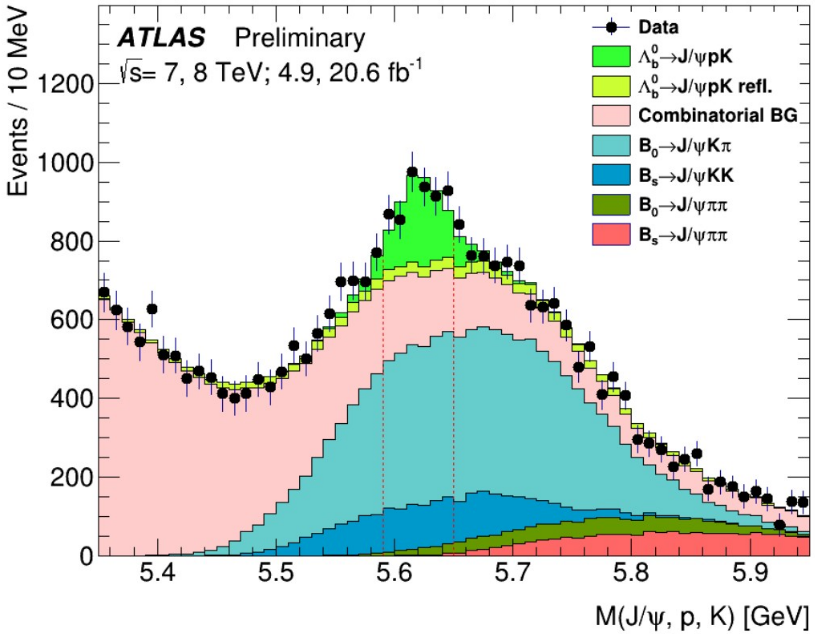
Clear structure in m(J/ψp)

Importance of particle identification

LHCb; PRL 115 (2015) 072001

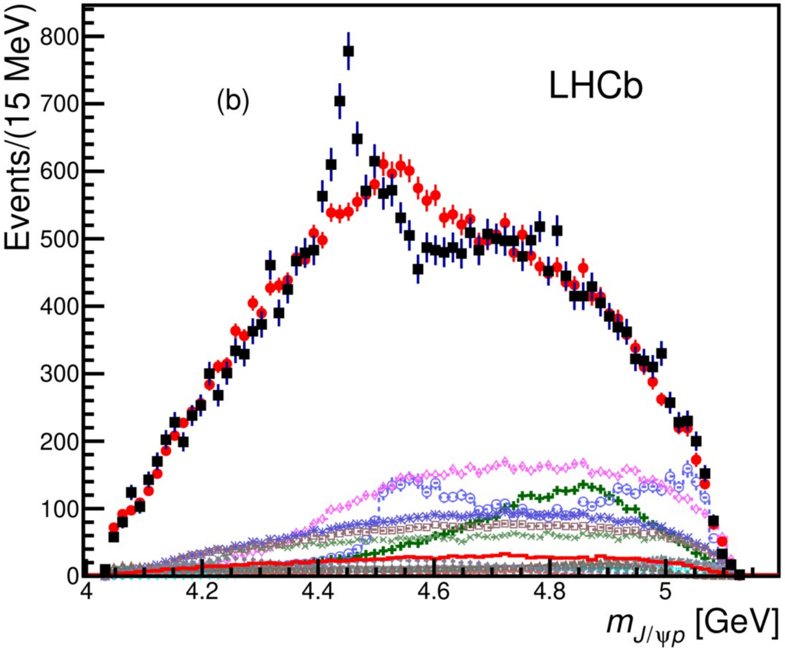
ATLAS-CONF-2019-048



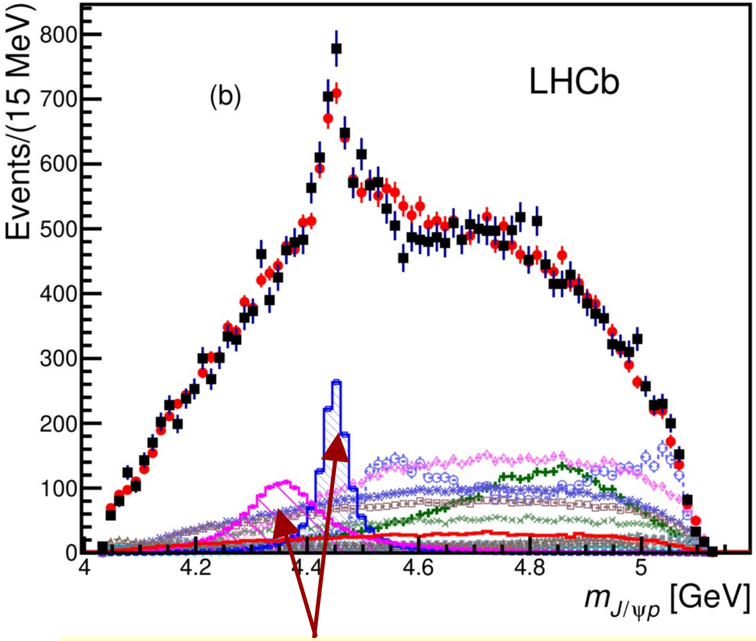


Charmonium pentaquark discovery

PRL 115 (2015) 072001



Fit without J/ψp resonances cannot describe data

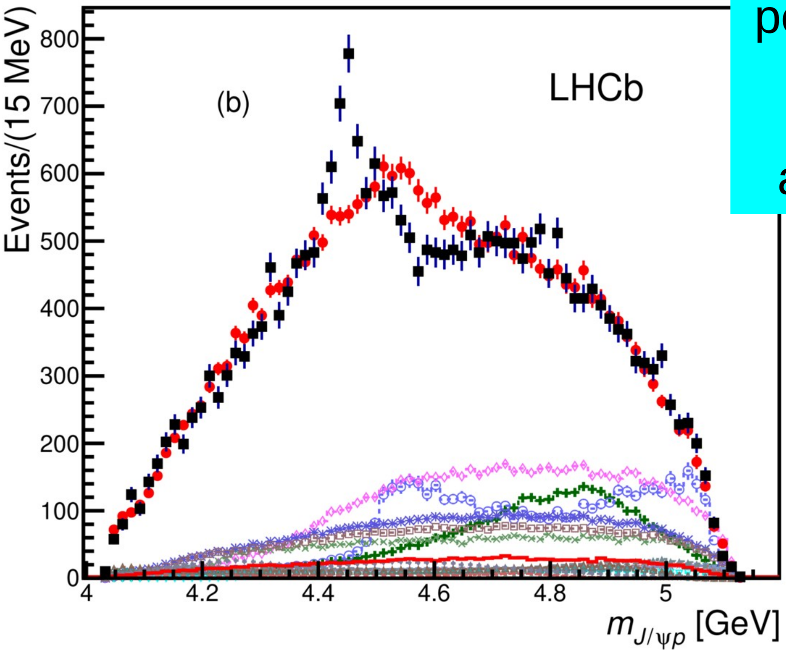


Two $P_{c\bar{c}}$ states needed to get reasonable fit

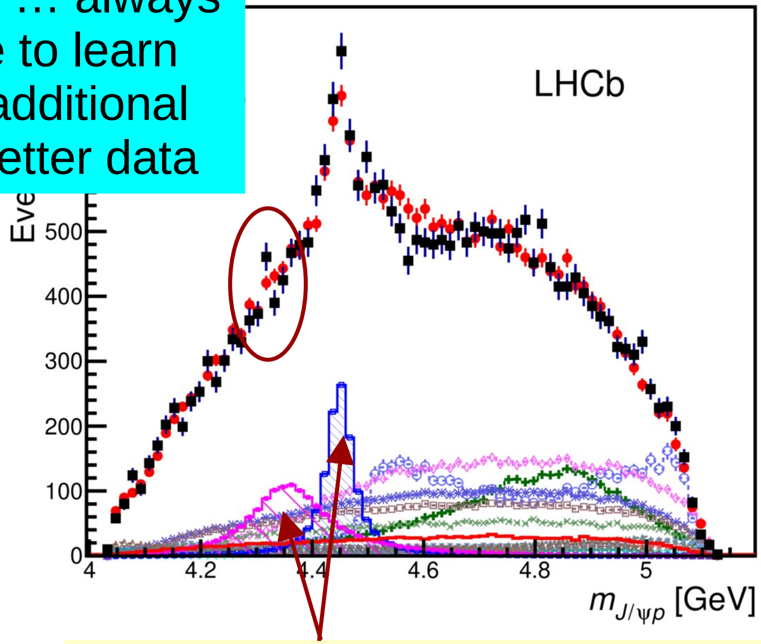
Charmonium pentaquark discovery

PRL 115 (2015) 072001

But fit is not perfect … always more to learn with additional and better data



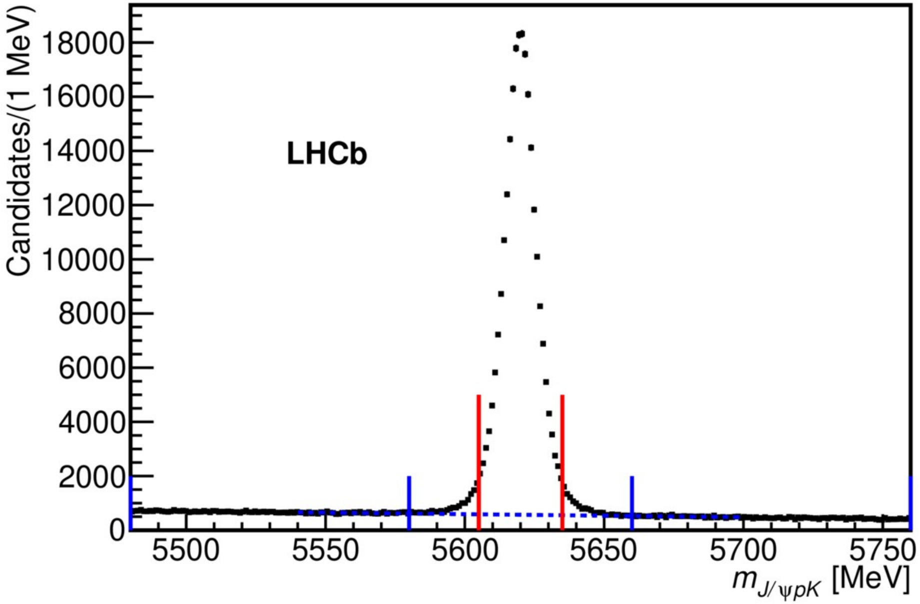
Fit without J/ψp resonances cannot describe data

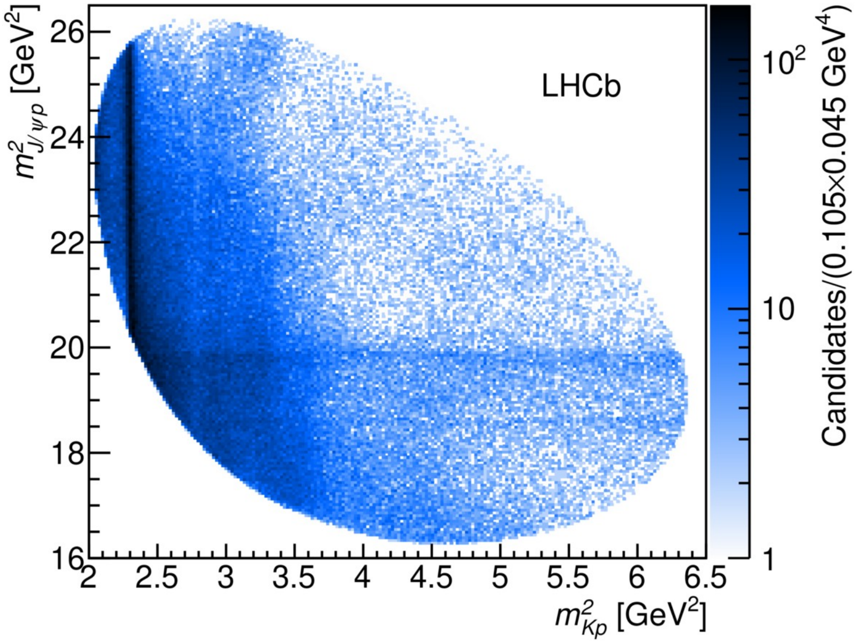


Two $P_{c\bar{c}}$ states needed to get reasonable fit

Latest on charmonium pentaquarks

PRL 122 (2019) 222001

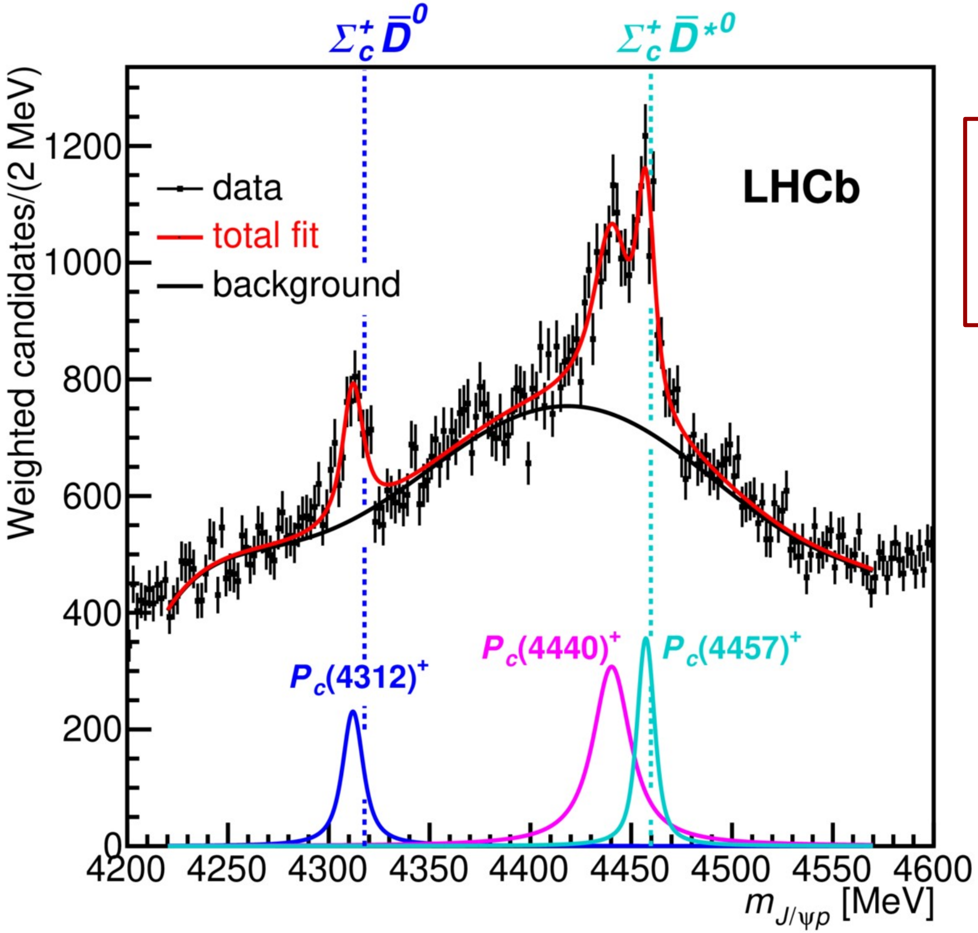




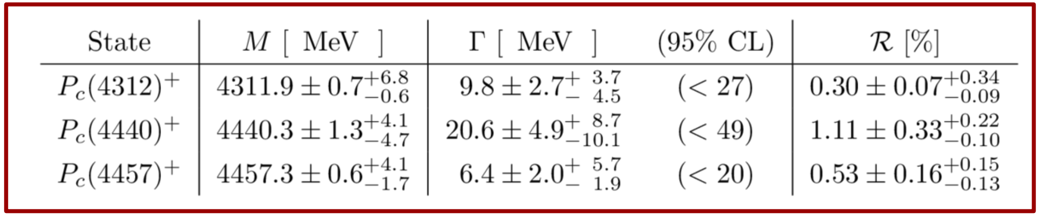
Order of magnitude increase in sample size

Structure in Dalitz plot even more evident

Latest on charmonium pentaquarks



PRL 122 (2019) 222001



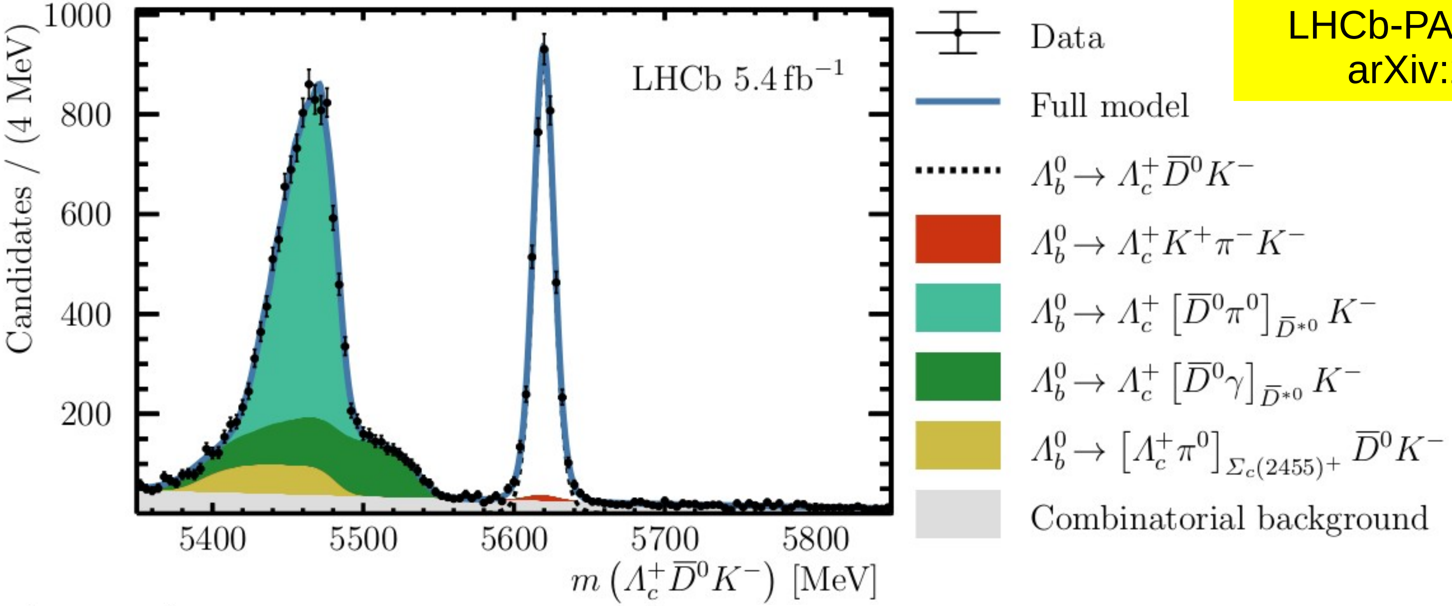
State	M [MeV]	Γ [MeV]	(95% CL)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$	(< 27)	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$	(< 49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3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

Striking proximity of peaks to $\Sigma_c^+ \bar{D}^{(*)0}$ thresholds → Coupled channel analyses of lineshapes may be necessary

Full amplitude analysis needed to determine quantum numbers (work in progress)

Charmonium pentaquarks → open charm?

