Recent results on exotic (hidden charm) hadrons from LHCb

Chen Chen

Center for High Energy Physics, Tsinghua University

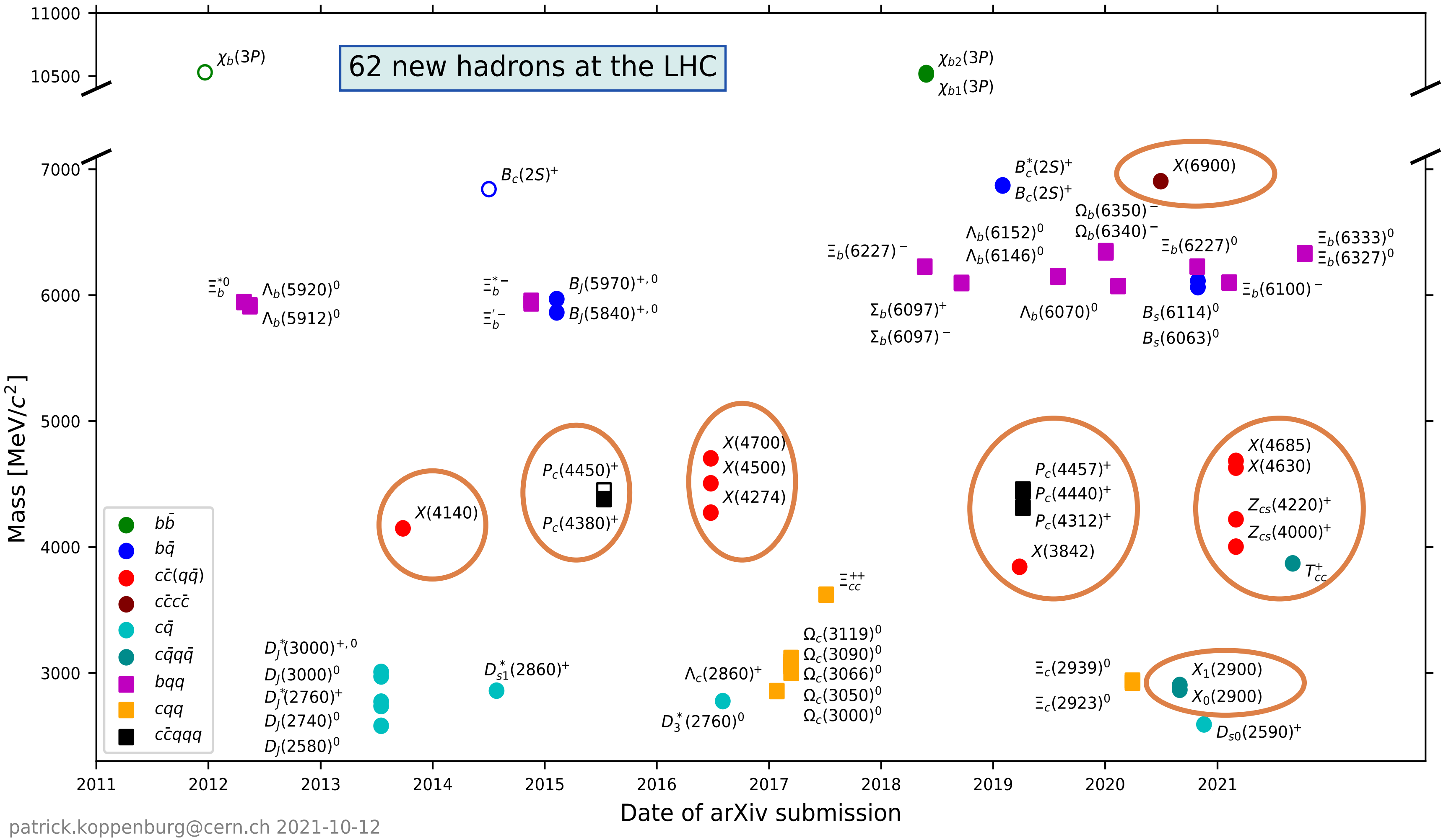
(On behalf of the LHCb collaboration)

LeptonPhoton 2021

11 Jan 2022, Manchester (virtual)

Exotic hadrons at LHC(b)

- 62 new hadrons at LHC, where 18 are exotic



- The dynamics and structure still unclear
- Experimental investigations provide more information
  - Lineshape, spin-parity
  - Decay schemes & properties
  - Production
  - …
- More new states continue bringing surprises

Topics

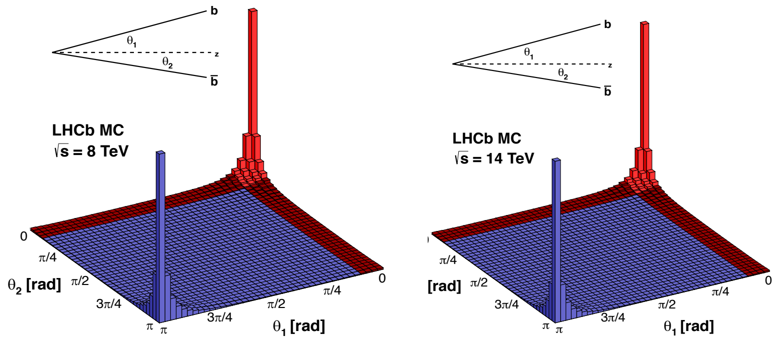
- Doubly charmed tetraquark T_{cc}^{+} [arXiv:2109.01056, arXiv:2109.01038]
- $\chi_{c1}(3872)$ production in pp collisions [arXiv:2109.07360]
- ω contribution in $\chi_{c1}(3872) \to \pi^{+}\pi^{-}J/\psi$ [LHCb-PAPER-2021-045, in preparation]
- Study of $B^{+} \to J/\psi\eta K^{+}$ [LHCb-PAPER-2021-047, in preparation]

LHCb detector

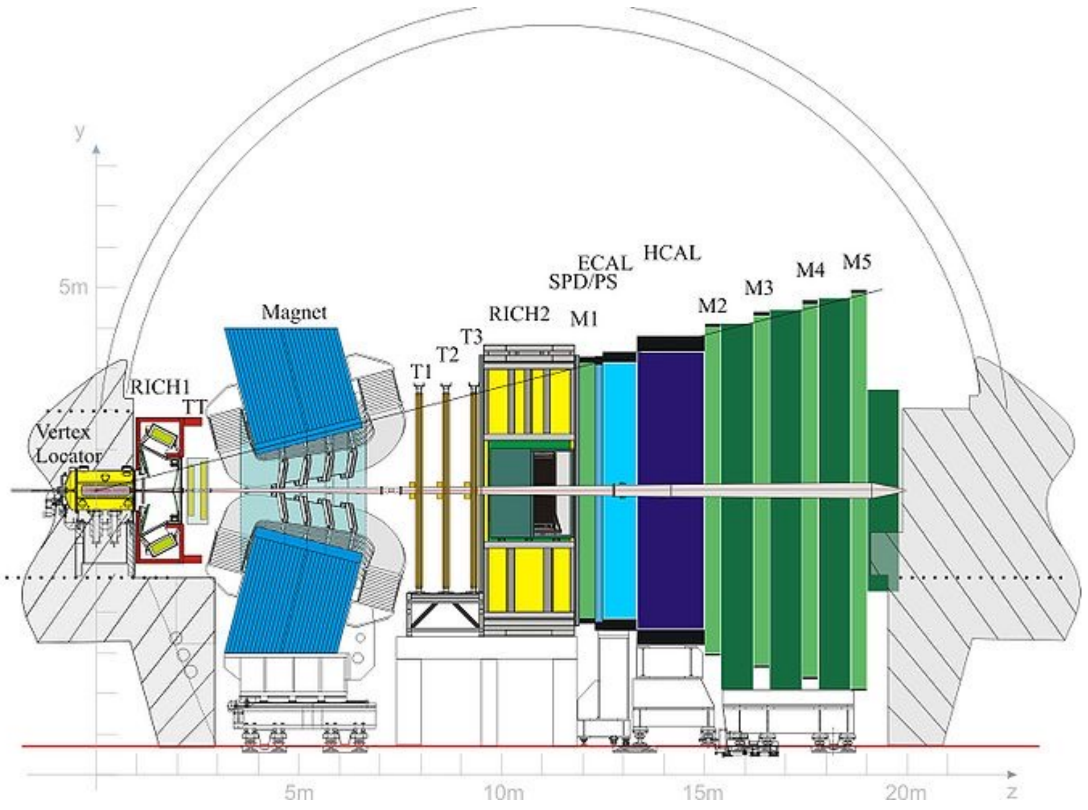
JINST 3 (2008) S08005, Int.J.Mod.Phys. A30 (2015) 1530022

- Single-arm forward spectrometer, dedicated for heavy flavour studies
  - Excellent vertex, IP and decay-time resolution
  - Good momentum resolution
  - Powerful hadron and muon identification

