B 介子纯湮灭两体非轻衰变的研究

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Outline

- Nonleptonic B decays and factorization approach
- Theoretical analysis of Annihilation diagrams
- Enhanced quark-loop contribution to Pure annihilation type B decays
- Enhanced quark-loop contribution in PQCD approaches

Why nonleptonic B decays

study on CP violation

determine CKM phase angle

test strong interaction theory

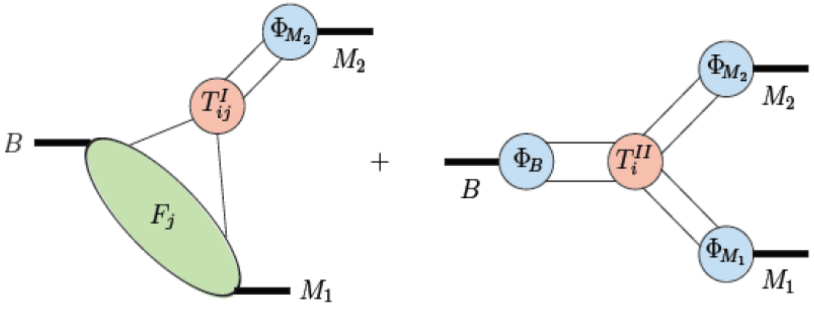
search for new physics signals

Factorization approaches @ leading power

- Naïve factorization(BSW1985) and Generalized factorization(Cheng etc. Ali, Kramer, Lü1998)

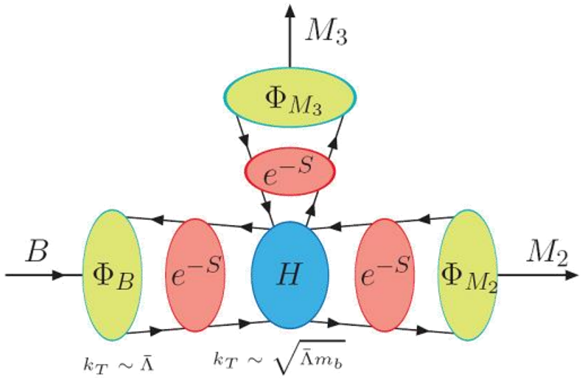
$$\langle M_1 M_2 | O_i | \bar{B} \rangle = \mathrm{C}_1 \mathrm{F}^{\mathrm{B}\to M_1} f_{M_2} + C_2 \mathrm{F}^{\mathrm{B}\to M_2} f_{M_1}$$

- QCD factorization (BBNS1999)
  SCET(Bauer et al 2001)



$$\langle M_1 M_2 | O_i | \bar{B} \rangle = \mathrm{F}^{\mathrm{B}\to M_1} \mathrm{T}_{\mathrm{i}}^{\mathrm{I}} \otimes \phi_{M_2} + \mathrm{T}_{\mathrm{i}}^{\mathrm{II}} \otimes \phi_B \otimes \phi_{M_1} \otimes \phi_{M_2}$$

- PQCD approach (Li, Lü, Xiao etc.)



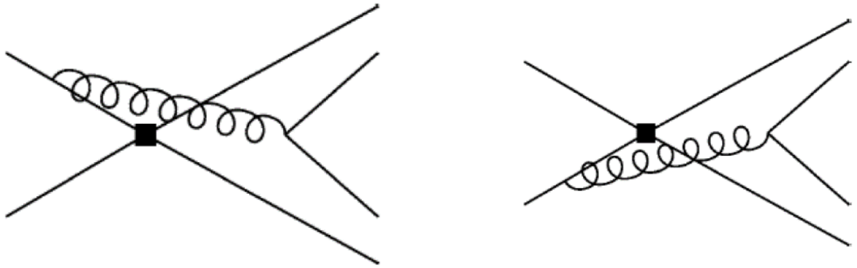
$$\langle M_1 M_2 | O_i | \bar{B} \rangle = H \otimes \phi_B \otimes \phi_{M_1} \otimes \phi_{M_2} \otimes \mathrm{e}^{-\sum S}$$

