Color meets Flavor Symposium

Siegen - July 15, 2026

Effective Field Theories for Color and Flavor

Philipp Böer

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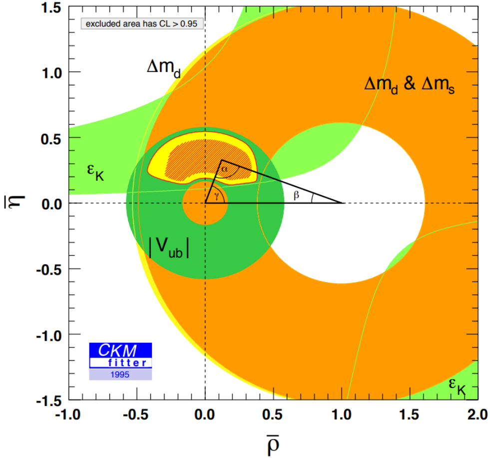
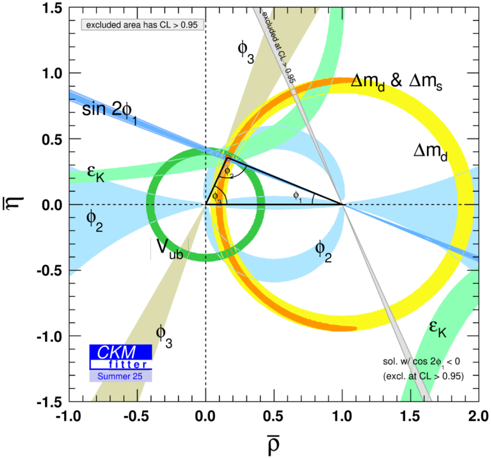
CERN

The precision era of flavor physics





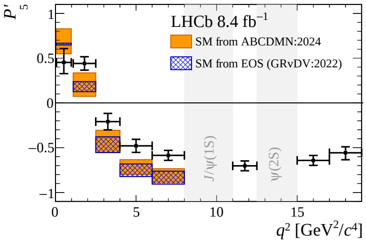
Amazing progress, but data will improve dramatically in the coming decade (HL-LHC, Belle II, . . .)

$\rightarrow$ Theory needs to catch up!

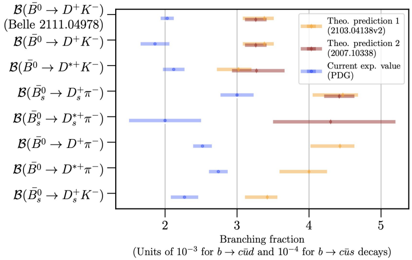
Anomalies in B-meson decays

- Precision flavour experiments test the CKM paradigm and search for new physics.
- Various tensions between theory predictions and measurements

$b \to s\ell\ell$ transitions



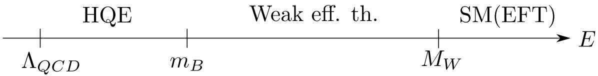
non-leptonic B decays



New physics or underestimated hadronic effects?

Effective field theories as a precision tool

Hierarchy of energy scales:



$\Lambda_{\mathrm{QCD}} \sim 0.5$ GeV $\ll m_B \sim 5$ GeV $\ll M_W \sim 80$ GeV

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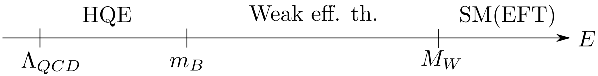

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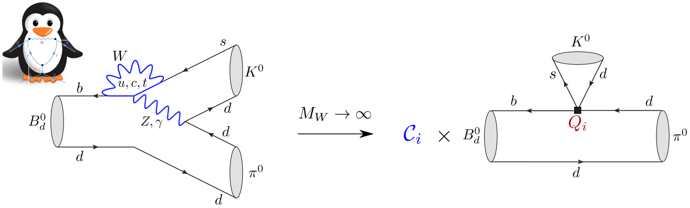
1) Effective low-energy description: $\mathcal{L}_{\text{SM}} \to \mathcal{L}_{\text{eff}} = \sum_i \mathcal{C}_i(\mu)\, Q_i(\mu)$

$\rightarrow$ Wilson coefficients $\mathcal{C}_i$ encode short-distance physics

$\rightarrow$ Main challenge is to compute hadronic matrix elements $\langle Q_i \rangle$



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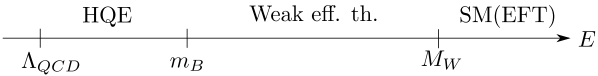
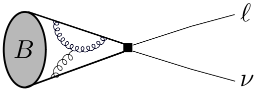
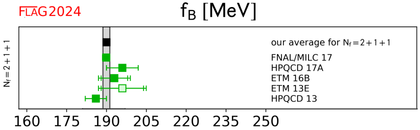


$\Lambda_{\rm QCD} \sim 0.5$ GeV $\ll m_B \sim 5$ GeV $\ll M_W \sim 80$ GeV

2) Hadronic matrix elements (leptonic decays)





decay constant $f_B = (190.0 \pm 1.3)$ MeV

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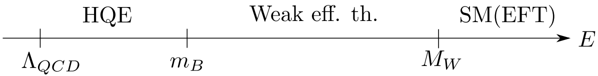