Ideal place for hadron spectroscopy studies



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



Doubly charmed tetraquark T_{cc}^{+}

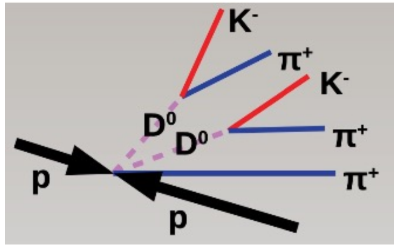
arXiv:2109.01056
arXiv:2109.01038

$T_{cc}^{+}[cc\bar{u}\bar{d}]$ observation

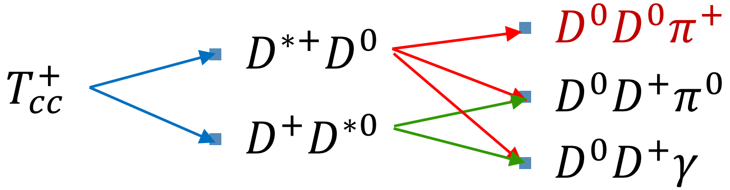
arXiv:2109.01056, arXiv:2109.01038

Motivated by the observation of hadrons containing at least two charm quarks: Ξ_{cc}^{++} $[ccu]$, $X(6900)[cc\bar{c}\bar{c}]$

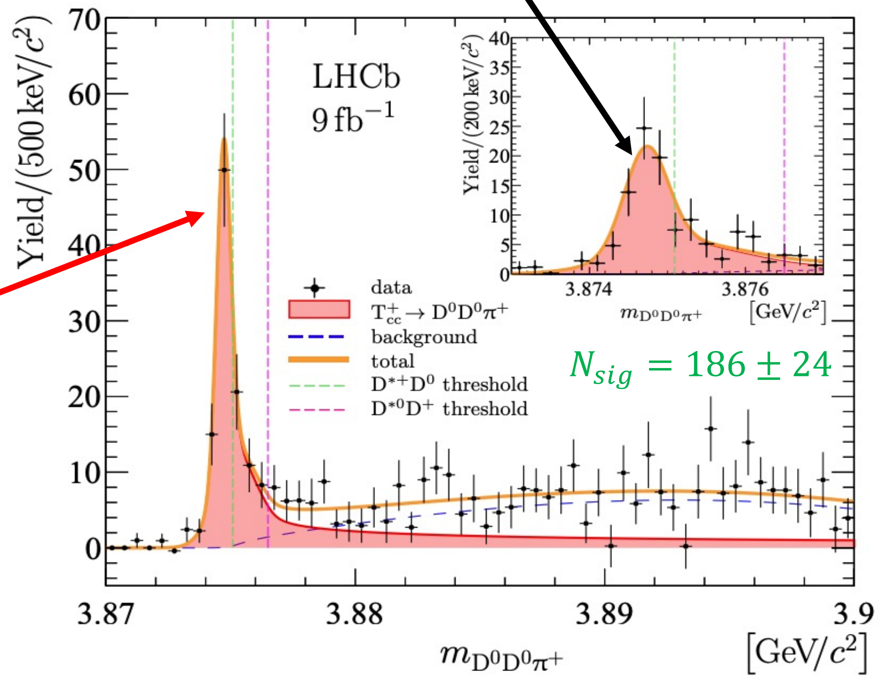
- 9fb^{-1}@$7, 8, 13$ TeV



- Significant peak in the $D^0D^0\pi^+$ mass
  - Slightly below $D^{*+}D^0$ threshold
- Two alternative lineshapes to model the peak
  - 2-body P-wave relativistic BW ($\mathcal{A}^{\text{BW}}$)
    - Existence of T_{cc}^{+}: 22σ
  - Unitarized 3-body RBW ($\mathcal{A}^{\text{U}}$)
    - Detailed investigation on the properties of T_{cc}^{+}



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



Fit results for unitarized 3-body RBW model

	δm [keV/c^2]	Γ [keV/c^2]
$\mathcal{A}^{\text{BW}}$	$-273 \pm 61 \pm 5^{+11}_{-14}$	$410 \pm 165 \pm 43^{+18}_{-38}$
$\mathcal{A}^{\text{U}}$	$-361 \pm 40^{+9}_{-8}$	47.8 ± 1.9

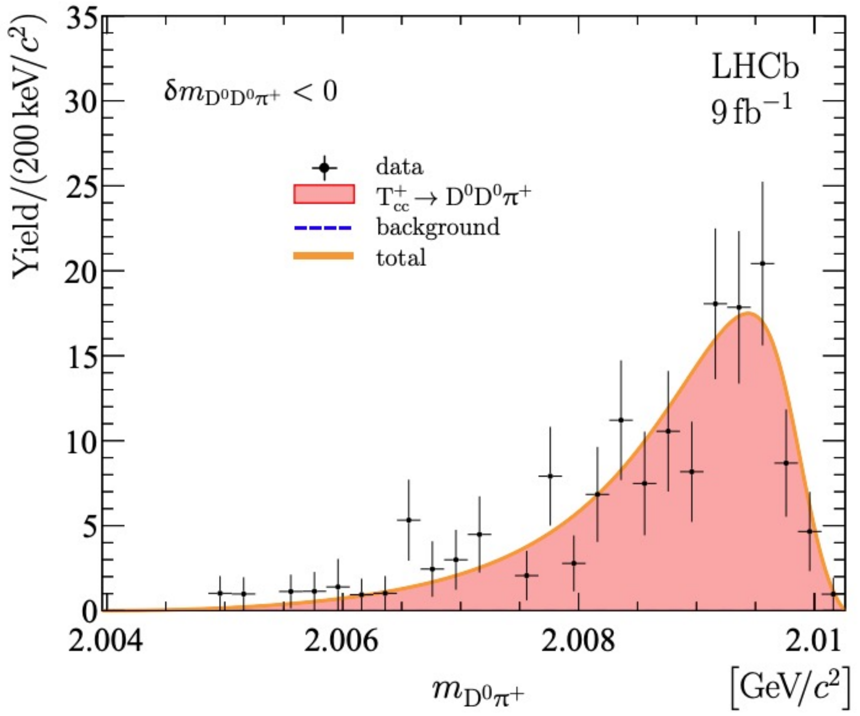
$$\delta m = m_{T_{cc}^{+}} - (m_{D^{*+}} + m_{D^0})$$

Intermediate offshell D^{*+}

arXiv:2109.01056, arXiv:2109.01038

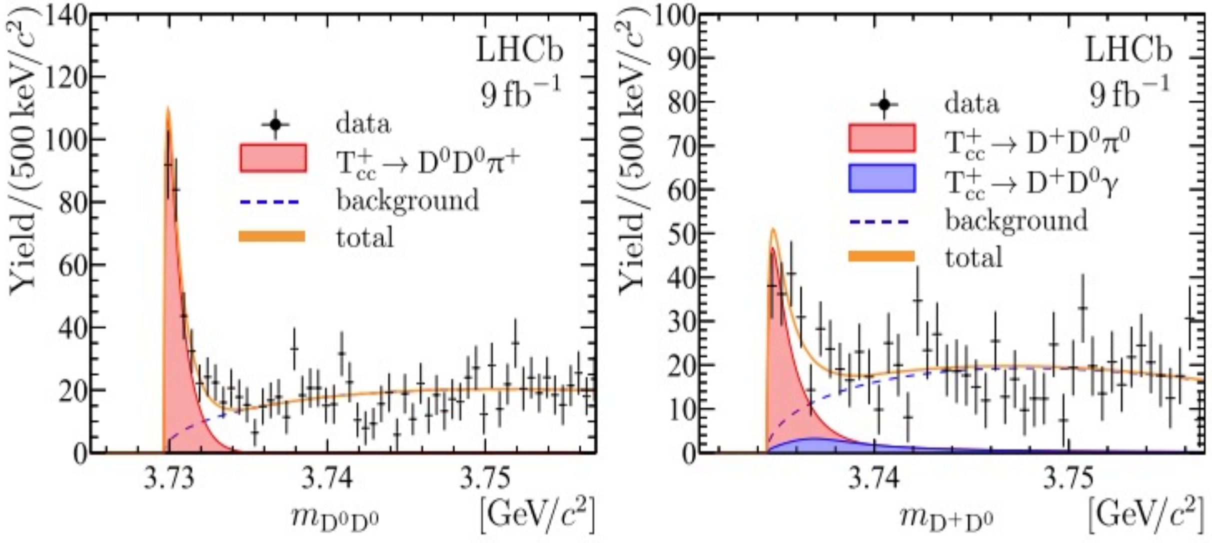
- $m_{D^0\pi^-}$ ：Unitarized model well describes data

-> True D^{*+} contribution



- Partially reconstructed $T_{cc}^+ \to D^0D^{*+}$ results in D^0D^0 and D^+D^0 masses