LHCb-PAPER-2023-034
arXiv:2311.14088



$$\frac{\mathcal{B}\left(\Lambda_b^0 \to J/\psi pK^-\right)}{\mathcal{B}\left(\Lambda_b^0 \to \Lambda_c^+\overline{D}^0K^-\right)} = 0.152^{+0.032}_{-0.028},$$

$$\frac{\mathcal{B}\left(\Lambda_b^0 \to J/\psi pK^-\right)}{\mathcal{B}\left(\Lambda_b^0 \to \Lambda_c^+\overline{D}^{*0}K^-\right)} = 0.049^{+0.011}_{-0.009},$$

$$\frac{\mathcal{B}\left(\Lambda_b^0 \to \Lambda_c^+\overline{D}^{*0}K^-\right)}{\mathcal{B}\left(\Lambda_b^0 \to \Lambda_c^+\overline{D}^0K^-\right)} = 3.09^{+0.11+0.09}_{-0.10-0.10}.$$

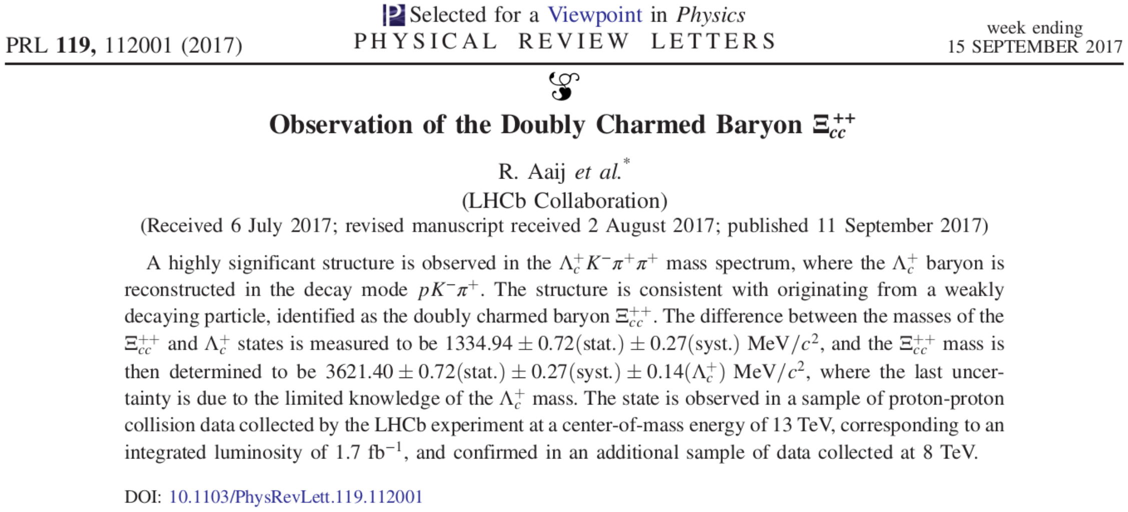
Amplitude analyses needed to determine possible $P_{c\bar{c}}$ contributions to these decays

$P_{c\bar{c}}$ states : open questions

- Determination of quantum numbers
  - Amplitude analysis required
- Decays to final states other than J/ψp
  - Potential to study $\eta_c p$, $\chi_{c1} p$ but larger samples needed
  - Similarly, good long-term prospects to study $\Lambda_c D^{(*)}$, $\Sigma_c D^{(*)}$ decays
- Other production mechanisms?
  - Other b decays? Prompt production in pp collisions? Photoproduction?
- What is the relevance of the proximity to $\Sigma_c D^{(*)}$ threshold?

Ξ_{cc}^{++} discovery

PRL 119 (2017) 112001



Selected for a Viewpoint in *Physics*

PRL **119,** 112001 (2017) PHYSICAL REVIEW LETTERS week ending 15 SEPTEMBER 2017

Observation of the Doubly Charmed Baryon Ξ_{cc}^{++}

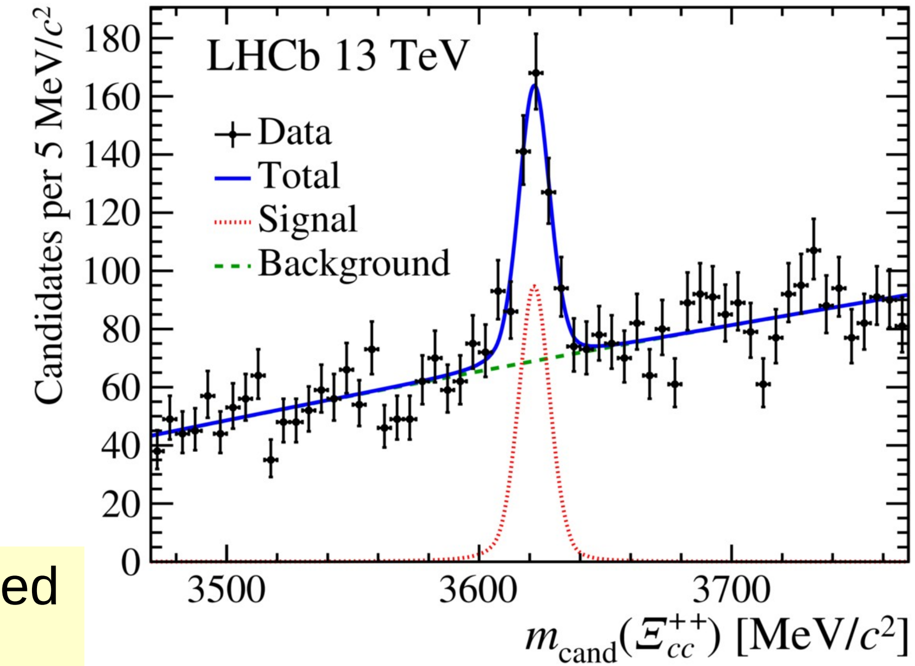
R. Aaij *et al.**

(LHCb Collaboration)

(Received 6 July 2017; revised manuscript received 2 August 2017; published 11 September 2017)

A highly significant structure is observed in the $\Lambda_c^+ K^- \pi^+ \pi^+$ mass spectrum, where the Λ_c^+ baryon is reconstructed in the decay mode $pK^-\pi^+$. The structure is consistent with originating from a weakly decaying particle, identified as the doubly charmed baryon Ξ_{cc}^{++}. The difference between the masses of the Ξ_{cc}^{++} and Λ_c^+ states is measured to be $1334.94 \pm 0.72(\mathrm{stat.}) \pm 0.27(\mathrm{syst.})\ \mathrm{MeV}/c^2$, and the Ξ_{cc}^{++} mass is then determined to be $3621.40 \pm 0.72(\mathrm{stat.}) \pm 0.27(\mathrm{syst.}) \pm 0.14(\Lambda_c^+)\ \mathrm{MeV}/c^2$, where the last uncertainty is due to the limited knowledge of the Λ_c^+ mass. The state is observed in a sample of proton-proton collision data collected by the LHCb experiment at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of $1.7\ \mathrm{fb}^{-1}$, and confirmed in an additional sample of data collected at 8 TeV.

DOI: 10.1103/PhysRevLett.119.112001



First doubly heavy hadron (unarguably) observed

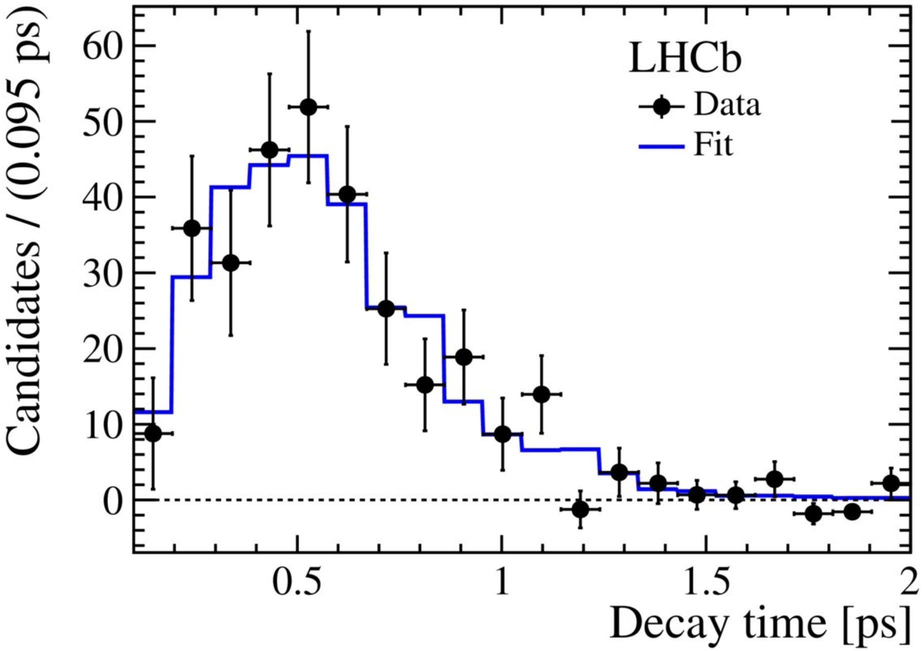
Discovery channel: $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^-$

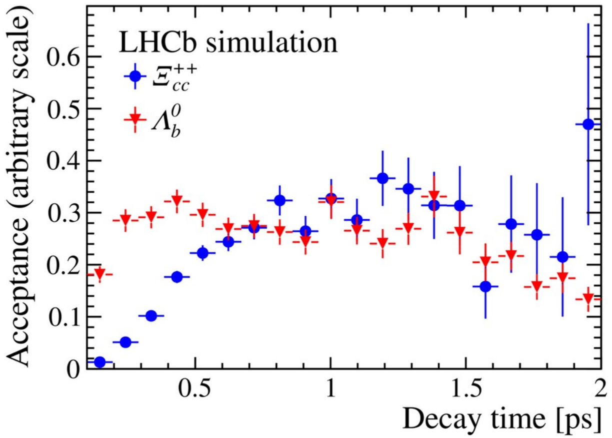
Subsequently seen also in $\Xi_c^{(\prime)+}\pi^+$ decays

First (so far only) weakly decaying hadron discovered at LHC

Lifetime measurement

PRL 121 (2018) 052002





$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^-$ channel

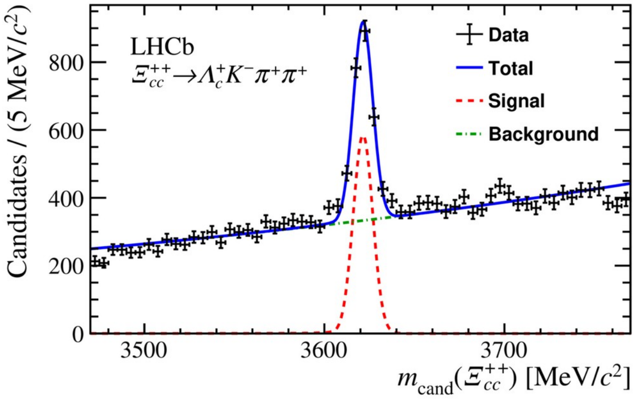
Non-trivial decay-time acceptance

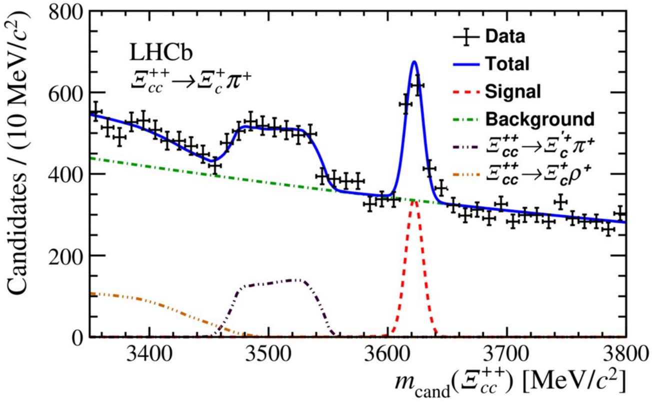
- use $\Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^+ \pi^-$ as control channel

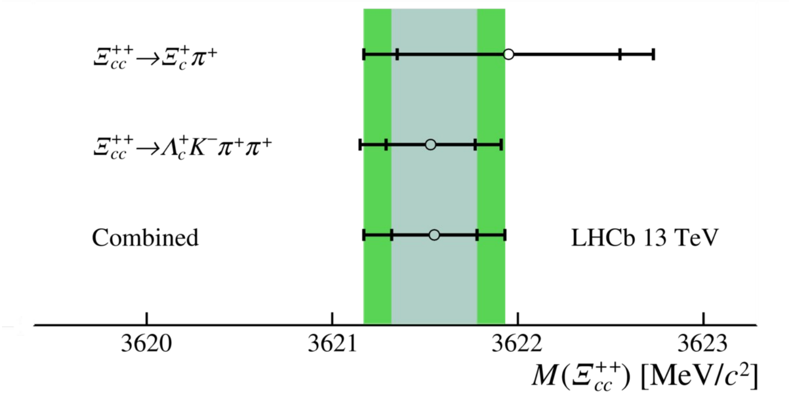
$\tau(\Xi_{cc}^{++}) = 0.256\ ^{+0.024}_{-0.022}\ \text{(stat)} \pm 0.014\ \text{(syst) ps}$

Mass measurement & production rate

JHEP 02 (2020) 049
CP C44 (2020) 022001







$$\frac{\sigma(\Xi_{cc}^{++}) \times \mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+)}{\sigma(\Lambda_c^+)}$$

$$= (2.22 \pm 0.27 \pm 0.29) \times 10^{-4}$$

- in LHCb acceptance:
  $4 < p_T < 15$ GeV/c & $2.0 < y < 4.5$
- for pp collisions at $\sqrt{s} = 13$ TeV
- assuming central value of $\tau(\Xi_{cc}^{++})$

Both $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^-$ and $\Xi_c^+ \pi^+$ channels

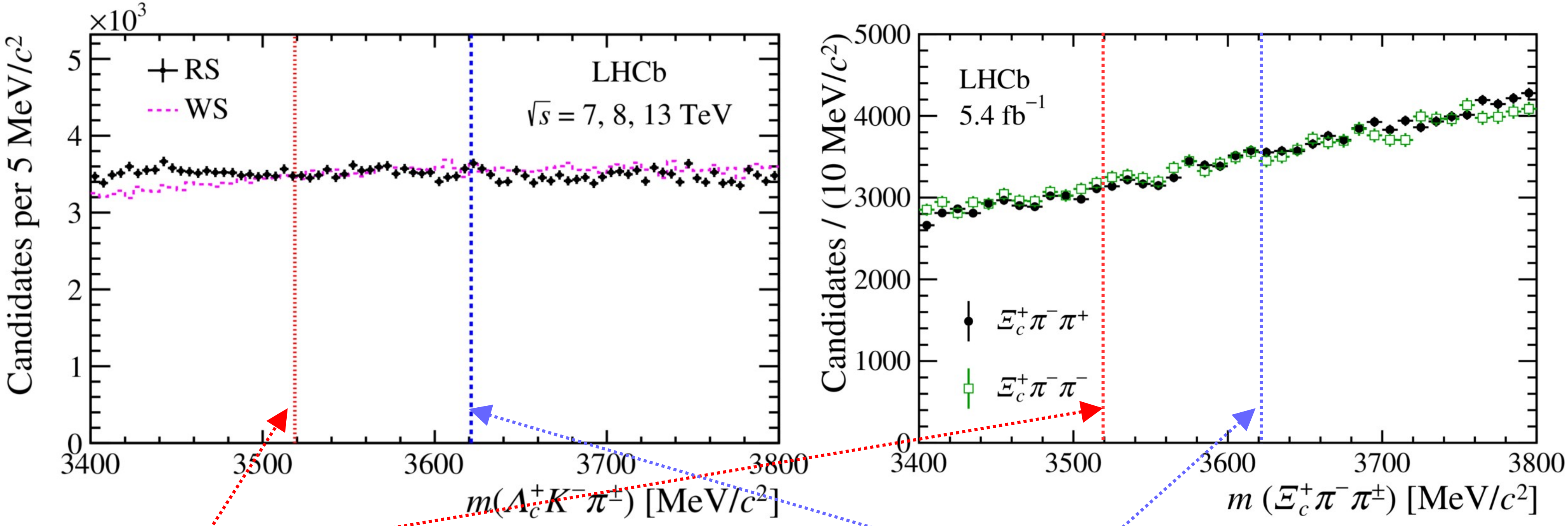
$m(\Xi_{cc}^{++}) = 3621.55 \pm 0.23$ (stat) $\pm$ 0.30 (syst) MeV/c^2

