NP in class-I B decays into heavy-light final states

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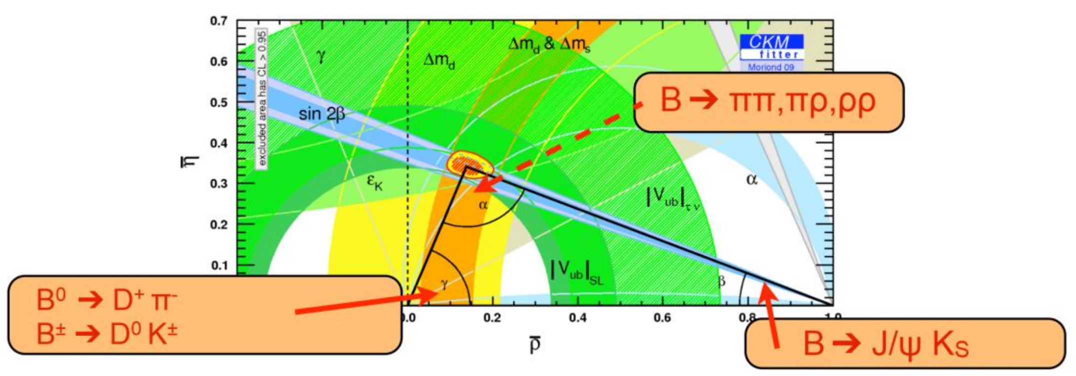
Mini-workshop on non-leptonic colour-allowed tree-level decays, Siegen, April 1, 2021

Outline

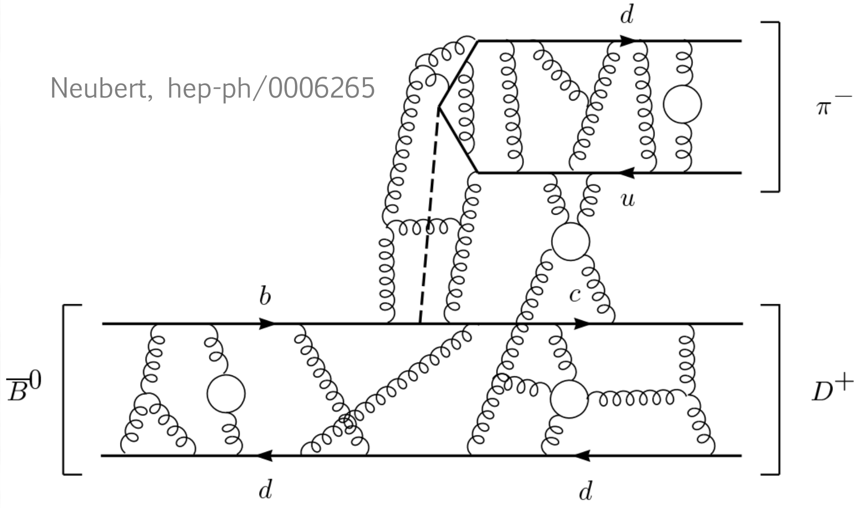
- Brief introduction
- NNLO predictions at leading power in QCDF
- Possible NP effects from four-quark operators
- Summary

Why hadronic B decays

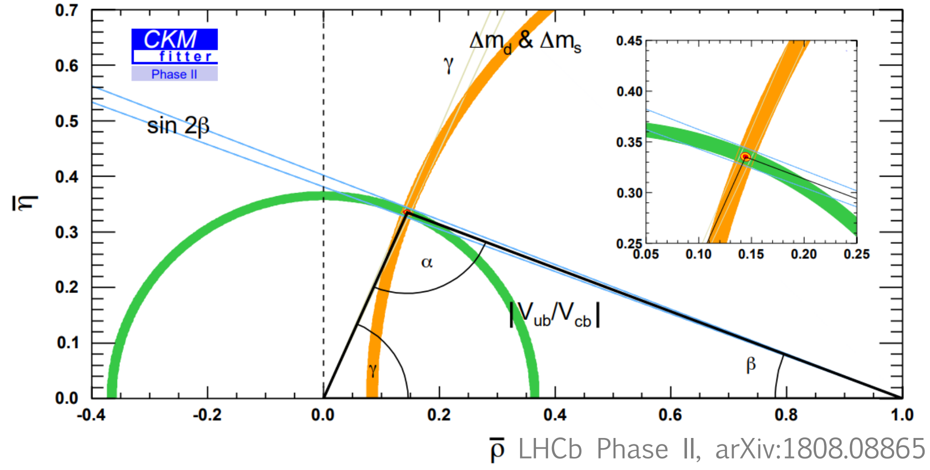
- ◻ **direct access to the CKM parameters, especially to the three angles of UT.**



- ◻ **further insight into strong-interaction effects involved in these decays.**



- ◻ **Thanks to BaBar, Belle, LHCb and Belle-II, we are now entering a *precision era!***

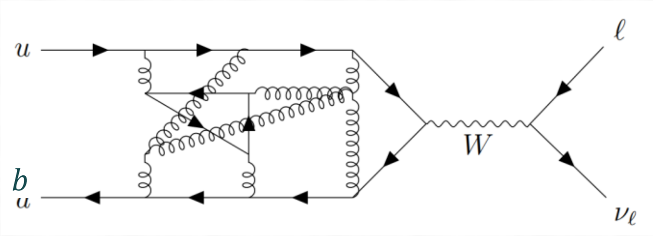


- ◻ **From the theory side, we need also keep up with the same precision.**

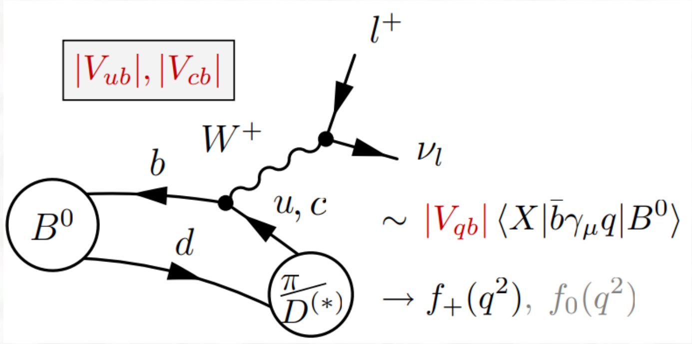
➡ ***very difficult but necessary!***

Main theoretical issues

□ Precision theory predictions challenged by complicated strong interactions!



$$\langle 0|\bar{q}_1\gamma_\mu\gamma_5 q_2|P(p)\rangle = ip_\mu f_P$$

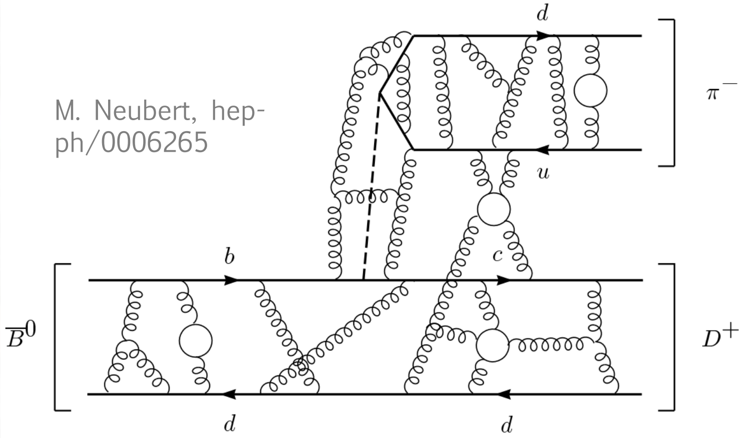


$$\langle D|\,\bar{c}\gamma^\mu b\,|\bar{B}\rangle \equiv f_+(q^2)(p_B+p_D)^\mu + [f_0(q^2)-f_+(q^2)]\,\frac{m_B^2-m_D^2}{q^2}\,q^\mu$$

$$\langle D^*|\,\bar{c}\gamma^\mu b\,|\bar{B}\rangle \equiv -ig(q^2)\,\epsilon^{\mu\nu\rho\sigma}\,\varepsilon^*_\nu\,(p_B+p_{D^*})_\rho\,q_\sigma\,,$$

$$\langle D^*|\,\bar{c}\gamma^\mu\gamma^5 b\,|\bar{B}\rangle \equiv \varepsilon^{*\mu} f(q^2) + a_+(q^2)\,\varepsilon^*\cdot p_B\,(p_B+p_{D^*})^\mu + a_-(q^2)\,\varepsilon^*\cdot p_B\,q^\mu$$

M. Neubert, hep-ph/0006265



reduced to simpler objects by factorization:

$$\mathcal{A}(\bar{B}^0\to D^+\pi^-) = i\,\frac{G_F}{\sqrt{2}}V_{cb}V^*_{uq}\,a_1(D^+\pi^-)\,f_\pi\,F_0^{B\to D}(m_\pi^2)$$

- develop strategies where hadronic uncertainties largely cancelled.

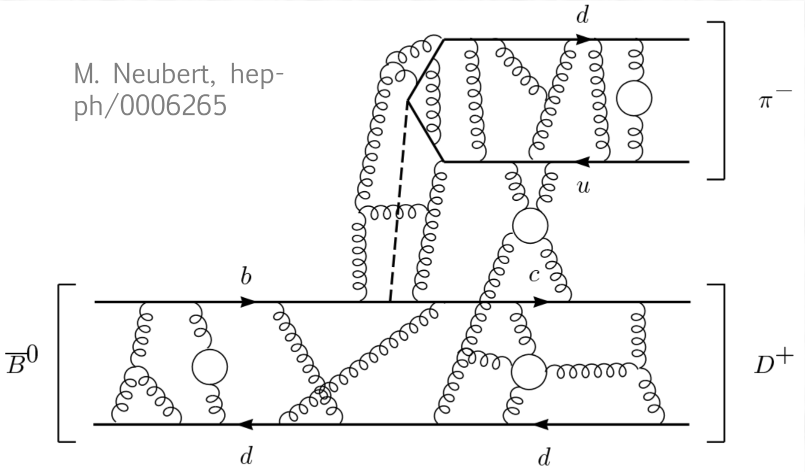
$$R(D^{(*)}) = \frac{Br(B\to D^{(*)}\tau\nu_\tau)}{Br(B\to D^{(*)}\ell\nu_\ell)}$$

$$R(K^{(*)}) = \frac{Br(B\to K^{(*)}\mu^+\mu^-)}{Br(B\to K^{(*)}e^+e^-)}$$

- need further progress from non-pert. methods like LQCD & LCSR.
- work out sub-leading corrections in α_s and $1/m_b$ in QCD or EFTs.
- need collaboration all together!

Effective Hamiltonian for B decays

☐ Hadronic decays: the most difficult!



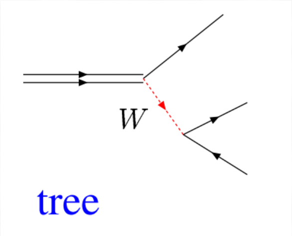
multi-scale problem with highly hierarchical scales!

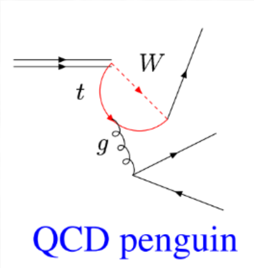
EW interaction scale	$\gg$	ext. mom'a in B rest frame	$\gg$	QCD-bound state effects
$m_W \sim 80$ GeV $m_Z \sim 91$ GeV	$\gg$	$m_b \sim 5$ GeV	$\gg$	$\Lambda_{\rm QCD} \sim 1$ GeV

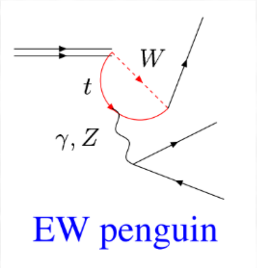
☐ **The starting point $\mathcal{H}_{\rm eff} = -\mathcal{L}_{\rm eff}$:** obtained after integrating out the heavy d.o.f. ($m_{W,Z,t} \gg m_b$);

[Buras, Buchalla, Lautenbacher '96; Chetyrkin, Misiak, Munz '98]

$$\mathcal{L}_{\rm eff} = -\frac{G_F}{\sqrt{2}} \sum_{p=u,c} V_{pb} V_{pD}^* \Big(C_1 \mathcal{O}_1 + C_2 \mathcal{O}_2 + \sum_{i={\rm pen}} C_i \mathcal{O}_{i,{\rm pen}} \Big)$$







☐ **Wilson coefficients C_i:** all physics above m_b; perturbatively calculable, and NNLL program now complete; [Gorbahn,Haisch '04]

Hadronic matrix elements

- **Decay amplitude for a given decay mode:**

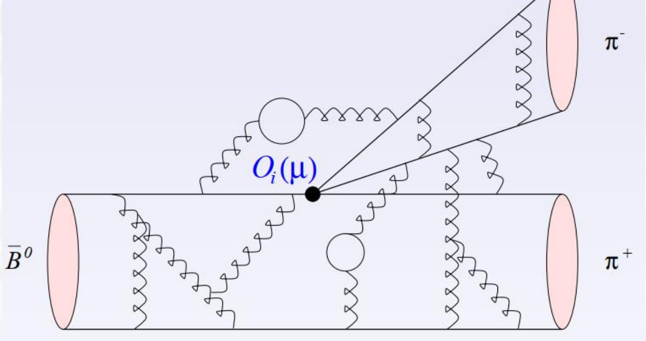
$$\mathcal{A}(\bar{B} \to f) = \sum_i \left[\lambda_{\rm CKM} \times C \times \langle f|\mathcal{O}|\bar{B}\rangle_{\rm QCD+QED} \right]_i$$

- $\langle M_1 M_2|\mathcal{O}_i|\bar{B}\rangle$: depend on spin and parity of $M_{1,2}$; final-state re-scattering introduces strong phases, and hence direct CPV; ⟶ *A quite difficult, multi-scale, strong-interaction problem!*

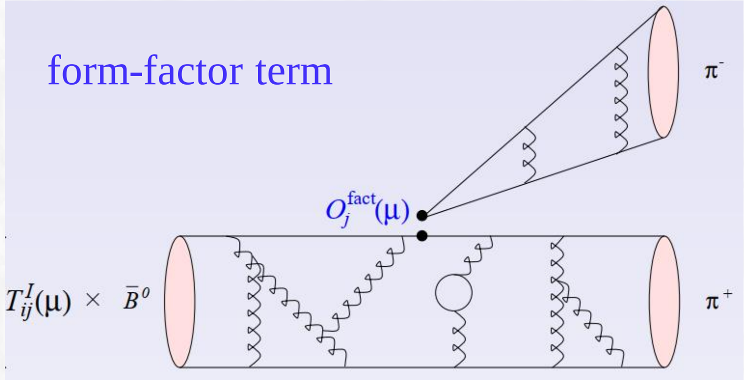
- **Different methods:**

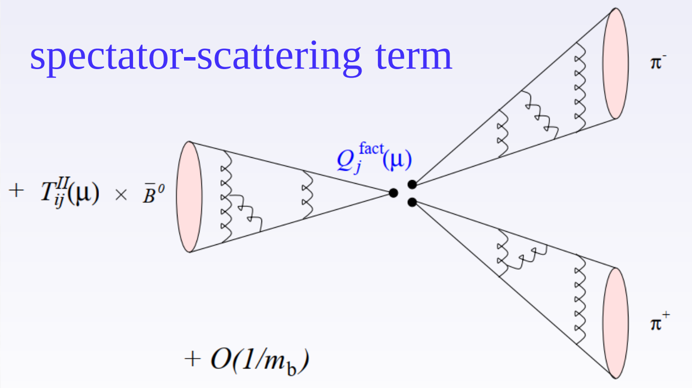
  - Dynamical approaches based on factorization theorems: PQCD, QCDF, SCET, ⋯ [Keum, Li, Sanda, Lü, Yang '00; Beneke, Buchalla, Neubert, Sachrajda, '00; Bauer, Flemming, Pirjol, Stewart, '01; Beneke, Chapovsky, Diehl, Feldmann, '02]
  - Symmetries of QCD: Isospin, U-Spin, V-Spin, and flavour SU(3) symmetries, ⋯ [Zeppenfeld, '81; London, Gronau, Rosner, He, Chiang, Cheng *et al.*]