Power suppressed contributions

- Chiral enhanced contributions
  - Chirally enhance twist-3 corrections(end point divergence)
  - The scalar QCD penguin amplitude $r_\chi a_6$
- Annihilation diagrams
  - Comparable to leading power contribution
  - Main source of strong phase
- Other power suppressed contributions: soft gluon exchange…

Annihilation diagrams in QCDF

- Example of the amplitude



$$A_1^i \supset \int_0^1 dxdy \left\{ \phi_1(x)\phi_2(y) \left[\frac{1}{y(1-x\bar{y})} + \frac{1}{\bar{x}^2 y} \right] + r_\chi^{M_1} r_\chi^{M_2} \frac{\phi_{m1}(x)\phi_{m2}(y)}{\bar{x}y} \right\}$$

- Endpoint singularity

$$\phi_M(x) \sim 6x(1-x)[1 + a_2 C_2^{3/2}(2x-1) + \cdots]$$

$$\phi_p(x) \sim 1$$

Annihilation diagrams in QCDF

- Parameterization of logarithmic divergence

$$\int_0^1 \frac{dy}{y} \to X_A^M \qquad \int_0^1 \frac{dy}{y} \ln y \to -\frac{1}{2}(X_A^M)^2$$

- Strong phase: assumed to be caused by the soft scattering

$$X_A^M = 1 + \rho_A e^{i\phi_A} \ln \frac{m_B}{\Lambda_h}$$

Fitted from experimental data:

Cheng etc. 0909.5229,0910.5237;

Zhu etc. , 1106.4709,1304.7438;

Chang etc, 1409.2995,1610.02747,1706.06381.

Annihilation diagrams in PQCD

- TMD factorization

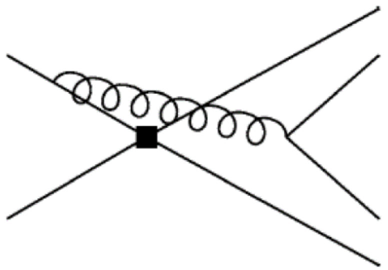
$$\frac{1}{xm_B^2 - k_T^2 + i\epsilon} = P\frac{1}{xm_B^2 - k_T^2} - i\pi\delta(xm_B^2 - k_T^2)$$

- Including the partonic transverse momentum:
  no endpoint singularity, nonvanishing strong phase

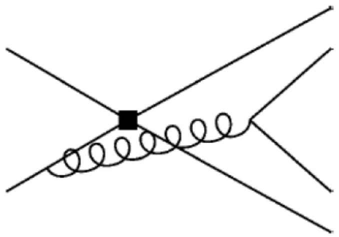
- TMD effect is regarded as part of higher twist contribution in QCDF

Revisiting Power counting

- The factorization amplitude(leading twist)



$$A_1^{ia} \supset \int_0^1 dxdy \frac{\phi_1(x)\phi_2(y)}{y(1-x\bar{y})}$$



$$A_1^{ib} \supset \int_0^1 dxdy \frac{\phi_1(x)\phi_2(y)}{\bar{x}^2 y}$$

	Momentum fractions	b quark-emission	light quark-emission
Hard gluon	$x \sim 1, \bar{x} \sim 1, dx \sim 1$ $y \sim 1, \bar{y} \sim 1, dy \sim 1$	1	1
Hard-collinear gluon	$x \sim 1, \bar{x} \sim \lambda, dx \sim \lambda$ $y \sim 1, \bar{y} \sim 1, dy \sim 1$	λ	**1**
Soft gluon	$x \sim 1, \bar{x} \sim \lambda, dx \sim \lambda$ $y \sim \lambda, \bar{y} \sim 1, dy \sim \lambda$	λ^3	λ

