Observation of ω contribution to $\chi_{c1}(3872) \to \pi^+\pi^- J/\psi$ decays at LHCb

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on behalf of the LHCb Collboration

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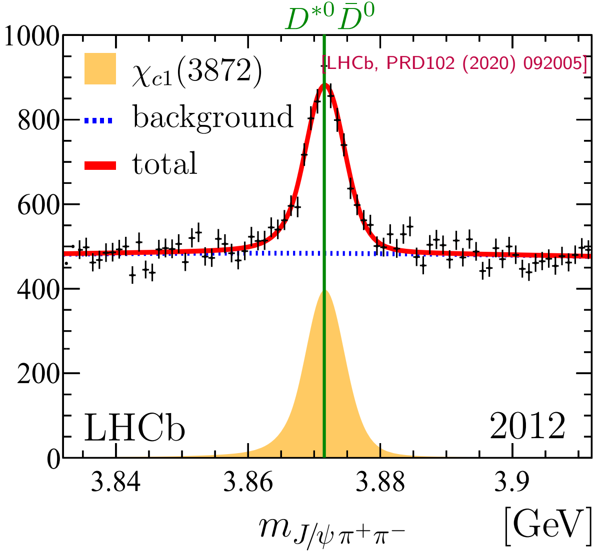
The first bird of the exotic era: $\chi_{c1}(3872) \to J/\psi\pi^+\pi^-$

First seen by Belle [PRL91 (2003), 262001]

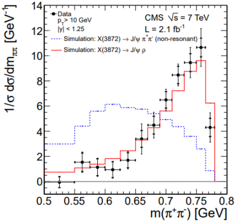
- Charmonium state ($c\bar{c}$), $\chi_{c1}(2P)$ is expected* 70 MeV above
- The peak right at the $D^{*0}\bar{D}^0$ threshold
- Large isospin violation in the strong decays to $J/\psi\pi^+\pi^-$ [LHCb 2022, 2204.12597]



Isospin violation in decays of $\chi_{c1}(3872)$

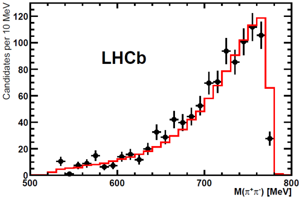
- $\chi_{c1}(3872)$ is mostly isosinglet, no $\chi_{c1} \to J/\psi \pi^{\pm}\pi^{0}$
  [BaBar PRD71, 031501 (2005); Belle PRD84, 052004 (2011)]
  - $\chi_{c1} \to J/\psi\omega$ conserves isospin
  - $\chi_{c1} \to J/\psi\rho$ violates isospin
- However, $(\pi\pi)$ in the decay is in isovector model:
  - No $\chi_{c1}(3872) \to \pi^0\pi^0 J/\psi$ observed
  - $\pi^+\pi^-$ distribution is consistent with ρ.

$pp \to \chi_{c1} + \ldots$



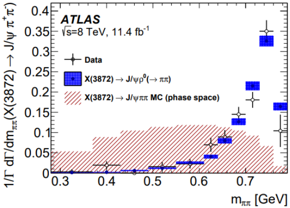
[CMS, JHEP 04, 154 (2013)]

$B^+ \to \chi_{c1} + K^+$



[LHCb, PRD92, 011102 (2015)]

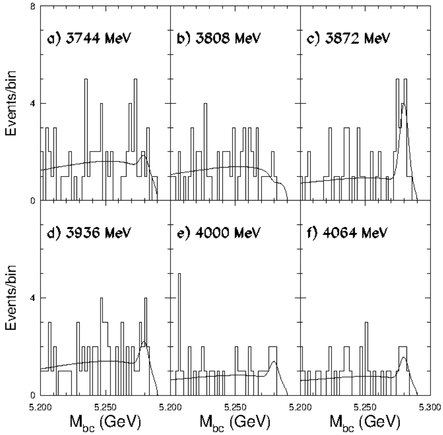
$pp \to \chi_{c1} + \ldots$



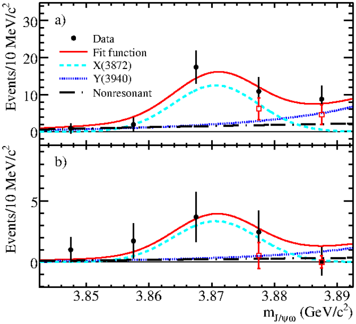
[ATLAS, JHEP 01, 117 (2017)]

