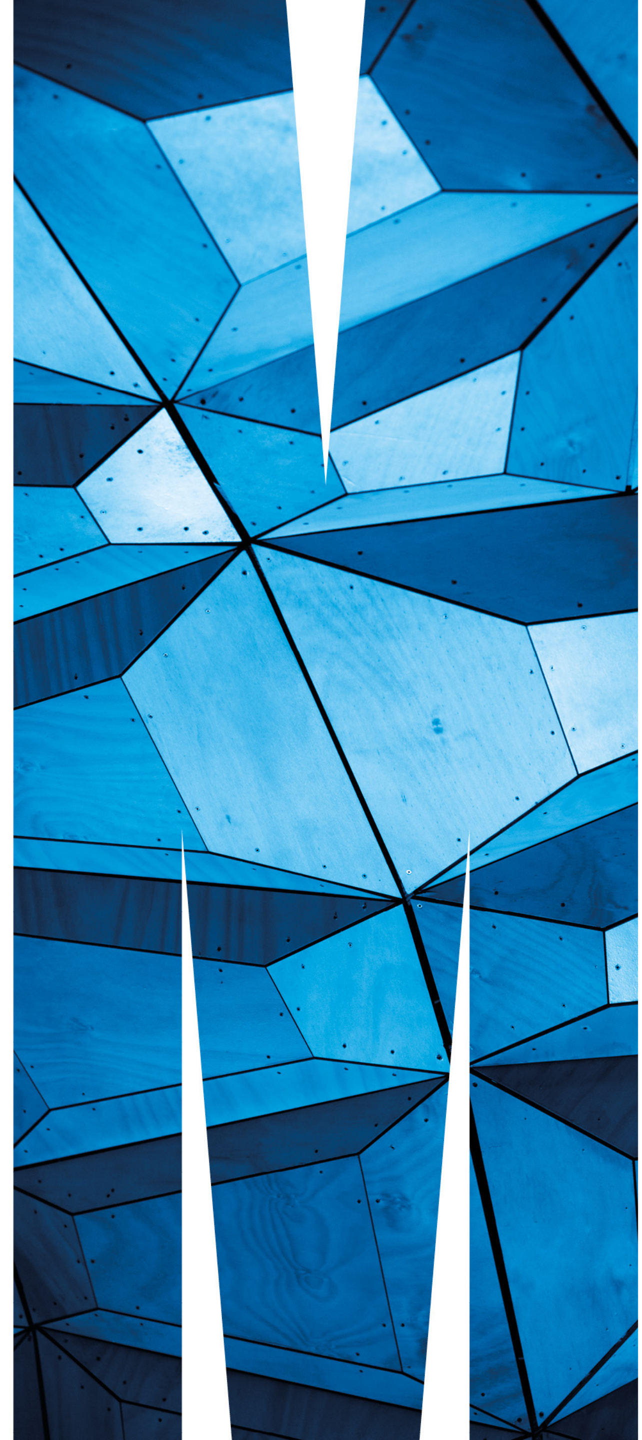
New physics in $B \to K^{(*)} + \text{invisible}$

Corfu Summer Institute:
Workshop on the Standard Model
and Beyond, 2024

German Valencia

based on work with Xiao-Gang He and Xiao-Dong Ma, Phys.Rev.D 109 (2024) 7, 075019, JHEP 03 (2023) 037 and Phys.Lett.B 821 (2021) 136607. Also with Michael Schmidt and Ray Volkas JHEP 07 (2024) 168

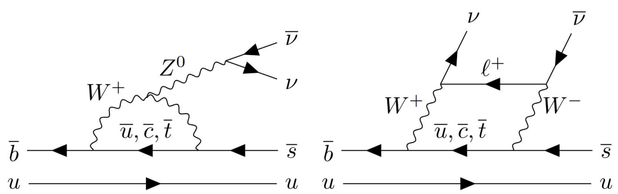


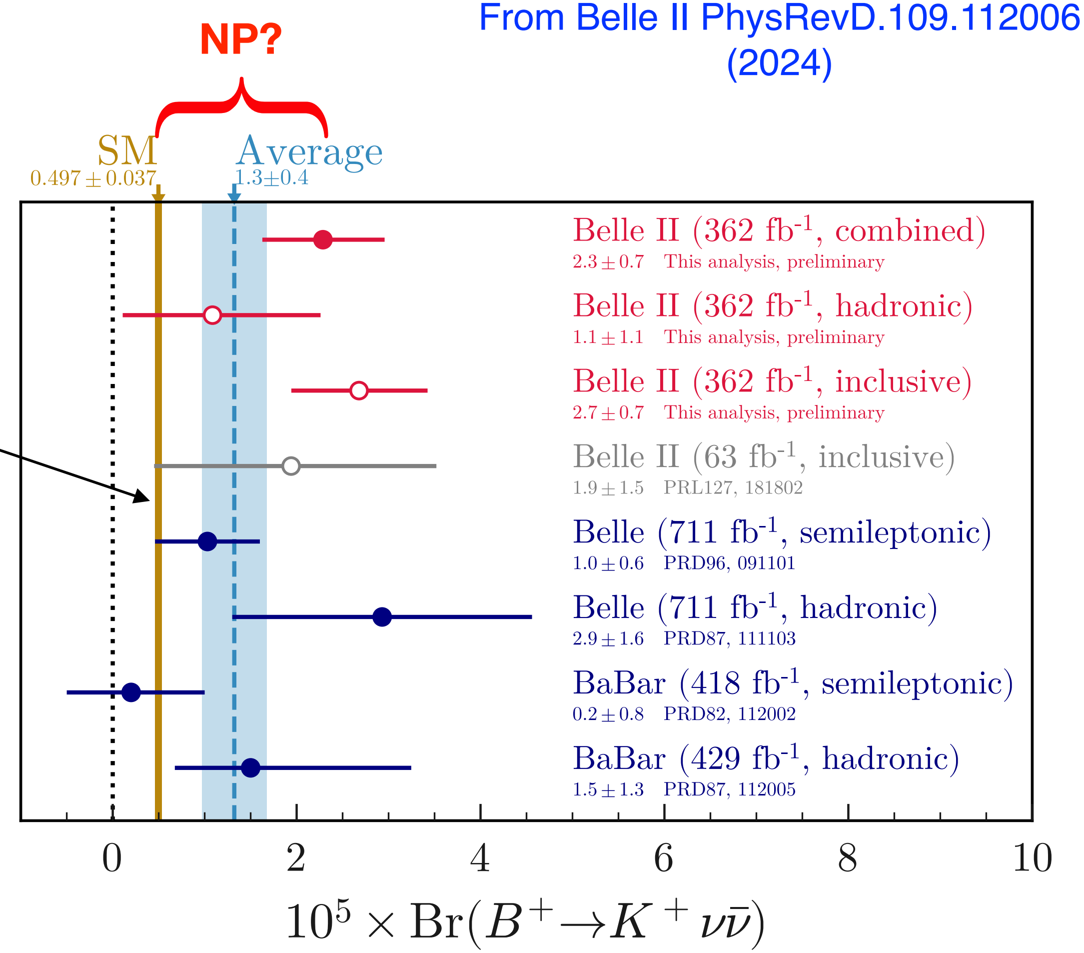
New Belle II result for $B^+ \to K^+ \nu\bar{\nu}$

- New result from Belle II presented in August 2023

From Belle II PhysRevD.109.112006 (2024)

SM very well known



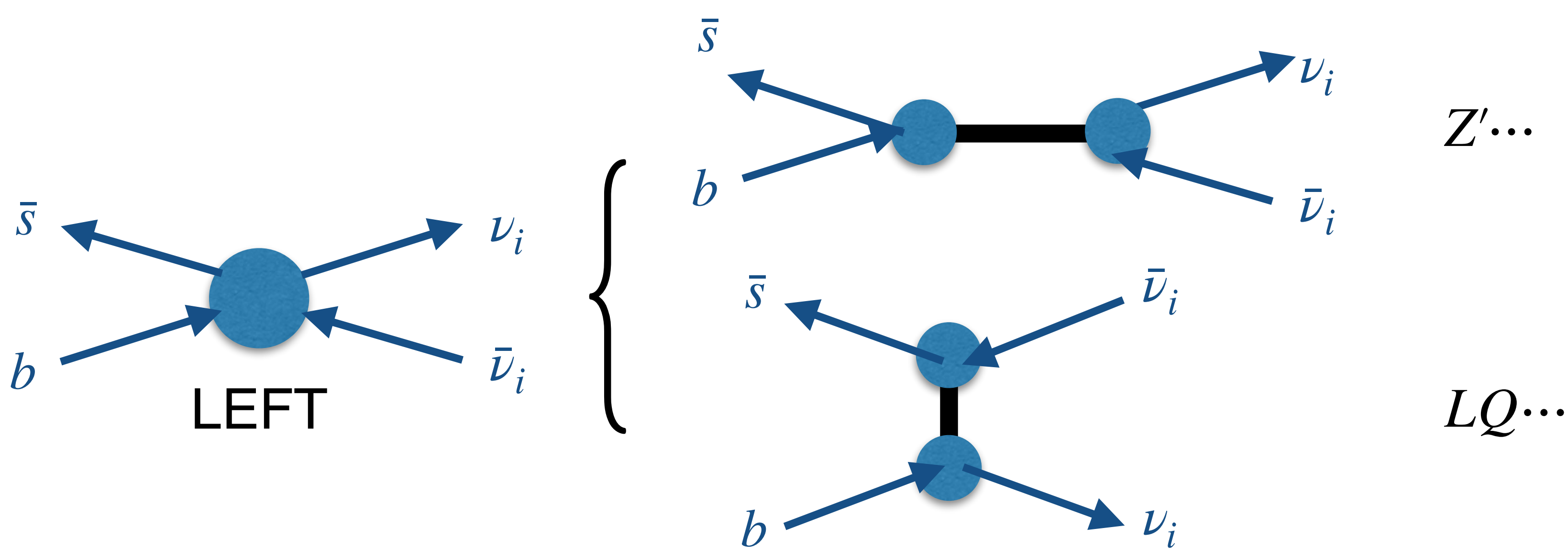


Observable	New physics bound $\mathcal{B}^{\mathrm{UL}}$
$\mathcal{B}(B^+ \to K^+ \not{E})$	1.3×10^{-5} PDG
$\mathcal{B}(B^0 \to K^0 \not{E})$	2.3×10^{-5} Belle
$\mathcal{B}(B^+ \to K^{*+} \not{E})$	3.1×10^{-5} Belle
$\mathcal{B}(B^0 \to K^{*0} \not{E})$	1.0×10^{-5} Belle

- Is it compatible with previously studied models and other measured modes?

