Class-I $B_q^0 \to D_q^{(*)-} L^+$ decays at NNLO and possible New Physics

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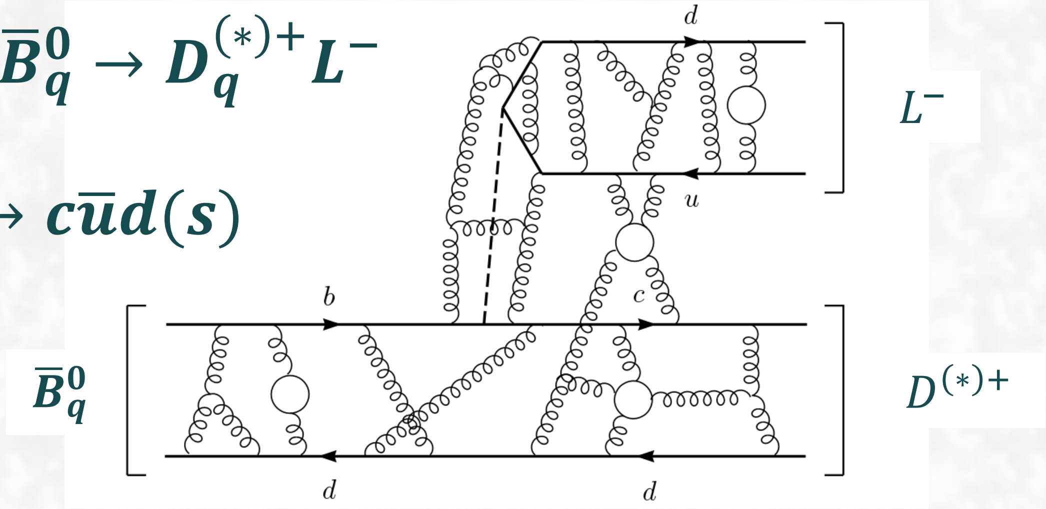
Outline

Class-I $\bar{B}_q^0 \to D_q^{(*)+} L^-$

$b \to c\bar{u}d(s)$

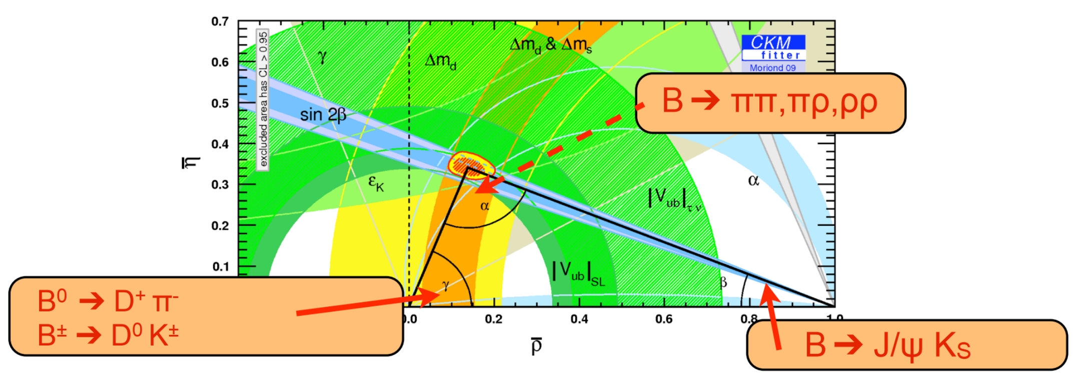


- ☐ **Introduction**
- ☐ **NNLO predictions at leading power in QCDF/SCET**
- ☐ **Possible New Physics effects from four-quark operators**
- ☐ **Summary**

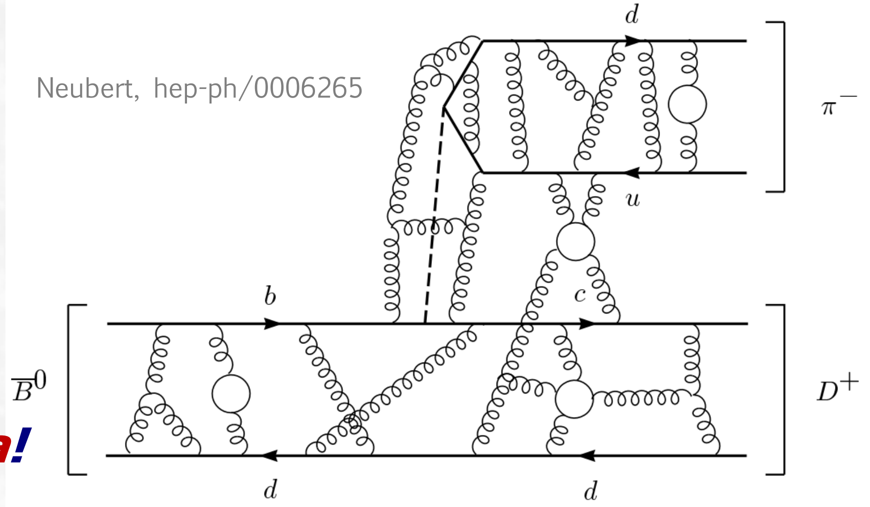
Introduction

Why hadronic B decays

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

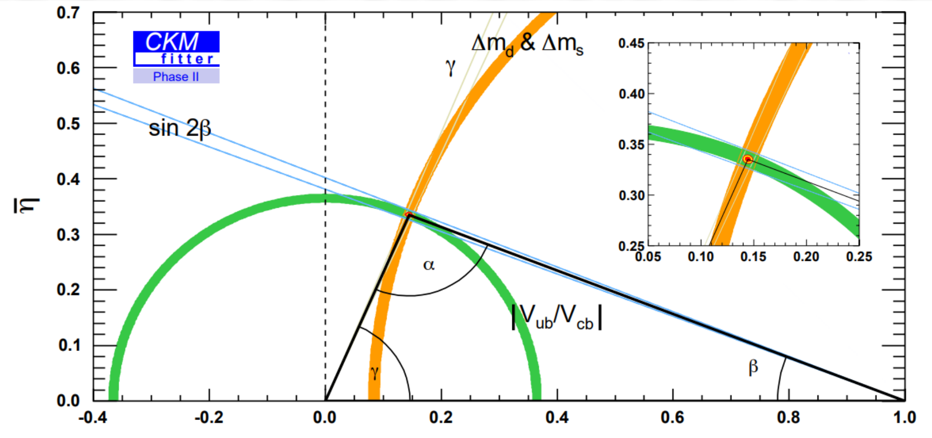


- **further insight into strong-interaction effects involved in these decays.**



Neubert, hep-ph/0006265

- **Thanks to exp. & theo., entering a *precision flavor era!***



LHCb Phase II, arXiv:1808.08865

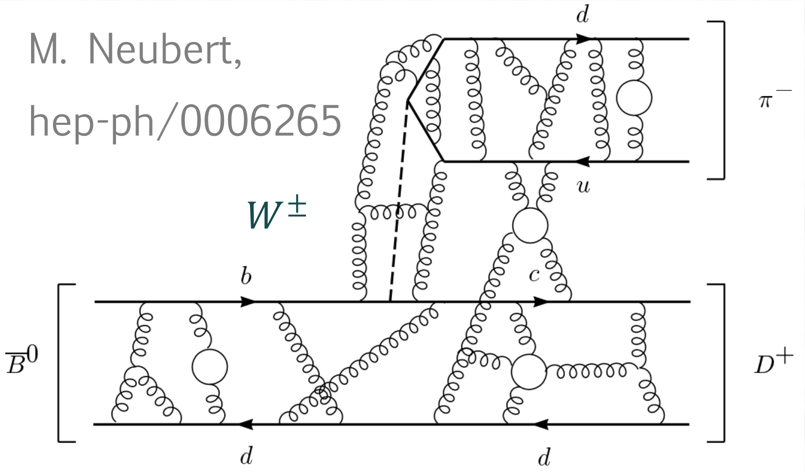
- **From the theory side, we need also keep up with the same precision from data.**

→ ***very difficult but necessary!***

Effective Hamiltonian for B decays

- **For hadronic decays:** simplicity of weak interactions overshadowed by complex QCD effects!

M. Neubert,
hep-ph/0006265



multi-scale problem with highly hierarchical scales!

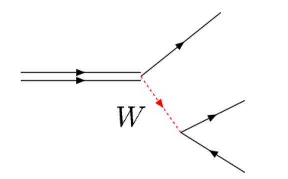
EW interaction scale	$\gg$	ext. mom'a in B rest frame	$\gg$	QCD-bound state effects
$m_W \sim 80$ GeV $m_Z \sim 91$ GeV	$\gg$	$m_b \sim 5$ GeV	$\gg$	$\Lambda_{\rm QCD} \sim 1$ GeV

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

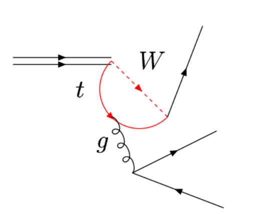
  [Buras, Buchalla, Lautenbacher '96; Chetyrkin, Misiak, Munz '98]

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

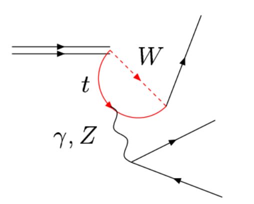
- **Wilson coefficients C_i:** all physics above m_b; perturbatively calculable, and NNLL program now complete; [Gorbahn,Haisch '04]



tree



QCD penguin



EW penguin

Hadronic matrix elements

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

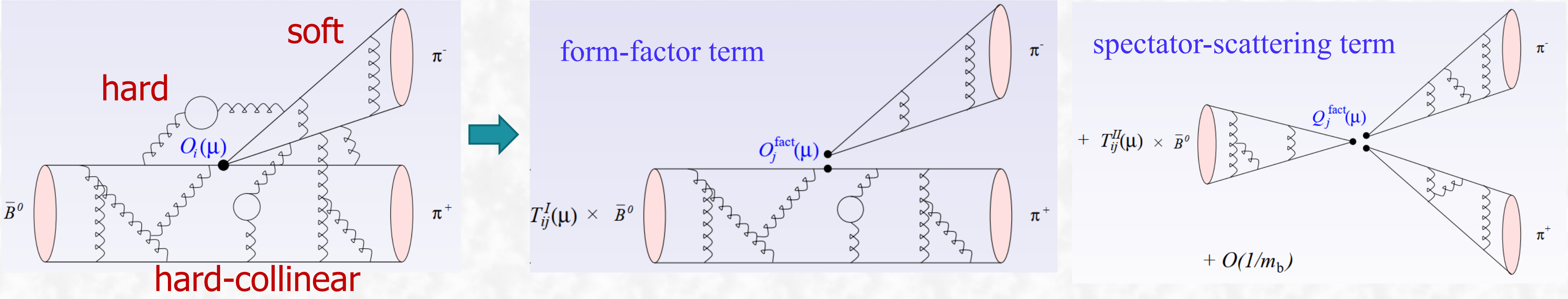
$$\mathcal{A}(\bar{B} \to f) = \sum_i [\lambda_{\rm CKM} \times C \times \langle f|\mathcal{O}|\bar{B}\rangle_{\rm QCD+QED}]_i$$

