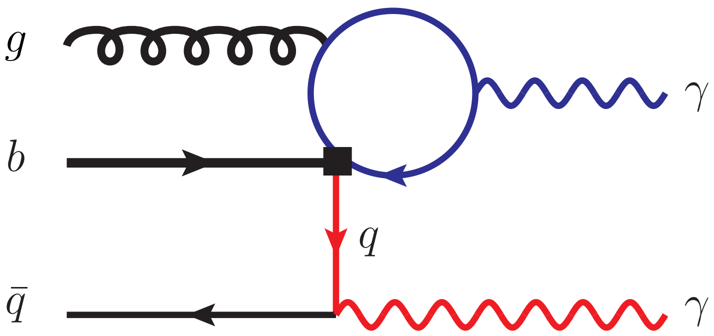

Deciphering the Long-distance Penguin contribution to $B \to \gamma\gamma$ decays

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QQ, Y.-L. Shen, C. Wang, Y.-M. Wang, *Phys.Rev.Lett.* 131(2023)091902

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- Why $\bar{B} \to \gamma\gamma$?
- History of (1) $\bar{B} \to \gamma\gamma$ and (2) the long-distance penguin contribution
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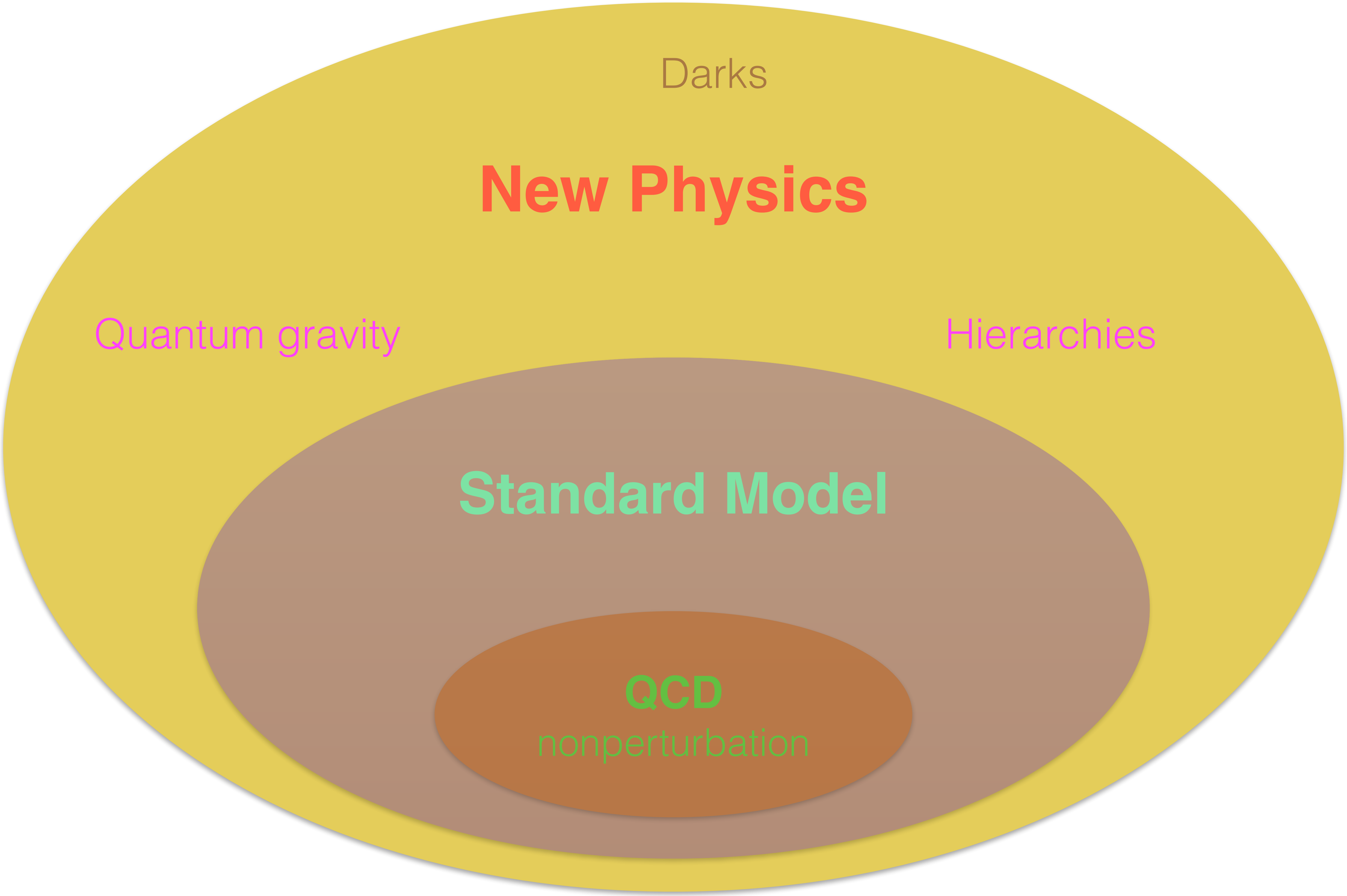
  —— a novel B-meson distribution amplitude
- Numerics
- Summary and Prospects

B decays are important!



Why $\bar{B} \to \gamma\gamma$?

