



Branching fractions of the X(3872)

arXiv: 1908.02807

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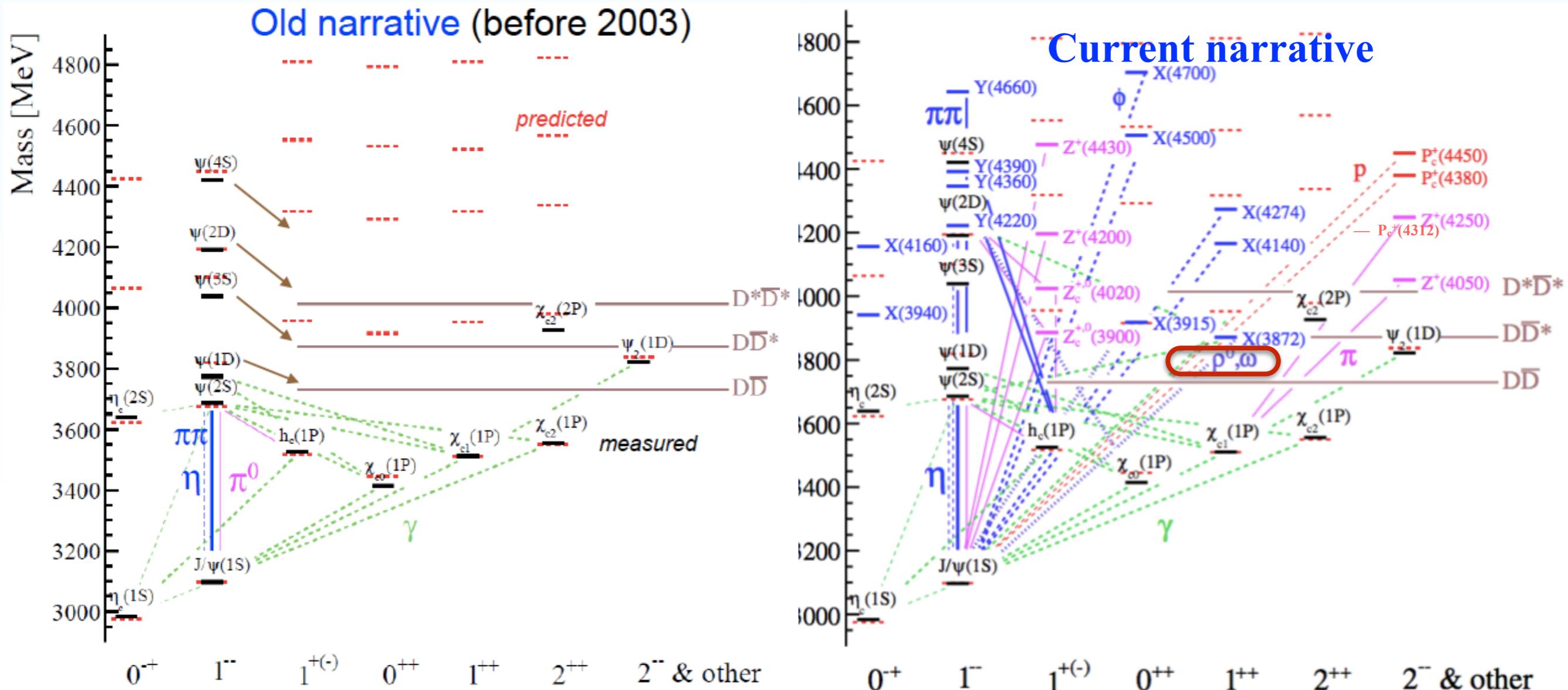
8th PIKIMO meeting, University of Cincinnati
November 2, 2019

Outline

- * Introduction to the X(3872)
- * Universal properties of near-threshold S-wave resonance
- * Branching fractions
- * Summary

Introduction to the X(3872)

Charmonium mass spectrum



Above the open flavor threshold, mesons are much more complicated.

Olson, Skwarnicki, Zieminska, Rev. Mod. Phys. 90, 015003(2018)

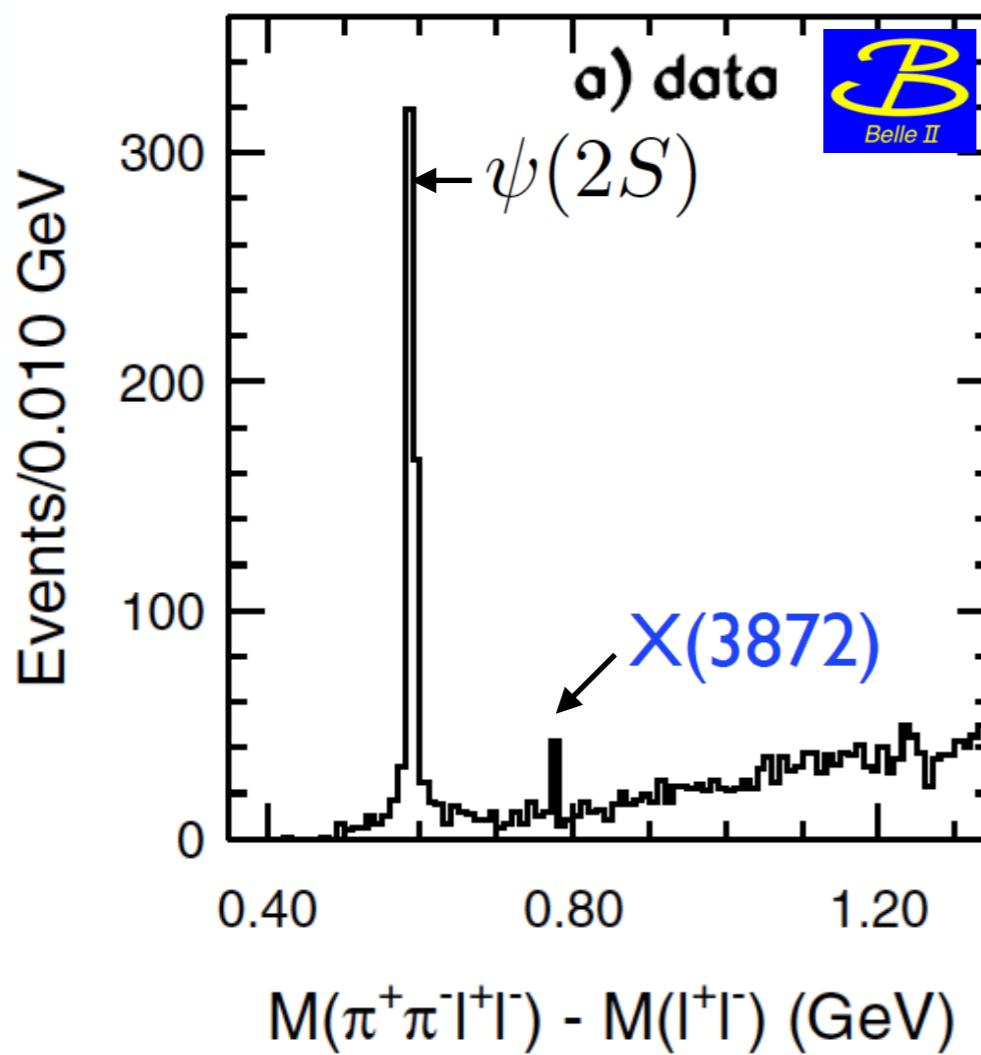
Introduction to the X(3872)

* Discovery

❖ Belle Collaboration (2003)

PRL 91,262001(2003)

