Momentum distributions for the $D^0\bar{D}^0\pi^0$ and $D^0\bar{D}^0\gamma$ decay modes of the X(3872) resonance

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Outline

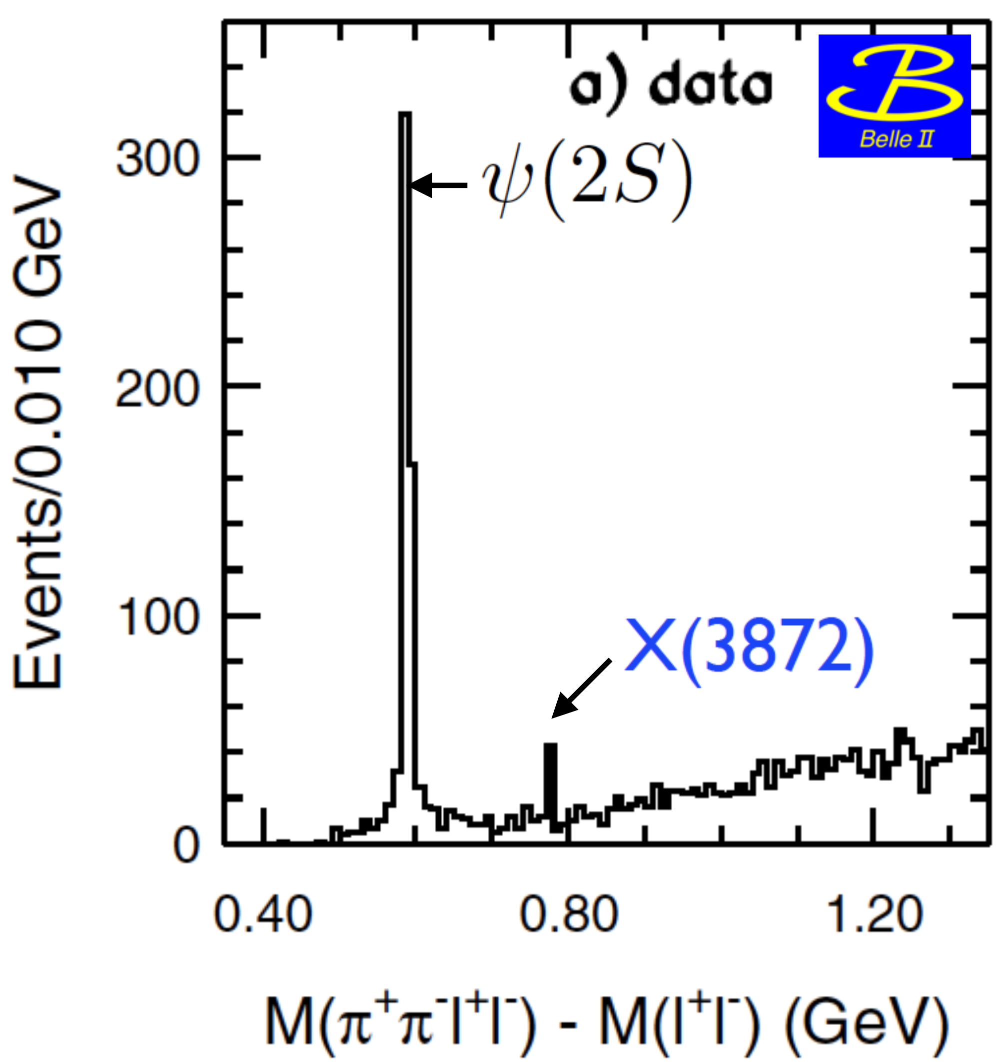
- Introduction to the X(3872)
- Universal properties of near- threshold S-wave resonance
- Line shapes for $D^0 \bar{D}^0 \pi^0$ / $D^0 \bar{D}^0 \gamma$
- Momentum distributions for $D^0 \bar{D}^0 \pi^0$ / $D^0 \bar{D}^0 \gamma$
- Summary

Introduction to the X(3872)

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

PRL 91,262001(2003)

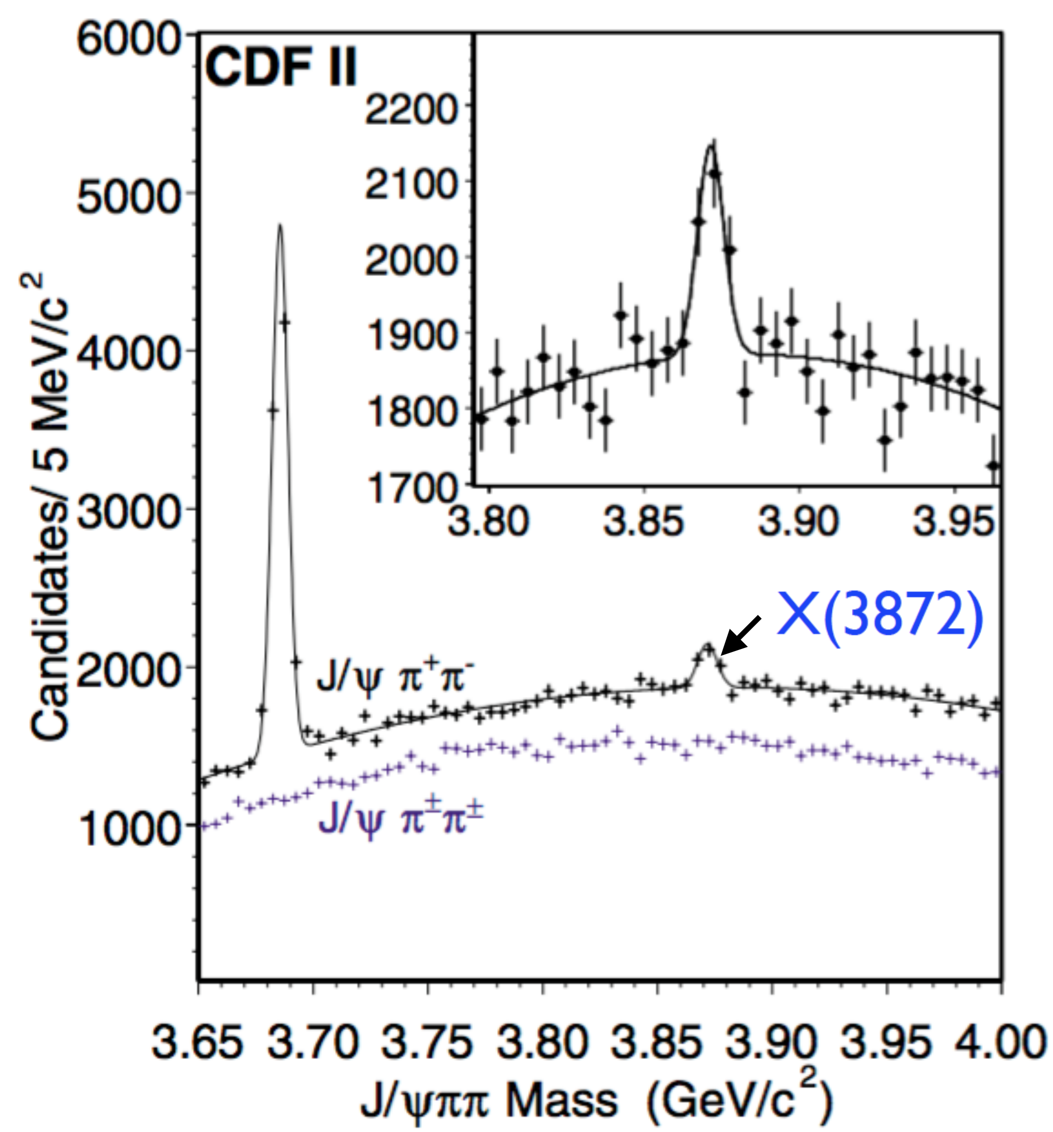
$$B^+ \longrightarrow K^+ + X$$
$$X \longrightarrow J/\psi\, \pi^+\pi^-$$