- **QCDF:** systematic framework to all orders in α_s, but precision limited by $1/m_b$ corrections. [BBNS '99-'03]



⟶





QCD factorization

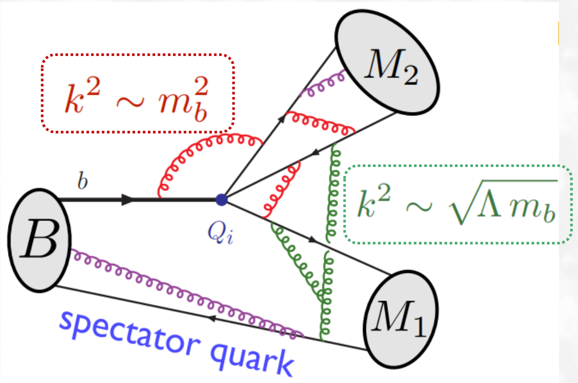
□ QCDF formulae for a two-body decay:

$$\langle M_1 M_2|Q_i|\bar{B}\rangle = F^{BM_1}(0)\int_0^1 du\, T_i^I(u)\Phi_{M_2}(u) \quad \text{form-factor term}$$

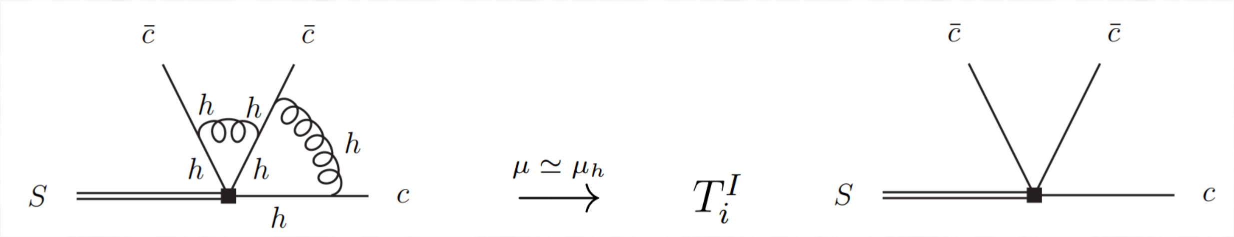
$$+\int_0^\infty d\omega \int_0^1 dudv\, T_i^{II}(\omega,u,v)\, \Phi_B(\omega)\Phi_{M_1}(v)\Phi_{M_2}(u) \quad \text{spectator-scattering term}$$

□ **SCET point of view:** SCET diagrams reproduce precisely QCD diagrams in collinear and soft momentum region; [Beneke 1501.07374]

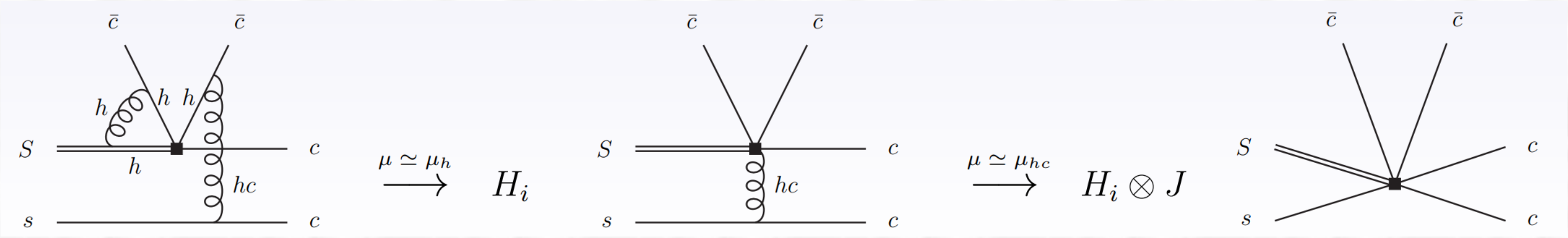
→ **QCD - SCET = $T^{I,II}$**



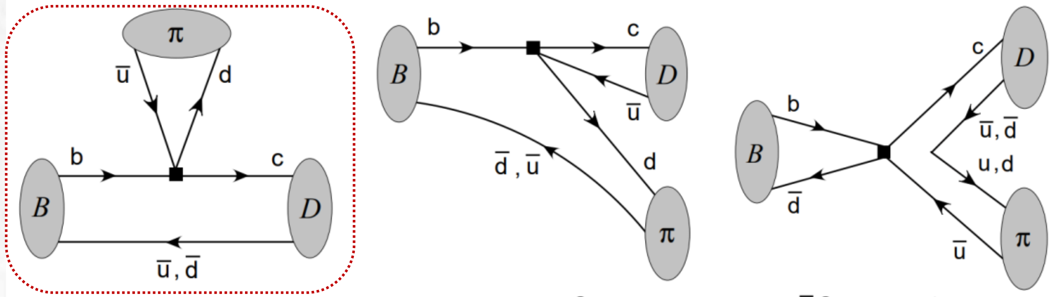
□ **For hard kernel T^I:** one-step matching, QCD → $\mathrm{SCET_I}(\mathrm{hc, c, s})$!



□ **For hard kernel T^{II}:** two-step matching, QCD → $\mathrm{SCET_I}(\mathrm{hc, c, s})$ → $\mathrm{SCET_{II}}(\mathrm{c, s})$!



Class-I $B \to D^{(*)} L$ decays



$\bar{B}^0 \to D^+\pi^-$ $B^- \to D^0\pi^-$ | $B^- \to D^0\pi^-$ $\bar{B}^0 \to D^0\pi^0$ | $\bar{B}^0 \to D^+\pi^-$ $\bar{B}^0 \to D^0\pi^0$

- **For B decays into heavy-light final states:**

  all four flavors different from each other, no penguin operators & no penguin topologies!

$$\mathcal{Q}_2 = \bar{d}\gamma_\mu(1-\gamma_5)u \;\; \bar{c}\gamma^\mu(1-\gamma_5)b$$
$$\mathcal{Q}_1 = \bar{d}\gamma_\mu(1-\gamma_5)T^A u \;\; \bar{c}\gamma^\mu(1-\gamma_5)T^A b$$

- **For class-I decays:** QCDF formulae much simpler;

  [Beneke, Buchalla, Neubert, Sachrajda '99-'03; Bauer, Pirjol, Stewart '01]

$$\langle D_q^{(*)+} L^- |\, \mathcal{Q}_i \,| \bar{B}_q^0 \rangle = \sum_j F_j^{\bar{B}_q \to D_q^{(*)}}(M_L^2) \times \int_0^1 du\, T_{ij}(u)\phi_L(u) + \mathcal{O}\left(\frac{\Lambda_{\rm QCD}}{m_b}\right)$$

i) only color-allowed tree topology a_1;

ii) spectator & annihilation power-suppressed;

iii) annihilation even absent in $B_s^0 \to D_s^- \pi^+$ etal;

iv) they are theoretically much cleaner!

- **Hard kernel T:** both NLO and NNLO results known;

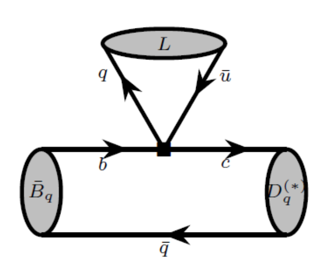
  [Beneke, Buchalla, Neubert, Sachrajda '01; Huber, Kränkl, XQL '16]

$$T = T^{(0)} + \alpha_s T^{(1)} + \alpha_s^2 T^{(2)} + O(\alpha_s^3)$$

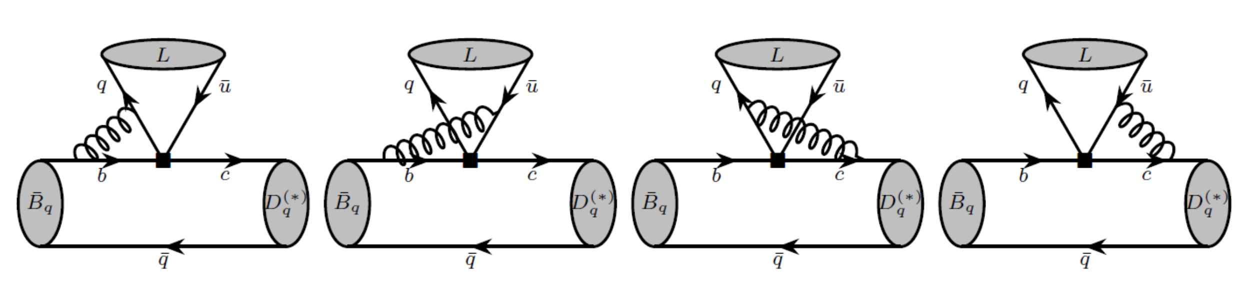
Calculation of T:

$$T = T^{(0)} + \alpha_s T^{(1)} + \alpha_s^2 T^{(2)} + O(\alpha_s^3)$$

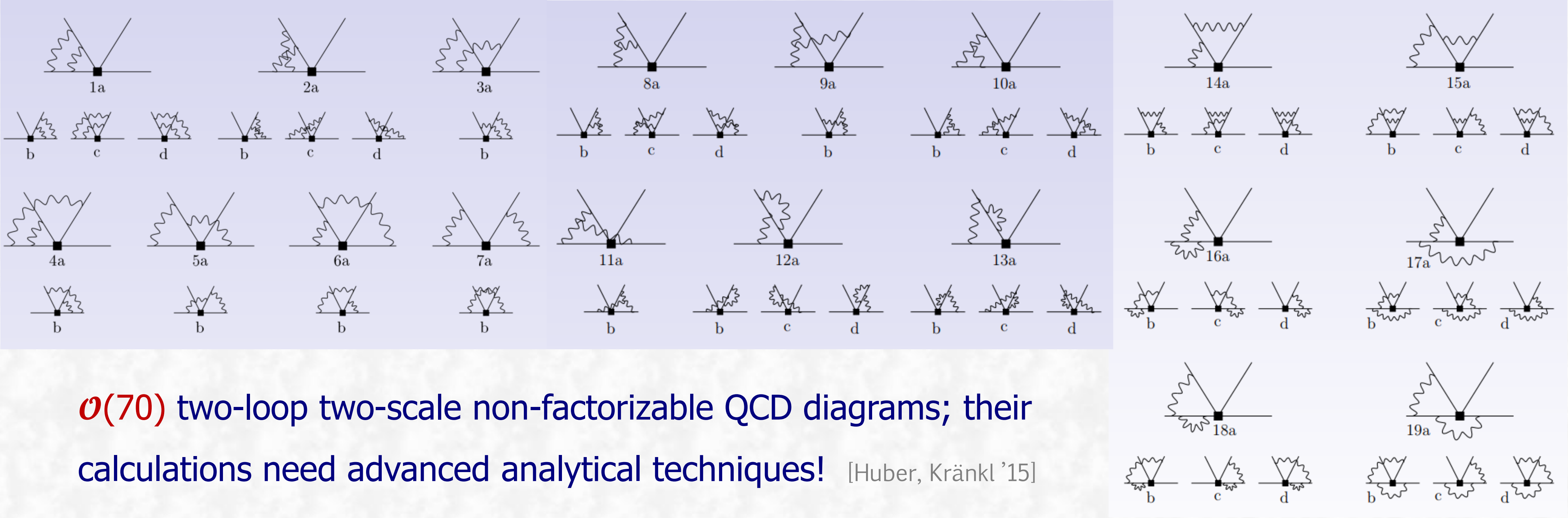
- **LO:**



- **NLO:** [Beneke, Buchalla, Neubert, Sachrajda '01]



- **NNLO:** [Huber, Kränkl, XQL '16]



$\mathcal{O}(70)$ two-loop two-scale non-factorizable QCD diagrams; their calculations need advanced analytical techniques! [Huber, Kränkl '15]

Calculation of T:

- **Matching QCD onto SCET:** [Huber, Kränkl, XQL '16]

  m_c is also heavy, keep m_c/m_b fixed as $m_b \to \infty$, thus needing two sets of SCET operator basis.

$$\langle \mathcal{Q}_i \rangle = \hat{T}_i \langle \mathcal{Q}^{\rm QCD} \rangle + \hat{T}_i' \langle \mathcal{Q}'^{\rm QCD} \rangle + \sum_{a>1} \left[H_{ia} \langle \mathcal{O}_a \rangle + H_{ia}' \langle \mathcal{O}_a' \rangle \right]$$

$$\begin{aligned}
\mathcal{O}_1 &= \bar{\chi} \frac{\not{n}_-}{2} (1-\gamma_5) \chi \;\; \bar{h}_{v'} \not{n}_+ (1-\gamma_5) h_v \,, \\
\mathcal{O}_2 &= \bar{\chi} \frac{\not{n}_-}{2} (1-\gamma_5) \gamma_\perp^\alpha \gamma_\perp^\beta \chi \;\; \bar{h}_{v'} \not{n}_+ (1-\gamma_5) \gamma_{\perp,\beta} \gamma_{\perp,\alpha} h_v \,, \\
\mathcal{O}_3 &= \bar{\chi} \frac{\not{n}_-}{2} (1-\gamma_5) \gamma_\perp^\alpha \gamma_\perp^\beta \gamma_\perp^\gamma \gamma_\perp^\delta \chi \;\; \bar{h}_{v'} \not{n}_+ (1-\gamma_5) \gamma_{\perp,\delta} \gamma_{\perp,\gamma} \gamma_{\perp,\beta} \gamma_{\perp,\alpha} h_v \\
\mathcal{O}_1' &= \bar{\chi} \frac{\not{n}_-}{2} (1-\gamma_5) \chi \;\; \bar{h}_{v'} \not{n}_+ (1+\gamma_5) h_v \,, \\
\mathcal{O}_2' &= \bar{\chi} \frac{\not{n}_-}{2} (1-\gamma_5) \gamma_\perp^\alpha \gamma_\perp^\beta \chi \;\; \bar{h}_{v'} \not{n}_+ (1+\gamma_5) \gamma_{\perp,\alpha} \gamma_{\perp,\beta} h_v \,, \\
\mathcal{O}_3' &= \bar{\chi} \frac{\not{n}_-}{2} (1-\gamma_5) \gamma_\perp^\alpha \gamma_\perp^\beta \gamma_\perp^\gamma \gamma_\perp^\delta \chi \;\; \bar{h}_{v'} \not{n}_+ (1+\gamma_5) \gamma_{\perp,\alpha} \gamma_{\perp,\beta} \gamma_{\perp,\gamma} \gamma_{\perp,\delta} h_v
\end{aligned}$$

