Production of X(3872) Accompanied by a Photon or Pion

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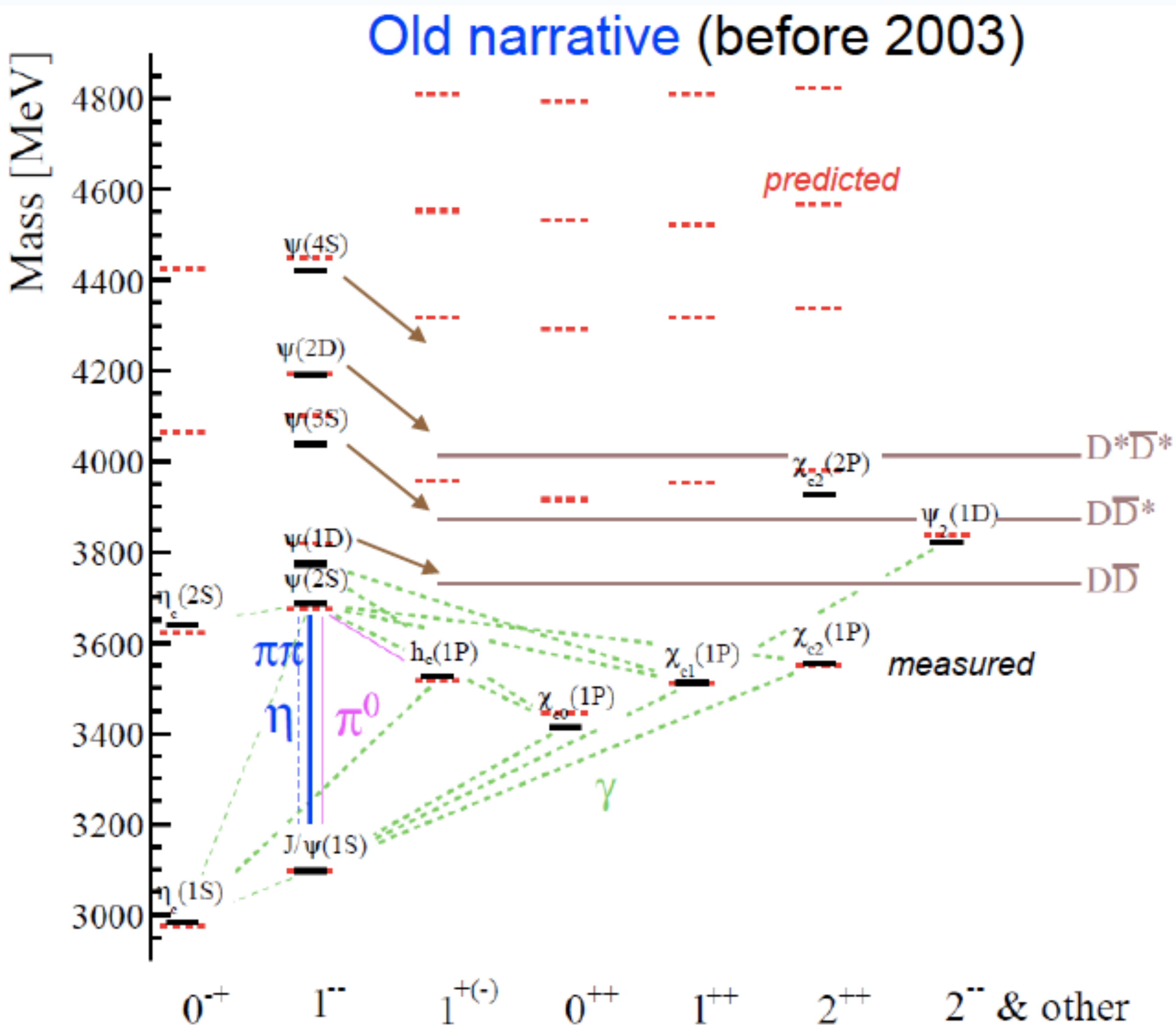
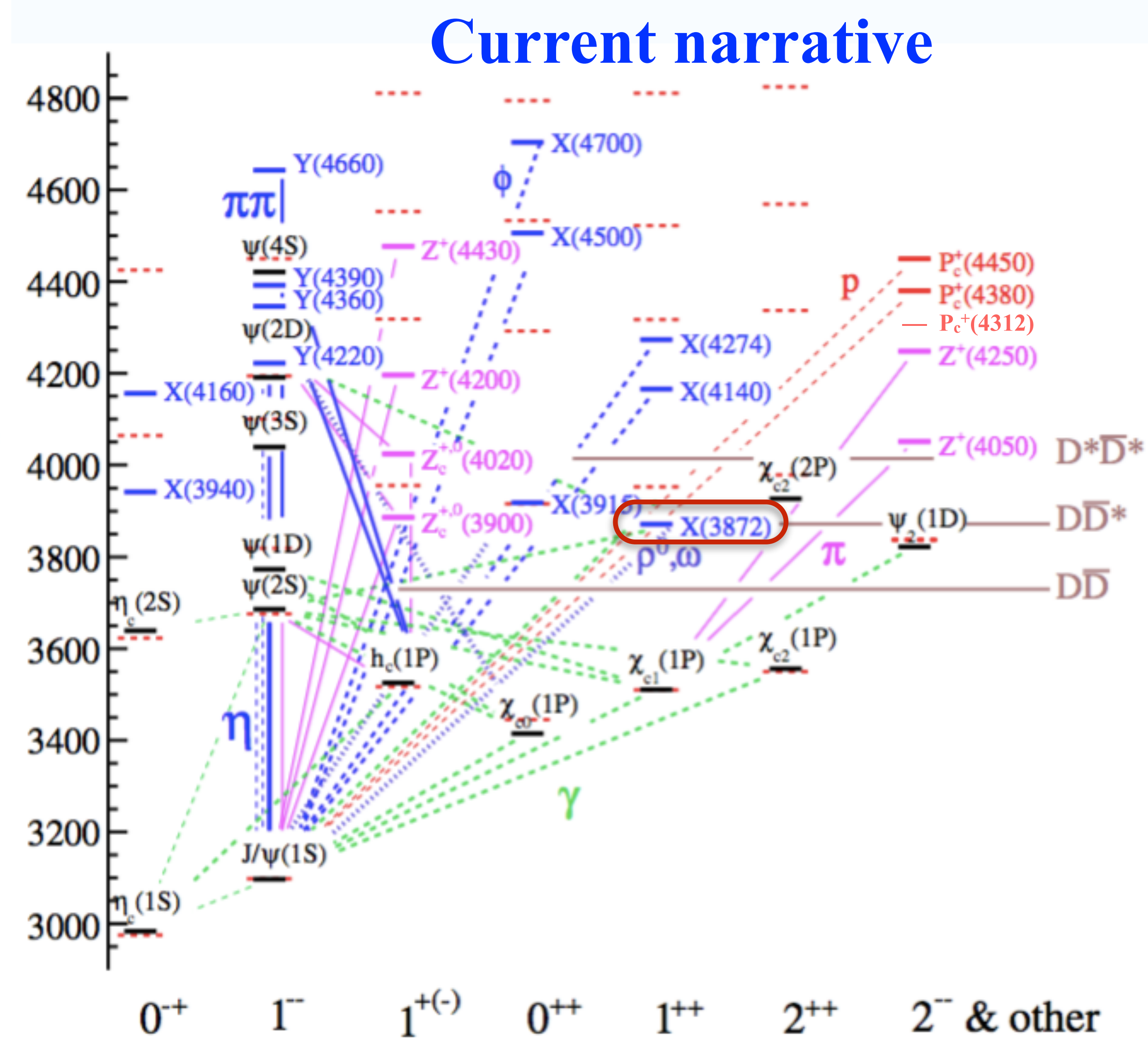
Introduction to the X(3872)

Charmonium mass spectrum





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

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

Outline

- Introduction to the X(3872)

- Universal properties of near-threshold S-wave resonance

- e^+e^- annihilation: production of X accompanied by a photon
  (Braaten, He, Ingles, arXiv: 1904.12915, long paper is in preparation)

- B meson decay: production of X accompanied by a pion
  (Braaten, He, Ingles, arXiv:1902.03259)

- Hadron colliders: production of X accompanied by a pion
  (Braaten, He, Ingles, arXiv:1811.08876, arXiv:1903.04355)

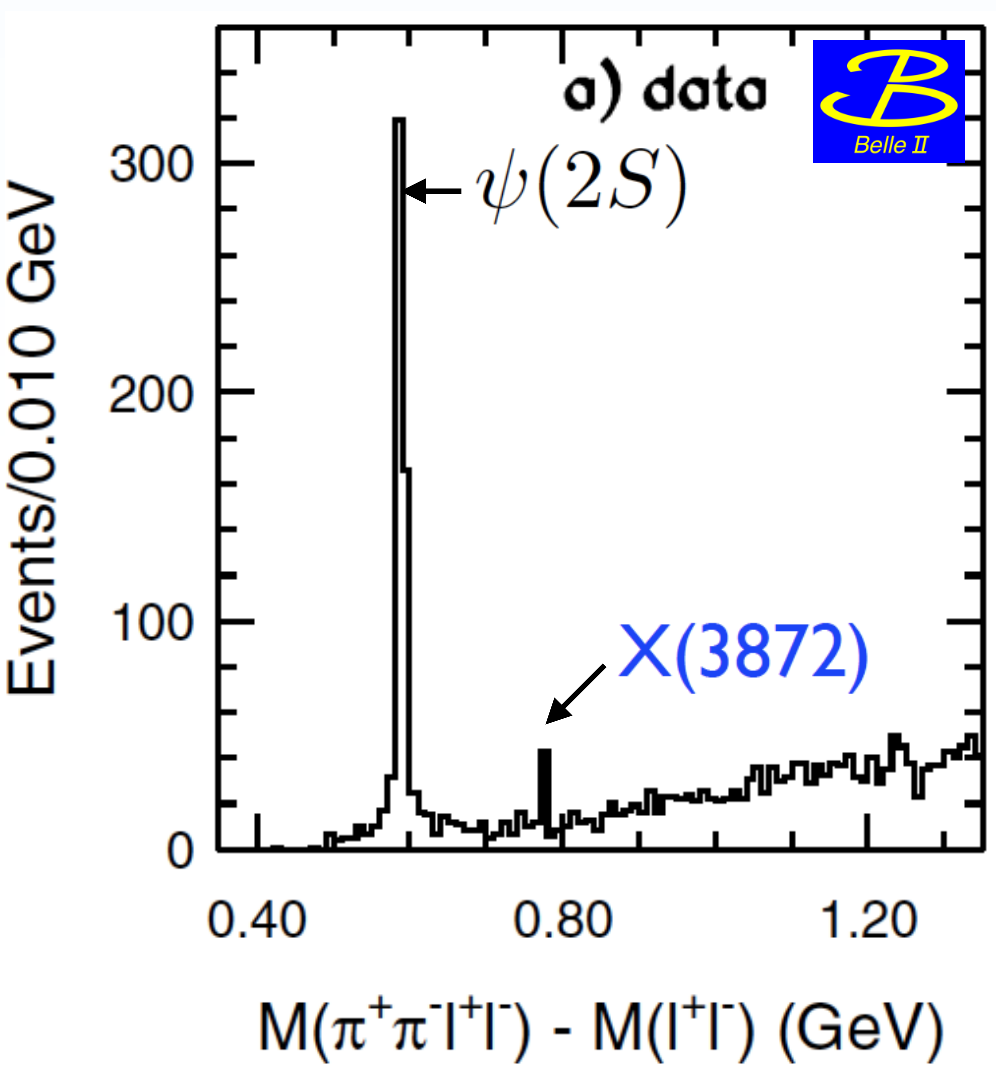
- Summary

Introduction to the X(3872)

- **Discovery**
  - **Belle Collaboration (2003)**

    PRL 91,262001(2003)

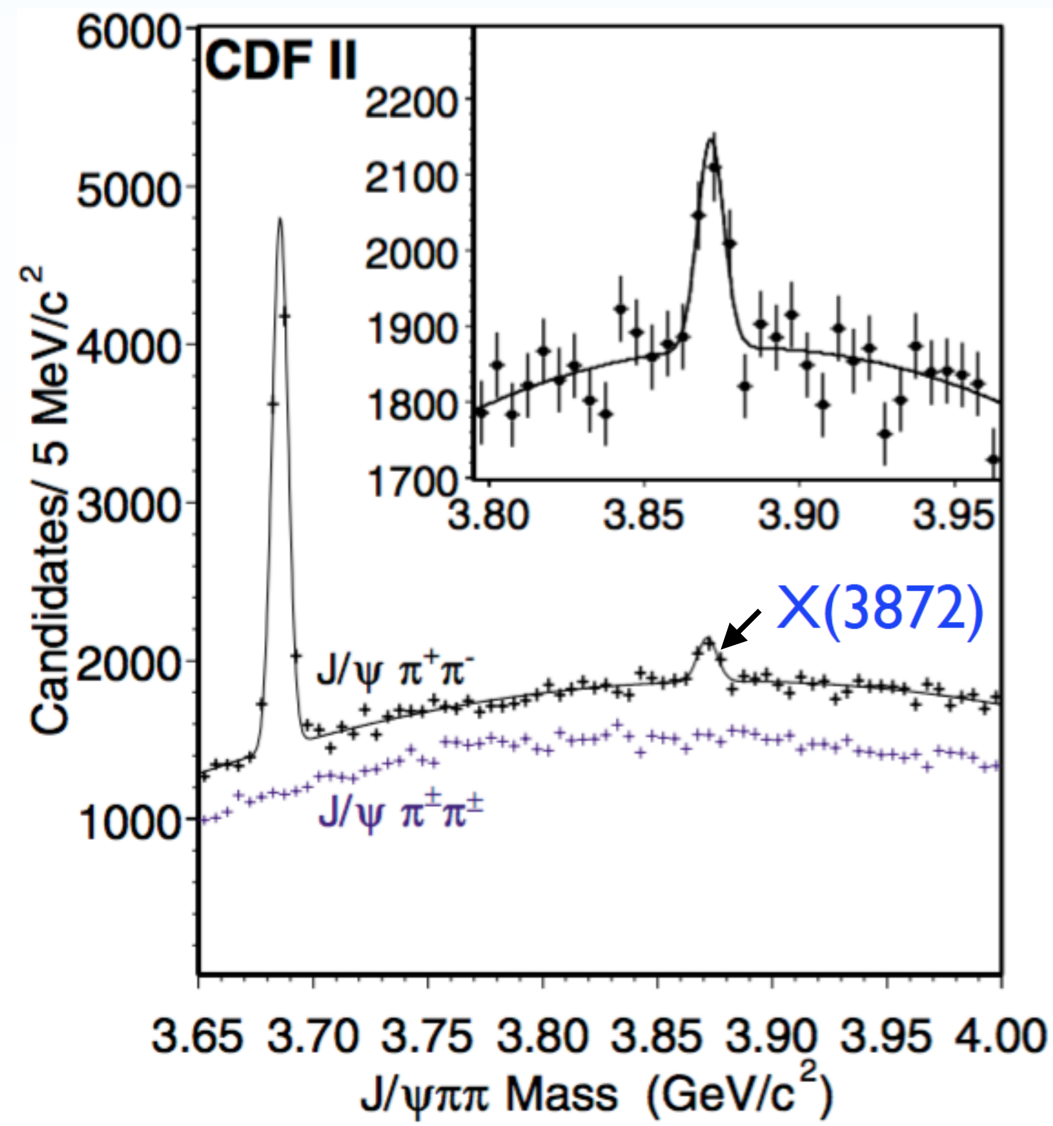
    $$B^+ \to K^+ + X$$
    $$X \to J/\psi\pi^+\pi^-$$