Observation of $\chi_{c1} \to \omega J/\psi$ using $B^{0,+} \to \chi_{c1} K^{0,+}$

[Belle, 0505037 (2005)]

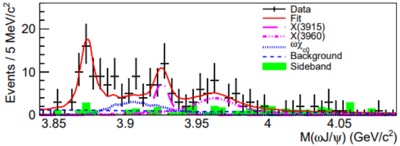


[BaBar, 1005.5190 (1010)]



Averaged value of the ratio:

$$\frac{\mathcal{B}(\chi_{c1}(3872) \to \omega J/\psi)}{\mathcal{B}(\chi_{c1}(3872) \to \pi^+\pi^- J/\psi)} = 1.4 \pm 0.3$$

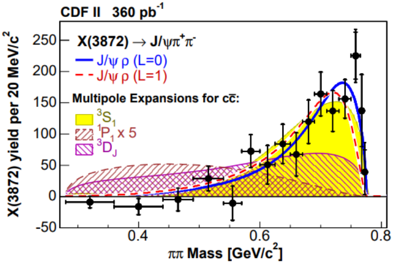


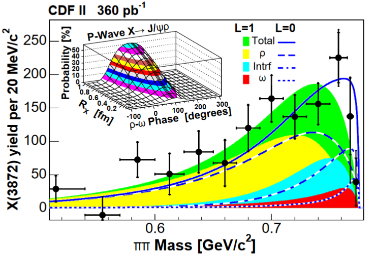
[BESIII PRL 122, 232002 (2019)]

Attempts to find ω in $\pi\pi$ by CDS II

[CDF II, PRL 96, 102002 (2006)]

$$pp \to \chi_{c1} + \ldots$$





- Prompt production
- $N_{\text{ev}} = 1260 \pm 130$
- Check of quantum numbers:
  - Consistent with S-wave, $J^{PC} = 1^{++}$

Contribution of ω:

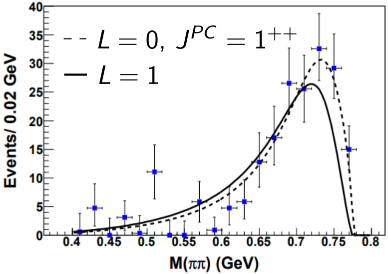
- $\mathcal{M} = \mathrm{BW}_\rho + A_\omega e^{i\phi_\omega}\mathrm{BW}_\omega$
  - $\phi_\omega = 95^\circ = \arctan \Gamma_\rho/(2\Delta m)$ [Goldhaber (1969)]
  - A_ω is fixed to match $J/\psi 3\pi$ rate [Belle, 0505037 (2005)]
  - gives worse fit, p-value: $55\% \to 19\%$
- **No evidence of** ω, however,
- contribution of ω on the level of $< 23\%$ is not excluded

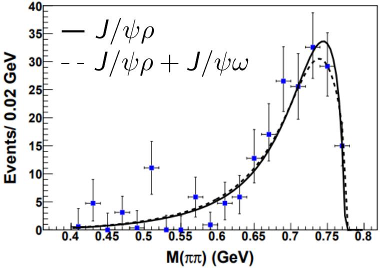
Note: sum of BW does not respect unitarity

Attempts to find ω in $\pi\pi$ by Belle

[Belle, PRD 84, 052004 (2011)]

$B^+ \to \chi_{c1} + K^+$





- clean B decays gives similar sensitivity as in the CDF II analysis
- $N_{\text{ev}} = 159 \pm 15$
- Check of quantum numbers:
  - S-wave $J^{PC} = 1^{++}$ fits better