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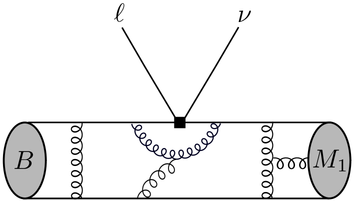
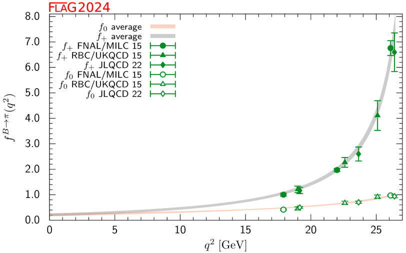
2) Hadronic matrix elements (semi-leptonic decays)



form factors $f(q^2)$



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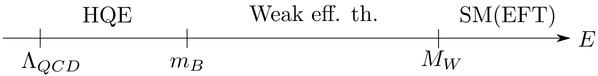

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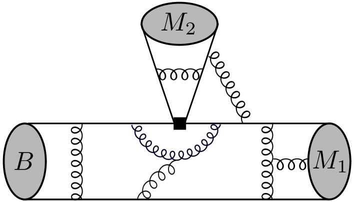
2) Hadronic matrix elements (non-leptonic decays)



complex hadronic transition

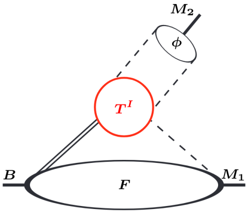
Currently not accessible on the lattice

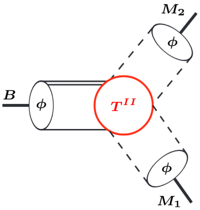
$\rightarrow$ Heavy-quark expansion based on EFTs

$\rightarrow$ Heavy-quark effective theory (HQET)

$\rightarrow$ Soft-collinear effective theory (SCET) and QCD factorization for energetic particles

QCD Factorization [BBNS 99-01]



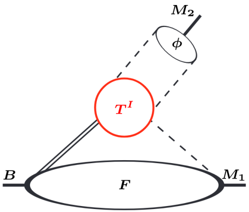


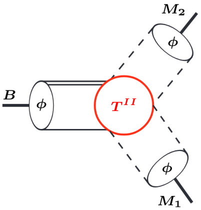
Matrix elements factorize in the heavy-quark limit $m_b \to \infty$:

$$\langle M_1 M_2 | Q_i | \bar{B} \rangle \sim F^{BM_1} \int_0^1 \mathrm{d}u \, T_i^{\mathrm{I}}(u) \, f_{M_2} \phi_{M_2}(u)$$
$$+ \int_0^\infty \mathrm{d}\omega \int_0^1 \mathrm{d}u \, \mathrm{d}v \; T_i^{\mathrm{II}}(u,v,\omega) \, f_{M_1} \phi_{M_1}(v) \, f_{M_2} \phi_{M_2}(u) \, f_B \phi_B^+(\omega) \; + \; \mathcal{O}(\Lambda/m_b, \alpha_{\mathrm{em}})$$

- perturbative hard-scattering kernels $\mathbf{T}_i^{\mathrm{I,II}}$
- non-perturbative (universal) decay constants f_i and light-cone distribution amplitudes ϕ_i

QCD Factorization [BBNS 99-01]





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- Perturbative corrections known to NNLO — e.g. [Bell, Beneke, Huber, Li]
- Decay constants and first Gegenbauer moments known from lattice — e.g. [FLAG, Braun et al.]
- parameters of $\phi_B^+(\omega)$ poorly constrained

Improving QCDF for non-leptonic B decays with EFT methods

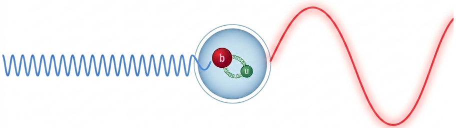
1) Electromagnetic effects [Beneke, PB, Finauri, Toelstede, Vos 20-22]
2) Constraining $\phi_B^+(\omega)$ from lattice data [Beneke, PB, Braun, Ji, Toelstede 26 (to appear)]
3) Power corrections in $\Lambda/m_b \sim 0.1$ [PB, Finauri 26 + PB, Neubert, Stillger 26 (both to appear)]

QED effects in exclusive B decays [Beneke, PB, Finauri, Toelstede, Vos 20-22]

Prime example for an EFT analysis: (Photon wavelength λ, meson radius $r \sim 1/\Lambda_{\mathrm{QCD}}$)

