Quarkonium hadronic transitions

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based on: **arXiv:1905.03794**

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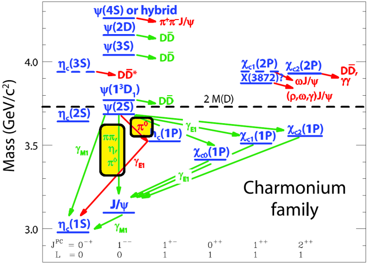
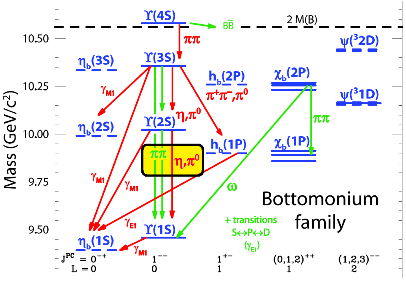
Introduction and Motivation

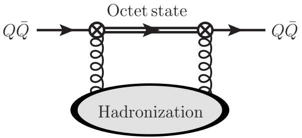




- Chiral Symmetry
  - Allowed because the energy release is small.
  - Parametrizes the decays in terms of a few Low-energy constants. Brown, Cahn Phys.rev.Lett.35 (1975); Mannel, Urech Z.Phys.C73 (1997); Casalbuoni *et al* Phys.Lett.B309 (1993)
  - Good descriptions of the processes.
  - However lacks predictive power.

Introduction and Motivation

- Adding microscopic information to constrain the chiral description:
  - Heavy quark mass $1/m_Q$ expansion: heavy quark spin symmetry.
  - Two step process. Gottfried Phys.Rev.Lett.40 (1978)



  - Multipole expansion:
    - $\boldsymbol{r} \cdot \boldsymbol{E}$ as the leading heavy-quark-gluon interaction.
    - Requires $m_Q v \gg \Lambda_{QCD}$
  - OPE of the octet propagator. Voloshin Nucl.Phys.B154 (1979)
    - Write the amplitude in terms of time-local gluonic operators.
    - Requires $\Lambda_{QCD} \ll m_Q v^2$ and the pion energy $E \ll m_Q v^2$.
  - The local gluonic operators can be hadronized using the axial and scale anomalies.

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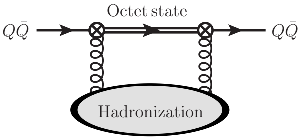

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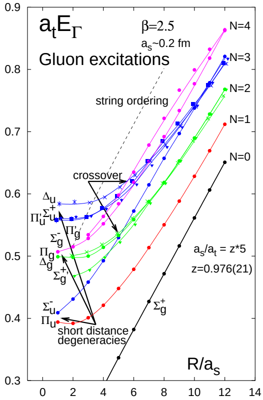
Not well justified for transitions between different principal quantum number: $E \sim m_Q v^2$

Luty, Sundrum Phys.Lett.B312 (1993)

Our approach



- **Quenched** lattice NRQCD.

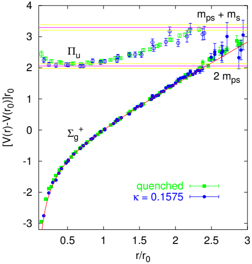
Juge, Kuti, Morningstar Phys.Rev.Lett.90 (2003)

- We propose an alternative way to compute the amplitudes:
  - Work in an EFT framework.
  - $1/m_Q$ expansion.
  - Still use the multipole expansion.
  - Take advantage that the **spectrum of the color-octet sector** corresponds to the **quarkonium hybrid** one (in the quenched approximation).
  - Organize the computation within a $1/N_c$ expansion.

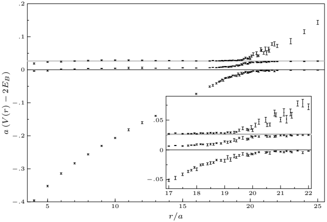
Our approach: what about light-quark states?

