New physics implications from B physics

- selected topics -

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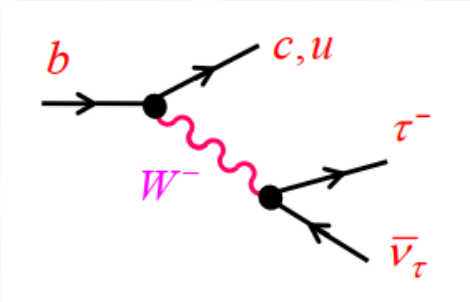
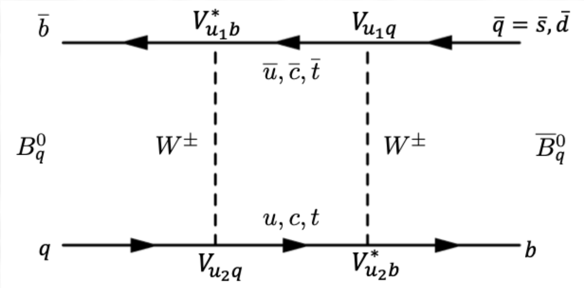
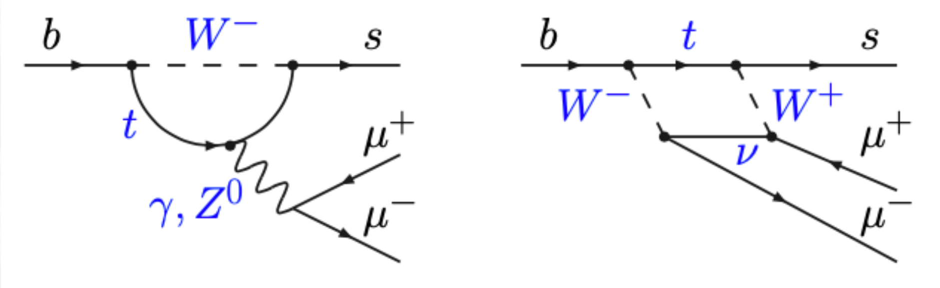
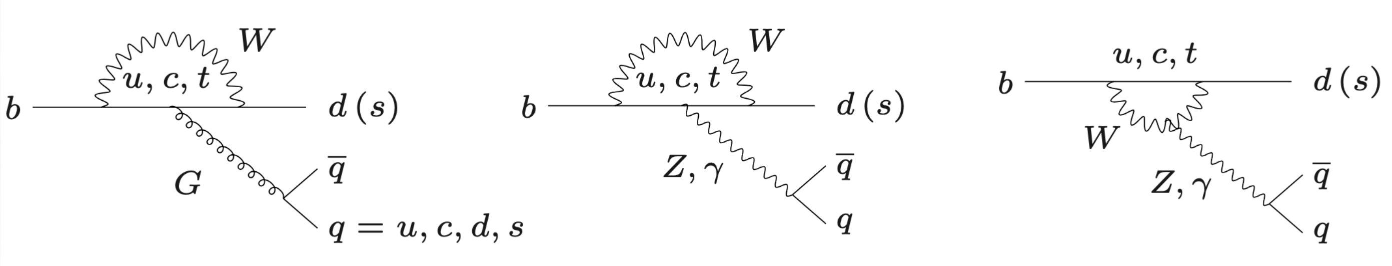
Outline

- ☐ Introduction
- ☐ Tree-level FCCC B decays
- ☐ Neutral B-meson mixings
- ☐ Rare FCNC B decays
- ☐ Hadronic B decays
- ☐ Summary



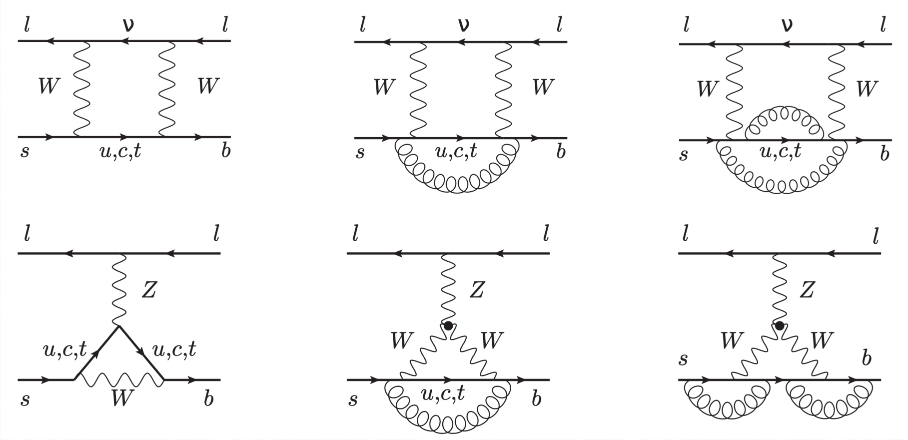




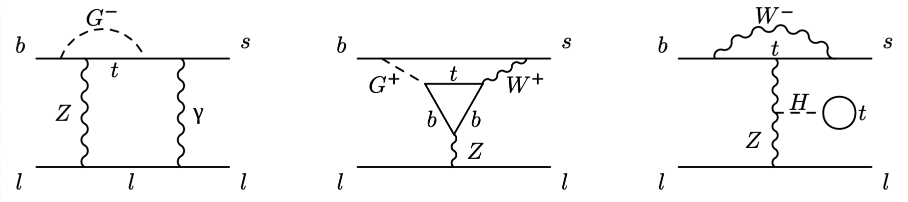


B physics theory: precision era

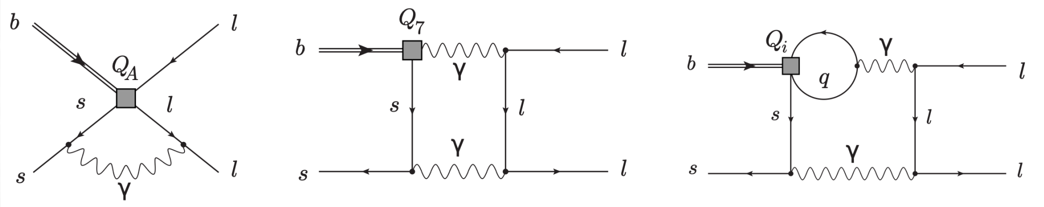
- **Much progress achieved thanks to various multi-loop techniques, EFTs and LQCD, ...**



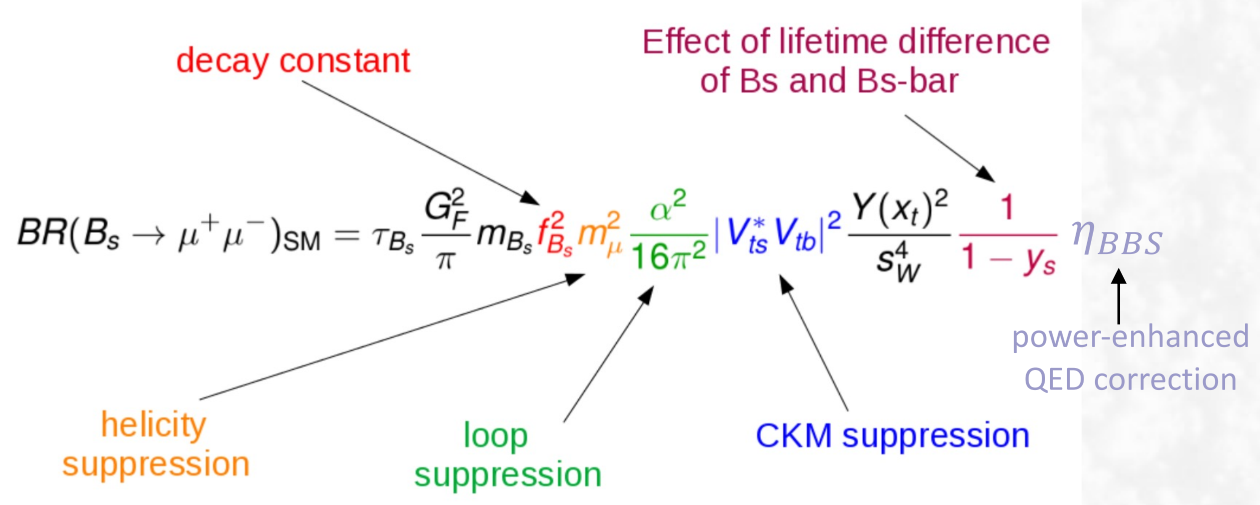
$O(\alpha_s^2)$ QCD correction



$O(\alpha_e)$ EW correction



power-enhanced QED correction



$$\mathrm{Br}(B_s \to \mu^+\mu^-)_{\mathrm{SM}} = (3.64 \pm 0.12)[(3.34 \pm 0.27)] \times 10^{-9}$$

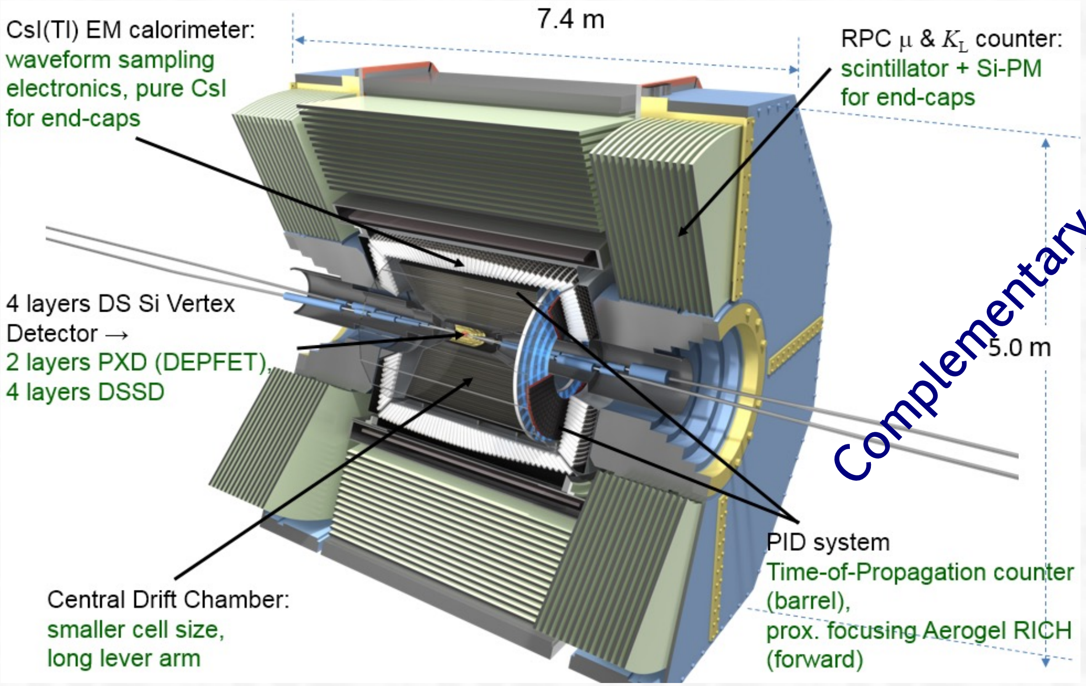
	f_{B_s}	CKM	τ_H^s	M_t	α_s	η_{BBS}	other	non-parametric	$\sum$
2024 [this paper]	1.1%	2.3%	0.5%	0.5%	0.1%	0.5%	< 0.1%	1.5%	3.2%
2013 [10]	4.0%	4.3%	1.3%	1.6%	0.1%	0.0%	< 0.1%	1.5%	6.4%

- ✓ parameter uncertainties dominated by $|V_{cb}|$
- ✓ non-parametric uncertainty from treating m_t as the pole mass

[Cjaza and Misiak, 2407.03810]

B physics experiments

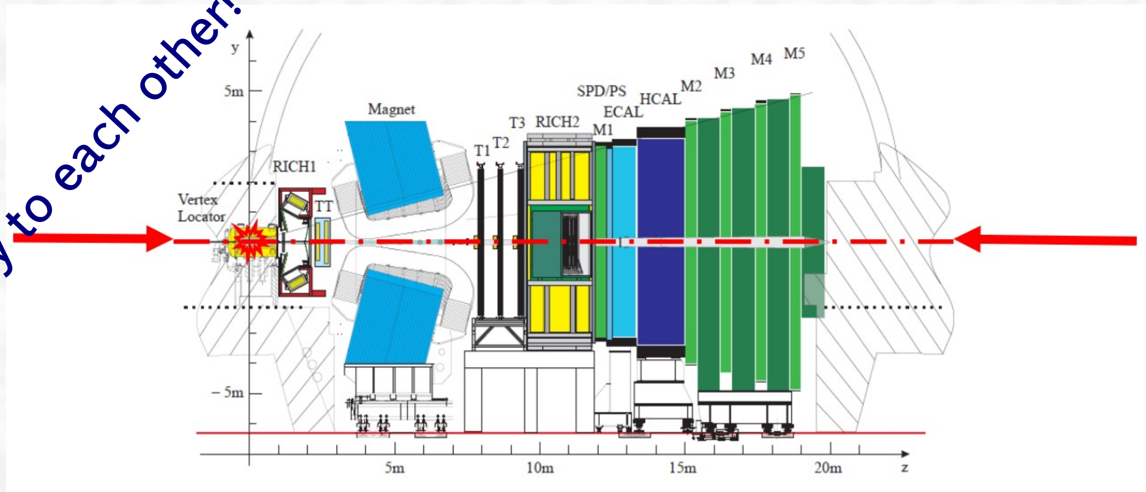
- **Super B-factories (e^+e^-): Belle II**



[E. Kou *et al.* [Belle II], PTEP 2019 (2019) 123C01]

- **Hadron colliders (pp): LHCb @LHC**

Complementary to each other!



[R. Aaij *et al.* [LHCb Collaboration], arXiv:1808.08865]

LHCb & Belle II: the two currently running experiments aimed at heavy flavor physics!