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

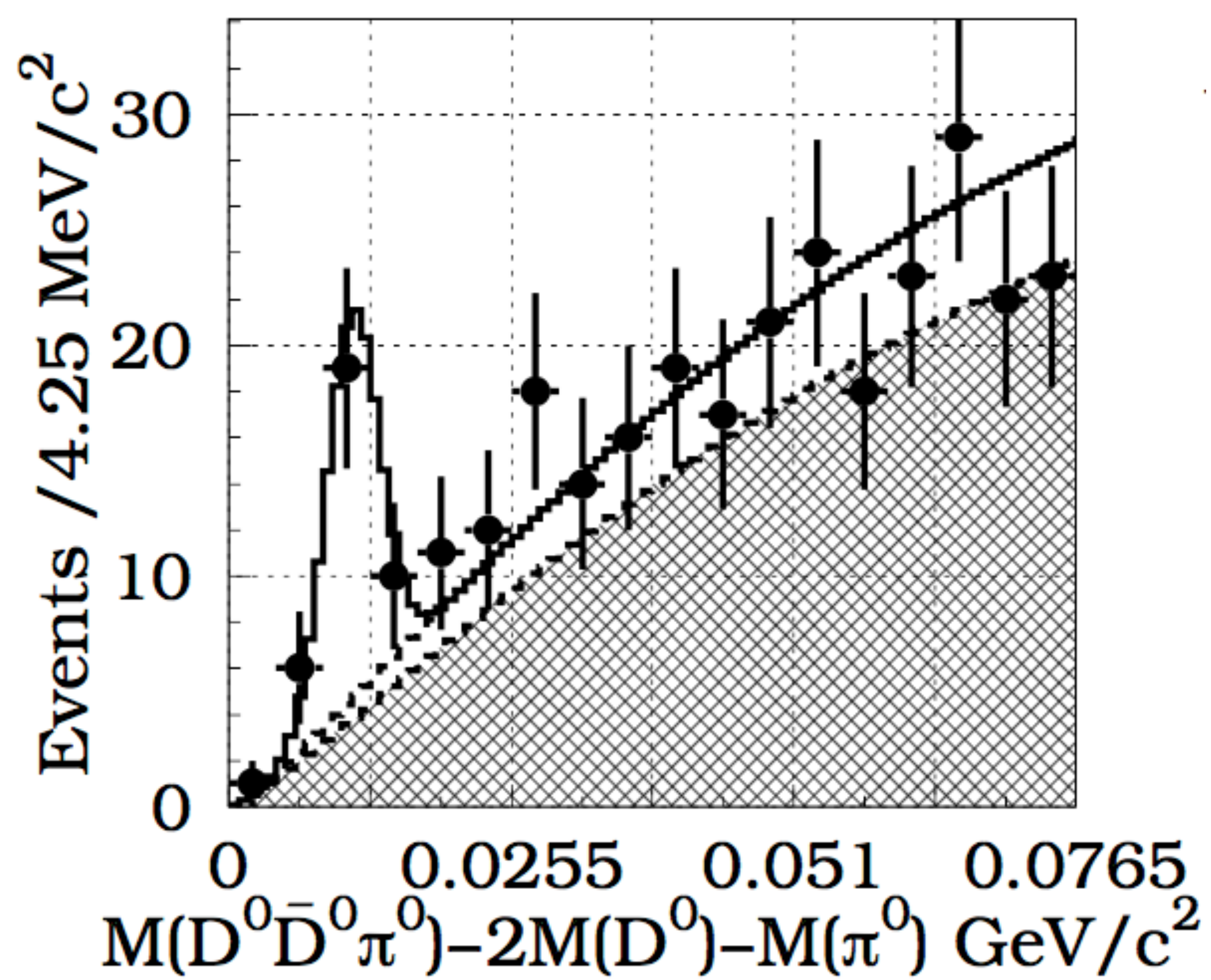
PRL 91,262001(2004)

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



Introduction to the X(3872)

- **Observation of $D^0\bar{D}^0\pi^0$ decay mode**
  - **Belle Collaboration (2006)** [PRL 97, 162002]



Introduction to the X(3872)

- **Mass: 3871.69 ± 0.17 MeV (PDG 2017)**

$$M_X - (M_{*0} + M_0) = (+0.01 \pm 0.18)\ \mathrm{MeV}$$

$$D^{*0}\bar{D}^0\ \textbf{threshold} = 3871.68 \pm 0.07\ \textbf{MeV}$$

- **Width: < 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** $D^{*0}\bar{D}^0$ **threshold**

    → **resonant coupling**

- **Conclusion: X(3872) is a charm meson molecule!**

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

Universal properties

Nonrelativistic Quantum Mechanics:

- Short-range interactions
- S-wave resonance close enough to threshold

large scattering length a (>> range)

→ universal features depend only on a, insensitive to shorter distances

X(3872) close to $D^{*0}\bar{D}^0$ threshold

→ universal features depend only on large scattering length a or complex inverse scattering length γ (1/a) for $D^{*0}\bar{D}^0$

Line shapes

The energy distribution summed over all resonant channels:

$$\frac{dR}{dE}[\text{total}] = R_0 \frac{\mathrm{Re}\left[\sqrt{2\mu(E + i\Gamma_{*0}/2)}\,\right] + \mathrm{Im}[\gamma]}{\left|-\gamma + \kappa(E)\right|^2}$$

R_0: normalization factor depends on production mechanism.

$$\kappa(E) = \sqrt{-2\mu(E + i\Gamma_{*0}/2)}$$

***E*: energy relative to the $D^{*0}\bar{D}^0$ threshold**

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

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

$D^0\bar{D}^0\pi^0 / D^0\bar{D}^0\gamma$

inelastic channels:

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

pole at *E* = $-E_X - i\Gamma_X/2$

$$\rightarrow \gamma = \sqrt{2\mu(E_X + i(\Gamma_X - \Gamma_{*0})/2)}$$

Previous theoretical work on $D^0\bar{D}^0\pi^0$ and $D^0\bar{D}^0\gamma$

- **Voloshin** [PLB 579, 316 (2004)]:
  - interference between $D^{*0}\bar{D}^0/\bar{D}^{*0}D^0$:

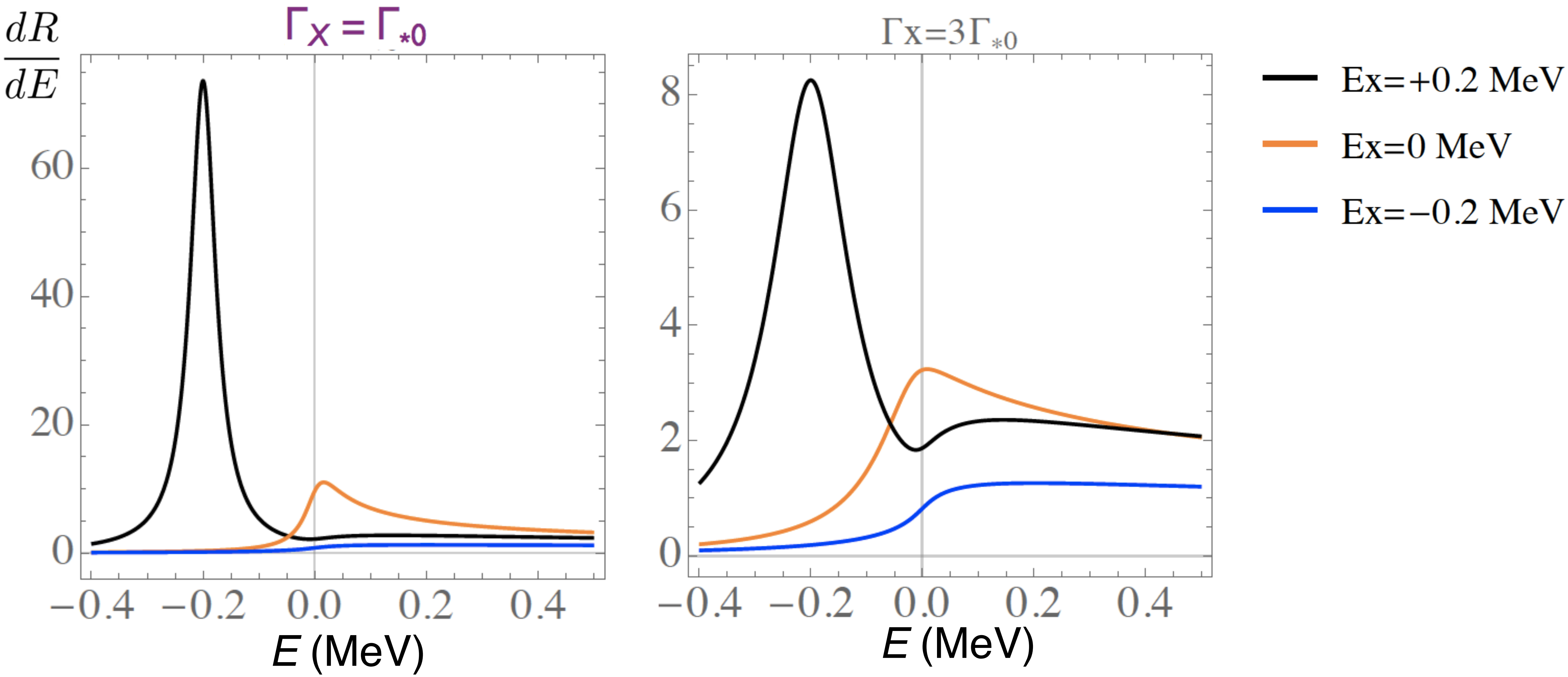
    $J^{PC}=1^{++}$ → constructive in $D^0\bar{D}^0\pi^0$
    destructive in $D^0\bar{D}^0\gamma$

  - momentum distributions reveal inner structure of X(3872)

- **Voloshin** [Int.J.Mod.Phys.A21 (2006)]
- **Colangelo, Fazio, Nicotri** [PLB 650, 166 (2007)]
- **Guo, Hidalgo-Duque, Nieves, Ozpineci, Valderrama** [Eur. Phys. J. C74, 2885 (2014)]
- **Schmidt, Jansen, Hammer** [arXiv: J. C74, 1804.00375]
- …

Widths of X and D^{*0} not treated consistently.

Line shapes in $D^0\bar{D}^0\pi^0$ / $D^0\bar{D}^0\gamma$

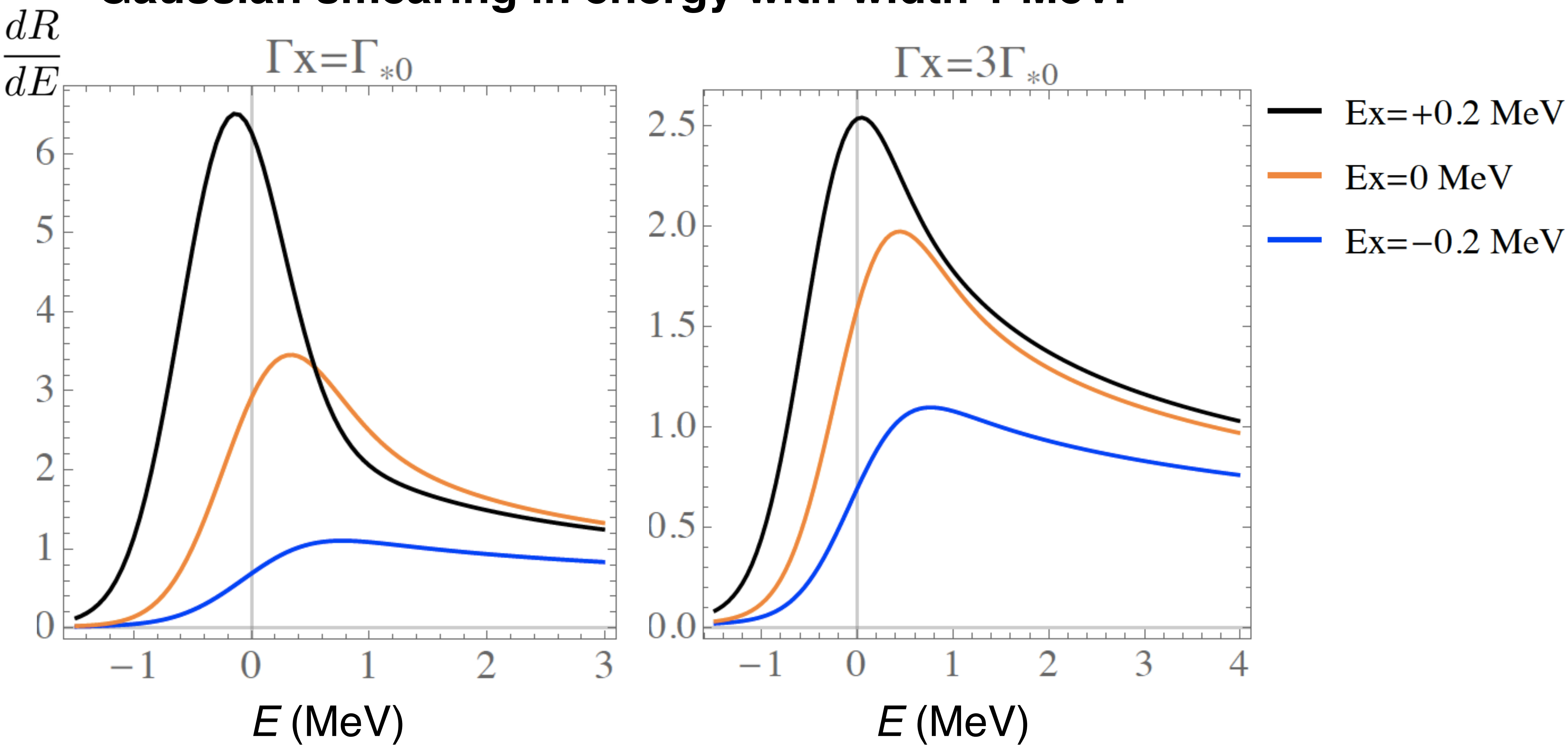


E: **energy relative to the** $D^{*0}\bar{D}^0$ **threshold.**

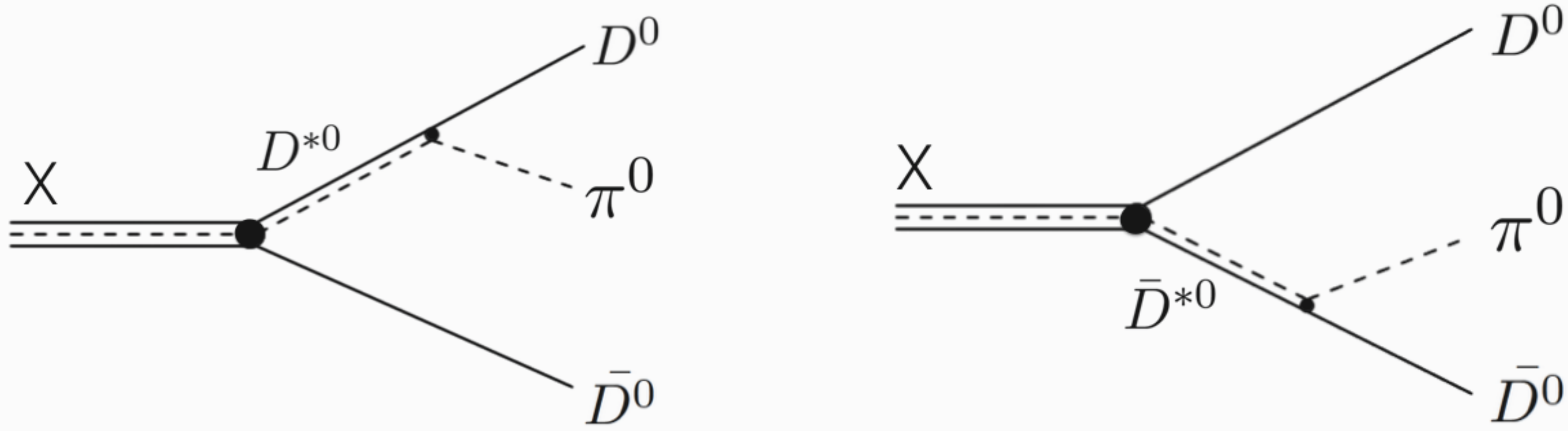
Line shape is sensitive to the binding energy Ex and decay width Γ_X

