Two nearby states in the X(3872) region?

Resolving the radiative-decay ratio tension with η_{c2}

arXiv: 2602.19165

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Introduction

X(3872) radiative-decay tension

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

$= 1.67 \pm 0.25$ from $B^+ \to K^+ X(3872)$

LHCb, JHEP 2024, 121 (2024)

~ 4.6σ tension

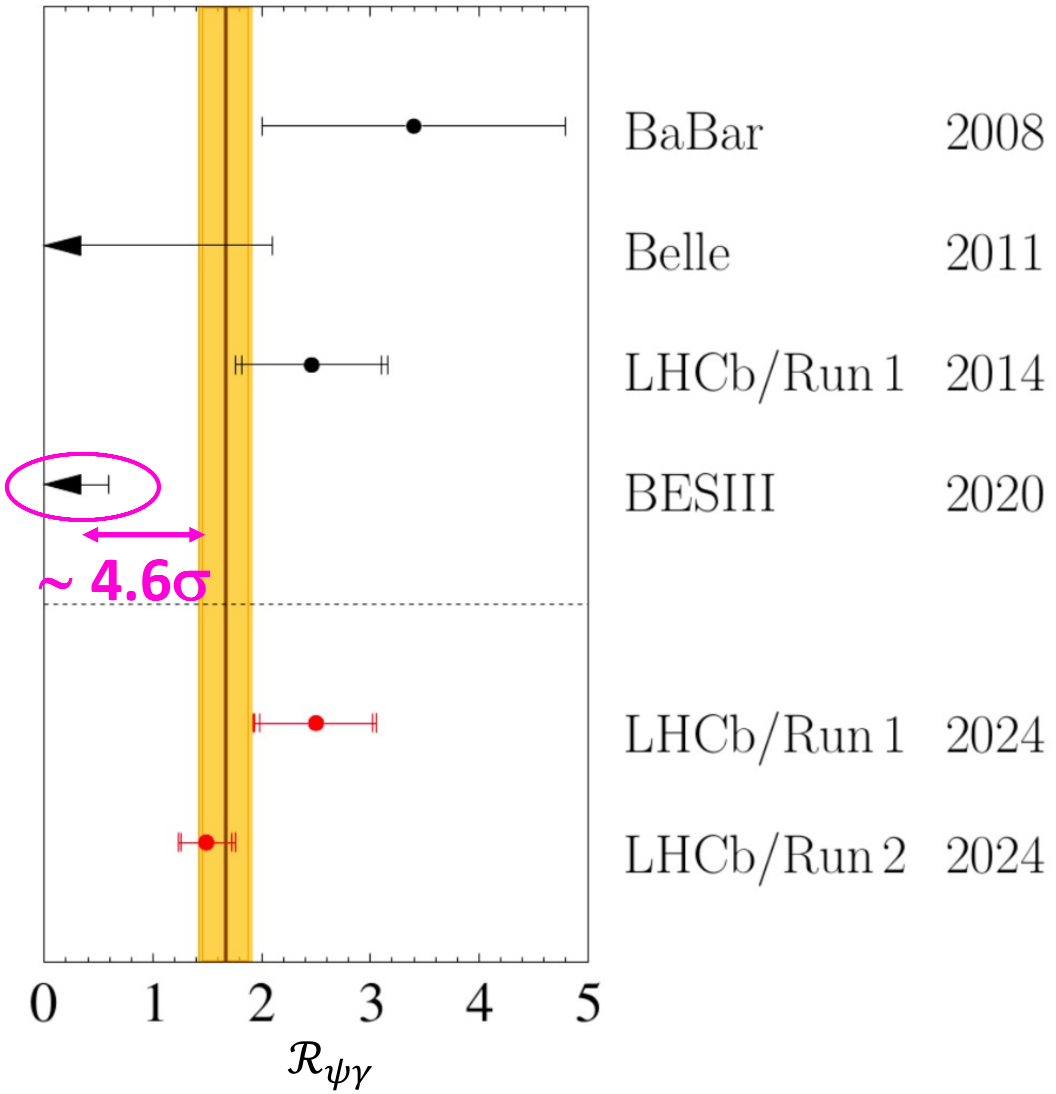
$= -0.04 \pm 0.28$ from $e^+e^- \to \gamma X(3872)$

BESIII, PRL 124, 242001 (2020)

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

How to reconcile the two measurements?

LHCb, JHEP 2024, 121 (2024)



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

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

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

How to reconcile LHCb and BESIII measurements?

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- $J/\psi\gamma$ is mostly from X_B-decay

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common

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

Condition to reconcile two measurements $\Rightarrow$

$$\frac{\Gamma[B \to KX_A]}{\Gamma[B \to KX_B]} > \frac{\sigma[e^+e^- \to \gamma X_A]}{\sigma[e^+e^- \to \gamma X_B]}$$

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

Two-state hypothesis

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

X_B → η_{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)

This talk

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

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

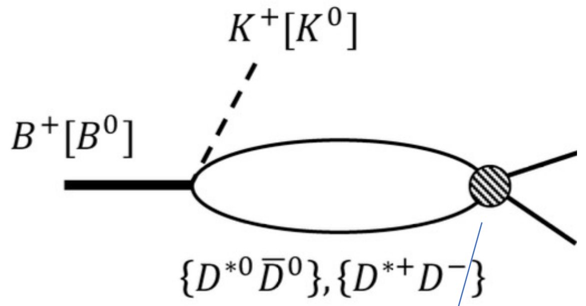
Show advantage of two-state model over single-state model

Predict helicity-angle distributions

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

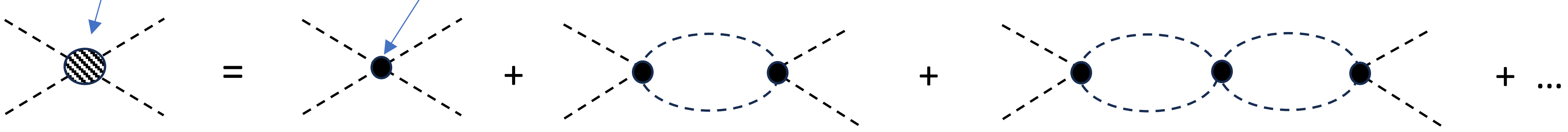
MODEL

B decay mechanisms



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

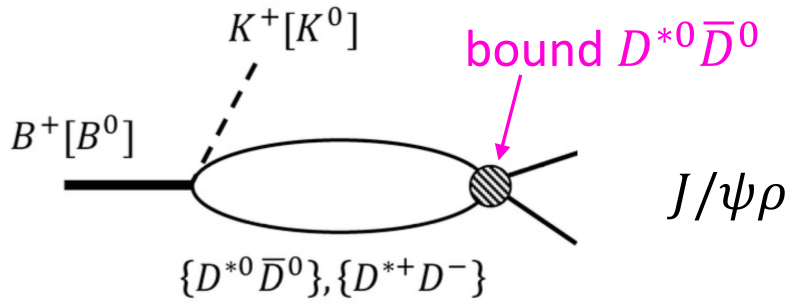
s-wave contact interactions (could effectively include bare $c\bar{c}$ excitation)



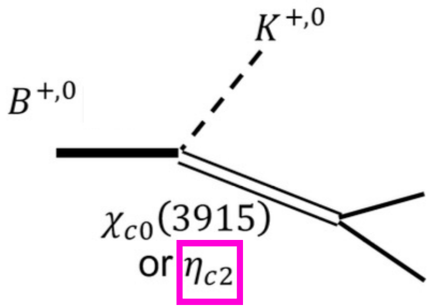
- $D^{*0}\bar{D}^0 - D^{*+}D^- - J/\psi\rho^0 - J/\psi\omega$ couple—channel scattering amplitude ($J^{PC} = 1^{++}$)
- $J/\psi\gamma$ and $\psi(2S)\gamma$ channels are included to first-order
- Mass difference between $D^{(*)\pm}$ and $D^{(*)0}$ → isospin violation

