OPEN CHARM and CHARMONIUM STATES

from EFFECTIVE FIELD THEORIES

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- Intro: Salient features of QCD
- Goldstone boson scattering off $D^{(\star)}$-mesons
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- Summary & outlook

Introduction

LIMITS of QCD

- **light quarks:** $\mathcal{L}_{\rm QCD} = \bar{q}_L \, i \not{D} q_L + \bar{q}_R \, i \not{D} q_R + \mathcal{O}(m_q/\Lambda_{\rm QCD})$
  - L- and R-handed quarks decouple $\Rightarrow$ chiral symmetry
  - spontaneous chiral symmetry breaking $\Rightarrow$ pseudo-Goldstone bosons
  - pertinent EFT $\Rightarrow$ chiral perturbation theory (CHPT)
- **heavy quarks:** $\mathcal{L}_{\rm QCD} = \bar{Q}_f \, iv \cdot D \, Q_f + \mathcal{O}(\Lambda_{\rm QCD}/m_Q)$
  - independent of quark spin and flavor
    $\Rightarrow$ SU(2) spin and SU(2) flavor symmetries
  - pertinent EFT $\Rightarrow$ heavy quark effective field theory
- **heavy-light systems:**
  - heavy hadrons act as matter fields coupled to light pions
  - combine CHPT and HQEFT Donoghue, Wise, Yan, . . .

Goldstone boson scattering off $D^{(\star)}$-mesons

Guo, Krewald, M., Phys. Lett. B **665** (2008) 157

Guo, Hanhart, Krewald, M., Phys. Lett. B **666** (2008) 251

Guo, Hanhart, M., Eur. Phys. J. A **40** (2009) 171

Cleven, Guo, Hanhart, M., arXiv:1009.3804 [hep-ph]

EFFECTIVE LAGRANGIAN for $\phi D \to \phi D$

- Goldstone boson octet (π, K, η) scatters off D-meson triplet (D^0, D^+, D_s^+)

- multi-scale/multi-faceted problem:

  – light particles, chiral symmetry $\longrightarrow$ chiral expansion in (p, m_q)

  – heavy particles, heavy quark symmetry $\longrightarrow$ expansion in $1/m_c$

  – isospin-violation $\longrightarrow$ strong = quark mass difference $m_d \neq m_u$

  $\longrightarrow$ electromagnetic = quark charge difference $q_u \neq q_d$

- 16 channels with different total strangeness and isospin

  – some are perturbative

  – some are non-perturbative, require resummation $\longrightarrow$ possible molecules

EFFECTIVE LAGRANGIAN for $\phi D \to \phi D$

- Effective Lagrangian at NLO:

$$\mathcal{L} = \mathcal{L}^{(1)} + \mathcal{L}^{(2)}$$

$$\mathcal{L}^{(1)} = \mathcal{D}_\mu D \mathcal{D}^\mu D^\dagger - \overset{\circ}{M}{}_D^2 D D^\dagger$$

$$\mathcal{L}^{(2)}_{\text{str.}} = D\big(-h_0\langle\chi_+\rangle - h_1\tilde{\chi}_+ + h_2\,\langle u_\mu u^\mu\rangle - h_3 u_\mu u^\mu\big)\bar{D} \\ + \mathcal{D}_\mu D\big(h_4\langle u^\mu u^\nu\rangle - h_5\{u^\mu, u^\nu\} - h_6[u^\mu, u^\nu]\big)\mathcal{D}_\nu \bar{D}$$

–drop terms with flavor traces (large N_C suppressed)

–fix h_1 from D-meson mass differences (incl. em effects)

–fix h_3 from $D^\star_{s0}(2317)$ mass (as DK molecule)

– h_5 varied within natural range, $h_5 \in [-1, +1]/M_D^2$

SCATTERING AMPLITUDE

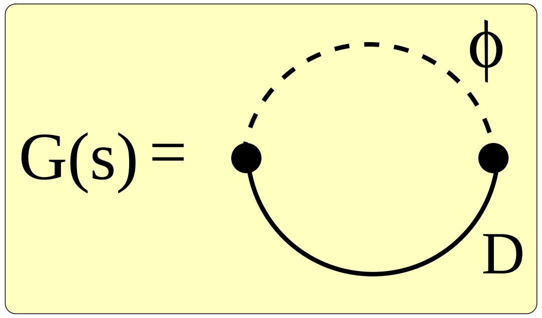
- Chiral expansion

$$T(s,t,u) = T^{(1)}(s,t,u) + T^{(2)}(s,t,u)$$
$$= \frac{C_0}{4F^2}(s-u) + \frac{2C_1}{3F^2}h_1 + \frac{2C_{35}}{F^2}H_{35}(s,t,u)$$

– C_0, C_1, C_{35}: channel-dependent Clebsch-Gordan coeffs

- Unitarization: iteration of the fundamental bubble

$$T(s) = V(s)\,[1 - G(s)\cdot V(s)]^{-1}$$



– once-subtracted dispersive representation

Oller, M. (2001)

– subtraction constant to fit mass of the $D^\star_{s0}(2317)$ at LO

RESULTS for $\phi D \to \phi D$ etc

- Width of the $D_{s0}^{\star}(2317)$ in the molecular picture

$$\Rightarrow \boxed{\Gamma(D_{s0}^{\star}(2317)^{+} \to D_s^{+}\pi^{0}) = (180 \pm 110)\,\mathrm{keV}}$$ testable prediction

  – uncertainty from exp. input and variation of h_5

  – note: much smaller in quark models (a few keV)

- expectation for the scattering length for $DK(I=0)$ in the molecular picture:

