

# Exotic to standard bottomonium transitions

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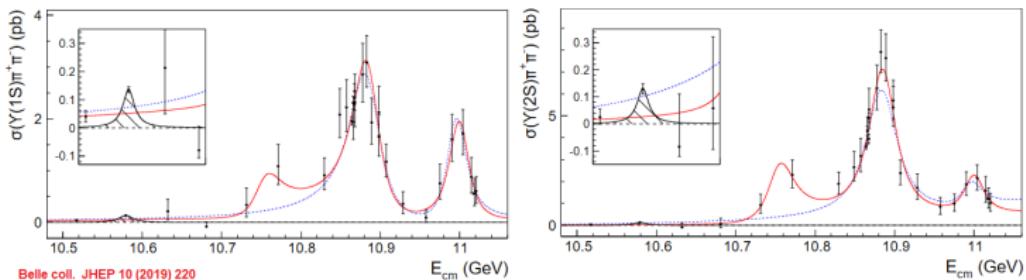
*based on:* JT, Passemar Phys.Rev.D 104 (2021)

**XVth Quark Confinement and the Hadron Spectrum**, August 1st 2022.



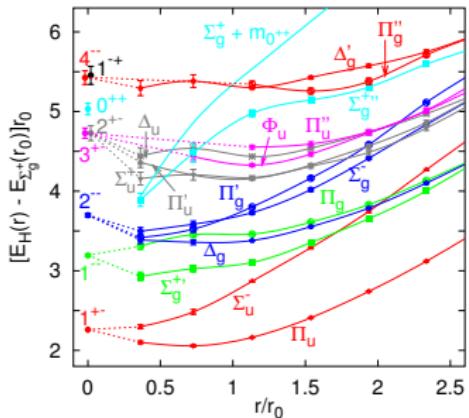
# Hybrid to standard bottomonium transitions

- ▶ Not many  $J^{PC}$  are easily accessible experimentally:
  - It is difficult to use spectrum predictions to validate different approaches.
  - Cannot test heavy quark spin symmetry multiplets in different approaches.
- ⇒ The nature of many **exotic quarkonium** states is still not settled.
- ▶ On the other hand information on decay channels is always available.
- ▶ Many exotic states **discovered in channels with standard quarkonium** and light-quark mesons.



- ▶ We have studied these **transitions in our EFT formalism** in the **short-distance approximation**.

# Quarkonium Hybrids



- Quenched lattice NRQCD from Juge, Kuti, Morningstar Phys.Rev.Lett.90 (2003) (Fig. from Bali, Pineda Phys.Rev.D 69 (2004)).
- Recent precision computation: Capitani et al Phys.Rev.D 99 (2019)

## Exotic quarkonium:

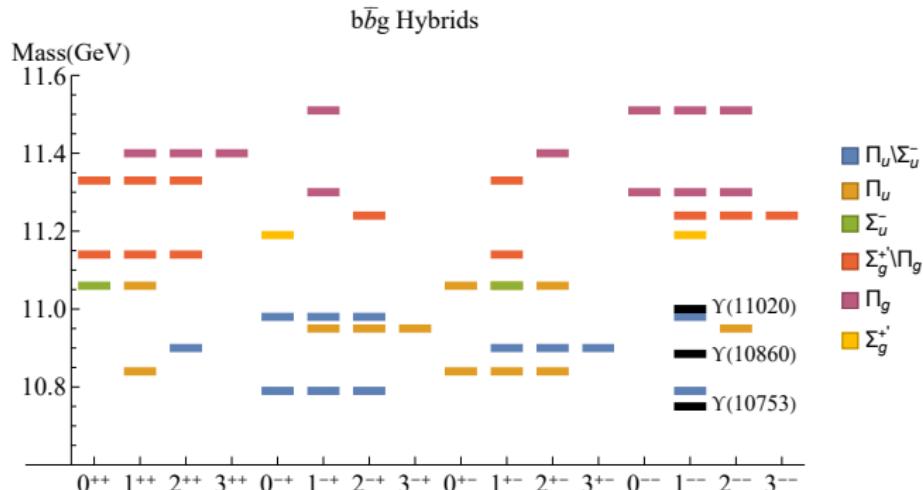
- ▶ Static energies: levels of the light d.o.f for static heavy quarks.
- ▶ Heavy quarks bound states in the static energies.