$T_{cc}^+ \to D^0D^{*+} \to D^0D^0\pi^+$ $\quad$ $T_{cc}^+ \to DD^* \to D^+D^0\pi/\gamma$



T_{cc}^{+} properties

arXiv:2109.01056, arXiv:2109.01038

- Consistent with isospin singlet
  - No hint for isospin partners: $T_{cc}^{0}[cc\bar{u}\bar{u}] \to D^0 D^0 \pi/\gamma$; $T_{cc}^{++}[cc\bar{d}\bar{d}] \to D^+ D^+ \pi/\gamma$ and $D^+ D^0 \pi^+$ [see backup]
- Pole:

$$\delta m_{\text{pole}} = -360 \pm 40^{+4}_{-0} \ \text{keV}/c^2$$
$$\Gamma_{\text{pole}} = 48 \pm 2^{+0}_{-14} \ \text{keV}$$

  - Consistent with the peak position and FWHM
- Scattering length:

$$a = \left[-(7.16 \pm 0.51) + i\,(1.85 \pm 0.28)\right] \text{fm}$$

  - Attractive force

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

arXiv:2109.07360

$\chi_{c1}(3872)$ nature and production

- Cross-section dependence on kinematics can be a probe for $\chi_{c1}(3872)$ nature

- $\sigma_{\chi_{c1}(3872)}/\sigma_{\psi(2S)}$ dependence on (p_T, η) measured by CMS and ATLAS

JHEP 04 (2013) 154, JHEP 01 (2017) 117

  - $D^0\overline{D}^{*0}$ molecule explanation of $\chi_{c1}(3872)$ unsupported [Phys. Rev. D81 (2010) 114018]
  - Consistent with $D^0\overline{D}^{*0} + \chi_{c1}(2P)$ mixture model [Phys. Rev. D96 (2017) 074014]

- LHCb can perform $\sigma_{\chi_{c1}(3872)}/\sigma_{\psi(2S)}$ measurement in the forward region

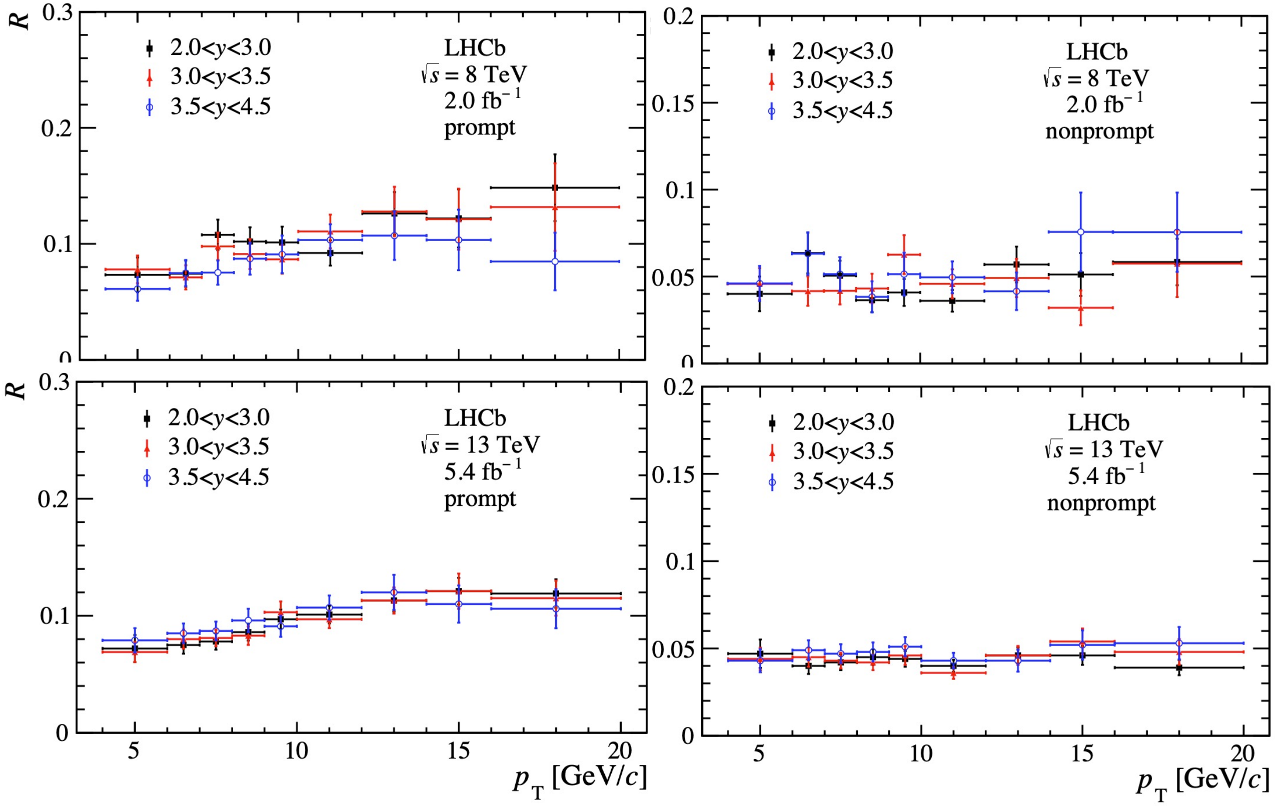
$\sigma_{\chi_{c1}(3872)}/\sigma_{\psi(2S)}$

- 2.0 fb^{-1}@8 TeV , 2012
- 5.4 fb^{-1}@13 TeV, Run2

arXiv:2109.07360

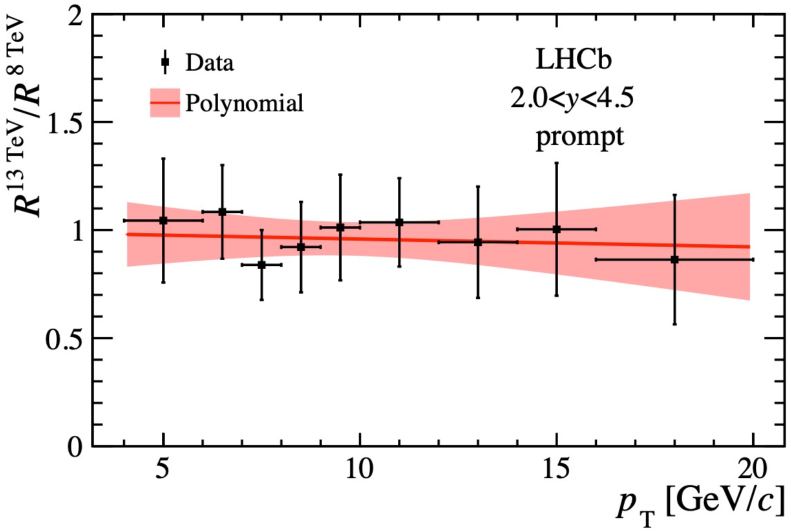
$J/\psi \to \mu^+\mu^-$

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



- R measured in p_T and η bins
  - From PV (prompt): R increases with p_T, similar to $\sigma_{\psi(2S)}/\sigma_{J/\psi}$

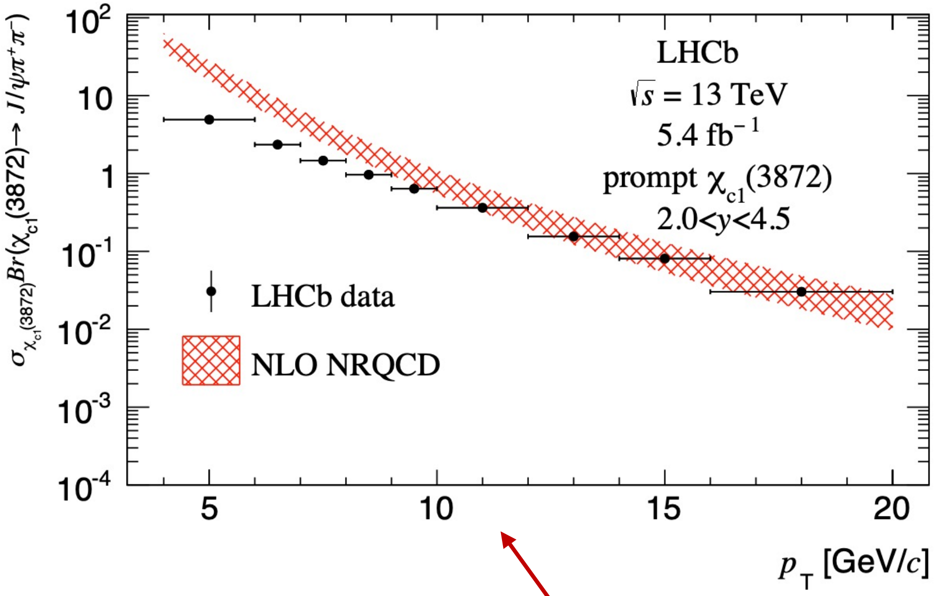
    [JHEP 02 (2012) 011, Eur. Phys. J. C72 (2012) 2100, Eur. Phys. J. C39 (2005) 163]
  - From b-decay (nonprompt): no dependence on p_T
- Prompt $R^{13\ \text{TeV}}/R^{8\ \text{TeV}} \approx 1$ for all p_T
  - R independent of collision energy and p_T