$$B^+ \rightarrow K^+ + X$$
$$X \rightarrow J/\psi \pi^+ \pi^-$$

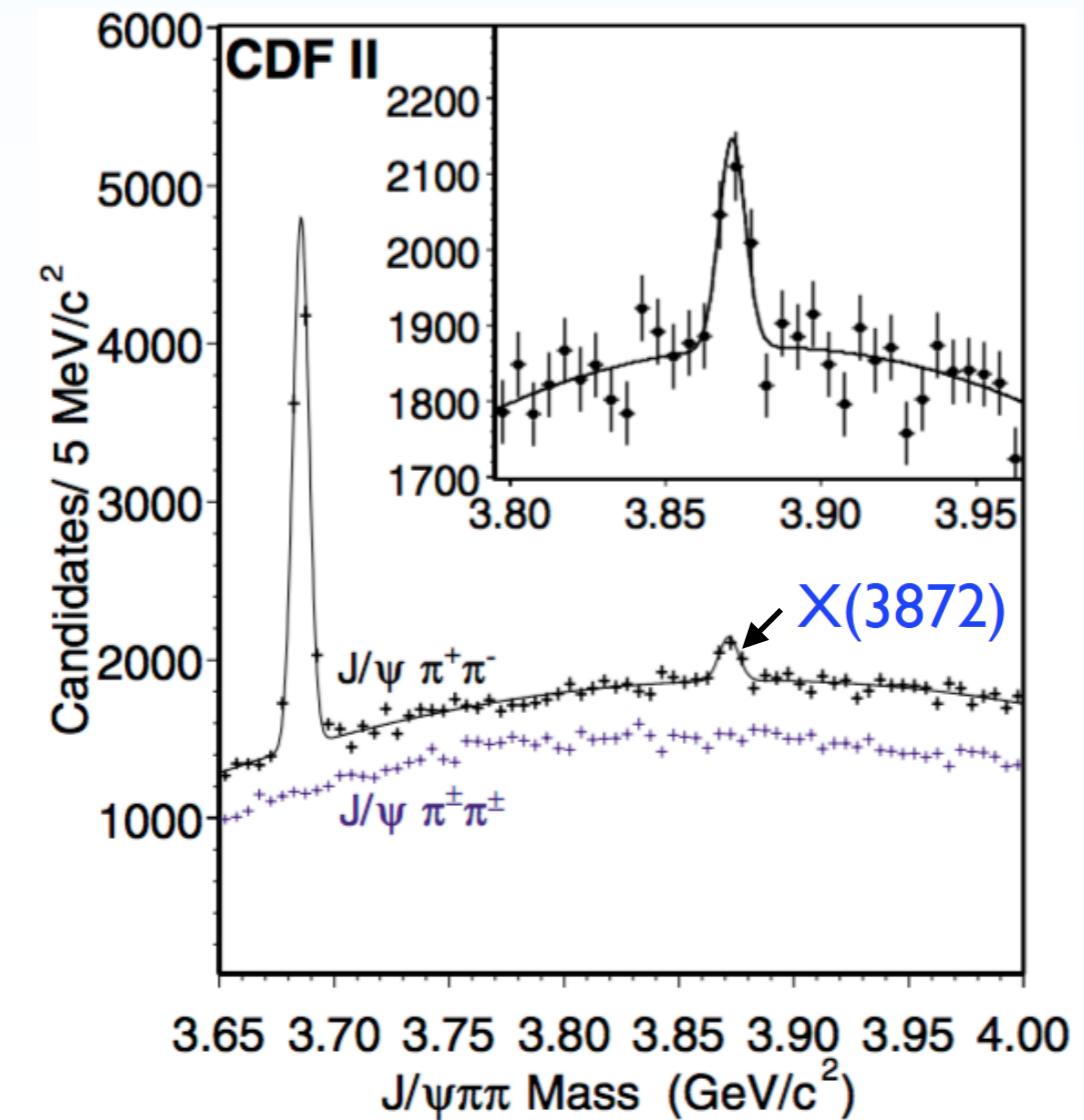


* Confirmation

❖ CDF Collaboration

PRL 91,262001(2004)

$$p\bar{p} \rightarrow X + \text{anything}$$



Introduction to the X(3872)

- * **Mass:** very close to $D^{*0}\bar{D}^0$ threshold

$$E_X = M_X - (M_{D^{*0}} + M_{\bar{D}^0}) = (0.01 \pm 0.18) \text{ MeV} \text{ [PDG 2018]}$$

- * **Width:** very narrow

< 1.2 MeV at 90% C.L. [Belle, PRD 84, 052004 (2011)]

- * **Quantum numbers:**

$$J^{PC} = 1^{++} \text{ [LHCb, PRL, 110, 222001(2013)]}$$

- * **Seven observed decay modes:**

$$J/\psi \pi^+ \pi^-, J/\psi \pi^+ \pi^- \pi^0, J/\psi \gamma, \psi(2S)\gamma, D^0 \bar{D}^0 \pi^0, D^0 \bar{D}^0 \gamma, \chi_{c1} \pi^0$$

Introduction to the X(3872)

* What is the X(3872)?

Two crucial experimental inputs:

- ❖ Quantum numbers: $J^{PC} = 1^{++}$
→ S-wave coupling to $D^{*0}\bar{D}^0/\bar{D}^{*0}D^0$
- ❖ Mass is extremely close to $D^{*0}\bar{D}^0$ threshold
→ resonant coupling

* Conclusion:

X(3872) is a charm-meson molecule:

$$|X(3872)\rangle = \frac{1}{\sqrt{2}} (|D^{*0}\bar{D}^0\rangle + |D^0\bar{D}^{*0}\rangle)$$

other components of wave functions have small probabilities:

- * $D^0\bar{D}^0\pi^0$ at long distances
- * $\chi_{c1}(2P)$, $D^{*+}D^-$, D^+D^{*-} at short distances

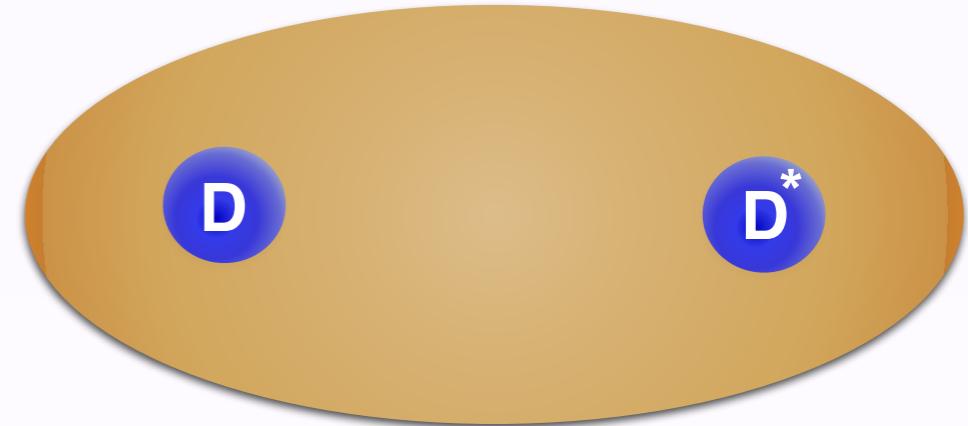
Introduction to the X(3872)

$$E_x = M_x - (M_{*0} + M_0) = (0.01 \pm 0.18) \text{ MeV} \text{ [PDG 2018]}$$

→ $|E_x| < 0.22 \text{ MeV} @ 90\% \text{ C.L}$

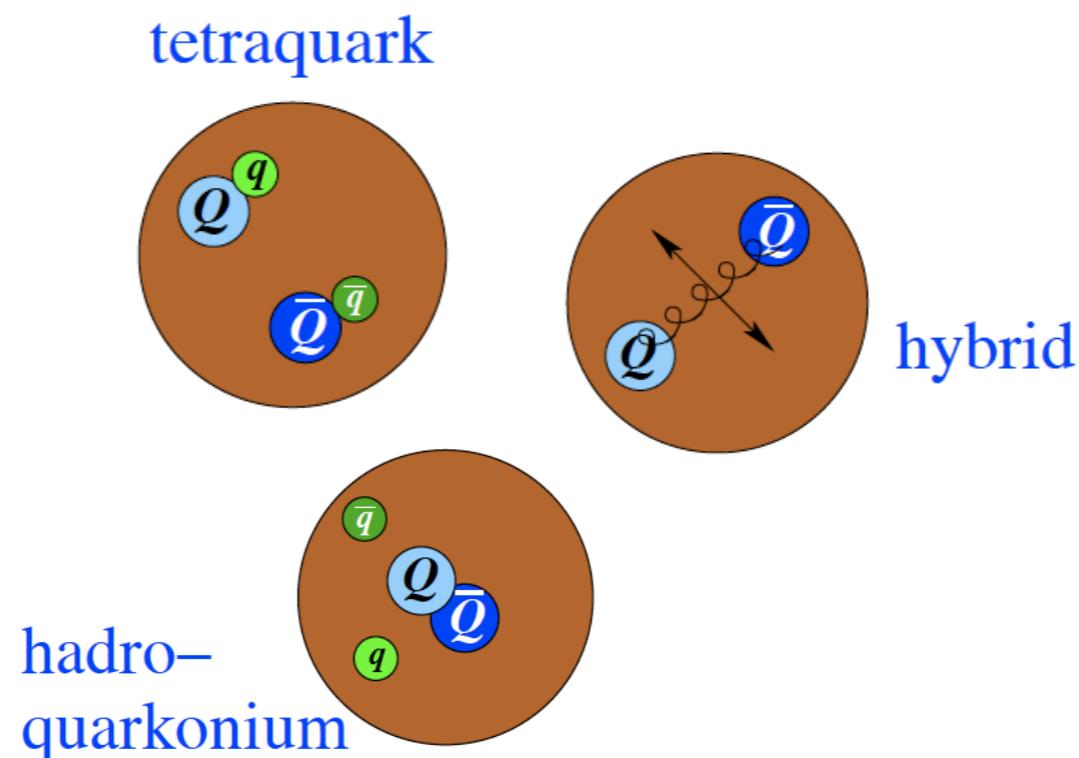
mean separation of charm mesons:

$$\langle r \rangle = 1 / [2 (2\mu E_x)^{1/2}] > 5 \text{ fm}$$



other interpretations
not informed by the
tiny binding energy:

mean radius
 $\langle r \rangle < 1 \text{ fm}$



Universal properties near threshold

* Nonrelativistic Quantum Mechanics:

- short-range interactions
- S-wave resonance close enough to **threshold**

-
- * large scattering length $|a| \gg \text{range}$
 - * universal features depend only on a (or $\gamma = 1/a$)

- * scattering amplitude at $(2\mu|E|)^{1/2} \ll 1/\text{range}$:

$$f(E) = \frac{1}{-\gamma + \sqrt{-2\mu(E + i\epsilon)}}$$

X(3872) has universal features that depend only on inverse scattering length γ_X for $D^{*0}\bar{D}^0/\bar{D}^{*0}D^0$ in C=+ channel, which is determined by binding energy $|E_X|$