- **Two main goals among others:**
  - **check if there are any extra new CP-violation mechanisms beyond the Kobayashi-Maskawa?**
  - **check if there are new particles/interactions that are sensitive to flavor structures?**

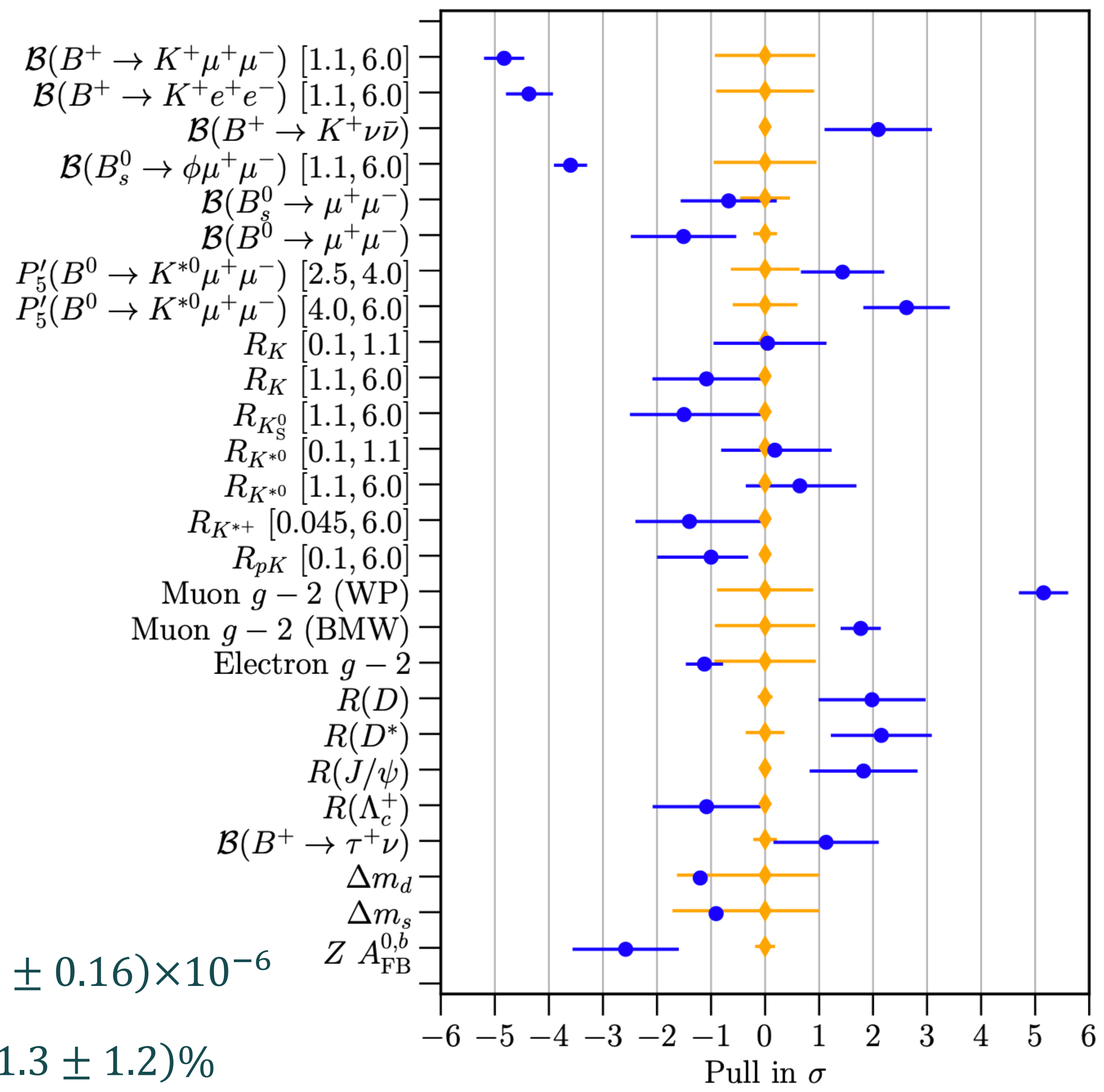
Flavor anomalies

- **Several interesting anomalies observed in flavor physics**
  - ✓ LFU violation in $R\left(D^{(*)}\right) = \frac{Br(B\to D^{(*)}\tau\nu_\tau)}{Br(B\to D^{(*)}l\nu_l)}$
  - ✓ optimized angular observable $P_5'(B^0 \to K^{*0}\mu^+\mu^-)$ with $P_5' = \frac{J_5}{2\sqrt{-J_{2s}J_{2c}}}$?
  - ✓ deviations between exp. & SM results of $Br(B^+ \to K^+\mu^+\mu^-)$, $Br(B_s^0 \to \phi\mu^+\mu^-)$, and $Br(B^+ \to K^+\nu\bar{\nu})$?

- **Two-body hadronic B decays**

$$\mathrm{Br}(B^0 \to \pi^0\pi^0) = (0.3 - 0.9)\times 10^{-6} \text{ vs } (1.55 \pm 0.16)\times 10^{-6}$$

$$\Delta A_{CP}(\pi K) = A_{CP}(\pi^0 K^-) - A_{CP}(\pi^+ K^-) = (11.3 \pm 1.2)\%$$



https://www.nikhef.nl/~pkoppenb/anomalies.html

Role of flavor physics in indirectly probing NP

- **Flavor physics plays a key in indirectly probing NP beyond the SM**

GIM mechanism in $K^0 \to \mu\mu$

Weak Interactions with Lepton-Hadron Symmetry*

S. L. Glashow, J. Iliopoulos, and L. Maiani†
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02139
(Received 5 March 1970)

We propose a model of weak interactions in which the currents are constructed out of four basic quark fields and interact with a charged massive vector boson. We show, to all orders in perturbation theory, that the leading divergences do not violate any strong-interaction symmetry and the next to the leading divergences respect all observed weak-interaction selection rules. The model features a remarkable symmetry between leptons and quarks. The extension of our model to a complete Yang-Milis theory is discussed.

splitting, beginning at order $G(G\Lambda^2)$, as well as contributions to such unobserved decay modes as $K_2 \to \mu^+ + \mu^-$, $K^+ \to \pi^+ + l + \bar{l}$, etc., involving neutral lepton

We wish to propose a simple model in which the divergences are properly ordered. Our model is founded in a quark model, but one involving four, not three, fundamental fermions; the weak interactions are medi-

new quantum number $\mathcal{C}$ for charm.

why $\frac{\Gamma(K_L \to \mu^+\mu^-)}{\Gamma(K^- \to \mu^-\bar{\nu}_\mu)} \simeq 10^{-8}$?

Glashow, Iliopoulos, Maiani,
Phys.Rev. D2 (1970) 1285

Rare decay implies charm quark

CP violation, $K_L^0 \to \pi\pi$

27 July 1964

EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey
(Received 10 July 1964)

This Letter reports the results of experimental studies designed to search for the 2π decay of the K_2^0 meson. Several previous experiments have

three-body decays of the K_2^0. The presence of a two-pion decay mode implies that the K_2^0 meson is not a pure eigenstate of CP. Expressed as $K_2^0 = 2^{-1/2}[(K_0 - \bar{K}_0) + \epsilon(K_0 + \bar{K}_0)]$ then $|\epsilon|^2 \cong R_T \tau_1 \tau_2$

Christenson, Cronin, Fitch, Turlay,
Phys.Rev.Lett. 13 (1964) 138-140

CP violation implies 3rd family

$B^0 \leftrightarrow \bar{B}^0$ mixing

DESY 87-029
April 1987

OBSERVATION OF B^0-$\bar{B}^0$ MIXING

The ARGUS Collaboration

In summary, the combined evidence of the investigation of B^0 meson pairs, lepton pairs and B^0 meson-lepton events on the $\Upsilon(4S)$ leads to the conclusion that B^0-$\bar{B}^0$ mixing has been observed and is substantial.

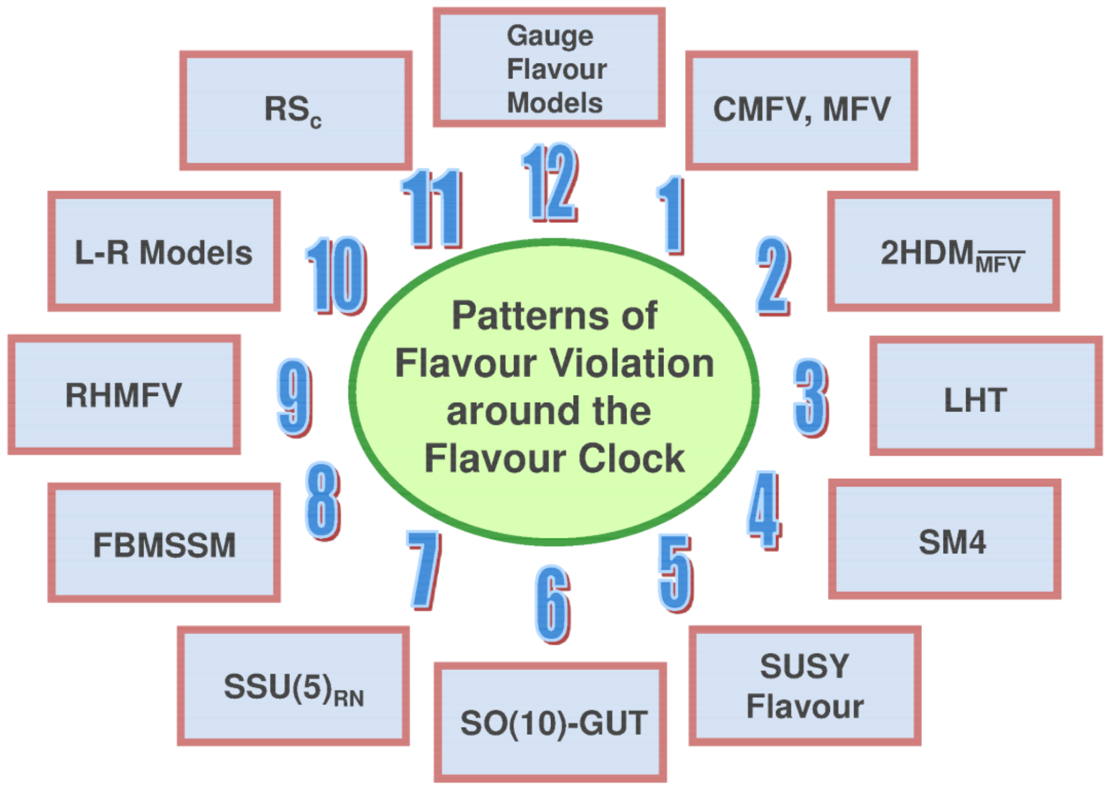
Parameters	Comments
$r > 0.09$ 90%CL	This experiment
$x > 0.44$	This experiment
$B^{\frac{1}{2}} f_B \approx f_\pi < 160$ MeV	B meson ($\approx$ pion) decay constant
$m_b < 5\mathrm{GeV}/c^2$	b-quark mass
$\tau_b < 1.4 \cdot 10^{-12}$s	B meson lifetime
$\lvert V_{td} \rvert < 0.018$	Kobayashi-Maskawa matrix element
$\eta_{QCD} < 0.86$	QCD correction factor [17]
$m_t > 50\mathrm{GeV}/c^2$	t quark mass

ARGUS Coll.
Phys.Lett.B192:245,1987

Mixing implies a heavy top quark

NP signals by precision flavor physics

- **To resolve the SM shortcomings, NP needed with new sources of flavor & CP violation**



[A. Buras and J. Girrbach,1306.3755]

- ✓ extra Higgses ⇒ Higgs-mediated FCNC's at tree-level, and helicity suppression absent
- ✓ squarks/gluinos ⇒ FCNC quark-squark-gluino coupling, and no CKM/GIM suppression
- ✓ vector-like quarks ⇒ FCNC couplings of an extra Z', with possibly new CPV sources
- ✓ $SU(2)_R$ gauge bosons ⇒ helicity suppression possibly absent

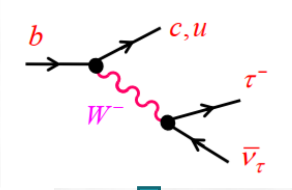
- **With precision data & theory predictions, could we firstly find any NP signals in flavor physics?**

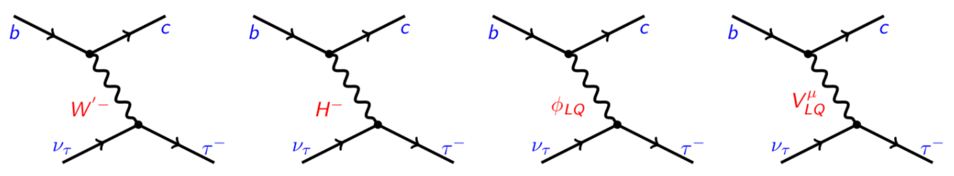
- ✓ observables with strong NP sensitivity
- ✓ clean and high theory prediction
- ✓ accessible to current experiments