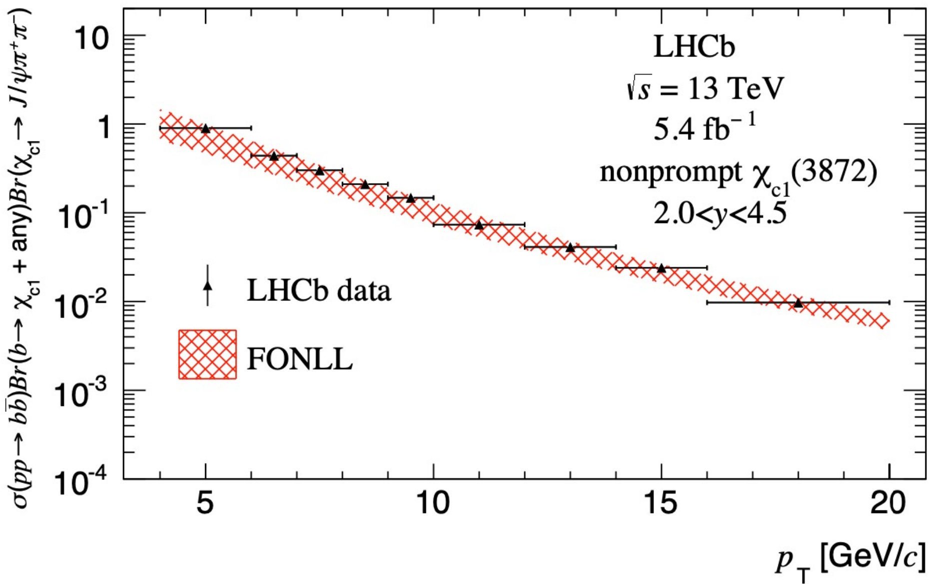


η dependence integrated out

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

arXiv:2109.07360





- In $p_T > 10\ \mathrm{GeV}/c$ region, consistent with NLO NRQCD calculations for the $D^0\bar{D}^{*0} + \chi_{c1}(2P)$ model

[Phys. Rev. D96 (2017) 074014]

ω contribution in $\chi_{c1}(3872) \rightarrow \pi^+\pi^- J/\psi$

LHCb-PAPER-2021-045, in preparation

$\chi_{c1}(3872) \to \pi^+\pi^- J/\psi$ contributions

- $\chi_{c1}(3872) \to \rho^0 J/\psi$
  - Isospin violating
    - $\chi_{c1}(3872)$ is mostly isospin singlet (non-observation of its charge partners)
  - An important probe of $\chi_{c1}(3872)$ nature
    - Isospin violating decays of charmonia highly suppressed
- $\chi_{c1}(3872) \to \omega J/\psi$
  - Isospin conserving
  - Normalisation for $\chi_{c1}(3872) \to \rho^0 J/\psi$ branching fraction
  - ~2% contribution to $\pi^+\pi^- J/\psi$ if no $\rho^0 - \omega$ interference
    - Could be largely enhanced if $\rho^0 - \omega$ interference exists
- Detailed investigation of $\pi^+\pi^-$ mass spectrum
  - Quantifying the ρ^0 and ω contributions and interference

Performed by CDF and Belle, but no conclusive results due to low statistics

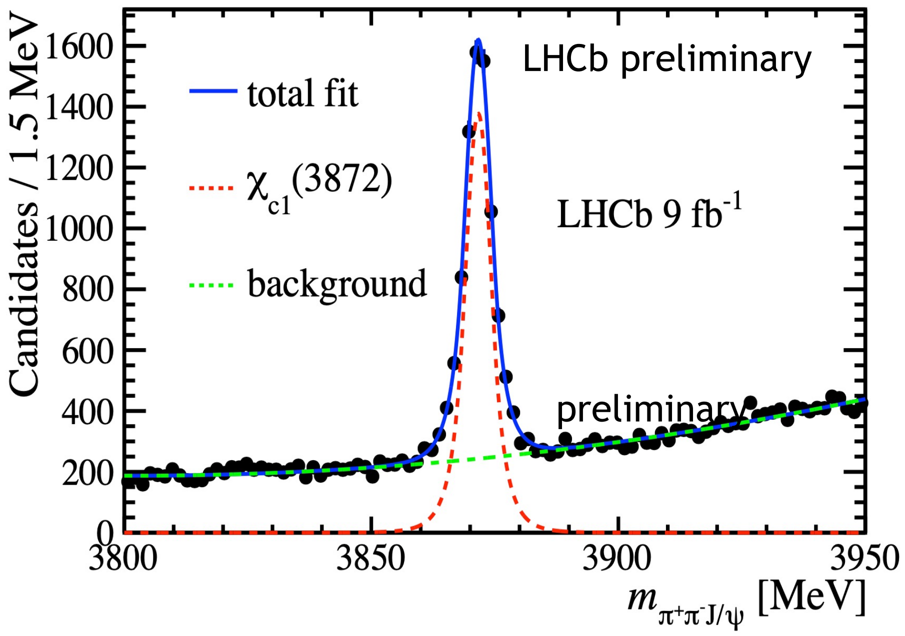
Phys. Rev. Lett. 96 (2006) 102002
Phys. Rev. D 84 (2011) 052004

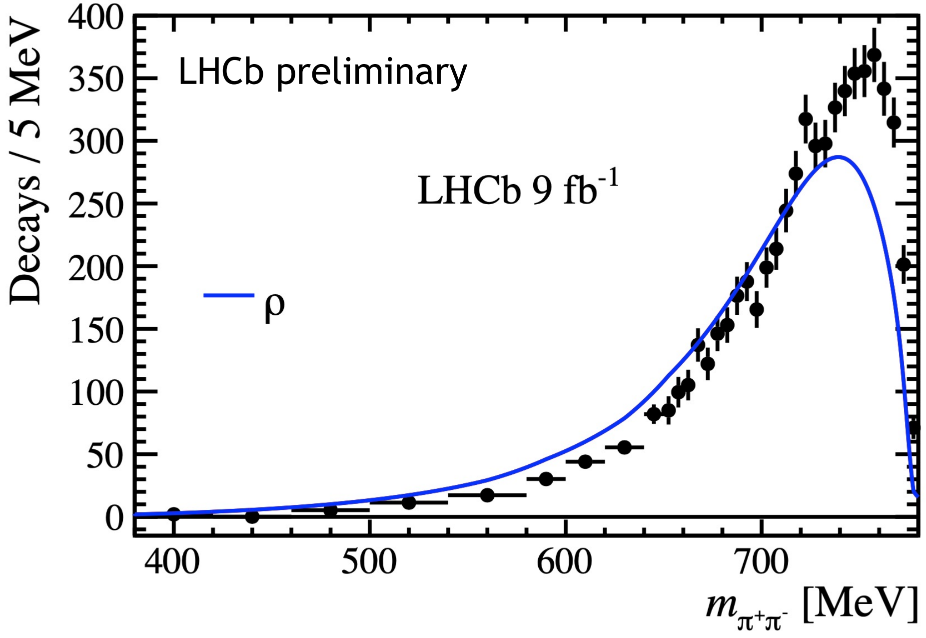
Data distributions

- $9\text{fb}^{-1}@7,8,13$ TeV

LHCb-PAPER-2021-045, in preparation

- Decay: $B^+ \to K^+\chi_{c1}(3872)$, $\chi_{c1}(3872) \to \pi^+\pi^- J/\psi$, $J/\psi \to \mu^+\mu^-$





$N_{\chi_{c1}} = 6788 \pm 117$

- $\pi^+\pi^-$ mass distribution
  - Determined from $\chi_{c1}(3872)$ mass fits in $\pi^+\pi^-$ mass slices
  - Cannot be well modelled by BW lineshapes
    - ρ^0 BW only ✗
    - ρ^0 BW + ω BW ✗