Largest systematic uncertainties from

- momentum scale
- Λ_c^+ and Ξ_c^+ masses

Searches for Ξ_{cc}^{+}

SCPMA 63 (2020) 221062
JHEP 12 (2021) 107

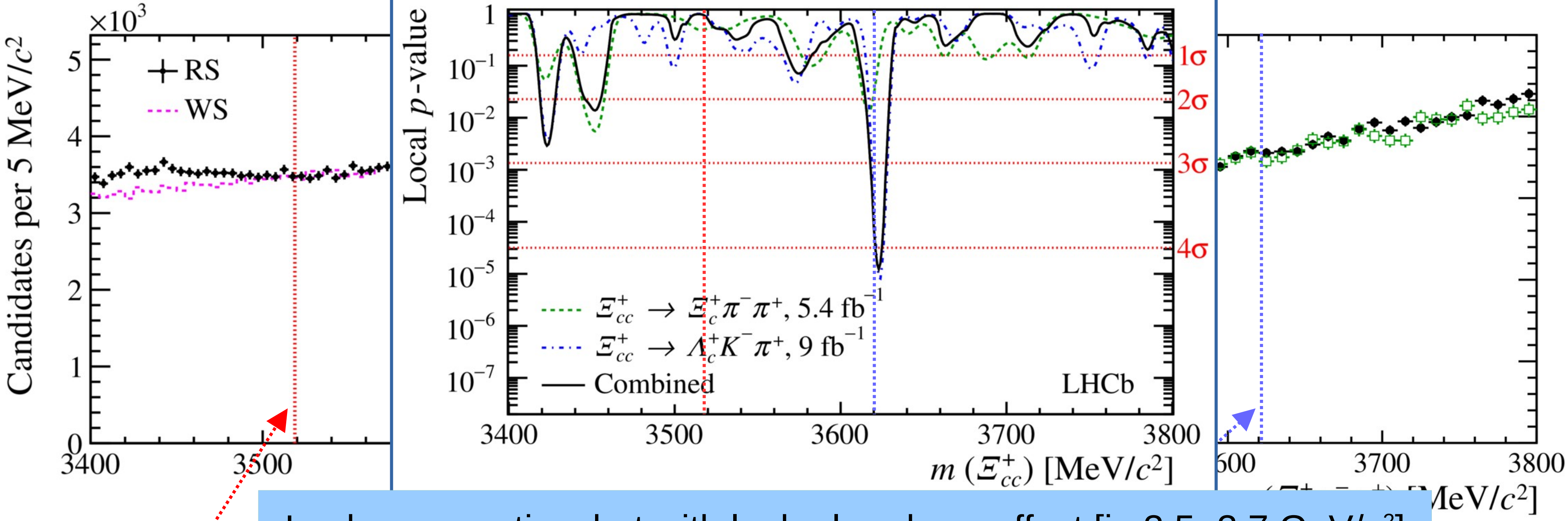


Mass of SELEX claim

Mass of Ξ_{cc}^{++}

Searches for Ξ_{cc}^{+}

SCPMA 63 (2020) 221062
JHEP 12 (2021) 107

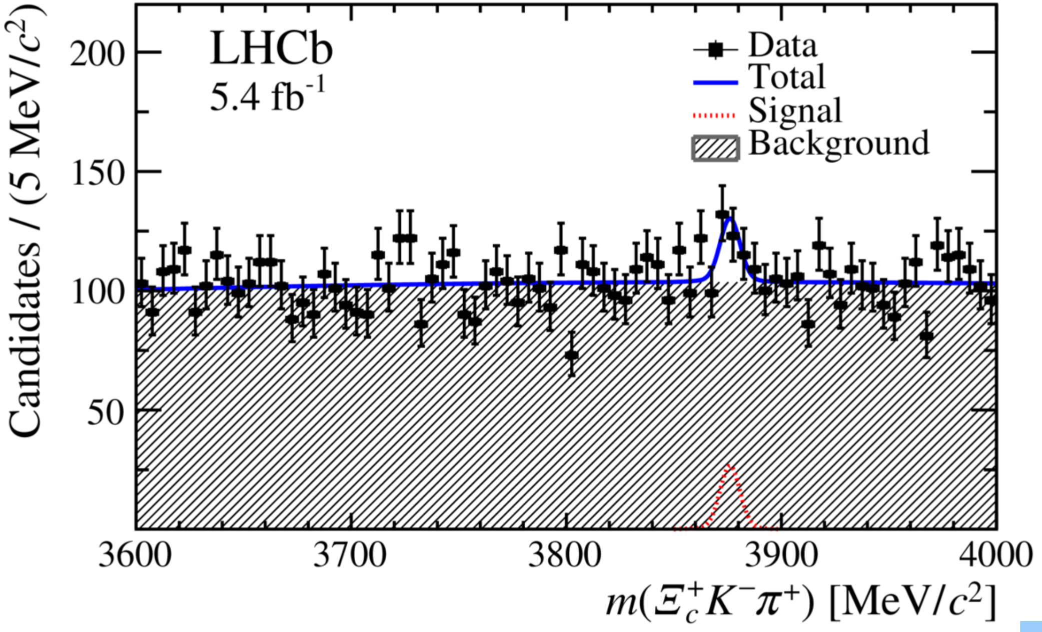


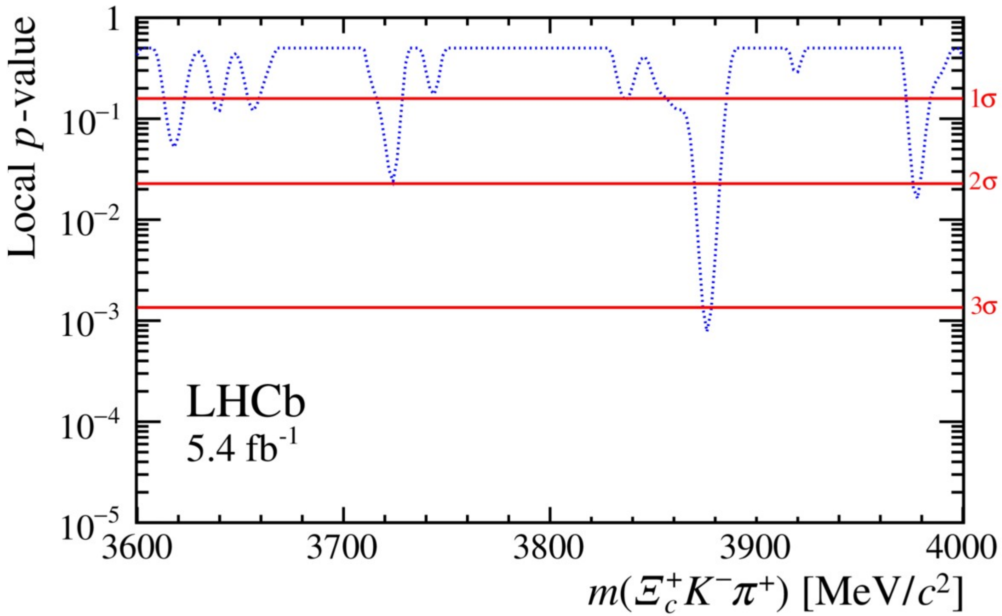
Mass of SE

Looks suggestive, but with look-elsewhere-effect [in 3.5−3.7 GeV/c^2] global significance is 2.9 σ

Search for Ω_{cc}^{+}

SCPMA 64 (2021) 101062





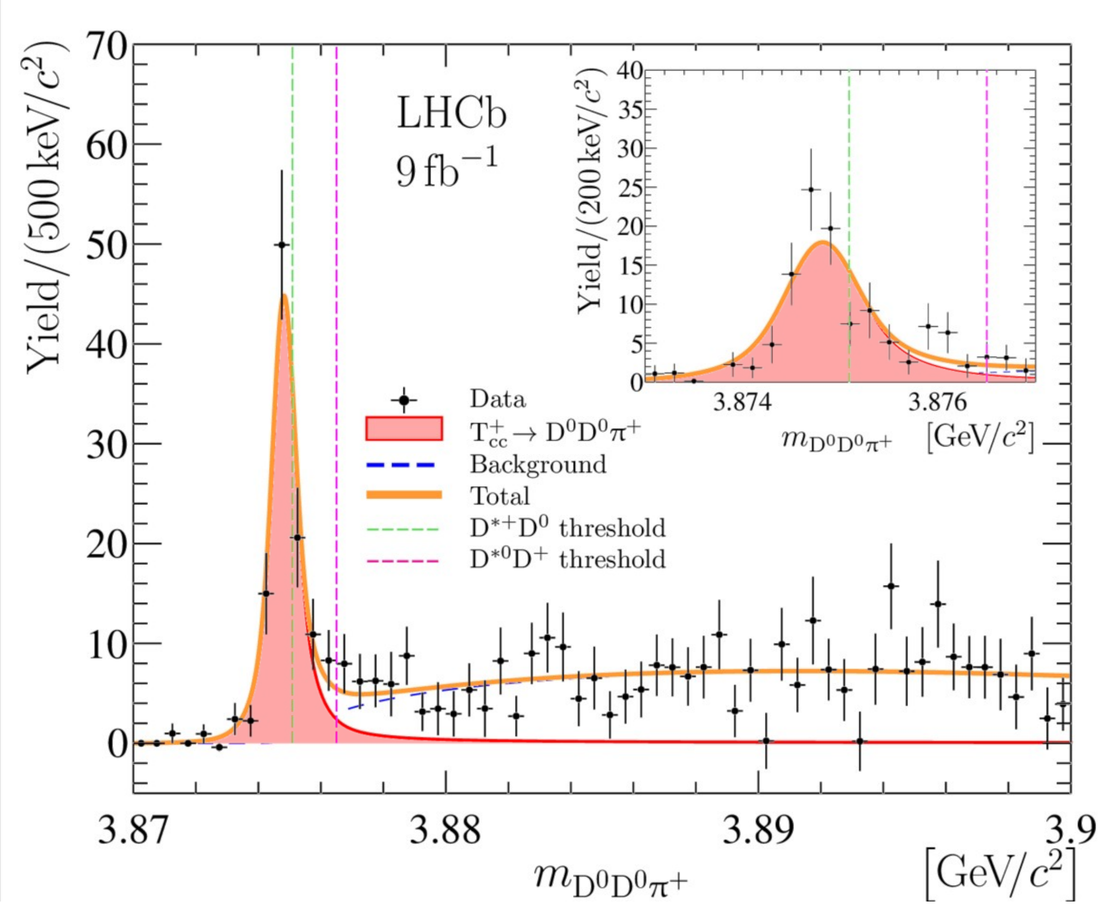
With look-elsewhere-effect [in 3.6−4.0 GeV/c^2]
global significance is 1.8 σ

Double charm baryons : open questions

- Discover partner states and measure their properties
  - More data, but also better vertexing capability important to improve sensitivity
    - Capability to separate decay position from production vertex crucial to reject potentially overwhelming background
- Can we study the spectrum of excited states?
- Can we observe other doubly heavy hadrons?
  - Main focus on Ξ_{bc}
  - Ξ_{cc}^{++} could become a tool to discover heavier multiquark states
    - Similarly for T_{cc}^{+} ...

Double charm tetraquark T_{cc}^+

Nature Phys. 18 (2022) 751
Nature Comm. 13 (2022) 3351



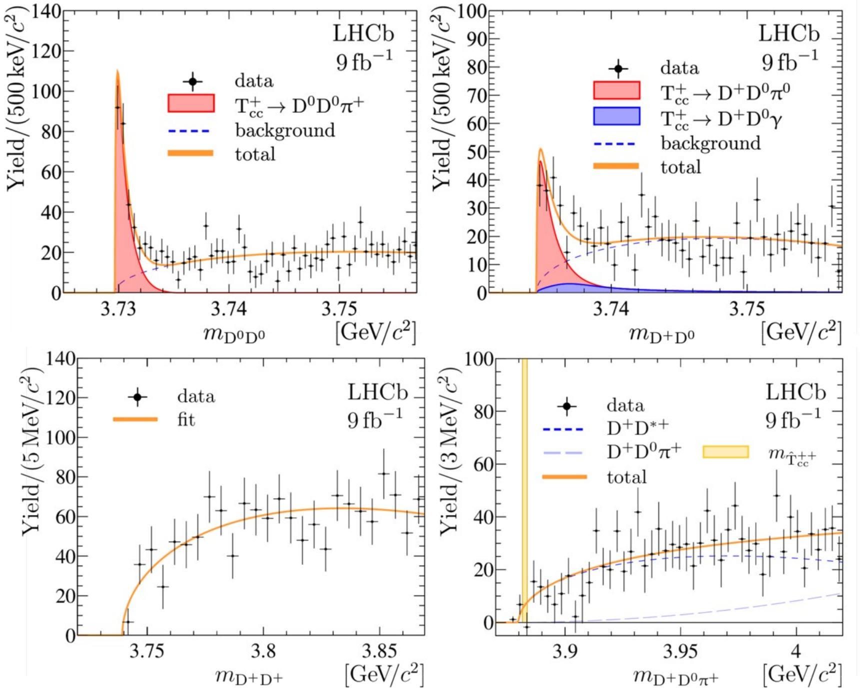
Clear and narrow peak just above threshold in $m(D^0D^0\pi^+)$

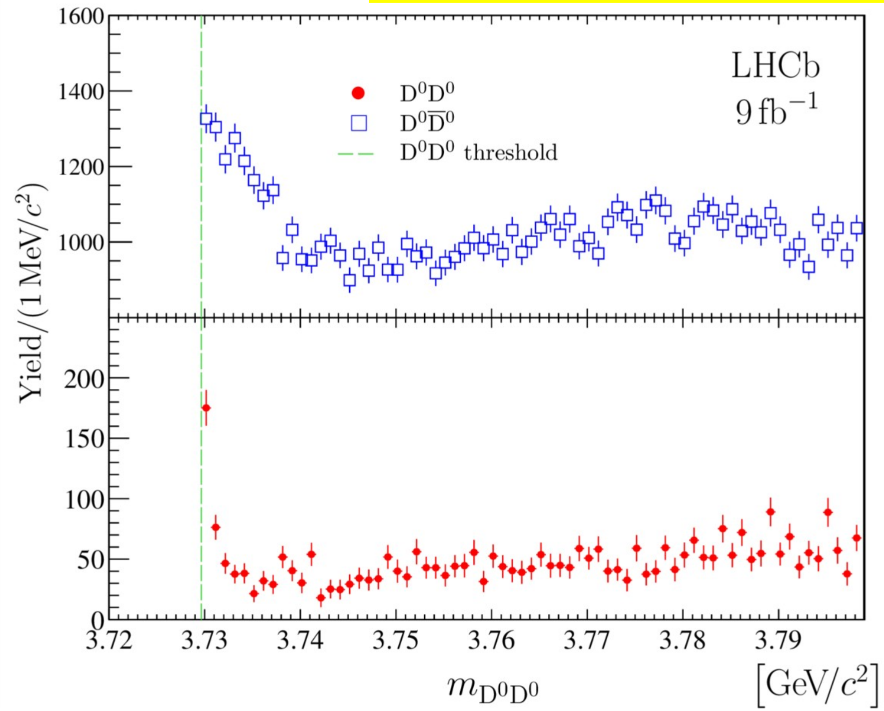
Below D^0D^{*0} threshold

Study of lineshape (similar methodology to $\chi_{c1}(3872)$ study)

Double charm tetraquark T_{cc}^+

Nature Phys. 18 (2022) 751
Nature Comm. 13 (2022) 3351





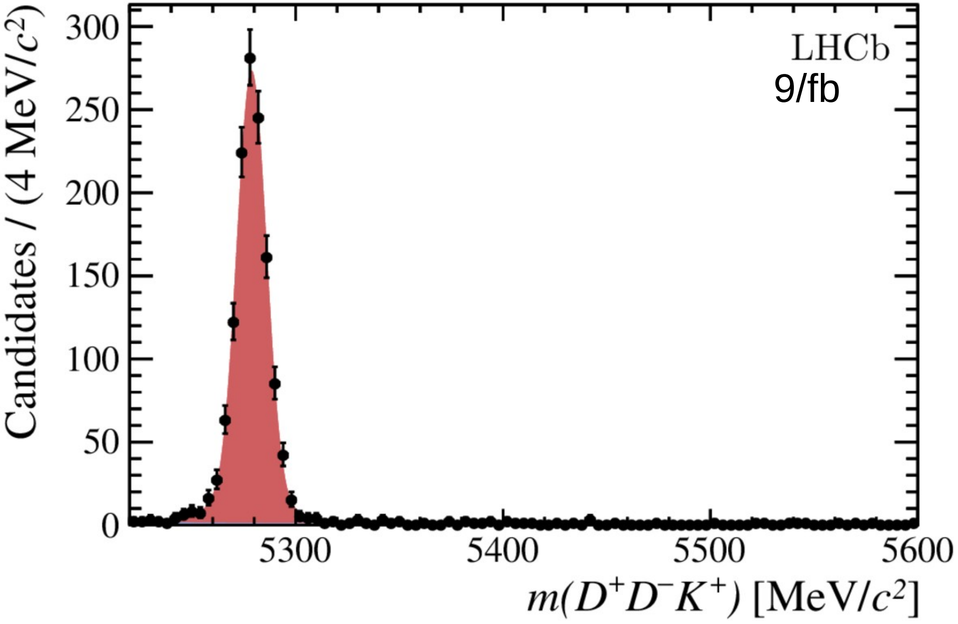
Partially reconstructed decays in different DD, DDπ and $D\overline{D}$ final states
Consistent with isosinglet expectation

T_{cc} : open questions

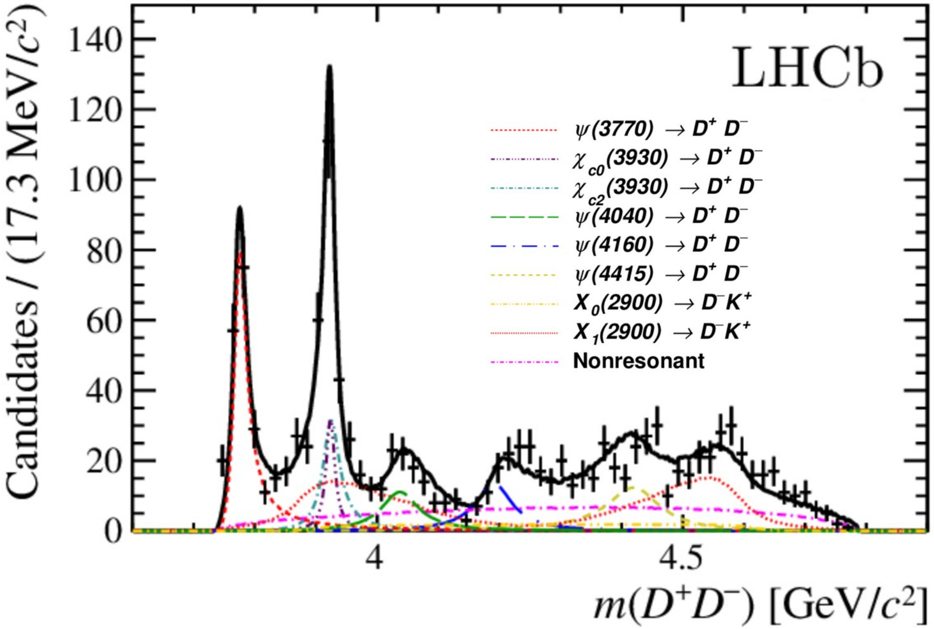
- T_{cc}^{+} observed just above threshold for strong decay
  - Does it imply T_{bc} and T_{bb} are below threshold, and hence weakly decaying?
  - How can we observe these states?
- Properties of production and decay to be studied in detail
  - Narrow width should help theoretical interpretation and understanding of binding mechanism
- Can we study the spectrum of excited states?
  - Is assumption that observed T_{cc}^{+} is a ground-state justified?

