BSM for $B \to K$ + invisible and connections to other physics

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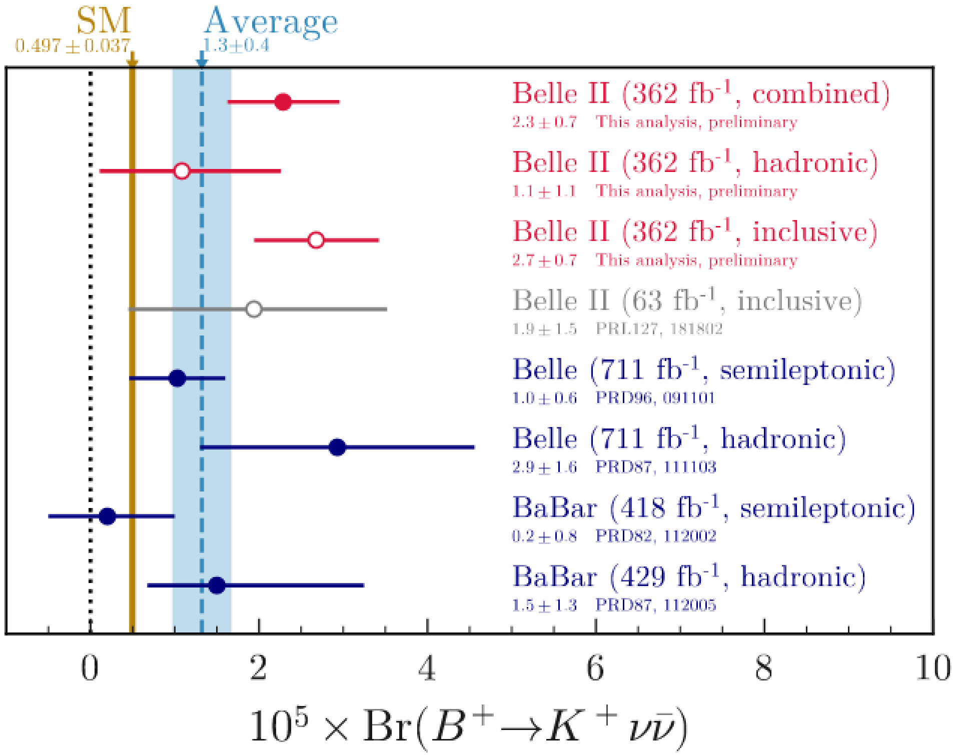
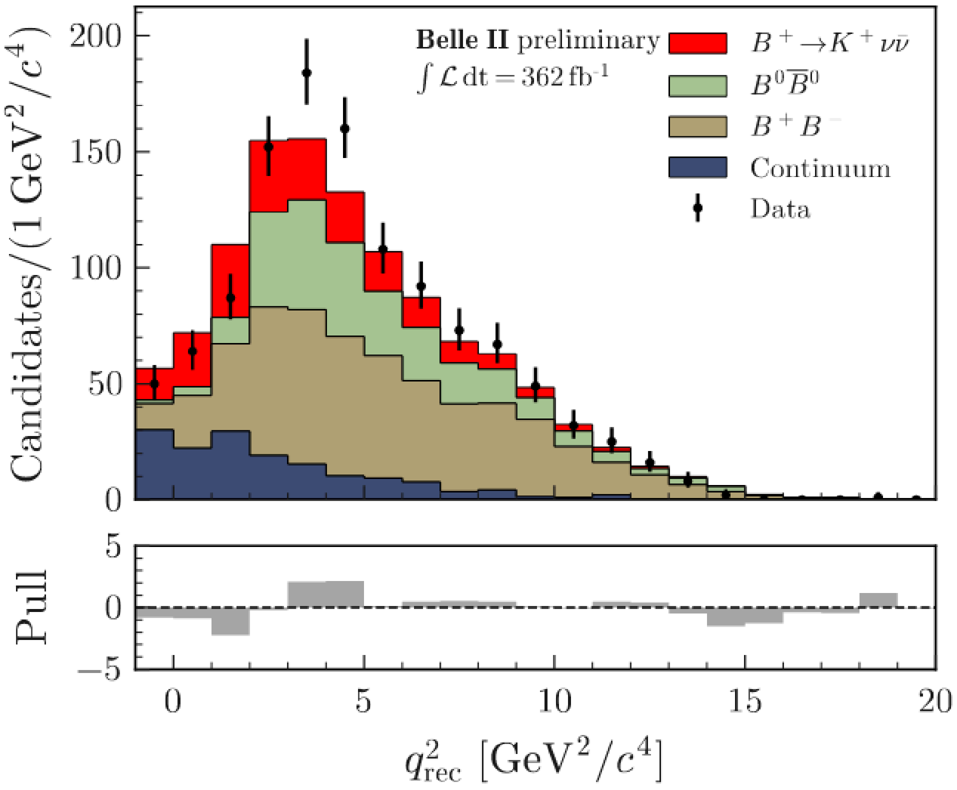
University of New South Wales

8 October 2025 @ Belle II physics week

$B^+ \to K^+\nu\bar{\nu}$ measurement Belle II [2311.14647]





Weighted average

$$\mathcal{B}(B^+ \to K^+\nu\bar{\nu})_{\mathrm{SD}} = (1.3 \pm 0.4) \cdot 10^{-5}$$

$$q^2_{\mathrm{rec}} = q^2 + (E_B - m_B)^2 - 2\boldsymbol{p_K} \cdot \boldsymbol{p_B}$$