Advanced K-matrix model

LHCb-PAPER-2021-045, in preparation

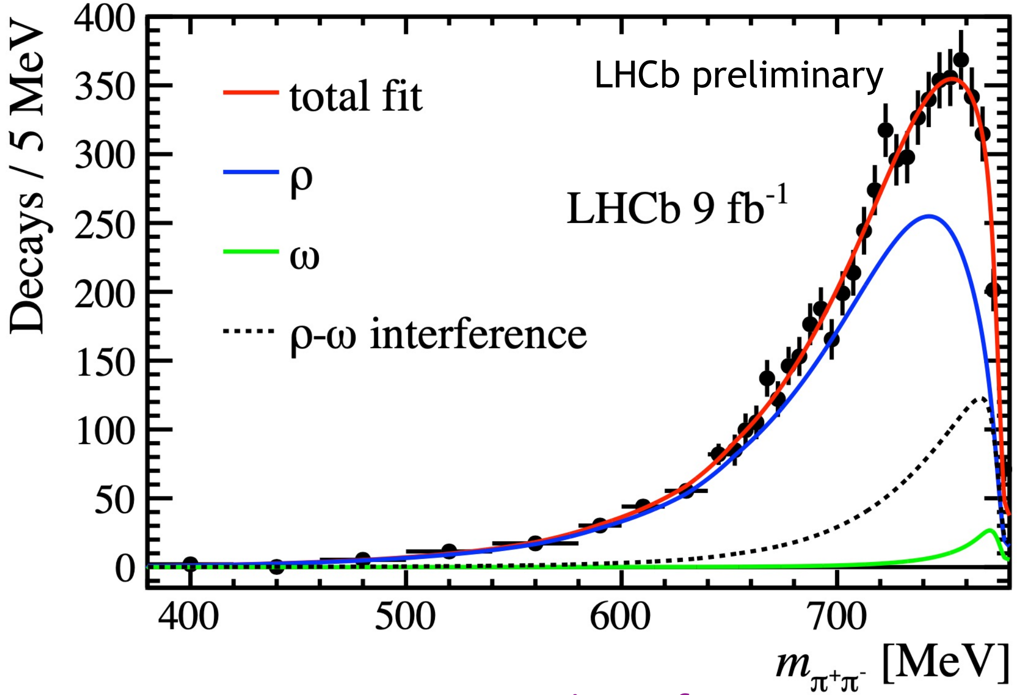
$$K = \frac{1}{{m_\rho}^2 - s}\begin{pmatrix} {g_{\rho\to 2\pi}}^2 & 0 \\ 0 & 0 \end{pmatrix} + \frac{1}{{m_\omega}^2 - s}\begin{pmatrix} {g_{\omega\to 2\pi}}^2 & g_{\omega\to 2\pi}\, g_{\omega\to 3\pi} \\ g_{\omega\to 2\pi}\, g_{\omega\to 3\pi} & {g_{\omega\to 3\pi}}^2 \end{pmatrix}$$

g couplings derived based on PDG

$$\hat{T} = [1 - i\,K\,\varrho]^{-1}\;K$$

$$\mathcal{M}_{2\pi} \sim \alpha_{2\pi}\hat{T}_{2\pi,2\pi} + \alpha_{3\pi}\hat{T}_{2\pi,3\pi}$$

$\hat{T}_{2\pi,2\pi} \approx \rho$ BW



Large $\rho - \omega$ interference

- Existence of ω contribution: 7.1σ (syst. considered)
  - Most significant to date

- Fit fraction:

$$\Gamma(\alpha_{2\pi}, \alpha_{3\pi}) = \int |\mathcal{M}|^2 d\Phi$$

  - $R_\omega^0 \equiv \frac{\Gamma(0, \alpha_{3\pi})}{\Gamma(\alpha_{2\pi}, \alpha_{3\pi})}$: $0.019 \pm 0.004 \pm 0.003$
  - $R_\omega^{all} = 1 - R_\rho^0$: $0.214 \pm 0.023 \pm 0.020$ $\quad R_\rho^0 = \frac{\Gamma(\alpha_{2\pi}, 0)}{\Gamma(\alpha_{2\pi}, \alpha_{3\pi})}$
    - ω contribution and $\rho - \omega$ interference
  - R_ω^0 / R_ρ^0: $0.025 \pm 0.006 \pm 0.005$

Acknowledgement to the JPAC collaboration

Interpretation of $\chi_{c1}(3872)$

LHCb-PAPER-2021-045, in preparation

- Extract the couplings

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

  - An order of magnitude larger than that of $c\bar{c}$ states
    - Indicate the large isospin violation of $\chi_{c1}(3872)$ decay
  - $\chi_{c1}(3872)$ is not likely an ordinary charmonium state

$$\frac{g_{\psi(2S)\to\pi^0 J/\psi}}{g_{\psi(2S)\to\eta J/\psi}} = 0.045 \pm 0.001$$

(Derived based on PDG)

- Other interpretations for the large isospin violation
  - Contain a significant $D\bar{D}^*$ molecule?

    [Phys. Rev. D 72 (2005) 114013, Phys. Rev. D 86 (2012) 074022, PTEP 2014 (2014) 123D01, etc]
  - Compact tetraquark?

    [Prog. Theor. Phys. 118 (2007) 821, Phys. Lett. B 778 (2018) 247, Phys. Rev. D 102 (2020) 034017]

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

LHCb-PAPER-2021-047, in preparation

Resonances in the $J/\psi\eta$ system

- X'_C: C-odd partner of $\chi_{c1}(3872)$
  - Predicted by many theoretical works
    [JPS Conf. Proc. 13 (2017) 020023, EPJ Web Conf. 137 (2017) 06002, …]
  - Searched for by Belle and BarBar

BarBar	$\mathcal{B}(B^+ \to X'_C K^+) \times \mathcal{B}(X'_C \to J/\psi\eta) < 7.7 \times 10^{-6}$	Phys. Rev. Lett. 93 (2004) 041801
Belle	$\mathcal{B}(B^+ \to X'_C K^+) \times \mathcal{B}(X'_C \to J/\psi\eta) < 3.8 \times 10^{-6}$	PTEP 2014 (2014) 043C01

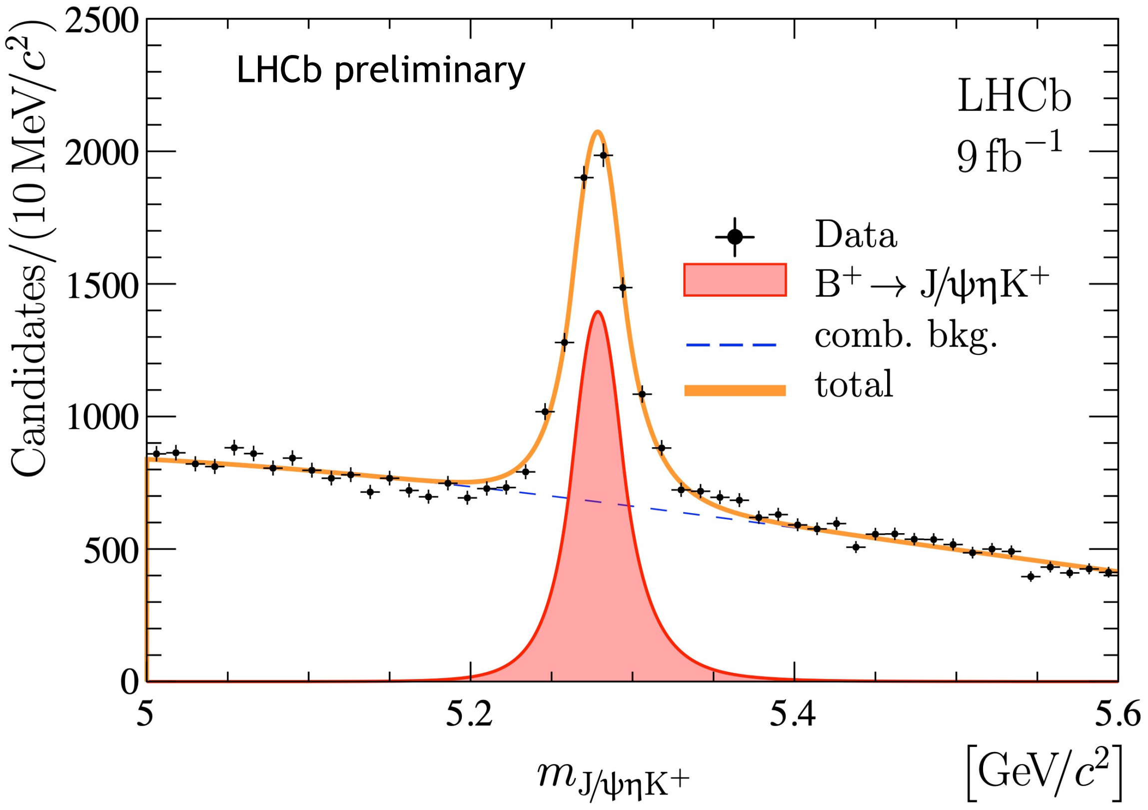
- Other charmonium-(like) states
  - $\psi_2(3823)$, $\psi(4040)$, etc