- **Confirmation**
  - **CDF Collaboration**

    PRL 91,262001(2004)

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



Introduction to the X(3872)

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

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

* Width: very narrow

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

* Quantum numbers:

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

* Seven observed decay modes:

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

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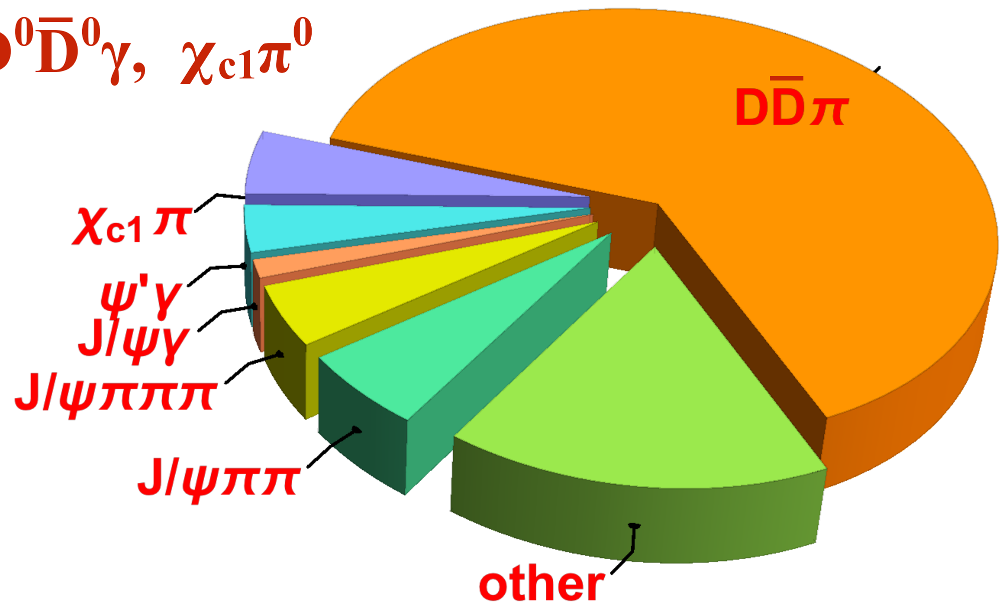
Br [$X\to J/\psi\, \pi^+ \pi^-$] = (4.1±1.3)%

G. Wormser's talk at QWG 2019, Torino May 2019



Introduction to the X(3872)

* **What is the X(3872)?**

Two crucial experimental inputs:

❖ Quantum numbers: $J^{PC} = 1^{++}$

→ S-wave coupling to $D^{*0}\bar{D}^0 / \bar{D}^{*0}D^0$

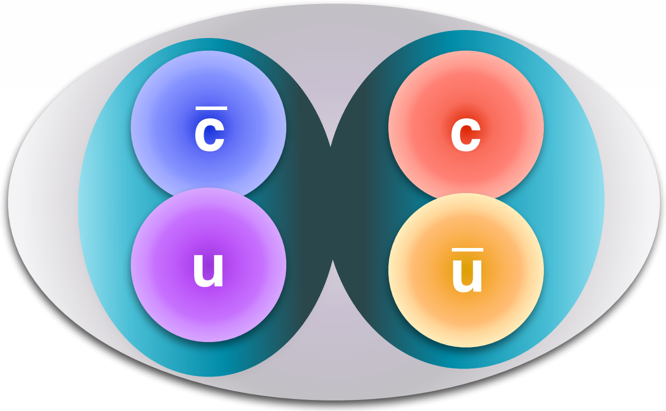
❖ Mass is extremely close to $D^{*0}\bar{D}^0$ threshold

→ resonant coupling

* **Conclusion:**

X(3872) is a charm-meson molecule:

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



other components of wave functions have small probabilities:

- $D^0 D^0 \pi^0$ at long large distances
- $\chi_{c1}(2P)$ at small distances

Introduction to the X(3872)

* What is the X(3872)?

Other explanations:

* QCD tetraquark
* Charmonium hybrid
* HadroCharmonium

* Conclusion:

X(3872) is a charm-meson molecule:

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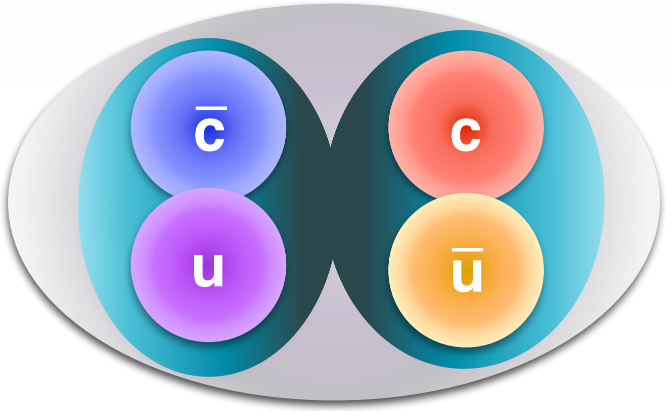

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Universal properties near threshold

* Nonrelativistic Quantum Mechanics:
  - short-range interactions
  - S-wave resonance close enough to threshold

→ * large scattering length |a| >> range
  * universal features depend only on a (or $\gamma = 1/a$)

* universal wave function at r >> range: $$\psi(r) = \frac{e^{-\gamma r}}{r}$$

* scattering amplitude at k << 1/range: $$f(k) = \frac{1}{-\gamma - ik}$$

X(3872) has universal features that depend only on inverse scattering length γ_X for $D^{*0}\bar{D}^0/D^{*0}\bar{D}^0$ in C=+ channel

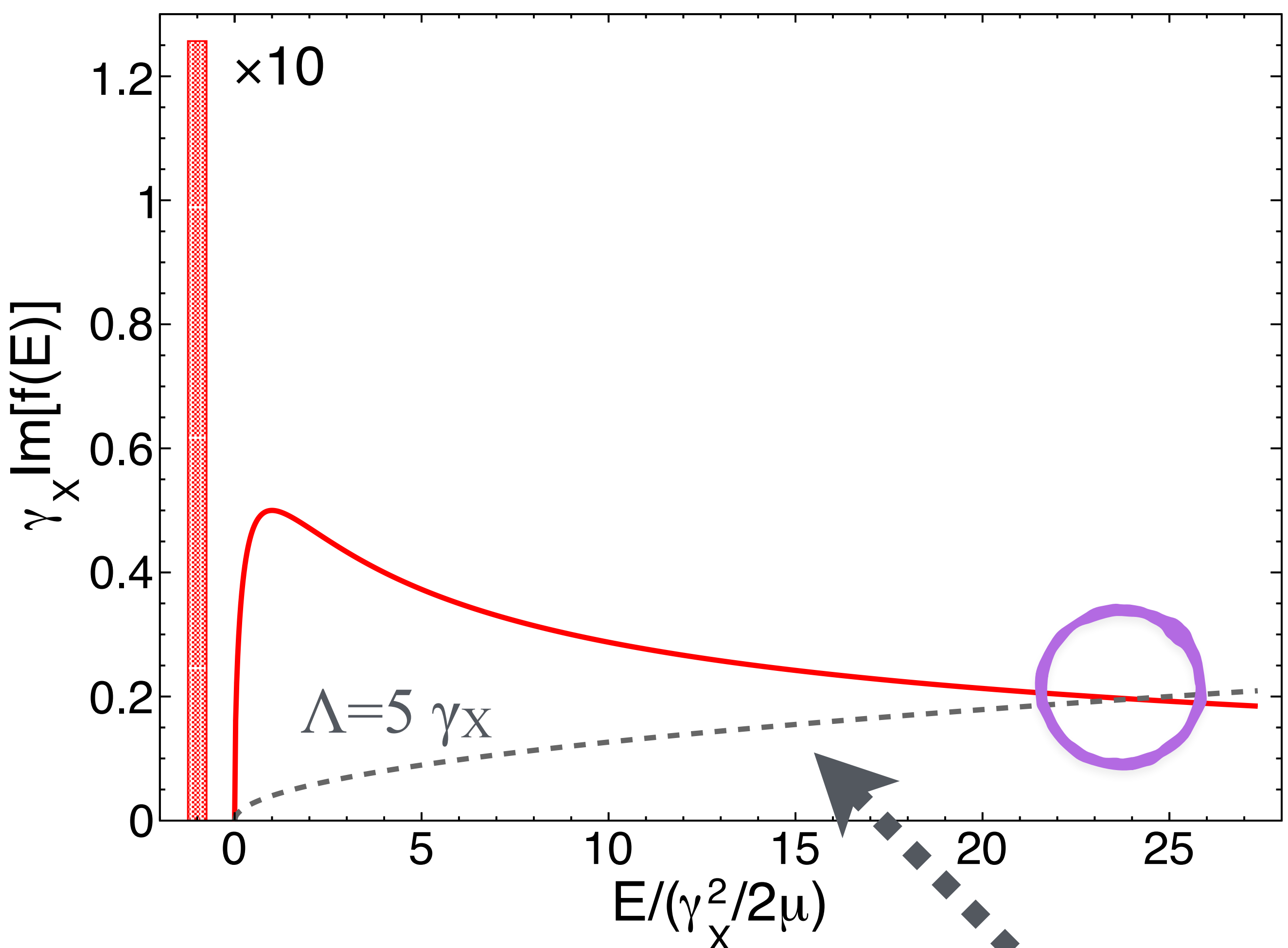
→ X(3872) has size greater than 10 fm ! $1/\sqrt{2\mu\,|E_X|}$

Universal properties near threshold

- Line shape of X(3872), $D^{*0}\bar{D}^0$, $\bar{D}^{*0}D^0$ at small energy E from optical theorem by using universal scattering amplitude:

$$\mathrm{Im}[f_X(E+i\epsilon)] = \frac{\pi\gamma_X}{\mu}\delta(E+\gamma_X^2/2\mu) + \frac{\sqrt{2\mu E}}{\gamma_X^2+2\mu E}\theta(E)$$

