Galilean-Invariant Effective Field Theory for the *X(3872)*

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X(3872) Meson

unexpected meson discovered by Belle in 2003

- decays into $J/\psi\ \pi^+\pi^- \approx J/\psi\ \rho^*$

- also decays into $J/\psi\ \omega$,
  which violates isospin symmetry

$\Longrightarrow$ cannot be charmonium!

What is the *X(3872)*?

$X(3872)$ Meson

- quantum numbers 1^{++} LHCb 2014

  $\Longrightarrow$ S-wave coupling to charm mesons $D^* \bar{D}$

- mass is extremely close to the threshold

  for the neutral charm mesons $D^{*0} \bar{D}^0$

  mass measured most accurately by CDF2, Belle, LHCb, Babar, BES3

  threshold measured most accurately by Babar, CLEOc, LHCb, KEDR

  $\Longrightarrow$ binding energy: 0.12 ± 0.26 MeV

$\Longrightarrow$ $X(3872)$ must be weakly bound molecule of $D^{*0} \bar{D}^0$

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

(or a virtual state)

X(3872) Meson

Quantum Mechanics

S-wave bound state sufficiently near a threshold
has universal properties
determined by its binding energy

universal properties include large mean radius

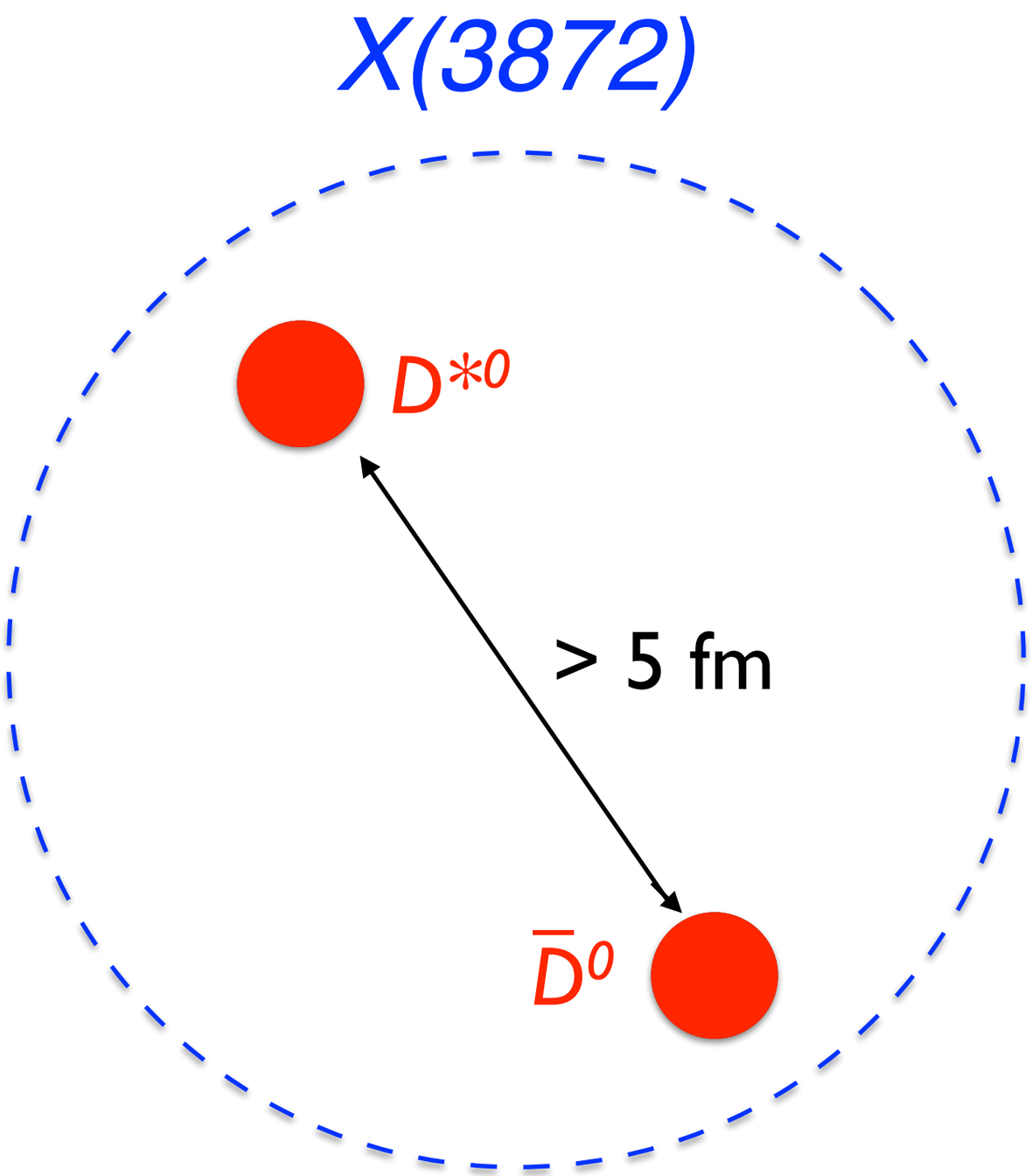
$$\langle r \rangle = (8\mu E_X)^{-1/2}$$