Exotic structures in $B^+ \to D^+D^-K^+$

PR D102 (2020) 112003



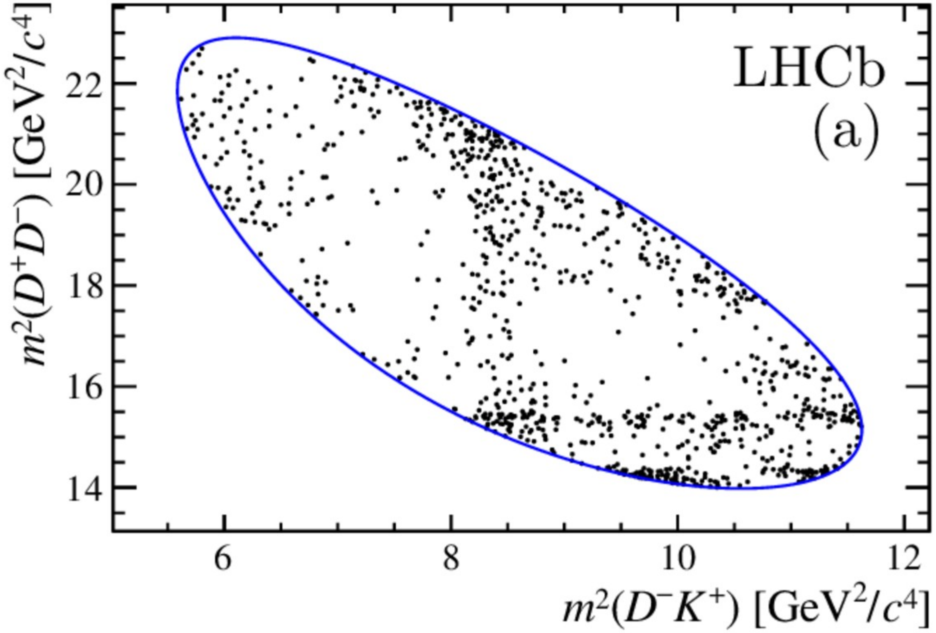
Signal yield of 1303 ± 37
(highly pure as optimised for amplitude analysis)



Expected to provide clean environment to study $c\bar{c} \to D^+D^-$ but need exotic contributions

Exotic structures in $B^+ \to D^+D^-K^+$

PR D102 (2020) 112003



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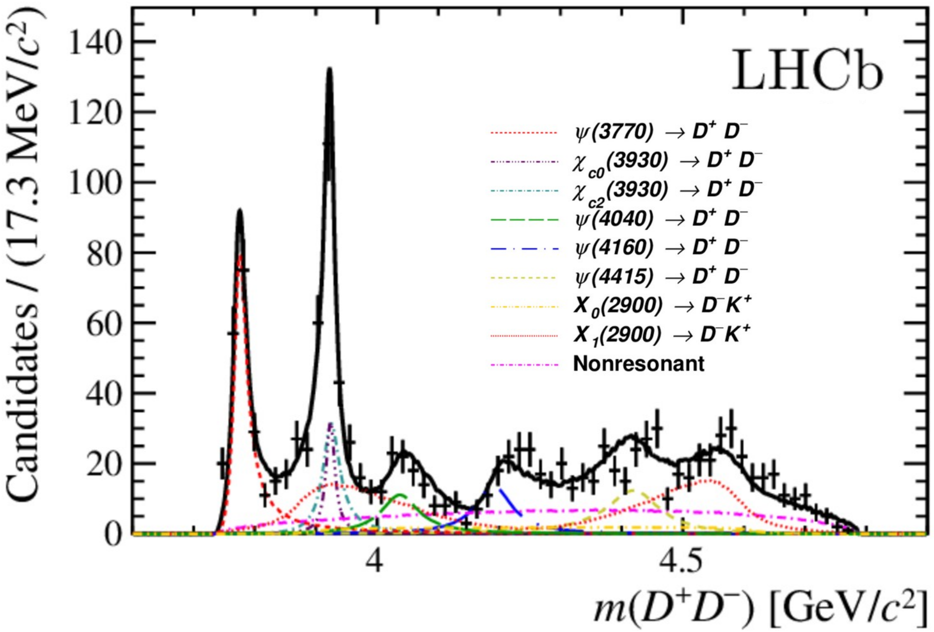

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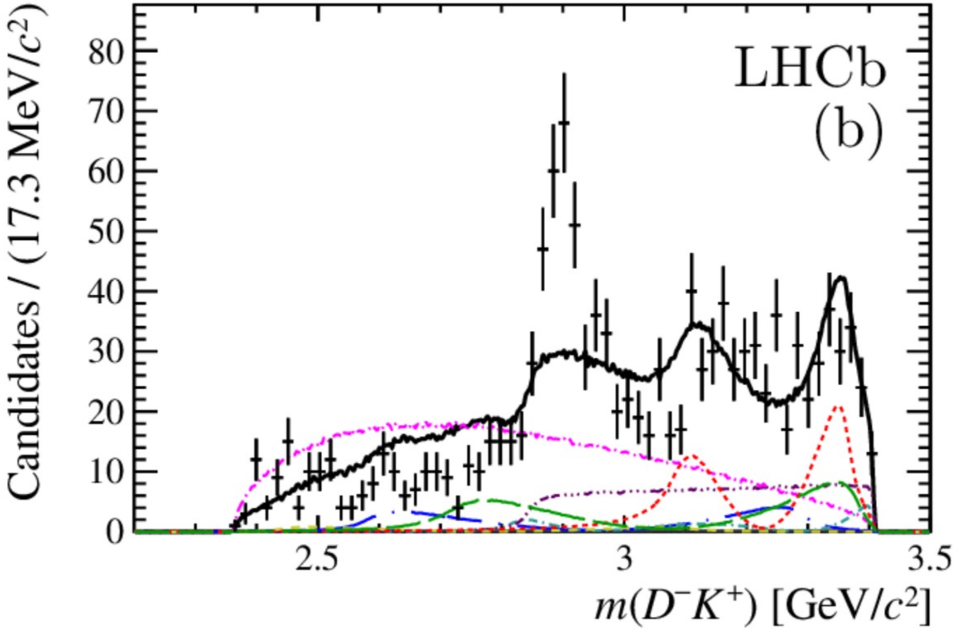
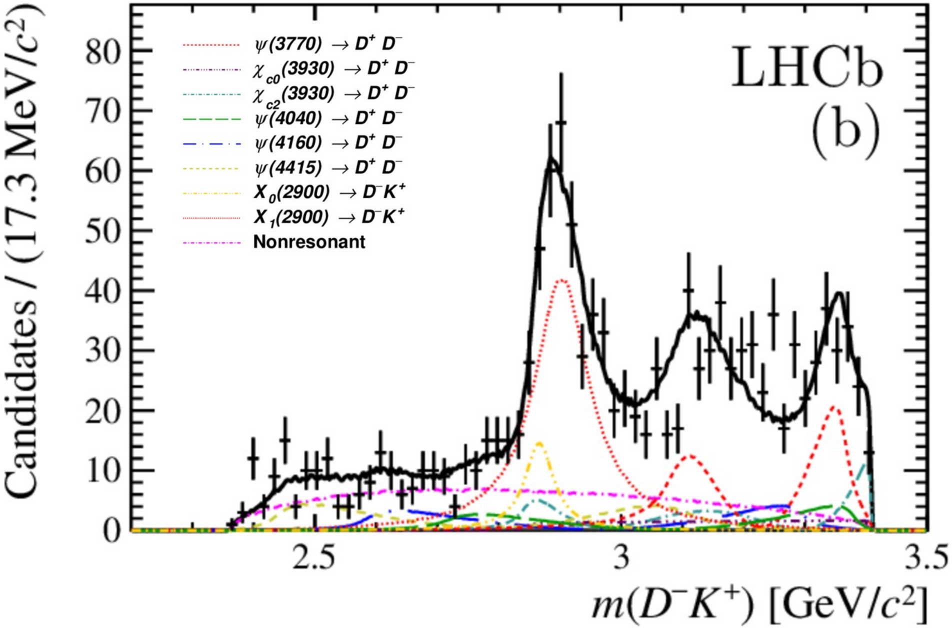
Exotic structures in $B^+ \to D^+D^-K^+$

PR D102 (2020) 112003



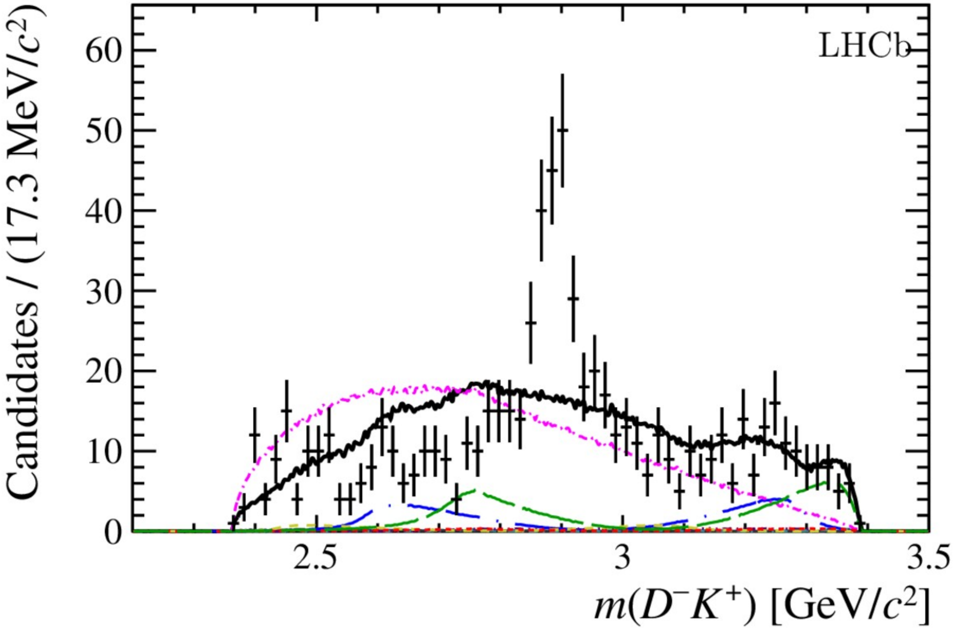


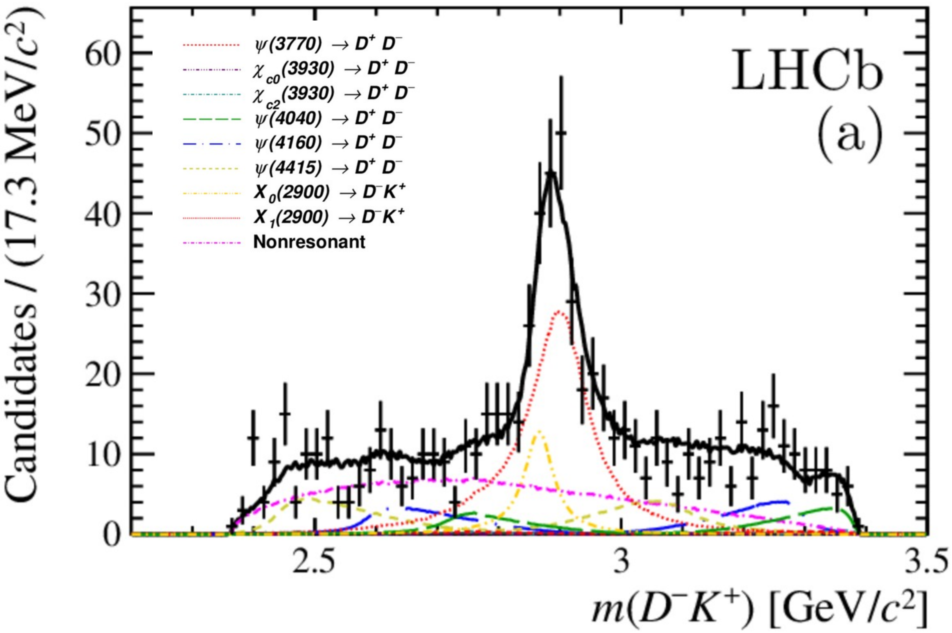
Need two T_{cs}(2900) states (spin-0 and spin-1) to fit the data
First exotic states with open charm

Exotic structures in $B^+ \to D^+ D^- K^+$

With additional cut to remove $c\bar{c}$ reflections

PR D102 (2020) 112003

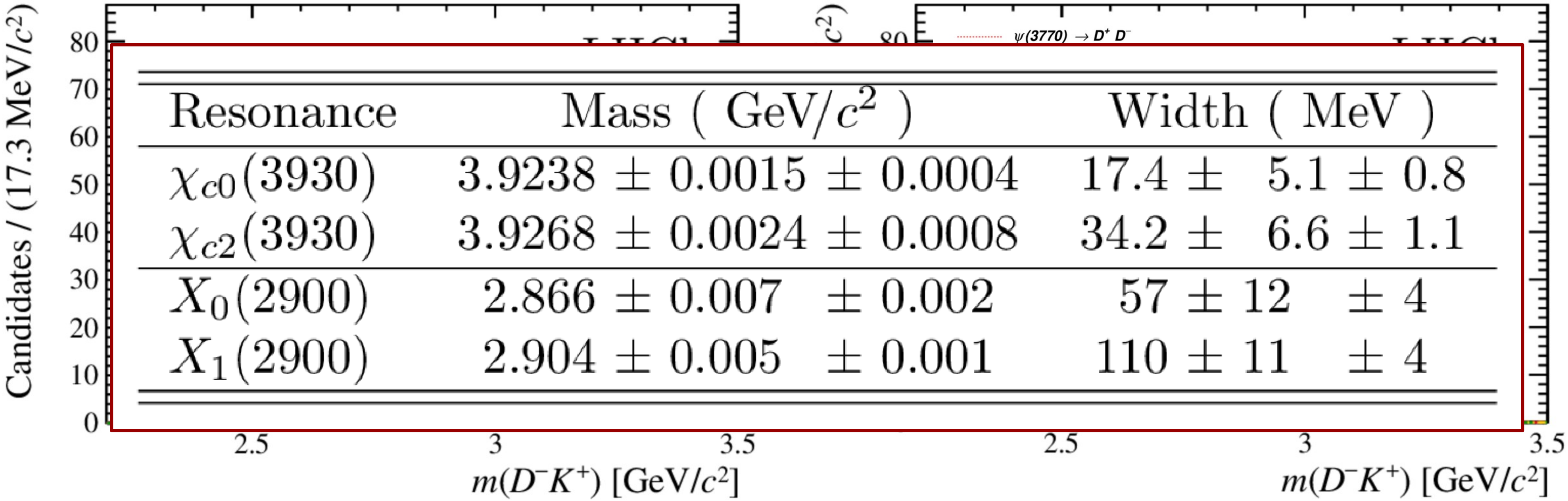




Need two $T_{cs}(2900)$ states (spin-0 and spin-1) to fit the data

Exotic structures in $B^+ \rightarrow D^+ D^- K^+$

PR D102 (2020) 112003

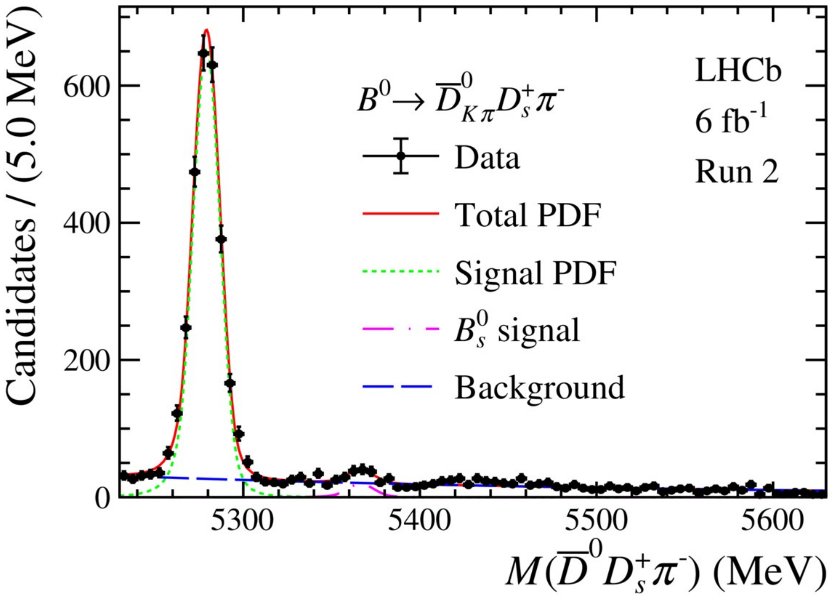


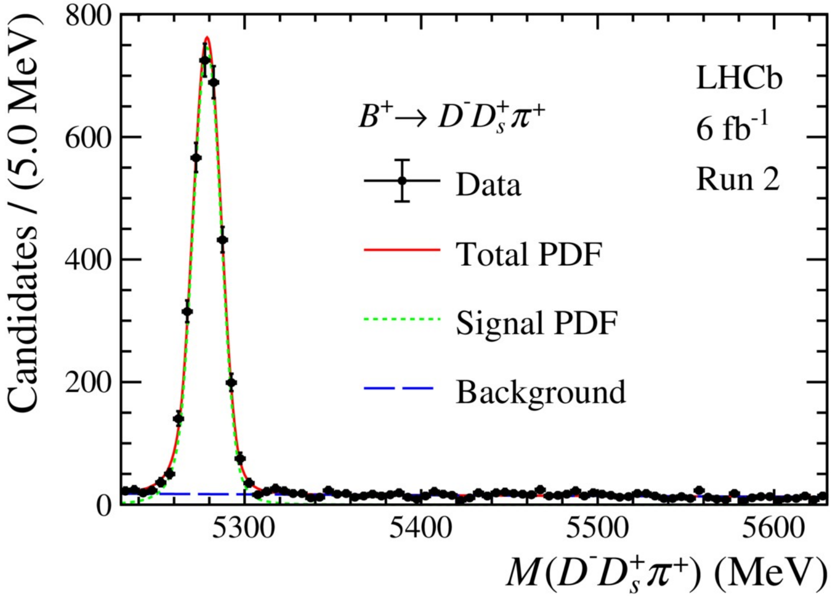
Resonance	Mass (GeV/c^2)	Width (MeV)
$\chi_{c0}(3930)$	$3.9238 \pm 0.0015 \pm 0.0004$	$17.4 \pm 5.1 \pm 0.8$
$\chi_{c2}(3930)$	$3.9268 \pm 0.0024 \pm 0.0008$	$34.2 \pm 6.6 \pm 1.1$
$X_0(2900)$	$2.866 \pm 0.007 \pm 0.002$	$57 \pm 12 \pm 4$
$X_1(2900)$	$2.904 \pm 0.005 \pm 0.001$	$110 \pm 11 \pm 4$