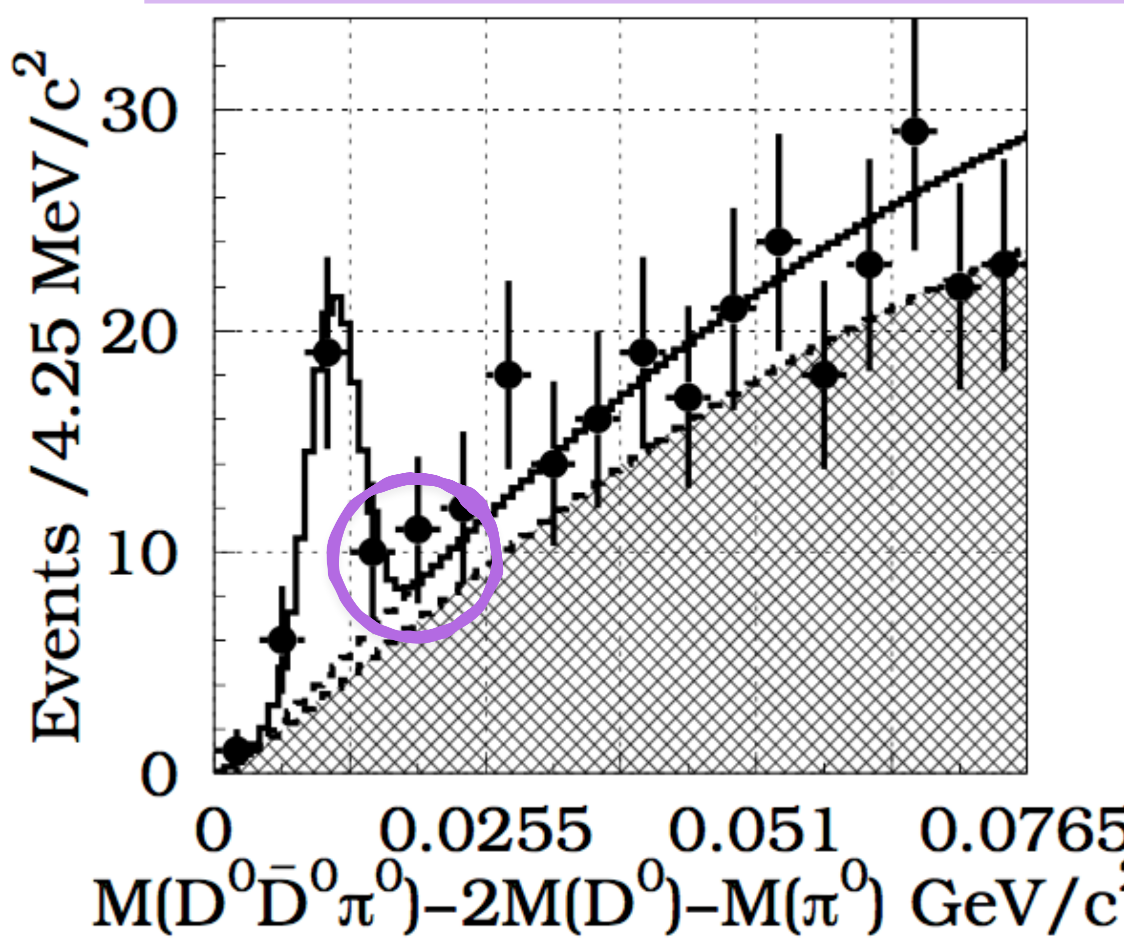
γ_X is real



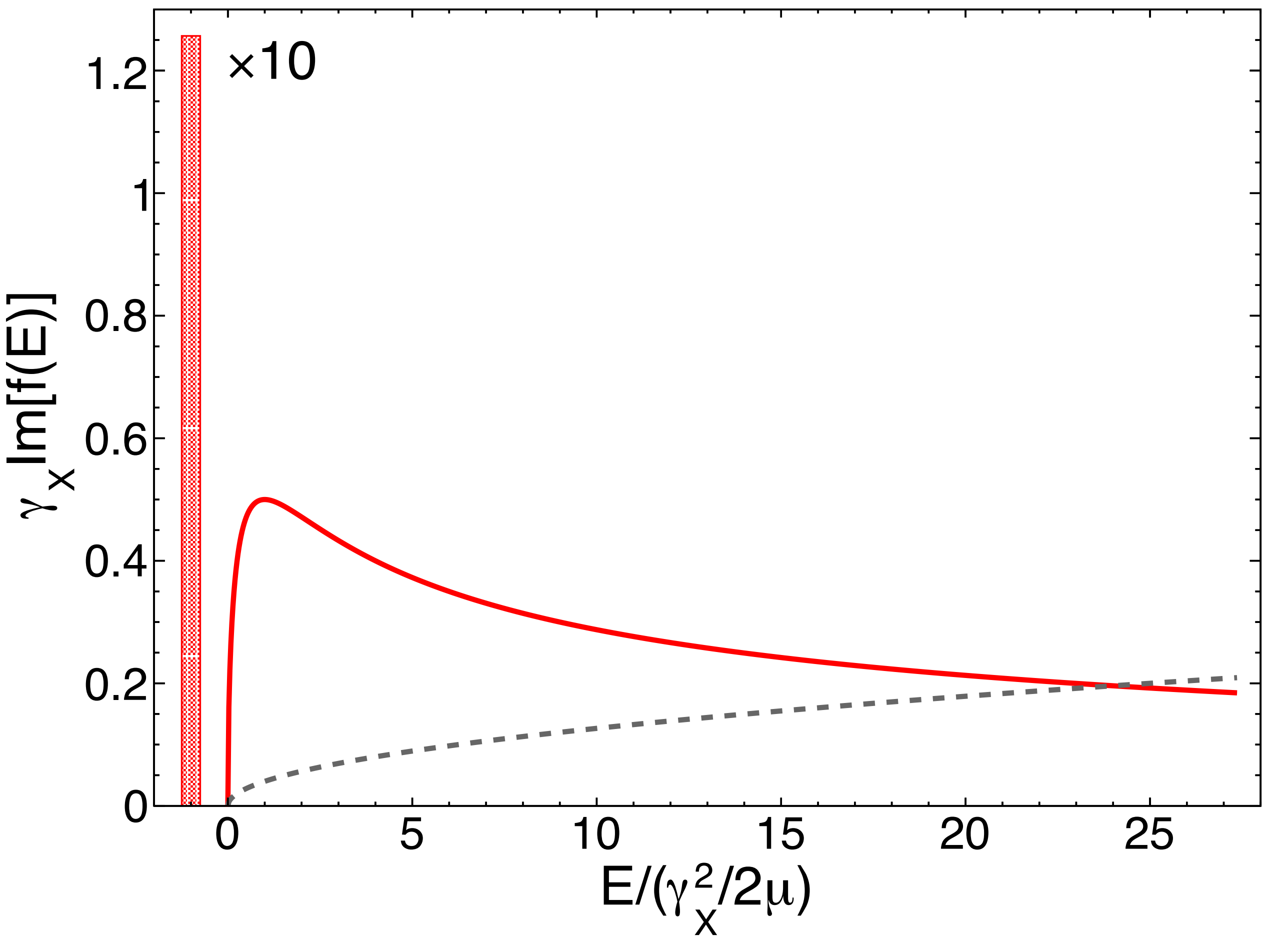
$$\mathrm{Im}[f_{\mathrm{naive}}(E+i\epsilon)] = \frac{1}{\Lambda^2}\sqrt{2\mu E}\ \theta(E)$$

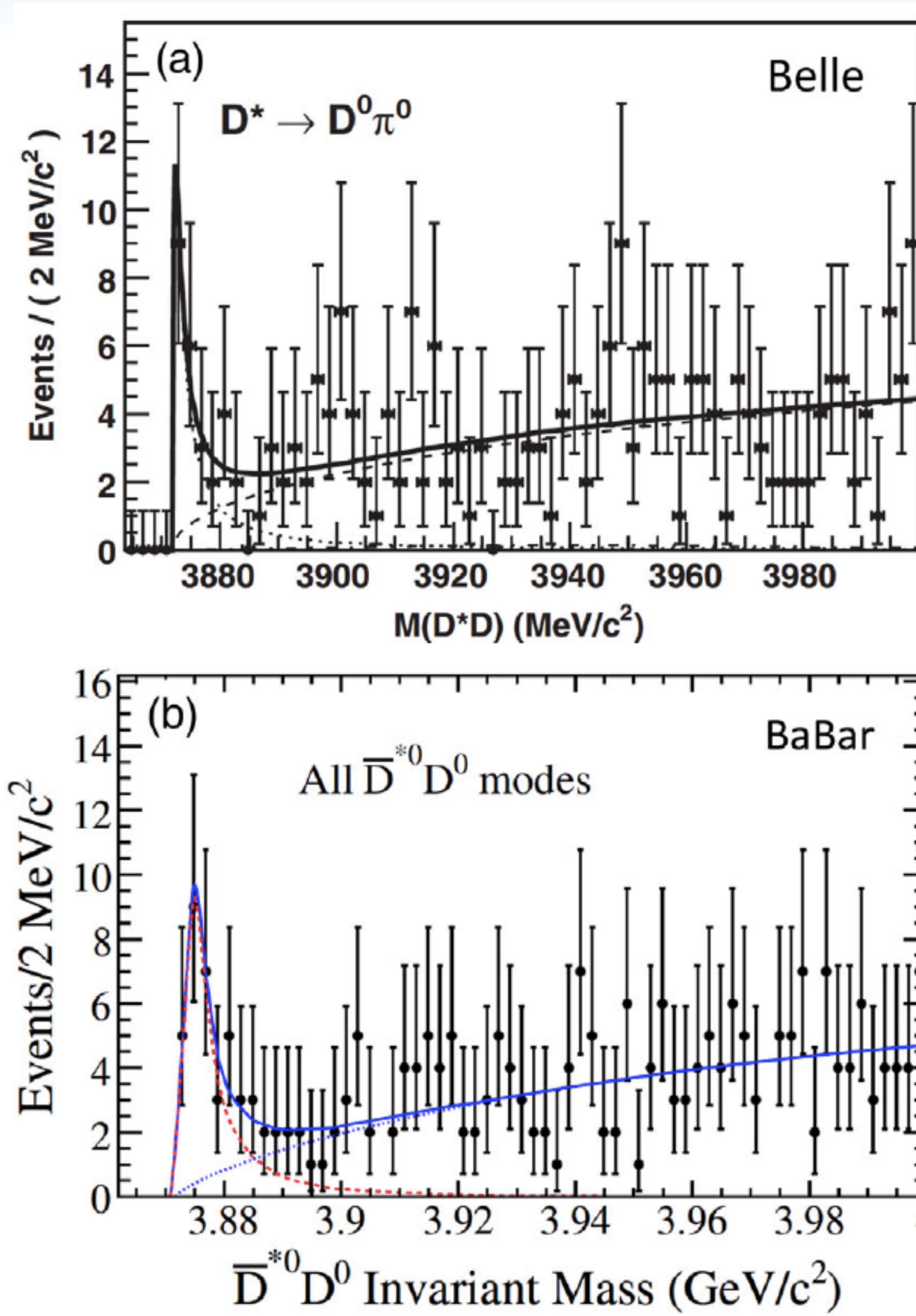
Belle: B→KX, X→$D^0D^0\pi^0$

[PRL 97, 162002 (2006)]



Universal properties near threshold





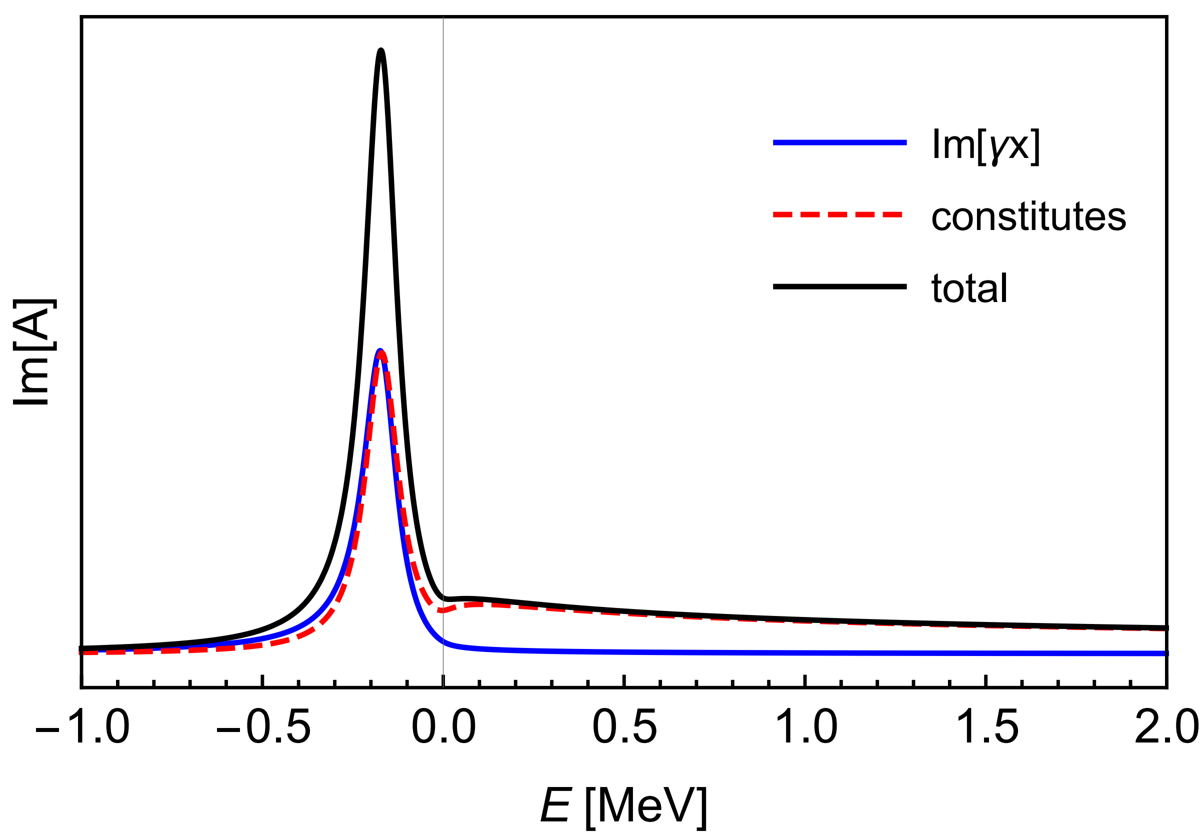
Universal properties near threshold

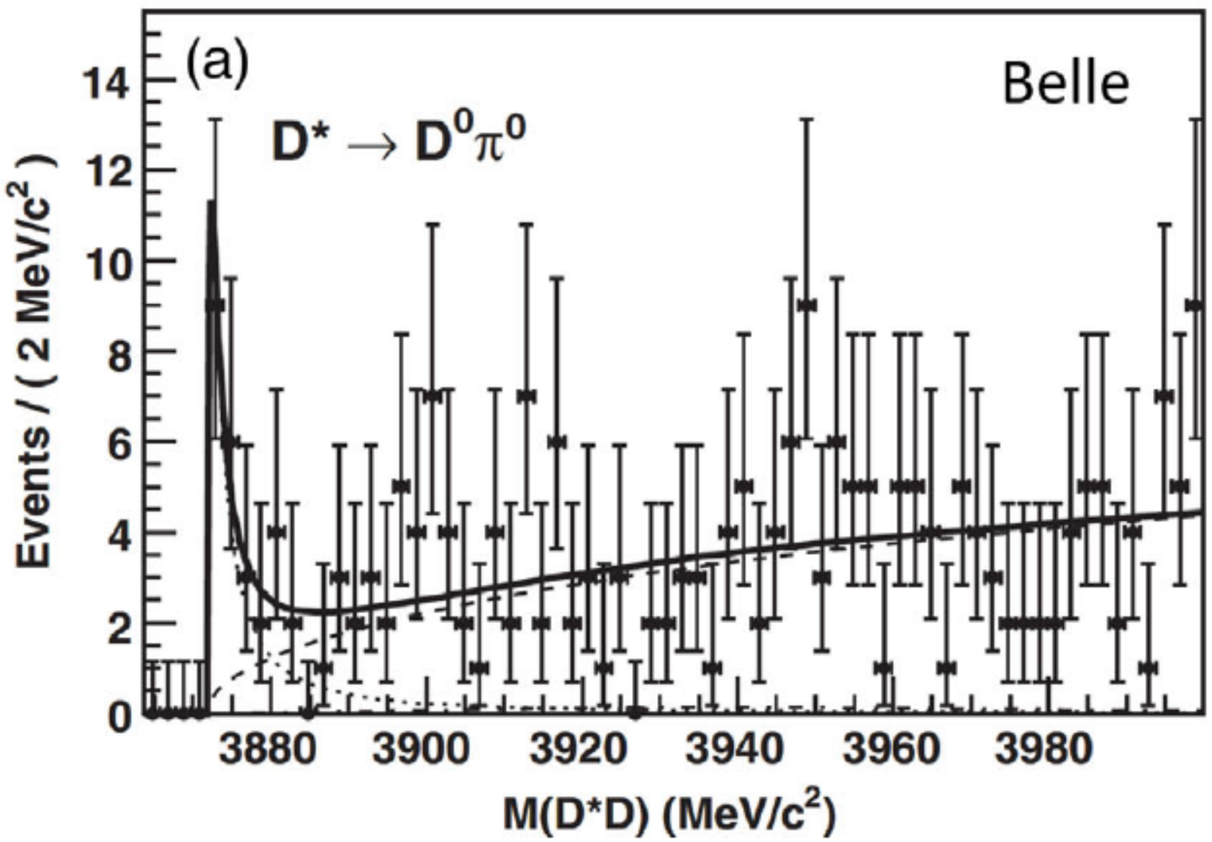
- **Line shape using scattering amplitude from zero-range EFT:**

$$\mathcal{A} = \frac{2\pi/\mu}{-\gamma_X + \sqrt{-2\mu\left(E + i\Gamma_{*0}/2\right)}}$$

$$\mathrm{Im}[\mathcal{A}] = \frac{\mu}{2\pi}|\mathcal{A}(E)|^2 \left(\mathrm{Im}\left[\gamma_X\right] + \sqrt{\mu}\sqrt{\sqrt{E^2 + \Gamma_{*0}^2/4} + E}\right)$$