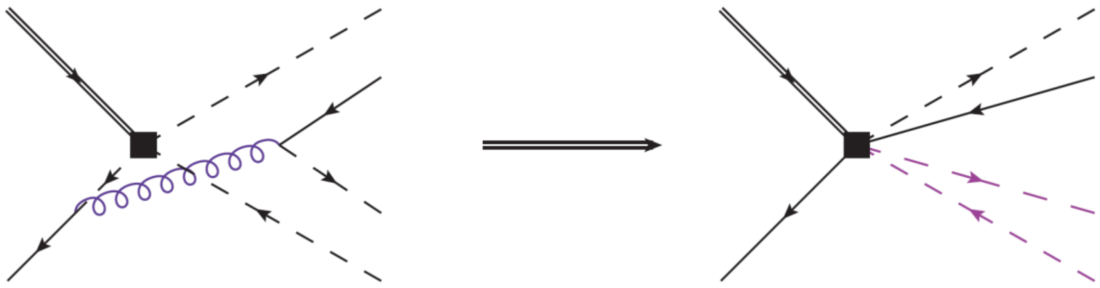
[Lu etc., 2202.08073]

Regularization of endpoint singularity at tree level

- Separation of hard and hard collinear region

$$\int_0^\infty d\omega \phi_B^+(\omega) \int_0^\Delta dx \int_0^1 dy \frac{\phi_1(x)\phi_2(y)}{\bar{x}^2 y}$$

$$+ \int_0^\infty d\omega \phi_B^+(\omega) \int_\Delta^1 dx \int_0^1 dy \frac{\phi_1(x)\phi_2(y)}{\bar{x}^2 y}$$



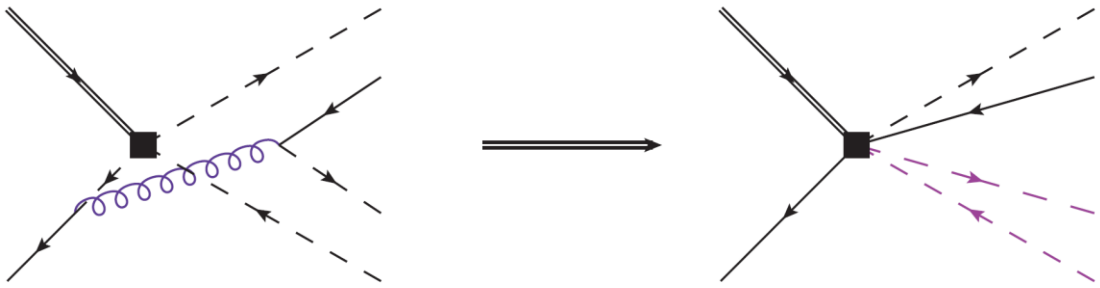
[Lu etc., 2022.08073]

$$\int_0^\infty d\omega \phi_B^+(\omega) \int_\Delta^1 dx \int_0^1 dy \frac{\phi_1(x)\phi_2(y)}{\bar{x} y (\bar{x} - \frac{\omega}{m_B} + i\epsilon)}$$

$$\sim 18 \left[\ln \frac{m_B}{\lambda_B} + \gamma_E - 2 - i\pi \right]$$

Expecting a soft-collinear factorization

$$\int_0^\infty d\omega \phi_B^+(\omega) \int_\Delta^1 dx \int_0^1 dy \frac{\phi_1(x)\phi_2(y)}{\bar{x}^2 y}$$



$$\int_0^\infty d\omega_1 \int_0^\infty d\omega_2 \int_\Delta^1 dx \int_0^1 dy H(y)\phi_2(y) \frac{\Theta_{BM_1}(\omega_1,\omega_2)}{y\omega_2(\omega_2-\omega_1+i\epsilon)}$$

- The soft-collinear function

$$\Theta_{BM}(\omega_1,\omega_2) = \int dt \int ds e^{i(\omega_1 t-\omega_2 s)} \langle M(p)|[\bar{q}_s(tn)\Gamma_1 h_v(0)][\bar{\xi}_{\bar{c}}(0)\Gamma_2 q_{\overline{sc}}(sn)]|\bar{B}_q(P)\rangle$$