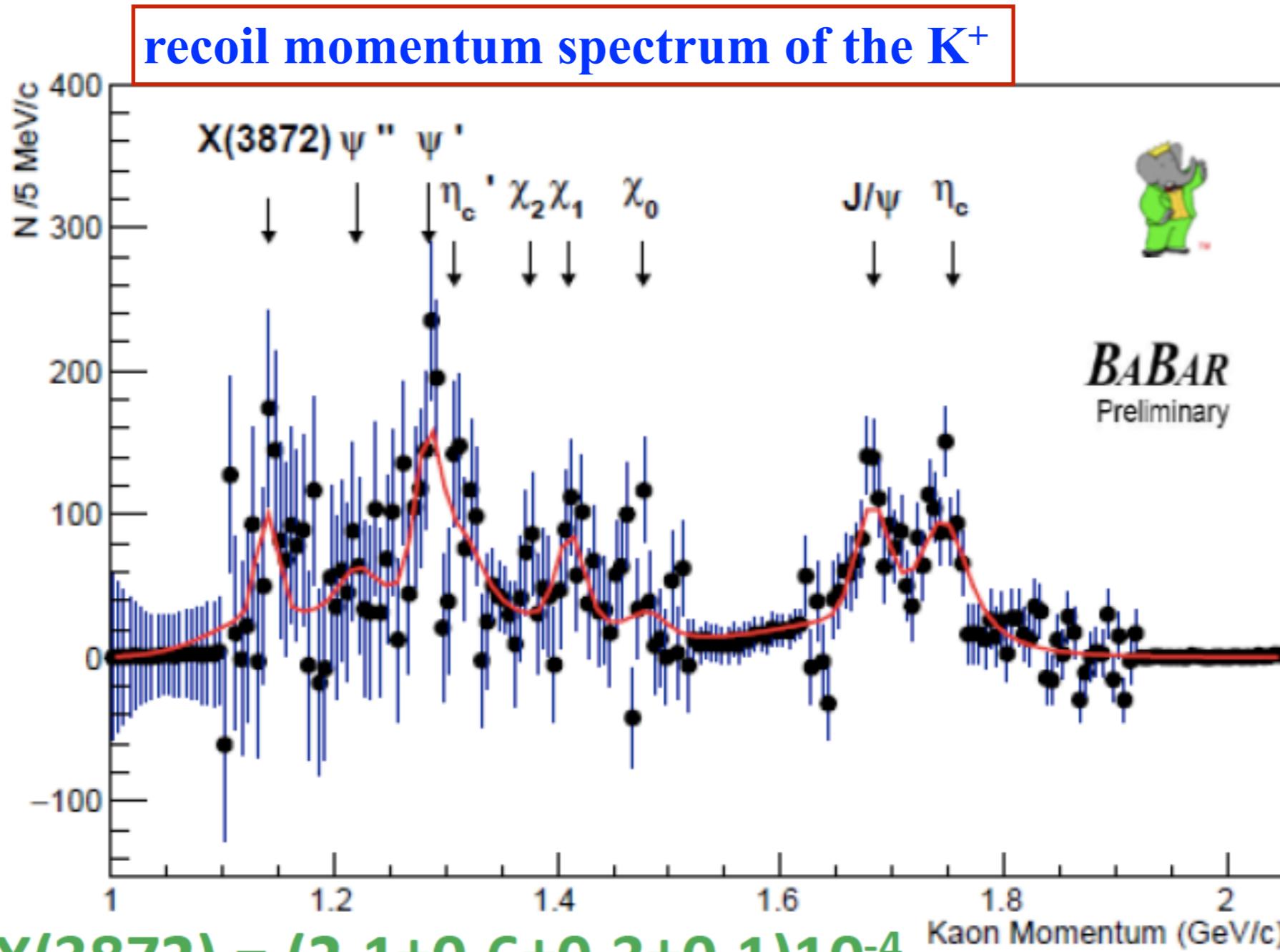
- decay width of D^* : $E \rightarrow E + i\Gamma_*/2$
- effect of short distance decay modes: γ_X is complex

$$f(E) = \frac{1}{-\gamma_X + \sqrt{-2\mu(E + i\Gamma_*/2)}}$$

Branching fractions from experiments

First evidence of the $B^+ \rightarrow X(3872) K^+$ transition

[G. Wormser presented at Quarkonium 2019 in Torino, May 2019]



$\rightarrow BR(X(3872) \rightarrow J/\psi \pi\pi) = (4.1 \pm 1.3)\%$

Branching fractions from experiments

BaBar: Br [X→J/ψ π⁺ π⁻] = (4.1±1.3)%

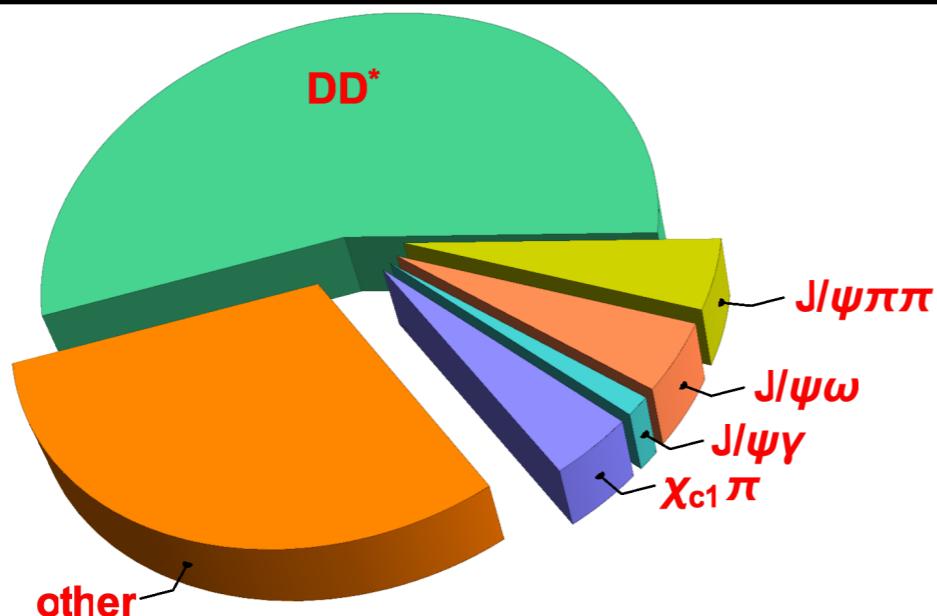
C.Z. Yuan's talk, June 25, 2019

[Exotic hadrons @ T.D Lee Institute, Shanghai]

A global fit to BaBar/Belle/LHCb/BESIII data ($\chi^2/\text{ndf}=7/3$, C.L.=6%):

- $B(X(3872) \rightarrow \pi^+ \pi^- J/\psi) = (4.5^{+2.3}_{-1.2})\%$
- $B(X(3872) \rightarrow \omega J/\psi) = (4.3^{+2.5}_{-1.4})\%$
- $B(X(3872) \rightarrow \gamma J/\psi) = (1.2^{+0.7}_{-0.4})\%$
- $B(X(3872) \rightarrow D^{*0} \bar{D}^0 + c.c.) = (55^{+31}_{-17})\%$
- $B(X(3872) \rightarrow \pi^0 \chi_{c1}) = (3.9^{+2.7}_{-1.7})\%$
- $B(X(3872) \rightarrow \text{unknown}) = (31^{+20}_{-37})\%$

BESIII



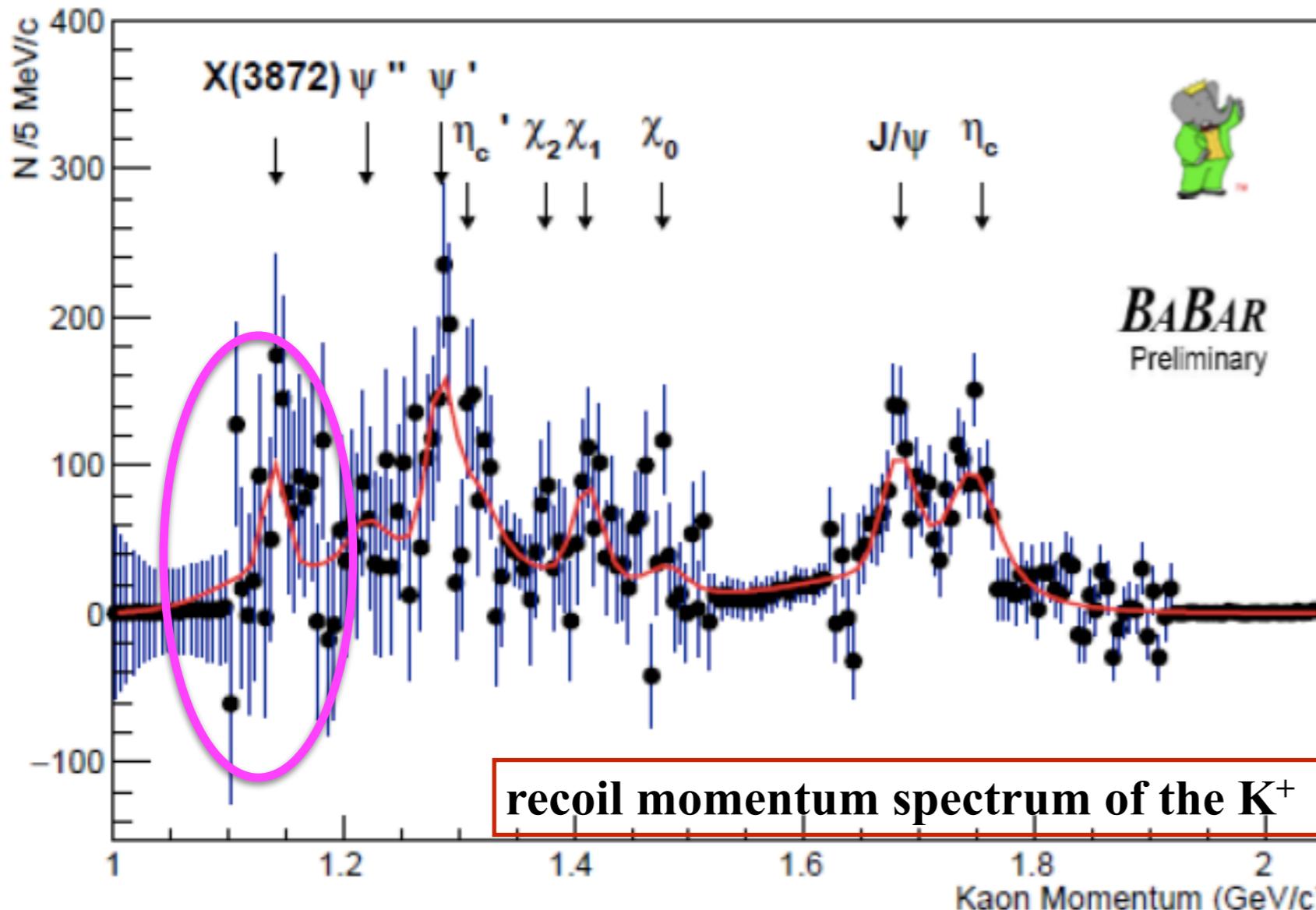
decay X(3872) → γψ(2S):