- binding energy: $E_X = 0.12 \pm 0.26$ MeV

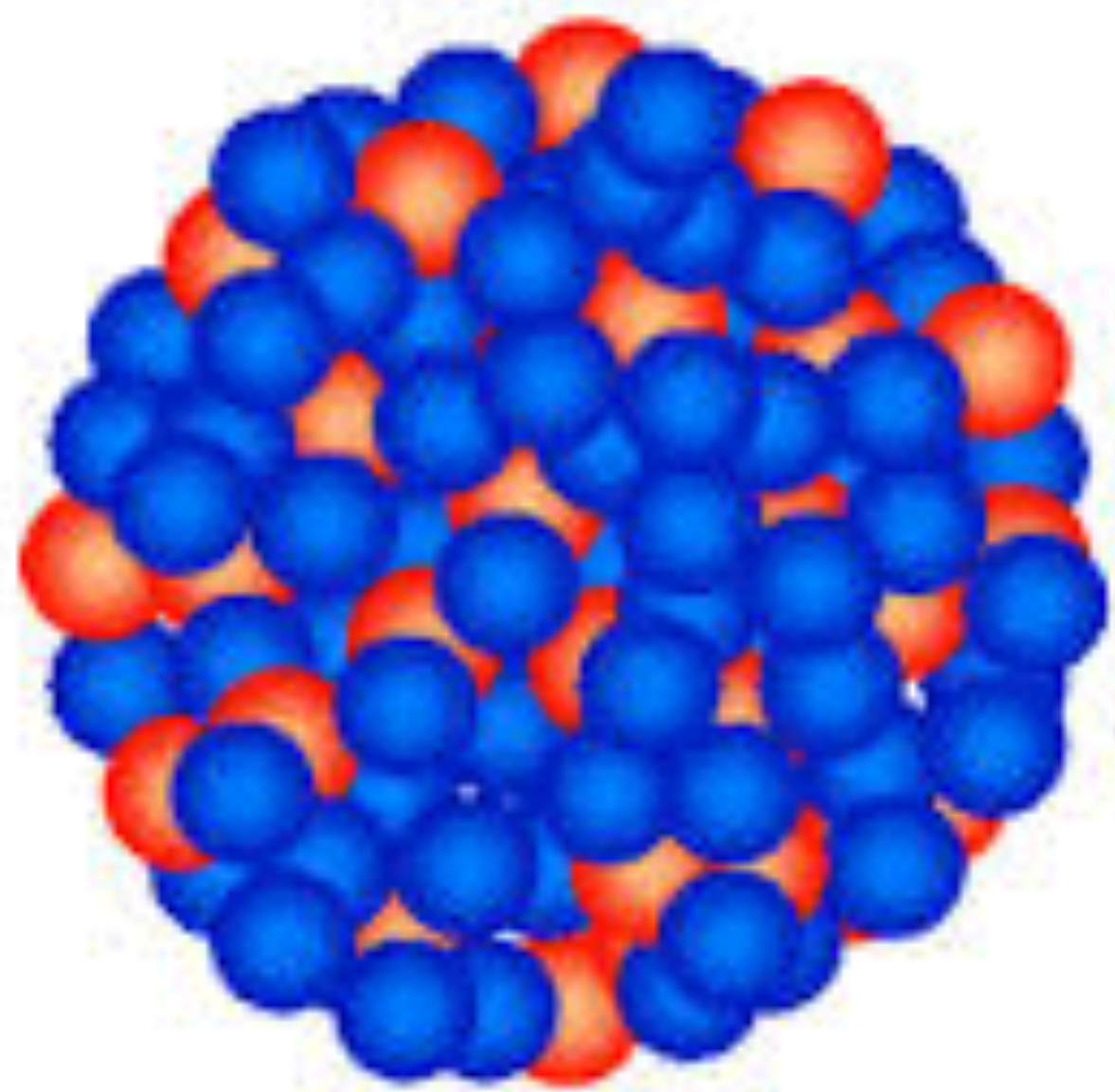
$\Longrightarrow$ *X(3872)* must be weakly bound molecule of $D^{*0}\,\bar{D}^0$
with huge mean radius!

