Production of X(3872) accompanied by a photon (γ) or a pion (π)

Liping He

In collaboration with Eric Braaten and Kevin Ingles

Department of Physics, The Ohio State University

8th Workshop of the APS Topical Group on Hadron Physics
April 10-12, 2019

Outline

- Introduction to the X(3872) state [X for later use]
- Universal properties of near-threshold S-wave resonance
- e^+e^- annihilation: production of X accompanied by a photon (γ)
  (in preparation)
- B meson decay: production of X accompanied by a pion (π)
  (Braaten, He, Ingles, arXiv:1902.03259)
- Hadron colliders: production of X, and X accompanied by a pion (π) (Braaten, He, Ingles, arXiv:1811.08876, arXiv:1903.04355)
- Summary

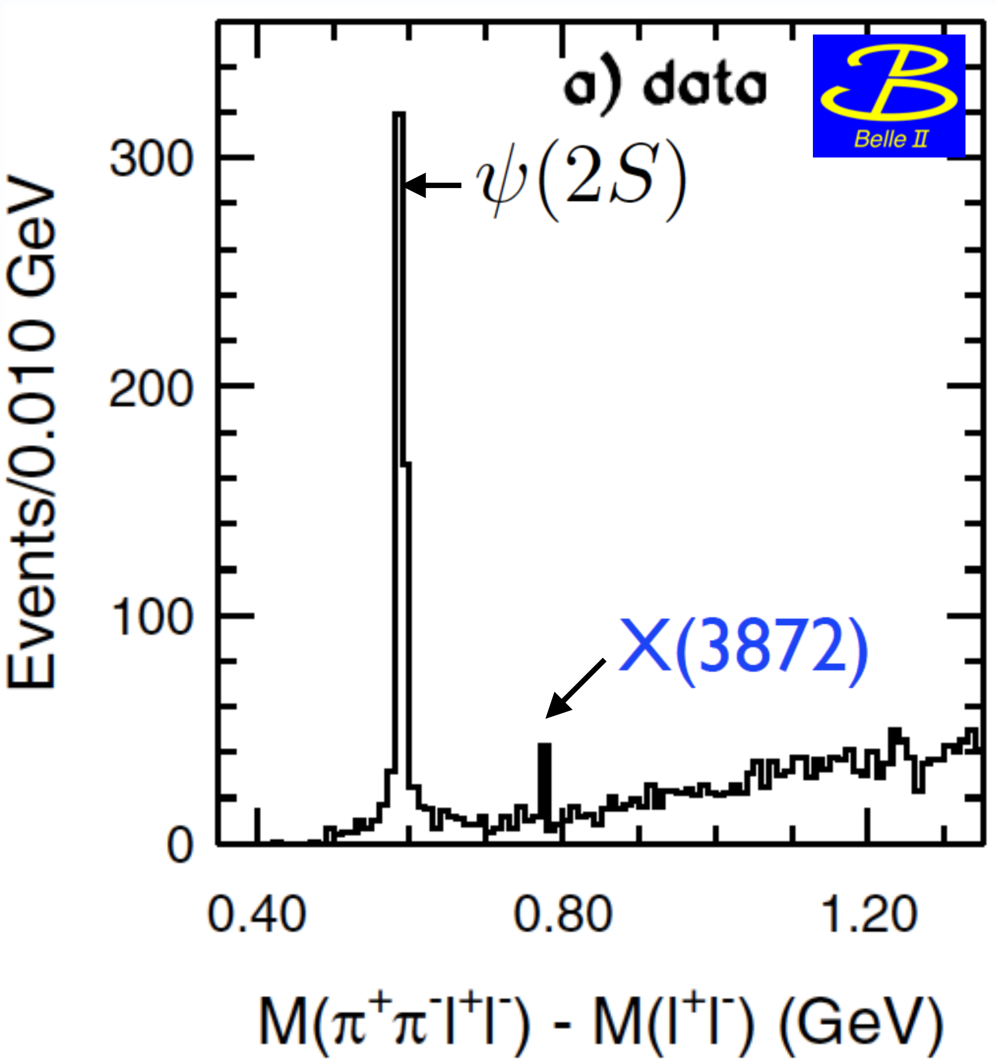
Introduction to the X(3872)

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

    PRL 91,262001(2003)