Outline

- first consider an effective theory and find the parameter region of interest
- look for simple models with heavy mediators and consider additional constraints



first we quantify the "excess"

- To constrain neutrino couplings we use

$$R_K^{\nu\nu} = \frac{\mathscr{B}(B^+ \to K^+ \nu\bar{\nu})}{\mathscr{B}(B^+ \to K^+ \nu\bar{\nu})_{\mathtt{SM}}} = 5.3 \pm 1.7 \quad \text{using new result}$$

$$= 3. \pm 1. \quad \text{or using average}$$

$$R_{K^*}^{\nu\nu} = \frac{\mathscr{B}(B \to K^* \nu\bar{\nu})}{\mathscr{B}(B \to K^* \nu\bar{\nu})_{\mathtt{SM}}} \lesssim 2.7 \quad \text{Belle combined}$$

$$\lesssim 1.9 \quad \text{best for neutral mode}$$

- As constraints on new invisible particles, we use instead

$$\mathscr{B}(B^+ \to K^+ + invisible)_{\mathtt{NP}} \equiv \mathscr{B}(B^+ \to K^+\nu\bar{\nu})_{\mathtt{exp}} - \mathscr{B}(B^+ \to K^+\nu\bar{\nu})_{\mathtt{SM}} = (1.9 \pm 0.7) \times 10^{-5}$$

$$\mathscr{B}(B^+ \to K^+ + invisible)_{\mathtt{NP}} \equiv \mathscr{B}(B^+ \to K^+\nu\bar{\nu})_{\mathtt{ave}} - \mathscr{B}(B^+ \to K^+\nu\bar{\nu})_{\mathtt{SM}} = (1.0 \pm 0.4) \times 10^{-5}$$

  - combined with limits obtained from 90% c.l upper limits
  - $\mathscr{B}(B^0 \to K^0 + invisible)_{\mathtt{NP}} \lesssim 2.3 \times 10^{-5}$
  - $\mathscr{B}(B^+ \to K^{*+} + invisible)_{\mathtt{NP}} \lesssim 3.1 \times 10^{-5}$, $\mathscr{B}(B^0 \to K^{*0} + invisible)_{\mathtt{NP}} \lesssim 1.0 \times 10^{-5}$

LEFT with ν final states

- start from an effective interaction at the B scale

$$\mathcal{H}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^\star \frac{e^2}{16\pi^2} \sum_{ij} \Big(C_L^{ij} \mathcal{O}_L^{ij} + C_R^{ij} \mathcal{O}_R^{ij} + C_L^{'\,ij} \mathcal{O}_L^{'\,ij} + C_R^{'\,ij} \mathcal{O}_R^{'\,ij}$$

$$+ C_9^{ij} \mathcal{O}_9^{ij} + C_{10}^{ij} \mathcal{O}_{10}^{ij} + C_{9'}^{ij} \mathcal{O}_{9'}^{ij} + C_{10'}^{ij} \mathcal{O}_{10'}^{ij} \Big) + \text{ h.c.}$$

$$\mathcal{O}_L^{ij} = (\bar{s}_L \gamma_\mu b_L)(\bar{\nu}_i \gamma^\mu (1-\gamma_5) \nu_j),\ \mathcal{O}_R^{ij} = (\bar{s}_R \gamma_\mu b_R)(\bar{\nu}_i \gamma^\mu (1-\gamma_5) \nu_j),$$

$$\mathcal{O}_L^{'\,ij} = (\bar{s}_L \gamma_\mu b_L)(\bar{\nu}_i \gamma^\mu (1+\gamma_5) \nu_j),\ \mathcal{O}_R^{'\,ij} = (\bar{s}_R \gamma_\mu b_R)(\bar{\nu}_i \gamma^\mu (1+\gamma_5) \nu_j)$$

$$\mathcal{O}_{9^{(\prime)}}^{ij} = (\bar{s}_{L(R)}, \gamma_\mu b_{L(R)})(\bar{\ell}_i \gamma^\mu \ell_j),\ \mathcal{O}_{10^{(\prime)}}^{ij} = (\bar{s}_{L(R)}, \gamma_\mu b_{L(R)})(\bar{\ell}_i \gamma^\mu \gamma_5 \ell_j)$$

- charged leptons are related in SMEFT or specific models
- at the weak scale we have in mind leptoquarks and/or Z' mediators
  - no scalar or tensor operators
  - $b \to s \ell^+ \ell^-$ processes also constrain both cases

$R_K^{\nu\nu}, \quad R_{K*}^{\nu\nu}$

- Approximate numerical results

$$R_K^{\nu\nu} \approx 1 - 0.1 \ \mathrm{Re} \sum_i \left(C_L^{ii} + C_R^{ii} \right) + 0.008 \ \sum_{ij} \left(\left| C_L^{ij} + C_R^{ij} \right|^2 + \left| C_L'^{\,ij} + C_R'^{\,ij} \right|^2 \right),$$

$$R_{K^*}^{\nu\nu} \approx 1 + \mathrm{Re} \sum_i \left(-0.1 \ C_L^{ii} + 0.07 \ C_R^{ii} \right)$$

$$+ \sum_{ij} \left[0.008 \left(C_L^{ij\,2} + C_R^{ij\,2} + C_L'^{\,ij\,2} + C_R'^{\,ij\,2} \right) - 0.01 \left(C_L^{ij} C_R^{ij} + C_L'^{\,ij} C_R'^{\,ij} \right) \right].$$

$$R_K^{\nu\nu} - R_{K^*}^{\nu\nu} = 2(1+\eta) \left[\frac{C_{L\,\mathrm{SM}}}{3\,|C_{L\,\mathrm{SM}}|^2} \sum_i \mathrm{Re}\left(C_R^{ii} \right) + \frac{1}{3\,|C_{L\,\mathrm{SM}}|^2} \sum_{ij} \mathrm{Re} \left(C_L^{ij} C_R^{*ij} + C_L'^{\,ij} C_R'^{*\,ij} \right) \right].$$

- No isospin breaking so rates for neutral and charged modes are the same
- Primed coefficients do not interfere with SM or with unprimed ones
- Several special cases result in $R_K^{\nu\nu} = R_{K^*}^{\nu\nu}$, for example, if there are only C_L terms
- Not so with only C_R terms due to SM contribution

t-channel mediators: leptoquarks

- scalar or vector leptoquarks with couplings to SM neutrinos

$$\mathscr{L}_S = \lambda_{LS_0}\bar{q}_L^c i\tau_2 \ell_L {S_0}^\dagger + \lambda_{L\tilde{S}_{1/2}}\bar{d}_R \ell_L \tilde{S}^\dagger_{1/2} + \lambda_{LS_1}\bar{q}_L^c i\tau_2 \vec{\tau}\cdot\vec{S}_1^\dagger \ell_L + \text{ h. c.}$$

$$\mathscr{L}_V = \lambda_{LV_{1/2}}\bar{d}_R^c \gamma_\mu \ell_L V^{\dagger\mu}_{1/2} + \lambda_{LV_1}\bar{q}_L\gamma_\mu\vec{\tau}\cdot\overrightarrow{V}_1^{\dagger\mu}\ell_L + \text{ h. c.}$$

- result in

$$S_0^\dagger: (\bar{3},1,1/3) \implies C_L^{ij}$$

$$\tilde{S}^\dagger_{1/2}: (3,2,1/6) \implies C_{9'}^{ij} = -C_{10'}^{ij} = 2C_R^{ij}$$

$$\vec{S}_1^\dagger: (\bar{3},3,1/3) \implies C_9^{ij} = -C_{10}^{ij} = 2C_L^{ij}$$

$$V_{1/2}^\dagger: (\bar{3},2,5/6) \implies C_{9'}^{ij} = -C_{10'}^{ij} = 2C_R^{ij}$$

$$\overrightarrow{V}_1^\dagger: (3,3,2/3) \implies C_9^{ij} = -C_{10}^{ij} = \frac{1}{2}C_L^{ij}$$

$$C_L^{ij} = \frac{\pi}{\sqrt{2}\alpha G_F V_{td}V_{ts}^*}\left(\frac{\lambda_{LS_0}^{bj}\lambda_{LS_0}^{*si}}{2{m_{S_0}}^2} + \frac{\lambda_{LS_1}^{bj}\lambda_{LS_1}^{*si}}{2{m_{S_1}}^2} - 2\frac{\lambda_{LV_1}^{sj}\lambda_{LV_1}^{*bi}}{{m_{V_1}}^2}\right),$$

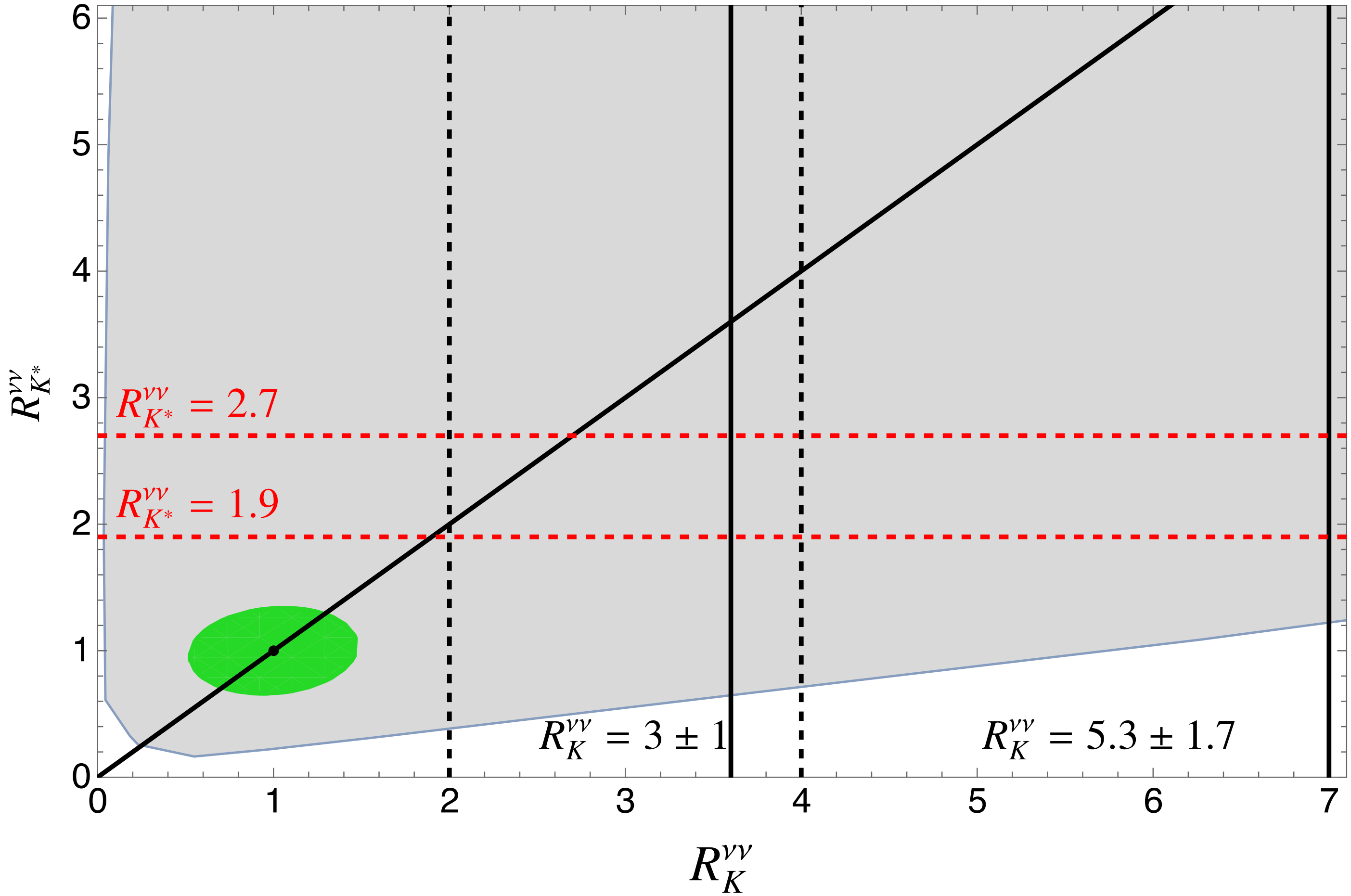
$$C_R^{ij} = C_{9'}^{ij} = -C_{10'}^{ij} = \frac{\pi}{\sqrt{2}\alpha G_F V_{td}V_{ts}^*}\left(-\frac{\lambda_{L\tilde{S}_{1/2}}^{sj}\lambda_{L\tilde{S}_{1/2}}^{*bi}}{2m_{\tilde{S}_{1/2}}^2} + \frac{\lambda_{LV_{1/2}}^{bj}\lambda_{LV_{1/2}}^{*si}}{m_{V_{1/2}}^2}\right),$$

$$C_9^{ij} = -C_{10}^{ij} = \frac{\pi}{\sqrt{2}\alpha G_F V_{td}V_{ts}^*}\left(\frac{\lambda_{LS_1}^{bj}\lambda_{LS_1}^{*si}}{{m_{S_1}}^2} - \frac{\lambda_{LV_1}^{sj}\lambda_{LV_1}^{*bi}}{{m_{V_1}}^2}\right).$$