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

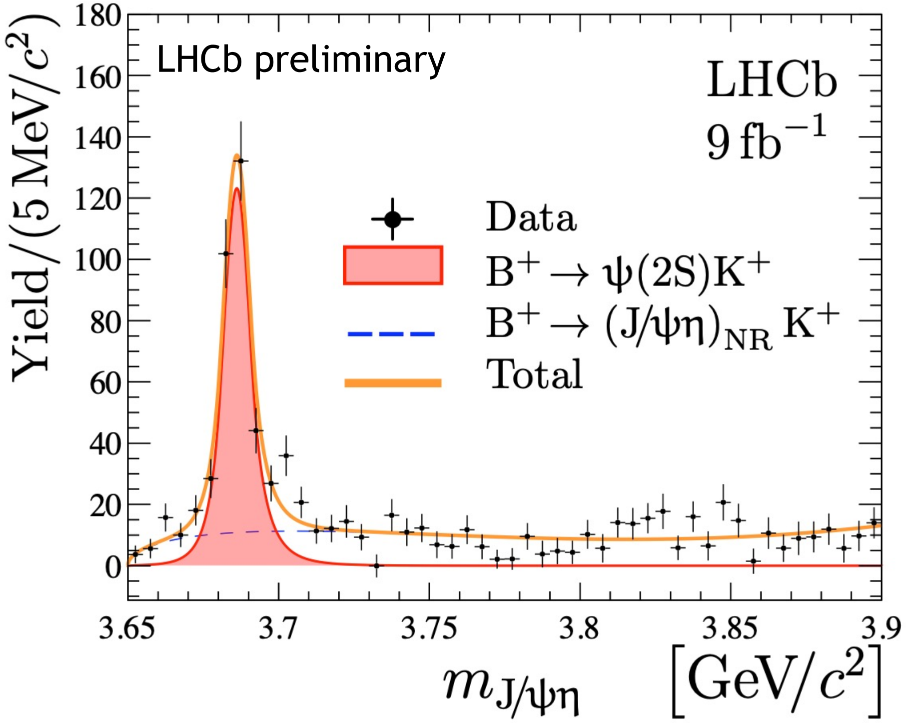
LHCb-PAPER-2021-047, in preparation

- Full LHCb data, $\mathcal{L} = 9\ \mathrm{fb}^{-1}$
- $B^+ \to J/\psi\eta K^+, J/\psi \to \mu^+\mu^-, \eta \to \gamma\gamma$

$N_{B^+}: (5.39 \pm 0.16)\times 10^3$



Clear signature of $\psi(2S) \to J/\psi\eta$



Resonances in the $J/\psi\eta$ system

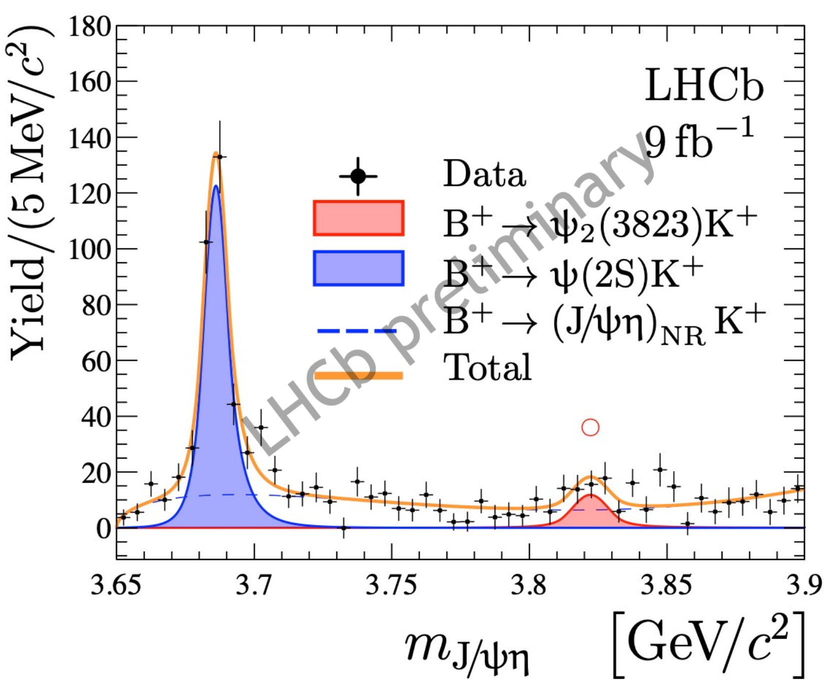
LHCb-PAPER-2021-047, in preparation

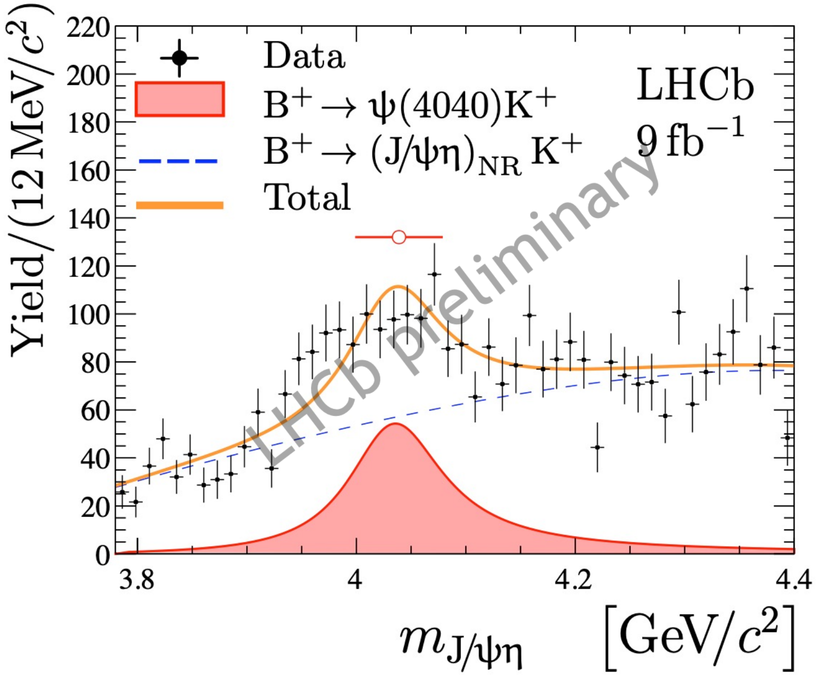
$$F_X \equiv \frac{\mathcal{B}(B^+ \to XK^+) \times \mathcal{B}(X \to J/\psi\eta)}{\mathcal{B}(B^+ \to \psi(2S)K^+) \times \mathcal{B}(\psi(2S) \to J/\psi\eta)}$$

- Evidence for $\psi_2(3823)$ [3.4σ] and $\psi(4040)$ [4.7σ]

First evidence: $F_{\psi_2(3823)} = (5.95 \pm 3.38)\times10^{-2}$

$F_{\psi(4040)} = (40.6 \pm 11.2)\times10^{-2}$





- Upper limit for other states

	Upper limit on 90% CL F_X [10^{-2}]	B_X [10^{-7}]
$\psi(3770)$	2.2	4.6
$\psi_3(3842)$	2.9	6.1
$\psi(4160)$	4.2	8.7
$\psi(4415)$	4.6	9.6
$R(3760)$	2.0	4.1
$R(3790)$	3.2	6.7
$Z_c(3900)^0$	2.1	4.3
$\psi(4230)$	1.9	3.9
$\psi(4360)$	6.0	12.4
$\psi(4390)$	11.6	24.1
$Z_c(4430)^0$	6.1	12.7
X'_C	1.9	3.9

LHCb preliminary

An order of magnitude improvement

Summary and prospects

- Topics in this talk:
  - Doubly charmed tetraquark T_{cc}^{+} : isospin singlet?
  - $\chi_{c1}(3872)$
    - ω contribution in $J/\psi\pi^{+}\pi^{-}$: large isospin violating coupling indicates it is inconsistent with conventional charmonium?
    - $\sigma_{\chi_{c1}(3872)}$ dependence on (p_T, η) shows it is consistent with $D^0\bar{D}^{*0} + \chi_{c1}(2P)$ model
    - Searching for its C-odd partner in $B^+ \to J/\psi\eta K^+$ decays
- LHCb upgrades:
  - 7× data by 2030
  - Opportunity for new exotic states
    - e.g. triply charmed (bottom) hadron ($\Sigma_c D$, $J/\psi D$, ...)
  - Precision investigation of properties

LHC			LH-LHC	
Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2022-24)	Run 4 (2027-30)	Run 5+ (2031+)
3 fb^{-1}	6 fb^{-1}	23 fb^{-1}	46 fb^{-1}	> 300 fb^{-1} (?)
		Upgrade I	Upgrade Ib	Upgrade II

arXiv:1808.08865

Decay mode	LHCb 23 fb^{-1}	LHCb 50 fb^{-1}	LHCb 300 fb^{-1}	Belle II 50 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
$B_c^+ \to D_s^+ D^0 \bar{D}^0$	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	—