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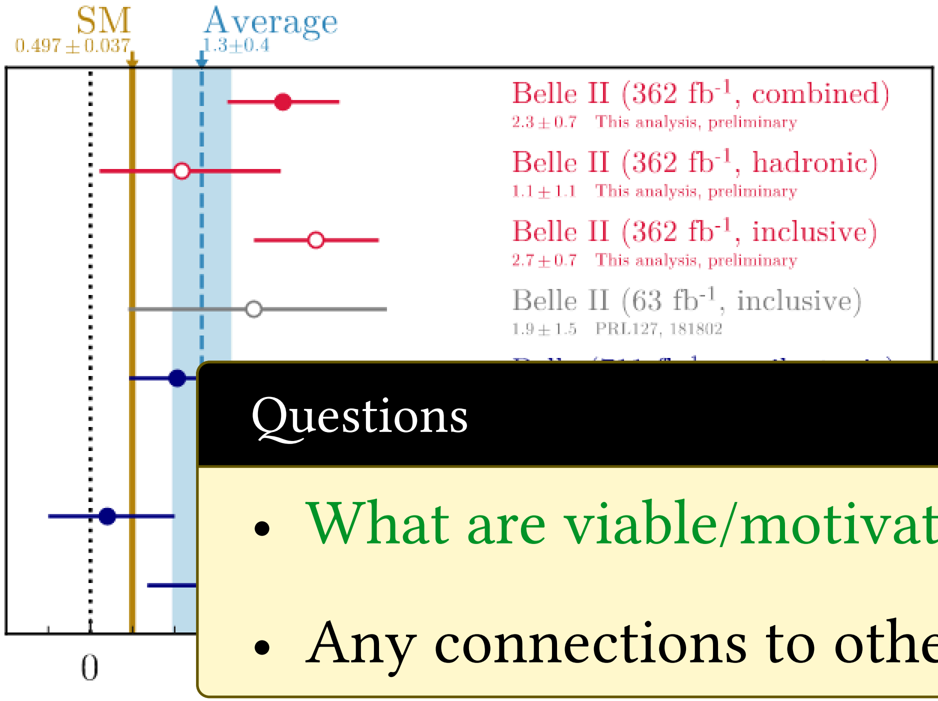

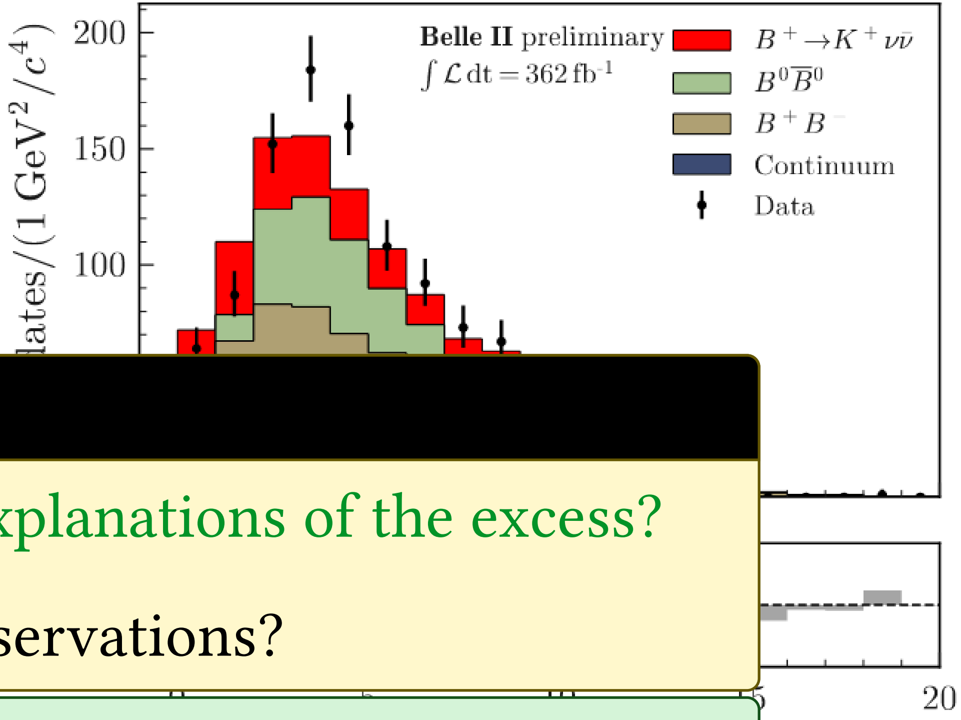

Questions

- What are viable/motivated explanations of the excess?
- Any connections to other observations?

- Independent of the excess, what can we learn about new physics?

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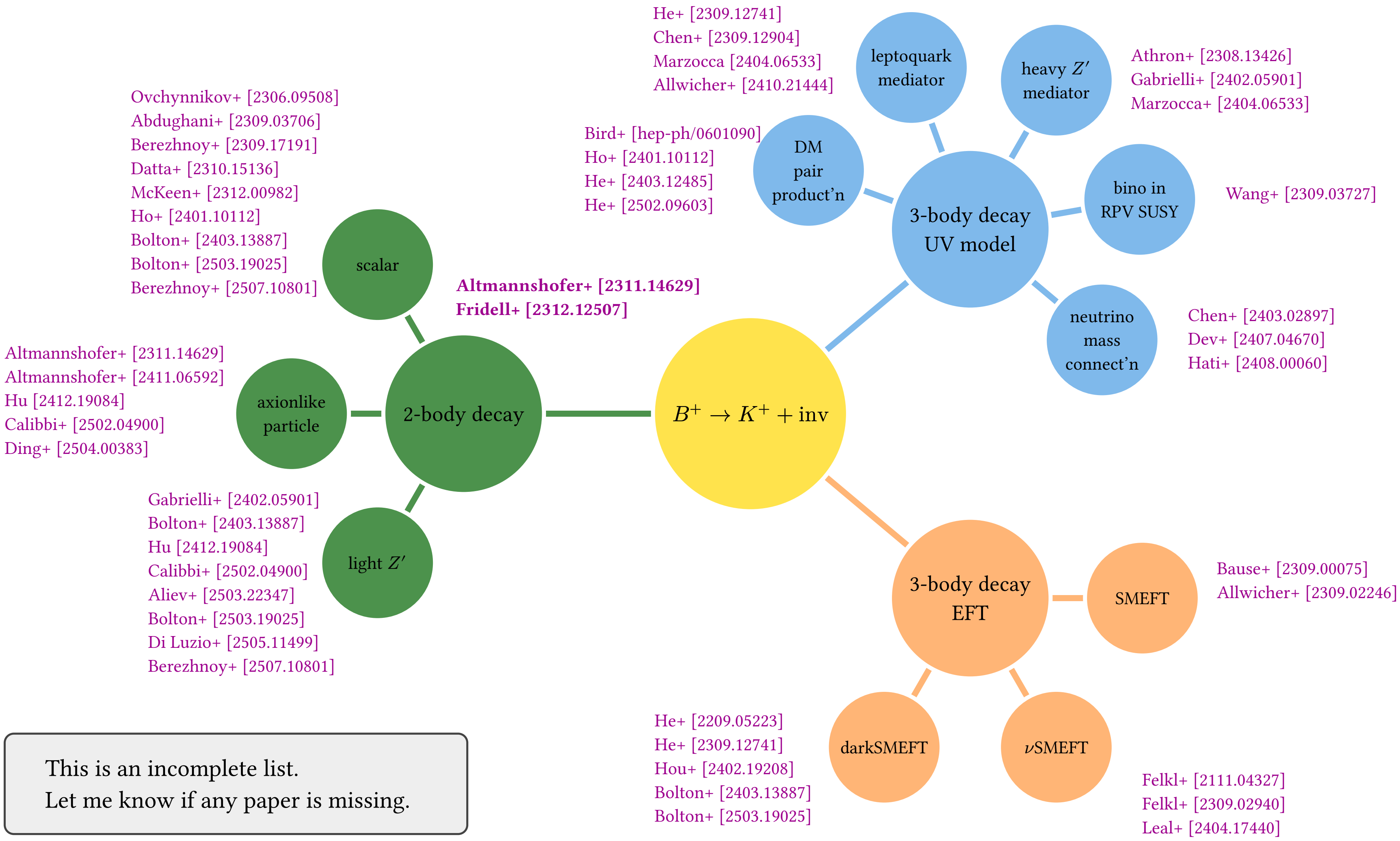
Proposed new physics explanations



