

Properties of the $X(3872)$ at LHCb

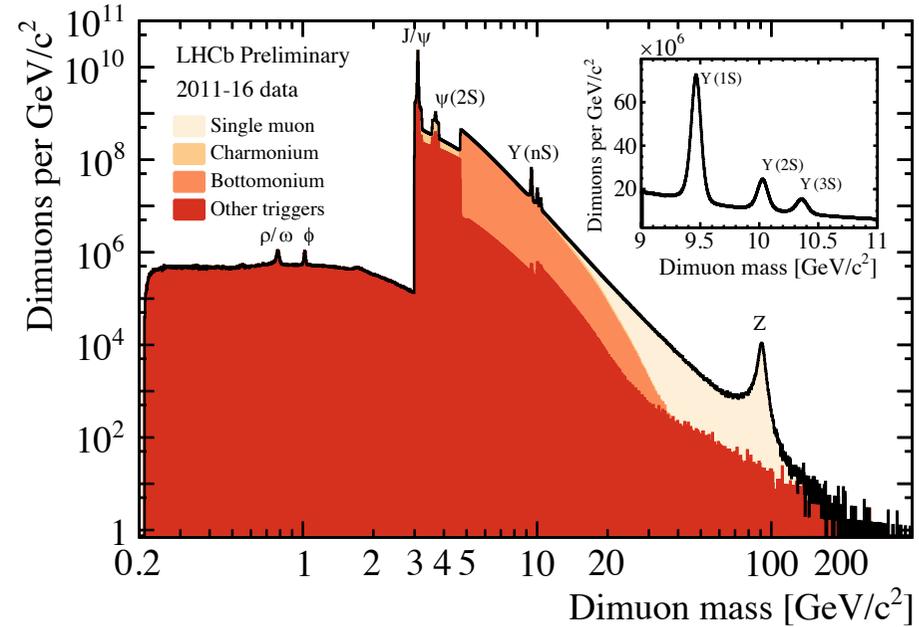
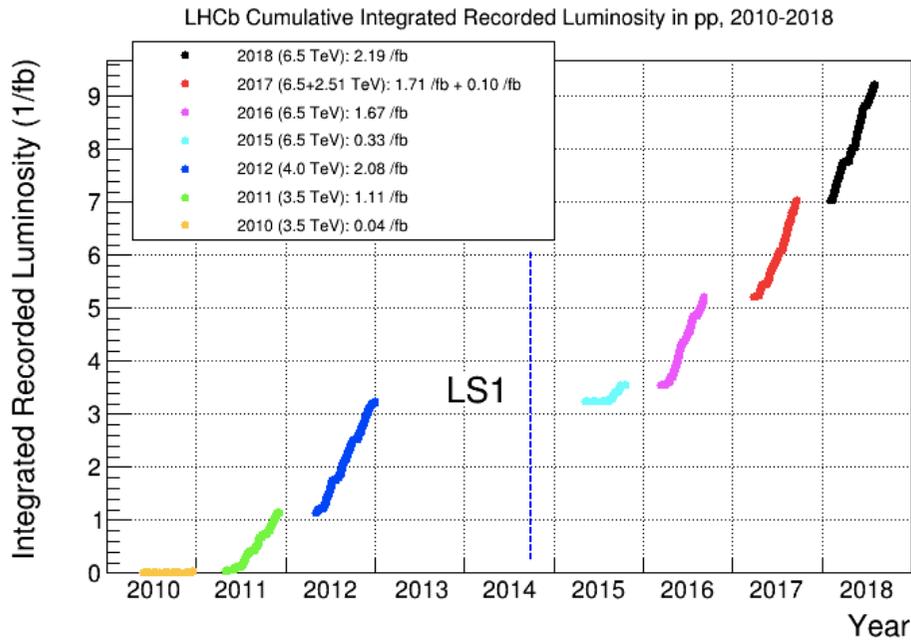
M. Needham

On behalf of the LHCb collaboration



QWG21: The 14th International Conference on Quarkonium
15th – 19th March 2021

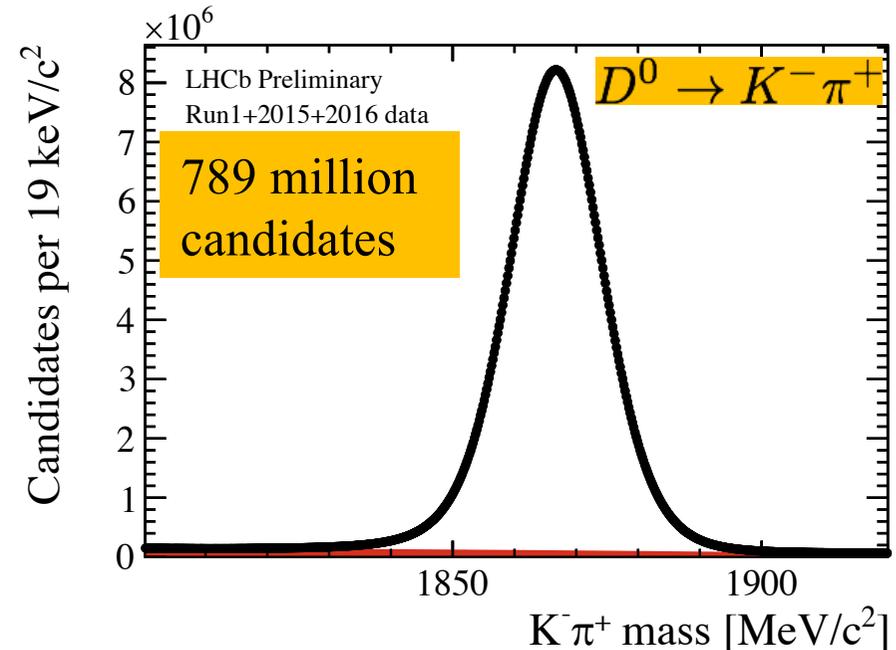
- Introduction
- Studies of the $X(3872)$ lineshape
 - JHEP 08 (2020) 123, PRD D102 (2020 092005)
- Multiplicity dependence of $X(3872)$ production
 - arXiv: 2009.06619
- Observation of the decay $B_s \rightarrow X(3872)\phi$
 - arXiv: 2011.01867



World largest heavy flavour dataset
(9 fb⁻¹) collected during Run1+Run2

- Precision tracking
- Excellent PID using RICH
- Trigger for fully hadronic decays

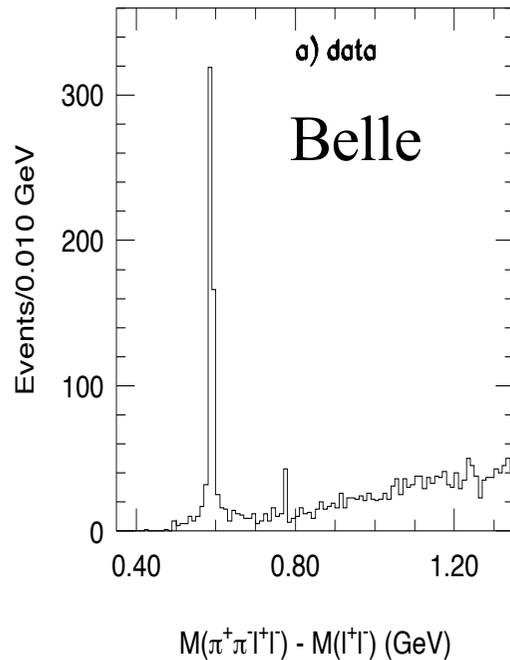
Int.J.Mod.Phys. A30 (2015) no.07, 1530022



arXiv: 2009.06619

The X(3872)

