

Two nearby states in the X(3872) region?

Resolving the radiative-decay ratio tension

arXiv: 2602.19165

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Introduction

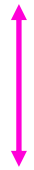
X(3872) radiative-decay tension

LHCb, JHEP 2024, 121 (2024)

$$\mathcal{R}_{\psi\gamma} = \frac{\Gamma[X(3872) \rightarrow \psi(2S)\gamma]}{\Gamma[X(3872) \rightarrow J/\psi\gamma]}$$

$$= 1.67 \pm 0.25 \quad \text{from } B^+ \rightarrow K^+ X(3872)$$

LHCb, JHEP 2024, 121 (2024)



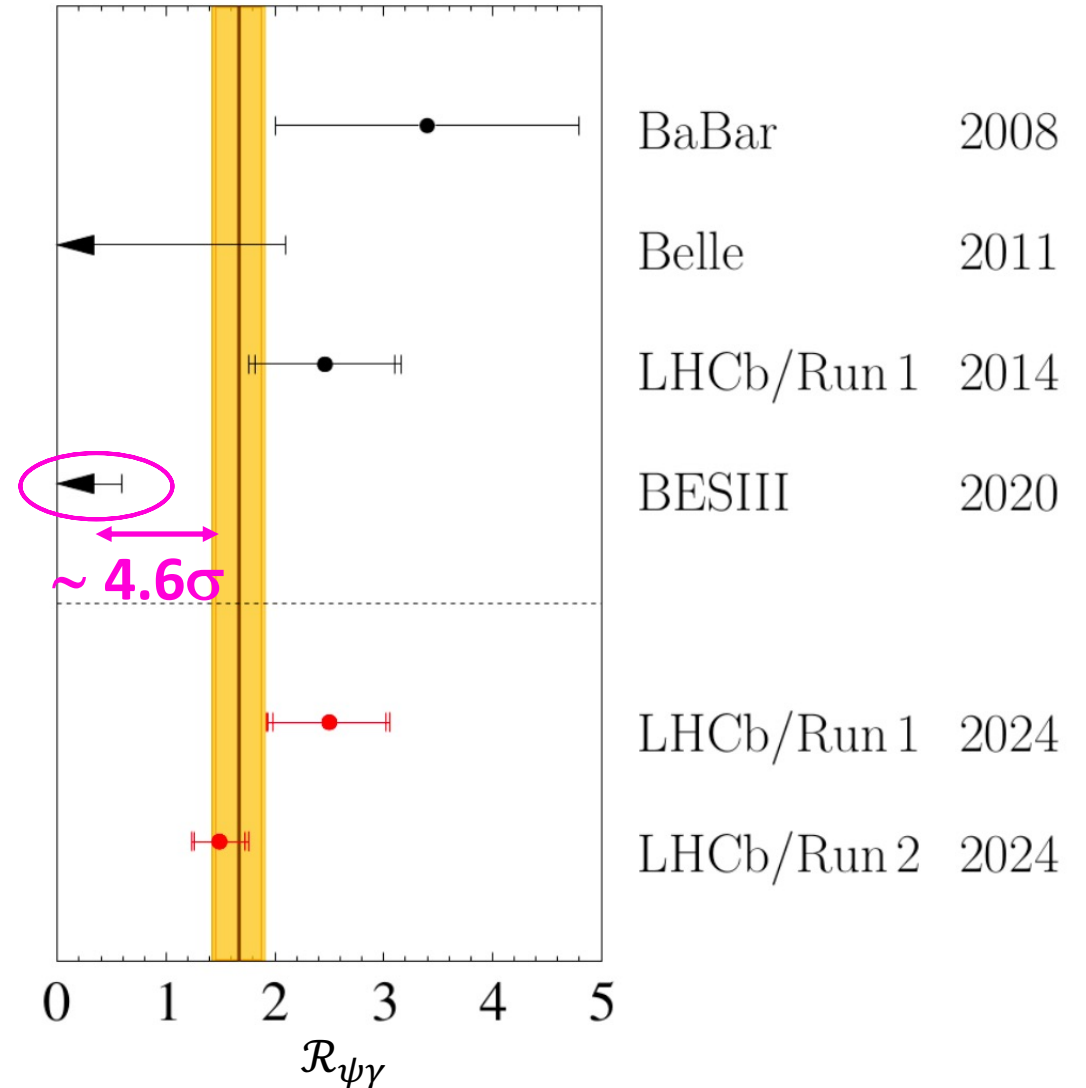
~ 4.6σ tension

$$= -0.04 \pm 0.28 \quad \text{from } e^+e^- \rightarrow \gamma X(3872)$$

BESIII, PRL 124, 242001 (2020)

$\mathcal{R}_{\psi\gamma}$ should not depend on how X(3872) is produced

How to reconcile the two measurements?



One answer (not taken here): experimental issue (underestimated systematics, background, extraction procedure...)

How to reconcile LHCb and BESIII measurements?

Assume two nearby states (X_A and X_B) in $X(3872)$ region

- $\psi(2S)\gamma$ is mostly from X_A -decay
- $J/\psi\gamma$ is mostly from X_B -decay

$$\mathcal{R}_{\psi\gamma}(B \text{ decay}) = \frac{\Gamma[B \rightarrow KX(3872)] \times \Gamma[X(3872) \rightarrow \psi(2S)\gamma]}{\Gamma[B \rightarrow KX(3872)] \times \Gamma[X(3872) \rightarrow J/\psi\gamma]} \sim \frac{\Gamma[B \rightarrow KX_A] \times \Gamma[X_A \rightarrow \psi(2S)\gamma]}{\Gamma[B \rightarrow KX_B] \times \Gamma[X_B \rightarrow J/\psi\gamma]} \sim 1.7$$

$$\mathcal{R}_{\psi\gamma}(e^+e^-) = \frac{\sigma[e^+e^- \rightarrow \gamma X(3872)] \times \Gamma[X(3872) \rightarrow \psi(2S)\gamma]}{\sigma[e^+e^- \rightarrow \gamma X(3872)] \times \Gamma[X(3872) \rightarrow J/\psi\gamma]} \sim \frac{\sigma[e^+e^- \rightarrow \gamma X_A] \times \Gamma[X_A \rightarrow \psi(2S)\gamma]}{\sigma[e^+e^- \rightarrow \gamma X_B] \times \Gamma[X_B \rightarrow J/\psi\gamma]} \sim 0$$

How to reconcile LHCb and BESIII measurements?

Assume two nearby states (X_A and X_B) in $X(3872)$ region

- $\psi(2S)\gamma$ is mostly from X_A -decay
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common

$$\mathcal{R}_{\psi\gamma}(e^+e^-) = \frac{\sigma[e^+e^- \rightarrow \gamma X(3872)] \times \Gamma[X(3872) \rightarrow \psi(2S)\gamma]}{\sigma[e^+e^- \rightarrow \gamma X(3872)] \times \Gamma[X(3872) \rightarrow J/\psi\gamma]} \sim \frac{\sigma[e^+e^- \rightarrow \gamma X_A] \times \Gamma[X_A \rightarrow \psi(2S)\gamma]}{\sigma[e^+e^- \rightarrow \gamma X_B] \times \Gamma[X_B \rightarrow J/\psi\gamma]} \sim 0$$

Condition to reconcile two measurements $\Rightarrow \frac{\Gamma[B \rightarrow KX_A]}{\Gamma[B \rightarrow KX_B]} > \frac{\sigma[e^+e^- \rightarrow \gamma X_A]}{\sigma[e^+e^- \rightarrow \gamma X_B]}$

- Two-state hypothesis naturally accommodates condition
- Single-state ($X_A = X_B$) cannot

Two-state hypothesis

$X_A \rightarrow$ shallow $D^{*0}\bar{D}^0$ bound state ($J^{PC} = 1^{++}$) \leftarrow well-established $X(3872)$

$X_B \rightarrow \eta_{c2} (2^{-+})$ slightly above $D^{*0}\bar{D}^0$ threshold

Why η_{c2} ?

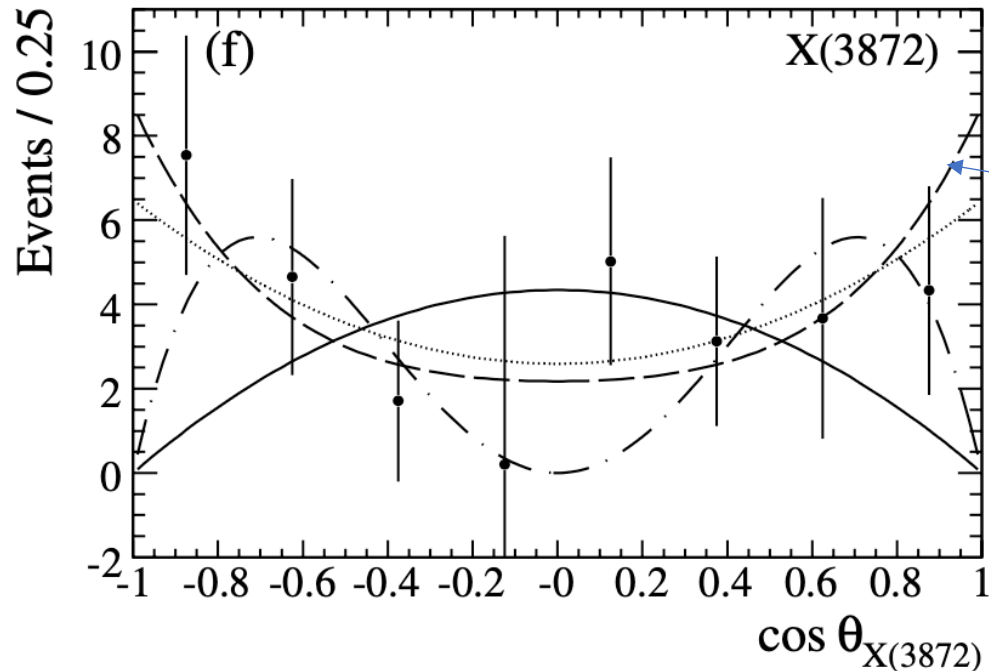
- Heavy-quark spin partner of $\psi(3770), \psi_2(3823), \psi_3(3842)$
- Quark models predict its existence in 3800-3900 MeV
Godfrey and Isgur (1985), Barnes and Godfrey (2004), Fulcher (1991)
- Lattice QCD predicts its existence
Dudek et al. (2008), CLQCD (2013)
- Not experimentally observed yet
Belle (2020), (2021)