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

- **Different methods for dealing with $\langle M_1 M_2|\mathcal{O}_i|\bar{B}\rangle$:**

  - 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 limited by $1/m_b$ corrections. [BBNS '99-'03]

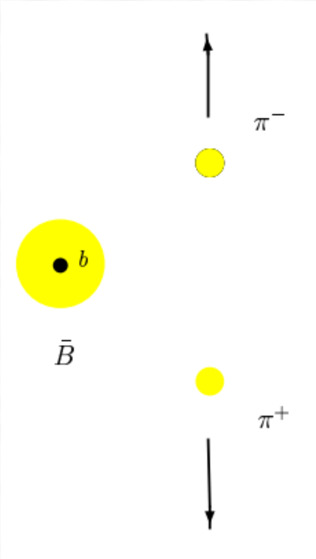


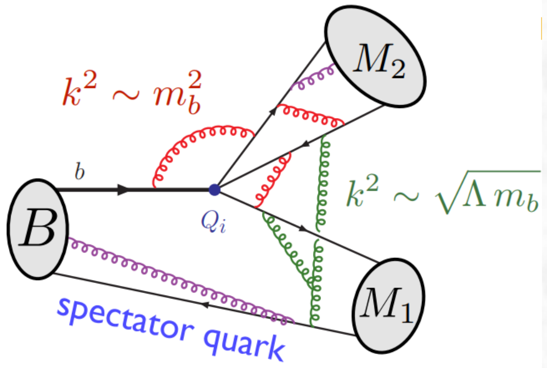
Soft-collinear factorization from SCET

- **QCDF formula:** based on diagrammatic factorization (method of regions, [Beneke, Smirnov '97]) combining $1/m_b$ expansion with light-cone expansion for hard processes; [Lepage, Brodsky '80]

- **SCET:** a suitable framework for studying factorization and re-summation for processes involving light but energetic particles; [Bauer etal. '00; Beneke etal. '02; Becher, Broggio, Ferroglia '14]

- **For a two-body decay:** simple kinematics, but complicated dynamics with several typical scales;





- low-virtuality modes:
  - ⋆ HQET fields: $p - m_b v \sim \mathcal{O}(\Lambda)$
  - ⋆ soft spectators in B meson: $p_s^\mu \sim \Lambda \ll m_b, \quad p_s^2 \sim \mathcal{O}(\Lambda^2)$
  - ⋆ collinear quarks and gluons in pion: $E_c \sim m_b, \quad p_c^2 \sim \mathcal{O}(\Lambda^2)$
- high-virtuality modes:
  - ⋆ hard modes: (heavy quark + collinear)$^2 \sim \mathcal{O}(m_b^2)$
  - ⋆ hard-collinear modes: (soft + collinear)$^2 \sim \mathcal{O}(m_b\Lambda)$

- **SCET point of view:** introduce different fields for different momentum regions;

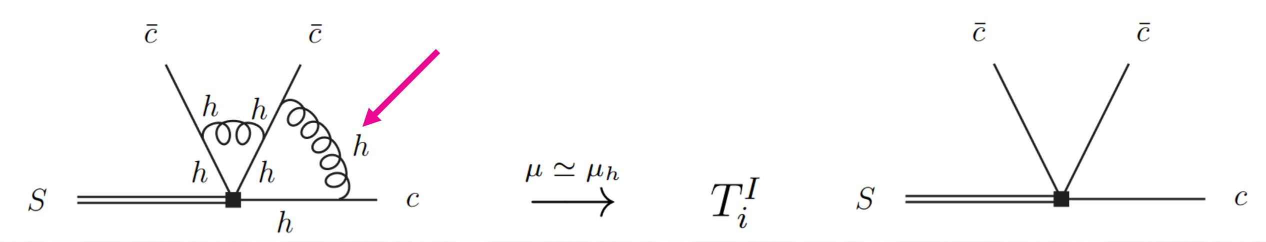
➡ achieve *soft-collinear factorization* via QFT machinery! [Beneke, 1501.07374]

Soft-collinear factorization from SCET

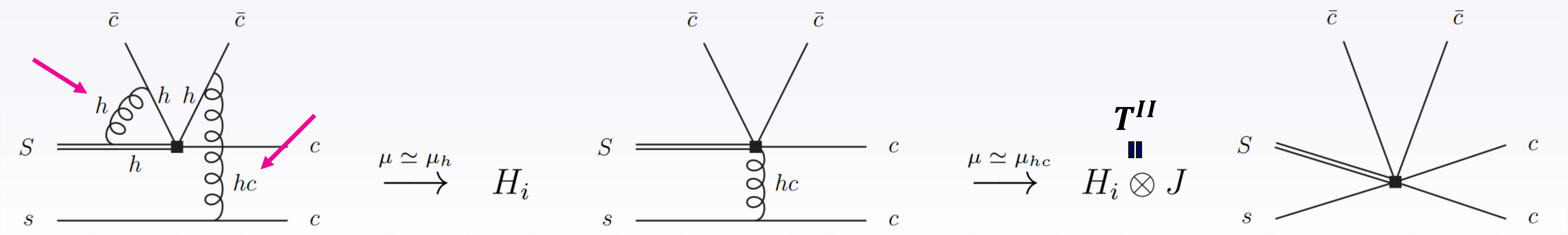
- **SCET diagrams reproduce precisely QCD diagrams in collinear & soft momentum regions**

→ **QCD - SCET = short-distance coefficients T^I & T^{II}**

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



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

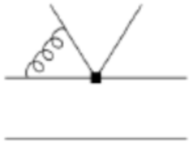
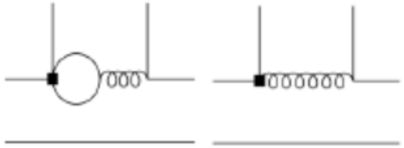
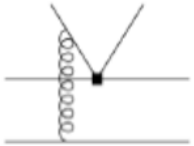
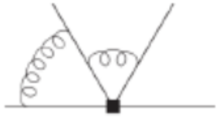
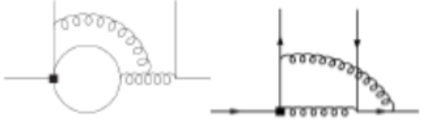
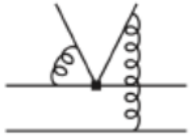
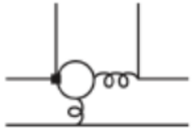


- **SCET result exactly the same as QCDF, but more apparent & efficient;** [Beneke, 1501.07374]

Status of the NNLO calculation of T^I & T^{II}

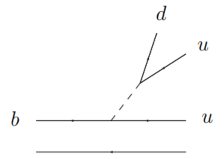
- **For each Q_i insertion, both tree & penguin topologies, and contribute to both T^I & T^{II}.**

$$\langle M_1 M_2 | Q_i | B \rangle \simeq F^{BM_1} \, T_i^I \otimes \phi_{M_2} + T_i^{II} \otimes \phi_B \otimes \phi_{M_1} \otimes \phi_{M_2}$$

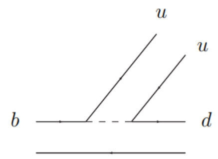
	T^I, tree	T^I, penguin	T^{II}, tree	T^{II}, penguin
LO: $\mathcal{O}(1)$		$T^I = 1 + \mathcal{O}(\alpha_s) + \cdots$	$T^{II} = \mathcal{O}(\alpha_s) + \cdots$	
NLO: $\mathcal{O}(\alpha_s)$ BBNS '99-'04				
NNLO: $\mathcal{O}(\alpha_s^2)$	 Bell '07,'09 Beneke, Huber, Li '09 **Huber, Krankl, Li '16**	 Kim, Yoon '11, Bell Beneke, Huber, Li '15 **Bell, Beneke, Huber, Li '20**	 Beneke, Jager '05 Kivel '06, Pilipp '07	 Beneke, Jager '06 Jain, Rothstein, Stewart '07

Status of the NNLO calculation of T^{I} & T^{II}

- **Complete NNLO calculation for T^{I} & T^{II} at leading power in QCDF/SCET now complete;**
- **Soft-collinear factorization at 2-loop established via explicit calculations;**
- **For tree amplitudes, cancellation between T^{I} & T^{II};**



colour-allowed tree α_1

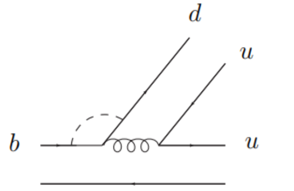


colour-suppressed tree α_2

$$\begin{aligned}\alpha_1(\pi\pi) &= 1.009 + [0.023 + 0.010\,i]_{\rm NLO} + [0.026 + 0.028\,i]_{\rm NNLO} \\ &\quad - \left[\frac{r_{\rm sp}}{0.445}\right]\left\{[0.014]_{\rm LOsp} + [0.034 + 0.027i\,]_{\rm NLOsp} + [0.008]_{\rm tw3}\right\} \\ &= 1.000^{+0.029}_{-0.069} + (0.011^{+0.023}_{-0.050})i\end{aligned}$$

$$\begin{aligned}\alpha_2(\pi\pi) &= 0.220 - [0.179 + 0.077\,i]_{\rm NLO} - [0.031 + 0.050\,i]_{\rm NNLO} \\ &\quad + \left[\frac{r_{\rm sp}}{0.445}\right]\left\{[0.114]_{\rm LOsp} + [0.049 + 0.051i\,]_{\rm NLOsp} + [0.067]_{\rm tw3}\right\} \\ &= 0.240^{+0.217}_{-0.125} + (-0.077^{+0.115}_{-0.078})i\end{aligned}$$

- **For leading-power QCD penguin amplitudes, cancellation between $Q^{p}_{1,2}$ & $Q_{3-6,8g}$**

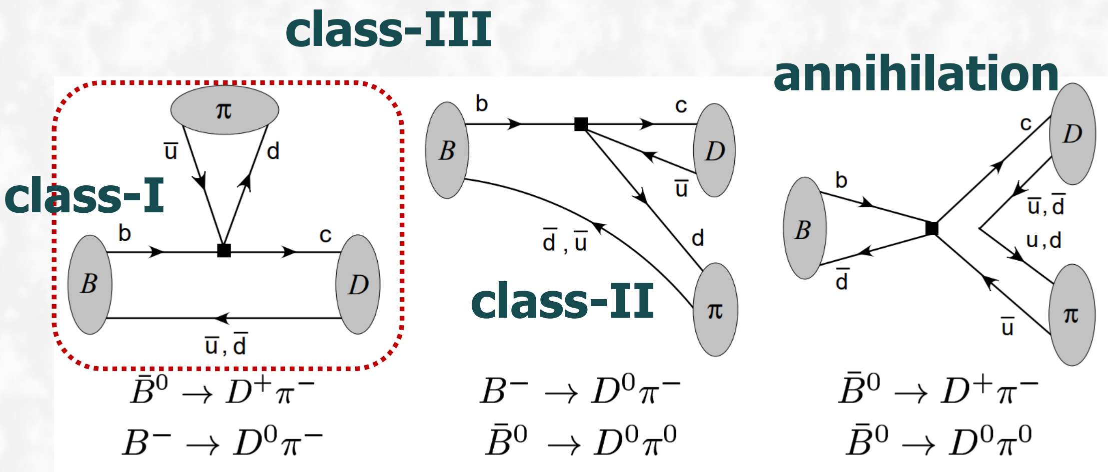


QCD penguins α_4

$$\begin{aligned}a_4^u(\pi\bar{K})/10^{-2} &= -2.87 - [0.09 + 0.09i]_{\rm V_1} + [0.49 - 1.32i]_{\rm P_1} - [0.32 + 0.71i]_{\rm P_2,\,Q_{1,2}} + [0.33 + 0.38i]_{\rm P_2,\,Q_{3-6,8}} \\ &\quad + \left[\frac{r_{\rm sp}}{0.434}\right]\left\{[0.13]_{\rm LO} + [0.14 + 0.12i]_{\rm HV} - [0.01 - 0.05i]_{\rm HP} + [0.07]_{\rm tw3}\right\} \\ &= (-2.12^{+0.48}_{-0.29}) + (-1.56^{+0.29}_{-0.15})i\,,\end{aligned}$$

Class-I $\bar{B}_q^0 \to D_q^{(*)+} L^-$ decays at NNLO in QCDF/SCET

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



- **At quark-level: mediated by $b \to c\bar{u}d(s)$**

  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 formula 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 are power-suppressed;

iii) annihilation absent in $B^0_{d(s)} \to D^-_{d(s)} K(\pi)^+$ etal;

iv) they are theoretically simpler and cleaner!