## EFT Expansions:

- ▶ Nonrelativistic heavy quarks:  $m_Q \gg \Lambda_{\text{QCD}}$  (QCD  $\rightarrow$  NRQCD).
- ▶ Multipole Expansion:  $m_Q v \gg \Lambda_{\text{QCD}}$  (NQCD  $\rightarrow$  weakly coupled pNRQCD).
- ▶ Adiabatic expansion:  $\Lambda_{\text{QCD}} \gg m_Q v^2$  (weakly coupled pNRQCD  $\rightarrow$  BOEFT).

# Heavy Hybrids: Bottomonium Spectrum at leading order

Berwein, Brambilla, JT, Vairo Phys.Rev.D92 (2015); Pineda, JT Phys.Rev.D 100 (2019)



There are only 3 neutral exotic bottomonium states, all  $1^{--}$ :

- $\Upsilon(10753)$  mass within 40 MeV of ground state hybrid.
- $\Upsilon(10860)$  lies very close to B mesons pair threshold, likely a molecular state.
- $\Upsilon(11020)$  mass within 20 MeV of first excited hybrid.

# Quarkonium states in pNRQCD

- ▶ Weakly coupled potential NRQCD (pNRQCD) is an EFT which incorporates the heavy quark mass and multipole expansions. Pineda, Soto Nucl.Phys.B Proc.Suppl. 64 (1998); Brambilla, Pineda, Soto, Vairo Nucl.Phys.B 566 (2000)
- ▶ S heavy quark pair singlet field, O heavy quark pair octet field.
- ▶ The standard quarkonium static states are just

$$|\mathbf{R}, \mathbf{r}; \Sigma_g^+ \rangle = S^\dagger(\mathbf{R}, \mathbf{r}) |0\rangle .$$

- ▶ The static potential corresponds to the  $\Sigma_g^+$  static energy

$$V_{\Sigma_g^+}^{(0)}(r) = \lim_{t \rightarrow \infty} \frac{i}{t} \ln \langle \mathbf{R}, \mathbf{r}; \Sigma_g^+; t/2 | \mathbf{R}, \mathbf{r}; \Sigma_g^+; -t/2 \rangle = E_{\Sigma_g^+}^{(0)}(r)$$

- ▶ A general standard quarkonium state

$$|S_m\rangle = \int d^3\mathbf{r} d^3\mathbf{R} \phi^{(m)}(\mathbf{R}, \mathbf{r}) |\mathbf{R}, \mathbf{r}; \Sigma_g^+ \rangle ,$$

- ▶ The wave function  $\phi^{(m)}$  is obtained solving the Shrödinger eq. with  $V_{\Sigma_g^+}^{(0)}(r)$ .

# Hybrid quarkonium states in pNRQCD

- The Hybrid static states contain a  $1^{+-}$ , color octet, gluonic operator  $\mathbf{G}_B^a \sim Z_B^{-1/2} \mathbf{B}^a + \dots$ :

$$|\mathbf{R}, \mathbf{r}; \lambda\rangle = \hat{\mathbf{r}}_\lambda \cdot \mathbf{G}_B^a(\mathbf{R}) O^{a\dagger}(\mathbf{R}, \mathbf{r}) |0\rangle$$

- The static potentials

$$V_\lambda^{(0)}(r) = \lim_{t \rightarrow \infty} \frac{i}{t} \ln \langle \mathbf{R}, \mathbf{r}; \lambda; t/2 | \mathbf{R}, \mathbf{r}; \lambda; -t/2 \rangle = E_{|\lambda|}^{(0)}(r)$$

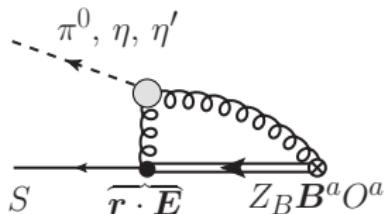
$E_0^{(0)}(r) = E_{\Sigma_u^-}^{(0)}(r)$  and  $E_{|\pm 1|}^{(0)}(r) = E_{\Pi_u}^{(0)}(r)$  from the lattice.