Two-state hypothesis

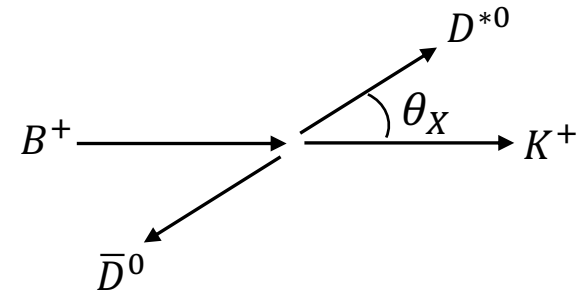
Experimental hint: Why η_{c2} ?

Helicity angle distribution of $B^+ \rightarrow K^+(D^{*0}\bar{D}^0 + c.c.)$

BaBar, PRD 77 011102(R) (2008)



$D^{*0}\bar{D}^0$ center-of-mass frame



2^{-+} (long-dash) best fits data; 1^{++} gives flat

Previous discussion:

$X(3872)$ may be a 2^{-+} state

→ Ruled out (LHCb established 1^{++})

Our scenario:

Both $1^{++} X(3872)$ and $2^{-+} \eta_{c2}$ coexist nearby

This talk

Develop two-state model that consistently describes broad set of $X(3872)$ data

- Both B -decays and e^+e^- annihilations
- $J/\psi\pi^+\pi^-$, $J/\psi\omega$, $D^{*0}\bar{D}^0 + c.c.$, $J/\psi\gamma$, $\psi(2S)\gamma$ final states
- invariant mass distributions (lineshapes)
- branching ratios

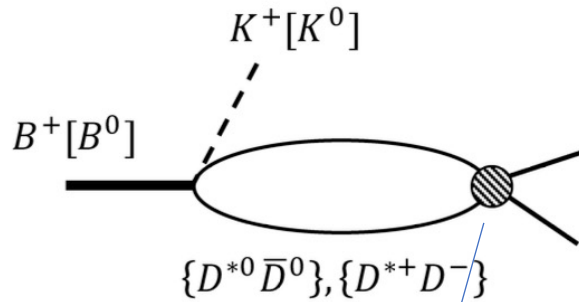
Show advantage of two-state model over single-state model

Predict helicity-angle distributions

Useful observable to test two-state hypothesis \rightarrow future experiments can do

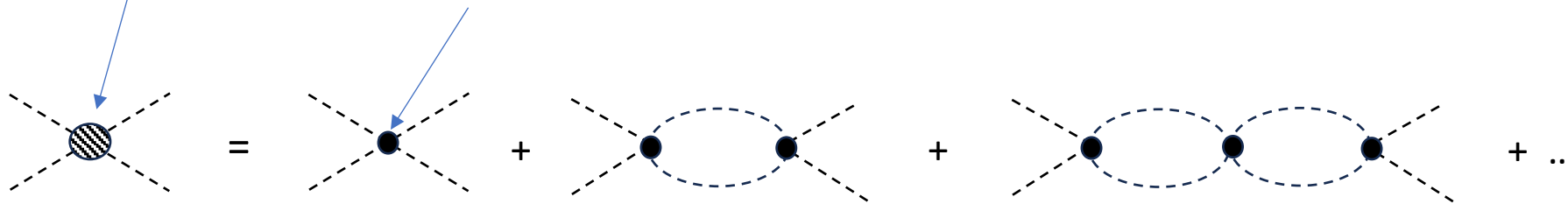
MODEL

B decay mechanisms



$J/\psi\rho^0, J/\psi\omega, D^{*0}\bar{D}^0, J/\psi\gamma, \psi(2S)\gamma$

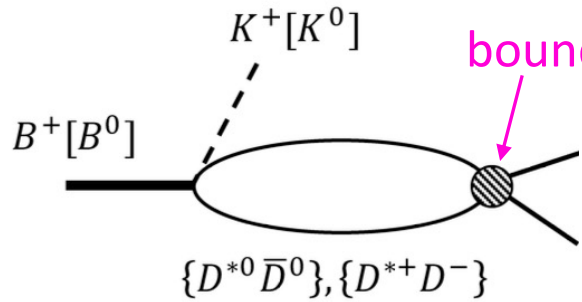
s-wave contact interactions (could effectively include bare $c\bar{c}$ excitation)



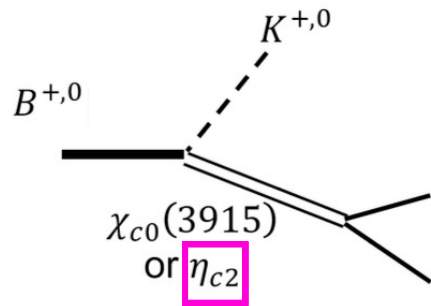
- $D^{*0}\bar{D}^0 - D^{*+}D^- - J/\psi\rho^0 - J/\psi\omega$ couple—channel scattering amplitude ($J^{PC} = 1^{++}$)
- $J/\psi\gamma$ and $\psi(2S)\gamma$ channels are included to first-order
- Mass difference between $D^{(*)\pm}$ and $D^{(*)0} \rightarrow$ isospin violation

Poles are generated: 1. $D^{*0}\bar{D}^0$ shallow bound state $\rightarrow X(3872)$; 2. $D^{*+}D^-$ virtual state $\rightarrow W_{c1}$

B decay mechanisms

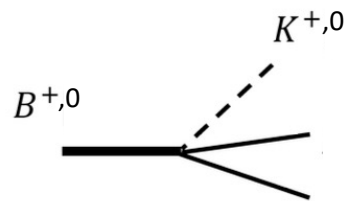


$J/\psi\rho^0, J/\psi\omega, D^{*0}\bar{D}^0, J/\psi\gamma, \psi(2S)\gamma$



~~$J/\psi\rho^0$~~ , $J/\psi\omega, D^{*0}\bar{D}^0, J/\psi\gamma, \psi(2S)\gamma$

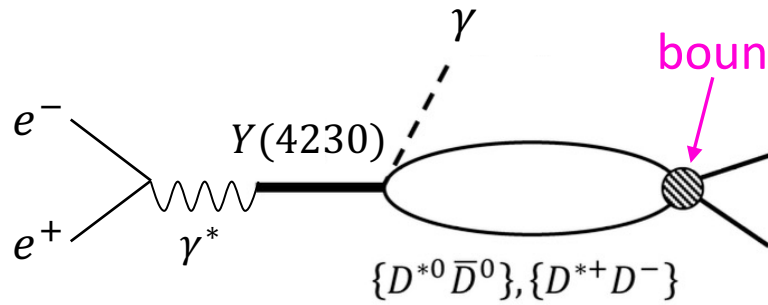
No isospin-violation



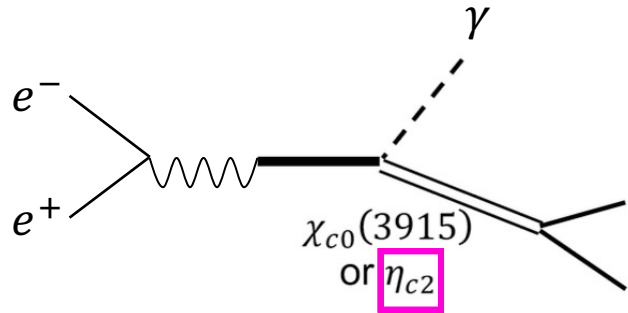
$D^{*0}\bar{D}^0$ only

Considered:
 $\rho^0 \rightarrow \pi^+\pi^-$
 $\omega \rightarrow \pi^+\pi^-\pi^0$
 $\omega \leftrightarrow \rho^0$ mixing

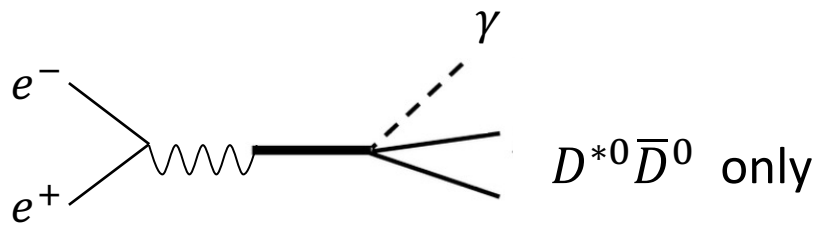
e^+e^- annihilation mechanisms



$J/\psi\rho^0, J/\psi\omega, D^{*0}\bar{D}^0, J/\psi\gamma, \psi(2S)\gamma$



~~$J/\psi\rho^0, J/\psi\omega, D^{*0}\bar{D}^0, J/\psi\gamma, \psi(2S)\gamma$~~



$X(3872)$ and η_{c2} produced differently in B decay and e^+e^-

$$\Rightarrow \frac{\Gamma[B \rightarrow KX]}{\Gamma[B \rightarrow K\eta_{c2}]} > \frac{\sigma[e^+e^- \rightarrow \gamma X]}{\sigma[e^+e^- \rightarrow \gamma\eta_{c2}]}$$

