THE OHIO STATE UNIVERSITY

Triangle singularities in production of X(3872)

Liping He

[he.1011@buckeyemail.osu.edu]

The Ohio State University

in collaboration with Eric Braaten, Kevin Ingles (Ohio State U.), and Jun Jiang (Shandong U.)

10th International Workshop on Charm Physics (CHARM 2020)

31 May 2021 to 4 June 2021

Outline

- **Brief review of X(3872)**
- **Charm-meson triangle singularity**
- **Production of X(3872):**
  - ✦ **e^+e^- annihilation** [PRD100, 031501(2019), PRD101, 014021(2020), PRD 101, 096020(2020)]
  - ✦ **B meson decays** [PRD100, 074028(2019)]
  - ✦ **hadron colliders** [PRD100, 094006(2019)]
- **Summary**
  - ✦ Triangle singularity produces **peaks in reaction rates**
  - ✦ The observation of the peaks would definitely **resolve the nature of X(3872)**

Brief review of X(3872) (≡ $\chi_{c1}(3872)$)

- ☑ discovery at e^+e^- collider [Belle (2003)]:

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

- ☑ confirmation at $p\bar{p}$ collider [CDF (2003)]:

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

- quantum numbers [LHCb (2013)]:

$J^{PC} = 1^{++}$

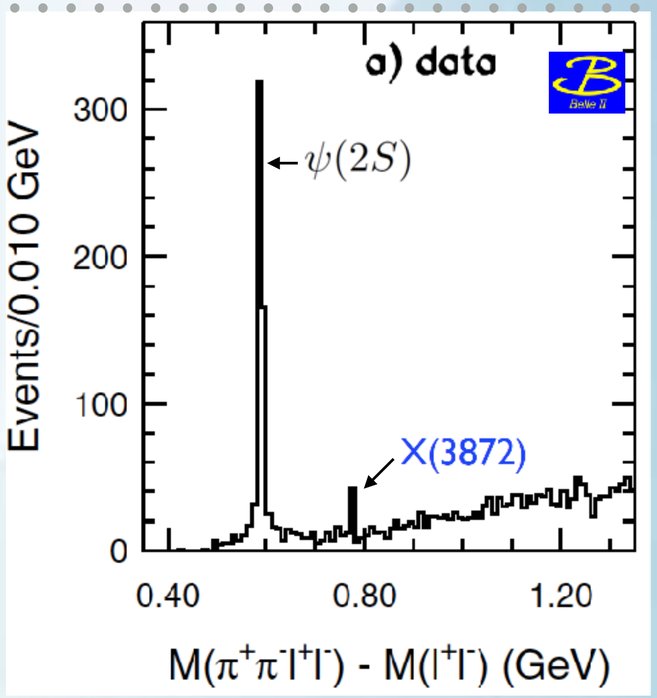
- mass [LHCb (2020)]:

$E_X = M_X - (M_{D^{*0}} + M_{D^0}) = (-0.07 \pm 0.12)$ MeV $|E_X| < 0.22$ MeV at 90% CL

- first measurement of width (Breit-Wigner) [LHCb (2020) average]:

$\Gamma_X = (1.19 \pm 0.19)$ MeV

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



see also F.-K. Guo's talk on Monday

Brief review of X(3872) (≡ $\chi_{c1}(3872)$)

What is the X(3872)?

$J^{PC} = 1^{++}$ → S-wave coupling to $D^{*0}\bar{D}^0 / \bar{D}^{*0}D^0$

$|E_X| < 0.22$ MeV → resonant coupling

S-wave loosely bound charm-meson molecule!!

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

other components of wave functions have small probabilities:

- at long distances: $D^0\bar{D}^0\pi^0$
- at short distances:
  - $\chi_{c1}(2P)$?
  - charged charm mesons
  - compact tetraquark $[cq][\bar{c}\bar{q}]$?

Universal properties determined by the binding energy $|E_X|$

* large scattering length: $|a| = 1/\sqrt{2\mu\,|E_X|}$, $|a| \gg$ range

* large mean separation: $\langle r \rangle = a/2$, $|E_X| < 0.22$ MeV implies $\langle r \rangle > 5$ fm

XEFT effective field theory for charm mesons and pions

Fleming, Kusunoki, Mehen & van Kolck [PRD 76, 034006(2007)]

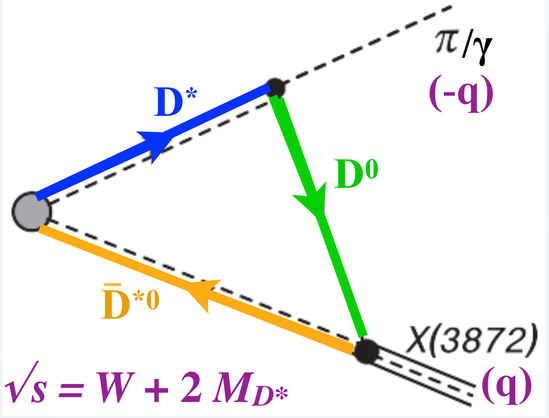
Galilean-invariant XEFT

Braaten [PRD 91, 114007(2015)]

Braaten, He & Jiang [PRD 103, 036014(2021)]