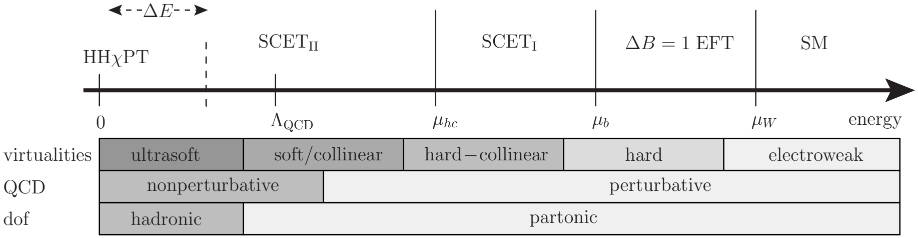
→ $\lambda \gg r$: photons couple effectively to point charge

→ $\lambda \lesssim r$: photons resolve the partonic substructure



QED effects in exclusive B decays [Beneke, PB, Finauri, Toelstede, Vos 20-22]

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



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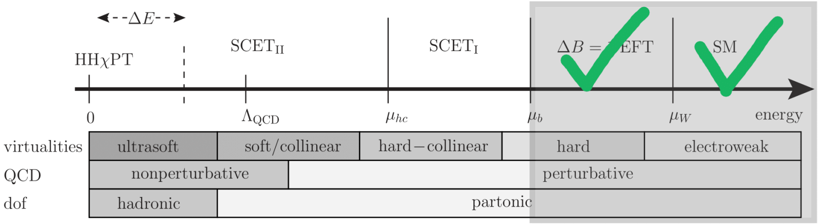

✓ short-distance QED at $\mu \gtrsim m_b \to$ Wilson coefficients of weak eff. Lagrangian

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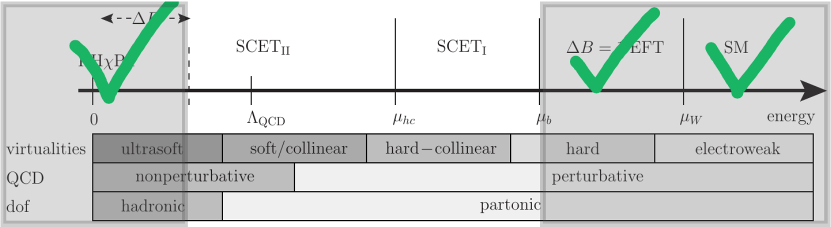

- ✓ short-distance QED at $\mu \gtrsim m_b \to$ Wilson coefficients of weak eff. Lagrangian
- ✓ Far IR (ultrasoft) region $\mu_{\rm us} \ll \Lambda_{\rm QCD}$ described by point-like hadrons ($\to$ PHOTOS)

QED effects in exclusive B decays [Beneke, PB, Finauri, Toelstede, Vos 20-22]

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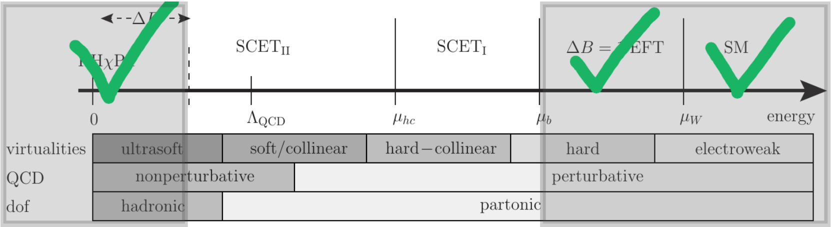


✓ We developed a theory for "structure dependent QED effects" using EFTs.

→ Theoretically interesting, with applications to (semi-)leptonic channels

→ Numerical impact small for non-leptonic decays. Cannot explain anomalies.

The B-meson light-cone distribution amplitude $\phi_B^+(\omega)$

$$\langle 0|\bar{q}(tn)[tn,0]\,\not{n}\gamma_5\,h_v(0)|\bar{B}_v\rangle = i\tilde{f}_B(\mu)\int_0^\infty d\omega\; e^{-i\omega t}\,\phi_B^+(\omega;\mu)\,, \qquad n^2 = 0$$

- Poorly constrained QCDF input. Its most important parameter is the first inverse moment:

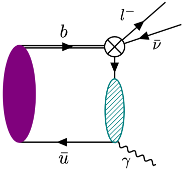
$$\lambda_B^{-1} = \int_0^\infty \frac{d\omega}{\omega}\phi_B^+(\omega) \sim 200\ \text{MeV} - 600\ \text{MeV}$$

- Use $B \to \ell\nu\gamma$ e.g. [Beneke, Rohrwild 11] or $B \to \ell\nu\ell\bar{\ell}$ data [Beneke, PB, Rigatos, Vos 21] to constrain $\phi_B(\omega)$.