Condition to reconcile $\mathcal{R}_{\psi\gamma}$ (LHCb) and $\mathcal{R}_{\psi\gamma}$ (BESIII)

Fitting parameters

- Weak B decay couplings and cutoffs (form factors)
- $Y(4230)$ decay couplings
- $1^{++} D^{*0}\bar{D}^0 - D^{*+}D^- - J/\psi\rho^0 - J/\psi\omega$ s-wave interaction couplings and common cutoff
- η_{c2} mass and decay couplings
- $\chi_{c0}(3915) \rightarrow J/\psi\omega$ coupling

Not fitted:

- η_{c2} width = 0.5 MeV; similar to quark model estimate X.-Y. Du et al. PRD 110, 113009 (2024)
- $\chi_{c0}(3915)$ mass and width \leftarrow BaBar's fit to $B \rightarrow J/\psi\omega K$ BaBar, PRD 82, 011101 (2010)

We use two models:

- Default (including all) ; 23 fit parameters
- η_{c2} -less ; 16 fit parameters

Results

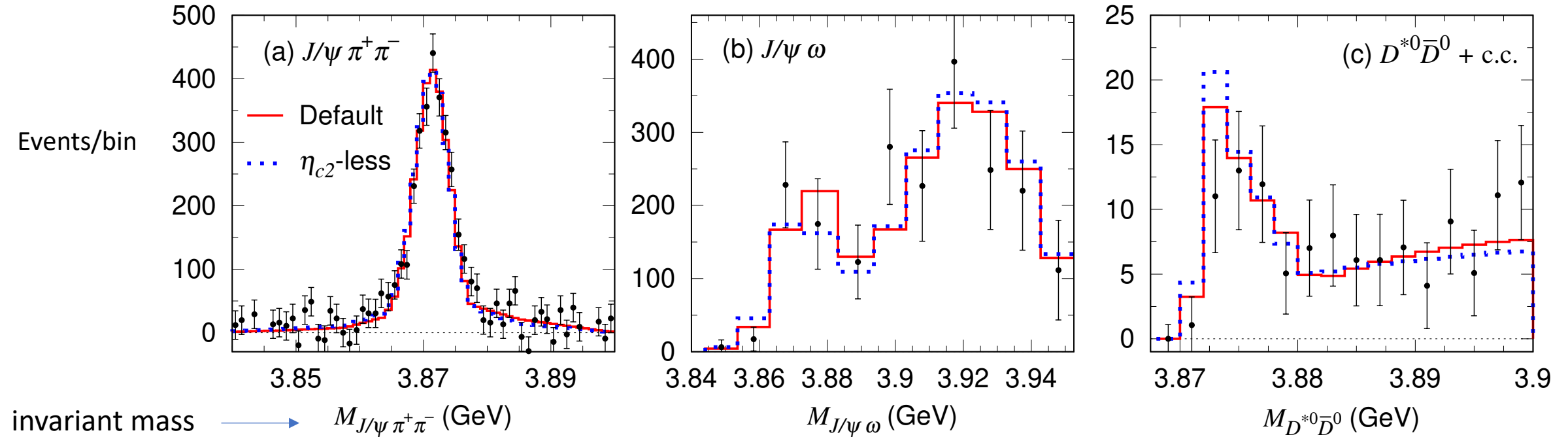
Fit to B decay lineshape data

Data

(a) LHCb 2020

(b) BaBar 2010

(c) Belle 2023



Both default and η_{c2} -less models fit lineshape data reasonably

Poles: $3871.4 - 0.022 i$ MeV ($D^{*0} \bar{D}^0$ bound state)

$3873.8 - 0.25 i$ MeV (η_{c2})

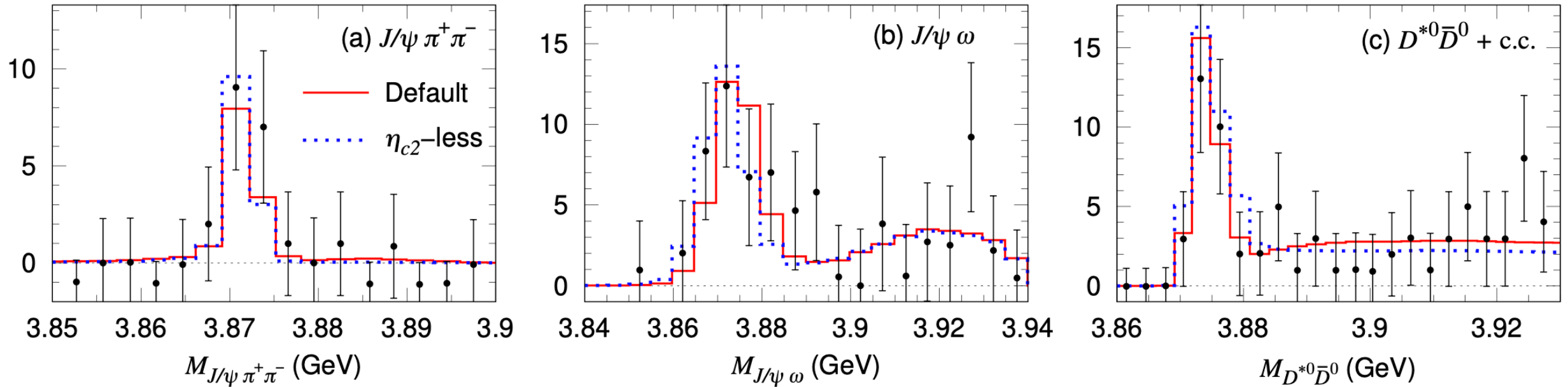
$3882.8 + 1.5 i$ MeV (W_{c1} , $D^{*+} D^-$ virtual state)

$D^{*0} \bar{D}^0$ threshold: 3871.7 MeV

Fit to e^+e^- annihilation lineshape data ($e^+e^- \rightarrow \gamma X$)

Events/bin

Data: BESIII



Both default and η_{c2} -less models fit lineshape data reasonably

→ Lineshape data alone do NOT discriminate default and η_{c2} -less models

Fit to branching ratios

$B^+ \rightarrow K^+ X$

$e^+ e^- \rightarrow \gamma X$

	$\frac{\Gamma[J/\psi\omega]}{\Gamma[J/\psi\pi^+\pi^-]}$	$\frac{\Gamma[D^{*0}\bar{D}^0]}{\Gamma[J/\psi\pi^+\pi^-]}$	$\frac{\Gamma[J/\psi\gamma]}{\Gamma[J/\psi\pi^+\pi^-]}$	$\mathcal{R}_{\psi\gamma}$	$\frac{\Gamma[J/\psi\omega]}{\Gamma[J/\psi\pi^+\pi^-]}$	$\frac{\Gamma[D^{*0}\bar{D}^0]}{\Gamma[J/\psi\pi^+\pi^-]}$	$\frac{\Gamma[J/\psi\gamma]}{\Gamma[J/\psi\pi^+\pi^-]}$	$\mathcal{R}_{\psi\gamma}$
Default	0.41	11.	0.20	1.6 ✓	2.0	14.	0.82	0.26 ✓
η_{c2} -less	0.72	12.	0.29	0.53 ✗	0.81	13.	0.22	0.53 ✗
Exp.	0.7 ± 0.3	$12.2^{+3.0}_{-2.6}$	0.22 ± 0.06	1.67 ± 0.25 (LHCb)	1.6 ± 0.4	11.77 ± 3.09	0.79 ± 0.28	-0.04 ± 0.28 (BESIII)

- Default model reproduces both LHCb and BESIII results on radiative-decay ratio $\mathcal{R}_{\psi\gamma} = \frac{\Gamma[\psi(2S)\gamma]}{\Gamma[J/\psi\gamma]}$
- η_{c2} -less model cannot $\rightarrow \mathcal{R}_{\psi\gamma}(B \text{ decay}) \sim \mathcal{R}_{\psi\gamma}(e^+e^-)$

