THE OHIO STATE UNIVERSITY

Triangle singularities in production of X(3872)

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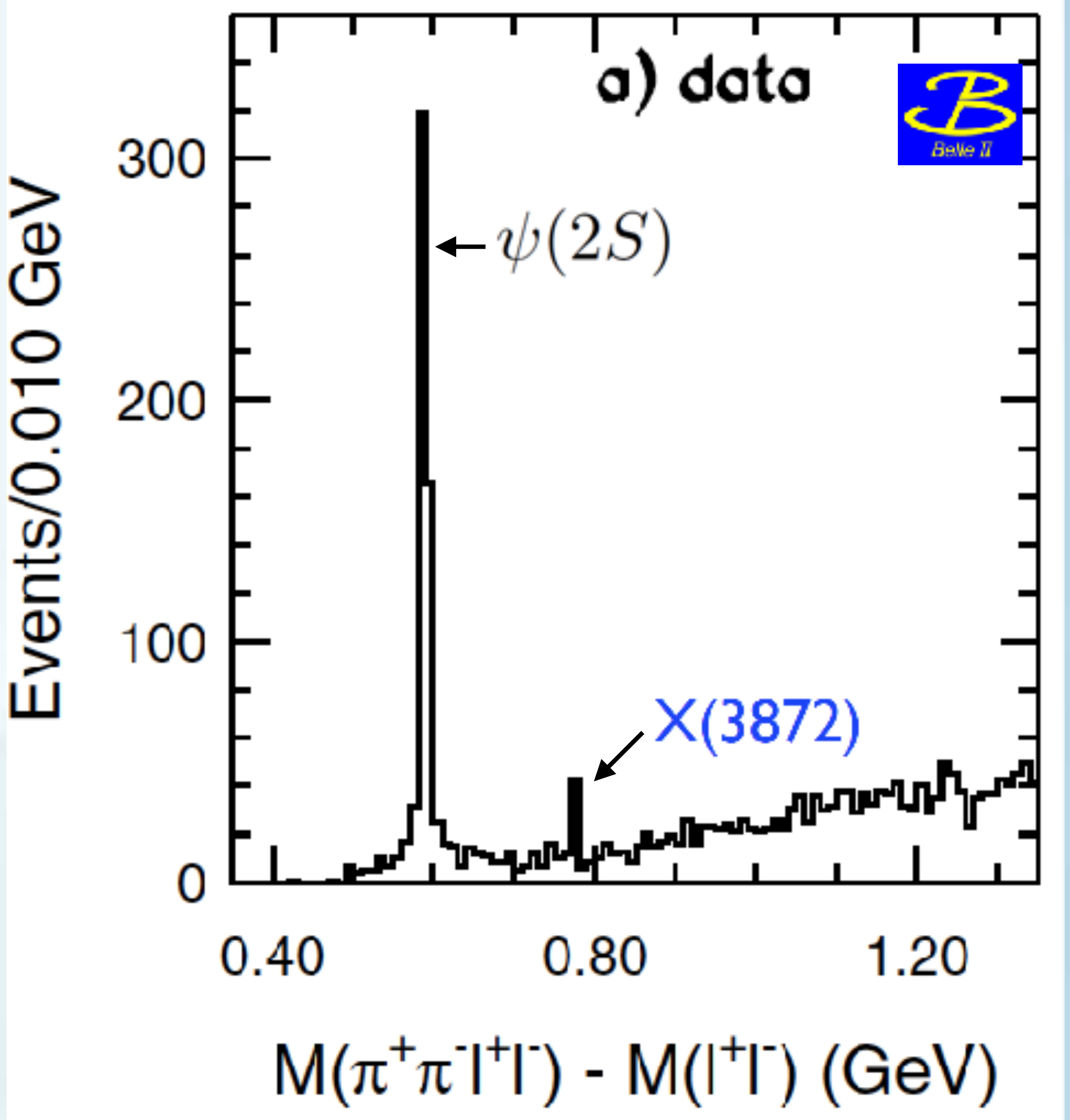
Outline

- 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) ($\equiv \chi_{c1}(3872)$)



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

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

- 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 $\quad$ $|E_X| < 0.22$ 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: $J/\psi\,\pi^+\pi^-$, $J/\psi\pi^+\pi^-\pi^0$, $J/\psi\,\gamma$, $\psi(2S)\gamma$, $D^0\bar{D}^0\pi^0$, $D^0\bar{D}^0\gamma$, $\chi_{c1}\pi^0$

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

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 $[cq][\bar{c}\bar{q}]$?

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

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$|E_X| < 0.22$ MeV → resonant coupling

S-wave loosely bound charm-meson molecule!!

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

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

- large scattering length: $|a| = \pm 1/\sqrt{2\mu\,|E_X|}$, $|a| >> \text{range}$
- large mean separation: $\langle r \rangle = a/2$, $|E_X| < 0.22$ MeV implies $\langle r \rangle > 5$ fm
- scattering amplitude at $E \ll 1/(2\mu\,\text{range}^2)$: $f(E) = 1/\left(-1/a + i\sqrt{2\mu E}\right)$
- wavefunction: $\psi(r) = e^{-r/a}/r$

XEFT

effective field theory for charm mesons and pions

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

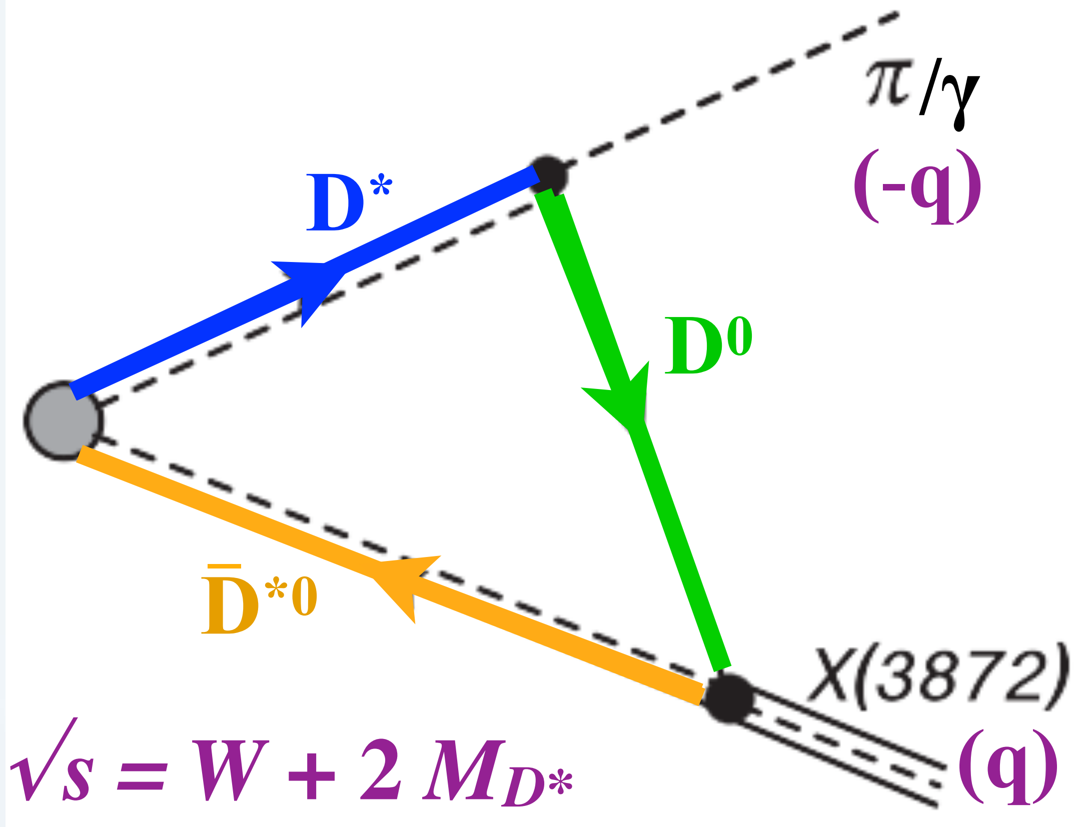
Galilean-invariant XEFT

Braaten [PRD 91, 114007(2015)]

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

Charm-meson triangle singularity

three charm mesons can be on shell simultaneously → $\log^2(s/s_\triangle)$ divergence in reaction rate at $s_\triangle$ determined by masses