Belle (0.4σ); BaBar (3.5σ); LHCb (4.4σ)

No clear evidence at BESIII

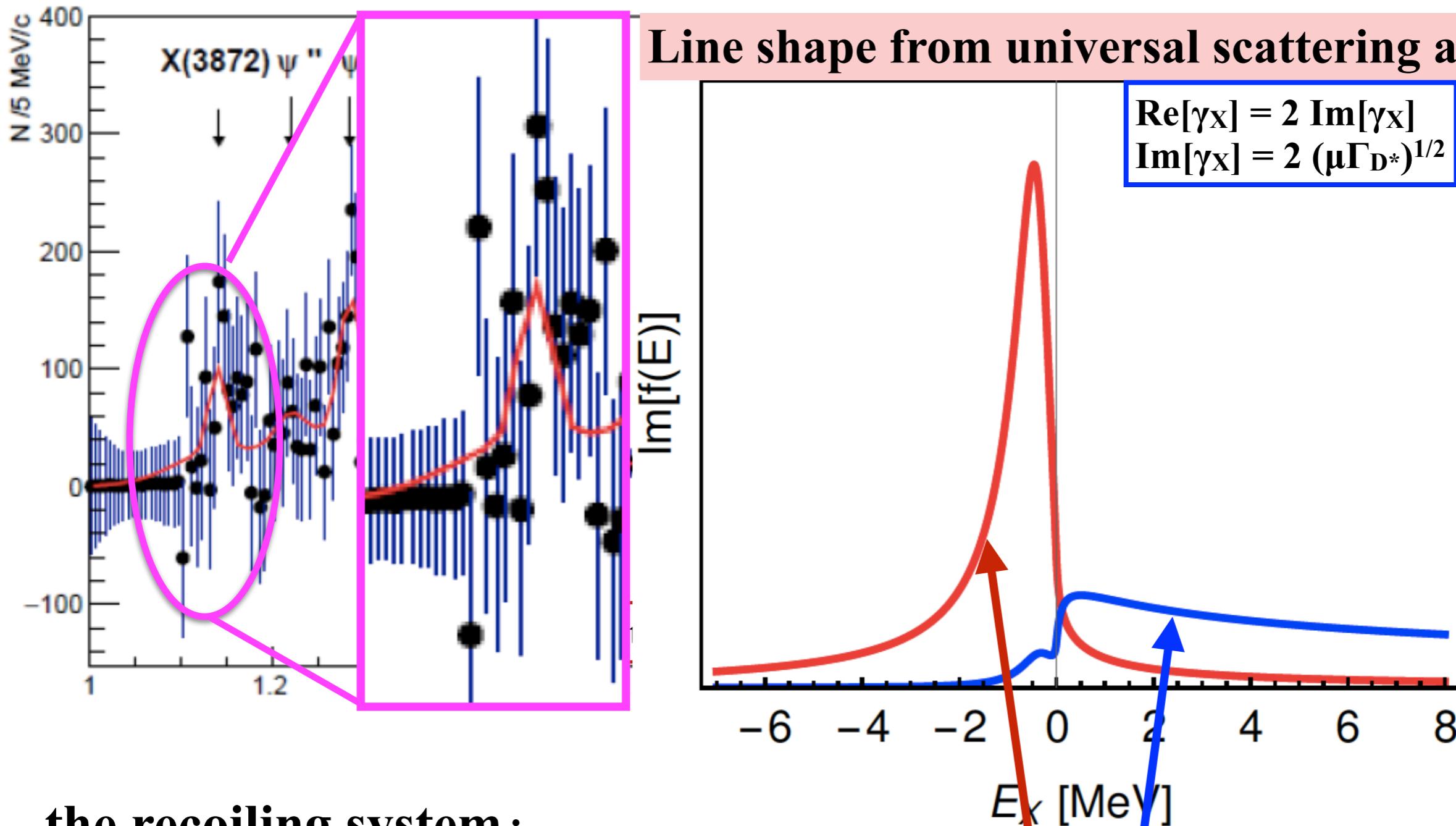
X Resonance feature (X_{RF}) vs. X bound state (X_{BS})

G. Wormser presented at Quarkonium 2019 in Torino, May 2019



X Resonance feature (X_{RF}) vs. X bound state (X_{BS})

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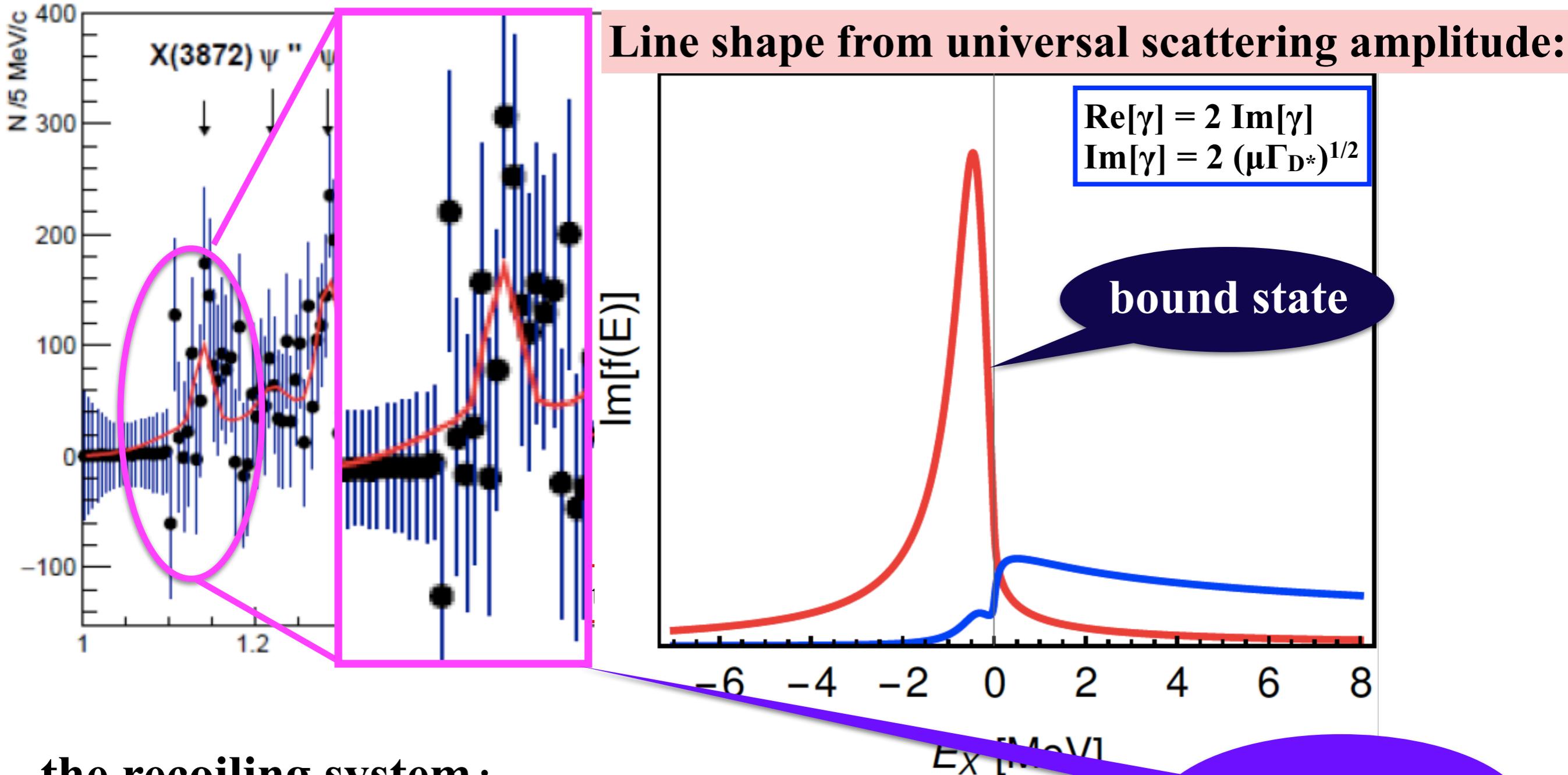


the recoiling system :

- threshold enhancement above D*D threshold
- peak from a possible X(3872) bound state

X Resonance feature (X_{RF}) vs. X bound state (X_{BS})

G. Wormser presented at Quarkonium 2019 in Torino, May 2019



the recoiling system :

- threshold enhancement above D*D threshold
- peak from a possible X(3872) bound state

resonance
feature

X Resonance feature (X_{RF}) vs. X bound state (X_{BS})

SDD: short-distance decay modes:

$J/\psi \pi^+ \pi^-$, $J/\psi \pi^+ \pi^- \pi^0$, $J/\psi \gamma$, $\psi(2S)\gamma$, $\chi_{c1}\pi^0$