γ_X is complex

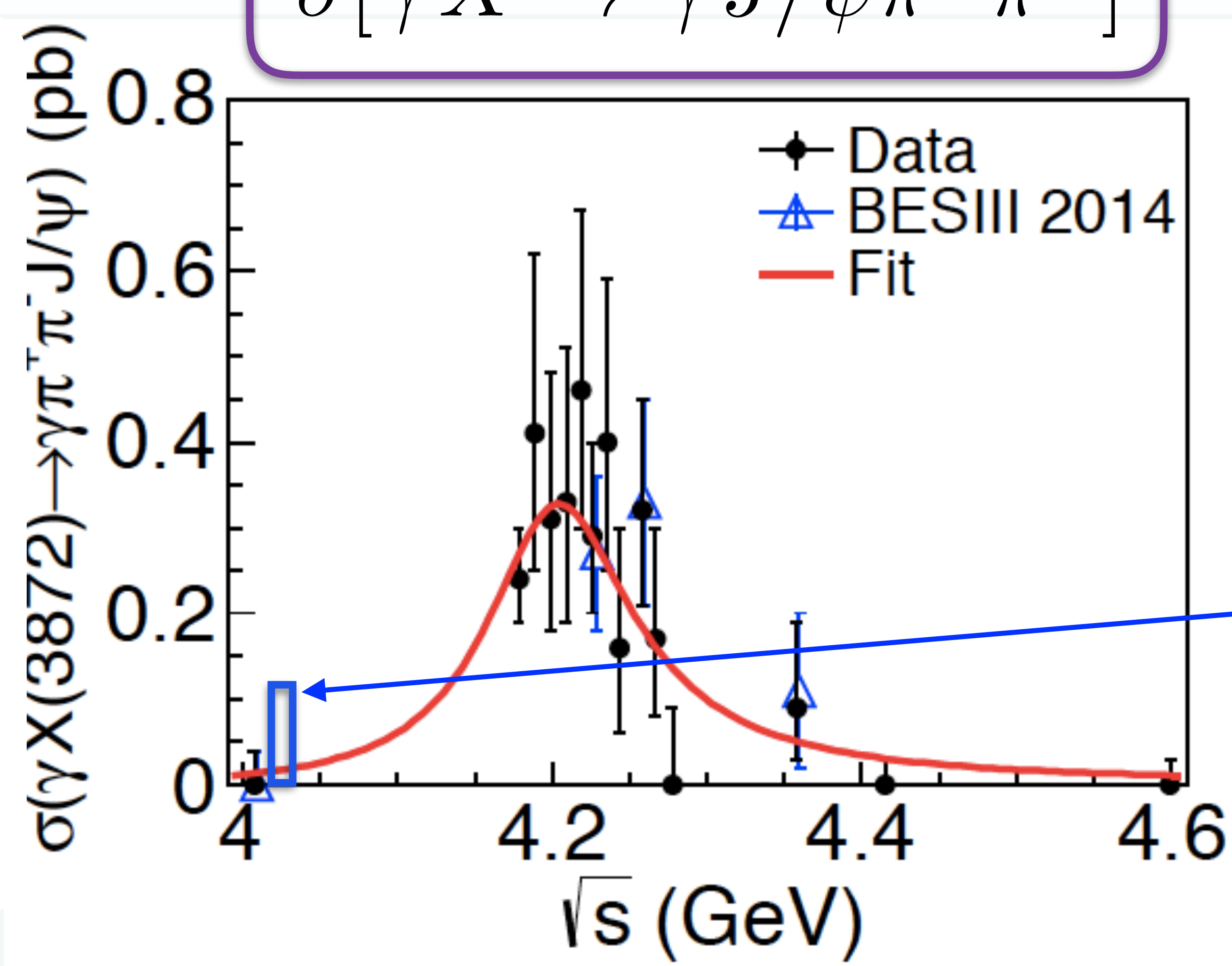




e^+e^-: production of X(3872) and a photon

- **Experimental observation**
  BESIII: $e^+e^- \to X\gamma$
  [PRL 112, 092001(2014), arXiv: 1903.04695]

$$\sigma[\gamma X \to \gamma J/\psi \pi^+ \pi^-]$$

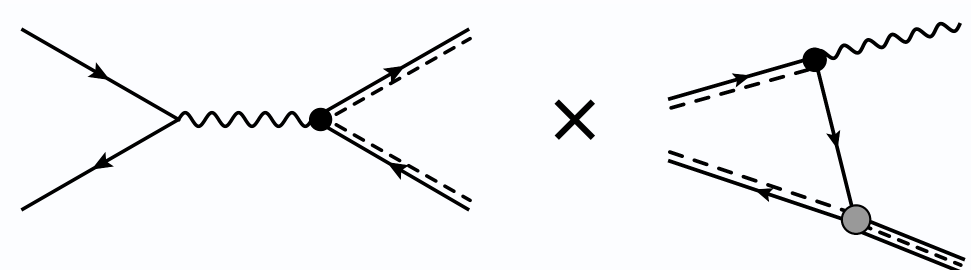


- **Dubynskiy and Voloshin**
  [PRD 74, 094017 (2006)]

absorptive contribution from

$$e^+ e^- \to D^{*0} \bar{D}^{*0} \to X \gamma$$

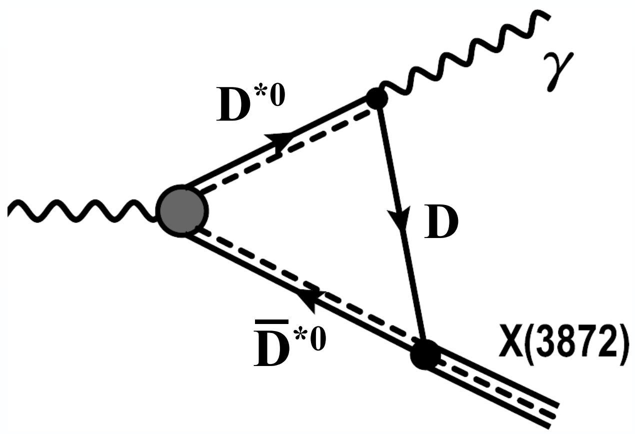
on mass shell



- **Line shape of $X\gamma$ has narrow peak a few MeV above $D^{*0}D^{*0}$ threshold**

e^+e^-: production of X(3872) and a photon

- Triangle singularity



three virtual charm mesons

- ❖ on shell simultaneously with energy-momentum conservation at each vertex

→ logarithmic singularity

- ❖ nonzero decay width for D*0
- ❖ nonzero binding energy for X

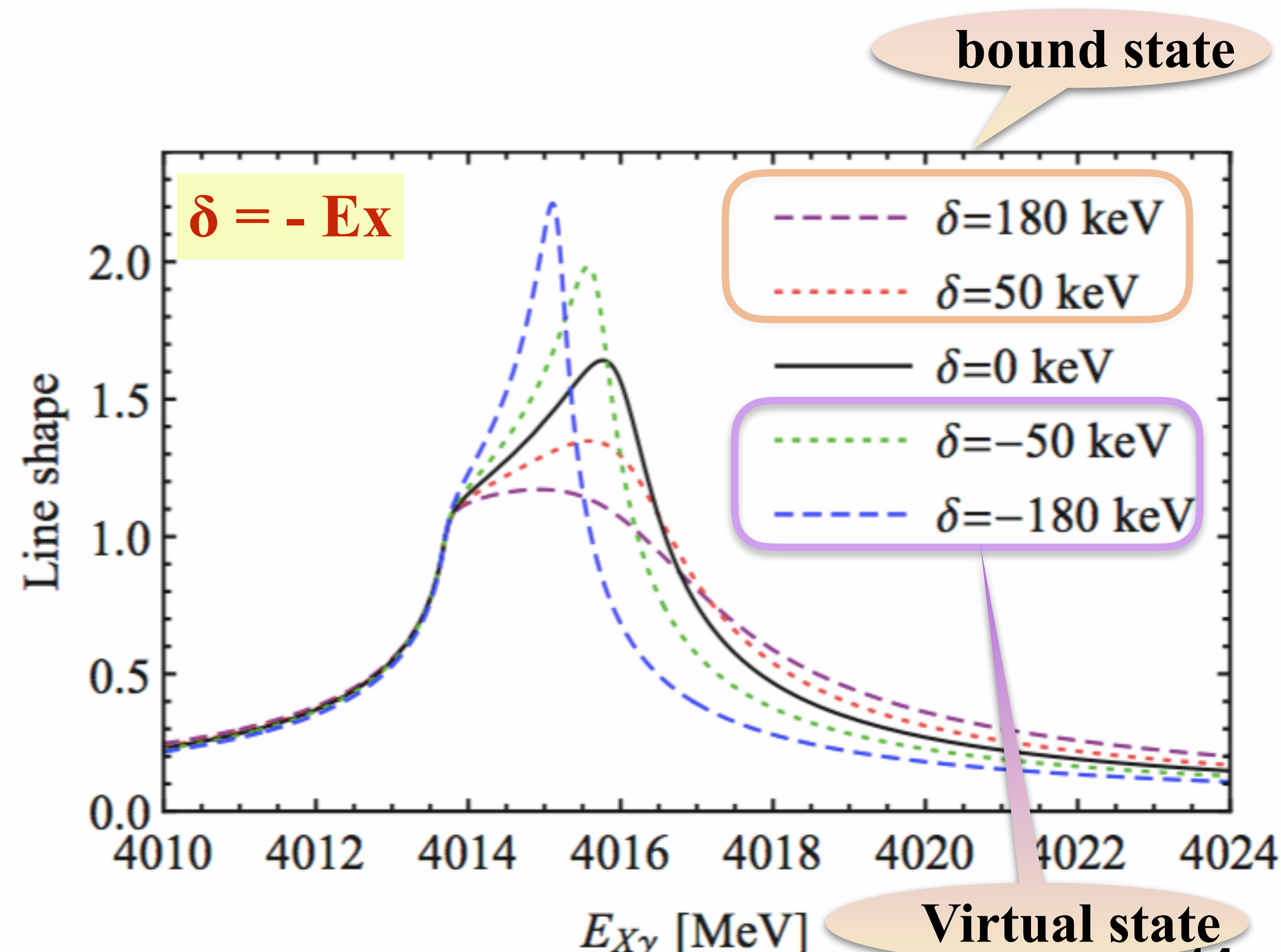
→ narrow peak in reaction rate

- Guo [arXiv: 1902.11221]

$e^+e^- \rightarrow D^{*0}\bar{D}^{*0}$(S-wave) + π → ($X\gamma$) + π

Line shape in Xγ:

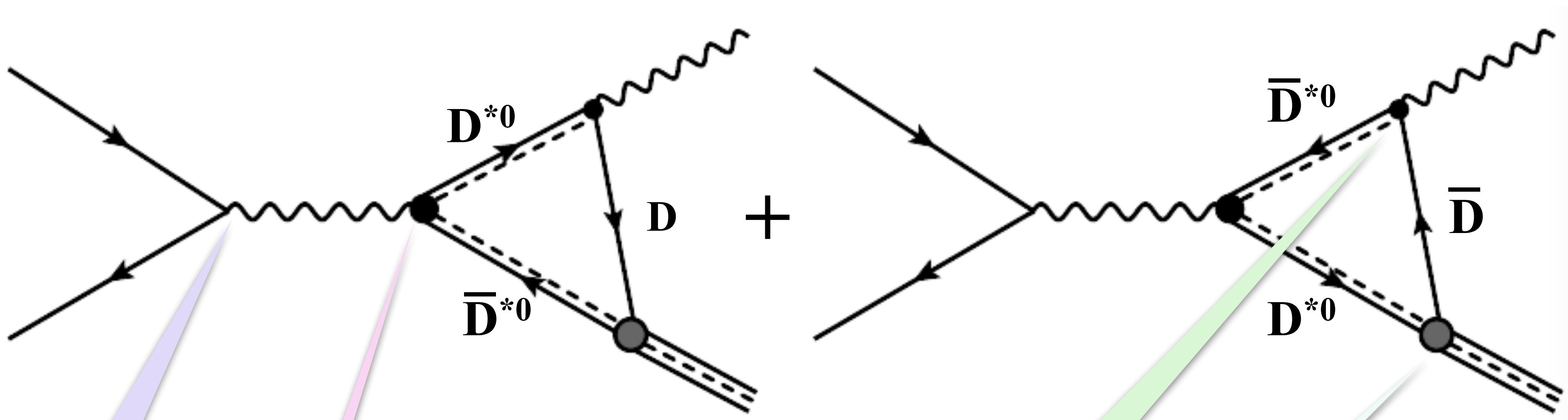
- ❖ peak a few MeV above $D^{*0}\bar{D}^{*0}$ threshold
- ❖ sensitive to E_X (can be used to measure E_X)



e^+e^-: production of X(3872) and a photon

Braaten, He, Ingles, arXiv:1904.12915

- e^+e^- annihilates into virtual photon that creates $D^{*0}\bar{D}^{*0}$(P-wave)
- virtual $D^{*0}\,\bar{D}^{*0}$ rescatters into X(3872) γ (calculate using XEFT)



QED vertex

$e\nu\epsilon^{ijm}k^m$

XEFT: $i\left(\pi\gamma_X/\mu^2\right)^{1/2}\delta^{kl}$

effective P-wave interaction

$$\left[A_0\delta^{ij}\delta^{kl}+\frac{3}{2\sqrt{5}}A_2\left(\delta^{ik}\delta^{jl}+\delta^{il}\delta^{jk}-\frac{2}{3}\delta^{ij}\delta^{kl}\right)\right]k^j$$