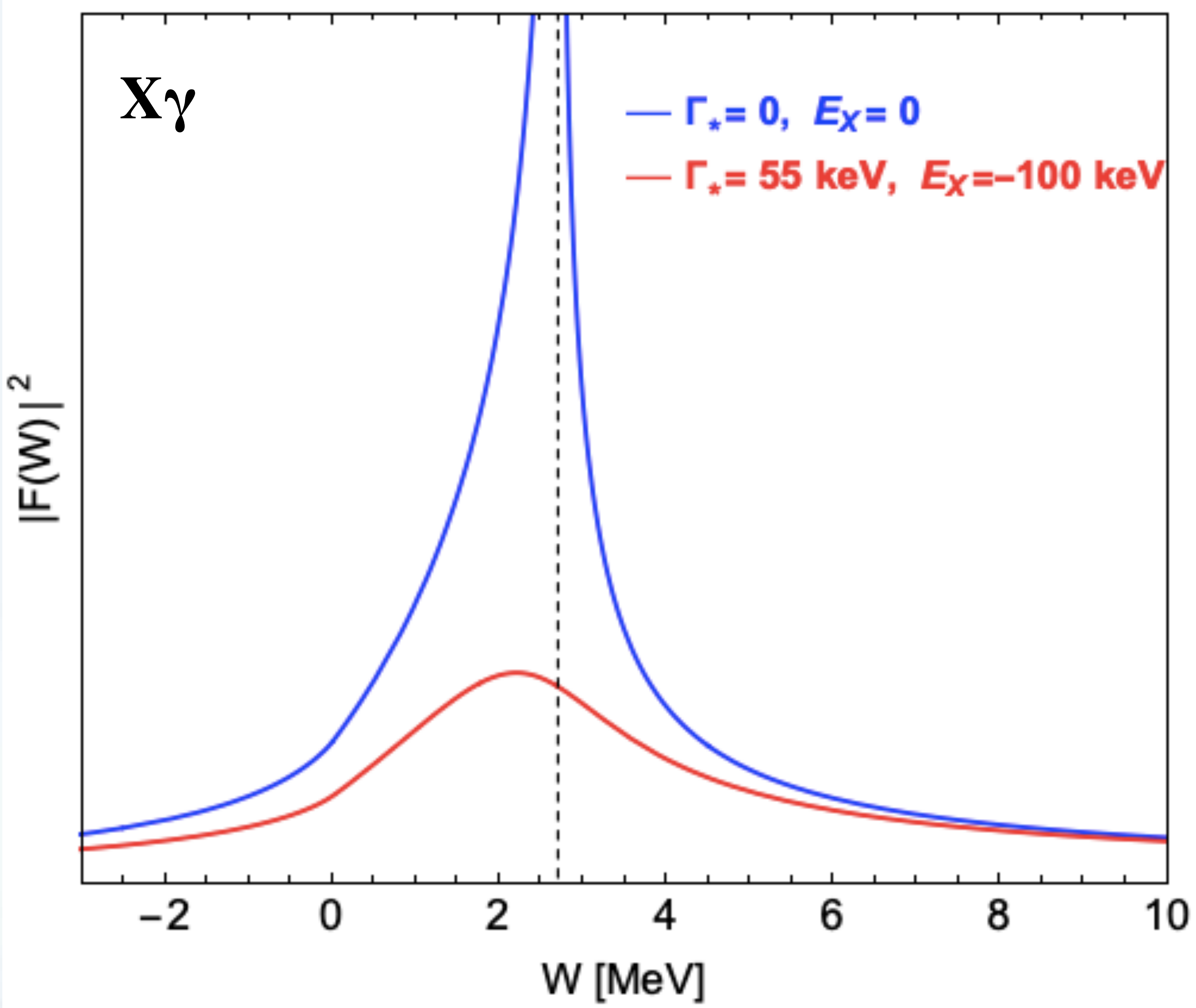
loop amplitude near singularity:

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

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

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

- $X\gamma$: $(M_{D^{*0}}/M_X^2)(M_{D^{*0}} - M_{D^0})^2 = 2.7$ MeV
- $X\pi^0$: $(m_{\pi^0}/2M_{D^0})(M_{D^{*0}} - M_{D^0} - m_{\pi^0}) = 0.3$ MeV
- $X\pi^\pm$: $(m_{\pi^0}/2M_{D^0})(M_{D^{*+}} - M_{D^0} - m_{\pi^+}) = 0.2$ MeV



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

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

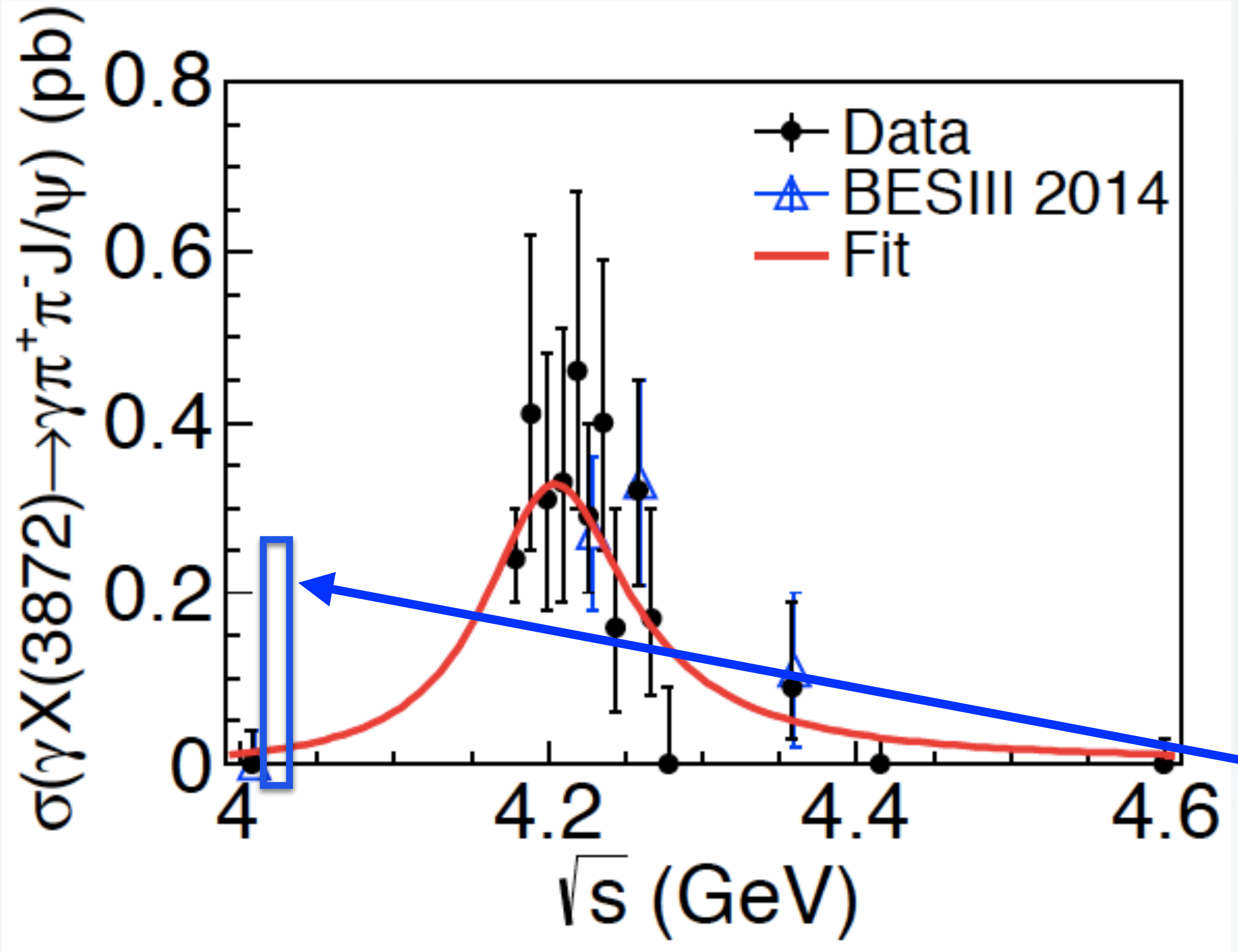
→ narrow peak in reaction rate

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

production of X(3872) + γ in e^+e^- annihilation

Experimental observation:

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



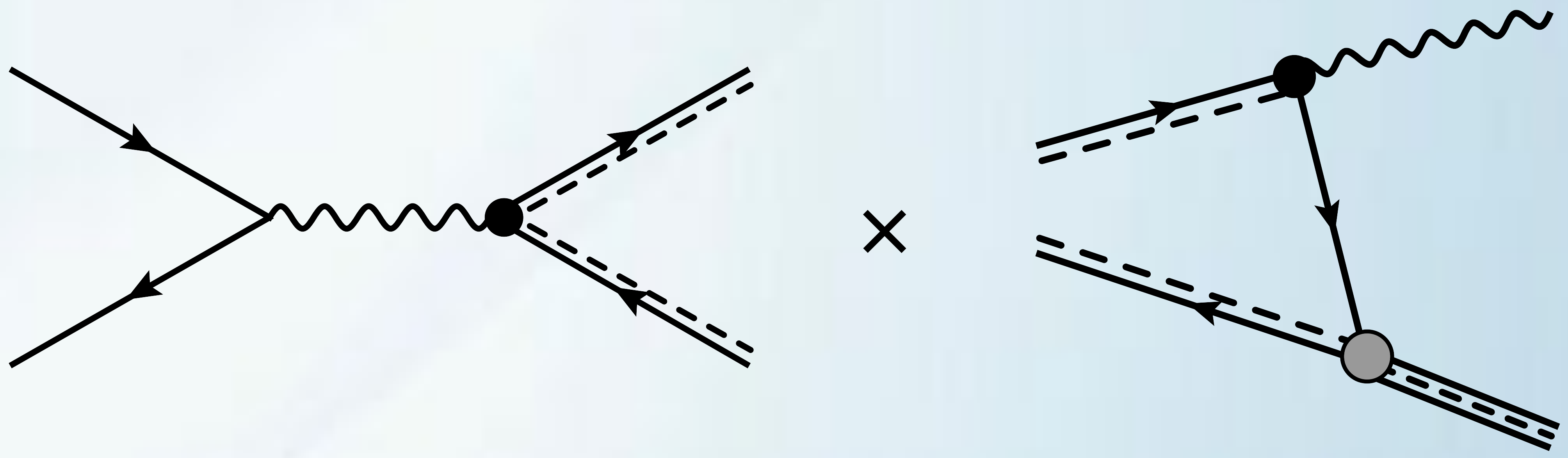
First theoretical calculation:

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 $X\gamma$



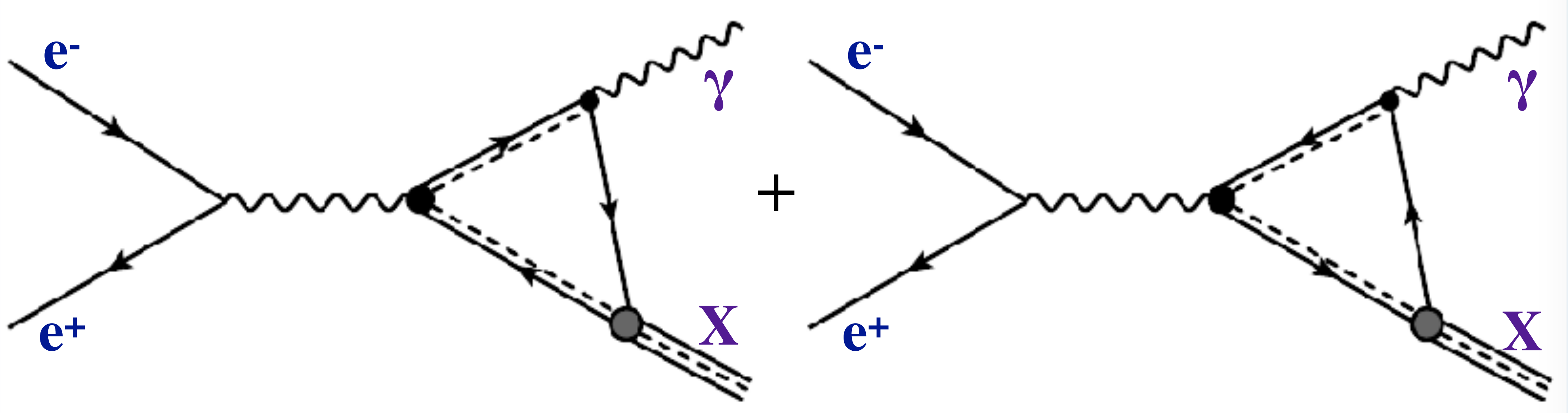
- ❖ Line shape of $X\gamma$ has narrow peak a few MeV above $D^{*0}\bar{D}^{*0}$ threshold
- ❖ σ[$X\gamma$]: of order 1pb near the peak

production of X(3872) + γ in e^+e^- annihilation

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 $X\gamma$

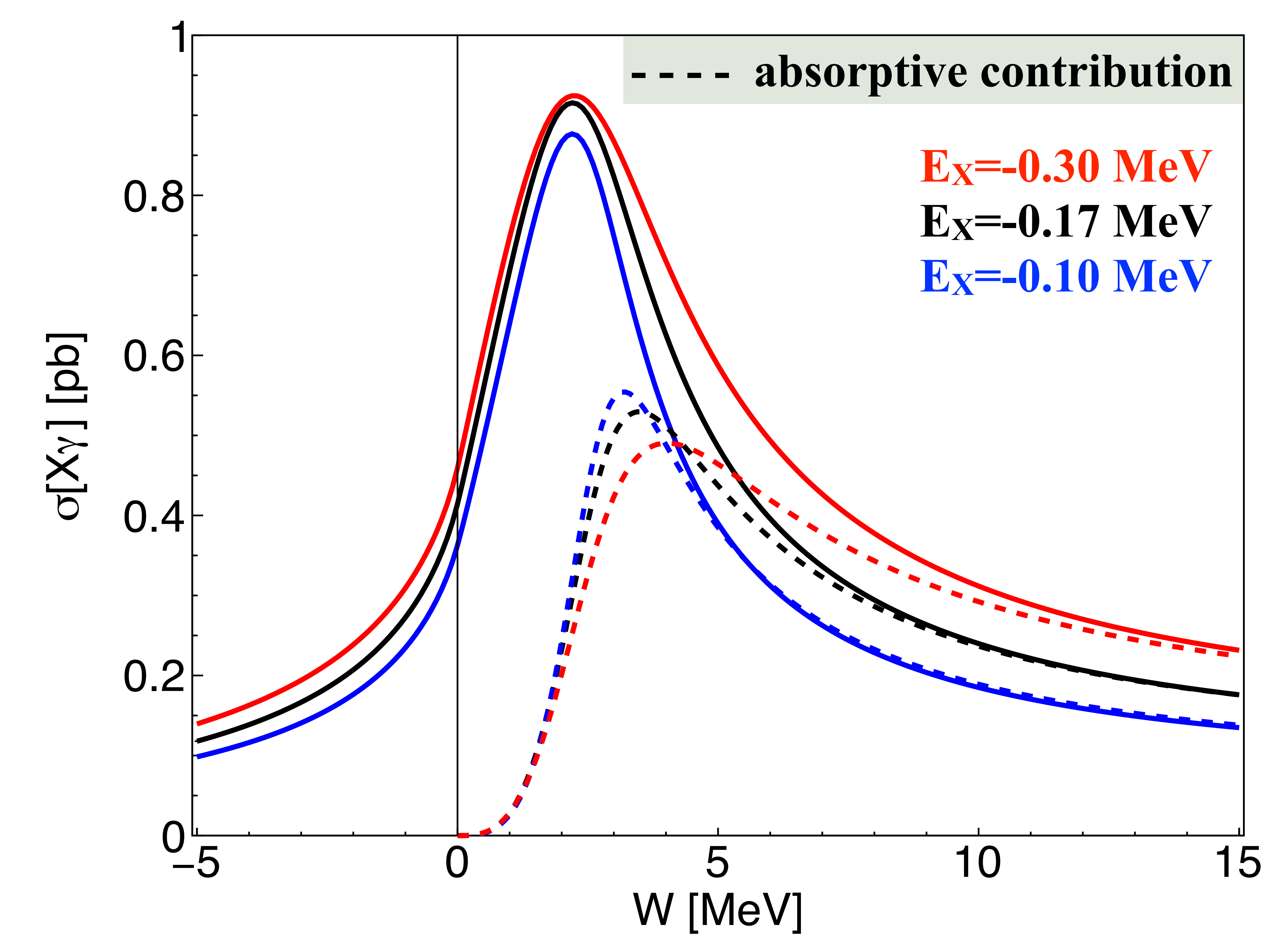


∗ improvements over Dubynskiy & Voloshin:

- ❖ 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 for Xγ

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



∗ cross section:

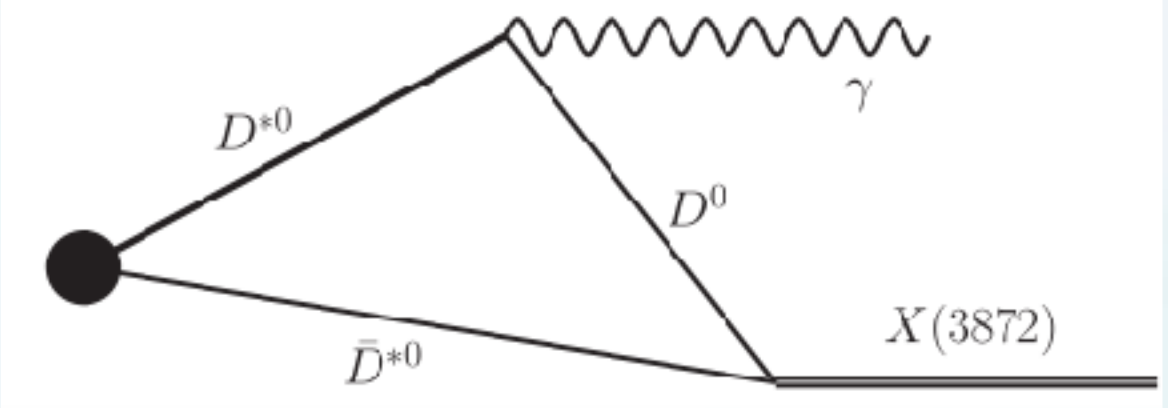
- ❖ triangle singularity gives narrow peak at 2.2 MeV
  above $D^{*0}\bar{D}^{*0}$ threshold at 4013.7 MeV
- ❖ position of peak insensitive to binding energy
- ❖ may be observable by BESIII detector!

absorptive contribution only is not a good approximation!

production of X(3872) + γ in e^+e^- annihilation

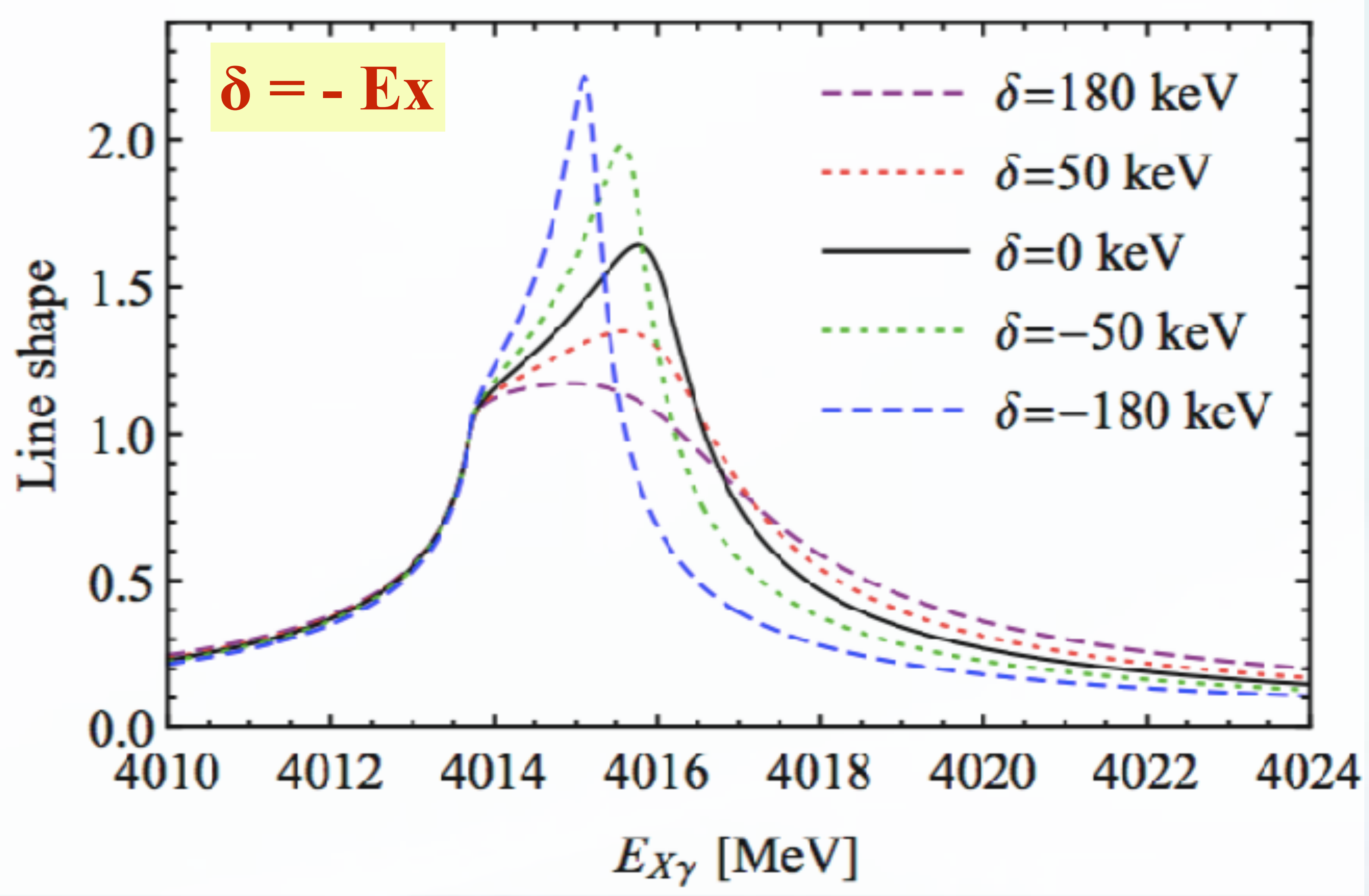
- **Guo** [PRL 112, 202002 (2019)]