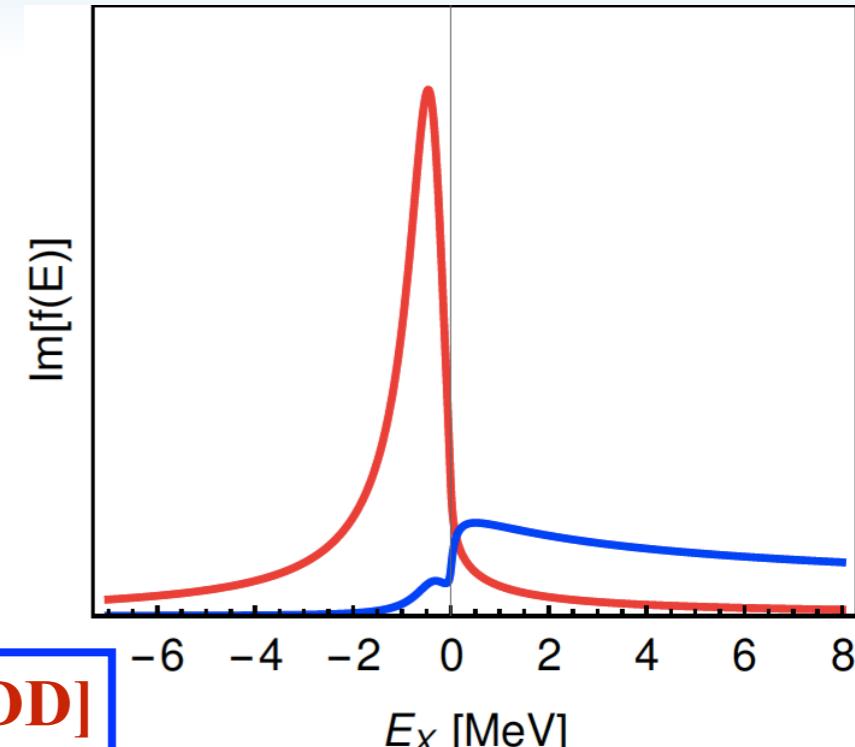
CD: constituent decay modes:

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

threshold enhancement only decays to CD modes

Branching fractions are different for RF and BS

$$\text{Br}[X_{RF} \rightarrow \text{CD}] > \text{Br}[X_{BS} \rightarrow \text{CD}] \quad \text{Br}[X_{RF} \rightarrow \text{SDD}] < \text{Br}[X_{BS} \rightarrow \text{SDD}]$$

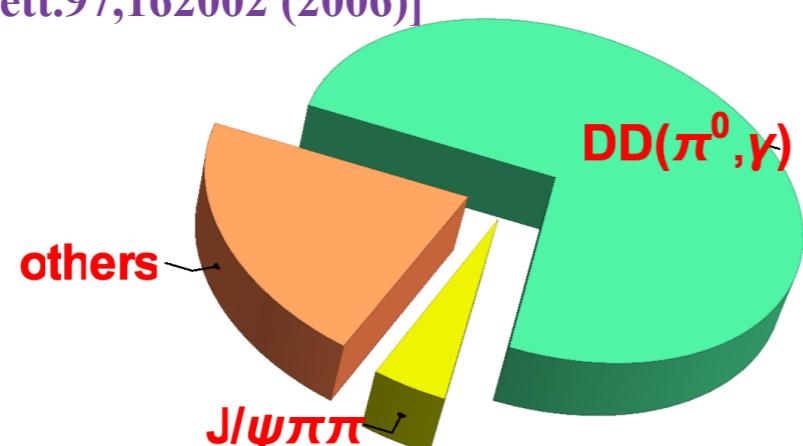


* $X(3872)$ resonance feature (X_{RF})

$$\text{Br}[X_{B^+ \rightarrow K^+} \rightarrow J/\psi \pi^+ \pi^-] = (4.1 \pm 1.3)\%$$

$$\text{Br}[X_{B^+ \rightarrow K^+} \rightarrow D^0 \bar{D}^0(\pi^0, \gamma)] \approx (75 \pm 40)\%$$

base on [Belle, PR Lett. 97, 162002 (2006)]



* $X(3872)$ bound state (X_{BS})

$$\text{Br}[X \rightarrow J/\psi \pi^+ \pi^-]:$$

loosely lower limit from recoil momentum spectrum:

~ 4%

upper limit: < 33% (90% C.L.)

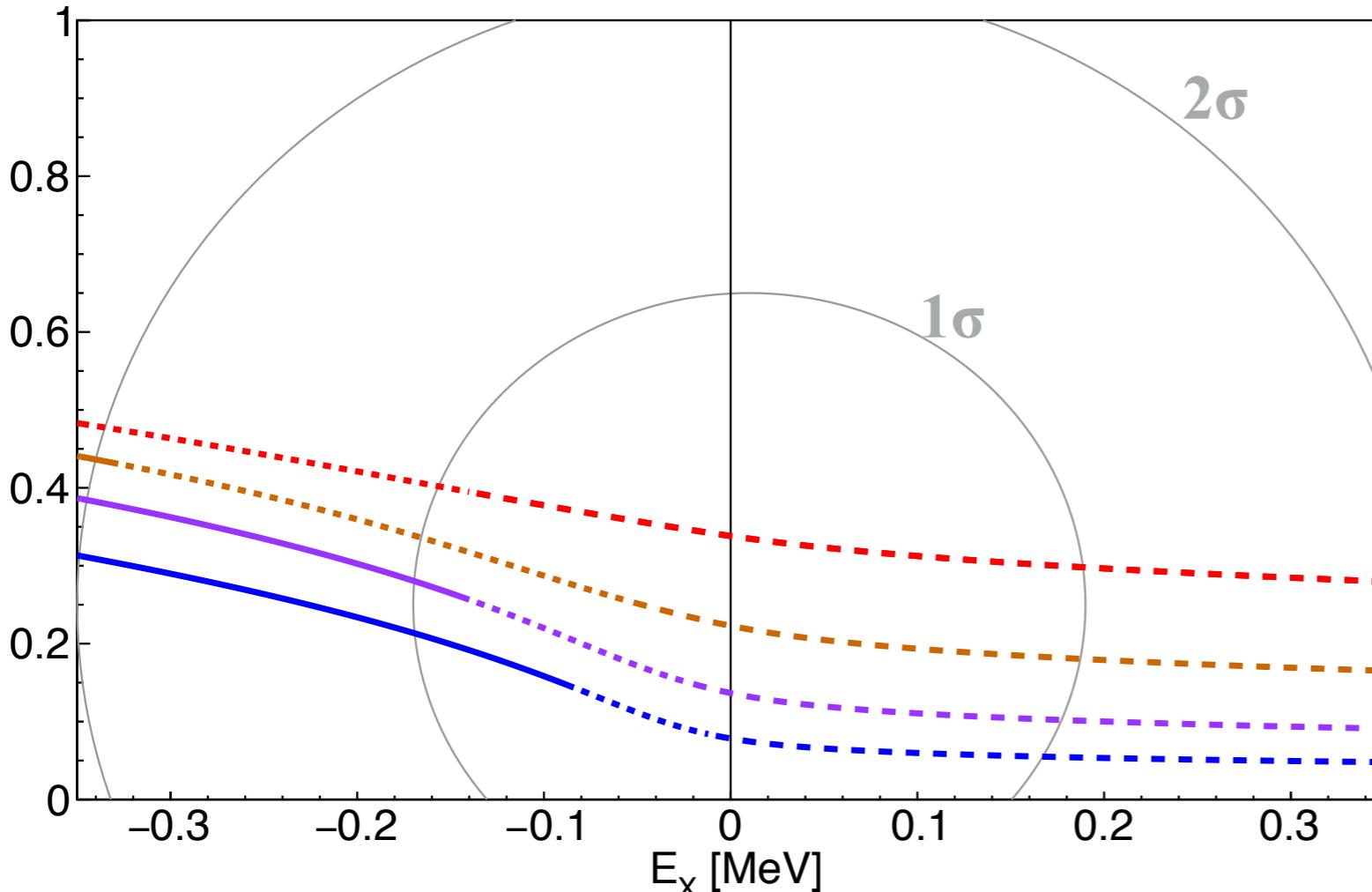
$$1 > \text{Br}[X \rightarrow J/\psi \pi^+ \pi^-] + \sum_i' \text{Br}[X \rightarrow i]$$

$$\frac{1}{\text{Br}[X \rightarrow J/\psi \pi^+ \pi^-]} > 1 + \sum_i' \frac{\text{Br}[X \rightarrow i]}{\text{Br}[X \rightarrow J/\psi \pi^+ \pi^-]}$$

Theoretical Br[X \rightarrow SDD]