- **FCNC:** Sensitive to dynamics beyond the SM, e.g. CP violation
- **Simplest** decay (as $B \to \mu^+\mu^-$): to address the intricate strong interaction mechanism of the heavy-meson systems

—— structure of the B meson

Belle II

Physics Book

Process	Observable	Theory	Sys. limit (Discovery) [ab^{-1}]	vs LHCb	vs Belle	Anomaly	NP
$B \to X_s l^+ l^-$	R_{X_s}	★★★	>50	★★★	★★★	★★	★★★
$B \to K^{(*)} e^+ e^-$	$R(K^{(*)})$	★★★	>50	★★	★★★	★★★	★★★
$B \to X_s \gamma$	$Br.$	★★	1-5	★★★	★	★	★★
$B_{d,(s)} \to \gamma\gamma$	$Br.$, A_{CP}	★★	> 50(5)	★★	★★	-	★★
$B \to K^* e^+ e^-$	P_5'	★★	>50	★★★	★★	★★★	★★★
$B \to K \tau l$	$Br.$	★★★	>50	★★	★★★	★★	★★★

Why $\bar{B} \to \gamma\gamma$?

- Sensitive to dynamics beyond the SM (FCNC), e.g. CP violation
- **Simplest** decay (as $B \to \mu^+\mu^-$) to address the intricate strong interaction mechanism of the heavy-meson systems

—— structure of the B meson

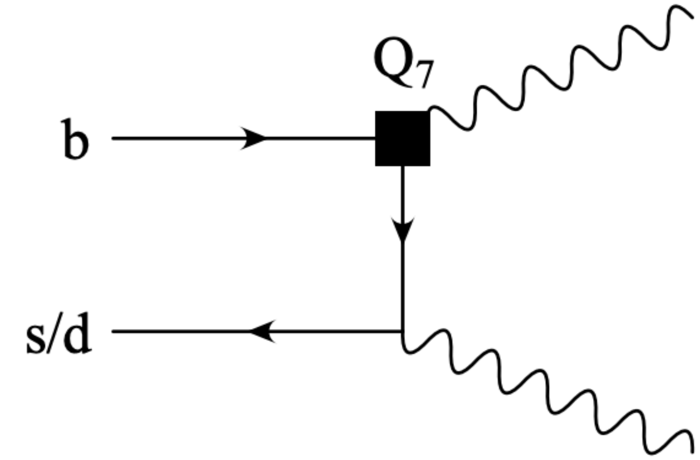
Belle II Physics Book

Observables	Belle $0.71\,\mathrm{ab}^{-1}$ $(0.12\,\mathrm{ab}^{-1})$	Belle II $5\,\mathrm{ab}^{-1}$	Belle II $50\,\mathrm{ab}^{-1}$
$\mathrm{Br}(B_d \to \gamma\gamma)$	$< 740\%$	30%	9.6%
$A_{CP}(B_d \to \gamma\gamma)$	–	78%	25%
$\mathrm{Br}(B_s \to \gamma\gamma)$	$< 250\%$	23%	–

$$\mathcal{BR}(B_d \to \gamma\gamma) = \left(1.352^{+1.242}_{-0.745}\right) \times 10^{-8}\,, \qquad \mathcal{BR}(B_s \to \gamma\gamma) = \left(2.964^{+1.800}_{-1.614}\right) \times 10^{-7}$$

[Y.-L. Shen, Y.-M. Wang, Y.-B. Wei, 2009.02723]

History of $\bar{B} \to \gamma\gamma$



- LO + NLO

$$\bar{A}(\bar{B}_q \to \gamma\gamma) = -\frac{4\,G_F}{\sqrt{2}}\frac{\alpha_{\rm em}}{4\pi}\,\epsilon^{*\alpha}(p)\,\epsilon^{*\beta}(q) \times \sum_{p=u,c} V_{pb}V^*_{pq}\sum_{i=1}^{8} C_i\,T^{(p)}_{i,\alpha\beta},$$

Leading power

$$T^{(p)}_{i,\alpha\beta} = i\,m^3_{B_q}\left[\left(g^{\perp}_{\alpha\beta} - i\,\varepsilon^{\perp}_{\alpha\beta}\right)F^{(p)}_{i,L} - \left(g^{\perp}_{\alpha\beta} + i\,\varepsilon^{\perp}_{\alpha\beta}\right)F^{(p)}_{i,R}\right],$$

$$F_L^{\rm LP} \propto m_b \int_0^\infty \frac{d\omega}{\omega}\,\phi_B^+(\omega,\mu) \propto \frac{m_b}{\lambda_b}$$

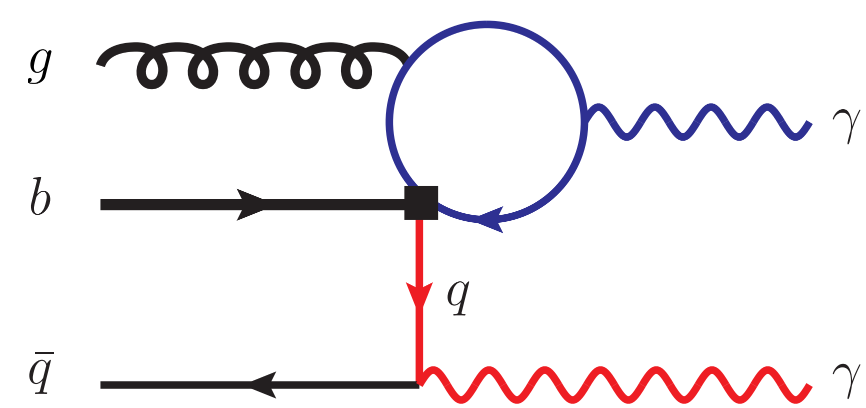
Two polarizations

[Bosch, Buchalla, hep-ph/0208202; Descotes-Genon, Sacharajda, hep-ph/0212162]

- NLL corrections + Systematic power corrections

both ~ $\mathcal{O}(10\%)$ [Y.-L. Shen, Y.-M. Wang, Y.-B. Wei, 2009.02723]

- One important but tough piece missing —— **long-distance penguin contribution**