- **Renormalized on-shell QCD amplitudes:**

$$\begin{aligned}
\langle \mathcal{Q}_i \rangle = \Big\{ & A_{ia}^{(0)} + \frac{\alpha_s}{4\pi} \left[A_{ia}^{(1)} + Z_{ext}^{(1)} A_{ia}^{(0)} + Z_{ij}^{(1)} A_{ja}^{(0)} \right] \\
& + \left(\frac{\alpha_s}{4\pi} \right)^2 \Big[A_{ia}^{(2)} + Z_{ij}^{(1)} A_{ja}^{(1)} + Z_{ij}^{(2)} A_{ja}^{(0)} + Z_{ext}^{(1)} A_{ia}^{(1)} + Z_{ext}^{(2)} A_{ia}^{(0)} + Z_{ext}^{(1)} Z_{ij}^{(1)} A_{ja}^{(0)} \\
& + (-i)\delta m_b^{(1)} A_{ia}^{*(1)} + (-i)\delta m_c^{(1)} A_{ia}^{**(1)} + Z_\alpha^{(1)} A_{ia}^{(1)} \Big] + \mathcal{O}(\alpha_s^3) \Big\} \langle \mathcal{O}_a \rangle^{(0)} \\
& + (A \leftrightarrow A') \langle \mathcal{O}_a' \rangle^{(0)} \,.
\end{aligned}$$

on QCD side

- **Renormalized on-shell SCET amplitudes:**

$$\begin{aligned}
\langle \mathcal{O}_a \rangle = \Big\{ & \delta_{ab} + \frac{\hat{\alpha}_s}{4\pi} \left[M_{ab}^{(1)} + Y_{ext}^{(1)} \delta_{ab} + Y_{ab}^{(1)} \right] \\
& + \left(\frac{\hat{\alpha}_s}{4\pi} \right)^2 \Big[M_{ab}^{(2)} + Y_{ext}^{(1)} M_{ab}^{(1)} + Y_{ac}^{(1)} M_{cb}^{(1)} + \hat{Z}_\alpha^{(1)} M_{ab}^{(1)} + Y_{ext}^{(2)} \delta_{ab} \\
& + Y_{ext}^{(1)} Y_{ab}^{(1)} + Y_{ab}^{(2)} \Big] + \mathcal{O}(\hat{\alpha}_s^3) \Big\} \langle \mathcal{O}_b \rangle^{(0)} \,,
\end{aligned}$$

on SCET side

- **Master formulas for hard kernels:**

$$T = T^{(0)} + \alpha_s T^{(1)} + \alpha_s^2 T^{(2)} + O(\alpha_s^3)$$

$$\begin{aligned}
\hat{T}_i^{(0)} &= A_{i1}^{(0)} \\
\hat{T}_i^{(1)} &= A_{i1}^{(1)nf} + Z_{ij}^{(1)} A_{j1}^{(0)} \\
\hat{T}_i^{(2)} &= A_{i1}^{(2)nf} + Z_{ij}^{(1)} A_{j1}^{(1)} + Z_{ij}^{(2)} A_{j1}^{(0)} + Z_\alpha^{(1)} A_{i1}^{(1)nf} - \hat{T}_i^{(1)} \left[C_{FF}^{\rm D(1)} + Y_{11}^{(1)} - Z_{\rm ext}^{(1)} \right] \\
& \quad - C_{FF}^{\rm ND(1)} \hat{T}_i'^{(1)} + (-i)\delta m_b^{(1)} A_{i1}^{*(1)nf} + (-i)\delta m_c^{(1)} A_{i1}^{**(1)nf} - \sum_{b\neq 1} H_{ib}^{(1)} Y_{b1}^{(1)} \,.
\end{aligned}$$

Decay amplitudes for $B_q^0 \to D_q^- L^+$

- **Decay amplitude at leading power in $1/m_b$:**

$$\mathcal{A}(\bar{B}^0_{(s)} \to D^+_{(s)} P^-) = i\,\frac{G_F}{\sqrt{2}} V_{cb} V^*_{uq}\, a_1(D^+_{(s)} P^-)\, f_P\, F_0^{B_{(s)}\to D_{(s)}}(m_P^2)\,(m^2_{B_{(s)}} - m^2_{D^+_{(s)}})\,,$$

$$\mathcal{A}(\bar{B}^0_{(s)} \to D^{*+}_{(s)} P^-) = -i\,\frac{G_F}{\sqrt{2}} V_{cb} V^*_{uq}\, a_1(D^{*+}_{(s)} P^-)\, f_P\, A_0^{B_{(s)}\to D^*_{(s)}}(m_P^2)\, 2m_{D^{*+}_{(s)}}\,(\epsilon^* \cdot p)\,,$$

$$\mathcal{A}(\bar{B}^0_{(s)} \to D^+_{(s)} V^-) = -i\,\frac{G_F}{\sqrt{2}} V_{cb} V^*_{uq}\, a_1(D^+_{(s)} V^-)\, f_V\, F_+^{B_{(s)}\to D_{(s)}}(m_V^2)\, 2m_V\,(\eta^* \cdot p)\,,$$

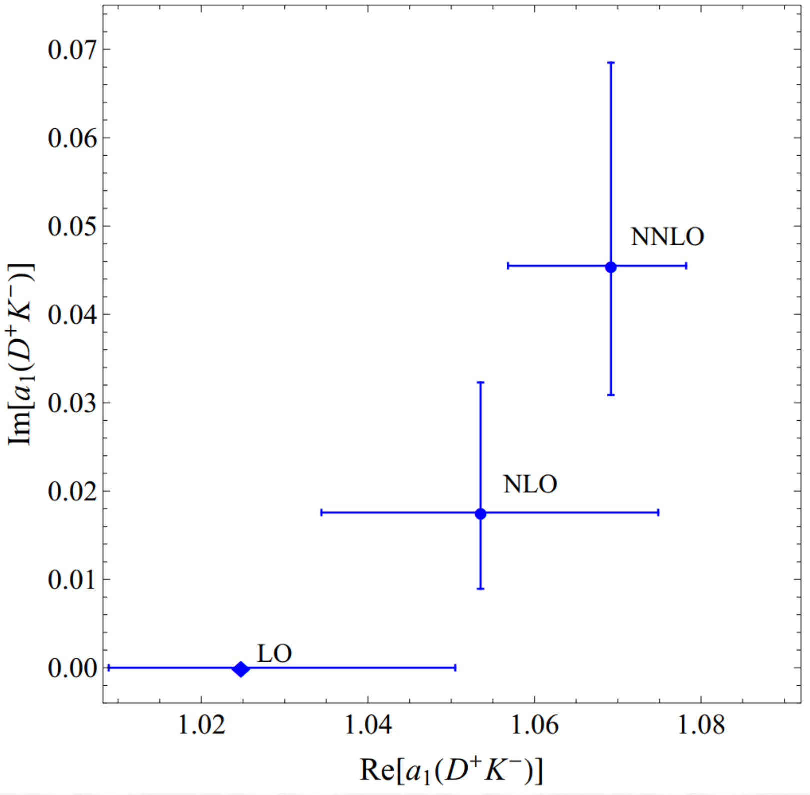
$$a_1(D^+L^-) = \sum_{i=1}^{2} C_i(\mu) \int_0^1 du \left[\hat{T}_i(u,\mu) + \hat{T}_i'(u,\mu)\right] \Phi_L(u,\mu)\,,$$

$$a_1(D^{*+}L^-) = \sum_{i=1}^{2} C_i(\mu) \int_0^1 du \left[\hat{T}_i(u,\mu) - \hat{T}_i'(u,\mu)\right] \Phi_L(u,\mu)\,,$$

- **Numerical result:**

$$\begin{aligned} a_1(D^+K^-) &= 1.025 + [0.029 + 0.018i]_{\rm NLO} + [0.016 + 0.028i]_{\rm NNLO} \\ &= (1.069^{+0.009}_{-0.012}) + (0.046^{+0.023}_{-0.015})i\,, \end{aligned}$$

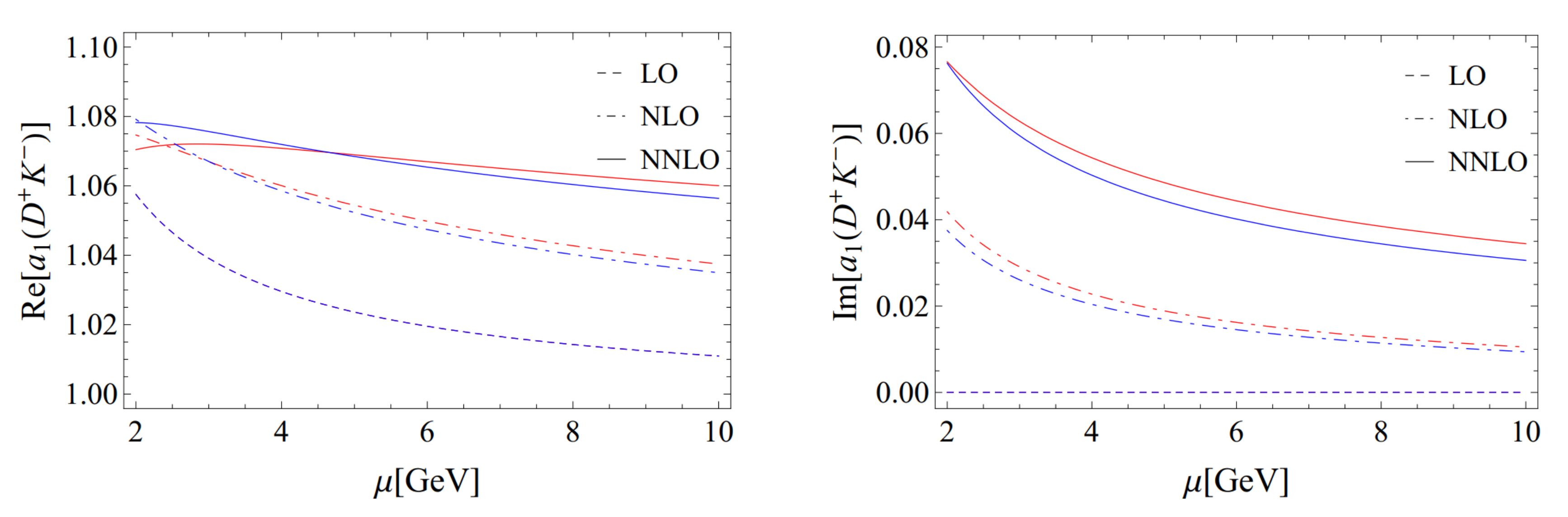
- both NLO and NNLO add always constructively to LO result!
- NNLO corrections quite small in the real (2%), but rather large in the imaginary part (60%).
- within QCDF, imaginary part appears firstly at NLO term and is color-suppressed and ∝ small $C_1 = -0.29$ vs $C_2 = 1.01$.



Scale dependence of a_1

$$a_1 = \sum_i C_i(\mu) \int_0^1 du \left[T_i(u,\mu) + T_i'(u,\mu)\right] \Phi_\pi(u,\mu)$$

- Due to perturbative truncation, a_1 depends on the renormalization scale.



- blue: pole scheme for m_c and m_b

- red: $\overline{\text{MS}}$ scheme for m_c and m_b

- ➢ scale dependence @ NNLO reduced for the real part, but not so obvious for the imaginary part.
- ➢ dependence on the b- and c-quark mass scheme is quite small, especially for the real part.

$$\begin{aligned}
a_1(D^+K^-) &= (1.069^{+0.009}_{-0.012}) + (0.046^{+0.023}_{-0.015})i\,,\\
a_1(D^+\pi^-) &= (1.072^{+0.011}_{-0.013}) + (0.043^{+0.022}_{-0.014})i\,,\\
a_1(D^{*+}K^-) &= (1.068^{+0.010}_{-0.012}) + (0.034^{+0.017}_{-0.011})i\,,\\
a_1(D^{*+}\pi^-) &= (1.071^{+0.012}_{-0.013}) + (0.032^{+0.016}_{-0.010})i\,.
\end{aligned}$$

- **For different decay modes:** quasi-universal, with small process-dep. from non-fact. correction.

Absolute branching ratios for $B_q^0 \to D_q^- L^+$

$B \to D^{(*)}$ transition form factors:

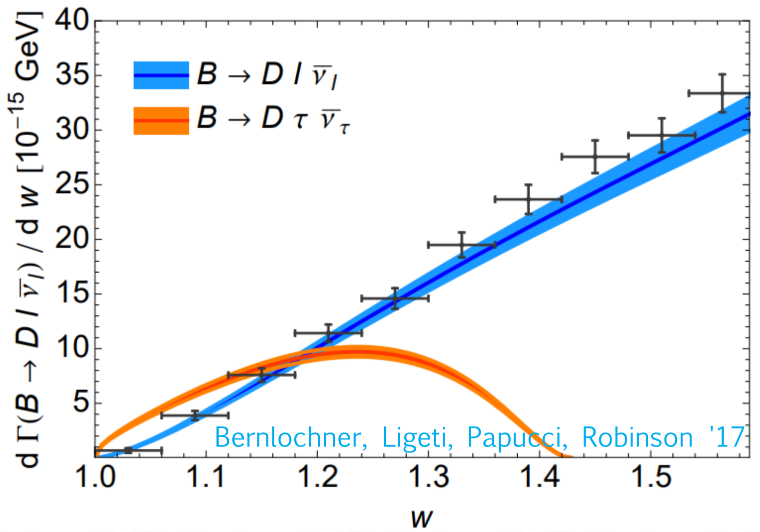
Precision results available based on LQCD & LCSR calculations, together with data on $B_q^0 \to D_q^- l^+ \nu$;

[Bernlochner, Ligeti, Papucci, Robinson '17; Bordone, Gubernari, Jung, van Dyk '19]

$$\mathcal{A}(\bar{B}^0_{(s)} \to D^+_{(s)} P^-) = i\,\frac{G_F}{\sqrt{2}} V_{cb} V^*_{uq}\, a_1(D^+_{(s)} P^-)\, f_P\, F_0^{B_{(s)}\to D_{(s)}}(m_P^2)\,(m^2_{B_{(s)}} - m^2_{D^+_{(s)}}),$$

$$\mathcal{A}(\bar{B}^0_{(s)} \to D^{*+}_{(s)} P^-) = -i\,\frac{G_F}{\sqrt{2}} V_{cb} V^*_{uq}\, a_1(D^{*+}_{(s)} P^-)\, f_P\, A_0^{B_{(s)}\to D^*_{(s)}}(m_P^2)\, 2m_{D^{*+}_{(s)}}\,(\epsilon^* \cdot p),$$

$$\mathcal{A}(\bar{B}^0_{(s)} \to D^+_{(s)} V^-) = -i\,\frac{G_F}{\sqrt{2}} V_{cb} V^*_{uq}\, a_1(D^+_{(s)} V^-)\, f_V\, F_+^{B_{(s)}\to D_{(s)}}(m_V^2)\, 2m_V\,(\eta^* \cdot p),$$



Updated predictions vs data:

[Huber, Kränkl, XQL '16; Cai, Deng, XQL, Yang '21]