- Factorization is yet to be proved

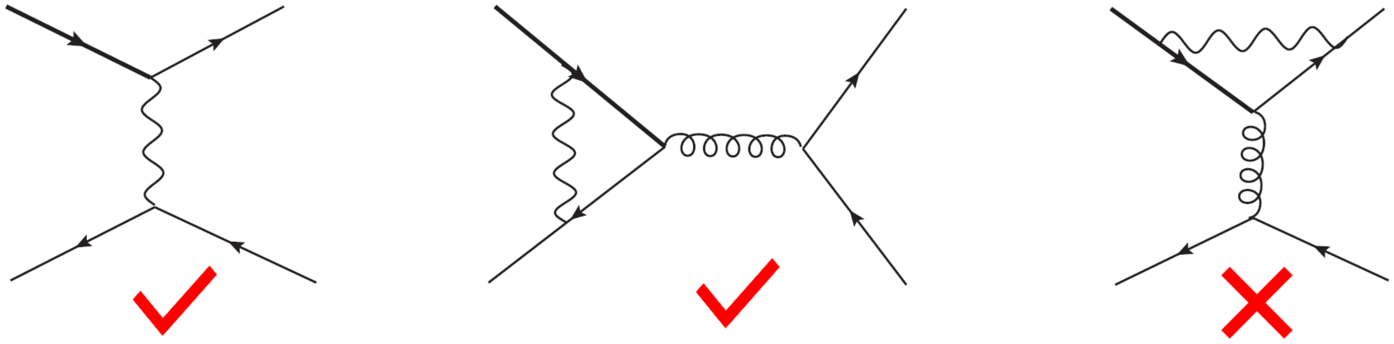
Pure annihilation charmless B decays

- Occur only via annihilation diagram, symmetric flavor structure

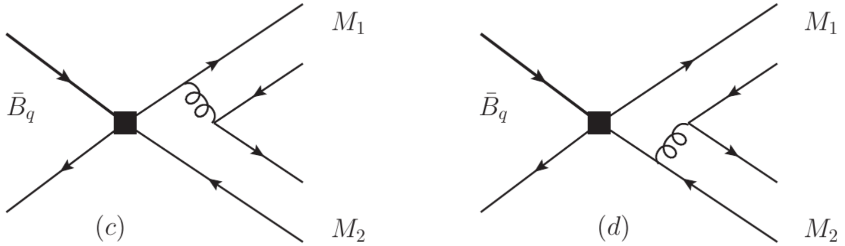
$\bar{B}_s \to \pi\pi, \rho\rho, \rho\omega, \omega\omega, \pi\rho, \pi\omega$ $\quad\quad$ $\bar{B}_d \to K^+K^-, K^{*+}K^{*-}, \phi\phi, K^{*+}K^-, K^+K^{*-}$

- No space-like penguin contribution

$$(V-A)(V+A)$$
$$\to -2(S-P)(S+P)$$



- Vanishing "factorizable" diagrams for $\bar{B}_q \to PP, V_LV_L$

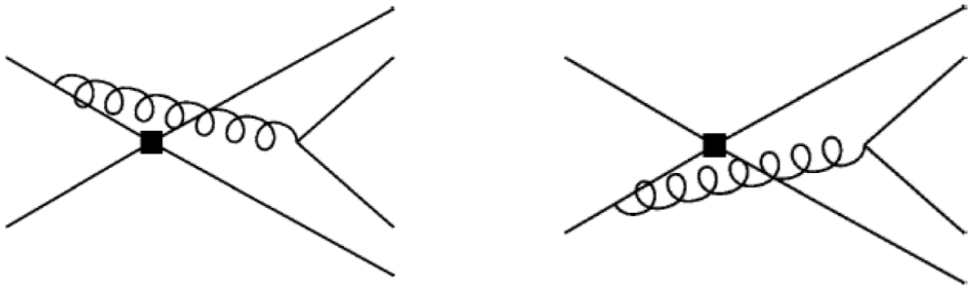


- PQCD calculation [Li, Lu etc. hep-ph/0404028 …]

The enhanced high order contribution for pure annihilation decays

- The pure annihilation decays such as $\bar{B}_s \to \pi^+\pi^-$ are penguin dominated