Dubynskiy and Voloshin [PRD 74, 094017 (2006)]

e^+e^-: production of X(3872) and a photon

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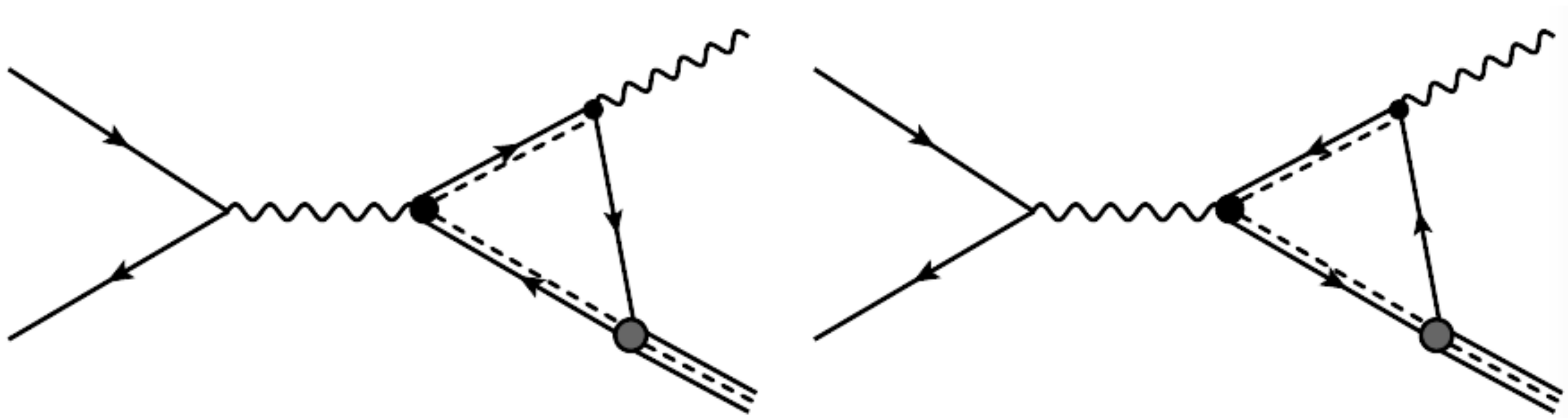
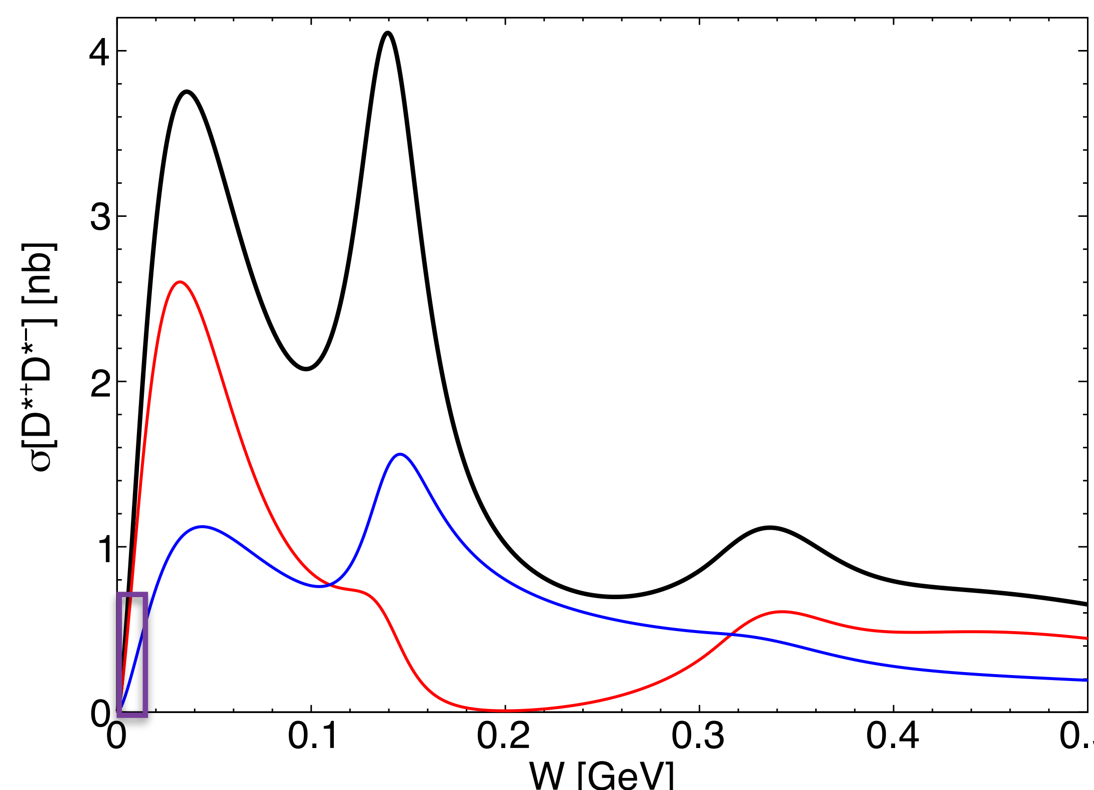


triangle singularity gives narrow peak in cross section

improvements over Dubynskiy and Voloshin

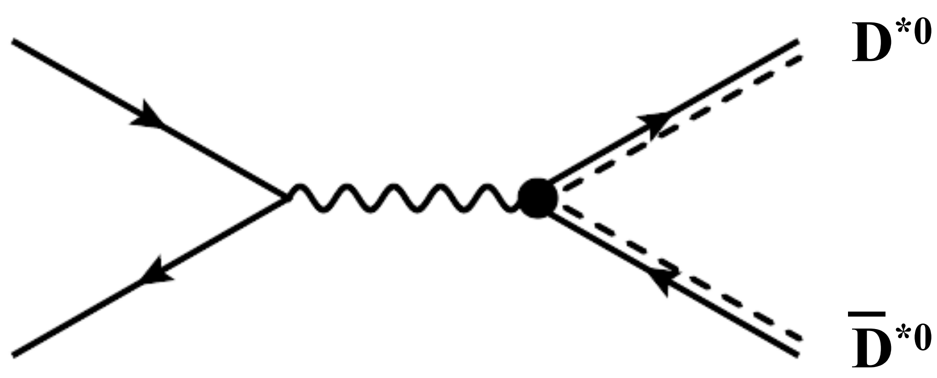
- include Re[M] as well as Im[M]
- include decay width of D^{*0}
- normalize cross section using $\sigma[D^{*+}D^{*-}]$
  Uglov *et al.* (JETP Lett. 105,1 (2017)



e^+e^-: production of X(3872) and a photon

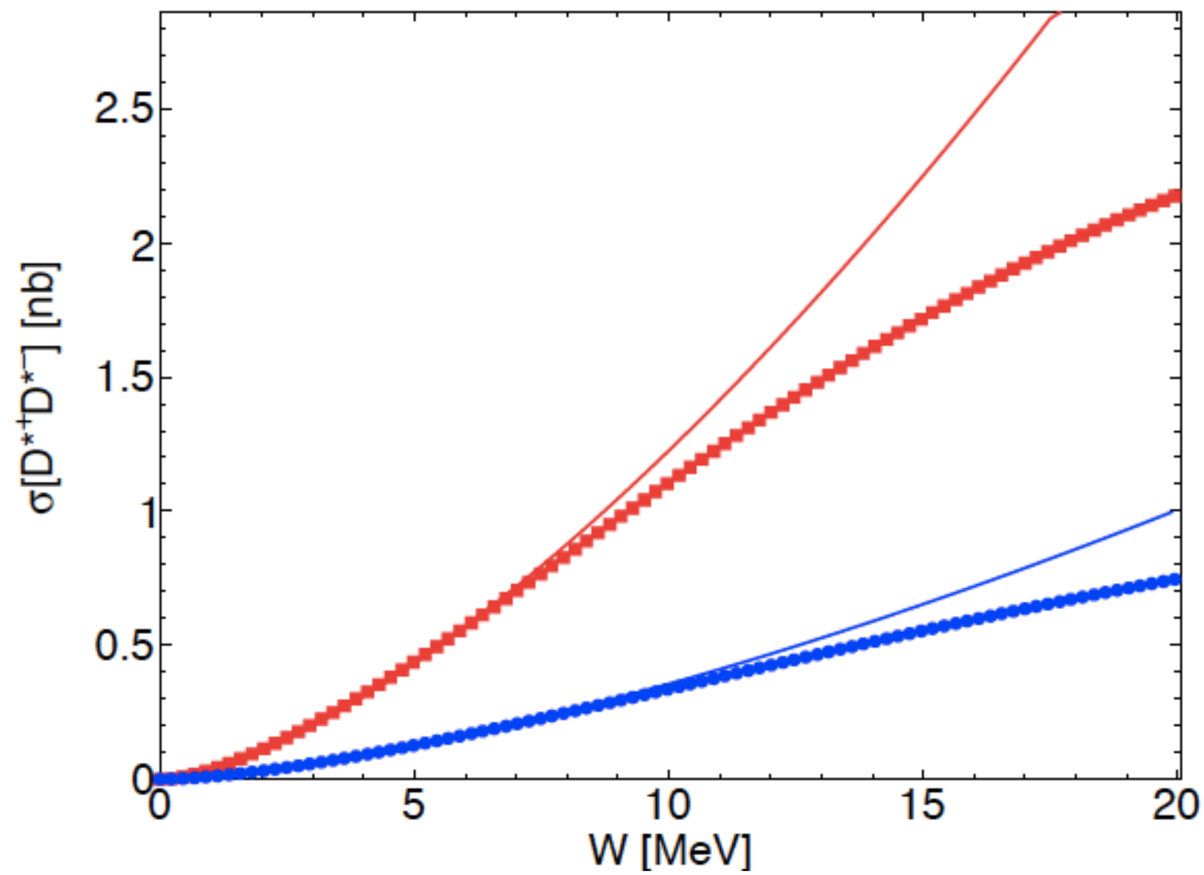
- **normalize cross section using σ[D*+D*-]**

  Uglov *et al.* (JETP Lett. 105,1 (2017))



$$\sigma\left[e^+e^-\bar{D}^{*0}\overline{D}^{*0}\right] = \frac{4\pi\alpha^2 M_{*0}}{s^2}\left[|A_0|^2 + |A_2|^2\right]k^3$$

$$|A_0| = 8\ \mathrm{GeV}^{-1}, \qquad |A_2| = 15\ \mathrm{GeV}^{-1}$$



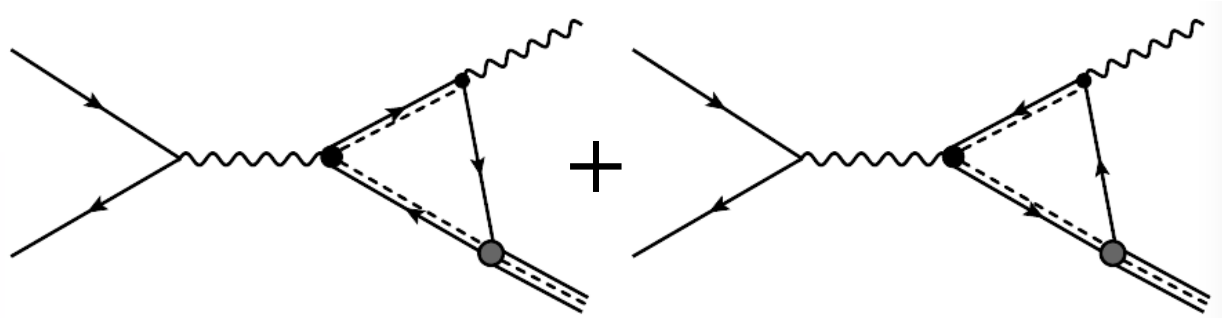
- **cross section of $e^+e^- \to$ X(3872) γ**

$$\sigma[e^+e^- \to X\gamma] = \frac{128\pi^2\alpha^3\nu^2(M_{*0}+M_0)^2}{3s^2[1+q/(M_{*0}+M_0)]}\left(\left|A_0 - \frac{1}{\sqrt{5}}A_2\right|^2 + \frac{9}{20}|A_2|^2\right) q|F(W)|^2$$

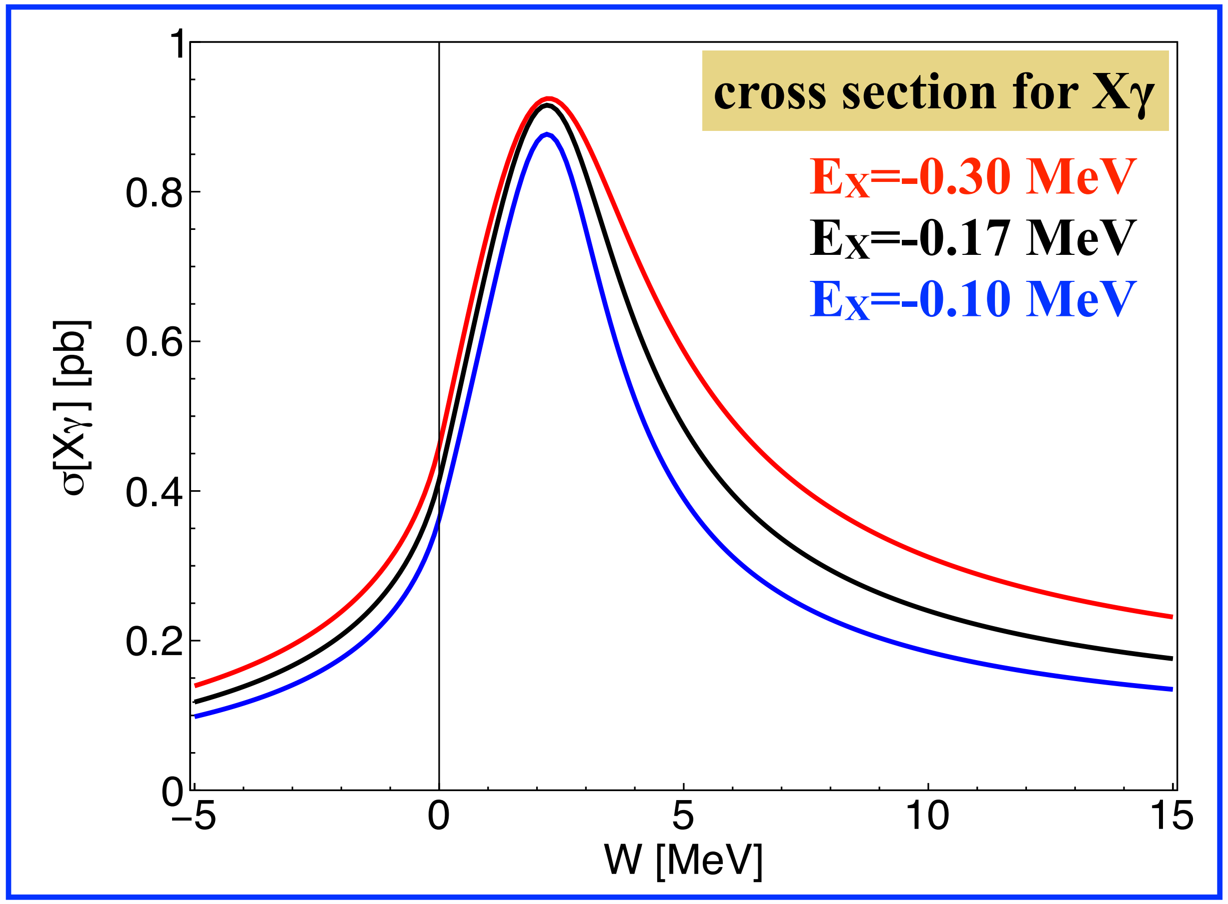
$$= 0.34 \sim 1.31\left[|A_0|^2 + |A_2|^2\right]$$