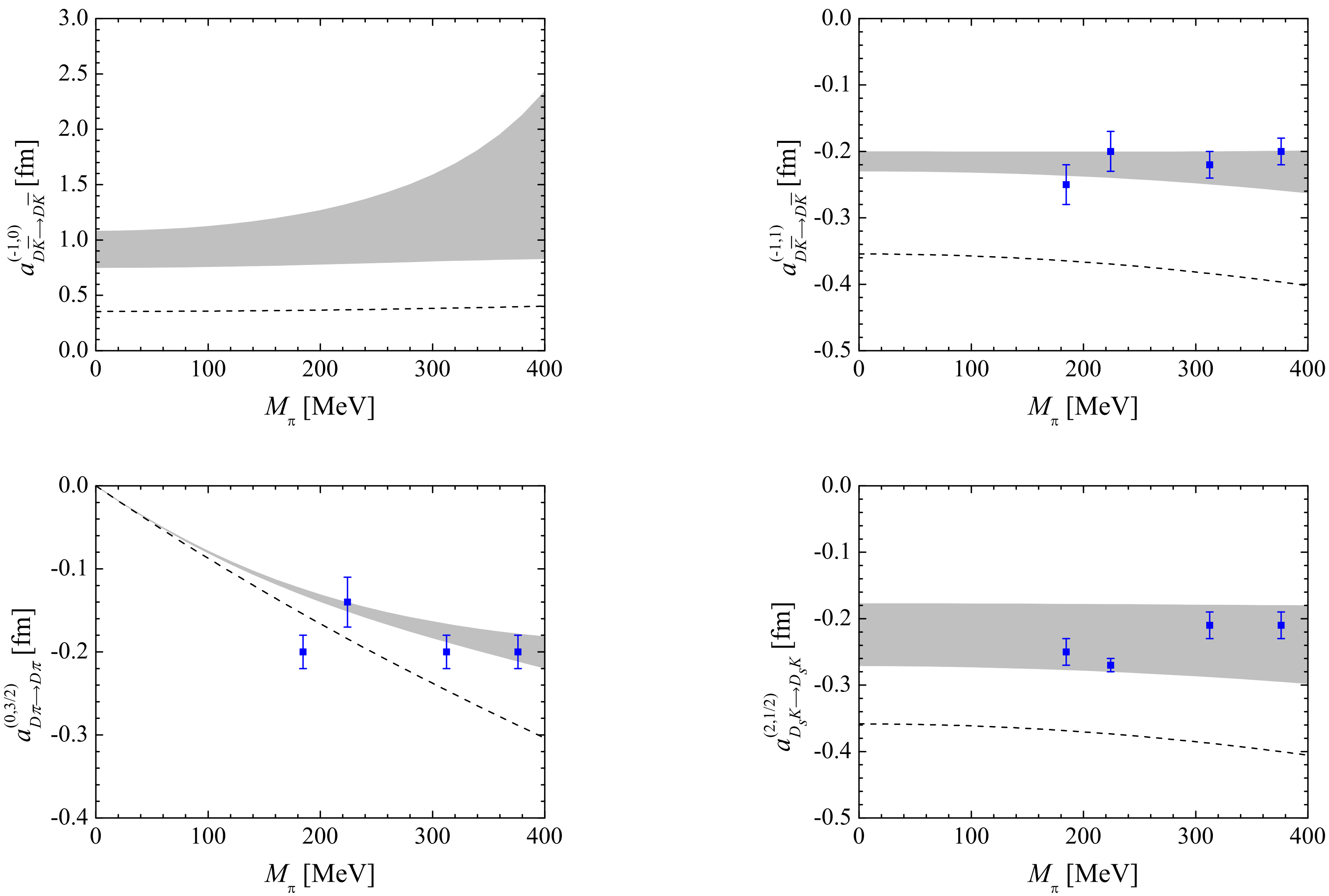
$$a_{DK}^{I=0} = -g_{\mathrm{eff}}^{2}\Delta_{DK} = -\frac{1}{2\sqrt{\mu_{DK}\varepsilon}} \simeq 1\,\mathrm{fm}$$

- no data, but first lattice investigations at varying quark masses

Liu, Lin, Orginos, PoS LATTICE2008:112,2008

QUARK MASS DEPENDENCE

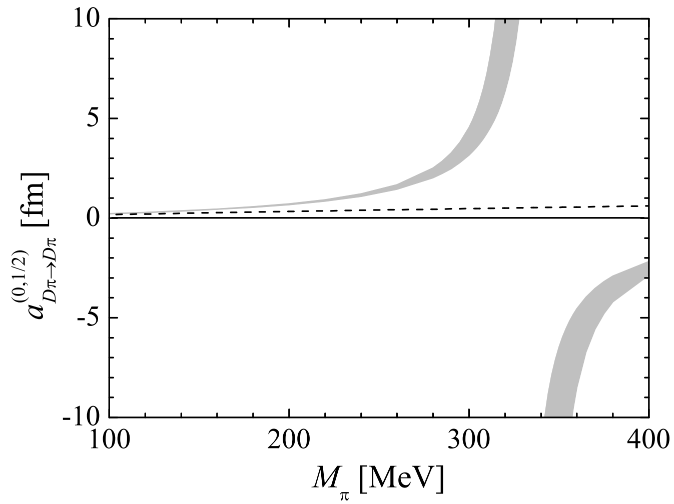
- *predictions:* channels with no poles



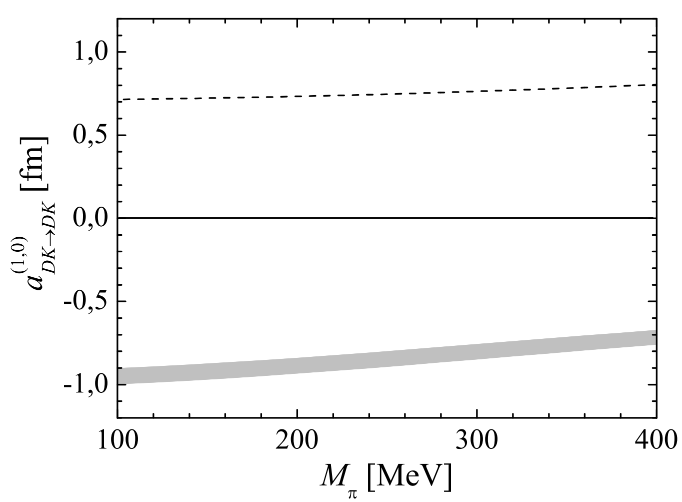
QUARK MASS DEPENDENCE cont'd

- *predictions:* channels with poles $\longrightarrow$ resonances or molecular states

$D\pi \to D\pi\ (0, 1/2)$



$DK \to DK\ (1, 0)$



a pair of poles above thr.

a bound states below thr. $D^*_{s0}(2317)$

$$a^{(0,1/2)}_{D\pi} = 0.35(1)\ \text{fm}$$

$$a^{(1,0)}_{DK} = -0.93(5)\ \text{fm}$$

$\Rightarrow$ lattice test of the molecular nature

NATURE of the $D_{s1}(2460)$

- Nature of the $D_{s1}(2460)$: $M_{D_{s1}(2460)} - M_{D^*_{s0}(2317)} \simeq M_{D^*} - M_D$

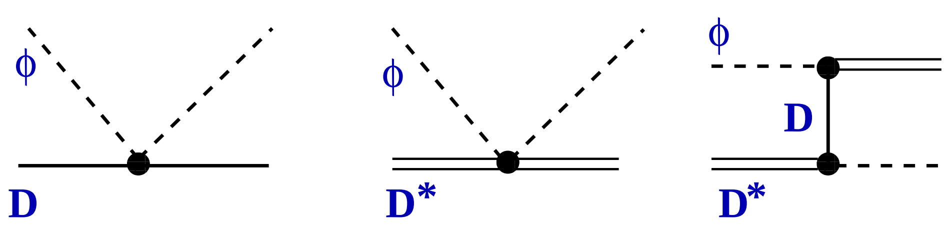
$\Rightarrow$ most likely a $D^\star K$ molecule (if the $D^\star_{s0}(2317)$ is DK)

$\Rightarrow$ study Goldstone boson scattering off D- and $D^\star$-mesons

- Use heavy meson chiral perturbation theory   Wise, Falk et al., Caslabuoni et al., ...

$$H_v = \frac{1+\not{v}}{2}\left[\not{V}_v + iP_v\gamma_5\right]$$
$$P = (D^0, D^+, D_s^+)\ , \quad V_\mu = (D_\mu^{*0}, D_\mu^{*+}, D_{s,\mu}^{*+})$$

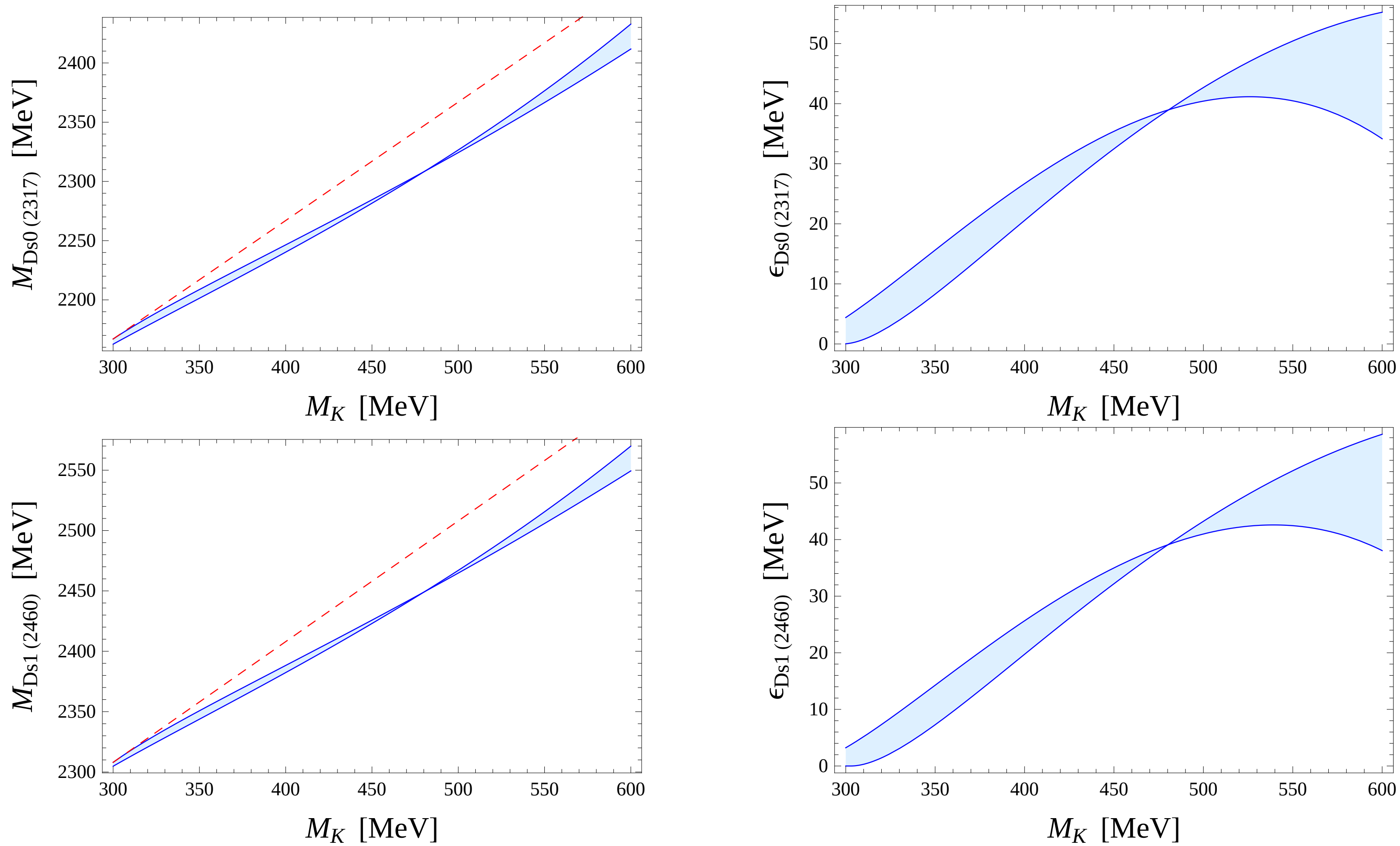
- T-matrix:



- Unitarization (as before) $\longrightarrow$ find poles in the complex plane

KAON MASS DEPENDENCE

- Mass and binding energy: $M_{\rm mol} = M_K + M_H - \epsilon$



$\Rightarrow$ typical for a molecule $\rightarrow$ test in LQCD

Symmetry tests in charmonium transitions

Guo, Hanhart, M., Phys. Rev. Lett. **103** (2009) 082003

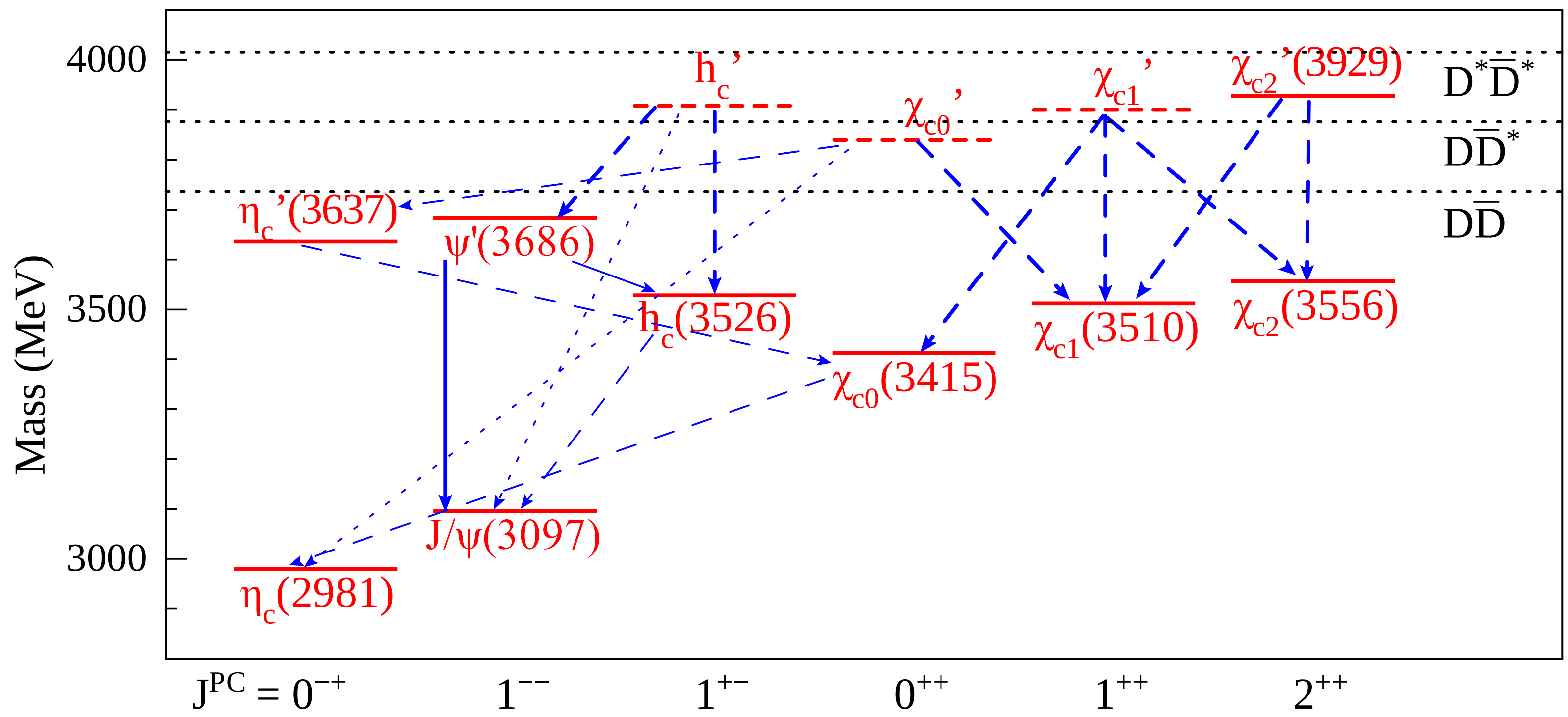
Guo, Hanhart, Li, M., Zhao, Phys. Rev. D **82** (2010) 034025

Guo, Hanhart, Li, M., Zhao, arXiv:1008.3632 [hep-ph]

Guo, Hanhart, M., Phys. Rev. Lett. **105** (2010) 162001

CHARMONIUM TRANSITIONS

- consider charmonium transitions with emission of one neutral pion or one η between S and P-wave states: SS, SP, PP



- analysis combining HQEFT and CHPT for most transitions possible
- $\mathcal{B}(\psi' \to J/\psi\pi^0)/\mathcal{B}(\psi' \to J/\psi\eta)$ long believed a fine probe for m_u/m_d

Ioffe, Voloshin, Donoghue, ...

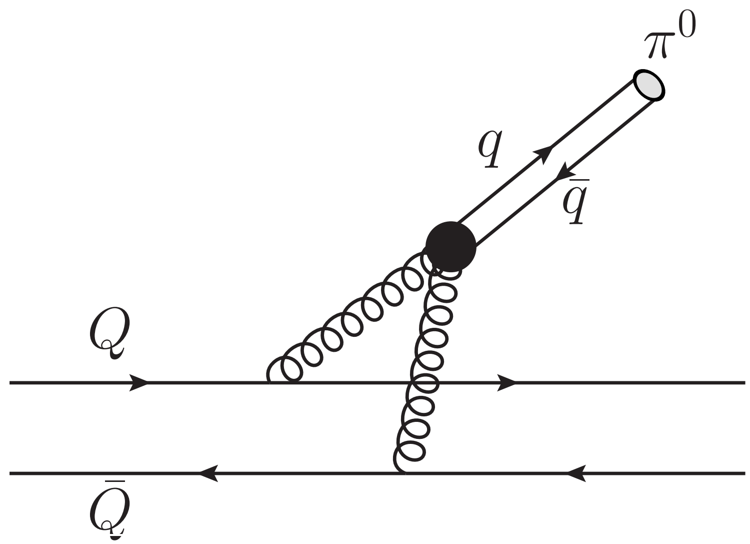
BASIC INGREDIENTS

- QCD multipole expansion:

$\Rightarrow$ soft gluon dominance/hadronization

$$\boldsymbol{\lambda}_{\mathbf{glue}} \gg \langle \boldsymbol{r} \rangle_{\mathbf{quarkonium}}$$

Gottfried (1978), Voloshin (1979), ...

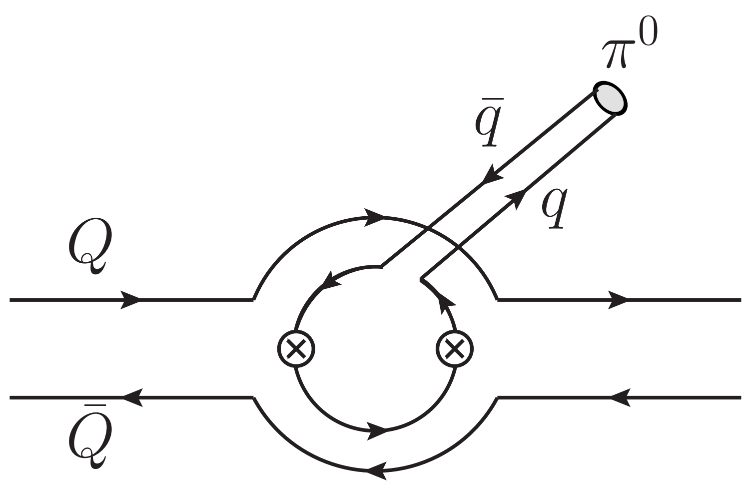


- Non-multipole (coupled-channel) effects:

$\Rightarrow$ intermediate meson loops

$\Rightarrow$ two-step OZI-violating process

Lipkin (1987), Lipkin, Tuan (1989), ...



EFFECTIVE LAGRANGIAN

Casalbuoni et al., Mehen, Yan et al., . . .

- Leading order effective Lagrangian:

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{SS} + \mathcal{L}_{SP} + \mathcal{L}_{PP}$$

$$\mathcal{L}_{SS} = \frac{A}{4}\left[\langle J'\sigma^i J^\dagger\rangle - \langle J^\dagger\sigma^i J'\rangle\right]\partial^i\left(\chi_-\right)_{aa}$$

$$\mathcal{L}_{SP} = \frac{i}{4}C\left[\langle\vec{\chi}^\dagger\cdot\vec{\sigma}J'\rangle + \langle J'\vec{\sigma}\cdot\vec{\chi}^\dagger\rangle\right]\left(\chi_-\right)_{aa}$$

$$\mathcal{L}_{PP} = i\frac{\gamma}{2}\epsilon^{ijk}\langle\chi'^i\chi^{j\dagger}\rangle\partial^k\left(\chi_-\right)_{aa}$$

- Building blocks:

$$\left.\begin{aligned} J &= \vec{\psi}\cdot\vec{\sigma} + \eta_c \\ \chi^i &= \sigma^j\left(-\chi_{c2}^{ij} - \tfrac{1}{\sqrt{2}}\epsilon^{ijk}\chi_{c1}^k + \tfrac{1}{\sqrt{3}}\delta^{ij}\chi_{c0}\right) + h_c^i \end{aligned}\right\}\ \text{heavy fields}$$

$$U = \exp(i\sqrt{2}\phi/F_\pi),\ \ U = u^2,\ \ \chi_- = u\chi^\dagger u - u^\dagger\chi u^\dagger \quad \text{light fields}$$

LEADING ORDER TRANSITIONS

- all transitions break SU(2) or SU(3) flavor $\longrightarrow$ sensitive to quark mass differences
- virtual photons can be shown to be absent at leading order
- transitions at leading order (LO):

$\psi' \to J/\psi \pi^0$	$i6A\epsilon^{ijk}\varepsilon^i(\psi')\varepsilon^j(J/\psi)q^k B_{du}$
$\psi' \to J/\psi \eta$	$i(8/\sqrt{3})A\epsilon^{ijk}\varepsilon^i(\psi')\varepsilon^j(J/\psi)q^k B_{sl}$
$\psi' \to h_c \pi^0$	$6C\vec{\varepsilon}(\psi')\cdot\vec{\varepsilon}(h_c)B_{du}$
$\eta_c' \to \chi_{c0}\pi^0$	$6\sqrt{3}CB_{du}$
$\chi_{c0}' \to \chi_{c1}\pi^0$	$-2\sqrt{6}i\gamma\vec{\varepsilon}(\chi_{c1})\cdot\vec{q}B_{du}$
$\chi_{c1}' \to \chi_{c1}\pi^0$	$-i3\gamma\epsilon^{ijk}\varepsilon^i(\chi_{c1}')\varepsilon^j(\chi_{c1})q^k B_{du}$
$\chi_{c1}' \to \chi_{c2}\pi^0$	$3\sqrt{2}i\gamma\varepsilon^i(\chi_{c1}')\varepsilon^{ij}(\chi_{c2})q^j B_{du}$
$\chi_{c2}' \to \chi_{c2}\pi^0$	$-i6\gamma\epsilon^{ijk}\varepsilon^{il}(\chi_{c2}')\varepsilon^{jl}(\chi_{c2})q^k B_{du}$
$h_c' \to h_c\pi^0$	$-i6\gamma\epsilon^{ijk}\varepsilon^i(h_c')\varepsilon^j(h_c)q^k B_{du}$

$$B_{du} \sim (m_d - m_u),\ B_{sl} \sim (m_s - m_l)\ \ [m_l = (m_d + m_u)/2]$$

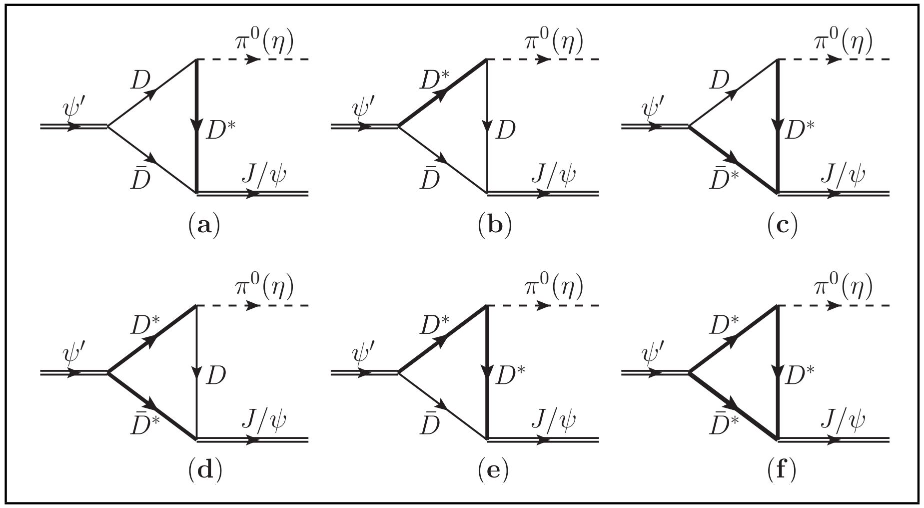
INCLUSION of CHARMED MESON LOOPS

- consider intermediate charmed mesons
- power counting scheme: 3 parameters

  q – momentum of the soft pion/eta

  δ – strength of SU(2)/SU(3) breaking

  v – heavy quark velocity, $v \simeq 0.5$



	SS	SP	PP
tree level	$q\delta$	δ	$q\delta$
loops	$q\frac{1}{v}\delta$	$\frac{q^2}{v^3 M_D^2}\delta$	$q\frac{1}{v^3}\delta$

GOOD NEWS and BAD NEWS I

- bad news first:

  charmed meson loops dominate $\psi' \to J/\psi\pi^0\ (\eta)$ transitions

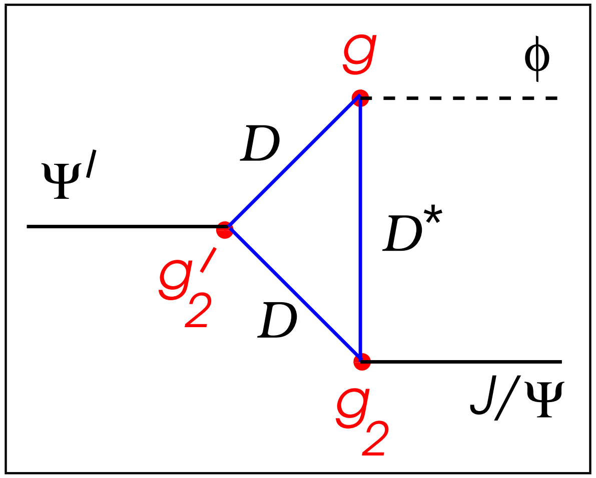
- $v = \sqrt{(2M_{\bar{D}} - M_{\bar{\psi}})/M_{\bar{D}}} \approx 0.53$

- results (coupling g from $D^* \to D\pi$):

$$\Gamma(\psi' \to J/\psi\pi^0) = (4.8 \pm 2.5) \cdot 10^{-2} g_2^2 (g_2')^2\ \mathrm{keV}$$

$$\Gamma(\psi' \to J/\psi\eta) = (4.3 \pm 2.3) \cdot 10^{-1} g_2^2 (g_2')^2\ \mathrm{keV}$$

$$\Rightarrow \boxed{R^{\mathrm{loop}}_{\pi^0/\eta} = 0.11 \pm 0.06\ \ [0.04 \pm 0.003]}$$



$\Rightarrow$ need higher order calculation in v $(1/m_c)$ to achieve the necessary precision for the extraction of m_u/m_d

GOOD NEWS and BAD NEWS II

- and now the good news:

charmed meson loops suppressed in $\psi' \to h_c\pi^0$ and $\eta_c' \to \chi_{c0}\pi^0$

$$\frac{1}{v^3}\frac{\vec{q}_\pi^{\,2}}{m_D^2} \simeq 0.02 \ [0.1] \quad \text{for} \quad \psi' \to h_c\pi^0 \ \ [\eta_c' \to \chi_{c0}\pi^0]$$

$\Rightarrow$ **predictions:**

- relative prediction from the tree graphs [accuracy $\sim \mathcal{O}(m_\pi/\Lambda_\chi, \Lambda_{\rm QCD}/m_c)$]:

$$\frac{\Gamma\left(\eta_c' \to \chi_{c0}\pi^0\right)}{\Gamma\left(\psi' \to h_c\pi^0\right)} = 5.86 \pm 0.94 \ \Rightarrow \ \boxed{\Gamma\left(\eta_c' \to \chi_{c0}\pi^0\right) = 1.5 \pm 0.3_{\rm exp} \pm 0.2_{\rm th}\ \text{keV}}$$

$\Rightarrow$ testable prediction ($\overline{\rm P}$ANDA at FAIR)

- absolute prediction using $m_u/m_d = 0.47 \pm 0.08$ Leutwyler 2010

$$\Gamma\left(\psi' \to h_c\pi^0\right) = (0.9 \pm 0.6)\tilde{C}^2\ \text{keV} \quad \textit{cf} \quad \Gamma(\psi' \to h_c\pi^0) = 0.26 \pm 0.05\ \text{keV}$$

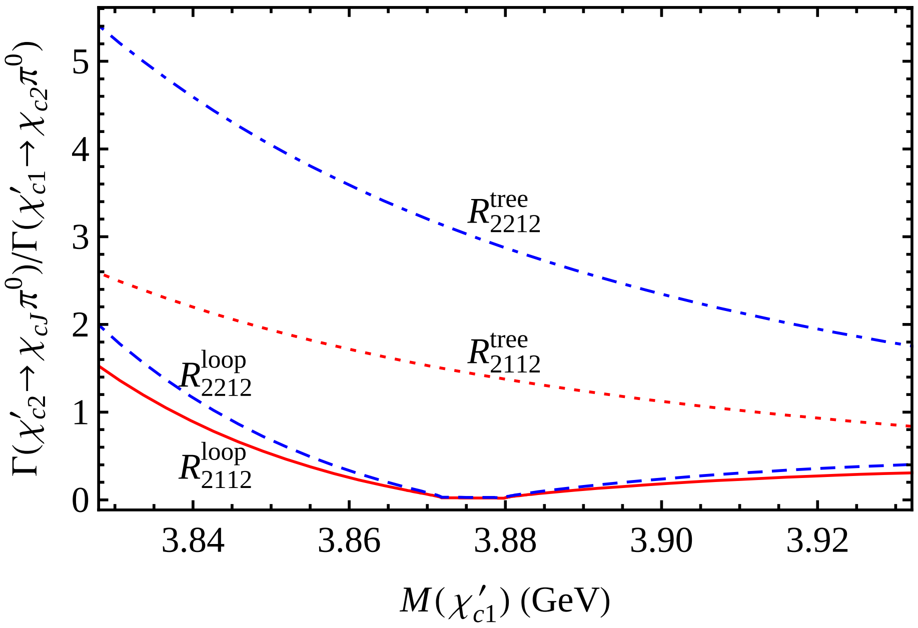
BES-III, PRL 105 (2010)

TESTING the LOOPS in PP TRANSITIONS

- consider χ'_{c2}, χ'_{c1} P-wave transitions

$$R_{2112} = \frac{\Gamma(\chi'_{c2} \to \chi_{c1}\pi^0)}{\Gamma(\chi'_{c1} \to \chi_{c2}\pi^0)}$$

$$R_{2212} = \frac{\Gamma(\chi'_{c2} \to \chi_{c2}\pi^0)}{\Gamma(\chi'_{c1} \to \chi_{c2}\pi^0)}$$



Note: – χ'_{c2} identified with $Z(3930)$ Belle (2006)

– mass of χ'_{c1} from quark model predictions

$\Rightarrow$ more testable predictions

. . . and EVEN BETTER NEWS

- Consider bottomonium transitions: $\Upsilon(4S) \to h_b \pi^0(\eta)$

- Loops are suppressed for two reasons:

$\star\ \vec{q}^{\,2}/(v^3 M_B^2) \simeq 0.6\ (0.2)$

$\star\ M_{B^0} - M_{B^+} = 0.33 \pm 0.06$ MeV $\ll m_d - m_u$

due to strong & em interference

Guo, Hanhart, M., JHEP 0809 (2008) 136

$\Rightarrow r = \dfrac{m_d - m_u}{m_d + m_u} \dfrac{m_s + \hat{m}}{m_s - \hat{m}}$ can be extracted with an accuracy of about 23 %

- by-product: $\Upsilon(4S) \to h_b \eta$ is a nice channel to search for the h_b (sizeable bf $\sim 10^{-3}$)

$\Rightarrow$ possible to measure at LHCb

SUMMARY & OUTLOOK

- Charm-strange mesons as DK resp. $D^\star K$ molecules
  - $\star$ unitarized CHPT at next-to-leading order
  - $\star$ various tests proposed for this scenario (exp., lattice)
- Charmonium transitions with emission of a neutral pion or eta
  - $\star$ charmed meson loops must be considered
  - $\star$ many tests of the loop scenario

    $\longrightarrow$ see talk by Qiang Zhao on Saturday
  - $\star$ m_u/m_d best from $\Upsilon(4S) \to h_b\pi^0$ (η)
- Need to improve theoretical framework, more connection to latttice QCD

$\Rightarrow$ golden times with BEPCII & FAIR ahead

SPARES etc.

RESULTS for the SCATTERING LENGTHS

(S,I)	Channel	LO	NLO	UChPT	CUChPT	Lattice
$(-1,0)$	$D\bar{K}\to D\bar{K}$	0.36	$0.31(2)$	$0.96(20)$		
$(-1,1)$	$D\bar{K}\to D\bar{K}$	-0.36	$-0.41(2)$	$-0.22(2)$		$-0.23(4)$
$(0,\frac{1}{2})$	$D\pi\to D\pi$	0.24	$0.23(0)$	$0.36(1)$	$0.35(1)$	
	$D\eta\to D\eta$	0	$-0.09(1)$	$-0.08(1)$	$0.19(9)+i0.02(2)$	
	$D_s\bar{K}\to D_s\bar{K}$	0.36	$0.31(6)$	$1.10(57)$	$-0.60(53)+i0.77(15)$	
$(0,\frac{3}{2})$	$D\pi\to D\pi$	-0.12	$-0.12(0)$	$-0.10(1)$		$-0.16(4)$
$(1,0)$	$DK\to DK$	0.72	$0.67(4)$	$-1.47(20)$	$-0.93(5)$	
	$D_s\eta\to D_s\eta$	0	$0.00(10)$	$0.02(10)$	$-0.33(4)+i0.05(1)$	
$(1,1)$	$D_s\pi\to D_s\pi$	0	-0.005	-0.005	$-0.0003(4)$	$0.00(1)$
	$DK\to DK$	0	-0.054	-0.049	$-0.04(6)+i0.29(11)$	
$(2,\frac{1}{2})$	$D_sK\to D_sK$	-0.36	$-0.41(6)$	$-0.23(5)$		$-0.31(2)$