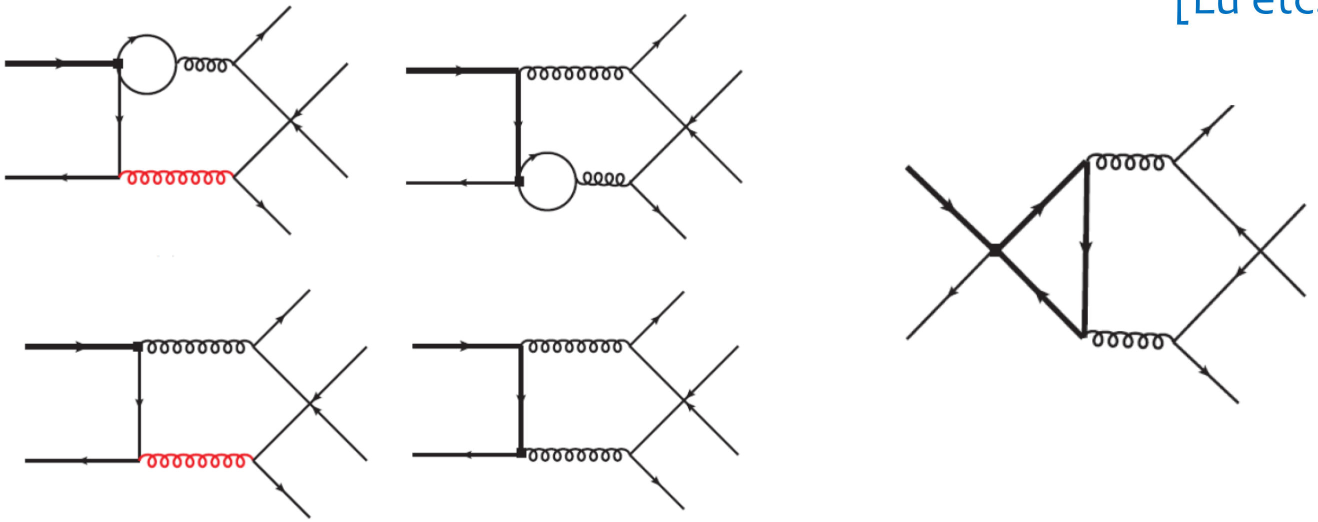
$$A = V_{tb}V_{ts}^*P + V_{ub}V_{us}^*T$$



- The tree operator can provide enhanced contribution through quark loop

[Lu etc., 2202.08073]

$$\frac{\alpha_s}{4\pi}V_{cb}V_{cs}^*T$$



General analysis

- The amplitude of $B \to g^* g^* \to M_1 M_2$

$$\langle g^*(p_g,\alpha) g^*(\tilde{p}_g,\beta)|\mathcal{H}_{eff}|\bar{B}_q\rangle = i\epsilon_{\alpha\beta p_g \tilde{p}_g} F_V(p_g^2,\tilde{p}_g^2) + g_{\alpha\beta}^{\perp} F_A(p_g^2,\tilde{p}_g^2)$$

$$\langle M_1(p) M_2(q)|g^*(p_g,\alpha) g^*(\tilde{p}_g,\beta)\rangle = \begin{cases} g_{\alpha\beta}^{\perp} A_{\parallel}(M_1 M_2) & \text{for } PP, V_L V_L \\ i\epsilon_{\alpha\beta p q} A_{\perp}(M_1 M_2) & \text{for } PV, VP \end{cases}$$

- Symmetry relation

$$F_V(p_g^2,\tilde{p}_g^2) = -F_V(\tilde{p}_g^2,p_g^2), \quad F_A(p_g^2,\tilde{p}_g^2) = F_A(\tilde{p}_g^2,p_g^2)$$

- Some conclusions

  - Only F_A will be relevant due to the symmetry properties
  - The displayed NLO diagrams will not contribute to $B \to VP, PV$

Enhanced NLO amplitudes

- The NLO amplitude $(\mathcal{O}(\alpha_s^2))$

$$\mathcal{T}^{p,(1)} \supset \sum_{i=1}^{6} C_i \, \mathcal{P}_i^{p,(1)}(M_1, M_2) + C_8^{eff} \, \mathcal{P}_{8g}^{(1)}(M_1, M_2)$$