- A general hybrid state

$$|H_n\rangle = \int d^3\mathbf{r} d^3\mathbf{R} \sum_\lambda \psi_\lambda^{(n)}(\mathbf{R}, \mathbf{r}) |\mathbf{R}, \mathbf{r}; \lambda\rangle .$$

- The wave functions  $\psi_\lambda^{(n)}$  are obtained from the coupled Shrödinger eqs. with  $V_{\Sigma_u^-}^{(0)}(r)$  and  $V_{\Pi_u}^{(0)}(r)$  Berwein, Brambilla, JTC, Vairo Phys.Rev.D92 (2015).

# LO Transitions



Transitions from the LO singlet-octet operator:

$$\langle S_m \mathcal{O}_\pi | g \text{Tr} [S^\dagger \mathbf{r} \cdot \mathbf{E} \mathbf{O}] | H_n \rangle \sim Z_B^{-1/2} \langle \mathcal{O}_\pi | g^2 \mathbf{E} \cdot \mathbf{B} | 0 \rangle \langle \phi^{(m)} | \mathbf{r} \cdot \hat{\mathbf{r}}_\lambda | \psi_\lambda^{(n)} \rangle$$

- ▶  $Z_B$  can be related to the **gluon condensate**.
- ▶ **Heavy quark matrix element:**
  - Selection rules for final quarkonium states:  $\Delta s = 0$ ,  $\ell = l$ .
  - $\Upsilon(10753)$  and  $\Upsilon(11020)$  decay into  $h_b(m^1 P_1)$  and light quark mesons.
- ▶ **Light-quark meson production:**
  - Allowed final light-quark states:  $0^{-+}$ ,  $l = 0$  such as  $\pi^0, \eta, \eta', \eta$ -like resonances or odd numbers of pseudoscalar mesons.
  - Matrix elements for production of  $\pi^0, \eta, \eta'$  can be determined from  $U(1)_A$  anomaly and a mixing scheme. Feldmann, Kroll, Stech, Phys.Rev.D58 (1998); Kroll, Mod. Phys. Lett. A20 (2005)

# LO Transitions

JT, *Passemar Phys.Rev.D* 104 (2021)

- ▶ LO Transition widths:

$$\Gamma_{\tau(10753) \rightarrow h_b(1P)\pi^0} = 2.57(\pm 1.03)_{\text{m.e.}} (\pm 0.14)_{z_B} (\pm 0.16)_{\omega_{\pi^0}} \text{ keV}$$

$$\Gamma_{\tau(10753) \rightarrow h_b(1P)\eta} = 2.29(\pm 0.92)_{\text{m.e.}} (\pm 0.13)_{z_B} (\pm 0.08)_{\omega_\eta} \text{ MeV}$$

$$\Gamma_{\tau(10753) \rightarrow h_b(2P)\pi^0} = 0.168(\pm 0.067)_{\text{m.e.}} (\pm 0.009)_{z_B} (\pm 0.010)_{\omega_{\pi^0}} \text{ keV}$$

$$\Gamma_{\tau(11020) \rightarrow h_b(1P)\pi^0} = 2.04(\pm 0.82)_{\text{m.e.}} (\pm 0.11)_{z_B} (\pm 0.13)_{\omega_{\pi^0}} \text{ keV}$$

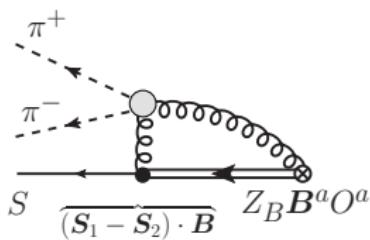
$$\Gamma_{\tau(11020) \rightarrow h_b(1P)\eta} = 2.04(\pm 0.81)_{\text{m.e.}} (\pm 0.11)_{z_B} (\pm 0.07)_{\omega_\eta} \text{ MeV}$$