Line shapes in $D^0\bar{D}^0\pi^0$ / $D^0\bar{D}^0\gamma$

Gaussian smearing in energy with width 1 MeV:



Momentum distributions for $D^0\bar{D}^0\pi^0$ decay modes



$$\frac{dR}{dEdp} = R_0 \frac{1}{|-\gamma + \kappa(E)|^2} \frac{d\Gamma}{dp} \qquad d\Gamma = \frac{1}{3}\sum_{spin} |M|^2 d\Pi_3$$

$$\gamma = \sqrt{2\mu(E_X + i(\Gamma_X - \Gamma_{*0})/2)} \quad \kappa(E) = \sqrt{-2\mu(E + i\Gamma_{*0}/2)}$$

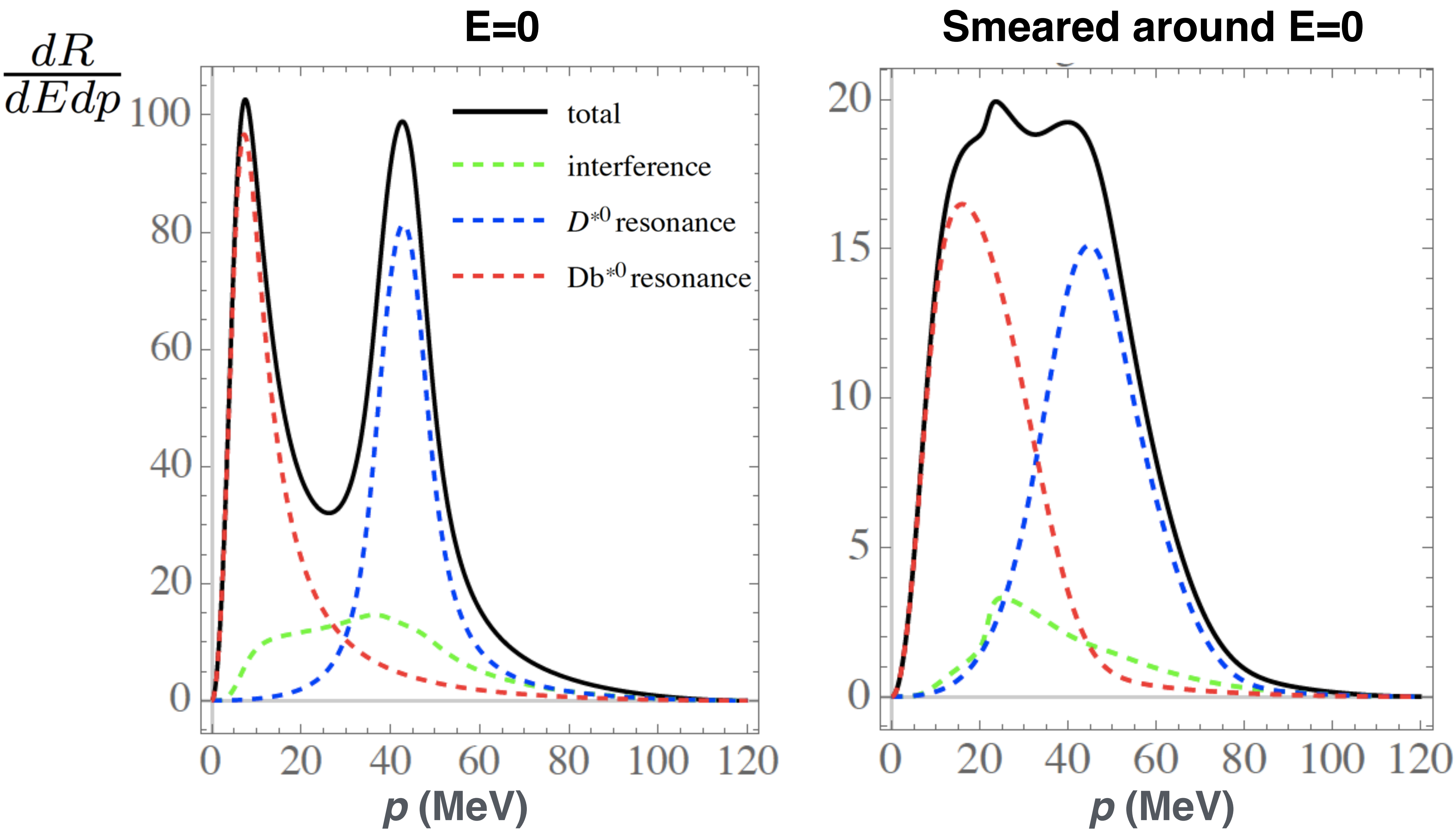
Kinematic variables in $D^0\bar{D}^0\pi^0$ rest frame:

E **= energy of $D^0\bar{D}^0\pi^0$ relative to $D^{*0}\bar{D}^0$ threshold**
p **= momentum of D^0**

The shape of D^0 momentum distribution is insensitive to the binding energy and width of X(3872) at fixed energy

Momentum distributions for $D^0 \bar{D}^0 \pi^0$ decay modes

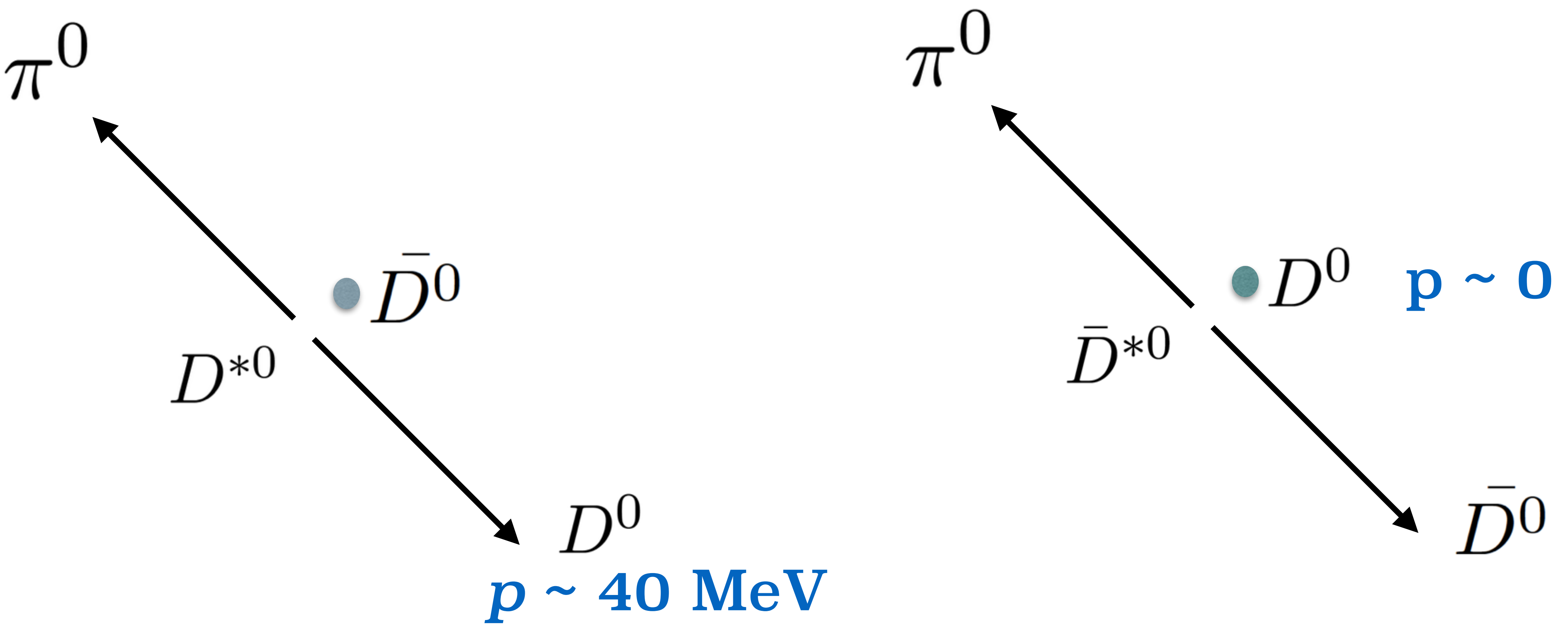
At Ex=0, $\Gamma_X = \Gamma_{*0}$:



Two peaks → **One wider peak**

Momentum distributions

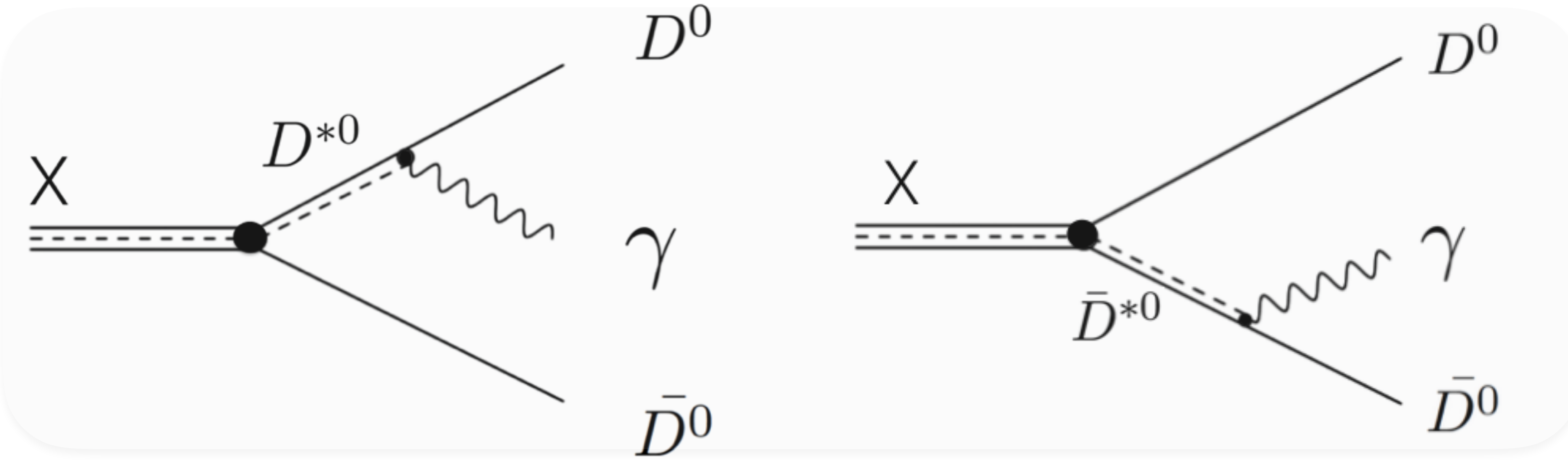
Explanation to double peak structure:



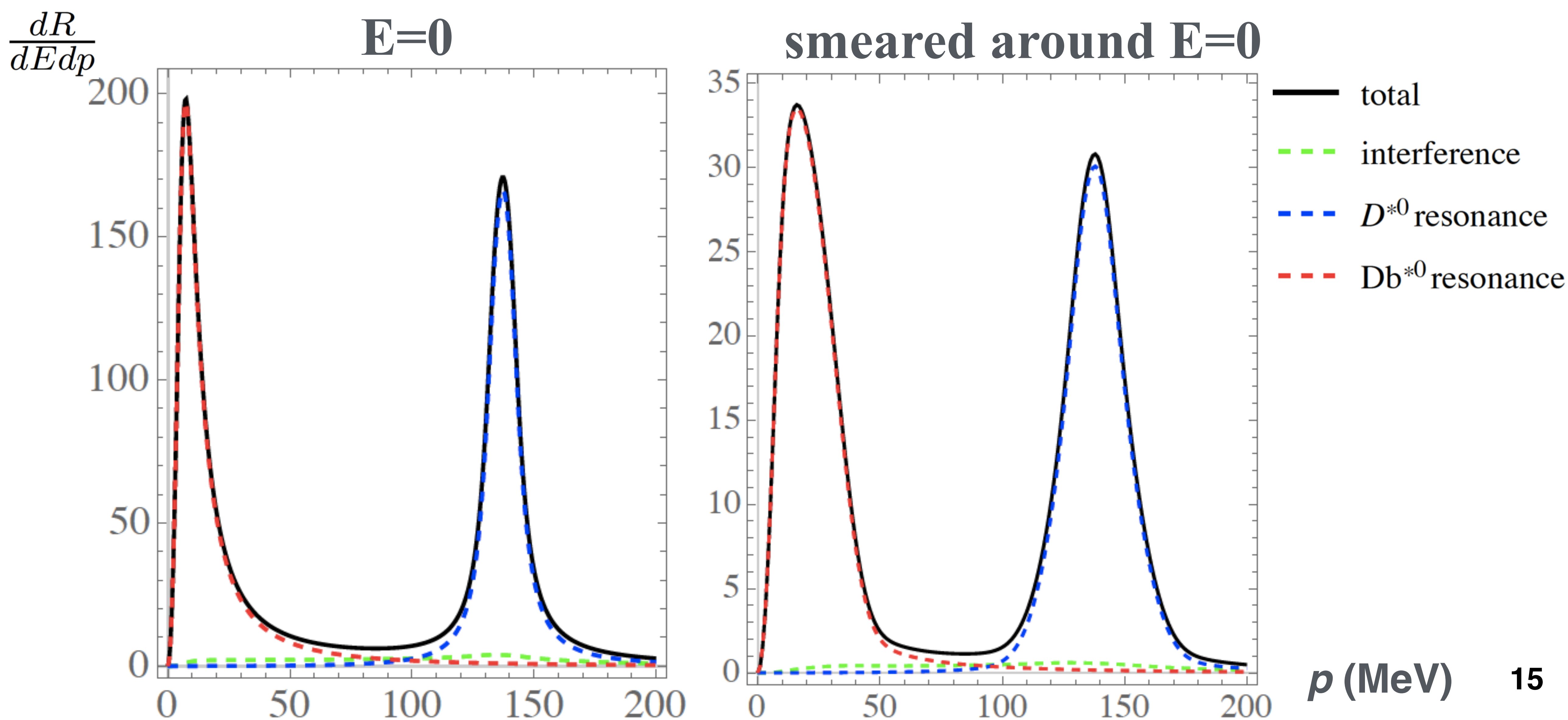
$D^0\bar{D}^0\pi^0$: **peaks are near p~0 and p~ 40 MeV**

$D^0\bar{D}^0\gamma$: **peaks are near p~0 and p~ 140 MeV**

Momentum distributions for $D^0 \bar{D}^0 \gamma$ decay modes



At Ex=0, $\Gamma_X = \Gamma_{*0}$:



Summary

- Double peaked structure in D^0 momentum distributions for $D^0\bar{D}^0\pi^0$ and $D^0\bar{D}^0\gamma$ decay modes of the X(3872).