This is an incomplete list.
Let me know if any paper is missing.

Selected explanations with connections to DM or neutrinos

3-body decay scenarios

- Heavy neutral leptons Felkl, Li, MS [2111.04327] Felkl, Giri, Mohanta, MS [2309.02940]
- Scalar dark matter He, Ma, MS, Valencia, Volkas [2403.12485]

2-body decay scenarios

- Higgs-like scalar and neutrinos Ovchynnikov, MS, Schwetz [2306.09508]
- Axion-like particle and DM Calibbi, Li, Mukherjee, MS [2502.04900]
- Dark sector with U(1) gauge symmetry and DM Calibbi, Li, Mukherjee, MS [2502.04900]

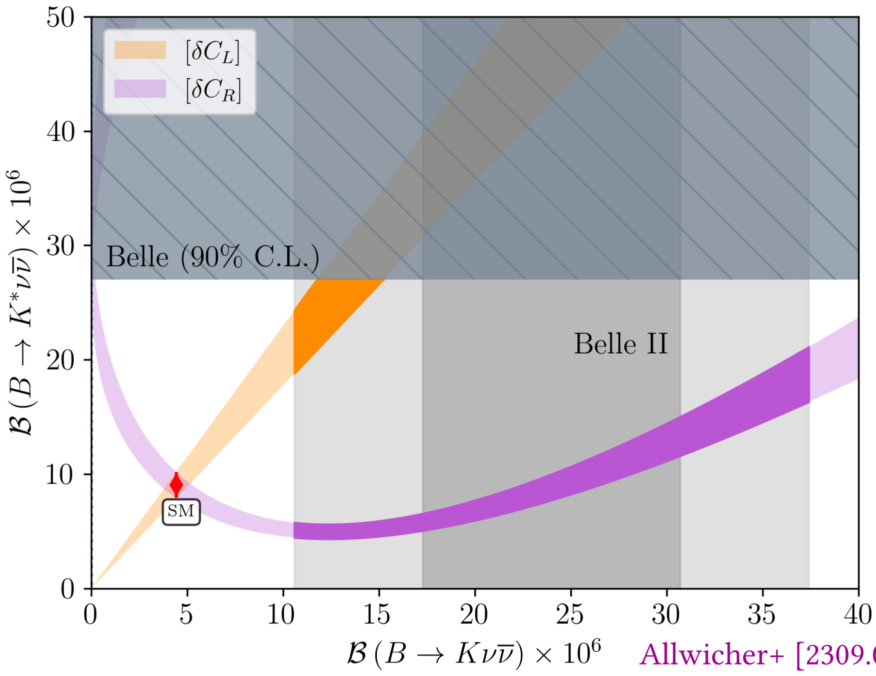
3-body decay

Weak effective theory (WET)

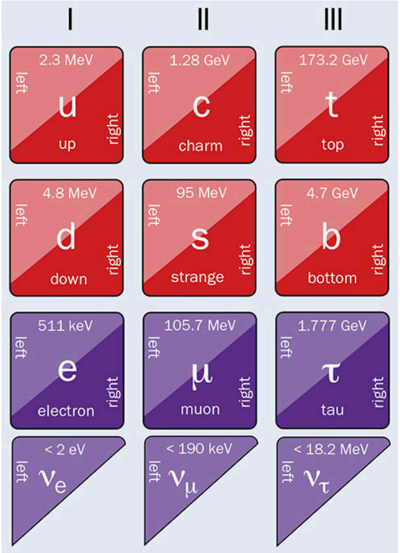
$$\delta\mathcal{L}_6 = 4\sqrt{2}G_F V_{ts}^* V_{tb} \frac{\alpha}{4\pi} \sum_i C_i O_i + \text{h.c.}$$

$$\mathcal{O}_{\mathrm{L,R}} = (\bar{\nu}_i \gamma^\mu P_{\mathrm{L}} \nu_j)(\bar{s}\gamma_\mu P_{\mathrm{L,R}} b)$$

- only vector operators
  - includes **only active neutrinos**
  - assumes **lepton number conservation**
- motivates ν_τ-philic scenarios



Allwicher+ [2309.02246]



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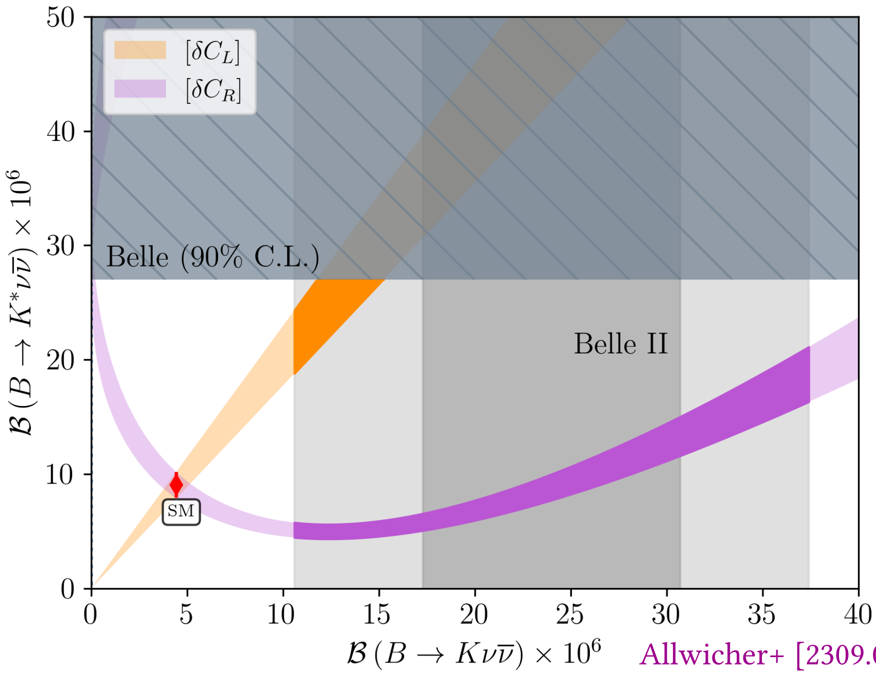