History of Long-distance penguin contribution

In inclusive $b \to s$ decays

- Realized in $\bar{B} \to X_s\gamma$, expansion of $\frac{\Lambda^2_{\rm QCD}}{m_c^2}(\frac{m_b\Lambda_{\rm QCD}}{m_c^2})^n$, beyond $\frac{\Lambda^n_{\rm QCD}}{m_b^n}$

  [Voloshin, '96; Ligeti, Randall, Wise, '97; Buchalla, Isidori, Rey, '97]

- Factorization in $\bar{B} \to X_s\gamma$ using SCET, $m_c^2 \sim m_b\Lambda_{\rm QCD}$

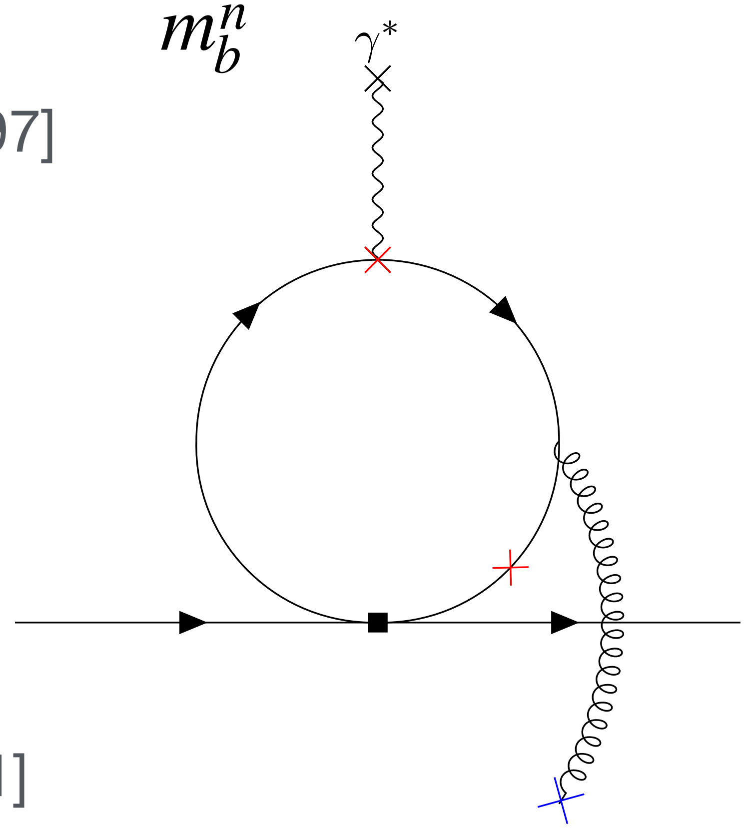
  [Benzke, Lee, Neubert, Paz, 1003.5012]

- Factorization in $\bar{B} \to X_s\ell\ell$

  [Benzke, Hurth, Turczyk, 1705.10366]

- Phenomenological Application in $\bar{B} \to X_{d,s}\ell\ell$

  [Huber, Hurth, Enrico, Jenkins, **QQ**, Vos,1908.07507, 2007.04191]



In exclusive $b \to s$ decays

Soft gluon from charm-loop

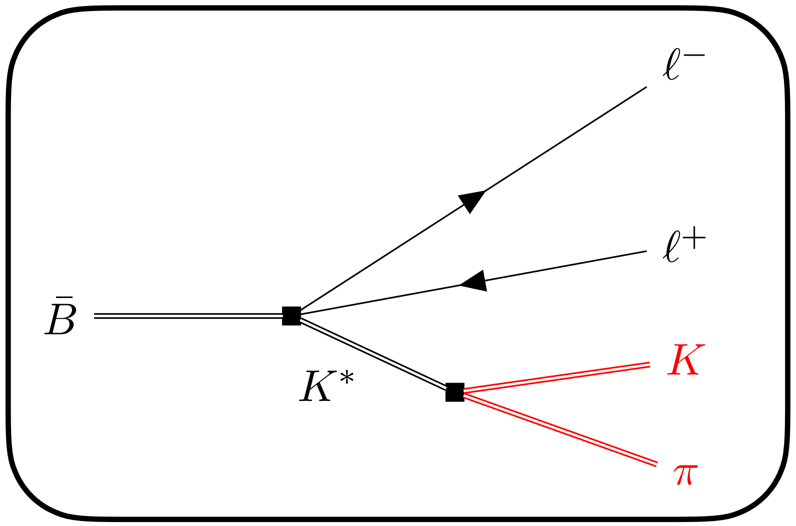
- Initiated in $B \to K^*\gamma$

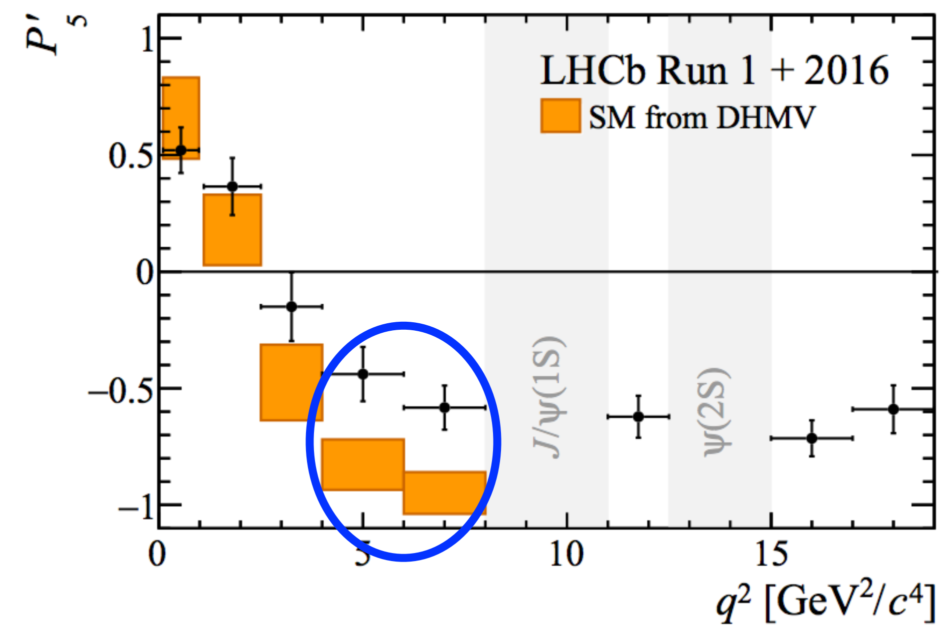
  [Khodjamirian, Ruckl, Stoll, Wyler, '97]