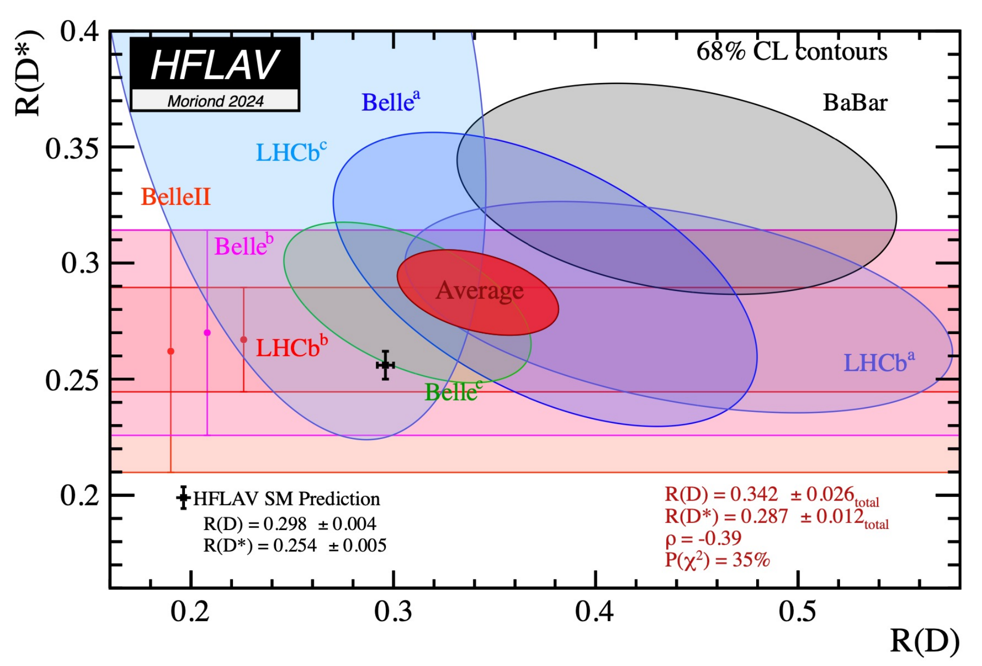
Tree-level FCCC B decays

- $R(D^{(*)})$ **anomalies: first observed by BaBar in 2012; currently still having ~3.31σ deviation**

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







- **Model-independent result for the** $R(D)$, $R(D^*)$ **&** $R(\Lambda_c)$:

$$\mathcal{H}_{\rm eff} = 2\sqrt{2} G_F V_{cb}\Big[(1+C_{V_L})O_{V_L} + C_{V_R}O_{V_R} + C_{S_L}O_{S_L} + C_{S_R}O_{S_R} + C_T O_T\Big]$$

with

$$O_{V_L} = (\bar{c}\gamma^\mu P_L b)(\bar{\tau}\gamma_\mu P_L \nu_\tau)\,, \qquad O_{V_R} = (\bar{c}\gamma^\mu P_R b)(\bar{\tau}\gamma_\mu P_L \nu_\tau)\,,$$
$$O_{S_L} = (\bar{c} P_L b)(\bar{\tau} P_L \nu_\tau)\,, \qquad O_{S_R} = (\bar{c} P_R b)(\bar{\tau} P_L \nu_\tau)\,,$$
$$O_T = (\bar{c}\sigma^{\mu\nu} P_L b)(\bar{\tau}\sigma_{\mu\nu} P_L \nu_\tau)\,,$$

$$\frac{R_P}{R_P^{\rm SM}} = |1 + C_{V_L}^{q\tau} + C_{V_R}^{q\tau}|^2 + a_P^{SS}|C_{S_L}^{q\tau} + C_{S_R}^{q\tau}|^2 + a_P^{TT}|C_T^{q\tau}|^2$$
$$+ a_P^{VS}{\rm Re}\left[\left(1 + C_{V_L}^{q\tau} + C_{V_R}^{q\tau}\right)\left(C_{S_L}^{q\tau *} + C_{S_R}^{q\tau *}\right)\right] + a_P^{VT}{\rm Re}\left[\left(1 + C_{V_L}^{q\tau} + C_{V_R}^{q\tau}\right) C_T^{q\tau *}\right]\,,$$

$$\frac{R_V}{R_V^{\rm SM}} = |1 + C_{V_L}^{q\tau}|^2 + |C_{V_R}^{q\tau}|^2 + a_V^{SS}|C_{S_L}^{q\tau} - C_{S_R}^{q\tau}|^2 + a_V^{TT}|C_T^{q\tau}|^2$$
$$+ a_V^{V_L V_R}{\rm Re}\left[\left(1 + C_{V_L}^{q\tau}\right) C_{V_R}^{q\tau *}\right] + a_V^{VS}{\rm Re}\left[\left(1 + C_{V_L}^{q\tau} - C_{V_R}^{q\tau}\right)\left(C_{S_L}^{q\tau *} - C_{S_R}^{q\tau *}\right)\right]$$
$$+ a_V^{V_L T}{\rm Re}\left[\left(1 + C_{V_L}^{q\tau}\right) C_T^{q\tau *}\right] + a_V^{V_R T}{\rm Re}\left[C_{V_R}^{q\tau} C_T^{q\tau *}\right]\,,$$

$$\frac{R_H}{R_H^{\rm SM}} = |1 + C_{V_L}^{q\tau}|^2 + |C_{V_R}^{q\tau}|^2 + a_H^{SS}\left[|C_{S_L}^{q\tau}|^2 + |C_{S_R}^{q\tau}|^2\right] + a_H^{TT}|C_T^{q\tau}|^2 + a_H^{V_L V_R}{\rm Re}\left[\left(1 + C_{V_L}^{q\tau}\right) C_{V_R}^{q\tau *}\right]$$
$$+ a_H^{V S_1}{\rm Re}\left[\left(1 + C_{V_L}^{q\tau}\right) C_{S_L}^{q\tau *} + C_{V_R}^{q\tau} C_{S_R}^{q\tau *}\right] + a_H^{V S_2}{\rm Re}\left[\left(1 + C_{V_L}^{q\tau}\right) C_{S_R}^{q\tau *} + C_{V_R}^{q\tau} C_{S_L}^{q\tau *}\right]$$
$$+ a_H^{S_L S_R}{\rm Re}\left[C_{S_L}^{q\tau} C_{S_R}^{q\tau *}\right] + a_H^{V_L T}{\rm Re}\left[\left(1 + C_{V_L}^{q\tau}\right) C_T^{q\tau *}\right] + a_H^{V_R T}{\rm Re}\left[C_{V_R}^{q\tau} C_T^{q\tau *}\right]\,.$$

Tree-level FCCC B decays

- **Sum rule for $R(D)$, $R(D^*)$ & $R(\Lambda_c)$:**

$$\frac{R_H}{R_H^{\rm SM}} = b\frac{R_P}{R_P^{\rm SM}} + c\frac{R_V}{R_V^{\rm SMM}} + \delta_H(C_i)$$

b & c not unique but determined by setting a desired condition so that $\delta_H(C_i)$ becomes small → $b + c = 1$ & $a_P^{VS} b + a_V^{VS} c = a_H^{VS_1}$ → ~~$|1 + C_{V_L}^{q\tau}|^2$~~, ~~$\mathrm{Re}[(1 + C_{V_L}^{q\tau})C_{S_L}^{q\tau*}]$~~

model-independent and holds for any tau-philic NP

- **State-of-the-art prediction:** [Duan, Li, and Watanabe, w.i.p]

$$\frac{R_{\Lambda_c}}{R_{\Lambda_c}^{SM}} = (0.270 \pm 0.015)\frac{R_D}{R_D^{SM}} + (0.730 \mp 0.015)\frac{R_{D^*}}{R_{D^*}^{SM}} + \delta_{\Lambda_c}$$

→ provide us with a unique prediction of $R(\Lambda_c)$ in a model-independent way

$$\begin{aligned}\delta_{\Lambda_c} =& (-0.001 \pm 0.005)\left(\left|C_{S_L}^{c\tau}\right|^2 + \left|C_{S_R}^{c\tau}\right|^2\right) + (-0.008 \pm 0.005)\,\mathrm{Re}\left(C_{S_L}^{c\tau} C_{S_R}^{c\tau*}\right)\\ &+ \underline{(-1.808 \pm 6.456)|C_T^{c\tau}|^2} + (-0.375 \pm 1.395)\,\mathrm{Re}\left(C_{V_R}^{c\tau} C_T^{c\tau**}\right)\\ &+ \mathrm{Re}\left[(1 + C_{V_L}^{c\tau})\left\{(0.060 \pm 0.034)C_{V_R}^{c\tau*} + (0.501 \pm 1.240)C_T^{c\tau*}\right\}\right]\\ &+ (-0.001 \pm 0.009)\,\mathrm{Re}\left[(1 + C_{V_L}^{c\tau})C_{S_R}^{c\tau*} + C_{S_L}^{c\tau} C_{V_R}^{c\tau*}\right]\end{aligned}$$

$$R_{\Lambda_c}^{\rm SR} = 0.370 \pm 0.017|_{R_X^{\rm SM,exp}} \pm (< 0.001)|_{\rm SR}$$

$$R_{\Lambda_c}^{\rm SM} = 0.332 \pm 0.010$$

$$R_{\Lambda_c}^{\rm LHCb} = 0.242 \pm 0.026 \pm 0.040 \pm 0.059$$

Tree-level FCCC B decays

- **Sum rule for $R(\pi)$, $R(\rho)$ & $R(p)$:**

$$\frac{\mathcal{R}_p}{\mathcal{R}_p^{\rm SM}} = (0.284 \pm 0.037)\,\frac{\mathcal{R}_\pi}{\mathcal{R}_\pi^{\rm SM}} + (0.716 \mp 0.037)\,\frac{\mathcal{R}_\rho}{\mathcal{R}_\rho^{\rm SM}} + \delta_p$$

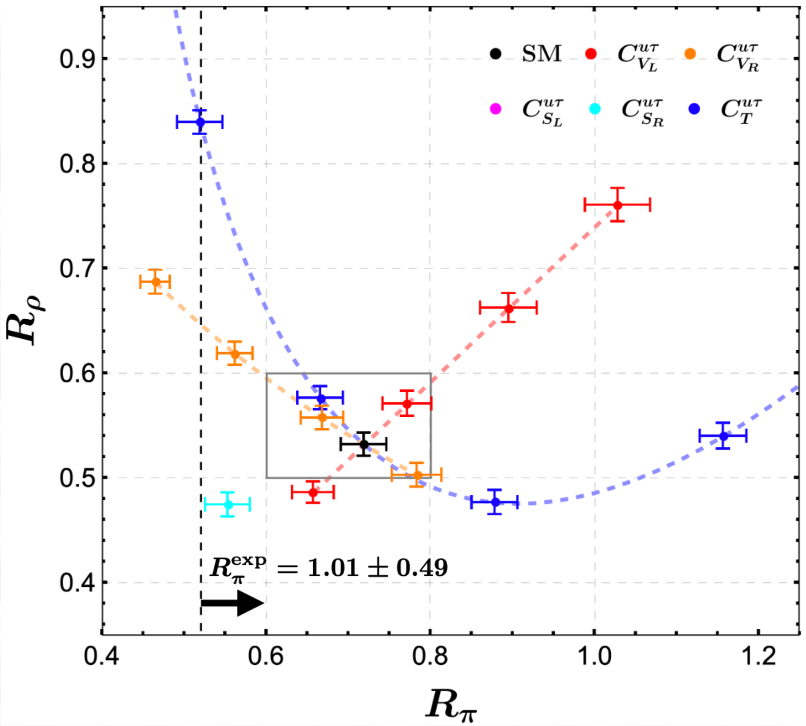
$$\begin{aligned}\delta_p = &\,(-0.090 \pm 0.059)\,\left(|C_{S_L}^{u\tau}|^2 + |C_{S_R}^{u\tau}|^2\right) + (-0.185 \pm 0.038)\,{\rm Re}\left(C_{S_L}^{u\tau} C_{S_R}^{u\tau *}\right)\\ &+ (-0.913 \pm 2.403)\,|C_T^{u\tau}|^2 + (-0.203 \pm 0.538)\,{\rm Re}\left(C_{V_R}^{u\tau} C_T^{u\tau *}\right)\\ &+ {\rm Re}\left[\left(1 + C_{V_L}^{u\tau}\right)\left\{(0.169 \pm 0.158) C_{V_R}^{u\tau *} + (0.370 \pm 0.632) C_T^{u\tau *}\right\}\right]\\ &+ (-0.079 \pm 0.056)\,{\rm Re}\left[\left(1 + C_{V_L}^{u\tau}\right) C_{S_R}^{u\tau *} + C_{S_L}^{u\tau} C_{V_R}^{u\tau *}\right] .\end{aligned}$$

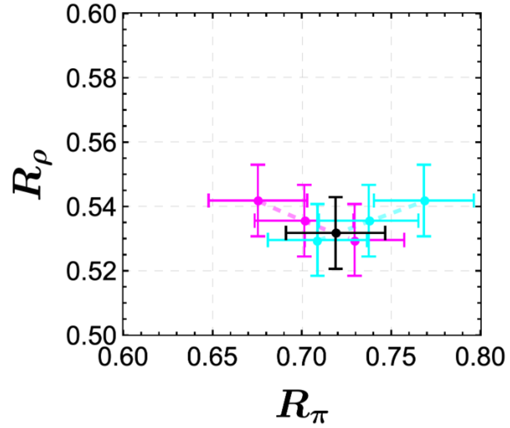
the sum rule for $b \to u$ is more (less) sensitive to the scalar (tensor) NP compared to $b \to c$

- **Purely leptonic decay puts strong constraints on all the operators except the tensor operator**

$$\mathcal{B}(B^- \to \tau^- \bar{\nu}) = \frac{\tau_{B^-} G_F^2 |V_{ub}|^2 f_B^2}{8\pi} m_{B^-} m_\tau^2 \left(1 - \frac{m_\tau^2}{m_{B^-}^2}\right)^2 \times \left|1 + C_{V_L}^{u\tau} - C_{V_R}^{u\tau} + \frac{m_{B^-}^2}{m_b m_\tau}\left(C_{S_R}^{u\tau} - C_{S_L}^{u\tau}\right)\right|^2$$

[Duan, Li, and Watanabe, w.i.p]





$\mathcal{B}(B \to \tau\nu)^{\rm exp} = (1.09 \pm 0.24) \times 10^{-4}$

$C_{V_L}^{u\tau} \supset [-0.04, 0.20]$

$C_{V_R}^{u\tau} \supset [-0.20, 0.04]$

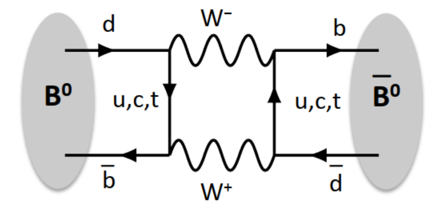
$C_{S_L}^{u\tau} \supset [-0.05, 0.01]\,,\ [0.51, 0.58]$