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



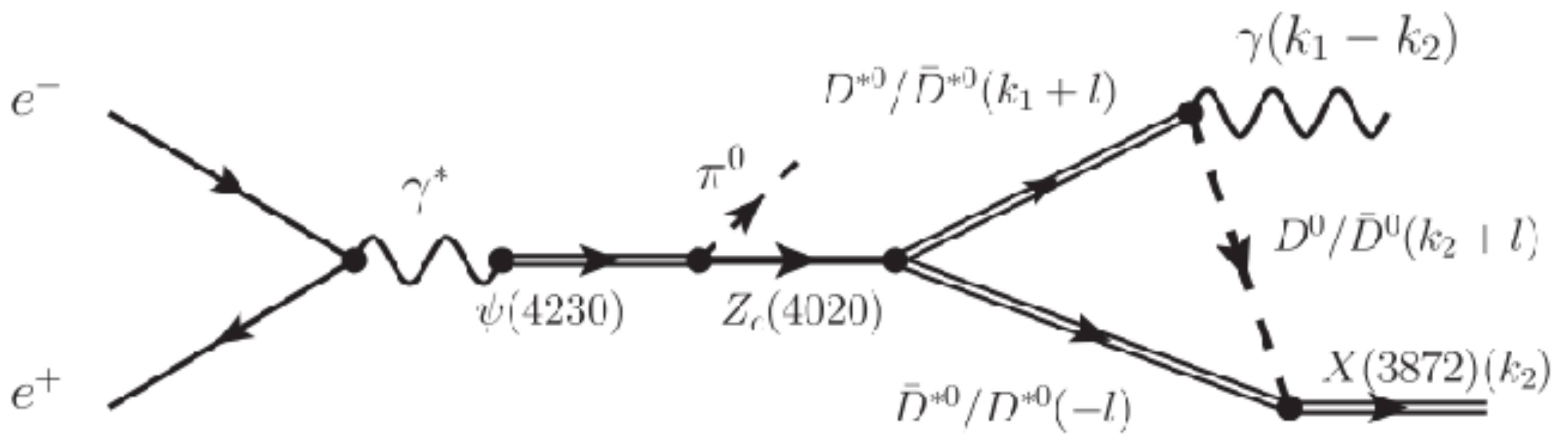
Line shape in Xγ:

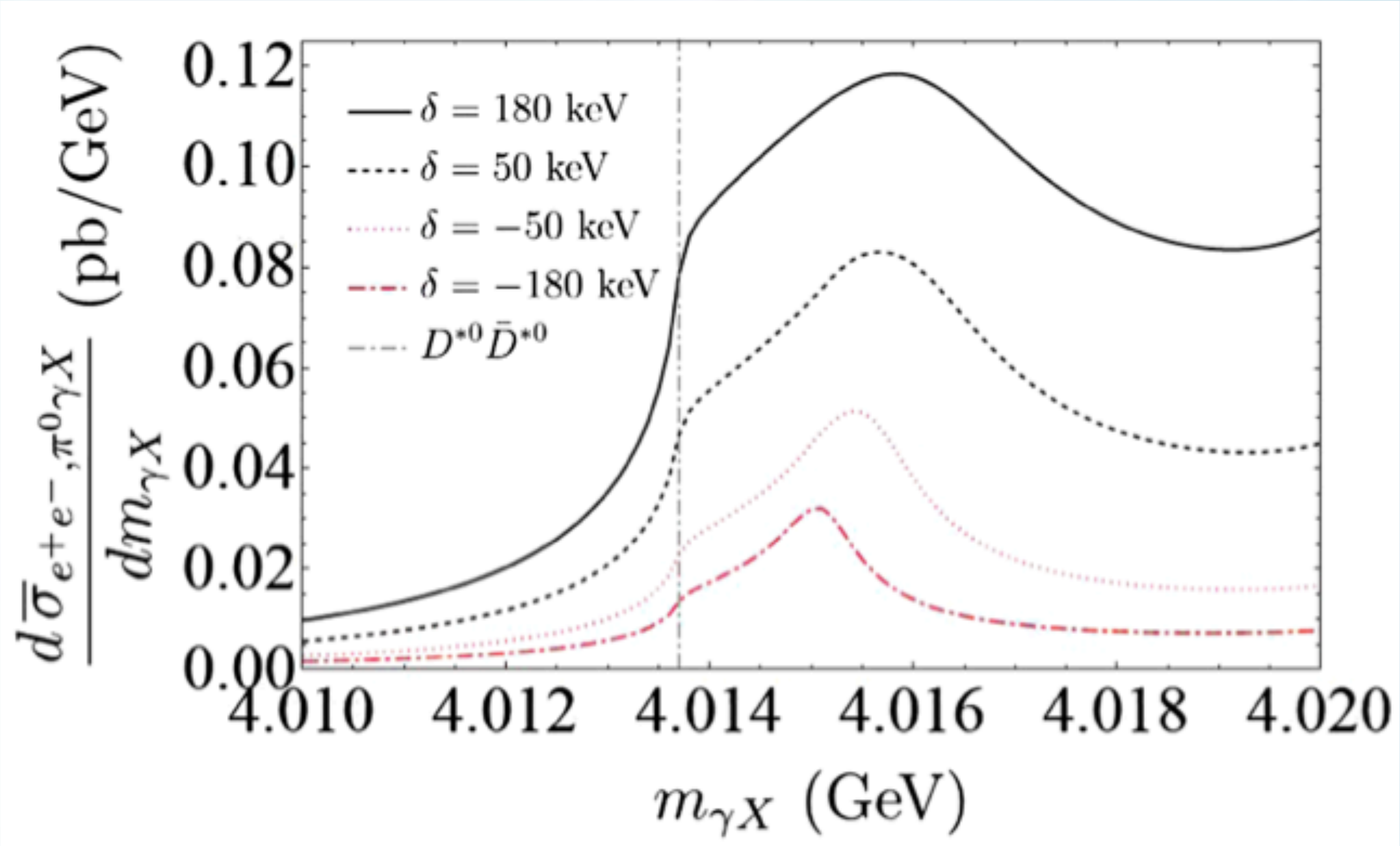
- peak a few MeV above $D^{*0}\bar{D}^{*0}$ threshold
- can be used to measure E_X