- How does the spectrum of static states change in **unquenched** case?

SESAM/TCL Col. G. Bali et al. Phys.Rev.D62 (2000)



Bulava *et al* arXiv:1902.04006



- What we know:
  - Σ_g^+ and Π_u^- do not change much below string breaking distance.
  - No information about other Λ_η^σ, but there is no reason to expect a different behavior.
  - One should consider $Q\bar{q}$-$\bar{Q}q$ and possible tetraquarks states.
  - For transitions **below threshold** the couplings of these states to quarkonium are $1/N_c$ **suppressed**.

Outline

0 EFT incorporating $1/m_Q$ and multipole expansions: weakly-coupled pNRQCD.

Pineda, Soto Nucl.Phys.Suppl 64 (1998); Brambilla, Pineda, Soto, Vairo Nucl.Phys.B566 (2000)

1 Write the most general hadronic version of pNRQCD.
   * Singlet, hybrid and pion fields as d.o.f.
   * Chiral, multipole, $1/m_Q$, $1/N_c$ expansions.

2 Match the hadronic and partonic versions of the theory.
   * No d.o.f integrated out.
   * Dynamical energy scale $E \sim \Lambda_{QCD}$.

3 Compute transition amplitudes in the hadronic EFT.

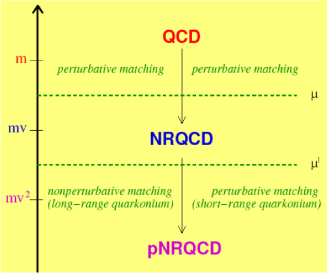
Potential Non–Relativistic QCD

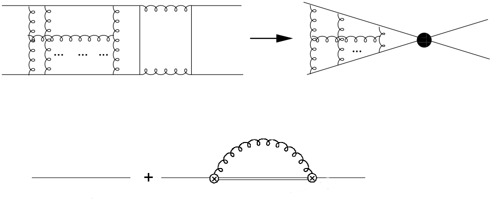
Motivation

- Quarkonium systems are non–relativistic bound states.
- **Multiscale system**: $m_Q \gg m_Q v \gg m_Q v^2$, and Λ_{QCD}. m is the heavy–quark mass, $v \ll 1$ the heavy quark velocity.
- We can exploit the **scale hierarchies** by building an **Effective Field Theory** (EFT).

Matching procedure

- Integrating out the m_Q scale leads to the well known NRQCD. Caswell, Lepage 1986; Bodwin, Braaten and Lepage 1995. Since $m_Q \gg \Lambda_{QCD}$ the matching is perturbative.
- The degrees of freedom in pNRQCD are a **color singlet** (S) and **octet fields** (O^a) and the ultrasoft gluons.
- $\boldsymbol{R}$ is the CoM coordinate and $\boldsymbol{r}$ the relative coordinate of the quark pair.
- **Multipole expansion**: Since $r \sim 1/m_Q v$, integrating out $m_Q v$ implies a multipole expansion of the gluon fields.





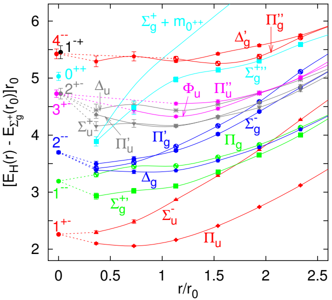
- At $E \sim m_Q v^2$ Quarkonium is described by pNRQCD, which takes a Schrödinger-like form with a potential interactions, but also (ultrasoft) gluon effects.

$$\mathcal{L} = \Phi(\boldsymbol{r})^\dagger (i\partial_0 - \boldsymbol{p}^2/2m_Q - V(r) + \text{int. with low–energy d.o.f})\Phi(\boldsymbol{r})$$

- When matching NRQCD to pNRQCD there are two possibilities:
  - Weak–couplig: $m_Q v \gg \Lambda_{\rm QCD}$ $\Rightarrow$ Perturbative matching.
  - Strong coupling: $m_Q v \sim \Lambda_{\rm QCD} \gg m_Q v^2$ $\Rightarrow$ Non–perturbative matching.

