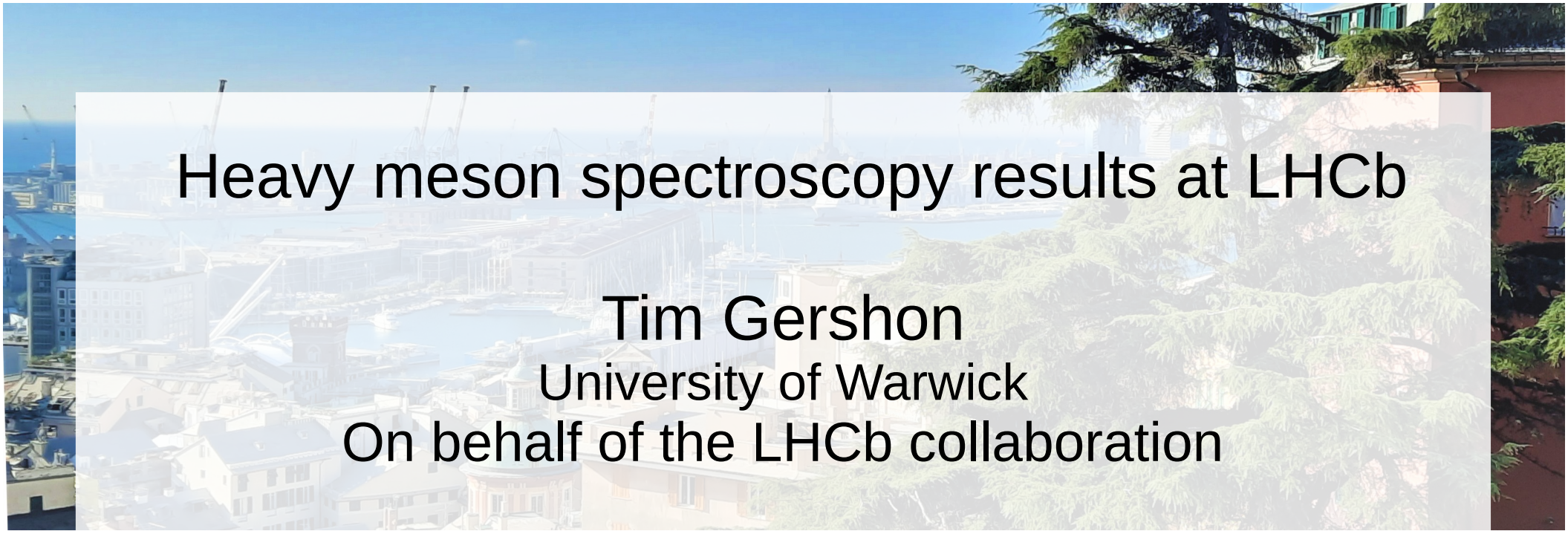


Heavy meson spectroscopy results at LHCb

Tim Gershon
University of Warwick
On behalf of the LHCb collaboration

Hadron 2023, Genova, Italy
9 June 2023

HADRON 2023

Contents

- LHCb basics
- Heavy meson spectroscopy
  - charmonia
  - charm & charge-strange
  - bottomonia
  - beauty, beauty-strange, beauty-charm
- Outlook and summary

Many new results … focus here, touch on others

Exotics covered by other speakers …
(I may mention one or two)
but many results from same analyses

The LHCb experiment

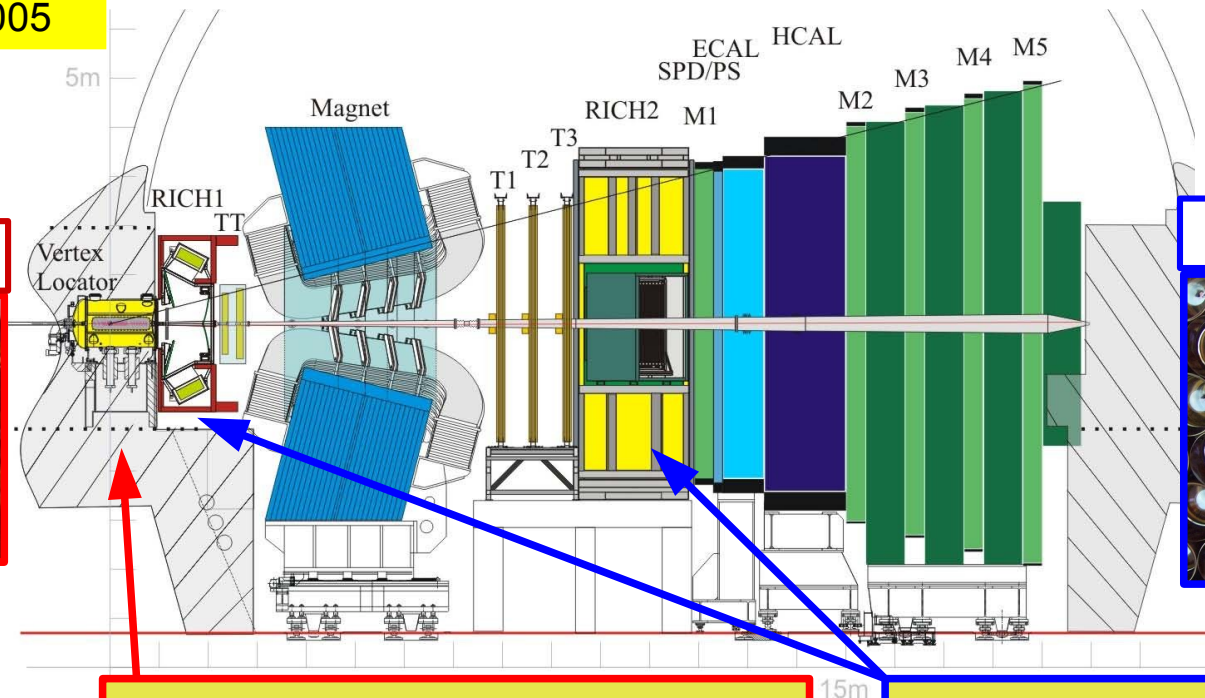
- Huge charm and beauty production cross-section in the forward direction in pp collisions at LHC energies
  - Essentially all hadrons produced
- Require superb detection capability to separate signal from potentially overwhelming background
  - LHCb strengths in vertexing, tracking and charged particle 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

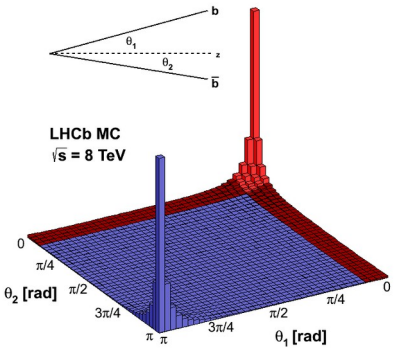
Most new results exploit production via B decays

The LHCb detector

(2011-18 edition)

The LHCb Detector
JINST 3 (2008) S08005





VELO silicon strips

RICH PMTs

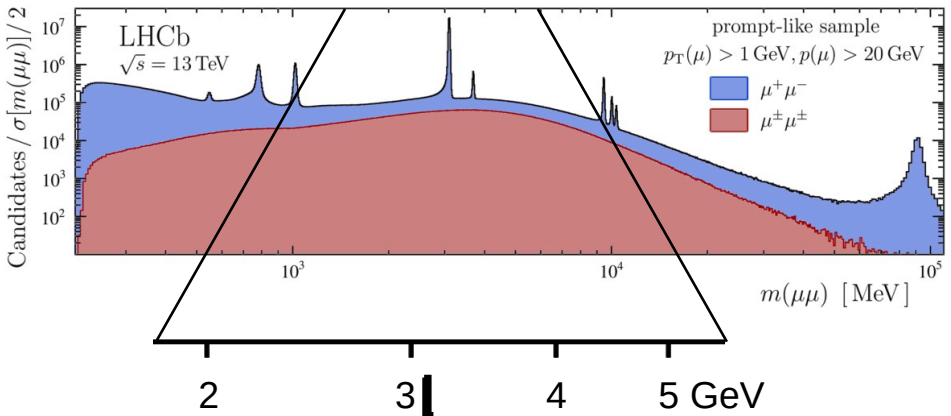
Precision primary and secondary vertex measurements

Excellent K/π separation capability

Prompt vs. B decays

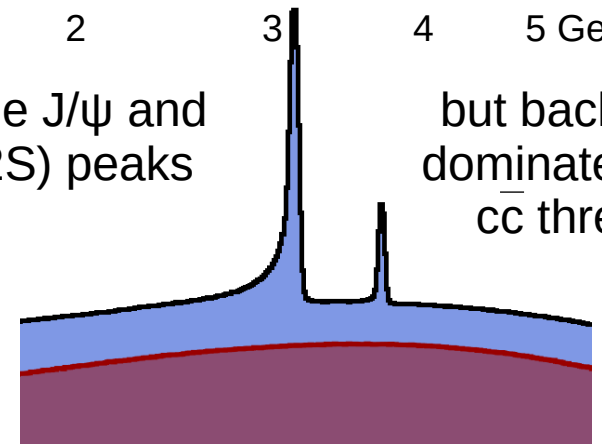
example with $\mu^+\mu^-$

PRL 120 (2018) 061801

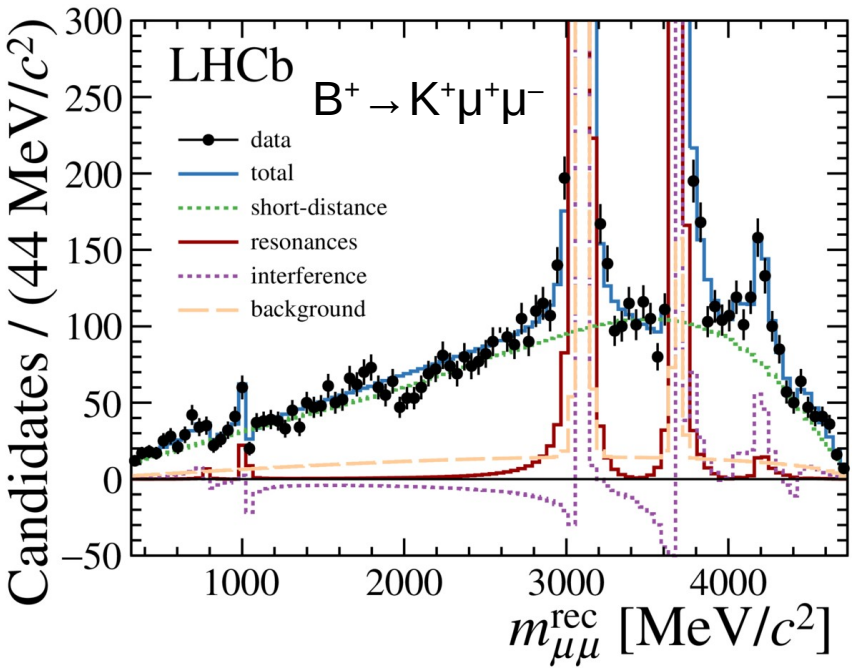


Huge J/ψ and ψ(2S) peaks

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



EPJ C77 (2017) 161



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

Charmonia

- Can be studied in huge range of final states at LHCb
  - leptonic ($\mu^+\mu^-$ on previous slide)
  - charmless hadrons: K^+K^-, $\varphi\varphi$, $p\bar{p}$, $K_SK\pi$, ...
  - charm-anticharm: $D\bar{D}$, $D_s^+D_s^-$, $D^{(*)}\bar{D}^{(*)}$, $\Lambda_c^+\bar{\Lambda}_c^-$, …
  - lighter charmonia + X: e.g. $J/\psi\gamma$, $J/\psi\pi^+\pi^-$, $J/\psi\varphi$, $J/\psi\eta$, $J/\psi\eta'$, …
- Decay modes and relative branching fractions provide information on nature of state