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

$e^+e^- \to$ Zc(4020) π^0, Zc(4020) → $D^{*0}\bar{D}^{*0}$(S-wave) → Xγ

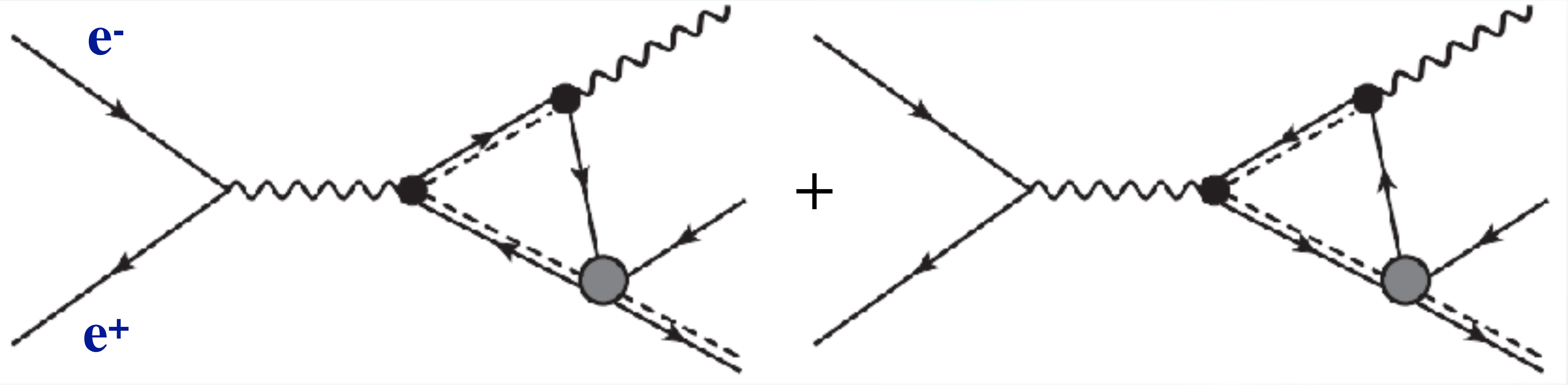


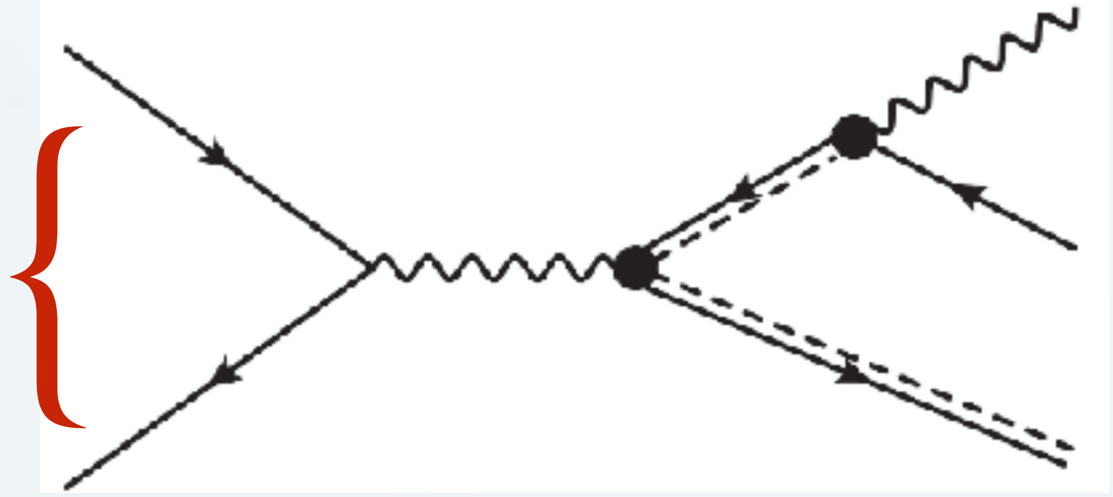


- **BESIII** [arXiv:2101.00644]: no significant signal
  $e^+e^- \to$ Zc(4020) π^0, Zc(4020) → $D^{*0}\bar{D}^{*0}$(S-wave) → Xγ

production of $D^{*0}\bar{D}^0 + \gamma$ in e^+e^- annihilation

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



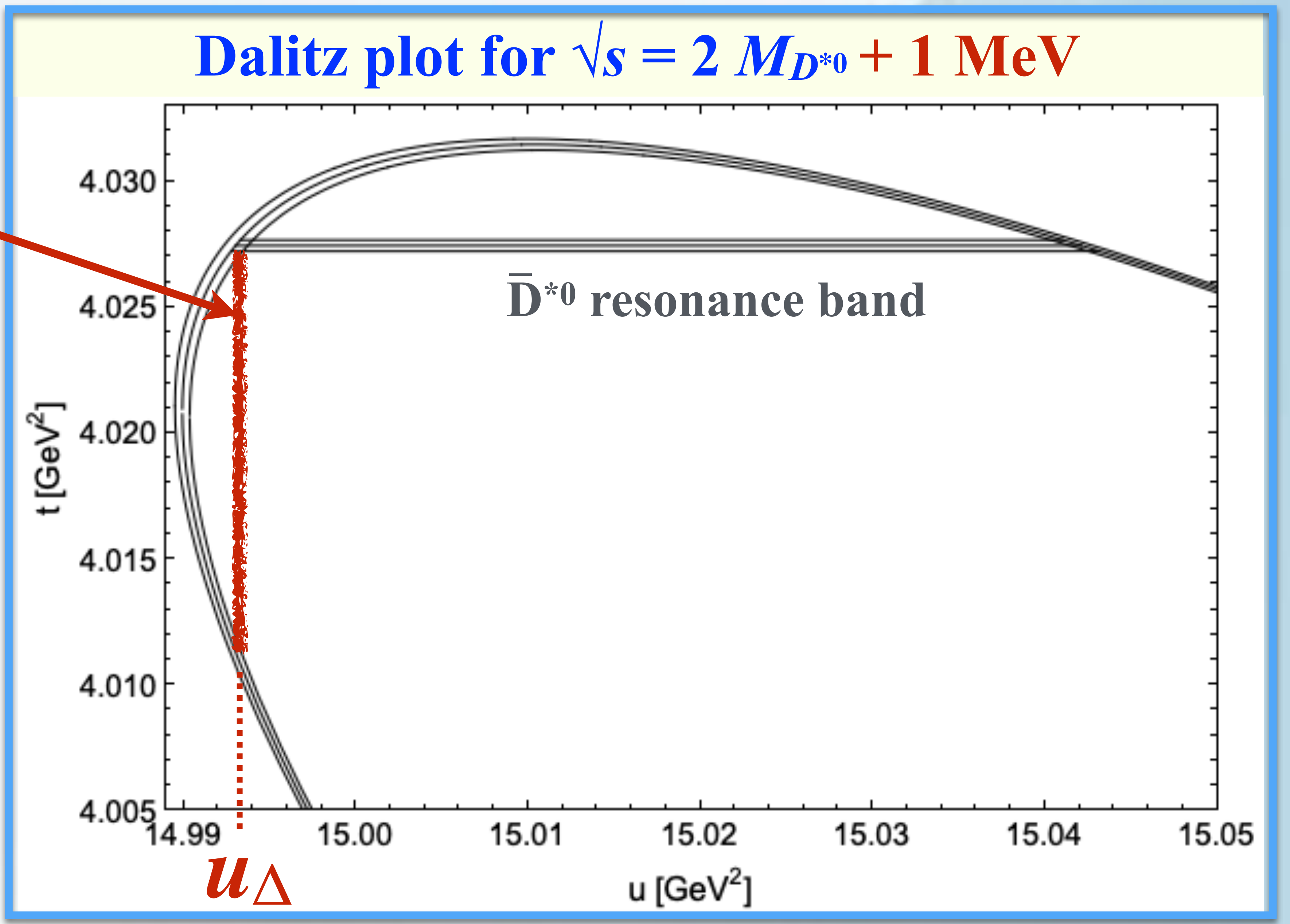


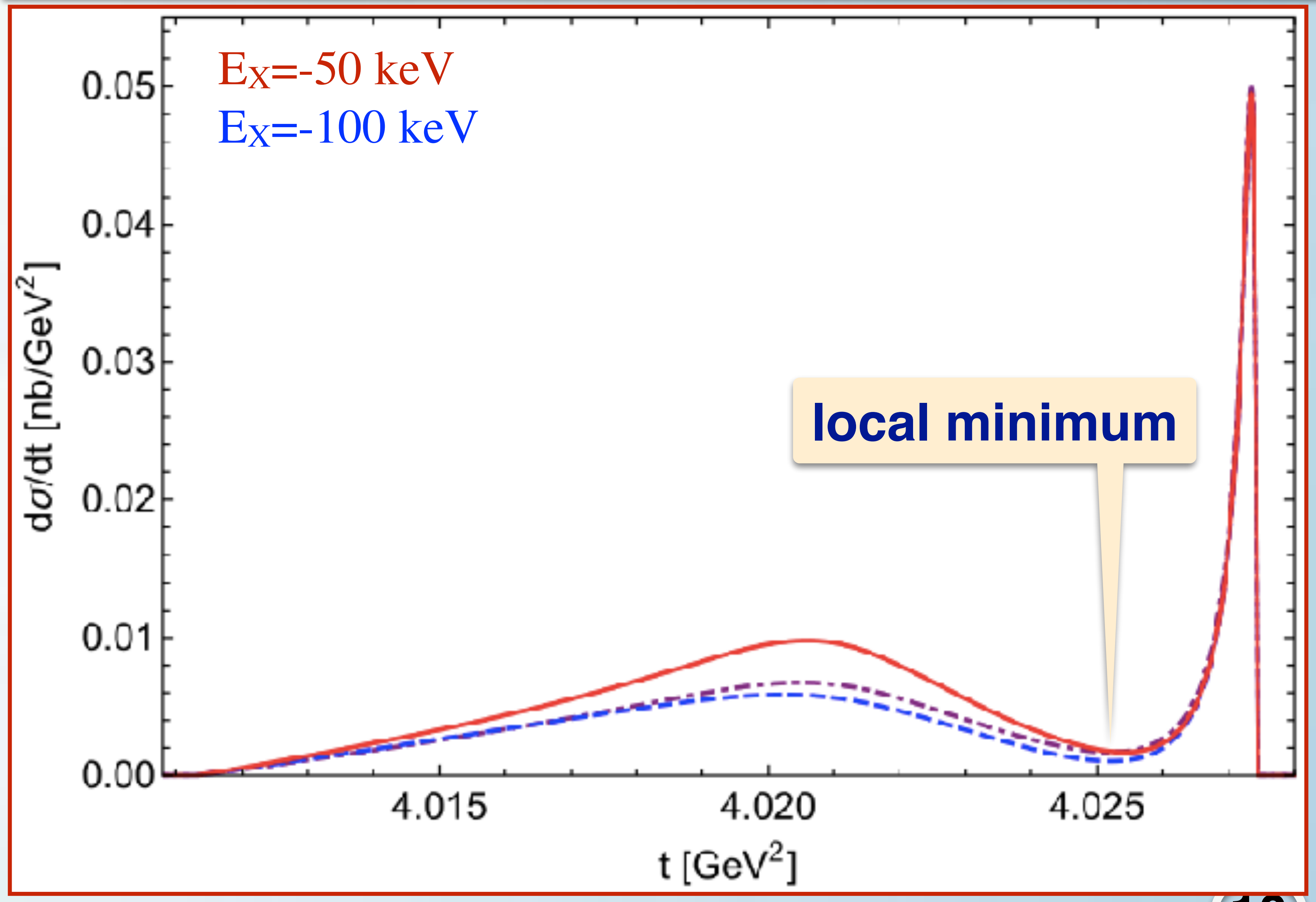
s

t = ($\bar{D}^0$ γ 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: log² 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

production of X(3872) + π from B meson decay

Belle [PRD 91, 051101 (2015)]