Hybrid states in pNRQCD

- In the short distance limit the static energies are characterized by $O(3) \times C$ instead of $D_{\infty\,h}$.



Foster, Michael Phys.Rev.D59 (1999)

Gluelumps

- $G_k^{i\,a}$ create a basis of color-octet eigenstates of $h_0(\boldsymbol{R})$ in the presence of a static, local, color-octet source O^a.

$$h_0(\boldsymbol{R})G_k^{i\,a}(\boldsymbol{R})|0\rangle = \Lambda_k G_k^{i\,a}(\boldsymbol{R})|0\rangle$$

- The gluon and light-quark Hamiltonian density leading order in the multipole expansion.

$$h_0 = \frac{1}{2}\left(\boldsymbol{E}^2 - \boldsymbol{B}^2\right) - \sum_{j=1}^{n_f} \bar{q}_j\,[i\boldsymbol{D}\cdot\boldsymbol{\gamma} - m_j]\,q_j$$

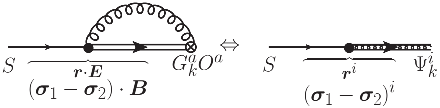
- States are constrained to satisfy the Gauss law.

- We project the pNRQCD Lagrangian to the Fock subspace spanned by

$$\int d^3r d^3R \sum_k P_{k\lambda}^i O^{a\,\dagger}(\boldsymbol{r},\boldsymbol{R})\,G_k^{i\,a}(\boldsymbol{R})|0\rangle\,\Psi_{k\lambda}(t,\,\boldsymbol{r},\,\boldsymbol{R})$$

- $P_{k\lambda}^i$ projects $G_k^{i\,a}$ into a representation of $D_{\infty\,h}$.

Mixing terms Matching



- Matching the partonic and hadronic versions of pNRQCD:

$$i\sqrt{\frac{T_F}{N_c}}\hat{\boldsymbol{r}}^{\dagger i}_{\lambda}\boldsymbol{r}^j\langle 0|G^{ai\dagger}_{1--}(\boldsymbol{R})g\boldsymbol{E}^{aj}(\boldsymbol{R})|0\rangle = i\boldsymbol{r}\cdot\hat{\boldsymbol{r}}^{\dagger}_{\lambda}t^{(r1^{--})}$$

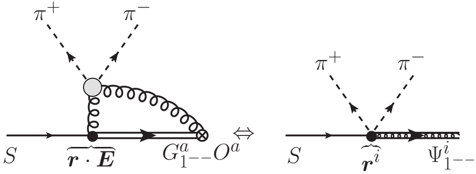
$$i\frac{gc_F}{2m_Q}\sqrt{\frac{T_F}{N_c}}\left(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2\right)^i\hat{\boldsymbol{r}}^{j\dagger}_{\lambda}\langle 0|G^{ai\dagger}_{1+-}(\boldsymbol{R})\boldsymbol{B}^{aj}(\boldsymbol{R})|0\rangle = i\left(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2\right)\cdot\hat{\boldsymbol{r}}^{\dagger}_{\lambda}t^{(S1^{+-})}$$

- If the gluelump is dominated by the lowest dimension gluonic operator

$$G^a_{1--} = Z_E^{-1/2}g\boldsymbol{E}^a + Z_{D\times B}^{-1/2}\left(\boldsymbol{D}\times g\boldsymbol{B}\right)^a+\cdots$$
$$G^a_{1+-} = Z_B^{-1/2}g\boldsymbol{B}^a + Z_{D\times E}^{-1/2}\left(\boldsymbol{D}\times g\boldsymbol{E}\right)^a+\cdots$$

$$\Rightarrow t^{(r1^{--})} = \sqrt{\frac{T_F Z_E}{N_c}}\,,\quad t^{(S1^{+-})} = \frac{c_F}{2m_Q}\sqrt{\frac{T_F Z_B}{N_c}}$$