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

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

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

Calculation of T:

☐ Matching QCD onto SCET$_\mathrm{I}$: [Huber, Kränkl, Li '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.

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

physical operators and factorizes into FF*LCDA.

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

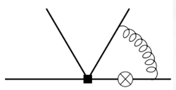
$$\mathcal{O}'_1 = \bar{\chi} \frac{\not{n}_-}{2} (1-\gamma_5) \chi \;\; \bar{h}_{v'} \not{n}_+ (1+\gamma_5) h_v \,,$$
$$\mathcal{O}'_2 = \bar{\chi} \frac{\not{n}_-}{2} (1-\gamma_5) \gamma_\perp^\alpha \gamma_\perp^\beta \chi \;\; \bar{h}_{v'} \not{n}_+ (1+\gamma_5) \gamma_{\perp,\alpha} \gamma_{\perp,\beta}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

evanescent operators and must be renormalized to zero.

☐ Renormalized on-shell QCD amplitudes:

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

on QCD side



☐ Renormalized on-shell SCET amplitudes:

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

on SCET side

☐ Master formulas for hard kernels:

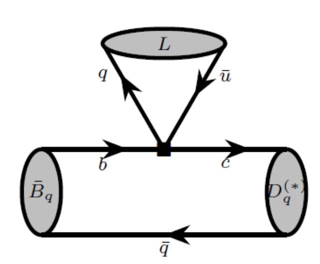
$$T = T^{(0)} + \alpha_s T^{(1)} + \alpha_s^2 T^{(2)} + O(\alpha_s^3)$$

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

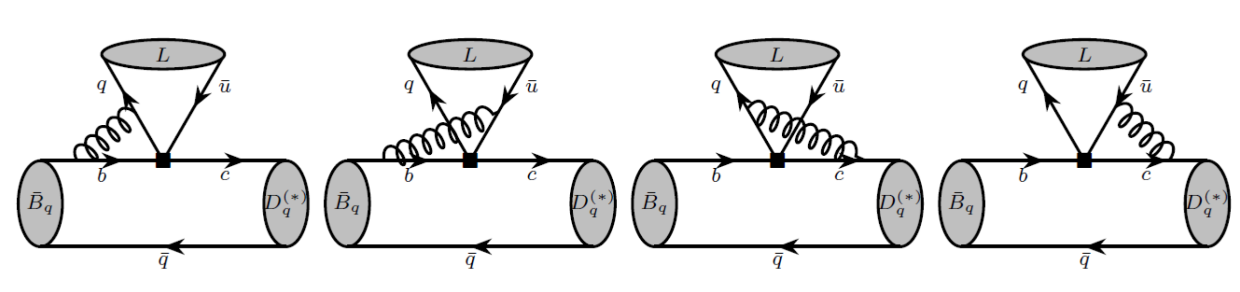
Calculation of T:

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

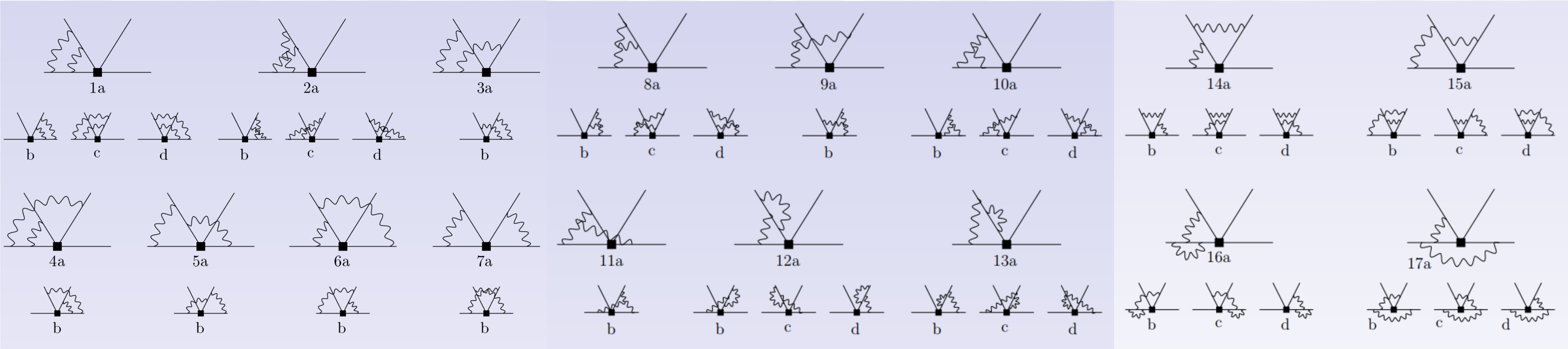
- $A_{i1}^{(0)}$:

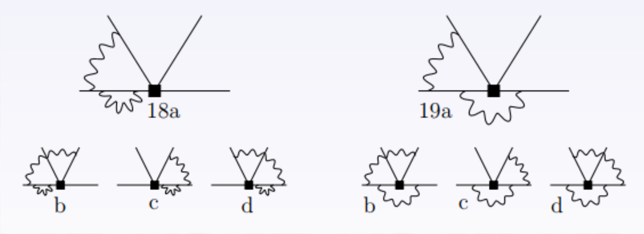


- $A_{i1}^{(1)nf}$: [Beneke, Buchalla, Neubert, Sachrajda '01]



- $A_{i1}^{(2)nf}$: [Huber, Kränkl, Li '16]





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

Calculation of T:

☐ Master formulas for hard kernels:

$$
\begin{aligned}
\hat{T}_i^{(0)} &= A_{i1}^{(0)} \\
\hat{T}_i^{(1)} &= A_{i1}^{(1)nf} + Z_{ij}^{(1)} A_{j1}^{(0)} \\
\hat{T}_i^{(2)} &= A_{i1}^{(2)nf} + Z_{ij}^{(1)} A_{j1}^{(1)} + Z_{ij}^{(2)} A_{j1}^{(0)} + Z_{\alpha}^{(1)} A_{i1}^{(1)nf} - \hat{T}_i^{(1)} \left[C_{FF}^{\mathrm{D}(1)} + Y_{11}^{(1)} - Z_{\mathrm{ext}}^{(1)} \right] \\
&\quad - C_{FF}^{\mathrm{ND}(1)} \hat{T}_i^{\prime(1)} + (-i)\delta m_b^{(1)} A_{i1}^{*(1)nf} + (-i)\delta m_c^{(1)} A_{i1}^{**(1)nf} - \sum_{b \neq 1} H_{ib}^{(1)} Y_{b1}^{(1)} .
\end{aligned}
$$

☐ Complete operator basis under renormalization:

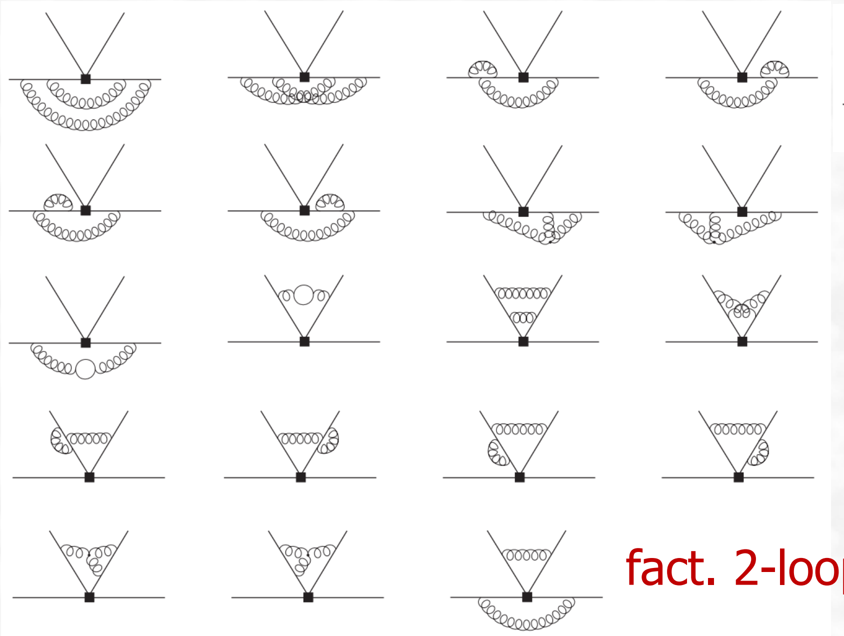
$$
\begin{aligned}
\mathcal{Q}_1^p &= \bar{p}\gamma^\mu(1-\gamma_5)T^A b \;\; \bar{d}\gamma_\mu(1-\gamma_5)T^A u \,, \\
\mathcal{Q}_2^p &= \bar{p}\gamma^\mu(1-\gamma_5) b \;\; \bar{d}\gamma_\mu(1-\gamma_5) u \,,
\end{aligned}
$$

physical operators

$$
\begin{aligned}
E_1^{(1)} &= [\bar{c}\gamma^\mu\gamma^\nu\gamma^\rho(1-\gamma_5)T^A b]\,[\bar{u}\gamma_\mu\gamma_\nu\gamma_\rho(1-\gamma_5)T^A d] - 16 Q_1^c \,, \\
E_2^{(1)} &= [\bar{c}\gamma^\mu\gamma^\nu\gamma^\rho(1-\gamma_5) b]\,[\bar{u}\gamma_\mu\gamma_\nu\gamma_\rho(1-\gamma_5) d] - 16 Q_2^c \,, \\
E_1^{(2)} &= [\bar{c}\gamma^\mu\gamma^\nu\gamma^\rho\gamma^\sigma\gamma^\lambda(1-\gamma_5)T^A b]\,[\bar{u}\gamma_\mu\gamma_\nu\gamma_\rho\gamma_\sigma\gamma_\lambda(1-\gamma_5)T^A d] - 20 E_1^{(1)} - 256 Q_1^c \,, \\
E_1^{(2)} &= [\bar{c}\gamma^\mu\gamma^\nu\gamma^\rho\gamma^\sigma\gamma^\lambda(1-\gamma_5) b]\,[\bar{u}\gamma_\mu\gamma_\nu\gamma_\rho\gamma_\sigma\gamma_\lambda(1-\gamma_5) d] - 20 E_2^{(1)} - 256 Q_2^c \,.
\end{aligned}
$$