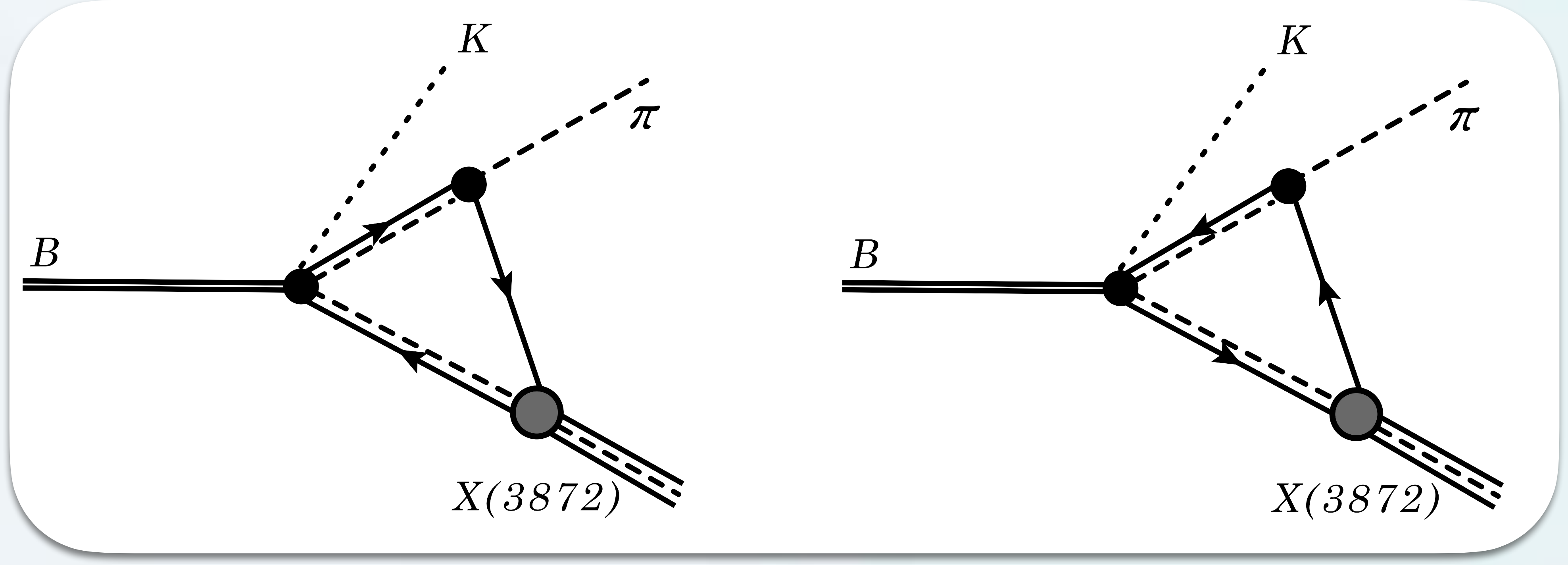
first observation of $B^0 \to K^+ \pi^- X$, $B^+ \to K^0 \pi^+ X$

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

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

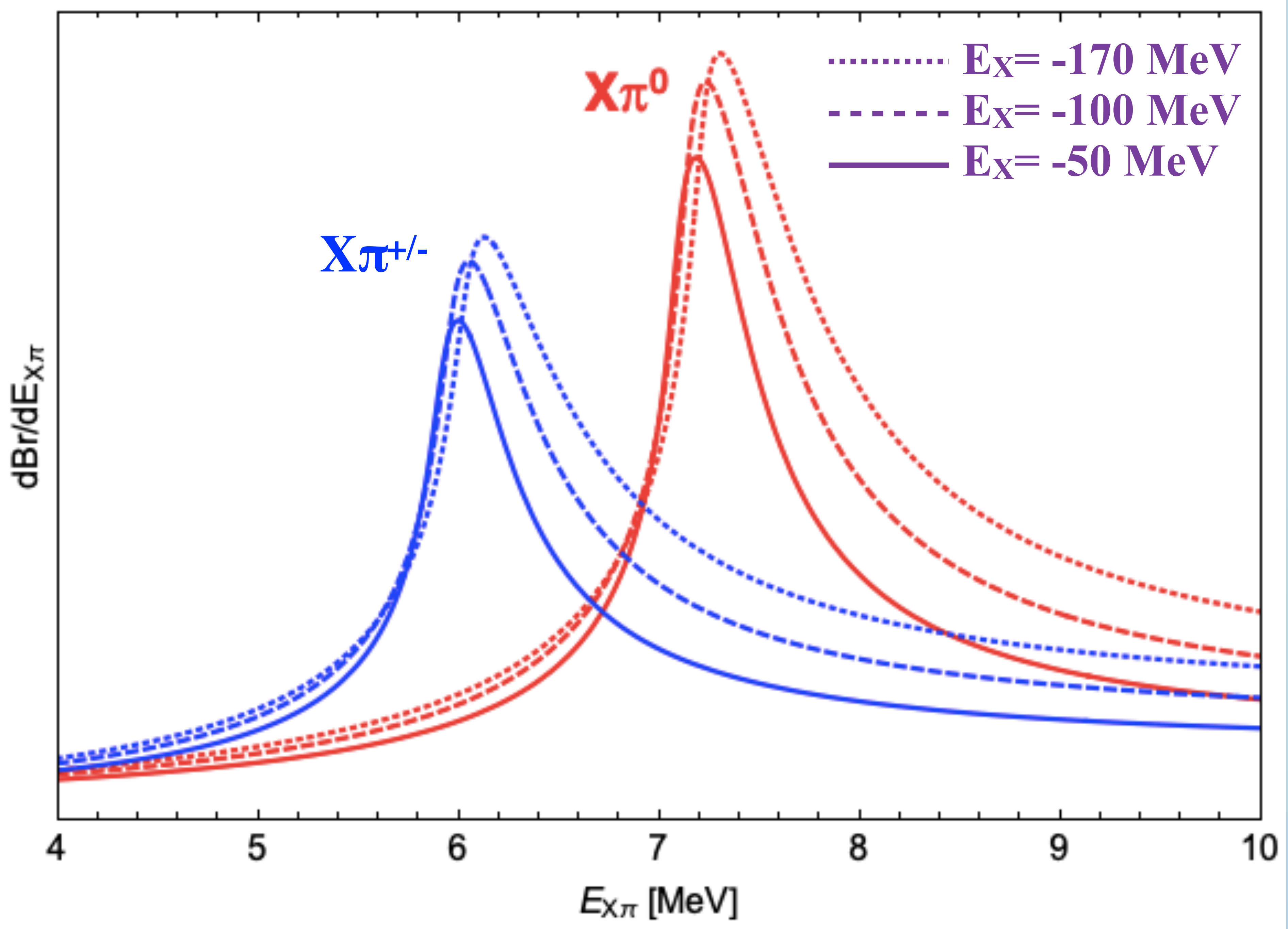
$B \to K\ D^*\bar{D}^* \to K\ X\pi$

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



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

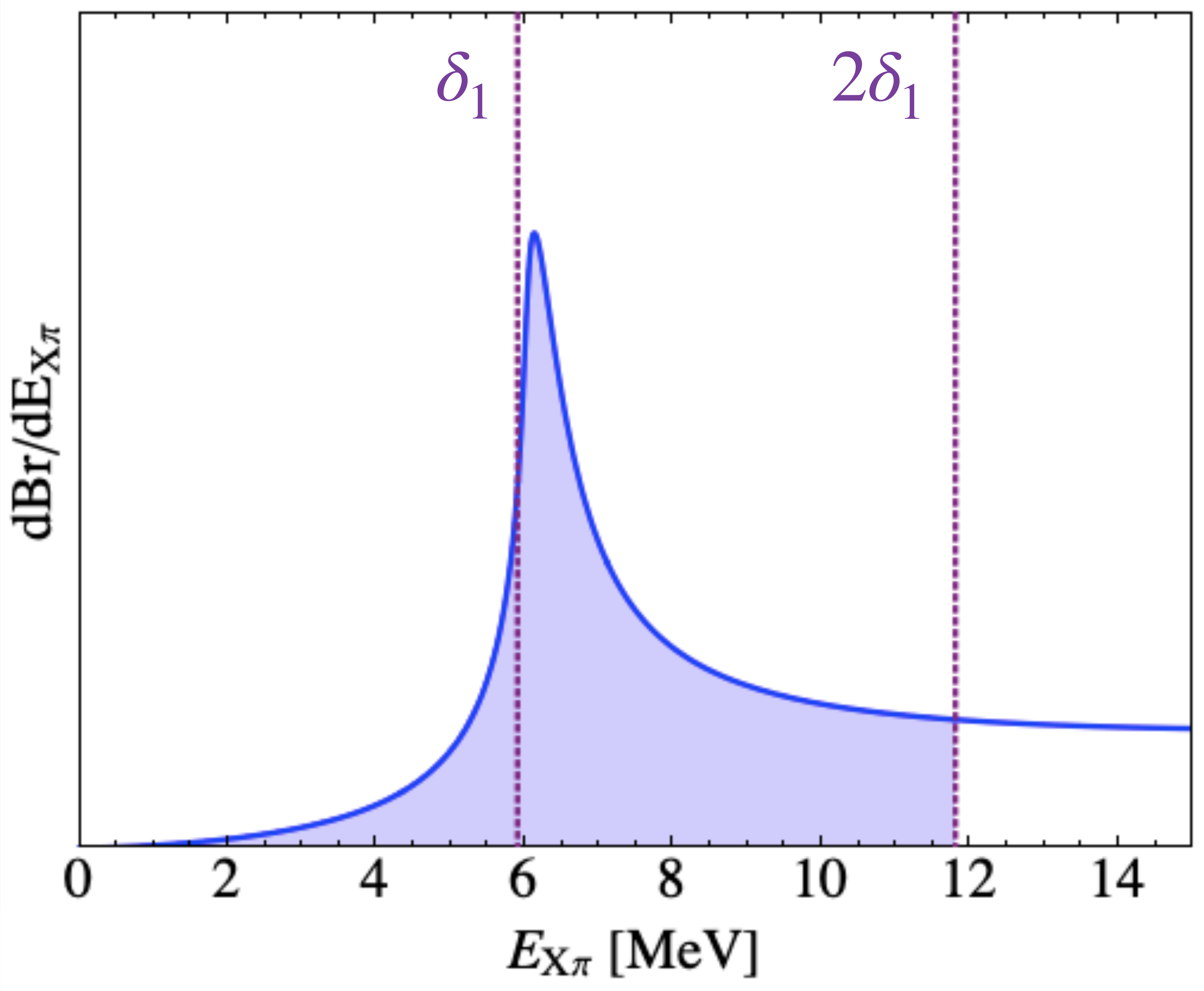


production of X(3872) + π from B meson decay

branching fractions for $X\pi^{\pm}$ from the peak:

integrated over

$E_{X\pi} \leq 2\delta_1 = 11.8$ **MeV,** $\delta_1 = M_{D^{*+}} - M_{D^0} - m_{\pi^+}$