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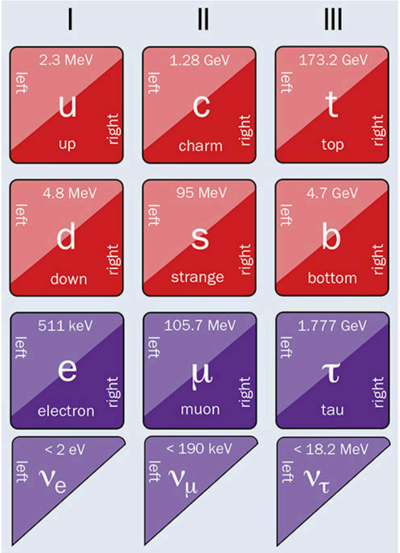
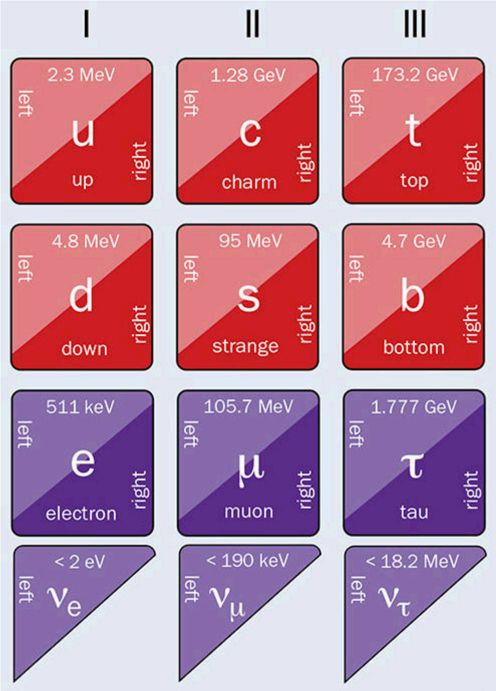
- motivates ν_τ-philic scenarios
- Is this the full picture?



Aside: Lepton number - neutrino masses



CERN courier 9 March

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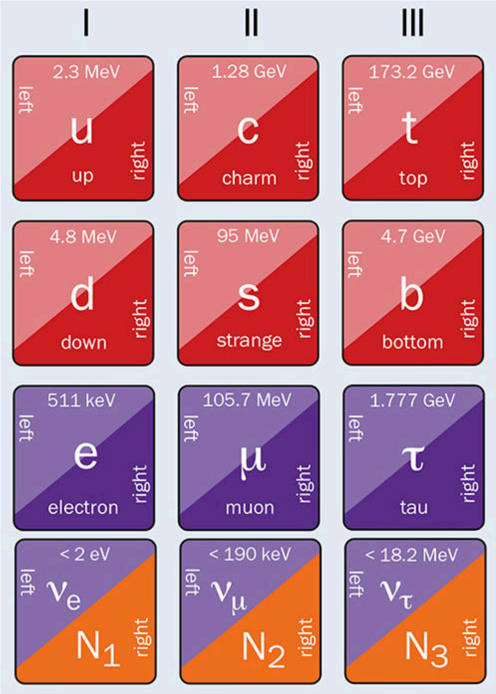

CERN courier 9 March

Dirac neutrinos

- Introduction of right-handed neutrinos N_R

Majorana neutrinos

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- Lepton number broken by Majorana mass term $\overline{N_R^c} N_R$

This motivates to consider lepton number violation...

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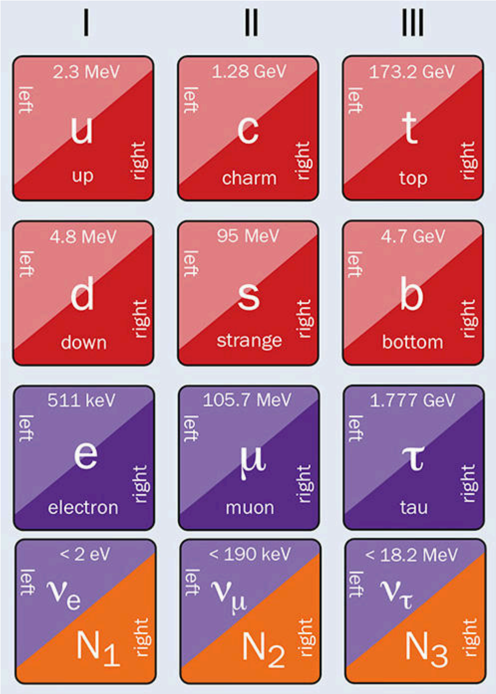

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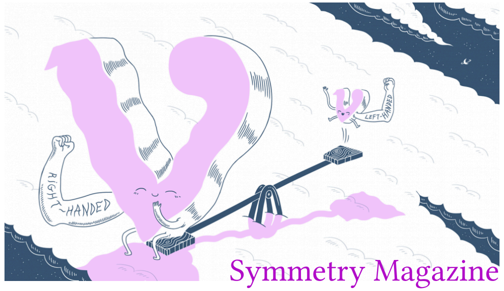

Symmetry Magazine

Dirac neutrinos

- Introduction of right-handed neutrinos N_R
- impose lepton number symmetry which is anomalous
- more motivated: gauged $U(1)_{B-L} \to Z_N$

Majorana neutrinos

- Introduction of right-handed neutrinos N_R
- Lepton number broken by Majorana mass term $\overline{N_R^c} N_R$
- Neutrino masses generated by seesaw mechanism
- also motivated from SMEFT point of view: *Weinberg operator* $\mathcal{O}_5 = \left(\overline{L^c}\tilde{H}^*\right)\left(\tilde{H}^\dagger L\right)$ *is lowest dimensional operator*

This motivates to consider lepton number violation...