Contribution of ω:

- $\mathcal{M} = \text{BW}_\rho + A_\omega e^{i\phi_\omega}\text{BW}_\omega$
- $\phi_\omega = 95^\circ$ is fixed
- A_ω is floated.
- Significance of ω is 1.3σ.
- with the contribution of $(12 \pm 10)\%$

Note: sum of BW does not respect unitarity

New LHCb analysis searching for ω [LHCb, JHEP 08 (2020) 123]

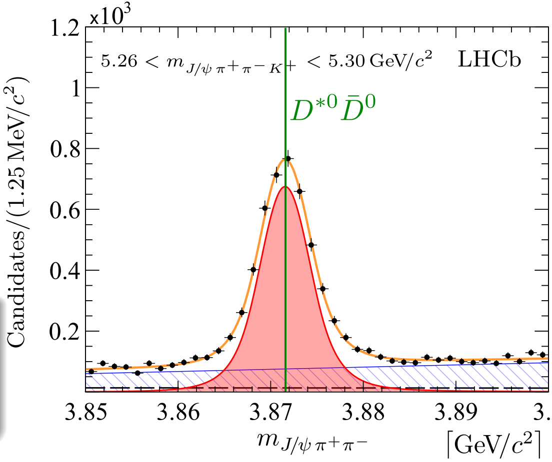
Details on the selection:

- displaced B-vertex
- $N_{ev} = 6788 \pm 117$ of $B^+ \to \chi_{c1} K^+$
- $\times 43$ events of Belle
- $\times 6$ better statistical errors than in Belle and CDF II

Extraction of χ_{c1} yield in bins of $\pi\pi$ spectrum:

- 2d unbinned fit of $m_{J/\psi\pi\pi} \times m_{\pi\pi}$

$B^+ \to \chi_{c1} + K^+$



$J/\psi\pi^+\pi^-$ spectrum from [LHCb, JHEP 08 (2020) 123]

Attempt to fit the spectrum by $\rho \to \pi\pi$ amplitude

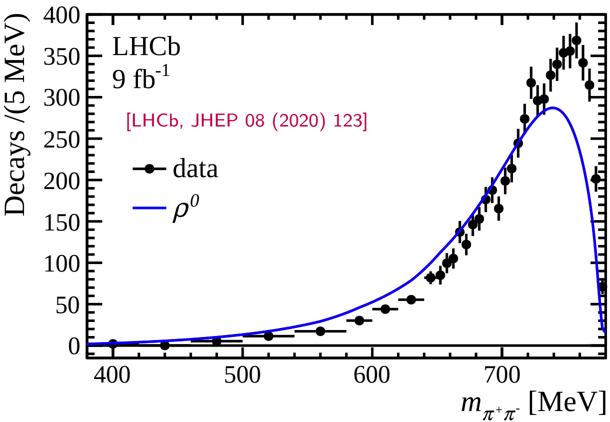
ρ lineshape is well known:

- combined analysis of $\pi\pi$ P-wave, GKPY [Garcia Martin et al, PRD83, 074004 (2011)]
- $e^+e^- \to \pi^+\pi^-$ well described by Gounaris-Sakurai [BaBar, PRD86, 032013 (2012)]
- P-wave Breit-Wigner with Blatt-Weisskopf barrier factor, $R = 1.45\,\mathrm{GeV}^{-1}$.

$$\frac{\mathrm{d}N}{\mathrm{d}m_{pi\pi}} = p_\pi p_{J/\psi} |\mathcal{A}|^2 \,.$$

$\chi_{c1}/\mathrm{ndf} = 366.6/34$:

- Can ρ shape be different in the decay?
- $\omega \to \pi^+\pi^-$
- Tails of higher ρ states?