$$\Gamma_{\tau(11020) \rightarrow h_b(1P)\eta'} = 9.23(\pm 3.69)_{\text{m.e.}} (\pm 0.51)_{z_B} (\pm 0.39)_{\omega_{\eta'}} \text{ MeV}$$

$$\Gamma_{\tau(11020) \rightarrow h_b(2P)\pi^0} = 0.104(\pm 0.042)_{\text{m.e.}} (\pm 0.006)_{z_B} (\pm 0.006)_{\omega_{\pi^0}} \text{ keV}$$

$$\Gamma_{\tau(11020) \rightarrow h_b(2P)\eta} = 81.8(\pm 32.7)_{\text{m.e.}} (\pm 4.6)_{z_B} (\pm 2.7)_{\omega_\eta} \text{ keV}$$

- ▶ Uncertainties labeled by the origin m.e.=multipole expansion,  $\omega$ =Production matrix element.



Transitions from the NLO singlet-octet operator:

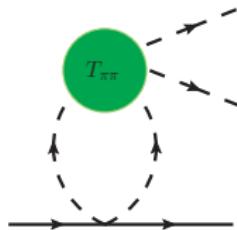
$$\langle S_m \mathcal{O}_{\pi\pi} | \frac{g c_F}{m_Q} \text{Tr} \left[ \mathbf{S}^\dagger (\mathbf{S}_1 - \mathbf{S}_2) \cdot \mathbf{B} \mathcal{O} \right] | H_n \rangle \sim \frac{c_F}{m_Q} Z_B^{-1/2} \langle \mathcal{O}_{\pi\pi} | \mathbf{B}^2 | 0 \rangle \langle \phi^{(m)} | (\mathbf{S}_1 - \mathbf{S}_2) \cdot \hat{\mathbf{r}}_\lambda | \psi_\lambda^{(n)} \rangle$$

► Heavy quark matrix element:

- Selection rules:  $\Delta s = 1$ ,  $I = \ell \pm 1$ .
- $\Upsilon(10753)$  and  $\Upsilon(11020)$  decay into  $\Upsilon(m^3 S_1)$  or  $\Upsilon(m^3 D_1)$  and light quark mesons.

► Light-quark meson production:

- Allowed final light-quark states:  $0^{++}$  and  $I = 0$  such as  $\pi^+ \pi^-$ ,  $K^+ K^-$ , pairs of  $\pi^0$  or  $\eta$  as well as  $f_0$  resonances.
- We use a dispersive representation for the matrix elements for the production  $\pi^+ \pi^-$ ,  $K^+ K^-$ . Donoghue, Gasser, Leutwyler, Nucl.Phys.B343 (1990); Moussallam, Eur.Phys.J.C 14 (2000)



- ▶ Decompose  $\langle \mathcal{O}_{\pi\pi} | \mathbf{B}^2 | 0 \rangle$  into  $S$  ( $F^{(0)}$ ) and  $D$  ( $F^{(2)}$ ) wave pieces.
- ▶ From [Watson's Theorem](#) we obtain the imaginary part of  $F^{(l)}$  corresponding to [two-pion](#) and [two-kaon rescattering](#).

## Muskhelishvili-Omnès problem:

Muskhelishvili, *Singular integral equations*; Omnes, *Nuovo Cim.* 8 (1958)

- Imaginary part is known.
  - Analytic in the complex  $s$ -plane, except on the cuts.
  - Real in the real  $s$  axis below the cuts.
- ⇒ A general form of the form factors is

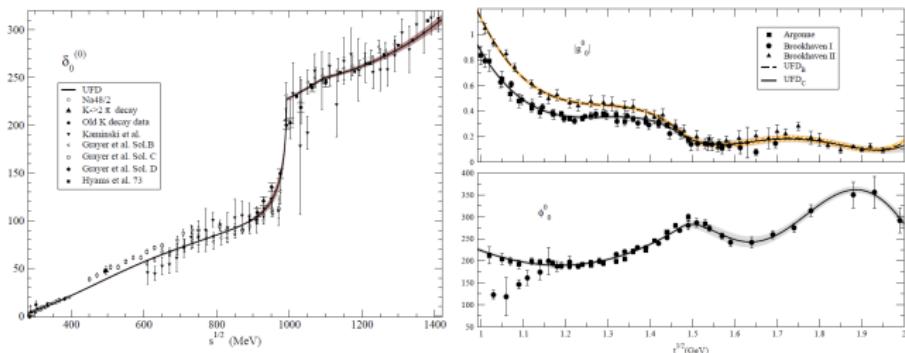
$$n_P F_P^{(l)}(s) = \Omega_{PP'}^{(l)}(s) Q_{P'}^{(l)}(s), \quad P, P' = \pi, K$$