    $B^+ \to K^+ + X$

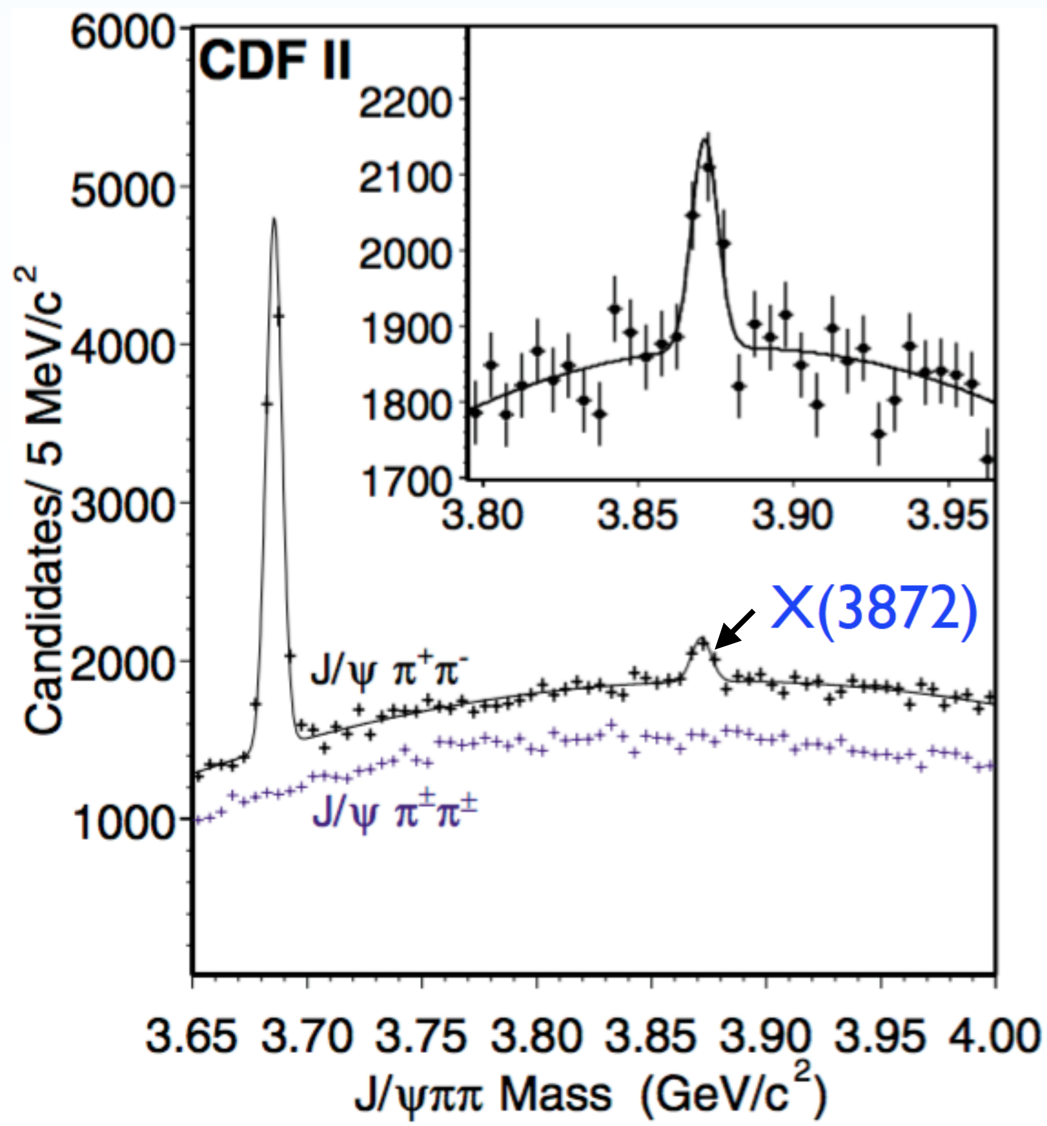
    $X \to J/\psi\pi^+\pi^-$



- **Confirmation**
  - CDF Collaboration

    PRL 91,262001(2004)

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



Introduction to the X(3872)

- **Observed decay modes:**

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

- **Mass: very close to $D^{*0}D^0$ 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)]

- **J^{PC} Quantum numbers:**

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

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 $D^{*0}D^0$ threshold

    → resonant coupling

* Conclusion:

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

  [short-distance wave function may have $\chi_{c1}(2P)$ component]

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: $$f(k) = \frac{1}{-\gamma - ik}$$

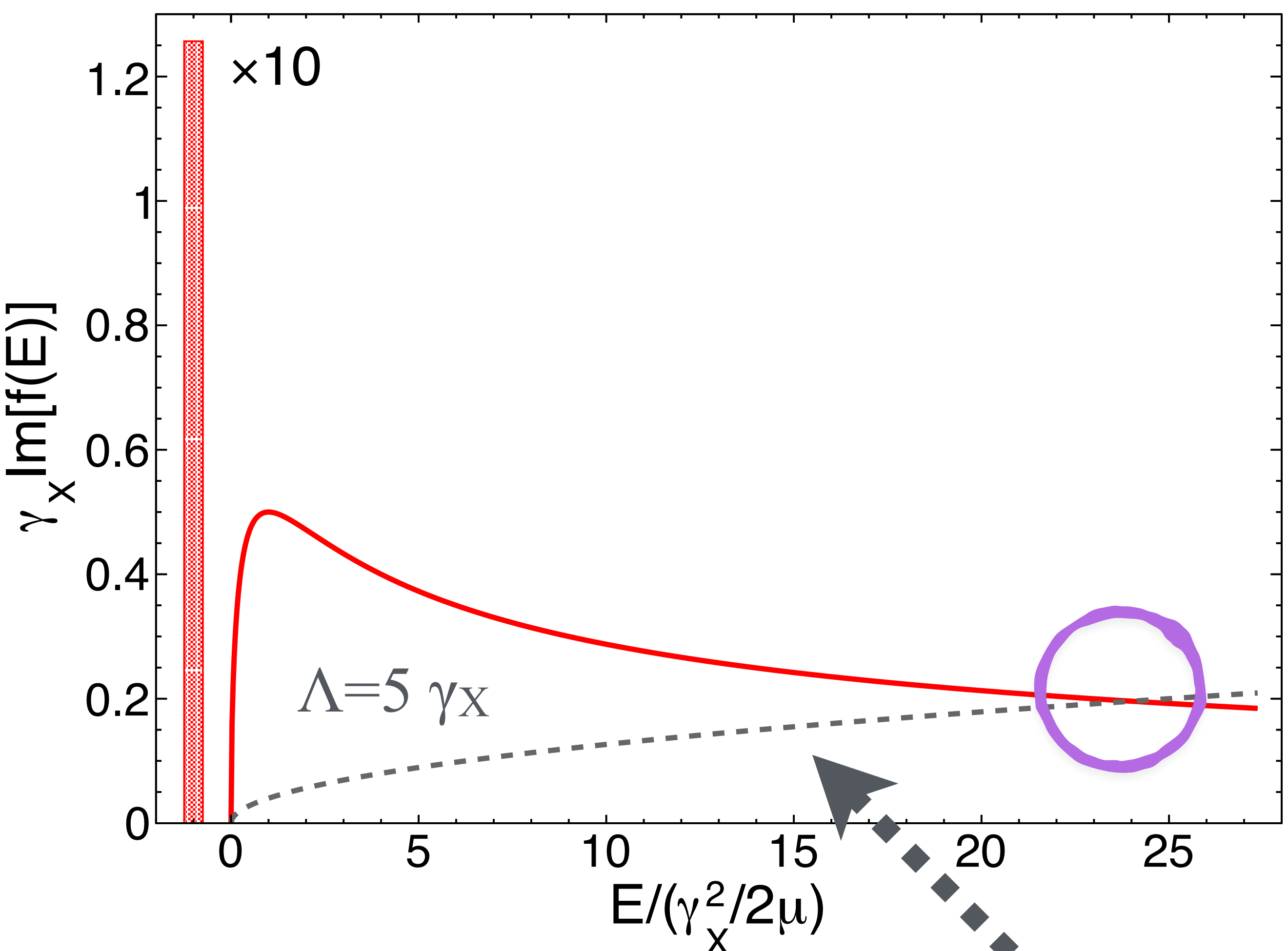
- X(3872) close to $D^{*0}D^0$ threshold:

→ * universal features depend only on inverse scattering length γ_X for $D^{*0}D^0$