- S_0 also modifies $R_D^{(*)}$ via the induced operator $\bar{c}b\bar{\tau}\nu^i$

Scanning over $C_L^{ij} - C_R^{ij}$ shows solutions in general

- One LQ at a time
- S_0, S_1, V_1 generate only C_L terms: $R_K^{\nu\nu} = R_{K^*}^{\nu\nu}$
- $S_{1/2}, V_{1/2}$ with only off-diagonal terms also: $R_K^{\nu\nu} = R_{K^*}^{\nu\nu}$



correlations with the B anomalies with C_L

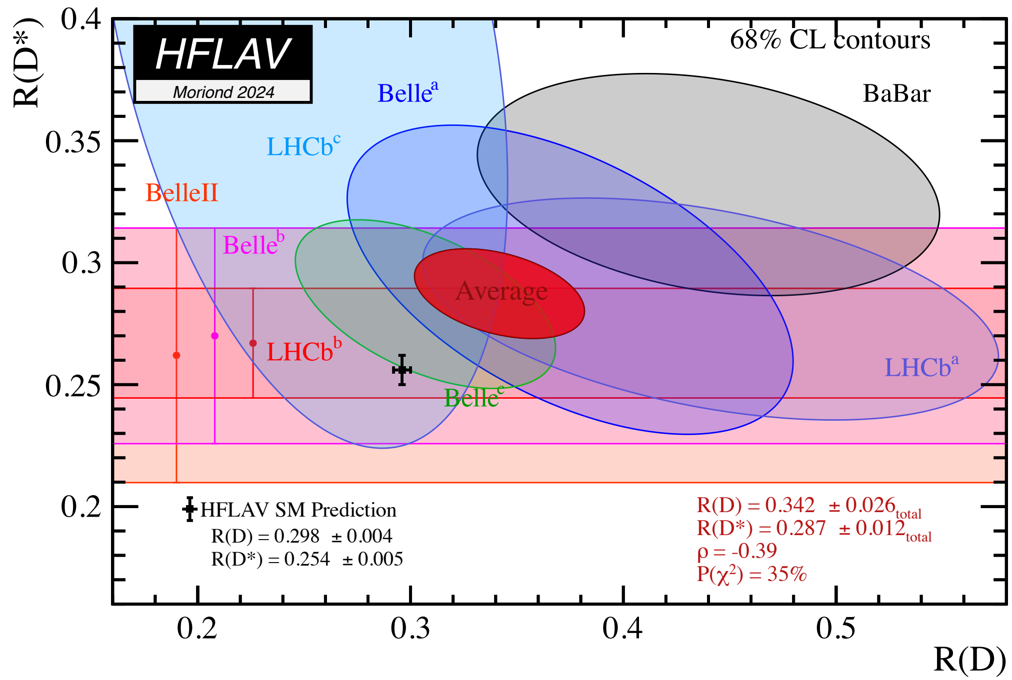
- for the case of S_0 there is a correlation with $r_{D^{(*)}}$

$$r_D = r_{D^*} = \left(\frac{\alpha}{2\pi}\right)^2 |\left(C_L^{3,1}|^2 + |C_L^{3,2}|^2\right) + |1 - \frac{\alpha}{2\pi} C_L^{3,3}|^2$$

$$r_{D^{(*)}} = \frac{R_{D^{(*)}}}{R_{D^{(*)}\ SM}}$$

$$r_D = 1.15 \pm 0.09$$

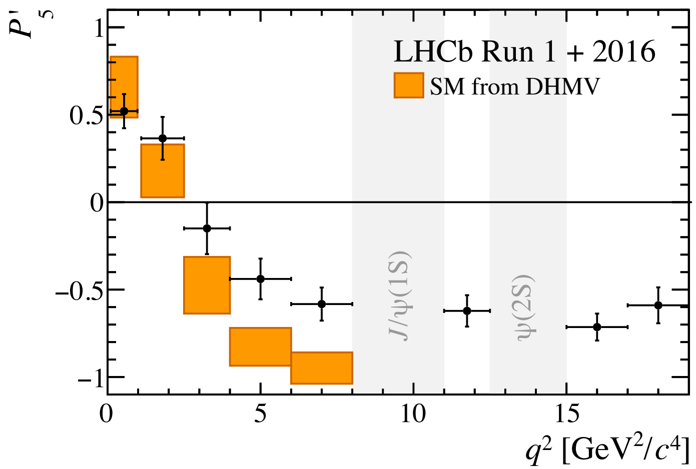
$$r_{D^*} = 1.13 \pm 0.05$$

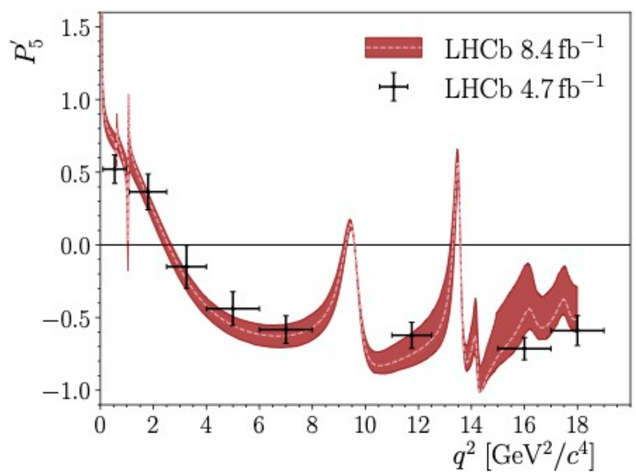


- S_0 predicts $R_K^{\nu\nu} = R_{K^*}^{\nu\nu}$
- If we take $R_K^{\nu\nu} = R_{K^*}^{\nu\nu} \sim 3.5$ then $r_{D^{(*)}} \lesssim 1.06$ about 1σ away
- Central value of $r_{D^{(*)}}$ with S_0 would lead to $R_K^{\nu\nu} = R_{K^*}^{\nu\nu} \gtrsim 14$

correlations with the B anomalies with C_L

- Recent global fits to $b \to s\ell^+\ell^-$ suggest values $C_9^{\mu\mu} \sim C_9^{ee} \lesssim -1$ with C_{10} somewhat smaller (for both muons and electrons)





$C_9 = -0.71 \pm 0.33$
$C_{10} = 0.29 \pm 0.24$

LHCb unbinned 2024
https://arxiv.org/abs/2405.17347

- for S_1, V_1 this means minimal effect on $R_K^{\nu\nu} = R_{K*}^{\nu\nu}$:

$$S_1 \Longrightarrow C_9^{\mu\mu} = -C_{10}^{\mu\mu} = 2C_L^{\mu\mu} \Longrightarrow R_K^{\nu\nu} = R_{K*}^{\nu\nu} \lesssim 1.1$$ 2(3)σ below av (new)

$$V_1 \Longrightarrow C_9^{\mu\mu} = -C_{10}^{\mu\mu} = \frac{1}{2}C_L^{\mu\mu} \Longrightarrow R_{K^{(*)}}^{\nu\nu} \lesssim 1.5$$

$S_{1/2}, V_{1/2}$ with both diagonal and off-diagonal terms

- These two LQs can reproduce the solution region

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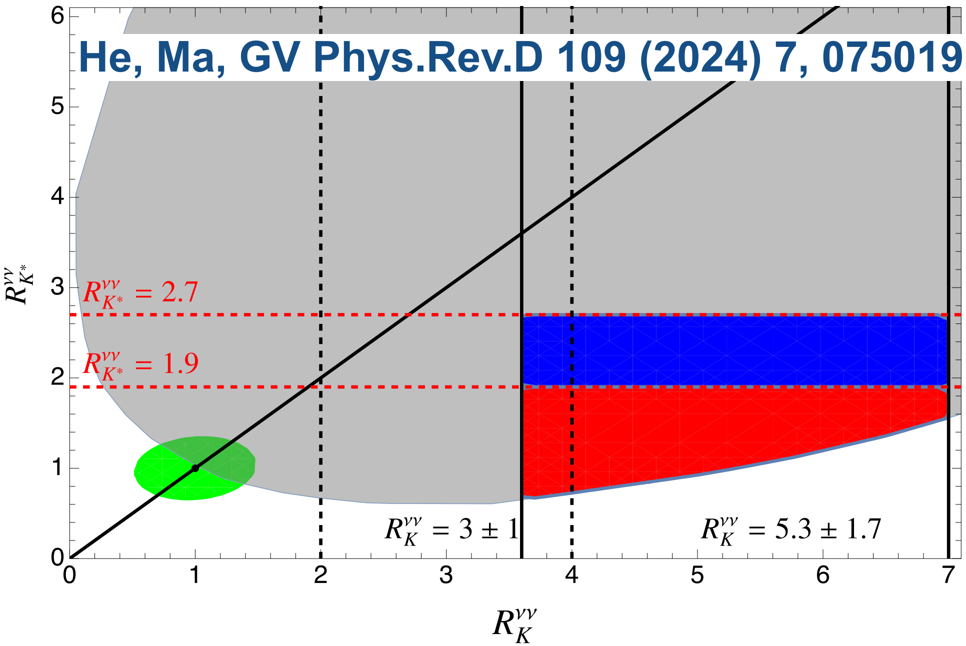
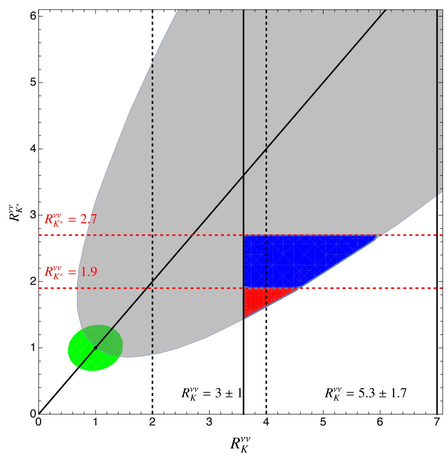


