Quarkonium hadronic transitions

Jaume Tarrús Castellà

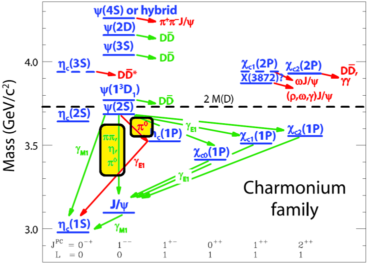
Institut de Física d'Altes Energies (UAB)

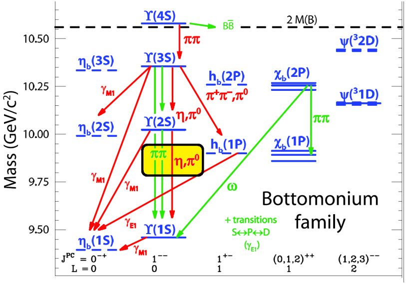
with: Antonio Pineda

based on: **arXiv:1905.03794**

The 13th International Workshop on Heavy Quarkonium, 13-17 May 2019.

Introduction and Motivation

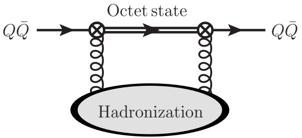




- Chiral Symmetry
  - Allowed because the energy release is small.
  - Parametrizes the decays in terms of a few Low-energy constants. Brown, Cahn Phys.rev.Lett.35 (1975); Mannel, Urech Z.Phys.C73 (1997); Casalbuoni *et al* Phys.Lett.B309 (1993)
  - Good descriptions of the processes.
  - However lacks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

Introduction and Motivation

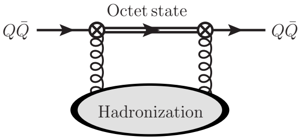
- Adding microscopic information to constrain the chiral description:
  - Heavy quark mass $1/m_Q$ expansion: heavy quark spin symmetry.
  - Two step process. Gottfried Phys.Rev.Lett.40 (1978)



  - 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.

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)

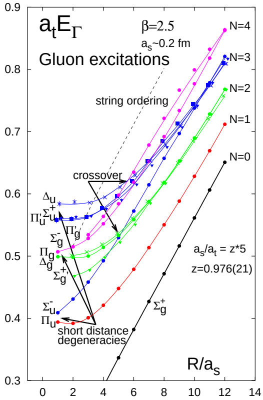


  - Multipole expansion:
    * $\boldsymbol{r} \cdot \boldsymbol{E}$ as the leading heavy-quark-gluon interaction.
    * Requires $m_Q v \gg \Lambda_{QCD}$
  - OPE of the octet propagator. Voloshin Nucl.Phys.B154 (1979)
    * Write the amplitude in terms of time local gluonic operators.
    * Requires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

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.

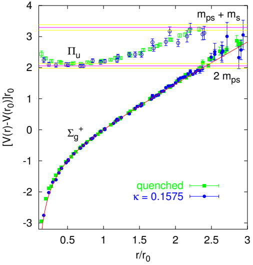
Juge, Kuti, Morningstar Phys.Rev.Lett.90 (2003)

- 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.

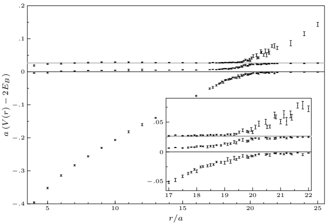
Our approach: what about light-quark states?

- 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)

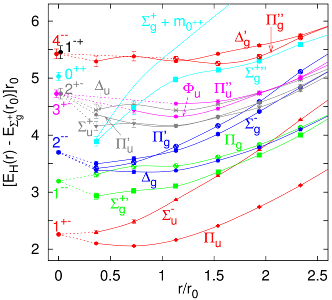
1 Write the most general hadronic version of pNRQCD.
   * Singlet, hybrid and pion fields as d.o.f.
   * Chiral, multipole, $1/m_Q$, $1/N_c$ expansions.

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.

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.

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

- States are constrained to satisfy the Gauss law.