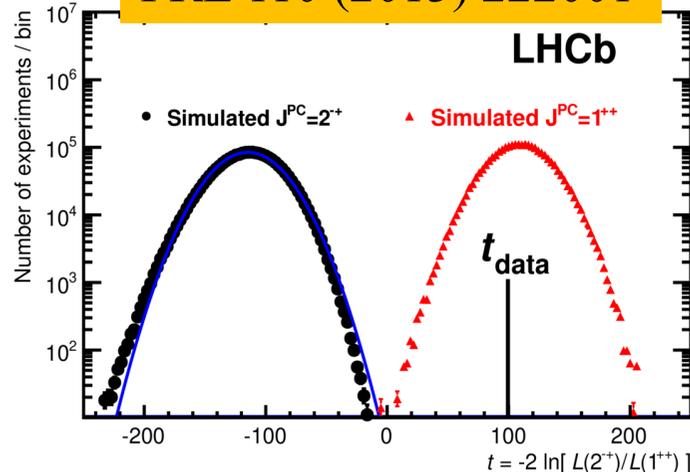
PRL 91 (2003) 262001



The discovery by Belle of the X(3872), also called the $\chi_{c1}(3872)$, in 2003 kick-started a golden era for hadronic spectroscopy

Since then, this state has been studied by many experiments: Babar, CDF, D0, ATLAS, CMS, LHCb and BESIII

PRL 110 (2013) 222001



Quantum numbers measured to be 1^{++} by LHCb using Run 1 data

Question: So what is this state?

The X(3872)

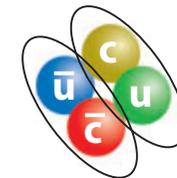
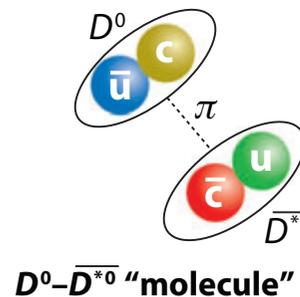
Striking features of the X(3872): Its very narrow, despite being above open charm threshold. Its mass is almost coincident with the DD^* threshold

Conventional charmonium? $\chi_{c1}(2P)$ has 1^{++} quantum numbers, but predicted mass and width are larger

DD^* molecule: Explains proximity to DD^* threshold but challenge to explain prompt production

Compact Tetraquark: where are the partners?

Mixed state: wavefunction with quarkonium core + sizeable DD^* component



Diquark-diantiquark



$q\bar{q}$ -gluon hybrid



X(3872) lineshape @ LHCb



Two complementary studies published last year of X(3872) lineshape in the decay $J/\psi\pi^+\pi^-$

Exclusive $B^+ \rightarrow X(3872) K^+$

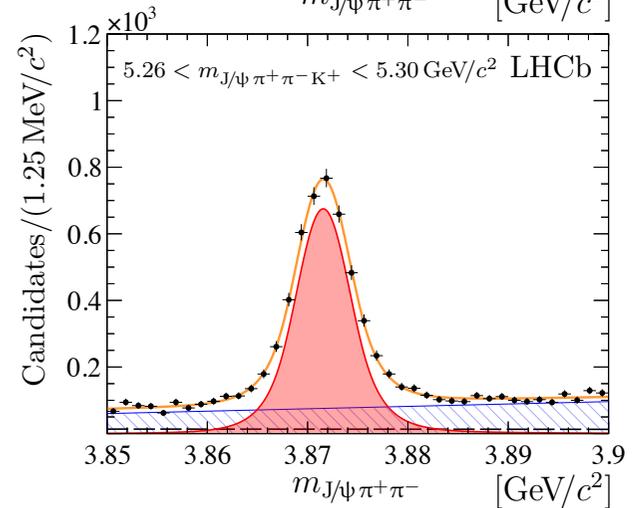
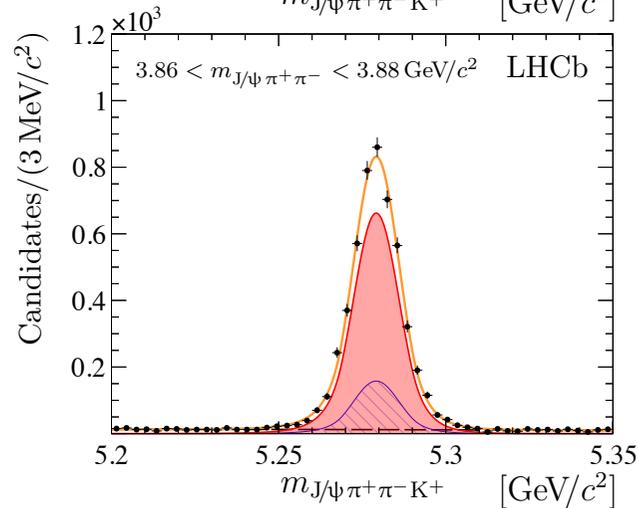
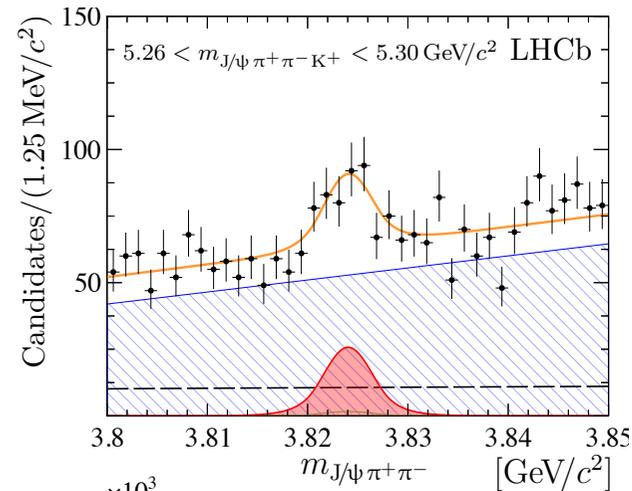
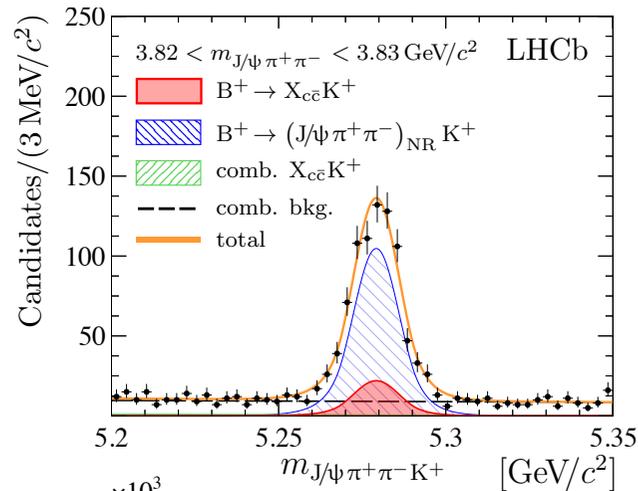
- Full Run 1+ 2 dataset, 9 fb^{-1}
- Very clean but statistically limited (4230 signal candidates)
- Can leverage constraints from B^+ mass and pointing of B^+ to primary vertex to have best mass resolution

Inclusive sample of detached X(3872) from b-hadron decays

- Analysis uses Run 1 dataset only (3 fb^{-1})
- More background but larger signal (~ 14000 signal candidates)

Study of $B^+ \rightarrow X(3872) K^+$

JHEP 08 (2020) 123



$\psi(3823)$ mass
 region: 137 ± 26
 signal candidates
 Significance 5.1σ

First observation of
 $J/\psi \pi^+ \pi^-$ decay mode

$X(3872)$ mass region:
 4230 ± 70
 signal candidates

Fit model Breit-Wigner
 convolved with detector
 resolution

Very clear signals for $X(3872)$ and $\psi(3823)$ decays to $J/\psi \pi^+ \pi^-$
 allowing to measure resonance parameters