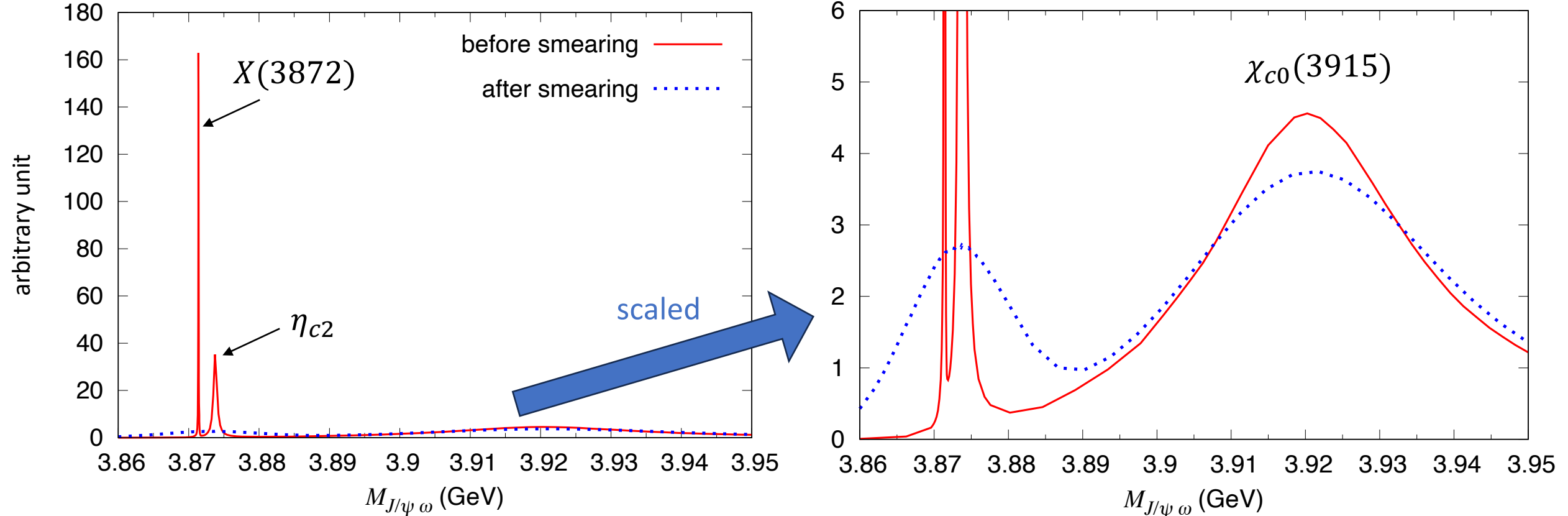
\rightarrow The radiative-ratio tension selects the two-state (default) model

Fitting both lineshape and $\mathcal{R}_{\psi\gamma}$ data is crucial to discriminate two-state and single-state scenarios

Why two peaks not seen in data?

Answer : Experimental resolution smearing

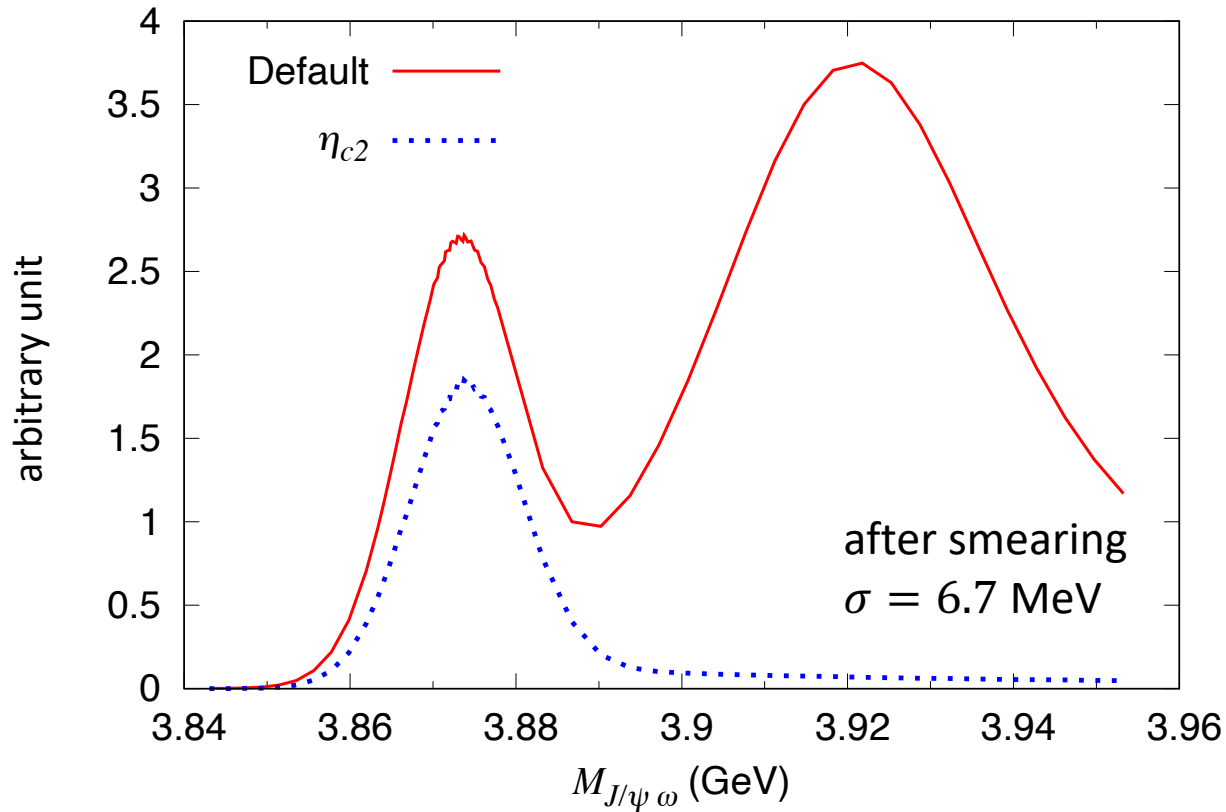
$B^+ \rightarrow J/\psi \omega K^+$ ($\sigma = 6.7$ MeV)



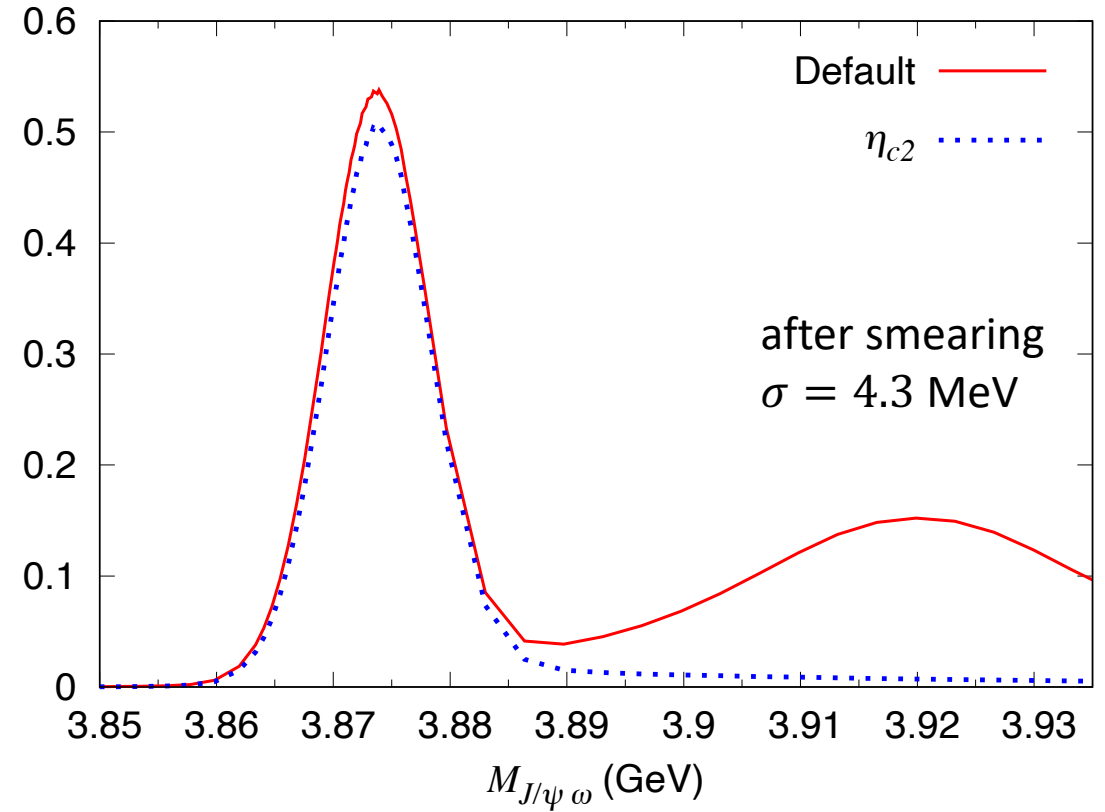
- Due to experimental resolution, two sharp peaks ($X(3872)$, η_{c2}) smeared \rightarrow single peak
- The issue is two nearby poles, not necessarily two experimentally resolved peaks