$Q\bar{Q}(2S) \to Q\bar{Q}(1S)\pi^+\pi^-$: Matching



- Partonic pNRQCD

$$ig\sqrt{\frac{T_F}{Z_E N_c}}\hat{\boldsymbol{r}}_\lambda \cdot \boldsymbol{r}\langle\pi^+(p_+)\pi^-(p_-)|\boldsymbol{E}^a\cdot\boldsymbol{E}^a|0\rangle$$

- Hadronic pNRQCD

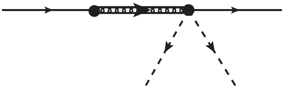
$$i4\boldsymbol{r}\cdot\hat{\boldsymbol{r}}_\lambda\left(-t_{d0}^{(r1^{--})}E_+E_- + t_{di}^{(r1^{--})}\boldsymbol{p}_+\cdot\boldsymbol{p}_- - t_m^{(r1^{--})}m_\pi^2\right)$$

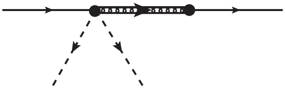
- The divergence on the scale current allows to determine the matrix element up to an unknown constant κ Voloshin, Zakharov Phys.Rev.Lett 45 (1980); Novikov, Shifman Z.Phys.C8 (1981); Chivukula *et all* Annals Phys.192 (1989)

$$\langle\pi^+(p_+)\pi^-(p_-)|\frac{\beta_0\alpha_s}{2\pi}\boldsymbol{E}^2|0\rangle = \left(2-\frac{9}{2}\kappa\right)E_+E_- - \left(2+\frac{3}{2}\kappa\right)\boldsymbol{p}_+\cdot\boldsymbol{p}_- + 3m_\pi^2$$

- Subject to potentialy large $\mathcal{O}(\alpha_s)$ corrections and neglected anomalous dimension of the $q\bar{q}$ operator.

$Q\bar{Q}(2S) \to Q\bar{Q}(1S)\pi^+\pi^-$





- Chiral amplitude up to $\mathcal{O}(p^2)$

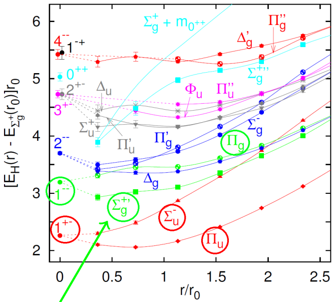
$$\mathcal{A}_\chi = -a_1 p_+^0 p_-^0 + a_2 \boldsymbol{p}_+ \cdot \boldsymbol{p}_- - a_3 m_\pi^2$$

- In our approach

$$a_1 = -\frac{8\pi^2 T_F}{3\beta_0 N_c}\beta_r^{(12)}\left(2 - \frac{9}{2}\kappa\right)$$

$$a_2 = -\frac{8\pi^2 T_F}{3\beta_0 N_c}\beta_r^{(12)}\left(2 + \frac{3}{2}\kappa\right)$$

$$a_3 = -\frac{8\pi^2 T_F}{\beta_0 N_c}\beta_r^{(12)}$$



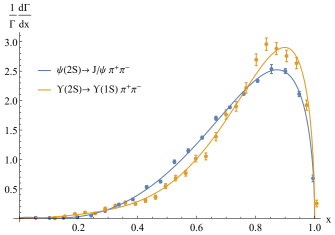
- The sum over hybrid intermediate states

$$\beta_r^{(n'\,n)} = \sum_m \langle S_{n'}|\hat{\boldsymbol{r}}_\lambda^\dagger \cdot \boldsymbol{r}|\Psi_m\rangle\left(\frac{1}{m_n - m_m} + \frac{1}{m_{n'} - m_m}\right)\langle\Psi_m|\hat{\boldsymbol{r}}_\lambda^\dagger \cdot \boldsymbol{r}|S_n\rangle$$

- See M. Berwein, N. Brambilla, JTC, A. Vairo. Phys.Rev.D92 (2015); R. Oncala, J. Soto Phys.Rev.D96 (2017) for the details on how to obtain the hybrid spectrum and wavefunctions.