- Developed in $B \to K^*\ell\ell$

  [Khodjamirian, Mannel, Pivorarov, Wang, 1006.4945]

History of Long-distance penguin contribution





P'_5: an angular-distribution observable

[LHCb, 2003.04831]

Charm-loop effect in $B \to K^{(*)}\ell^+\ell^-$ and $B \to K^*\gamma$

A. Khodjamirian (Siegen U.), Th. Mannel (Siegen U.), A.A. Pivovarov (Siegen U.), Y.-M. Wang (Siegen U.)

Jun, 2010

35 pages

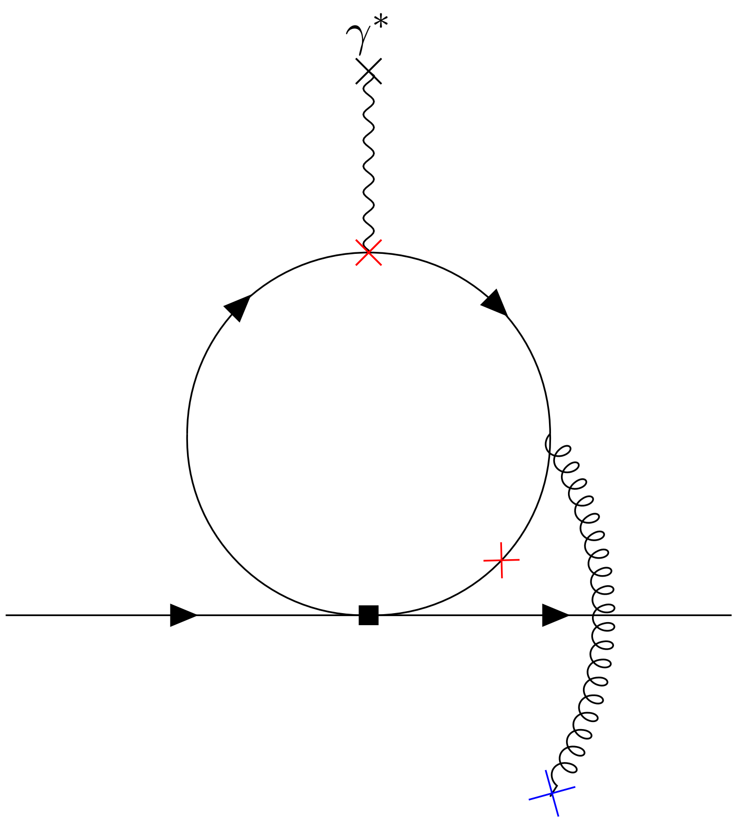
Published in: *JHEP* 09 (2010) 089

e-Print: 1006.4945 [hep-ph]

pdf cite claim reference search 472 citations

History of Long-distance penguin contribution

- Long-distance penguin contribution exist in basically all $b \to s$ decays
- Factorization completed in inclusive decays, but not yet in exclusive decays
- Attempt in the simplest decay $\bar{B} \to \gamma\gamma$



Soft gluon from charm-loop

Factorization

Factorization

$$\mathcal{H}_{\rm eff} = \frac{4\,G_F}{\sqrt{2}} \sum_{p=u,c} V_{pb} V^*_{pq} \Big[C_1(\nu)\, P^p_1(\nu) + C_2(\nu)\, P^p_2(\nu) + \sum_{i=3}^{8} C_i(\nu)\, P_i(\nu)$$

$$+ \sum_{i=3}^{6} C_i(\nu)\, P^Q_i(\nu) \Big] + \text{h.c.}\,,$$

$$P^p_1 = (\bar{q}_L \gamma_\mu T^a p_L)\,(\bar{p}_L \gamma^\mu T^a b_L)\,, \qquad P^p_2 = (\bar{q}_L \gamma_\mu p_L)\,(\bar{p}_L \gamma^\mu b_L)\,,$$

$$P_3 = (\bar{q}_L \gamma_\mu b_L) \sum_{q'} (\bar{q}' \gamma^\mu q')\,, \qquad P_4 = (\bar{q}_L \gamma_\mu T^a b_L) \sum_{q'} (\bar{q}' \gamma^\mu T^a q')\,,$$

$$P_5 = (\bar{q}_L \gamma_{\mu_1} \gamma_{\mu_2} \gamma_{\mu_3} b_L) \sum_{q'} (\bar{q}' \gamma^{\mu_1} \gamma^{\mu_2} \gamma^{\mu_3} q')\,,$$

$$P_6 = (\bar{q}_L \gamma_{\mu_1} \gamma_{\mu_2} \gamma_{\mu_3} T^a b_L) \sum_{q'} (\bar{q}' \gamma^{\mu_1} \gamma^{\mu_2} \gamma^{\mu_3} T^a q')\,,$$

Factorization

Integrate out the hard and hard-collinear d.o.f.