$C_{S_R}^{u\tau} \supset [-0.58, -0.51]\,,\ [-0.01, 0.05]$

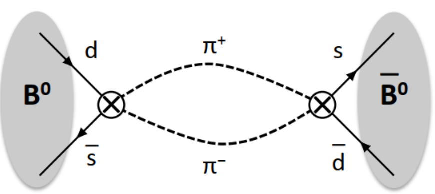
$C_T^{u\tau}$: no constraint

Neutral B-meson mixings

- **For B_q^0 meson:** flavor eigenstates ≠ mass eigenstates ⇒ mix with each other via box diagrams
- **Time evolution of a decaying particle** $$i\frac{d}{dt}\begin{pmatrix}|B(t)\rangle\\|\bar{B}(t)\rangle\end{pmatrix}=\left(\hat{M}-\frac{i}{2}\hat{\Gamma}\right)\begin{pmatrix}|B(t)\rangle\\|\bar{B}(t)\rangle\end{pmatrix}$$



"short-distance"
(=virtual particle exchange)



"long-distance"
(=real particle exchange)

- **Three observables for B mixings**
  - **Mass difference:** $\Delta M := M_H - M_L \approx 2|M_{12}|$ **(off-shell)**
    $|M_{12}|$: heavy internal particles: t, SUSY, ...
  - **Decay rate difference:** $\Delta\Gamma := \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}|\cos\phi$ **(on-shell)**
    $|\Gamma_{12}|$: light internal particles: u, c, ... (almost) no NP!!!
  - **Flavor specific/semi-leptonic CP asymmetries:** e.g. $B_q \to Xl\nu$ (*semi-leptonic*)

$$a_{sl} \equiv a_{fs} = \frac{\Gamma(\overline{B}_q(t)\to f)-\Gamma(B_q(t)\to \overline{f})}{\Gamma(\overline{B}_q(t)\to f)+\Gamma(B_q(t)\to \overline{f})} = \left|\frac{\Gamma_{12}}{M_{12}}\right|\sin\phi$$

$$M_{12} = \frac{G_F^2}{12\pi^2}\left(V_{tq}^* V_{tb}\right)^2 M_W^2 S_0(x_t) B_{B_q} f_{B_q}^2 M_{B_q}\hat{\eta}_B$$

† 1-loop calculation $S_0\left(x_t = m_t^2/M_W^2\right)$

† 2-loop perturbative QCD corrections $\hat{\eta}_B$

† $\frac{8}{3}B_{B_q}f_{B_q}^2 M_{B_q} = \left\langle \overline{B}_q\middle|(\bar{b}q)_{V-A}(\bar{b}q)_{V-A}\middle|B_q\right\rangle$

$$\Gamma_{12} = \left(\frac{\Lambda}{m_b}\right)^3\left(\Gamma_3^{(0)} + \frac{\alpha_s}{4\pi}\Gamma_3^{(1)} + \ldots\right) + \left(\frac{\Lambda}{m_b}\right)^4\left(\Gamma_4^{(0)} + \ldots\right) + \left(\frac{\Lambda}{m_b}\right)^5\left(\Gamma_5^{(0)} + \ldots\right) + \ldots$$

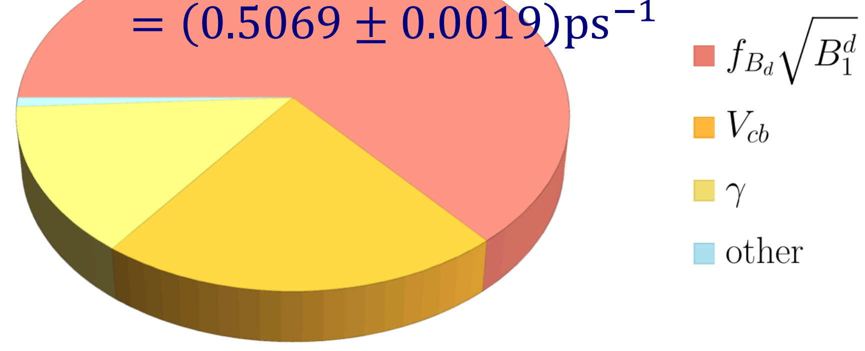
HQE

➡
- ✓ M_{12}: dispersive part of the box diagram
- ✓ Γ_{12}: absorptive part of the box diagram
- ✓ $\phi = \arg(-M12/\Gamma12)$: relative phase between them

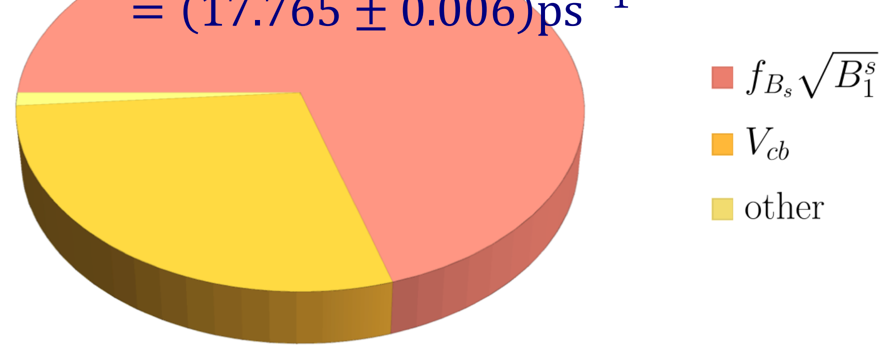
Neutral B-meson mixings

☐ Status of theory predictions [https://arxiv.org/pdf/2402.04224]

$\Delta M_d = (0.535 \pm 0.021)\text{ps}^{-1}$
$= (0.5069 \pm 0.0019)\text{ps}^{-1}$



$\Delta M_s = (18.23 \pm 0.63)\text{ps}^{-1}$
$= (17.765 \pm 0.006)\text{ps}^{-1}$



$$\frac{\Delta M_d^{\rm SM}}{\Delta M_d^{\rm Exp.}} = 1.056 \pm 0.042\,, \qquad \frac{\delta \Delta M_d^{\rm SM}}{\delta \Delta M_d^{\rm Exp.}} \simeq 11\,,$$
$$\frac{\Delta M_s^{\rm SM}}{\Delta M_s^{\rm Exp.}} = 1.026 \pm 0.036\,, \qquad \frac{\delta \Delta M_s^{\rm SM}}{\delta \Delta M_s^{\rm Exp.}} \simeq 105\,,$$

- ✓ theoretical errors much larger than exp. ones
- ✓ still dominated by non-pert. bag parameters
- ✓ M_{12}: a 2nd-order weak process and thus very sensitive to tree-level Z' and leptoquarks

☐ Generic parametrization of NP contribution to the B mixings:

$$C_{B_q} e^{2i\phi_{B_q}} = \frac{\left\langle B_q^0 \middle| \mathcal{H}_{\rm eff}^{\rm full} \middle| \bar{B}_q^0 \right\rangle}{\left\langle B_q^0 \middle| \mathcal{H}_{\rm eff}^{\rm SM} \middle| \bar{B}_q^0 \right\rangle} \Leftrightarrow A_q = \left(1 + \frac{A_q^{\rm NP}}{A_q^{\rm SM}} e^{2i(\phi_q^{\rm NP} - \phi_q^{\rm SM})}\right) A_q^{\rm SM} e^{2i\phi_q^{\rm SM}}$$

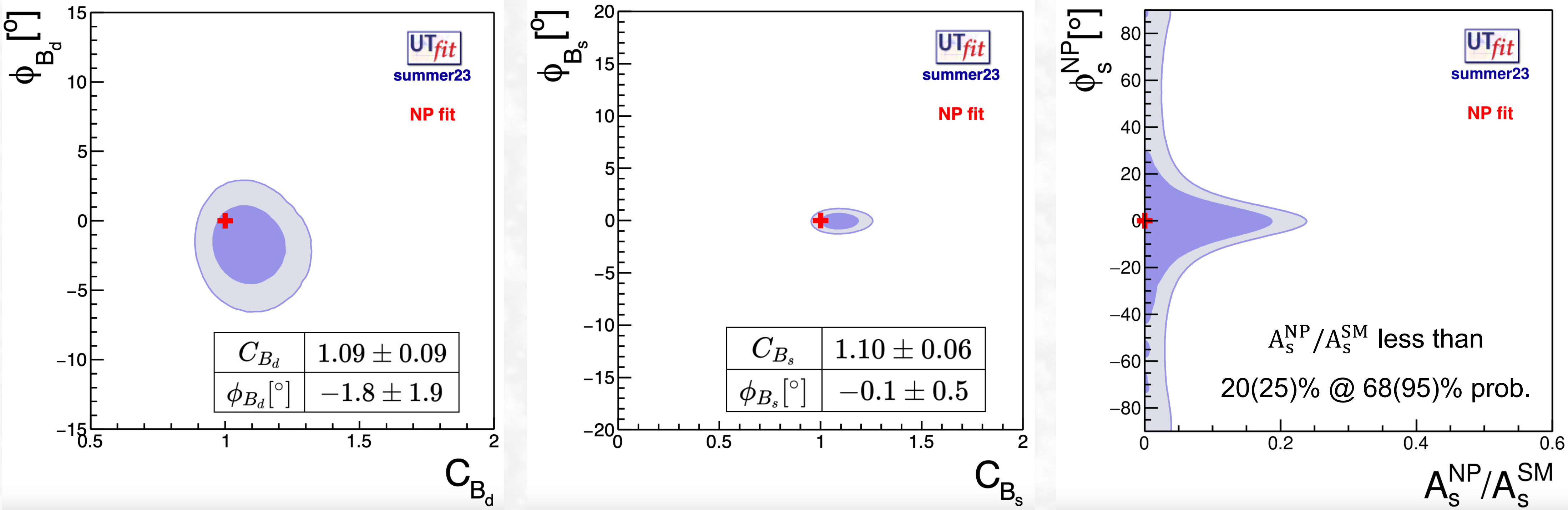
Neutral B-meson mixings

- Exp. observables are related to the SM and NP parameters:

$$\Delta M_d^{\rm exp} = C_{B_d} \Delta M_d^{\rm SM}\,, \qquad \sin 2\beta^{\rm exp} = \sin\left(2\beta^{\rm SM} + 2\phi_{B_d}\right)$$

$$\Delta M_s^{\rm exp} = C_{B_s} \Delta M_s^{\rm SM}\,, \qquad \phi_s^{\rm exp} = \left(\beta_s^{\rm SM} - \phi_{B_s}\right)$$

- Latest fit results by the UTfit group

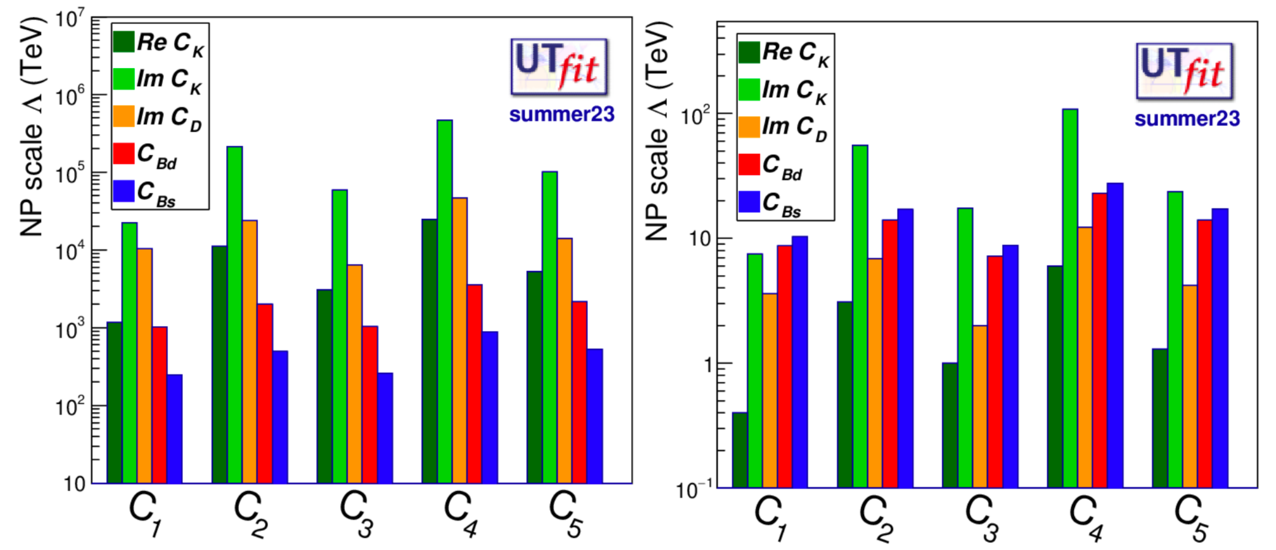


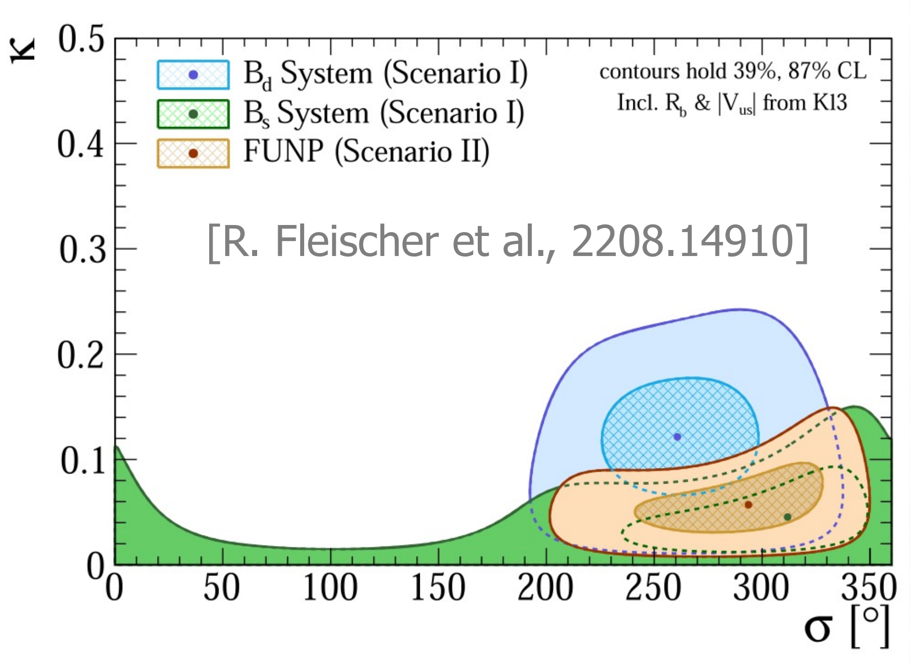
consistency between data & SM of B mixing observables puts stringent constraint on NP