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

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

$|E_X| = 0.17$ **MeV**

6×10^{-7}

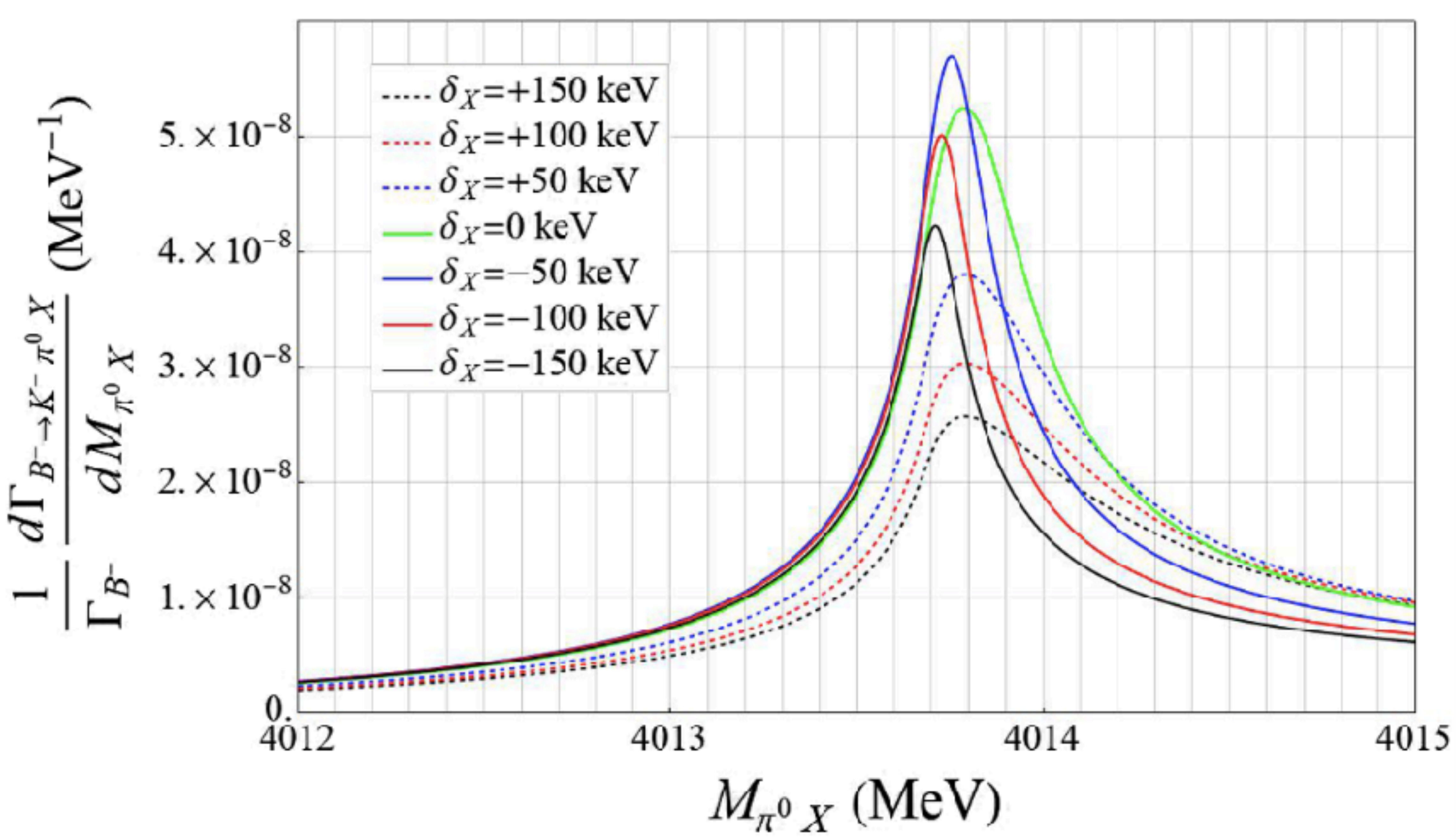
could contribute an observable fraction of the decay of $B^0 \to K^+ X\pi^-$

production of X(3872) + π from B meson decay

- **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)]

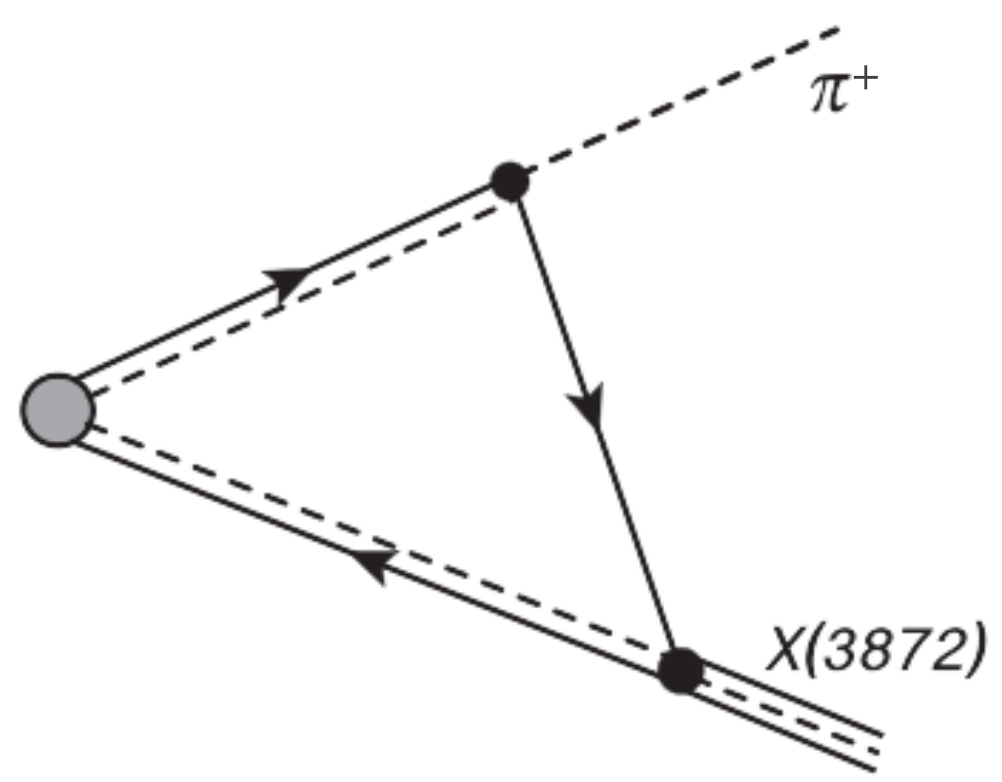
$B^- \to K^- X,\ X \to (D^*\bar{D}, \bar{D}^*D) \to \pi^0(\pi^+\pi^-)$

triangle singularity in decay of X

prompt production of X(3872) +π at Hadron colliders

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

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



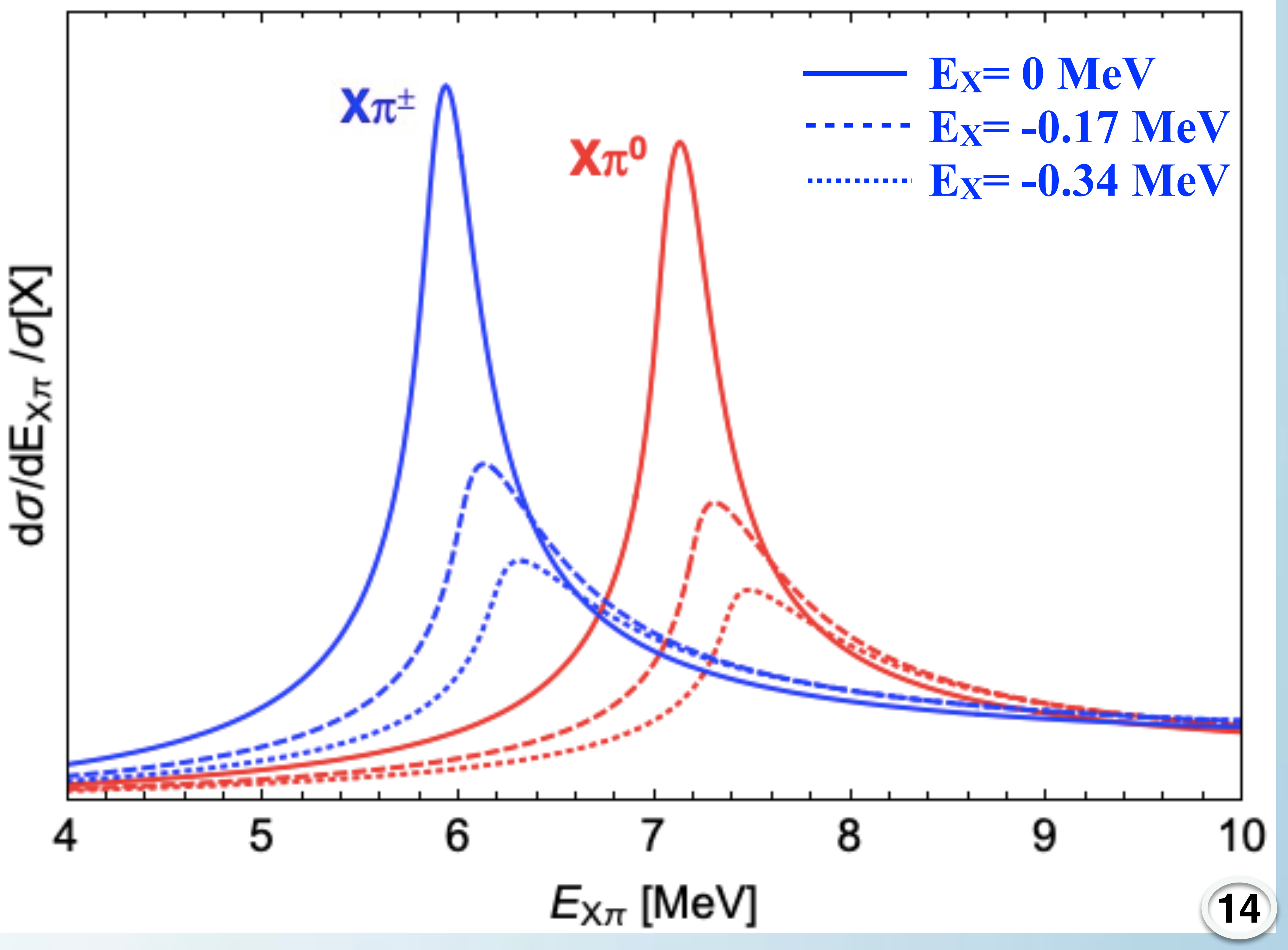
- creation of $D^{*+}\bar{D}^{*0}$ at short distance
- rescattering of virtual $D^{*+}\bar{D}^{*0}$ into $X\pi^+$