Charm-meson triangle singularity

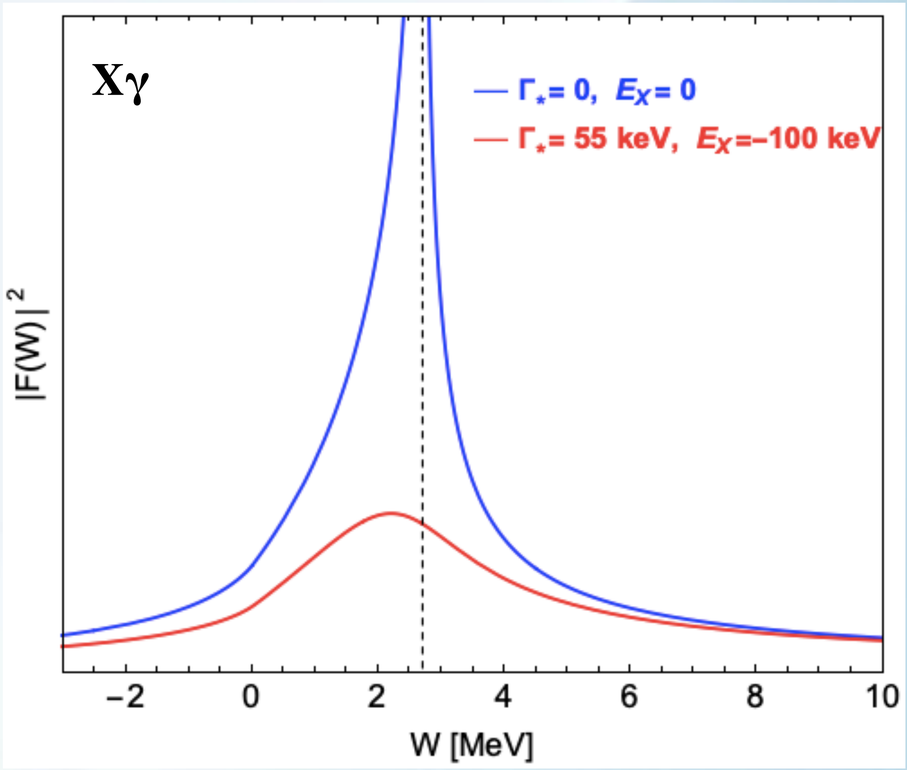
three charm mesons can be on shell simultaneously → log² divergence in reaction rate



loop amplitude near singularity:

$$F(W) \propto \log \frac{\sqrt{M_* W} + (M_*/M_X)q}{\sqrt{M_* W} - (M_*/M_X)q}$$

$(M_* = M_{D^*})$



divergence at energy W above $D^*\bar{D}^*$ threshold:

- **Xγ:** $(M_{D^{*0}}/M_X^2)(M_{D^{*0}} - M_{D^0})^2 = 2.7$ MeV
- **Xπ⁰:** $(m_{\pi^0}/2M_{D^0})(M_{D^{*0}} - M_{D^0} - m_{\pi^0}) = 0.3$ MeV
- **Xπ±:** $(m_{\pi^0}/2M_{D^0})(M_{D^{*+}} - M_{D^0} - m_{\pi^+}) = 0.2$ MeV

BUT

- nonzero decay width for D*
- nonzero binding energy (-Ex) for X

→ narrow peak in reaction rate

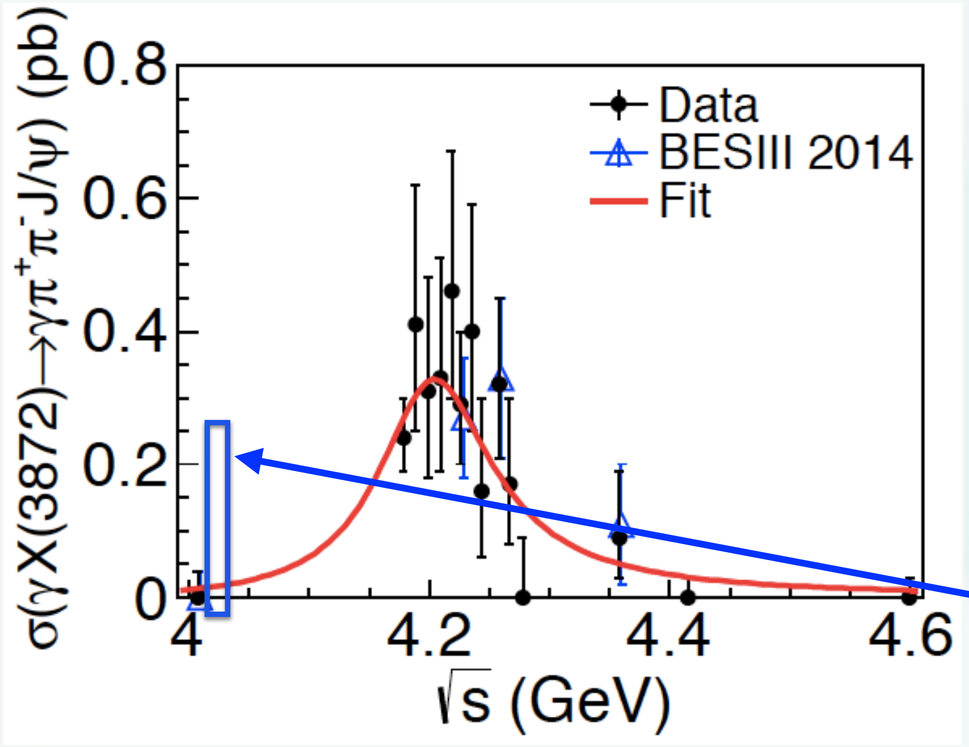
$$F(W) \propto \log \frac{\sqrt{2\mu E_X + i\mu\Gamma_*} + \sqrt{M_*(W + i\Gamma_*)} + (M_*/M_X)q}{\sqrt{2\mu E_X + i\mu\Gamma_*} + \sqrt{M_*(W + i\Gamma_*)} - (M_*/M_X)q}$$

review on TS: Guo, Liu, Sakai [Prog. Part. Nucl. Phys. 112, 103757 (2020)]

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

Experimental observation:

BESIII: $e^+e^- \to X\gamma$, $X \to J/\psi\,\pi^+\pi^-$, $J/\psi\,\omega$
[PRL122,232002 (2019)]