New (since Hadron2021) and covered today

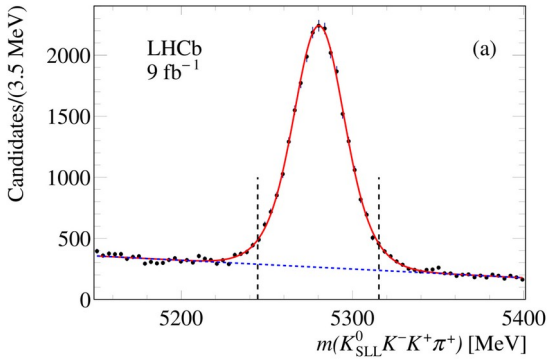
Not new but recapped today

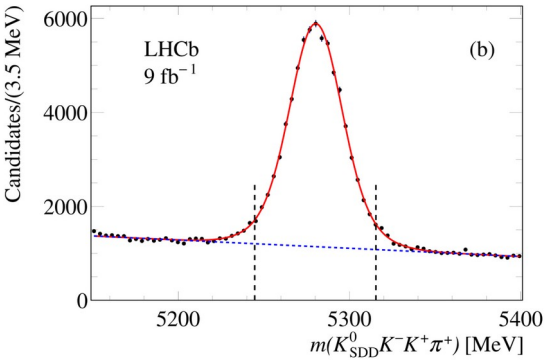
In back-up, please ask if interested

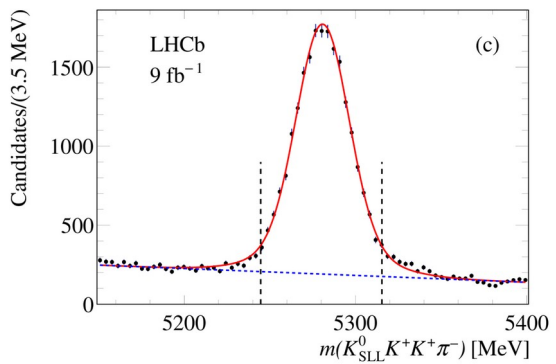
Charmonia decaying to $K_S K\pi$

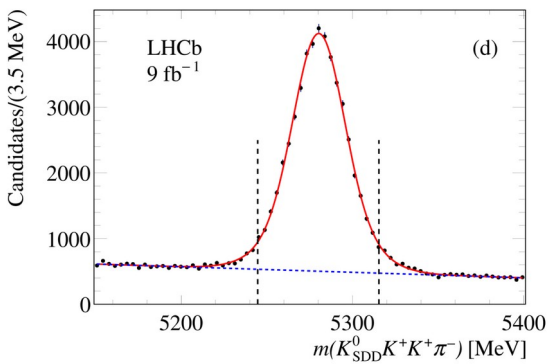
$B^+ \to K_S K\pi K^+$

arXiv:2304.14891
submitted to PRD

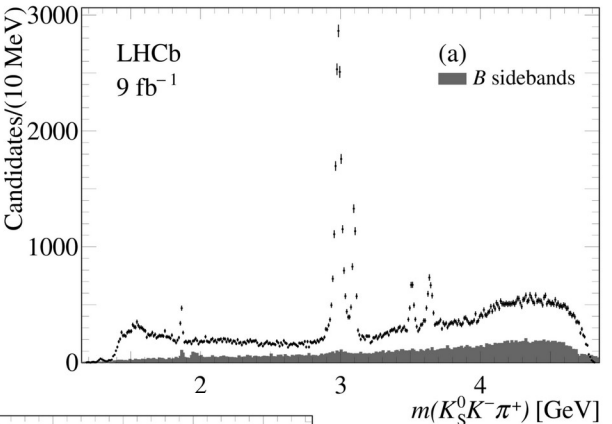


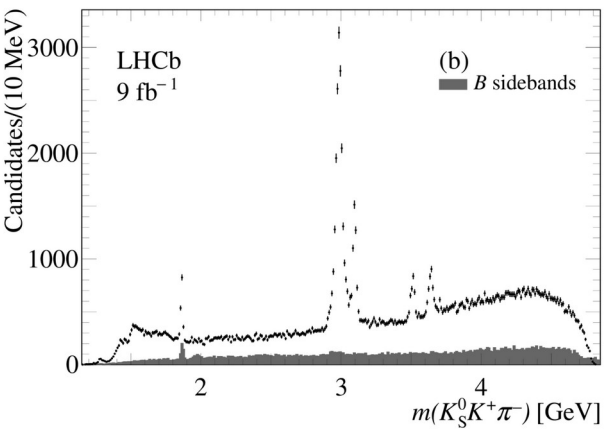






η_c, J/ψ, χ_{c1}, $\eta_c(2S)$ peaks apparent



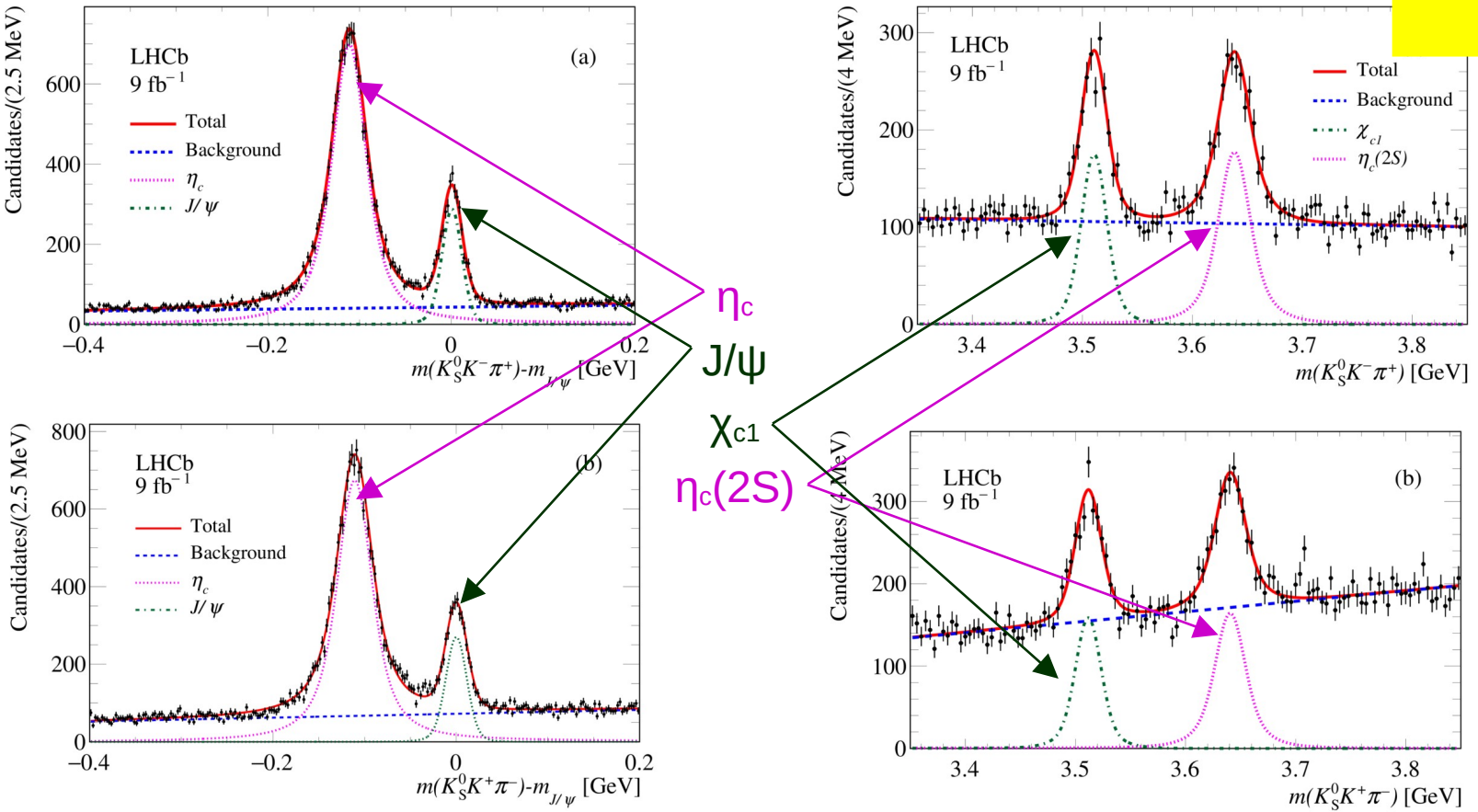


[$\chi_{c0,2} \to K^+K^-$ also seen]

Two K_S reconstruction methods (LL, DD)
Two final states (opposite or same sign $K^{\pm}$)
Total signal yield 132,610 ± 610

Charmonia decaying to $K_S K\pi$

arXiv:2304.14891
submitted to PRD



η_c

J/ψ

χ_{c1}

$\eta_c(2S)$

Charmonia decaying to $K_S K\pi$

$B^+ \to K_S K\pi K^+$

arXiv:2304.14891
submitted to PRD

- Improved knowledge of η_c and $\eta_c(2S)$ resonance parameters

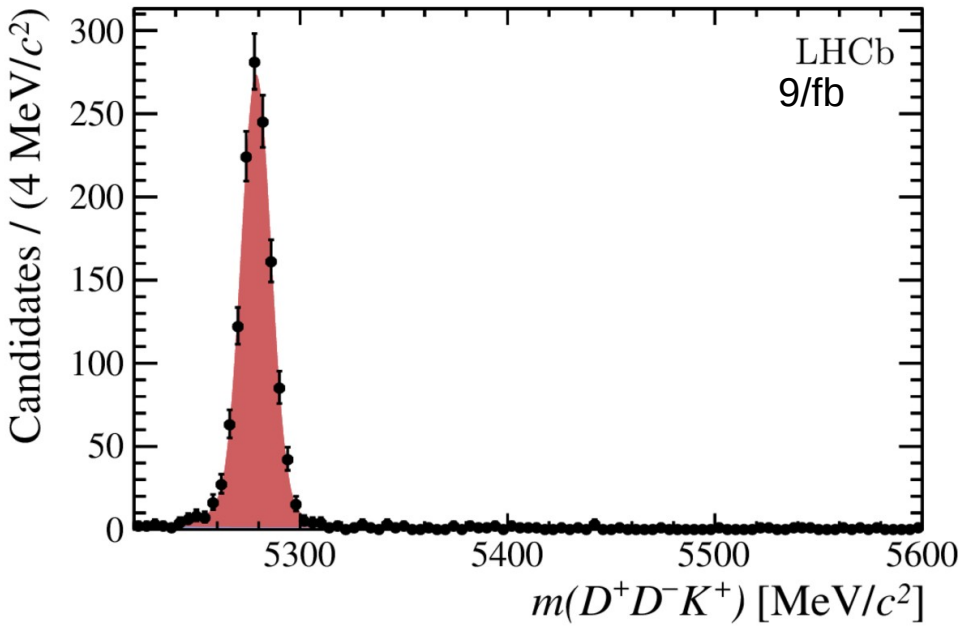
	Mass [MeV]	Width [MeV]
η_c	$2985.01 \pm 0.17 \pm 0.89$	$29.7 \pm 0.5 \pm 0.2$
$\eta_c(2S)$	$3637.90 \pm 0.54 \pm 1.40$	$10.77 \pm 1.62 \pm 1.08$
χ_{c1}	$3509.84 \pm 0.69 \pm 0.64$	[fixed]

- Dalitz plot analyses of η_c and $\eta_c(2S) \to K_S K\pi$ decays provide information on kaon spectroscopy ($K\pi$ S-wave)
  - Study of $\chi_{c1} \to K_S K\pi$ decays also performed