$|V_{cb}|$ and $B \to D^{(*)}$ form factors

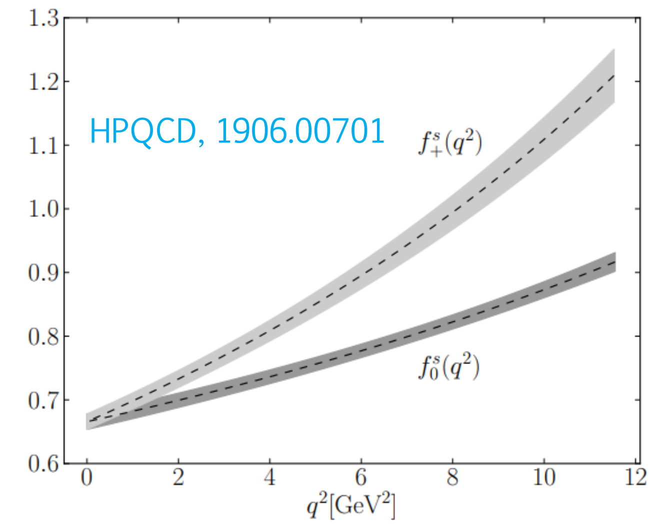
Decay mode	LO	NLO	NNLO	Ref. [36]	Exp. [7, 8]
$\bar{B}^0 \to D^+\pi^-$	4.07	$4.32^{+0.23}_{-0.42}$	$4.43^{+0.20}_{-0.41}$	$3.93^{+0.43}_{-0.42}$	2.65 ± 0.15
$\bar{B}^0 \to D^{*+}\pi^-$	3.65	$3.88^{+0.27}_{-0.41}$	$4.00^{+0.25}_{-0.41}$	$3.45^{+0.53}_{-0.50}$	2.58 ± 0.13
$\bar{B}^0 \to D^+\rho^-$	10.63	$11.28^{+0.84}_{-1.23}$	$11.59^{+0.79}_{-1.21}$	$10.42^{+1.24}_{-1.20}$	7.6 ± 1.2
$\bar{B}^0 \to D^{*+}\rho^-$	9.99	$10.61^{+1.35}_{-1.56}$	$10.93^{+1.35}_{-1.57}$	$9.24^{+0.72}_{-0.71}$	6.0 ± 0.8
$\bar{B}^0 \to D^+K^-$	3.09	$3.28^{+0.16}_{-0.31}$	$3.38^{+0.13}_{-0.30}$	$3.01^{+0.32}_{-0.31}$	2.19 ± 0.13
$\bar{B}^0 \to D^{*+}K^-$	2.75	$2.92^{+0.19}_{-0.30}$	$3.02^{+0.18}_{-0.30}$	$2.59^{+0.39}_{-0.37}$	2.04 ± 0.47
$\bar{B}^0 \to D^+K^{*-}$	5.33	$5.65^{+0.47}_{-0.64}$	$5.78^{+0.44}_{-0.63}$	$5.25^{+0.65}_{-0.63}$	4.6 ± 0.8
$\bar{B}^0_s \to D^+_s\pi^-$	4.10	$4.35^{+0.24}_{-0.43}$	$4.47^{+0.21}_{-0.42}$	$4.39^{+1.36}_{-1.19}$	3.03 ± 0.25
$\bar{B}^0_s \to D^+_s K^-$	3.12	$3.32^{+0.17}_{-0.32}$	$3.42^{+0.14}_{-0.31}$	$3.34^{+1.04}_{-0.90}$	1.92 ± 0.22

Non-leptonic/semi-leptonic ratios

☐ Non-leptonic/semi-leptonic ratios : [Bjorken '89; Neubert, Stech '97; Beneke, Buchalla, Neubert, Sachrajda '01]

$$R_{(s)L}^{(*)} \equiv \frac{\Gamma(\bar{B}_{(s)}^0 \to D_{(s)}^{(*)+} L^-)}{d\Gamma(\bar{B}_{(s)}^0 \to D_{(s)}^{(*)+} \ell^- \bar{\nu}_\ell)/dq^2 \,|_{q^2=m_L^2}} = 6\pi^2 \, |V_{uq}|^2 \, f_L^2 \, |a_1(D_{(s)}^{(*)+} L^-)|^2 \, X_L^{(*)}$$

free from uncertainties from $|V_{cb}|$ & $B \to D^{(*)}$ form factors.



☐ Updated predictions vs data: [Huber, Kränkl, XQL '16; Cai, Deng, XQL, Yang '21]

$R_{(s)L}^{(*)}$	LO	NLO	NNLO	Exp.	Deviation (σ)
R_π	1.01	$1.07^{+0.04}_{-0.04}$	$1.10^{+0.03}_{-0.03}$	0.74 ± 0.06	5.4
R_π^*	1.00	$1.06^{+0.04}_{-0.04}$	$1.10^{+0.03}_{-0.03}$	0.80 ± 0.06	4.5
R_ρ	2.77	$2.94^{+0.19}_{-0.19}$	$3.02^{+0.17}_{-0.18}$	2.23 ± 0.37	1.9
R_K	0.78	$0.83^{+0.03}_{-0.03}$	$0.85^{+0.01}_{-0.02}$	0.62 ± 0.05	4.4
R_K^*	0.72	$0.76^{+0.03}_{-0.03}$	$0.79^{+0.01}_{-0.02}$	0.60 ± 0.14	1.3
R_{K^*}	1.41	$1.50^{+0.11}_{-0.11}$	$1.53^{+0.10}_{-0.10}$	1.38 ± 0.25	0.6
$R_{s\pi}$	1.01	$1.07^{+0.04}_{-0.04}$	$1.10^{+0.03}_{-0.03}$	0.72 ± 0.08	4.4
R_{sK}	0.78	$0.83^{+0.03}_{-0.03}$	$0.85^{+0.01}_{-0.02}$	0.46 ± 0.06	6.3

Measurement of $|V_{cb}|$ with $B_s^0 \to D_s^{(*)-}\mu^+\nu_\mu$ decays

2001.03225

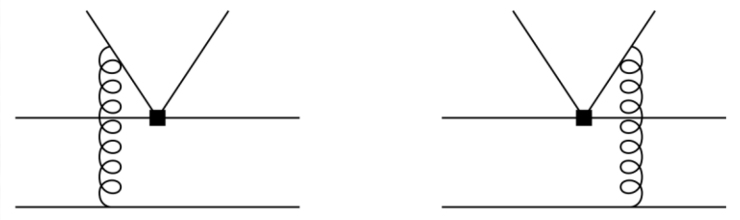
LHCb collaboration†

Power corrections

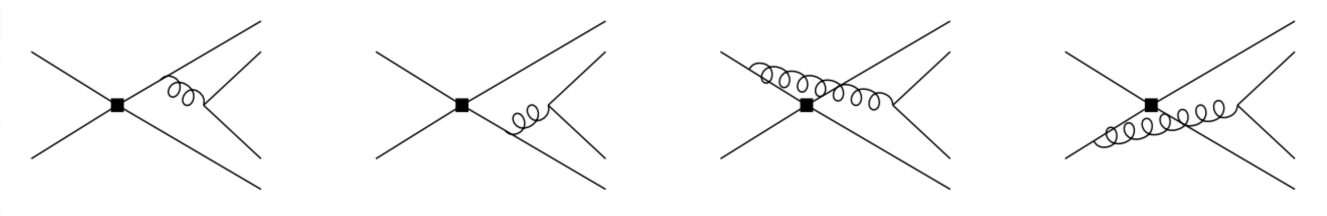
$$\langle D_q^{(*)+} L^- |\, \mathcal{Q}_i \,| \bar{B}_q^0 \rangle = \sum_j F_j^{\bar{B}_q \to D_q^{(*)}}(M_L^2) \times \int_0^1 du\, T_{ij}(u)\phi_L(u) + \mathcal{O}\left(\frac{\Lambda_{\rm QCD}}{m_b}\right)$$

◻ Sources of sub-leading power corrections: [Beneke, Buchalla, Neubert, Sachrajda '01; Bordone, Gubernari, Huber, Jung, van Dyk '20]

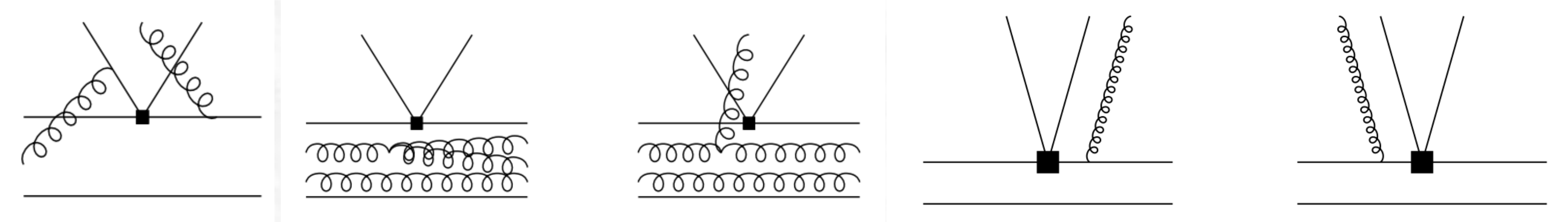
➢ Non-factorizable spectator interactions;



➢ Annihilation topologies;



➢ Non-leading Fock-state contributions;



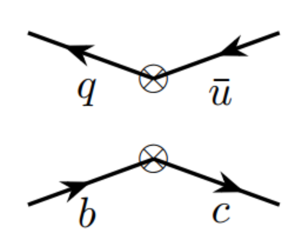
◻ Scaling of the leading-power contribution: [BBNS '01]

$$\mathcal{A}(\bar{B}_d \to D^+\pi^-) \sim G_F m_b^2\, F^{B\to D}(0)\, f_\pi \sim G_F m_b^2\, \Lambda_{\rm QCD}$$

➢ Based on general power counting and rough ESTIMATES, all are power-suppressed!

➢ Current data could not be easily explained within the SM, at least within QCDF.

Possible NP in $B_q^0 \to D_q^- L^+$?



- **Impossible or at least quite difficult to explain the data within the SM.**
- **Possible NP four-quark operators with different Dirac structures:** [Buras, Misiak, Urban '00]

$$\mathcal{L}_{\text{WET}} = -\frac{4G_F}{\sqrt{2}} V_{cb} V_{uq}^* [\mathcal{C}_1^{SM}(\mu) \mathcal{Q}_1^{SM} + \mathcal{C}_2^{SM}(\mu) \mathcal{Q}_2^{SM}$$

SM current-current operators

$$+ \sum_{\substack{i=1,2;\\ j=1,2,3,4.}} (\mathcal{C}_i^{VLL} \mathcal{Q}_i^{VLL} + \mathcal{C}_i^{VLR} \mathcal{Q}_i^{VLR} + \mathcal{C}_i^{SLR} \mathcal{Q}_i^{SLR} + \mathcal{C}_j^{SLL} \mathcal{Q}_j^{SLL})] + [L \leftrightarrow R]$$

NP four-quark operators

$$\mathcal{Q}_1^{VLL} = (\bar{c}_\alpha \gamma^\mu P_L b_\beta)(\bar{q}_\beta \gamma_\mu P_L u_\alpha) \qquad \mathcal{Q}_1^{VLR} = (\bar{c}_\alpha \gamma^\mu P_L b_\beta)(\bar{q}_\beta \gamma_\mu P_R u_\alpha)$$

$$\mathcal{Q}_2^{VLL} = (\bar{c}_\alpha \gamma^\mu P_L b_\alpha)(\bar{q}_\beta \gamma_\mu P_L u_\beta) \qquad \mathcal{Q}_2^{VLR} = (\bar{c}_\alpha \gamma^\mu P_L b_\alpha)(\bar{q}_\beta \gamma_\mu P_R u_\beta)$$

$$\mathcal{Q}_1^{SLL} = (\bar{c}_\alpha P_L b_\beta)(\bar{q}_\beta P_L u_\alpha) \qquad \mathcal{Q}_1^{SLR} = (\bar{c}_\alpha P_L b_\beta)(\bar{q}_\beta P_R u_\alpha)$$

$$\mathcal{Q}_2^{SLL} = (\bar{c}_\alpha P_L b_\alpha)(\bar{q}_\beta P_L u_\beta) \qquad \mathcal{Q}_2^{SLR} = (\bar{c}_\alpha P_L b_\alpha)(\bar{q}_\beta P_R u_\beta)$$

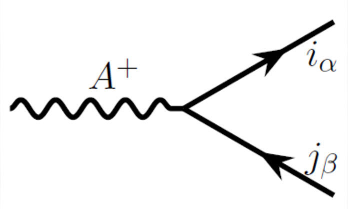
$$\mathcal{Q}_3^{SLL} = (\bar{c}_\alpha \sigma^{\mu\nu} P_L b_\beta)(\bar{q}_\beta \sigma_{\mu\nu} P_L u_\alpha)$$

$$\mathcal{Q}_4^{SLL} = (\bar{c}_\alpha \sigma^{\mu\nu} P_L b_\alpha)(\bar{q}_\beta \sigma_{\mu\nu} P_L u_\beta)$$

totally 20 linearly-independent operators, further split into 8 separate sectors!

Possible sources of these NP operators

- For VLL, VRR, VLR, VRL sectors: generated by a colorless charged gauge boson A^+;

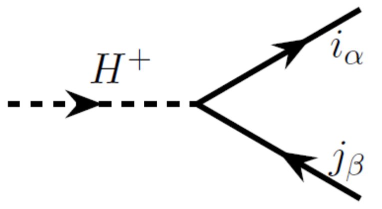


$$\mathcal{H}_{\text{eff}}^{\text{gauge}} = \frac{G_F}{\sqrt{2}} V_{cb} V_{uq}^* \Big\{ \lambda_{LL}(A) \left[C_1^{VLL}(\mu) Q_1^{VLL}(\mu) + C_2^{VLL}(\mu) Q_2^{VLL}(\mu) \right] + \lambda_{LR}(A) \left[C_1^{VLR}(\mu) Q_1^{VLR}(\mu) + C_2^{VLR}(\mu) Q_2^{VLR}(\mu) \right] + (L \leftrightarrow R) \Big\}$$

$$i\frac{g_2}{\sqrt{2}} V_{ij} \gamma^\mu \delta_{\alpha\beta} \left[\Delta_{ij}^L(A) P_L + \Delta_{ij}^R(A) P_R \right]$$

$$\lambda_{LL}(A) = \frac{m_W^2}{m_A^2} \Delta_{cb}^L(A) \left(\Delta_{uq}^L(A) \right)^*, \qquad \lambda_{LR}(A) = \frac{m_W^2}{m_A^2} \Delta_{cb}^L(A) \left(\Delta_{uq}^R(A) \right)^*$$

- For SLL, SRR, SLR, SRL sectors: generated by a colorless charged scalar H^+;



$$\mathcal{H}_{\text{eff}}^{\text{scalar}} = -\frac{G_F}{\sqrt{2}} V_{cb} V_{uq}^* \Big\{ \lambda_{LL}(H) \left[C_1^{SLL}(\mu) Q_1^{SLL}(\mu) + C_2^{SLL}(\mu) Q_2^{SLL}(\mu) + C_3^{SLL}(\mu) Q_3^{SLL}(\mu) + C_4^{SLL}(\mu) Q_4^{SLL}(\mu) \right] + \lambda_{LR}(H) \left[C_1^{SLR}(\mu) Q_1^{SLR}(\mu) + C_2^{SLR}(\mu) Q_2^{SLR}(\mu) \right] + (L \leftrightarrow R) \Big\}$$

$$i\frac{g_2}{\sqrt{2}} V_{ij} \delta_{\alpha\beta} \left[\Delta_{ij}^L(H) P_L + \Delta_{ij}^R(H) P_R \right]$$

$$\lambda_{LL}(H) = \frac{m_W^2}{m_H^2} \Delta_{cb}^L(H) \left(\Delta_{uq}^L(H) \right)^*, \qquad \lambda_{LR}(H) = \frac{m_W^2}{m_H^2} \Delta_{cb}^L(H) \left(\Delta_{uq}^R(H) \right)^*$$