η_{c2} contributions

$B^+ \rightarrow J/\psi \omega K^+$



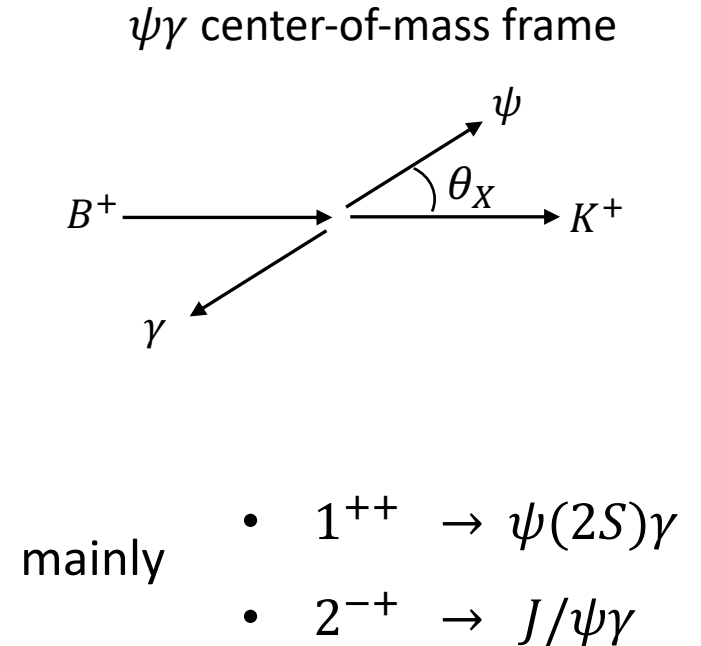
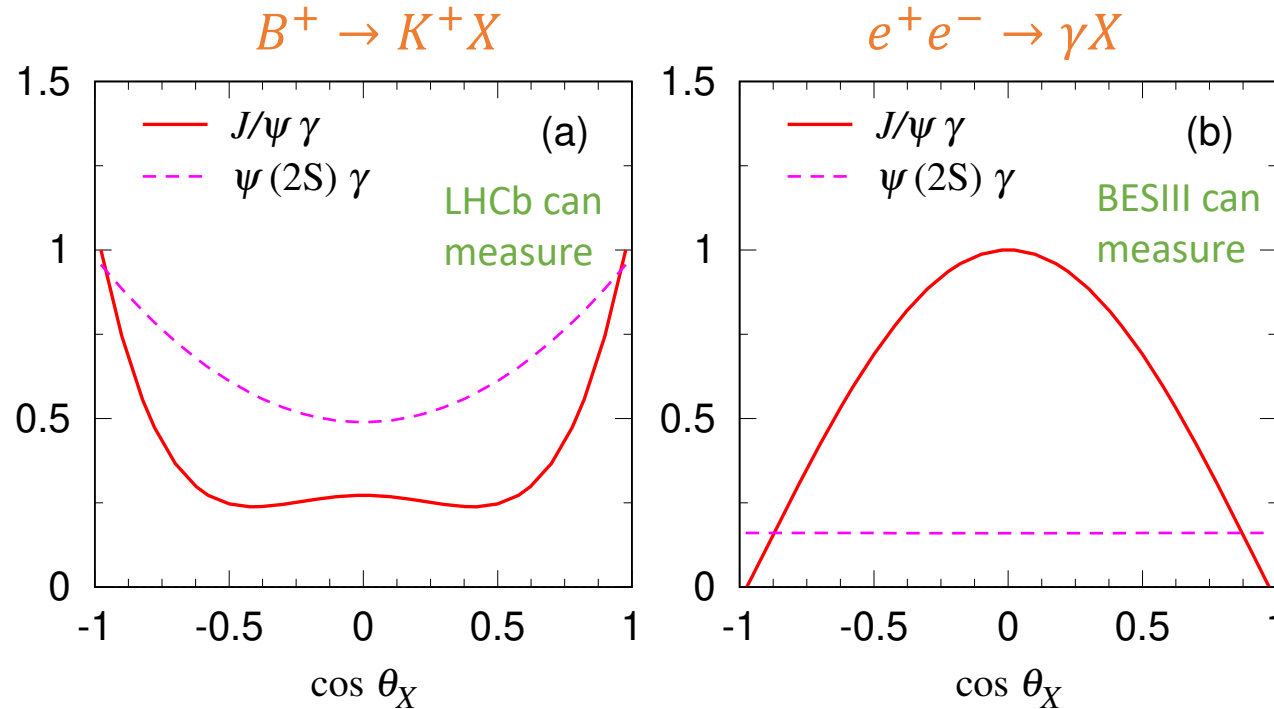
$e^+e^- \rightarrow J/\psi \omega \gamma$



- η_{c2} contributions are dominant in $X(3872)$ region; even larger in e^+e^-
- Very small η_{c2} contributions to $J/\psi \pi^+ \pi^-$ because:
 - (i) via $\omega \rightarrow \rho^0$ mixing ($\eta_{c2} \nrightarrow J/\psi \rho^0$)
 - (ii) no interference with $X(3872) \rightarrow J/\psi \rho^0$

What should experiments look for next?

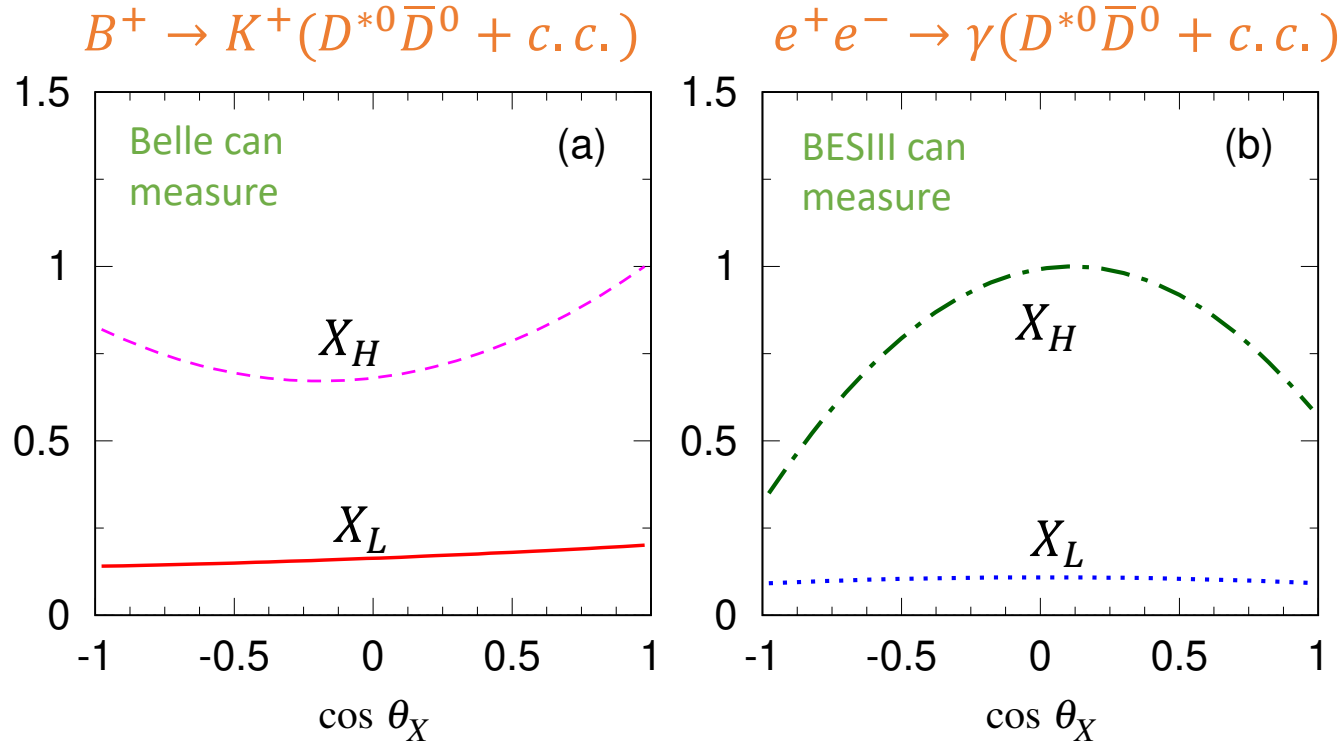
Two-state model predicts helicity angle distribution



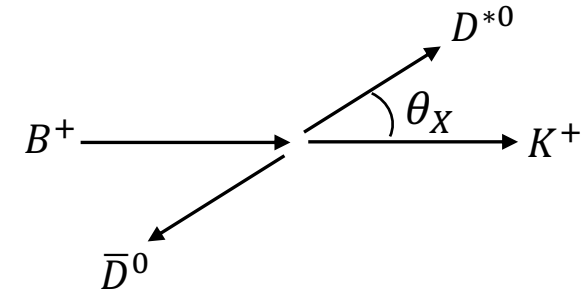
- Distinctly different helicity angle distribution between $J/\psi\gamma$ and $\psi(2S)\gamma$
- If single 1^{++} state exists \rightarrow same angular dependence as magenta dashed curve

What should experiments look for next?

Two-state model predicts helicity angle distribution



$D^{*0}\bar{D}^0$ center-of-mass frame



Kinematical cut to separate 1^{++} and 2^{-+}

$$M_{D^{*0}\bar{D}^0} < 3872 \text{ MeV} \quad \rightarrow \quad X_L \sim 1^{++}$$

$$3872 < M_{D^{*0}\bar{D}^0} < 3875 \text{ MeV} \quad \rightarrow \quad X_H \sim 2^{-+}$$

$M_{D^{*0}\bar{D}^0}$ resolution considered before cut

- Distinctly different helicity angle distribution between X_L and X_H
- If single 1^{++} state exists \rightarrow angular dependence is flat

Summary

Summary

- X(3872) radiative-decay tension ($\sim 4.6\sigma$) between LHCb and BESIII
 - motivate two-state interpretation
- Ordinary lineshape data alone do not distinguish two-state and single-state scenarios
- Two-state model reproduces the radiative tension, while single-state model does not, within the model comparison in our analysis
- Our analysis should be viewed as a testable interpretation, not yet a discovery claim
 - Future experiments will make decisive confirmation of two-state hypothesis

Measurements of helicity angle distributions and improved radiative data are important

Back up

Two-state hypothesis

Experimental hint: Why two nearby states slightly below and above $D^{*0}\bar{D}^0$ threshold ?

