The Implications of QED on non-leptonic B decays

Keri Vos

in collaboration with M. Beneke, P. Boër and J-N. Toelstede

arXiv:2008.10615

QED Factorization in non-leptonic B decays

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Non-Leptonic Charmless B Decays

- Non-leptonic B decays important probes of CP violation and CKM phases
  - $\rightarrow$ Challenging due to fully hadronic initial and final states
- Huge advantage compared to charm: $\Lambda_{\mathrm{QCD}}/m_b \sim 0.2$
- Heavy m_b quark allows for precision predictions!
  - $\rightarrow$ Disentangle perturbative (calculable) and non-perturbative dynamics
  - $\rightarrow$ Systematic expansion in α_s and $1/m_b$: QCD factorization
  - $\rightarrow$ Studied up to NNLO (α_s^2) e.g. [Bell, Beneke, Huber, Li]
  - $\rightarrow$ Theoretical challenge: reliable computations of observables
- Wealth of experimental data $\rightarrow$ unprecedented precision

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Precision Frontier in B Decays

- Next step: systematically include electromagnetic effects $\sim \mathcal{O}(\alpha_{\rm em})$

- QED corrections in $B_s \to \mu^+\mu^-$ already studied [Beneke, Bobeth, Szafron]
  - $\to$ power-enhanced QED effects

- QED in non-leptonic decays
  - $\to$ can mimic isospin-breaking electroweak penguin effects
  - $\to$ perturbative and non-perturbative dynamics disentangled using Heavy-Quark Expansion

- QED more complicated than QCD due to charged external states

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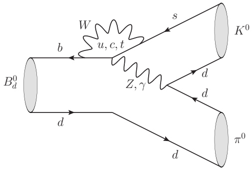

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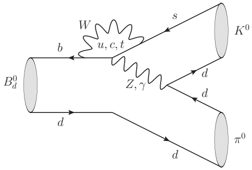

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Electromagnetic Effects

$$\Gamma[\bar{B} \to M_1 M_2](\Delta E) \equiv \Gamma[\bar{B} \to M_1 M_2 + X_s]\Big|_{E_{X_s} \leq \Delta E} ,$$

- IR finite observable (width) must include ultra-soft photon radiation
- X_s are soft photons with total energy less than ultrasoft scale ΔE
- Factorizes in non-radiative amplitude and ultrasoft function

$$\Gamma[\bar{B} \to M_1 M_2](\Delta E) = |\mathcal{A}(\bar{B} \to M_1 M_2)|^2 \sum_{X_s} |\langle X_s|(\bar{S}_v^{(Q_B)} S_{v_1}^{\dagger(Q_{M_1})} S_{v_2}^{\dagger(Q_{M_2})})|0\rangle|^2 \, \theta(\Delta E - E_{X_s})$$

Simple classification:

- Ultra-soft photons: eikonal approximation, well understood

$$\Delta E \ll \Lambda_{\rm QCD}$$

- Non-universal, structure dependent corrections
- Both effects important: virtual photons can resolve the structure of the meson!

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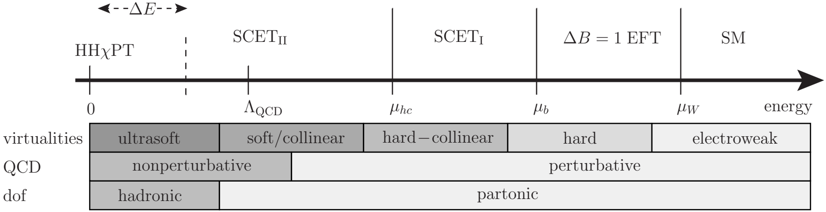
- Often done: Assume pointlike approximation up to the scale m_B [Baracchini, Isidori]
  - $\to$ fails to account for all large logarithms (and scales)!
  - $\to$ photons with energy $\gtrsim \Lambda_{\rm QCD}$ probe the partonic structure of the mesons

Multi-Scale Problem: Tower of EFTs

Hierarchy of energy scales:

$M_W \sim 80\,\text{GeV} \gg m_b \sim 4.2\,\text{GeV} \gg \text{few times}\,\Lambda_{\text{QCD}} \gg \Delta E \sim 60\,\text{MeV}$



(figure from [Beneke, Bobeth, Szafron '19])

- Decoupling of W, Z bosons at $\mu_W \sim 80\,\text{GeV}$: RG evolution from $\mu_W \to \mu_b$
- Soft-collinear effective field theory (SCET): $\mu_b \sim m_b \sim 4.2\,\text{GeV} \gg \text{few times}\,\Lambda_{\text{QCD}}$
  - → NEW: include structure dependent
- Ultrasoft region $\mu_{\text{us}} \ll \Lambda_{\text{QCD}}$
  - → Point-like meson approximation well understood

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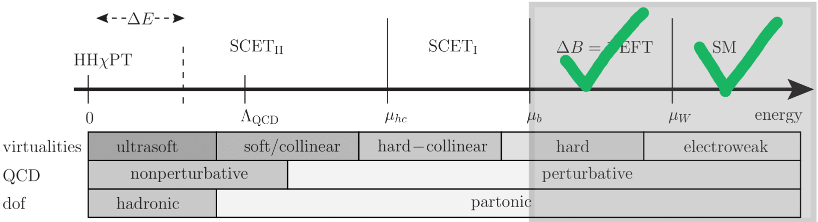

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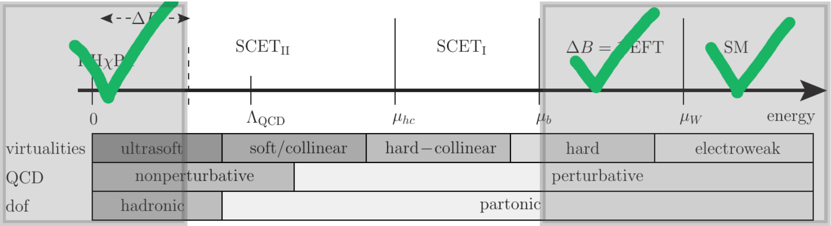

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Our work:

Derive all-order factorization formula in QCD$\times$QED for *non-radiative amplitude*

QED Factorization for non-leptonic B decays

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Derive all-order factorization formula in QCD$\times$QED for *non-radiative amplitude*

Phenomenological implications on $B \to \pi K$ decays

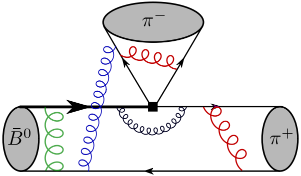
$\rightarrow$ include effects above m_b

$\rightarrow$ structure dependent contributions between m_b and a few times Λ_{QCD}

$\rightarrow$ include ultrasoft effects below Λ_{QCD}

QCD$\times$QED Factorization

QCD Factorization Formula



QCD Factorization Formula

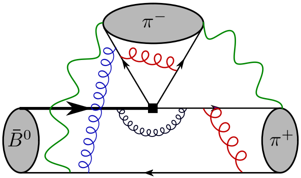
[Beneke, Buchalla, Neubert, Sachrajda]

$$\langle M_1 M_2 | Q_i | B \rangle = F^{BM_1}(q^2 = 0) \int_0^1 \mathrm{d}u \, T_i^{\mathrm{I}}(u) f_{M_2} \phi_{M_2}(u)$$

$$+ \int_0^\infty \mathrm{d}\omega \int_0^1 \mathrm{d}u \, \mathrm{d}v \, T_i^{\mathrm{II}}(u, v, \omega) \, f_{M_1} \phi_{M_1}(v) \, f_{M_2} \phi_{M_2}(u) \, f_B \phi_B(\omega)$$

- hard & hard-collinear scattering kernels $T_i^{\mathrm{I,II}}$ (perturbative, process-dependent)
- light-meson LCDAs ϕ_{M_i} contain (anti-)collinear dynamics (non-perturbative, universal)
- B-meson LCDA ϕ_B contains soft dynamics (non-perturbative, universal)
- full QCD form factor $F^{BM_1}(0)$ absorbs endpoint divergent convolutions