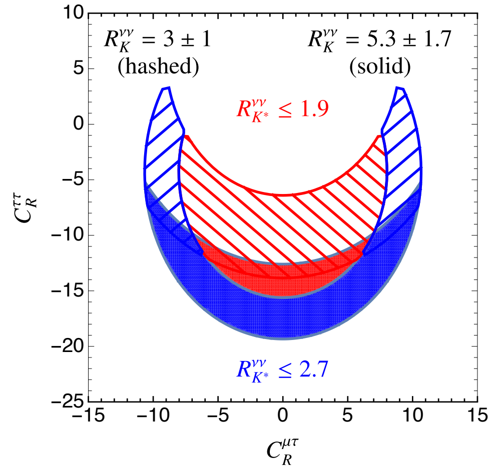
check animation here

- Find the parameters and see if the models are viable
- recall that $C_R^{ij} = \dfrac{1}{2} C_{9'}^{ij} = -\dfrac{1}{2} C_{10'}^{ij}$ affecting $b \to s\ell^+\ell^-$
- at least one of the diagonal terms is large (around 10)
- cannot be $C_R^{ee,\mu\mu}$ from global fits to $b \to s\ell^+\ell^-$
- the only possibility is then to have a large $C_R^{\tau\tau}$

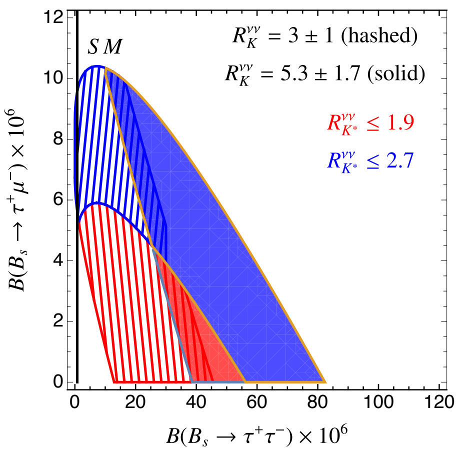
Only non-zero diagonal term $C_R^{\tau\tau}$

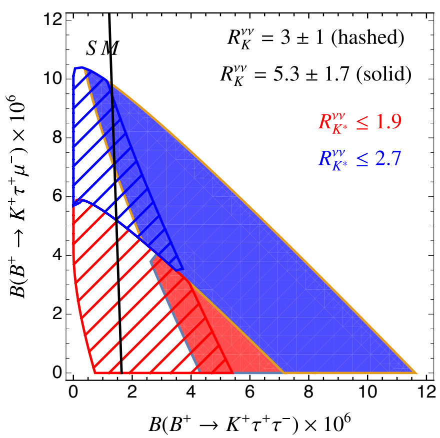
- Scan of C_R^{ij} with $i \neq j$ or $i = j = 3$ showing solutions in this case and map of solutions to the allowed region of $C_R^{\tau\tau}$ and $C_R^{\mu\tau} = C_R^{\tau\mu}$





Lead to enhanced modes with taus, both LFC and LFV





Current experimental limits

$$B(B_s \to \tau^+\tau^-) \leq 6.8 \times 10^{-3}$$
$$B(B_s \to \tau^+\mu^-) \leq 42 \times 10^{-6}$$
$$B(B^+ \to K^+\tau^+\tau^-) \leq 2.25 \times 10^{-3}$$
$$B(B^+ \to K^+\tau^+\mu^-) \leq 28 \times 10^{-6}$$

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CLFV and $B \to K^{(*)}\nu\bar{\nu}$

LQ	upper bound on $C^{ij}_{L,R}$			$R^\nu_K = R^\nu_{K^*}$		
				μe	$e\tau$	$\mu\tau$
$\tilde{S}_{1/2}$	$\lvert C^{\mu e}_R\rvert \lesssim 0.4$	$\lvert C^{e\tau}_R\rvert \lesssim 26$	$\lvert C^{\mu\tau}_R\rvert \lesssim 35$	1.001	6.4	11
S_1	$\lvert C^{\mu e}_L\rvert \lesssim 0.2$	$\lvert C^{e\tau}_L\rvert \lesssim 13$	$\lvert C^{\mu\tau}_L\rvert \lesssim 18$	1.0003	2.4	3.5
$V_{1/2}$	$\lvert C^{\mu e}_R\rvert \lesssim 0.4$	$\lvert C^{e\tau}_R\rvert \lesssim 26$	$\lvert C^{\mu\tau}_R\rvert \lesssim 35$	1.001	6.4	11
$V_1^\dagger$	$\lvert C^{\mu e}_L\rvert \lesssim 0.8$	$\lvert C^{e\tau}_L\rvert \lesssim 52$	$\lvert C^{\mu\tau}_L\rvert \lesssim 70$	1.005	23	40

- allowing only off-diagonal terms, each LQ produces only C_L or only C_R resulting in $R^{\nu\nu}_K = R^{\nu\nu}_{K^*}$
- The current upper bound from CLFV processes is less restrictive than the bound from $R^{\nu\nu}_K$ except for μe flavours
- This bound for the case of S_1 is comparable to that from $R^{\nu\nu}_K$ but less restrictive than the one from $R^{\nu\nu}_{K^*}$

Mode	90% c.l
$\mathcal{B}(B_s \to e^\pm\mu^\mp)$	5.4×10^{-9}
$\mathcal{B}(B_s \to \mu^\pm\tau^\mp)$	4.2×10^{-5}
$\mathcal{B}(B^+ \to K^+ e^-\mu^+)$	6.4×10^{-9}
$\mathcal{B}(B^+ \to K^+ e^-\tau^+)$	1.5×10^{-5}
$\mathcal{B}(B^+ \to K^+ \mu^-\tau^+)$	2.8×10^{-5}
$\mathcal{B}(B^+ \to K^{*+} e^-\mu^+)$	9.9×10^{-7}
$\mathcal{B}(B^0 \to K^{*0} e^-\mu^+)$	1.2×10^{-7}

Scanning over $C_L^{\prime ij} - C_R^{\prime ij}$

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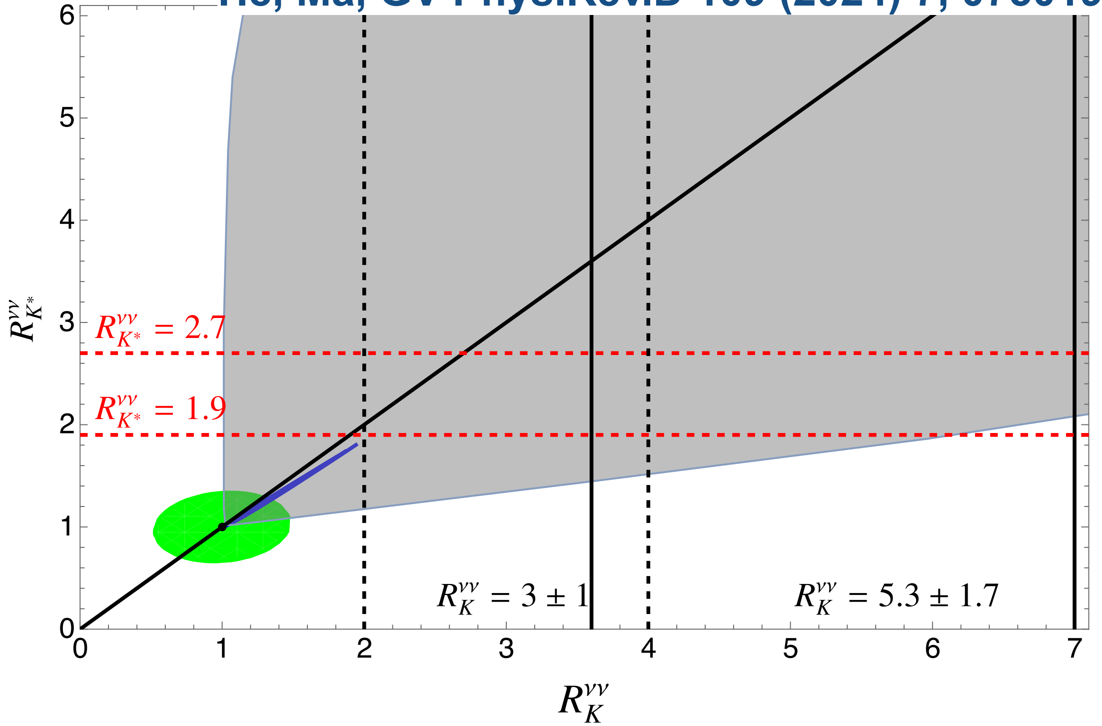

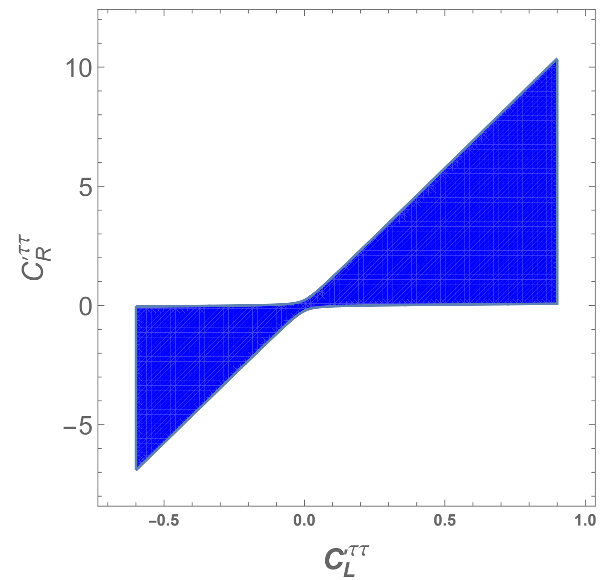

- in general, this scenario can also reproduce the new result but it is harder to reconcile a high $R_K^{\nu\nu}$ with a low $R_{K^*}^{\nu\nu}$
- in a Z' model B_s mixing limits the allowed parameter space to the blue region, resulting in $R_K^{\nu\nu} \approx R_{K^*}^{\nu\nu}$ and at most 2

New light invisible particles

- mass window to invisible light particles: $m < m_B - m_K$
- we assume they are pair-produced (3 body decay)
- we consider spins $0,\ \frac{1}{2},\ 1$
- Mediators are assumed at the weak scale and integrated out to produce a ϕLEFT of the form $\mathscr{L} = \sum C_i\, O_i$
- we look for an enhancement in $3 \leq q^2 \leq 7\ \mathrm{GeV}^2$ as suggested by Belle data
- Propose a UV completion where scalars are dark matter

scalars up to dim 6 that contribute to $B^+ \to K^+ + invisible$

- $\mathcal{O}_{q\phi}^{S,sb} = (\bar{s}b)(\phi^\dagger\phi)$, $\mathcal{O}_{q\phi}^{V,sb} = (\bar{s}\gamma^\mu b)(\phi^\dagger i\overleftrightarrow{\partial}_\mu \phi)$
- use $C_{q\phi}^{S,sb} \equiv \Lambda_{\rm eff}^{-1}$, $C_{q\phi}^{V,sb} \equiv \Lambda_{\rm eff}^{-2}$ i.e. $\mathcal{L} = \frac{1}{\Lambda_{\rm eff}}\mathcal{O}_{q\phi}^{S,sb} + \frac{1}{\Lambda_{\rm eff}^2}\mathcal{O}_{q\phi}^{V,sb}$
- they both arise at dim 6 in ϕSMEFT (blue vanishes for real scalar fields), $\frac{1}{\Lambda_{\rm eff}}\mathcal{O}_{q\phi}^{S,sb} \in \frac{v}{\Lambda_{\rm eff}^2}(\bar{q}_{2L} b_R H)(\phi^\dagger\phi)$