Quark loop

CM penguin

- The charming loop : large Wilson coefficient +large CKM matrix element

- The triangle diagrams is vanishing for tree operator: negligible

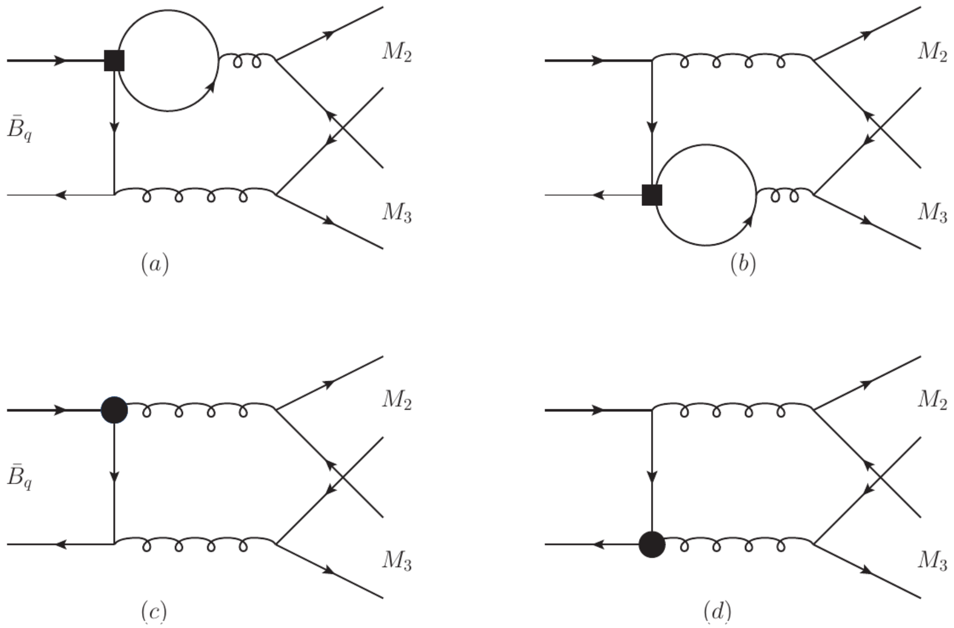
Numerical results(QCDF @ leading order, leading twist)

	$\mathcal{A}_{\rm CP}^{\rm dir}$	$\mathcal{A}_{\rm CP}^{\rm mix}$
$\bar{B}_s \to \pi^+\pi^-,\ \pi^0\pi^0$	$-36.3^{+8.2}_{-1.3}\ (0.0\pm0.0)$	$-4.2^{+21.4}_{-9.0}\ (35.9^{+15.6}_{-11.2})$
$\bar{B}_s \to \rho_L^+\rho_L^-,\ \rho_L^0\rho_L^0$	$-36.3^{+8.3}_{-1.8}\ (0.0\pm0.0)$	$-4.3^{+21.5}_{-9.0}\ (35.9^{+15.6}_{-11.2})$
$\bar{B}_s \to \omega_L\omega_L$	$-36.3^{+8.3}_{-3.1}\ (0.0\pm0.0)$	$-3.8^{+21.8}_{-9.7}\ (35.9^{+15.6}_{-11.2})$
$\bar{B}_s \to \rho_L\omega_L$	$0.0\pm0.0\ (0.0\pm0.0\ )$	$-71.0^{+6.3}_{-5.4}\ (-71.0^{+6.3}_{-5.4})$
$\bar{B}_d \to K^+K^-$	$39.0^{+3.2}_{-5.6}\ (0.0\pm0.0)$	$-2.2^{+19.1}_{-26.4}\ (-47.0^{+15.7}_{-18.8})$
$\bar{B}_d \to K_L^{*+}K_L^{*-}$	$39.6^{+4.9}_{-6.7}\ (0.0\pm0.0)$	$-1.4^{+19.7}_{-26.9}\ (-47.0^{+15.7}_{-18.8})$
$\bar{B}_d \to \phi_L\phi_L$	$38.3^{+11.4}_{-15.8}\ (0.0\pm0.0)$	$27.8^{+5.7}_{-25.9}\ (0.0\pm0.0)$
$\bar{B}_s \to \pi^+\rho^-$	$-1.3^{+29.0}_{-20.1}\ (-1.3^{+29.0}_{-20.1})$	$-99.7^{+15.7}_{-0.3}\ (-99.7^{+15.7}_{-0.3})$
$\bar{B}_s \to \pi^-\rho^+$	$1.3^{+25.3}_{-24.0}\ (1.3^{+25.3}_{-24.0})$	$-99.9^{+15.2}_{-0.1}\ (-99.9^{+15.2}_{-0.1})$
$\bar{B}_s \to \pi^0\rho^0$	$0.0\pm0.0\ (0.0\pm0.0)$	$-99.8^{+14.8}_{-0.2}\ (-99.8^{+14.8}_{-0.2})$
$\bar{B}_d \to K^{*+}K^-$	$-0.4^{+4.1}_{-2.7}\ (-0.4^{+4.1}_{-2.7})$	$9.2^{+10.8}_{-8.7}\ (\ 9.2^{+10.8}_{-8.7})$
$\bar{B}_d \to K^+K^{*-}$	$0.4^{+3.3}_{-3.6}\ (0.4^{+3.3}_{-3.6})$	$9.8^{+10.9}_{-8.8}\ (9.8^{+10.9}_{-8.8})$