Universal properties near threshold

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

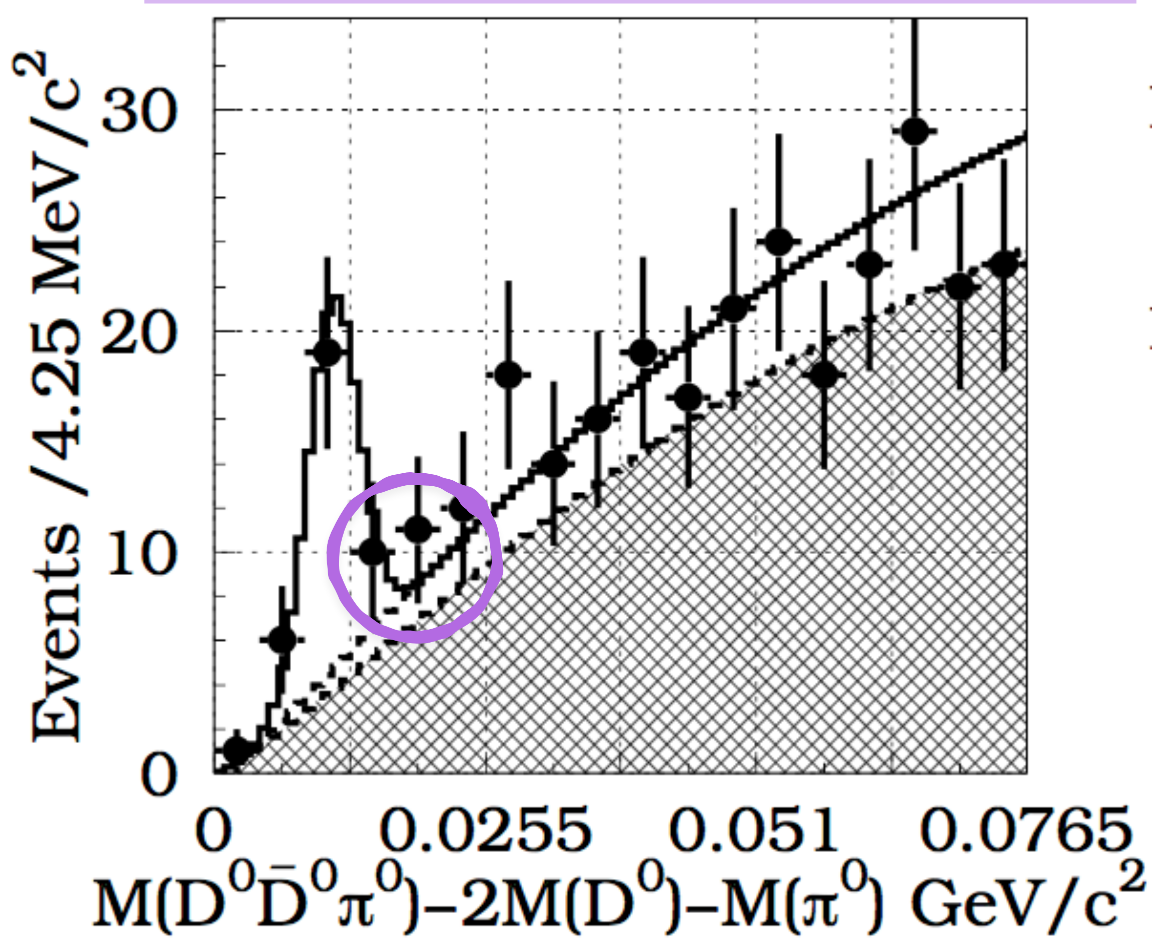
$$\mathrm{Im}[f_X(E+i\epsilon)] = \frac{\pi\gamma_X}{\mu}\delta(E+\gamma_X^2/2\mu) + \frac{\sqrt{2\mu E}}{\gamma_X^2+2\mu E}\theta(E)$$



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

Belle: $B\to KX$, $X\to D^0D^0\pi^0$

[PRL 97, 162002 (2006)]