Study of $B^+ \rightarrow X(3872) K^+$

- Measure mass splitting with respect to the $\psi(2S)$ to minimize systematics

$$m_{\chi_{c1}(3872)} - m_{\psi_2(3823)} = 47.50 \pm 0.53 \pm 0.13 \text{ MeV}/c^2$$

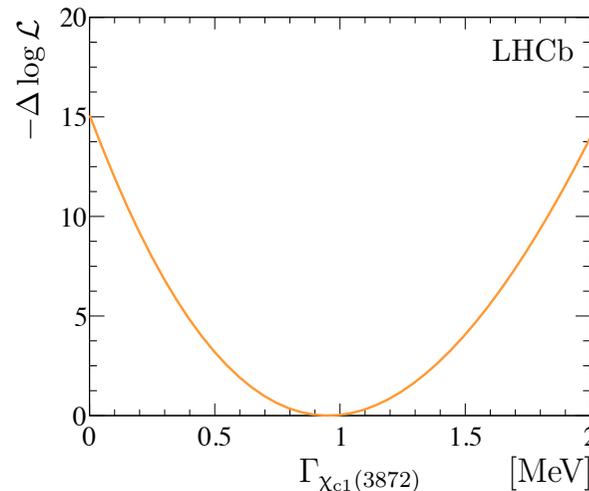
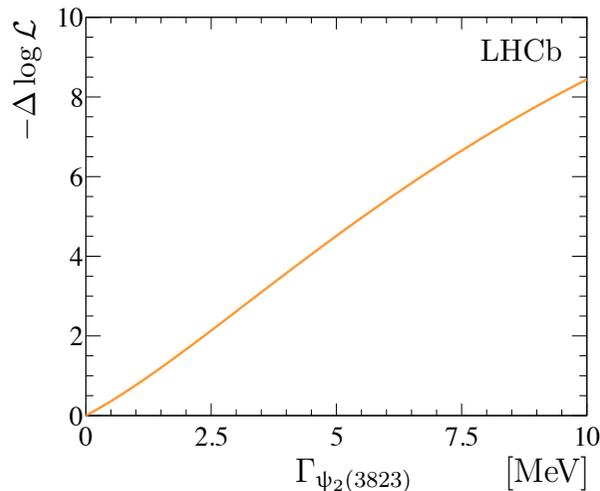
$$m_{\psi_2(3823)} - m_{\psi(2S)} = 137.98 \pm 0.53 \pm 0.14 \text{ MeV}/c^2$$

$$m_{\chi_{c1}(3872)} - m_{\psi(2S)} = 185.49 \pm 0.06 \pm 0.03 \text{ MeV}/c^2$$

Dominant systematic for $X(3872)$ mass measurement from B^+ mass

- $B^+ \rightarrow \psi(2S)K^+$ with $\psi(2S) \rightarrow J/\psi\pi^+\pi^-$ for data driven calibration of the resolution scale between data and MC

JHEP 08 (2020) 123



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

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

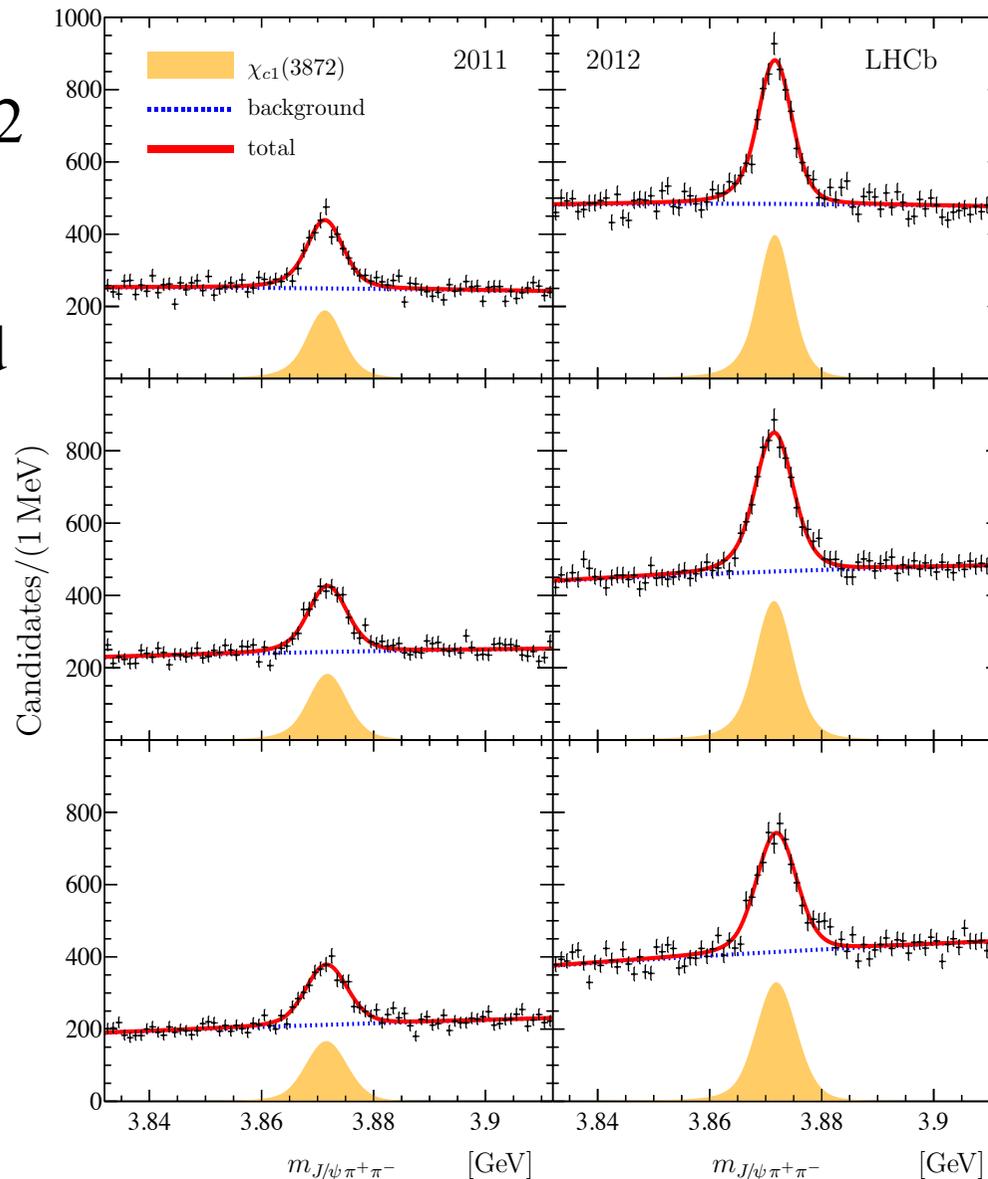
(including systematics)

Simultaneous fit to data separated into 2011 and 2012

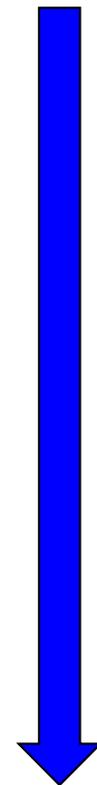
Also divide data into 3 bins of $P(\pi^+ \pi^-)$: highly correlated with mass resolution

Initial fits assume a Breit-Wigner lineshape for signal which is convolved with detector resolution