QCD×QED Factorization Formula



QCD×QED Factorization Formula

$$\langle M_1 M_2|Q_i|\bar{B}\rangle = \mathcal{F}^{BM_1}_{Q_2}(0)\int_0^1 du\, T^{\mathrm{I}}_{i,Q_2}(u)\mathscr{F}_{M_2}\Phi_{M_2}(u) + \int_{-\infty}^{\infty} d\omega \int_0^1 du\, dv\, T^{\mathrm{II}}_{i,\otimes}(u,v,\omega)\mathscr{F}_{M_1}\Phi_{M_1}(v)\mathscr{F}_{M_2}\Phi_{M_2}(u)\mathscr{F}_{B,\otimes}\Phi_{B,\otimes}(\omega)\,.$$

- retains its form but non-perturbative objects need to be generalized
- soft photons sensitive to charge and direction of final-state mesons $\otimes = (Q_1, Q_2)$

  $\rightarrow$ process dependent!
- endpoint divergences are still absorbed in $\mathcal{F}^{BM_1}_{Q_2}$

Phenomenological Implications

Pheno implications

$$A_{M_1 M_2} \equiv i \frac{G_F}{\sqrt{2}} m_B^2 F_0^{BM_1}(0) f_{M_2}$$

Amplitude parametrization

$$\begin{aligned}
\mathcal{A}_{B^- \to \pi^- \bar{K}^0} &= A_{\pi K} \hat{\alpha}_4^p \,, \\
\sqrt{2}\mathcal{A}_{B^- \to \pi^0 K^-} &= A_{\pi K}\left[\delta_{pu}\alpha_1 + \hat{\alpha}_4^p\right] + A_{K\pi}\left[\delta_{pu}\alpha_2 + \delta_{pc}\frac{3}{2}\alpha_{3,\mathrm{EW}}^c\right] \,, \\
\mathcal{A}_{\bar{B}^0 \to \pi^+ K^-} &= A_{\pi K}\left[\delta_{pu}\alpha_1 + \hat{\alpha}_4^p\right] \,, \\
\sqrt{2}\mathcal{A}_{\bar{B}^0 \to \pi^0 \bar{K}^0} &= A_{\pi K}\left[-\hat{\alpha}_4^p\right] + A_{K\pi}\left[\delta_{pu}\alpha_2 + \delta_{pc}\frac{3}{2}\alpha_{3,\mathrm{EW}}^c\right] \,,
\end{aligned}$$

- α_1 and α_2 color-allowed and color-suppressed tree coefficients
- α_4 and $\alpha_{3,\mathrm{EW}}$ penguin and electromagnetic penguin coefficients
- contain all perturbative effects (α_s^2)

Different QED effects

$$\mathcal{A}(M_1 M_2) \equiv i \frac{G_F}{\sqrt{2}} m_B^2 \mathcal{F}_{Q_2}^{BM_1}(0) \mathscr{F}_{M_2}$$

$$\mathcal{A}(M_1 M_2)\alpha_i(M_1 M_2) = A_{M_1 M_2}\left(\alpha_i^{\rm QCD}(M_1 M_2) + \delta\alpha_i(M_1 M_2)\right)$$

- Electroweak scale to m_B: QED corrections to the Wilson coefficients
- m_B to μ_c: QED corrections to the hard-scattering kernels, form factors and decay constants
- below $\Lambda_{\rm QCD}$: Ultrasoft QED effects (for the rate!)

$$\delta\alpha_i(M_1 M_2) \equiv \delta\alpha_i^{\rm WC}(M_1 M_2) + \delta\alpha_i^{\rm K}(M_1 M_2) + \delta\alpha_i^{\rm F,V}(M_1 M_2) + \delta\alpha_i^{\rm F,sp}(M_1 M_2)\,.$$

$\rightarrow$ $\delta\alpha_i^{\rm WC} = \mathcal{O}(10^{-3})$

$\rightarrow$ $\delta\alpha_i^{\rm K} = \mathcal{O}(10^{-3})$ structure dependent effects