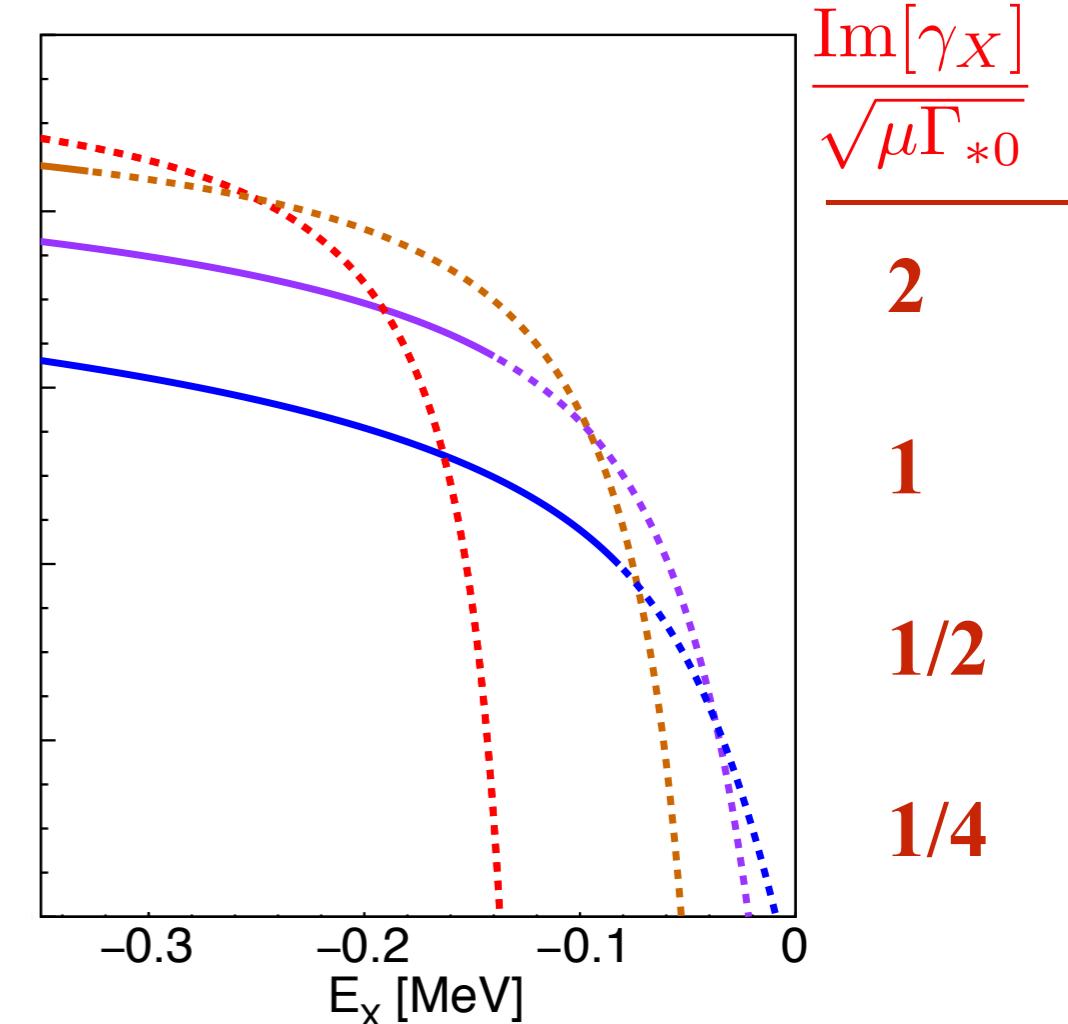
* resonance feature

— narrow bound state($|Re[E_{pole}]| > |Im[E_{pole}]|$)



* bound state

- - - virtual state



- larger $Im[\gamma_X] \rightarrow$ larger $Br[SDD]$ (Im part from the effect of SDD modes)
- $Br[X_{RF} \rightarrow SDD] < Br[X_{BS} \rightarrow SDD]$
- The majority of the area inside the 1σ error ellipse corresponds to virtual states

X(3872) γ production in e⁺e⁻

- * Experimental observation

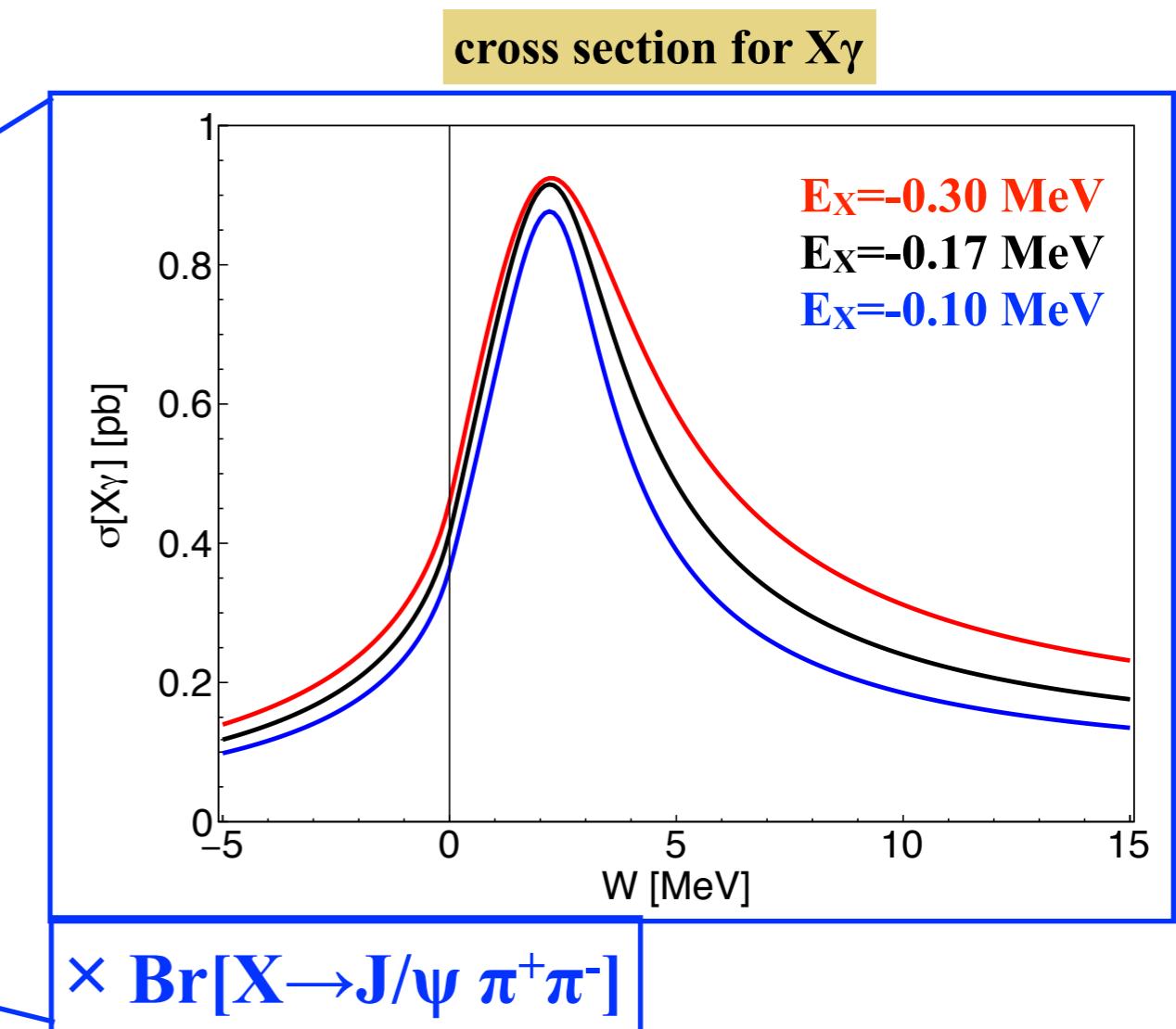
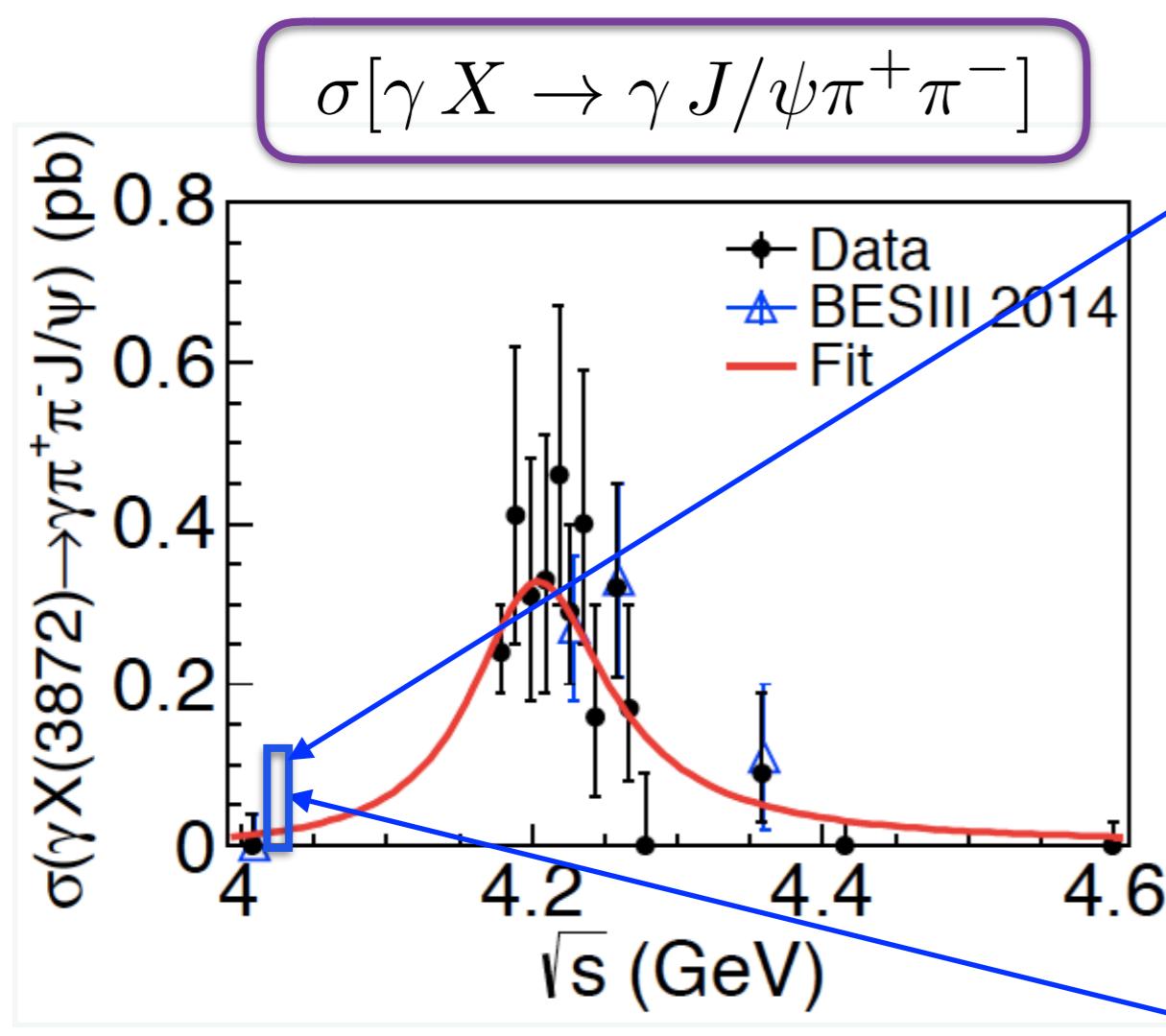
BESIII: e⁺e⁻ → X γ