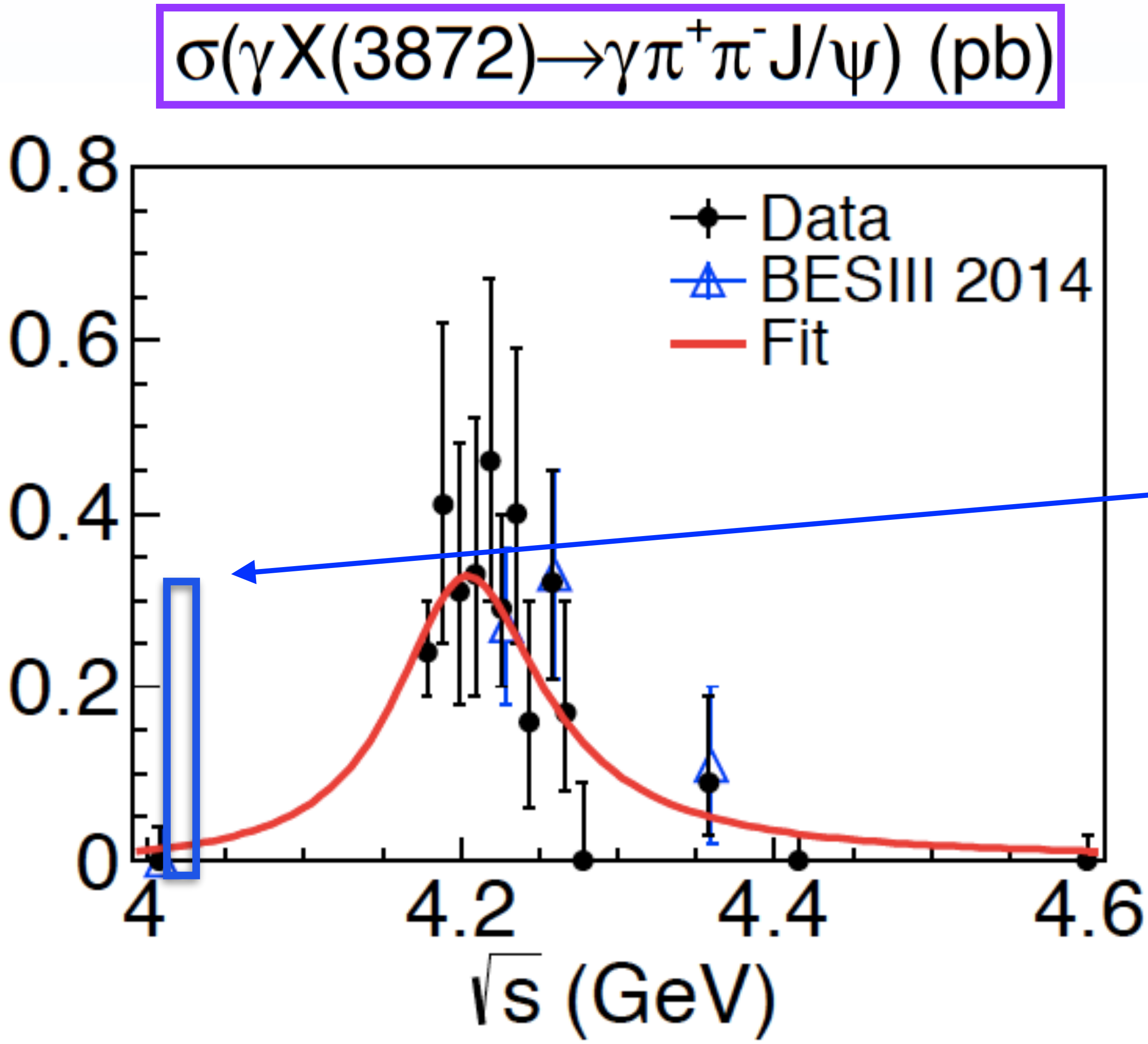


e^+e^-: production of X(3872) and a photon

* **Experimental observation**

  BESIII: $e^+e^- \to X\gamma$

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



* **Dubynskiy and Voloshin**

  [PRD 74, 094017 (2006)]

  absorptive contribution
  (imaginary part of amplitude):

  $e^+e^- \to D^{*0}\bar{D}^{*0}$(P-wave)$\to X\gamma$

  on mass shells

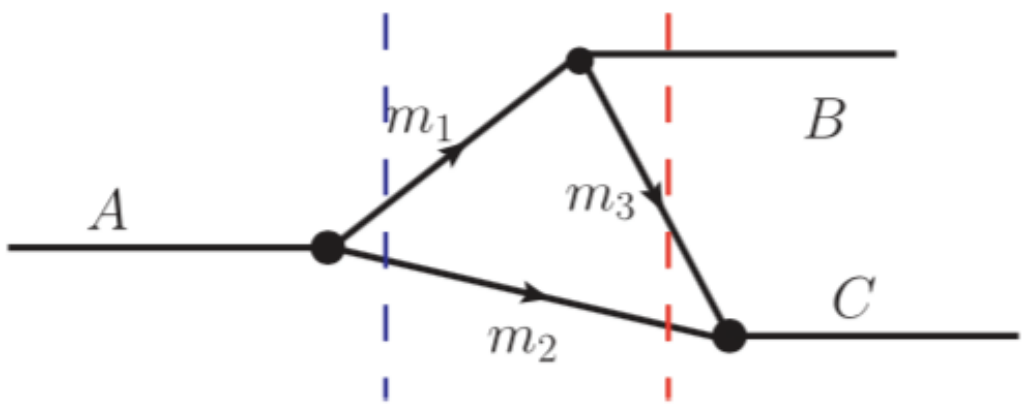
❖ **Line shape of $X\gamma$:**

◇ **peak at a few MeV above $D^{*0}\bar{D}^{*0}$ threshold**

◇ **depends on binding energy**

Production of X(3872) and a photon

* **Triangle singularity**



❖ All three virtual particles could be on shell with 4-momentum conservation at each vertex.

❖ Decay width =0, binding energy =0 ➡ kinematic singularity

❖ Nonzero decay width and binding energy ➡ narrow peak in reaction rate

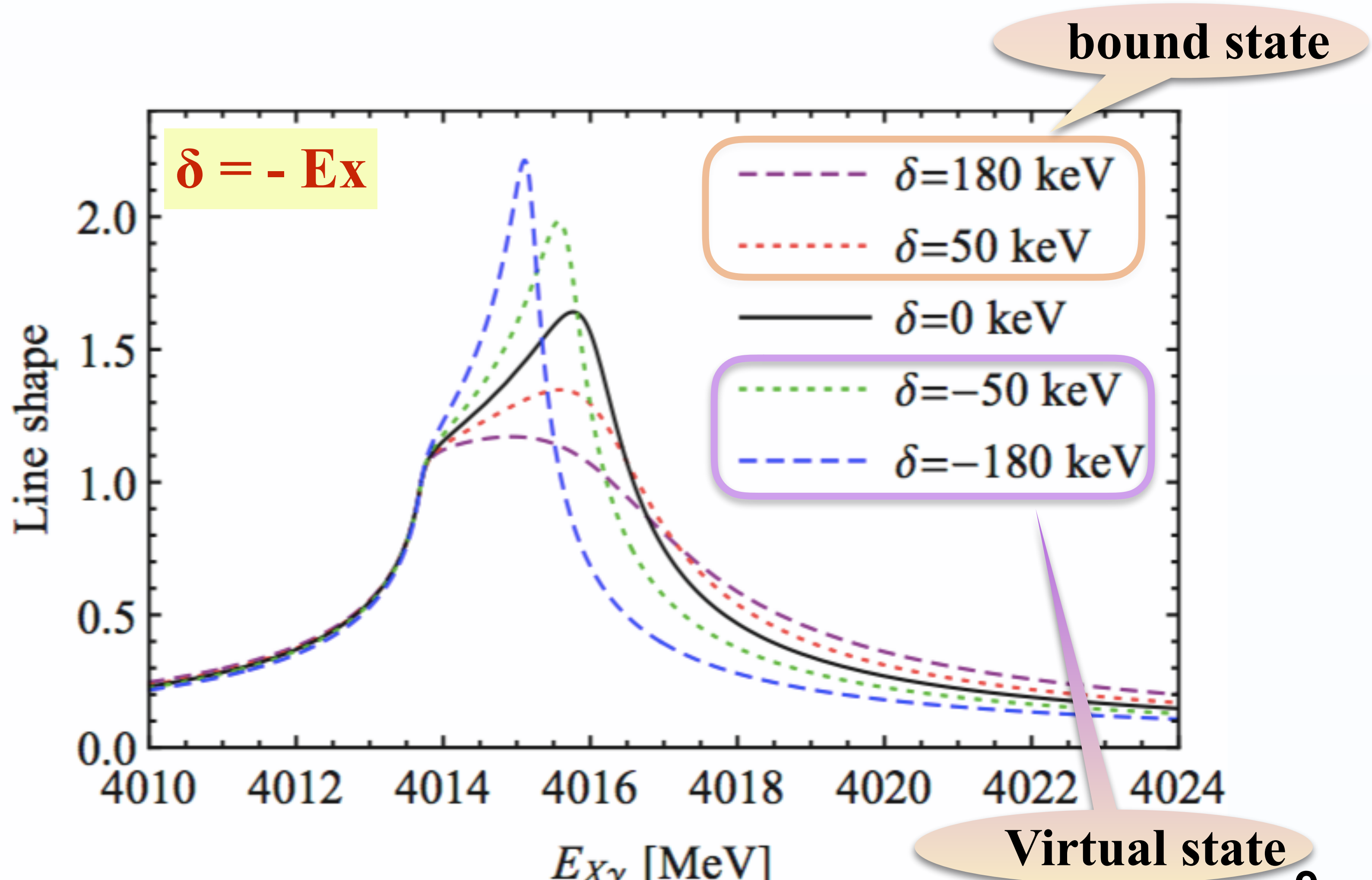
* **Guo** [arXiv: 1903.11221]