Possible sources of these NP operators

- **Both 1-loop matching conditions & 2-loop QCD ADMs known;** [Buras, Misiak, Urban '00; Buras, Girrbach '12]

$$C_1^{\rm SLR}(\mu) = 3\frac{\alpha_s}{4\pi}\,,$$

$$C_2^{\rm SLR}(\mu) = 1 - \frac{\alpha_s}{4\pi}\frac{3}{N} = 1 - \frac{\alpha_s}{4\pi}\,,$$

$$C_1^{\rm SLL}(\mu) = 0\,,$$

$$C_2^{\rm SLL}(\mu) = 1\,,$$

$$C_3^{\rm SLL}(\mu) = \frac{\alpha_s}{4\pi}\left(-\frac{1}{2}\log\frac{M_H^2}{\mu^2} + \frac{3}{4}\right)\,,$$

$$C_4^{\rm SLL}(\mu) = \frac{\alpha_s}{4\pi}\left(\frac{1}{2N}\log\frac{M_H^2}{\mu^2} - \frac{3}{4N}\right) = \frac{\alpha_s}{4\pi}\left(\frac{1}{6}\log\frac{M_H^2}{\mu^2} - \frac{1}{4}\right)\,.$$

a colorless charged scalar H^+.

$$C_1^{\rm VLL}(\mu) = \frac{\alpha_s}{4\pi}\left(-3\log\frac{M_A^2}{\mu^2} + \frac{11}{2}\right)\,,$$

$$C_2^{\rm VLL}(\mu) = 1 + \frac{\alpha_s}{4\pi}\left(\frac{3}{N}\log\frac{M_A^2}{\mu^2} - \frac{11}{2N}\right) = 1 + \frac{\alpha_s}{4\pi}\left(\log\frac{M_A^2}{\mu^2} - \frac{11}{6}\right)\,,$$

$$C_1^{\rm VLR}(\mu) = \frac{\alpha_s}{4\pi}\left(3\log\frac{M_A^2}{\mu^2} + \frac{1}{2}\right)\,,$$

$$C_2^{\rm VLR}(\mu) = 1 + \frac{\alpha_s}{4\pi}\left(-\frac{3}{N}\log\frac{M_A^2}{\mu^2} - \frac{1}{2N}\right) = 1 + \frac{\alpha_s}{4\pi}\left(-\log\frac{M_A^2}{\mu^2} - \frac{1}{6}\right)\,.$$

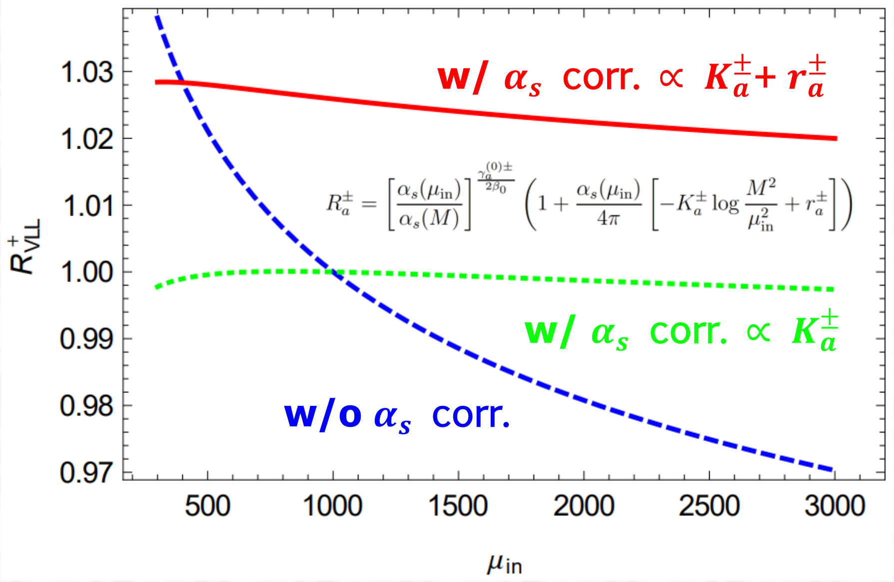
a colorless charged gauge boson A^+.

- **RG evolution from down m_A to m_b;**

[Buras, Misiak, Urban '00; Buras, Girrbach '12]

$$\vec{C}(\mu_b) = \left(\mathbb{1} + \frac{\alpha_s(\mu_b)}{4\pi}\hat{J}\right)\hat{U}^{(0)}(\mu_b,\mu_{\rm in})\left(\mathbb{1} - \frac{\alpha_s(\mu_{\rm in})}{4\pi}\left(\vec{C}_1 + \hat{J}\vec{C}_0\right)\right)$$

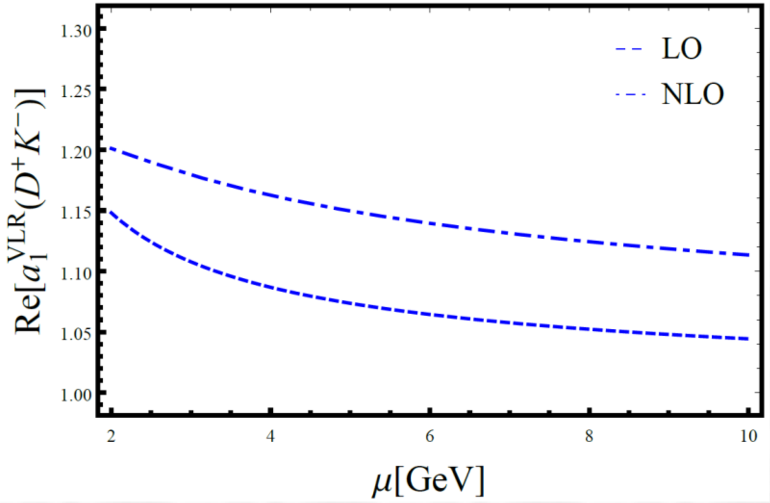
$$\hat{U}^{(0)}(\mu_b,\mu_{\rm in}) = \hat{V}\left(\left[\frac{\alpha_s(\mu_{\rm in})}{\alpha_s(\mu_b)}\right]^{\frac{\vec{\gamma}^{(0)}}{2\beta_0}}\right)_D \hat{V}^{-1}$$



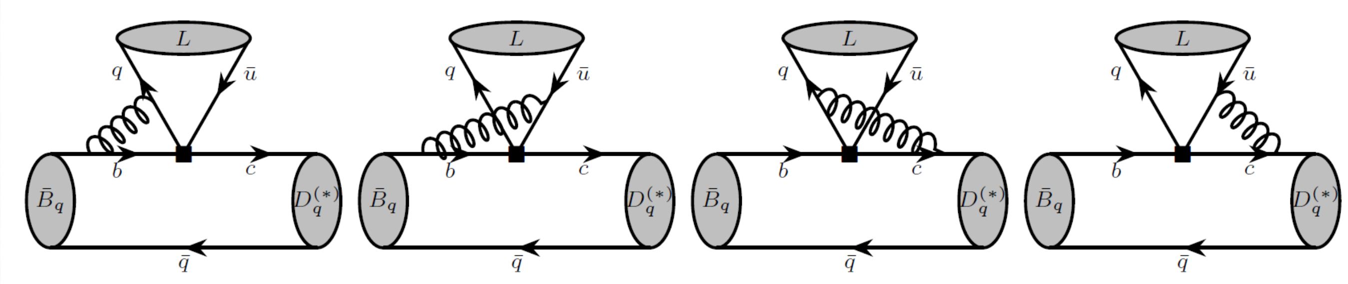
Matrix elements of NP operators

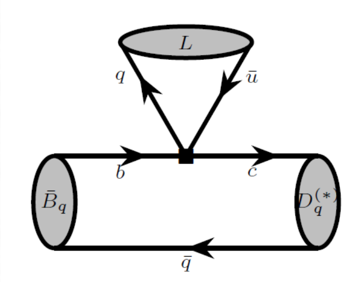
- **NP Wilson coefficients easily obtained at NLO in α_s;** [Buras, Misiak, Urban '00; Buras, Girrbach '12]

$$\vec{C}(\mu_b) = \left(\mathbb{1} + \frac{\alpha_s(\mu_b)}{4\pi}\hat{J}\right)\hat{U}^{(0)}(\mu_b,\mu_{\rm in})\left(\mathbb{1} - \frac{\alpha_s(\mu_{\rm in})}{4\pi}\left(\vec{C}_1 + \hat{J}\vec{C}_0\right)\right)$$

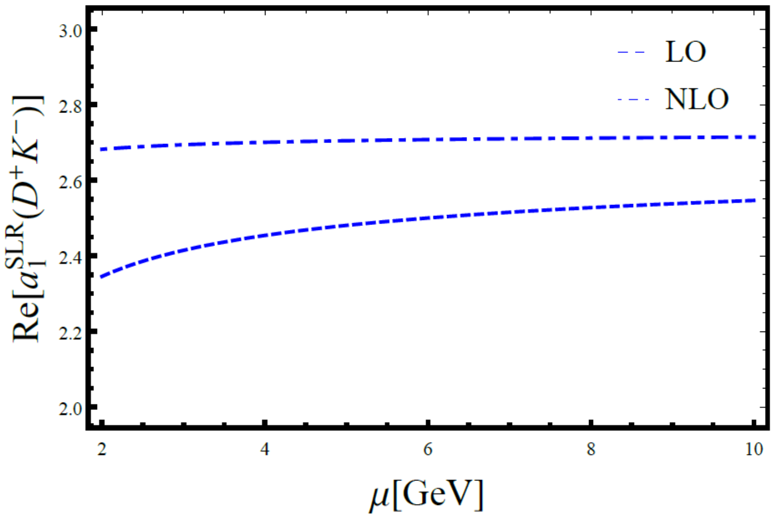


- $\langle D^+L^-|\mathcal{O}_i|\bar{B}^0\rangle$ **:** calculated in QCDF at leading-power in $1/m_b$, but including $\mathcal{O}(\alpha_s)$ vertex correction.





- **unphysical scale- & scheme-dependences cancelled in the final decay amplitude.**



Model-independent analysis

- NP $\mathcal{C}_i^{NP}$: real and take a CKM-like flavor structure for $b \to c\bar{u}d$ and $b \to c\bar{u}s$ transitions.

$$\mathcal{L}_{\text{WET}} = -\frac{4G_F}{\sqrt{2}} V_{cb}V_{uq}^* [\mathcal{C}_1^{SM}(\mu)\mathcal{Q}_1^{SM} + \mathcal{C}_2^{SM}(\mu)\mathcal{Q}_2^{SM} + \sum_{\substack{i=1,2;\\ j=1,2,3,4.}} (\mathcal{C}_i^{VLL}\mathcal{Q}_i^{VLL} + \mathcal{C}_i^{VLR}\mathcal{Q}_i^{VLR} + \mathcal{C}_i^{SLR}\mathcal{Q}_i^{SLR} + \mathcal{C}_j^{SLL}\mathcal{Q}_j^{SLL})] + L \leftrightarrow R$$

- Use 8 ratios to constrain $\mathcal{C}_i^{NP}$;

$R_{(s)L}^{(*)}$	LO	NLO	NNLO	Exp.	Deviation (σ)
R_π	1.01	$1.07^{+0.04}_{-0.04}$	$1.10^{+0.03}_{-0.03}$	0.74 ± 0.06	5.4
R_π^*	1.00	$1.06^{+0.04}_{-0.04}$	$1.10^{+0.03}_{-0.03}$	0.80 ± 0.06	4.5
R_ρ	2.77	$2.94^{+0.19}_{-0.19}$	$3.02^{+0.17}_{-0.18}$	2.23 ± 0.37	1.9
R_K	0.78	$0.83^{+0.03}_{-0.03}$	$0.85^{+0.01}_{-0.02}$	0.62 ± 0.05	4.4
R_K^*	0.72	$0.76^{+0.03}_{-0.03}$	$0.79^{+0.01}_{-0.02}$	0.60 ± 0.14	1.3
R_{K^*}	1.41	$1.50^{+0.11}_{-0.11}$	$1.53^{+0.10}_{-0.10}$	1.38 ± 0.25	0.6
$R_{s\pi}$	1.01	$1.07^{+0.04}_{-0.04}$	$1.10^{+0.03}_{-0.03}$	0.72 ± 0.08	4.4
R_{sK}	0.78	$0.83^{+0.03}_{-0.03}$	$0.85^{+0.01}_{-0.02}$	0.46 ± 0.06	6.3

- Note: different modes show different dependences on NP WCs!

$$\langle \pi^-(q)|\bar{d}\gamma_\mu\gamma_5 u|0\rangle = -if_\pi q_\mu$$

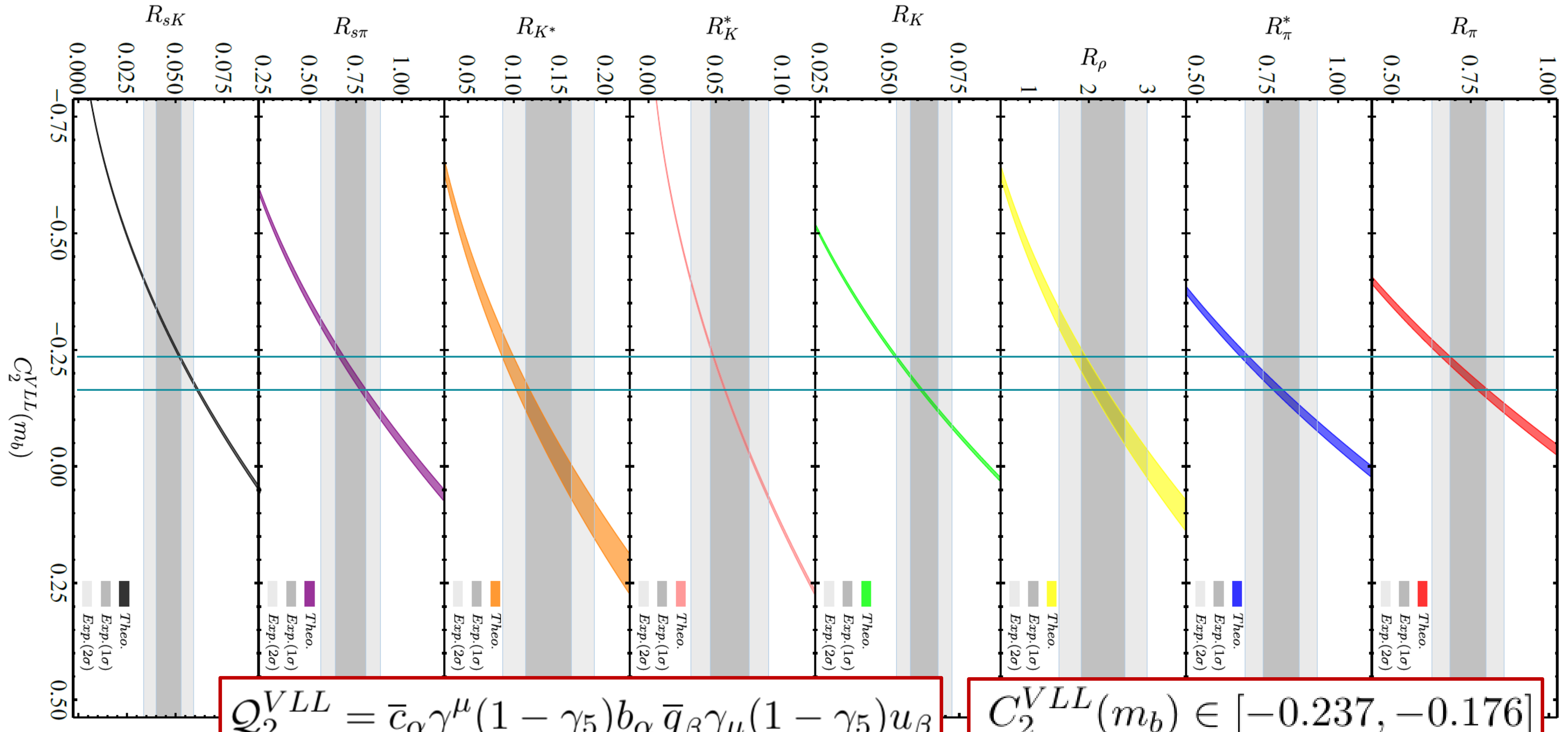
$$\langle \rho^-(q)|\bar{d}\gamma_\mu u|0\rangle = -if_\rho m_\rho \epsilon_\mu^*$$

$$\langle D^+|\bar{c}\not{q}b|\bar{B}^0\rangle = (m_B^2 - m_D^2)F_0^{B\to D}(q^2)$$

$$\langle D^{*+}|\bar{c}\not{q}\gamma_5 b|\bar{B}^0\rangle = 2m_{D^*}(\epsilon^*\cdot q)A_0^{B\to D^*}(q^2)$$