X(3872) Meson

loosely bound charm meson molecule
comparable in size to the largest nuclei!



Uranium nucleus



Effective Field Theories for the *X(3872)*

- formulated in terms of low-energy degrees of freedom but takes into account high-energy degrees of freedom

- systematically improvable approximations
  $\Longrightarrow$ precise predictions

- resolve conceptual issues

Zero-Range EFT

(or Pionless EFT)

Effective field theory for $D^{*0}\bar{D}^0$ and $D^0\bar{D}^{*0}$
near their scattering threshold

- describes explicitly the $D^{*0}\bar{D}^0$ and $D^0\bar{D}^{*0}$ components of the $X(3872)$

- soft scales: binding energy of $X(3872)$ [input]
  hard scales: $M_{D^+} - M_{D^0} = 5$ MeV, $M_{D^*} - M_D - M_\pi = 7$ MeV

- does not describe $D^{*+}D^-$, D^+D^{*-} components of $X(3872)$
  or $DD\pi$ components
  or $\chi_{c1}(2P)$ or $J/\psi\ \omega$ or …

XEFT

Effective field theory for charm mesons and pions
near their scattering thresholds
Fleming, Kusunoki, Mehen, van Kolck 2007

- describes explicitly
  the $\bar{D}^*D$, $\bar{D}D^*$, and $\bar{D}D\pi$ components of the $X(3872)$

- soft scales: binding energy of $X(3872)$ [input]
  $M_{D^+}-M_{D^\circ} = 5$ MeV, $M_{D^*}-M_D-M_\pi = 7$ MeV
  hard scales: M_π, M_D, $4\pi f_\pi$

- pion exchange can be treated perturbatively
  even though exchanged π^0 can be on shell

Applications of XEFT

$D\bar{D}\pi$ Sector

$X(3872) \to D^0\bar{D}^0\pi^0$ (NLO)	Fleming, Kusunoki, Mehen, van Kolck	hep-ph/0703168
$X(3872) \to \chi_{cJ}\pi\pi$	Fleming, Mehen	arXiv:0807.2674,1110.0265
$X(3872) \to \psi(2S)\,\gamma$	Mehen, Springer	arXiv:1101.5175
$\psi(4160) \to X(3872)\,\gamma$	Margaryan, Springer	arXiv:1304.8101
$D^{*0}\bar{D}^0$ scattering length (NLO)	Jansen, Hammer, Jia	arXiv:1310.6937
partial width: $D^0\bar{D}^0\pi^0$ (NLO)	"	"
$X(3872) \to \chi_{cJ}\pi^0$	Mehen	arXiv:1503.02719

$DD\bar{D}\pi$, $DD\bar{D}\pi\pi$ sectors

$D + X(3872)$, $D^* + X(3872)$ scattering Canham, Hammer, Springer arXiv:0906.1263

$D\bar{D}\pi\pi$ sector

$\pi + X(3872)$ scattering Braaten, Hammer, Mehen arXiv:1005.1688

Problems with XEFT

- can simplify results by expanding in $(m_\pi/M_D)^{1/2} = 0.3$
  but decreases accuracy
  and gives incorrect behavior at $D^0\bar{D}^0\pi^0$ threshold
  Alhakami and Birse arXiv:1501.06750

- UV divergences at NLO
  unless expansion in m_π/M_D is truncated

- decay of D^{*0} into $D^0\gamma$ (38% branching fraction)

- decay of $X(3872)$ into modes other than $D^0\bar{D}^0\pi^0$
  (such as $J/\psi\ \pi^+\pi^-$)