full WET operator basis

Felkl, Li, MS [2111.04327]

Extended operator basis

$$\mathcal{O}_{\nu d}^{\mathrm{VLX}} = \left(\overline{\nu}\gamma_\mu P_L \nu\right)\left(\overline{d}\gamma^\mu P_X d\right)$$

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$$\mathcal{O}_{\nu d}^{\mathrm{TLL}} = \left(\overline{\nu^c}\sigma_{\mu\nu} P_L \nu\right)\left(\overline{d}\sigma^{\mu\nu} P_L d\right)$$

- LNV interactions $\mathcal{O}_{\nu d}^{\mathrm{SLL}}$, $\mathcal{O}_{\nu d}^{\mathrm{SLR}}$, $\mathcal{O}_{\nu d}^{\mathrm{TLL}}$ originate from D7 SMEFT operators
- heavy neutral leptons/sterile RH neutrinos using $N_R \leftrightarrow \nu_L^c$ originate from D6 or D7 νSMEFT operators
- D6 νSMEFT op's most relevant for $b \to s\nu\overline{\nu}$

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Points to consider

- unavoidable contribution to neutrino mass
- unavoidable contribution to neutrinoless double beta decay
- new physics model considerations

Unavoidable contribution to neutrino masses

- Neutrino masses are not protected by symmetry and will be generated.
  How large are the induced neutrino masses?

$$\Lambda_{K\nu\nu} \sim 2\ \text{TeV} \leftrightarrow \Lambda_\nu \sim 10^{14}\ \text{GeV}.$$

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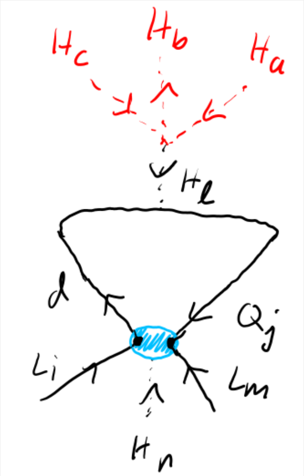
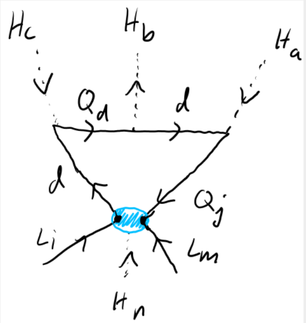
active neutrinos

$$\mathcal{O}_{\bar{d}LQLH1} = \varepsilon_{ij}\varepsilon_{mn}\left(\bar{d}L_i\right)\left(\overline{Q_j^c}L_m\right)H_n \qquad \mathcal{O}_{\bar{d}LQLH2} = \varepsilon_{im}\varepsilon_{jn}\left(\bar{d}L_i\right)\left(\overline{Q_j^c}L_m\right)H_n$$

Babu+ [hep-ph/0106054]Lehman+ [1410.4193]Liao+ [1607.07309]Fridell+ [2306.08709]



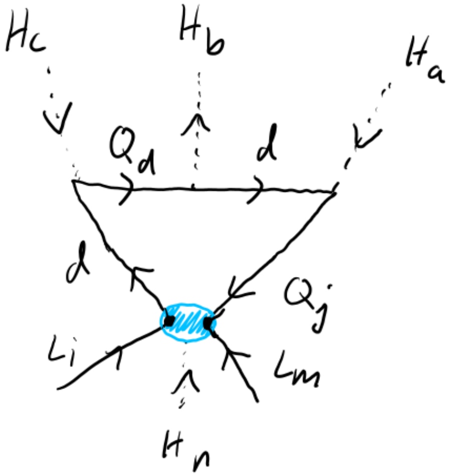


- RG mixing into $\mathcal{O}_{LH} = (L \cdot H)^T C (L \cdot H) H^\dagger H$, see Zhang [2306.03008]Zhang [2310.11055]

$$\dot{C}_{LH} = -3C^{\gamma\alpha\lambda\beta}_{\bar{d}LQLH1}\left[\lambda(Y_d) - \left(Y_d Y_d^\dagger Y_d\right)\right]_{\lambda\gamma} + \dots$$

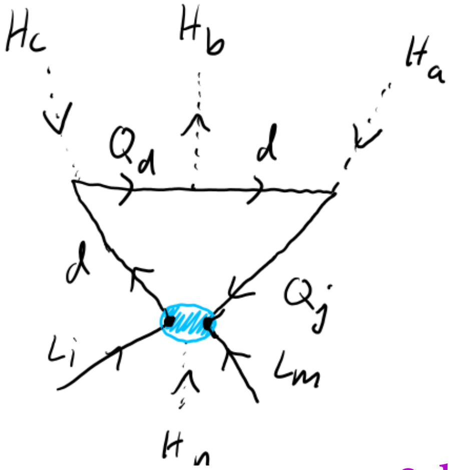
- no flavour-changing contribution at 1-loop
  (in down-quark mass basis)

Unavoidable contribution to neutrino masses



- $\mathcal{O}_{\bar{d}LQLH1} = \varepsilon_{ij}\varepsilon_{mn}\left(\bar{d}L_i\right)\left(\overline{Q^c_j}L_m\right)H_n$
- no flavour-changing contribution at 1-loop from down-type quarks
- How about up-type quarks?
- No up-type quark contribution at 1-loop due to $\mathrm{SU}(2)_L$ structure

Unavoidable contribution to neutrino masses



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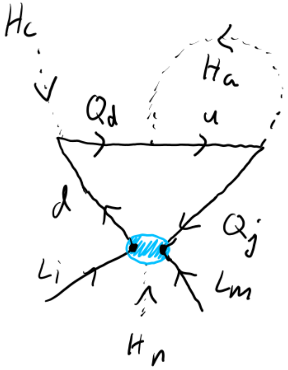
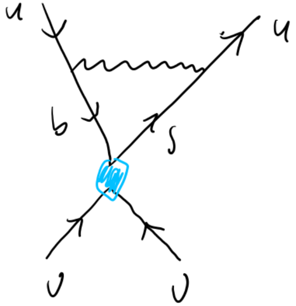


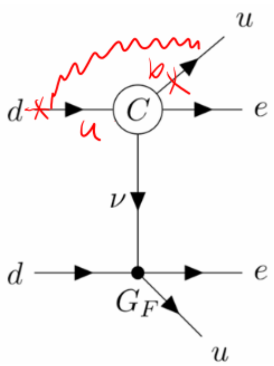
- 2-loop contribution to Weinberg operator from top loop.