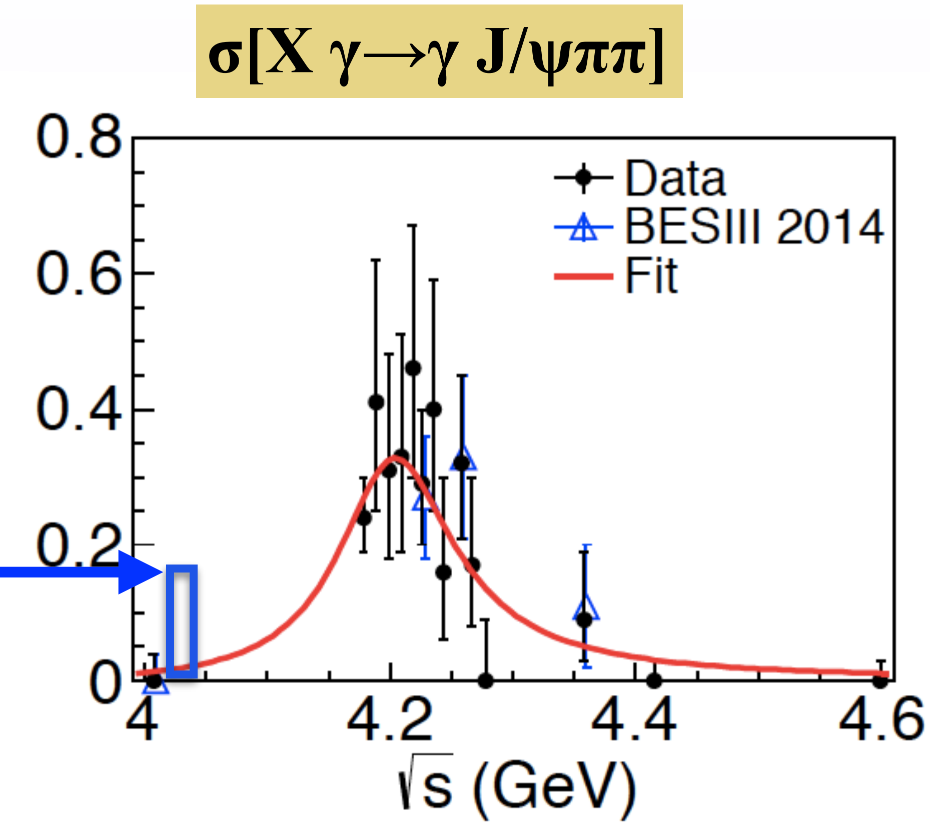
e^+e^-: production of X(3872) and a photon

- $e^+e^- \rightarrow D^{*0}\bar{D}^{*0}$(P-wave) $\rightarrow$ X(3872) γ



- **triangle singularity** gives **narrow peak 2 MeV above $D^{*0}\bar{D}^{*0}$ threshold**
- **position of peak** insensitive to **binding energy** **(4014 MeV)**
- may be observable by **BESIII detector**!

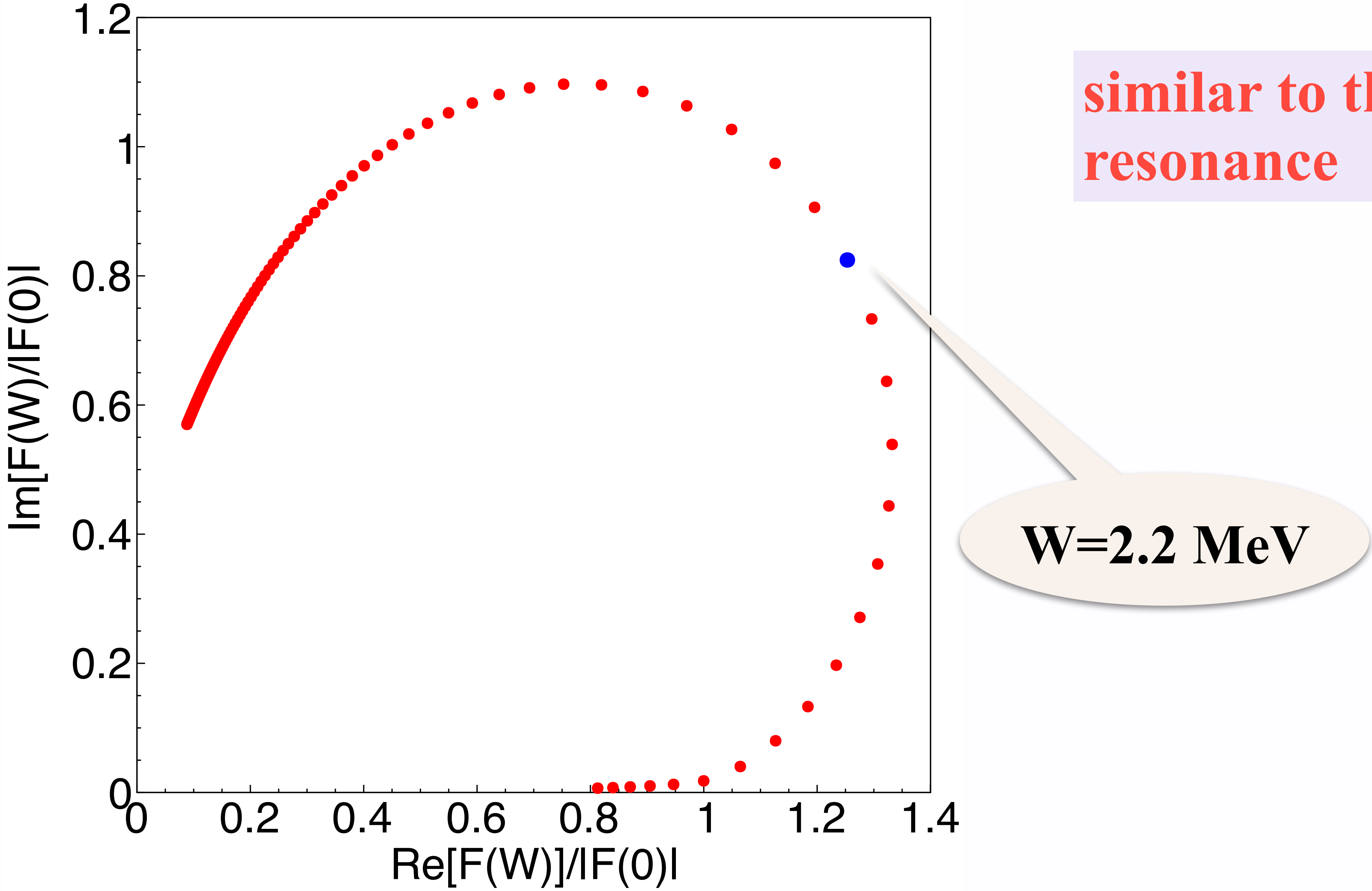




e^+e^-: production of X(3872) and a photon

- $e^+e^- \rightarrow D^{*0}\bar{D}^{*0}$(P-wave) $\rightarrow$ X(3872) γ

Argand diagram

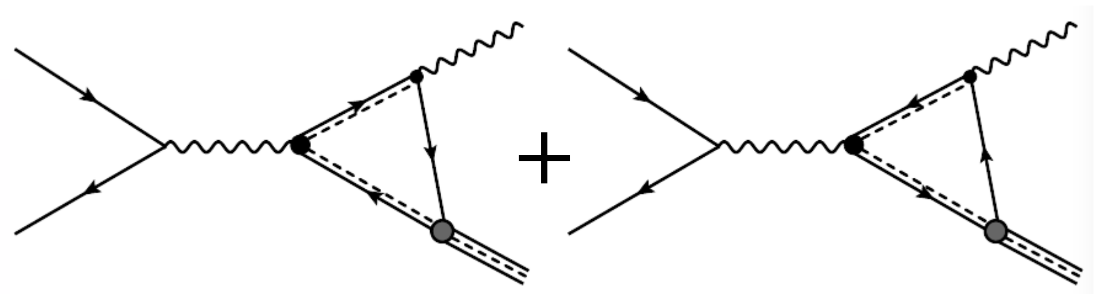


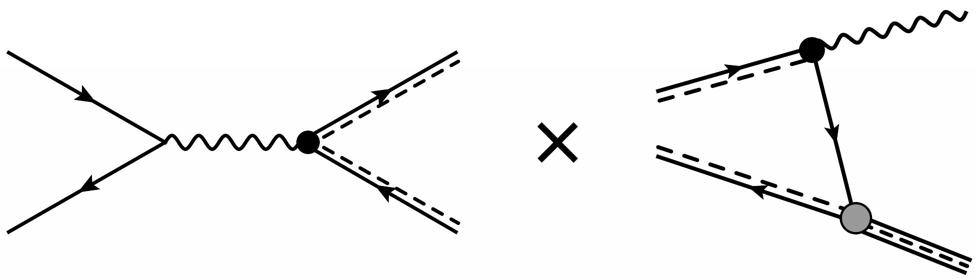
similar to the behavior as a resonance

W [-1,20]

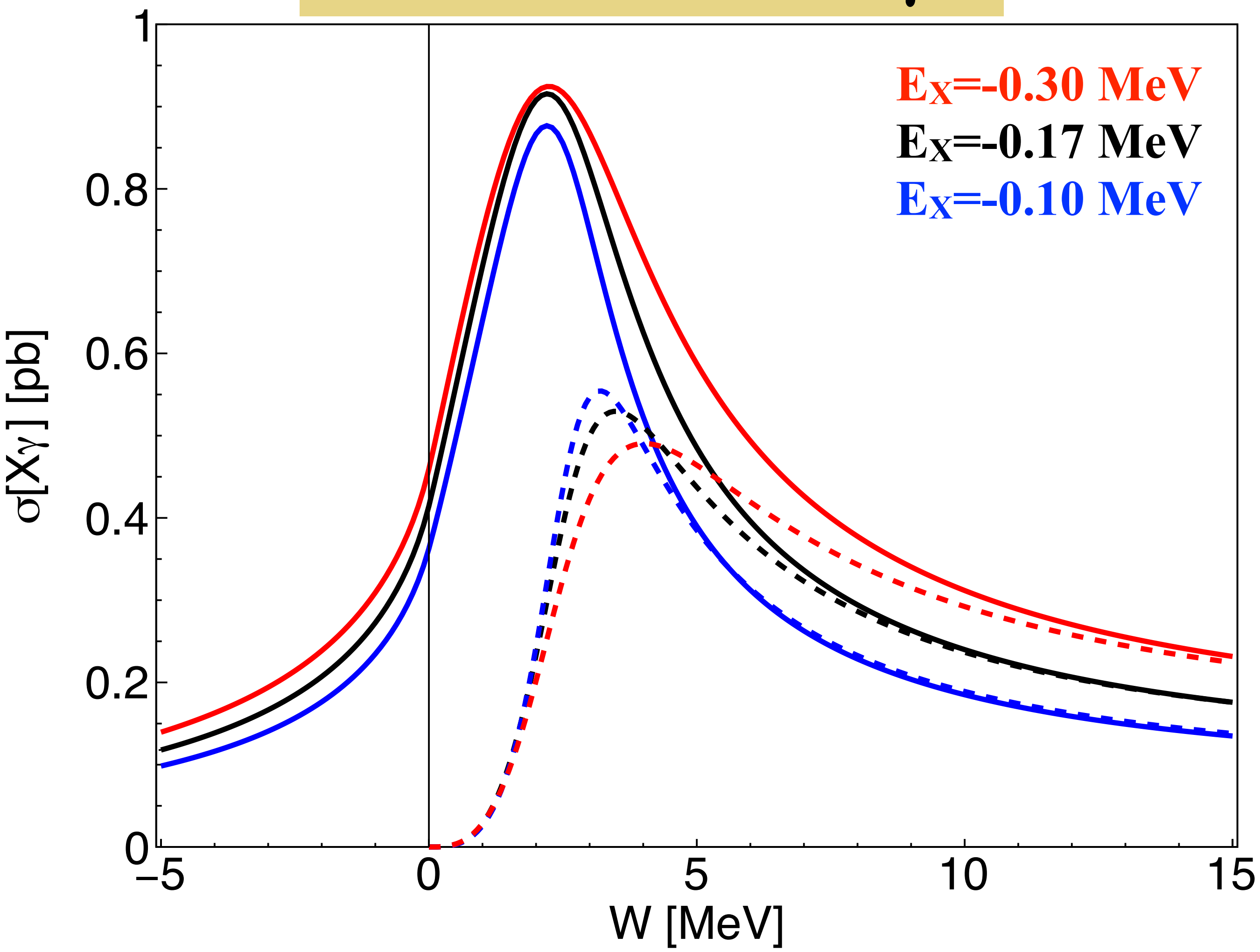
e^+e^-: production of X(3872) and a photon

* $e^+e^- \rightarrow D^{*0}\bar{D}^{*0}$(P-wave) $\rightarrow$ X(3872) γ





cross section for Xγ



absorptive contribution (dashed lines):

- zero below threshold
- peak position depends on binding energy

not a good approximation!

Production of X and a Pion in B meson decay

* **Belle** [PRD 91, 051101(2015)]: $B^0 \to K^+ X \pi^-, B^+ \to K^0 X \pi^+$

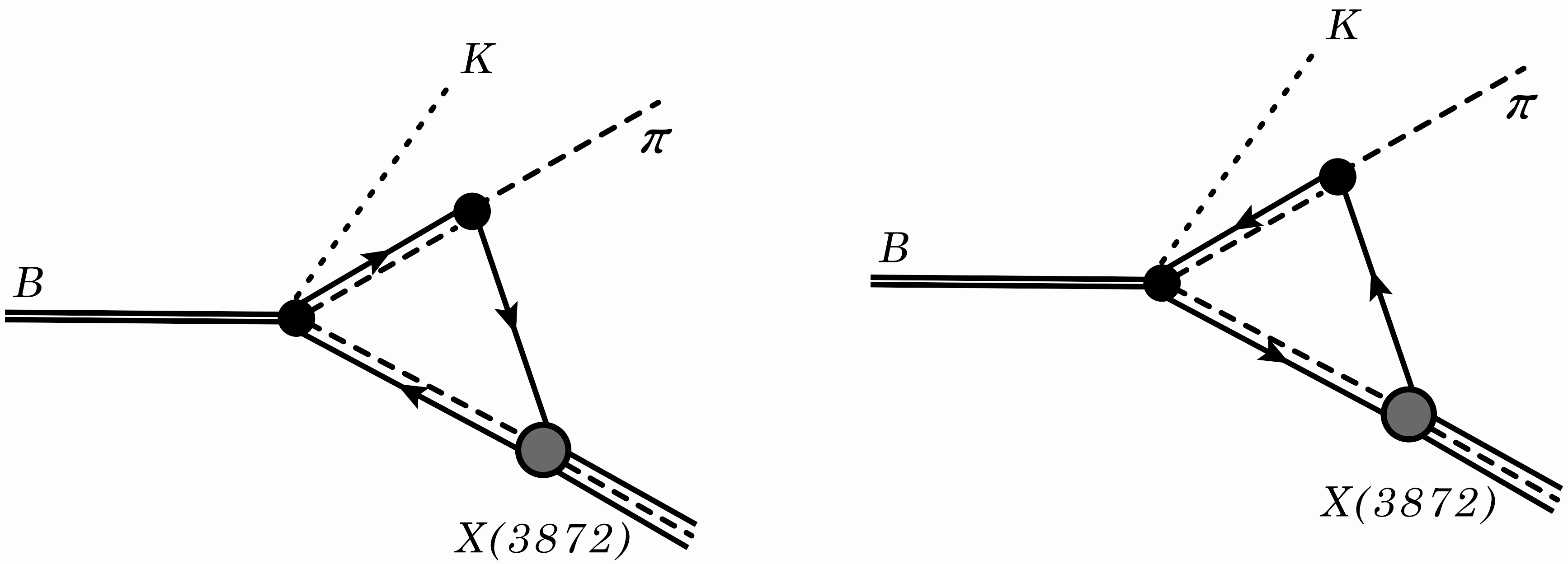
$$\frac{\mathrm{Br}\left(B^0 \to X K^*\right) \mathrm{Br}\left(K^* \to K^+\pi^-\right)}{\mathrm{Br}\left(B^0 \to X K^+\pi^-\right)} = (34 \pm 9)\%$$