$Q\bar{Q}(2S) \to Q\bar{Q}(1S)\pi^+\pi^-$: Normalized Line-shape and decay widths

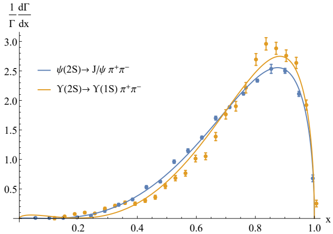
- Chiral EFT



$x = (m_{\pi\pi} - 2m_\pi)/(m_{2S} - m_{1S} - 2m_\pi)$

$$a_1^c/a_2^c = -0.20^{+3.93}_{-0.98}\,, \quad a_3^c/a_2^c = 3.12^{+3.78}_{-15.05}\,, \quad \chi^2_{\rm d.o.f} = 0.13\,,$$
$$a_1^b/a_2^b = 4.41^{+1.93}_{-3.07}\,, \quad a_3^b/a_2^b = -15.05^{13.06}_{-7.50}\,, \quad \chi^2_{\rm d.o.f} = 0.29\,,$$

- Hadronic pNRQCD



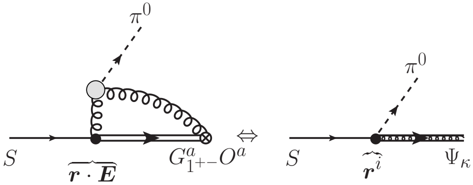
$$\kappa_c = 0.277 \pm 0.015\,, \quad \chi^2_{\rm d.o.f} = 0.17\,,$$
$$\kappa_b = 0.342^{+0.015}_{-0.017}\,, \quad \chi^2_{\rm d.o.f} = 1.25\,,$$
$$\boxed{\boldsymbol{\kappa = 0.301(31)}}$$

∗ Data: ATLAS JHEP 1701 (2017) (charm) Belle Phys.Rev. D96 (2017) (bottom).

- Decay widths:

$$\Gamma_{\psi(2S)\to J/\psi\pi^+\pi^-} = 38.0(^{-8.5}_{+13.0})_{\Lambda_1}(^{-4.1}_{+4.5})_\kappa(\pm 17.4)_{\rm s.p.}\,{\rm keV}\,, \quad \Gamma^{\rm exp} = 102.1(2.9)\,{\rm keV}\,,$$
$$\Gamma_{\Upsilon(2S)\to\Upsilon(1S)\pi^+\pi^-} = 2.51(^{-0.47}_{+0.66})_{\Lambda_1}(^{-0.28}_{+0.31})_\kappa(\pm 1.21)_{\rm s.p.}\,{\rm keV}\,, \quad \Gamma^{\rm exp} = 5.71(48)\,{\rm keV}\,.$$

$Q\bar{Q}(2S) \to Q\bar{Q}(1P)\pi^0$: Matching



- Partonic pNRQCD

$$\frac{i}{3}\sqrt{\frac{T_F}{N_c Z_B}}\hat{\boldsymbol{r}}_\lambda \cdot \boldsymbol{r}\langle\pi^0|g^2\boldsymbol{E}\cdot\boldsymbol{B}|0\rangle$$

- Hadronic pNRQCD: We need **isospin breaking** operators

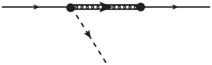
$$-it^{(r1^{+-})}\boldsymbol{r}\cdot\hat{\boldsymbol{r}}_\lambda\, 2m_\pi^2\frac{m_d-m_u}{m_u+m_d}$$