- choice of preferred frame

Galilean Invariance

possible space-time symmetry of a nonrelativistic field theory

invariance under Galilean boost with velocity $\vec{v}$

$$E \longrightarrow E + m\vec{v}\cdot\vec{p} + \frac{1}{2}m\vec{v}^2$$
$$\vec{p} \longrightarrow \vec{p} + m\vec{v}$$

where m is the kinetic mass
(denominator of kinetic energy $p^2/2m$)

Galilean invariant: $E - p^2/2m$

Galilean invariance requires
exact conservation of kinetic mass

Galilean Invariance

mass is very nearly conserved

in the transition $D^{*0} \rightarrow D^0 \pi^0$

masses:

D^0	1864.8 MeV
π^0	135.0
	1999.8
D^{*0}	2007.0

difference = 7.14 ± 0.07 MeV

mass conservation is violated by only 3.5%

Galilean invariance requires

exact conservation of <u>kinetic</u> mass

kinetic energy of D^{*0} must be $p^2/\left(2(M_{D^0} + M_{\pi^0})\right)$

mass difference $M_{D^{*0}} - (M_{D^0} + M_{\pi^0})$

can be taken into account in rest energies

Galilean Invariant XEFT

Galilean invariance can be imposed as a symmetry
of XEFT at leading order
(violations of kinetic mass conservation
can be treated as perturbations)

- frame independence
  $\Longrightarrow$ can simplify calculations

- strong constraints on ultraviolet divergences
  $\Longrightarrow$ fewer phenomenological parameters
  at any given level of accuracy

- no need to expand in powers of m_π/M_D
  $\Longrightarrow$ higher accuracy

Galilean Invariant XEFT

interactions must be invariant under $\nabla \to \nabla + m\,\vec{v}$
(where m is kinetic mass)

pion interactions

original XEFT

$$\mathcal{L}_\pi = \frac{g}{2\sqrt{m} f_\pi} \vec{D}^\dagger \cdot D \overrightarrow{\nabla} \pi$$

Galilean invariant XEFT

$$\mathcal{L}_\pi = \frac{g}{2\sqrt{m} f_\pi (M+m)} \vec{D}^\dagger \cdot D [M \overrightarrow{\nabla} - m \overleftarrow{\nabla}] \pi$$

Complex Mass Renormalization Scheme

high accuracy requires taking into account
decays into final states with momenta too large
to be described explicitly in XEFT

- decay of D^{*0} into $D^0\gamma$ (38% branching fraction)
  take into account in imaginary part
  of complex rest energy of D^{*0}

- decay of $X(3872)$ into modes other than $D^0D^0\pi^0$
  (such as $J/\psi\ \pi^+\pi^-$)
  take into account by complex rest energy of $X(3872)$
  [inputs: binding energy and width]

Parameters of Galilean-Invariant XEFT

Leading Order

masses of D^0, D^{*0}, π^0, D^+, D^{*+}, π^+
widths of D^{*0}, D^{*+}
coupling constant for $D^* \to D\pi$
2 adjustable parameters: mass and width of $X(3872)$