evanescent operators

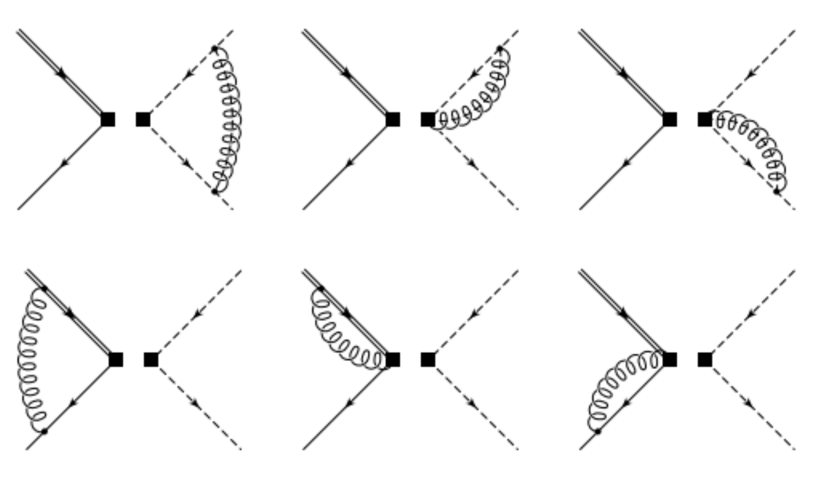
☐ Factorizable QCD and SCET diagrams:



fact. 2-loop

fact. 1-loop

☐ Renormalization constants of SCET operators:



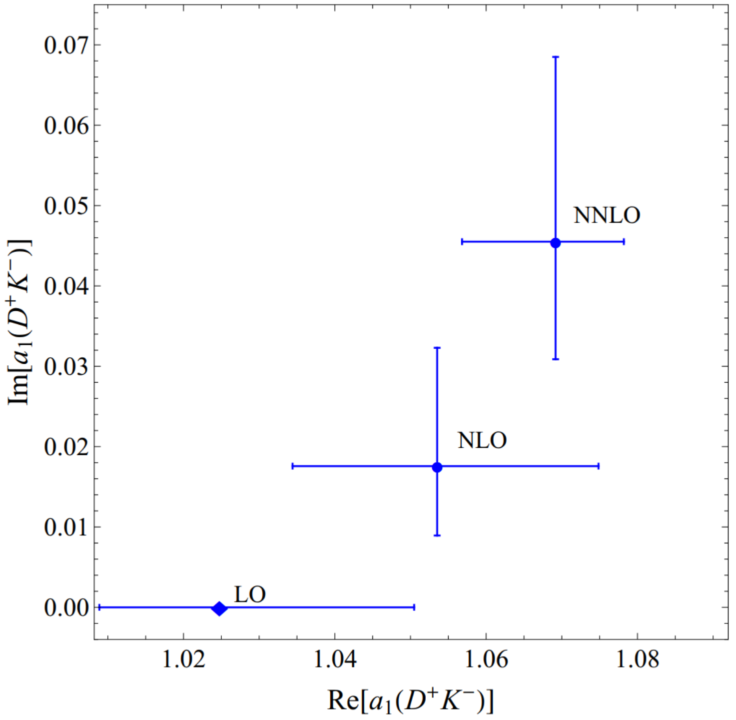
Decay amplitudes for $B_q^0 \to D_q^- L^+$

☐ Color-allowed tree amplitude:

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

☐ Numerical result:

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



◆ **both NLO and NNLO add always constructively to LO result!**

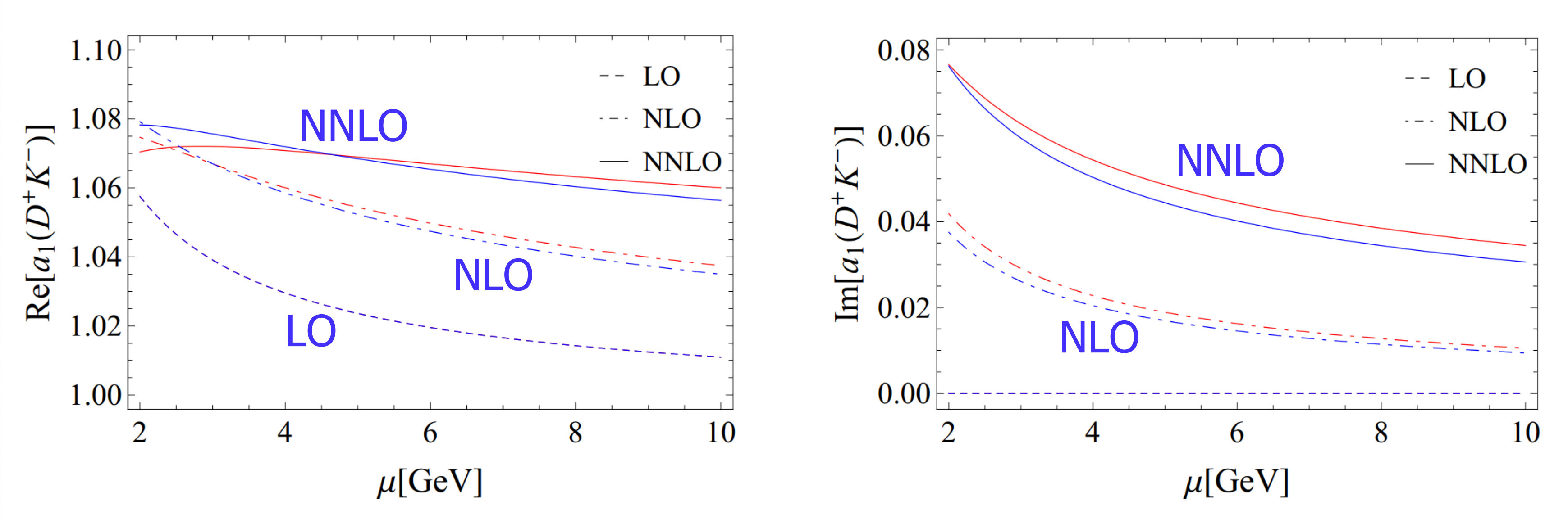
◆ **NNLO corrections quite small in real (2%), but rather large in imaginary part (60%).**

within QCDF/SCET, imaginary part appears firstly at NLO term and the NLO result is *color-suppressed* and $\propto$ *small* $C_1 = -0.29$, while the NNLO term $\propto C_2 = 1.01$.

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.

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

- **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:**

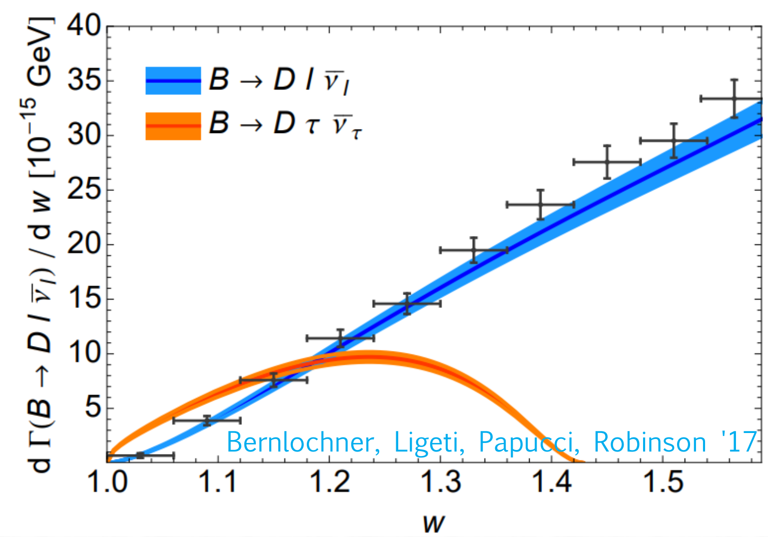
Precision results available based on LQCD & LCSR calculations, together with data on $B_q^0 \to D_q^- l^+ \nu$;

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

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

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

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



- **Updated predictions vs data:**

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

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

$|V_{cb}|$ and $B_{d,s} \to D^{(*)}_{d,s}$ form factors

Non-leptonic/semi-leptonic ratios

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

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

free from uncertainties from $|V_{cb}|$ & $B_{d,s} \to D_{d,s}^{(*)}$ form factors.

Updated predictions vs data: [Huber, Kränkl, Li '16; Cai, Deng, Li, 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

For a rough estimate:

$$\frac{Br^{Exp.}}{Br^{SM}} \simeq \frac{|a_1^{BSM}|^2}{|a_1^{SM}|^2} = 0.6$$

$$\Longrightarrow \frac{a_1^{BSM}}{a_1^{SM}} \simeq 0.77 = 1 - 0.23$$

$$= \frac{a_1^{SM} + \delta a_1^{BSM}}{a_1^{SM}} \simeq 1 + \frac{\delta a_1^{BSM}}{a_1^{SM}}$$

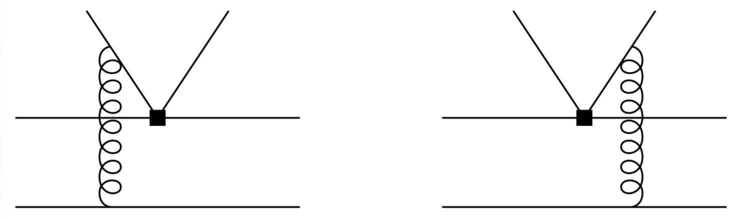
$$\Longrightarrow \quad \delta a_1^{BSM} \simeq -0.2$$

Power corrections

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

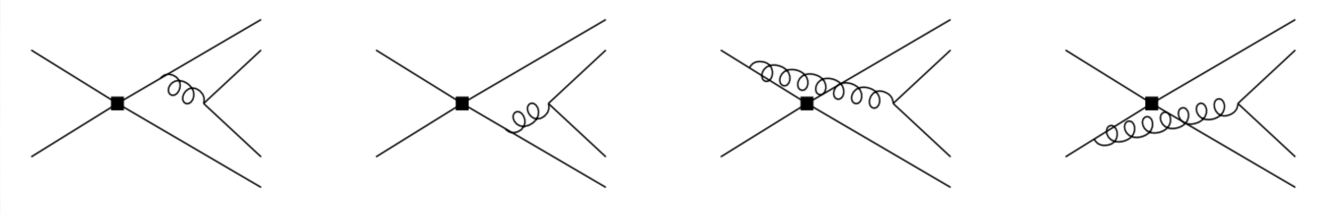
◻ Sources of sub-leading power corrections: [Beneke, Buchalla, Neubert, Sachrajda '01; Bordone, Gubernari, Huber, Jung, van Dyk '20]