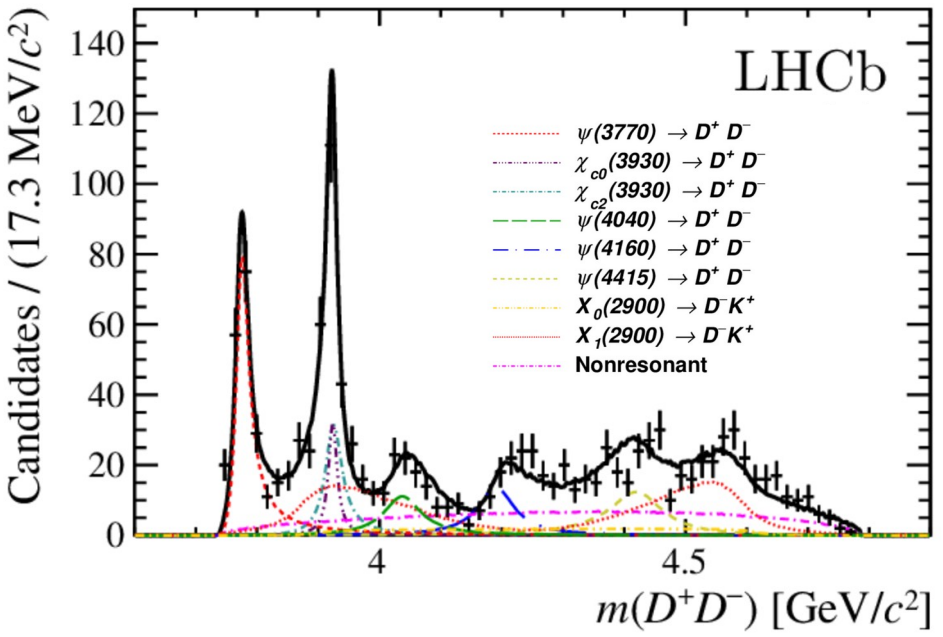
Charmonia decaying to D^+D^-

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

PR D102 (2020) 112003



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



Unexpected exotic components observed,
but also interesting D^+D^- structures

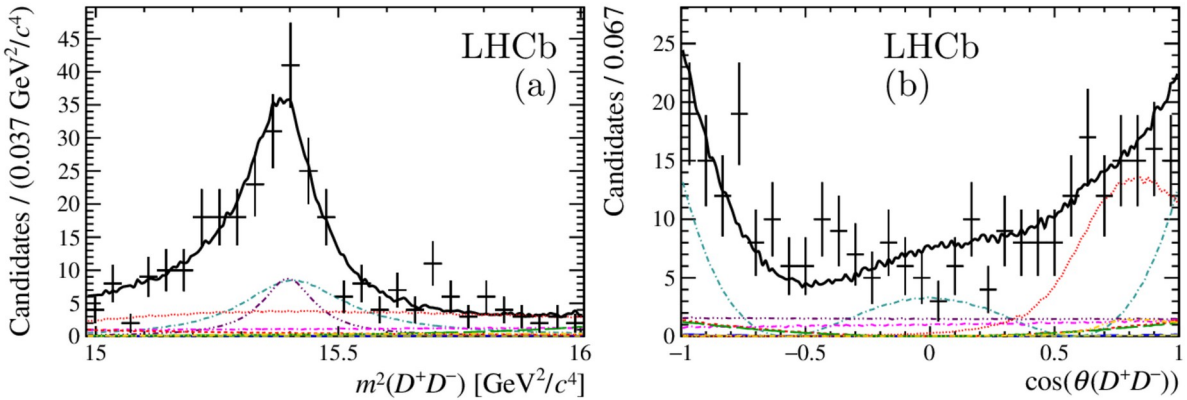
Charmonia decaying to D^+D^-

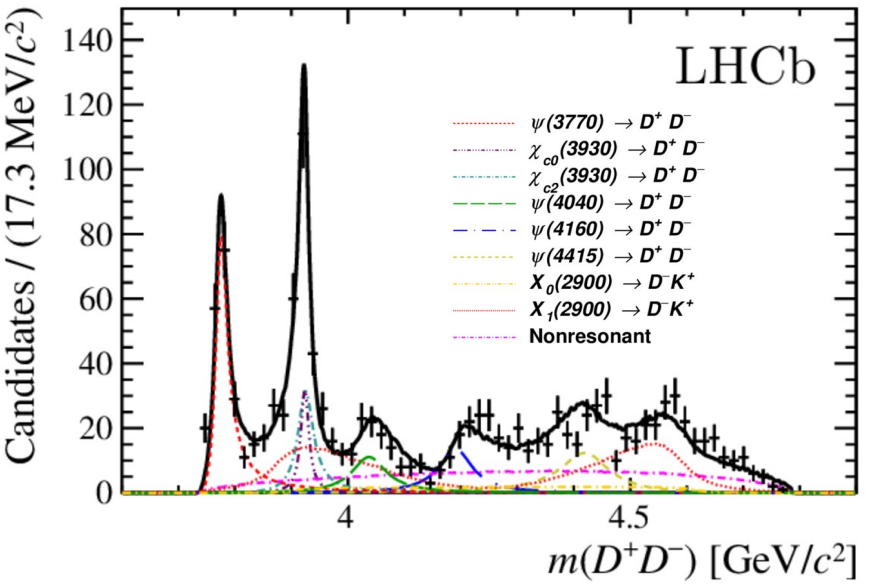
PR D102 (2020) 112003

Structure around 3930 MeV seen in $D\bar{D}$ 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)
$\chi_{c0}(3930)$	$3.9238 \pm 0.0015 \pm 0.0004$	$17.4 \pm 5.1 \pm 0.8$
$\chi_{c2}(3930)$	$3.9268 \pm 0.0024 \pm 0.0008$	$34.2 \pm 6.6 \pm 1.1$





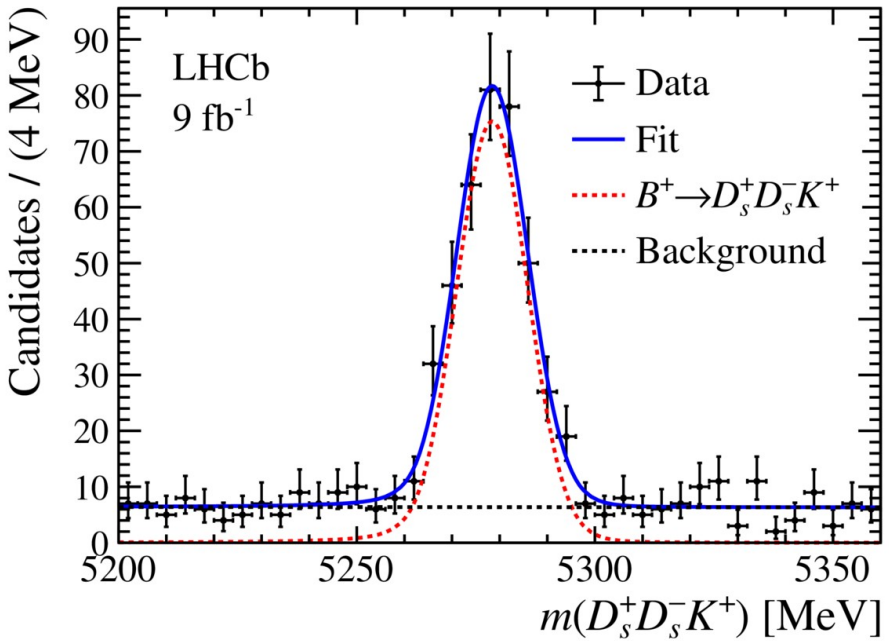
No $\chi_{c0}(3860)$ contribution
[state claimed by Belle]

Charmonia decaying to $D_s^+D_s^-$

arXiv:2211.05034
to appear in PRD

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

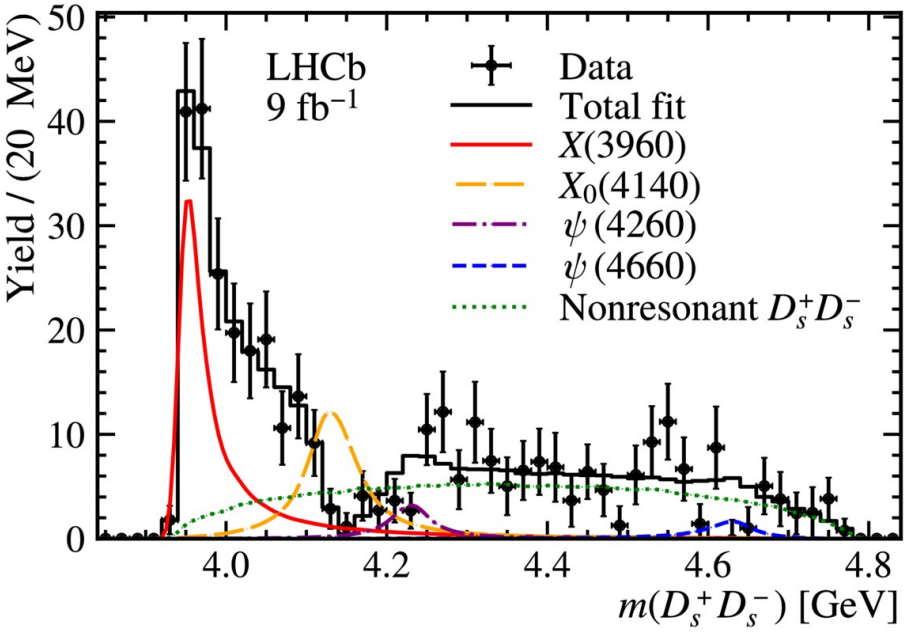
arXiv:2210.15153
to appear in PRL



Signal yield of 360 ± 22

[first observation!]

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



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

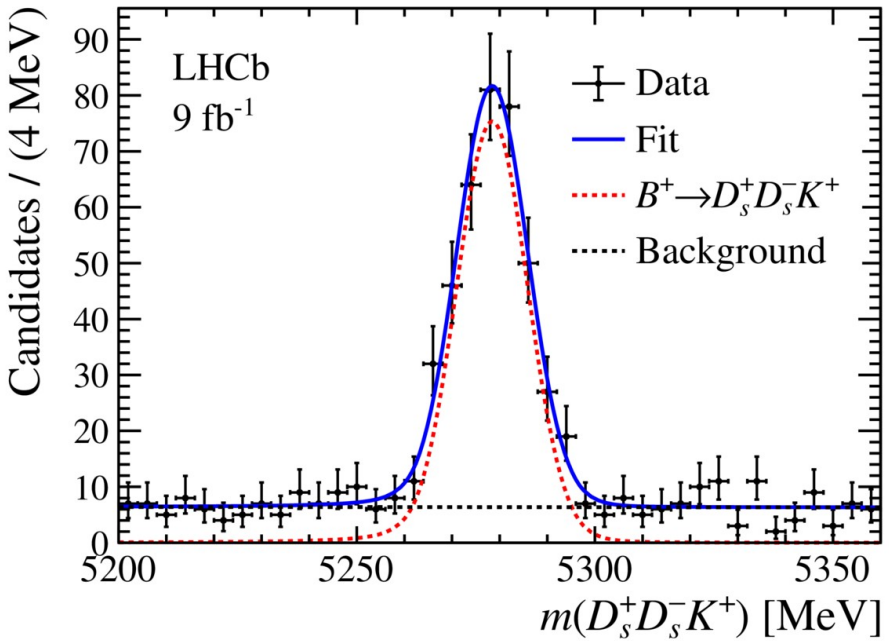
[modelled here with interfering spin-0 resonances]

Charmonia decaying to $D_s^+D_s^-$

arXiv:2211.05034
to appear in PRD

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

arXiv:2210.15153
to appear in PRL



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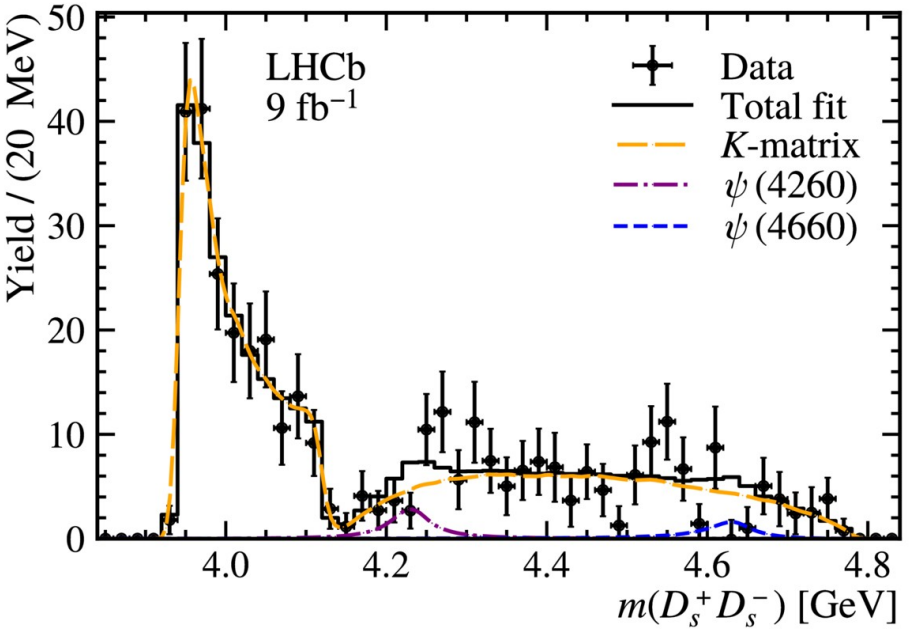
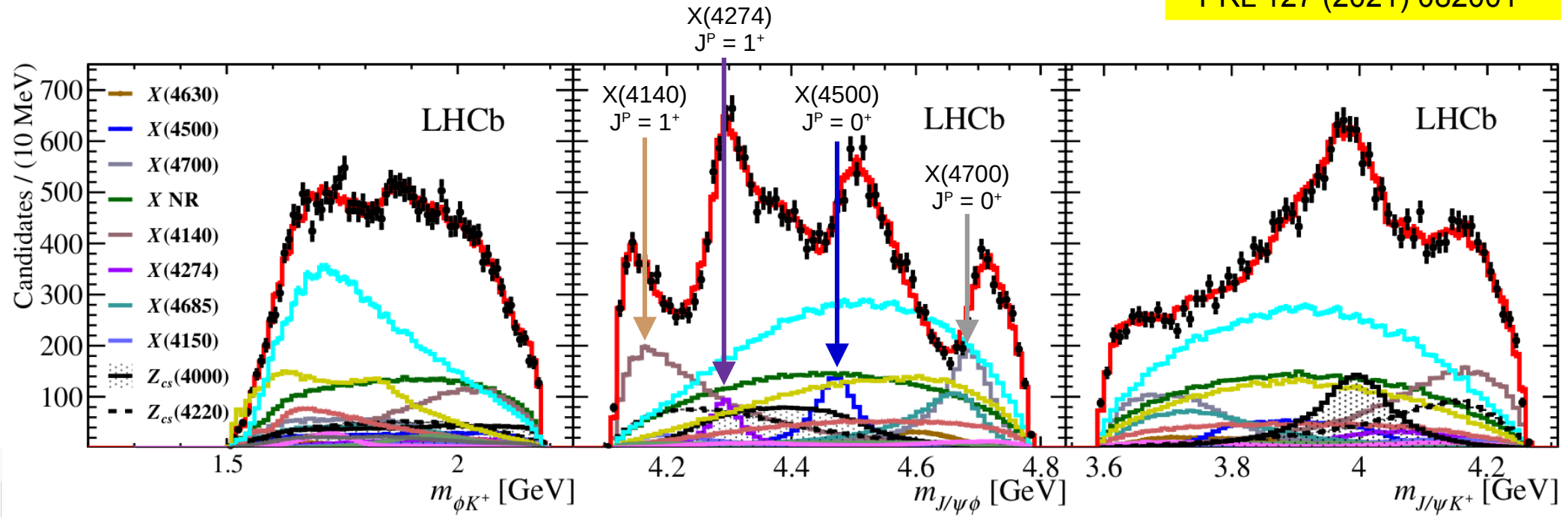