Neutral B-meson mixings

- **Very high energy scales are probed by the neutral meson mixings:**

$$\mathcal{O}_1 = (\bar b^\alpha \gamma_\mu L q^\alpha)(\bar b^\beta \gamma_\mu L q^\beta) \qquad \mathcal{O}_4 = (\bar b^\alpha L q^\alpha)(\bar b^\beta R q^\beta)$$
$$\mathcal{O}_2 = (\bar b^\alpha L q^\alpha)(\bar b^\beta L q^\beta) \qquad \mathcal{O}_5 = (\bar b^\alpha L q^\beta)(\bar b^\beta R q^\alpha)$$
$$\mathcal{O}_3 = (\bar b^\alpha L q^\beta)(\bar b^\beta L q^\alpha)$$





- **Flavor universal NP scenario:** NP couples predominantly to the 3rd-generation quarks and leptons, and can be easily realized in NP models with a U(2) symmetry

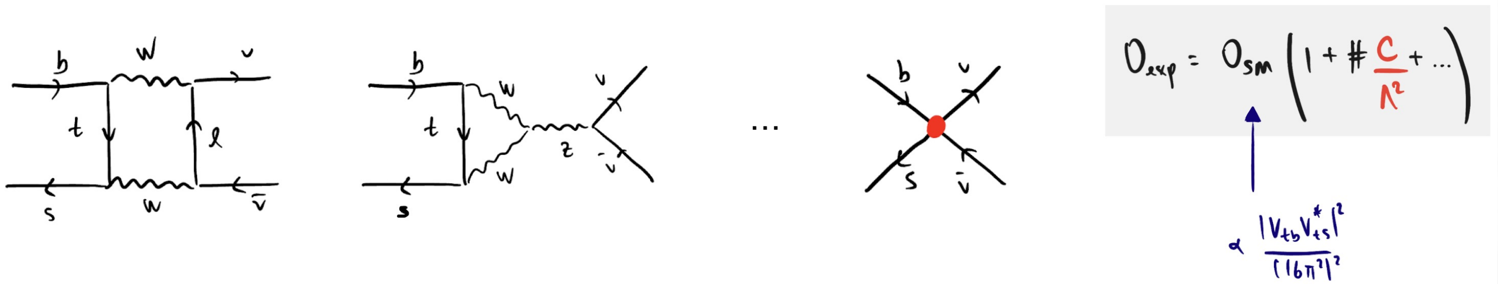
$$\kappa_d = \kappa_s \equiv \kappa, \qquad \sigma_d = \sigma_s \equiv \sigma$$

$$\Delta m_q = \Delta m_q^{\rm SM} |1 + \kappa_q e^{i\sigma_q}|,$$

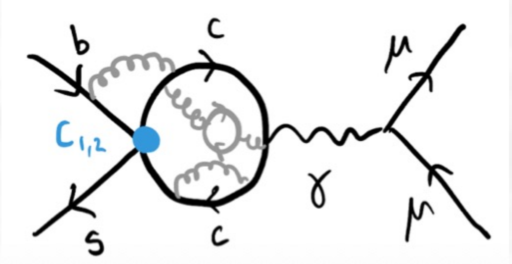
$$\phi_q = \phi_q^{\rm SM} + \phi_q^{\rm NP} = \phi_q^{\rm SM} + \arg(1 + \kappa_q e^{i\sigma_q}).$$

Rare FCNC B decays

- $b \to s$ **transition with missing energy in the final state:** $B \to K^{(*)}\nu\bar{\nu}$ **and** $B \to K^{(*)} + \text{invisible}$



- ❖ $b \to s\nu\bar{\nu}$ **decays theoretically cleaner than** $b \to s\ell\ell$ **decays due to the absence of long-distance** $c\bar{c}$ **loop contributions**



- **State-of-the-art SM prediction**

- **Effective Hamiltonian** in the SM:

see e.g. [Buras et al. '14]

$$\mathcal{L}_{\rm eff}^{b\to s\nu\nu} = \frac{4G_F\lambda_t}{\sqrt{2}}\frac{\alpha_{\rm em}}{2\pi}\sum_i C_L^{\rm SM}(\bar{s}_L\gamma_\mu b_L)(\bar{\nu}_{Li}\gamma^\mu\nu_{Li}) + \text{h.c.}\,,$$

$$\lambda_t = V_{tb}V_{ts}^*$$

- **Short-distance** contributions known to **good precision**:

$$C_L^{\rm SM} = -X_t/\sin^2\theta_W = -6.32(7)$$

Including NLO QCD and two-loop EW contributions:

$$X_t = 1.462(17)(2)$$

[Buchala et al. '93, '99], [Misiak et al. '99], [Brod et al. '10]

$$\langle K^{(*)}|\bar{s}_L\gamma^\mu b_L|B\rangle = \sum_a K_a^\mu\,\mathcal{F}_a(q^2)$$

Form-factors (e.g., LQCD)

$$|V_{tb}V_{ts}^*| = |V_{cb}|\,(1+\mathcal{O}(\lambda^2))$$

Rare FCNC B decays

□ $B \to K^{(*)}$ form factors from LQCD + LCSR:

$$\mathcal{B}(B \to K\nu\bar{\nu})^{\rm SM}/|\lambda_t|^2 = \begin{cases} (1.33 \pm 0.04)_{K_S} \times 10^{-3} \\ (2.87 \pm 0.10)_{K^+} \times 10^{-3} \end{cases}$$

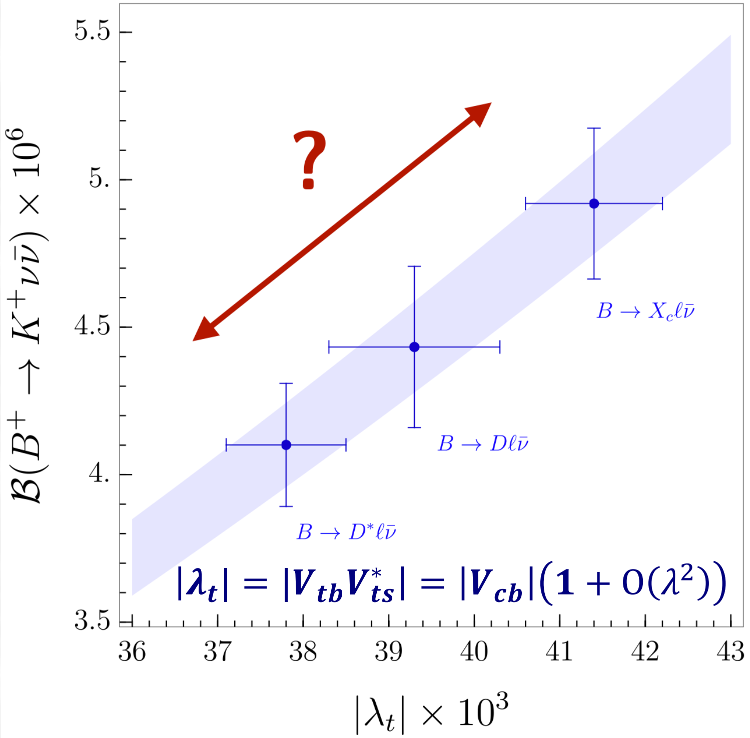
[$\approx 3\,\%$ uncertainty]

Becirevic et al., 2301.06990

$$\mathcal{B}(B \to K^*\nu\bar{\nu})^{\rm SM}/|\lambda_t|^2 = \begin{cases} (5.9 \pm 0.8)_{K^{*0}} \times 10^{-3} \\ (6.4 \pm 0.9)_{K^{*+}} \times 10^{-3} \end{cases}$$

[$\approx 15\,\%$ uncertainty]

□ CKM matrix element input from $|V_{cb}|$:



*Using V_{cb} from $B \to D\ell\bar{\nu}$ for illustration

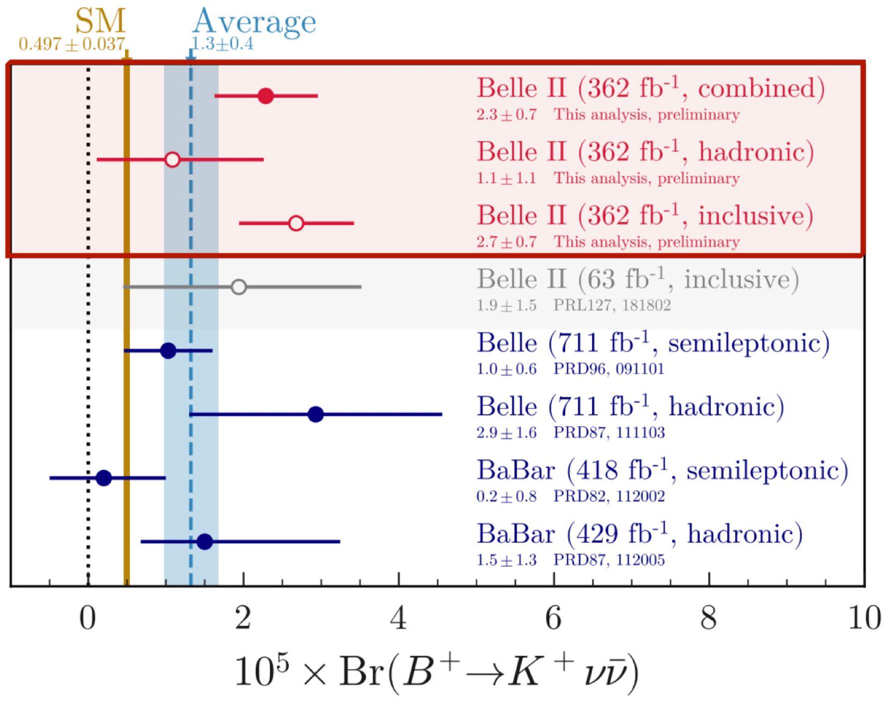
Decay	Branching ratio
$B^+ \to K^+\nu\bar{\nu}$	$(4.44 \pm 0.14 \pm 0.27) \times 10^{-6}$
$B^0 \to K_S\nu\bar{\nu}$	$(2.05 \pm 0.07 \pm 0.12) \times 10^{-6}$
$B^+ \to K^{*+}\nu\bar{\nu}$	$(9.79 \pm 1.30 \pm 0.60) \times 10^{-6}$
$B^0 \to K^{*0}\nu\bar{\nu}$	$(9.05 \pm 1.25 \pm 0.55) \times 10^{-6}$

FF CKM

Rare FCNC B decays

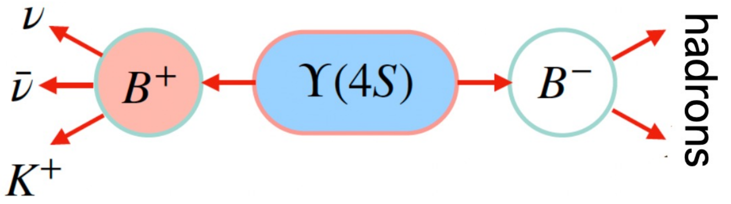
- **Belle-II first evidence of $B^+ \to K^+\nu\bar{\nu}$: exp. data $\simeq 3\sigma$ above the SM prediction**

[Belle-II, 2311.14647]

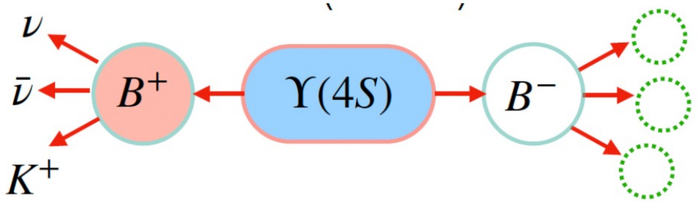


$$\mathcal{B}(B^+ \to K^+\nu\bar{\nu})^{\rm exp} = \left[2.3 \pm 0.5\,({\rm stat})^{+0.5}_{-0.4}\,({\rm syst})\right] \times 10^{-5}$$

Hadronic Tag analysis (HTA)
more conventional



Inclusive Tag analysis (ITA):
more sensitive



- **NP signal:** new heavy mediators in the loop or new light invisible particles in the final state?