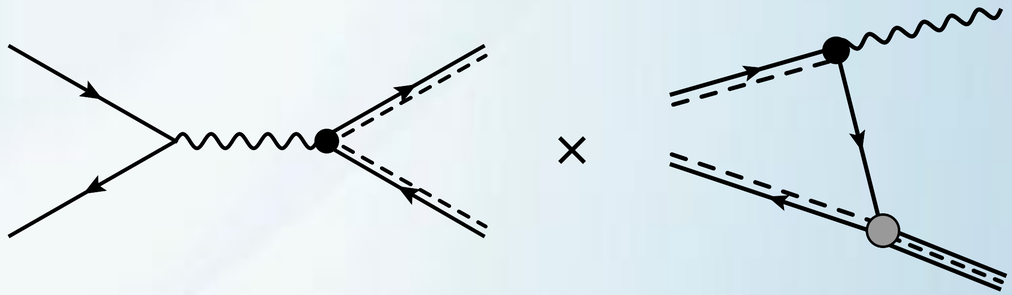
First theoretical calculation:

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

absorptive contribution only:

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

- e^+e^- annihilation creates $D^{*0}\bar{D}^{*0}$(P-wave)
- rescattering of real $D^{*0}\,\bar{D}^{*0}$ into $X\gamma$



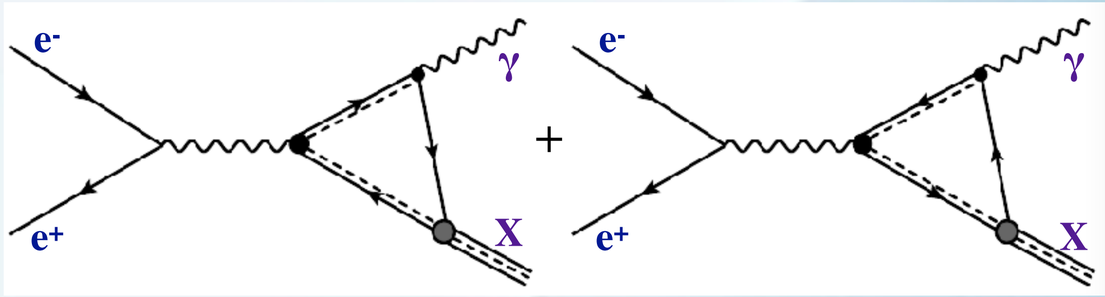
- Line shape of $X\gamma$ has narrow peak a few MeV above $D^{*0}\bar{D}^{*0}$ threshold
- $\sigma[X\gamma]$: of order 1pb near the peak

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

Braaten, He & Ingles [PRD 100, 031501(2019), PRD 101, 014021(2020)]

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

- e^+e^- annihilation creates $D^{*0}\bar{D}^{*0}$(P-wave)
- rescattering of virtual $D^{*0}\,\bar{D}^{*0}$ into $X\gamma$



* **improvements** over Dubynskiy & 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)

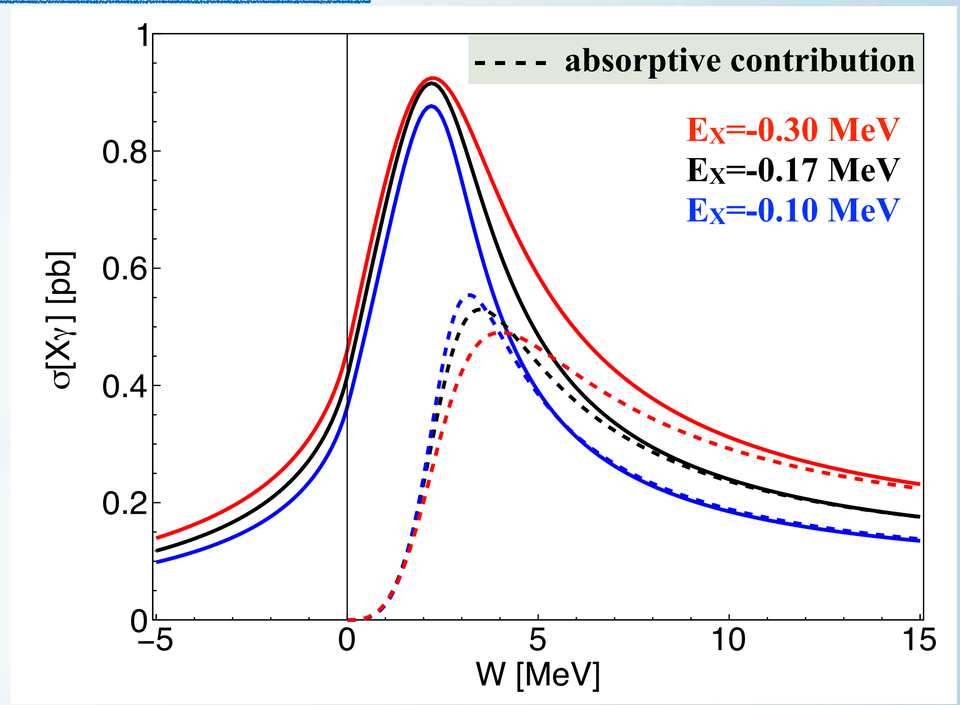
* **cross section:**

- triangle singularity gives narrow peak at 2.2 MeV above $D^{*0}\bar{D}^{*0}$ threshold at 4013.7 MeV
- position of peak insensitive to binding energy
- may be observable by BESIII detector!

absorptive contribution only is not a good approximation!