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

B decay mechanisms



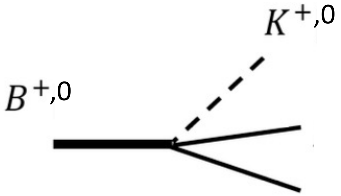
$J/\psi\rho^0,\quad J/\psi\omega,\quad D^{*0}\bar{D}^0,\ J/\psi\gamma,\quad \psi(2S)\gamma$



$\chi_{c0}(3915)$ necessary to fit $M_{J/\psi\omega}$ lineshape

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

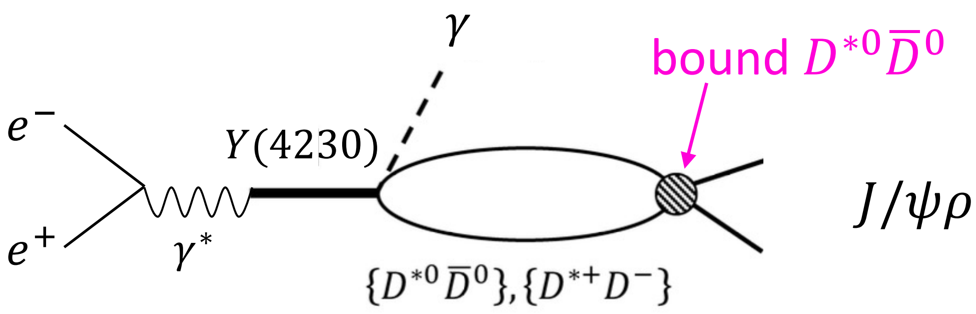
No isospin-violation



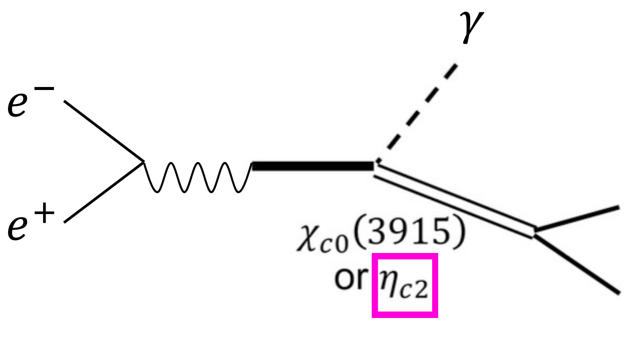
$D^{*0}\bar{D}^0$ only

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

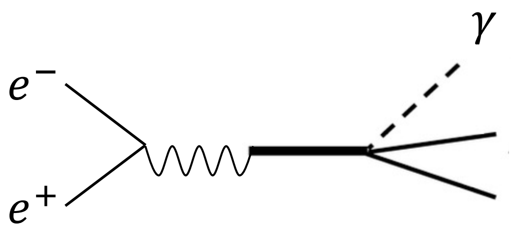
e^+e^- annihilation mechanisms



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



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



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

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

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

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

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
- $\chi_{c0}(3915) \to J/\psi\omega$ 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 ← BaBar's fit to $B \to J/\psi\omega\, K$ BaBar, PRD 82, 011101 (2010)

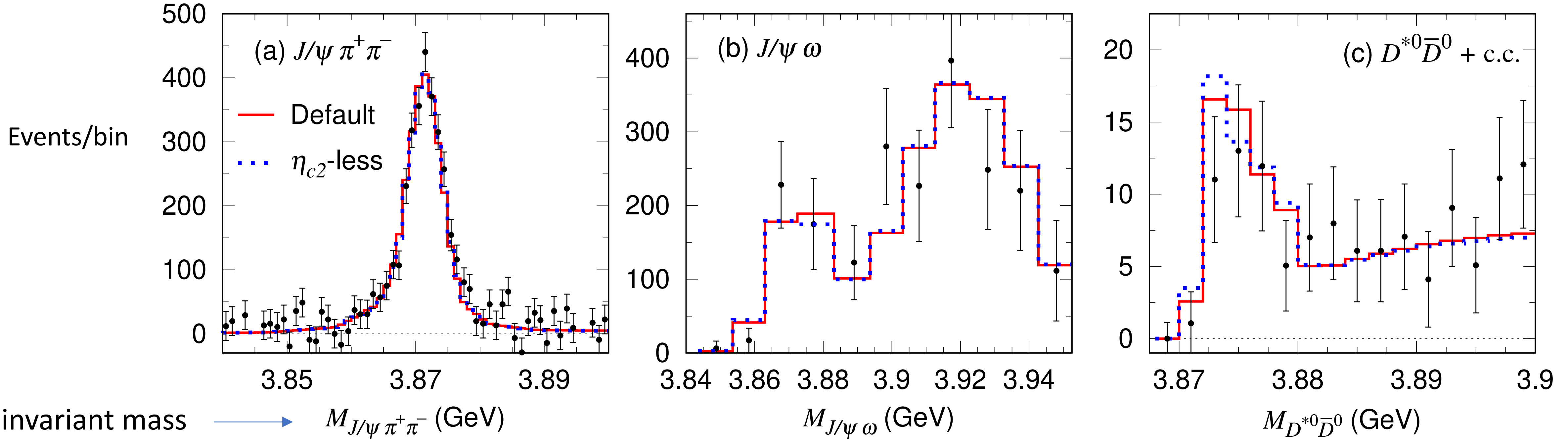
We use two models:

- 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

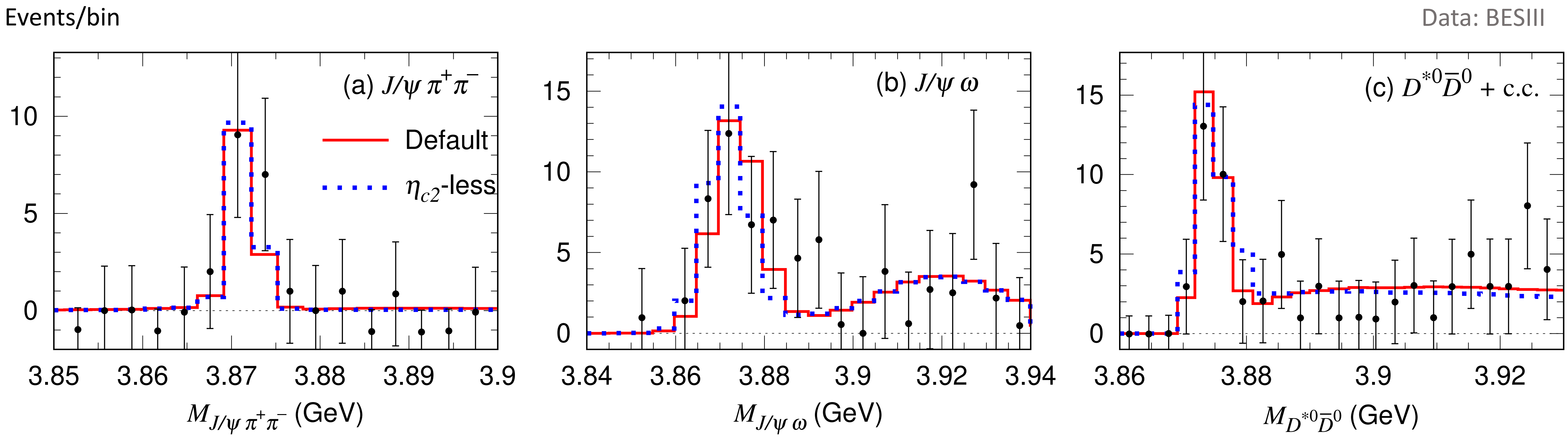
Poles: $3871.4 - 0.022\,i$ MeV ($D^{*0}\bar{D}^0$ bound state)

$3874.2 - 0.25\,i$ MeV (η_{c2})

$3882.6 + 1.5\,i$ MeV (W_{c1}, $D^{*+}D^-$ virtual state)

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

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



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 ratios of X's partial widths