Analysis at m_b scale

- Keep only C_2^{VLL} nonzero;
- SM: $\mathcal{C}_1(m_b) = -0.143$ and $\mathcal{C}_2(m_b) = 1.058$

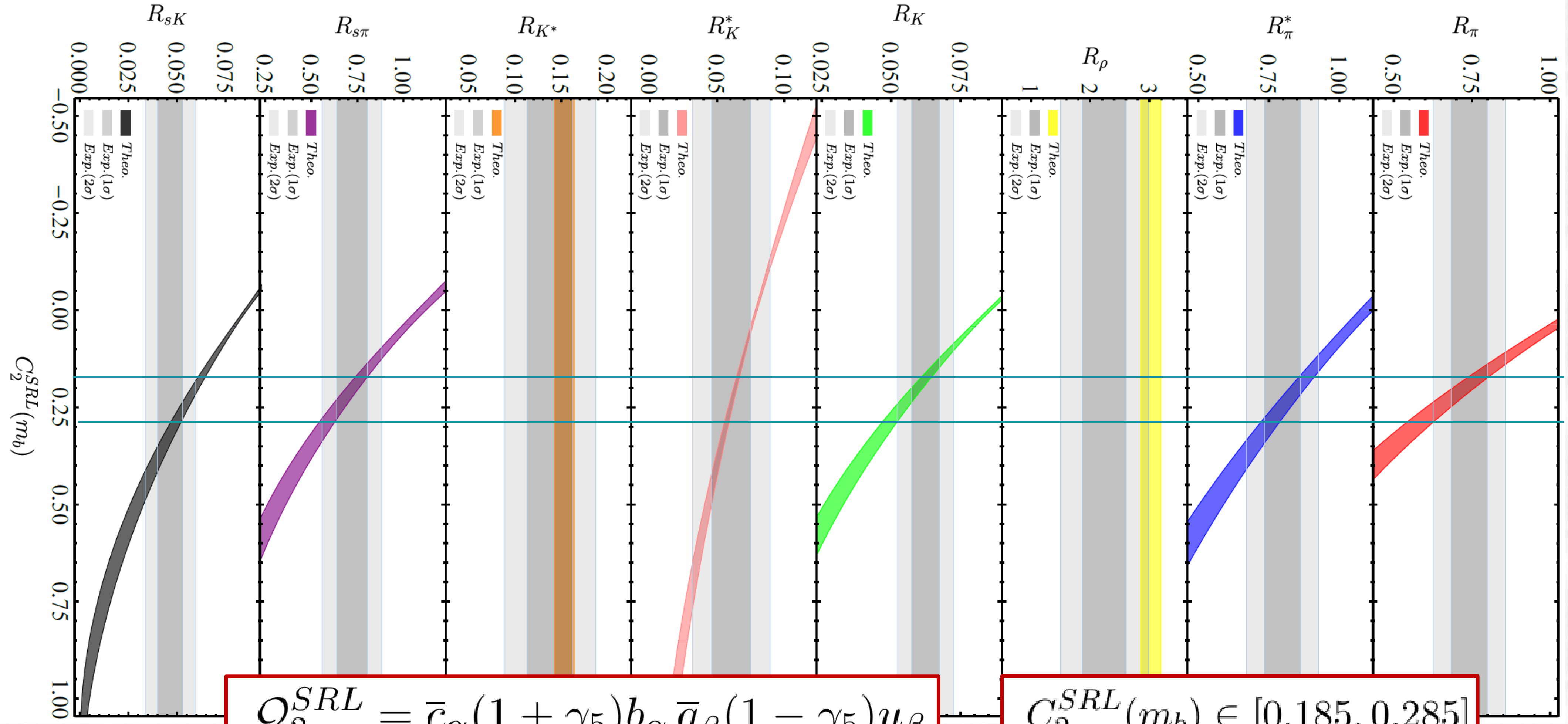


$$\mathcal{Q}_2^{VLL} = \bar{c}_\alpha \gamma^\mu (1-\gamma_5) b_\alpha \, \bar{q}_\beta \gamma_\mu (1-\gamma_5) u_\beta$$

$$C_2^{VLL}(m_b) \in [-0.237, -0.176]$$

Analysis at m_b scale

- **Keep only C_2^{SRL} nonzero;**
- **SM:** $\mathcal{C}_1(m_b) = -0.143$ and $\mathcal{C}_2(m_b) = 1.058$

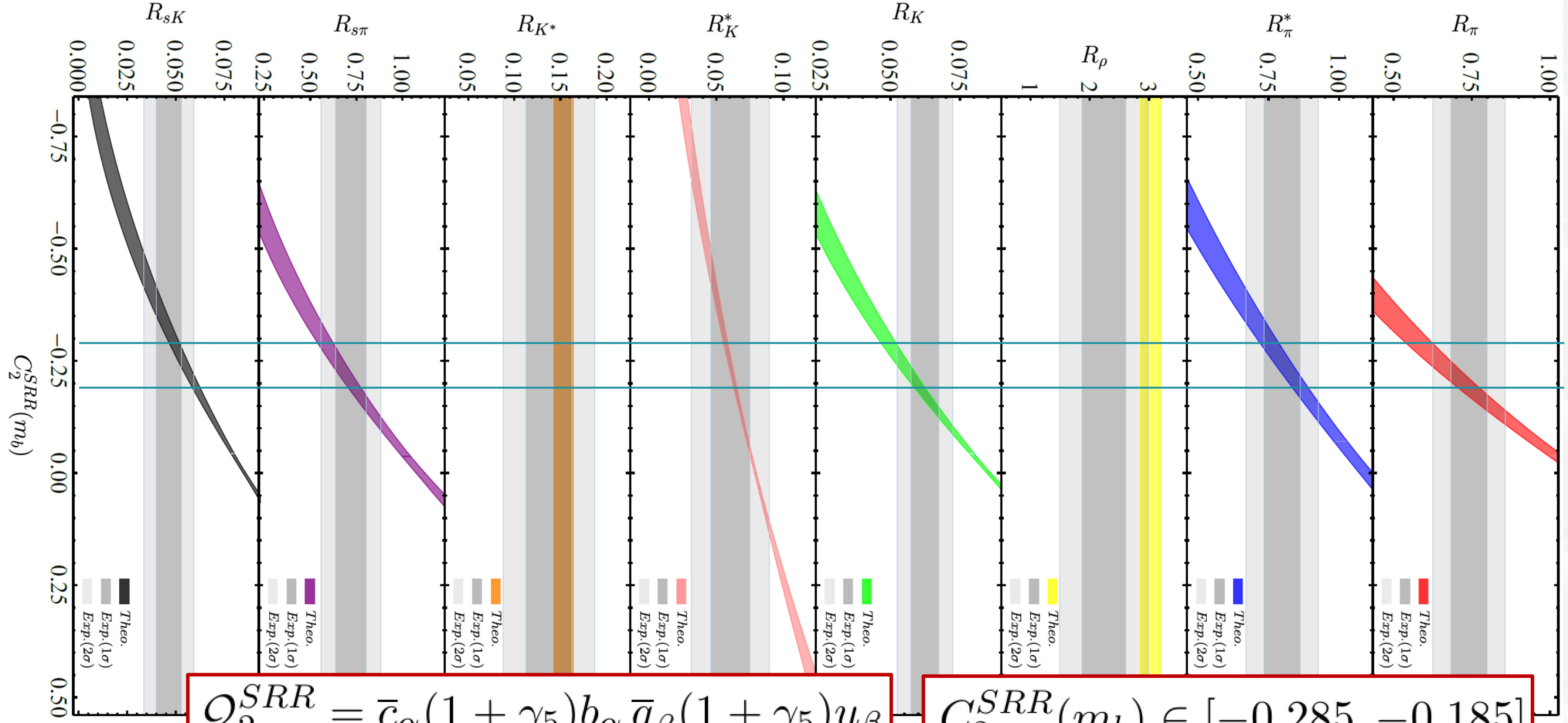


$$\mathcal{Q}_2^{SRL} = \bar{c}_\alpha(1+\gamma_5)b_\alpha\,\bar{q}_\beta(1-\gamma_5)u_\beta$$

$$C_2^{SRL}(m_b) \in [0.185, 0.285]$$

Analysis at m_b scale

- Keep only C_2^{SRR} nonzero;
- SM: $\mathcal{C}_1(m_b) = -0.143$ and $\mathcal{C}_2(m_b) = 1.058$



$$\mathcal{Q}_2^{SRR} = \bar{c}_\alpha(1+\gamma_5)b_\alpha\,\bar{q}_\beta(1+\gamma_5)u_\beta$$

$$C_2^{SRR}(m_b) \in [-0.285, -0.185]$$

Analysis at m_b scale

R_K	0.78	$0.83^{+0.03}_{-0.03}$	$0.85^{+0.01}_{-0.02}$	0.62 ± 0.05	4.4
R_{sK}	0.78	$0.83^{+0.03}_{-0.03}$	$0.85^{+0.01}_{-0.02}$	0.46 ± 0.06	6.3

- With only one NP C_i^{NP} in each time, NP four-quark operators with three Dirac structures;

NP Coeff. \ C.L.\Obs.	C.L.	R_π	R_π^*	R_ρ	R_K	R_K^*	R_{K^*}	$R_{s\pi}$	R_{sK}	Combined
C_1^{VLL}	1σ	[-1.40,-0.847]	[-1.18,-0.626]	[-1.50,-0.267]	[-1.18,-0.662]	[-1.54,-0.145]	[-1.05,0.392]	[-1.57,-0.835]	[-2.12,-1.31]	$\varnothing$
	2σ	[-1.63,-0.656]	[-1.41,-0.426]	[-2.06,0.135]	[-1.42,-0.462]	[-2.41,0.402]	[-1.70,0.856]	[-1.92,-0.567]	[-2.55,-1.02]	[-1.41,-1.02]
C_2^{VLL}	1σ	[-0.237,-0.148]	[-0.205,-0.111]	[-0.254,-0.047]	[-0.198,-0.116]	[-0.261,-0.026]	[-0.183,0.070]	[-0.264,-0.146]	[-0.345,-0.226]	$\varnothing$
	2σ	[-0.273,-0.115]	[-0.244,-0.075]	[-0.340,0.024]	[-0.237,-0.081]	[-0.401,0.071]	[-0.288,0.155]	[-0.318,-0.099]	[-0.406,-0.176]	[-0.237,-0.176]
C_1^{SRR}	1σ	[-0.748,-0.418]	[-1.03,-0.502]	$\varnothing$	[-0.711,-0.368]	[-1.50,-0.133]	R	[-0.839,-0.412]	[-1.25,-0.712]	$\varnothing$
	2σ	[-0.867,-0.326]	[-1.23,-0.344]	R	[-0.854,-0.259]	[-2.32,0.395]	R	[-1.02,-0.283]	[-1.48,-0.556]	[-0.854,-0.556]
C_2^{SRR}	1σ	[-0.249,-0.139]	[-0.343,-0.167]	$\varnothing$	[-0.237,-0.123]	[-0.500,-0.044]	R	[-0.280,-0.137]	[-0.417,-0.237]	$\varnothing$
	2σ	[-0.289,-0.109]	[-0.410,-0.115]	R	[-0.285,-0.086]	[-0.773,0.132]	R	[-0.339,-0.094]	[-0.492,-0.185]	[-0.285,-0.185]
C_1^{SRL}	1σ	[0.487,0.873]	[0.585,1.20]	$\varnothing$	[0.429,0.829]	[0.155,1.75]	R	[0.480,0.979]	[0.830,1.46]	$\varnothing$
	2σ	[0.381,1.01]	[0.401,1.44]	R	[0.302,0.996]	[-0.460,2.71]	R	[0.330,1.18]	[0.648,1.72]	[0.648,0.996]
C_2^{SRL}	1σ	[0.139,0.249]	[0.167,0.343]	$\varnothing$	[0.123,0.237]	[0.044,0.500]	R	[0.137,0.280]	[0.237,0.416]	$\varnothing$
	2σ	[0.109,0.289]	[0.115,0.410]	R	[0.086,0.285]	[-0.132,0.773]	R	[0.094,0.339]	[0.185,0.492]	[0.185,0.285]

$$Q_{1,2}^{VLL} = \bar{c}_\alpha \gamma_\mu (1-\gamma_5) b_{\beta(\alpha)}\, \bar{q}_\beta \gamma^\mu (1-\gamma_5) u_{\alpha(\beta)}$$

$(V-A) \otimes (V-A)$

$$Q_{1,2}^{SRL} = \bar{c}_\alpha (1+\gamma_5) b_{\beta(\alpha)}\, \bar{q}_\beta (1-\gamma_5) u_{\alpha(\beta)}$$

$(S+P) \otimes (S-P)$

$$Q_{1,2}^{SRR} = \bar{c}_\alpha (1+\gamma_5) b_{\beta(\alpha)}\, \bar{q}_\beta (1+\gamma_5) u_{\alpha(\beta)}$$