$\psi(2S)$ used to provide data driven calibration of mass resolution



Best Resolution
low $P(\pi^+ \pi^-)$



Worst Resolution
high $P(\pi^+ \pi^-)$

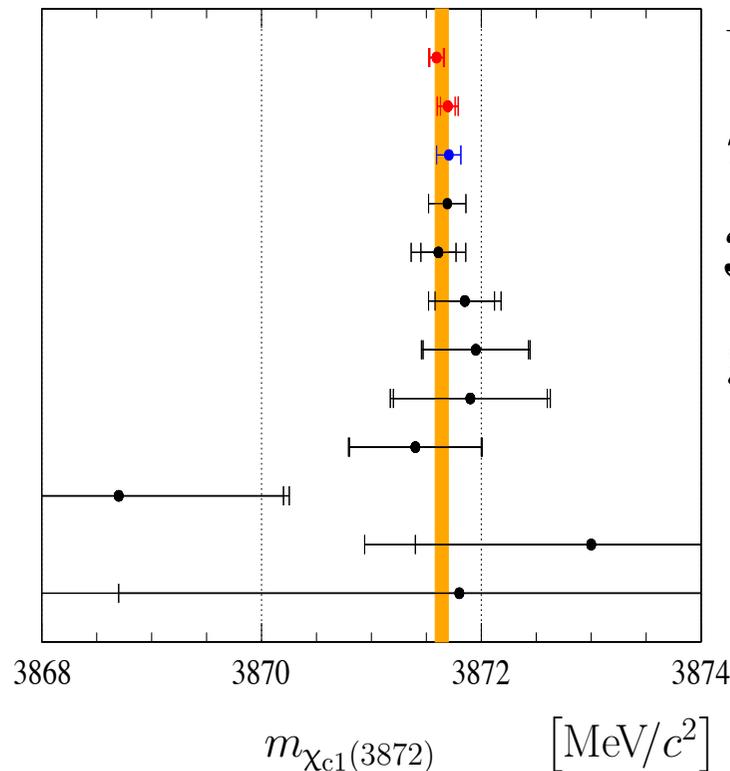
Mass splitting to $\psi(2S)$: $\Delta m = 185.598 \pm 0.067 \pm 0.068 \text{ MeV}$

Dominant systematic
momentum scale

Averaging LHCb
measurements:

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

- LHCb $B^+ \rightarrow \chi_{c1}(3872)K^+$
- LHCb $b \rightarrow \chi_{c1}(3872)X$
- $m_{D^0} + m_{D^{*0}}$
- PDG 2018
- CDF $p\bar{p} \rightarrow \chi_{c1}(3872)X$
- Belle $B \rightarrow \chi_{c1}(3872)K$
- LHCb $pp \rightarrow \chi_{c1}(3872)X$
- BES III $e^+e^- \rightarrow \chi_{c1}(3872)\gamma$
- BaBar $B^+ \rightarrow \chi_{c1}(3872)K^+$
- BaBar $B^0 \rightarrow \chi_{c1}(3872)K^0$
- BaBar $B \rightarrow (\chi_{c1}(3872) \rightarrow J/\psi \omega) K$
- D0 $p\bar{p} \rightarrow \chi_{c1}(3872)X$



Using:

$$m(D^0) + m(D^{*0}) = 3871.70 \pm 0.11 \text{ MeV}/c^2$$

gives

$$\delta E \Big|_{\text{LHCb}} = 0.07 \pm 0.12 \text{ MeV}$$

Detached $X(3872) \rightarrow J/\psi\pi^+\pi^-$

Breit-Wigner
width

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

LHCb average: $\Gamma_{\text{BW}} = 1.19 \pm 0.19 \text{ MeV}$

LHCb $B^+ \rightarrow \chi_{c1}(3872)K^+$

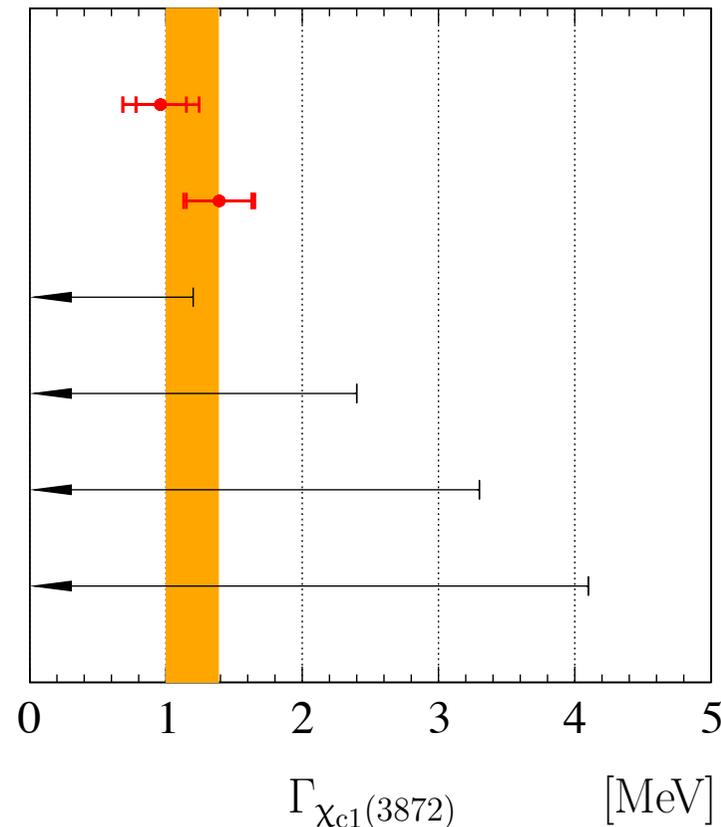
LHCb $b \rightarrow \chi_{c1}(3872)X$

Belle

BES III

BaBar

BaBar



First measurement
of non-zero width
for $X(3872)$

Flatte fits to $X(3872) \rightarrow J/\psi \pi^+ \pi^-$

Since $X(3872)$ is narrow and close to opening of DD^* threshold, Breit-Wigner may not be valid as lineshape

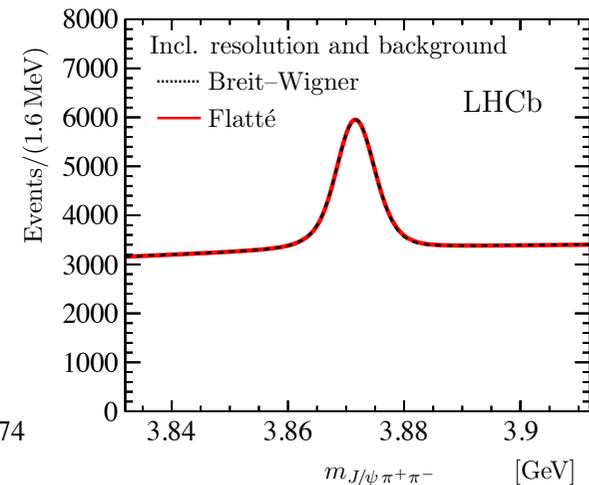
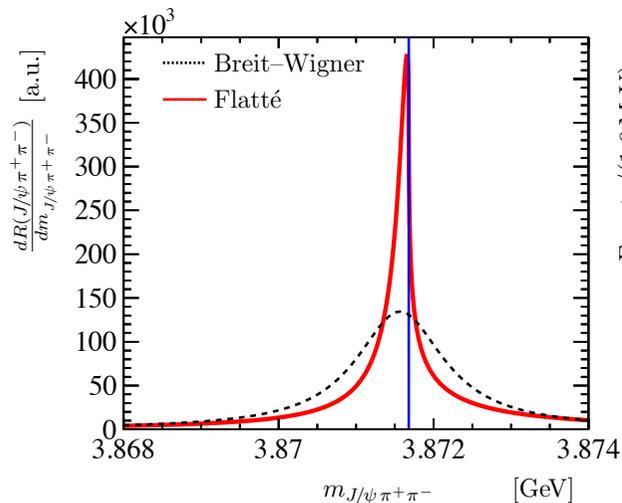
Explore Flatte-like parameterization (PRD76 (2007) 0345007, PRD80 (2009) 074004, PRD 81 (2010) 090028)

	g	$f_\rho \times 10^3$	Γ_0 [MeV]	m_0 [MeV]
Best fit Flatte parameters	0.108 ± 0.003	1.8 ± 0.6	1.4 ± 0.4	3864.5 (fixed)