[Lu etc., 2022.08073]

Enhanced NLO contribution in PQCD approach

- The predicted branching ratio from factorization contribution in QCDF is too small .
- Higher twist contribution can be included in PQCD approach



+ crossing diagrams

[Sheng etc., 2504.15002]

Enhanced NLO contribution in PQCD approach

	$\mathcal{A}_{\rm LO}$	$\mathcal{A}_{\rm NLO}$	$\frac{\lvert\mathcal{A}_{\rm NLO}\rvert}{\lvert\mathcal{A}_{\rm LO}\rvert}$	$\frac{\lvert\mathcal{A}_{\rm LO+NLO}\rvert}{\lvert\mathcal{A}_{\rm LO}\rvert}$
$\bar{B}_s^0 \to \pi^+\pi^-$	$4.97 + 3.97\,i$	$1.26 - 2.07\,i$	0.38	1.02
$\bar{B}_s^0 \to \rho_L^+\rho_L^-$	$7.06 + 11.5\,i$	$3.83 - 2.90\,i$	0.36	1.02

	$\Delta\delta\rvert_{\rm twist-2}$	$\Delta\delta\rvert_{\rm twist-3}$	$\Delta\delta\rvert_{\rm total}$	$\Delta\delta\rvert_{\rm LO}$
$\bar{B}_s^0 \to \pi^+\pi^-$	35.8°	33.6°	38.0°	7.2°
$\bar{B}_s^0 \to \rho_L^+\rho_L^-$	-166.0°	-112.7°	30.3°	-8.9°

$A_{CP} \propto \sin\Delta\delta$

Amplitudes and strong phases

[Sheng etc., 2504.15002]

Enhanced NLO contribution in PQCD approach

Branching ratios

[Sheng etc., 2504.15002]

	$10^6\mathcal{B}\|_{\text{Theory}}$	$10^6\mathcal{B}\|_{\text{Exp.}}$	f_L
$\bar{B}_s \to \pi^+\pi^-,$	$0.39^{+0.19}_{-0.18}\ (0.36^{+0.21}_{-0.18})$	0.72 ± 0.10	-
$\bar{B}_s \to \pi^0\pi^0$	$0.19^{+0.10}_{-0.09}\ (0.18^{+0.11}_{-0.10})$	< 7.7	$1.0\ (1.0)$
$\bar{B}_s \to \rho^0\rho^0$	$0.89^{+0.19}_{-0.17}\ (0.82^{+0.19}_{-0.16})$	< 320	$\sim 1.0\ (\sim 1.0)$
$\bar{B}_s \to \rho^+\rho^-,$	$1.71^{+0.36}_{-0.32}\ (1.58^{+0.36}_{-0.30})$	-	$\sim 1.0\ (\sim 1.0)$
$\bar{B}_s \to \omega\omega$	$0.62^{+0.27}_{-0.25}\ (0.55^{+0.31}_{-0.25})$	-	$\sim 1.0\ (\sim 1.0)$
$\bar{B}_s \to \rho\omega$	$\sim 0\ (\sim 0\ )$	-	$\sim 1.0\ (\sim 1.0)$
$\bar{B}_d \to K^+K^-$	$0.12^{+0.05}_{-0.03}\ (0.11^{+0.04}_{-0.03})$	0.078 ± 0.015	-
$\bar{B}_d \to K^{*+}K^{*-}$	$0.14^{+0.06}_{-0.05}\ (0.12^{+0.06}_{-0.04})$	< 0.4	$\sim 1.0\ (\sim 1.0)$
$\bar{B}_d \to \phi\phi$	$0.029^{+0.010}_{-0.010}\ (0.015^{+0.007}_{-0.005})$	< 0.027	$0.99\ (0.97)$