$$m_\nu \sim \frac{3}{(4\pi)^4}\frac{m_b V_{tb}^* V_{ts} m_t^2 v}{\Lambda^3}\ln\left(\frac{m_h}{\Lambda}\right) \sim \mathcal{O}(10)\ \mathrm{eV}$$

- requires some tuning for LH neutrinos to cancel this contribution
- This is no issue for operators with RH (sterile) neutrinos,
  e.g. $\left(\overline{L}N\right)\varepsilon\left(\overline{Q}d\right) \to m_{\alpha 4} \sim 100$ eV, but $m_N \gtrsim 100$ MeV and thus $\theta_{\alpha 4} \sim 10^{-6}$
  $\to \delta m_\nu \sim 10^{-4}$ eV



Unavoidable contribution to neutrinoless double beta decay



- $\left[C^{\bar{d}LQLH1}_{s\alpha b\beta}\right]^{-\frac{1}{3}} \sim 2$ TeV $\quad\leftrightarrow\quad \left[C^{\bar{d}LQLH1}_{1\alpha 1\beta}\right]^{-\frac{1}{3}} \gtrsim 200$ TeV

  Graf+ [2504.00081] see also Fridell+ [2306.08709]

- Operator with first generation quark induced through Higgs exchange above SSB scale Zhang [2310.11055] or W boson exchange after SSB.
  It is loop, CKM, GIM suppressed

$$C^{\bar{d}LQLH1}_{1\alpha 1\beta} \sim \frac{V_{ub} G_F m_b m_d}{16\pi^2} V^*_{us} C^{\bar{d}LQLH1}_{b\alpha s\beta} \sim 10^{-12} C^{\bar{d}LQLH1}_{b\alpha s\beta}$$

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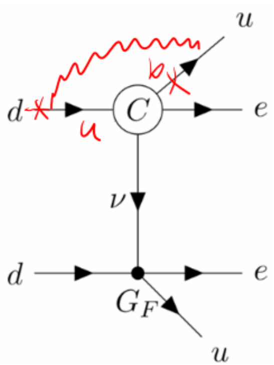

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Model considerations

- large off-diagonal bs couplings with small diagonal dd couplings could originate from **dominant coupling to third generation**
- excess in $B^+ \to K^+ \nu\bar{\nu}$ sizeable
  - non-trivial flavour structure required, e.g. large coupling to third generation

Lessons from history of neutrino physics

before 1998 (Super-K discovery of neutrino oscillations)

- SM predicts massless neutrinos

  $\rightarrow$ at least two neutrinos are have mass
- If $m_\nu \neq 0$, lepton mixing is expected to be small, similar to quark mixing

  $\rightarrow$ There is large lepton mixing: $\sin^2\theta_{23} \simeq \frac{1}{2}$ and $\sin^2\theta_{12} \simeq \frac{1}{3}$

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2000s - before Daya Bay (2012):

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- Great, that Belle II is publishing a likelihood which allows to reinterpret data!
- We have to be open-minded (and critical) about results and their explanation.

WET with lepton number violation

Felkl, Li, MS [2111.04327]

Extended operator basis

$$\mathcal{O}_{\nu d}^{\mathrm{VLX}} = \left(\overline{\nu}\gamma_\mu P_L \nu\right)\left(\overline{d}\gamma^\mu P_X d\right)$$

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- $\mathcal{C}_{\nu d}^{\mathrm{VLX}}$ hermitian
- $\mathcal{C}_{\nu d}^{\mathrm{SLX}}$ symmetic in ν flavour indices
- $\mathcal{C}_{\nu d}^{\mathrm{TLL}}$ antisymmetic in ν flavour indices
- light RH sterile neutrinos (heavy neutral leptons) can be included using $N_R \leftrightarrow \nu_L^c$

Differential branching ratio for $B \to K\nu\overline{\nu}$ takes simple form in massless limit

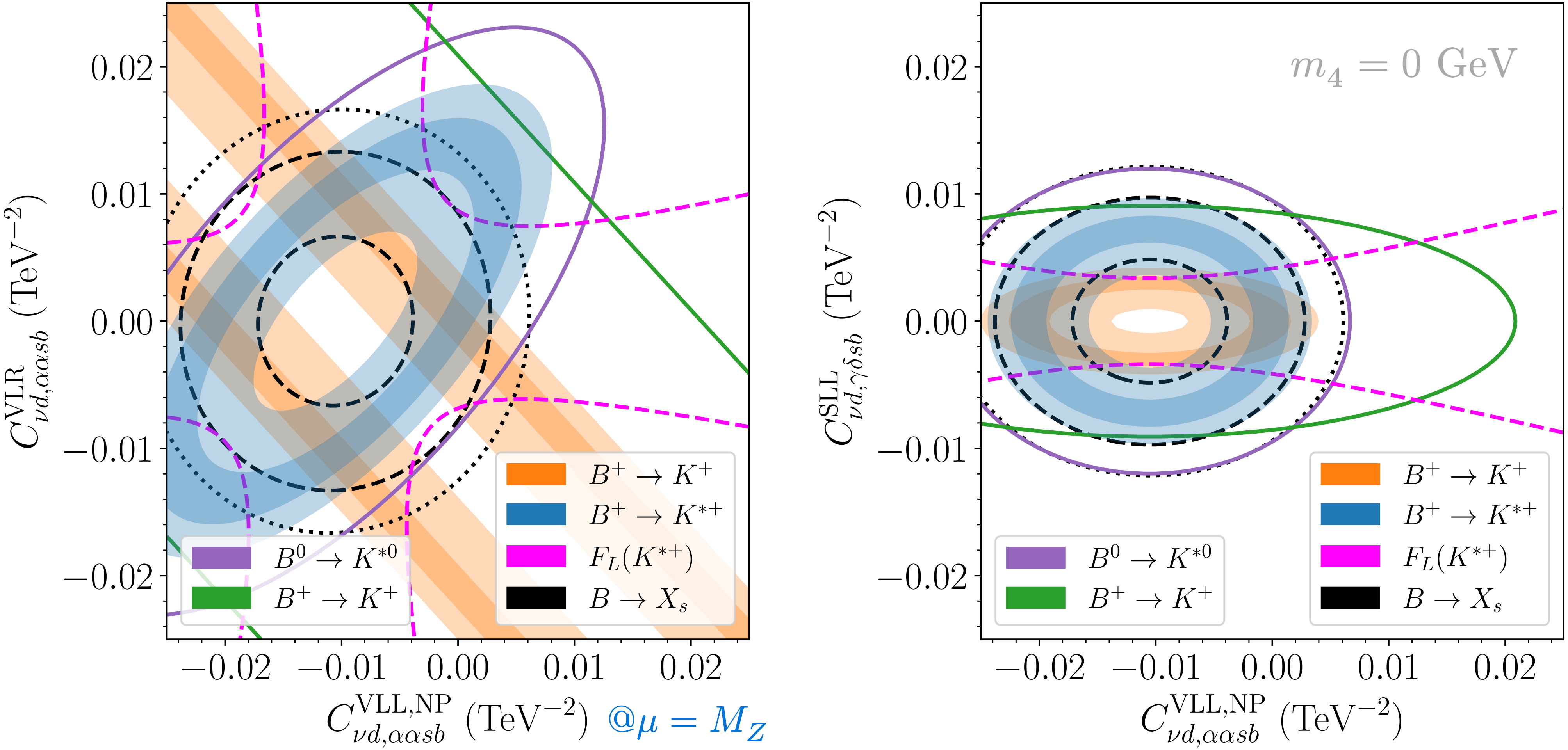
$$\frac{\mathrm{d}\mathcal{B}}{\mathrm{d}q^2} = A(q^2)\ \left|C_{\nu d,\alpha\beta sb}^{\mathrm{VLL}} + C_{\nu d,\alpha\beta sb}^{\mathrm{VLR}}\right|^2 + B(q^2)\left[\left|C_{\nu d,\alpha\beta sb}^{\mathrm{SLL}} + C_{\nu d,\alpha\beta sb}^{\mathrm{SLR}}\right|^2 + (b \leftrightarrow s)\right]$$
$$+ C(q^2)\ \left|C_{\nu d,\alpha\beta sb}^{\mathrm{TLL}} + C_{\nu d,\alpha\beta bs}^{\mathrm{TLR}}\right|^2 + (\alpha \leftrightarrow \beta)$$