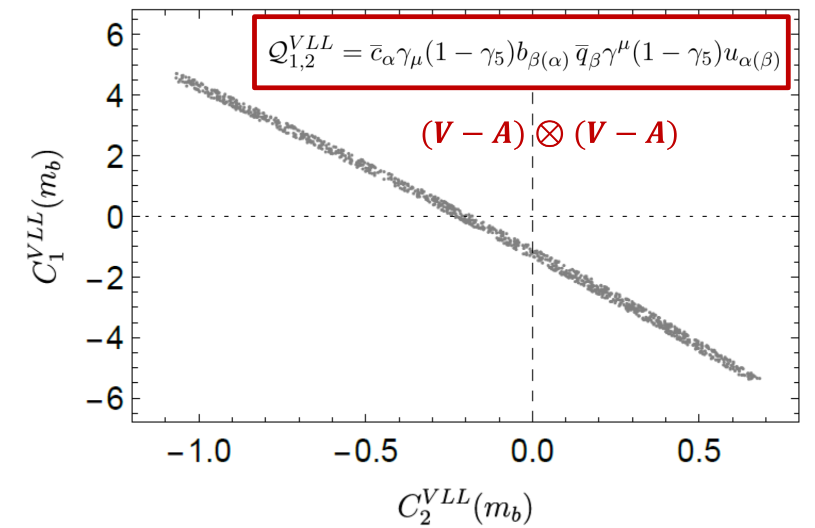
$(S+P) \otimes (S+P)$

- Constraints on C_2^{NP} much stronger than on C_1^{NP}: C_1^{NP} suppressed by $1/N_C$ at LO and further by $C_F/4\pi$ at NLO in QCDF;

- (Pseudo-)scalar operators associated with a chirally-enhanced factor $\frac{2m_L^2}{(m_b \pm m_c)(m_u + m_{d,s})}$;
- NP operators with other Dirac structures already ruled out by combined constraints from eight ratios;

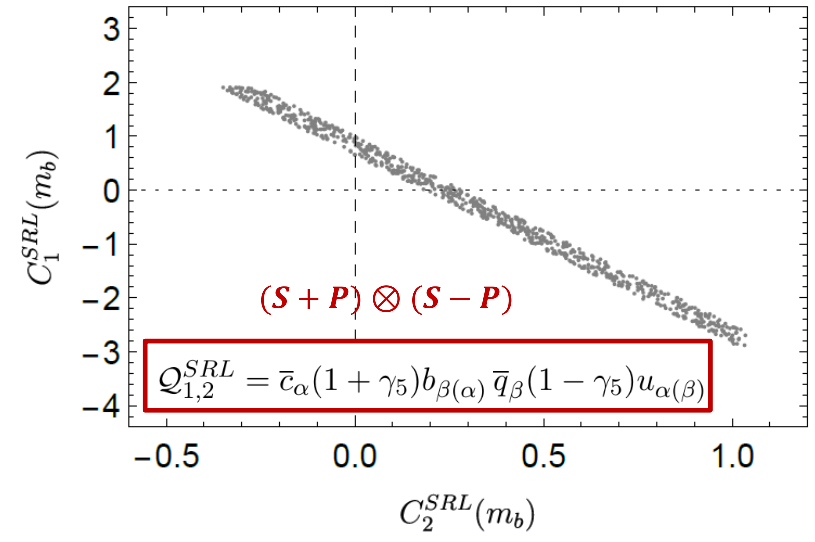
Analysis at m_b scale

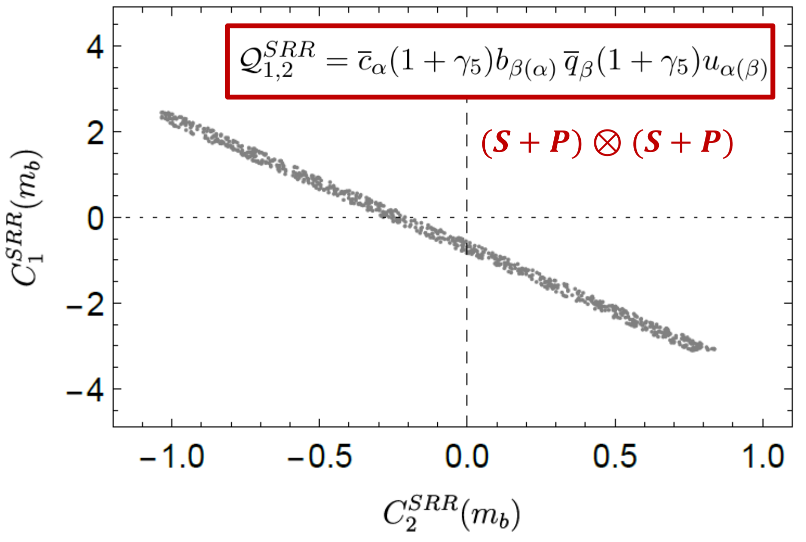
- **Two NP operators with the same Dirac but different color structures;**



$C_2^{NP} + C_1^{NP}/N_C$

- Due to partial cancellation between C_2^{NP} & C_1^{NP}, allowed regions potentially larger than in previous case.
- For NP operators with other Dirac structures, no allowed regions even at the 2σ level.





Analysis at m_W scale

- **Variable solutions: NP four-quark operators with the following three Dirac structures;**

$$\mathcal{Q}_{1,2}^{VLL} = \bar{c}_\alpha \gamma_\mu (1-\gamma_5) b_{\beta(\alpha)}\, \bar{q}_\beta \gamma^\mu (1-\gamma_5) u_{\alpha(\beta)}$$

$(V-A)\otimes(V-A)$

$$\mathcal{Q}_{1,2}^{SRL} = \bar{c}_\alpha (1+\gamma_5) b_{\beta(\alpha)}\, \bar{q}_\beta (1-\gamma_5) u_{\alpha(\beta)}$$

$(S+P)\otimes(S-P)$

$$\mathcal{Q}_{1,2}^{SRR} = \bar{c}_\alpha (1+\gamma_5) b_{\beta(\alpha)}\, \bar{q}_\beta (1+\gamma_5) u_{\alpha(\beta)}$$

$(S+P)\otimes(S+P)$

$$\vec{C}(\mu_b) = \hat{U}(\mu_b, \mu_W)\, \vec{C}(\mu_W)$$

What implications for the NP Wilson coefficients at the higher scale m_W ?

- **With RG evolutions for C_i^{NP} taken into account, the following regions obtained:**

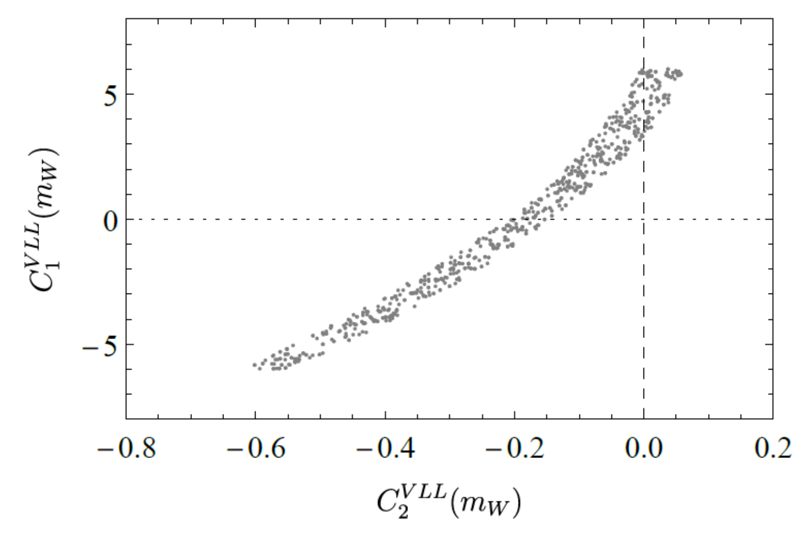
$C_2^{VLL}(M_W) \in [-0.220, -0.164]$ **vs** $C_2^{VLL}(m_b) \in [-0.237, -0.176]$

→ small RG evolution effect!

$C_2^{SRL}(m_W) \in [0.091, 0.139]$ **vs** $C_2^{SRL}(m_b) \in [0.185, 0.285]$

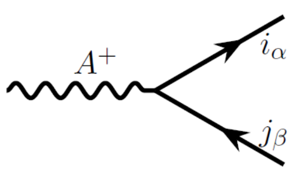
$C_2^{SRR}(m_W) \in [-0.129, -0.084]$ **vs** $C_2^{SRR}(m_b) \in [-0.285, -0.185]$

→ large RG evolution effect!



Case with a colorless gauge boson

- **Heff mediated by a colorless charged gauge boson A^+ ;**



$$\mathcal{H}_{\rm eff}^{\rm gauge} = \frac{G_F}{\sqrt{2}} V_{cb} V_{uq}^* \Big\{ \lambda_{LL}(A) \left[C_1^{VLL}(\mu) Q_1^{VLL}(\mu) + C_2^{VLL}(\mu) Q_2^{VLL}(\mu) \right] + \lambda_{LR}(A) \left[C_1^{VLR}(\mu) Q_1^{VLR}(\mu) + C_2^{VLR}(\mu) Q_2^{VLR}(\mu) \right] + (L \leftrightarrow R) \Big\}$$

$$i \frac{g_2}{\sqrt{2}} V_{ij} \gamma^\mu \delta_{\alpha\beta} \left[\Delta_{ij}^L(A) P_L + \Delta_{ij}^R(A) P_R \right]$$

$$\lambda_{LL}(A) = \frac{m_W^2}{m_A^2} \Delta_{cb}^L(A) \left(\Delta_{uq}^L(A) \right)^*, \qquad \lambda_{LR}(A) = \frac{m_W^2}{m_A^2} \Delta_{cb}^L(A) \left(\Delta_{uq}^R(A) \right)^*$$

- **With $m_A = 1\ \mathrm{TeV}$, 1- & 2-loop ADMs and 1-loop matching conditions:** [Buras, Misiak, Urban '00; Buras, Girrbach '12]

$$\vec{C}(\mu_b) = \hat{U}(\mu_b, \mu_W) \hat{U}(\mu_W, \mu_0) \vec{C}(\mu_0)$$

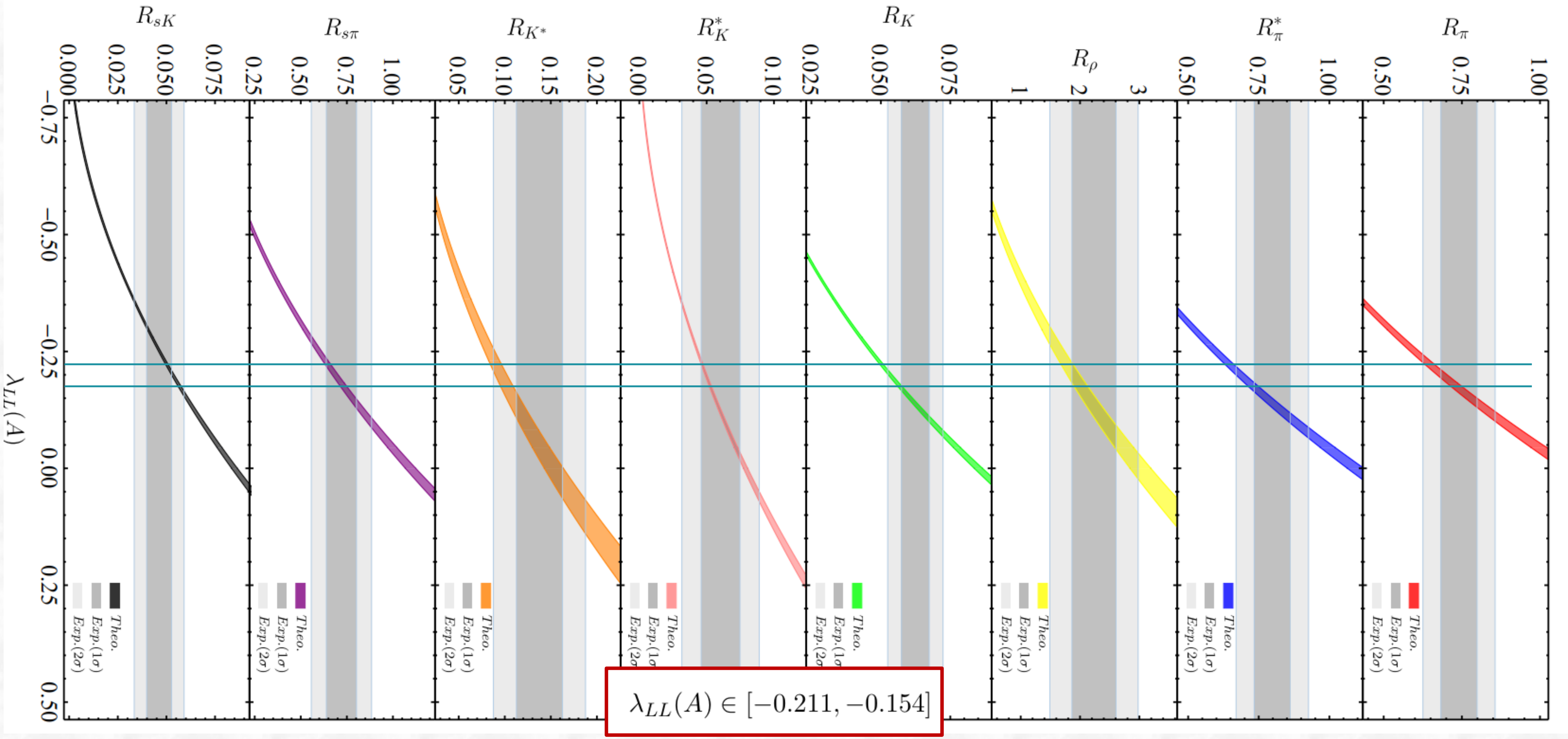
$$\boxed{\lambda_{LL}(A) \in [-0.211, -0.154]}$$

- **4 NP parameters: $\lambda_{LL}(A), \lambda_{LR}(A), \lambda_{RR}(A), \lambda_{RL}(A)$;**
  - Scenario I: only one effective coefficient nonzero;
  - Scenario II: $\Delta_{cb}^L(A) = \Delta_{cb}^R(A)$, $\Delta_{uq}^L(A) = \Delta_{uq}^R(A)$; ⟶ $\lambda_{LL}(A) = \lambda_{RR}(A) = \lambda_{LR}(A) = \lambda_{RL}(A)$
  - Scenario III: $\Delta_{cb}^L(A) = -\Delta_{cb}^R(A)$, $\Delta_{uq}^L(A) = -\Delta_{uq}^R(A)$; ⟶ $\lambda_{LL}(A) = \lambda_{RR}(A) = -\lambda_{LR}(A) = -\lambda_{RL}(A)$

A^+ coupling to quarks either vectorial or axial-vectorial!