- Non-factorizable spectator interactions;



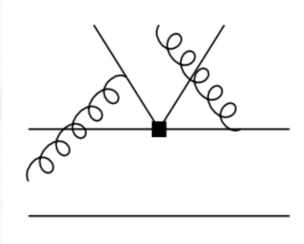
$\frac{\Lambda_{\rm QCD}}{m_b}$

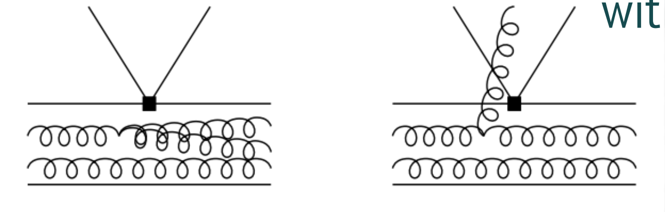
- Annihilation topologies;



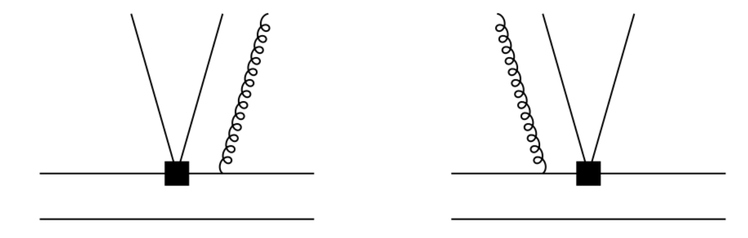
- Non-leading Fock-state contributions;

included into FFs.





estimated with LCSR



$\left(\frac{\Lambda_{\rm QCD}}{m_b}\right)^2$

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

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

- $\propto \frac{C_1}{a_1} \simeq -\frac{1}{3}$, all are ESTIMATED to be power-suppressed; not chirality-enhanced due to (V-A)(V-A) structure
- Current exp. data could not be easily explained within the SM, at least within the QCDF/SCET framework.

Possible New Physics effects from four-quark operators

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

- **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

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

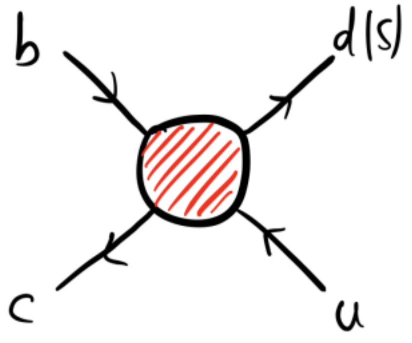
$$\mathcal{Q}_2^{VLL} = (\bar{c}_\alpha \gamma^\mu P_L b_\alpha)(\bar{q}_\beta \gamma_\mu P_L u_\beta) \qquad \mathcal{Q}_2^{VLR} = (\bar{c}_\alpha \gamma^\mu P_L b_\alpha)(\bar{q}_\beta \gamma_\mu P_R u_\beta)$$

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

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

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

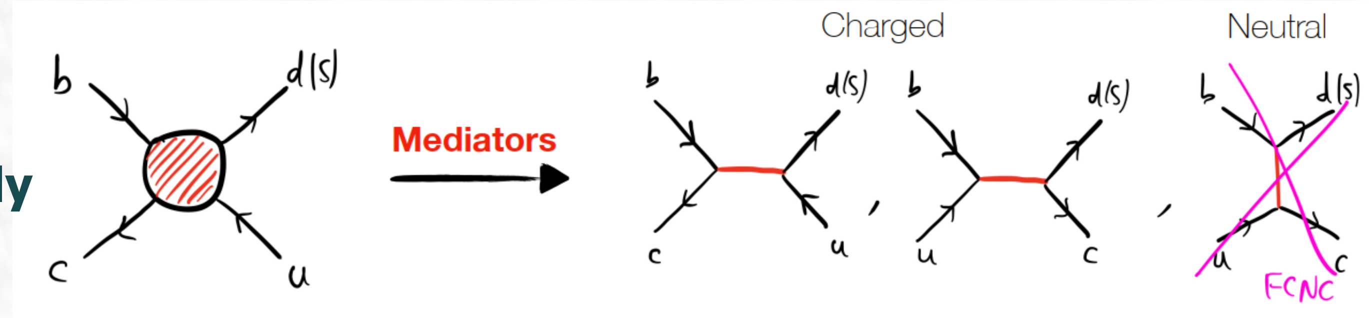
$$\mathcal{Q}_4^{SLL} = (\bar{c}_\alpha \sigma^{\mu\nu} P_L b_\alpha)(\bar{q}_\beta \sigma_{\mu\nu} P_L u_\beta)$$



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

Possible sources of these NP operators

- **Possible tree-level mediators:**

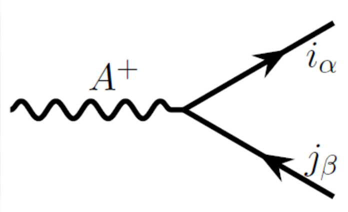


  - **For neutral mediators, necessarily couple to FCNC at tree level;**
    ➡ **excluded by FCNC processes!**

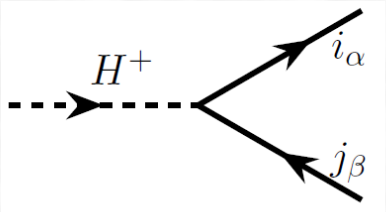
  - **For charged mediators: colorless or colored (limited by di-jet resonance searches)**

[Bordone, Greljo, Marzocca, 2103.10332]

- **For VLL, VRR, VLR, VRL sectors: generated by a colorless charged gauge boson A^+ (spin-1);**



- **For SLL, SRR, SLR, SRL sectors: generated by a colorless charged scalar H^+ (spin-0);**



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^+.

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

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

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

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

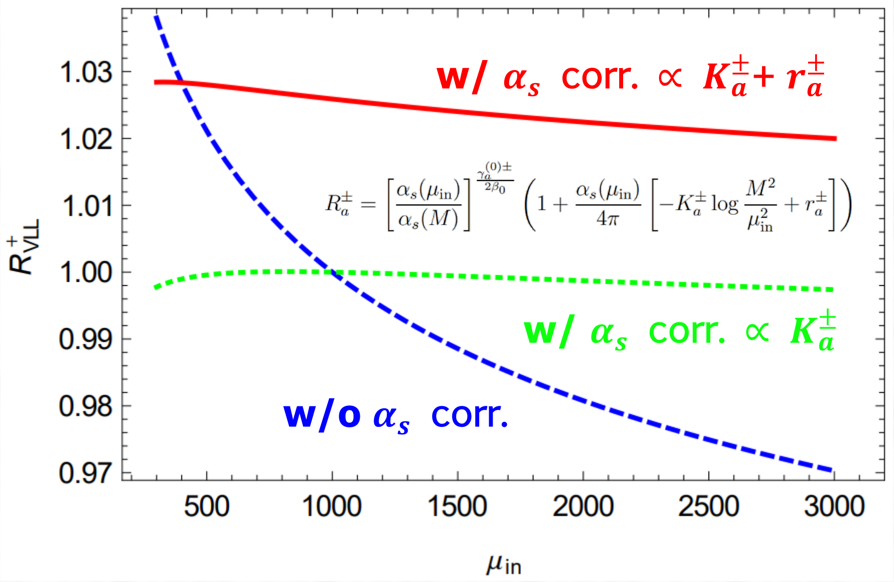
a colorless charged gauge boson A^+.

- **RG evolution from down $M_{A,H}$ to m_b at NLL;**

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

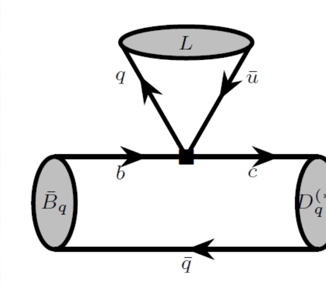
$$\vec{C}(\mu_b) = \left(\mathbb{1} + \frac{\alpha_s(\mu_b)}{4\pi}\hat{J}\right)\hat{U}^{(0)}(\mu_b,\mu_{\rm in})\left(\mathbb{1} - \frac{\alpha_s(\mu_{\rm in})}{4\pi}\left(\vec{C}_1 + \hat{J}\vec{C}_0\right)\right)$$

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



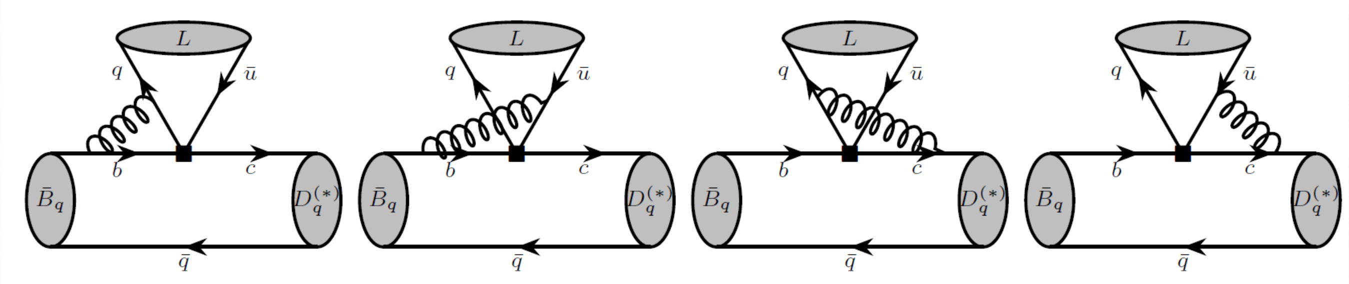
Matrix elements of NP operators

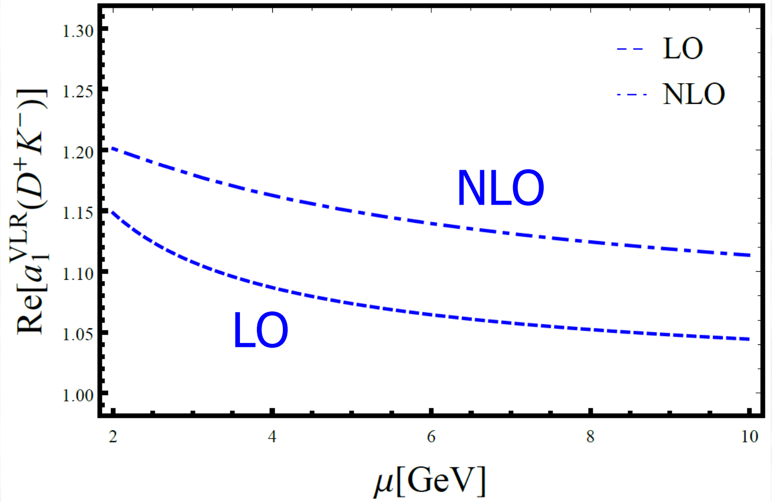
- $\langle D^+ L^- | \mathcal{O}_i | \bar{B}^0 \rangle$: calculated in QCDF at leading-power in $1/m_b$, but including $\mathcal{O}(\alpha_s)$ vertex correction.