Need two T_{cs}(2900) states (spin-0 and spin-1) to fit the data
Masses close to DK* threshold

Exotic structures in B → $D_s^+\pi\bar{D}$ decays

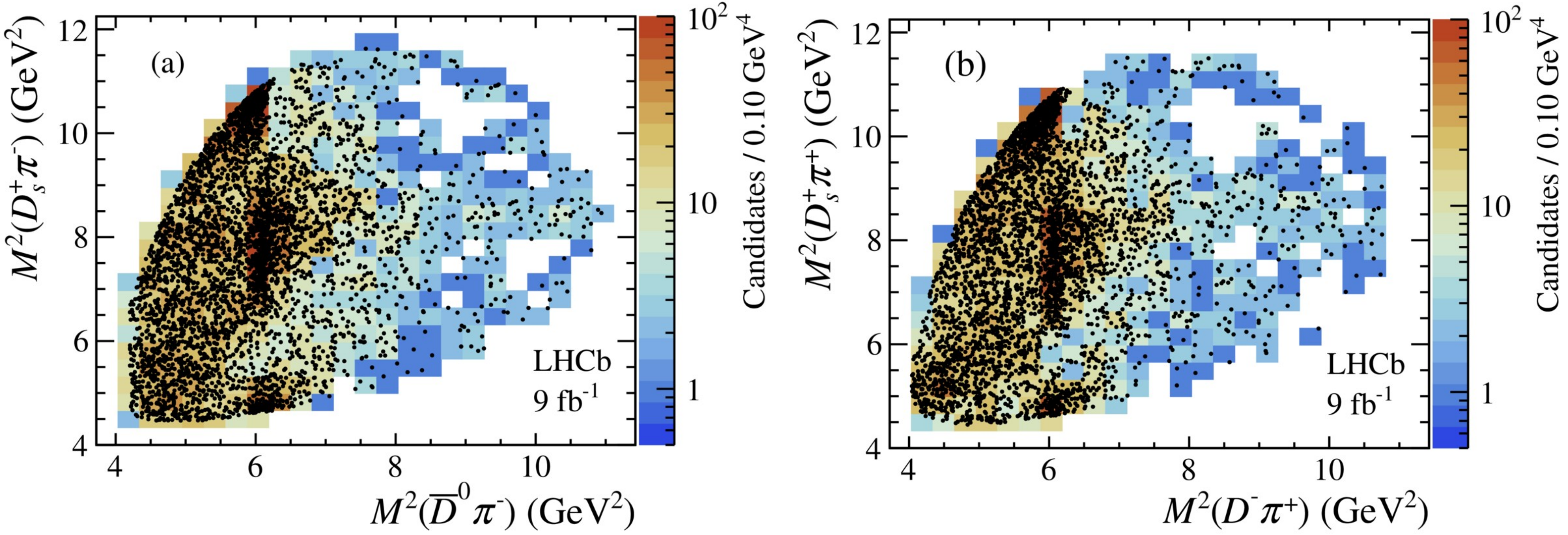
PRL 131 (2023) 041902





Exotic structures in B → $D_s^+\pi\overline{D}$ decays

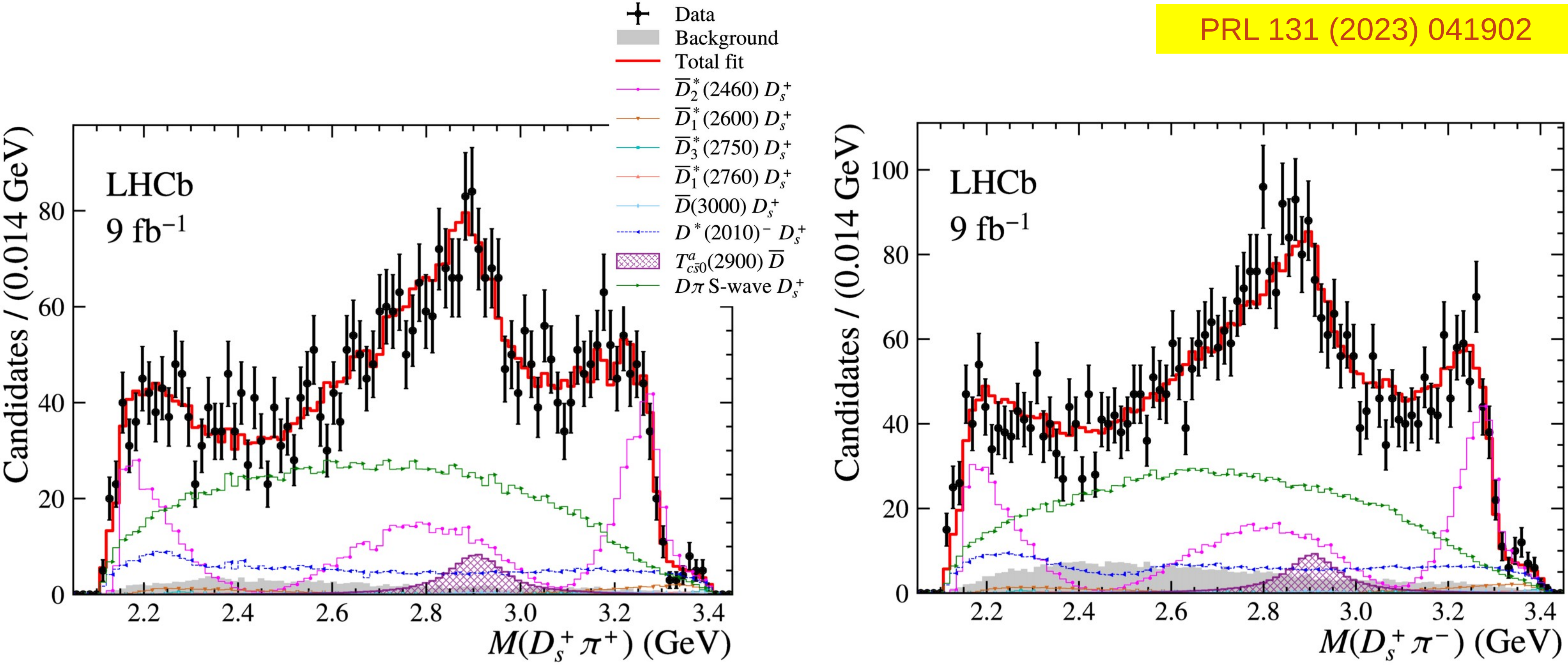
PRL 131 (2023) 041902



Decays related by isospin and similar structures seen
Motivates simultaneous amplitude analysis to both decays

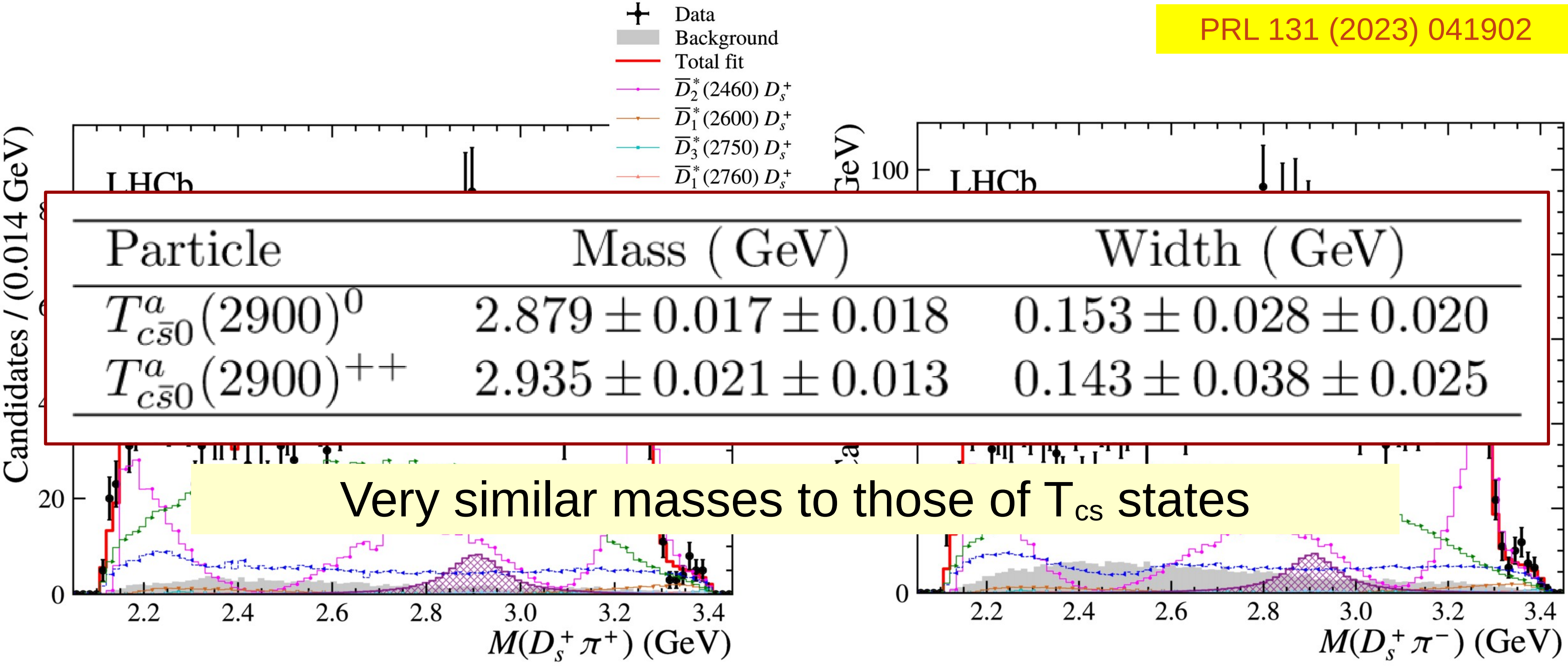
Exotic structures in B → $D_s^+\pi\overline{D}$ decays

PRL 131 (2023) 041902



Exotic structures in B → $D_s^+\pi\bar{D}$ decays

PRL 131 (2023) 041902



Particle	Mass (GeV)	Width (GeV)
$T^a_{c\bar{s}0}(2900)^0$	$2.879 \pm 0.017 \pm 0.018$	$0.153 \pm 0.028 \pm 0.020$
$T^a_{c\bar{s}0}(2900)^{++}$	$2.935 \pm 0.021 \pm 0.013$	$0.143 \pm 0.038 \pm 0.025$

Very similar masses to those of T_{cs} states

To the future, and beyond!

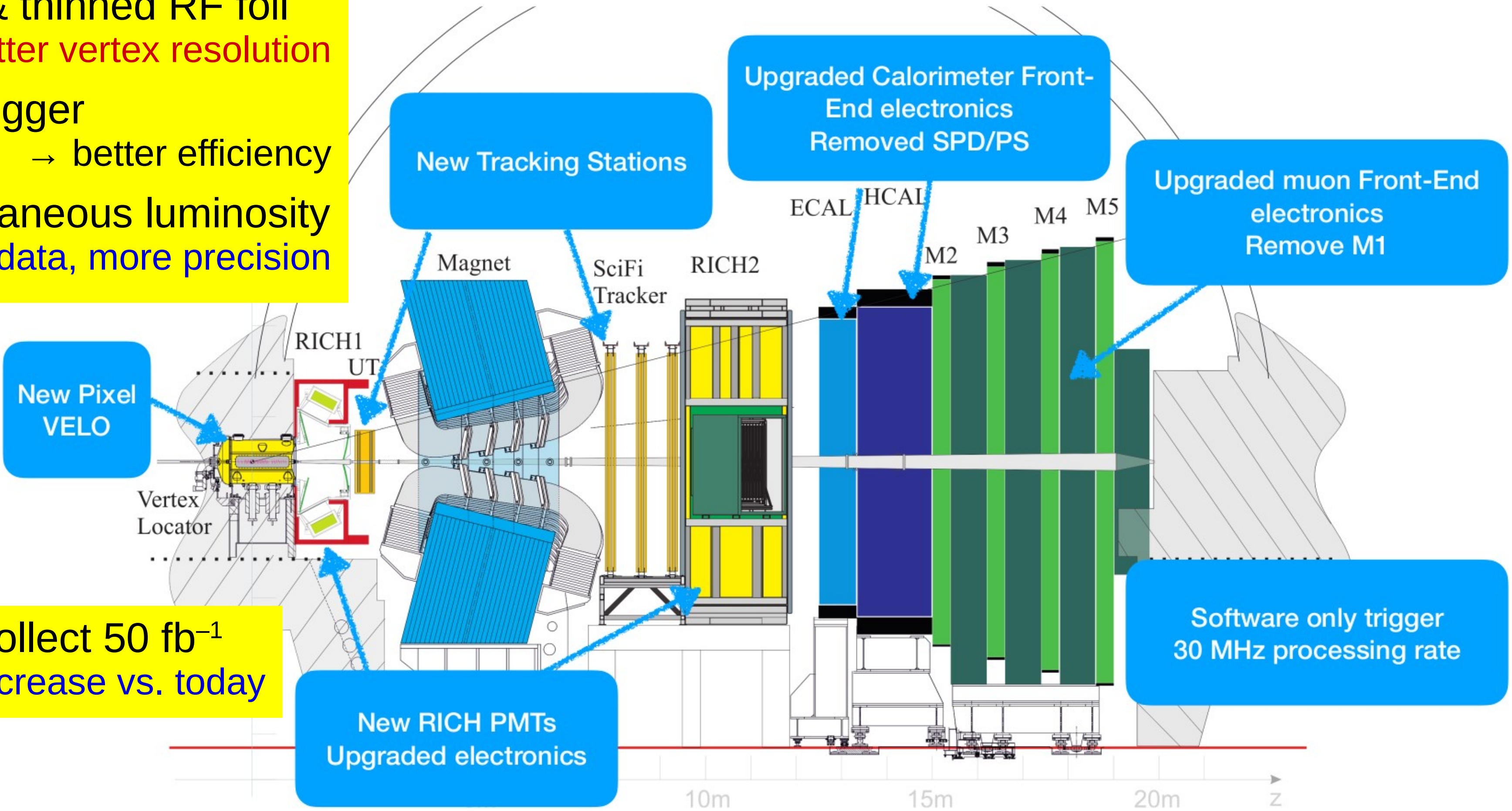
- More yet to be learned from the Run 1+2 data sample
- But fundamental limits due to sample size and detector performance
  - improve both in Runs 3 (2022-25) & 4 (2029-32)
  - reasons to be optimistic for further discovery of multiquark states
- No reason to think that should be the end of the road
  - ambitious plans for LHCb Upgrade 2
  - aim for the ultimate LHC flavour experiment
  - reasons to be optimistic for even more discoveries of multiquark states