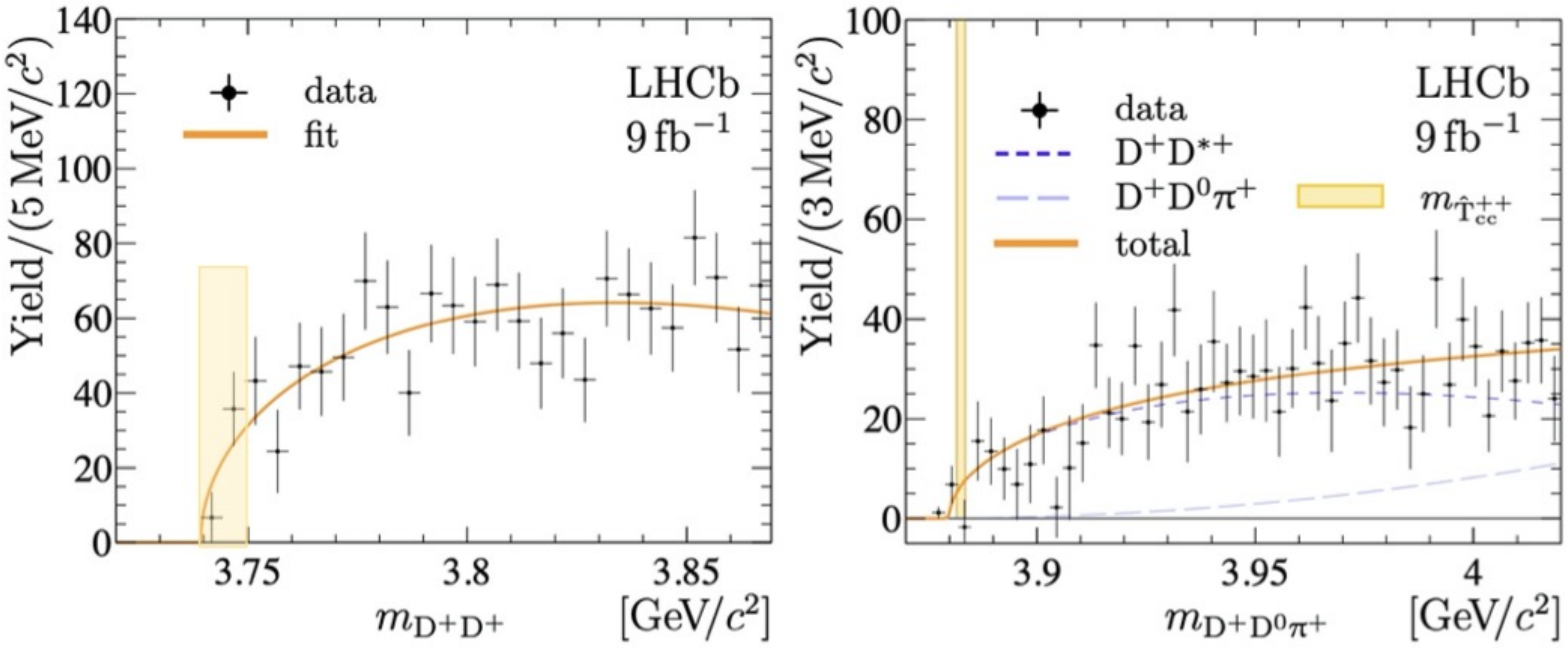
Thank you for your attention!

Backup slides

Backup for T_{cc}^{+}

D^+D^+ and $D^+D^0\pi^+$ masses

arXiv:2109.01056, arXiv:2109.01038



- No hint for $T_{cc}^{++}[cc\bar{d}\bar{d}] \rightarrow D^+D^+\pi^0/\gamma$ and $D^+D^0\pi^+$

Backup for $\chi_{c1}(3872)$ production

$\sigma_{\chi_{c1}(3872)}/\sigma_{\psi(2S)}$ strategy

arXiv:2109.07360

- Reconstruction: $\chi_{c1}(3872),\ \psi(2S) \to \pi^+\pi^- J/\psi(\to \mu^+\mu^-)$

- Differential cross section ratio in different regions of (p_T, η)

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

  - Signal yields determined from fits in each (p_T, η) region
  - Efficiencies determined from MC

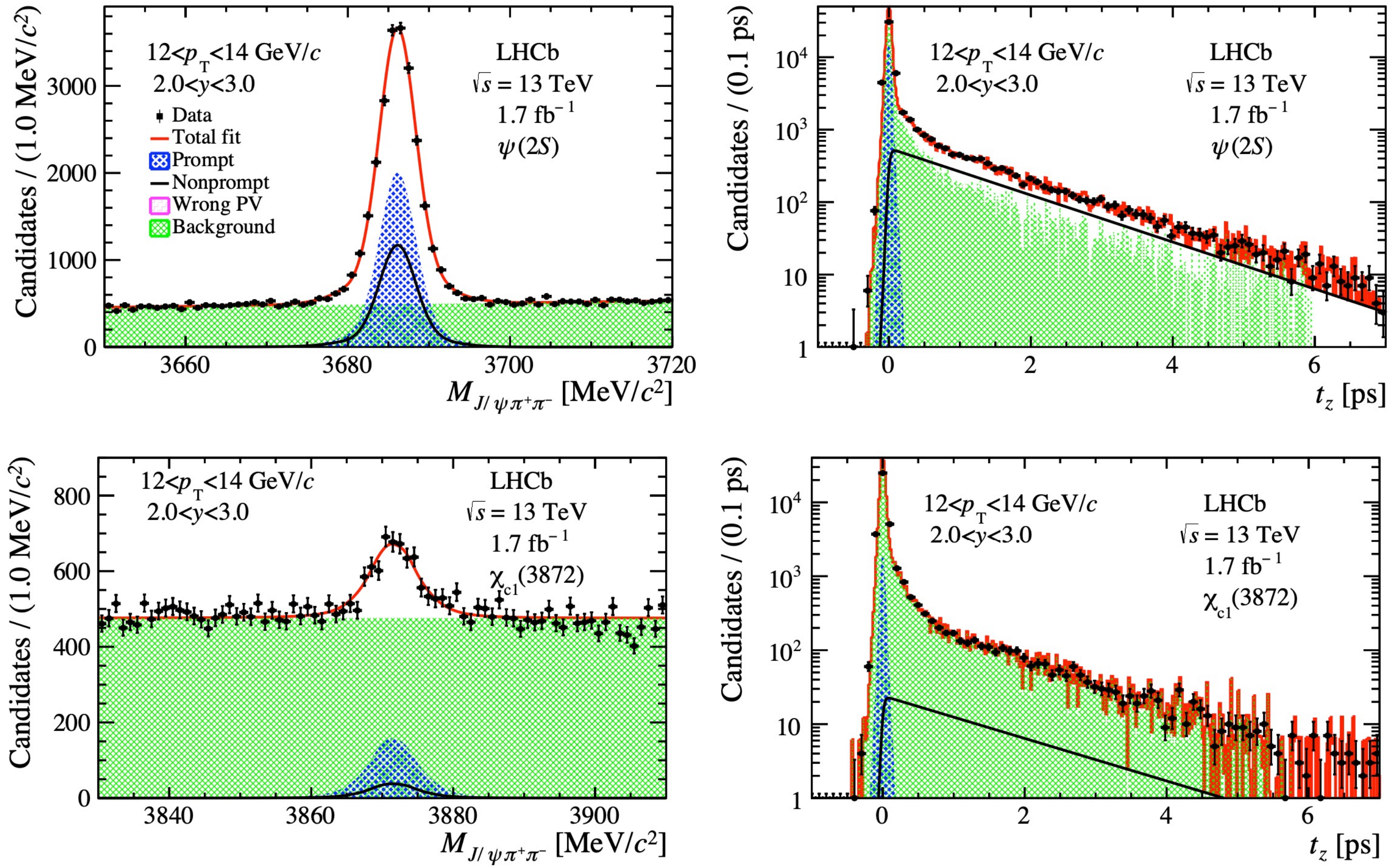
(See next slides)