Rare FCNC B decays

- **Model-indep. LEFT analysis:**

$$\mathcal{L}_{\rm eff}^{b\to s\nu\nu} = \frac{4G_F\lambda_t}{\sqrt{2}}\frac{\alpha_{\rm em}}{2\pi}\sum_{ij}\left[C_L^{\nu_i\nu_j}(\bar{s}_L\gamma_\mu b_L)(\bar{\nu}_{Li}\gamma^\mu\nu_{Lj}) + C_R^{\nu_i\nu_j}(\bar{s}_R\gamma_\mu b_R)(\bar{\nu}_{Li}\gamma^\mu\nu_{Lj})\right]$$

neutrino still left-handed

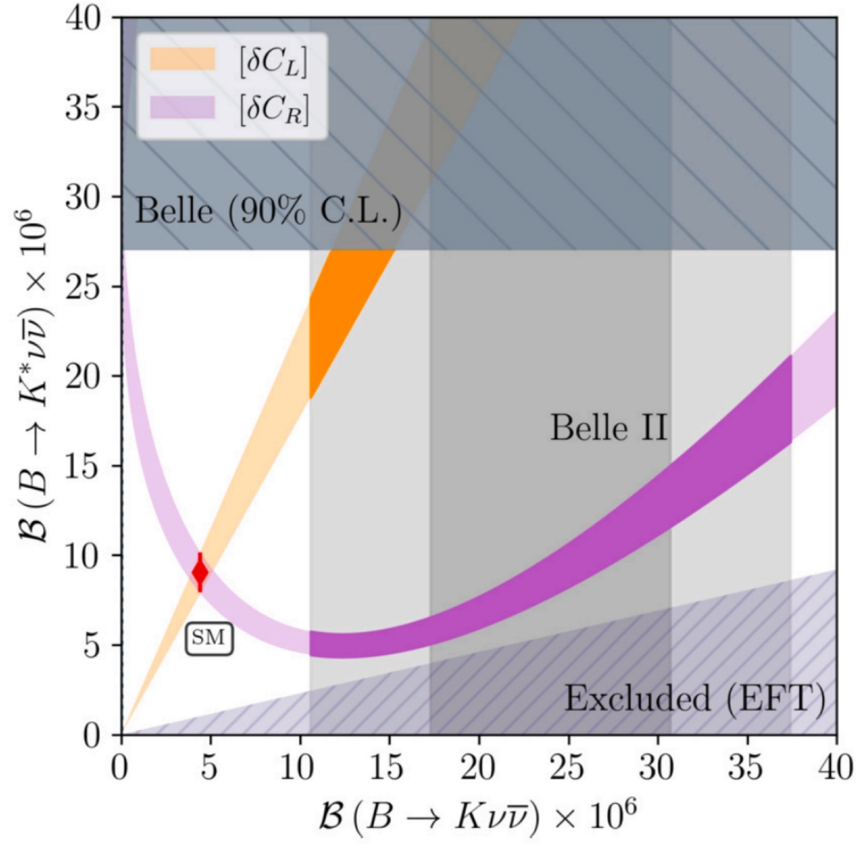
- **Correlations between $B\to K\nu\bar{\nu}$ & $B\to K^*\nu\bar{\nu}$**

$$\frac{\mathcal{B}(B\to K^{(*)}\nu\bar{\nu})}{\mathcal{B}(B\to K^{(*)}\nu\bar{\nu})^{\rm SM}} = 1 + \sum_i \frac{2{\rm Re}[C_L^{\rm SM}(\delta C_L^{\nu_i\nu_i} + \delta C_R^{\nu_i\nu_i})]}{3|C_L^{\rm SM}|^2} + \sum_{i,j}\frac{|\delta C_L^{\nu_i\nu_j} + \delta C_R^{\nu_i\nu_j}|^2}{3|C_L^{\rm SM}|^2} - \eta_{K^{(*)}}\sum_{i,j}\frac{{\rm Re}[\delta C_R^{\nu_i\nu_j}(C_L^{\rm SM}\delta_{ij} + \delta C_L^{\nu_i\nu_j})]}{3|C_L^{\rm SM}|^2}$$

$\eta_K = 0$

$\eta_{K^*} = 3.5(1)$

[Becirevic et al., '22]



- **A measurement of $B\to K^*\nu\bar{\nu}$ would be a key model-indep. test of the Belle-II result**

Rare FCNC B decays

☐ SMEFT analysis: $d = 6$ four-fermion contributions at tree level; [Buchmuller & Wyler, '85; Gradkowski et al., '10]

- ψ^4 operators invariant under $SU(2)_L \times U(1)_Y$:

$$[\mathcal{O}_{lq}^{(1)}]_{ijkl} = (\overline{L}_i\gamma^\mu L_j)(\overline{Q}_k\gamma_\mu Q_l)$$
$$[\mathcal{O}_{lq}^{(3)}]_{ijkl} = (\overline{L}_i\gamma^\mu\tau^I L_j)(\overline{Q}_k\tau^I\gamma_\mu Q_l)$$
$$[\mathcal{O}_{ld}]_{ijkl} = (\overline{L}_i\gamma^\mu L_j)(\overline{d}_k\gamma_\mu d_l)$$
$$[\mathcal{O}_{eq}]_{ijkl} = (\overline{e}_i\gamma^\mu e_j)(\overline{Q}_k\gamma_\mu Q_l)$$
$$[\mathcal{O}_{ed}]_{ijkl} = (\overline{e}_i\gamma^\mu e_j)(\overline{d}_k\gamma_\mu d_l)$$

$b \to s\ell\ell$ $b \to s\nu\bar{\nu}$

$$[\mathcal{O}_{lq}^{(1)}]_{ijkl} = (\overline{L}_i\gamma^\mu L_j)(\overline{Q}_k\gamma_\mu Q_l) = (\overline{\ell}_{Li}\gamma^\mu\ell_{Lj})(\overline{d}_{Lk}\gamma_\mu d_{Ll}) + (\overline{\nu}_{Li}\gamma^\mu\nu_{Lj})(\overline{d}_{Lk}\gamma_\mu d_{Ll}) + \ldots$$

$$[\mathcal{O}_{lq}^{(3)}]_{ijkl} = (\overline{L}_i\gamma^\mu\tau^I L_j)(\overline{Q}_k\gamma_\mu\tau^I Q_l) = (\overline{\ell}_{Li}\gamma^\mu\ell_{Lj})(\overline{d}_{Lk}\gamma_\mu d_{Ll}) - (\overline{\nu}_{Li}\gamma^\mu\nu_{Lj})(\overline{d}_{Lk}\gamma_\mu d_{Ll}) + \ldots$$

$$[\mathcal{O}_{ld}]_{ijkl} = (\overline{L}_i\gamma^\mu L_j)(\overline{d}_k\gamma_\mu d_l) = (\overline{\ell}_{Li}\gamma^\mu\ell_{Lj})(\overline{d}_{Rk}\gamma_\mu d_{Rl}) + (\overline{\nu}_{Li}\gamma^\mu\nu_{Lj})(\overline{d}_{Rk}\gamma_\mu d_{Rl})$$

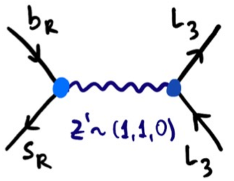
- Correlations for concrete mediators:
  - $Z' \sim (\mathbf{1},\mathbf{1},0)$: $\mathcal{C}_{lq}^{(1)}$, $\mathcal{C}_{ld}$
  - $V \sim (\mathbf{1},\mathbf{3},0)$: $\mathcal{C}_{lq}^{(3)}$
  - $U_1 \sim (\mathbf{3},\mathbf{1},2/3)$: $\mathcal{C}_{lq}^{(1)} = \mathcal{C}_{lq}^{(3)}$
  - $S_3 \sim (\bar{\mathbf{3}},\mathbf{3},1/3)$: $\mathcal{C}_{lq}^{(1)} = 3\,\mathcal{C}_{lq}^{(3)}$
  - $\widetilde{R}_2 = (\mathbf{3},\mathbf{2},1/6)$: $\mathcal{C}_{ld}$

  …

$(SU(3)_c,\, SU(2)_L,\, U(1)_Y)$

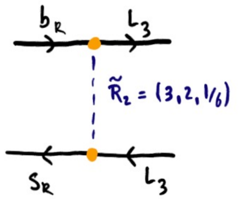
☐ More correlations among observables arise in concrete models

- Z':

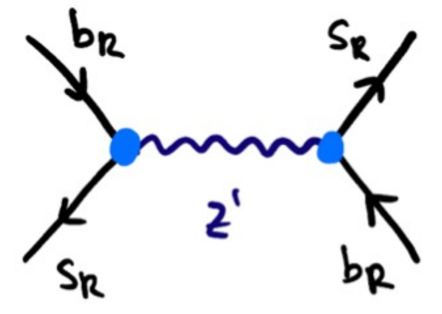


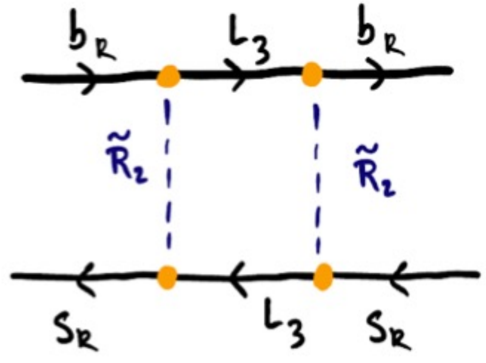
$\mathcal{L}_{Z'} \supset g_{ij}^{\psi}\,(\bar{\psi}_i\gamma^\mu\psi_j)Z'_\mu$

- LQs:



$\mathcal{L}_{\widetilde{R}_2} \supset y_{ij}^{R}\,(\bar{d}_{Ri}\widetilde{R}_2 i\tau_2 L_j) + \text{h.c.}$





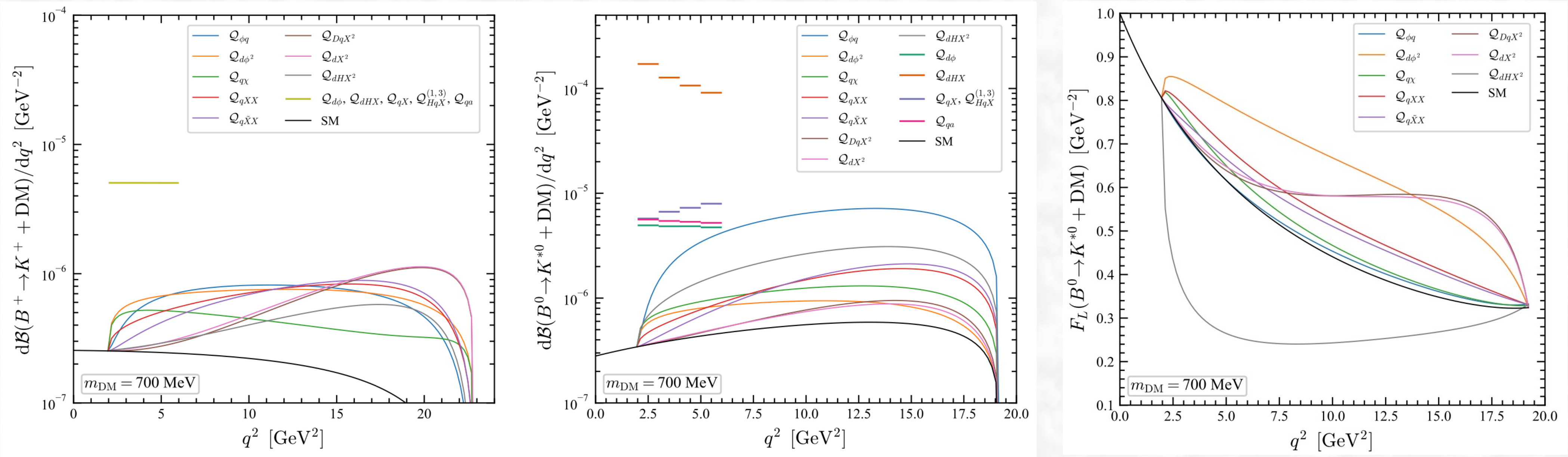
↳ **difficult to explain Belle-II excess, but possible in certain models**

Rare FCNC B decays

- **The Belle-II excess can also be mimicked by $B \to K + \text{invisible}$;** [Hou, Li, Shen, Yang and Yuan, '24]

$$\mathcal{L}_{\rm DSMEFT} \supset \frac{1}{\Lambda}\sum_i \mathcal{C}_i \mathcal{Q}_i^{(5)} + \frac{1}{\Lambda^2}\sum_j \mathcal{C}_j \mathcal{Q}_j^{(6)},$$

$$\mathcal{L}_{\rm DLEFT} \supset \frac{1}{\Lambda}\sum_i L_i \mathcal{O}_i^{(5)} + \frac{1}{\Lambda^2}\sum_j L_j \mathcal{O}_j^{(6)},$$



22 DSMEFT operators can explain the Belle-II excess, and they can be distinguished from each other by more dedicated measurements of differential decay rate & F_L

Hadronic B decays

- **For a typical two-body decay $\bar{B} \to M_1 M_2$:**

$$\mathcal{A}(\bar{B} \to M_1 M_2) = \sum_i [\lambda_{\text{CKM}} \times C_i \times \langle M_1 M_2 | \mathcal{O}_i | \bar{B} \rangle]$$

- **Different methods proposed for dealing with $\langle M_1 M_2 | \mathcal{O}_i | \bar{B} \rangle$:** naïve fact., generalized fact., ……

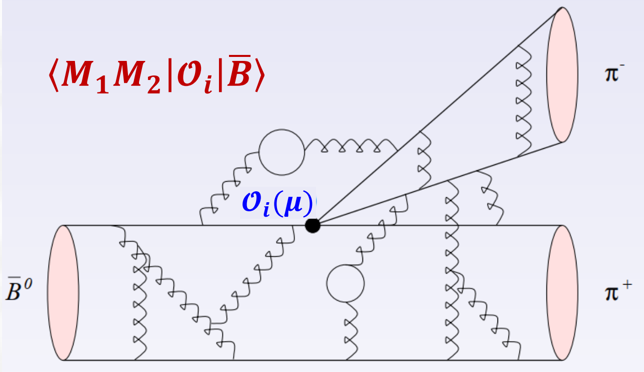
  - Dynamical approaches based on factorization theorems: PQCD, QCDF, SCET, · · ·
    [Keum, Li, Sanda, Lü, Yang '00;
    Beneke, Buchalla, Neubert, Sachrajda, '00;
    Bauer, Flemming, Pirjol, Stewart, '01; Beneke, Chapovsky, Diehl, Feldmann, '02]