estimated ratio of cross sections:

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

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

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



Experimental observation of X(3872) $+\pi^{\pm}$ in $p\bar{p}$ collisions

D0 Collaboration [PRD 102, 072005 (2020)]

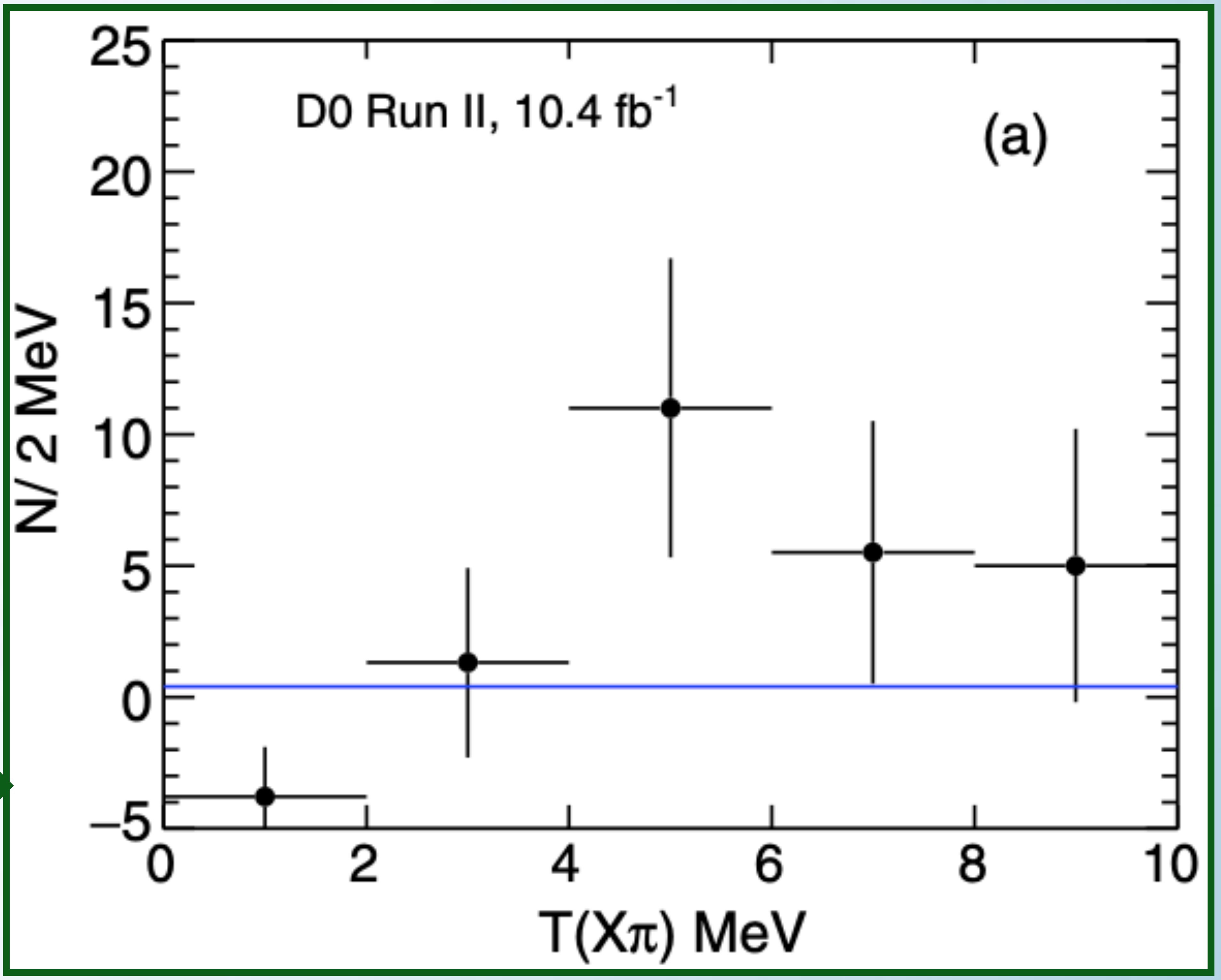
prompt and b-hadron decay production of X(3872) + soft $\pi^{\pm}$

$\mathrm{T}(X\pi) < 11.8\ \mathrm{MeV}$	observed events	X + random π
prompt production:	18 ± 16	6
b-decay:	27 ± 12	2

conclusions:

* prompt production: no evidence for an enhancement as expected from the triangle singularity
* b-decay: no "significant" evidence for an enhancement as expected from the triangle singularity

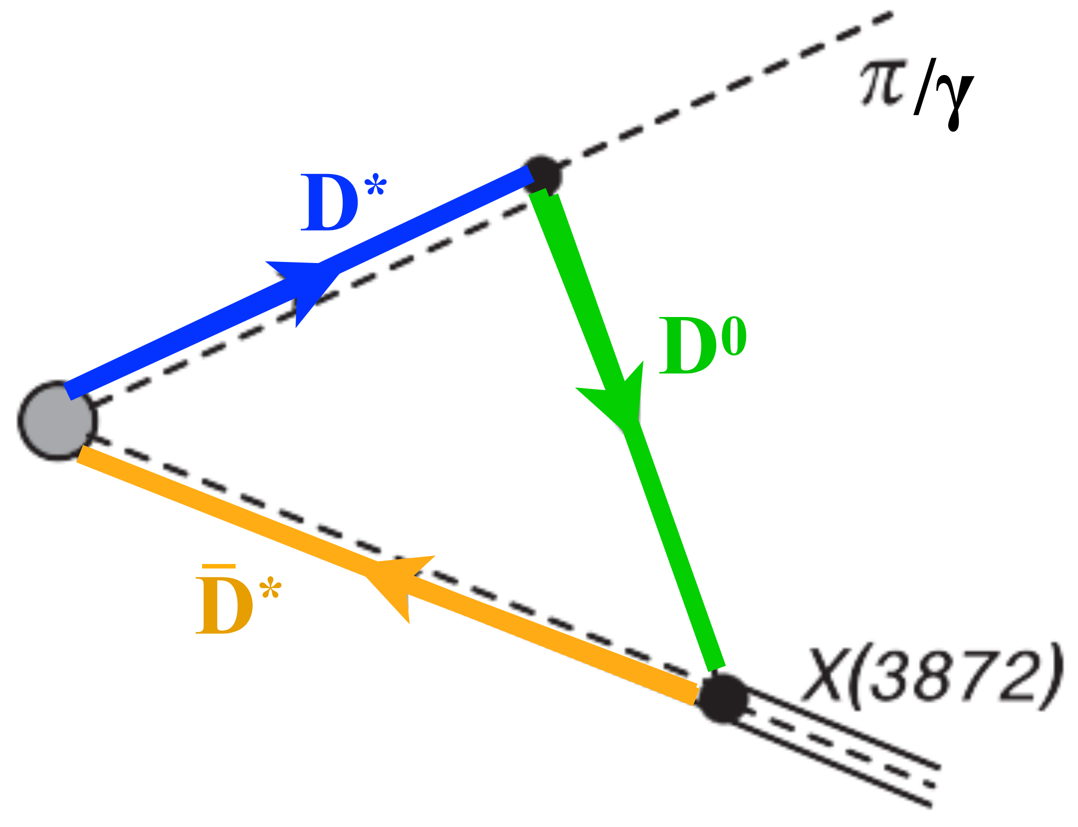
a small excess in small $T(X\pi)$ region, significance of 2σ



Summary

Production of X+γ or X+π

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



- **e⁺e⁻ annihilation**
  - ◇ σ[Xγ]: 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
  - ◇ could be observed by Belle II or LHCb
- **Hadron colliders**
  - ◇ $d\sigma[X\pi^\pm]/dE_{X\pi}$: peak near 6.1 MeV above $X\pi^+$ threshold
  - ◇ hint of peak at $p\bar{p}$ collider by D0
  - ◇ could be observed at pp collider by LHCb, CMS, ATLAS

Thank you!

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

Backup

B meson decay

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

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

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

$$Br[B^0 \to K^+X\pi^-]Br[X \to J\psi\pi^+\pi^-]$$
$$= (7.9 \pm 1.3 \pm 0.4)\times 10^{-6}$$

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

Hadron collider

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

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

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

✦ **prompt production by QCD mechanisms:**

decay products emerge from primary collision vertex

✦ **production by *b* hadron decay:**

decay products emerge from displaced secondary vertex