[PRL 112, 092001(2014), arXiv: 1903.04695]

Braaten, He, Ingles,

PRD 100, 031501 (2019), [arXiv: 1904.12915]

arXiv: 1909.03901



Br[X → J/ ψ $\pi^+ \pi^-$] is needed to predict the cross section near D*D* threshold

Summary

- Branching fractions for X(3872) resonance feature and bound state are different

$$\text{Br}[X_{\text{RF}} \rightarrow \text{CD}] > \text{Br}[X_{\text{BS}} \rightarrow \text{CD}] \quad \text{Br}[X_{\text{RF}} \rightarrow \text{SDD}] < \text{Br}[X_{\text{BS}} \rightarrow \text{SDD}]$$

- Estimates for branching fractions for resonance feature and bound state

Thank you!

Backup slides

Simple model for X(3872) line shape

- decay width of D^* : $E \rightarrow E + i\Gamma_{*0}/2$

- effect of short distance decay modes: γ_X is complex

$$f(E) = \frac{1}{-\gamma_X + \sqrt{-2\mu(E + i\Gamma_{*0}/2)}}$$

the parameter γ_X is determined by physics at short distance

optical theorem: line shape is proportional to $\text{Im}[f(E)]$ at real energy

short-distance decay (SDD):

$J/\psi \pi^+ \pi^-$, $J/\psi \pi^+ \pi^- \pi^0$, $J/\psi \gamma$, ...

constituent decay (CD):

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

$$\text{Im}[f(E)] = |f(E)|^2 \left(\text{Im}[\gamma_X] + \left[\mu \sqrt{E^2 + \Gamma_{*0}^2/4} + \mu E \right]^{1/2} \right)$$

$$\text{Im}[\gamma_X] > 0$$

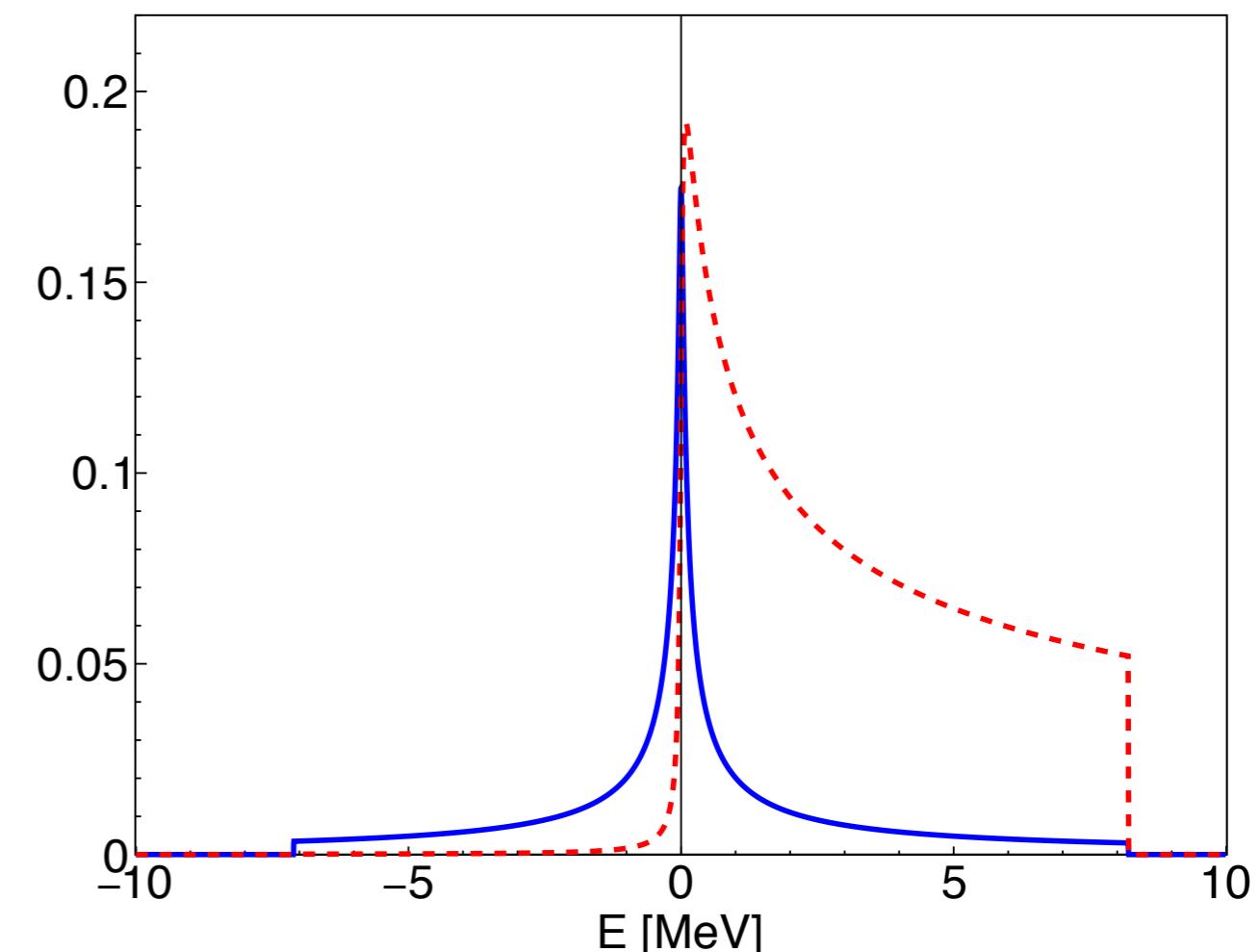
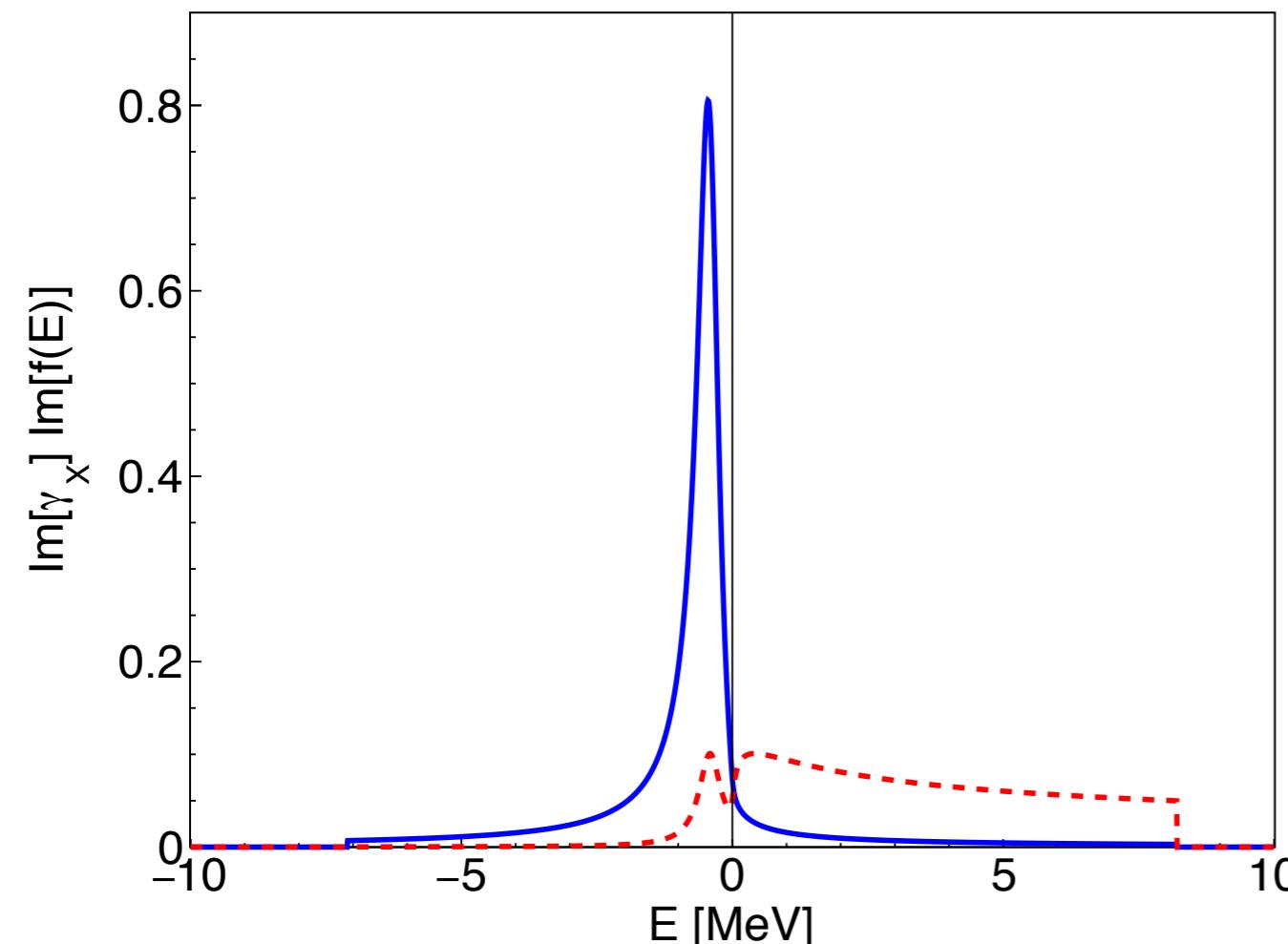
$$|f(E)|^2 = \left[\left(-\text{Re}[\gamma_X] + \left[\mu(E^2 + \Gamma_{*0}^2/4)^{1/2} - \mu E \right]^{1/2} \right)^2 + \left(\text{Im}[\gamma_X] + \left[\mu(E^2 + \Gamma_{*0}^2/4)^{1/2} + \mu E \right]^{1/2} \right)^2 \right]^{-1}$$