$\chi_{c1}(3872)$ MASS FROM $J/\psi X$ MODE (PDG)

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
3871.64 ± 0.06	OUR AVERAGE			
3870.2 ± 0.7 ± 0.3	24.6	ABLIKIM	23W BES3	$e^+e^- \rightarrow J/\psi(1S)\pi^+\pi^-\omega$
3871.64 ± 0.06 ± 0.01	19.8k	¹ AAIJ	20S LHCB	$B^+ \rightarrow J/\psi\pi^+\pi^-K^+$
3871.9 ± 0.7 ± 0.2	20	ABLIKIM	14 BES3	$e^+e^- \rightarrow J/\psi\pi^+\pi^-\gamma$
3871.95 ± 0.48 ± 0.12	0.6k	AAIJ	12H LHCB	$pp \rightarrow J/\psi\pi^+\pi^-X$
3871.85 ± 0.27 ± 0.19	170	² CHOI	11 BELL	$B \rightarrow K\pi^+\pi^-J/\psi$
3873 $\begin{smallmatrix} + 1.8 \\ - 1.6 \end{smallmatrix}$ ± 1.3	27	³ DEL-AMO-SA..10B	BABR	$B \rightarrow \omega J/\psi K$
<u>3873.3 ± 1.1 ± 1.0</u>	45	⁹ ABLIKIM	19V BES	<u>$e^+e^- \rightarrow \gamma\omega J/\psi$</u>

Why $X(3872)$ mass from $X(3872) \rightarrow J/\psi\omega$ seems ~ 2 MeV larger ?

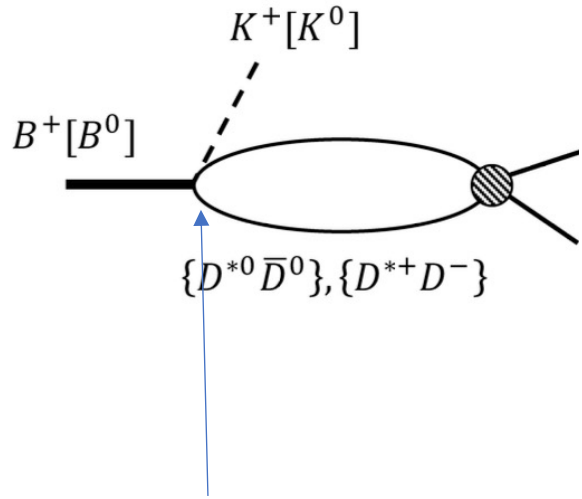
→ Consistent with two states of:

- Shallow bound $D^{*0}\bar{D}^0$
- η_{c2} slightly above $D^{*0}\bar{D}^0$ thres.

$\eta_{c2} \rightarrow J/\psi\omega$ possible

$\eta_{c2} \nrightarrow J/\psi\pi^+\pi^-$ due to isospin symmetry

B decay mechanisms



$J/\psi\rho^0, J/\psi\omega, D^{*0}\bar{D}^0, J/\psi\gamma, \psi(2S)\gamma$

Initial weak decay couplings prefer color-favored external W^+ emission mechanism

color-favored

$$B^+ \rightarrow K^+ D^{*0} \bar{D}^0$$

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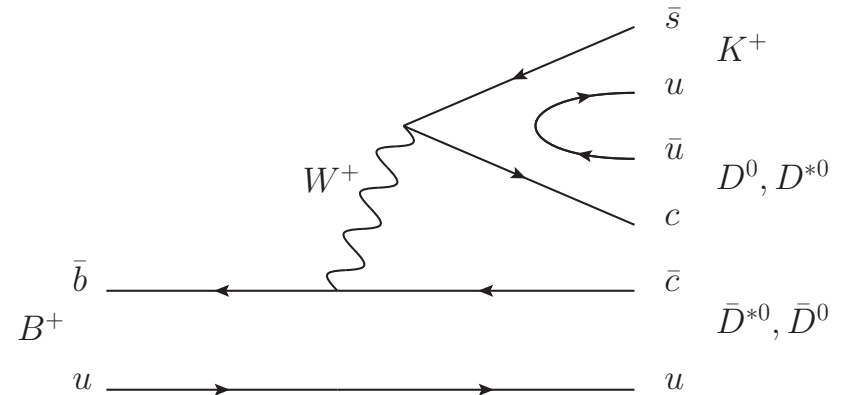
color-suppressed

$$B^+ \rightarrow K^0 D^{*+} D^-$$

$$B^0 \rightarrow K^0 D^{*+} D^-$$

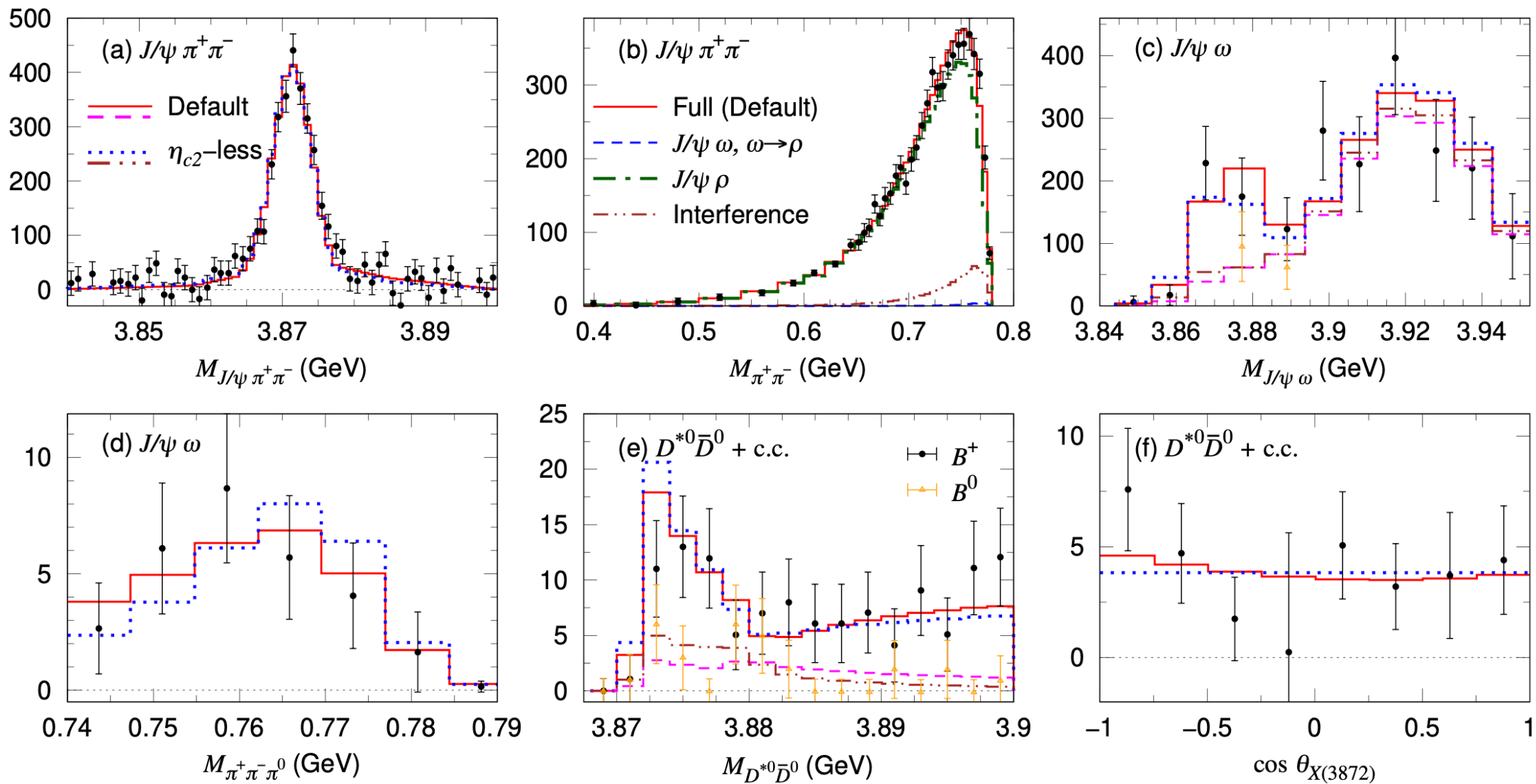
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$$B^0 \rightarrow K^0 D^{*0} \bar{D}^0$$



H.N. Wang et al., Chin. Phys. Lett. 40, 021301 (2023)