Striking low-mass enhancement + interference dip near J/ψφ threshold

[modelled here with K matrix]

Reminder: states in J/ψφ

PRL 127 (2021) 082001



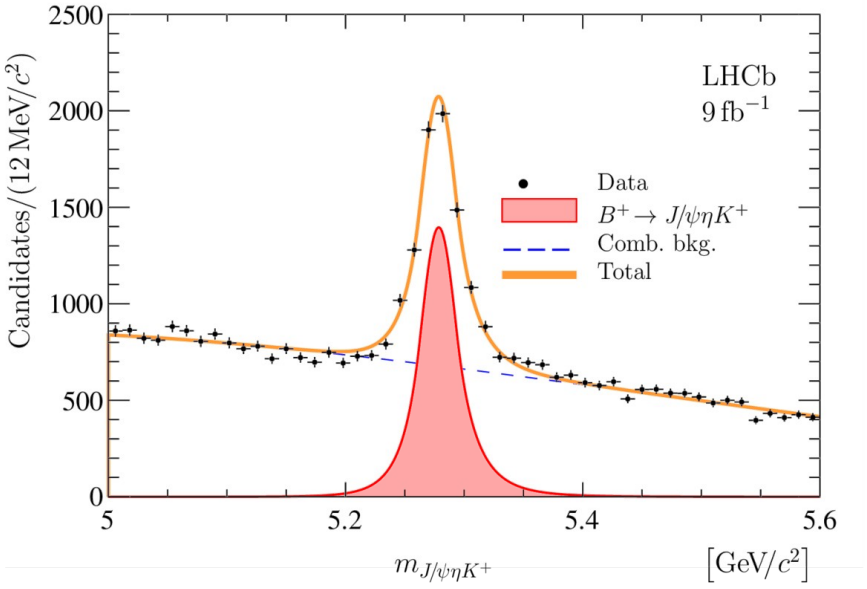
No sign (yet) of X(4500) or X(4700) in $D_s^+D_s^-$ final state

No $J^P = 0^+$ state near threshold in J/ψφ

Charmonia decaying to J/ψη

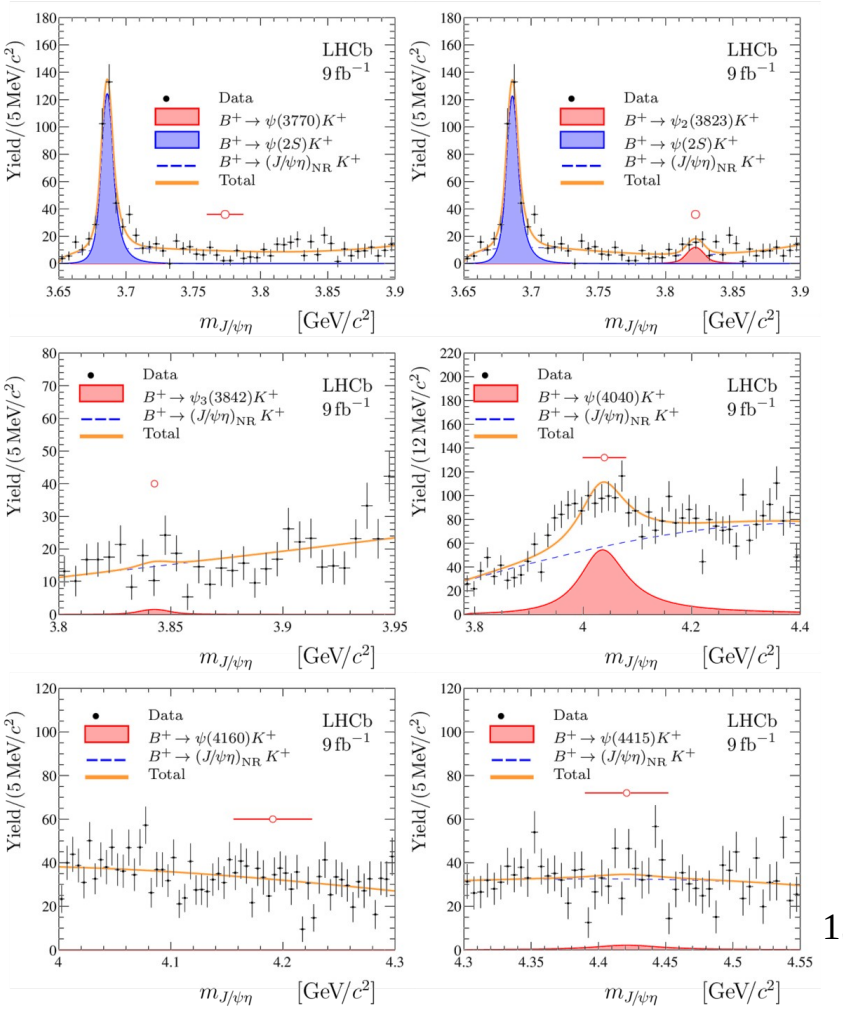
arXiv:2202.04045
to appear in JHEP

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



Signal yield of 5390 ± 160

Evidence for $\psi_2(3823)$ and $\psi(4040) \to J/\psi\eta$
(3.4σ and 4.7σ, respectively)

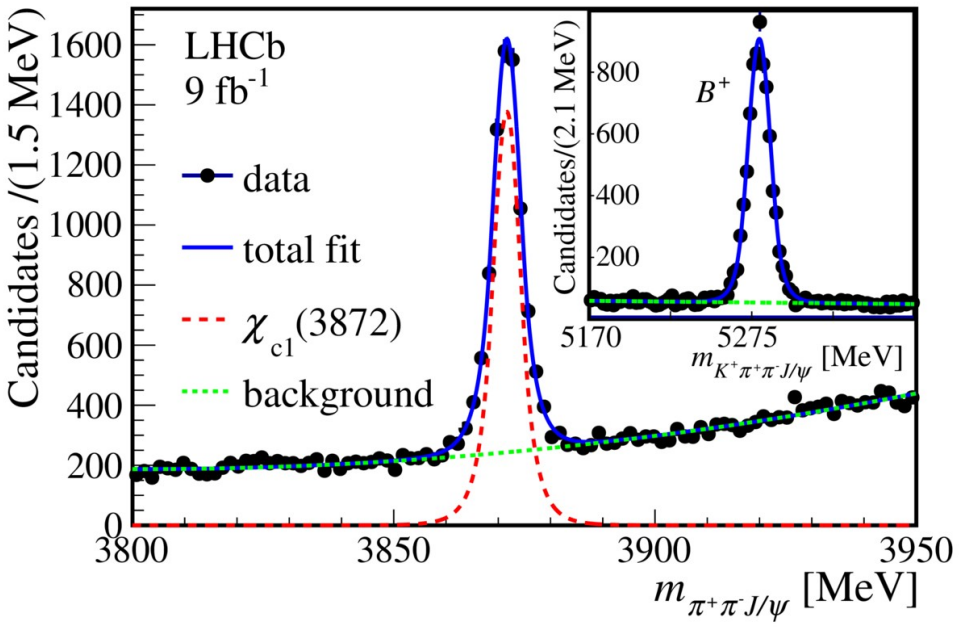


Charmonia decaying to $J/\psi\pi^+\pi^-$

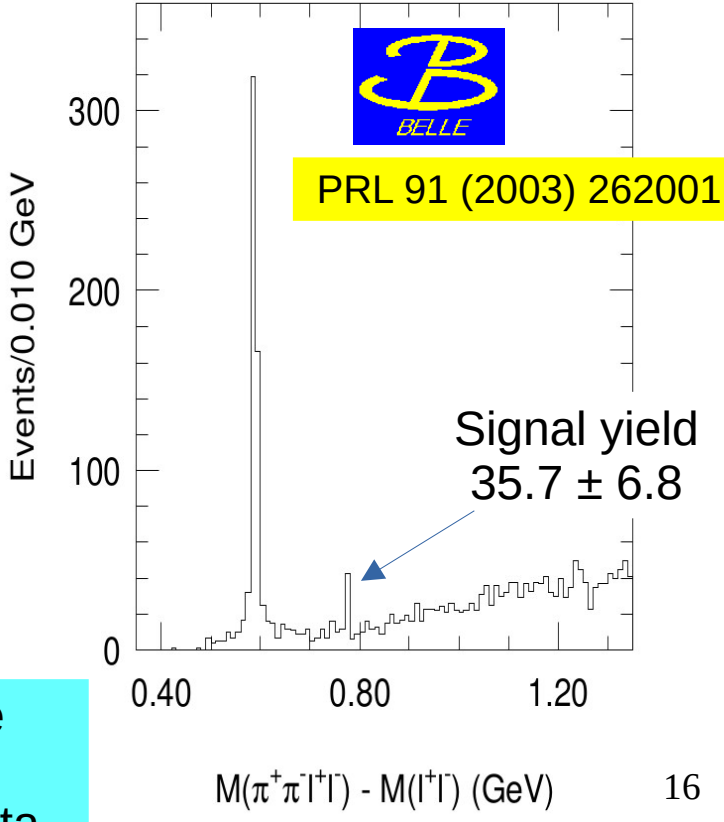
specifically $\chi_{c1}(3872)$ a.k.a X(3872)

arXiv:2204.12597
to appear in PRD

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



Signal yield of 6788 ± 117



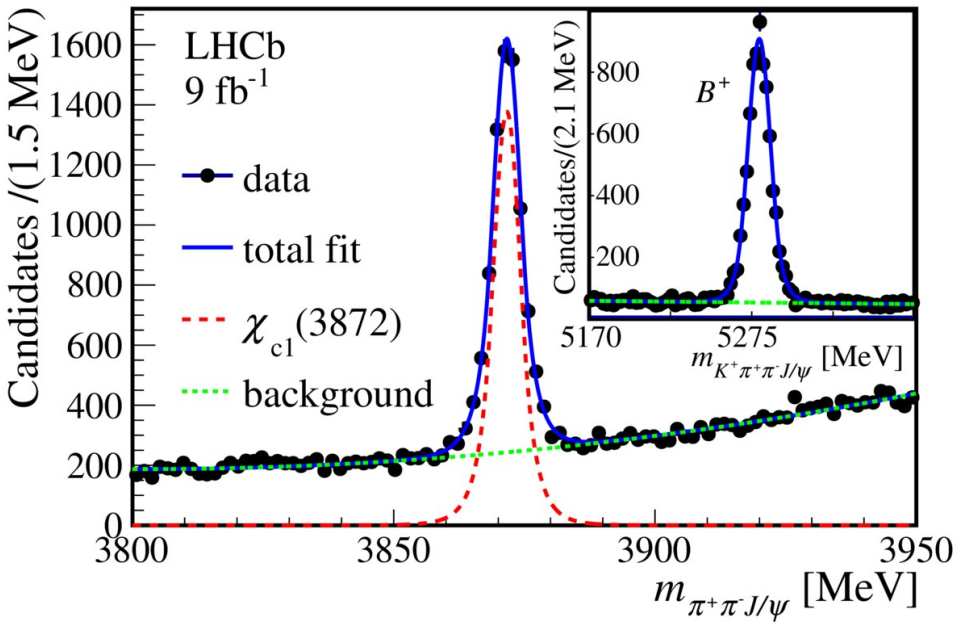
20 years since discovery
~200 × more data