Coupled-channel model of $\pi\pi/3\pi$ scattering

[LHCb, JHEP 08 (2020) 123]

- Two-channel K-matrix approach, $T = [1 - iK\rho]^{-1}K$ with $\pi\pi \leftrightarrow \rho\pi$

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

- ρ is diag. loop matrix,
  - $\rho_{2\pi}$: $\pi\pi$ P-wave,
  - $\rho_{3\pi}$: $\rho\pi$ P-wave with $\rho \to \pi\pi$.
- The paremeters of K are fixed from PDG:

$$\begin{aligned} g^2_{\rho\to 2\pi} &= m_\rho\, \Gamma_\rho / \rho_{2\pi}(m_\rho^2), \\ g^2_{\omega\to 3\pi} &= m_\omega\, \Gamma_\omega \mathcal{B}(\omega\to 3\pi)/\rho_{3\pi}(m_\omega^2), \qquad && \mathcal{B}(\omega \to 3\pi) = (89.3 \pm 0.6)\,\% \\ g^2_{\omega\to 2\pi} &= m_\omega\, \Gamma_\omega \mathcal{B}(\omega\to \pi^+\pi^-)/\rho_{2\pi}(m_\omega^2), \qquad && \mathcal{B}(\omega \to 2\pi) = (1.53 \pm 0.06)\,\% \end{aligned}$$

- Use Q-vector approach with the production parameters α – subject to fit,

$$A_{2\pi} = (\alpha_{2\pi}\, T_{2\pi,2\pi} + \alpha_{3\pi}\, T_{3\pi,2\pi})\sqrt{B_1} \qquad P\text{-wave amplitude}$$

Parametrization of the production

[LHCb, JHEP 08 (2020) 123]

Intuitive understanding in LO

Can simplify by neglecting the second-order terms, $g^2_{\omega\to 2\pi}/g^2_{\rho\to 2\pi} \sim 0.0009$

$$\hat{T}_{2\pi,2\pi} \approx g^2_{\rho\to 2\pi}\mathrm{BW}_\rho, \qquad \mathrm{BW}_\rho = 1/(m_\rho^2 - s - ig^2_{\rho\to 2\pi}\rho_{2\pi})$$
$$\hat{T}_{2\pi,3\pi} \approx g_{\omega\to 2\pi}\, g_{\omega\to 3\pi}\, (m_\rho^2 - s)\mathrm{BW}_\rho \mathrm{BW}_\omega.$$

Parametrization of the production, $\hat{A}_{2\pi} = \alpha_{2\pi} T_{2\pi,2\pi} + \alpha_{3\pi} T_{3\pi,2\pi}$:

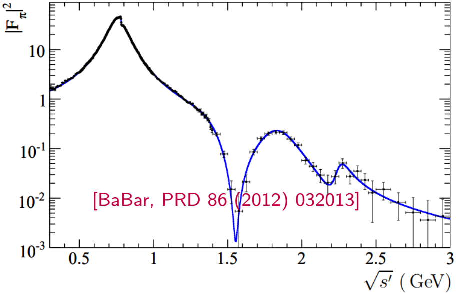
- $\alpha_{2\pi}$ is the 1st-order real polynomial
- $\alpha_{3\pi} = A_\omega/(m_\rho^2 - s)$ kills the artificial K-matrix zero

$$\text{LO} \qquad \Rightarrow \qquad \hat{A}_{2\pi} = \mathrm{BW}_\rho\,(1 + k\mathrm{BW}_\omega)$$

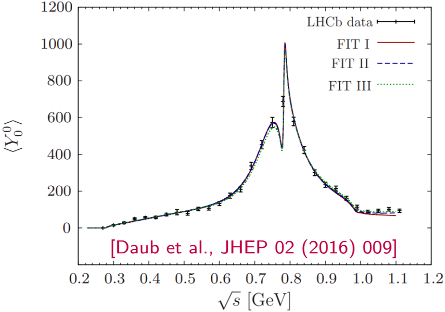
For the fit, the amplitude with **no-approximation** is used.