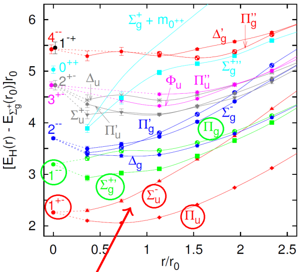
- From the axial anomaly Gross, Treiman, Wilczek Phys.RevD19 (1979); Novikov, Shifman, Vainshtein, Zakharov Nucl.PhysB165 (1980):

$$\langle\pi^0|\frac{\alpha_s}{\pi}\boldsymbol{E}\cdot\boldsymbol{B}|0\rangle = \frac{m_d-m_u}{m_u+m_d}F_\pi m_{\pi^0}^2$$

$$\Rightarrow t^{(r1^{+-})} = -\frac{2\pi^2}{3}F_\pi\sqrt{\frac{T_F}{N_c Z_B}}$$

$Q\bar{Q}(2S) \to Q\bar{Q}(1P)\pi^0$





- Amplitude:

$$i\mathcal{A} = -F_\pi m_\pi^2 \frac{2\pi^2 c_F}{3m_Q} \frac{T_F}{N_c} \frac{m_d - m_u}{m_u + m_d} \beta_\sigma^{(12)}$$

- The sum over hybrid intermediate states

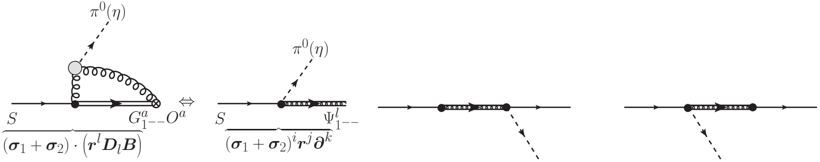
$$\beta_\sigma^{(12)} \equiv \sum_m \Big(\langle h_c(1^1P_1)|\hat{\boldsymbol{r}}_\lambda \cdot \boldsymbol{r}|\Psi_m\rangle \frac{i}{m_{h_c} - m_m} \langle \Psi_m|\hat{\boldsymbol{r}}_\lambda^\dagger \cdot (\boldsymbol{\sigma}_1 - \boldsymbol{\sigma}_2)\,|\psi(2^3S_1)\rangle$$

$$+ \langle h_c(1^1P_1)|\hat{\boldsymbol{r}}_\lambda \cdot (\boldsymbol{\sigma}_1 - \boldsymbol{\sigma}_2)\,|\Psi_m\rangle \frac{i}{m_{\psi(2S)} - m_m} \langle \Psi_m|\hat{\boldsymbol{r}}_\lambda^\dagger \cdot \boldsymbol{r}|\psi(2^3S_1)\rangle \Big)\ .$$

- Spectrum & wave funtions, see: Berwein, Brambilla, JTC, Vairo. Phys.Rev.D92 (2015); Oncala, Soto Phys.Rev.D96 (2017)
- Total width:

$$\Gamma_{\psi(2S)\to h_c(1P)\pi^0} = 104(^{-35}_{+80})_{\Lambda_1}(\pm 21)_{\rm l.q.}(\pm 1)_{\rm s.p}\,{\rm eV}\,, \quad \Gamma^{\rm exp} = 255(39)\,{\rm eV}$$

$Q\bar{Q}(2S) \to Q\bar{Q}(1S)\pi^0(\eta)$



- Amplitudes (including $\pi^0-\eta$ mixing)

$$i\mathcal{A}_{\pi^0} = -i\frac{T_F}{N_c}\frac{c_F}{m_Q}\frac{8\pi^2}{45}\frac{m_d-m_u}{m_d+m_u}F_\pi m_\pi^2\left(\epsilon^*_{1S}\times\epsilon_{2S}\right)\cdot\boldsymbol{p}\beta_r^{(12)}$$

$$i\mathcal{A}_{\eta} = -i\frac{T_F}{N_c}\frac{c_F}{m_Q}\frac{8\pi^2}{45\sqrt{3}}\left(m_\eta^2-m_\pi^2\right)F_\pi\left(\epsilon^*_{1S}\times\epsilon_{2S}\right)\cdot\boldsymbol{p}\beta_r^{(21)}$$