LHCb Upgrade I

VELO pixels & thinned RF foil
→ better vertex resolution

All software trigger
→ better efficiency

Higher instantaneous luminosity
→ more data, more precision



New Pixel VELO

New Tracking Stations

Upgraded Calorimeter Front-End electronics
Removed SPD/PS

Upgraded muon Front-End electronics
Remove M1

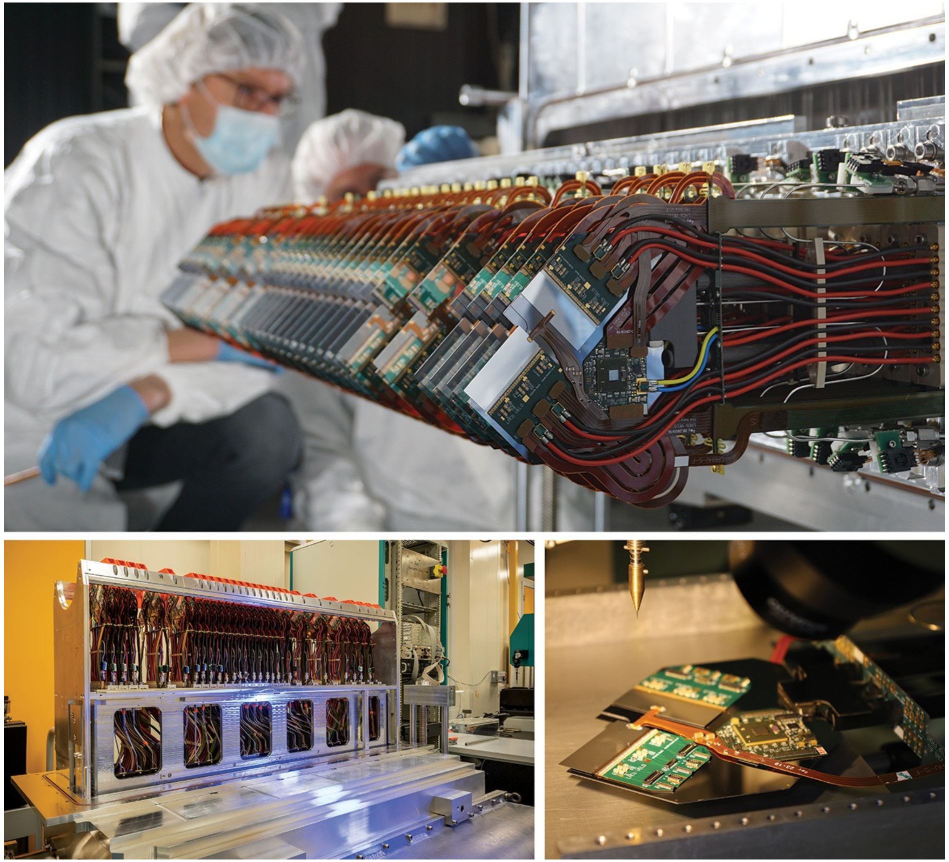
Software only trigger
30 MHz processing rate

New RICH PMTs
Upgraded electronics

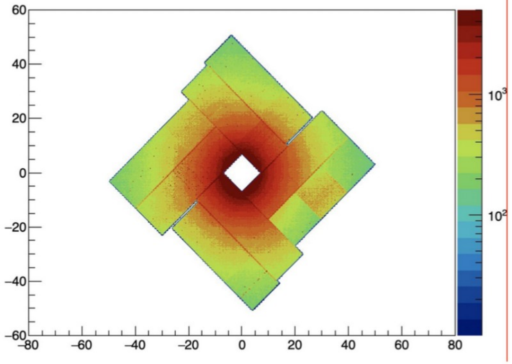
Designed to collect 50 fb^{-1}
→ ×10 data increase vs. today

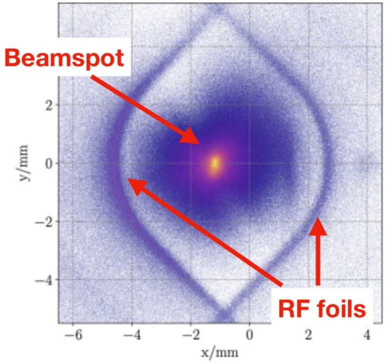
Pixel VELO

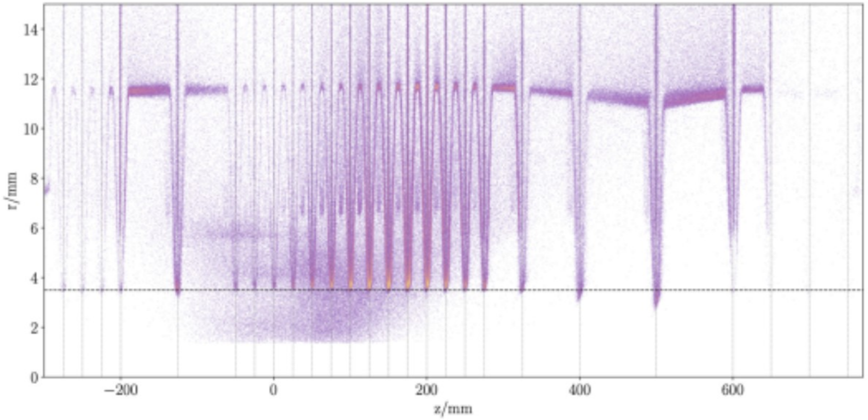
Identification of displaced vertices crucial to identify B decays at hadron colliders



Commissioning ongoing!







Data processing at 30 MHz

Traditional HEP trigger model:
 – select interesting events with loose criteria for later offline analysis

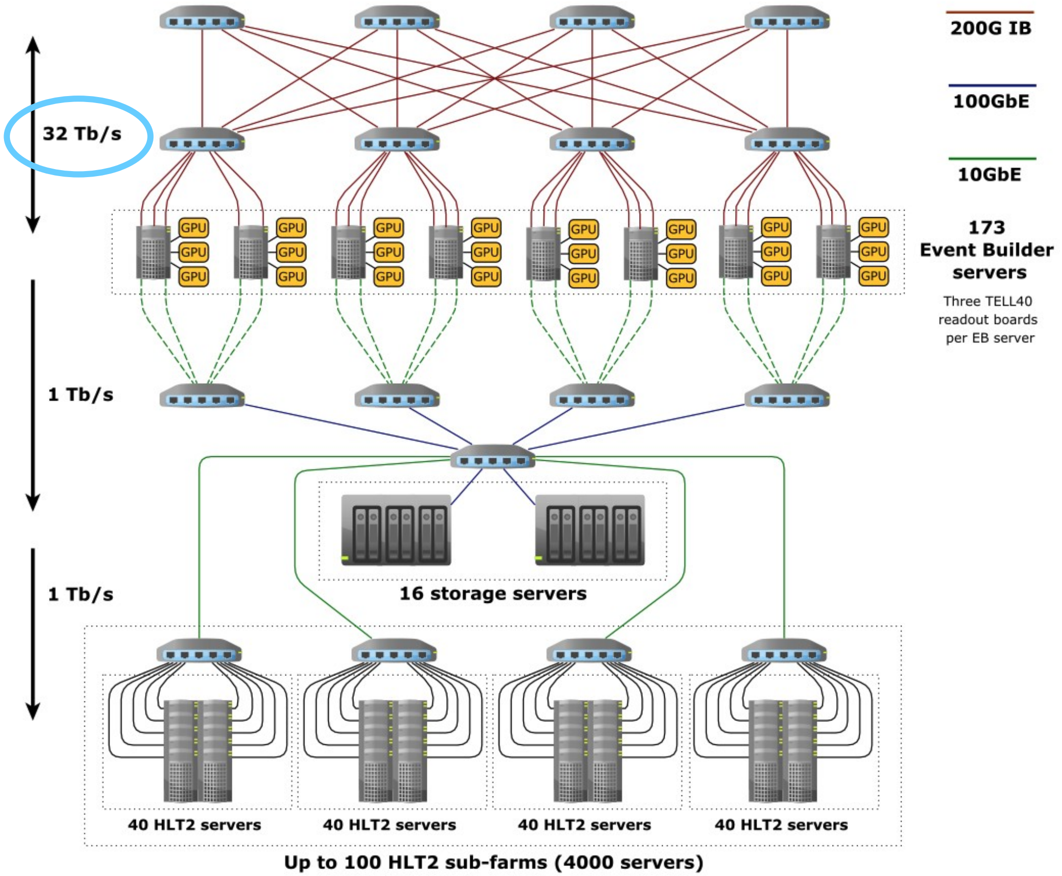
At high luminosity, every pp bunch-crossing contains a potentially interesting event

Need a new paradigm
 – full software trigger
 – first level trigger (HLT1) implemented in GPUs
 – offline quality reconstruction: calibration and alignment performed before HLT2
 – select relevant information in each event to store for offline analysis

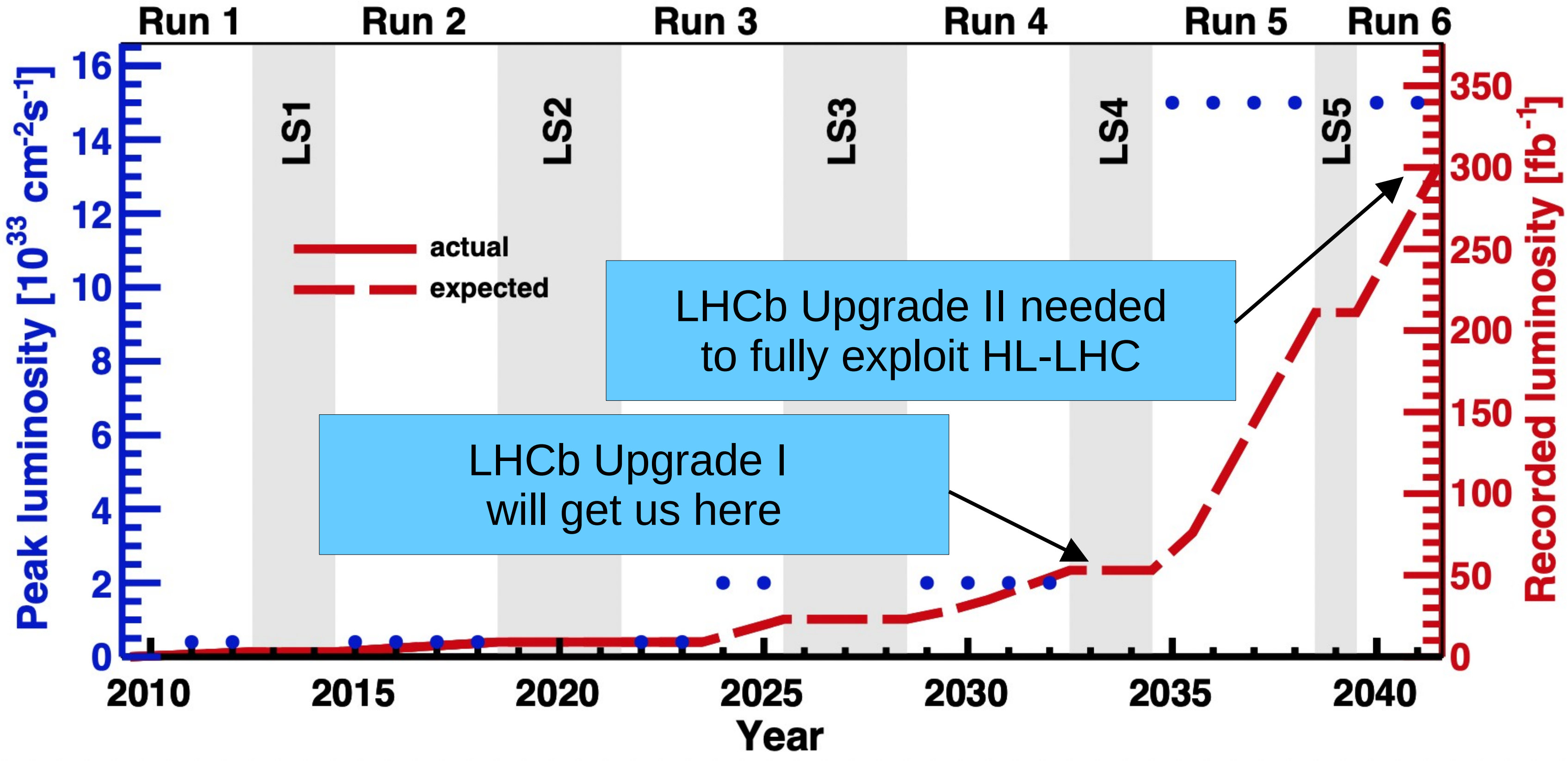
n.b:

data rate from LHCb detector (32 Tb/s)
global internet traffic 2022 (997 Tb/s)

Comput.Softw.Big Sci. 6 (2022) 1



Why stop there?



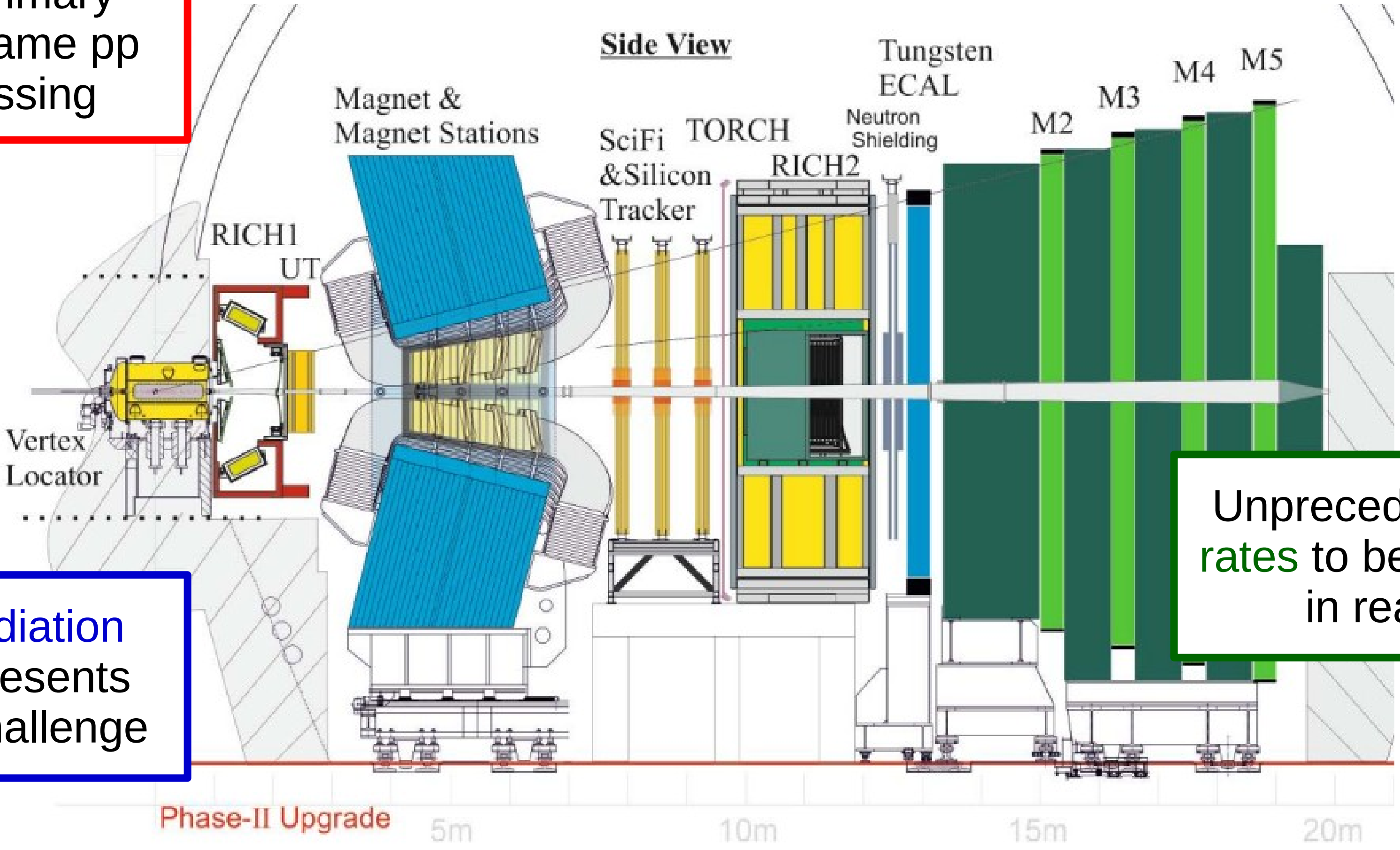
LHCb Upgrade II needed
to fully exploit HL-LHC

LHCb Upgrade I
will get us here

LHCB-TDR-023

LHCb Upgrade II

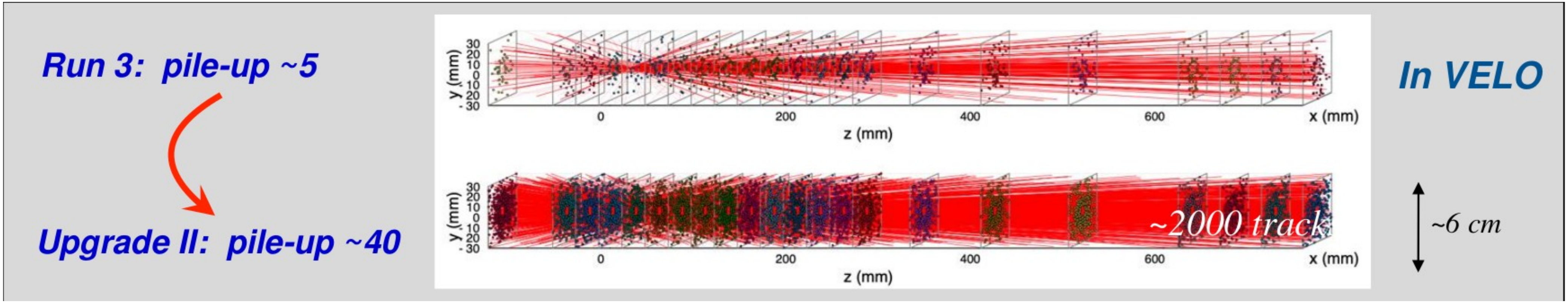
Crucial to use precision timing information to separate primary vertices in same pp bunch crossing