$e^+e^- \to D^{*0}\bar{D}^{*0}$(S-wave) + $\pi \to (X\gamma) + \pi$

Line shape in Xγ:

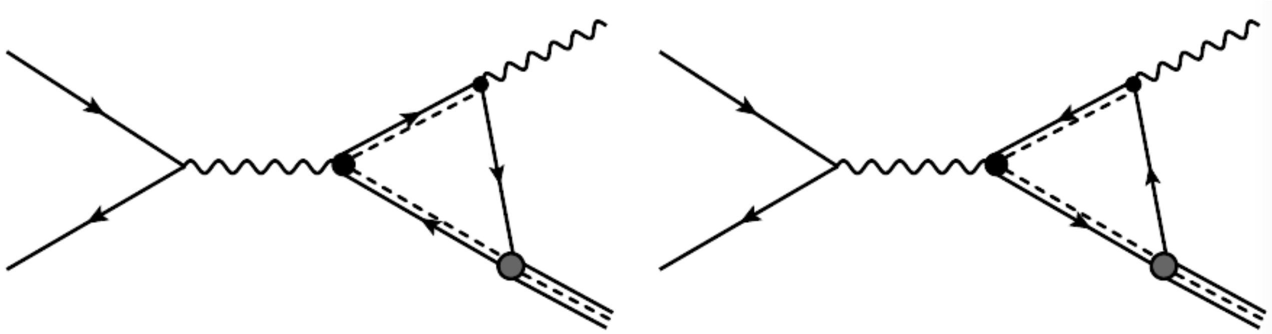
❖ sensitive to Ex (can be used to measure Ex)

❖ peak at ~ 2 MeV above $D^{*0}\bar{D}^{*0}$ threshold (bound state)



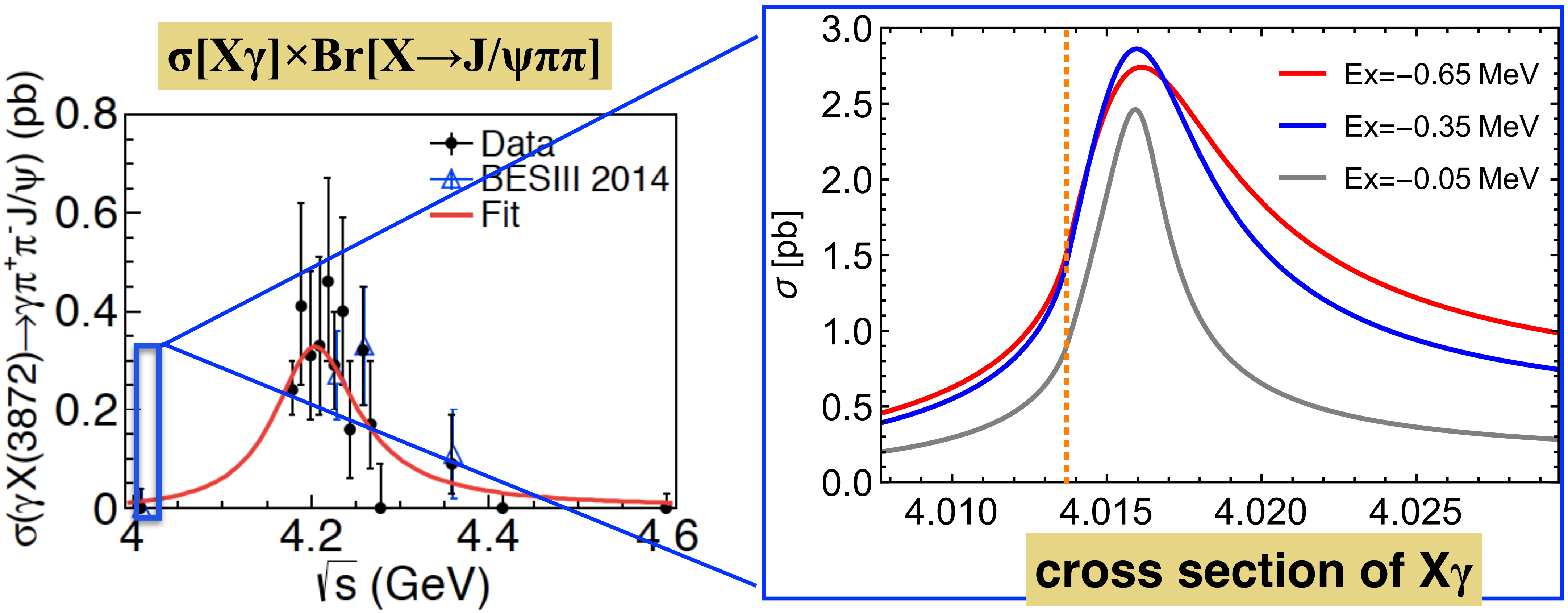
Production of X(3872) and a photon

* $e^+e^- \to D^{*0}\bar{D}^{*0}$(P-wave) $\to$ X(3872) γ [Braaten, He, Ingles, to appear on arXiv]



Triangle singularity gives a narrow peak ~2 MeV above $D^{*0}\bar{D}^{*0}$ threshold

- Include Re[M] as well as Im[M] (absorptive part)
- Include decay width of D*
- Peak insensitive to binding energy (unless $E_X \sim 0$ or $|E_X| >$ a few MeV)
- Normalized cross section using $\sigma[D^{*+}D^{*-}]$ [Uglov *et al.* (JETP Lett. 105,1 (2017))]
- Should be observable at BESIII!