cross section for Xγ

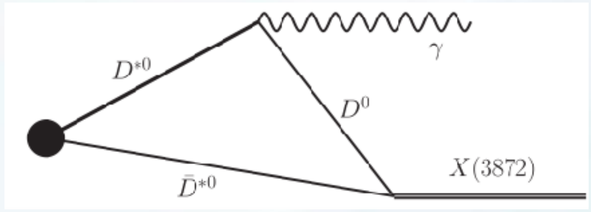
$\sqrt{s} = W + 2\,M_{D^*}$



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

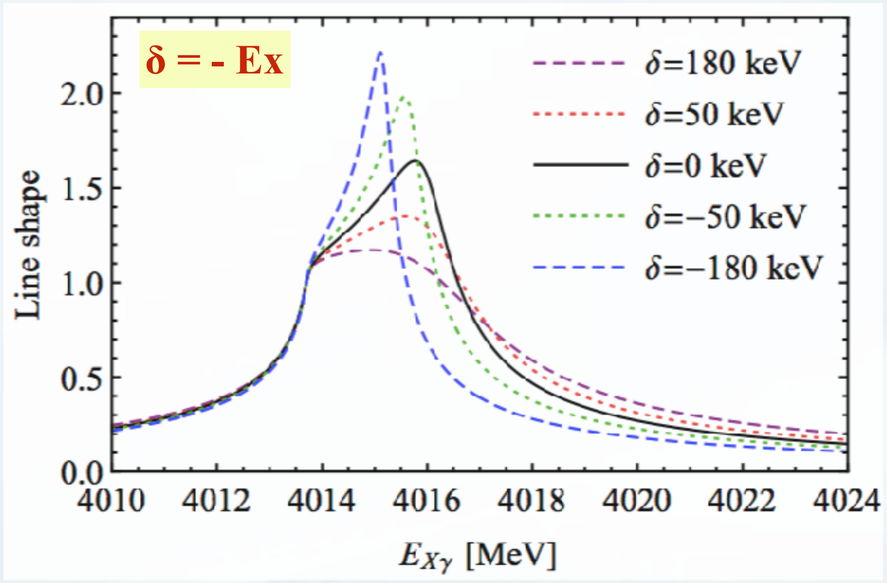
Guo [PRL 112, 202002 (2019)]

- creation of $D^{*0}\bar{D}^{*0}$(S-wave) at short distance
- rescattering of virtual $D^{*0}\bar{D}^{*0}$ into $X\gamma$



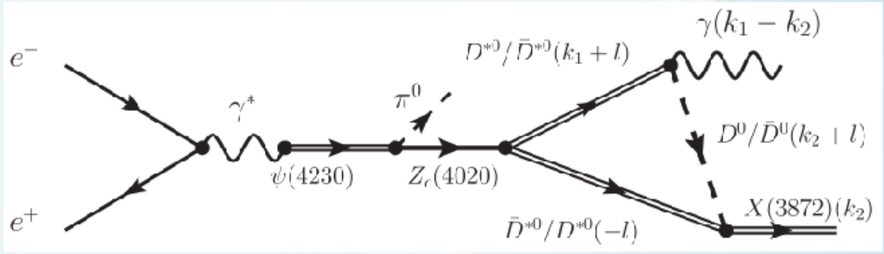
Line shape in $X\gamma$:

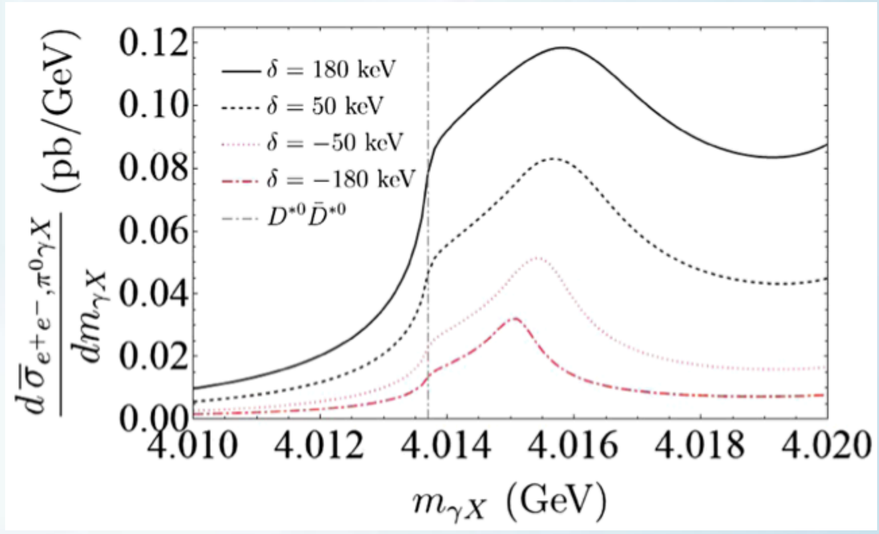
- peak a few MeV above $D^{*0}\bar{D}^{*0}$ threshold
- can be used to measure E_X



Sakai, Jing & Guo [PRD 102, 114041(2020)]

$e^+e^- \to Zc(4020)\,\pi^0$, $Zc(4020) \to D^{*0}\bar{D}^{*0}$(S-wave) $\to X\gamma$





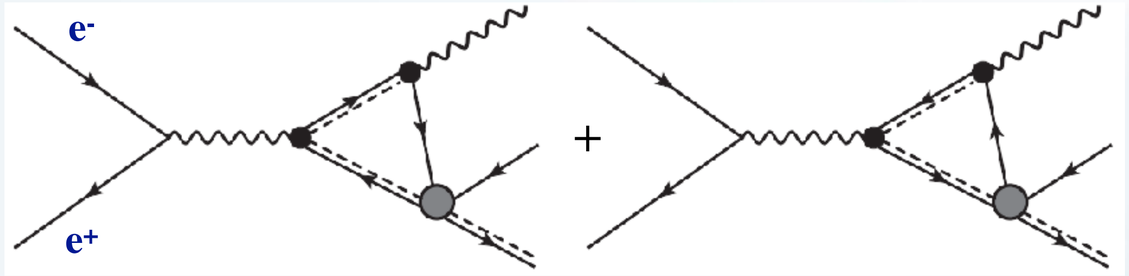
see also F.-K. Guo's talk on Monday

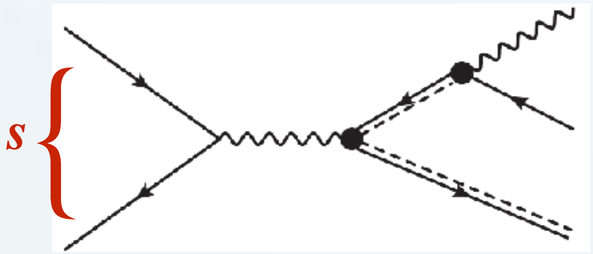
- **BESIII** [arXiv:2101.00644]: no significant signal