	$B^+ \to K^+ X$				$e^+e^- \to \gamma X$			
	$\frac{\Gamma[J/\psi\omega]}{\Gamma[J/\psi\pi^+\pi^-]}$	$\frac{\Gamma[D^{*0}\bar{D}^0]}{\Gamma[J/\psi\pi^+\pi^-]}$	$\frac{\Gamma[J/\psi\gamma]}{\Gamma[J/\psi\pi^+\pi^-]}$	$\mathcal{R}_{\psi\gamma}$	$\frac{\Gamma[J/\psi\omega]}{\Gamma[J/\psi\pi^+\pi^-]}$	$\frac{\Gamma[D^{*0}\bar{D}^0]}{\Gamma[J/\psi\pi^+\pi^-]}$	$\frac{\Gamma[J/\psi\gamma]}{\Gamma[J/\psi\pi^+\pi^-]}$	$\mathcal{R}_{\psi\gamma}$
Default	0.77	12.	0.20	1.6 ✅	1.9	13.	0.85	0.24 ✅
η_{c2}-less	0.95	13.	0.27	0.62 ❌	0.98	12.	0.20	0.62 ❌
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 → $\mathcal{R}_{\psi\gamma}(B \text{ decay}) \sim \mathcal{R}_{\psi\gamma}(e^+e^-)$

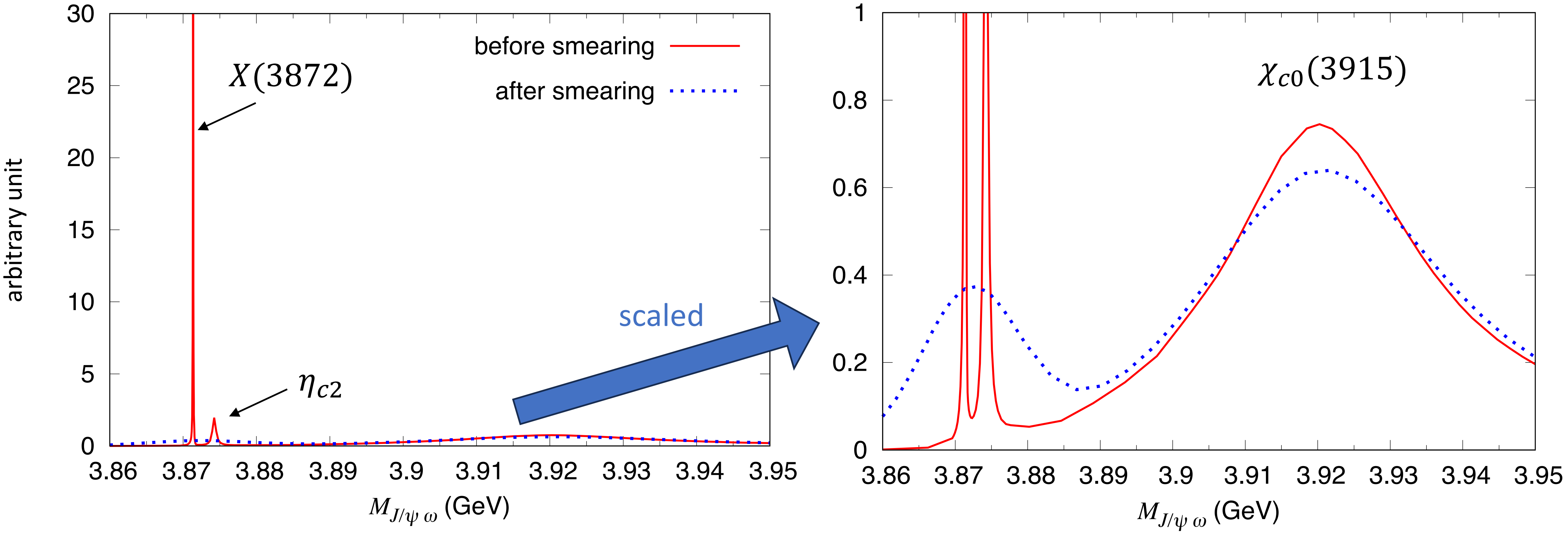
→ The radiative-ratio tension selects the two-state (default) model

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

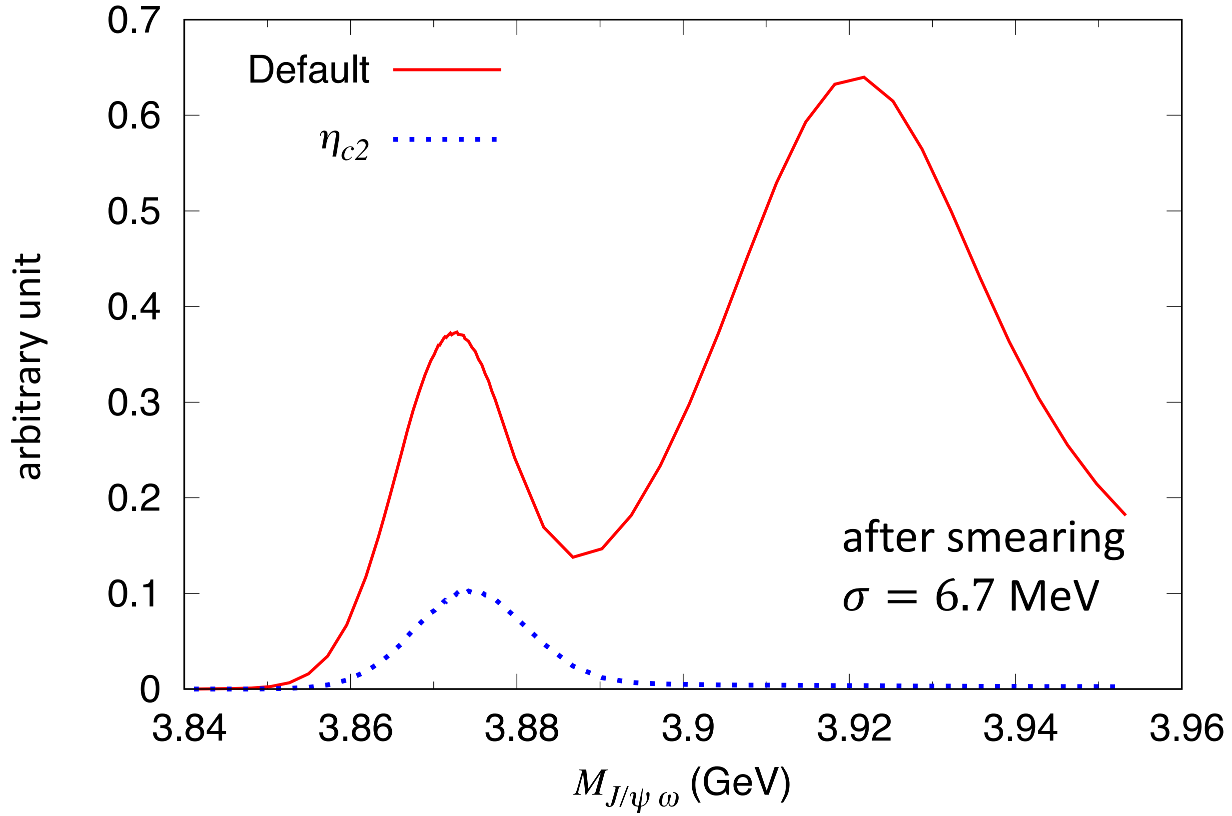
$B^+ \to J/\psi\omega\, K^+$ ($\sigma = 6.7$ MeV)