$\rho - \omega$ interference in pion form-factor

$e^+e^- \to \pi^+\pi^-$



$B^0 \to J/\psi\pi^+\pi^-$



A recipe for accounting for $\rho - \omega$ interference,
LO in isospin violation, [Gardner-O'Connell (1998)]

$$\mathrm{BW}_\rho \to \mathrm{BW}_\rho \left(1 + \frac{k_{\mathrm{e.m.}} s}{m_\omega^2 - s - i m_\omega \Gamma_\omega}\right)$$

$\rho - \omega$ interference in pion form-factor

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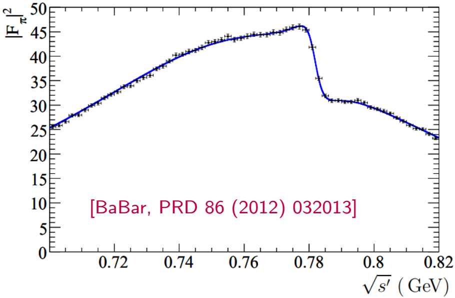

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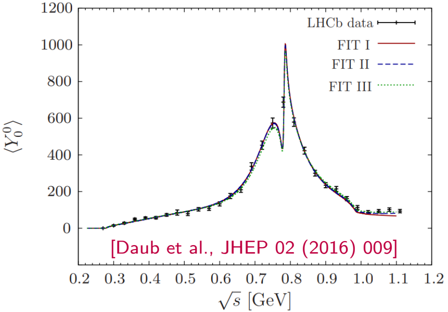

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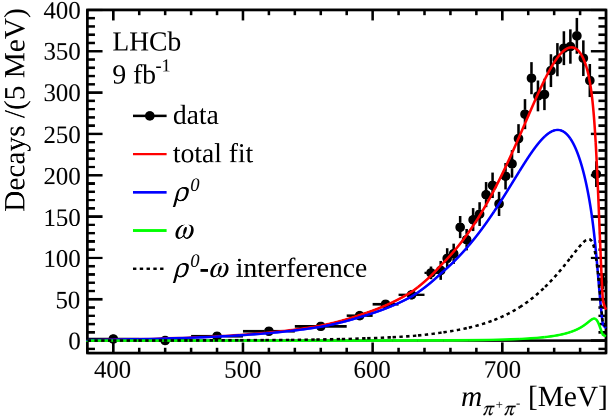
The default fit

[LHCb, JHEP 08 (2020) 123]



- 3 parameter fit
- $\chi^2/\text{ndf} = 24.7/32$
- $R_\omega^{\text{all}} = 0.214 \pm 0.023$ due to the large interference

!! Pure contribution of ρ is $(78.6 \pm 2.3)\%$

using $\omega \to 2\pi$ (this) : $R_\omega = (1.93 \pm 0.44)\%$

using $\omega \to 3\pi$ (PDG) : $\dfrac{\mathcal{B}(\chi_{c1}(3872) \to \omega J/\psi)\mathcal{B}(\omega \to 2\pi)}{\mathcal{B}(\chi_{c1}(3872) \to \pi^+\pi^- J/\psi)} = (2.1 \pm 0.5)\%$

Systematic studies

[LHCb, JHEP 08 (2020) 123]