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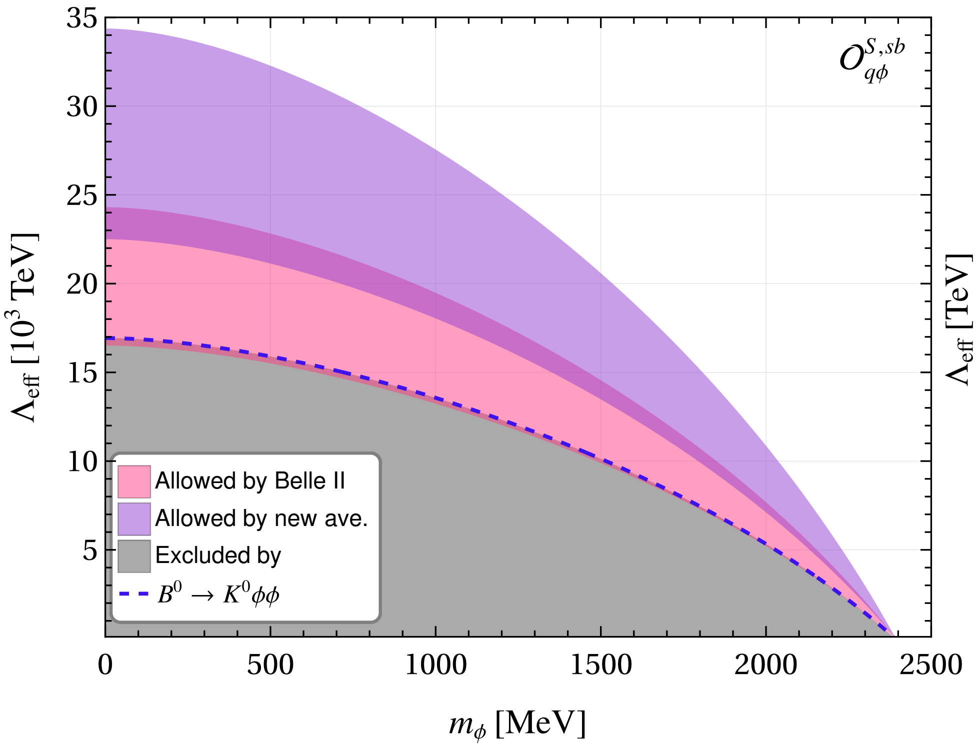
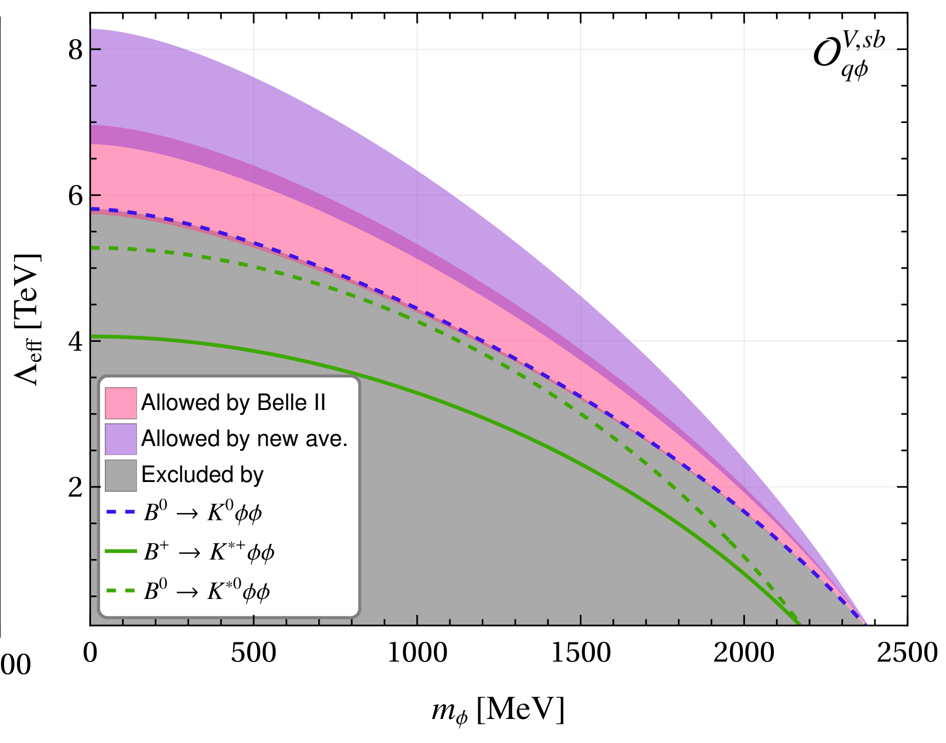




fermions: six operators at dim 6

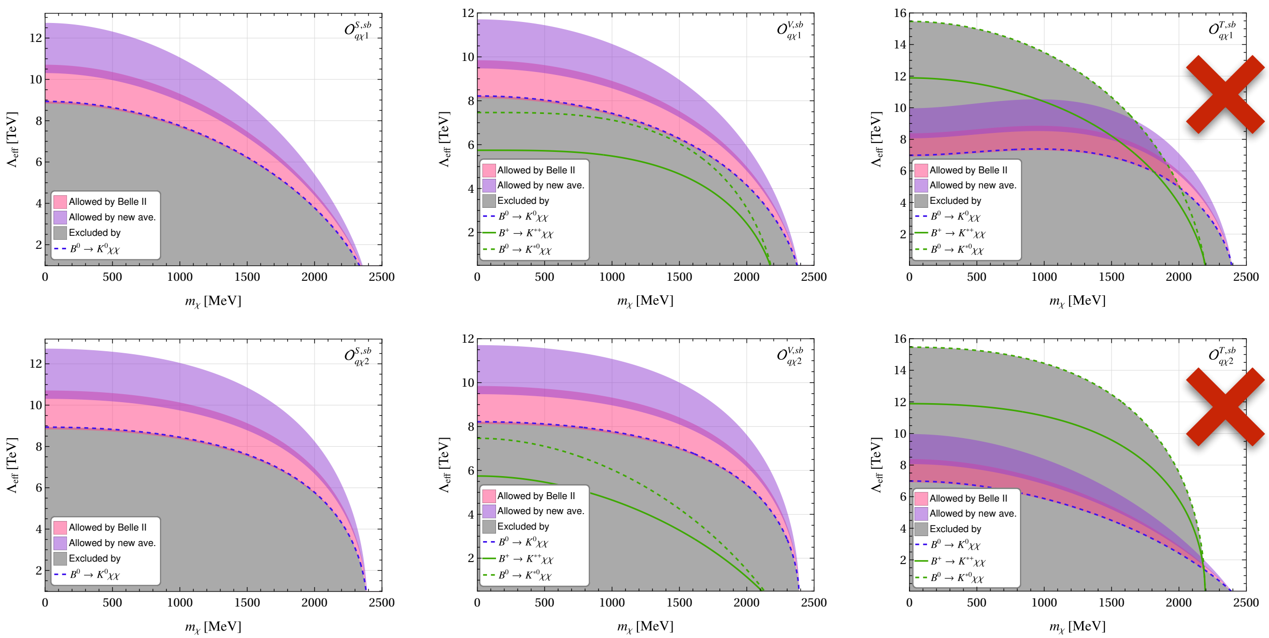
$$\mathcal{O}^{S,sb}_{q\chi 1} = (\bar{s}b)(\bar{\chi}\chi), \qquad \mathcal{O}^{S,sb}_{q\chi 2} = (\bar{s}b)(\bar{\chi}i\gamma_5\chi),$$

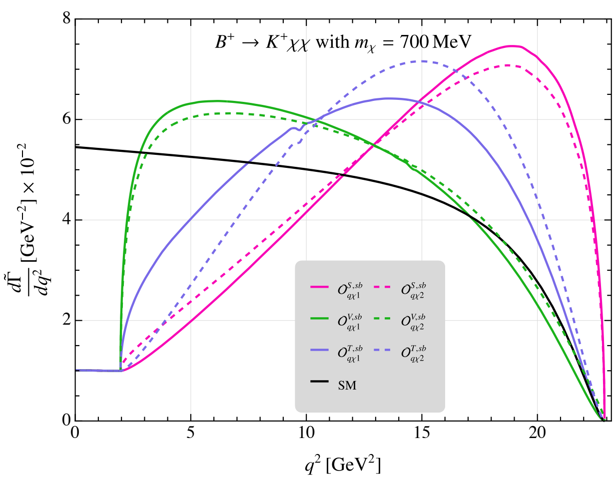
$$\mathcal{O}^{V,sb}_{q\chi 1} = (\bar{s}\gamma^\mu b)(\bar{\chi}\gamma_\mu\chi), \qquad \mathcal{O}^{V,sb}_{q\chi 2} = (\bar{s}\gamma^\mu b)(\bar{\chi}\gamma_\mu\gamma_5\chi),$$

$$\mathcal{O}^{T,sb}_{q\chi 1} = (\bar{s}\sigma^{\mu\nu} b)(\bar{\chi}\sigma_{\mu\nu}\chi), \qquad \mathcal{O}^{T,sb}_{q\chi 2} = (\bar{s}\sigma^{\mu\nu} b)(\bar{\chi}\sigma_{\mu\nu}\gamma_5\chi),$$

$$C_i^j \equiv \Lambda_{\rm eff}^{-2}$$

- blue vanishes for Majorana fermions
- green preferred by spectrum





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vectors up to dim 6

- vector field formulation

$$\mathcal{O}_{qX}^{S,sb} = (\bar{s}b)(X_\mu^\dagger X^\mu),$$

$$\mathcal{O}_{qX1}^{T,sb} = \frac{i}{2}(\bar{s}\sigma^{\mu\nu}b)(X_\mu^\dagger X_\nu - X_\nu^\dagger X_\mu),$$

$$\mathcal{O}_{qX2}^{T,sb} = \frac{1}{2}(\bar{s}\sigma^{\mu\nu}\gamma_5 b)(X_\mu^\dagger X_\nu - X_\nu^\dagger X_\mu),$$

$$\mathcal{O}_{qX2}^{V,sb} = (\bar{s}\gamma_\mu b)\partial_\nu(X^{\mu\dagger}X^\nu + X^{\nu\dagger}X^\mu)$$

$$\mathcal{O}_{qX3}^{V,sb} = (\bar{s}\gamma_\mu b)(X_\rho^\dagger \overleftrightarrow{\partial}_\nu X_\sigma)\epsilon^{\mu\nu\rho\sigma},$$

$$\mathcal{O}_{qX4}^{V,sb} = (\bar{s}\gamma^\mu b)(X_\nu^\dagger i\overleftrightarrow{\partial}_\mu X^\nu),$$

$$\mathcal{O}_{qX5}^{V,sb} = (\bar{s}\gamma_\mu b)i\partial_\nu(X^{\mu\dagger}X^\nu - X^{\nu\dagger}X^\mu),$$

$$\mathcal{O}_{qX6}^{V,sb} = (\bar{s}\gamma_\mu b)i\partial_\nu(X_\rho^\dagger X_\sigma)\epsilon^{\mu\nu\rho\sigma}$$

- operators in blue vanish for real fields
- these operators produce amplitudes that diverge in the massless limit
- this known problem is addressed by assuming that X is a gauge boson, and gauge invariance forbids its direct appearance
- these operators are thus assumed to inherit a coefficient that vanishes for massless X