Euclidean correlators as lattice probes of $\phi_B^+(\omega)$ [Beneke, PB, et al. 26 (to appear)]

We use lattice data for $P \to \gamma^*$ form factors for Euclidean $p^2 < 0$ [e.g. Giusti et al. 25] to constrain ϕ_B^+

$$\int d^4x\, e^{ip\cdot x}\, \langle 0|\, \mathcal{T}\, \{ j^\mu_{\rm em}(x)\, j^\nu_{\rm weak}(0)\}\, |\bar{B}(p+q)\rangle \sim \int_0^\infty d\omega\, \frac{\phi_+^B(\omega;\mu)}{2E_\gamma \omega - p^2} \;+\; \mathcal{O}(\alpha_s, \Lambda/m_b)\,,$$



[Fig from Galda, Neubert, Wang 22]

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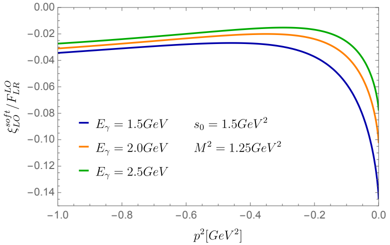
Theoretically under good control

- ✓ radiative corrections and power corrections up to twist-6 included
- ✓ soft power correction strongly suppressed for $p^2 < 0$ (sum rule estimate)



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Theoretically under good control

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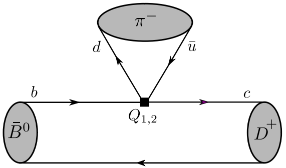
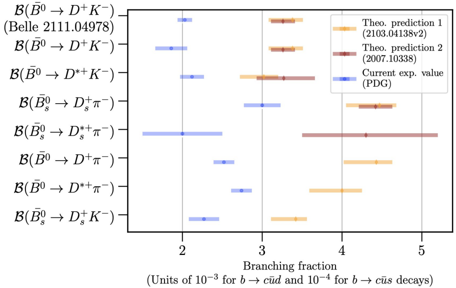
Exploratory stage, but promising new approach to constrain $\phi_B^+(\omega)$.

Power corrections in $B \to D\pi$ and $B \to DK$ [PB, Finauri 26 (to appear)]



$$\langle DL|Q_{1,2}|\bar{B}\rangle \sim F^{B\to D} \int_0^1 \mathrm{d}u\, \mathbf{T}_i^{\mathrm{I}}(u)\, f_L \phi_L(u) \; + \; \mathcal{O}(\Lambda/m_b, \alpha_{\mathrm{em}})$$

- Theoretically among the cleanest non-leptonic channels. Yet, large $\sim 4\sigma$ deviations.



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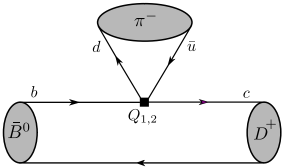

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- Theoretically among the cleanest non-leptonic channels. Yet, large $\sim 4\sigma$ deviations.
- Non-factorizable power correction from soft-gluon exchange [BBNS 00]

$$\sim \mathcal{C}_1 \times \langle D|\bar{c}(0)\gamma^\mu(1-\gamma_5)\tilde{G}_{\mu\nu}(-sn)b(0)|\bar{B}\rangle$$

- LCSR estimate yields permille effect. Cannot explain -15% amplitude deficit. [Bordone et al. 20]

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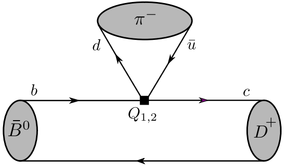

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Clear power counting rules of the EFT shows this picture is incomplete:

$\rightarrow$ Additional hadronic matrix elements contribute at the same order in Λ/m_b, e.g.

$$\sim \mathcal{C}_2 \times \langle D|(\bar{c}\gamma^\mu(1-\gamma_5)b)(0)\,\mathrm{tr}\{\mathcal{A}_\perp^\mu \mathcal{A}_{\perp,\mu}\}(-sn)|\bar{B}\rangle$$

$\rightarrow$ Naive condensate ansatz yields (preliminary)

$$\mathcal{A}_{\mathrm{NLP}}/\mathcal{A}_{\mathrm{LP}} \approx -0.5 \times \Delta \quad \text{with} \quad \Delta = \langle 0|g_s^2 \mathrm{tr}\{\mathcal{A}_\perp^\mu \mathcal{A}_{\perp,\mu}\}|0\rangle/\text{GeV}^2$$

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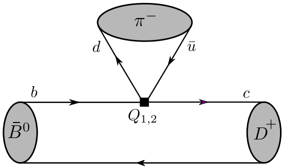

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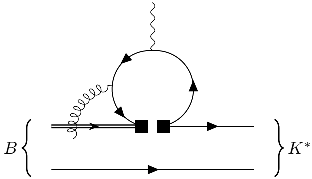
Hadronic effects provide potential explanation of the observed deficit.