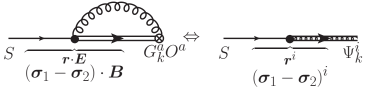
- We project the pNRQCD Lagrangian to the Fock subspace spanned by

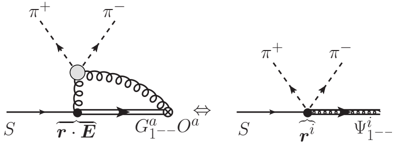
$$\int d^3r d^3R \sum_k P^i_{k\lambda} O^{a\,\dagger}(\boldsymbol{r},\boldsymbol{R})\, G_k^{i\,a}(\boldsymbol{R})|0\rangle\, \Psi_{k\lambda}(t,\,\boldsymbol{r},\,\boldsymbol{R})$$

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

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

Partonic pNRQCD ⇔ Hadronic pNRQCD





- We **assume** the gluelumps are dominated by the **lowest dimension** gluonic operator with the same J^{PC}

$$G^a_{1--} = Z_E^{-1/2} g\boldsymbol{E}^a + \cdots$$
$$G^a_{1+-} = Z_B^{-1/2} g\boldsymbol{B}^a + \cdots$$

- The **divergence on the scale current** allows to determine the matrix element **up to** $\mathcal{O}(p^2)$ and 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)
- 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 $\mathcal{O}(p^2)$

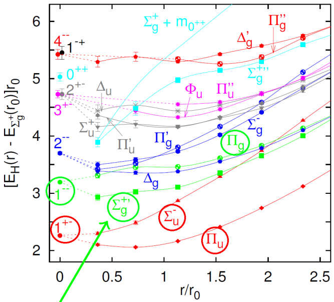
$$\mathcal{A}_\chi = -a_1 p_+^0 p_-^0 + a_2 \boldsymbol{p}_+ \cdot \boldsymbol{p}_- - a_3 m_\pi^2$$

- In our approach

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

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

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



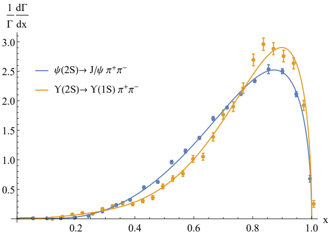
- The sum over hybrid intermediate states

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

- 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

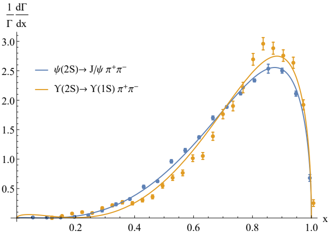


$x = (m_{\pi\pi} - 2m_\pi)/(m_{2S} - m_{1S} - 2m_\pi)$

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

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

- Hadronic pNRQCD



$$\kappa_c = 0.277 \pm 0.015\,, \quad \chi^2_{\rm d.o.f} = 0.17\,,$$

$$\kappa_b = 0.342^{+0.015}_{-0.017}\,, \quad \chi^2_{\rm d.o.f} = 1.25\,,$$

$$\boldsymbol{\kappa = 0.301(31)}$$

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

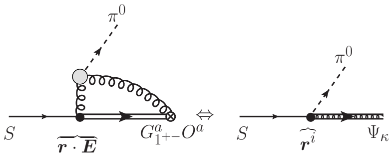
- Decay widths:

$$\Gamma_{\psi(2S)\to J/\psi\pi^+\pi^-} = 38.0\left({}^{-8.5}_{+13.0}\right)_{\Lambda_1}\left({}^{-4.1}_{+4.5}\right)_\kappa(\pm 17.4)_{\rm s.p.}\ \mathrm{keV}\,, \quad \Gamma^{\rm exp} = 102.1(2.9)\ \mathrm{keV}\,,$$

$$\Gamma_{\Upsilon(2S)\to\Upsilon(1S)\pi^+\pi^-} = 2.51\left({}^{-0.47}_{+0.66}\right)_{\Lambda_1}\left({}^{-0.28}_{+0.31}\right)_\kappa(\pm 1.21)_{\rm s.p.}\ \mathrm{keV}\,, \quad \Gamma^{\rm exp} = 5.71(48)\ \mathrm{keV}\,.$$

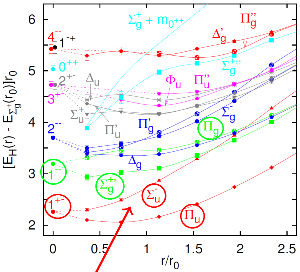
$Q\bar{Q}(2S) \to Q\bar{Q}(1P)\pi^0$: Matching

Partonic pNRQCD $\Leftrightarrow$ Hadronic pNRQCD



- We need **isospin breaking** operators in the hadronic EFT.
- Hadronization using the **axial anomaly**. Gross, Treiman, Wilczek Phys.RevD19 (1979); Novikov, Shifman, Vainshtein, Zakharov Nucl.PhysB165 (1980)