- symmetric in $\alpha \leftrightarrow \beta$ and $sb \leftrightarrow bs$ (holds also for non-zero neutrino masses)
- no interference between vector, scalar, and tensor operators (holds also for $B \to K^*\nu\overline{\nu}$ and $B \to X_s\nu\overline{\nu}$ and for any mass for D6 νSMEFT operators)

WET with LNV - complementarity

Felkl, Li, MS [2111.04327]

3-body decay



Assumption: SM observed; (light) shaded 50(5) ab^{-1}; black dotted (dashed) equates to 50% (20%) precision

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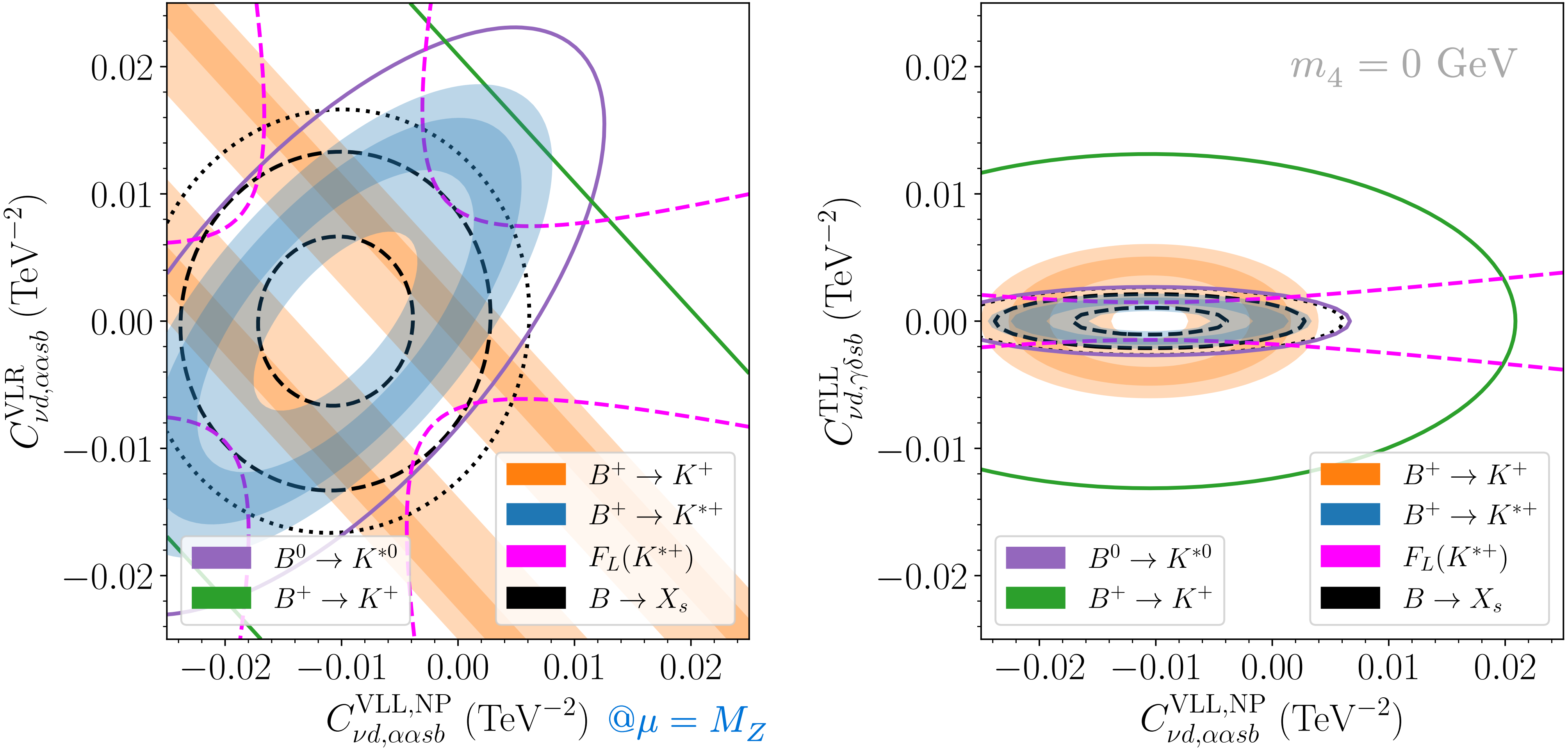