  $e^+e^- \to Zc(4020)\,\pi^0$, $Zc(4020) \to D^{*0}\bar{D}^{*0}$(S-wave) $\to X\gamma$

e^+e^-: production of $D^{*0}\bar{D}^0$ and a photon

Braaten, He, Ingles & Jiang [PRD 101, 096020(2020)]

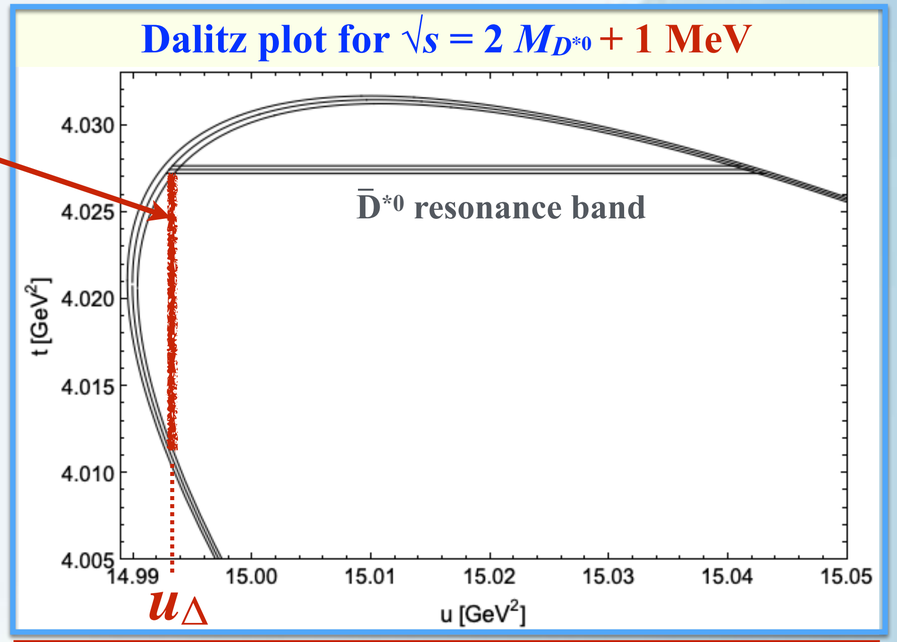




t = ($\bar{D}^0\,\gamma$ invariant mass)^2

u = ($D^{*0}\,\bar{D}^0$ invariant mass)^2

triangle singularity at $u = u_\Delta$



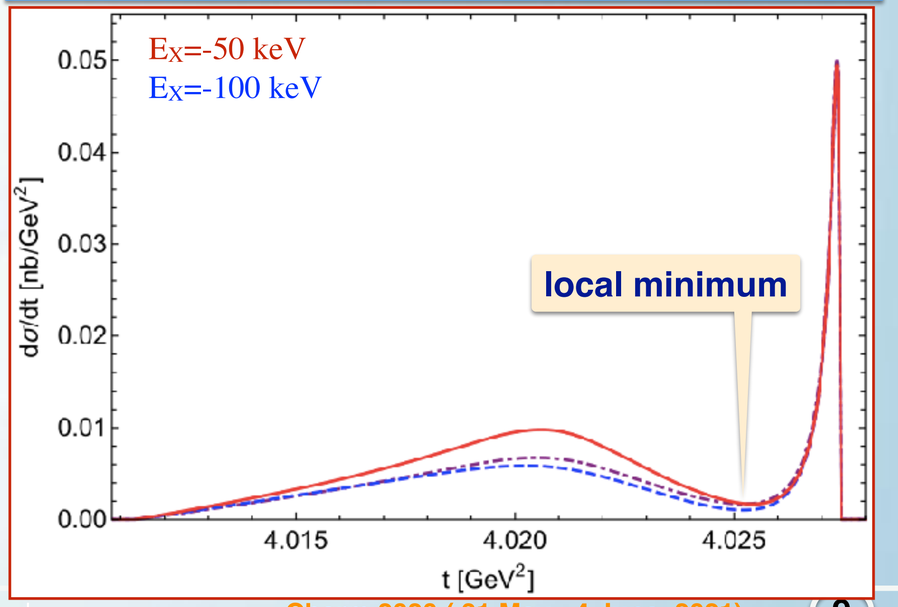
- **Schmid cancellation:**

  Schmid [PR154, 1363(1967)]
  Anisovich &Anisovich [PLB345, 321(1995)]

- $d\sigma/(du\,dt)$ at fixed t: log^2 divergence
- $d\sigma/du$ integrated over t: log divergence

- **indirect way to observe triangle singularity:**

$d\sigma/dt$ integrated over $u < u_\Delta$ has local minimum in t



B meson decay: production of X(3872) and a pion

Belle [PRD 91, 051101 (2015)]

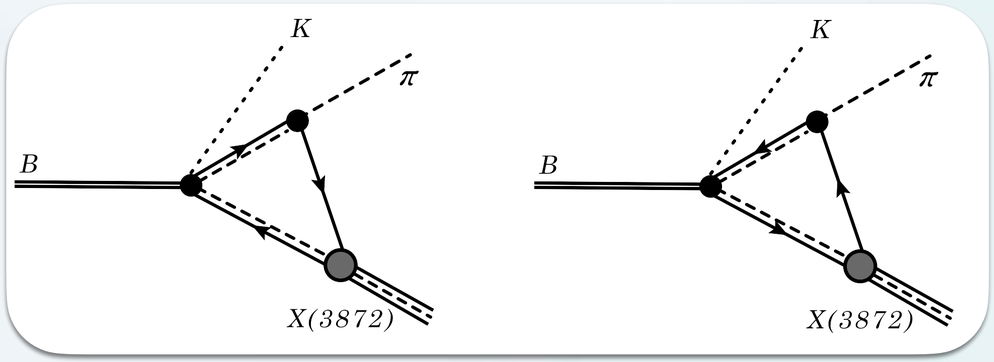
first observation of $B^0 \to K^+ \pi^- X$, $B^+ \to K^0 \pi^+ X$

