RUHR UNIVERSITÄT BOCHUM RUB

Non-perturbative pion dynamics for the *X*(3872)

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in collaboration with
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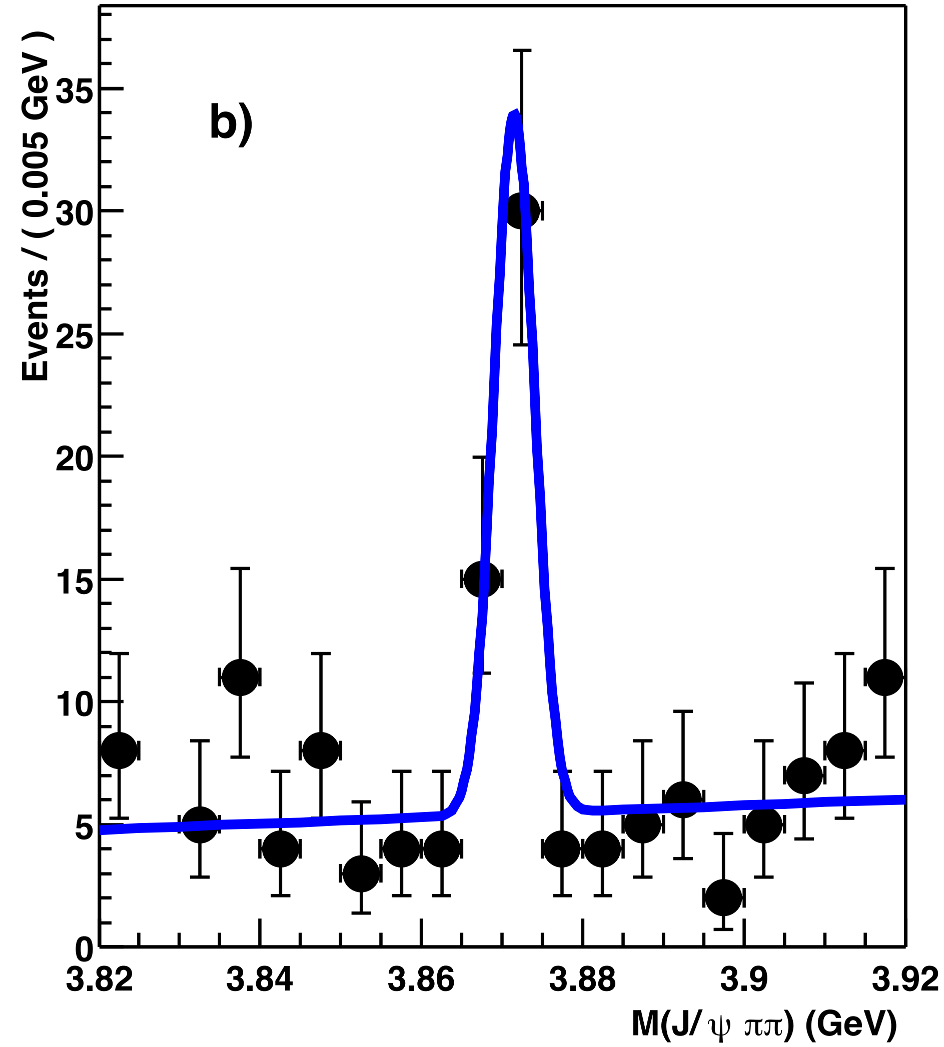
related articles: PLB 726, 537 (2013), PRD 84, 074029 (2011)

X(3872). Known facts

Discovered by the Belle: $B^{\pm} \to K^{\pm} J/\Psi\, \pi^+ \pi^-$

Observed: CDF, D0, BABAR, LHCb, BESIII

M_X= 3871.68 ± 0.17 MeV PDG (2013)



- $\Gamma_X < 2.3$ MeV Belle
- $X \to J/\Psi\gamma \implies C = +$ Belle
- $Br(X \to J/\Psi\omega)/Br(X \to J/\Psi\rho) \approx 0.8 \pm 0.3$ Belle (2003), BABAR(2010)

  $\implies$ isospin violation

- Quantum numbers: 1^{++} and 2^{-+} from BABAR/Belle angular distributions

- LHCb (2013): 2^{-+} is rejected with CL = 8 σ $\implies$ X is 1^{++}

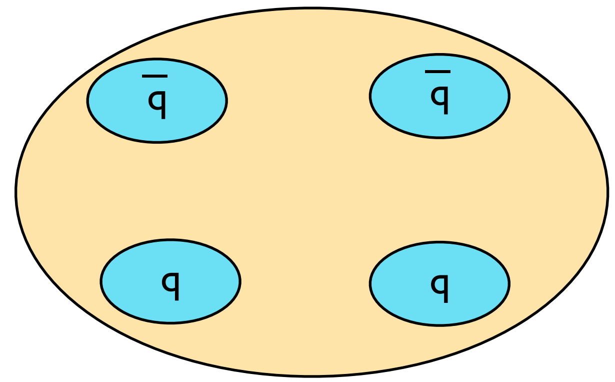
X(3872). Mechanisms

- Conventional charmonium: $\eta_{c2}(1^1D_2)$ ruled out by LHCb

  $\chi'_{c1}(2^3P_1)$

- Exotics: tetraquark, molecular, mixture....

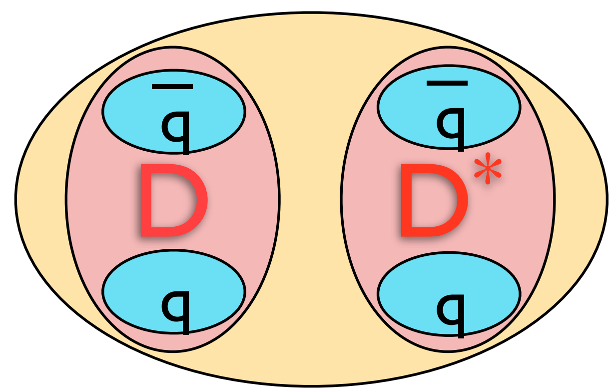
tetraquarks Maiani,...



compact state

molecular

Okun, Voloshin (1976), many works



☛ Strong hadronic interactions with large s-wave scatt. length

☛ natural effective range

☛ specific analytic properties: $\bar{D}D^*$ unitarity cut

Weinberg (1963-65)

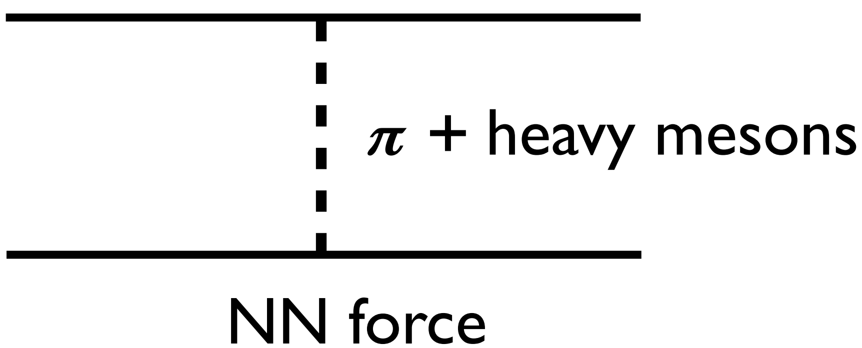
M_X= 3871.68 ± 0.17 MeV; $M_{D^0D^{0*}}$= 3871.80 ± 0.35 MeV

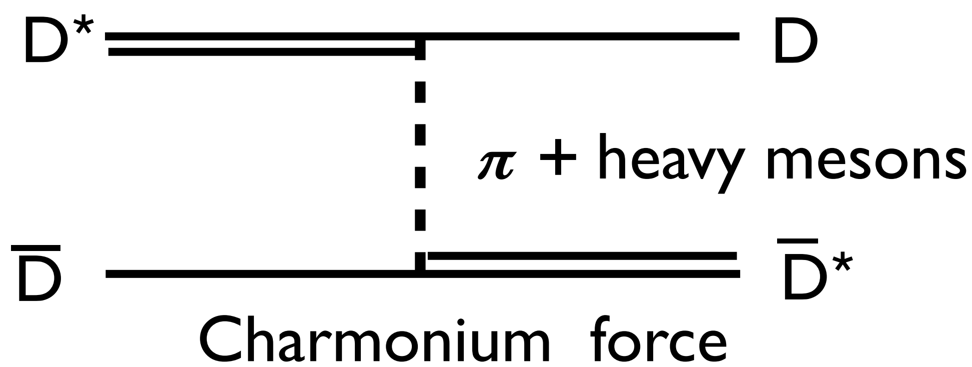
$\Longrightarrow$ X is the S-wave bound state of $D\bar{D}^*$ with E_B= 0.12 ± 0.26 MeV

From NN system to charm sector

Prediction of the $\bar{D}D^*$ molecular state in analogy to the deuteron

Okun, Voloshin (1976), Törnqvist (1991)





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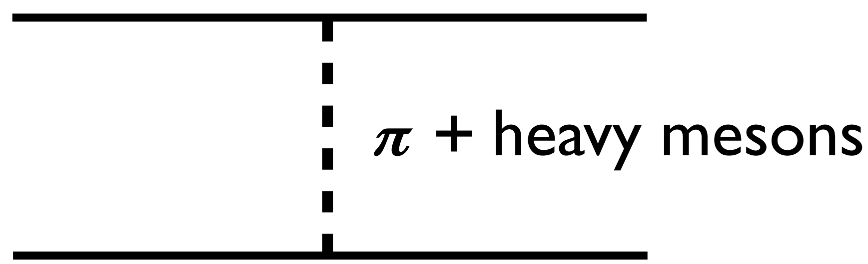
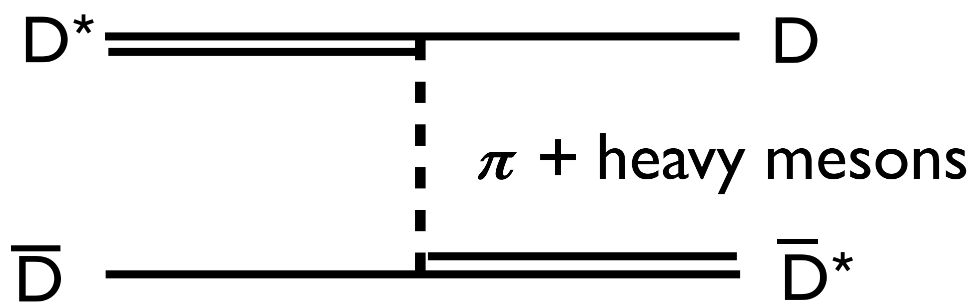
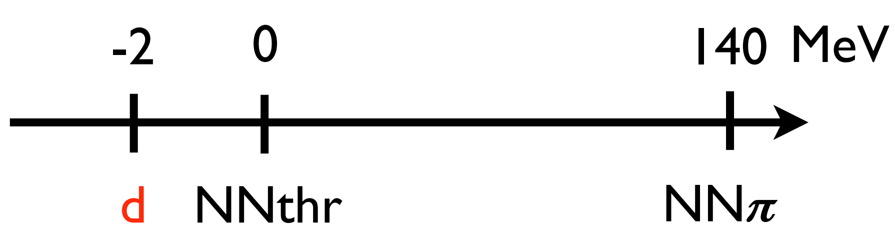
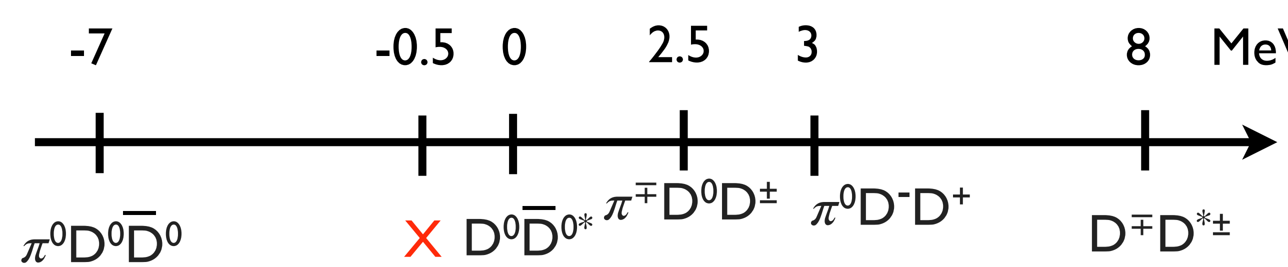


NN force



Charmonium force

	NN	X(3872)
Thresholds		
binding momentum	45 MeV	20-30 MeV
range of interaction	m_π	$\pi^0 D^0 \bar{D}^0$ can go on shell $\Longrightarrow$ Im part $\mu = \sqrt{2m_\pi(m_{D*} - m_D - m_\pi)} \simeq 45$ MeV
static OPE	good approximation	questionable $\Longrightarrow$ 3-body unitarity is spoiled

Small scales << $m_\pi \Longrightarrow$ NR kinematics

X(3872) as a $\bar{D}D^*$ bound state. Status.

Pionless:

- Asymptotic behavior of the X w.f. Voloshin (2004)
- Contact theory AlFiky et al. (2006), Nieves, Valderrama (2012)

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Pionful:

- X-EFT: resummation of LO contact operators + perturbative pions —similar to KSW in NN sector Flemming et al. (2007), Hammer et al. (2014), Mehen, Braaten et al. (2010-2011)
- Phenomenological deuteron-like studies with nonperturb. static OPE and formfactors For example: Liu et al. (2008), Thomas and Close (2008), Törnqvist (2004)

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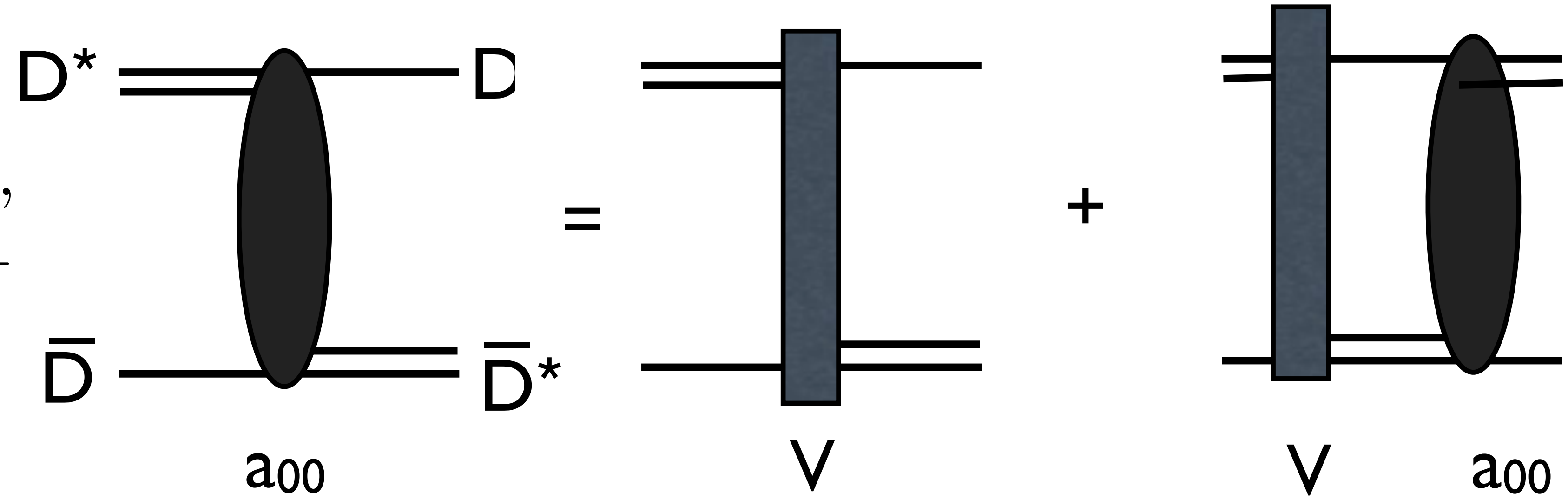
Goals of our study

- Investigate the role of 3-body $\pi\bar{D}D$ dynamics on a near threshold resonance
- Check the validity of the static pion approximation
- Investigate the role of coupled channel effects: $D^0\bar{D}^{*0}, D^+\bar{D}^{*-}$
Needed to explain isospin violation: Br(J/ψρ) ≃ Br(J/ψω) Gamermann, Oset (2009)
- Study the dependence of the X binding energy on the light quark masses
(chiral extrapolations)

Formalism. Faddeev-type integral Eqs. for 1^{++} $\bar{D}D^*$

Channels:

$$|0\rangle = D^0\bar{D}^{*0}, \quad |\bar{0}\rangle = \bar{D}^0 D^{*0},$$
$$|c\rangle = D^+ D^{*-}, \quad |\bar{c}\rangle = D^- D^{*+}$$



$$a_{00}^{nn'}(\mathbf{p},\mathbf{p}',E) = \lambda_0 V_{00}^{nn'}(\mathbf{p},\mathbf{p}') - \sum_{i=0,c} \lambda_i \int \frac{d^3s}{\Delta_i(s)} V_{0i}^{nm}(\mathbf{p},\mathbf{s}) a_{i0}^{mn'}(\mathbf{s},\mathbf{p}',E)$$

$$a_{c0}^{nn'}(\mathbf{p},\mathbf{p}',E) = \lambda_c V_{c0}^{nn'}(\mathbf{p},\mathbf{p}') - \sum_{i=0,c} \lambda_i \int \frac{d^3s}{\Delta_i(s)} V_{ci}^{nm}(\mathbf{p},\mathbf{s}) a_{i0}^{mn'}(\mathbf{s},\mathbf{p}',E),$$

isospin coefficients

- Partial waves of DD*: ${}^3S_1, {}^3D_1$ $\Longrightarrow$ projection operators
- Δ_0 and Δ_c — $D\bar{D}^*$ propagators of the states $|0\rangle$ and $|c\rangle$
- $a_0 = (a_{00} - a_{c0})/2$ — the X-amplitude

$D\bar{D}^*$ potential within chiral EFT

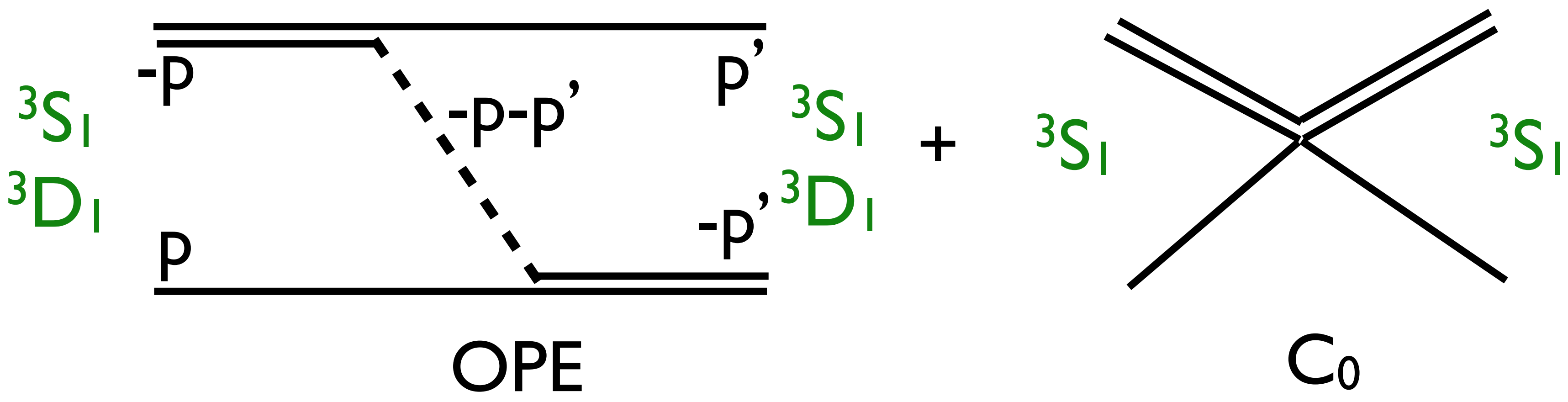
$$V_{EFT} = V^{(0)} + \chi V^{(1)} + \chi^2 V^{(2)} + \cdots \qquad \chi = \frac{q}{\Lambda_{\chi PT}}$$

small scale: bind. momentum, range

large scale: m_ρ

LO:

$V^{(0)} =$



$$V_{OPE}(\vec{p}, \vec{p}') = g^2 \frac{(\vec{p} \cdot \vec{\varepsilon}_d)(\vec{p}' \cdot \vec{\varepsilon}_d)}{M - (2m_D + m_\pi) - \frac{(\vec{p}+\vec{p}')^2}{2m_\pi} - \frac{p^2}{2m_D} - \frac{p'^2}{2m_D} + i0}$$

3-body $D\bar{D}\pi$ prop.

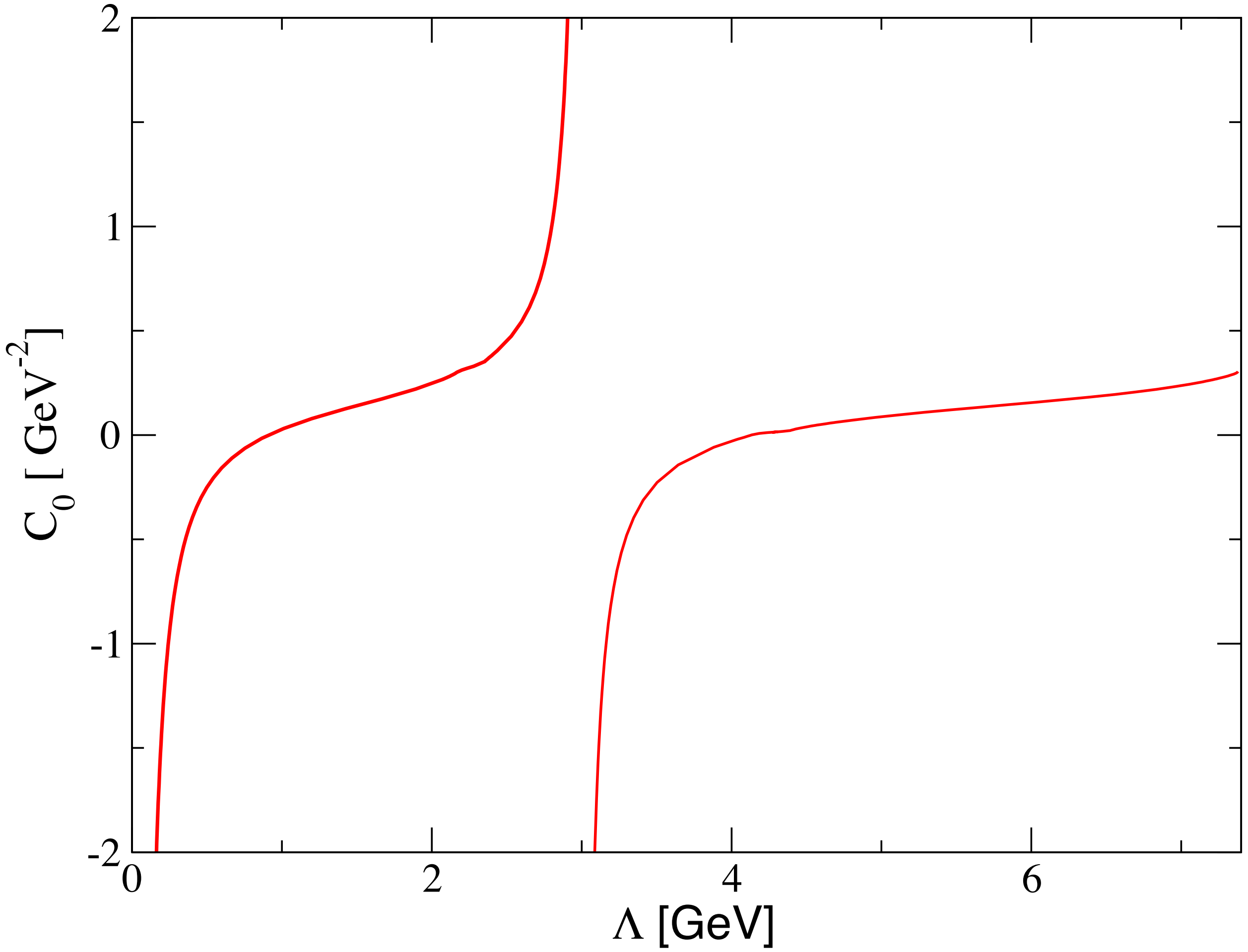
- Coupling constant g from $\Gamma(D^{*0} \to D^0 \pi^0) = 42$ KeV
- Same 3-body cut appears due to dressing the D^* propagator by πD loops

Renormalization of OPE

- Similar to NN   Lepage (1997), Nogga et al. (2005), Epelbaum et al. (2006-2009), ...

- $V_{OPE} \xrightarrow{p\to\infty}$ const $\Longrightarrow$ divergent integrals $\Longrightarrow$ regularize, e.g., with cutoff $\Lambda \Longrightarrow$ renormalize tuning $C_0(\Lambda)$ to reproduce the binding energy

- Renormalization group limit cycle Nogga et al. (2005), Bedaque et al.(1999), Braaten and Phillips (2004)

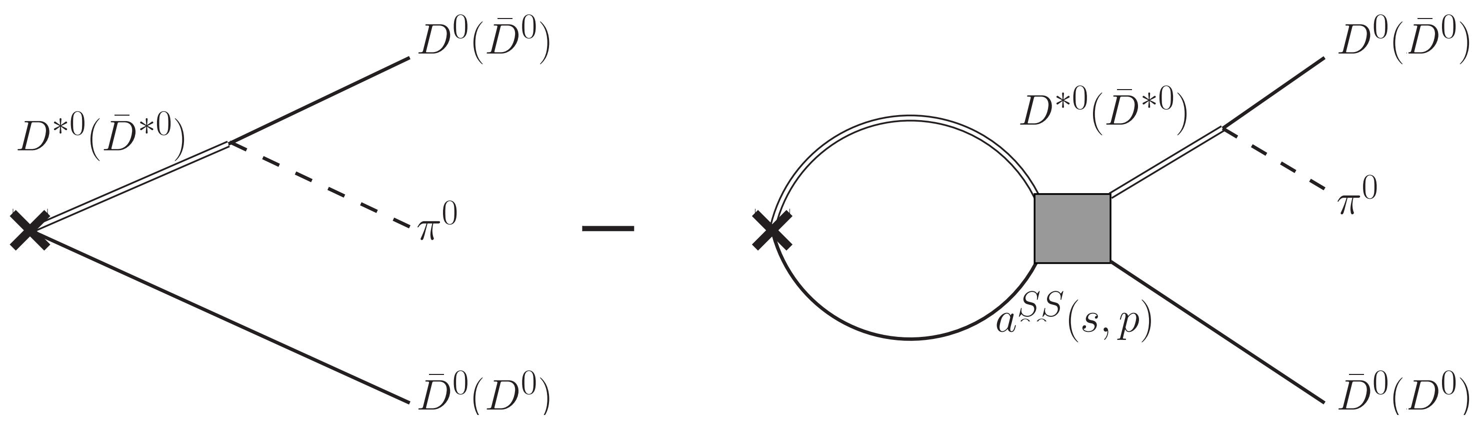


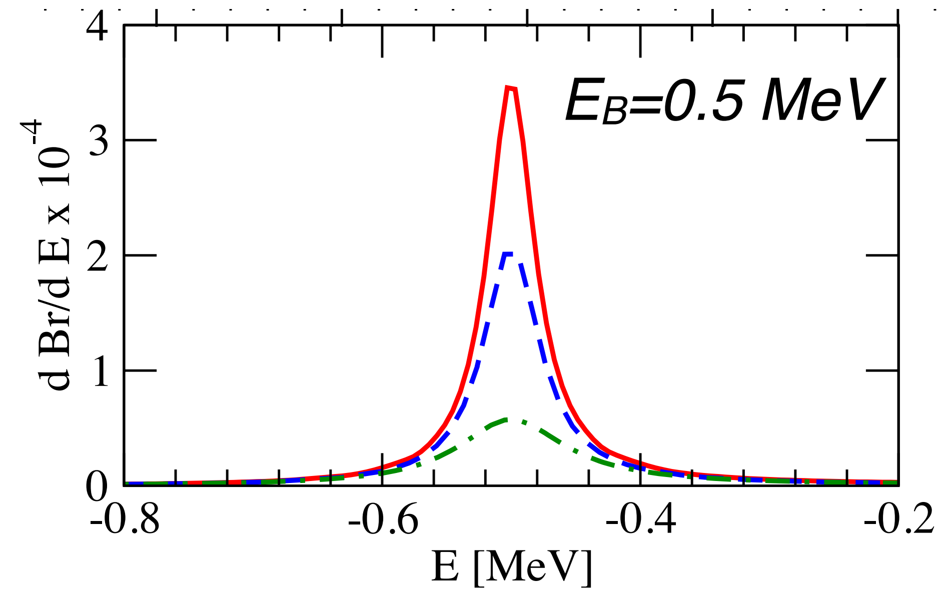
Once renormalized, observables should not depend on Λ within the range of applicability!

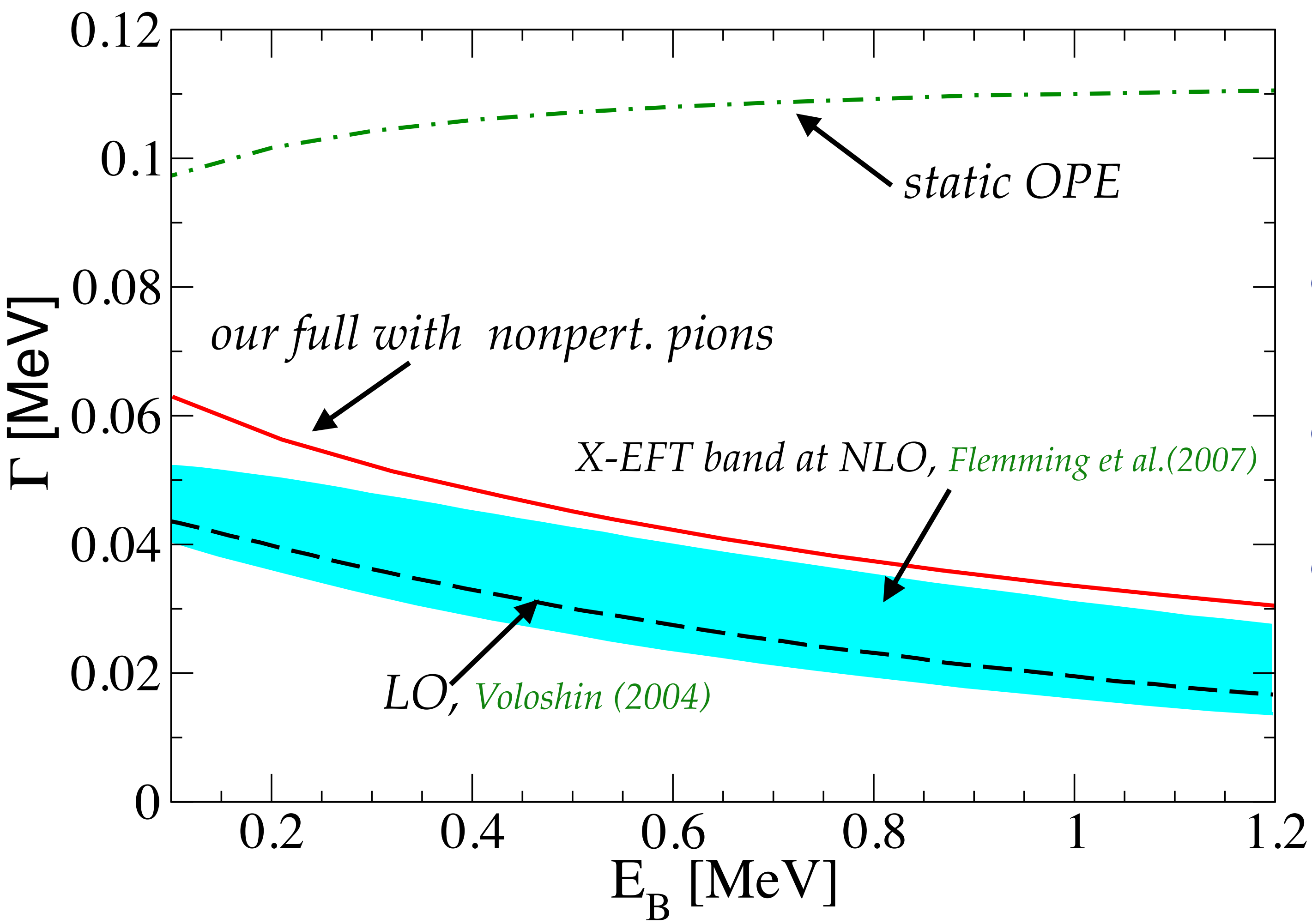
Partial width of the X(3872) due to the decay to $\pi^0 D^0 \bar{D}^0$

VB, Filin, Hanhart, Kalashnikova, Kudryavtsev, Nefediev (2011)

$\pi^0 D^0 \bar{D}^0$ production rate near the X(3872) pole







Conclusions:

- Perturbative inclusion of pions is justified
- Static approx. with nonpert. pions fails!
- Keeping 3-body dynamics in pionfull schemes is mandatory

for a study of the $D\bar{D}$ FSI see Guo et al (2014)

Chiral Extrapolations of the X(3872) with m_π

VB, Epelbaum Filin, Hanhart, Meißner, Nefediev (2013)

Strategy: vary all quantities with m_π, expand around physical pion mass $m_\pi^{\rm ph}$

- $f(\Lambda)$ is needed to absorb extra $\Lambda-$dependence when $m_\pi \neq m_\pi^{\rm ph}$

$$C_0(\Lambda, m_\pi) = C_0(\Lambda)\left(1 + f(\Lambda)\frac{m_\pi^2 - {m_\pi^{\rm ph}}^2}{\mathrm{M}^2}\right) + O\left(\frac{\delta m_\pi^4}{\mathrm{M}^4}\right)$$

- could be fixed if we knew the slope $\left(\partial E_B/\partial m_\pi\right)\big|_{m_\pi = m_\pi^{\rm ph}}$ from lattice

- Estimate $f(\Lambda)$: from two-pion exchange $\Longrightarrow$ $|f(\Lambda)| \sim 1$, more conservatively: $f(\Lambda) \in [-5, 5]$

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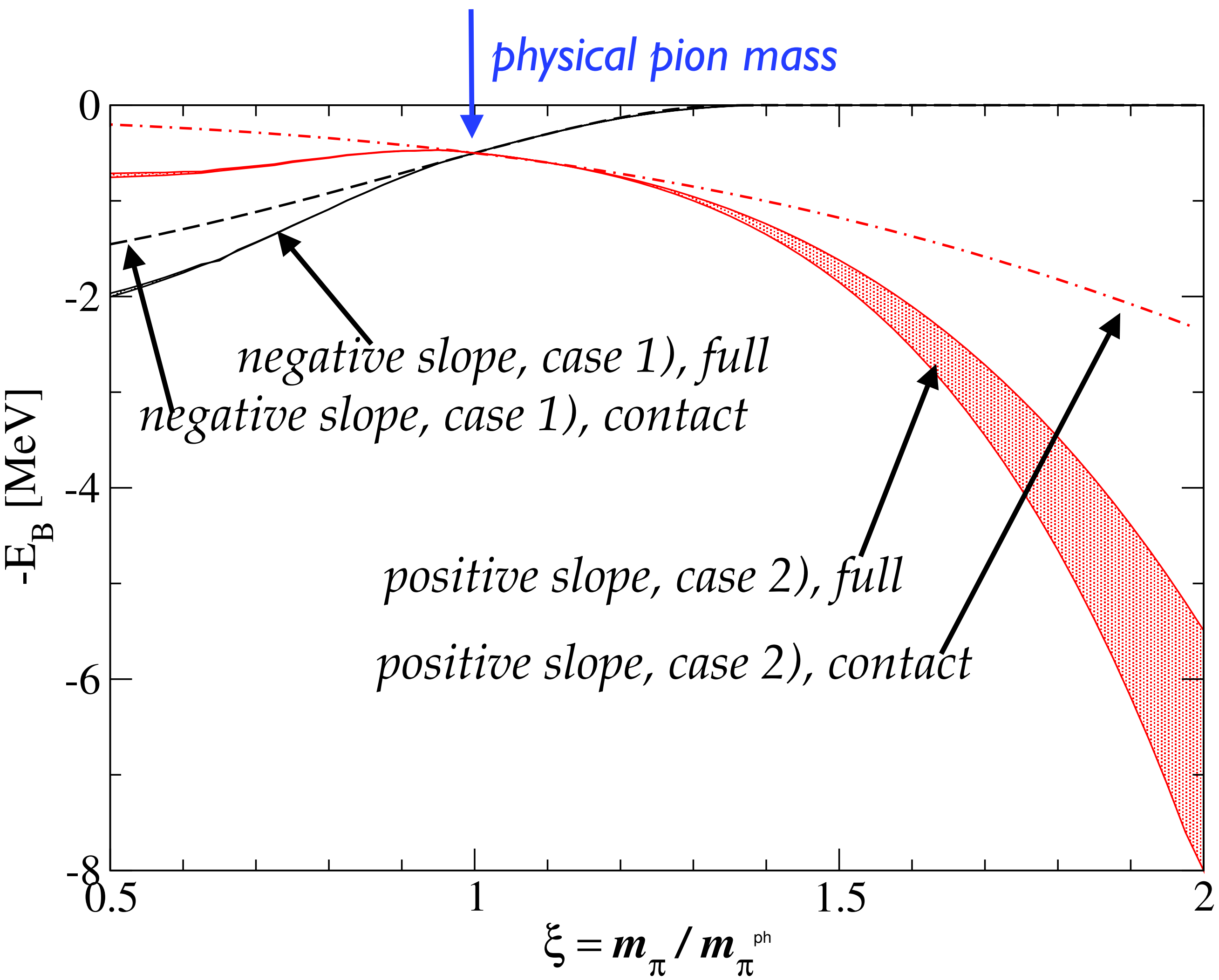

Conclusions:

1) If $(\partial E_B/\partial m_\pi)\big|_{m_\pi = m_\pi^{\rm ph}} < 0 \Rightarrow f(\Lambda) < 0 \Longrightarrow$

bound state disappears quickly with m_π growth. Dominated by short-range physics

2) If $(\partial E_B/\partial m_\pi)\big|_{m_\pi = m_\pi^{\rm ph}} > 0 \Rightarrow f(\Lambda) > 0 \Longrightarrow$

The X is bound deeper with m_π growth. Strong influence of pion dynamics

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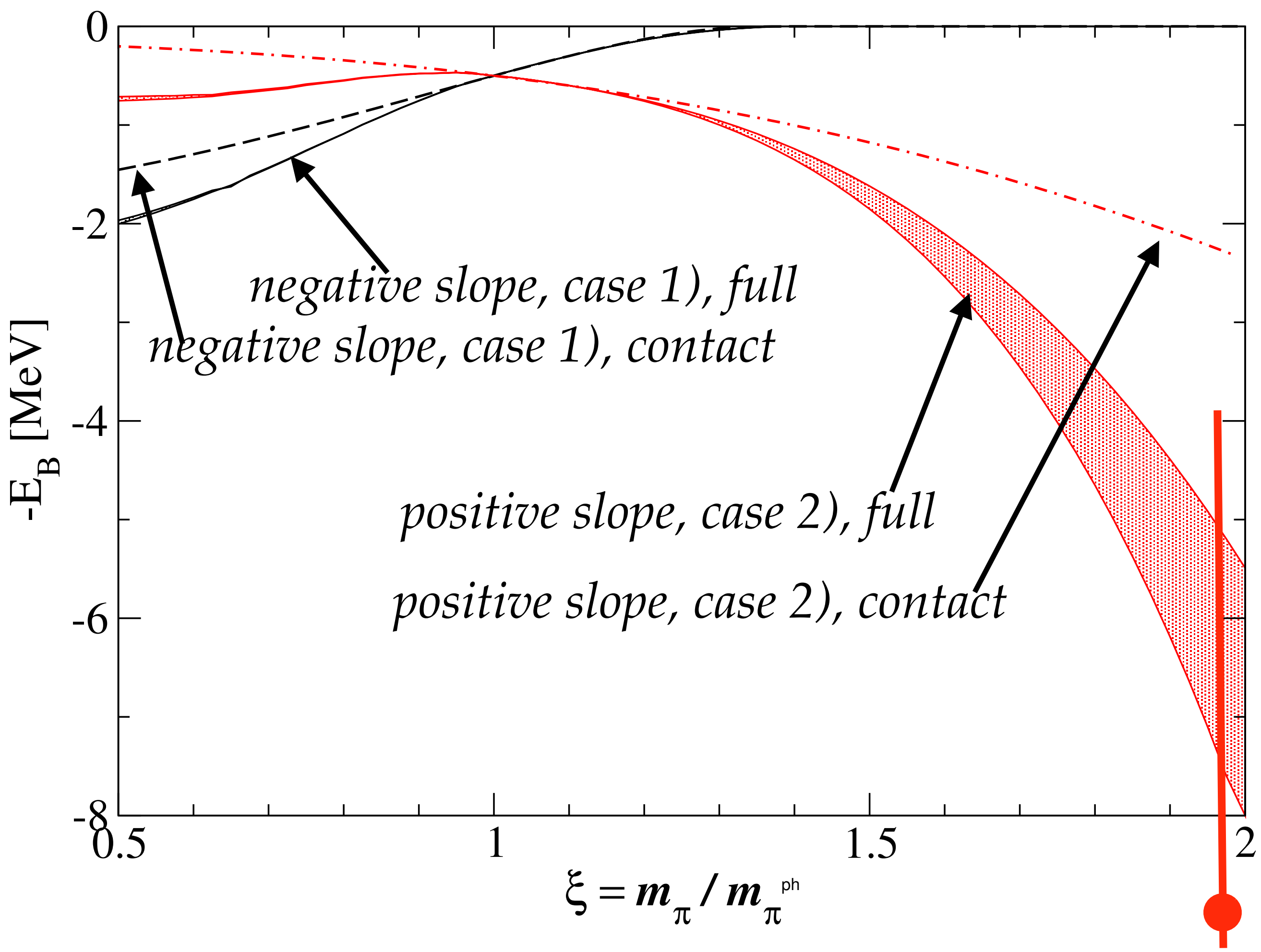

Conclusions ctd :

▶ First lattice measurement of the X(3872)

Prelovsek and Leskovec PRL(2013), talk on Saturday

E_B = -11 ± 7 MeV m_π =266(4) MeV

$\Longrightarrow$ scenario 2) seems to be preferred

Comparison to other EFT studies

- chiral extrapol. of the binding energy with m_π to NLO in X-EFT M.Jansen et al. (2013)

  Conclusion : qualitative agreement with our results

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- chiral extrapol. of the binding energy with m_π with non perturbative pions

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Claims:

1) *OPE alone is sufficient to bind* $D^0\bar{D}^{*0}$

2) *Short range contr'n (CT) — a small correction*

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<u>Our opinion</u>

- All claims are scheme dependent. OPE due to its short ranged part is always tuned with CT

<u>*Example:*</u>

in cutoff regularization X has the same E_B if $C_0(\Lambda)=0$ ($\Lambda\simeq 1$ GeV) or $C_0(\Lambda)=\infty$ ($\Lambda\simeq 3$ GeV)

- 3) is in conflict with recent lattice results Prelovsek and Leskovec PRL(2013)

Conclusions

- We studied the role of nonperturbative long-range $\pi D\bar{D}$ dynamics on the X(3872) within a molecular picture

  ▶ *3-body effects are important in pionful approaches but pion is essentially perturbative*

  ▶ *static pion approximation is not appropriate*

  ▶ $\Gamma(X \to D^0 \bar{D}^0 \pi^0) = 44\,\mathrm{KeV}$ *for E_B=0.5 MeV*

- The dependence of the X-binding energy on m_π is highly nontrivial — may provide insights on the binding mechanism

  ▶ *the X bound state may either disappear or get more bound depending on the interplay of long- and short-range forces*

  ▶ *First lattice results: more bound*

  ▶ *More accurate lattice data with better controlled finite volume corrections would be important*