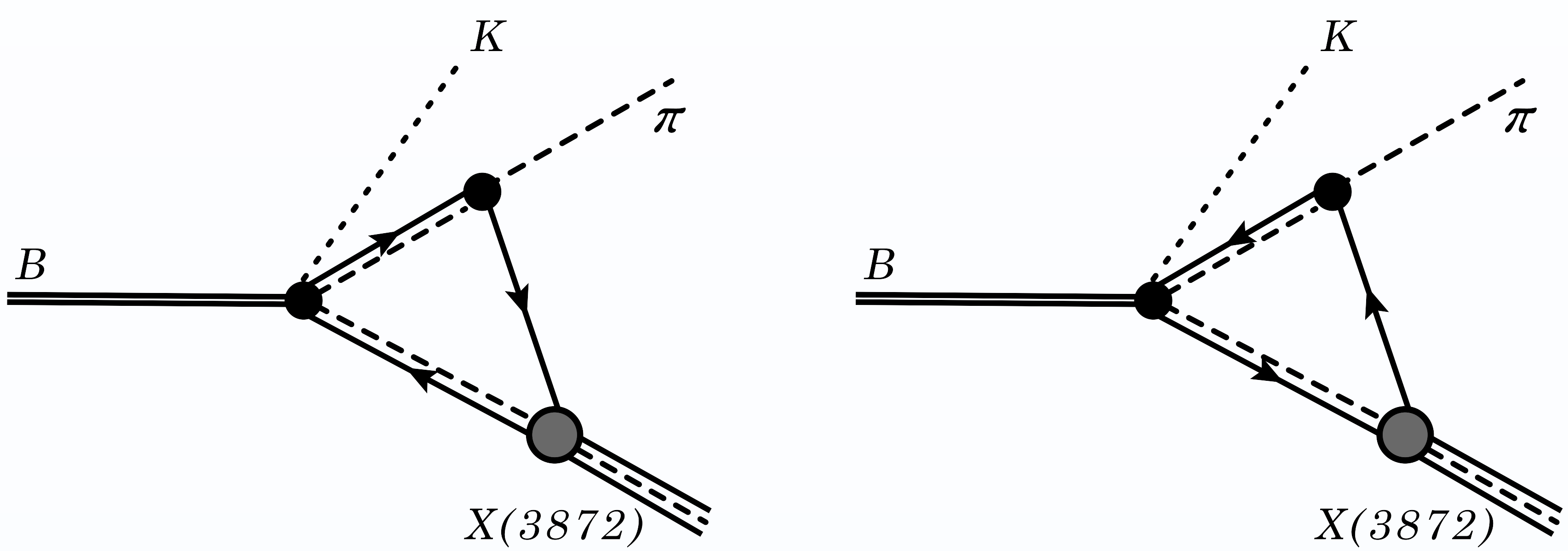
Production of X and a Pion in B meson decay

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

  fraction of $B^0 \to K^*(892)^0$ X : 34%

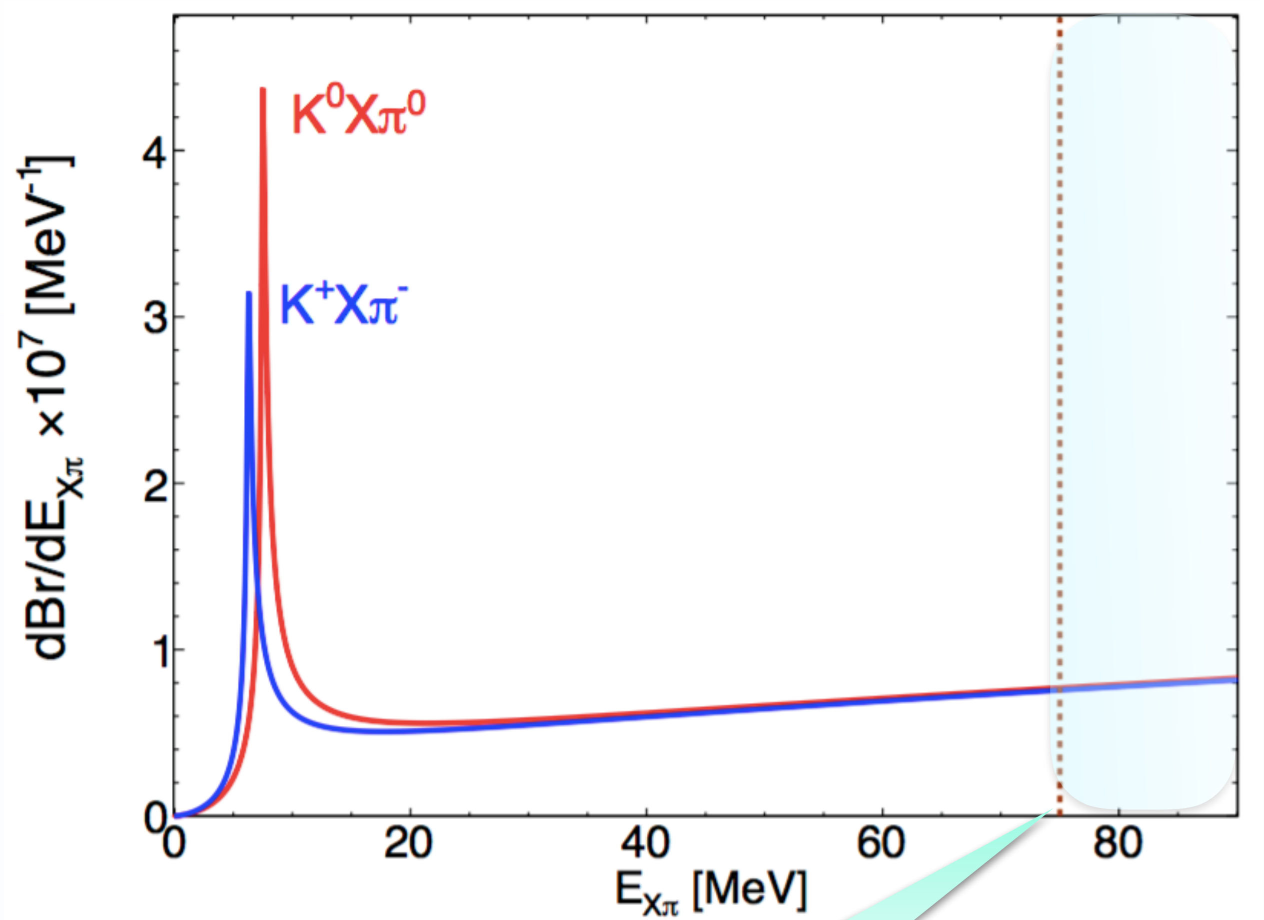
- **B meson decay into K + D*D*, then D*D* rescattering into Xπ**