$\rightarrow$ $\delta\alpha_i^{\rm F,V} = ??$

$\rightarrow$ $\delta\alpha_i^{\rm F,sp} = ??$ but also $\mathcal{O}(\alpha_{\rm em}\alpha_s)$

Ultrasoft Contribution

- Ultrasoft effects dress braching ratio
- Key point: scale dependence cancels!!

$$U(M_1 M_2) = \left(\frac{2\Delta E}{m_B}\right)^{-\frac{\alpha_{\rm em}}{\pi}\left(Q_B^2 + Q_{M_1}^2\left[1+\ln\frac{m_{M_1}^2}{m_{B_q}^2}\right] + Q_{M_2}^2\left[1+\ln\frac{m_{M_2}^2}{m_B^2}\right]\right)}$$

- Recover the standard QED factor
- ΔE is the window of the πK invariant mass around m_B
- Theory requires $\Delta E \ll \Lambda_{\rm QCD} = 60\,\text{MeV}$
- Large effects:

  $\rightarrow$ $U(\pi^+ K^-) = 0.914$, $U(\pi^0 K^-) = U(K^- \pi^0) = 0.976$ and $U(\pi^- \bar{K}^0) = 0.954$
- Experimentally usoft effects included using PHOTOS
- Challenging to compare theory with experiment!

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Ratios and isospin sumrules

- QED gives sub-percent corrections to Branching ratios
- Beneficial to consider ratios in which QCD is suppressed

$$R_L = \frac{2\mathrm{Br}(\pi^0 K^0) + 2\mathrm{Br}(\pi^0 K^-)}{\mathrm{Br}(\pi^- K^0) + \mathrm{Br}(\pi^+ K^-)} = R_L^{\mathrm{QCD}} + \cos\gamma \mathrm{Re}\,\delta_{\mathrm{E}} + \delta_U$$

- QED corrections to kernels enter linearly, QCD only quadratically

$$\delta_E = (-1.12 + 0.16i) \cdot 10^{-3}$$

- Ultrasoft effects dominant

$$\delta_U \equiv \frac{1 + U(\pi^0 K^-)}{U(\pi^- \bar{K}^0) + U(\pi^+ K^-)} - 1 = 5.8\%$$

- Combined QED effect larger than QCD uncertainty!

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Isospin sumrule

$$\Delta(\pi K) \equiv A_{\rm CP}(\pi^+ K^-) + \frac{\Gamma(\pi^- \bar{K}^0)}{\Gamma(\pi^+ K^-)} A_{\rm CP}(\pi^- \bar{K}^0) - \frac{2\Gamma(\pi^0 K^-)}{\Gamma(\pi^+ K^-)} A_{\rm CP}(\pi^0 K^-)$$
$$- \frac{2\Gamma(\pi^0 \bar{K}^0)}{\Gamma(\pi^+ K^-)} A_{\rm CP}(\pi^0 \bar{K}^0) \equiv \Delta(\pi K)^{\rm QCD} + \delta\Delta(\pi K)$$

- Sensitive to new physics effects: $\Delta(\pi K)^{\rm QCD} = (0.5 \pm 1.1)\%$ [Bell, Beneke, Huber, Li]
- QED contribution $\delta\Delta(\pi K) = -0.42\%$ [Beneke, Boër , Toelstede, KKV]
- Isospin sumrule also robust against QED effects!

CP asymmetries:

- QED effects smaller than QCD uncertainties

$$\delta(\pi K) \equiv A_{\rm CP}(\pi^0 K^-) - A_{\rm CP}(\pi^+ K^-) = \delta^{\rm QCD}(\pi K) + 0.02\%$$

- $\delta^{\rm QCD}(\pi K) = 2.1 \pm 3.5\%$ [Bell, Beneke, Huber, Li] versus experiment
  $\delta^{\rm exp}(\pi K) = 12.2 \pm 2.2\%$