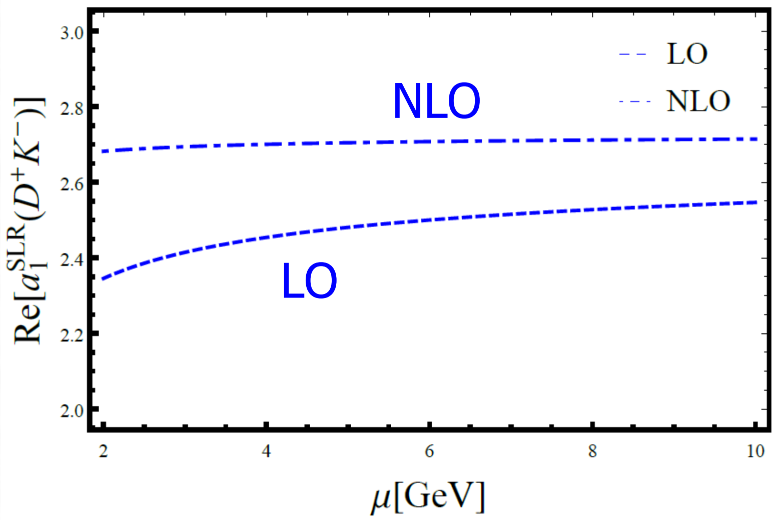


LO

NLO non-factorizable vertex corrections







- **With NLL Wilson coefficients and NLO matrix elements, un-physical scale- & scheme-dependences cancelled in the final decay amplitude.**

Model-independent analysis

- NP 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 allowed 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!

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

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

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

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

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]	∅
	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]	∅
	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]	∅	[-0.711,-0.368]	[-1.50,-0.133]	R	[-0.839,-0.412]	[-1.25,-0.712]	∅
	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]	∅	[-0.237,-0.123]	[-0.500,-0.044]	R	[-0.280,-0.137]	[-0.417,-0.237]	∅
	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]	∅	[0.429,0.829]	[0.155,1.75]	R	[0.480,0.979]	[0.830,1.46]	∅
	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]	∅	[0.123,0.237]	[0.044,0.500]	R	[0.137,0.280]	[0.237,0.416]	∅
	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]

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

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

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

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

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

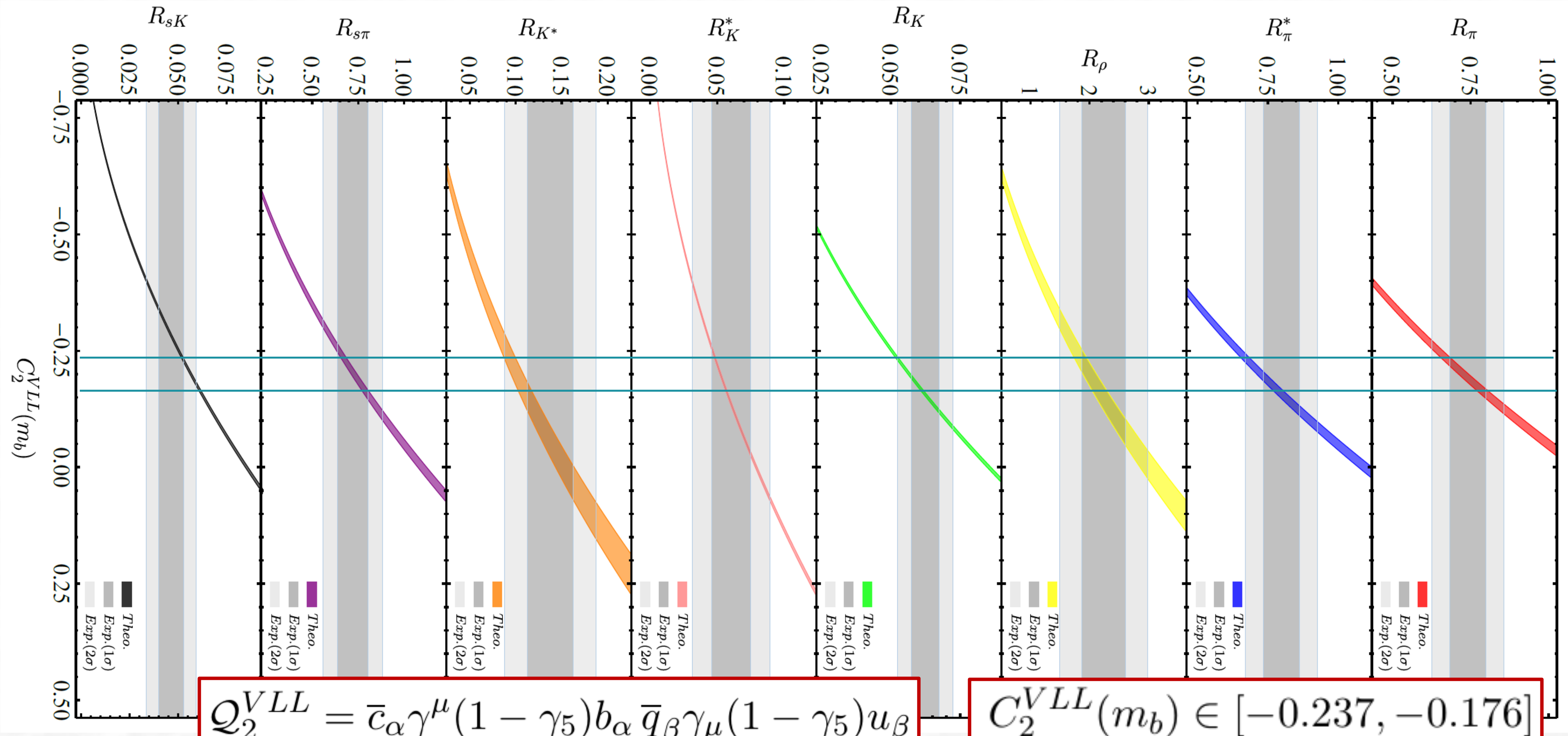
$(S+P)\otimes(S+P)$

- 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 8 ratios;

Analysis at m_b scale

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

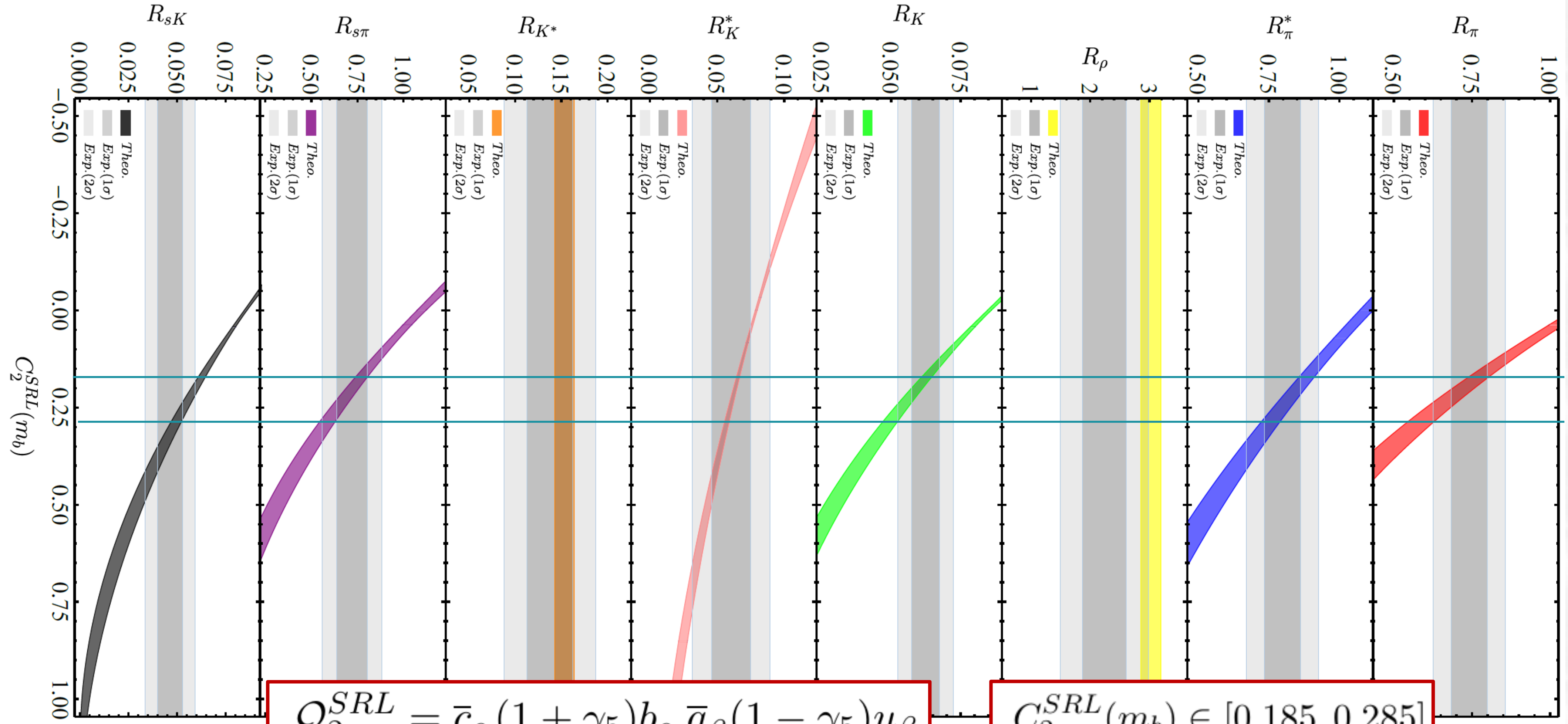


$$Q_2^{VLL} = \bar{c}_\alpha \gamma^\mu (1-\gamma_5) b_\alpha \, \bar{q}_\beta \gamma_\mu (1-\gamma_5) u_\beta$$