  (Braaten, He, Ingles, arXiv:1902.03259)

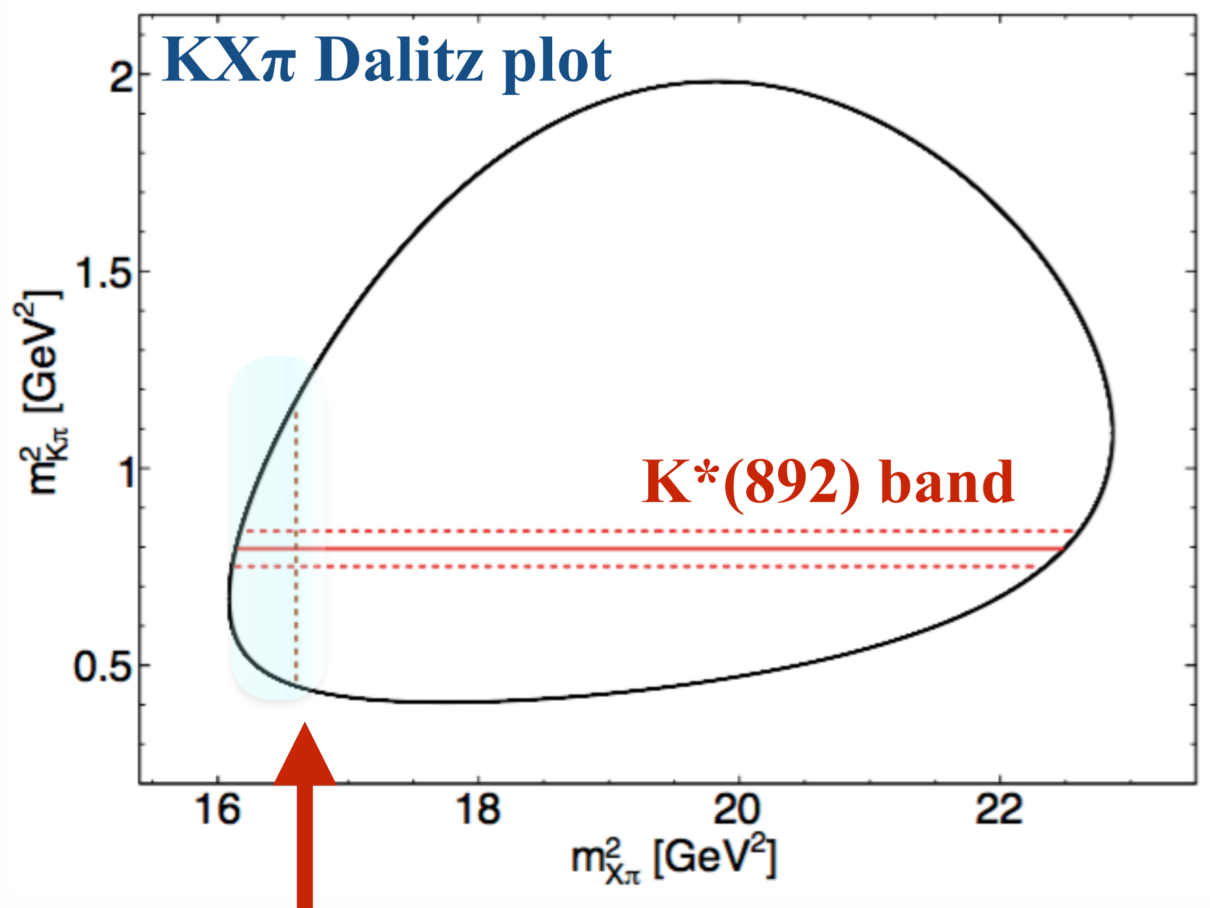


Production of X and a Pion in B meson decay

- Isospin symmetry and heavy quark symmetry
- Triangle singularity predicts a peak too narrow to be observable
- D*D* rescattering produces events near edge of Dalitz plot



not applicable beyond dashed line



D*D* rescattering region

Production of X at hadron colliders

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?

Upper bound in terms of $D^{*0}D^0$ cross section:

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

- **Bignamini *et al.*** [PRL 103, 162001 (2009)]
- **Esposito *et al.*** [Chin. Phys. C41, 121001 (2017)]

$k_{max} \sim \gamma_X$

$\gamma_X = \sqrt{2\mu E_X}$

2 orders of magnitude smaller than lower bound

- **Artoisenet and Braaten** [PRD 81, 114018 (2010)]
- **Albaladejo *et al.*** [Chin. Phys. C41, 121001 (2017)]

$k_{max} \sim m_\pi$

compatible with cross section at Tevatron and LHC

Production of X at hadron colliders

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

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

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

- **Resonant $D^{*0}D^0$ cross section:**

  $k_{max} = 7.73\ \gamma_X \sim \gamma_X$, but a much larger coefficient

- **Naive $D^{*0}D^0$ cross section (no resonant):**

  $k_{max} = (3\pi m_\pi^2\ \gamma_X)^{1/3}$, ~ 150 MeV for Ex = 0.17 MeV

- **Cross section for producing X accompanied by a pion may be larger than the cross without a pion**

- **Compatible with cross section at Tevatron and LHC**

Summary

Production of $X+\gamma$, or $X+\pi$

- e^+e^- annihilation
  - ◇ Narrow peak in the cross section of $X\gamma$ near D*D* threshold in region not yet measured by BESIII
- B meson decay
  - ◇ $B \to KX\pi$ dominated and by D*D* rescatering near $X\pi$ threshold and by K*(892) resonance band
- Hadron colliders
  - ◇ Prompt cross section of $X+\pi$ is larger than that of X without π
  - ◇ Prompt production of X at Tevatron, LHC compatible with weakly bound charm meson molecule

Thank you!