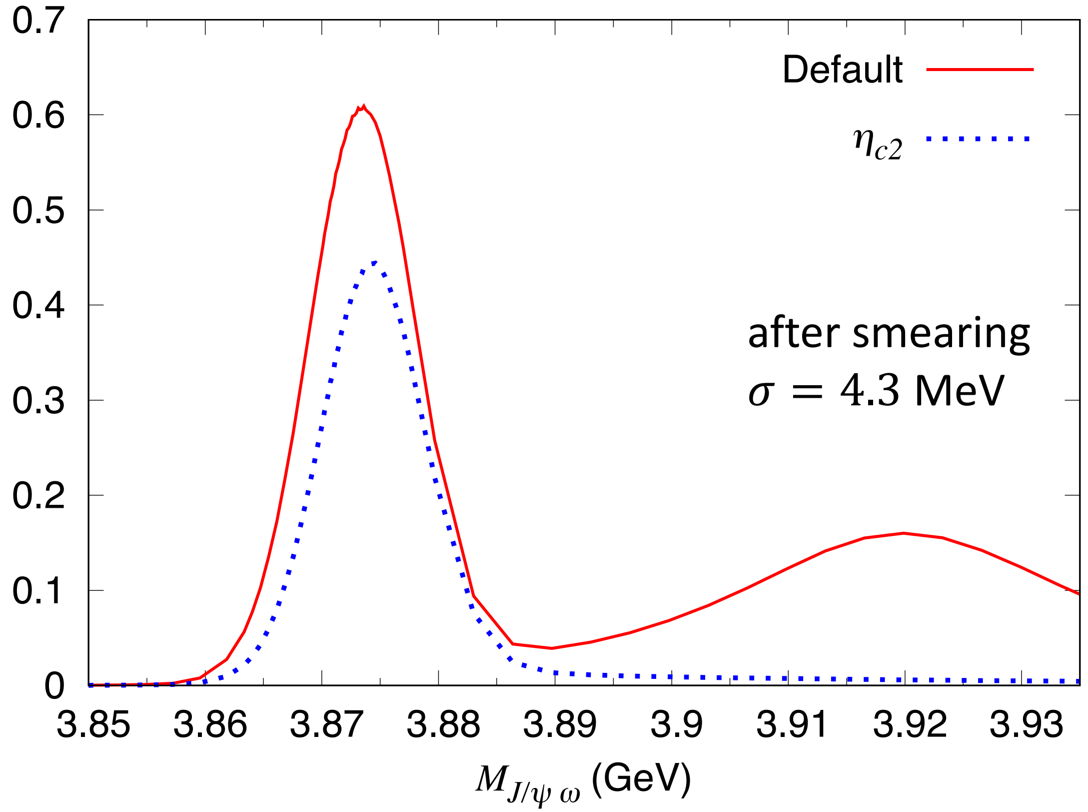
- Due to experimental resolution, two sharp peaks ($X(3872)$, η_{c2}) smeared → single peak
- The issue is two nearby poles, not necessarily two experimentally resolved peaks

η_{c2} contributions

$B^+ \to J/\psi\omega\, K^+$



$e^+e^- \to J/\psi\omega\,\gamma$



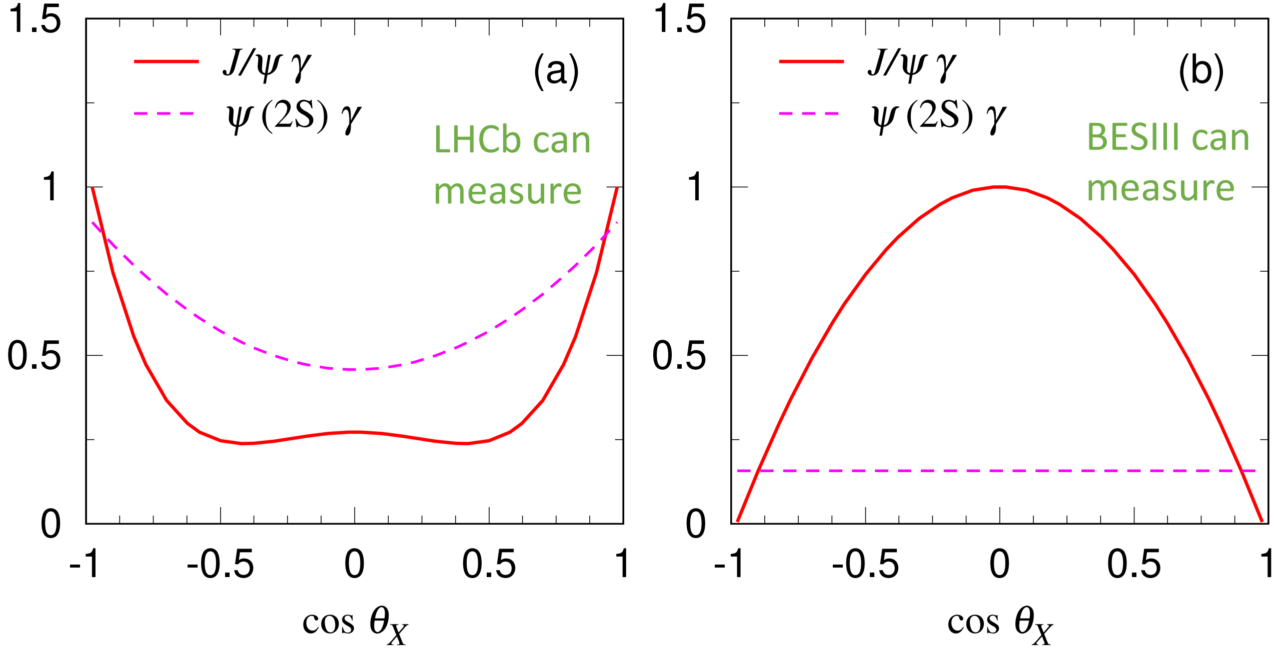
- η_{c2} contributions are large in $X(3872)$ region; even larger in e^+e^-
- Very small η_{c2} contributions to $J/\psi\pi^+\pi^-$ because:

(i) via $\omega \to \rho^0$ mixing ($\eta_{c2} \nrightarrow J/\psi\rho^0$) (ii) no interference with $X(3872) \to J/\psi\rho^0$

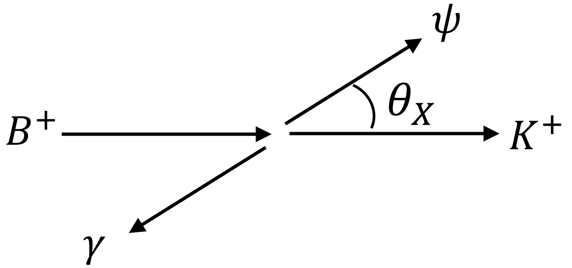
What should experiments look for next?