Non-local charm-loop contributions in $b \to s\gamma$ and $b \to s\ell\ell$ decays

1) Resolved-photon contributions in $\bar{B} \to X_s\gamma$ [Bartocci, PB, Hurth 24 + 26 (to appear)]

2) A new approach to non-factorisable charm-loop effects in $B \to K^{(*)}\ell\ell$ decays

[Bartocci, PB, Feldmann, Ferré, Gubernari, Vladimirov 26]



Resolved-photon contributions in $\bar{B} \to X_s\gamma$ [Bartocci, PB, Hurth 24 + 26 (to appear)]

Tensions in mesonic $b \to s$ transitions motivate study of modes affected by independent uncertainties:

$\rightarrow$ Baryonic Λ_b decays [PB, Feldmann, van Dyk et al. 14-19]

$\rightarrow$ Inclusive $\bar{B} \to X_s\gamma$ and $\bar{B} \to X_s\ell\ell$ decays

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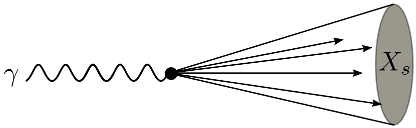

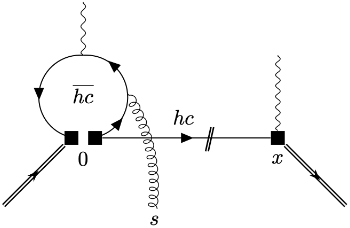

Jet-like configuration close to kinematic endpoint $m_b - 2E_\gamma \sim \mathcal{O}(\Lambda)$

$\rightarrow$ photon-energy spectrum described by SCET factorization formula.

$\rightarrow$ Q_1-$Q_{7\gamma}$ interference constitutes the largest uncertainty: $\mathcal{F}_{17} \in [2.9\%, 11.7\%]$ [Benzke, Garzelli, Hurth '25]

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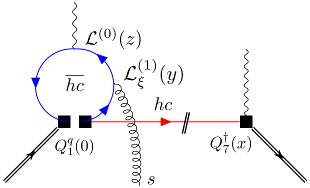
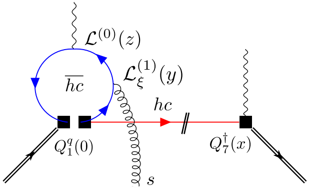
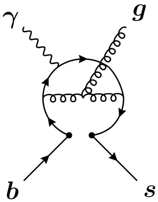


Factorization formula [Benzke, Lee, Neubert, Paz 10 + Bartocci, PB, Hurth 26]

$$d\Gamma(\bar{B} \to X_s\gamma) \sim \int_0^1 du\, \mathbf{H}(u;\mu) \int_{-\infty}^{\infty} \frac{d\omega_1}{\omega_1 + i0} \bar{J}(u,\omega_1;\mu) \int_{-\infty}^{\bar{\Lambda}} d\omega\, J(\omega;\mu)\, g_{17}(\omega,\omega_1;\mu)\,,$$

Resolved-photon contributions in $\bar{B} \to X_s\gamma$ [Bartocci, PB, Hurth 24 + 26 (to appear)]





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- ✓ Hard matching contributions $\mathbf{H}(u;\mu)$ at NLO
- ✓ Quark jet function $J(\omega;\mu)$ at NLO
- ✓ One-loop renormalization of subleading shape function $g_{17}(\omega,\omega_1;\mu)$ [Bartocci, PB, Hurth 24]
- (✓) two-loop "charm-loop jet function" $\bar{J}(u,\omega_1;\mu)$ (finished for $m_c \to 0$ [Bartocci, PB, Hurth 26 (to appear)])

A new approach to non-factorizable charm-loop effects [Bartocci, PB, et al. 26]

Use similar approach to describe non-factorisable soft-gluon effects in exclusive rare decays. [Qin et al. 22]

→ B-meson Di-light-cone distribution amplitudes (DLCDAs)

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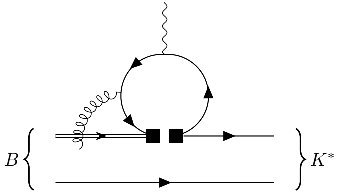

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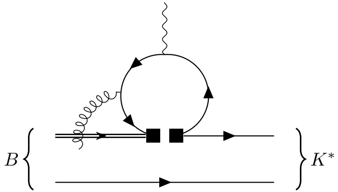

We initiated a systematic study of DLCDAs:

- ✓ eight three-particle DLCDAs: 1 at twist-3; 3 at twist-4 and twist-5; 1 at twist-6
- ✓ tree-level relations for normalisation and first moments from eom's
- ✓ simple momentum-space models for all DLCDAs
- ✓ radiative tail at $\mathcal{O}(\alpha_s)$ for the leading-twist distribution

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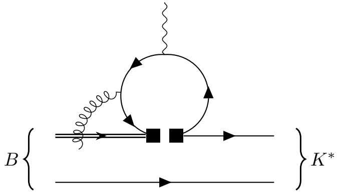

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Application to rare $B \to K^{(*)}\ell\ell$ decays could shed new light on anomalies!