- Total widths:

$$\Gamma_{\psi(2S)\to J/\psi\pi^0} = 40(^{-9}_{+14})_{\Lambda_1}(\pm 8)_{\mathrm{l.q.}}(\pm 18)_{\mathrm{s.p.}}\ \mathrm{eV}\,, \qquad \Gamma^{\mathrm{exp}} = 373(14)\ \mathrm{eV}\,,$$

$$\Gamma_{\psi(2S)\to J/\psi\eta} = 1.19(^{-0.27}_{+0.41})_{\Lambda_1}(\pm 0.5)_{\mathrm{s.p.}}\ \mathrm{keV}\,, \qquad \Gamma^{\mathrm{exp}} = 9.91(30)\ \mathrm{keV}\,,$$

$$\Gamma_{\Upsilon(2S)\to\Upsilon(1S)\pi^0} = 0.21(^{-0.04}_{+0.06})_{\Lambda_1}(\pm 0.05)_{\mathrm{l.q.}}(\pm 0.10)_{\mathrm{s.p.}}\ \mathrm{eV}\,, \qquad \Gamma^{\mathrm{exp}} < 1.28\ \mathrm{eV}\,,$$

$$\Gamma_{\Upsilon(2S)\to\Upsilon(1S)\eta} = 1.58(^{-0.80}_{+0.42})_{\Lambda_1}(\pm 0.76)_{\mathrm{s.p.}}\ \mathrm{eV}\,, \qquad \Gamma^{\mathrm{exp}} = 9.3(1.5)\ \mathrm{eV}\,.$$

Ratios

- Chiral Symmetry check:

$$R\left(\frac{\psi(2S)\to J/\psi\pi^0}{\psi(2S)\to J/\psi\eta}\right)=3.34(\pm0.39)_{\mathrm{l.q}}\cdot10^{-2}\,,\qquad R^{\mathrm{exp}}=3.76(25)\cdot10^{-2}\,,$$

$$R\left(\frac{\Upsilon(2S)\to\Upsilon(1S)\pi^0}{\Upsilon(2S)\to\Upsilon(1S)\eta}\right)=13.5(\pm2.8)_{\mathrm{l.q}}\cdot10^{-2}\,,\qquad R^{\mathrm{exp}}<13.8\cdot10^{-2}\,.$$

- Uncertainties: $\mathcal{O}(\alpha_s)$ corrections to hadronization, hybrid interpolating operators, NLO chiral:

$$R_{c,\pi}\equiv R\left(\frac{\psi(2S)\to J/\psi\pi^+\pi^-}{\psi(2S)\to J/\psi\pi^0}\right)=955(\mp191)_{\mathrm{l.q.}}(^{-103}_{+114})_{\kappa}\,,\qquad R^{\mathrm{exp}}_{c,\pi}=274(13)\,,$$

$$R_{c,\eta}\equiv R\left(\frac{\psi(2S)\to J/\psi\pi^+\pi^-}{\psi(2S)\to J/\psi\eta}\right)=31.9(^{-3.5}_{+3.8})_{\kappa}\,,\qquad R^{\mathrm{exp}}_{c,\eta}=10.3(4)\,,$$

$$R_{b,\pi}\equiv R\left(\frac{\Upsilon(2S)\to\Upsilon(1S)\pi^+\pi^-}{\Upsilon(2S)\to\Upsilon(1S)\pi^0}\right)=11.8(\mp2.4)_{\mathrm{l.q.}}(^{-1.3}_{+1.5})_{\kappa}\times10^3\,,\qquad R^{\mathrm{exp}}_{b,\pi}>4.5(4)\times10^3\,,$$

$$R_{b,\eta}\equiv R\left(\frac{\Upsilon(2S)\to\Upsilon(1S)\pi^+\pi^-}{\Upsilon(2S)\to\Upsilon(1S)\eta}\right)=1.59(^{-0.18}_{+0.20})_{\kappa}\times10^3\,,\qquad R^{\mathrm{exp}}_{b,\eta}=0.61(11)\times10^3\,.$$