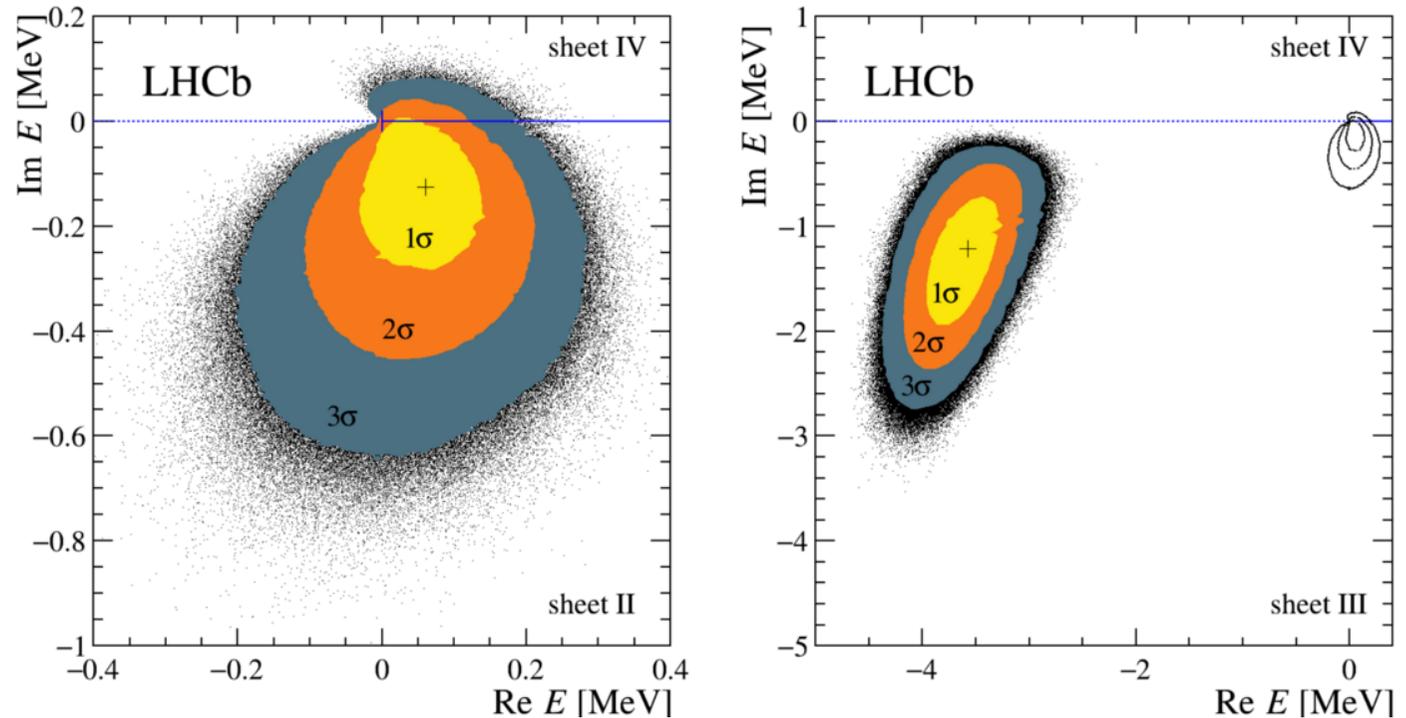
	Mode [MeV]	Mean [MeV]	FWHM [MeV]
	$3871.69^{+0.00+0.05}_{-0.04-0.13}$	$3871.66^{+0.07+0.11}_{-0.06-0.13}$	$0.22^{+0.06+0.25}_{-0.08-0.17}$

Mode of Flatte agrees well with BW mean

FWHM is less by factor five



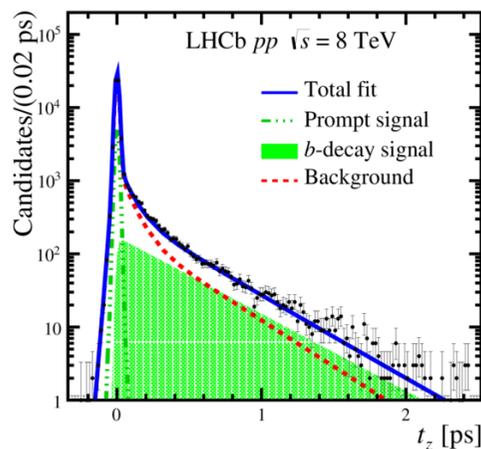
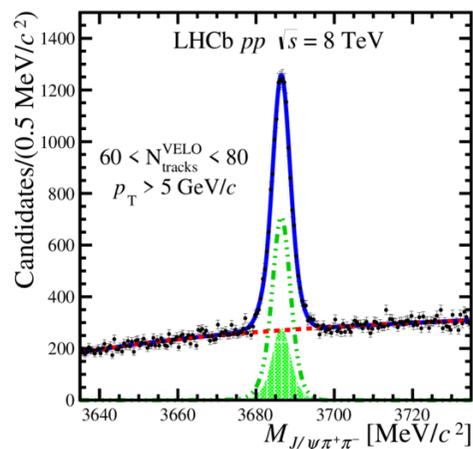
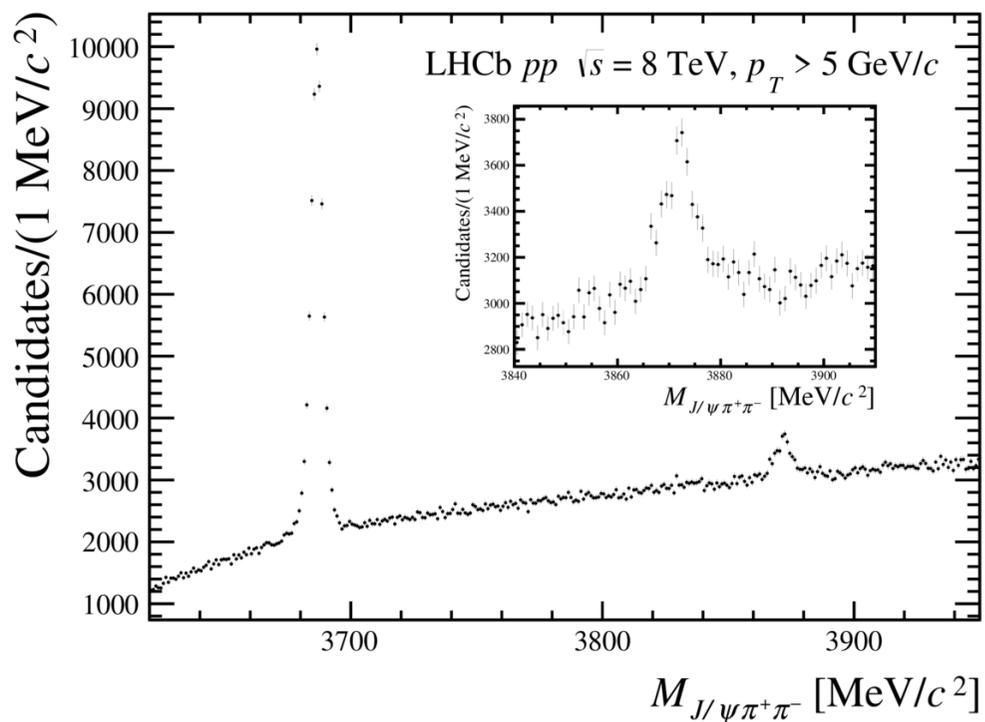
Poles found on the unphysical sheet II and III with respect to the $J/\psi\pi^+\pi^-$ channel