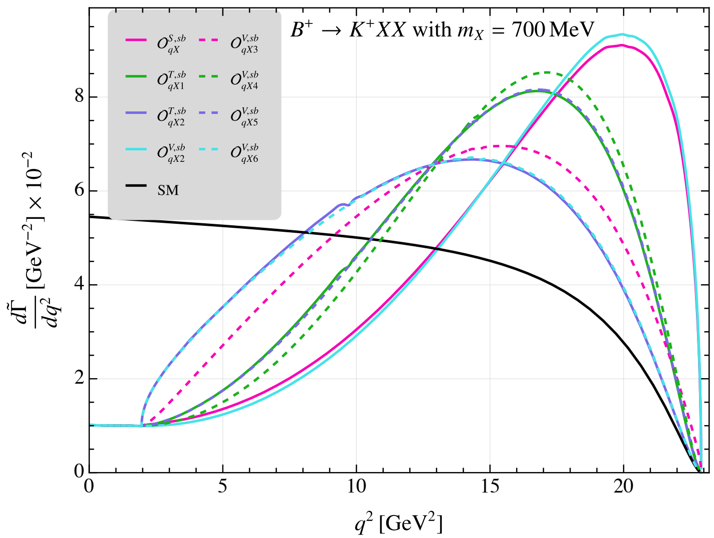
results with vector operators

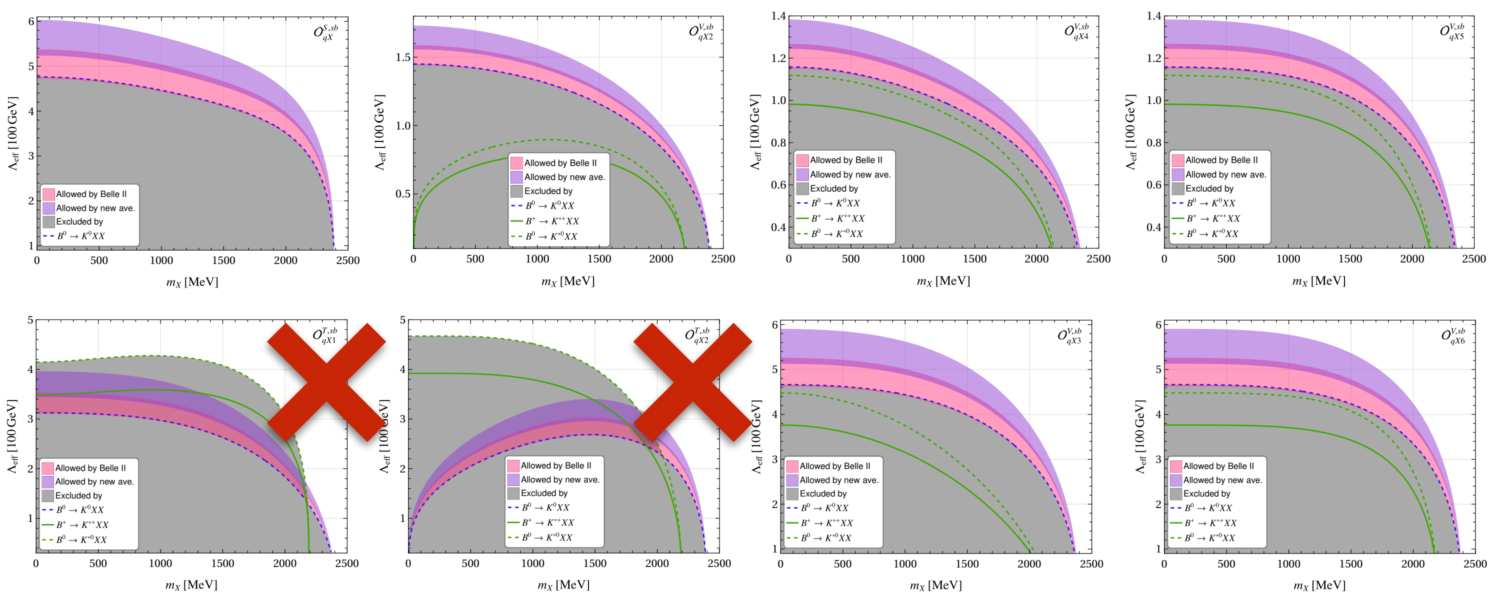
- scaling including mass factors to address divergence

$$C^S_{qX} \equiv \frac{m^2}{\Lambda^3_{\rm eff}}, \quad C^T_{qX1,2} \equiv \frac{m^2}{\Lambda^3_{\rm eff}}, \quad C^V_{qX2,4,5} \equiv \frac{m^2}{\Lambda^4_{\rm eff}}, \quad C^V_{qX3,6} \equiv \frac{m}{\Lambda^3_{\rm eff}}$$

- Two of the operators, $\mathcal{O}^{T,sb}_{qX1}$, $\mathcal{O}^{T,sb}_{qX2}$, are mostly ruled out by other modes

- Appear disfavoured by shape of spectrum





He, Ma, GV JHEP 03 (2023) 037

From Belle II PhysRevD.109.112006 (2024)

POST-FIT q^2_{rec} DISTRIBUTIONS

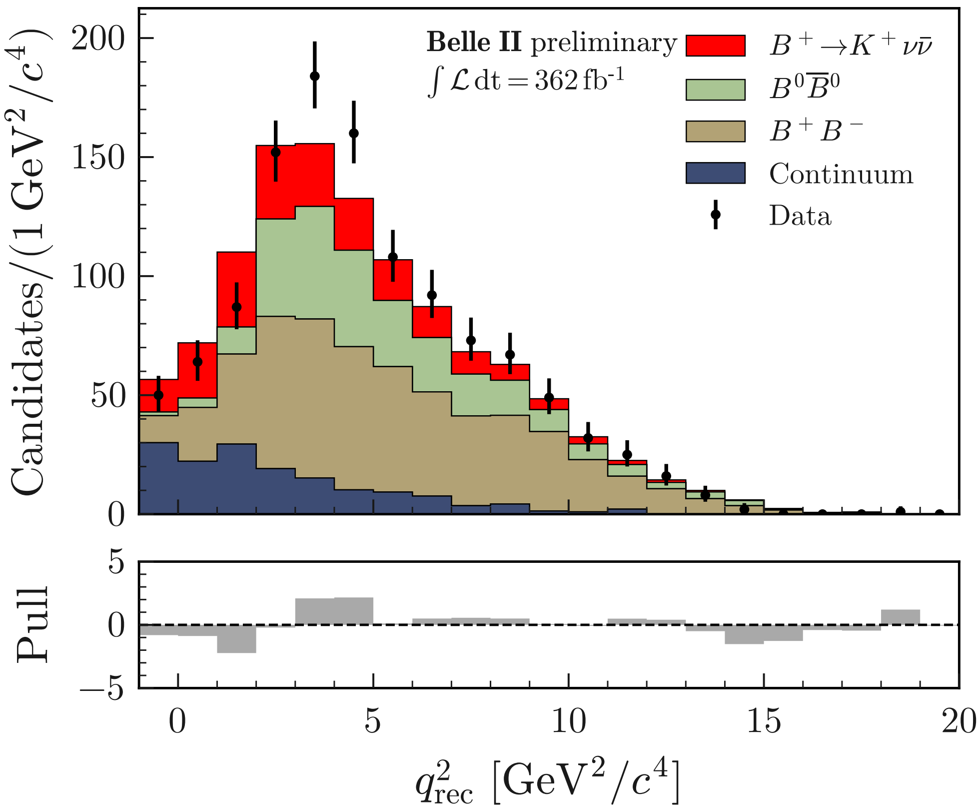
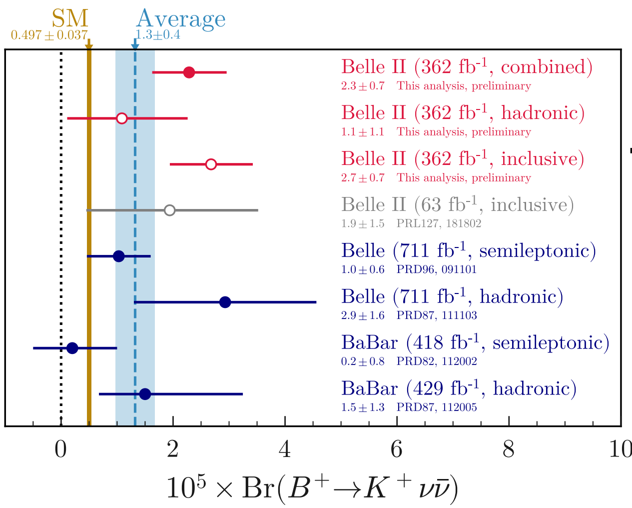
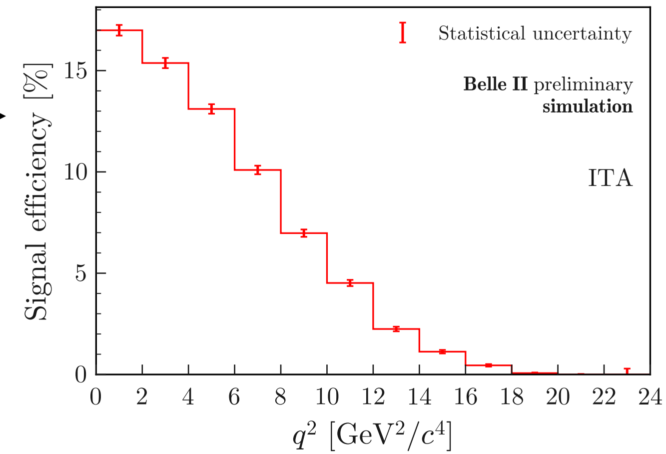


FIG. 17. Distributions of $\eta(\mathrm{BDT}_2)$, q^2_{rec}, beam-constrained mass of the ROE $M_{\mathrm{bc,ROE}}$, ΔE_{ROE}, Fox-Wolfram R_2, and modified Fox-Wolfram $H^{\mathrm{so}}_{m,2}$ in data (points with error bars) and simulation (filled histograms) shown individually for the $B^+ \to K^+\nu\bar{\nu}$ signal, neutral and charged B-meson decays, and the sum of the five continuum categories in the ITA. Events in the full signal region, with $\eta(\mathrm{BDT}_2) > 0.92$, are shown. Data and simulation are normalized to an integrated luminosity of 362 fb^{-1}. The pull distributions are shown in the bottom panels.