Variations of the model

Fit type	χ^2/NDoF	p-value	$\mathcal{R}_{\omega}^{\text{all}}$	$\mathcal{R}_{\omega}^{0}$	$\mathcal{R}_{\omega/\rho}^{0}$	n_σ
Default	24.7/32	0.82	0.214 ± 0.023	0.019 ± 0.004	0.025 ± 0.006	8.1σ
$P_2 \neq 0$	24.6/31	0.78	0.206 ± 0.035	0.018 ± 0.006	0.023 ± 0.009	5.5σ
Gaussian $\chi_{c1}(3872)$	20.0/32	0.95	0.194 ± 0.024	0.016 ± 0.004	0.020 ± 0.006	7.3σ
cubic $\epsilon(m_{\pi^+\pi^-})$	24.5/32	0.83	0.221 ± 0.023	0.021 ± 0.005	0.027 ± 0.007	8.1σ
had.ID corrections	24.6/32	0.82	0.214 ± 0.023	0.019 ± 0.004	0.025 ± 0.006	8.1σ
BDT selection	24.6/32	0.82	0.207 ± 0.022	0.018 ± 0.004	0.023 ± 0.006	7.9σ
$\sigma(m_{\pi^+\pi^-}) \times 1.0$	26.6/32	0.74	0.213 ± 0.023	0.019 ± 0.004	0.025 ± 0.006	8.1σ
$\sigma(m_{\pi^+\pi^-}) \times 1.14$	22.6/32	0.89	0.215 ± 0.023	0.020 ± 0.004	0.026 ± 0.006	8.1σ
$m_{\pi^+\pi^-} < 775$ MeV	18.0/31	0.97	0.196 ± 0.024	0.016 ± 0.004	0.021 ± 0.006	7.1σ
$\cos\theta_X < 0$	26.9/32	0.72	0.211 ± 0.035	0.019 ± 0.007	0.024 ± 0.010	5.2σ
$\cos\theta_X > 0$	42.2/32	0.11	0.217 ± 0.030	0.021 ± 0.006	0.027 ± 0.009	4.2σ
NR prod. of 2π	24.7/32	0.82	0.214 ± 0.022	0.019 ± 0.004	0.025 ± 0.006	8.1σ
D-wave free	24.5/31	0.79	0.210 ± 0.029	0.017 ± 0.005	0.021 ± 0.007	7.8σ
D-wave fixed at 4%	24.5/32	0.82	0.208 ± 0.023	0.018 ± 0.004	0.023 ± 0.006	7.9σ
ρ'	25.1/32	0.80	0.209 ± 0.023	0.018 ± 0.004	0.024 ± 0.006	8.1σ
$R_{\text{prod}} = 0$ GeV^{-1}	24.7/32	0.82	0.209 ± 0.023	0.019 ± 0.004	0.024 ± 0.006	7.9σ
$R_{\text{prod}} = 30$ GeV^{-1}	24.6/32	0.82	0.229 ± 0.022	0.021 ± 0.004	0.028 ± 0.006	8.7σ
$R = 1.3$ GeV^{-1}	24.7/32	0.82	0.216 ± 0.022	0.020 ± 0.004	0.026 ± 0.006	8.2σ
$R = 1.6$ GeV^{-1}	24.7/32	0.82	0.212 ± 0.023	0.019 ± 0.004	0.025 ± 0.006	8.0σ
GS model	24.8/32	0.81	0.221 ± 0.024	0.021 ± 0.005	0.028 ± 0.007	7.8σ
Summary			$0.214 \pm 0.023 \pm 0.020$	$0.019 \pm 0.004 \pm 0.003$	$0.025 \pm 0.006 \pm 0.005$	$> 7.1\sigma$

Testing the Gounaris-Sakurai shape

[LHCb, JHEP 08 (2020) 123]

[Barkov et al., NPB 256 (1985) 365-384], [BaBar, PRD86, 032013 (2012)]

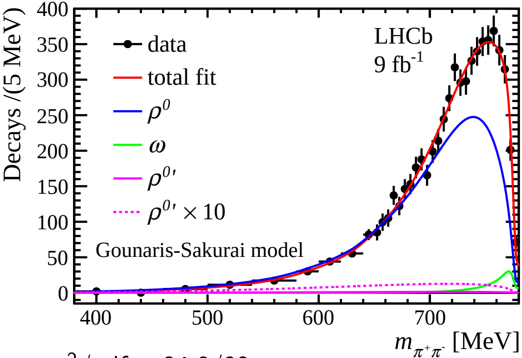
$$\mathcal{A}_{2\pi} = p_\pi(s)\left\{\mathrm{BW}_\rho^{\mathrm{GS}}(1 + A_\omega e^{i\phi_\omega}\mathrm{BW}_\omega) + A_{\rho'} e^{i\phi_{\rho'}}\mathrm{BW}_{\rho'}^{\mathrm{GS}}\right\}$$