Ratios

- Measure of $\beta^{(21)}_{r,b}/\beta^{(21)}_{r,c}$, most uncertainties cancel or are reduced.

$$R_{bc,\pi\pi} \equiv R\left(\frac{\Upsilon(2S)\to\Upsilon(1S)\pi^+\pi^-}{\psi(2S)\to J/\psi\pi^+\pi^-}\right) = 6.60(^{+0.30}_{-0.38})_{\Lambda_1}(\pm0.03)_{\kappa}(\pm0.31)_{\rm s.p.}\times 10^{-2}\,,$$

$$R^{\rm exp}_{bc,\pi\pi} = 5.59(0.50)\times 10^{-2}$$

$$R_{bc,\pi} \equiv R\left(\frac{\Upsilon(2S)\to\Upsilon(1S)\pi^0}{\psi(2S)\to J/\psi\pi^0}\right) = 5.3(^{+0.2}_{-0.3})_{\Lambda_1}(\pm0.25)_{\rm s.p.}\times 10^{-3}\,,\,,$$

$$R^{exp}_{bc,\pi} < 3.4(1)\times 10^{-3}\,,$$

$$R_{bc,\eta} \equiv R\left(\frac{\Upsilon(2S)\to\Upsilon(1S)\eta}{\psi(2S)\to J/\psi\eta}\right) = 1.33(^{+0.06}_{-0.08})_{\Lambda_1}(\pm0.06)_{\rm s.p.}\times 10^{-3}\,,\,,$$

$$R^{exp}_{bc,\eta} = 0.94(15)\times 10^{-3}\,.$$

- Uncertainties: Hybrid interpolating operators. Test of the computational scheme.

$$\frac{R_{bc,\pi}}{R_{bc,\pi\pi}} = 0.08\,,\quad \frac{R^{\rm exp}_{bc,\pi}}{R^{\rm exp}_{bc,\pi\pi}} < 0.06(1)\,,\quad \frac{R_{bc,\eta}}{R_{bc,\pi\pi}} = 2.0\times 10^{-2}\,,\quad \frac{R^{\rm exp}_{bc,\eta}}{R^{\rm exp}_{bc,\pi\pi}} = 1.7(3)\times 10^{-2}$$

Outlook and Conclusions

- Details and further discussion in arXiv:1905.03794
- Approach summary:
  - We have studied one-pion or eta and two-pion transition between quarkonium states below threshold.
  - Previous approaches using the twist expansion are not well justified.
  - EFT incorporating $1/m_Q$, multipole, chiral and $1/N_c$ expansions systematically.
  - The intermediate octet states in the transitions correspond to the hybrid spectrum.
- $Q\bar{Q}(2S) \to Q\bar{Q}(1S)\pi^+\pi^-$
  - Good description of the decay width spectrum, depending on one parameter.
  - Large uncertainties on the decay widths: sensitivity to the long distance part of the potentials, $\mathcal{O}(\alpha_s)$ corrections to the gluon hadronization.
- $Q\bar{Q}(2S) \to Q\bar{Q}(1P)\pi^0$ Predictions compatible with experiments
- $Q\bar{Q}(2S) \to Q\bar{Q}(1S)\pi^0$ Predictions smaller than experimental values.
- Uncertainties cancel in particular ratios of the decay widths
  - We can asses the importance of different sources of uncertainties.
  - Clean(er) tests of the of our approach and comparison with the twist expansion.

Thank you for your attention