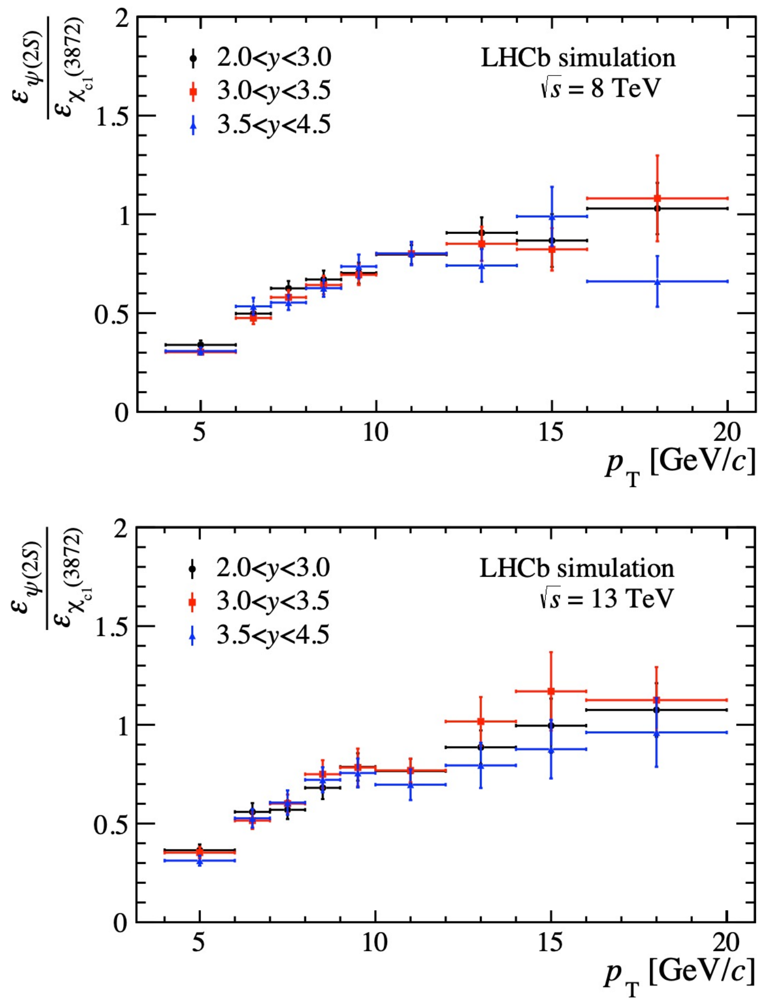
Fits and efficiencies

arXiv:2109.07360

- Pseudo decay time to separate prompt and non-prompt contributions

$$t_z = \frac{(z - z_{\mathrm{PV}}) \times m}{p_z}$$





Backup for ω contribution in $\chi_{c1}(3872)$

Estimation of ω contribution

LHCb-PAPER-2021-045, in preparation

$\mathcal{B}(\chi_{c1}(3872) \to \omega J/\psi)/\mathcal{B}(\chi_{c1}(3872) \to \pi^+\pi^- J/\psi)$ is 1.4 ± 0.3.

Phys. Rev. Lett. 122 (2019) 232002
arXiv:hep-ex/0505037
Phys. Rev. D82 (2010) 011101

$$\mathcal{B}(\omega \to \pi^+\pi^-) = (1.53 \pm 0.12)\%$$

BW formula for $\pi^+\pi^-$

LHCb-PAPER-2021-045, in preparation

$$PDF(m_{\pi\pi}) = S\, p_{J/\psi}\, p\, |M|^2$$

ρ^0 BW

$$\begin{aligned}
M = BW_\rho(m_{\pi\pi}|m_\rho,\Gamma_\rho) &= \frac{m_\rho \Gamma_\rho F_1(p,p_\rho)}{{m_\rho}^2 - m_{\pi\pi}^2 - i\, m_\rho \Gamma_\rho(m_{\pi\pi})},\\
\Gamma_\rho(m_{\pi\pi}) &= \Gamma_\rho \frac{p}{p_\rho} \frac{m_\rho}{m_{\pi\pi}} F_1(p,p_\rho)^2,\\
F_1(p,p_\rho) &= \sqrt{\frac{B_1(p)}{B_1(p_\rho)}},\\
B_1(p) &= p^2 \frac{1}{1+(Rp)^2},\\
p_\rho &= p(m_\rho),
\end{aligned}$$

ρ^0 BW + ω BW

$$M = BW_\rho(m_{\pi\pi}|m_\rho,\Gamma_\rho) + A_\omega\, e^{i\phi}\, BW_\omega(m_{\pi\pi}|m_\omega,\Gamma_\omega).$$

Detailed K matrix formula

LHCb-PAPER-2021-045, in preparation

$$K = \frac{1}{{m_\rho}^2 - s}\begin{pmatrix} {g_{\rho\to 2\pi}}^2 & 0 \\ 0 & 0 \end{pmatrix} + \frac{1}{{m_\omega}^2 - s}\begin{pmatrix} {g_{\omega\to 2\pi}}^2 & g_{\omega\to 2\pi}\, g_{\omega\to 3\pi} \\ g_{\omega\to 2\pi}\, g_{\omega\to 3\pi} & {g_{\omega\to 3\pi}}^2 \end{pmatrix}$$

$$\hat{T} = [1 - i\,K\,\rho]^{-1}\ K \qquad \rho = \begin{pmatrix} \rho_{2\pi}(s) & 0 \\ 0 & \rho_{3\pi}(s) \end{pmatrix}$$

$$\begin{pmatrix} \hat{A}_{2\pi} \\ \hat{A}_{3\pi} \end{pmatrix} = \hat{T}\begin{pmatrix} \alpha_{2\pi} \\ \alpha_{3\pi} \end{pmatrix} \qquad M = \hat{A}_{2\pi}\sqrt{B_1(p)}.$$

$$\begin{aligned} g^2_{\rho\to 2\pi} &= m_\rho\,\Gamma_\rho/\rho_{2\pi}(m_\rho^2), \\ g^2_{\omega\to 3\pi} &= m_\omega\,\Gamma_\omega\mathcal{B}(\omega\to 3\pi)/\rho_{3\pi}(m_\omega^2), \\ g^2_{\omega\to 2\pi} &= m_\omega\,\Gamma_\omega\mathcal{B}(\omega\to \pi^+\pi^-)/\rho_{2\pi}(m_\omega^2); \end{aligned}$$

$$g^2_{\omega\to 2\pi}/g^2_{\rho\to 2\pi} \sim 0.0009$$

$$g_{\omega\to 2\pi}\, g_{\omega\to 3\pi}/g^2_{\rho\to 2\pi} \sim 0.01$$

$$\hat{A}_{2\pi} \sim \alpha_{2\pi}\hat{T}_{2\pi,2\pi} + \alpha_{3\pi}\hat{T}_{2\pi,3\pi}$$

$$\hat{T}_{2\pi,2\pi} \approx \frac{g^2_{\rho\to 2\pi}}{{m_\rho}^2 - s - i\,g^2_{\rho\to 2\pi}\varrho_{2\pi}(s)}$$

$$\hat{T}_{2\pi,3\pi} \approx \frac{g_{\omega\to 2\pi}\, g_{\omega\to 3\pi}\,(m_\rho^2 - s)}{({m_\rho}^2 - s - i\,g^2_{\rho\to 2\pi}\varrho_{2\pi}(s))({m_\omega}^2 - s - i\,g^2_{\omega\to 3\pi}\varrho_{3\pi}(s))}$$

Coupling relations

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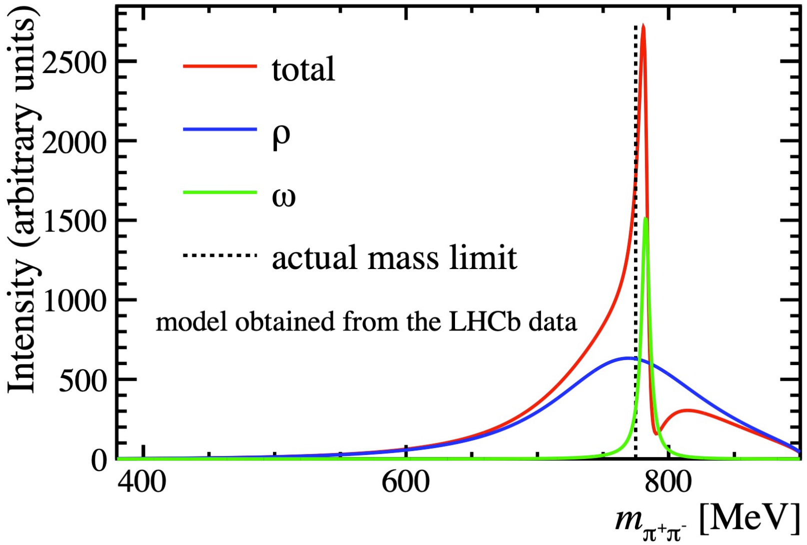
$$\frac{g_{\chi_{c1}(3872)\to\rho^0 J/\psi}}{g_{\chi_{c1}(3872)\to\omega J/\psi}} = \sqrt{\frac{\mathcal{B}(\omega\to\pi^+\pi^-)}{R_{\omega/\rho}{}^{0\prime}}} = 0.29 \pm 0.04.$$

$R^{0\prime}_{\omega\rho} = R^{0\prime}_{\omega}/R^{0\prime}_{\rho}$, where the contributions above the mass limit are also included



$$\frac{g_{\psi(2S)\to\pi^0 J/\psi}}{g_{\psi(2S)\to\eta J/\psi}} = \sqrt{\frac{\mathcal{B}(\psi(2S)\to\pi^0 J/\psi)}{\mathcal{B}(\psi(2S)\to\eta J/\psi)}\frac{p_\eta{}^3}{p_{\pi^0}{}^3}} = 0.045 \pm 0.001$$

Investigation of full $J/\psi\eta$ mass spectrum

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