Charmonia decaying to $J/\psi\pi^+\pi^-$

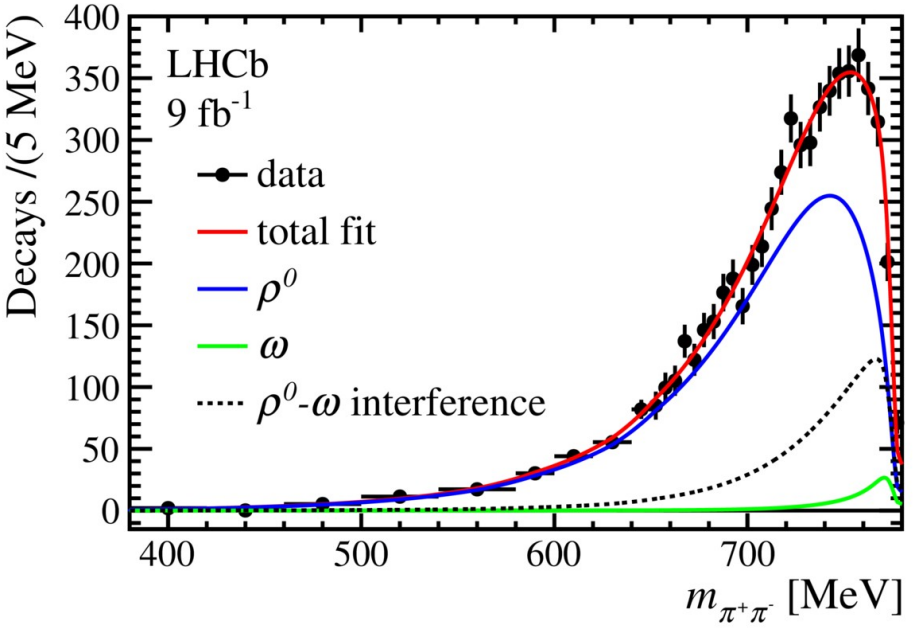
specifically $\chi_{c1}(3872)$ a.k.a X(3872)

arXiv:2204.12597
to appear in PRD

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



Signal yield of 6788 ± 117



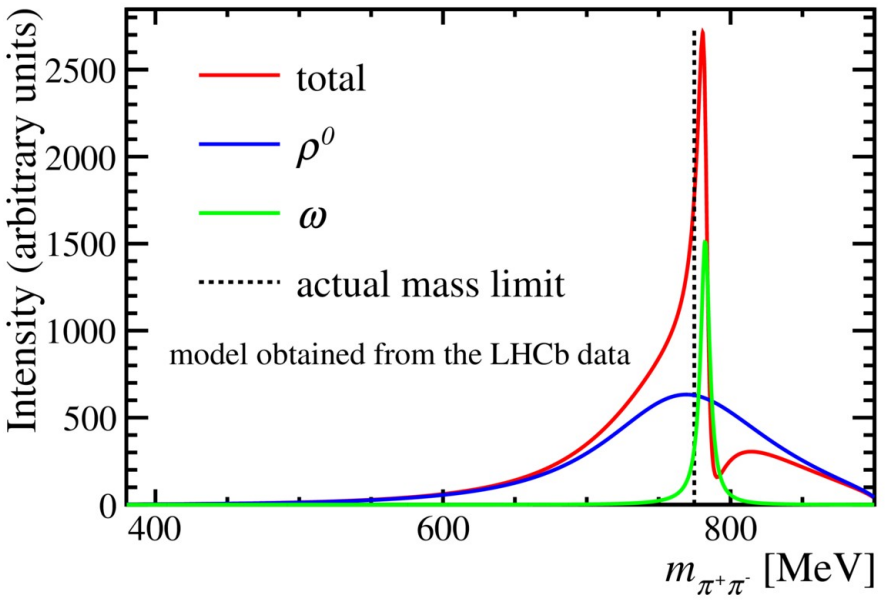
Clear need for ω contribution, and interference, to fit $m(\pi^+\pi^-)$ spectrum

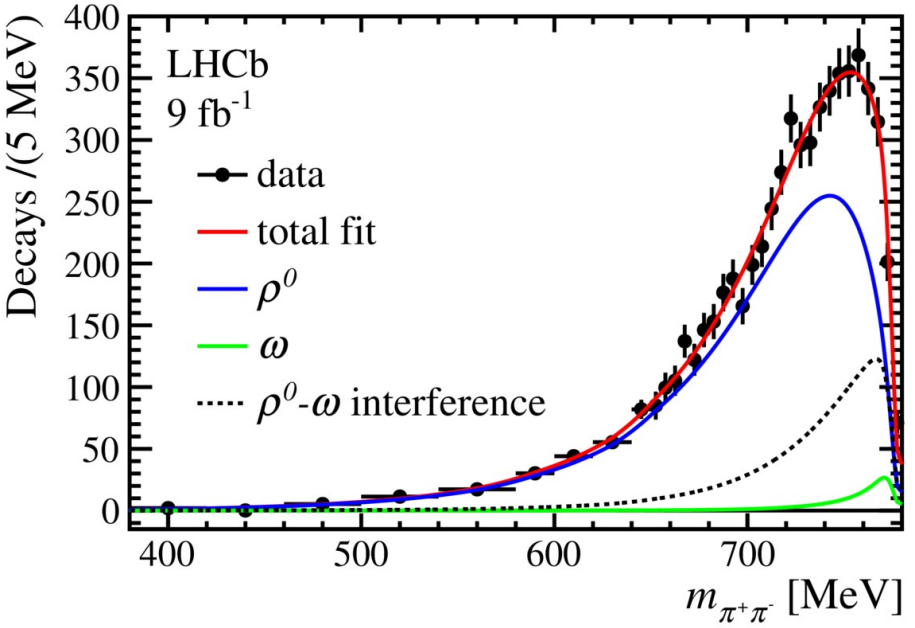
Charmonia decaying to $J/\psi\pi^+\pi^-$

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

arXiv:2204.12597
to appear in PRD

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





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

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

Charmonia summary

- Much new information on charmonia from LHCb
  - especially exploiting production in B decays
- Several important channels still missing
  - much work is in progress!
- Larger samples needed to obtain complete picture of resonances in different final states
  - e.g. $D^{(*)}\overline{D}^{(*)} \leftrightarrow D_s^{(*)+}D_s^{(*)-}$, $J/\psi\varphi \leftrightarrow D_s^{(*)+}D_s^{(*)-}$
- With much larger samples, possible to exploit production in B_c decays
  - extend kinematic limit from [m(B)-m(K)] ~ 4.8 GeV to [$m(B_c)$-m(π)] ~ 6.1 GeV

Charm & charm-strange mesons

- Production in B decay provides great opportunities for charm(-strange) meson spectroscopy
  - $B^+ \to D^- \pi^+ \pi^+$, $B^+ \to D^{*-} \pi^+ \pi^+$
  - $B^0 \to \overline{D}^0 \pi^- \pi^+$
  - $B_s^0 \to \overline{D}^0 K^- \pi^+$

PR D94 (2016) 072001;
PR D101 (2020) 032005

PR D92 (2015) 032002

PRL 113 (2014) 162001;
PR D90 (2014) 072003

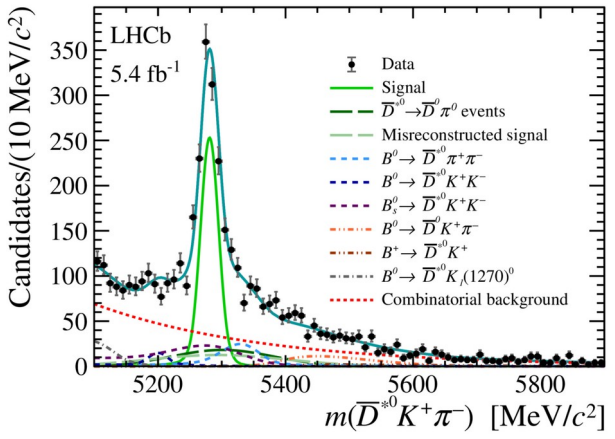
- Modes with neutral pions are harder – but not impossible!
  - $\overline{D}^{*0} \to \overline{D}^0 \pi^0$, $\overline{D}^0 \gamma$

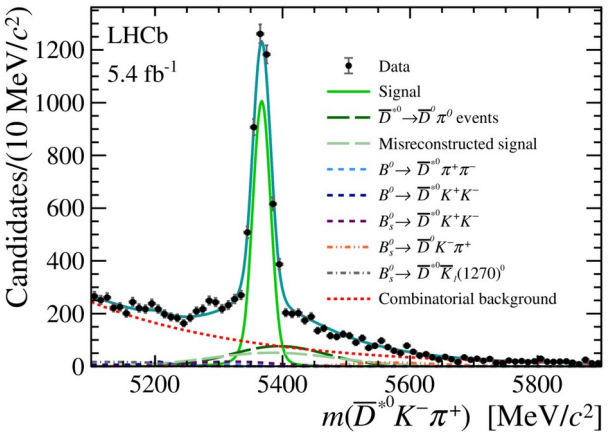
Studies also in $B \to D\overline{D}h(h)$ decays
e.g. $D_{s0}(2590)^+$ seen in $B^0 \to D^+ D^- K^+ \pi^-$
PRL 126 (2021) 122002

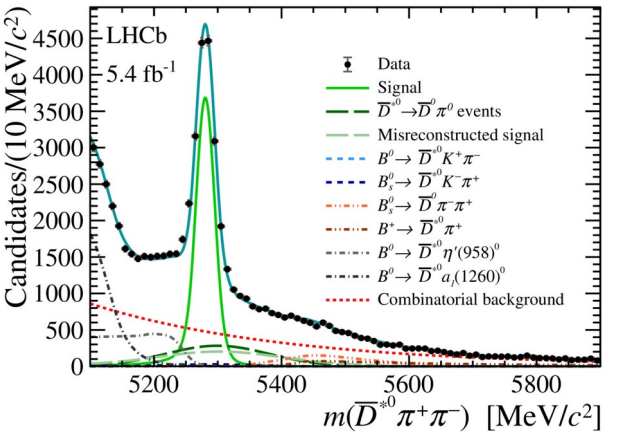
$B_{(s)}^0 \to \overline{D}^{*0} h^+ h'^-$

PR D105 (2022) 072005

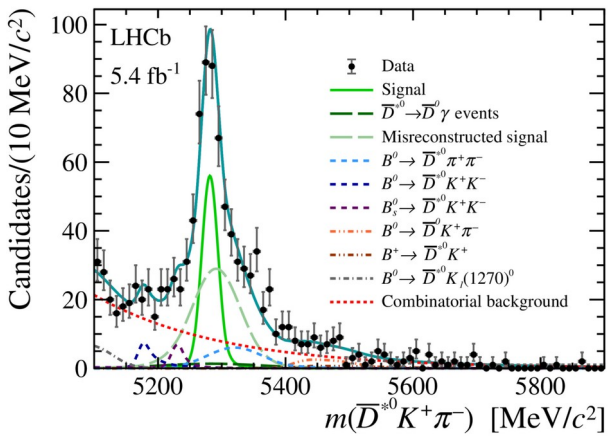
$\overline{D}^{*0} \to \overline{D}^0 \pi^0$