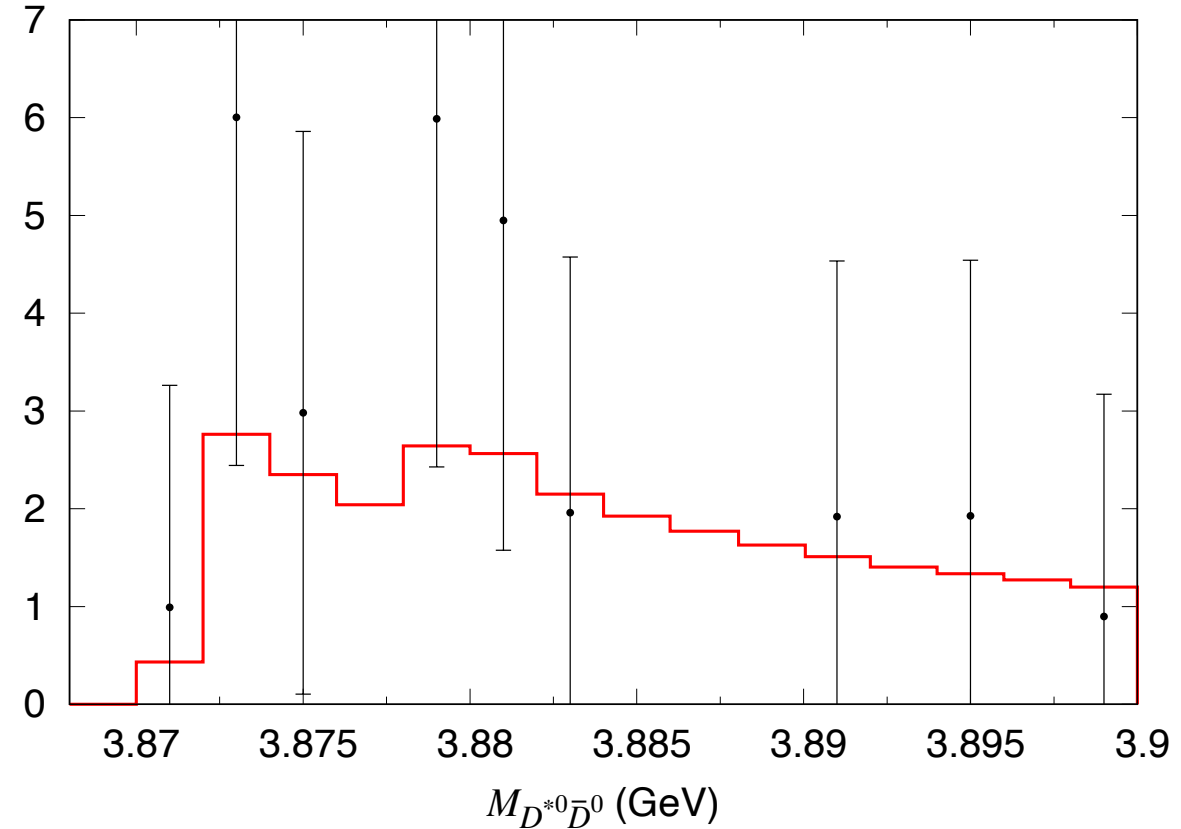
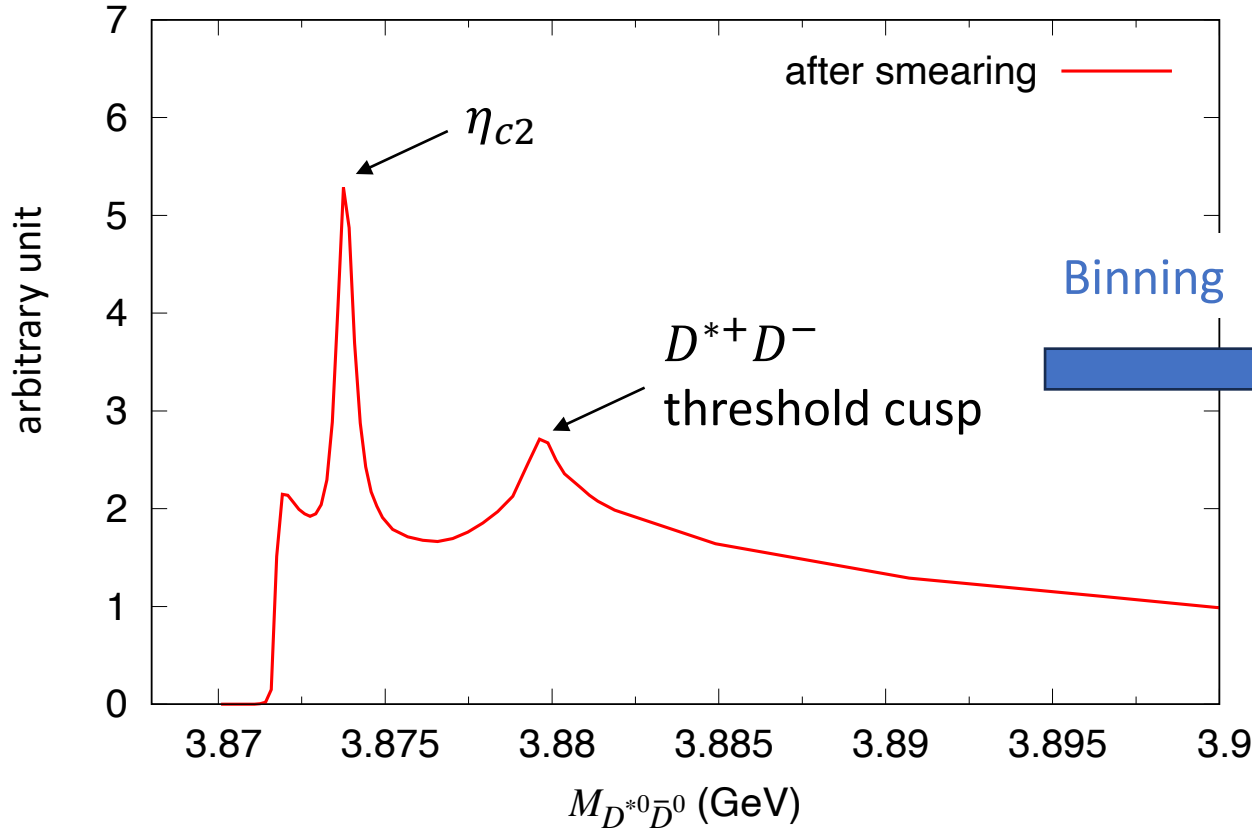
Fit to B decay lineshape data ($B^+ \rightarrow K^+ X$)



W_{c1} contributions

$B^0 \rightarrow K^0 (D^{*0}\bar{D}^0 + c.c.)$ bin width = 2 MeV

Data: Belle, PRD 107, 112011 (2023)



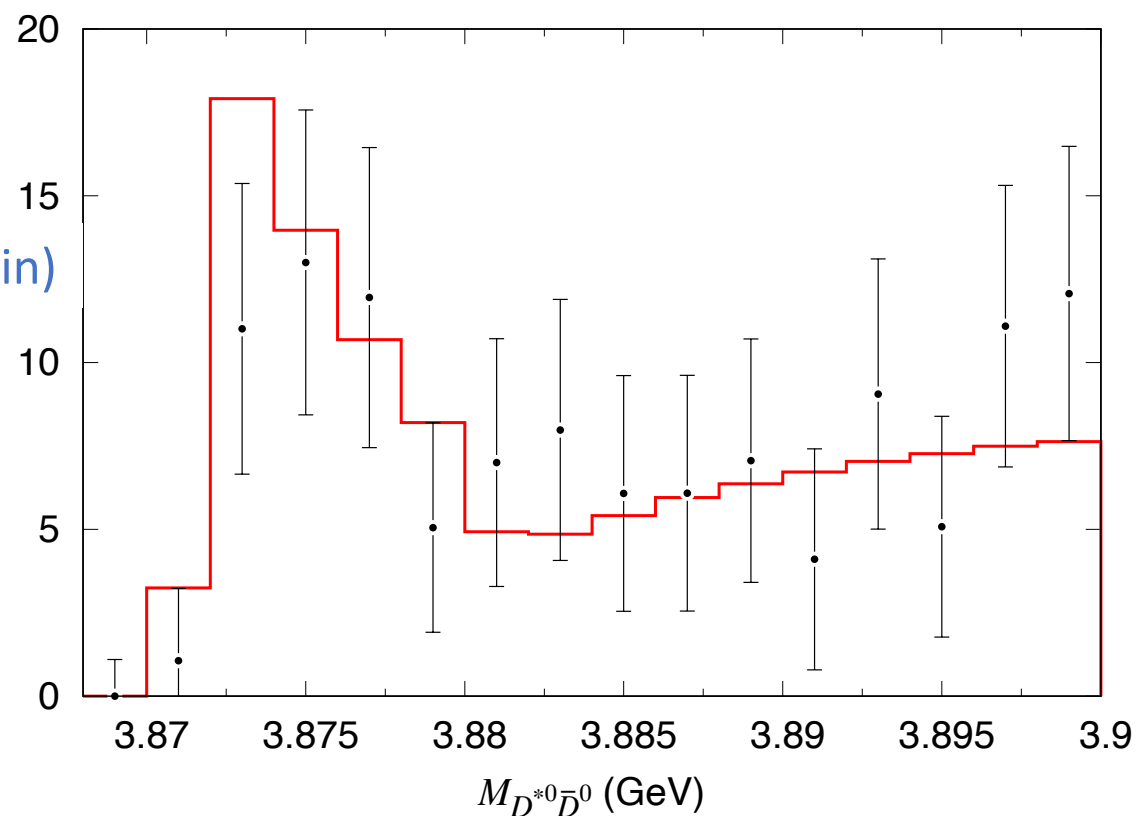
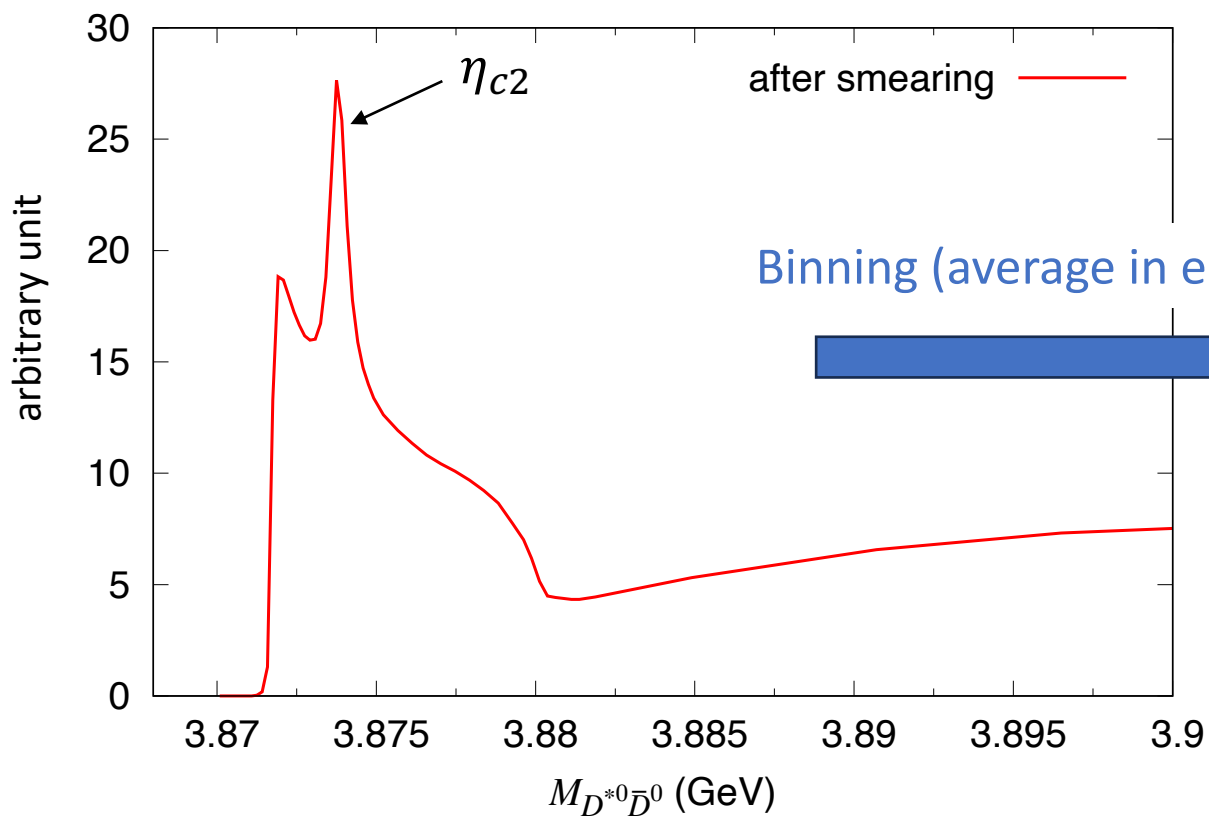
- Initial weak decay prefers $B^0 \rightarrow K^0 D^{*+} D^-$ (color-favored) to $B^0 \rightarrow K^0 D^{*0} \bar{D}^0$ (color-suppressed)
 $\rightarrow D^{*+} D^-$ threshold cusp is more prominent in B^0 decay than in B^+ decay
- W_{c1} (virtual pole) enhances $D^{*+} D^-$ Threshold cusp