$\rho - \omega$ is equivalent to the coupled-channel, ρ' is added by sum of BW.

$$\mathrm{BW}_\rho^{\mathrm{GS}} = \frac{1}{m_\rho^2 - s - i m_\rho \tilde{\Gamma}_\rho(s)}$$

with $i\tilde{\Gamma}_\rho(s)$ calculated from using dispersion relations ()

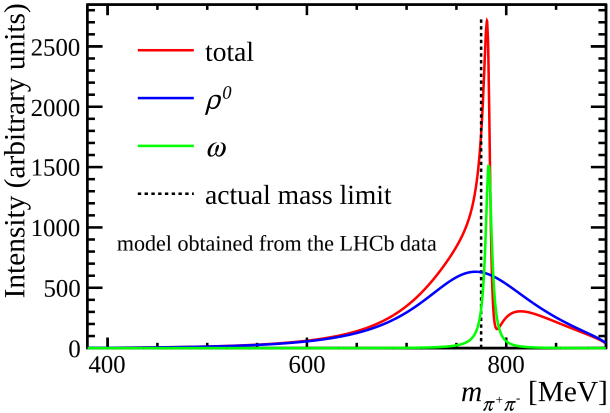
- P-wave
  $\mathrm{Im}(i\tilde{\Gamma}_\rho(s)) = \Gamma \frac{m_\rho}{\sqrt{s}}\left[\frac{p(s)}{p(m^2)}\right]^3$
- Twice-subtracted DR
- Two subt.constants are fixed at $\sqrt{s} = m_\rho$,



- $\chi^2/\mathrm{ndf} = 24.8/32$
- Compatible results

Size of the isospin violation

[LHCb, JHEP 08 (2020) 123]



- Extend the upper limit of ph.sp: $m_{\chi_{c1}} \to 4\,\text{GeV}$
- Ratio of the integrals:

$$R_{\omega/\rho} = 0.18 \pm 0.05(\text{stat})$$

The estimate for couplings:

$$\frac{g_{\chi_{c1}\to\rho J/\psi}}{g_{\chi_{c1}\to\omega J/\psi}} = \sqrt{\frac{\mathcal{B}(\omega\to 2\pi)}{\mathcal{B}(\rho\to 2\pi)}\frac{1}{R_{\omega/\rho}}} = 0.29 \pm 0.04$$

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

Summary

- Significant, $> 7\sigma$ contribution of ω is found in $\chi_{c1} \to J\psi\pi^+\pi^-$,
- Pure contribution of ρ: $R_\rho = (78.6 \pm 2.3 \pm 2.0)\%$,
- $\boxed{R_\omega = (1.9 \pm 0.4 \pm 0.3)\%}$
- Consistent with the direct measurements using $\omega \to 3\pi$

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- Consistent with the direct measurements using $\omega \to 3\pi$

$$g_{\chi_{c1}\to\rho J/\psi} \,/\, g_{\chi_{c1}\to\omega J/\psi} \approx 0.3$$

The isospin violation is larger by an order of magnitude that for ordinary charmonium state

- Possible in molecular picture due to the proximity to $D^{*0}\bar{D}^0$ rather than $D^{*+}\bar{D}^-$ [Törnqvist(2003, 2004), Voloshin(2004), Swanson(2004), Suzuki(2005), ...]
- Also also possible in compact tetraquark picture[Terasaki,(2007), Maiani(2018,2020)]

Thank you for the attention

How well we know the $\pi\pi$ P-wave

Three shapes are consistent:

- GKPY: combined analysis with th. constrains
- GS (P-wave CM, 2 subtracted)
- P-wave BW with Blatt-Weisskopf barrier factor, $R = 1.5\,\mathrm{GeV}^{-1}$.

$$B_1(p) = p^2\,\frac{1}{1+(pR)^2}\,.$$

- CDF-II and Belle used $R = 1.5\,\mathrm{GeV}^{-1}$
- PDG(1983): $R = 5.3^{+0.9}_{-0.7}\,\mathrm{GeV}^{-1}$