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Conclusion

- QED factorization more complicated than in QCD due to charged external states
- QCD×QED factorization formula . . .
  - → same structure as in QCD but with generalized non-pert. functions
  - → endpoint-divergences still universal
- Non-perturbative objects . . .
  - → become process dependent
  - → interesting theoretical consequences [Beneke, Boër, Toelstede, KKV [in progress!]]
- Structure dependent QED effects small
  - → can compete with QCD uncertainty
- Theoretical versus experimental branching ratio

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Thank you for your attention

Backup-Slides

Isospin relation

- Isospin relation Nir, Quin [1991]; Gronau, Hernandez, London, Rosner [1995]

$$\begin{aligned}\sqrt{2}A(B^0 \to \pi^0 K^0) + A(B^0 \to \pi^- K^+) \\ &= \sqrt{2}A(B^+ \to \pi^0 K^+) + A(B^+ \to \pi^+ K^0) \\ &= -(\hat{T} + \hat{C})\left(e^{i\gamma} - qe^{i\phi}e^{i\omega}\right) \equiv 3A_{3/2} = 3|A_{3/2}|e^{i\phi_{3/2}} \ ,\end{aligned}$$

- QCD penguin and color-suppressed EWPs cancel
- Extract ϕ_{00} from amplitude traingles in clean way
- If q and ϕ known, only $SU(3)$ input:

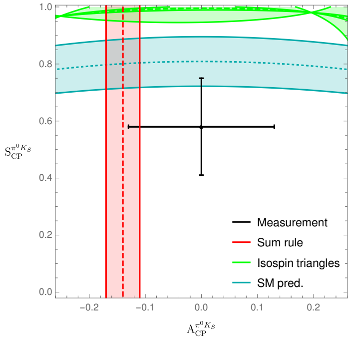
$$|\hat{T} + \hat{C}| = R_{T+C}\left|\frac{V_{us}}{V_{ud}}\right|\sqrt{2}|A(B^+ \to \pi^+\pi^0)| \ ,$$

- $R_{T+C} \sim f_K/f_\pi = 1.2 \pm 0.2$
- Minimal hadronic input

New Physcis in Electroweak Penguins

Nir, Quin [1991]; Gronau, Hernandez, London, Rosner [1995]

Fleischer, Jaeger, Pirjol, Zupan [2008]; Fleischer, Jaarsma, KKV [2018]



Hints towards New Physics in the EWP sector?

- Limited by neutral π modes...
- Change in $B_d^0 \to K^0\pi^0$ branching ratio
- Also $B_s \to \pi^+\pi^-$ and $B_d \to K^+K^-$ interesting!

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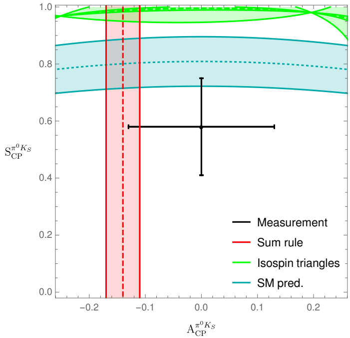

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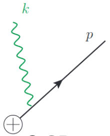
QED effects

Eikonal approximation:

- Only works for point-like coupling

$$\epsilon_\mu(k)\bar{u}(p)\gamma^\mu \frac{\not{p}+\not{k}+m}{(k+p)^2-m^2} \to \epsilon_\mu(k)\frac{p^\mu}{p\cdot k}\bar{u}(p)$$



- Ultra-soft corrections exponentiate and dress the pure-QCD amplitude

$$\sum_{X_s} |\langle X_s|(\bar{S}_v^{(Q_B)} S_{v_1}^{\dagger(Q_{M_1})} S_{v_2}^{\dagger(Q_{M_2})})|0\rangle|^2 \sim \left(\frac{\Delta E}{\Lambda}\right)^{A(\alpha\to\beta)}$$

- $\Lambda \ll \Lambda_{\rm QCD}$ cut-off!
- Often done: Assume pointlike approximation up to the scale m_B [Baracchini, Isidori]

  $\to$ fails to account for all large logarithms (and scales)!

  $\to$ photons with energy $\gtrsim \Lambda_{\rm QCD}$ probe the partonic structure of the mesons