# Dispersive representation: Omnès Functions

- $\Omega$ -matrix satisfies the singular integral equations

$$\Omega(s) = \frac{1}{\pi} \int_{4m_\pi^2/\pi}^{\infty} \frac{ds'}{s' - s} \left( T_I^0(s') \right)^* \Sigma(s') \Omega(s')$$

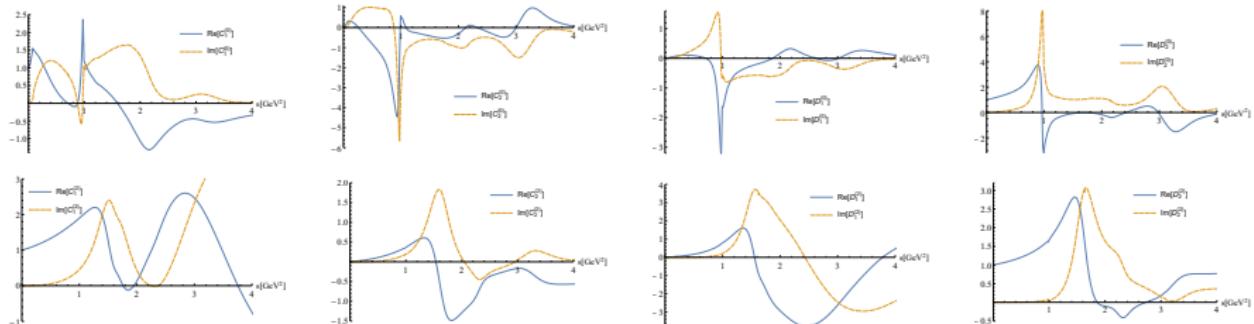
- Input needed:  $\pi\pi \rightarrow \pi\pi$  and  $\pi\pi \rightarrow K\bar{K}$  T-matrix for each partial wave.



- Parametrizations (and figure) from Garcia-Martin et al Phys.Rev.D83 (2011); Pelaez, Rodas Eur.Phys.J. C78 (2018)

# Dispersive representation

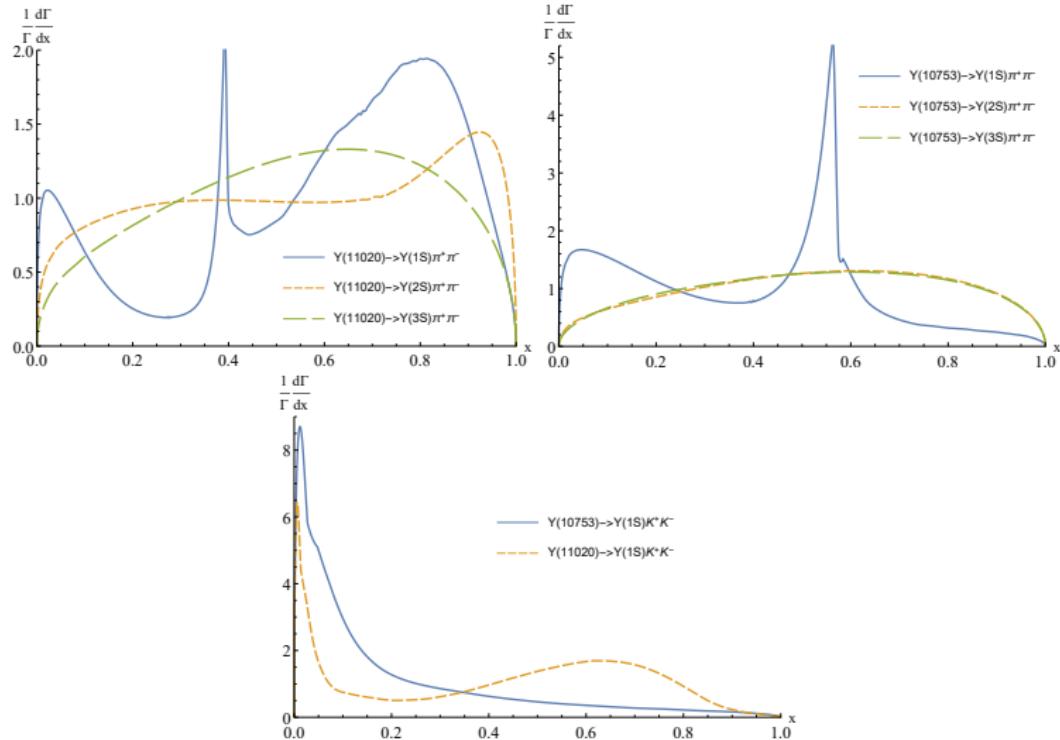
- (Numerical)  $\Omega^{(I)}$  solutions Moussallam, Eur.Phys.J.C 14 (2000); Descotes-Genon Ph.D. thesis (2000)