- First consistent theoretical treatment of width of X and D^{*0}.

- Position and width of the peaks are insensitive to the binding energy and width of X(3872)

- Smearing from experimental energy resolution :

* two peaks for $D^0\bar{D}^0\pi^0$ smeared together
* two peaks for $D^0\bar{D}^0\gamma$ still separated

- The D^0 momentum distributions should be measured at Belle II.

Thank you!

backup slides

- **Branching ratios:**

$$\frac{\mathrm{Br}[X \to J/\psi\, \pi^+\pi^-\pi^0]}{\mathrm{Br}[X \to J/\psi\, \pi^+\pi^-]} = \begin{cases} 1.0 \pm 0.5 & \textbf{Belle} \\ 0.8 \pm 0.3 & \textbf{BaBar} \end{cases}$$

$J/\psi\, \pi^+\pi^-\pi^0 \approx J/\psi\, \omega^*$ → **isospin 0**

$J/\psi\, \pi^+\pi^- \approx J/\psi\, \rho^*$ → **isospin 1**

- **large violation of isospin symmetry**
- **stronger coupling to isospin 0**

$$\frac{|G_{X\, J/\psi\, \rho}|^2}{|G_{X\, J/\psi\, \omega}|^2} \approx 0.08 \pm 0.04$$

$$\mathcal{L}_{X D^{*0} D^0} = G g_{\mu\nu} X^\mu D^{*0\nu\dagger} D^{0\dagger} + h.c.,$$

$$\mathcal{L}_{D^{*0} D^0 \gamma} = g_\gamma \epsilon_{\mu\nu\alpha\beta} \partial^\beta D^{*0\nu} D^{0\dagger} \partial^\alpha A^{\mu\dagger} + h.c.$$

$$\mathcal{L}_{D^{*0} D^0 \pi^0} = \frac{g}{2\sqrt{m_0} f_\pi (M_0 + m_0)} \boldsymbol{D}^{*0} [D^0 (M_0 \overrightarrow{\boldsymbol{\nabla}} - m_0 \overleftarrow{\boldsymbol{\nabla}}) \pi^0]^\dagger + h.c.$$

Γ_{*0} : width of D^{*0}, **obtained by chiral symmetry and isospin symmetry:**

$$\frac{\mathrm{Br}[D^{*0} \to D^0\pi^0]\Gamma_{*0}}{\mathrm{Br}[D^{*+} \to D^0\pi^+]\Gamma_{*1}} = \frac{1}{2}\frac{\lambda^{3/2}(M_{*0}^2, M_0^2, m_0^2)/M_{*0}^5}{\lambda^{3/2}(M_{*1}^2, M_0^2, m_1^2)/M_{*1}^5}$$

$$\Gamma_{*1} = (83.4 \pm 1.8)\ \mathrm{keV} \quad \longrightarrow \quad \Gamma_{*0} = (55.4 \pm 1.8)\ \mathrm{keV}$$

$$\frac{dR}{dE} \propto R_0 \frac{\mathrm{Re}[2\mu(E + i\Gamma_{*0}/2)]}{|-\gamma + \kappa(E)|^2}$$

$$\gamma = \sqrt{2\mu(E_X + i(\Gamma_X - \Gamma_{*0})/2)}$$

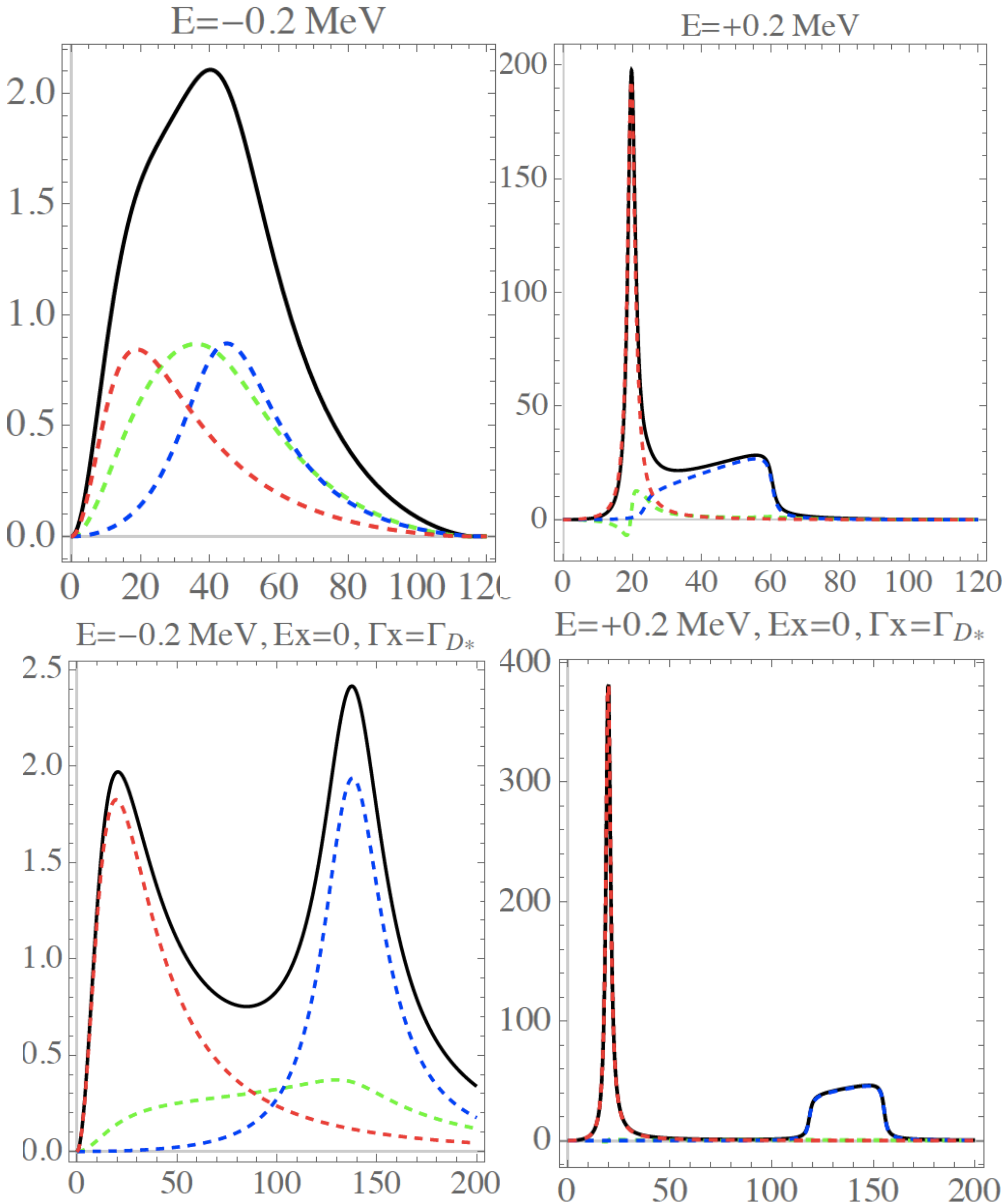
$$dR[D^0\bar{D}^0\pi^0] = R_0 \frac{1}{|-\gamma + \kappa(E)|^2} dE\, d\Gamma[D^0\bar{D}^0\pi^0]$$