With respect to the DD^* channel, one channel on the physical sheet corresponding to a quasi-bound DD^* , with binding energy < 100 keV (at 90 % CL)

X(3872) production versus event multiplicity

arXiv: 2009.06619



Use data taken at 8 TeV in 2012

Select inclusive samples of X(3872) and $\psi(2S)$

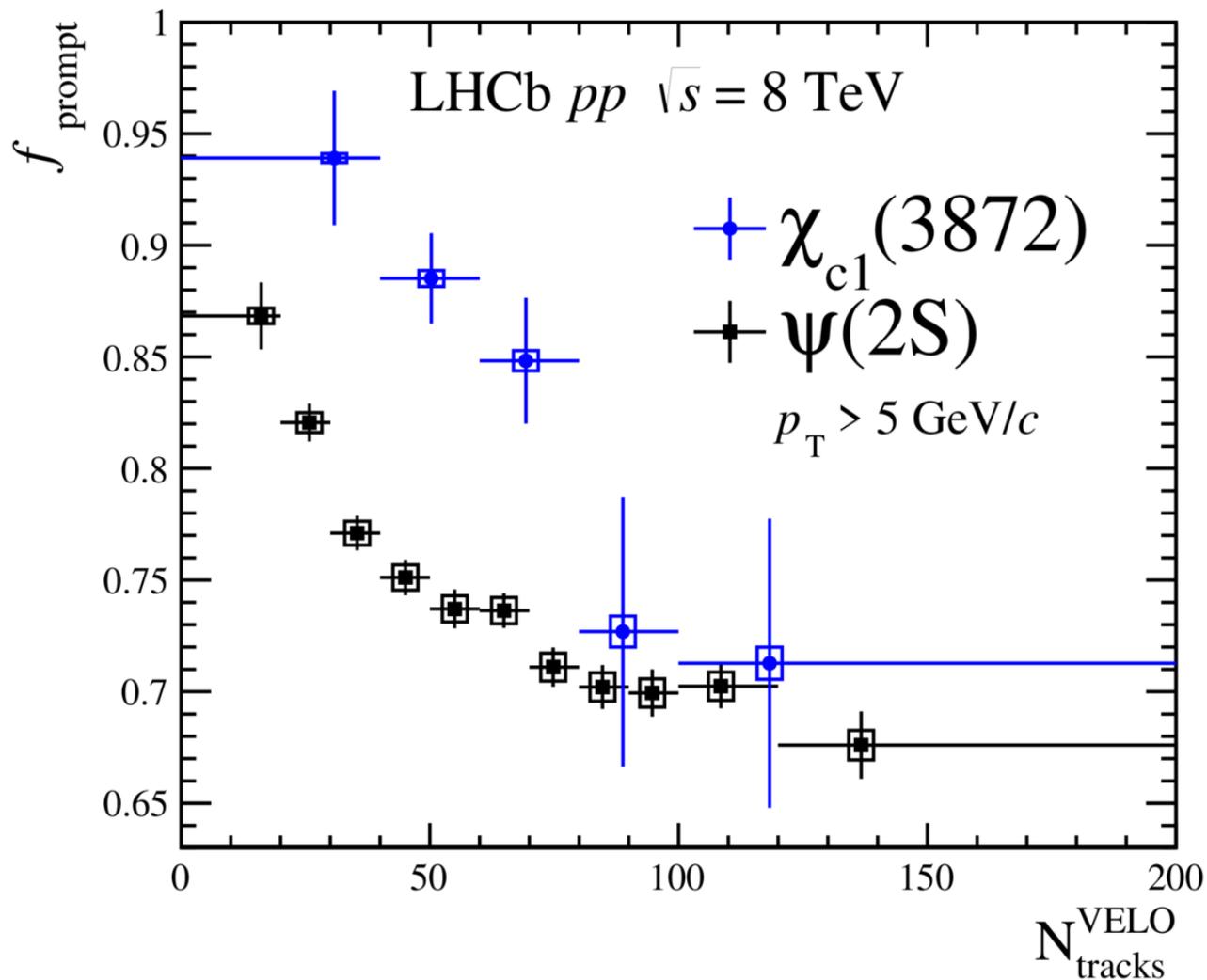
Bin in number of vertex detector tracks (estimator of multiplicity)