- $Q^{(I)}(s) = (Q_1^{(I)}, Q_2^{(I)})$  are subtraction polynomials obtained by matching to a chiral representation.
- Chiral low-energy constants determined using the Scale anomaly, Feynman-Hellmann theorem, and one free parameter from quarkonium transitions.

Voloshin, Zakharov, Phys.Rev.Lett.45 (1980); Novikov, Shifman, Z.Phys.C8 (1981); Chivukula et al, Annals Phys. 192 (1989); Pineda, JTC, Phys.Rev.D100 (2019)

# NLO Transitions differential widths



$$x = (s - 4m_{GB}^2) / (m_{\bar{Q}Qg} - m_{\bar{Q}Q} - 4m_{GB}^2)$$

# NLO Transitions widths

JT, Passemar, accepted to Phys.Rev.D arXiv:2104.03975

## ► NLO transition widths:

$$\Gamma_{\Upsilon(10753) \rightarrow \Upsilon(1S)\pi^+\pi^-} = 43.4(\pm 17.3)_{\text{m.e.}}(\pm 2.4)z_B(\pm 8.6)_{\alpha_s}^{(+0.5)}{}_{(-0.0)}\kappa \text{ keV}$$

$$\Gamma_{\Upsilon(10753) \rightarrow \Upsilon(2S)\pi^+\pi^-} = 2.75(\pm 1.10)_{\text{m.e.}}(\pm 0.15)z_B(\pm 0.55)_{\alpha_s}^{(+0.13)}{}_{(-0.12)}\kappa \text{ keV}$$

$$\Gamma_{\Upsilon(10753) \rightarrow \Upsilon(3S)\pi^+\pi^-} = 0.98(\pm 0.39)_{\text{m.e.}}(\pm 0.05)z_B(\pm 0.19)_{\alpha_s}(\pm 0.03)\kappa \text{ eV}$$

$$\Gamma_{\Upsilon(11020) \rightarrow \Upsilon(1S)\pi^+\pi^-} = 99.1(\pm 39.6)_{\text{m.e.}}(\pm 5.5)z_B(\pm 19.7)_{\alpha_s}^{(+26.3)}{}_{(-21.8)}\kappa \text{ keV}$$

$$\Gamma_{\Upsilon(11020) \rightarrow \Upsilon(2S)\pi^+\pi^-} = 3.96(\pm 1.58)_{\text{m.e.}}(\pm 0.22)z_B(\pm 0.70)_{\alpha_s}^{(-0.16)}{}_{(+0.17)}\kappa \text{ keV}$$

$$\Gamma_{\Upsilon(11020) \rightarrow \Upsilon(3S)\pi^+\pi^-} = 1.33(\pm 0.53)_{\text{m.e.}}(\pm 0.07)z_B(\pm 0.27)_{\alpha_s}(\pm 0.02)\kappa \text{ keV}$$