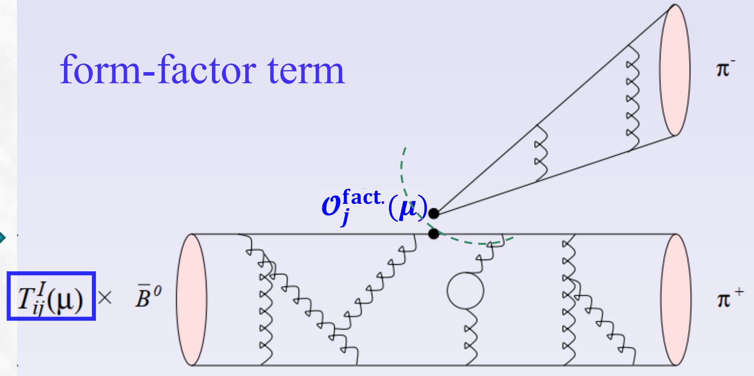
    → **how to include the higher-order perturbative & power corrections?**

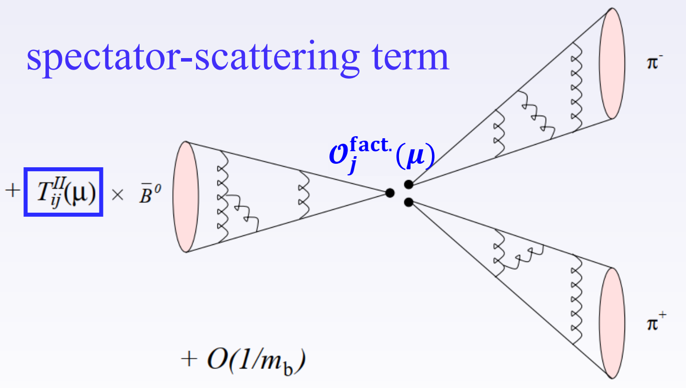
  - Symmetries of QCD: Isospin, U-Spin, V-Spin, and flavour SU(3) symmetries, · · ·
    [Zeppenfeld, '81;
    London, Gronau, Rosner, He, Chiang, Cheng *et al.*]

    → **how to estimate systematically the symmetry-breaking effects?**

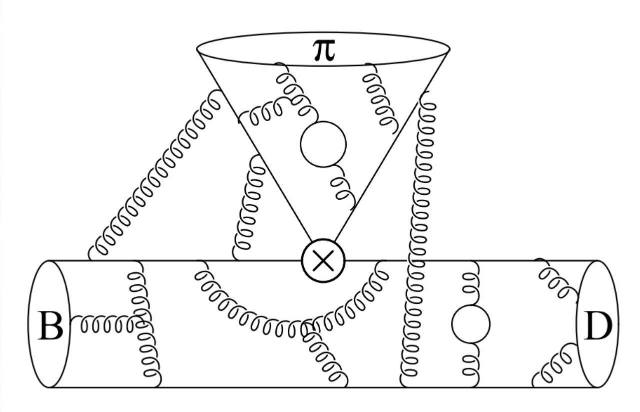
- **QCDF for $\bar{B} \to M_1 M_2$:**







$B_q^0 \to D_q^{(*)-} L^+$ class-I decays



- **At the quark-level, these decays 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;

  only the form-factor term at leading power

  [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 $T = a_1$

ii) spectator & annihilation power-suppressed

iii) annihilation absent in $B_{d(s)}^0 \to D_{d(s)}^- K(\pi)^+$ etc.

iv) they are theoretically simpler and cleaner

→ these decays used to test factorization theorems

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

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

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

Non-leptonic/semi-leptonic ratios

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

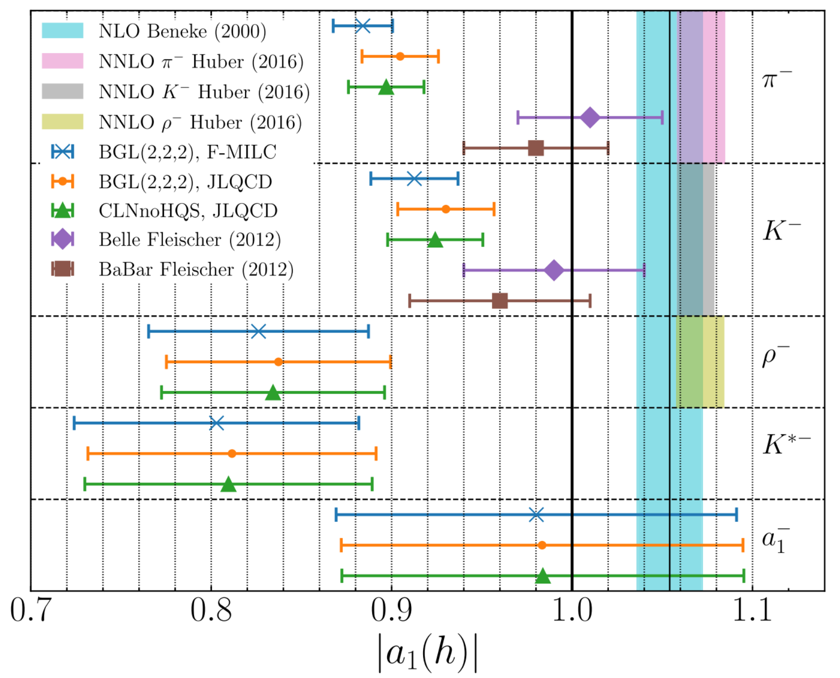
$$R^{(*)}_{(s)L} \equiv \frac{\Gamma(\bar{B}^0_{(s)} \to D^{(*)+}_{(s)} L^-)}{d\Gamma(\bar{B}^0_{(s)} \to D^{(*)+}_{(s)} \ell^- \bar{\nu}_\ell)/dq^2 \,|_{q^2=m_L^2}} = 6\pi^2 \, |V_{uq}|^2 \, f_L^2 \, |a_1(D^{(*)+}_{(s)} L^-)|^2 \, X_L^{(*)}$$

free from the 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 ($\bar{B} \to D^+ K^-$)	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
$R_{s\pi}$ ($\bar{B}_s \to D_s^+ \pi^-$)	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

- **Confirmed by Belle:** 2207.00134



$|a_1(\bar{B} \to D^{*+}\pi^-)| = 0.884 \pm 0.004 \pm 0.003 \pm 0.016 \; [1.071^{+0.020}_{-0.016}]$

15% lower than SM

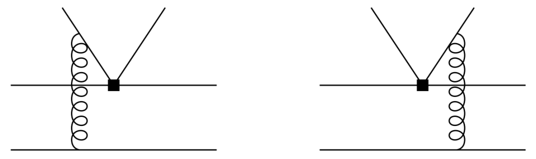
$|a_1(\bar{B} \to D^{*+}K^-)| = 0.913 \pm 0.019 \pm 0.008 \pm 0.013 \; [1.069^{+0.020}_{-0.016}]$

Large power corrections?

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

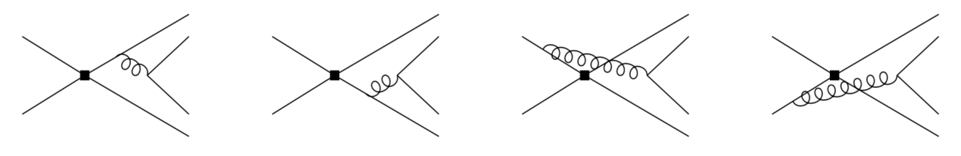
☐ **Sources of sub-leading power corrections:** [Beneke, Buchalla, Neubert, Sachrajda '01; Bordone, Gubernari, Huber, Jung, van Dyk '20]

- non-factorizable spectator interactions

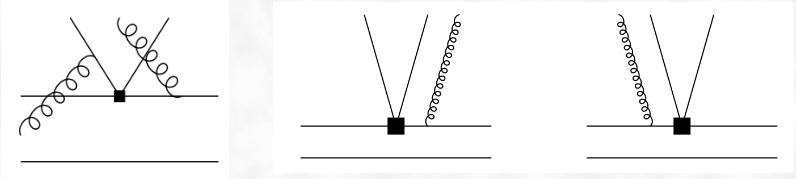


$\frac{\Lambda_{\rm QCD}}{m_b}$

- annihilation topologies

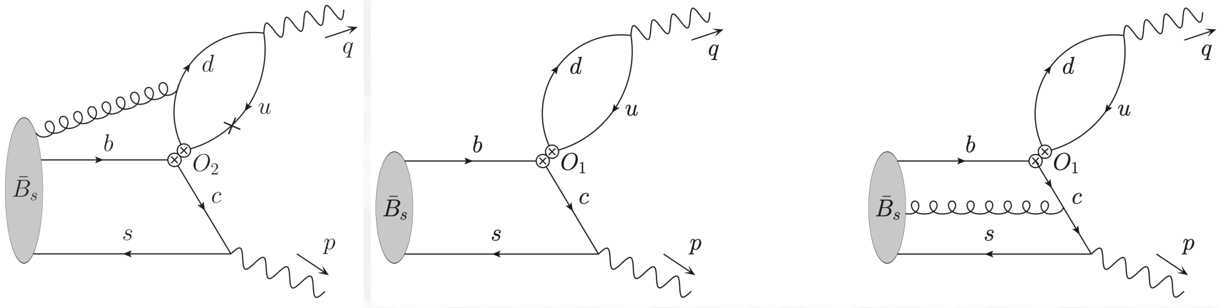


- non-leading higher Fock-state contributions



➡

- all are estimated to be power-suppressed, and no chirality-enhancement due to $(V-A) \otimes (V-A)$ structure
- very difficult to explain why the measured values of $|a_1(h)|$ several σ smaller than the SM predictions
- *must consider sub-leading power corrections more carefully*



☐ **Non-factorizable soft-gluon contributions in LCSR with B-meson LCDA:** [Maria Laura Piscopo, Aleksey V. Rusov, '23]

$$\mathrm{Br}(\bar{B}_s^0 \to D_s^+ \pi^-) = \left(2.15^{+2.14}_{-1.35}\right)\ [2.98 \pm 0.14] \times 10^{-3}$$

$$\mathrm{Br}(\bar{B}^0 \to D^+ K^-) = \left(2.04^{+2.39}_{-1.20}\right)\ [2.05 \pm 0.08] \times 10^{-4}$$

Model-indep. NP in $B_q^0 \to D_q^- L^+$?

- **Possible NP four-quark operators with different Dirac structures:** [Buras, Misiak, Urban '00]

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

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

NP four-quark operators

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

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

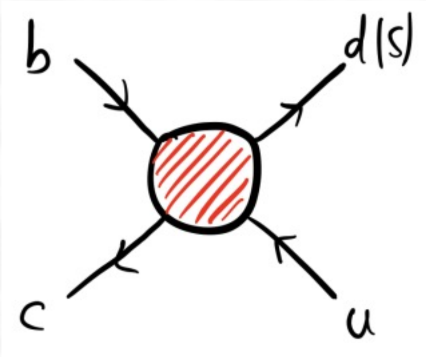
$$\mathcal{Q}_1^{SLL} = (\bar{c}_\alpha P_L b_\beta)(\bar{q}_\beta P_L u_\alpha) \qquad \mathcal{Q}_1^{SLR} = (\bar{c}_\alpha P_L b_\beta)(\bar{q}_\beta P_R u_\alpha)$$

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

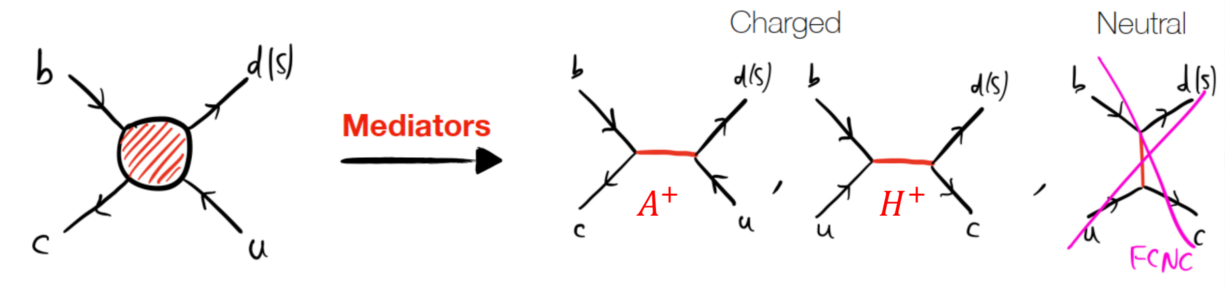
$$\mathcal{Q}_3^{SLL} = (\bar{c}_\alpha \sigma^{\mu\nu} P_L b_\beta)(\bar{q}_\beta \sigma_{\mu\nu} P_L u_\alpha)$$

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

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



- **Various possible tree-level heavy mediators:**



- **neutral mediators: necessarily couple to FCNC ➡ excluded by tree-level FCNCs!**
- **charged mediators: colorless or colored (constrained by di-jet resonance searches)**

[Bordone, Greljo, Marzocca, 2103.10332]

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 1 NP C_i^{NP} in each time, NP 4-quark operators with only three Dirac structures**

C.L.\Obs. / NP Coeff.	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]

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

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

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

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

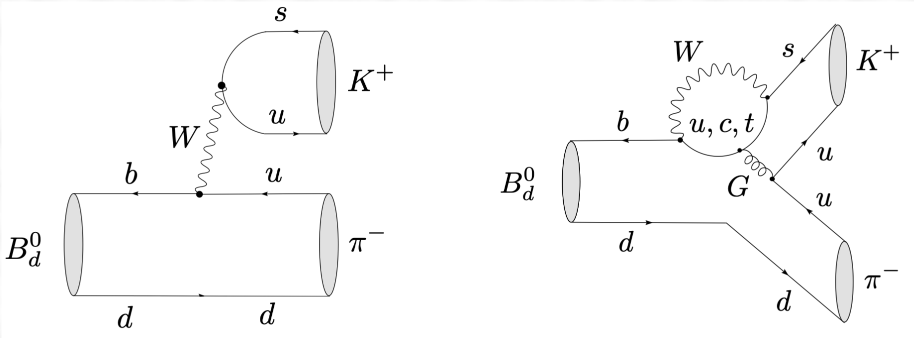
$$\mathcal{Q}_{1,2}^{SRL} = \bar{c}_\alpha (1+\gamma_5) b_{\beta(\alpha)}\, \bar{q}_\beta (1-\gamma_5) u_{\alpha(\beta)}$$