Need for radiation hardness presents significant challenge

Unprecedented data rates to be processed in real time

The need for timing



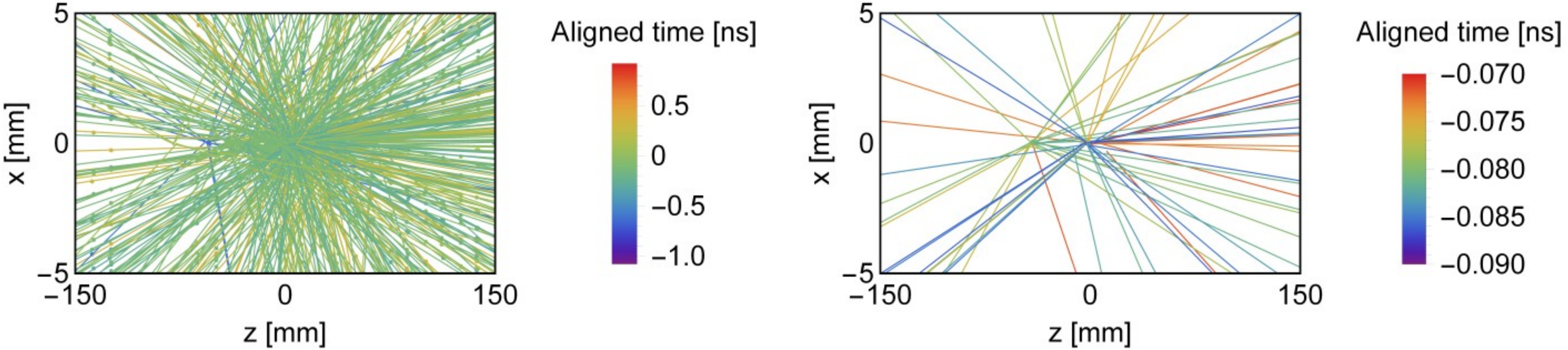
Run 3: pile-up ~5

Upgrade II: pile-up ~40

In VELO

- High LHC luminosity achieved by increasing number of pp interactions per bunch crossing
- Large detector occupancies → many possible fake combinations
- But LHC bunches are long (~50 mm); collisions in each bunch crossing occur over ~0.2 ns
- Detection with ~20 ps resolution per track gives new handle to associate hits correctly

The need for timing



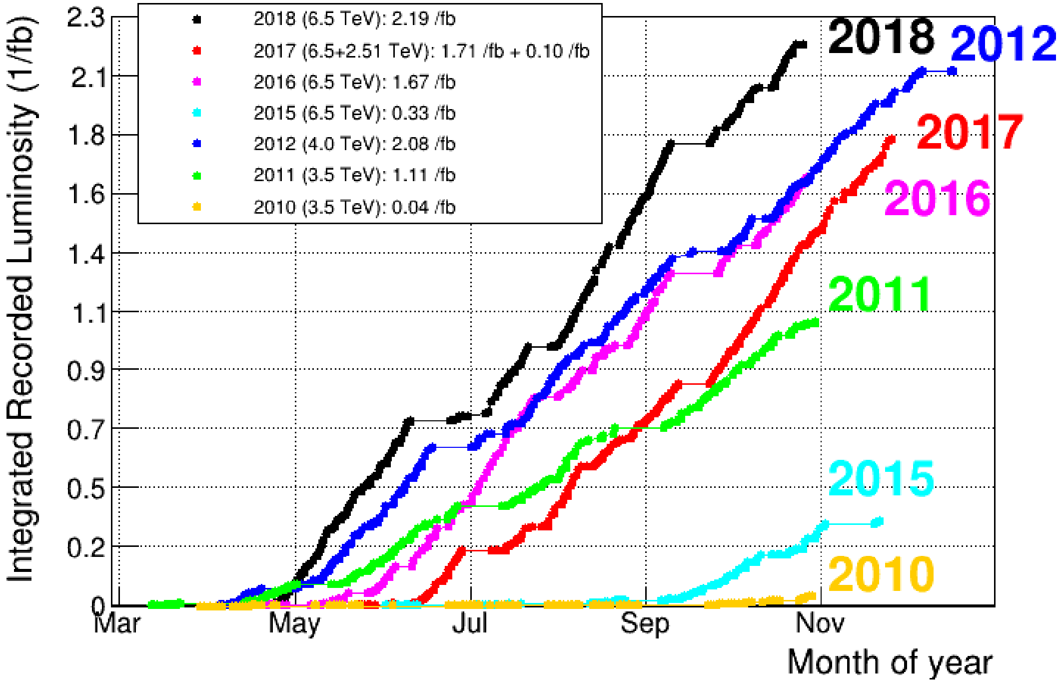
- High LHC luminosity achieved by increasing number of pp interactions per bunch crossing
- Large detector occupancies → many possible fake combinations
- But LHC bunches are long (~50 mm); collisions in each bunch crossing occur over ~0.2 ns
- Detection with ~20 ps resolution per track gives new handle to associate hits correctly

Summary

- Hard to predict what new discoveries will be coming
  - But certain that new discoveries will be coming

Back it up

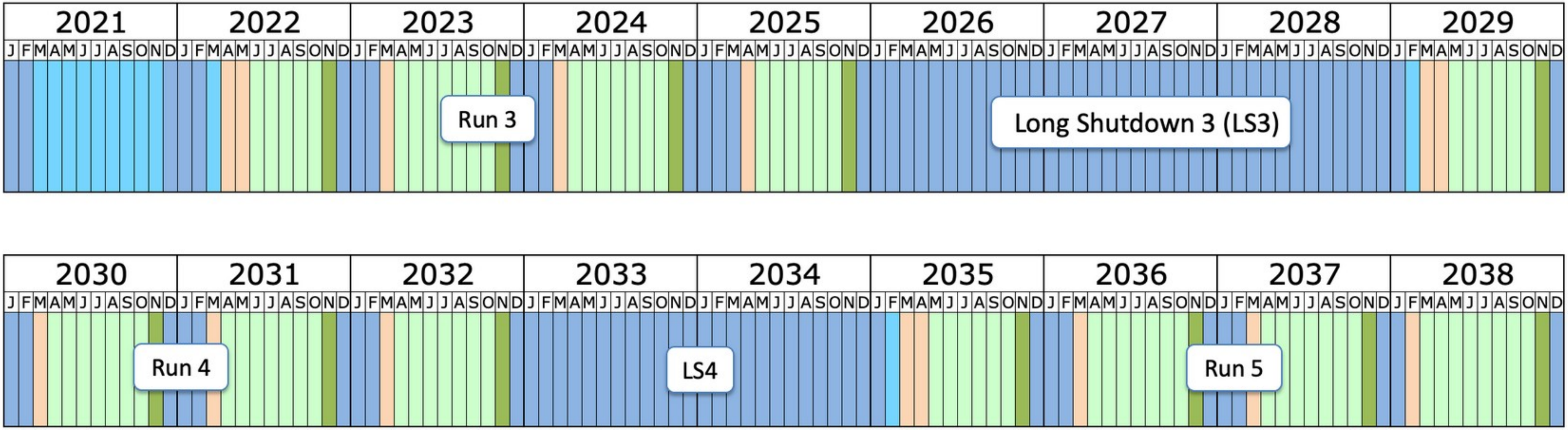
LHCb Run 1+2 integrated luminosity



Unprecedented samples of charm and beauty

Dependence of production rate on √s means (for LHCb)
2015+16 ≈ 2 x Run 1 (2011+12); 2017+18 ≈ 2 x 2011–16

HL-LHC schedule



Last updated: January 2022

to be followed by LS5 (1-2 years) and Run 6

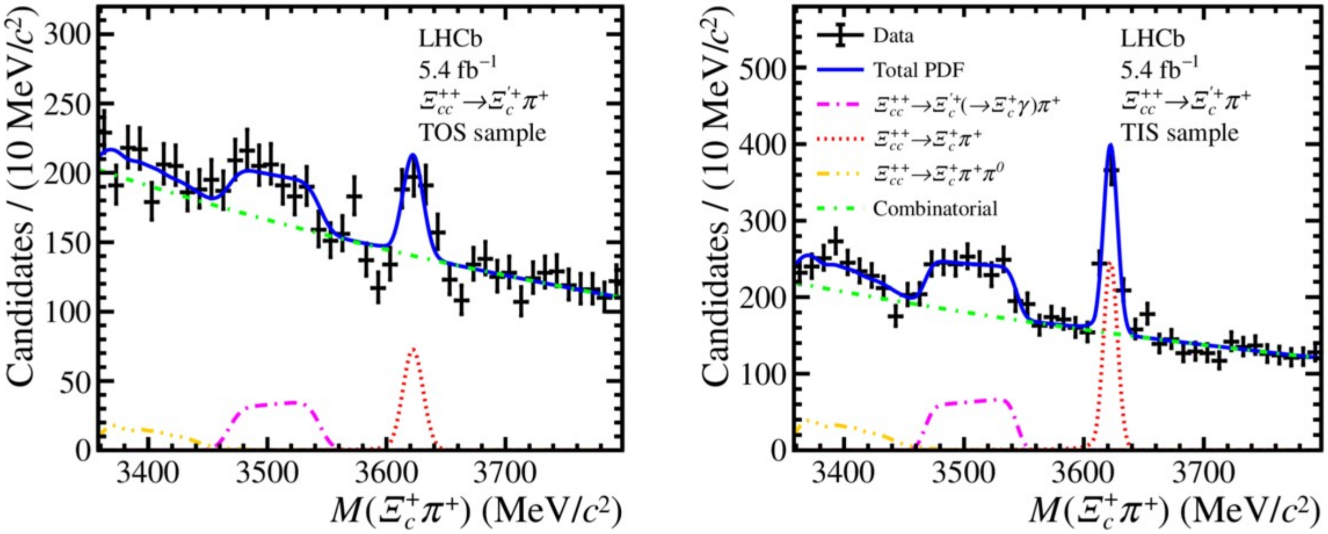
$\Xi_{cc}^{++} \to \Xi_c^{(\prime)+}\pi^+$

PRL 121 (2018) 162002
JHEP 05 (2022) 038

- $\Xi_{cc}^{++} \to \Xi_c^{\prime+}\pi^+$ appears as partially reconstructed peak in $m(\Xi_c^+\pi^+)$ spectrum
  - missing photon from $\Xi_c^{\prime+} \to \Xi_c^+\gamma$ decay
- Reconstruct $\Xi_c^+ \to pK^-\pi^+$ decay
  - Cabibbo-suppressed but good efficiency (3 tracks)

Separate hardware trigger decision samples

- on signal (TOS)
- independent of signal (TIS)



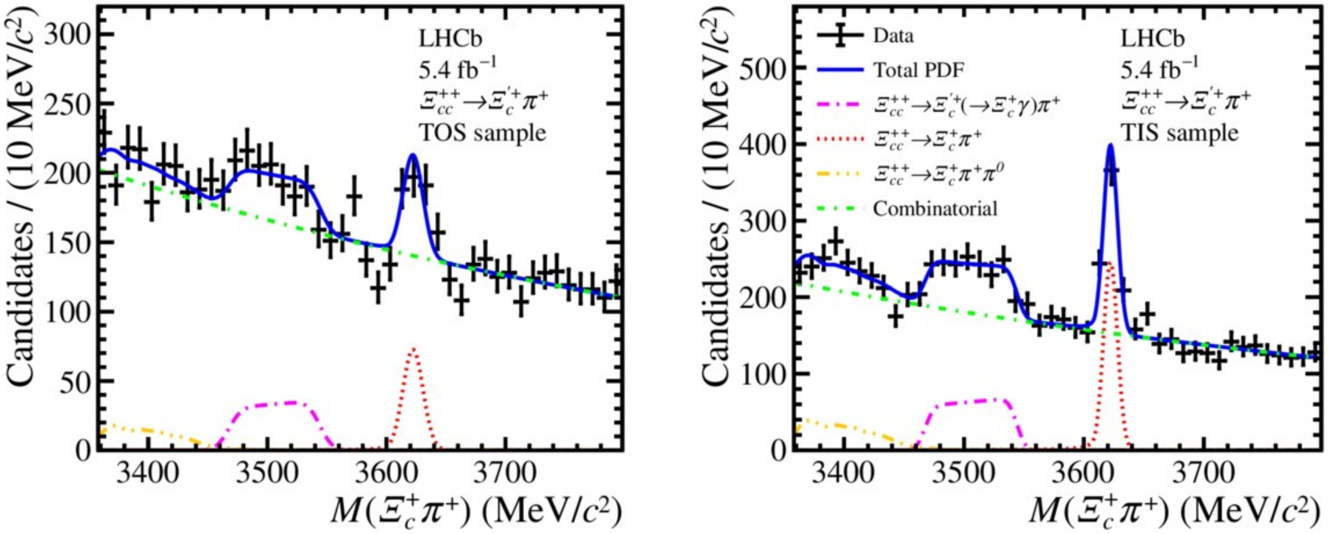
$\Xi_{cc}^{++} \rightarrow \Xi_c^{(\prime)+}\pi^+$

PRL 121 (2018) 162002
JHEP 05 (2022) 038

$$\frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+\pi^+) \times \mathcal{B}(\Xi_c^+ \to pK^-\pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^-\pi^+\pi^+) \times \mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} = 0.035 \pm 0.009\,(\text{stat}) \pm 0.003\,(\text{syst}).$$

Separate hardware trigger decision samples

- on signal (TOS)
- independent of signal (TIS)

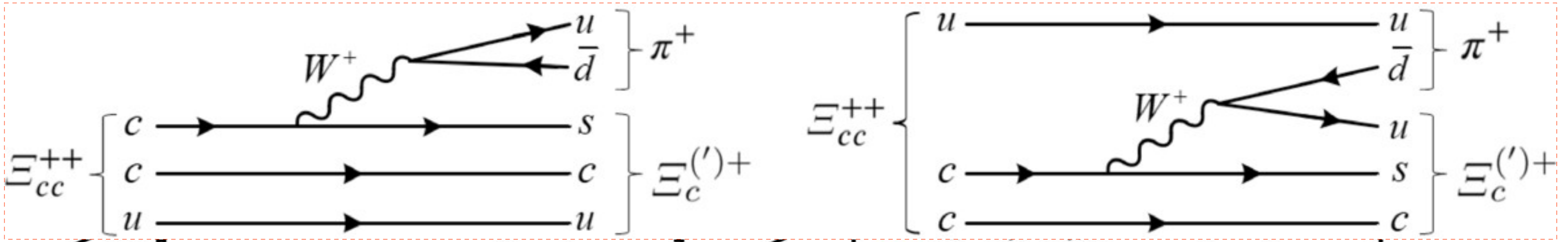


$\Xi_{cc}^{++} \to \Xi_c^{(')+}\pi^+$

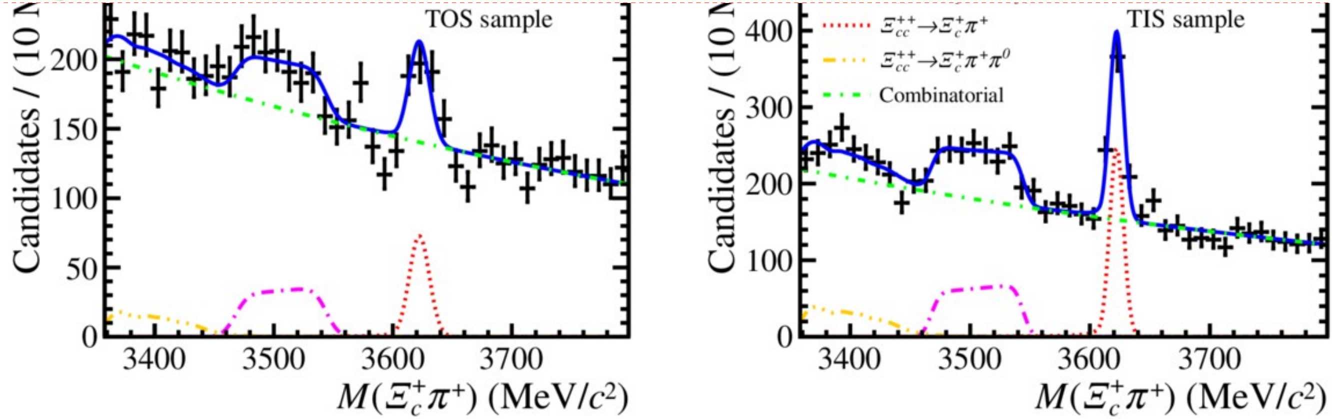
PRL 121 (2018) 162002
JHEP 05 (2022) 038

$$\frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^{\prime +}\pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^{+}\pi^+)} = 1.41 \pm 0.17 \pm 0.10.$$

Theory predictions range from 0.4 – 7 depending on relative contributions of two amplitudes

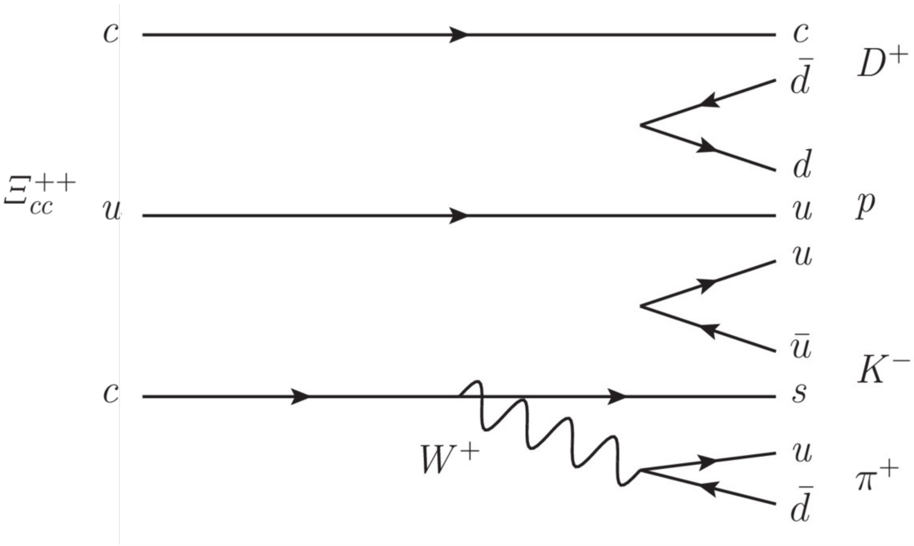


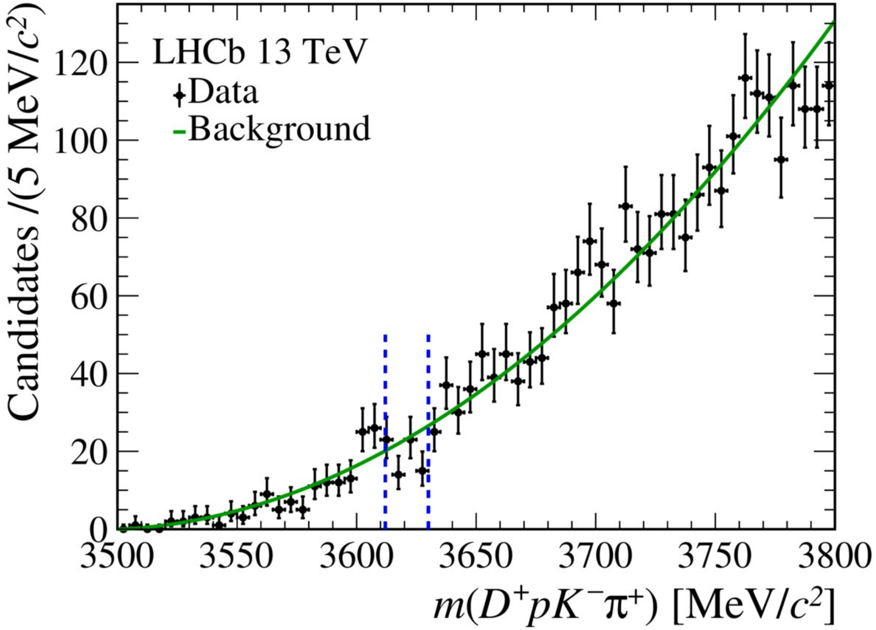
Separate hardware trigger decision samples
- on signal (TOS)
- independent of signal (TIS)