Enhanced NLO contribution in PQCD approach

CP asymmetries

$$\mathcal{A}_{\rm CP}(t) = \frac{\Gamma(\bar{B}_q \to M_1 M_2) - \Gamma(B_q \to M_1 M_2)}{\Gamma(\bar{B}_q \to M_1 M_2) + \Gamma(B_q \to M_1 M_2)} = -\frac{\mathcal{A}^{\rm dir}_{\rm CP}\cos(\Delta m_q t) + \mathcal{A}^{\rm mix}_{\rm CP}\sin(\Delta m_q t)}{\cosh(\Delta\Gamma_q t/2) + \mathcal{A}_{\Delta\Gamma}\sinh(\Delta\Gamma_q t/2)}$$

	$\mathcal{A}^{\rm dir}_{\rm CP}$	$\mathcal{A}^{\rm mix}_{\rm CP}$
$\bar{B}_s \to \pi^+\pi^-,\ \pi^0\pi^0$	$-6.0^{+1.1}_{-2.5}\ (-3.6^{+1.8}_{-3.1})$	$-4.2^{+21.4}_{-9.0}\ (35.9^{+15.6}_{-11.2})$
$\bar{B}_s \to \rho^+_L\rho^-_L,\ \rho^0_L\rho^0_L$	$-4.2^{+0.7}_{-0.5}\ (-1.9^{+0.7}_{-0.7})$	$-4.3^{+21.5}_{-9.0}\ (35.9^{+15.6}_{-11.2})$
$\bar{B}_s \to \omega_L\omega_L$	$-4.6^{+1.2}_{-2.0}\ (-2.6^{+1.6}_{-2.4})$	$-3.8^{+21.8}_{-9.7}\ (35.9^{+15.6}_{-11.2})$
$\bar{B}_s \to \rho_L\omega_L$	$0.0 \pm 0.0\ (0.0 \pm 0.0\ )$	$-71.0^{+6.3}_{-5.4}\ (-71.0^{+6.3}_{-5.4})$
$\bar{B}_d \to K^+K^-$	$41.6^{+12.5}_{-12.3}\ (38.7^{+13.2}_{-12.2})$	$-2.2^{+19.1}_{-26.4}\ (-47.0^{+15.7}_{-18.8})$
$\bar{B}_d \to K^{*+}_L K^{*-}_L$	$36.7^{+16.0}_{-9.5}\ (25.4^{+17.4}_{-11.1})$	$-1.4^{+19.7}_{-26.9}\ (-47.0^{+15.7}_{-18.8})$
$\bar{B}_d \to \phi_L\phi_L$	$-39.7^{+6.1}_{-8.4}\ (0.0)$	$27.8^{+5.7}_{-25.9}\ (0.0 \pm 0.0)$

[Sheng etc., 2504.15002]

Summary

- We found the hard-collinear gluon exchange can contribute at leading power of annihilation diagram which is missed in the previous studies.
- Based on a factorization assumption of the soft function, the annihilation diagrams(initial state emission) are factorizable at leading twist.
- The higher order contribution from quark loop can significantly modify the CP violation of pure annihilation B decays.
- In PQCD approach, the predicted branching ratios can be consistent with the experimental data(after including the NLO contribution), the predicted CP asymmetries need to be tested.

Thanks for your attention.