experimental efficiency

- affects constraints on NP because BR limits assume the SM spectrum



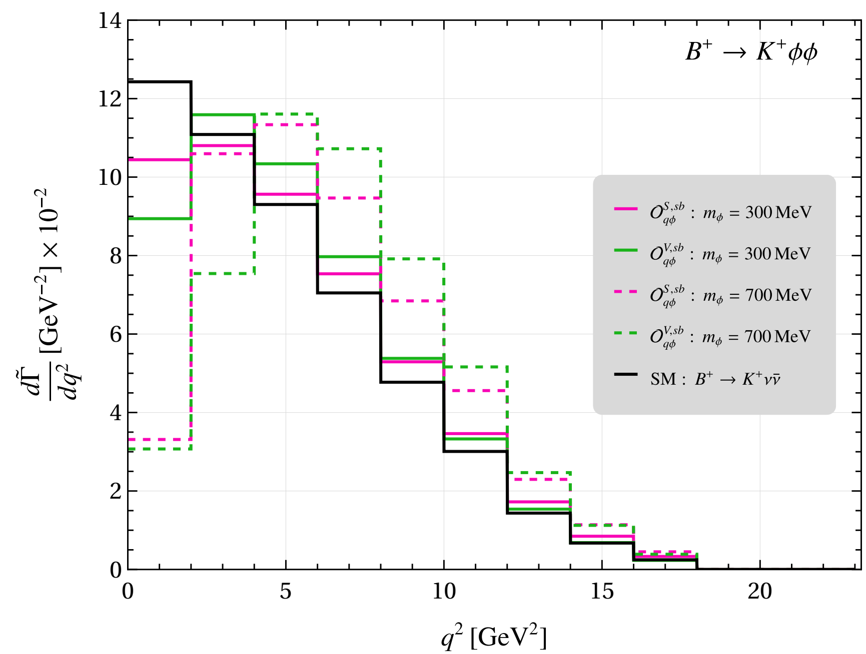


- For scalars, for example,

$\mathcal{O}^{V,sb}_{q\phi}$ with $m_\phi \sim 300$ MeV or

$\mathcal{O}^{S,sb}_{q\phi}$ with $m_\phi \sim 700$ MeV

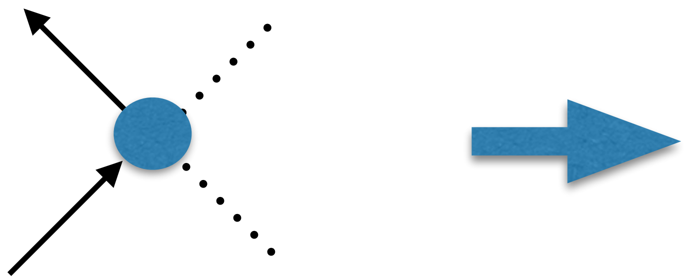
would be slightly preferred by the spectrum

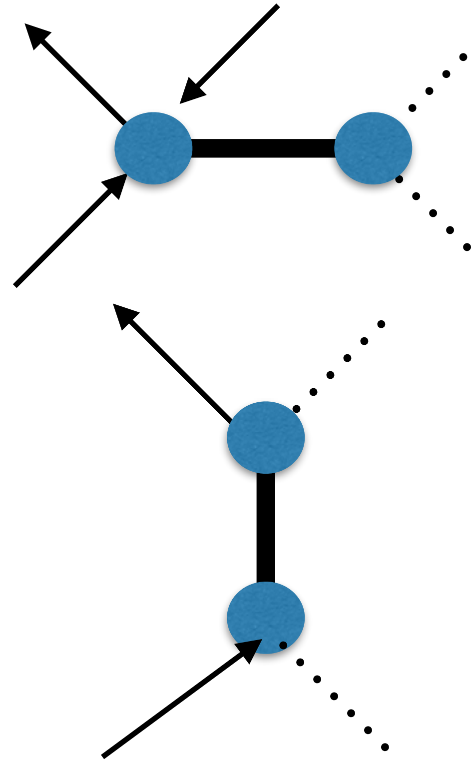


mediators and dark matter

- new constraints from mediators:
- $\mathcal{O}_{q\phi}^{S,sb} = (\bar{s}b)(\phi^\dagger\phi)$

$B_S - \bar{B}_S$ mixing





- s-channel mediator, hard to explain B_s mixing
- look for t-channel mediator instead

specific t-channel model

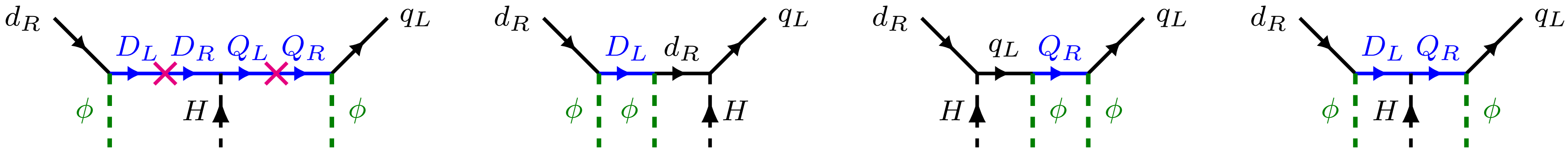


Figure 1. Feynman diagrams contributing to the matching to the ϕSMEFT-like operator $\mathcal{O}_{qdH\phi^2}$ via t-channel exchange of the vector-like fermions Q and D. The magenta crosses represent mass insertions.

- introduce two heavy vector-like quarks $Q \sim (\mathbf{3}, \mathbf{2}, 1/6)$, $D \sim (\mathbf{3}, \mathbf{1}, -1/3)$ (write $Q_R \equiv P_R Q \ldots$)
- and a light scalar field $\phi \sim (\mathbf{1}, \mathbf{1}, 0)$
- All new fields are odd under a $\mathbb{Z}_2$ symmetry to stabilise dark matter particle ϕ

$$
\begin{aligned}
\mathcal{L}^{\mathtt{NP}}_{\mathtt{kinetic}} &= \bar{Q} i \not{D} Q - m_Q \bar{Q} Q + \bar{D} i \not{D} D - m_D \bar{D} D + \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - \frac{1}{2} m_\phi^2 \phi^2 , \\
\mathcal{L}^{\mathtt{NP}}_{\mathtt{Yukawa}} &= y_q^p \bar{q}_{Lp} Q_R \phi + y_d^p \bar{D}_L d_{Rp} \phi - y_1 \bar{Q}_L D_R H - y_2 \bar{Q}_R D_L H + \text{h.c.} \, , \\
V^{\mathtt{NP}}_{\mathtt{potential}} &= \frac{1}{4} \lambda_\phi \phi^4 + \frac{1}{2} \kappa \, \phi^2 H^\dagger H \, ,
\end{aligned}
$$

$B \to K^{(*)}$ + invisible

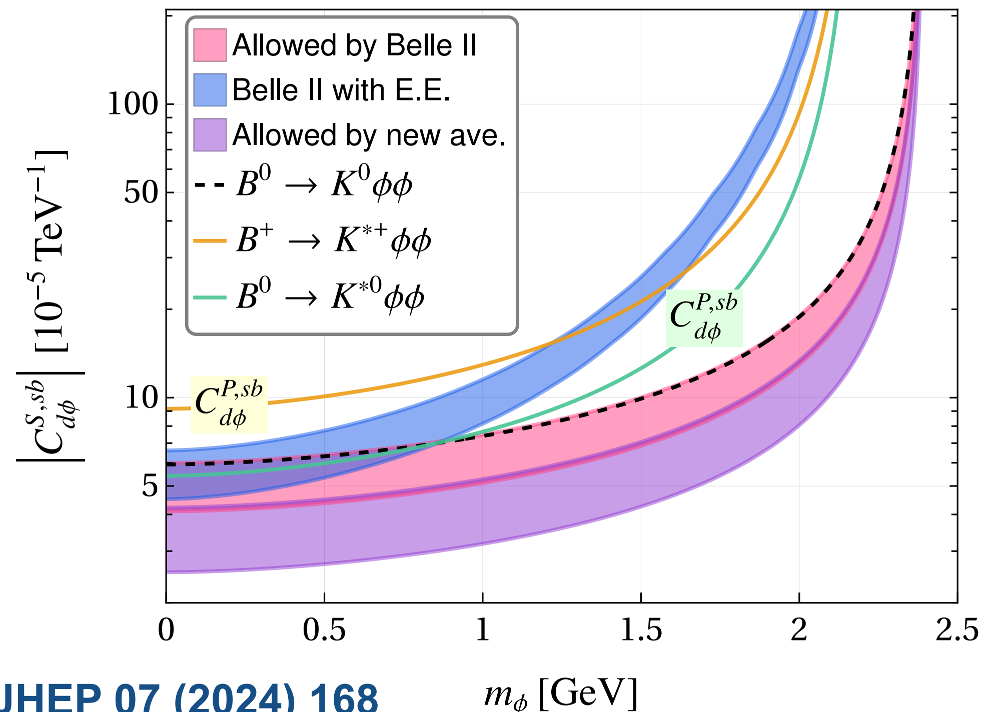
- at low energy, this leads to

$$\mathscr{L}_{\phi\phi qq}^{\texttt{LEFT}} = \frac{1}{2}C_{d\phi}^{S,ij}(\bar{d}_i d_j)\phi^2 + \frac{1}{2}C_{d\phi}^{P,ij}(\bar{d}_i i\gamma_5 d_j)\phi^2 + \frac{1}{2}C_{u\phi}^{S,ij}(\bar{u}_i u_j)\phi^2 + \frac{1}{2}C_{u\phi}^{P,ij}(\bar{u}_i i\gamma_5 u_j)\phi^2,$$

$$C_{d\phi}^{S,ij} = \frac{(y_q^i y_d^j y_1 + y_q^{j*} y_d^{i*} y_1^*)v}{\sqrt{2}m_Q m_D} + \left(\frac{y_q^i y_q^{j*}}{2m_Q^2} + \frac{y_d^{i*} y_d^j}{2m_D^2}\right)(m_{d_i} + m_{d_j}), \quad iC_{d\phi}^{P,ij} = \frac{(y_q^i y_d^j y_1 - y_q^{j*} y_d^{i*} y_1^*)v}{\sqrt{2}m_Q m_D} - \left(\frac{y_q^i y_q^{j*}}{2m_Q^2} - \frac{y_d^{i*} y_d^j}{2m_D^2}\right)(m_{d_i} - m_{d_j}),$$

$$C_{u\phi}^{S,ij} = \frac{\tilde{y}_q^i \tilde{y}_q^{j*}}{2m_Q^2}(m_{u_i} + m_{u_j}), \quad iC_{u\phi}^{P,ij} = -\frac{\tilde{y}_q^i \tilde{y}_q^{j*}}{2m_Q^2}(m_{u_i} - m_{u_j}),$$

- excess can be explained, i.e. with $C_{d\phi}^{S,sb} \sim (3-8)/(10^5\,\text{TeV})$ for $m_\phi = 1$ GeV



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ϕ as dark matter

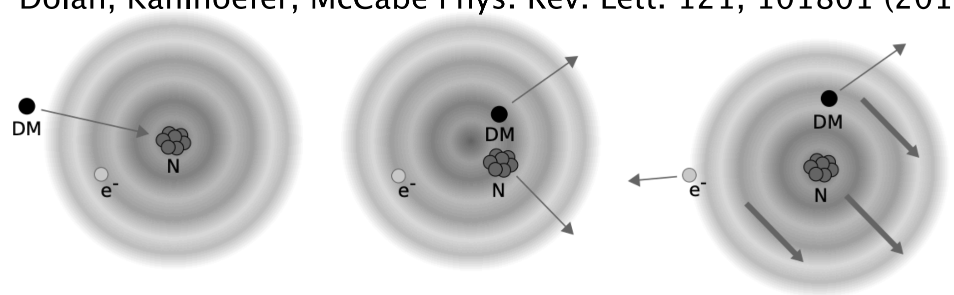
- dark matter relic density
  - with a leading order chiral realisation, we can calculate the possible annihilation cross-sections into pions, kaons and etas
  - to produce the correct relic density $\Omega\hbar^2 = 0.12$,

Steigman, Dasgupta, Beacom, 10.1103/PhysRevD.86.023506

$$\langle \sigma v \rangle \simeq 2.4 \times 10^{-26} \frac{\mathrm{cm^3 s^{-1}}}{(\hbar c)^2 c} = 2.2 \times 10^{-9}\,\mathrm{GeV}^{-2} \text{ need } C_{d\phi}^{S,ss} \sim (0.1)/(\mathrm{TeV})$$