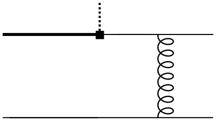
[w.i.p. with Bartocci, PB, Feldmann, Ferré, Gubernari, Vladimirov]

From flavor physics to high-energy physics

1) $B_c \to \eta_c$ form factors at large recoil [Bell, PB, Feldmann, Horstmann, Shtabovenko 22-26]
2) Resummation of double-logarithms in Di-Higgs production [PB 26 (to appear)]
3) Multi-leg amplitudes with massive quarks [PB, Jaskiewicz, Monni (in progress)]

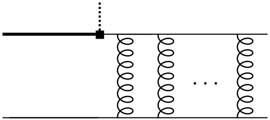
Heavy-to-light form factors for NR bound states [Bell, PB et al. 22-26]

Hard-scattering picture well understood



$$\int_0^1 \frac{dx}{x}\phi_\pi(x) = \text{finite}$$

Soft form factor leads to endpoint divergences



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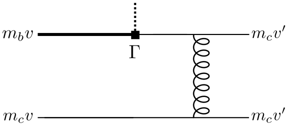

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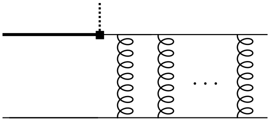

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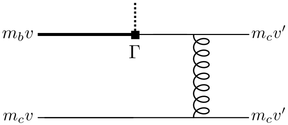

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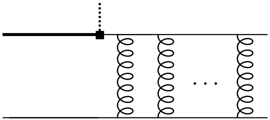

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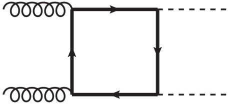
$\rightarrow$ perturbative setup with scale hierarchy $m_b \gg m_c \gg \Lambda_{\mathrm{QCD}}$

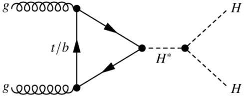
We performed an all-order resummation of the leading log-enhanced contributions from soft-quark exchange

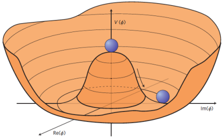
$\rightarrow$ For the first time, we have unraveled the dynamics of this mechanism.

Important step to overcome this decades-old problem of QCDF for power corrections.

Double Logarithms in Higgs-Boson Pair Production [PB 26 (to appear)]







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- To measure trilinear Higgs self-coupling need good control over QCD corrections

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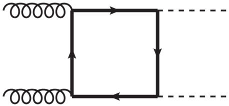

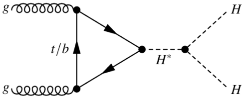

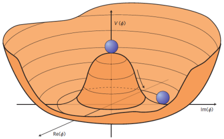

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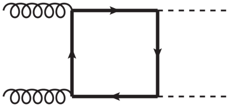

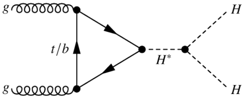

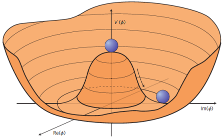

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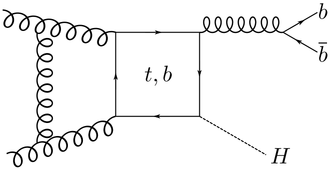
$$F_1\Big|_{\text{Box}} \simeq \rho^2 L^2 {}_2F_2\left(1,1;\frac{3}{2},2;-\frac{z}{4}\right)\left(8 - \frac{\alpha_s}{2\pi}L^2\left(C_F - \frac{C_A}{2}\right)\frac{s^2}{t(s+t)}\,{}_2F_2\left(1,1;\frac{3}{2},2;-\frac{z}{4}\right)\right)$$

$\rightarrow$ $z = \frac{\alpha_s}{2\pi}(C_F - C_A)L^2$ and $\rho = m_q^2/s$

Multi-leg amplitudes with massive quarks [PB, Monni, Jaskiewicz (in progress)]

Two-loop amplitudes with massive quarks constitute bottleneck calculations for important LHC processes.

$\rightarrow$ e.g. $pp \rightarrow (b\bar{b}H, b\bar{b}W, t\bar{t}H, HH)$



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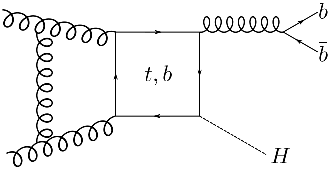


We use EFT methods to derive controlled approximations around the high-energy limit.

→ explore the universality of the subleading soft and jet functions across different channels.

→ exploit methodological synergies with $B_c \to \eta_c$ analysis

Conclusion

1) Flavor physics and HEP have entered the precision era. Great success of the Standard Model. Intriguing tensions in various B decays could show evidence for physics beyond the SM.

   $\rightarrow$ Sensitivity to new physics is determined by the accuracy of SM predictions.

   $\rightarrow$ Control over complicated QCD dynamics of utmost importance.

2) My research is centered around the use of Effective Field Theories of color as a tool for precision predictions for flavor observables within the SM.

   $\rightarrow$ Systematically improvable, and clear scaling behaviour of subleading contributions

   $\rightarrow$ Disentangle energy scales from hadronic to electroweak physics

   $\rightarrow$ Synergies between heavy flavor and Higgs physics

3) With the HL-LHC and Belle II, data will improve dramatically.

   $\rightarrow$ Fruitful future ahead, but theory has to catch up.

Thank you!