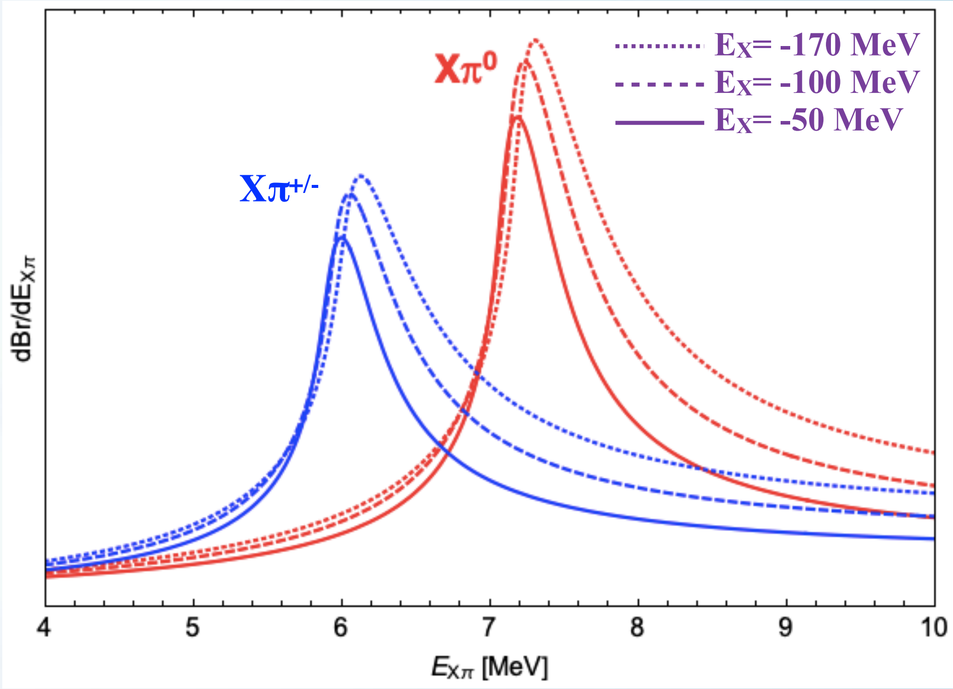
34% of $B^0 \to K^+\pi^- X$ from $B^0 \to K^{*0}(892)\ X$

Braaten, He, Ingles [PRD 100, 074028(2019)]

$B \to K\, D^*\bar{D}^* \to K\, X\pi$

decay of B meson into K+D*$\bar{D}$*, rescattering of virtual D*$\bar{D}$* into Xπ





triangle singularity produces narrow peaks in dBr[B→K Xπ]

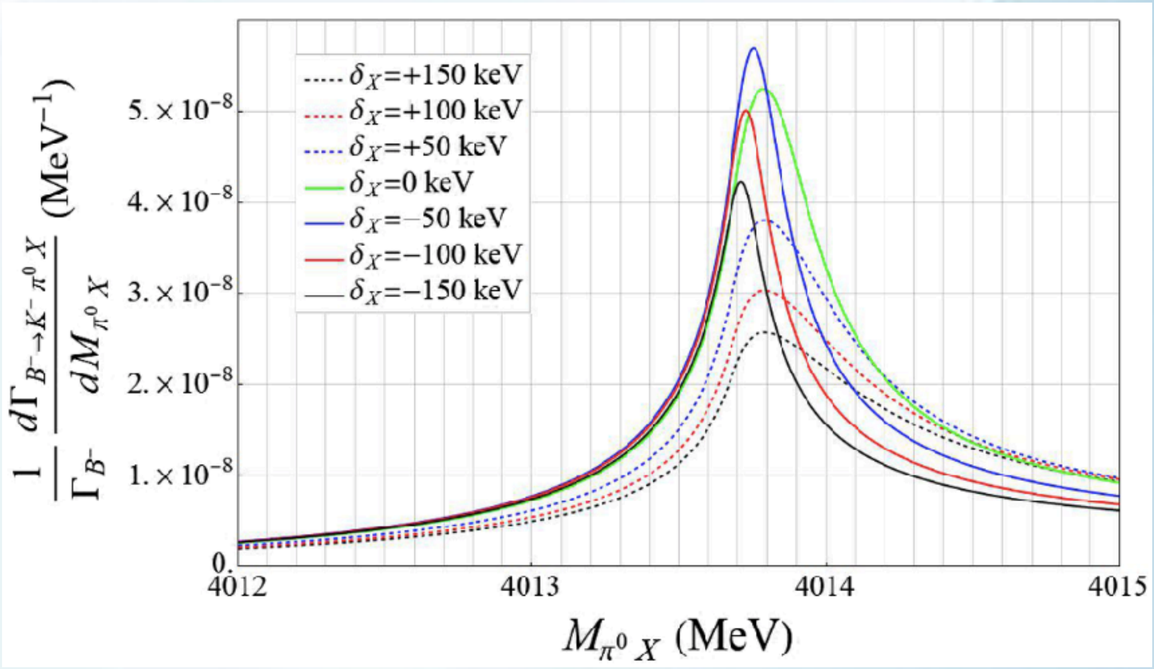
- $X\pi^{\pm}$: near 6.1 MeV above $X\pi^+$ threshold
- $X\pi^0$: near 7.3 MeV above $X\pi^0$ threshold

B meson decay: production of X(3872) and a pion

- **Sakai, Oset & Guo** [PRD 101, 054030(2020)]

$B^- \to K^- D^{*0}\bar{D}^{*0} \to K^- X\pi^0$

Ex (= -δx) may be extracted from the asymmetry of the Xπ line shape



- **Nakamura** [PRD 102, 074004(2020)]

$B^0 \to K^+ D^{*0}D^{*-} \to K^+ (J/\psi\ \rho\ \pi^-)$

triangle singularity could produce narrow peak in J/ψρ invariant mass near 3872 MeV even without X(3872) resonance

- **Molina & Oset** [EPJC 80, 451(2020)]