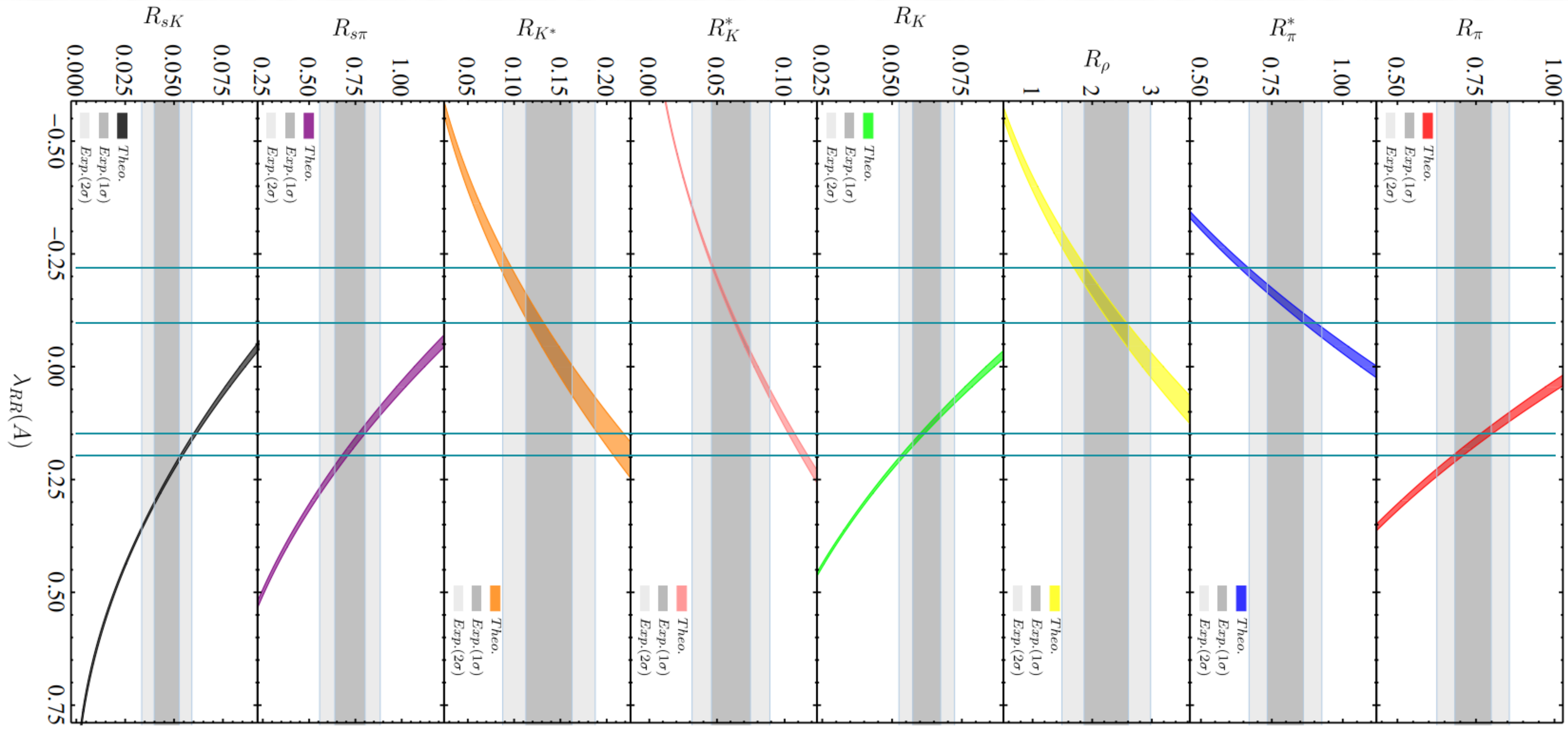
Case with a colorless gauge boson

- **Scenario I: only $\lambda_{LL}(A)$ nonzero;**

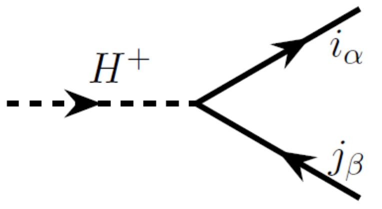


Case with a colorless gauge boson

- **Scenario I: only $\lambda_{RR}(A)$ nonzero;**



Case with a colorless scalar



- **Heff mediated by a colorless charged scalar H^+ ;**

$$\mathcal{H}_{\rm eff}^{\rm scalar} = -\frac{G_F}{\sqrt{2}} V_{cb} V_{uq}^* \Big\{ \lambda_{LL}(H) \Big[C_1^{SLL}(\mu) Q_1^{SLL}(\mu) + C_2^{SLL}(\mu) Q_2^{SLL}(\mu) + C_3^{SLL}(\mu) Q_3^{SLL}(\mu) + C_4^{SLL}(\mu) Q_4^{SLL}(\mu) \Big] + \lambda_{LR}(H) \Big[C_1^{SLR}(\mu) Q_1^{SLR}(\mu) + C_2^{SLR}(\mu) Q_2^{SLR}(\mu) \Big] + (L \leftrightarrow R) \Big\}$$

$$i \frac{g_2}{\sqrt{2}} V_{ij} \delta_{\alpha\beta} \left[\Delta_{ij}^L(H) P_L + \Delta_{ij}^R(H) P_R \right]$$

$$\lambda_{LL}(H) = \frac{m_W^2}{m_H^2} \Delta_{cb}^L(H) \left(\Delta_{uq}^L(H)\right)^* , \qquad \lambda_{LR}(H) = \frac{m_W^2}{m_H^2} \Delta_{cb}^L(H) \left(\Delta_{uq}^R(H)\right)^*$$

- **With $m_H = 1$ TeV, 1- & 2-loop ADMs and 1-loop matching conditions:** [Buras, Misiak, Urban '00; Buras, Girrbach '12]

$$\vec{C}(\mu_b) = \hat{U}(\mu_b, \mu_W) \hat{U}(\mu_W, \mu_0) \vec{C}(\mu_0)$$

- **4 NP parameters: $\lambda_{LL}(H), \lambda_{LR}(H), \lambda_{RR}(H), \lambda_{RL}(H)$;**

    - Scenario I: only one effective coefficient nonzero; →

$$\lambda_{RL}(H) \in [0.059, 0.100]$$

$$\lambda_{RR}(H) \in [-0.090, -0.054]$$

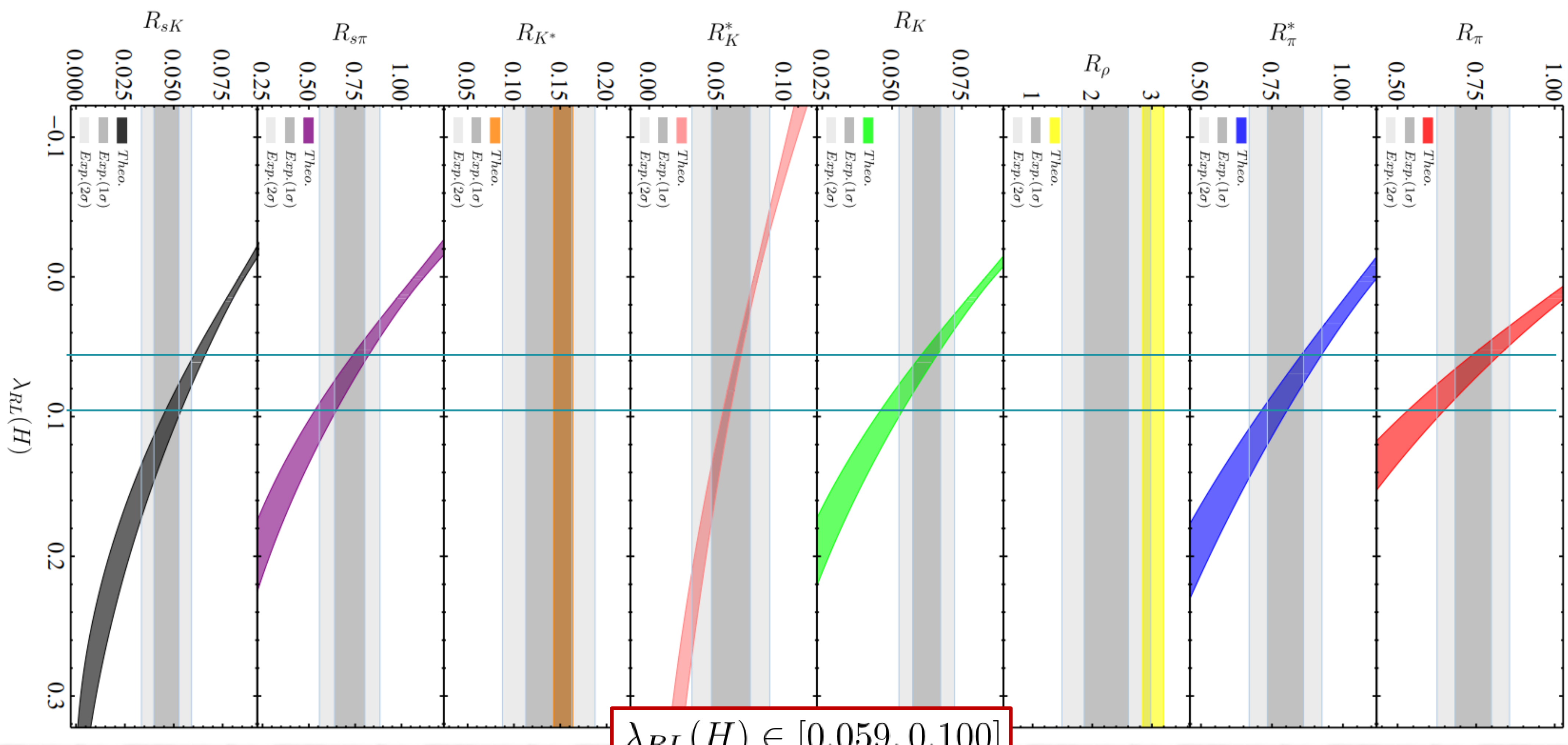
H^+ coupling to quarks either scalar or pseudo-scalar!

    - Scenario II: $\Delta_{cb}^L(H) = \Delta_{cb}^R(H)$, $\Delta_{uq}^L(H) = \Delta_{uq}^R(H)$; → $\lambda_{LL}(H) = \lambda_{RR}(H) = \lambda_{LR}(H) = \lambda_{RL}(H)$

    - Scenario III: $\Delta_{cb}^L(H) = -\Delta_{cb}^R(H)$, $\Delta_{uq}^L(H) = -\Delta_{uq}^R(H)$; → $\lambda_{LL}(H) = \lambda_{RR}(H) = -\lambda_{LR}(H) = -\lambda_{RL}(H)$

Case with a colorless scalar

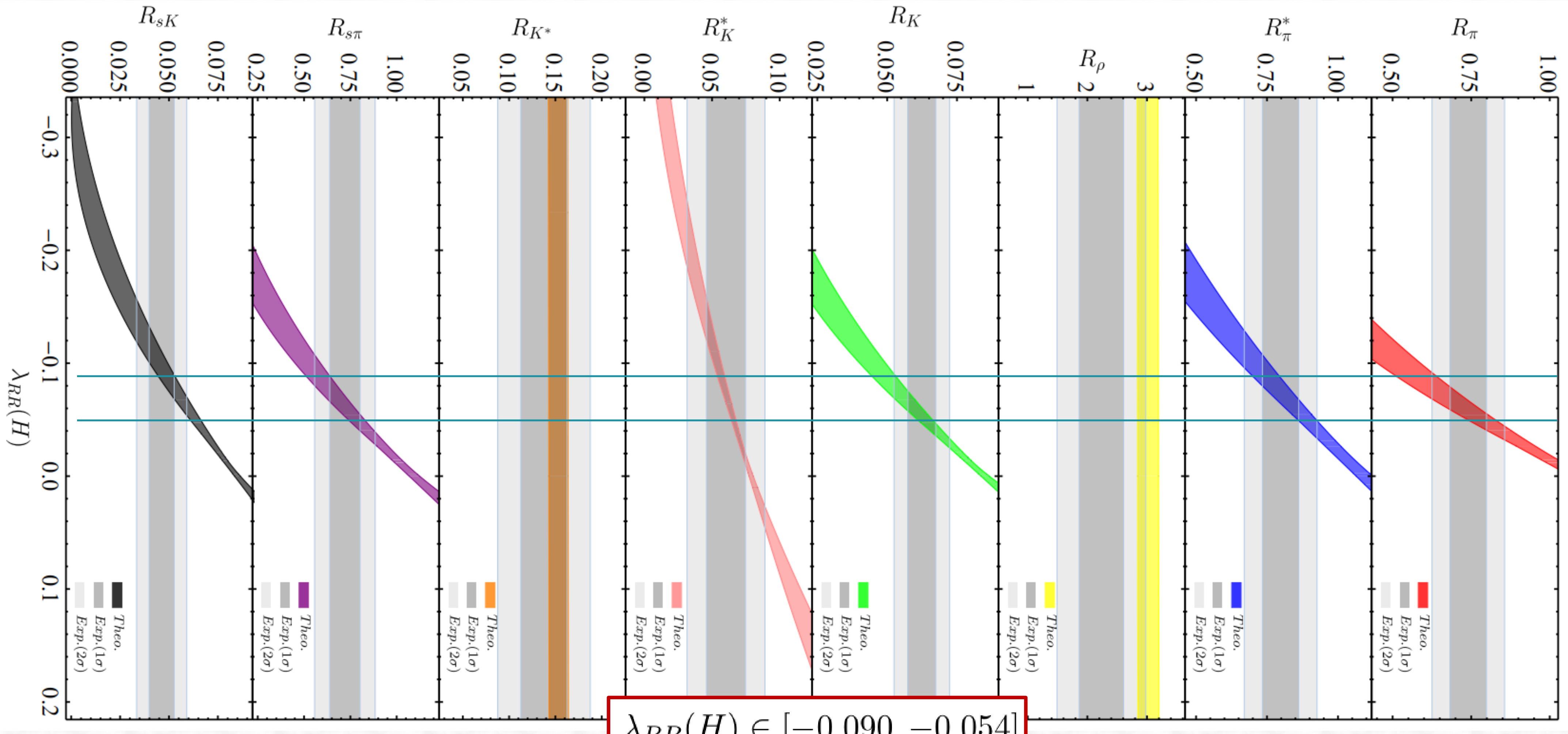
- Scenario I: only $\lambda_{RL}(H)$ nonzero;



$\lambda_{RL}(H) \in [0.059, 0.100]$

Case with a colorless scalar

- ☐ **Scenario I: only $\lambda_{RR}(H)$ nonzero;**



$$\lambda_{RR}(H) \in [-0.090, -0.054]$$

Summary

- NNLO predictions for class-I $B_q^0 \to D_q^- L^+$ decays at leading power within QCDF complete.
- Thanks to improved measurements and updated SM predictions, $\mathcal{O}(4{-}5\sigma)$ discrepancies observed; ⟹ sub-leading power corrections in QCDF or possible NP beyond the SM?
- Model-indep. analysis reveals that only NP operators with 3 Dirac structures possible:

$$\mathcal{Q}_{1,2}^{VLL} = \bar{c}_\alpha \gamma_\mu (1-\gamma_5) b_{\beta(\alpha)}\, \bar{q}_\beta \gamma^\mu (1-\gamma_5) u_{\alpha(\beta)}$$

$$\mathcal{Q}_{1,2}^{SRL} = \bar{c}_\alpha (1+\gamma_5) b_{\beta(\alpha)}\, \bar{q}_\beta (1-\gamma_5) u_{\alpha(\beta)}$$

$$\mathcal{Q}_{1,2}^{SRR} = \bar{c}_\alpha (1+\gamma_5) b_{\beta(\alpha)}\, \bar{q}_\beta (1+\gamma_5) u_{\alpha(\beta)}$$

$(V-A) \otimes (V-A)$ $\qquad$ $(S+P) \otimes (S-P)$ $\qquad$ $(S+P) \otimes (S+P)$

generated by a colorless charged gauge boson or by a colorless charged scalar.

- Once additional flavor-university assumptions were made, how about constraints from other $b \to c\bar{c}d(s)$ and $b \to d(s)q\bar{q}$ processes? ⟹ *see the following talks*

Thank You for your attention!

For questions, email me:

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