Backup-Slides

Numerical Estimates of QED effects for πK Final States

Universal contributions:

$\rightarrow$ from ultra-soft radiation and universal part of virtual corrections

$\rightarrow$ resums large soft $\sim \ln \Delta E/m_B$ and collinear $\sim \ln m_i/m_B$ logarithms

$$U(M_1 M_2) = \left(\frac{2\Delta E}{m_B}\right)^{-\frac{\alpha_{\rm em}}{\pi}\left(Q_B^2 + Q_1^2\left[1+\ln\frac{m_1^2}{m_B^2}\right] + Q_2^2\left[1+\ln\frac{m_2^2}{m_B^2}\right]\right)}$$

For $\Delta E = 60$ MeV: ($\Delta E = \pi K$ invariant mass window around m_B)

$$U(\pi^+ K^-) = 0.914 \qquad U(\pi^0 K^-) = 0.976$$

$$U(\pi^- \bar{K}^0) = 0.954 \qquad U(\bar{K}^0 \pi^0) = 1$$

Structure-dependent (virtual) corrections in non-rad. amplitude partly included

✓ Electroweak scale to m_B: QED corrections to Wilson coefficients

✓ m_B to $\Lambda_{\rm QCD}$: $\mathcal{O}(\alpha_{\rm em})$ corrections to short-distance kernels

↯ QED effects in LCDAs/form factors, but log-enhanced effects $\sim \ln \Lambda/m_B$ under control.

Ratios and Isospin Sum Rules

1. Consider ratios where QCD uncertainties drop out:

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

[Beneke, Neubert '03]

$$R_L^{\mathrm{QCD}} - 1 \approx (1 \pm 2)\% \qquad \delta_E \approx 0.1\% \qquad \delta_U \approx 5.8\%$$

$\rightarrow$ QED corrections larger than QCD and QCD uncertainty, but short-distance QED negligible

2. Isospin sumrule

$$\begin{aligned}\Delta(\pi K) &\equiv A_{\mathrm{CP}}(\pi^+ K^-) + \frac{\Gamma(\pi^- \bar{K}^0)}{\Gamma(\pi^+ K^-)} A_{\mathrm{CP}}(\pi^- \bar{K}^0) - \frac{2\Gamma(\pi^0 K^-)}{\Gamma(\pi^+ K^-)} A_{\mathrm{CP}}(\pi^0 K^-) - \frac{2\Gamma(\pi^0 \bar{K}^0)}{\Gamma(\pi^+ K^-)} A_{\mathrm{CP}}(\pi^0 \bar{K}^0) \\ &\equiv \Delta(\pi K)^{\mathrm{QCD}} + \delta\Delta(\pi K)\end{aligned}$$

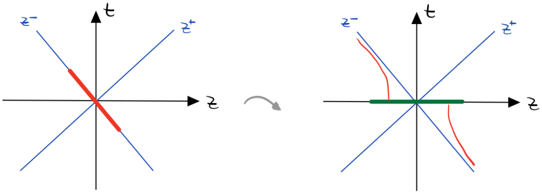
[Gronau, Rosner '06]

$$\Delta(\pi K)^{\mathrm{QCD}} = (0.5 \pm 1.1)\% \qquad \delta_\Delta(\pi K) \approx -0.4\%$$

$\rightarrow$ Isospin sumrule robust against QED effects (QED of similar size but small)

The B-meson light-cone distribution amplitude

$$\langle 0|\bar{q}(tn)[tn,0]\,\not{n}\gamma_5\, h_v(0)|\bar{B}_v\rangle = i\tilde{f}_B(\mu)\int_0^\infty d\omega\; e^{-i\omega t}\,\phi_B^+(\omega;\mu)$$



First-principles lattice determination desirable, but lattice intrinsically Euclidean (no light-cone)!

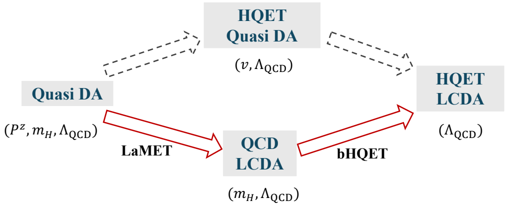
Ji's proposal [Ji '13+'14]:

→ Euclidean equal-time correlators ("Quasi-DAs" with small $z^2 < 0$) (Quasi-/Pseudo-PDFs etc.)

$$\tilde{\phi}(x,P^z) \sim \int \frac{dz}{2\pi} e^{-ixP^z z}\,\langle 0|\,\bar{q}(z)\Gamma[z,0]Q(0)\,|H(P^z)\rangle$$

→ …are related to light-like correlators in the large-momentum limit $P^z \gg m_H, \Lambda_{\rm QCD}$ via a factorization formula in large momentum effective theory ("LaMET")

Two-step matching [Han et al. '24+'25]



Scale hierarchy: $P^z \gg m_H \gg \Lambda_{\rm QCD}$

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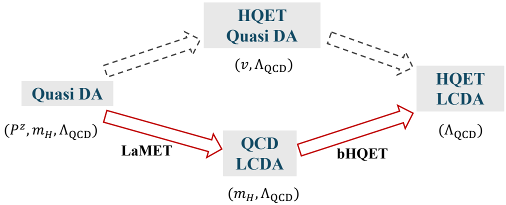