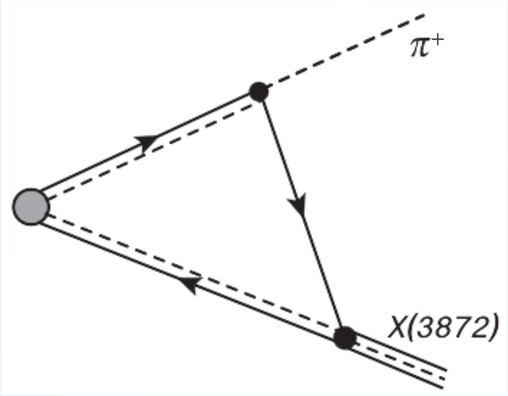
$B^- \to K^- X,\ X \to (D^*\bar{D}, \bar{D}^*D) \to \pi^0(\pi^+\pi^-)$

triangle singularity in decay of X

Hadron colliders: prompt production of X(3872) and a pion

- **Braaten, He & Ingles** [PRD 100, 094006(2019)]

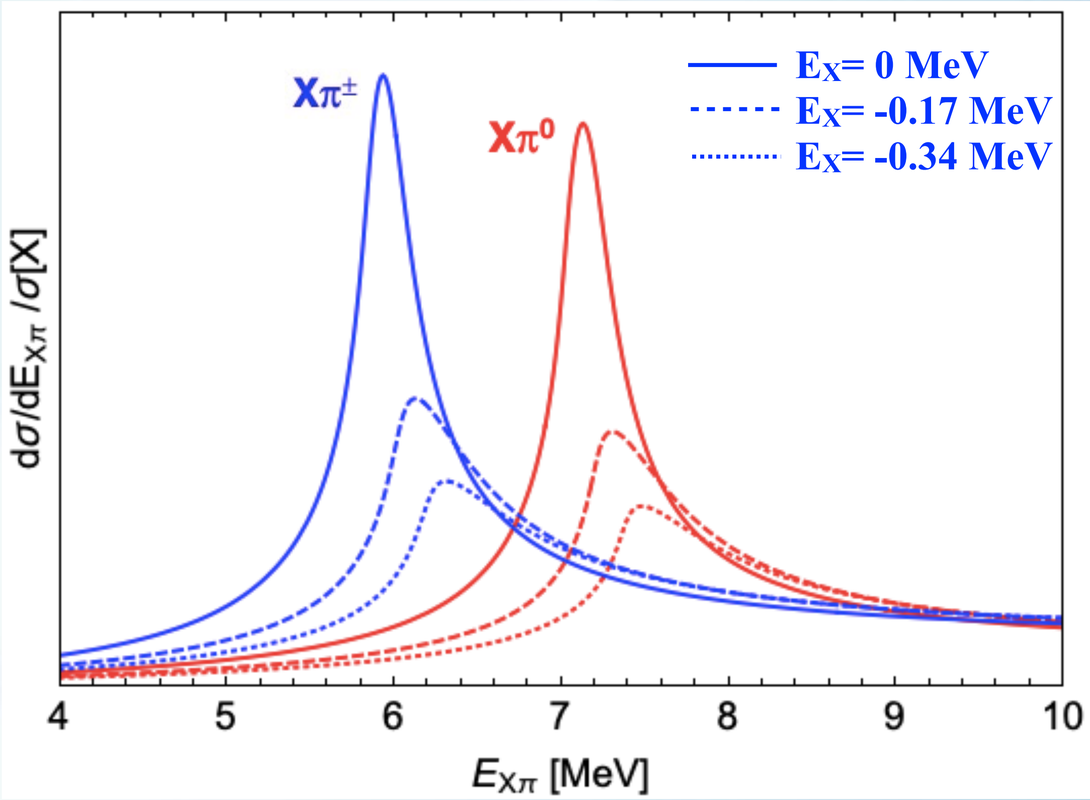
$D^{*+}\bar{D}^{*0} \to X(3872)\ \pi^+$



- ❖ creation of $D^{*+}\bar{D}^{*0}$ at short distance
- ❖ rescattering of virtual $D^{*+}\bar{D}^{*0}$ into $X\pi^+$

triangle singularity produces narrow peak in $X\pi^\pm$ invariant mass

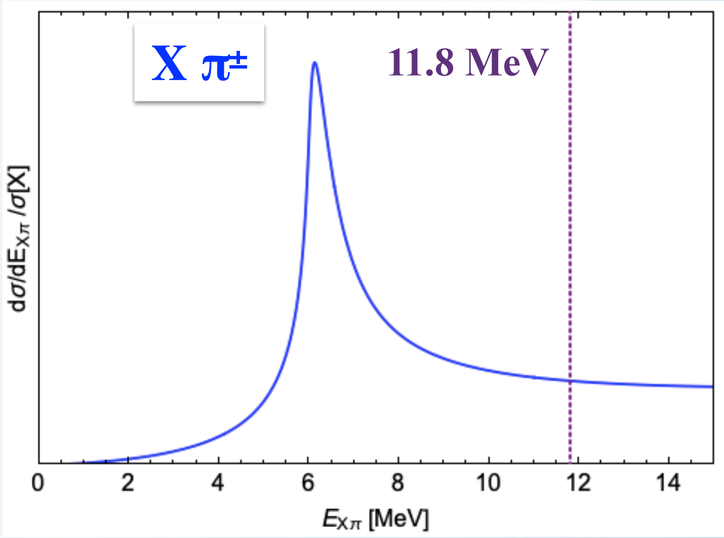
peak near 6.1 MeV above $X\pi^+$ threshold



Experimental observation: production of X(3872) and a pion

contributions from the triangle peak: E_X= -0.17 MeV

- **prompt production:** $\frac{\sigma[(X\pi^{\pm})_{\Delta}]}{\sigma[X]} \approx 14\%$
- **B-meson decay:** $\frac{\mathrm{Br}[B^0 \to K^+(X\pi^-)_{\Delta}]}{\mathrm{Br}[B^0 \to K^0 X]} \approx 14\%$