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



- 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

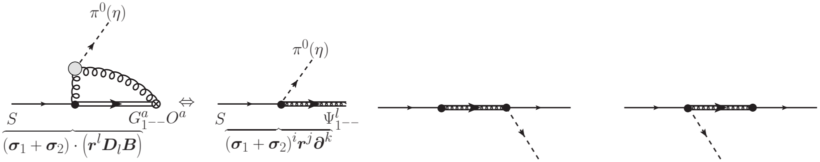
$$\beta_\sigma^{(12)} \equiv \sum_m \Bigg(\langle h_c(1^1P_1)|\hat{\boldsymbol{r}}_\lambda \cdot \boldsymbol{r}|\Psi_m\rangle \frac{i}{m_{h_c} - m_m} \langle\Psi_m|\hat{\boldsymbol{r}}_\lambda^\dagger \cdot (\boldsymbol{\sigma}_1 - \boldsymbol{\sigma}_2)\,|\psi(2^3S_1)\rangle$$

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

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

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

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



- 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:

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

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

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

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

Ratios

- Chiral Symmetry check:

$$R\left(\frac{\psi(2S)\to J/\psi\pi^0}{\psi(2S)\to J/\psi\eta}\right) = 3.34(\pm 0.39)_{\rm l.q}\cdot 10^{-2}\,, \qquad R^{\rm exp} = 3.76(25)\cdot 10^{-2}\,,$$

$$R\left(\frac{\Upsilon(2S)\to \Upsilon(1S)\pi^0}{\Upsilon(2S)\to \Upsilon(1S)\eta}\right) = 13.5(\pm 2.8)_{\rm l.q}\cdot 10^{-2}\,, \qquad R^{\rm exp} < 13.8\cdot 10^{-2}\,.$$

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

$$R_{c,\pi} \equiv R\left(\frac{\psi(2S)\to J/\psi\pi^+\pi^-}{\psi(2S)\to J/\psi\pi^0}\right) = 955(\mp 191)_{\rm l.q.}(^{-103}_{+114})_\kappa\,, \qquad R^{\rm exp}_{c,\pi} = 274(13)\,,$$

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

$$R_{b,\pi} \equiv R\left(\frac{\Upsilon(2S)\to \Upsilon(1S)\pi^+\pi^-}{\Upsilon(2S)\to \Upsilon(1S)\pi^0}\right) = 11.8(\mp 2.4)_{\rm l.q.}(^{-1.3}_{+1.5})_\kappa\times 10^3\,, \qquad R^{\rm exp}_{b,\pi} > 4.5(4)\times 10^3\,,$$

$$R_{b,\eta} \equiv R\left(\frac{\Upsilon(2S)\to \Upsilon(1S)\pi^+\pi^-}{\Upsilon(2S)\to \Upsilon(1S)\eta}\right) = 1.59(^{-0.18}_{+0.20})_\kappa\times 10^3\,, \qquad R^{\rm exp}_{b,\eta} = 0.61(11)\times 10^3\,.$$

Ratios

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

$$R_{bc,\pi\pi} \equiv R\left(\frac{\Upsilon(2S)\to\Upsilon(1S)\pi^+\pi^-}{\psi(2S)\to J/\psi\pi^+\pi^-}\right) = 6.60(^{+0.30}_{-0.38})_{\Lambda_1}(\pm 0.03)_{\kappa}(\pm 0.31)_{\mathrm{s.p.}}\times 10^{-2}\,,$$
$$R^{\mathrm{exp}}_{bc,\pi\pi} = 5.59(0.50)\times 10^{-2}$$
$$R_{bc,\pi} \equiv R\left(\frac{\Upsilon(2S)\to\Upsilon(1S)\pi^0}{\psi(2S)\to J/\psi\pi^0}\right) = 5.3(^{+0.2}_{-0.3})_{\Lambda_1}(\pm 0.25)_{\mathrm{s.p.}}\times 10^{-3}\,,\,,$$
$$R^{exp}_{bc,\pi} < 3.4(1)\times 10^{-3}\,,$$
$$R_{bc,\eta} \equiv R\left(\frac{\Upsilon(2S)\to\Upsilon(1S)\eta}{\psi(2S)\to J/\psi\eta}\right) = 1.33(^{+0.06}_{-0.08})_{\Lambda_1}(\pm 0.06)_{\mathrm{s.p.}}\times 10^{-3}\,,\,,$$
$$R^{exp}_{bc,\eta} = 0.94(15)\times 10^{-3}\,.$$

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

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

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