Simple model for X(3872) line shape

- * Examples for line shapes with different γ_X

$$\text{Im}[\gamma_X] = \sqrt{\mu\Gamma_{*0}}, \text{Re}[\gamma_X] = 4\text{Im}[\gamma_X]$$

$$\text{Im}[\gamma_X] = \sqrt{\mu\Gamma_{*0}}, \text{Re}[\gamma_X] = -\text{Im}[\gamma_X]$$



zero energy resonance

$$E_{\min} = m(D^0 D^0 \pi^0) - m(D^{*0} D^0)$$

$$E_{\max} = m(D^{*+} D^{*-}) - m(D^{*0} D^0)$$

Simple model for X(3872) line shape

* pole in the complex E plane

$$f(E) = \frac{1}{-\gamma_X + \sqrt{-2\mu(E + i\Gamma_{*0}/2)}}$$

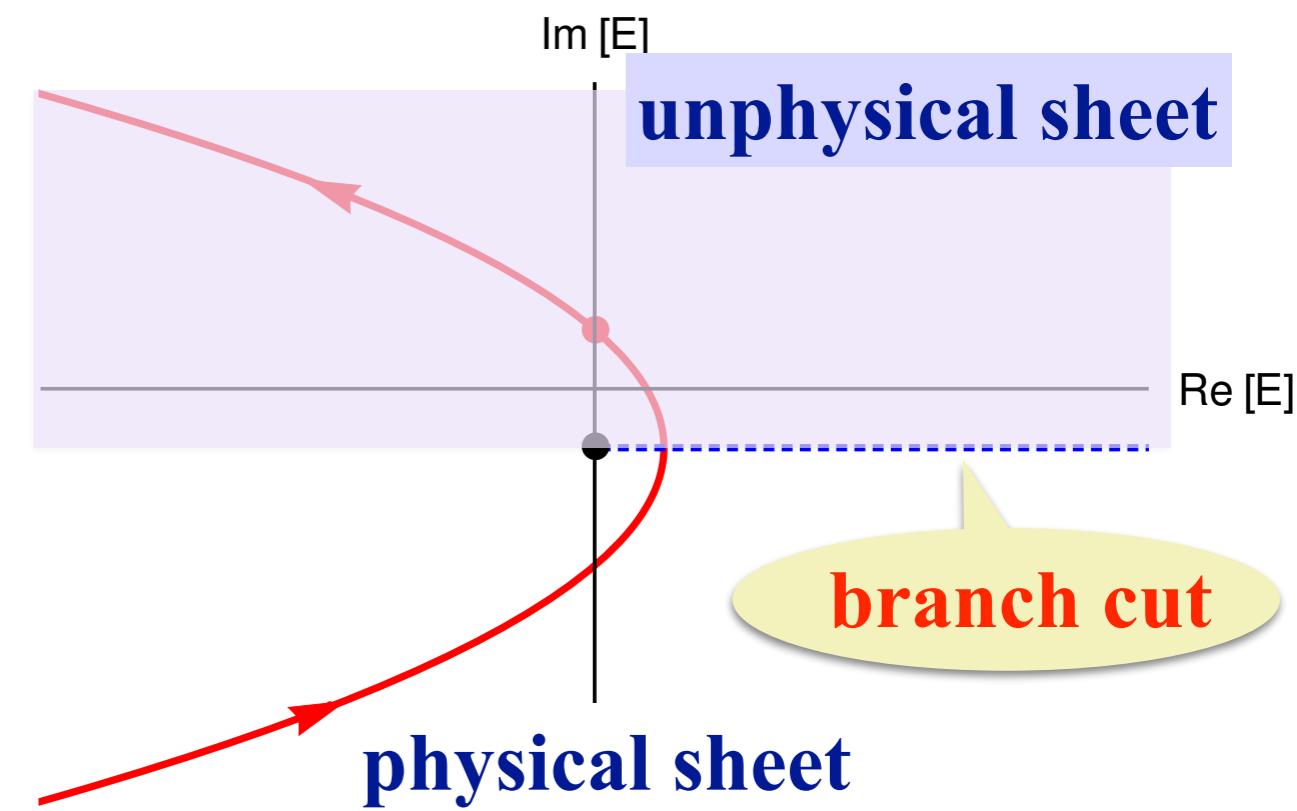
$$E_{\text{pole}} = -\frac{\text{Re}[\gamma_X]^2 - \text{Im}[\gamma_X]^2}{2\mu} - \frac{i}{2} \left(\Gamma_{*0} + \frac{2\text{Re}[\gamma_X]\text{Im}[\gamma_X]}{\mu} \right)$$

arrow: γ_X decreases from $+\infty$ to $-\infty$

$$\text{Im}[\gamma_X] \sim \sqrt{\mu\Gamma_{*0}}$$

- $\gamma_X > 0$: pole on physical sheet
bound state

- $\gamma_X < 0$: pole on unphysical sheet
virtual state



Resonance energy

The most convenient decay mode for defining the resonance energy is $J/\psi\pi\pi$

$$\int_{E_{\min}}^{E_X} dE |f(E)|^2 = \int_{E_X}^{E_{\max}} dE |f(E)|^2$$

- **Bound-state limit** $\text{Im}[\gamma_X] \sim \sqrt{\mu\Gamma_{*0}}$, $\text{Re}[\gamma_X] \gg \sqrt{\mu\Gamma_{*0}}$

$$E_X = -\frac{\text{Re}[\gamma_X]^2}{2\mu} - \frac{\text{Im}[\gamma_X]\Gamma_{*0}}{2\text{Re}[\gamma_X]} + \dots$$

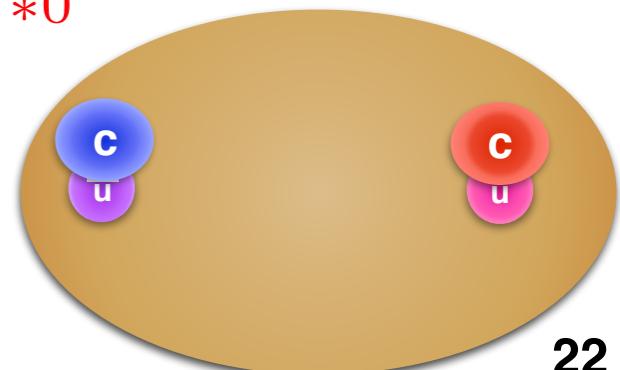
$$\Gamma_X = \Gamma_{*0} + \frac{2\text{Re}[\gamma_X]\text{Im}[\gamma_X]}{\mu}$$

- **Zero-energy resonance** $\text{Re}[\gamma_X] = -\text{Im}[\gamma_X]$

$$E_X = 0$$

- **Virtual-state limit** $\text{Im}[\gamma_X] \sim \sqrt{\mu\Gamma_{*0}}$, $\text{Re}[\gamma_X] \ll -\sqrt{\mu\Gamma_{*0}}$

$$E_X \approx \left(e \sqrt{\frac{E_{\max}}{|E_{\min}|}} - 1 \right) \frac{\text{Re}[\gamma_X]^2}{2\mu}$$



Branching fractions from theory

* X(3872) resonance feature

- Br[SDD]/Br[D⁰D⁰(π⁰, γ)]:

$$\frac{\text{Br}[X_{\text{res}} \rightarrow \text{SDD}]}{\text{Br}[X_{\text{res}} \rightarrow D^0 \bar{D}^0(\pi^0, \gamma)]} = \frac{\text{Im}[\gamma_X] \int_{E_{\min}}^{E_{\max}} dE |f(E)|^2}{\int_{E_{\min}}^{E_{\max}} dE |f(E)|^2 [\mu \sqrt{E^2 + \Gamma_{*0}^2/4} + \mu E]^{1/2}}$$

* X(3872) as a narrow bound state (Re[E_{pole}] > Im[E_{pole}])

- Br[SDD]/Br[D⁰D⁰(π⁰, γ)]:

$$\frac{\text{Br}[X \rightarrow \text{SDD}]}{\text{Br}[X \rightarrow D^0 \bar{D}^0(\pi^0, \gamma)]} \approx \frac{2 \text{Re}[\gamma_X] \text{Im}[\gamma_X]}{\mu \Gamma_{*0}}$$

$$\text{Br}[X_{B^+ \rightarrow K^+} \rightarrow D^0 \bar{D}^0 \pi^0] \equiv \frac{\text{Br}[B^+ \rightarrow K^+(D^0 \bar{D}^0 \pi^0)]}{\text{Br}[B^+ \rightarrow K^+ X_{B^+ \rightarrow K^+}]} = (49 \pm 26)\%,$$