Two-state model predicts helicity angle distribution

$B^+ \to K^+X$ $\qquad$ $e^+e^- \to \gamma X$



$\psi\gamma$ center-of-mass frame



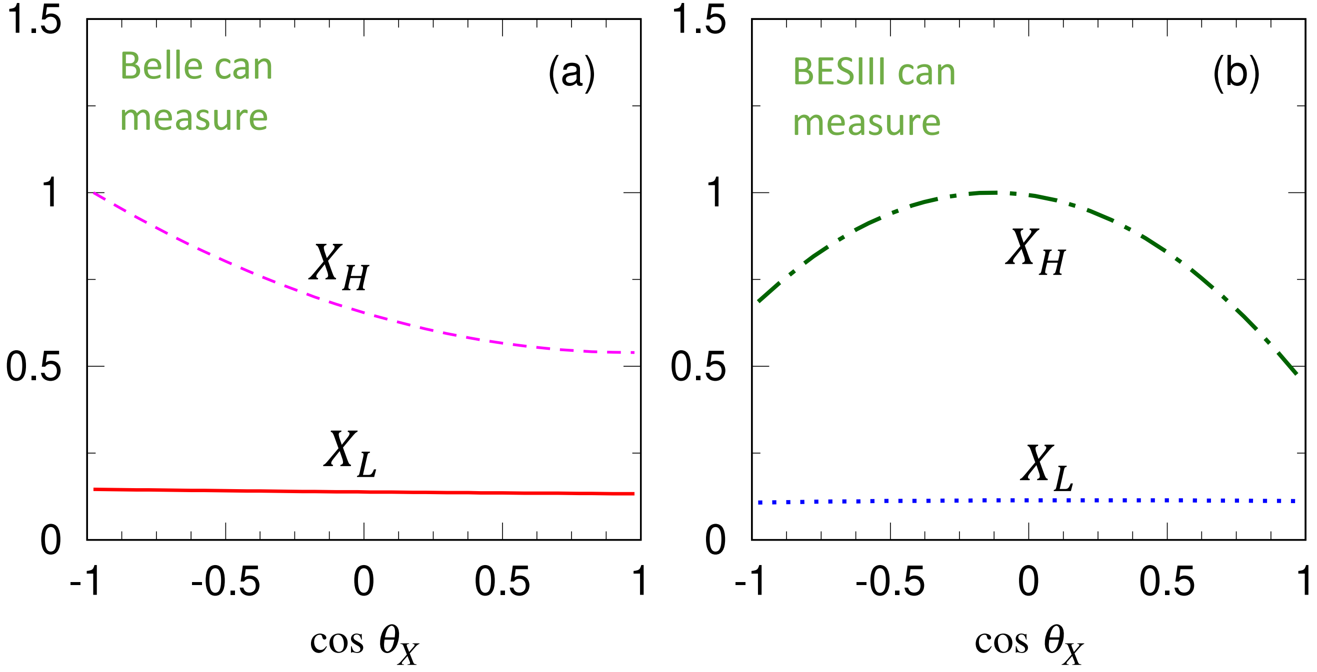
mainly
- $1^{++} \to \psi(2S)\gamma$
- $2^{-+} \to J/\psi\gamma$

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

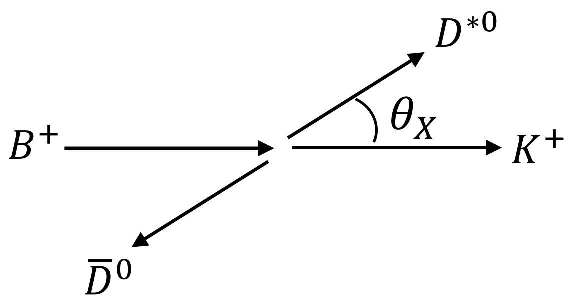
What should experiments look for next?

Two-state model predicts helicity angle distribution

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



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



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

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

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

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

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

Summary

Summary

- X(3872) radiative-decay tension (~4.6σ) 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 test of two-state hypothesis

  Measurements of helicity angle distributions and improved radiative data are important

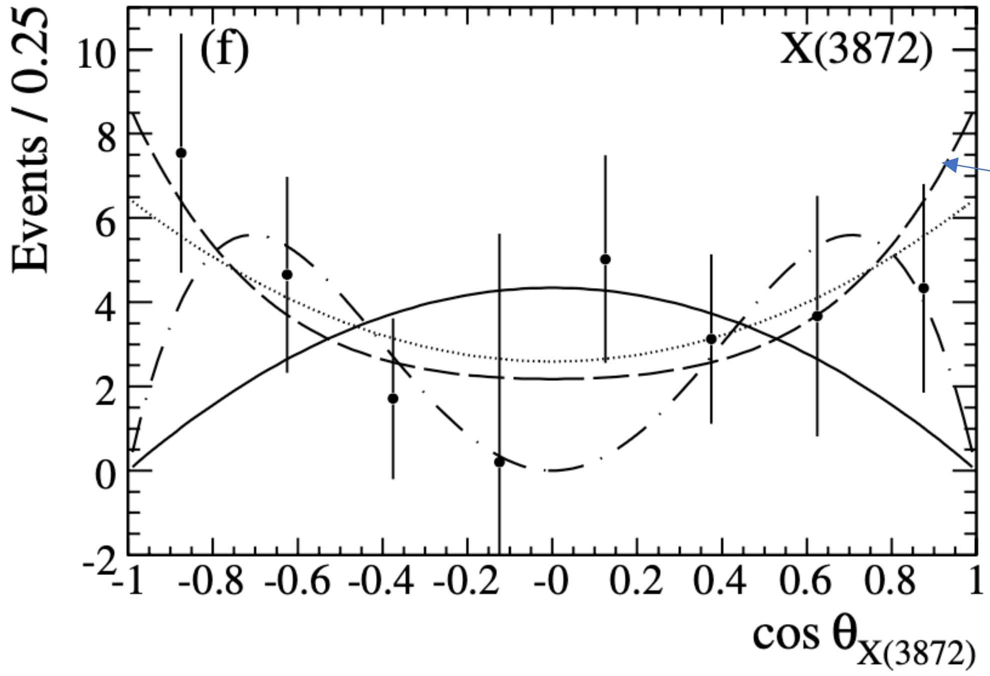
Back up

Two-state hypothesis

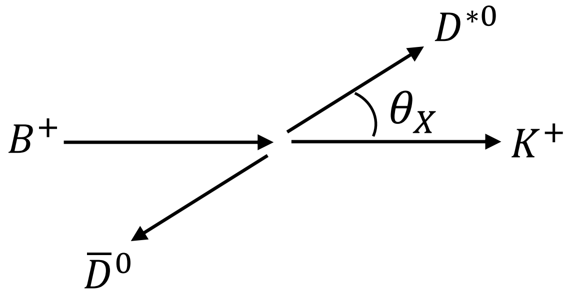
Experimental hint: Why η_{c2} ?

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

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^{-+} η_{c2} coexist nearby

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	$e^+e^- \to J/\psi(1S)\pi^+\pi^-\omega$
3871.64 ± 0.06 ±0.01	19.8k	[1] AAIJ	20S	LHCB	$B^+ \to J/\psi\pi^+\pi^-K^+$
3871.9 ± 0.7 ±0.2	20	ABLIKIM	14	BES3	$e^+e^- \to J/\psi\pi^+\pi^-\gamma$
3871.95 ± 0.48 ±0.12	0.6k	AAIJ	12H	LHCB	$pp \to J/\psi\pi^+\pi^-X$
3871.85 ± 0.27 ±0.19	170	[2] CHOI	11	BELL	$B \to K\pi^+\pi^-J/\psi$
3873 $^{+1.8}_{-1.6}$ ±1.3	27	[3] DEL-AMO-SA..	10B	BABR	$B \to \omega J/\psi K$
3873.3 ± 1.1 ±1.0	45	[9] ABLIKIM	19V	BES	$e^+e^- \to \gamma\omega J/\psi$

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

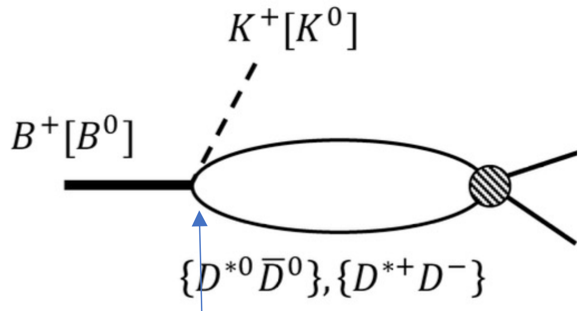
→ Consistent with two states of:

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

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

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

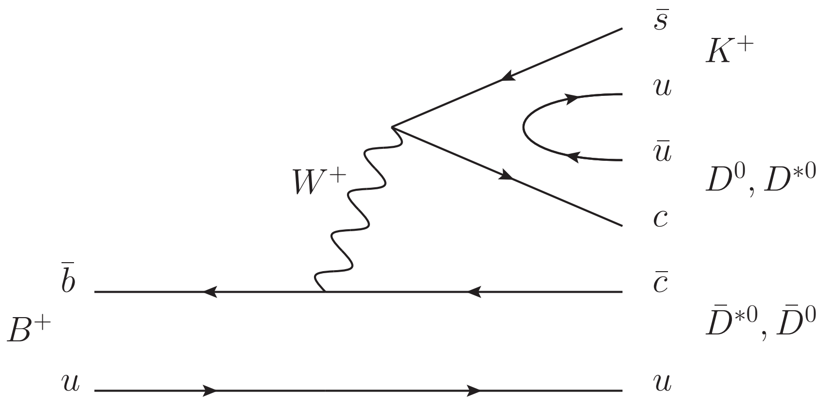
B decay mechanisms



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

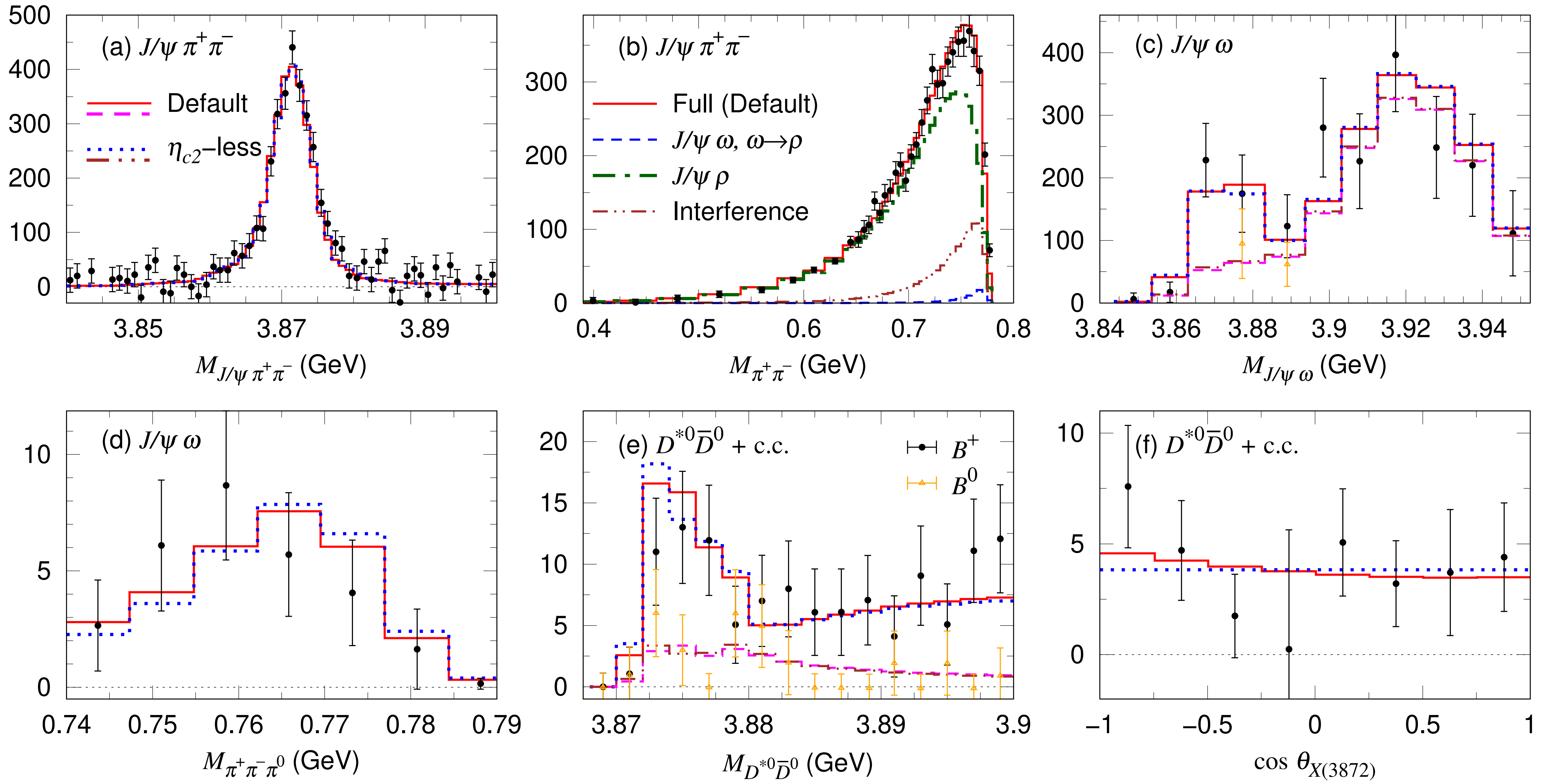
Initial weak decay couplings prefer color-favored external W^+ emission mechanism

color-favored		color-suppressed
$B^+ \to K^+D^{*0}\bar{D}^0$	>	$B^+ \to K^0D^{*+}D^-$
$B^0 \to K^0D^{*+}D^-$	>	$B^0 \to K^0D^{*0}\bar{D}^0$



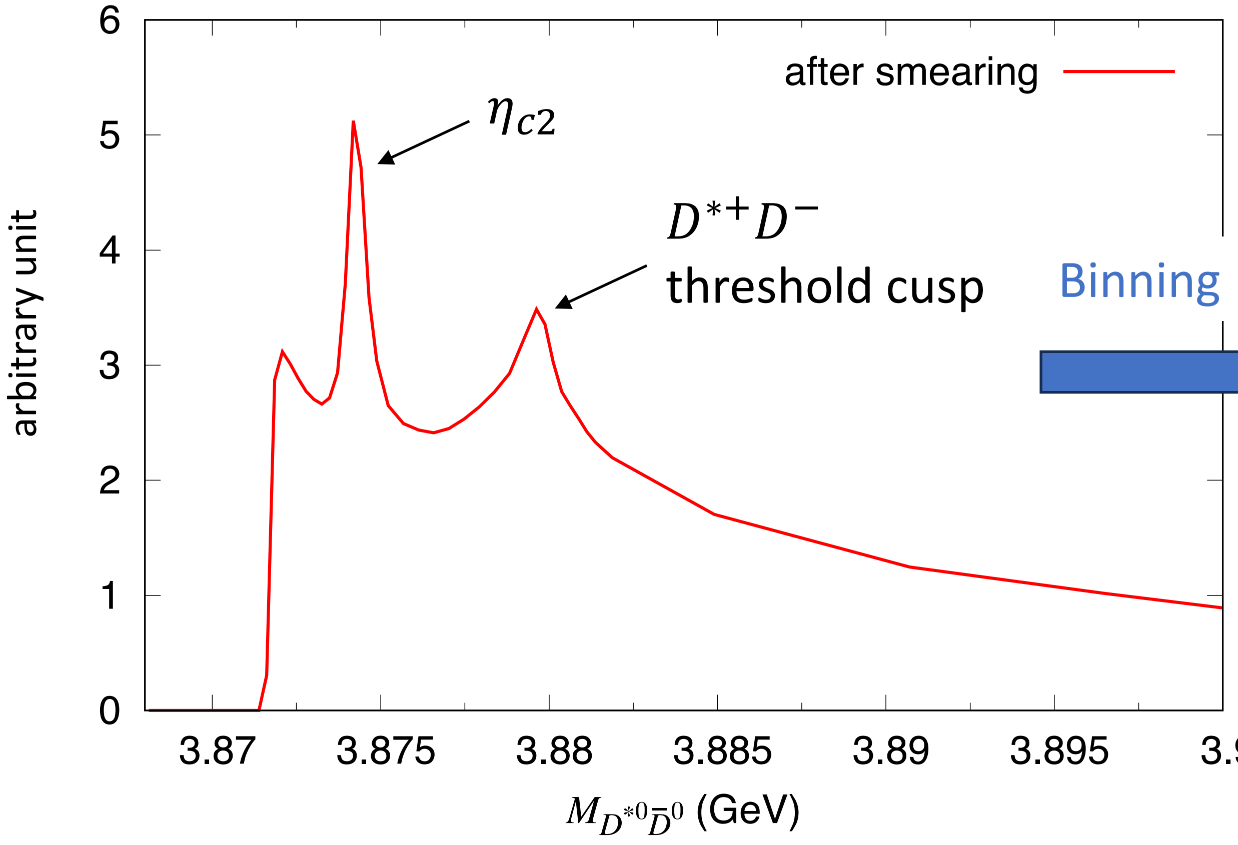
H.N. Wang et al., Chin. Phys. Lett. 40, 021301 (2023)