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

Analysis at m_b scale

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

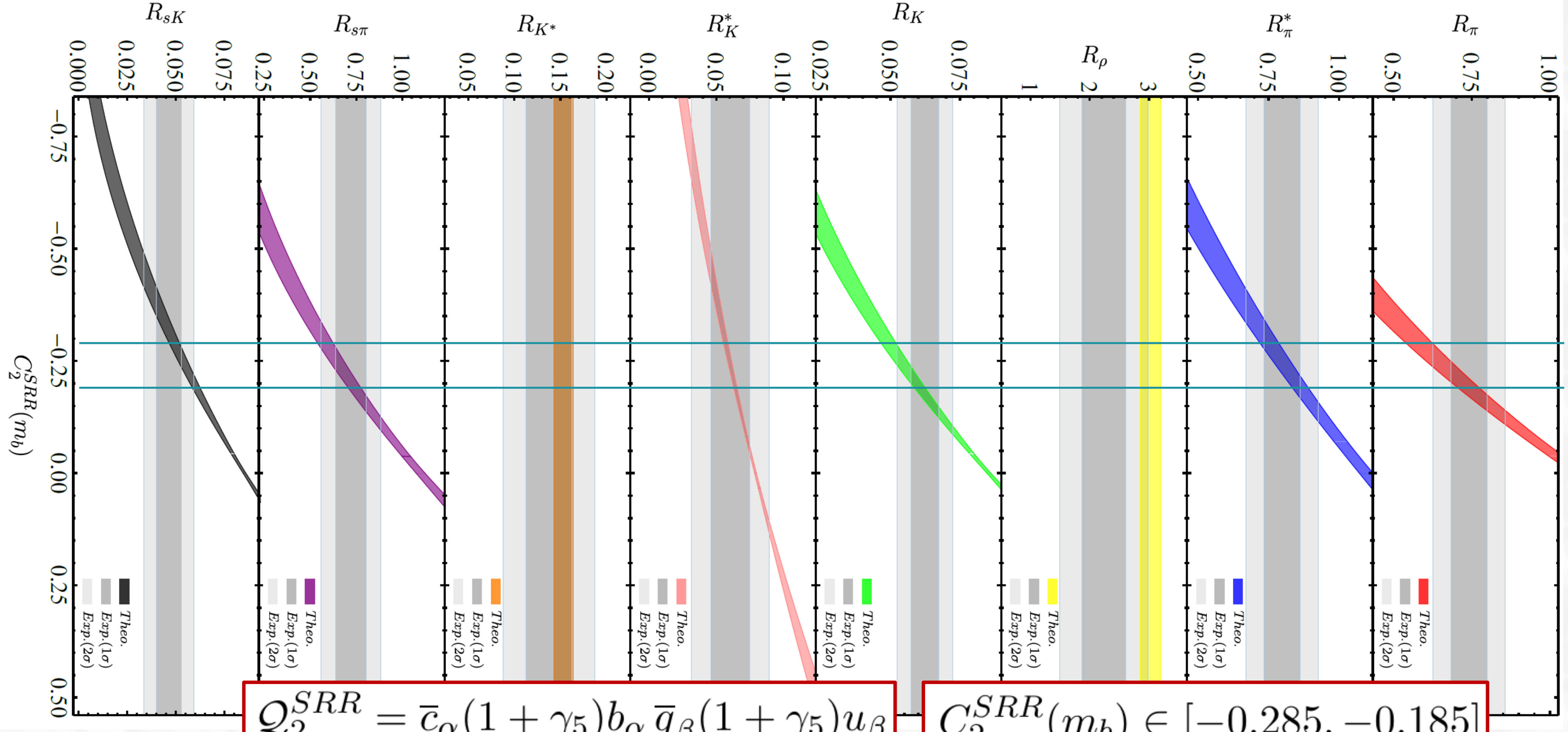


$$\mathcal{Q}_2^{SRL} = \bar{c}_\alpha(1+\gamma_5)b_\alpha\,\bar{q}_\beta(1-\gamma_5)u_\beta$$

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

Analysis at m_b scale

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

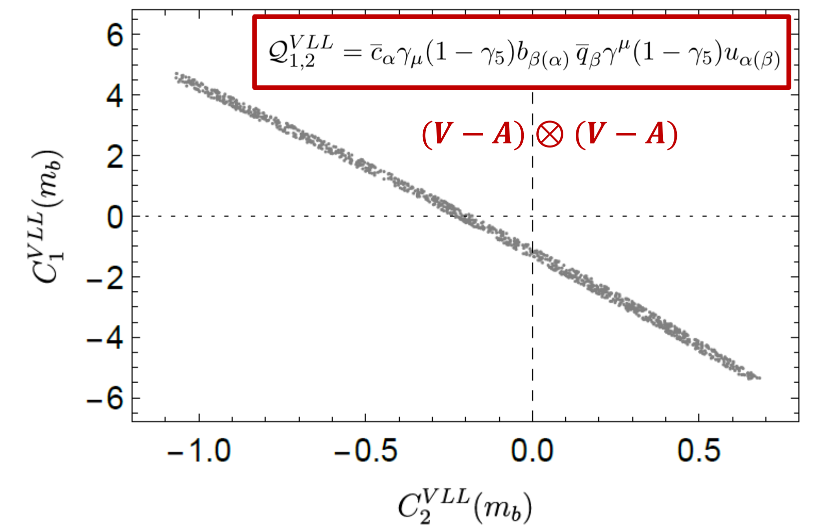


$$\mathcal{Q}_2^{SRR} = \bar{c}_\alpha(1+\gamma_5)b_\alpha\,\bar{q}_\beta(1+\gamma_5)u_\beta$$

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

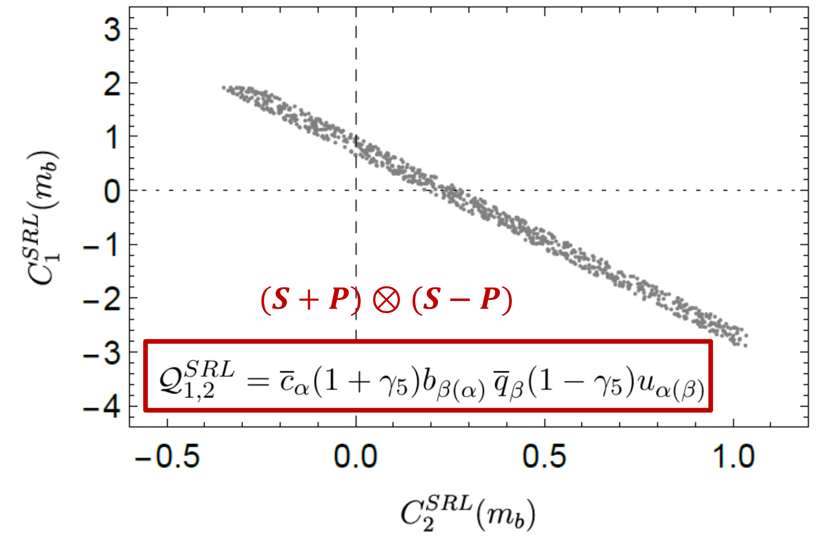
Analysis at m_b scale

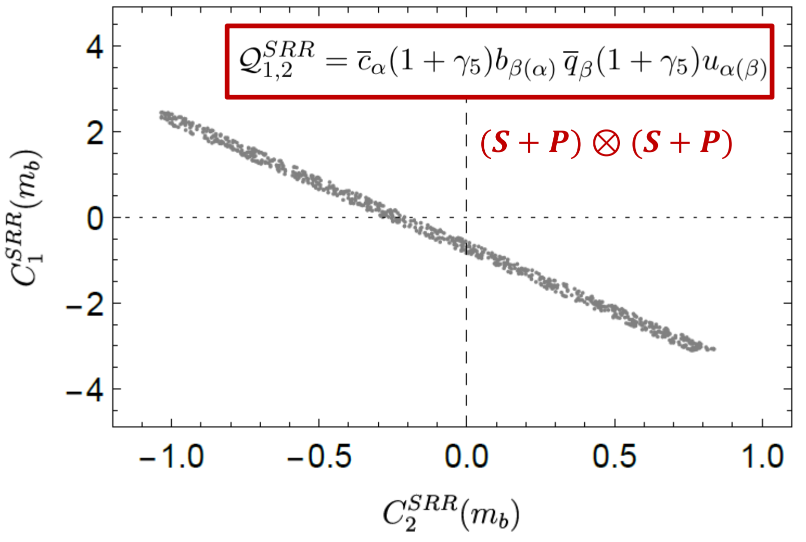
- **Two NP operators with the same Dirac but different color structures;**



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

- 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;**

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

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

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

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

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

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

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

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:**

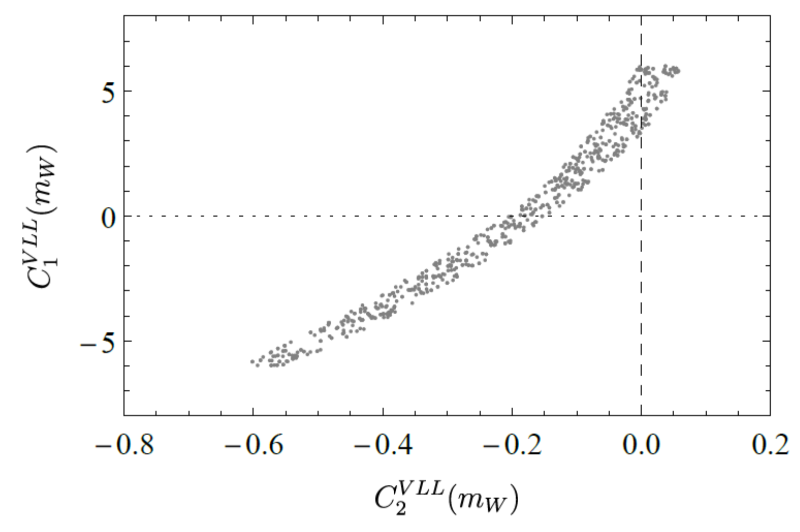
$C_2^{VLL}(M_W) \in [-0.220, -0.164]$ **vs** $C_2^{VLL}(m_b) \in [-0.237, -0.176]$

→ small RG evolution effect!

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

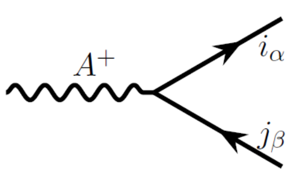
$C_2^{SRR}(m_W) \in [-0.129, -0.084]$ **vs** $C_2^{SRR}(m_b) \in [-0.285, -0.185]$

→ 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]