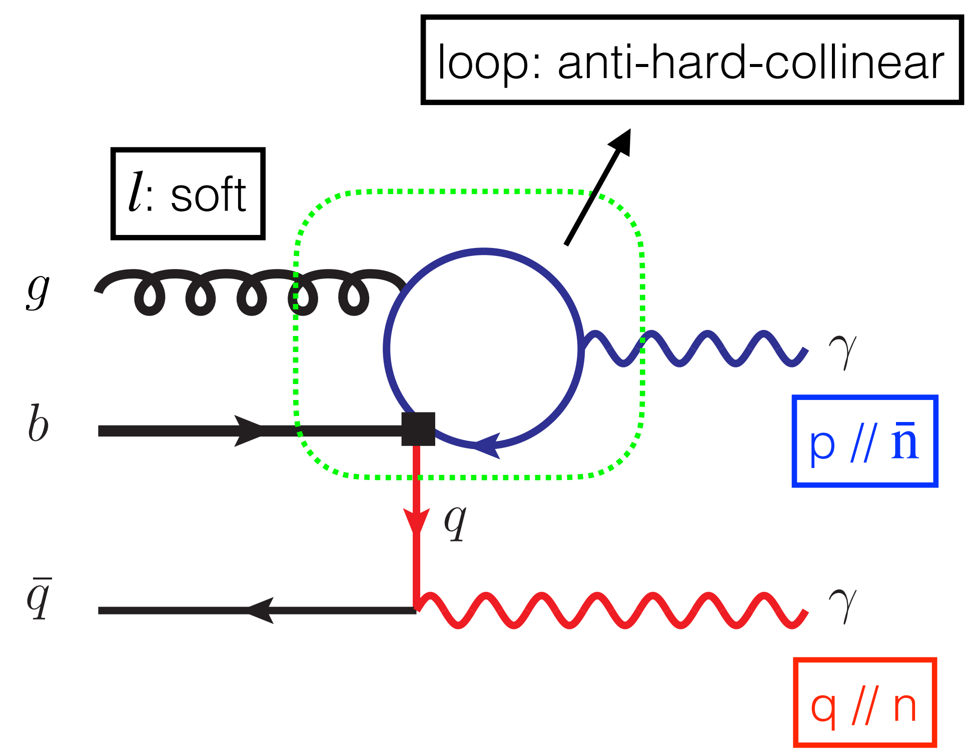
$$M = H * J * S \qquad (m_b \gg m_c \sim \mathcal{O}(\sqrt{\Lambda\, m_b}) \gg \Lambda_{\mathrm{QCD}})$$

First-step match:

$$M \ni \left(C_2 - \frac{C_1}{2N_c}\right) Q_p \left[F\left(\frac{m_p^2 - i0^+}{(p-l)^2}\right) - 1\right] \frac{p^\alpha}{(p-l)^2} \left[\bar{q}(\tilde{q})\, \gamma_\beta P_L G_{\mu\alpha}\, \tilde{F}^{\mu\beta} b(v)\right]$$

$$F(x) = 4\,x\ \arctan^2\left(\frac{1}{\sqrt{4\,x-1}}\right)$$

$$(p-l)^2 = -\,2p \cdot l = -\,m_b \bar{n} \cdot l$$



Non-local operator!

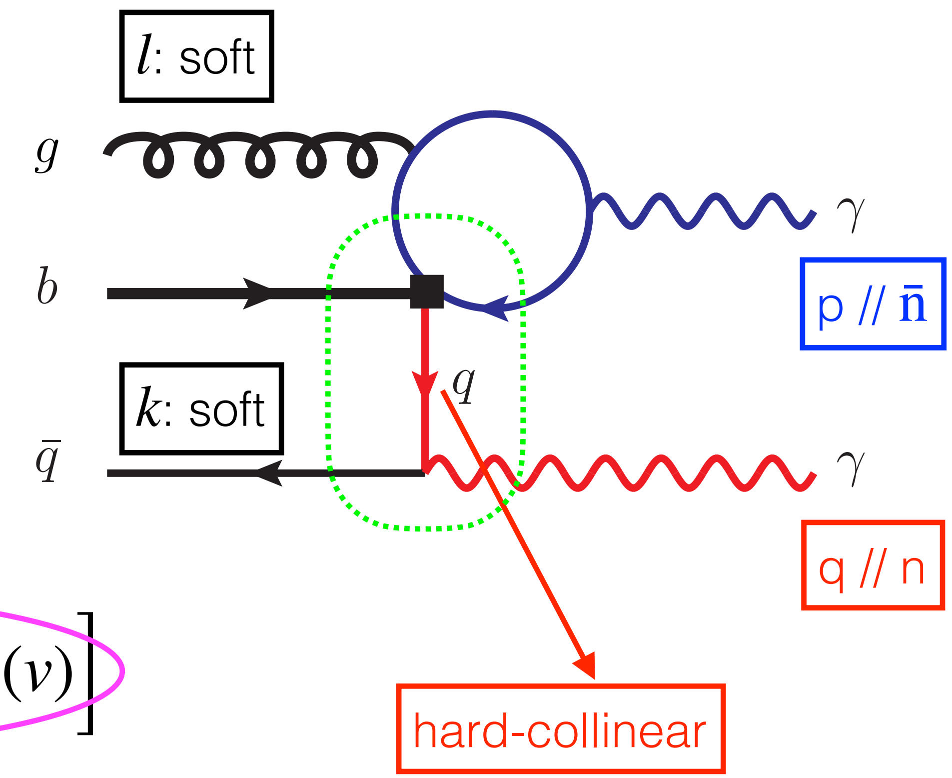
Factorization

<u>Second-step match:</u>

$$\langle \gamma(p)\, \gamma(q)\, |\, \bar{q}\, \gamma_\beta\, P_L\, G_{\mu\alpha}\; \tilde{F}^{\mu\beta}\, b\, |\, g(l)\, b(v)\, \bar{q}(k) \rangle$$

$$\Rightarrow \frac{i\, g_{\rm em}\, e_q}{(q-k)^2}\, \epsilon^{\mu\beta\lambda\tau}\, p_\lambda\, \epsilon^*_\tau(p)\, \epsilon^*_\rho(q) \times \left[\bar{q}(k)\, \gamma^\rho_\perp\;\, \not{q}\, \gamma_\beta\, P_L\, G_{\mu\alpha}(\ell)\, b(v) \right]$$

$$(q-k)^2 = -\,2q \cdot k = -\,m_b n \cdot k$$



- The hard-kernel (jet functions) depends on <u>2 different light-cone components</u> of the gluon and light quark momenta.
- It becomes evident to introduce the <u>3-particle</u> B-meson distribution amplitude with <u>2 light-cone directions</u>.