$\Xi_{cc}^{++} \to D^+pK^-\pi^+$

JHEP 10 (2019) 124

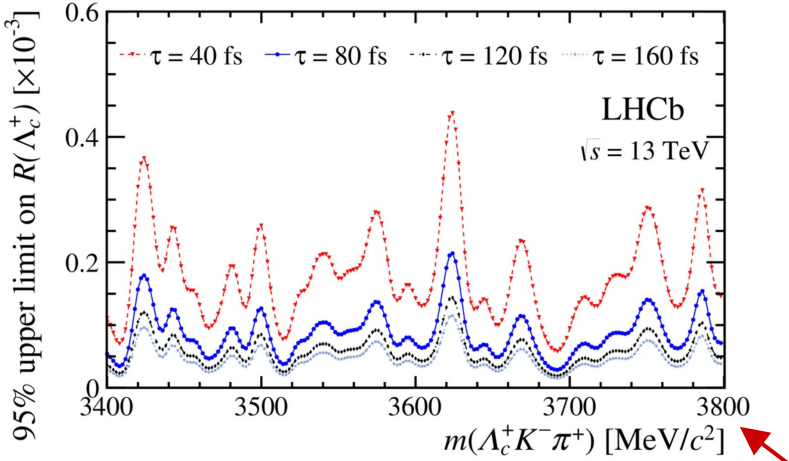


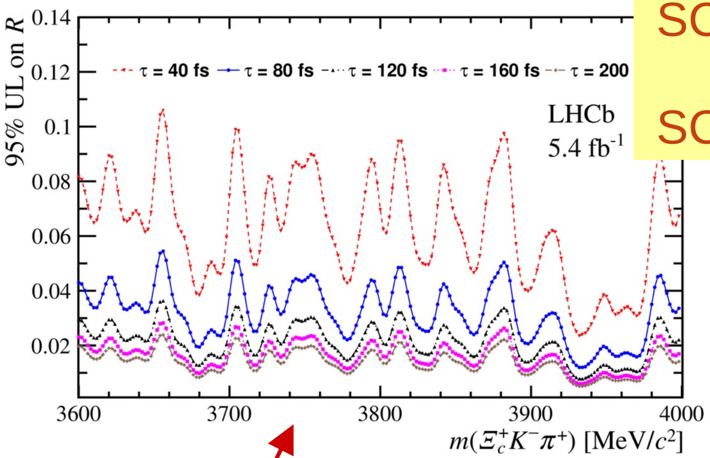


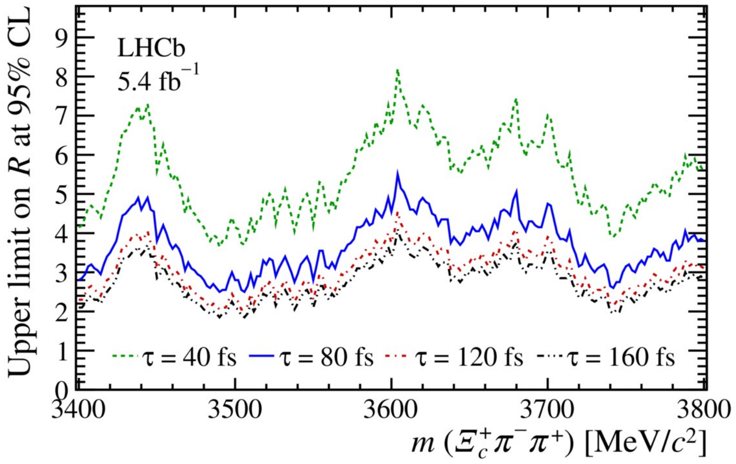
$$\frac{\mathcal{B}(\Xi_{cc}^{++} \to D^+pK^-\pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+K^-\pi^+\pi^+)} < 1.7\ (2.1) \times 10^{-2} \ \text{at} \ 90\%\ (95\%)\ \text{CL}$$

Production rate limits for Ξ_{cc}^{+} and Ω_{cc}^{+}

SCPMA 63 (2020) 221062
JHEP 12 (2021) 107
SCPMA 64 (2021) 101062







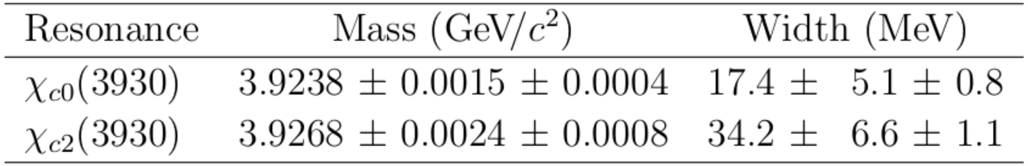
- $\Omega_{cc}^{+} \rightarrow \Xi_c^{+}K^{-}\pi^{+}$ relative to $\Xi_{cc}^{++} \rightarrow \Lambda_c^{+}K^{-}\pi^{+}\pi^{+}$
- $\Xi_{cc}^{+} \rightarrow \Lambda_c^{+}K^{-}\pi^{+}$ relative to Λ_c^{+}
- $\Xi_{cc}^{+} \rightarrow \Xi_c^{+}\pi^{+}\pi^{-}$ relative to $\Xi_{cc}^{++} \rightarrow \Xi_c^{+}\pi^{+}$
- Strong dependence on assumed lifetime
  - Little sensitivity for low lifetimes

Charmonia decaying to D^+D^-

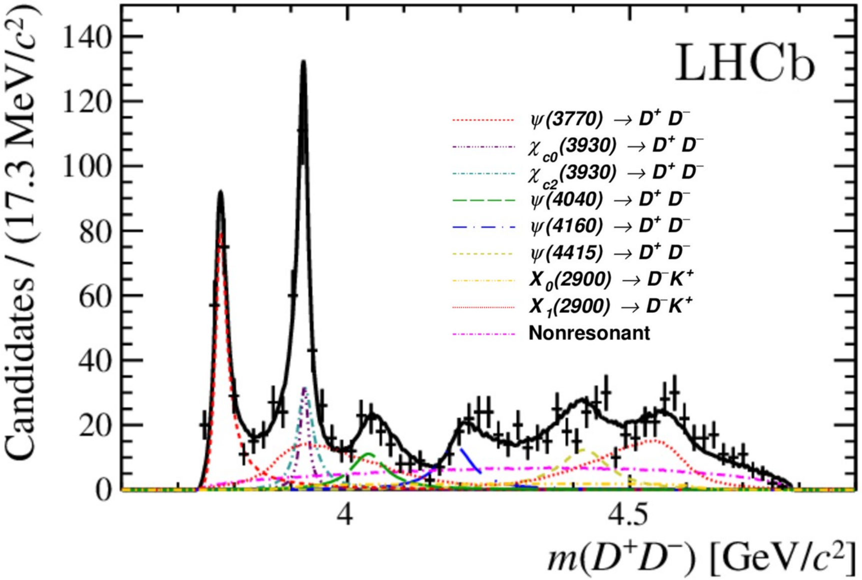
PR D102 (2020) 112003

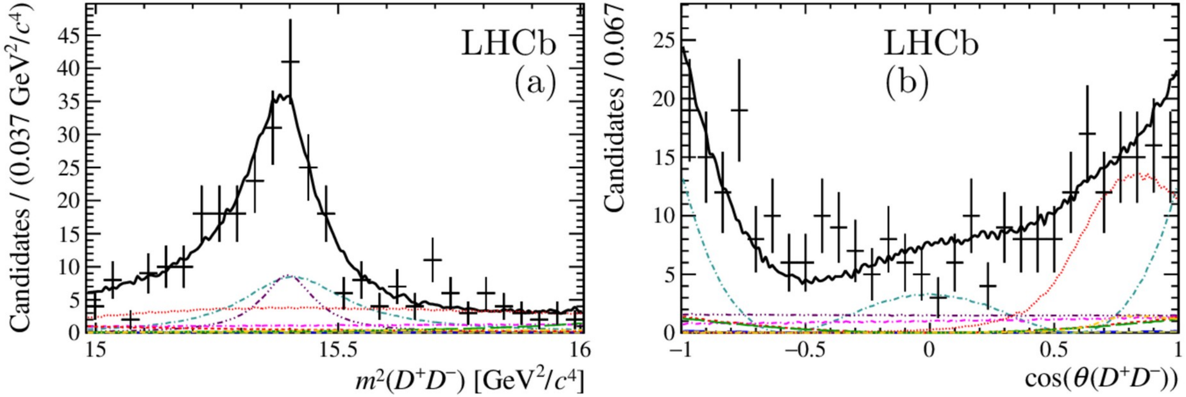
Structure around 3930 MeV seen in $D\overline{D}$ and $J/\psi\omega$ previously assumed to be $J^P = 2^+$ state, i.e. $\chi_{c2}(2P)$

LHCb analysis shows there to be two states in that region, with $J^P = 0^+$ and 2^+



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





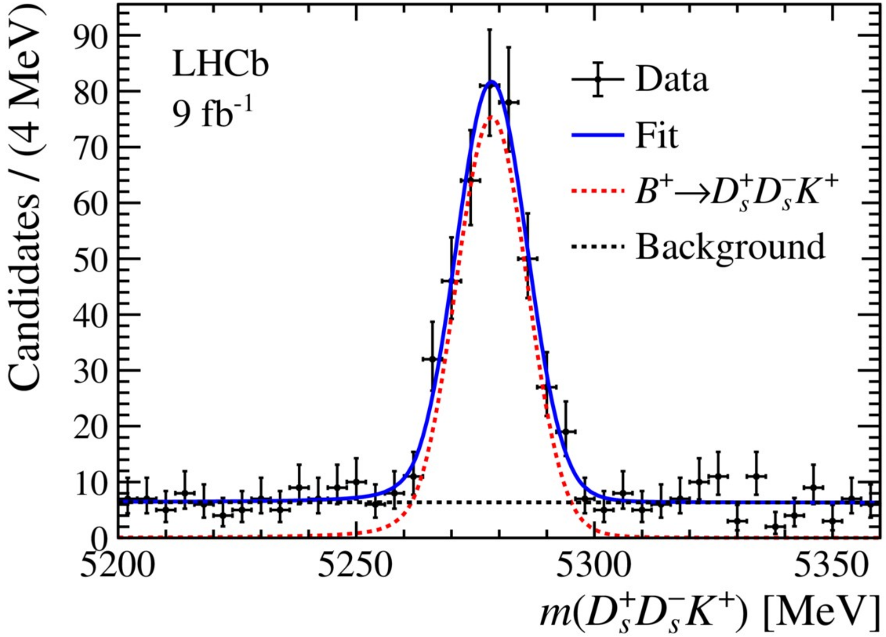
No $\chi_{c0}(3860)$ contribution
[state claimed by Belle]

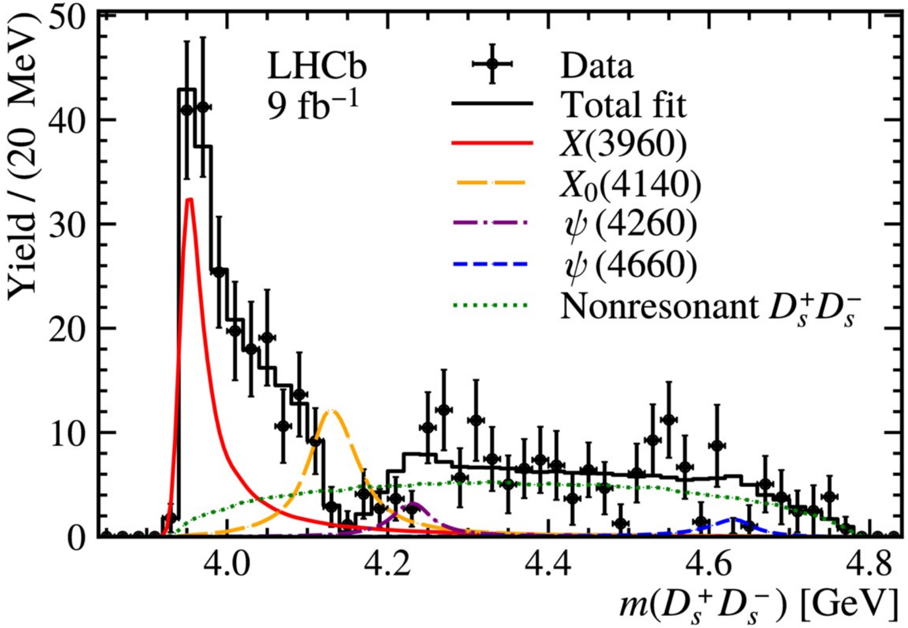
Charmonia decaying to $D_s^+D_s^-$

arXiv:2211.05034
to appear in PRD

$B^+ \rightarrow D_s^+D_s^-K^+$

arXiv:2210.15153
to appear in PRL





Signal yield of 360 ± 22

[first observation!]

n.b. Seven final state tracks, incl. 5 kaons ($D_s \rightarrow KK\pi$)

Striking low-mass enhancement + interference dip near J/ψφ threshold

[modelled here with interfering spin-0 resonances]

Charmonia decaying to $D_s^+D_s^-$

arXiv:2211.05034
to appear in PRD

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

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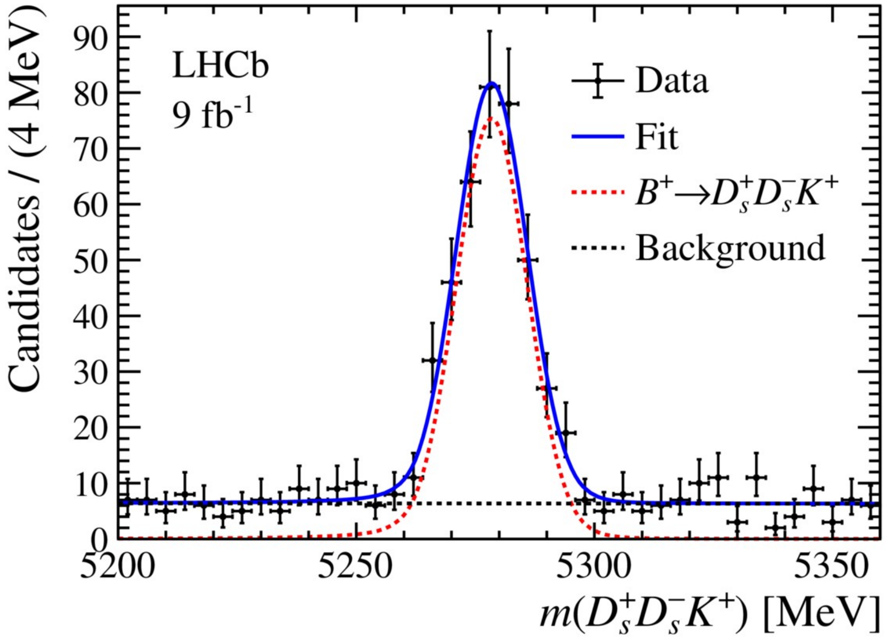

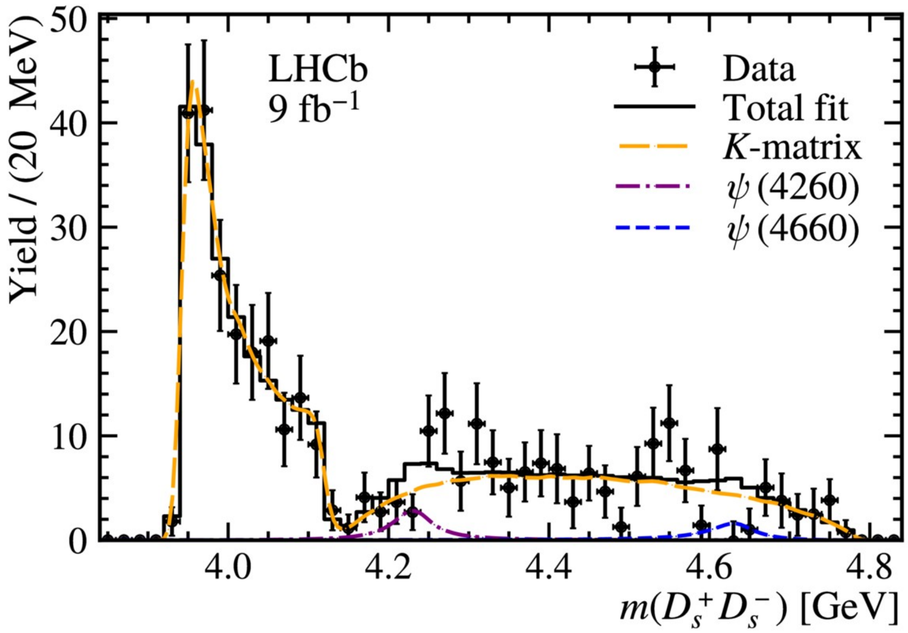

Signal yield of 360 ± 22

[first observation!]

n.b. Seven final state tracks, incl. 5 kaons ($D_s \to KK\pi$)

Striking low-mass enhancement + interference dip near $J/\psi\phi$ threshold

[modelled here with K matrix]