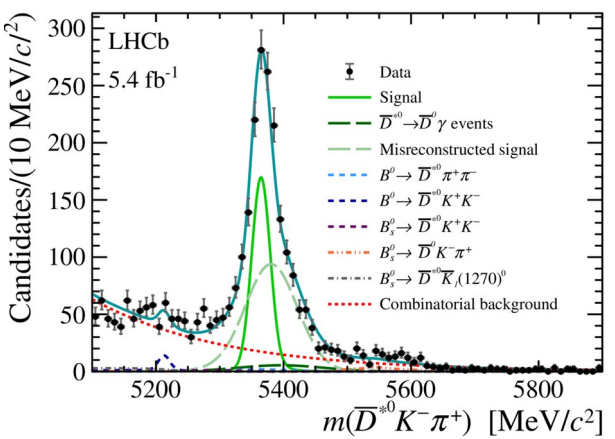


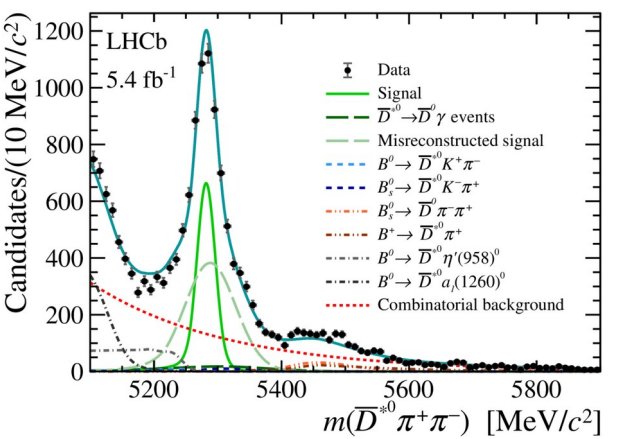




$\overline{D}^{*0} \to \overline{D}^0 \gamma$



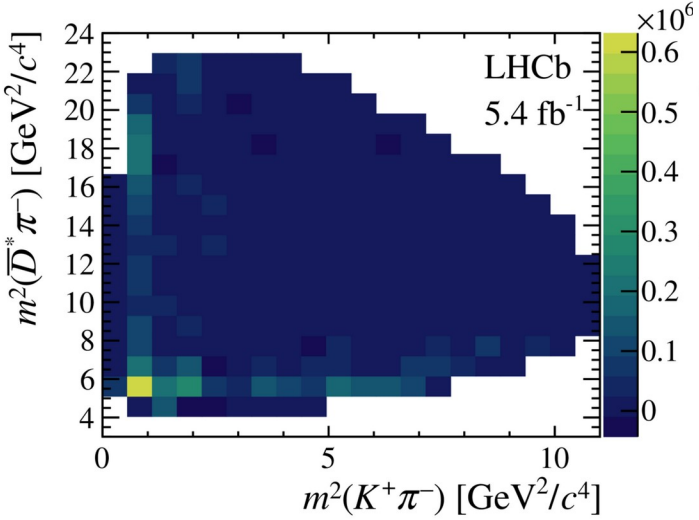




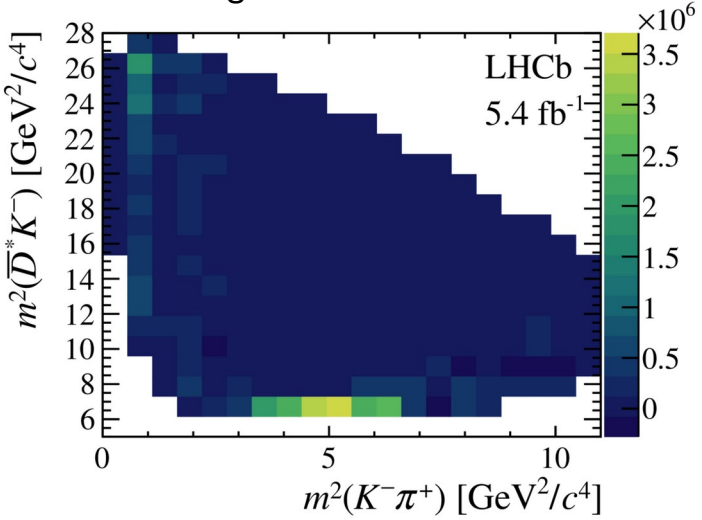
$B_{(s)}^0 \to \overline{D}^{*0} h^+ h'^-$

PR D105 (2022) 072005

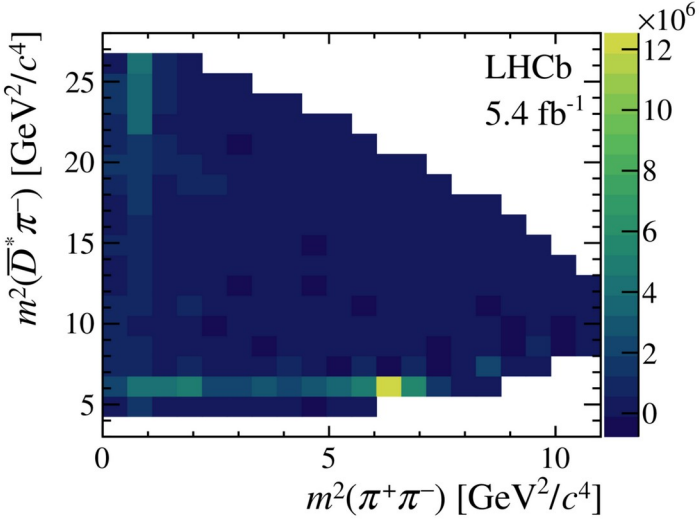
$B^0 \to \overline{D}^{*0} K^+ \pi^-$



$B_s^0 \to \overline{D}^{*0} K^- \pi^+$



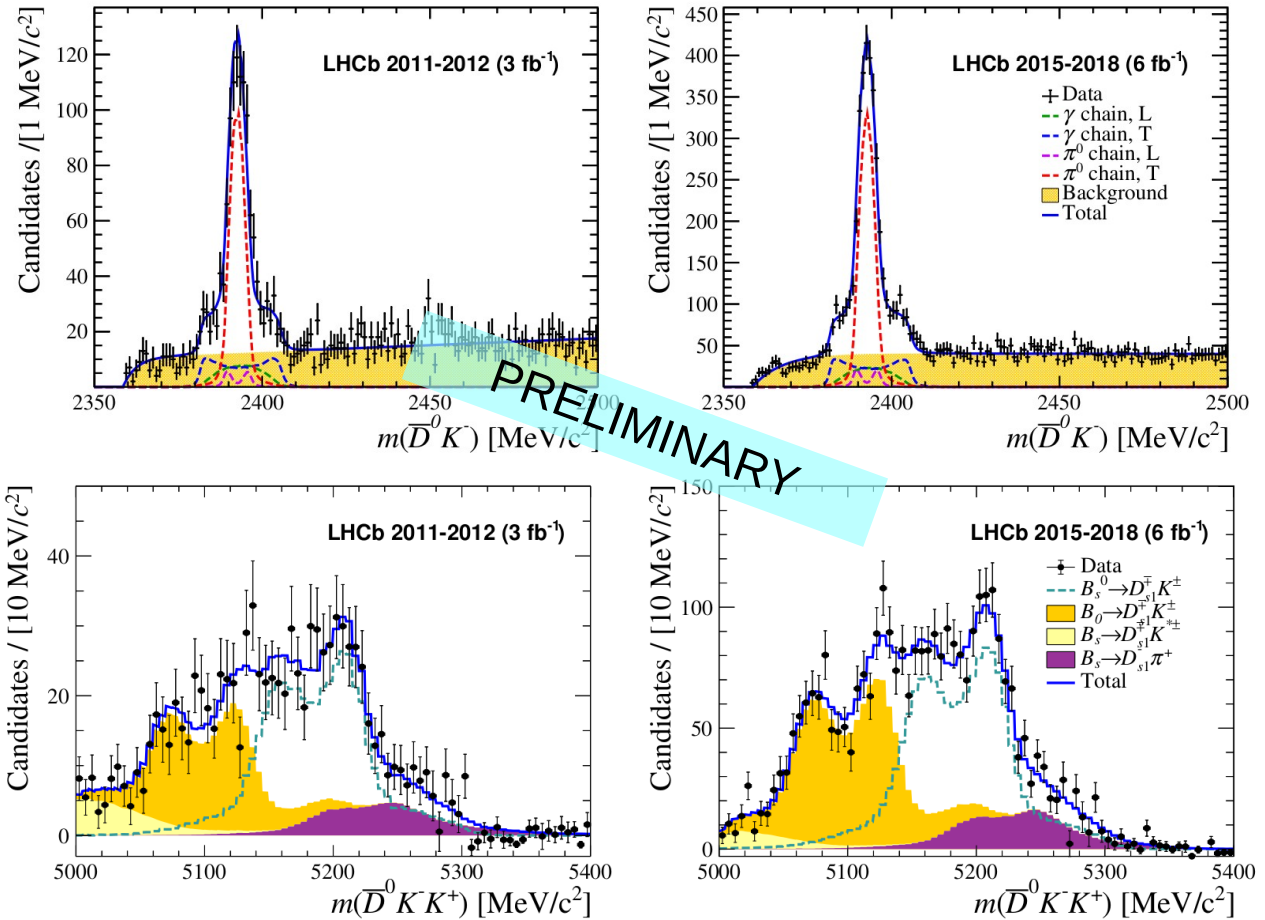
$B^0 \to \overline{D}^{*0} \pi^+ \pi^-$



First inspection of the Dalitz plots

Clear structures from (left and right) $D_1(2420)^-$, (middle) $D_{s1}(2536)^-$

Observation of $B_{(s)}^0 \to D_{s1}(2536)^{\mp} K^{\pm}$



LHCb-PAPER-2023-014
in preparation

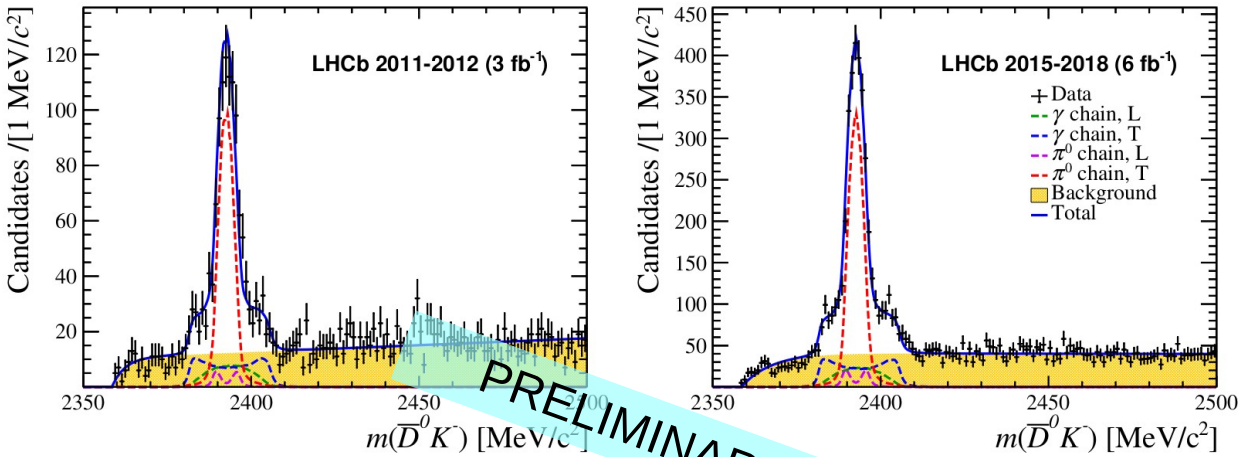
Partial reconstruction technique

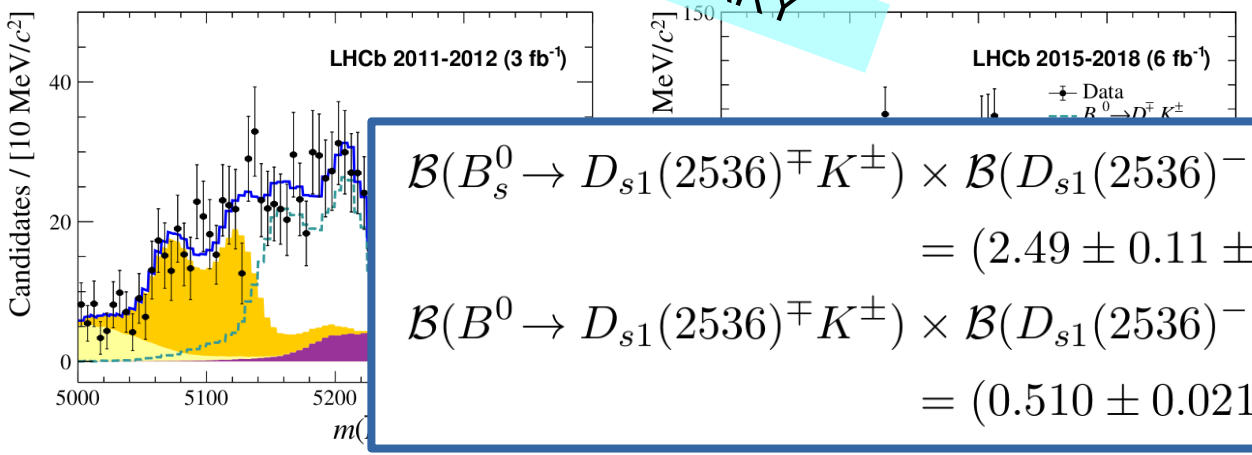
(soft neutral particles from D^{*0} decay not included in reconstructed final state)