$$\Gamma_{\Upsilon(10753) \rightarrow \Upsilon(1S)\kappa^+\kappa^-} = 3.98(\pm 1.59)_{\text{m.e.}}(\pm 0.22)z_B(\pm 0.79)_{\alpha_s}^{(-0.50)}{}_{(+0.67)}\kappa \text{ keV}$$

$$\Gamma_{\Upsilon(11020) \rightarrow \Upsilon(1S)\kappa^+\kappa^-} = 5.93(\pm 2.37)_{\text{m.e.}}(\pm 0.33)z_B(\pm 1.18)_{\alpha_s}^{(+1.75)}{}_{(-1.18)}\kappa \text{ keV}$$

## ► Experimental ranges for the widths Belle col. JHEP 10, 220 (2019)

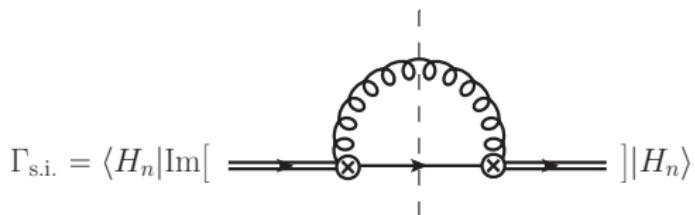
$$\Gamma_{\Upsilon(11020) \rightarrow \Upsilon(1S)\pi^+\pi^-}^{\text{exp}} = 49 - 118 \text{ keV} \Leftarrow \text{Promising agreement!}$$

$$\Gamma_{\Upsilon(11020) \rightarrow \Upsilon(2S)\pi^+\pi^-}^{\text{exp}} = 13 - 225 \text{ keV}$$

$$\Gamma_{\Upsilon(11020) \rightarrow \Upsilon(3S)\pi^+\pi^-}^{\text{exp}} = 13 - 98 \text{ keV}$$

## Semi-inclusive widths

- If the **energy gap** between a hybrid and a standard quarkonium state is **large** semi-inclusive transition widths can be computed. Oncala, Soto Phys.Rev.D96 (2017)



$$\Gamma_{\Upsilon(11020) \rightarrow h_b(1P)}^{\text{LO}} = 20(\pm 9)_{\alpha_s} \text{ MeV}$$

$$\Gamma_{\Upsilon(10753) \rightarrow \Upsilon(1S)}^{\text{NLO}} = 9.7(\pm 3.8)_{\alpha_s} \text{ MeV}$$

$$\Gamma_{\Upsilon(11020) \rightarrow \Upsilon(1S)}^{\text{NLO}} = 7.3(\pm 2.5)_{\alpha_s} \text{ MeV}$$

$$\Gamma_{\Upsilon(11020) \rightarrow \Upsilon(2S)}^{\text{NLO}} = 1.1(\pm 0.5)_{\alpha_s} \text{ MeV}$$

- The sum of semi-inclusive widths for  $\Gamma_{\Upsilon(11020)}^{\text{LO+NLO}} = 28.4 \pm 9.4 \text{ MeV}$  is **compatible** with the experimental value of the total width  $\Gamma_{\Upsilon(11020)}^{\text{exp}} = 24^{+8}_{-6} \text{ MeV}$ .

- ▶ We have computed the transition widths of  $\Upsilon(10753)$  and  $\Upsilon(11020)$  into standard bottomonium states and light quark mesons.
- ▶ We have assumed that these two states are the first two lowest laying  $1^{--}$  hybrid bottomonium states.
- ▶ EFT incorporating the heavy quark mass, adiabatic and multipole expansions (pN-RQCD).
  - LO :  $\Upsilon(10753)/\Upsilon(11020)$  to  $h_b(mP)$  and  $\pi^0, \eta, \eta'$ .
  - NLO:  $\Upsilon(10753)/\Upsilon(11020)$  to  $\Upsilon_b(mS)$  and  $\pi^+\pi^-, K^+K^-$ .
- ▶ Total width, mass and transition width to  $\Upsilon(1S)\pi^+\pi^-$  are consistent with the interpretation of  $\Upsilon(11020)$  as a hybrid.

Thank you for your attention