Next-to-Leading Order

1 additional adjustable parameter

Applications of Galilean-Invariant XEFT

- $D^{*0}\,\bar{D}^0$ scattering length at NLO arXiv:1503.0479

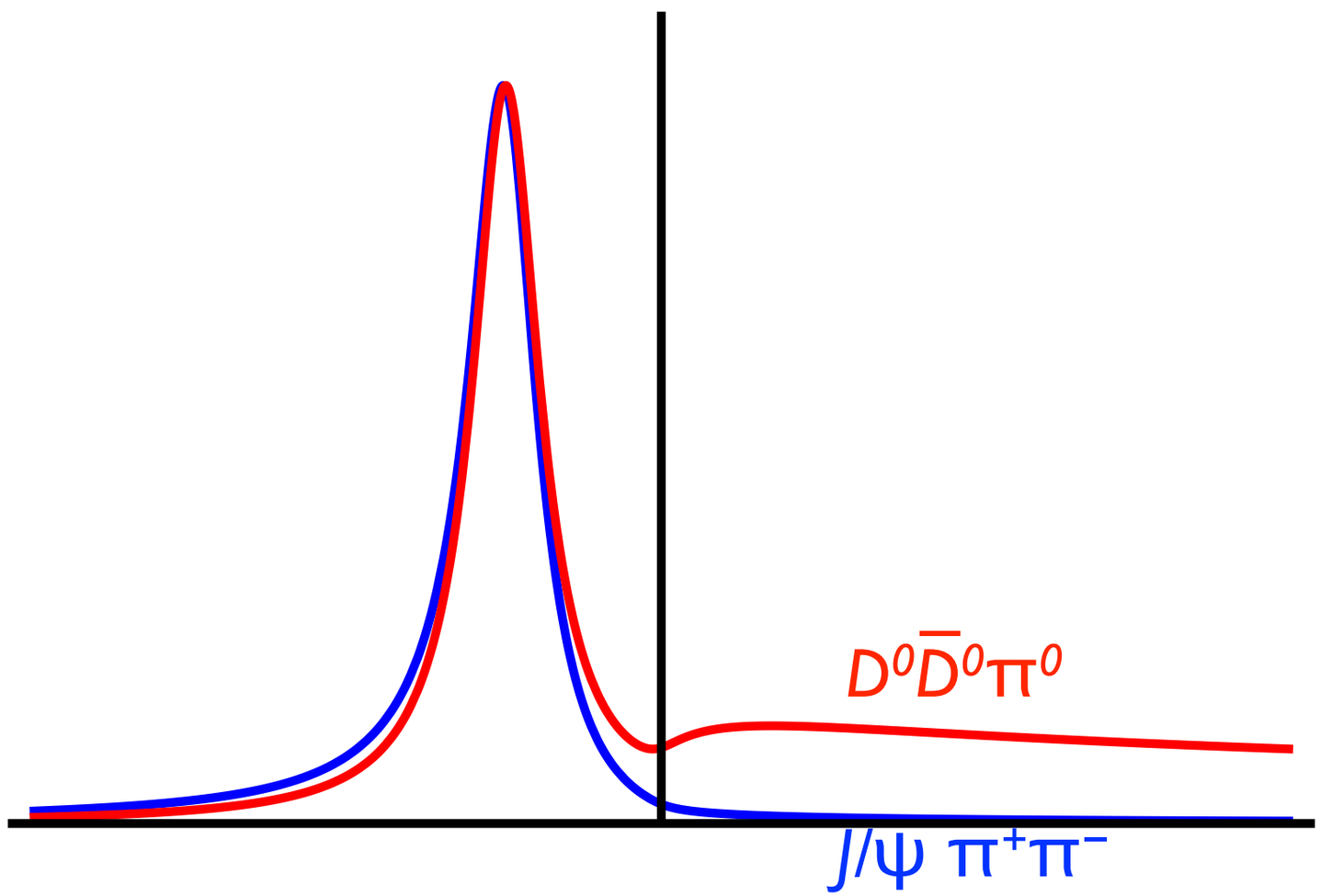
compare to NLO calculation in original XEFT
Jansen, Hammer, Jia arXiv:1310.6937

convenient choice for additional parameter
of Galilean-invariant XEFT at NLO

Applications of Galilean-Invariant XEFT

- $D^0\bar{D}^0\pi^0$ momentum distributions (in progress)

Belle II	$\Delta E \sim$ 1 MeV
Panda (high luminosity)	$\Delta E \sim 0.4$ MeV
Panda (high resolution)	$\Delta E \sim 0.1$ MeV



Summary

Galilean-invariant formulation of XEFT

- frame independence
- simpler UV divergences
- fewer phenomenological parameters
- higher accuracy

Complex Mass renormalization scheme

to take into account $D^{*0} \to D^0 \gamma$

$X(3872) \to J/\psi\, \pi^+\pi^-, \ldots$

Goals

- precise predictions involving $X(3872)$
  e.g. momentum distributions for $D^0\bar{D}^0\pi^0$
- resolve conceptual issues involving $X(3872)$

Misconceptions about *X(3872)*

The *X(3872)* cannot be a charm-meson molecule:

… the radiative branching ratio for $\psi(2S)\gamma$ and $J/\psi\gamma$ is too large

NO! Mehen & Springer (2011)

see also Guo et al. (2015),
Molnar, Luiz & Higa (2016)

… it can be mixed with the $\chi_{c1}(2P)$ charmonium state

$$\cos\theta \frac{1}{\sqrt{2}} \left| D^{*0}\bar{D}^{0} + D^{0}\bar{D}^{*0} \right\rangle + \sin\theta \left| \chi_{c1}(2P) \right\rangle$$

NO!

… it is produced too strongly in hadron collisions NO!