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

- (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

$B \to \pi K$ puzzle

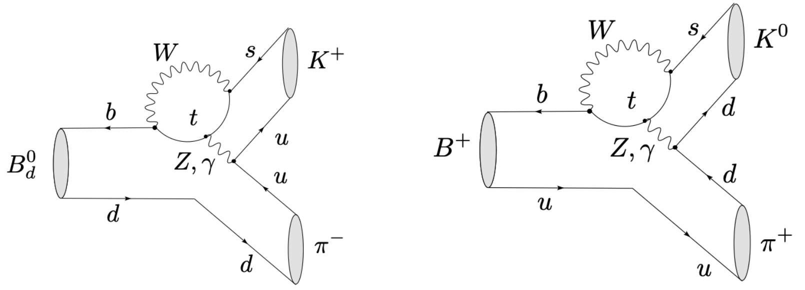
- $B \to \pi K$ **decays dominated by QCD penguin**
- **For direct CPV, tree & EW penguin also crucial**



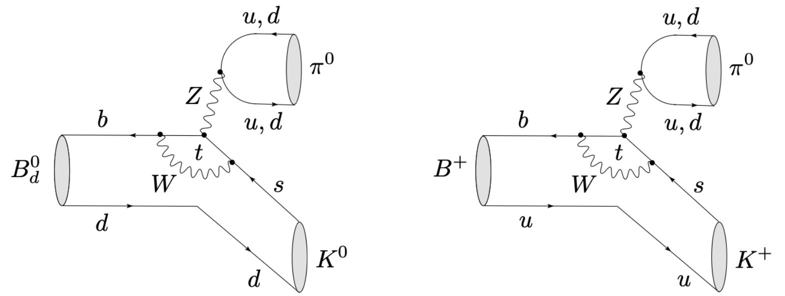
$\propto A\lambda^4 R_b e^{i\gamma}$ $\propto A\lambda^2$

$\lambda^2 R_b = \mathcal{O}(0.02) \Rightarrow$ QCD penguins *dominate*

- EW penguins are *colour-suppressed*: $\to$ *tiny* contributions ...



- EW penguins are *colour-allowed*: $\to$ *sizeable*, competing with trees!



$$\sqrt{2}\,A_{B^- \to \pi^0 K^-} = A_{\pi \bar{K}}\left[\delta_{pu}\,\alpha_1 + \hat{\alpha}_4^p\right] + A_{\bar{K}\pi}\left[\delta_{pu}\alpha_2 + \delta_{pc}\tfrac{3}{2}\alpha^c_{3,\mathrm{EW}}\right],$$
$$A_{\bar{B}^0 \to \pi^+ K^-} = A_{\pi \bar{K}}\left[\delta_{pu}\,\alpha_1 + \hat{\alpha}_4^p\right],$$

$$A_{\mathrm{CP}}(\pi^0 K^\pm) - A_{\mathrm{CP}}(\pi^\mp K^\pm) = -2\sin\gamma\left(\mathrm{Im}(r_C) - \mathrm{Im}(r_T\, r_{\mathrm{EW}})\right) + \ldots$$

$$\Delta A_{CP}(\pi K) = A_{CP}(\pi^0 K^-) - A_{CP}(\pi^+ K^-)$$

$$= (11.3 \pm 1.2)\%$$ **differs from 0 by ~9σ**

find some mechanism (sub-leading power corrections or NP) to enhance $C = \alpha_2$ or $P_{\mathrm{EW}} = \alpha^p_{3,\mathrm{EW}}$ [Buras et al., '03]

$\Delta A_{CP}(\pi K)$ puzzle

$B \to PP$ based on $\mathrm{SU}(3)$ flavor symmetry

- **Analysis based on $\mathrm{SU}(3)$ flavor symmetry & its breaking effect**

all $B \to PP$ decays ($B \in \{B^+, B^0, B_s^0\}$, $P \in \{\pi, K\}$) are related under $\mathrm{SU}(3)_\mathrm{F}$: $A(B \to PP) = \langle (8 \otimes 8)_s | H_\mathrm{eff} | 3 \rangle$ ⇒ $B \to PP$ decays amplitudes expressed in terms of $\mathrm{SU}(3)_\mathrm{F}$ RMEs & CG coefficients, and then perform a fit to all the data

- **Enough data for the fit with only 7 RMEs in exact $\mathrm{SU}(3)_F$ without any assumptions**

$\Delta S = 0$ decays:

Decay	$\mathcal{B}_{CP}$ ($\times 10^{-6}$)	A_{CP}	S_{CP}
$B^+ \to K^+ \overline{K}^0$	1.31 ± 0.14	0.04 ± 0.14	
$B^+ \to \pi^+ \pi^0$	5.59 ± 0.31	0.008 ± 0.035	
$B^0 \to K^0 \overline{K}^0$	1.21 ± 0.16	0.06 ± 0.26	-1.08 ± 0.49
$B^0 \to \pi^+ \pi^-$	5.15 ± 0.19	0.311 ± 0.030	-0.666 ± 0.029
$B^0 \to \pi^0 \pi^0$	1.55 ± 0.16	0.30 ± 0.20	
$B^0 \to K^+ K^-$	0.080 ± 0.015	??	??
$B_s^0 \to \pi^+ K^-$	$5.90^{+0.87}_{-0.76}$	0.225 ± 0.012	
$B_s^0 \to \pi^0 \overline{K}^0$	??	??	??

$\Delta S = 1$ decays:

Decay	$\mathcal{B}_{CP}$ ($\times 10^{-6}$)	A_{CP}	S_{CP}
$B^+ \to \pi^+ K^0$	23.52 ± 0.72	-0.016 ± 0.015	
$B^+ \to \pi^0 K^+$	13.20 ± 0.46	0.029 ± 0.012	
$B^0 \to \pi^- K^+$	19.46 ± 0.46	-0.0836 ± 0.0032	
$B^0 \to \pi^0 K^0$	10.06 ± 0.43	-0.01 ± 0.10	0.57 ± 0.17
$B_s^0 \to K^+ K^-$	$26.6^{+3.2}_{-2.7}$	-0.17 ± 0.03	0.14 ± 0.03
$B_s^0 \to K^0 \overline{K}^0$	17.4 ± 3.1	??	??
$B_s^0 \to \pi^+ \pi^-$	$0.72^{+0.11}_{-0.10}$	??	??
$B_s^0 \to \pi^0 \pi^0$	2.8 ± 2.8		

- **Key point:** no any theoretical assumptions on RMEs ⇒ completely rigorous on group-theoretical side

$B \to PP$ based on $SU(3)$ flavor symmetry

- **State-of-the-art $SU(3)_F$ fit** [Huber, Li, Malami, Tetlalmatzi-Xolocotzi, w.i.p; D. London et al., 2311.18011]

$$\lambda_u^{(q)} : A_1 = \langle \mathbf{1} \| \mathbf{3}_1^* \| \mathbf{3} \rangle\,, \quad A_8 = \langle \mathbf{8} \| \mathbf{3}_1^* \| \mathbf{3} \rangle\,,$$
$$\lambda_t^{(q)} : B_1 = \langle \mathbf{1} \| \mathbf{3}_2^* \| \mathbf{3} \rangle\,, \quad B_8 = \langle \mathbf{8} \| \mathbf{3}_2^* \| \mathbf{3} \rangle\,,$$
$$\lambda_u^{(q)}\ \&\ \lambda_t^{(q)} : R_8 = \langle \mathbf{8} \| \mathbf{6} \| \mathbf{3} \rangle\,, \quad P_8 = \langle \mathbf{8} \| \mathbf{15}^* \| \mathbf{3} \rangle\,,$$
$$P_{27} = \langle \mathbf{27} \| \mathbf{15}^* \| \mathbf{3} \rangle\,.$$

$$B_1 = -\frac{4}{\sqrt{3}}\left(\frac{3}{2}PA_{tc} + P_{tc}\right)\,, \quad B_8 = -\sqrt{\frac{5}{3}}P_{tc}\,.$$

$$A_1 = \frac{1}{2\sqrt{3}}\left(-3\widetilde{T} + \widetilde{C} - 8\widetilde{P}_{uc} - 12\widetilde{PA}_{uc}\right)\,,$$
$$A_8 = \frac{1}{8}\sqrt{\frac{5}{3}}\left(-3\widetilde{T} + \widetilde{C} - 8\widetilde{P}_{uc} - 3\widetilde{A}\right)\,,$$
$$R_8 = \frac{\sqrt{5}}{4}\left(\widetilde{T} - \widetilde{C} - \widetilde{A}\right)\,,$$
$$P_8 = \frac{1}{8\sqrt{3}}\left(\widetilde{T} + \widetilde{C} + 5\widetilde{A}\right)\,,$$
$$P_{27} = -\frac{1}{2\sqrt{3}}\left(\widetilde{T} + \widetilde{C}\right)\,.$$

$\Delta S = 0$ fit:

$\lvert\widetilde{T}\rvert$	$\lvert\widetilde{C}\rvert$	$\lvert\widetilde{P}_{uc}\rvert$	$\lvert\widetilde{A}\rvert$	$\lvert P_{tc}\rvert$
4.0 ± 0.5	6.6 ± 0.7	3 ± 4	6 ± 5	0.8 ± 0.4

$\Delta S = 1$ fit:

$\lvert\widetilde{T}'\rvert$	$\lvert\widetilde{C}'\rvert$	$\lvert\widetilde{P}'_{uc}\rvert$	$\lvert\widetilde{A}'\rvert$	$\lvert P'_{tc}\rvert$
48 ± 14	41 ± 14	48 ± 15	81 ± 28	0.78 ± 0.16

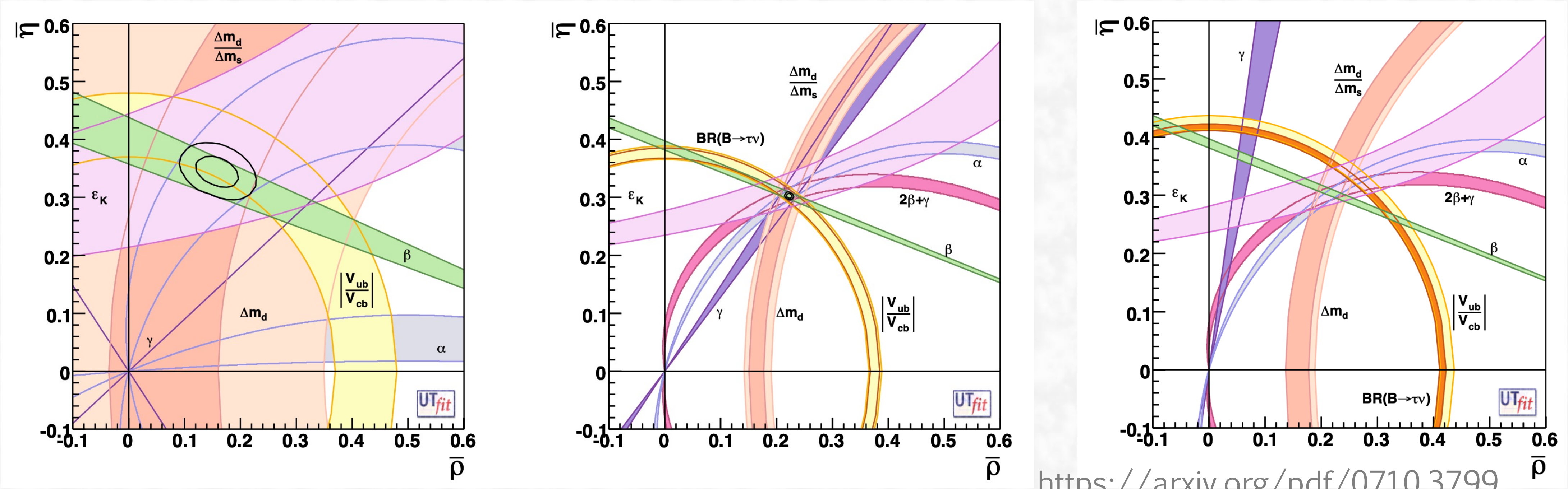
- ✓ for only ΔS = 0 decays: excellent fit
- ✓ for only ΔS = 1 decays: good fit
- ✓ $\left|\frac{\tilde{C}}{\tilde{T}}\right| = 1.65$ (ΔS=0), 0.85 (ΔS = 1), 1.23 ($SU(3)_F$) vs $0.13 \leq \left|\frac{\tilde{C}}{\tilde{T}}\right| = 0.23 \leq 0.43$ based on QCDF
- ✓ for combined ΔS = 0 & ΔS = 1 decays: very poor fit, with 3.6σ disagreement with the $SU(3)_F$ limit
- ✓ a 1000% $SU(3)_F$ breaking effect required, much large than naive expectation of $f_K/f_\pi - 1 \sim 20\%$

- **More precise measurements, especially of the missing observables (e.g. $B_s^0 \to K^0\bar{K}^0$ and $B_s^0 \to \pi^0\bar{K}^0$) may help to figure out true dynamical mechanism behind charmless B decays**

Summary

- With exp. and theor. progress, we are now entering a precision era for flavor physics
- Several deviations between data & SM observed ⟶ NP signals beyond the SM?
- More precise exp. measurements, theor. predictions, and LQCD inputs needed

many opportunities to explore SM & BSM physics in heavy flavor physics



https://arxiv.org/pdf/0710.3799