Effective for narrow resonances

Spin structure imprinted on invariant mass distributions

Observation of $B_{(s)}^0 \to D_{s1}(2536)^{\mp} K^{\pm}$





LHCb-PAPER-2023-014
in preparation

Partial reconstruction technique

(soft neutral particles from D^{*0} decay not included in reconstructed final state)

Effective for narrow resonances

Spin structure imprinted on invariant mass distributions

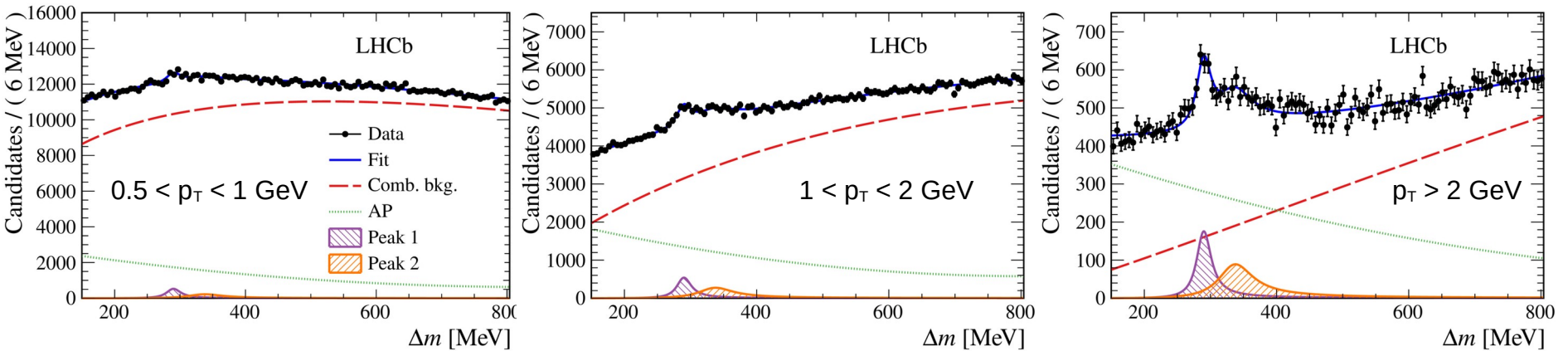
$$\mathcal{B}(B_s^0 \to D_{s1}(2536)^{\mp} K^{\pm}) \times \mathcal{B}(D_{s1}(2536)^- \to \overline{D}^{*0} K^-) = (2.49 \pm 0.11 \pm 0.12 \pm 0.25 \pm 0.06) \times 10^{-5},$$

$$\mathcal{B}(B^0 \to D_{s1}(2536)^{\mp} K^{\pm}) \times \mathcal{B}(D_{s1}(2536)^- \to \overline{D}^{*0} K^-) = (0.510 \pm 0.021 \pm 0.036 \pm 0.050) \times 10^{-5}.$$

Beauty & beauty-strange mesons

- Studies of prompt production background dominated
  - e.g. BK spectrum

EPJ C81 (2021) 601

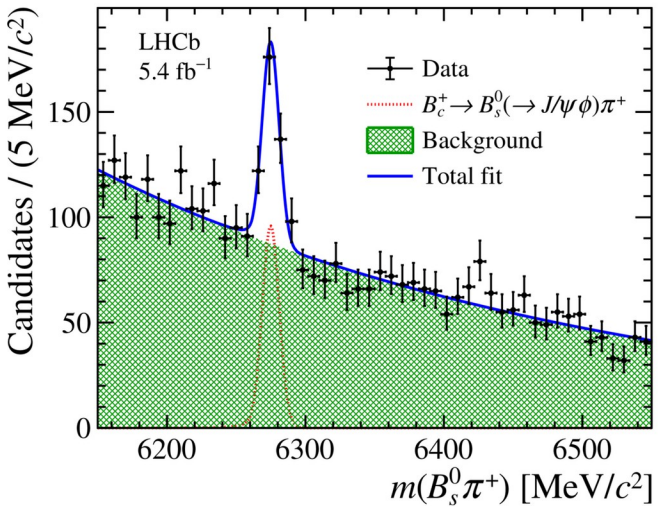


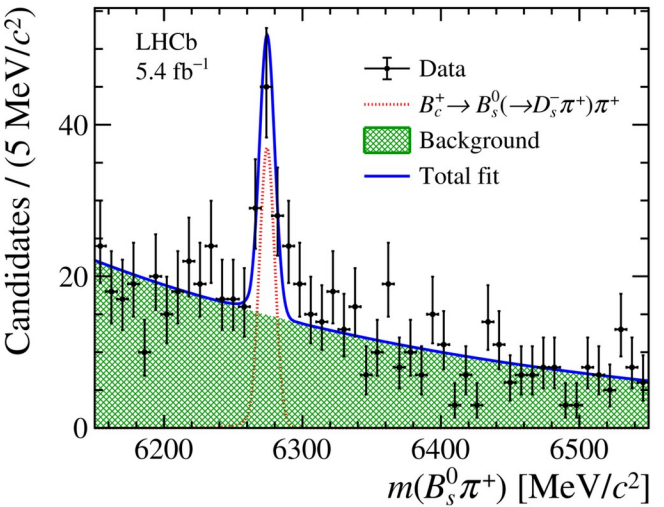
Two peaks observed but do they originate from decays to BK or B*K?

$B_c \rightarrow B_{(s)}$

arXiv:2210.12000
to appear in JHEP

- However, samples approaching size where B_c decays can be used to study $B_{(s)}$ spectroscopy
  - will open many possibilities ...





$B_c^+ \to B_s^0\pi^+$ previously observed in PRL 111 (2013) 181801 and used for B_c^+ mass measurement in JHEP 07 (2020) 123

The LHCb detector

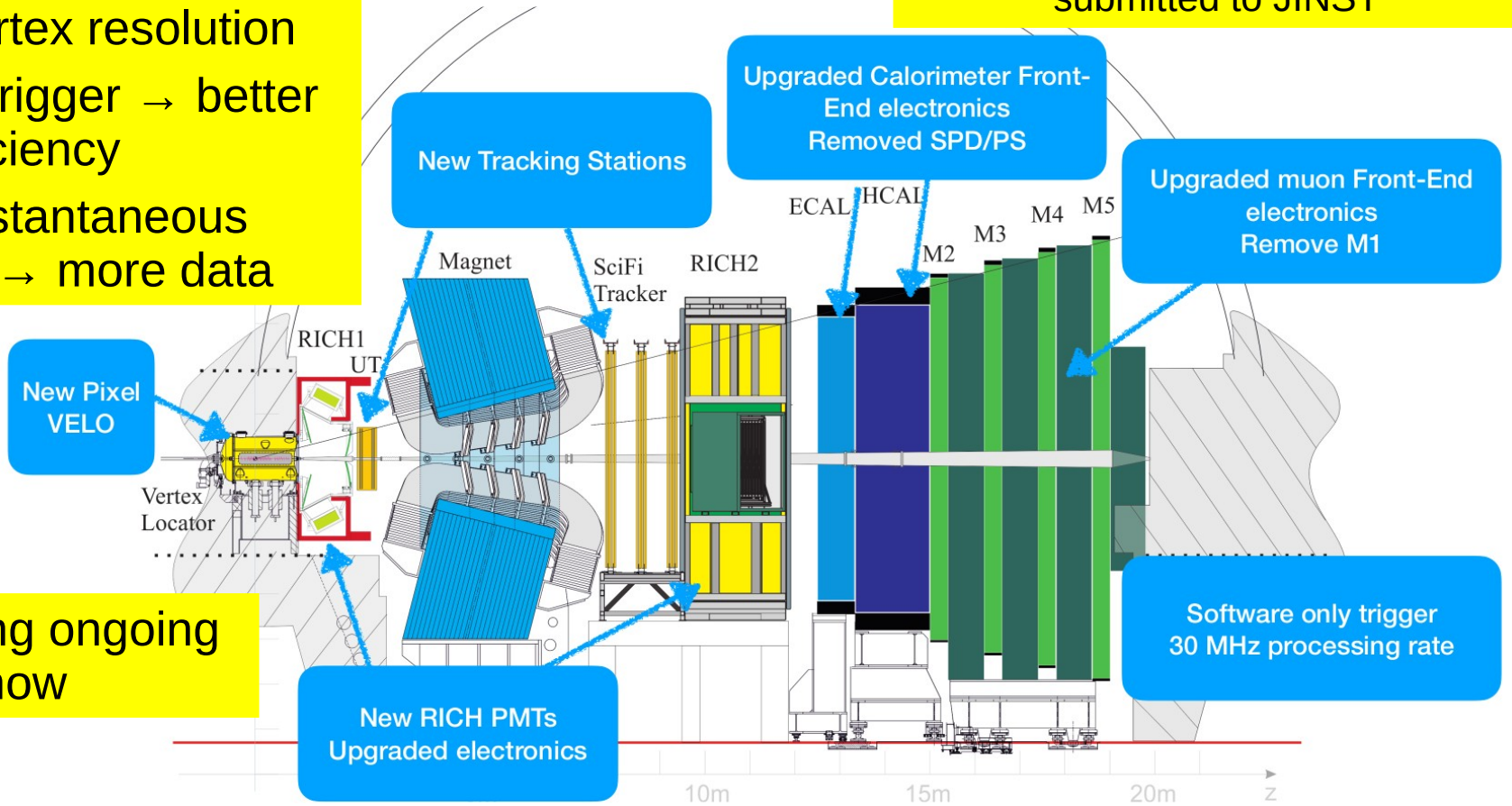
(2022-32 edition)

arXiv:2305.10515
submitted to JINST

VELO pixels & thinned RF foil → better vertex resolution

All software trigger → better efficiency

Higher instantaneous luminosity → more data



Commissioning ongoing right now

The LHCb detector

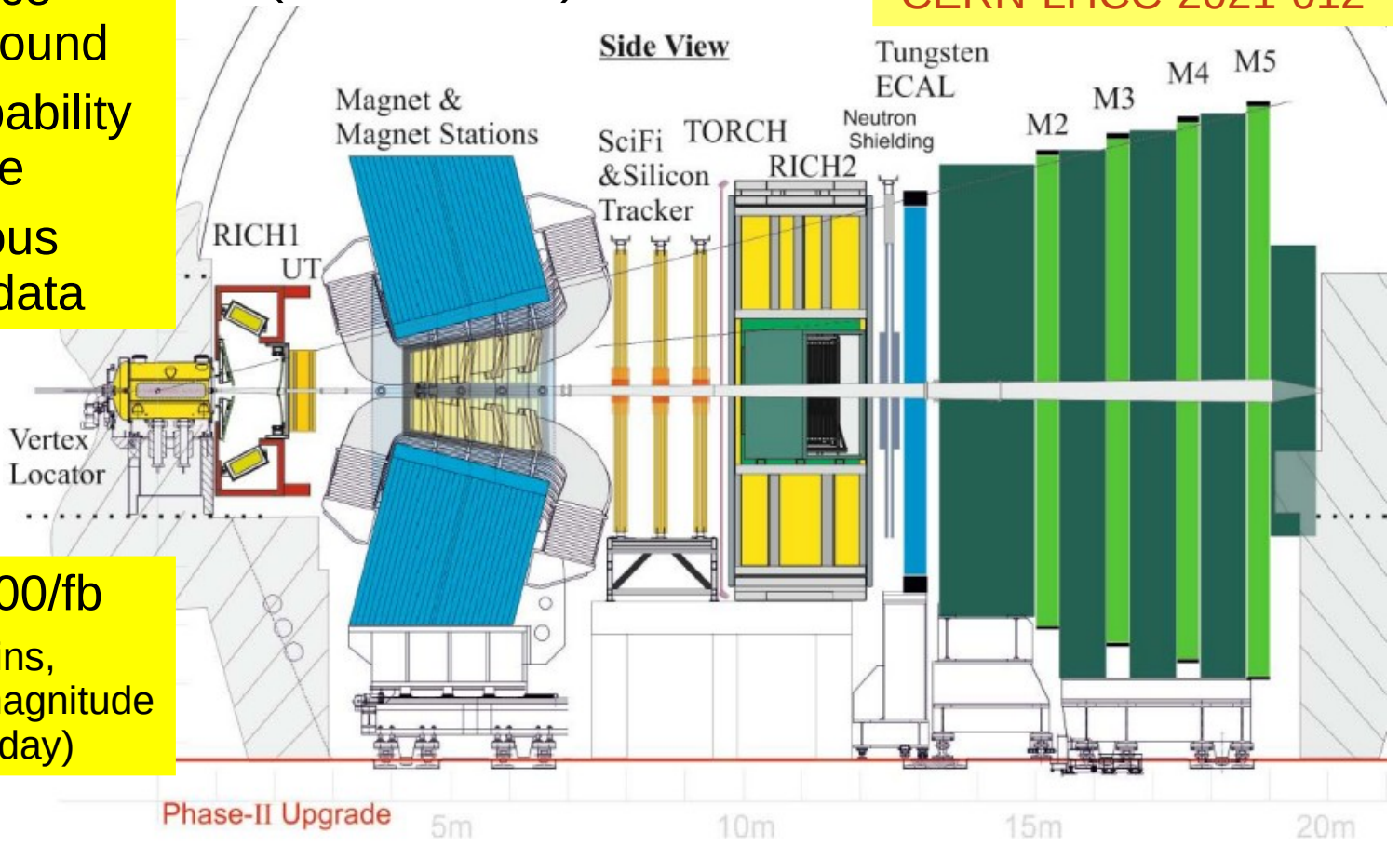
(final edition)