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



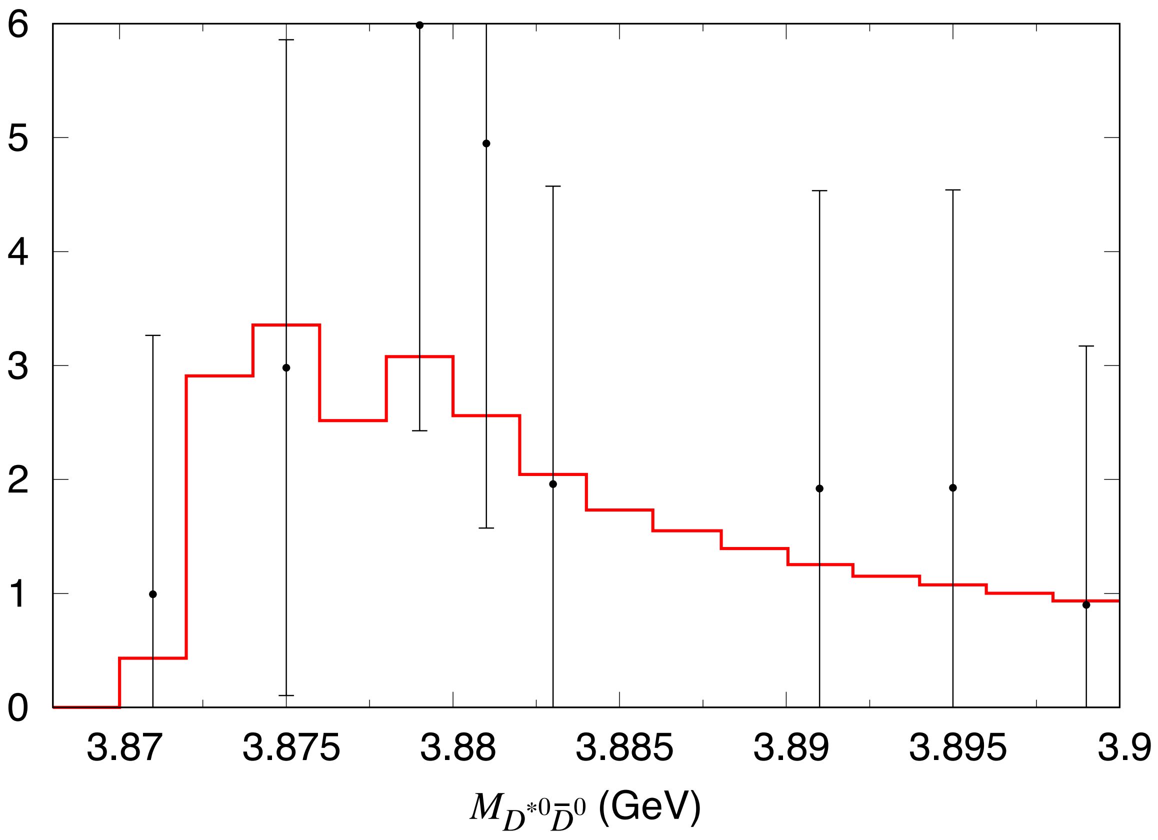
W_{c1} contributions

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



Binning

Data: Belle, PRD 107, 112011 (2023)



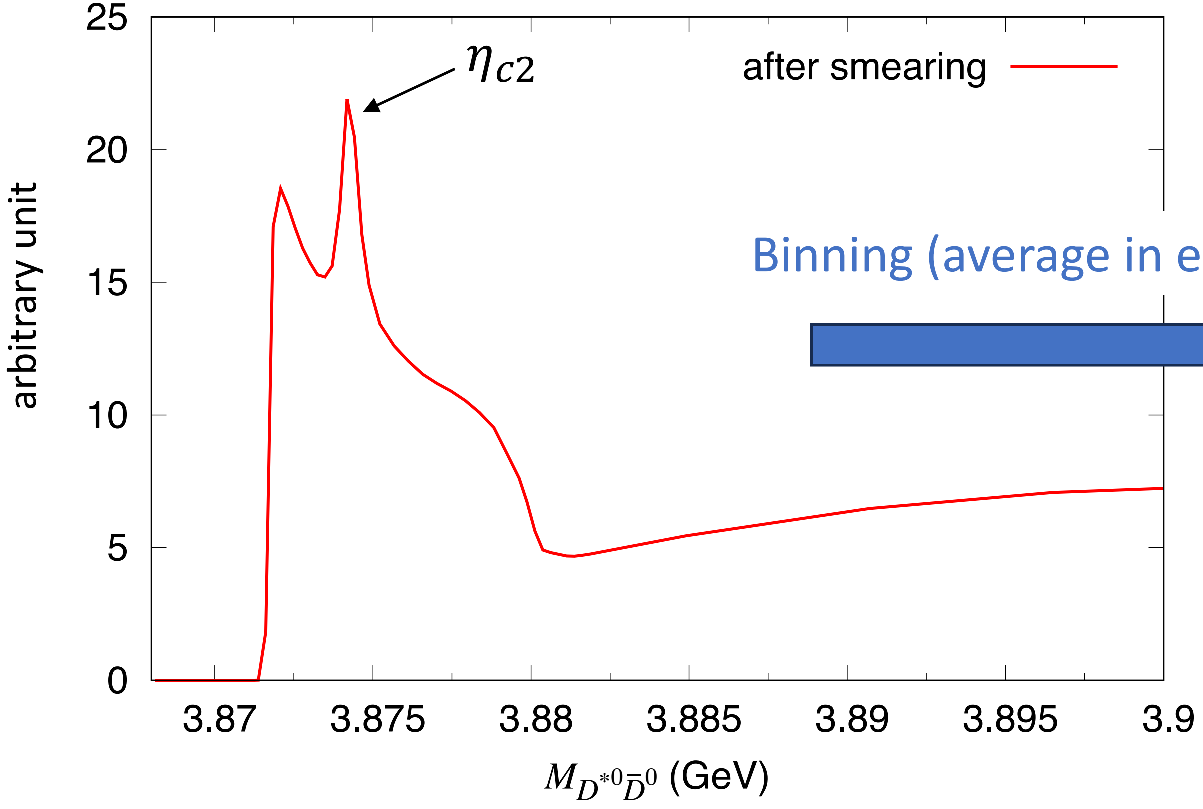
- Initial weak decay prefers $B^0 \to K^0 D^{*+}D^-$ (color-favored) to $B^0 \to K^0 D^{*0}\bar{D}^0$ (color-suppressed)
  → $D^{*+}D^-$ threshold cusp is more prominent in B^0 decay than in B^+ decay
- W_{c1} (virtual pole) enhances $D^{*+}D^-$ Threshold cusp

Why two peaks not seen in data?