Transition amplitude in the C=+ S-wave channel:

$$\mathcal{A}(E) = \frac{2\pi/\mu}{-\gamma + \kappa(E)}$$

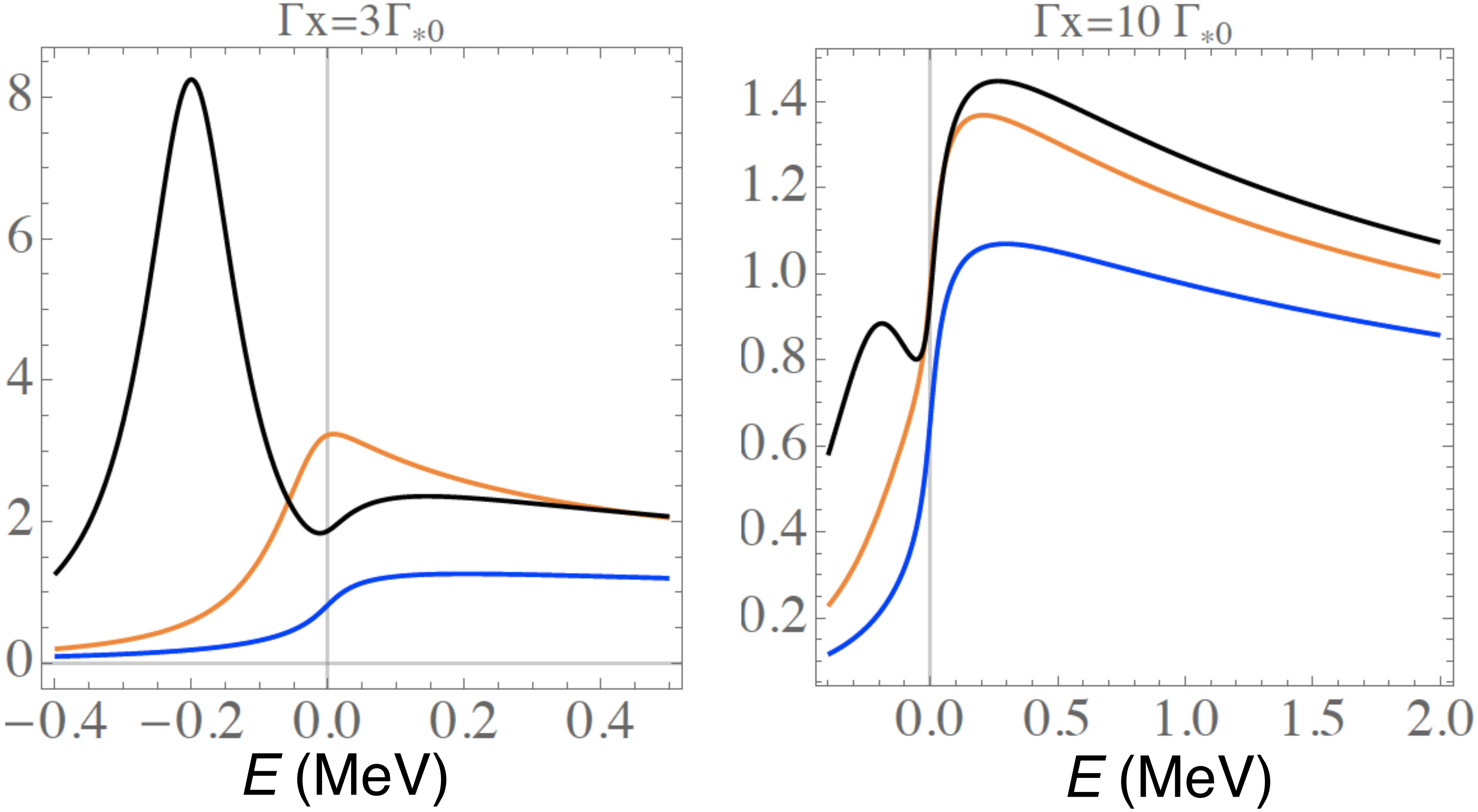
$$\kappa(E) = \sqrt{-2\mu(E + i\Gamma_{*0}/2)}$$