CERN-LHCC-2017-003
CERN-LHCC-2021-012

Use timing to reduce combinatorial background

Improve detection capability wherever possible

Higher instantaneous luminosity → more data



Aim to record over 300/fb

(Including efficiency gains, approximately two order of magnitude increase compared to today)

Summary

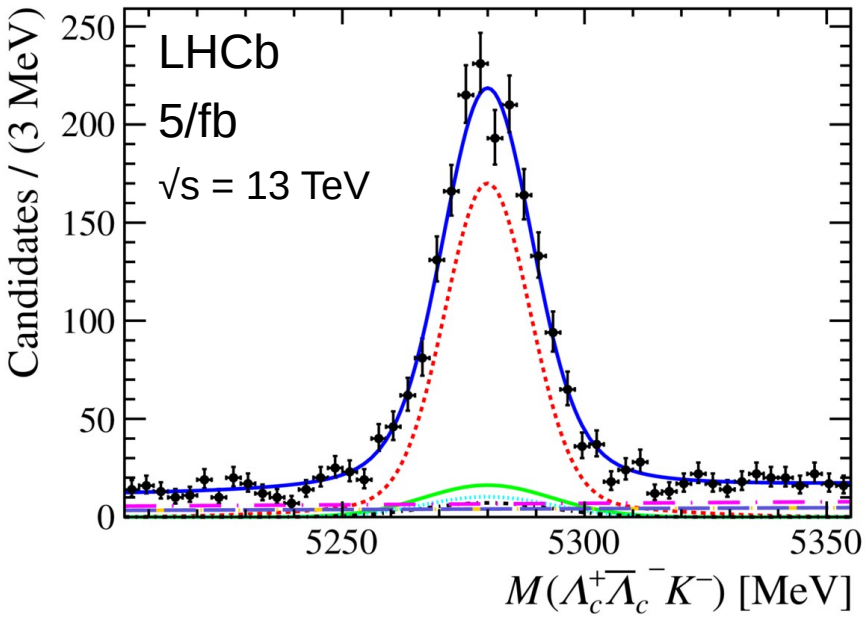
- LHCb's unique data sample providing novel insights into heavy meson spectroscopy
  - including many results on exotics, not covered in this talk
- Plenty more to come with existing data
  - … and Run 3 will provide increased yields with an upgraded detector
- Intriguing possibilities for improved understanding with larger samples
  - exploiting production in B_c decays
  - connecting signatures seen in different final states
- LHCb Upgrade 2 will be the ultimate LHC flavour physics experiment
  - two orders of magnitude more data compared to data

Back it up

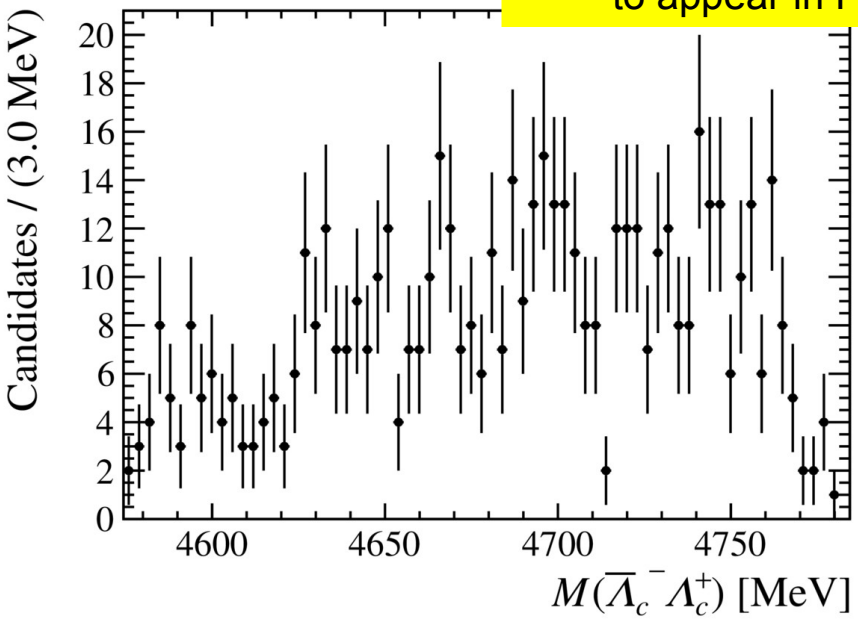
Charmonia decaying to $\Lambda_c^+\overline{\Lambda}_c^-$?

$B^+ \to \Lambda_c^+\overline{\Lambda}_c^- K^+$

arXiv:2211.00812
to appear in PRD



Signal yield of 1365 ± 42



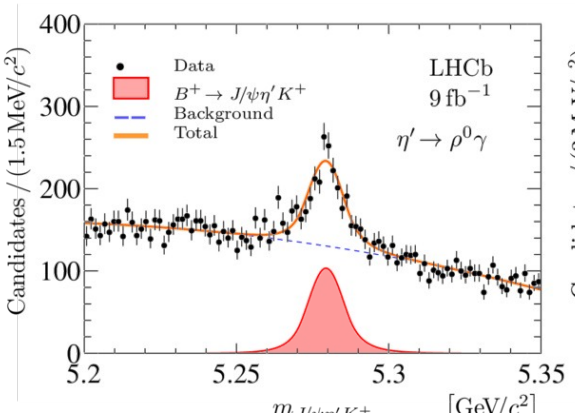
No clear structure

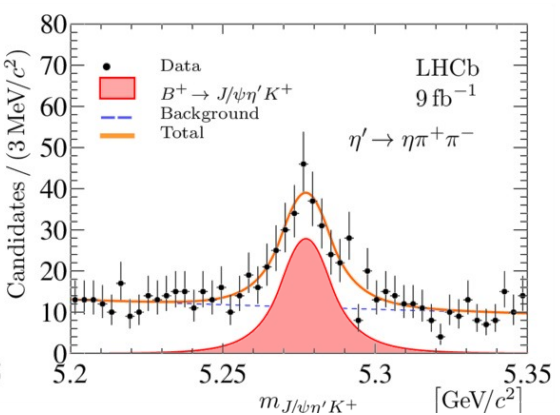
[2900 < m($\overline{\Lambda}_c^-K^+$) < 2970 MeV veto applied]

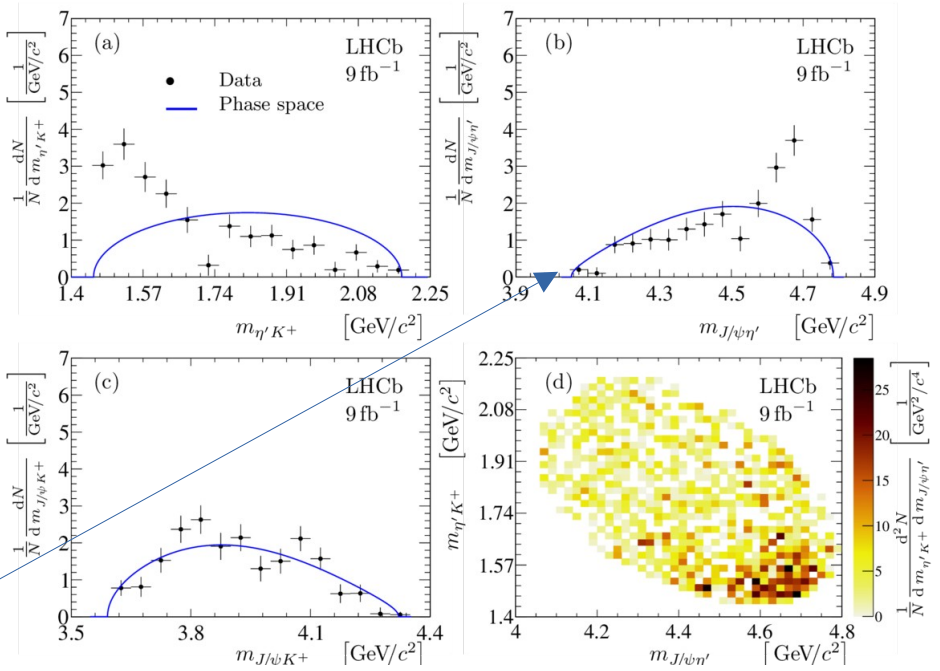
Charmonia decaying to J/ψη′?

arXiv:2303.09443
to appear in JHEP

$B^+ \to J/\psi\eta' K^+$





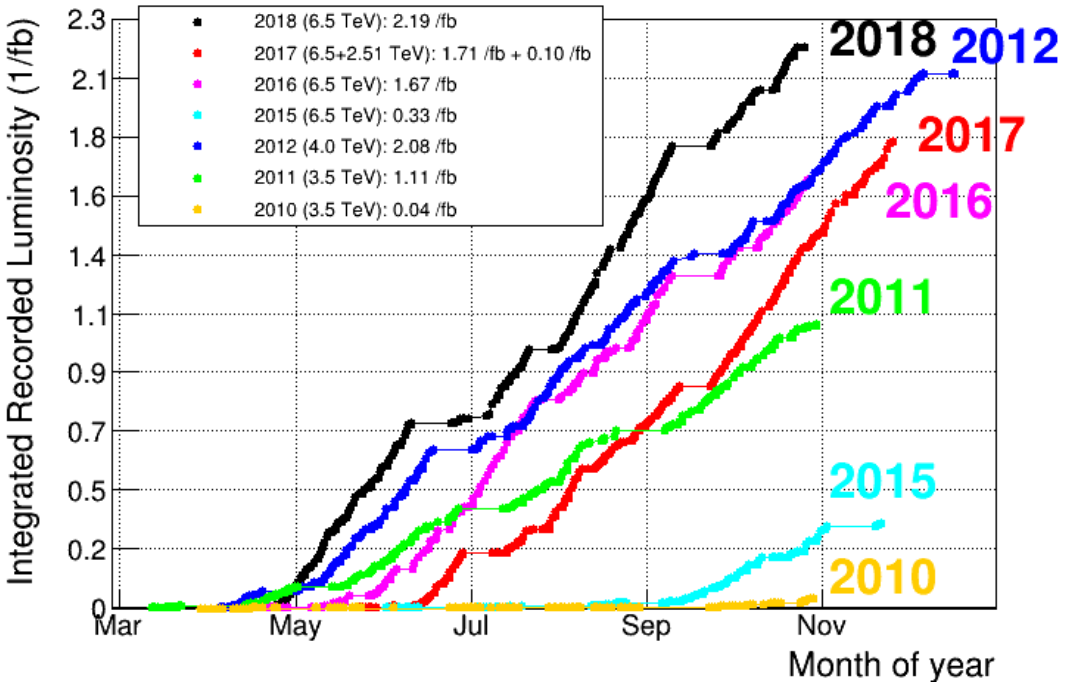


Signal yields of

- 1110 ± 110 [η′→ργ]
- 228 ± 28 [η′→ηπ⁺π⁻]

No clear charmonium structures

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