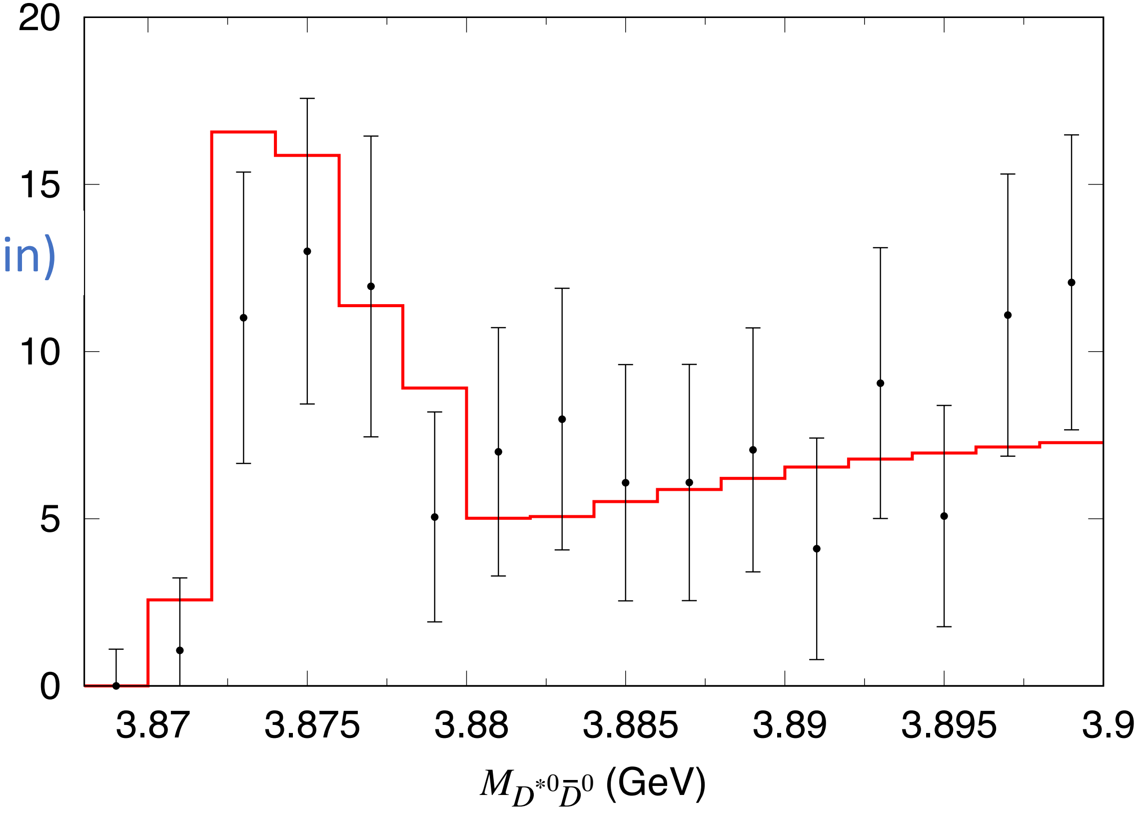
Answer 2: Experimental binning

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

Data: Belle, PRD 107, 112011 (2023)



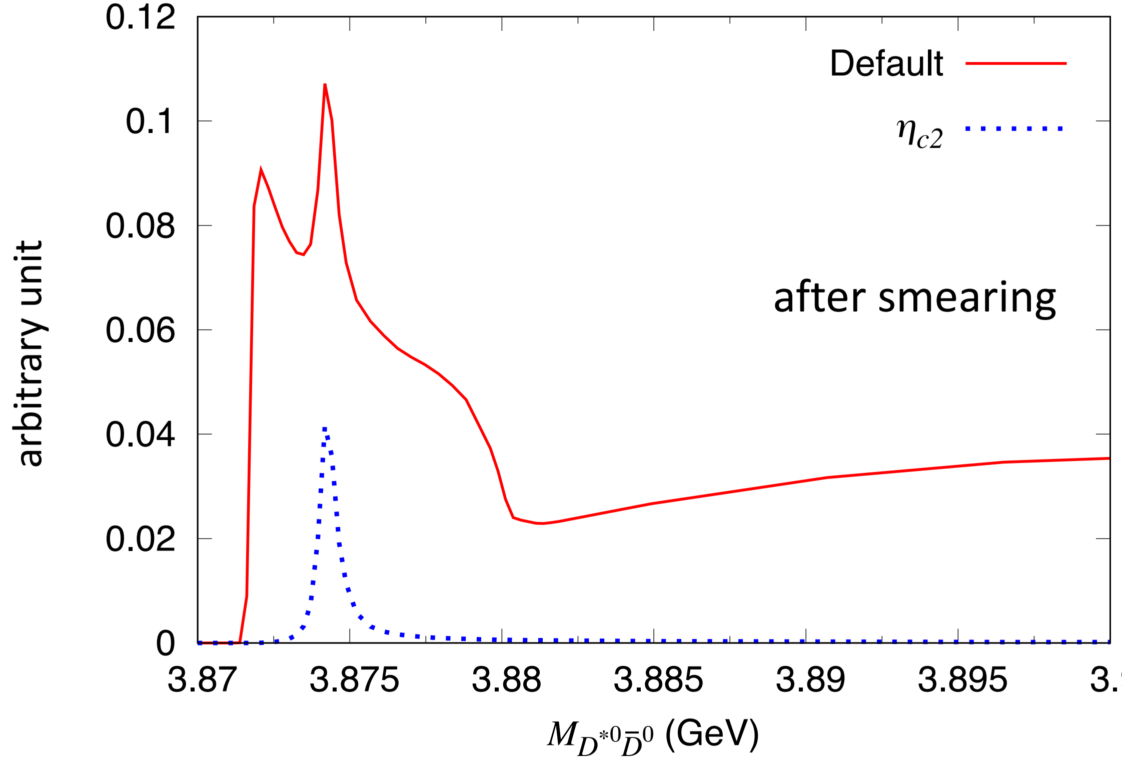
Binning (average in each bin)



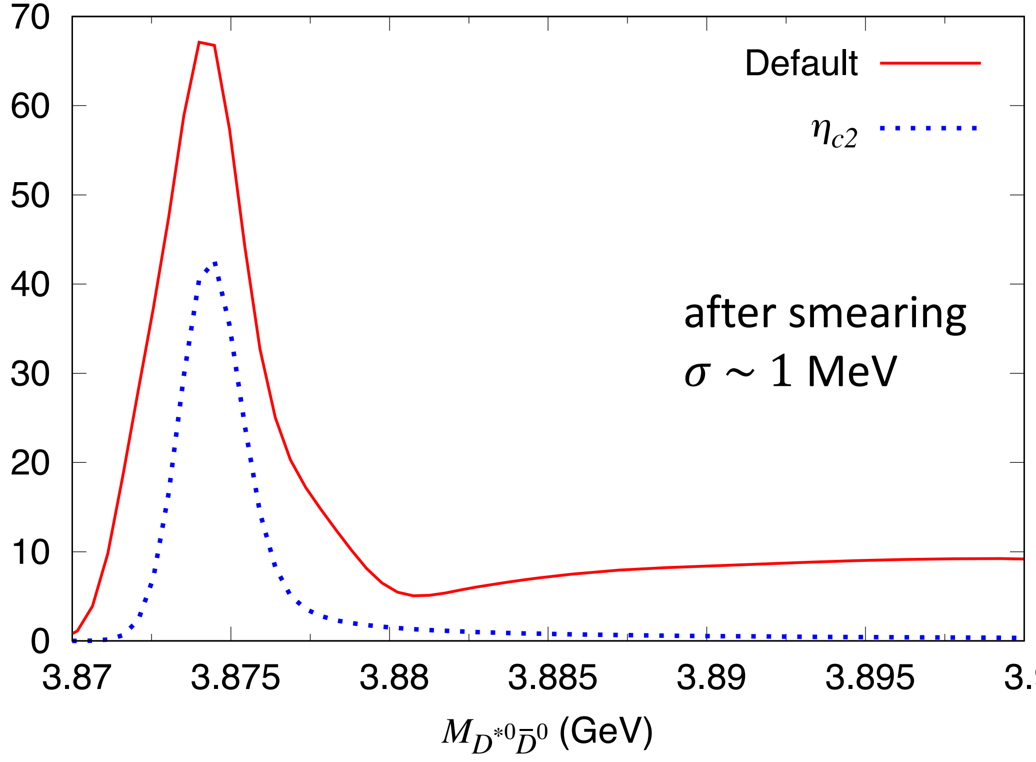
Due to binning, η_{c2} peak is absorbed by threshold enhancement

η_{c2} contributions

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



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



- η_{c2} contributions are substantial in $X(3872)$ region
- Very small η_{c2} contributions to $J/\psi\pi^+\pi^-$ because:

  (i) via $\omega \to \rho^0$ mixing ($\eta_{c2} \nrightarrow J/\psi\rho^0$) (ii) no interference with $X(3872) \to J/\psi\rho^0$