34% of $B^0 \to K^+\pi^- X$ from $B^0 \to K^{*0}(892)$ X

Production of Xπ near threshold

(Braaten, He, Ingles, arXiv:1902.03259)

* B meson transition to K creates $D^*\bar{D}^*$(S-wave)
* virtual $D^*\bar{D}^*$ rescatters into Xπ (calculate using XEFT)

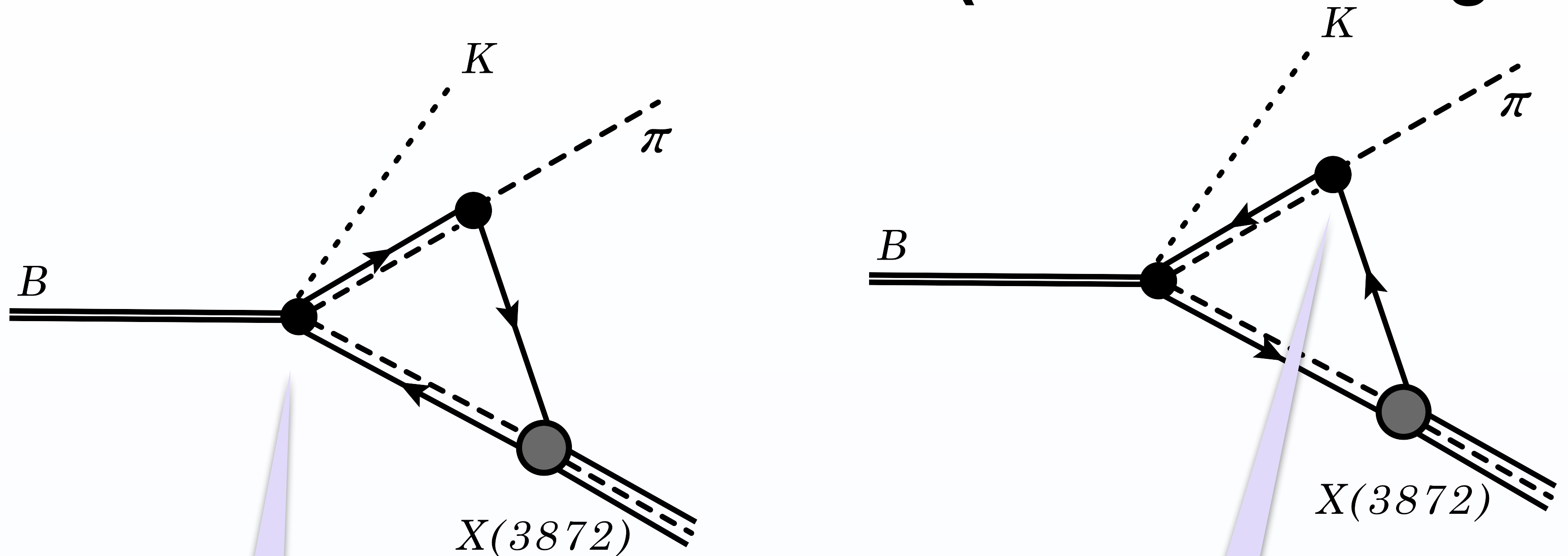


Production of X and a Pion in B meson decay

Production of $X\pi$ near threshold

(Braaten, He, Ingles, arXiv:1902.03259)

- B meson transition to K creates $D^*\bar{D}^*$(S-wave)
- virtual $D^*\bar{D}^*$ rescatters into $X\pi$ (calculate using XEFT)



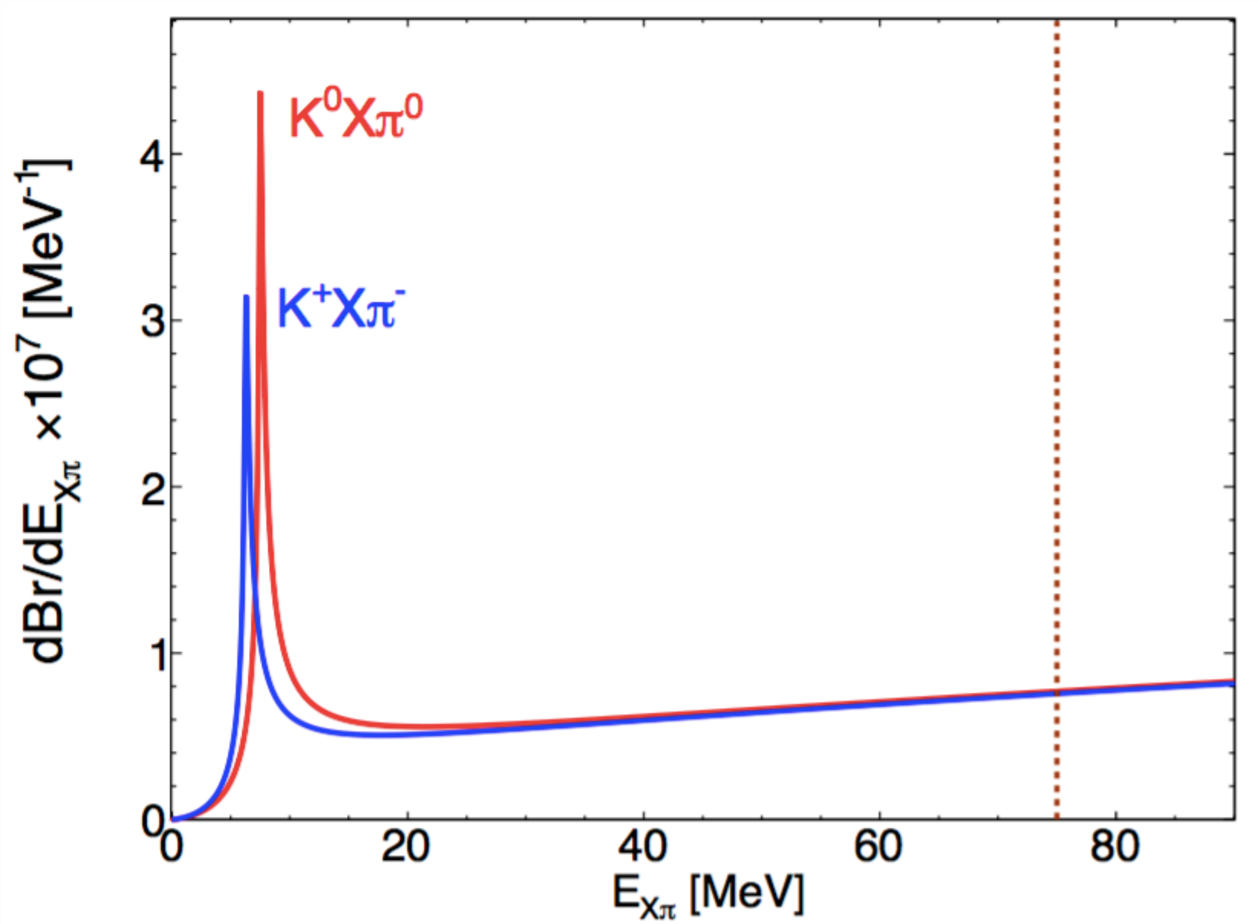
HQEFT and isospin symmetry

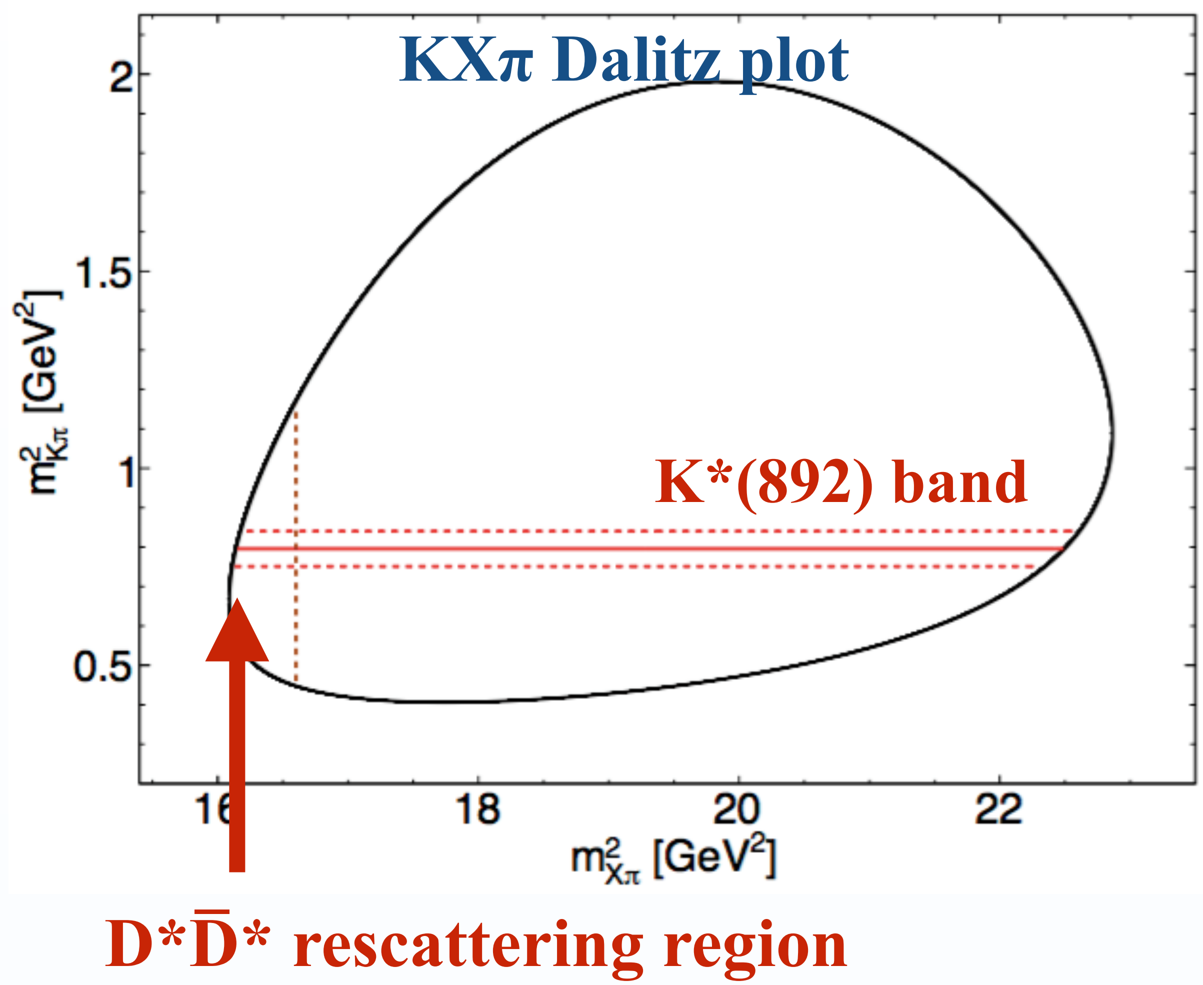
XEFT: ~ q

$$\frac{\mathrm{Br}\left[B^+ \to K^0 X \pi^+\right]}{\mathrm{Br}\left[B^0 \to K^+ X \pi^-\right]} = \frac{\tau[B^+]}{\tau[B^0]} = 1.076 \pm 0.004$$

Production of X and a Pion in B meson decay

- B meson decays into K + D*D̄*, virtual D*D̄* rescatters into Xπ
- triangle singularity produces narrow peak near threshold
- D*D̄* rescattering produces events near edge of Dalitz plot





Production of X at hadron colliders

Prompt cross sections at hadron colliders:

$$\text{Tevatron}: \quad \sigma[X(3872)]\,\text{Br}[X \to J/\psi\,\pi^+\pi^-] \approx (3.1 \pm 0.7)\ \text{nb}$$

$p_T > 5$ GeV, $|y| < 0.6$

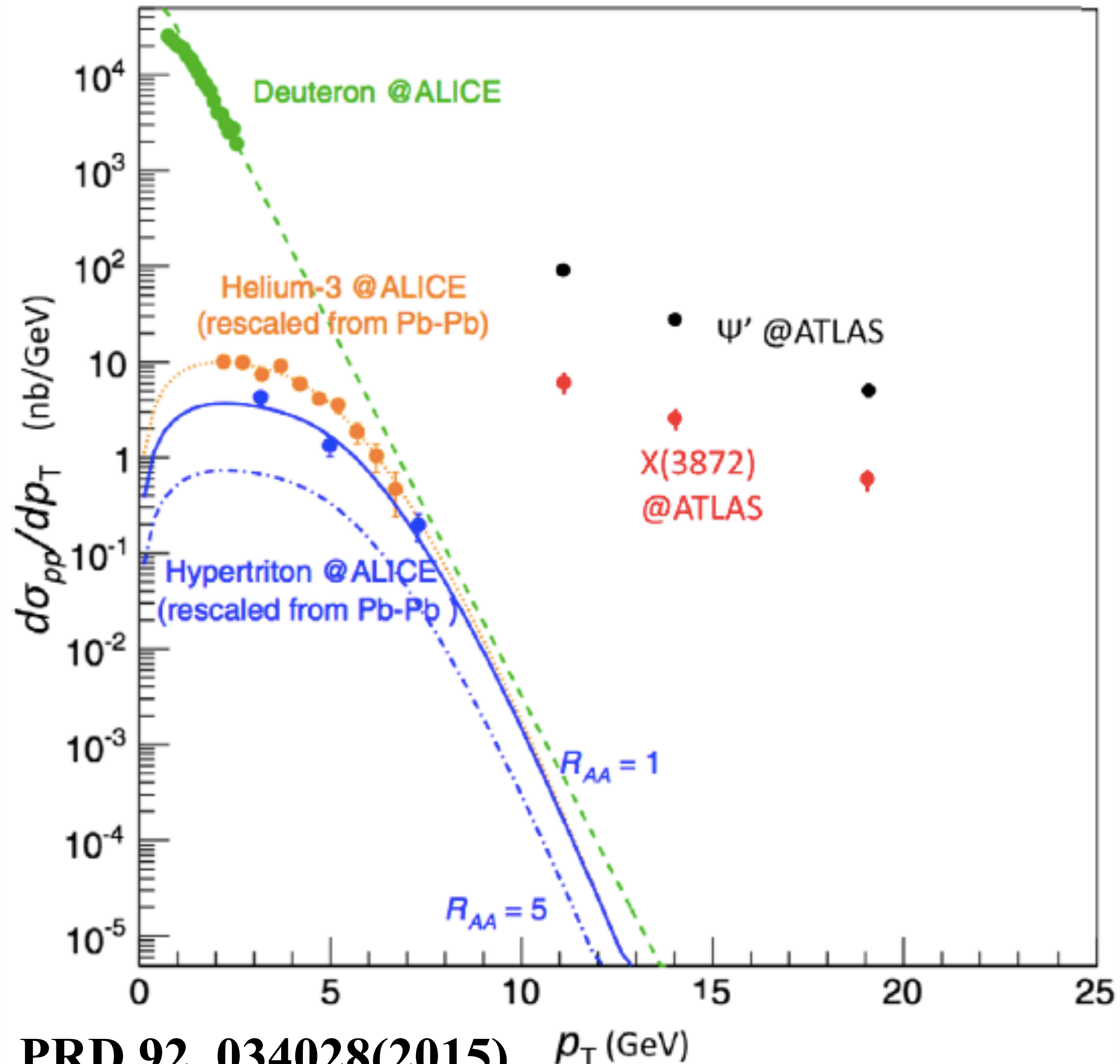
CDF [Int. J. Mod. Phys. A21,959 (2006)]

$$\text{LHC}: \quad \sigma[X(3872)]\,\text{Br}[X \to J/\psi\,\pi^+\pi^-] = (1.06 \pm 0.11 \pm 0.15)\ \text{nb}$$

CMS [JHEP 1304, 154 (2013)]

10 GeV < p_T <30 GeV, $|y| < 1.2$

too large by orders of magnitude for weakly bound charm-meson molecule ??