Fit mass and time to separate prompt and from b components

$$t_z \equiv \frac{(z_{\text{decay}} - z_{\text{PV}}) \times M}{p_z}$$

X(3872) production versus multiplicity

arXiv: 2009.06619

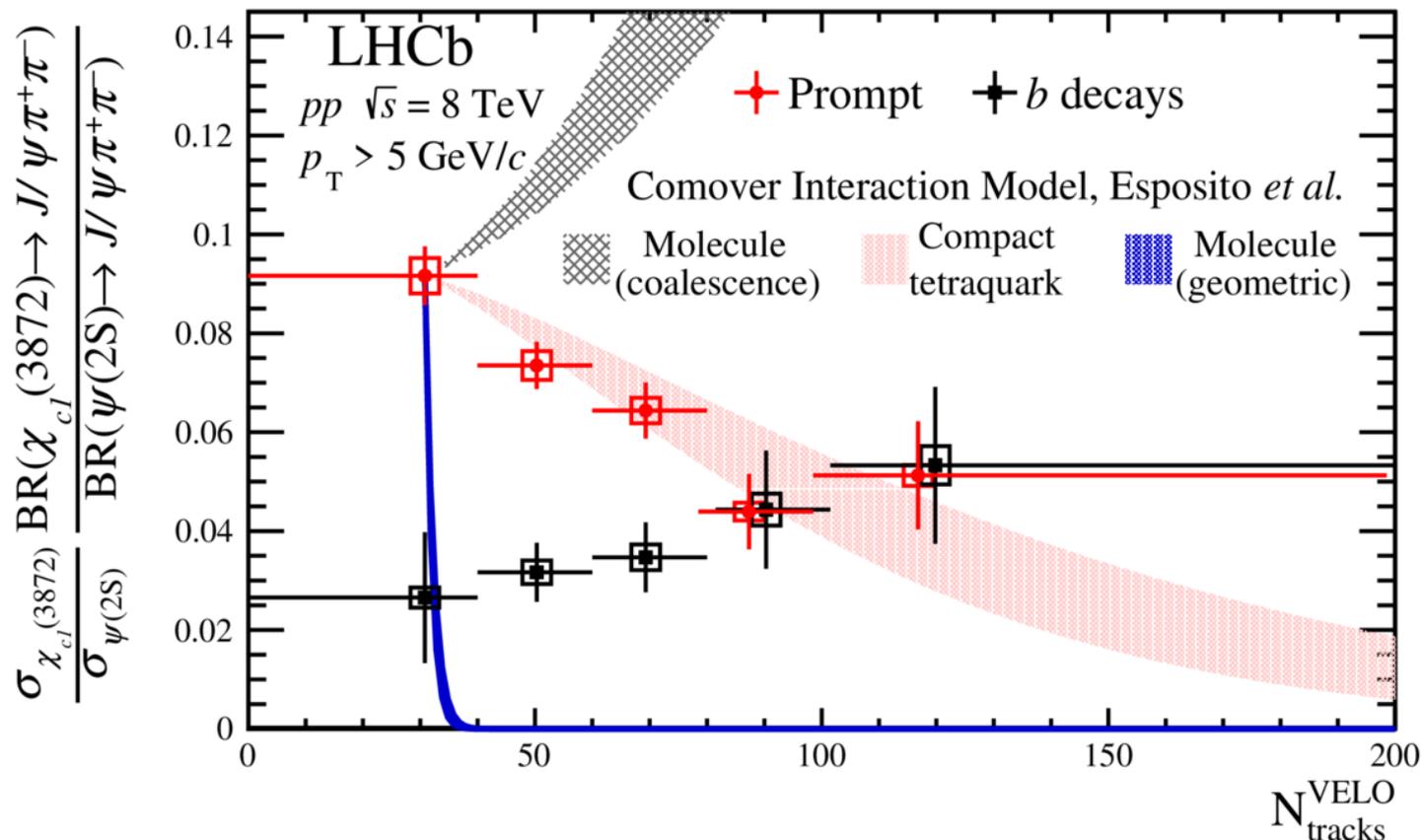


Prompt fraction decreases with multiplicity for both states

X(3872) production versus multiplicity

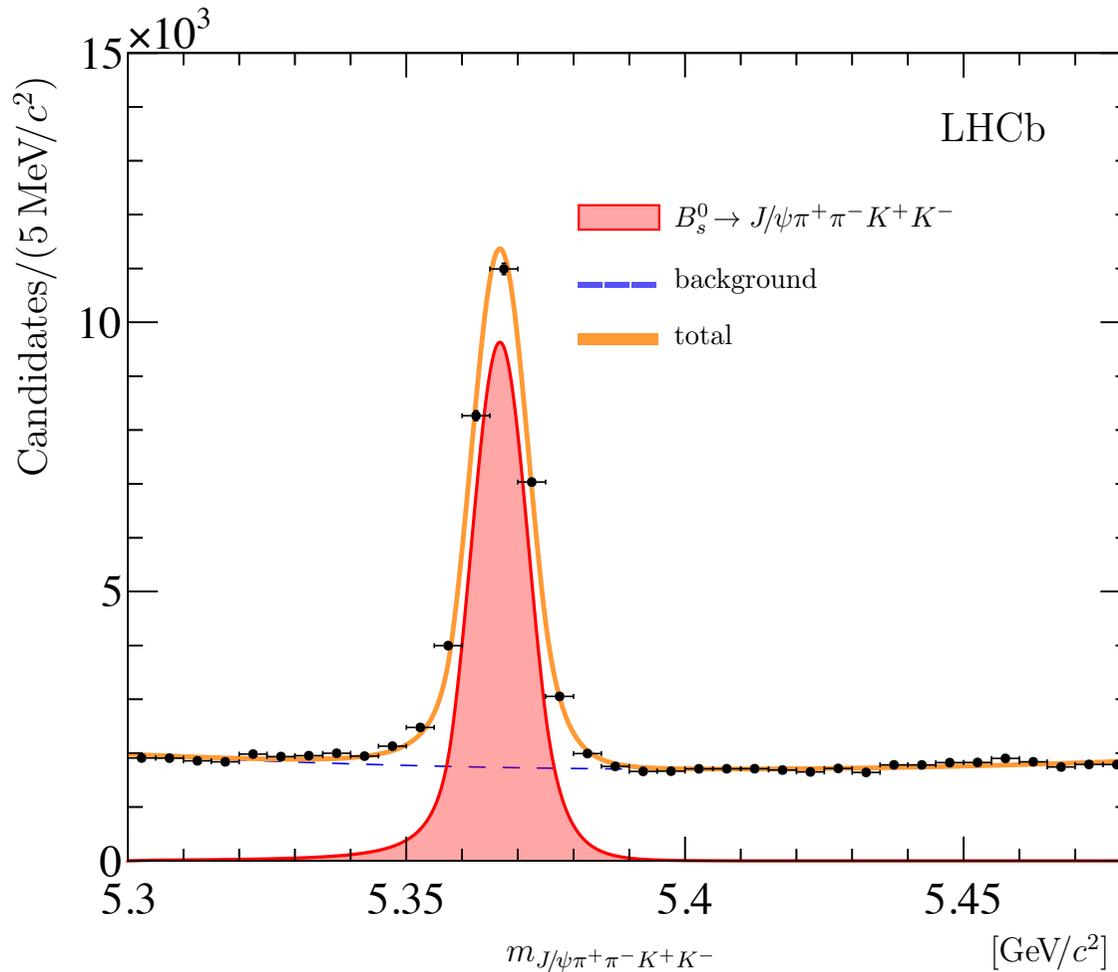
Also extract the ratio of cross-sections * BF versus multiplicity and compare to predictions of Comover model in arXiv:2006.15044. See also arxiv:2012.13499 for a discussion of this paper.

arXiv: 2009.06619



$B_s \rightarrow X(3872) \phi$

arXiv: 2011.01867

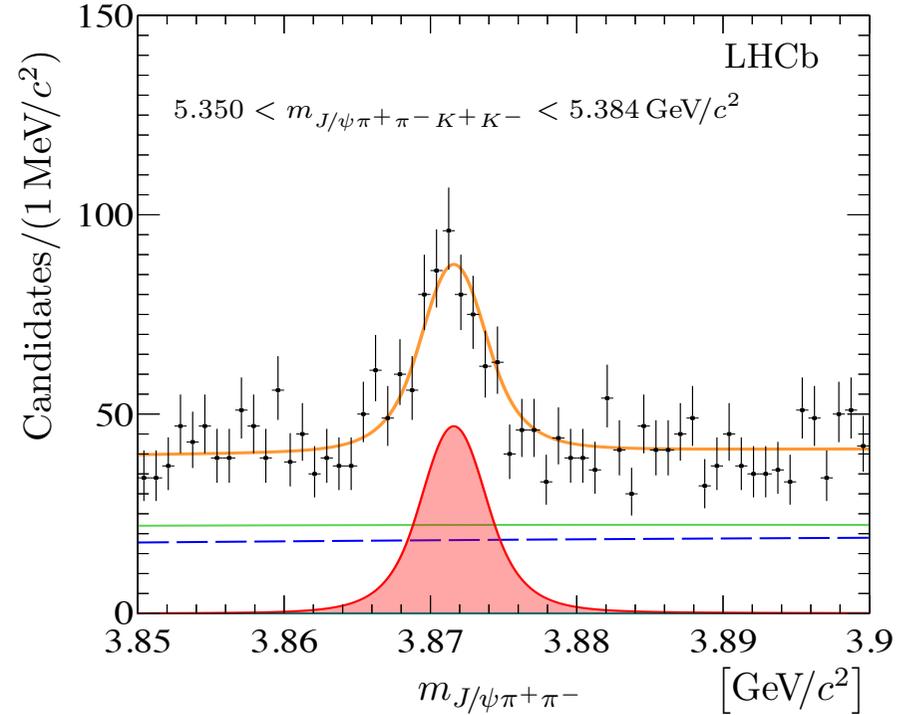
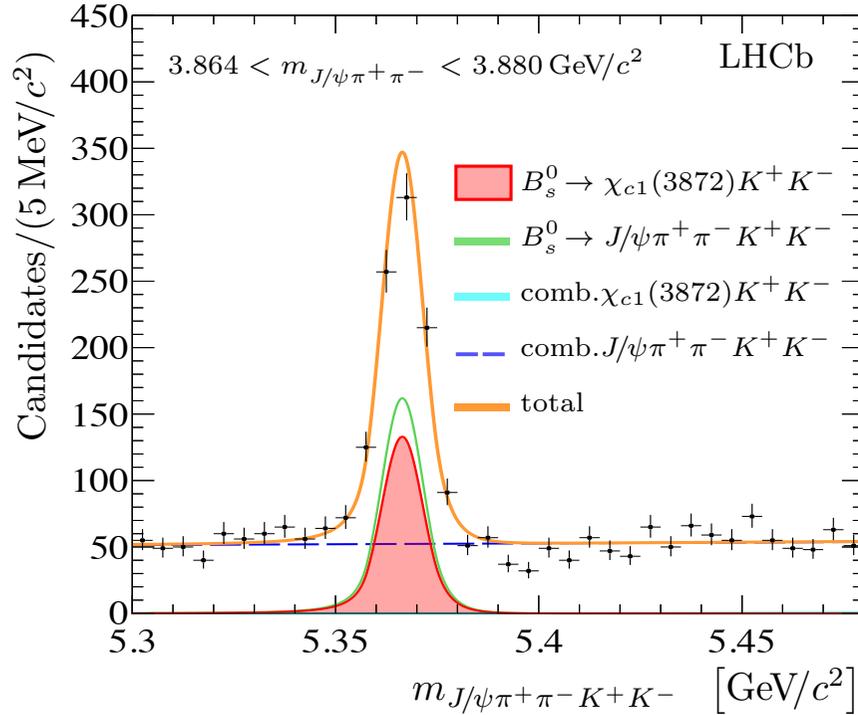