Backup

* k_{max} with threshold enhancement

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

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

$$\sigma[X(3872)] = \sigma[D^{*0}\bar{D}^0(k<7.73\,\gamma_X)]$$

* k_{max} without threshold enhancement
(event generators are not informed about the resonance)

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

$$\sigma[X(3872)] \approx \sigma_{\mathrm{naive}}[D^{*0}\bar{D}^0(k<(3\pi\Lambda^2\gamma_X)^{1/3}]$$

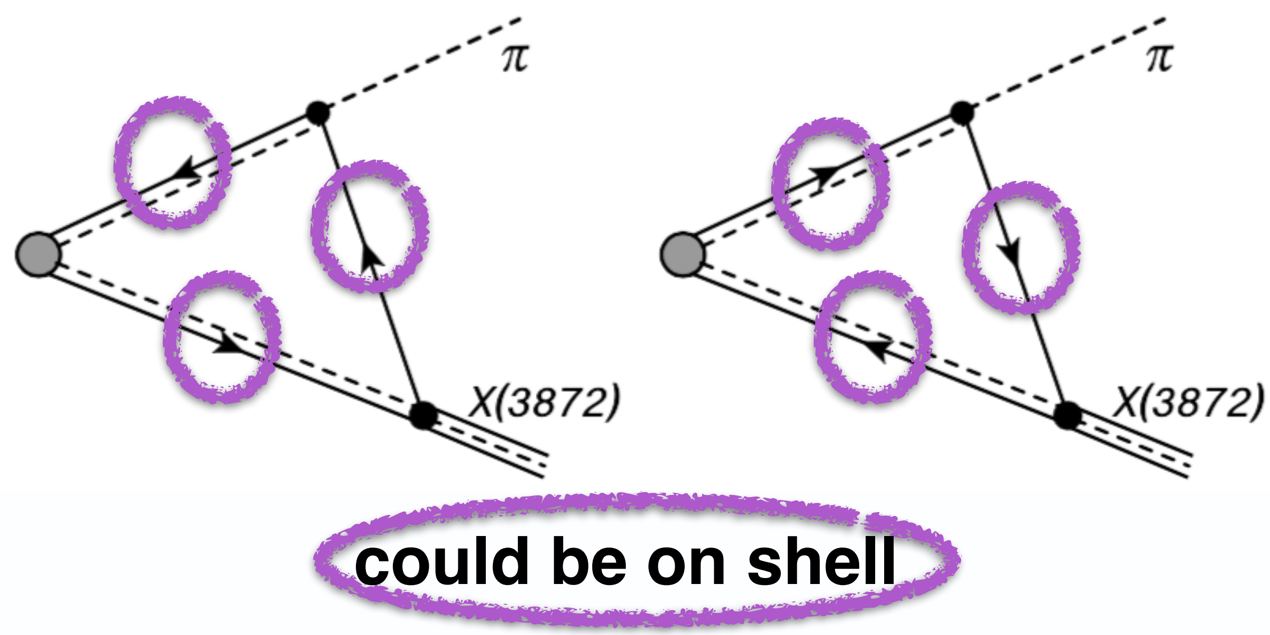
$\Lambda \sim m_\pi$ → $k_{max} \sim 150$ MeV

$$\frac{d\sigma}{d^3q}[X\pi^0] \sim \frac{q^2/2m_0}{|q^2/2m_0-\delta_0|}$$

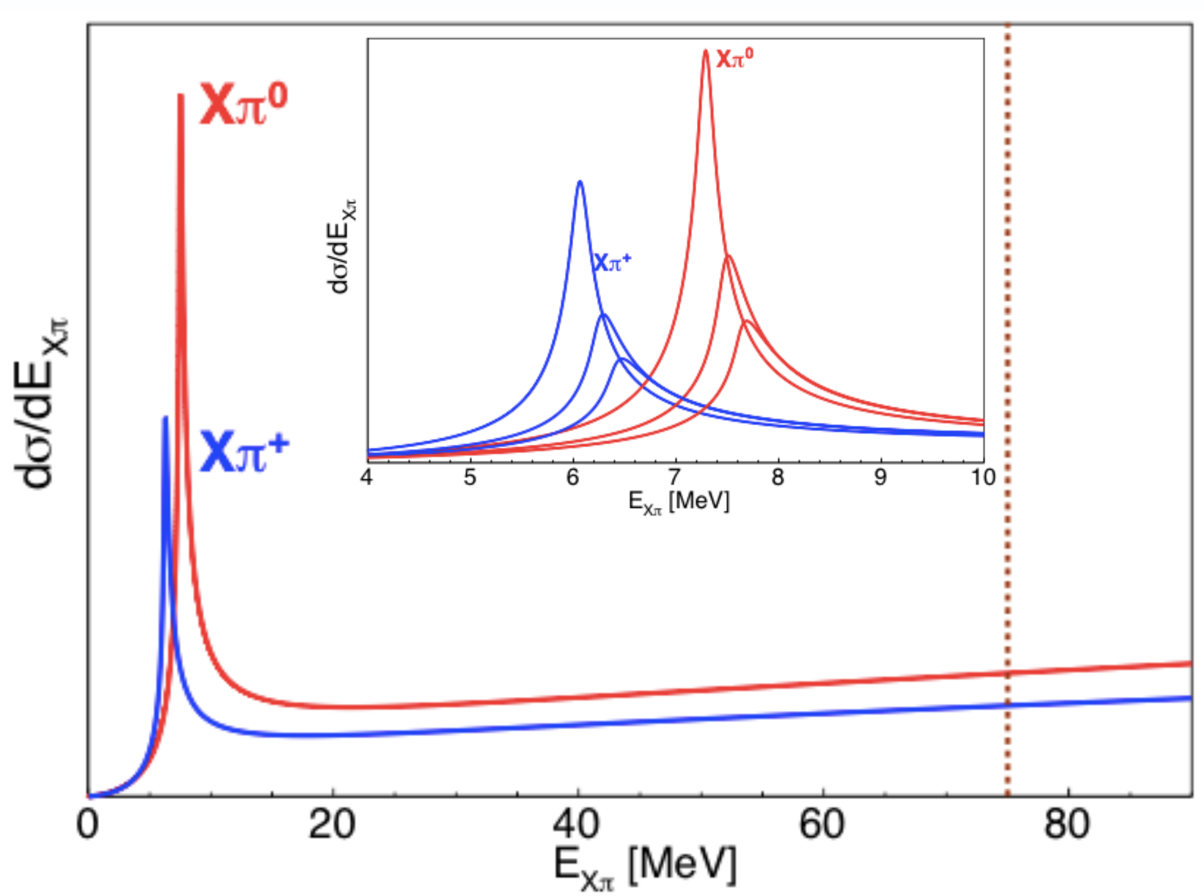
Production of X and a Pion at hadron colliders

Short distance production of D*D*, then rescattering into Xπ

(arXiv:1811.08876, arXiv:1903.04355)



- **Triangle singularity:**
  kinematic singularity in the limit
  $E_X \to 0$, $\Gamma_{*0} \to 0$,
  narrow peak in cross section for Xπ



- **Predicted ratios:**

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

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

- **Differential cross section turns over at $E_{X\pi}$ near $E_{\max}$** (finite cross section)

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 $B \to K\,X$