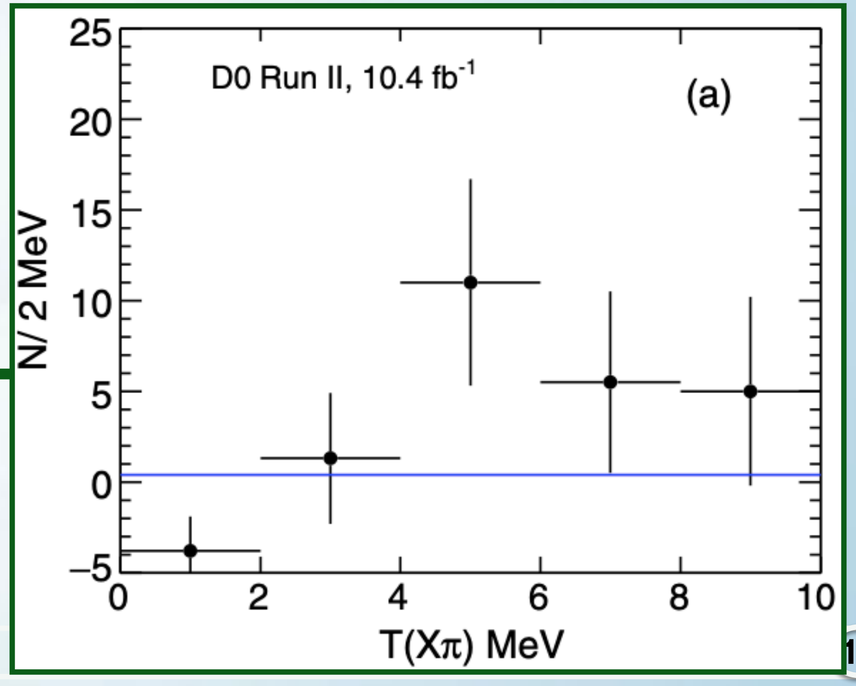


- **D0 Collaboration** [PRD 102, 072005 (2020)]

prompt and non prompt production of X(3872) + soft $\pi^{\pm}$

$T(X\pi) < 11.8$ MeV

	observed events	expected events
prompt production:	12 ± 16	245 – 730
b-decay:	25 ± 12	30 – 90

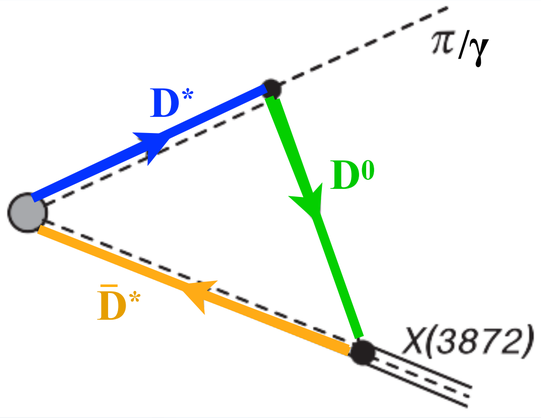


* prompt production : no evidence for the accompanying $\pi^{\pm}$
* b-decay: agreement with the expectation, significance: 2σ

Summary

Production of X+γ or X+π

charm meson triangle singularity produces narrow peaks just above $D^*\bar{D}^*$ threshold



- e^+e^- annihilation
  - ◇ $\sigma[X\gamma]$: narrow peak at 4015.9 MeV
  - ◇ peak is in region not yet measured by BESIII
- B meson decay
  - ◇ $dBr[X\pi^0]/dE_{X\pi}$: peak near 7.3 MeV above $X\pi^0$ threshold
  - ◇ $dBr[X\pi^\pm]/dE_{X\pi}$: peak near 6.1 MeV above $X\pi^+$ threshold
- Hadron colliders
  - ◇ $d\sigma[X\pi^\pm]/dE_{X\pi}$: peak near 6.1 MeV above $X\pi^+$ threshold

Thank you!

The observation of the peaks would definitely resolve the nature of X(3872)

Backup

B meson decay

$$\frac{d\Gamma}{d^3q}[B^+ \to K^+ X\pi^0] = \frac{|\mathcal{A}[K^+ X\pi^0]|^2}{4|\mathcal{A}[K^0 X\pi^0]|^2}\frac{d\Gamma}{d^3q}[B^0 \to K^0 X\pi^0], \tag{36a}$$

$$\frac{d\Gamma}{d^3q}[B^+ \to K^0 X\pi^+] = \frac{d\Gamma}{d^3q}[B^0 \to K^+ X\pi^-]. \tag{36b}$$

$$\mathrm{Br}[B^0 \to K^+(X\pi^-)_\triangle] \approx (2.4\times 10^{-7})\left(\frac{|E_X|}{0.17\ \mathrm{MeV}}\right)^{1/2} \times \left[2.64 - \log\frac{|E_X|}{0.17\ \mathrm{MeV}}\right].$$

$$\mathrm{Br}[B^0 \to K^0(X\pi^0)_\triangle] < (8\times 10^{-8})\left(\frac{|E_X|}{0.17\ \mathrm{MeV}}\right)^{1/2} \times \left[2.82 - \log\frac{|E_X|}{0.17\ \mathrm{MeV}}\right].$$

Hadron collider

$$d\sigma[D^{*0}\bar{D}^{*0}] \approx d\sigma[X(3872)]\frac{12\pi\mu}{\gamma_X\Lambda^2}\frac{d^3k}{(2\pi)^3 M_{*0}}$$

$$\frac{\sigma[(X\pi^0)_\Delta]}{\sigma[X]} \approx 0.049\left(\frac{m_\pi}{\Lambda}\right)^2\left[2.82 - \log\frac{|E_X|}{0.17\,\mathrm{MeV}}\right],$$

$$\frac{\sigma[(X\pi^+)_\Delta]}{\sigma[X]} \approx 0.028\left(\frac{m_\pi}{\Lambda}\right)^2\left[2.64 - \log\frac{|E_X|}{0.17\,\mathrm{MeV}}\right].$$