$$H \star J \star \bar{J} \star \Phi_{\rm G}$$

Factorization

The explicit factorization formula:

$$\sum_{i=1}^{8} C_i F_{i,L}^{(p),\,\text{soft 4q}} = -\frac{Q_q f_{B_q}}{m_{B_q}} \int_{-\infty}^{+\infty} \frac{d\omega_1}{\omega_1} \int_{-\infty}^{+\infty} \frac{d\omega_2}{\omega_2} \left(C_2 - \frac{C_1}{2N_c} \right) Q_p \left[F(-\frac{m_p^2}{m_b \omega_2}) - 1 \right] \times \Phi_G(\omega_1, \omega_2, \mu)$$

The light quark momentum component $\omega_1 = n \cdot k$;
The soft gluon momentum component $\omega_2 = \bar{n} \cdot l$.

The novel B-meson DA:

$$\langle 0 \,|\, \bar{q}_s(\tau_1 n)(g_s G_{\mu\nu})(\tau_2 \bar{n}) \bar{n}^\nu \; \not{n} \gamma_\perp^\mu \gamma_5 \, h_v(0) \,|\, \bar{B}_v \rangle$$

$$= 2 \tilde{f}_B(\mu)\, m_B \int_{-\infty}^{+\infty} d\omega_1 \int_{-\infty}^{+\infty} d\omega_2 \exp\left[-i(\omega_1 \tau_1 + \omega_2 \tau_2)\right] \, \Phi_G(\omega_1, \omega_2, \mu)$$

- The quark and gluon fields are localized on 2 distinct light-cone directions.

Non-trivial RG evolution of this soft function, mixing positive into negative support of $\omega_{1,2}$. See an upcoming paper [Huang,Ji,Shen,Wang,Wang,Zhao,2312.15439]. See also Yong-Kang's talk.

Factorization

The (tree-level) normalization conditions of $\Phi_{\rm G}$:

Matching the conventional 3-particle B meson DAs as τ_1 or $\tau_2 \to 0$.

$$\langle 0 | \bar{q}(z_1)(g_s G_{\mu\nu})(z_2)\, \bar{n}^{\nu} \;\; \not{n}\gamma_{\perp}^{\mu}\gamma_5\, h_v(0) | \bar{B}_v \rangle = 2\tilde{f}_B(\mu)\Phi_4(z_1, z_2, \mu)$$ **Twist 4**

$$\langle 0 | \bar{q}(z_1)(g_s G_{\mu\nu})(z_2)\, n^{\nu} \;\; \not{\bar{n}}\gamma_{\perp}^{\mu}\gamma_5\, h_v(0) | \bar{B}_v \rangle = 2\tilde{f}_B(\mu)\Phi_5(z_1, z_2, \mu)$$ **Twist 5**

[Braun, Ji, Manashov, 1703.02446]

$$\int_0^\infty d\omega_1\, \Phi_{\rm G}(\omega_1, \omega_2, \mu) = \int_0^\infty d\omega_1\, \Phi_4(\omega_1, \omega_2, \mu)\,,$$
$$\int_0^\infty d\omega_2\, \Phi_{\rm G}(\omega_1, \omega_2, \mu) = \int_0^\infty d\omega_2\, \Phi_5(\omega_1, \omega_2, \mu)\,,$$
$$\int_0^\infty d\omega_1 \int_0^\infty d\omega_2\, \Phi_{\rm G}(\omega_1, \omega_2, \mu) = \frac{\lambda_E^2 + \lambda_H^2}{3}\,,$$

The power counting: $F_L^{\rm soft,4q}/F_L^{\rm LP} \sim \lambda_B/m_b$

Factorization

The asymptotic behaviors of Φ_G:

$$\Phi_G(\omega_1, \omega_2, \mu) \sim \omega_1\, \omega_2^2 \text{ at } \omega_1,\, \omega_2 \to 0$$

The explicit factorization formula:

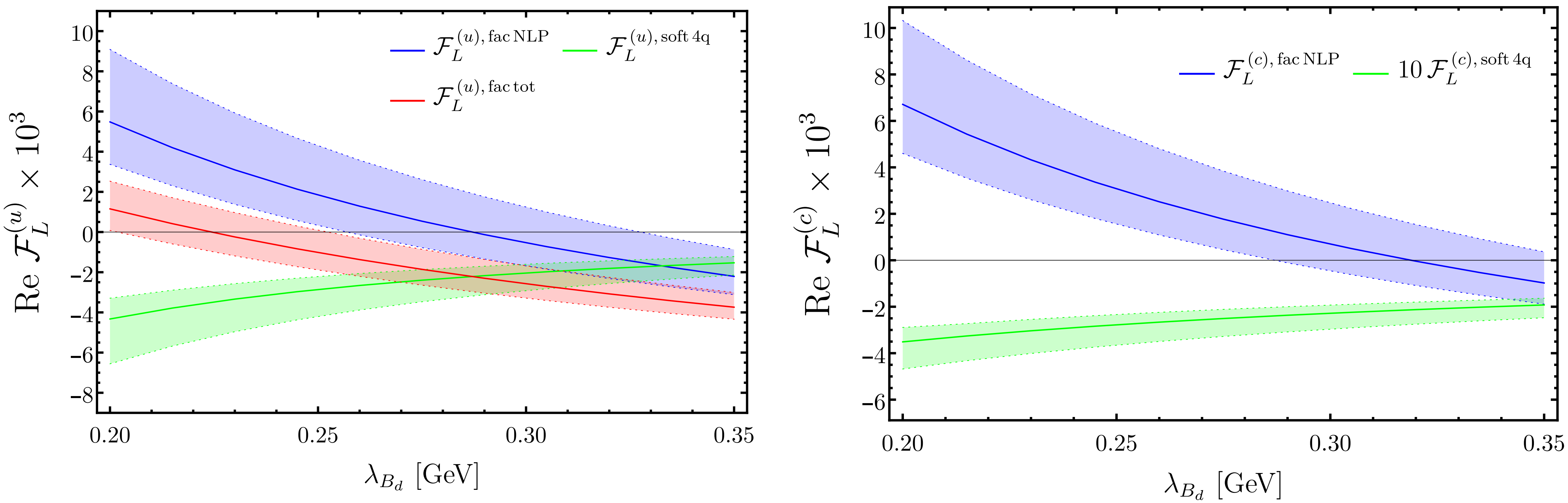
$$\sum_{i=1}^{8} C_i\, F_{i,L}^{(p),\,\mathrm{soft}\,4q} = -\frac{Q_q\, f_{B_q}}{m_{B_q}} \int_0^{+\infty} \frac{d\omega_1}{\omega_1} \int_0^{+\infty} \frac{d\omega_2}{\omega_2} \left(C_2 - \frac{C_1}{2N_c} \right) Q_p \left[F(-\frac{m_p^2}{m_b \omega_2}) - 1 \right] \times \Phi_G(\omega_1, \omega_2, \mu)$$

➡ The convolution integral converges.

Numerics

The Φ_G parametrization:

$$\Phi_G(\omega_1, \omega_2, \mu_0) = \frac{\lambda_E^2 + \lambda_H^2}{6} \frac{\omega_1 \omega_2^2}{\omega_0^5} \exp\left(-\frac{\omega_1 + \omega_2}{\omega_0}\right) \frac{\Gamma(\beta+2)}{\Gamma(\alpha+2)}\, U\left(\beta - \alpha, 4 - \alpha, \frac{\omega_1 + \omega_2}{\omega_0}\right)$$



- The up-loop contribution dominates; the charm-loop is 1-order smaller.
- The new power correction accidentally cancels the previous ones.

➡ Clean channel to determine λ_B and to probe new physics.

Numerics

The B_d results:

	Central Value	Total Error	λ_{B_d}	$\{\widehat{\sigma}^{(1)}_{B_d}, \widehat{\sigma}^{(2)}_{B_d}\}$	μ	ν	μ_h	$\bar{\Lambda}$	m_c^{PS}
$10^8 \times \mathcal{BR}$	1.929 [1.900]	$^{+1.096}_{-1.012}$	$^{+0.680}_{-0.439}$	$^{+0.736}_{-0.779}$	$^{+0.083}_{-0.299}$	$^{+0.278}_{-0.287}$	$^{+0.246}_{-0.066}$	$^{+0.212}_{-0.200}$	$^{+0.043}_{-0.043}$
$f_\parallel$	0.408 [0.407]	$^{+0.044}_{-0.046}$	$^{+0.015}_{-0.015}$	$^{+0.016}_{-0.033}$	$^{+0.002}_{-0.009}$	$^{+0.037}_{-0.026}$	$^{+0.007}_{-0.002}$	$^{+0.005}_{-0.006}$	$^{+0.002}_{-0.002}$
$f_\perp$	0.592 [0.593]	$^{+0.046}_{-0.044}$	$^{+0.015}_{-0.015}$	$^{+0.033}_{-0.016}$	$^{+0.009}_{-0.002}$	$^{+0.026}_{-0.037}$	$^{+0.002}_{-0.007}$	$^{+0.006}_{-0.005}$	$^{+0.002}_{-0.002}$
$\mathcal{A}_{CP}^{dir,\parallel}$	0.126 [0.129]	$^{+0.043}_{-0.027}$	$^{+0.007}_{-0.004}$	$^{+0.017}_{-0.010}$	$^{+0.013}_{-0.008}$	$^{+0.027}_{-0.018}$	$^{+0.024}_{-0.012}$	$^{+0.007}_{-0.007}$	$^{+0.004}_{-0.004}$
$\mathcal{A}_{CP}^{mix,\parallel}$	-0.197 [-0.154]	$^{+0.053}_{-0.084}$	$^{+0.019}_{-0.036}$	$^{+0.001}_{-0.002}$	$^{+0.021}_{-0.047}$	$^{+0.026}_{-0.040}$	$^{+0.015}_{-0.029}$	$^{+0.011}_{-0.013}$	$^{+0.008}_{-0.009}$
$\mathcal{A}_{\Delta\Gamma}^{\parallel}$	-0.972 [-0.980]	$^{+0.024}_{-0.013}$	$^{+0.009}_{-0.004}$	$^{+0.003}_{-0.002}$	$^{+0.013}_{-0.005}$	$^{+0.013}_{-0.007}$	$^{+0.010}_{-0.004}$	$^{+0.004}_{-0.003}$	$^{+0.002}_{-0.002}$
$\mathcal{A}_{CP}^{dir,\perp}$	0.330 [0.326]	$^{+0.078}_{-0.053}$	$^{+0.015}_{-0.012}$	$^{+0.060}_{-0.035}$	$^{+0.035}_{-0.014}$	$^{+0.012}_{-0.024}$	$^{+0.014}_{-0.010}$	$^{+0.018}_{-0.016}$	$^{+0.018}_{-0.017}$
$\mathcal{A}_{CP}^{mix,\perp}$	0.136 [0.101]	$^{+0.087}_{-0.066}$	$^{+0.043}_{-0.028}$	$^{+0.015}_{-0.035}$	$^{+0.025}_{-0.014}$	$^{+0.060}_{-0.038}$	$^{+0.026}_{-0.012}$	$^{+0.003}_{-0.003}$	$^{+0.009}_{-0.008}$
$\mathcal{A}_{\Delta\Gamma}^{\perp}$	0.934 [0.940]	$^{+0.017}_{-0.030}$	$^{+0.000}_{-0.003}$	$^{+0.009}_{-0.019}$	$^{+0.007}_{-0.017}$	$^{+0.001}_{-0.002}$	$^{+0.005}_{-0.009}$	$^{+0.006}_{-0.007}$	$^{+0.007}_{-0.008}$