Why two peaks not seen in data?

Answer 2: Experimental binning

$B^+ \rightarrow K^+ (D^{*0}\bar{D}^0 + c.c.)$ bin width = 2 MeV

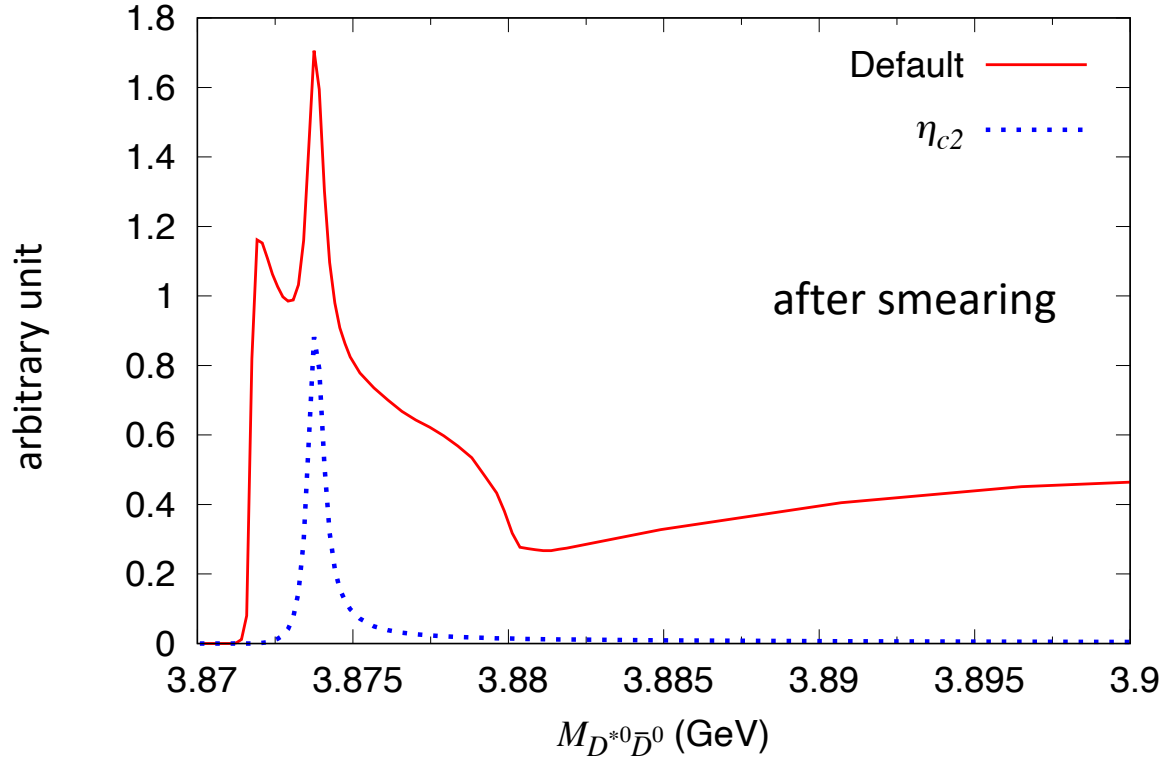
Data: Belle, PRD 107, 112011 (2023)



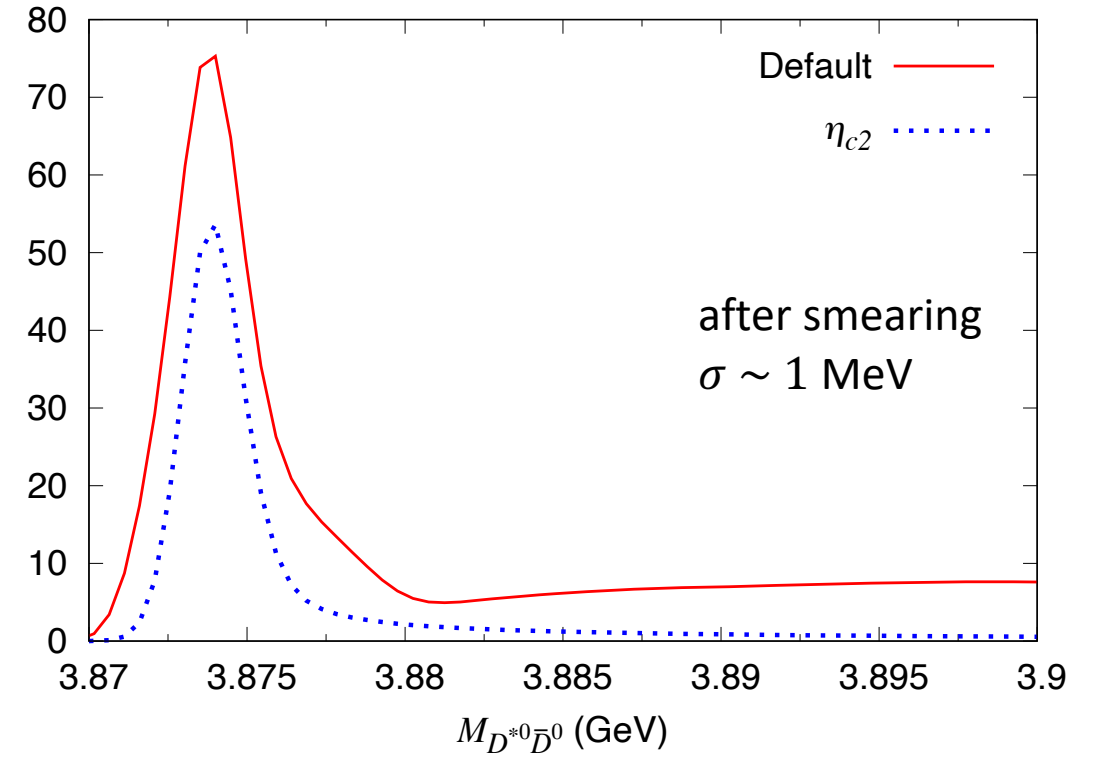
Due to binning, η_{c2} peak is absorbed by threshold enhancement

η_{c2} contributions

$$B^+ \rightarrow K^+ (D^{*0}\bar{D} + c.c.)$$



$$e^+e^- \rightarrow \gamma(D^{*0}\bar{D} + c.c.)$$



- η_{c2} contributions are substantial in $X(3872)$ region
- Very small η_{c2} contributions to $J/\psi\pi^+\pi^-$ because:
 - (i) via $\omega \rightarrow \rho^0$ mixing ($\eta_{c2} \nrightarrow J/\psi\rho^0$)
 - (ii) no interference with $X(3872) \rightarrow J/\psi\rho^0$