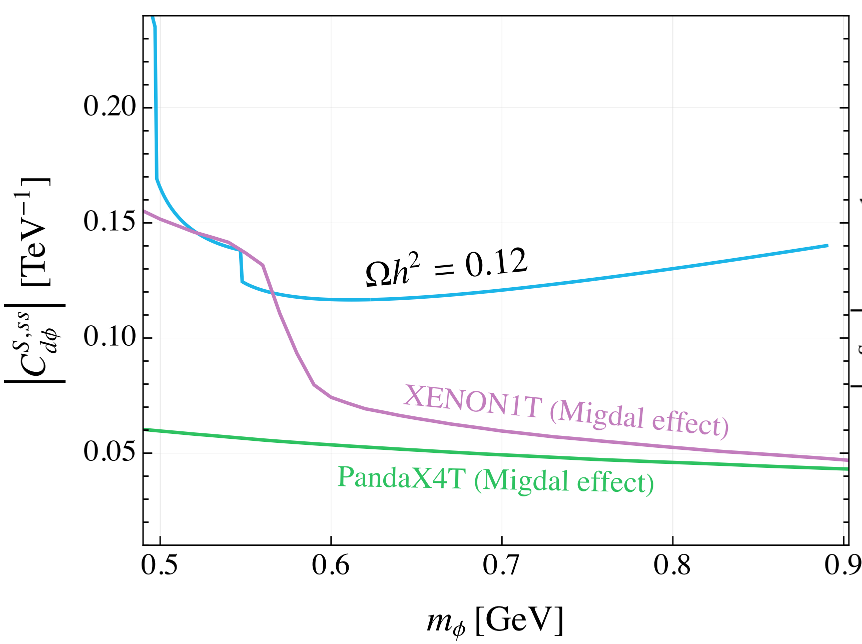
  - but we also need to avoid direct detection constraints, in particular, those using the Migdal effect for sub-GeV dark matter
  - this requires an interplay between different parameters, i.e, introducing $C_{d\phi}^{S,dd}$

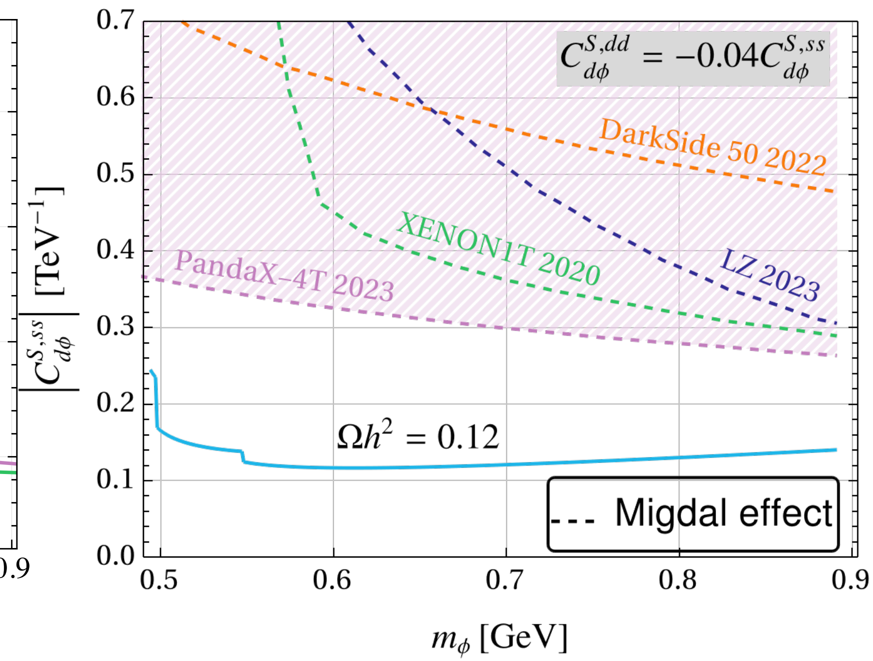
Dolan, Kahlhoefer, McCabe Phys. Rev. Lett. 121, 101801 (2018)



ϕ as dark matter

- to produce the correct relic density $\Omega\hbar^2 = 0.12$, and a compatible excess in $B \to K^{(*)} + \text{invisible}$ we only need $C^{S,sb}_{d\phi}$ and $C^{S,ss}_{d\phi}$ but this scenario is ruled out by Panda X4T (left figure)
- viable models require an interplay between different parameters, one example is shown below (right figure) with $|y^d_{q,d}| \sim 0.2|y^s_{q,d}|$ implying $|C^{S,dd}_{d\phi}| \sim 0.2|C^{S,ds}_{d\phi}| \sim 0.04|C^{S,ss}_{d\phi}|$





- thermal average cross-sections

$$\mathscr{L}_{\phi P} \ni \frac{B}{2}\phi^2 \left\{ C^{S,dd}_{d\phi}\left(\pi^+\pi^- + \frac{1}{2}\pi^0\pi^0\right) + C^{S,ss}_{d\phi}K^+K^- + (C^{S,dd}_{d\phi} + C^{S,ss}_{d\phi})K^0\bar{K}^0 + (C^{S,dd}_{d\phi} + 4C^{S,ss}_{d\phi})\frac{1}{6}\eta^2 + \cdots \right\}$$

$$\langle \sigma v(\phi\phi \to K^+K^-, K^0\bar{K}^0)\rangle = \frac{B^2 |C^{S,ss}_{d\phi}|^2 \eta(x, z_K)}{64\pi m_\phi^2} \quad \langle \sigma v(\phi\phi \to \eta\eta)\rangle = \frac{B^2 |C^{S,ss}_{d\phi}|^2 \eta(x, z_\eta)}{72\pi m_\phi^2}$$

- $\eta(x, z)$ a function that takes values between $0.5 - 1.7$ in the relevant parameter range and $x \equiv m_\phi/T,\ z_{K,\eta} = m^2_{K,\eta}/m^2_\phi$

- direct detection via Migdal effect ($R_{d/s} \equiv C^{S,dd}_{d\phi}/C^{S,ss}_{d\phi}$)

E. Del Nobile, arXiv:2104.12785

$$\sigma_{\phi N} = \frac{\mu^2_{\phi N}}{4\pi m^2_\phi}\left|\frac{m_N}{m_s}f^{(N)}_{T_s}C^{S,ss}_{d\phi}\right|^2 \left|\left(1 + \frac{m_s}{m_d}\frac{f^{(p)}_{T_d}}{f^{(p)}_{T_s}}R_{d/s}\right)\frac{Z}{A} + \left(1 + \frac{m_s}{m_d}\frac{f^{(n)}_{T_d}}{f^{(n)}_{T_s}}R_{d/s}\right)\frac{A-Z}{A}\right|^2,$$

$$\approx \frac{\mu^2_{\phi N}}{4\pi m^2_\phi}\left|\frac{m_N}{m_s}f^{(N)}_{T_s}C^{S,ss}_{d\phi}\right|^2 \left|(1 + 16.84R_{d/s})\frac{Z}{A} + (1 + 24.82R_{d/s})\frac{A-Z}{A}\right|^2,$$

$m_s = 93.4\,\mathrm{MeV},\ \mathrm{m_s/m_d} \approx 19.5,$ $m_s = 93.4\,\mathrm{MeV},\ \mathrm{m_s/m_d} \approx 19.5,$

$f^{(N)}_{T_s} = 0.044,\ f^{(p)}_{T_d} = 0.038,\ f^{(n)}_{T_d} = 0.056$$f^{(N)}_{T_s} = 0.044,\ f^{(p)}_{T_d} = 0.038,\ f^{(n)}_{T_d} = 0.056$

other constraints

- $gg \to H,\ H \to \gamma\gamma$

  t in SM

  – $$\Delta\mathscr{L}_{h\to gg} = -\frac{\text{Re}[y_1 y_2^*]v^2}{m_D m_Q}\left[\underbrace{\frac{\alpha_s}{12\pi}\frac{h}{v}}_{t \text{ in SM}} G^A_{\mu\nu}G^{A\mu\nu}\right] - \frac{\alpha_s}{4\pi}\frac{\text{Im}[y_1 y_2^*]v}{2m_D m_Q} h G^A_{\mu\nu}\tilde{G}^{A\mu\nu}$$

  – with Yukawas of order one and VLQ masses around 3 TeV $v^2/(m_Q m_D) \sim 0.007$

- $B_s \to \phi\phi$

  – $$\mathscr{B}(B_s \to \phi\phi) = \frac{|C^{P,sb}_{d\phi}|^2 \tau_{B_s} m_{B_s} f^2_{B_s}}{32\pi}\left(\frac{m_{B_s}}{m_b + m_s}\right)^2 \sqrt{1 - 4m_\phi^2/m^2_{B_s}}$$

  – For $|C^{S,ss}_{d\phi}| \sim 0.13/\text{TeV}$ we find $\mathscr{B}(B_s \to \phi\phi) \sim 4 \times 10^{-5}$ four times larger than expected Belle II sensitivity for 5 ab^{-1}

additional flavour constraints

- Can check that with this benchmark parameters the model satisfies constraints from
  - $B \to X_s\gamma$
    - model induces $O^{ij}_{d\gamma} = \bar{d}_i \sigma^{\mu\nu} P_R d_j F_{\mu\nu}$ with $\tilde{C}^{sb}_{d\gamma}$ the same order as $C^{S,sb}_{d\phi}$
    - global fits allow $\tilde{C}^{sb}_{d\gamma} \lesssim 260/(10^5\,\mathrm{TeV})$ and for $B \to K^{(*)} + \mathrm{invisible}$ we need $C^{S,sb}_{d\phi} \sim (3-8)/(10^5\,\mathrm{TeV})$
  - $B_s - \bar{B}_s, B_d - \bar{B}_d, K - \bar{K}$ mixing
    - they appear at dim 8, B mixing is fine, K mixing requires a small $C^{S,ds}_{d\phi}$
  - $D \to \pi\phi\phi$, $D \to \phi\phi$ also satisfied by our benchmark parameters

conclusions

- motivated by the recent Belle II result, we explored the NP physics window that could enhance the mode $B^+ \to K^+ + \texttt{invisible}$ over the SM $B^+ \to K^+\nu\bar{\nu}$
- at the same time we require consistency with existing 90% c.l upper bounds on the related modes $B \to K^{(*)}\nu\bar{\nu}$ and $B^0 \to K^0\nu\bar{\nu}$
- we also consider correlations with charged lepton modes
- neutrino LFV couplings with only LH neutrinos can reproduce the rates for these modes
  - when induced by a single LQ exchange, $S_{1/2}, V_{1/2}$ can reproduce the rates provided at least one LF diagonal coupling is ~ 10
  - the $b \to s\ell^+\ell^-$ global fits rule out this possibility for $e^+e^-, \mu^+\mu^-$ modes
  - This solution results in enhanced modes with taus that can be probed experimentally.

conclusions continued

- pairs of new invisible scalars, vectors or fermions
  - we constructed the lowest dimension ϕLEFT for these three cases and selected the operators relevant to these modes
  - there are viable regions of parameter space to explain the desired pattern in $B \to K^{(*)}\nu\bar{\nu}$ rates for all three cases
  - matching the q^2 spectrum from Belle II narrows the list of possibilities
- a t-channel mediator model with two VLQ was used to illustrate that a pair of light scalars enhancing $B^+ \to K^+ + \quad \text{invisible}$ is viable
  - the scalar also satisfies annihilation constraints to produce the correct relic density
  - there is viable parameter space to simultaneousl avoid direct detection constraints including via Mignal effect