Numerics

Giulio Dujany, Moriond 2024

	$\mathcal{B}(B^0 \to \gamma\gamma)$	$\mathcal{B}(B^0 \to \gamma\gamma)$ (at 90% CL)
Belle	$(5.4^{+3.3}_{-2.6} \pm 0.5) \times 10^{-8}$	$< 9.9 \times 10^{-8}$
Belle II	$(1.7^{+3.7}_{-2.4} \pm 0.3) \times 10^{-8}$	$< 7.4 \times 10^{-8}$
Combined	$(3.7^{+2.2}_{-1.8} \pm 0.7) \times 10^{-8}$	$< 6.4 \times 10^{-8}$

Summary and prospects

- We have factorized the long-distance penguin contribution to $\bar{B} \to \gamma\gamma$ decay, for the first time in an exclusive decay.

- A novel B-meson DA is introduced, with quark and gluon fields localized on two different light-cone directions. It provides a new window to probe the inner structure of the B meson.

- The new contribution cancels the known factorizable power corrections, making $\bar{B} \to \gamma\gamma$ a clean channel to determine λB and to probe the non-standard dynamics.

- The developed formalism has a broad field of applications to the entire spectrum of the exclusive FCNC B-meson decays, including flagship modes, e.g. $B \to K^*\gamma$, $B \to K^*\mu\mu$.

Thank you!

Backup

	B_d	B_s
$\mathcal{A}^{\rm LP,NLL}\,[10^{-4}]$	$3.4+1.9\,i$	$-20-0.37\,i$
$\mathcal{A}^{\rm fac,NLP}\,[10^{-4}]$	$-0.15-0.53\,i$	$0.92+2.6\,i$
$\mathcal{A}_R^{\rm fac,NLP}\,[10^{-4}]$	$0.25-0.36\,i$	$-1.6+2.6\,i$
$\mathcal{A}^{{\rm had},\gamma}\,[10^{-4}]$	$-0.30-0.17\,i$	$1.4-0.0021\,i$
$\mathcal{A}^{\rm soft,\,4q}\,[10^{-4}]$	$(-0.0079+0.078\,i)$	$-0.11+0.016\,i$
$(F_u^{\rm LP,NLL}, F_c^{\rm LP,NLL})$	$(-0.056-0.0092i,\ -0.048-0.0019i)$	$(-0.057-0.0094i,\ -0.049-0.0020i)$
$(F_u^{{\rm had},\gamma}, F_c^{{\rm had},\gamma})$	$(0.0051+0.00092i,\ 0.0043+0.00019i)$	$(0.0094+0.0016i,\ 0.0034+0.00016i)$
$(F_u^{\rm soft,4q}, F_c^{\rm soft,4q})$	$(-0.0024,\ -0.00025)$	$(-0.0021,\ -0.00025)$
$(F_u^{\rm HC}, F_c^{\rm HC})$	$(0.0055,\ 0.0055)$	$(0.0067,\ 0.0067)$
$(F_u^{\rm m_q}, F_c^{\rm m_q})$	$(0.000049,\ 0.000049)$	$(0.00078,\ 0.00078)\ [0.00079]$
$(F_u^{\rm A_2}, F_c^{\rm A_2})$	$(-0.0010,\ -0.0010)$	$(-0.0011,\ -0.0011)$
$(F_u^{\rm HT}, F_c^{\rm HT})$	$(0.0046,\ 0.0046)\ [0.0047]$	$(0.0048,\ 0.0048)\ [0.0050]$
$(F_u^{\rm Q_b}, F_c^{\rm Q_b})$	$(-0.0036,\ -0.0036)$	$(-0.0043,\ -0.0043)$
$(F_u^{\rm WA}, F_c^{\rm WA})$	$(-0.0049+0.000092i,\ -0.0037+0.0056i)$	$(-0.0059+0.00011i,\ -0.0045+0.0065i)$
$(F_u^{\rm fac,NLP}, F_c^{\rm fac,NLP})$	$(0.00054+0.000092i,\ 0.0018+0.0056i)$	$(0.00098+0.00011i,\ 0.0023+0.0065i)$
	$[(0.00063+0.000092i,\ 0.0019+0.0056i)]$	$(0.0011+0.00011i,\ 0.0024+0.0065i)$
$(F_{R,u}^{\rm fac,NLP}, F_{R,c}^{\rm fac,NLP})$	$(-0.0046+0.000092i,\ -0.0033+0.0056i)$	$(-0.0054+0.00011i,\ -0.0041+0.0065i)$

$$A = V_{uq}^* V_{ub} F_u + V_{cq}^* V_{cb} F_c \ (q = d, s)$$