E: **energy relative to the $D^{*0}\bar{D}^0$ threshold.**

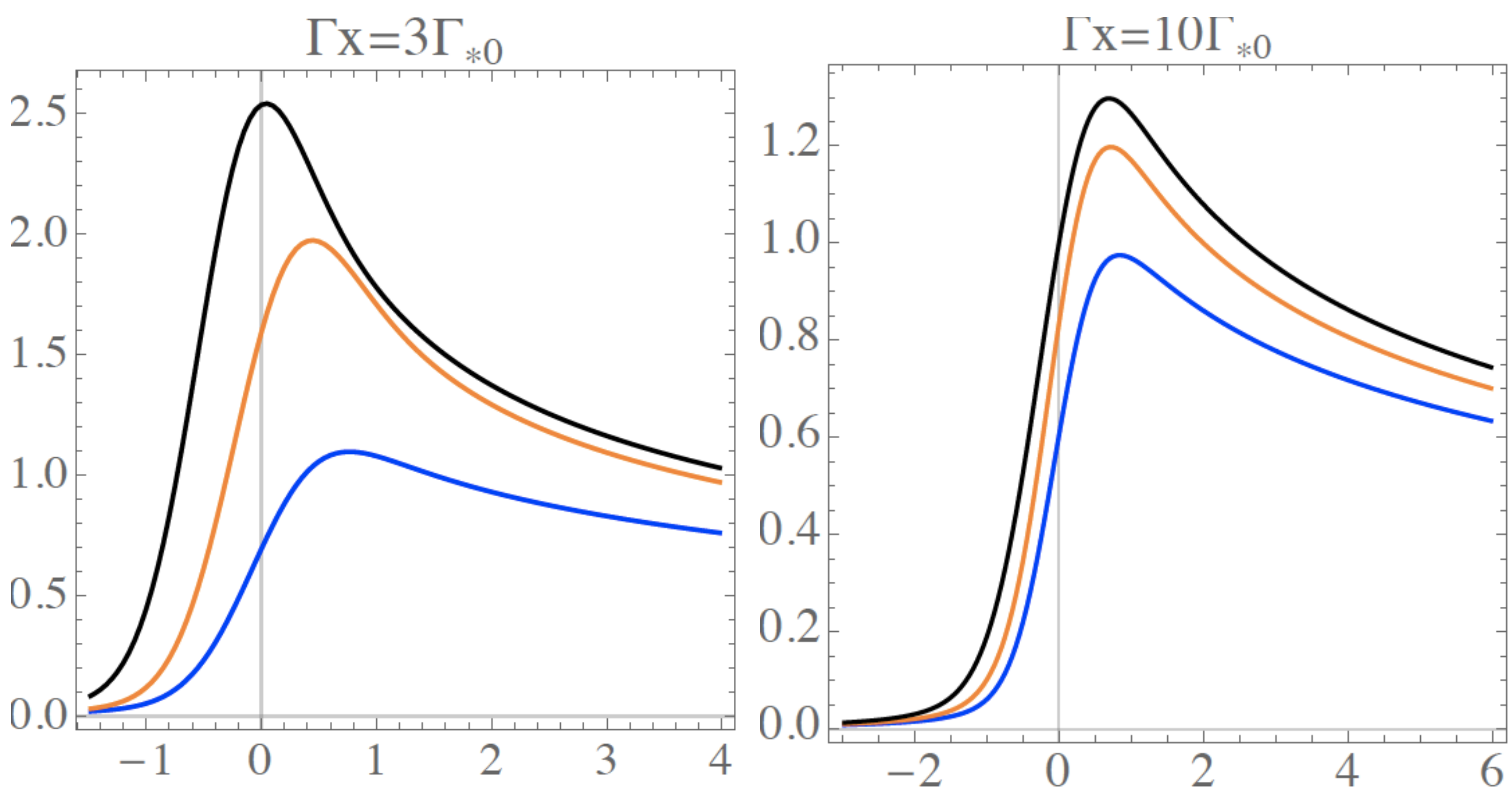


$D^0\bar{D}^0\pi^0$

$D^0\bar{D}^0\gamma$



Line shape



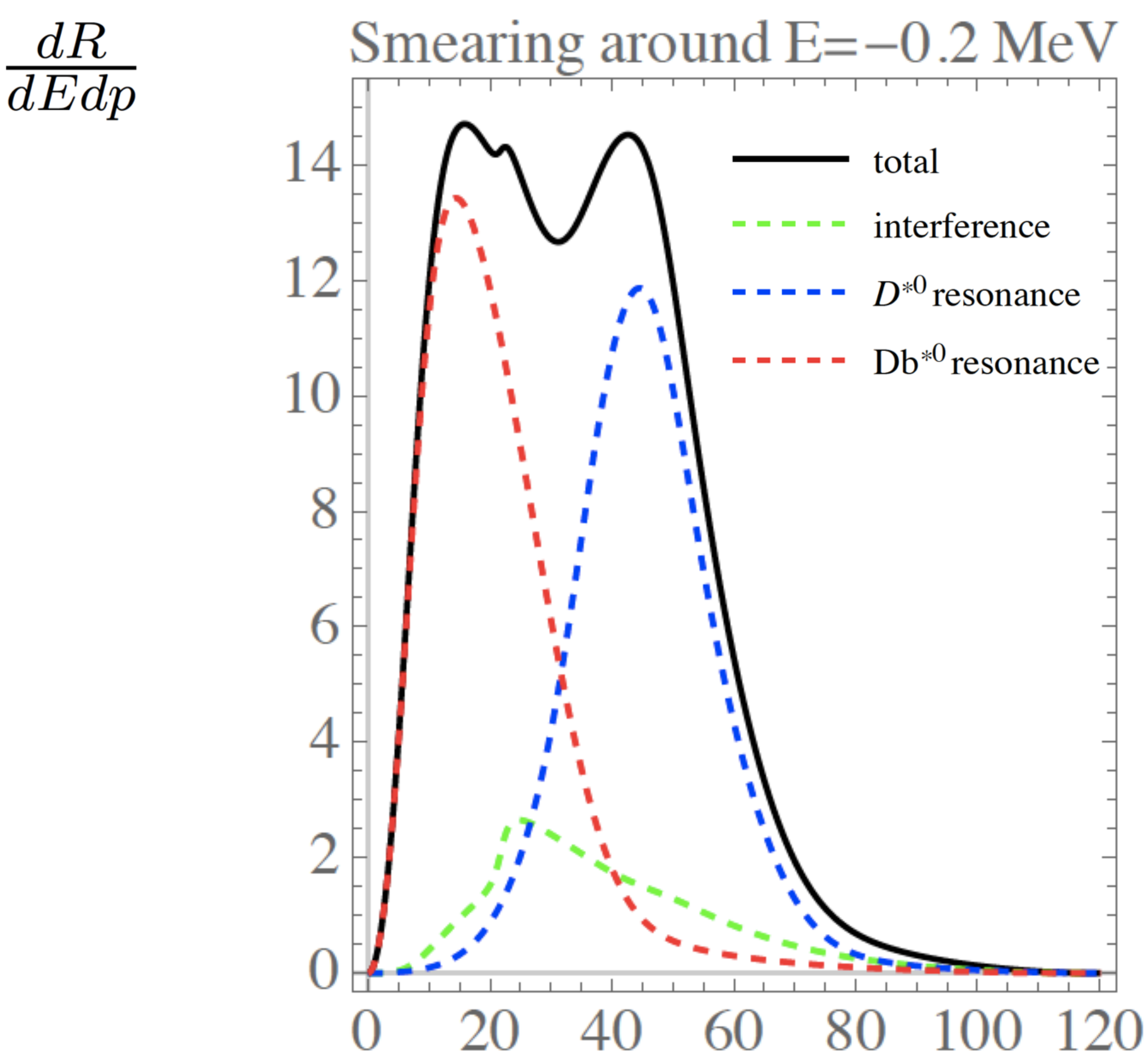
smearing

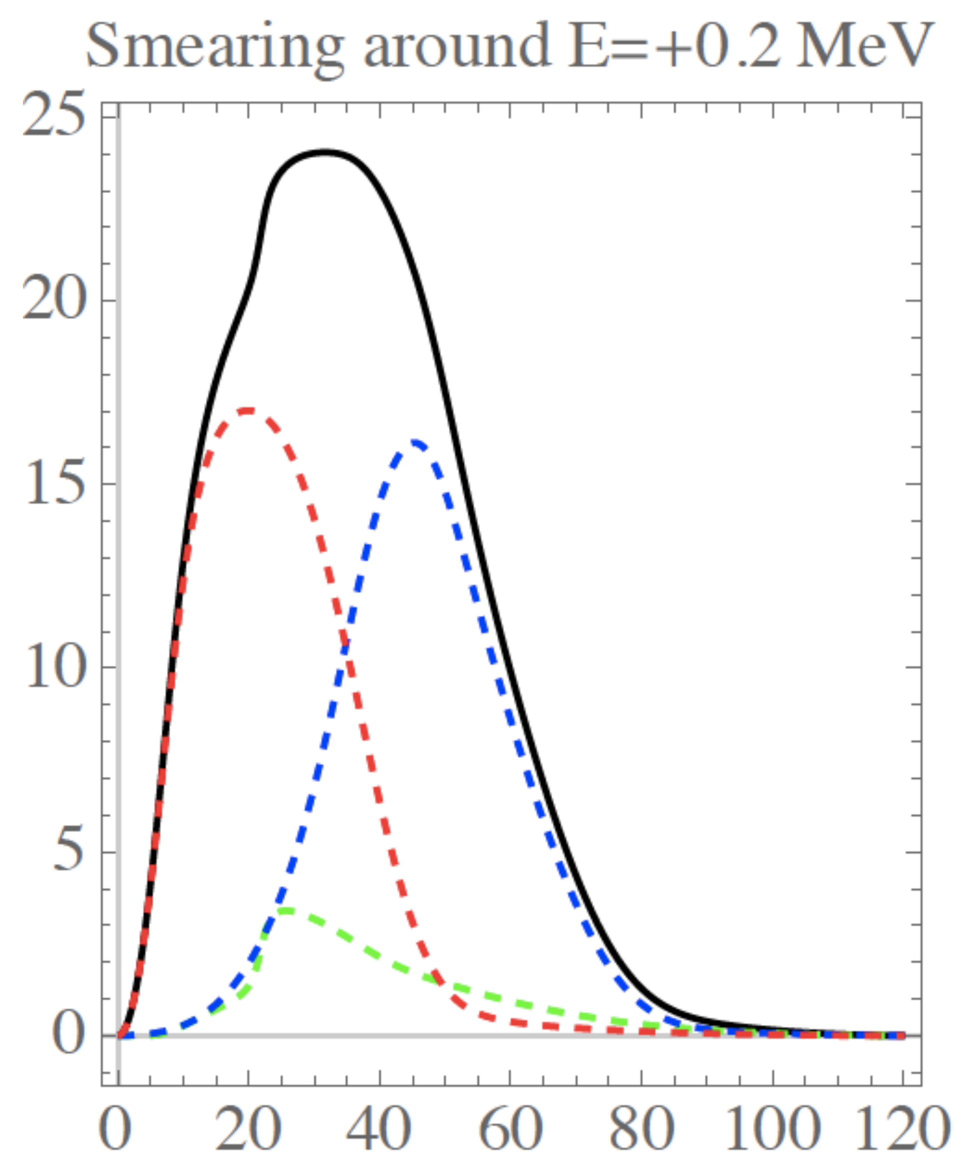
Momentum distributions for $D^0 \bar{D}^0 \pi^0$ decay modes

Gaussian smearing in energy with width 1 MeV:

E = energy of $D^0 \bar{D}^0 \pi^0$ relative to $D^{*0} \bar{D}^0$ threshold
p = momentum of D^0

momentum distributions at Ex=0, $\Gamma_X = \Gamma_{*0}$:





p **(MeV)**

Momentum distributions for $D^0 \bar{D}^0 \gamma$ decay modes

Gaussian smearing in energy with width 1 MeV:

E = energy of $D^0 \bar{D}^0 \pi^0$ relative to $D^{*0} \bar{D}^0$ threshold
p = momentum of D^0

momentum distributions at Ex=0, $\Gamma_X = \Gamma_{*0}$: