Extraction of the light quark mass ratio from heavy quarkonia transitions

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Collaborators: *Christoph Hanhart, Gang Li, Ulf-G. Meißner and Qiang Zhao*

Strong interactoins: From methods to structures

Bad Honnef, Feb.12-16, 2011

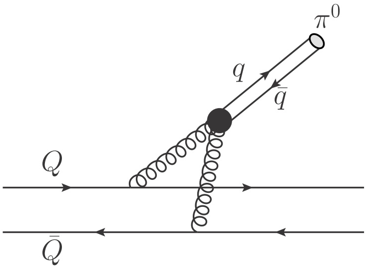
Based on the following papers:

F.-K.G., Hanhart, Meißner, *Phys.Rev.Lett.*103(2009)082003; *Phys.Rev.Lett.*105(2010)162001

F.-K.G., Hanhart, Li, Meißner, Zhao, *Phys.Rev.D*82(2010)034025; *Phys.Rev.D*83(2011)034013

m_u/m_d: $\psi' \to J/\psi\pi^0(\eta)$ vs light meson masses

The decays $\psi' \to J/\psi\pi^0$ and $\psi' \to J/\psi\eta$ were widely used to extract light quark mass ratio. Ioffe (1979), Ioffe, Shifman (1980), Donoghue, Wyler (1992), Leutwyler (1996),...



QCD multipole expansion ($\lambda_{\rm gluon} \gg r_{Q\bar{Q}}$) $\Rightarrow$

$$R_{\pi^0/\eta} \equiv \frac{\Gamma\left(\psi' \to J/\psi\pi^0\right)}{\Gamma(\psi' \to J/\psi\eta)} = \left(\frac{\langle 0|G\tilde{G}|\pi^0\rangle}{\langle 0|G\tilde{G}|\eta\rangle}\right)^2 \frac{q_\pi^3}{q_\eta^3}$$

axial anomaly $\Rightarrow$ Donoghue, Wyler (1992)

$$\left\langle 0 \left| G\tilde{G} \right| \pi^0 \right\rangle = \frac{3F^2}{2F_\pi}(m_u - m_d) + \mathcal{O}(p^4)$$

$$\left\langle 0 \left| G\tilde{G} \right| \eta \right\rangle = \frac{2F^2}{\sqrt{3}F_\eta}(\bar{m} - m_s) + \mathcal{O}(p^4), \quad \bar{m} \equiv \frac{m_u - m_d}{2}$$

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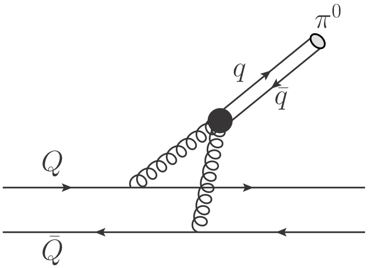

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	$R_{\pi^0/\eta}$	m_u/m_d
CLEO(2008)	$(3.88 \pm 0.23 \pm 0.05)\%$	0.40 ± 0.01
BES(2004)	$(4.8 \pm 0.5)\%$	0.35 ± 0.02
PDG(2008) fit	$(4.0 \pm 0.3)\%$	0.39 ± 0.02

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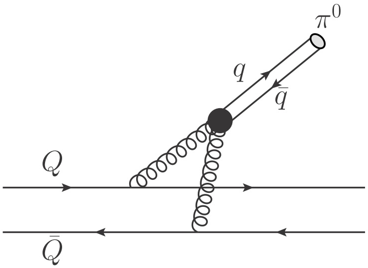

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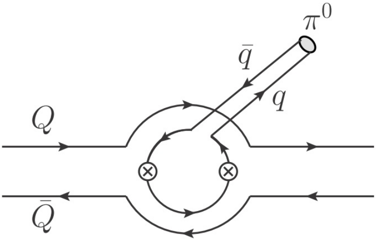
LO ChPT	Using M_{K^0,K^+}, M_{π^0,π^+}	0.56

Large discrepancy, why?

Non-multipole effects



Intermediate loops: non-multipole effects:

Lipkin, Tuan, PLB206(1988)349
Moxhay, PRD39(1989)3497
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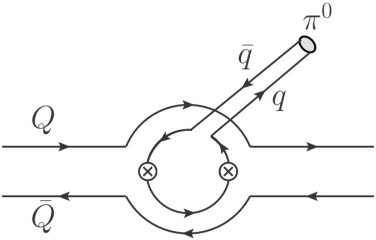

Many evidences for Importance of heavy meson loops in heavy quarkonia decays:

- the $M1$ radiative transitions between two charmonia — Li, Zhao (2008)
- the $\psi(3770)$ non-$D\bar{D}$ decays — Liu, Zhang, Li (2009), Zhang, Li, Zhao (2009)
- the $\Upsilon(5S)$ dipion transitions — Meng, Chao (2008)
- ..., see talk by Q. Zhao

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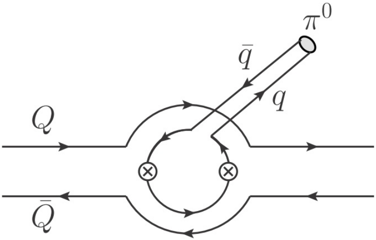

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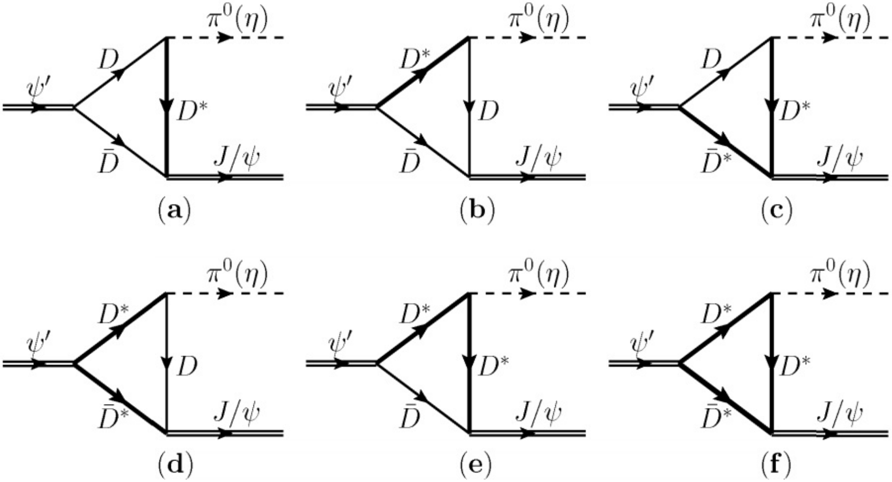
How to set up an EFT for heavy meson loops in heavy quarkonia transitions?

Charmed meson loops

F.-K.G., Hanhart, Meißner, PRL102(2009)242004; F.-K.G., Hanhart, Li, Meißner, Zhao, PRD83(2011)034013



Lagrangians

$J = \vec{\psi} \cdot \vec{\sigma} + \eta_c$: field for the S wave charmonia J/ψ and η_c

$H_a = \vec{V}_a \cdot \vec{\sigma} + P_a$: field for the charmed mesons $D_{(s)}$ and $D^*_{(s)}$

$\bar{H}_a = -\vec{\bar{V}}_a \cdot \vec{\sigma} + \bar{P}_a$: field for the anti-charmed mesons

The coupling of charmonia to the charmed and anti-charmed mesons:

Colangelo et al. (2004), F.-K.G., Hanhart, Meißner (2009)

$$\mathcal{L}_\psi = i\frac{g_2}{2}\mathrm{Tr}\left[J^\dagger H_a \vec{\sigma} \cdot \overleftrightarrow{\partial} \bar{H}_a\right] + \mathrm{h.c.}$$

The coupling of the charmed mesons to the Goldstone bosons:

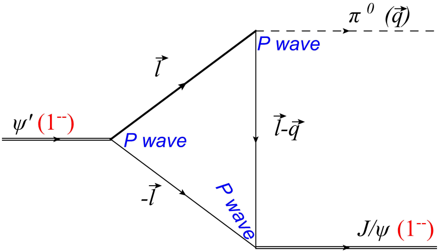
Burdman, Donoghue (1992), Wise (1992), Yan et al. (1992), Hu, Mehen (2006)

$$\mathcal{L}_\phi = -\frac{g}{2}\mathrm{Tr}\left[H_a^\dagger H_b \vec{\sigma} \cdot \vec{u}_{ba}\right], \qquad \vec{u}_{ba} = -\sqrt{2}\frac{\vec{\partial}\phi_{ba}}{F} + \ldots$$

Heavy quark spin symmetry relates the couplings for the heavy mesons within the same spin multiplet.

Power counting analysis — loops

$2M_D - M_{c\bar c} \sim \Lambda_{\rm QCD} \ll M_D \Rightarrow$ Nonrelativistic in charmed meson velocity $v \sim \sqrt{\frac{|2M_D - M_{c\bar c}|}{M_D}}$



Counting rules:
energy $\sim v^2$; momentum $\sim v$

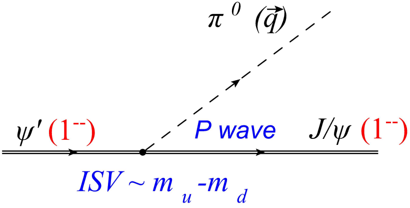
$$\frac{v^5}{(v^2)^3} v^2 q_\pi \frac{\Delta}{v^2} = \frac{1}{v} \Delta q_\pi$$

v^5:	non-relativistic integral measure
$(v^2)^{-3}$:	NR propagators
$v^2 q_\pi$:	P wave couplings
Δ:	$M_{D^+} - M_{D^0}$

$v \approx 0.5$: charmed meson velocity

Including scaling of the coupling constants does not spoil the picture.

Tree-level



LO chiral Lagrangian for the charmonia and Goldstone bosons — Casalbuoni et al. (1993)

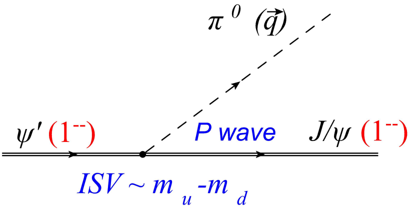
$$\mathcal{L}_{SS} = \frac{A}{4}\left(\mathrm{Tr}\left[J'\sigma^i J^\dagger\right] - \mathrm{Tr}\left[J^\dagger\sigma^i J'\right]\right)\partial^i(\chi_-)_{aa}$$
$$= \frac{4A}{F}\epsilon^{ijk}\psi'^j\psi^{k\dagger}\partial^i\left[\frac{3}{2}B_0(m_d - m_u)\pi^0 + \frac{2}{\sqrt{3}}B_0(m_s - \bar{m})\eta\right] + \ldots$$

$J = \vec{\psi}\cdot\vec{\sigma} + \eta_c,\ J' = \vec{\psi}'\cdot\vec{\sigma} + \eta_c'$, and $\chi_- = u^\dagger\chi u^\dagger - u\chi^\dagger u$.

Heavy quark spin symmetry breaking, isospin / SU(3) breaking ($\pi^0 - \eta$ mixing included)

QCDME result reproduced.

Tree-level



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QCDME result reproduced.

Amplitude: $\mathcal{M}(\psi' \to J/\psi\pi^0) \propto (m_d - m_u)q_\pi$

Loops: $\frac{1}{v}\Delta q_\pi$, $\Delta = M_{D^+} - M_{D^0} \sim m_d - m_u$. Loops are enhanced by a factor of $\frac{1}{v}$!

Loop contribution

Mass differences of the intermediate charmed mesons give isospin / SU(3) breaking.

- For $\psi' \to J/\psi\eta$, SU(3) breaking, charged, neutral and strange charmed mesons contribute:

$$\mathcal{M}(\psi' \to J/\psi\eta) \propto \epsilon^{ijk} q_\eta^i \varepsilon_{\psi'}^j \varepsilon_{J/\psi}^k \frac{1}{\sqrt{3}} (I_c + I_n - 2I_s).$$

  Loop functions I_c, I_n and I_s are for the charged, neutral and strange charmed mesons, respectively. Spin symmetry also broken.

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- For $\psi' \to J/\psi\pi^0$, isospin breaking, charged and neutral charmed mesons contribute, and $\pi^0 - \eta$ mixing also contributes:

$$\mathcal{M}(\psi' \to J/\psi\pi^0) \propto \epsilon^{ijk} q_\pi^i \varepsilon_{\psi'}^j \varepsilon_{J/\psi}^k \left[(I_c - I_n) + \frac{\epsilon_{\pi^0\eta}}{\sqrt{3}} (I_c + I_n - 2I_s) \right],$$

  $\epsilon_{\pi^0\eta}$: $\pi^0 - \eta$ mixing angle

Results

Can we get sensible results considering only the contribution from the meson loops?

- Comparing with data. Our result

$$R_{\pi^0/\eta} = \frac{\Gamma\left(\psi' \to J/\psi\pi^0\right)}{\Gamma\left(\psi' \to J/\psi\eta\right)} = 0.11 \pm 0.06$$

Data	$R_{\pi^0/\eta}$
CLEO(2008)	$(3.88 \pm 0.23 \pm 0.05)\%$
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- Comparing the extracted coupling constant with models

PDG: $\Gamma(\psi' \to J/\psi\pi^0) = 0.40 \pm 0.03$ keV
$\Gamma(\psi' \to J/\psi\eta) = 10.0 \pm 0.4$ keV

$$\Rightarrow \sqrt{g_{\psi DD}g_{\psi' DD}} = 6...8$$

Models	$g_{\psi DD}$	Refs.
QCD sum rules	8.2 ± 1.3	Matheus et al (2002)
VMD	7.7	Matinyan, Müller (1998)
VMD	8.0 ± 0.5	Deandrea et al (2003)

- Solution of the puzzle:

  The value of m_u/m_d extracted from the $\psi' \to J/\psi\pi^0(\eta)$ is NOT reliable since it suffers from very large meson loop contributions!

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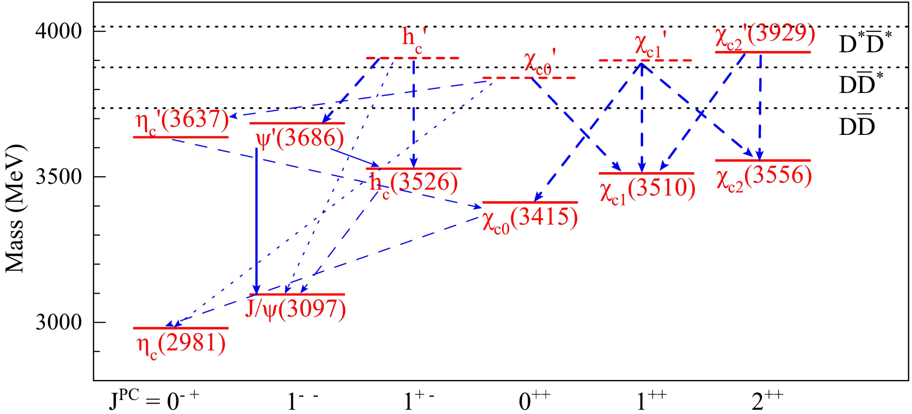
- Role of the charmed loops in other charmonia transitions?

Charmonia transitions with the emission of one pion / eta

F.-K.G., Hanhart, Li, Meißner, Zhao, PRD83(2011)034013

S-wave charmonia: $\eta_c^{(\prime)}$, J/ψ, ψ'; *P*-wave charmonia: $h_c^{(\prime)}$, $\chi_{cJ}^{(\prime)}(J = 0, 1, 2)$



Cross-checked with the effective Lagrangian approach: quantitative agreement

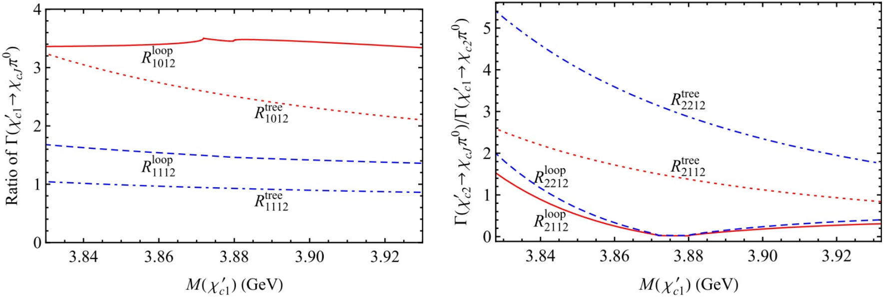
- ♡ *SS* transitions — Enhancement of loops
- ♡ *PP* transitions — Enhancement of loops
- ♡ *SP* transitions — Process dependent, sometimes high suppression

Parameter-free predictions

PP transitions: Loops enhanced by $1/v^3$!

Ratios of decay widths $R_{mn12} \equiv \frac{\Gamma(\chi'_{cm}\to\chi_{cn}\pi^0)}{\Gamma(\chi'_{c1}\to\chi_{c2}\pi^0)}$: free of any parameter.

Comparison of the loop results with the tree-level results — testable



Power counting analysis for *SP* transitions — A different case

F.-K.G., Hanhart, Li, Meißner, Zhao, PRD82(2010)034025; PRD83(2011)034013

- $J^{PC}(\psi') = 1^{--}, J^{PC}(h_c) = 1^{+-}$, *S*-wave decay:
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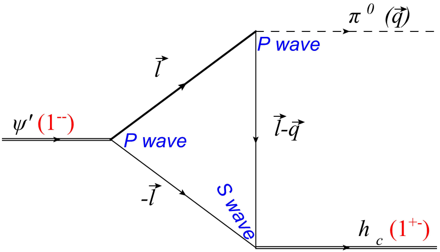
- Charmed meson loops:



$q_\pi = 86$ MeV$\ll M_D = 1870$ MeV

$$\frac{v^3}{(v^2)^2}\frac{q_\pi^2}{M_D^2}\frac{\Delta}{v^2} = \frac{q_\pi^2}{v^3 M_D^2}\Delta \sim \frac{\Delta}{50}$$

v^3: non-relativistic integral measure

$(v^2)^{-2}$: two NR propagators

q_π^2: *P* wave couplings [vector loop $I^i(q) = q_\pi^i I^{(1)}(q)$]

Charmed meson loops are highly suppressed here, confirmed by explicit calculation.

Bottomonia *SP* transitions $\Upsilon(4S) \to h_b\pi^0(\eta)$

F.-K.G., Hanhart, Meißner, PRL105(2010)162001

$\Upsilon(4S)$: radial excitation of the *S*-wave vector bottomonium $M_{\Upsilon(4S)} = 10.579$ GeV

h_b: *P*-wave ground state 1^{+-} $b\bar{b}$, still missing

$M_{h_b} = \frac{1}{9}(M_{\chi_{b0}} + 3M_{\chi_{b1}} + 5M_{\chi_{b2}}) = 9.900$ GeV

See, e.g., Godfrey, Rosner (2002)

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For $\Upsilon(4S) \to h_b\pi^0(\eta)$, $v \approx 0.3$, there are two different suppressions:

- $q^2_{\pi(\eta)}/(v^3 M_B^2) \approx 0.6(0.2)$
- $\Delta = M_{B^0} - M_{B^+} = 0.33 \pm 0.06$ MeV $\ll m_d - m_u$

  This is due to the destructive interference between the e.m. and strong contributions F.-K.G., Hanhart, Meißner, JHEP09(2008)136

$\Upsilon(4S) \to h_b\pi^0(\eta)$ can be used to extract the light quark mass ratio!

$\Upsilon(4S) \to h_b \pi^0(\eta)$

- Multipole contribution dominates ⇒

$$\frac{\Gamma(\Upsilon(4S) \to h_b \pi^0)}{\Gamma(\Upsilon(4S) \to h_b \eta)} = r^2_{G\tilde{G}} \left| \frac{\vec{q}_\pi}{\vec{q}_\eta} \right| \qquad \text{with } r_{G\tilde{G}} \equiv \frac{\langle 0|G\tilde{G}|\pi^0\rangle}{\langle 0|G\tilde{G}|\eta\rangle}$$

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- From CHPT with $U(1)_A$ anomaly, the NLO expressions for $\langle 0|G\tilde{G}|\pi^0(\eta)\rangle$ have been worked out. Donoghue, Wyler (1992)

  Extracting the combined light quark mass ratio:

$$\frac{m_d - m_u}{m_d + m_u} \frac{m_s + \hat{m}}{m_s - \hat{m}} = \frac{4}{3\sqrt{3}} r_{G\tilde{G}} \frac{F_\pi}{F_\eta} \frac{F_K^2 M_K^2 - F_\pi^2 M_\pi^2}{F_\pi^2 M_\pi^2} (1 - \delta_{\rm GMO}) \left[1 + \frac{4 L_{14}}{F_\pi^2} (M_\eta^2 - M_\pi^2) \right]$$

  $\mathcal{O}(p^4)$ Deviation from Gell-Mann–Okubo relation: $\delta_{\rm GMO} = -0.06$

  Resonance saturation ⇒ $L_{14} = (2.3 \pm 1.1) \times 10^{-3}$

Theoretical uncertainty due to loops can be reduced

- Considering only the bottom meson loops,

$$\Gamma(\Upsilon(4S) \to h_b\eta)^{\rm loop} = 0.16 g_{1b}^2 \,\rm keV$$

Once g_{1b}^2 is measured, the 20% uncertainty due to loops can be reduced.

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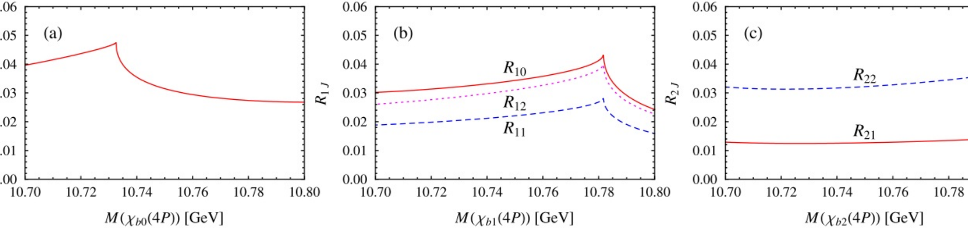
- How to measure g_{1b}^2:

$$R_{01} \equiv \frac{\Gamma(\chi_{b0}(4P) \to \chi_{b1}\eta)}{\Gamma(\chi_{b0}(4P) \to B^+B^-)}, \quad R_{1J} \equiv \frac{\Gamma(\chi_{b1}(4P) \to \chi_{bJ}\eta)}{\Gamma(\chi_{b1}(4P) \to B^+B^{*-})}, \ [J = 0, 1, 2],$$

$$R_{2J} \equiv \frac{\Gamma(\chi_{b2}(4P) \to \chi_{bJ}\eta)}{\Gamma(\chi_{b2}(4P) \to B^{*+}B^{*-})}, \ [J = 1, 2].$$

All the ratios are proportional to g_{1b}^2.



The value of g_{1b}^2 has been set to 1 GeV$^{-1/2}$ in the figure.

Summary and outlook

- Having available an EFT that allows one to study both direct transitions as well as those mediated via heavy loops
- The charmed meson loops play an important role in the decays $\psi' \to J/\psi\pi^0(\eta)$. Hence the previous extraction of light quark mass ratio from these decays is not reliable.
- m_u/m_d can be extracted from the $\Upsilon(4S) \to h_b\pi^0(\eta)$

Summary and outlook

- Having available an EFT that allows one to study both direct transitions as well as those mediated via heavy loops
- The charmed meson loops play an important role in the decays $\psi' \to J/\psi\pi^0(\eta)$. Hence the previous extraction of light quark mass ratio from these decays is not reliable.
- m_u/m_d can be extracted from the $\Upsilon(4S) \to h_b\pi^0(\eta)$

Outlook:

- Radiative transitions of heavy quarkonia
- Dipion transitions between two heavy quarkonia
- Higher orders
- To be tested at BES-III, PANDA, LHC-b, …

If taking into account the scaling of coupling constants

	Tree-level	Loops
SS	$\frac{1}{m_c} q\delta$	$\frac{1}{4\pi v_c^3} \frac{1}{m_c} \frac{q\Delta}{v}$
SP	δ	$\frac{1}{2\sqrt{3}\pi v_c^4} \frac{q^2}{v^3 M_D^2} \Delta$
PP	$\frac{1}{\Lambda_{\rm QCD}} q\delta$	$\frac{1}{3\pi v_c^5} \frac{1}{\Lambda_{\rm QCD}} \frac{q\Delta}{v^3}$

For details, see Guo et al, PRD83(2011)034013