- parameter-free predictions $\to$ agreement wit LQCD (where available)
- in most channels, sizeable unitarization effects

EFFECTIVE LAGRANGIAN for $\phi D^\star \to \phi D^\star$

- Effective Lagrangian at NLO:

$$\mathcal{L} = \mathcal{L}^{(1)} + \mathcal{L}^{(2)}$$

$$\mathcal{L}^{(1)} = -i\mathrm{Tr}[\bar{H}_a v_\mu D^\mu H_b] + g_\pi \mathrm{Tr}[\bar{H}_a H_b \gamma_\nu \gamma_5] u^\nu_{ba} + \frac{\lambda}{m_Q} \mathrm{Tr}[\bar{H}_a \sigma_{\mu\nu} H_a \sigma^{\mu\nu}]$$

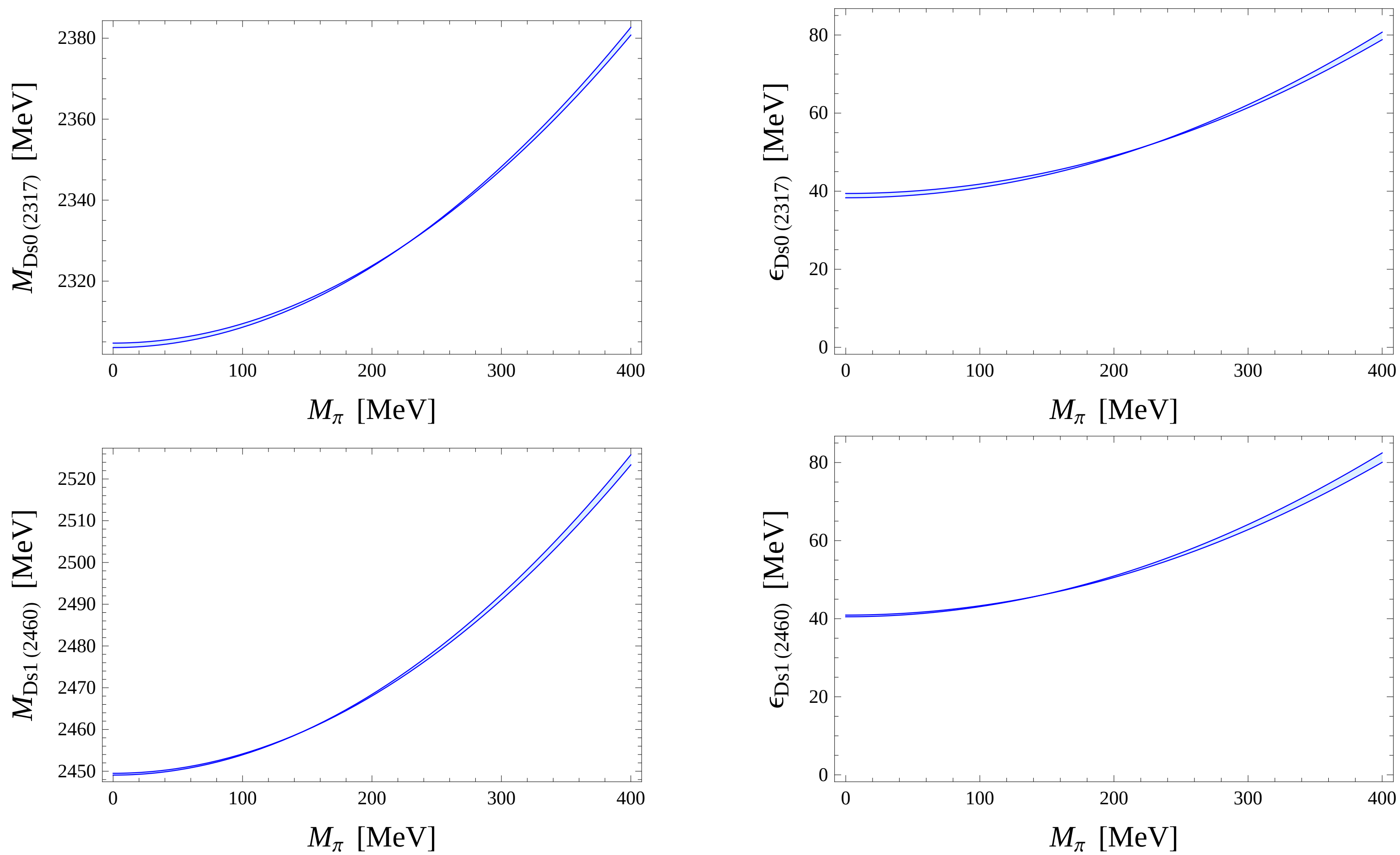
  – g_π from $D^\star \to D\pi$ decay, $g_\pi = 0.30 \pm 0.08$

  – spin-splitting $\Delta = m_{V^*} - m_P = -8\dfrac{\lambda}{m_Q}$ from phys. masses

  – $\mathcal{L}^{(2)}[H_v, U]$ with LECs $h_1, \ldots, h_5$ as before

PION MASS DEPENDENCE

- Mass and binding energy



$\Rightarrow$ different in strength from a quark-antiquark state