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

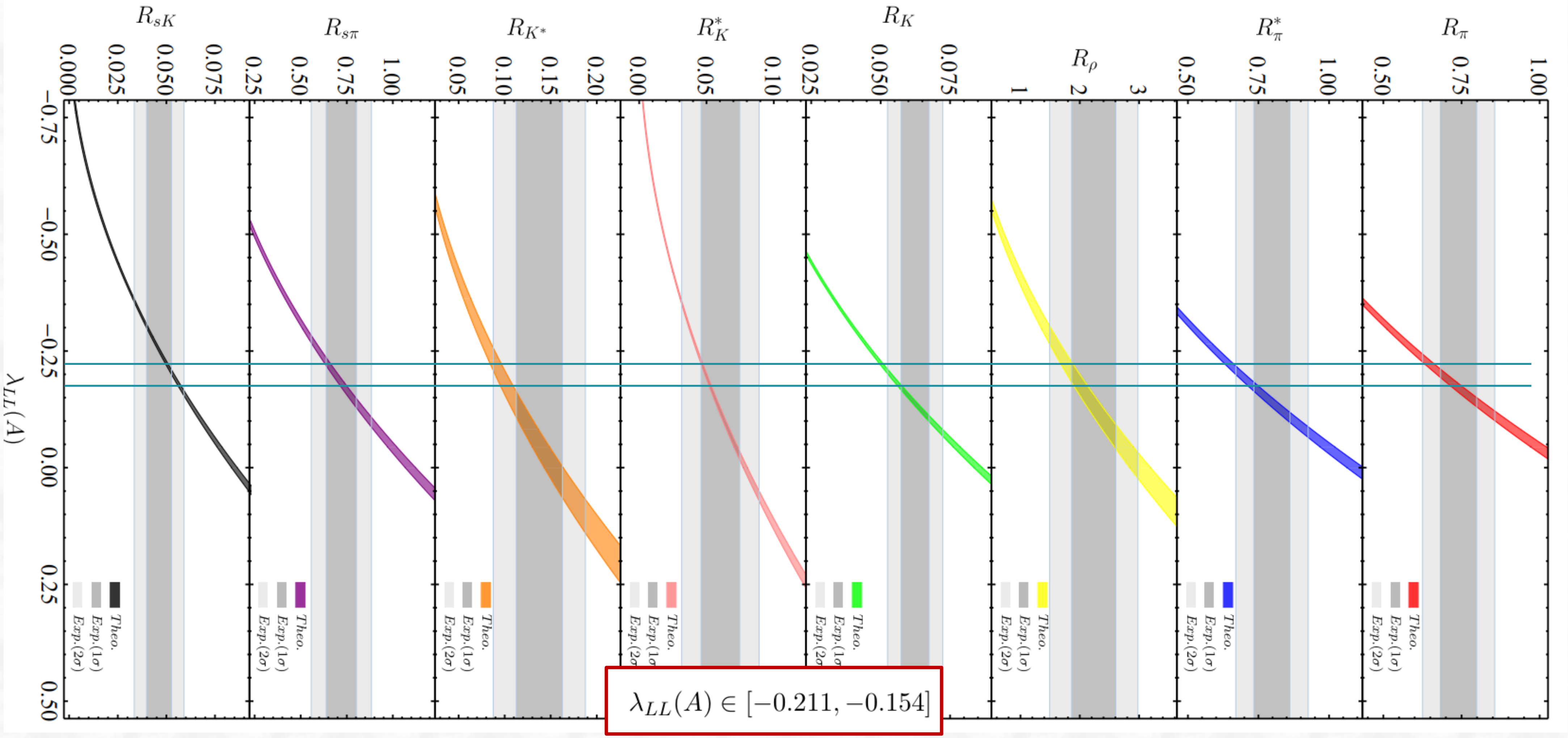
$$\lambda_{LL}(A) \in [-0.211, -0.154]$$

- **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⁺ couplings to quarks either vectorial or axial-vectorial!

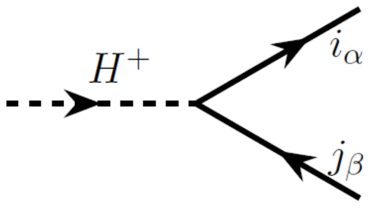
Case with a colorless gauge boson

- **Scenario I: only $\lambda_{LL}(A)$ nonzero; need A^+ couplings to quarks being of $V-A$ structure!**



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

Case with a colorless scalar



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

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

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

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

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

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

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

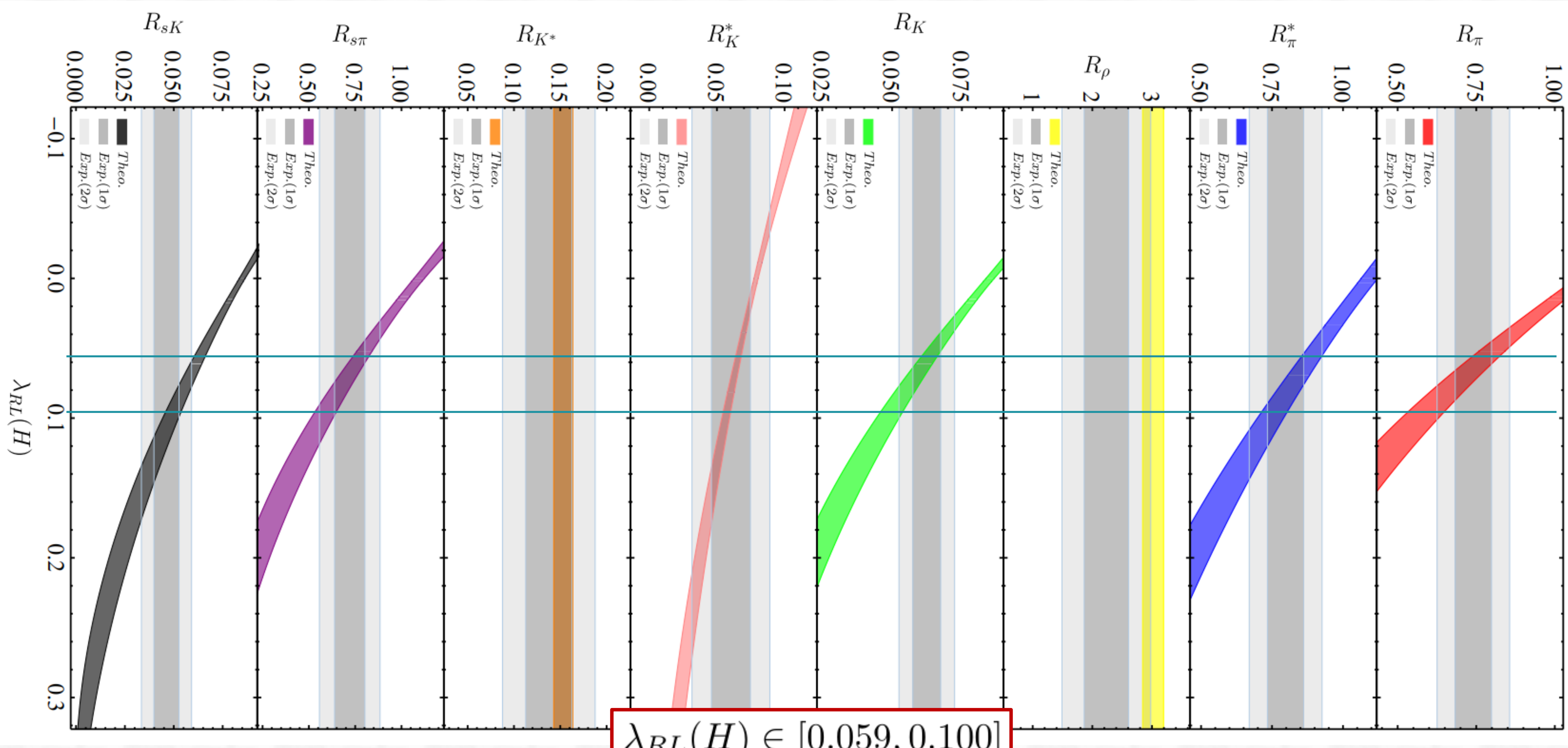
  - Scenario I: only one effective coefficient nonzero;

  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

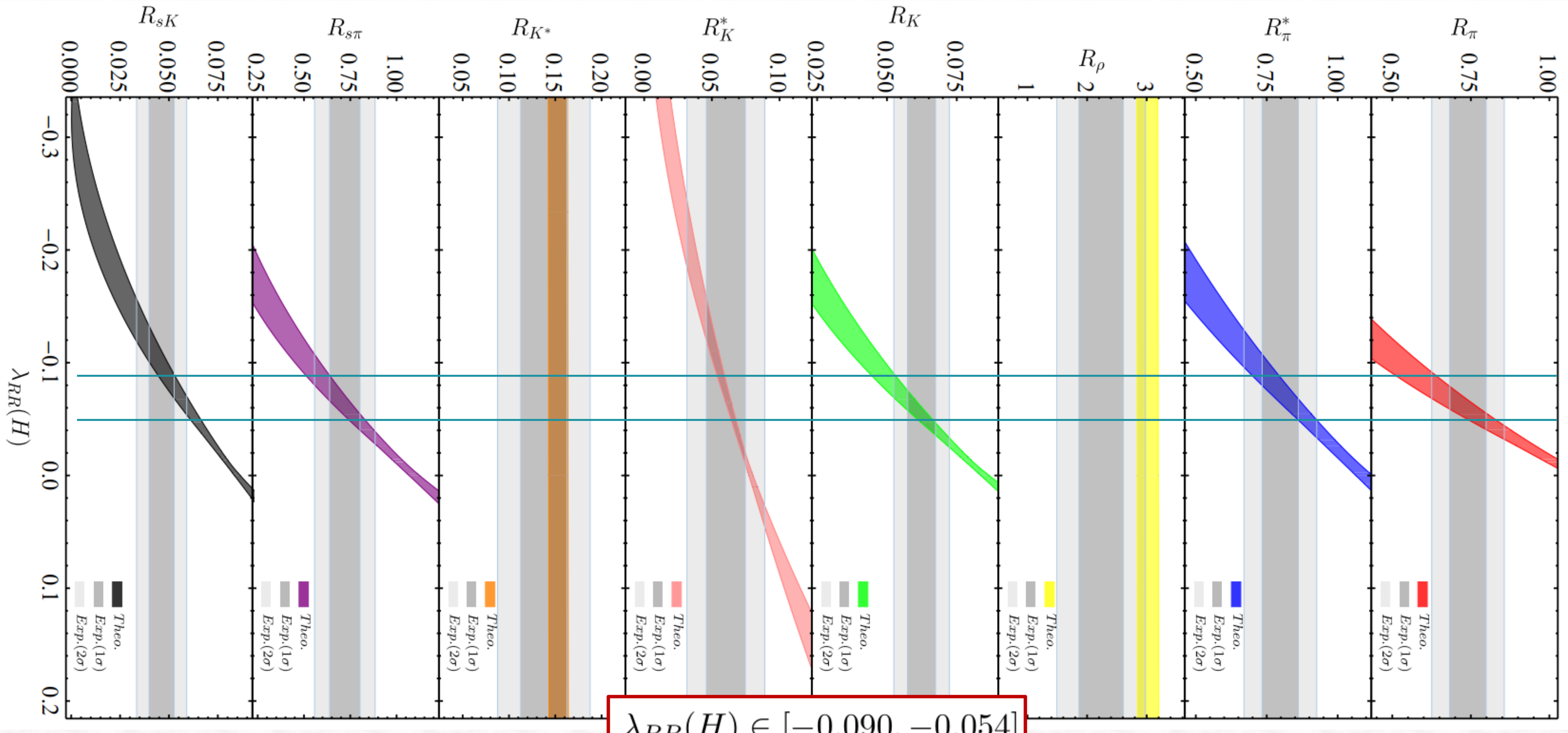
- ◻ **Scenario I: only $\lambda_{RL}(H)$ nonzero; need H^+ couplings to quarks being of $S \pm P$ structure!**



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

Case with a colorless scalar

- **Scenario I: only $\lambda_{RR}(H)$ nonzero; need H^+ couplings to quarks being of $S \pm P$ structure!**



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

Summary

- NNLO predictions for class-I $B_q^0 \to D_q^{(*)-} L^+$ decays at LP in QCDF/SCET complete.

- $\mathcal{O}(4\text{–}5\sigma)$ discrepancies observed between updated SM predictions and current exp. data;

  → sub-leading power corrections in QCDF/SCET or possible NP beyond the SM?

- Model-indep. analysis shows that only NP operators with 3 Dirac structures possible:

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

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

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

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

Thank You for your attention!