Esposito et al. PRD 92, 034028(2015)

Production of X at hadron colliders

too large by orders of magnitude for weakly bound charm-meson molecule ??

- Bignamini *et al.* [PRL 103, 162001 (2009)]

  upper bound on σ[X] in terms of σ[$D^{*0}\bar{D}^0$] (Schwarz inequality)

$$\sigma[X(3872)] < \sigma\left[D^{*0}\bar{D}^0\,(k < k_{\rm max})\right]$$

$k_{max} \sim \gamma_X$, $\gamma_X = \sqrt{2\mu E_X}$

if $|E_X|$ = 0.25 MeV, upper bound is 3 orders of magnitude smaller than observed cross sections

- Artoisenet and Braaten [PRD 81, 114018 (2010)]

$k_{max} \sim m_\pi$

upper bound is marginally compatible with observed cross sections

Production of X at hadron colliders

- Braaten, He, Ingles [arXiv: 1811.08876, 1903. 04355]

Equality for σ[X] in terms of σ[$D^{*0}\bar{D}^0$] (optical theorem):

$$\sigma[X(3872)] = \sigma[D^{*0}\bar{D}, k < k_{\max}]$$

- **resonant $D^{*0}\bar{D}^0$ cross section (weakly bound molecule)**

$$d\sigma[D^{*0}\bar{D}^0] = d\sigma[X(3872)] \frac{\pi/\gamma_X}{\gamma_X^2 + k^2} \frac{d^3k}{(2\pi)^3}$$

$k_{max} = 7.73\ \gamma_X$ $\quad$ $k_{max} \approx 140$ MeV for $|E_X| = 0.17$ MeV

- **naive $D^{*0}D^0$ cross section (no resonance):**

$$d\sigma\left[D^{*0}\bar{D}^0\right]_{\text{naive}} \approx d\sigma[X(3872)] \frac{2\pi/\gamma_X}{\Lambda^2} \frac{d^3k}{(2\pi)^3}$$

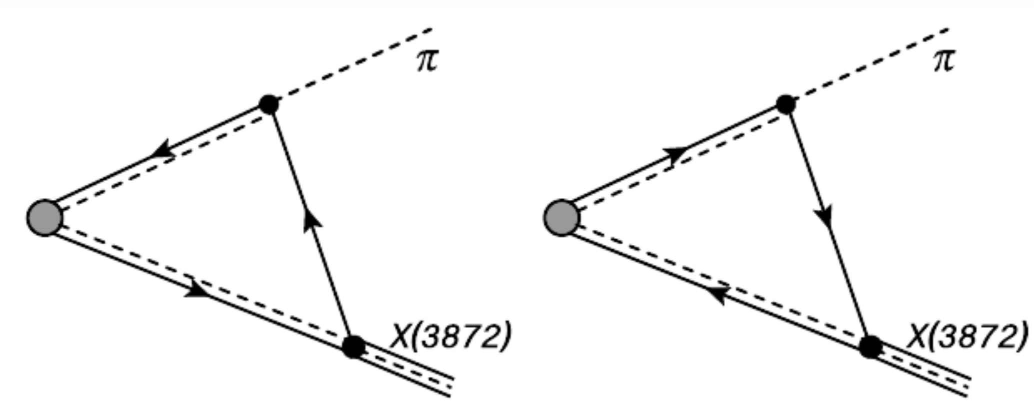
$k_{max} = (\ 3\pi m_\pi^2\ \gamma_X)^{1/3}$ $\quad$ $k_{max} \approx 150$ MeV for $|E_X| = 0.17$ MeV

compatible with observed cross sections at Tevatron and LHC

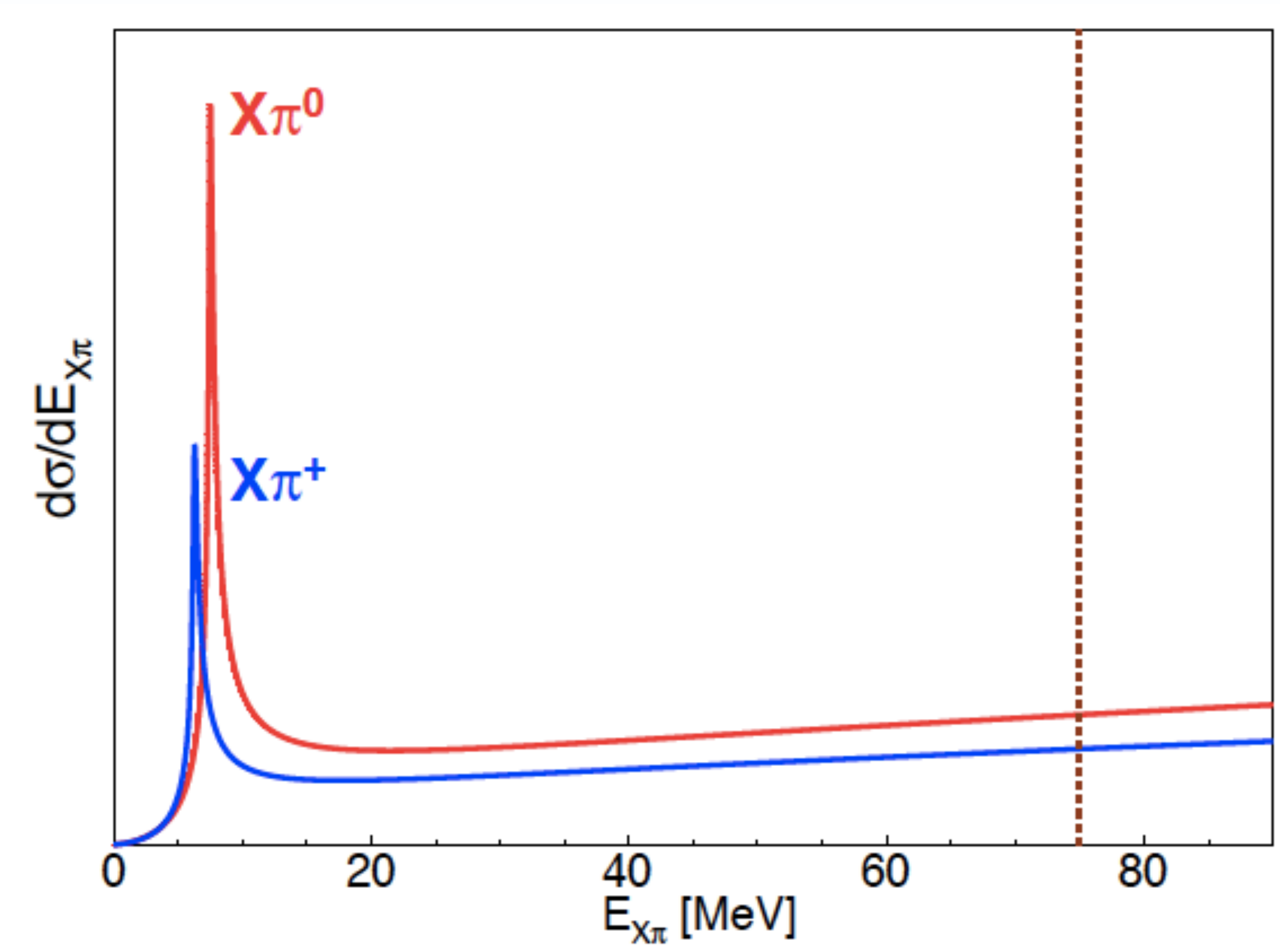
Production of X at hadron colliders

- **Braaten, He, Ingles** **[arXiv: 1811.08876, 1903. 04355]**

**prompt cross section for X+π from rescattering of D*$\bar{D}$*
may be comparable to cross section for X without π**



$$\frac{\sigma[X + (\text{soft}\ \pi^0)]}{\sigma[X + (\text{soft}\ \pi^+)]} \approx \frac{4}{3}$$



$$\frac{\sigma[X + (\text{soft}\ \pi)]}{\sigma[X(\text{no soft}\ \pi)]} \approx 3.2 \left(\frac{m_\pi}{\Lambda}\right)^2 \left(\frac{E_{\max}}{m_\pi}\right)^{3/2}$$

Summary

Production of X+γ or X+π

- e^+e^- annihilation
  - ◇ narrow peak from triangle singularity in cross section for Xγ
    peak is 2 MeV above $D^{*0}\bar{D}^{*0}$ threshold in region not yet measured by BESIII

- B meson decay
  - ◇ B → KXπ Dalitz plot: 34% of events in K*(892) resonance band (Belle)
  - ◇ nonresonant events may come from $D^*\bar{D}^*$ rescattering
    narrow peak from triangle singularity near Xπ threshold

- Hadron colliders
  - ◇ prompt cross section for X+π from rescattering of $D^*\bar{D}^*$
    may be comparable to cross section for X from $D^*\bar{D}$
  - ◇ equality: $\sigma[X(\text{no } \pi)] \approx \sigma[D^{*0}D^0, k<k_{max}]$ for $k_{max} \approx m_\pi$
  - ◇ prompt production of X at Tevatron, LHC is compatible
    with weakly bound charm-meson molecule

**Production of X(3872) accompanied by π or γ
may help resolve the issue of the nature of the X(3872)**

Thank you!

Back up

Table 1. Products of branching ratios for B decay and subsequent X decay in PDG[2018].

$\mathcal{B}_{XK^+}\mathcal{B}_{X\to J\psi\pi^+\pi^-}$	$\mathcal{B}_{XK^+}\mathcal{B}_{X\to J\psi\gamma}$	$\mathcal{B}_{XK^+}\mathcal{B}_{X\to\psi'\gamma}$	$\mathcal{B}_{XK^+}\mathcal{B}_{X\to D^0\bar{D}^0\pi^0}$
$(8.6\pm 0.8)\times 10^{-6}$	$(2.1\pm 0.4)\times 10^{-6}$	$(4\pm 4)\times 10^{-6}$	$(1.0\pm 0.4)\times 10^{-4}$
$\mathcal{B}_{X\to J/\psi\omega}/\mathcal{B}_{X\to J/\psi\pi^+\pi^-} = 0.8\pm 0.3$		$\Gamma_{X\to\psi'\gamma}/\Gamma_{X\to J/\psi\gamma} = 2.6\pm 0.6$	
$\mathcal{B}_{X\to J/\psi\gamma}/\mathcal{B}_{X\to J/\psi\pi^+\pi^-} = 0.244\pm 0.052$			
$\mathcal{B}_{X\to\psi'\gamma}/\mathcal{B}_{X\to J/\psi\pi^+\pi^-} = 0.465\pm 0.467$ [a]		or $= 0.635\pm 0.199$ [b]	
$\mathcal{B}_{X\to D^0\bar{D}^0\pi^0}/\mathcal{B}_{X\to J/\psi\pi^+\pi^-} = 11.628\pm 4.775$			
$\mathcal{B}_{XK^+}\mathcal{B}_{X\to\bar{D}^{*0}D^0} = (8.5\pm 2.6)\times 10^{-5}$			
$\mathcal{B}_{X\to\bar{D}^{*0}D^0}/\mathcal{B}_{X\to J/\psi\pi^+\pi^-} = 9.88\pm 3.16$			

Production of X and a Pion in B meson decay

- **Belle observation:** [PRD 91, 051101(2015)]

$$\frac{\mathrm{Br}\left[B^+ \to K^0 X \pi^+\right]}{\mathrm{Br}\left[B^0 \to K^+ X \pi^-\right]} = 1.34 \pm 0.46$$

$$\frac{\mathrm{Br}\left(B^0 \to X K^*\right) \mathrm{Br}\left(K^* \to K^+ \pi^-\right)}{\mathrm{Br}\left(B^0 \to X K^+ \pi^-\right)} = (34 \pm 9)\%$$

the fraction through K* in $B^0 \to XK^+\pi^-$

- **Predicted ratios:**

Heavy quark symmetry
isospin symmetry →

$$\frac{\mathrm{Br}\left[B^+ \to K^0 X \pi^+\right]}{\mathrm{Br}\left[B^0 \to K^+ X \pi^-\right]} = \frac{\tau[B^+]}{\tau[B^0]} = 1.076 \pm 0.004$$

$$\frac{\mathrm{Br}\left(B^+ \to X K^*\right) \mathrm{Br}\left(K^* \to K^0 \pi^+\right)}{\mathrm{Br}\left(B^+ \to X K^0 \pi^+\right)} = (47 \pm 20)\%$$

predicted fraction through K* in $B^+ \to XK^0\pi^+$

$$\frac{\mathrm{Br}\left[B^0 \to (K^+ X \pi^-)_{\mathrm{no}K^*}\right]}{\mathrm{Br}\left[B^0 \to K^0 X\right]} \sim 1.2$$

production of X is comparable to that from $B \to K X$