Scale hierarchy: $P^z \gg m_H \gg \Lambda_{\rm QCD}$

1.) $P^z \gg m_H$: match quasi-DA $\to$ QCD-LCDA in LaMET

$$\tilde{\phi}(x, P^z) = \int_0^1 dy\, C\left(x, y; \frac{\mu}{P^z}\right) \phi(y;\mu) + \mathcal{O}\left(\frac{m_H^2}{(P^z)^2}, \frac{\Lambda_{\rm QCD}^2}{(xP^z, \bar{x}P^z)^2}\right)$$

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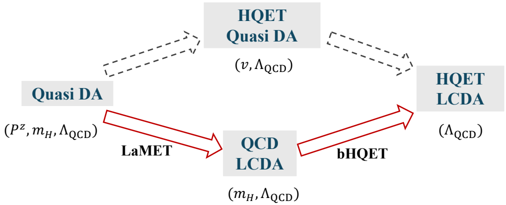

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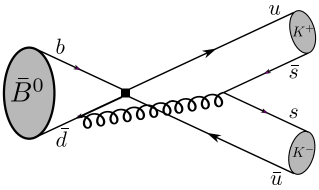
2.) $m_H \gg \Lambda_{\rm QCD}$: match QCD-LCDA $\to$ HQET-LCDA (boosted HQET) [Beneke et al. '23]

$$\phi(y;\mu;m_H) = m_H \frac{\tilde{f}_H}{f_H}\left[\mathcal{J}_{\rm peak}\,\phi_B^+(\omega;\mu) + \phi_B^+(\omega;\mu)|_{\rm tail}\right] + \mathcal{O}\left(\frac{\Lambda_{\rm QCD}}{m_H}\right) \qquad (\omega = y m_H)$$

$\to$ two perturbative matching steps: $C(x,y) = \delta(x-y) + \mathcal{O}(\alpha_s)$, $\mathcal{J}_{\rm peak} = 1 + \mathcal{O}(\alpha_s)$

Weak annihilation amplitudes [PB, Neubert, Stillger 26 (to appear)]



- Currently no EFT description due to conceptual problem of endpoint singularities
- A rigorous EFT analysis of weak annihilation amplitudes reveals

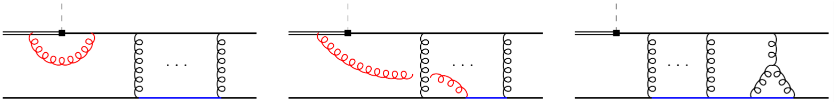
  $\rightarrow$ $\mathcal{O}(10)$ unknown hadronic matrix elements

  $$\langle K^+|[\bar{u}(0)\Gamma s(t_2 n)]\,[\bar{d}(t_1 n)\tilde{\Gamma} b(0)]|\bar{B}^0\rangle \qquad \langle 0|[\bar{q}(t_1 n)\Gamma q(u\bar{n})]\,[\bar{d}(t_2 n)\tilde{\Gamma} b(0)]|\bar{B}^0\rangle$$

  $\rightarrow$ Endpoint divergences can be absorbed into generalized form factors

  $\rightarrow$ implications for data-driven analysis [see Fang, Huber, Li, Malami, Tetlalmatzi-Xolocotzi 26]

Double logarithms in $B_c \to \eta_c$ form factors



Soft-overlap form factor can be expressed in terms of two functions $f_{1,2}$: $(\bar{u}_0 = m_2/m_\eta = 1/2)$

$$F(\gamma) = \xi_0 \exp\left\{-\frac{\alpha_s C_F}{4\pi} L^2\right\} \left(2\frac{1+\bar{u}_0}{\bar{u}_0^3} f_2(m_2,m_2) + \frac{C_A}{2C_F\bar{u}_0^3}(1 - f_1(m_2,m_2)) - \frac{1}{\bar{u}_0^2}\right)$$

which obey a novel type of implicit integral equations:

$$f_1(q_+,q_-) = 1 + \frac{\alpha_s}{4\pi}\int_{q_-}^{p_{2-}} \frac{dk_-}{k_-} \int_{m_2^2/k_-}^{q_+} \frac{dk_+}{k_+} \exp\left\{-S\left(\frac{q_+}{k_+},\frac{p_-}{k_-}\right)\right\} 2C_F f_1(k_+,k_-)$$

$$f_2(q_+,q_-) = 1 + \frac{\alpha_s}{4\pi}\int_{q_-}^{p_{2-}} \frac{dk_-}{k_-} \int_{m_2^2/k_-}^{q_+} \frac{dk_+}{k_+} \exp\left\{-S\left(\frac{q_+}{k_+},\frac{p_-}{k_-}\right)\right\} \left[2C_F f_2(k_+,k_-) - \left(C_F - \frac{C_A}{2}\right) f_1(k_+,k_-) + \frac{C_A}{2}\right]$$

$\rightarrow$ Sudakov factor $S(x,y) = \frac{\alpha_s C_F}{2\pi} \ln x \ln y$