Large clean sample of $B_s \rightarrow J/\psi K^+ K^- \pi^+ \pi^-$ from full Run 1+2 dataset

Use to study the decay $B_s \rightarrow X(3872) \phi$

$B_s \rightarrow X(3872) \phi$

arXiv: 2011.01867



Clear signal observed Significance $> 10\sigma$, Measure

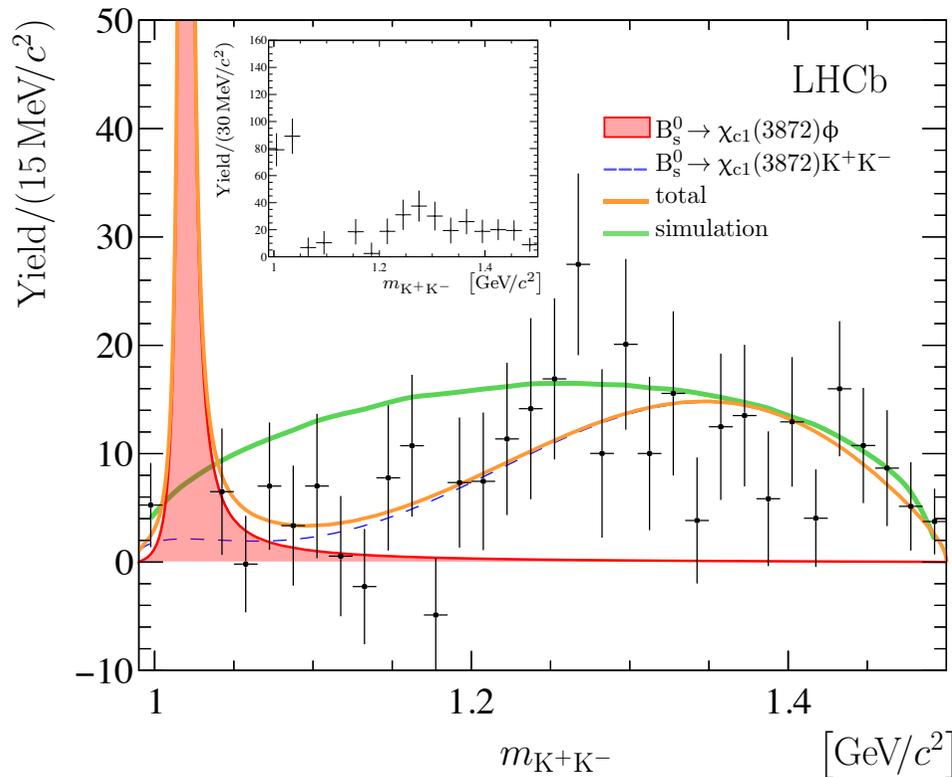
$$\mathcal{R}_{\psi(2S)\phi}^{\chi_{c1}(3872)\phi} \equiv \frac{\mathcal{B}(B_s^0 \rightarrow \chi_{c1}(3872)\phi) \times \mathcal{B}(\chi_{c1}(3872) \rightarrow J/\psi\pi^+\pi^-)}{\mathcal{B}(B_s^0 \rightarrow \psi(2S)\phi) \times \mathcal{B}(\psi(2S) \rightarrow J/\psi\pi^+\pi^-)}$$

$$\mathcal{R}_{\psi(2S)\phi}^{\chi_{c1}(3872)\phi} = (2.42 \pm 0.23 \pm 0.07) \times 10^{-2}$$

Consistent with CMS value $(2.21 \pm 0.29 \pm 0.17) \times 10^{-2}$

$B_s \rightarrow X(3872) \phi$

Also see significant signal with KK mass above the ϕ resonance



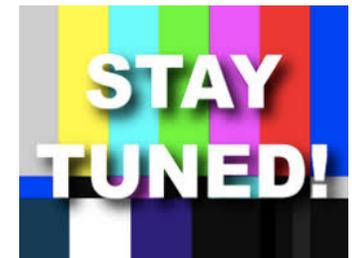
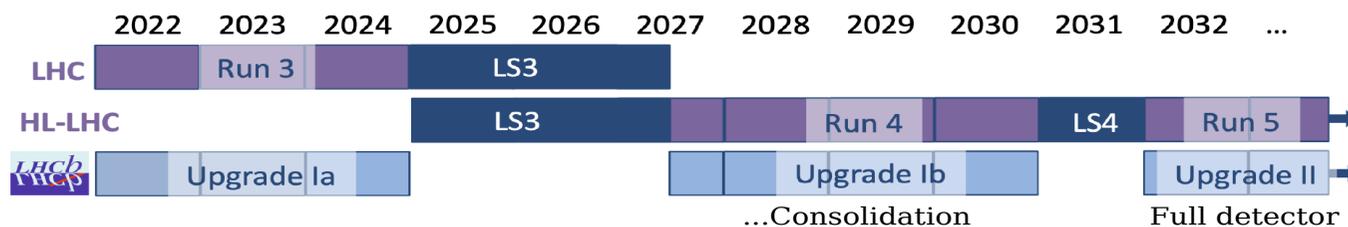
Define:

$$\mathcal{R}_{K^+K^-} \equiv \frac{\mathcal{B}(B_s^0 \rightarrow \chi_{c1}(3872) (K^+K^-)_{\text{non-}\phi})}{\mathcal{B}(B_s^0 \rightarrow \chi_{c1}(3872)\phi) \times \mathcal{B}(\phi \rightarrow K^+K^-)}$$

Fit KK mass with resonant ϕ and non-resonant components

$$\mathcal{R}_{K^+K^-} = 1.57 \pm 0.32 \pm 0.12$$

- The nature of the X(3872) still continues to puzzle us
- Further progress on the location of the resonance with respect to DD* threshold requires better knowledge of D⁰ and kaon mass
- Closeness of peak to threshold means fits with Breit-Wigner lineshape do not tell the whole story
- Still more to come on the X(3872) with Run 1+ 2 data from LHCb
- LHCb upgrade running from 2022 will give larger datasets and has different systematics





Backup



The LHCb Detector