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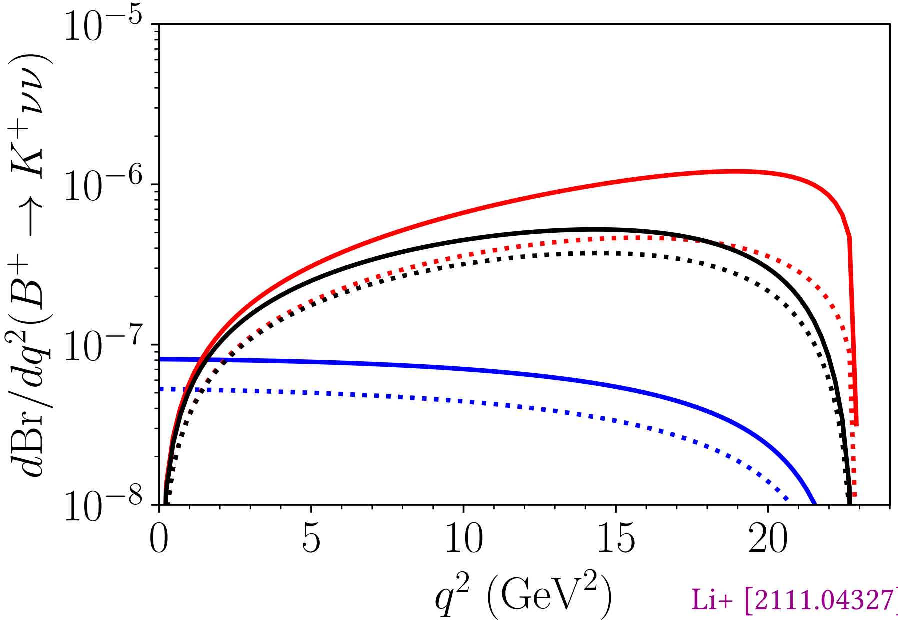
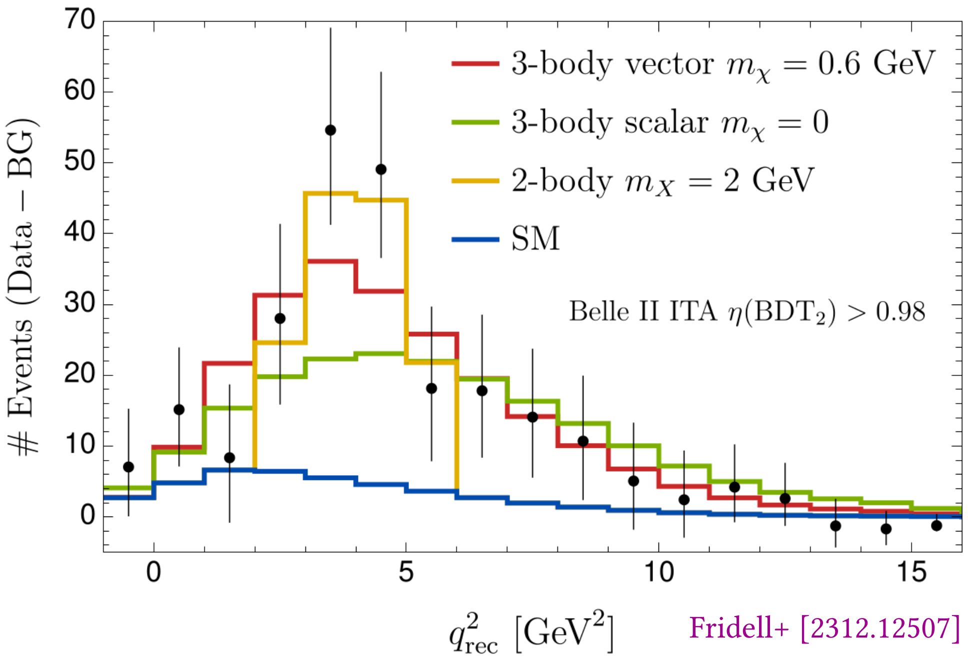
q^2 distribution

- above only branching ratio included
- q^2 distrib'n depends on Lorentz structure
- fit to $B \to K\nu\bar{\nu}$ data prefers tensor operator, see Belle II [2507.12393]
  $(C_V, C_S, C_T) = (11.3, 0, 8.21)$



Li+ [2111.04327]



Fridell+ [2312.12507]

$\chi^2_{\min} - 100$	2b	V	V′	S	T	SM
Belle II	**6.8**	15.2	**4.7**	15.1	11.9	44.6
+ BaBar SR	27.6	30.4	**22.1**	31.8	29.8	61.0
+ BaBar $s_B < 0.8$	**73.3**	78.8	**72.9**	90.2	86.9	106.7

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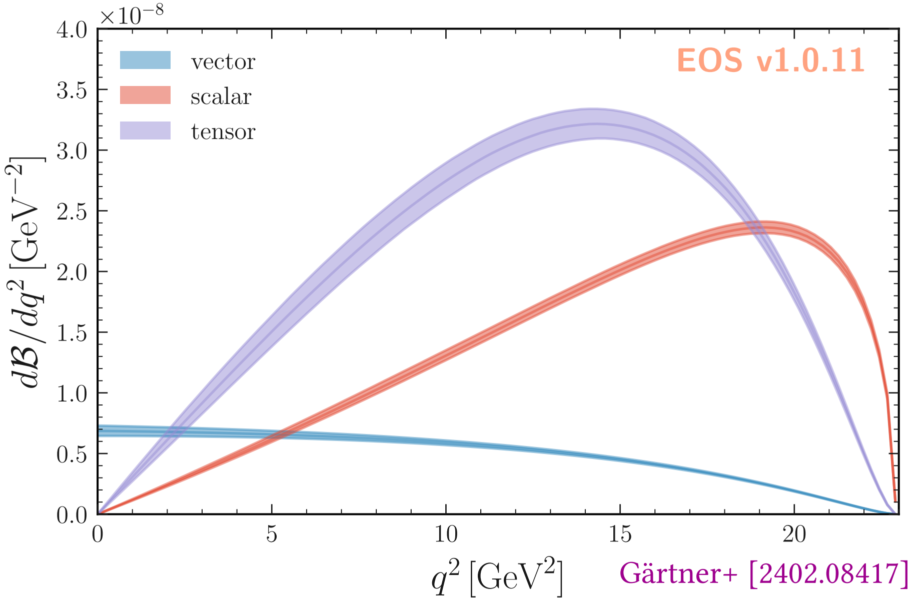
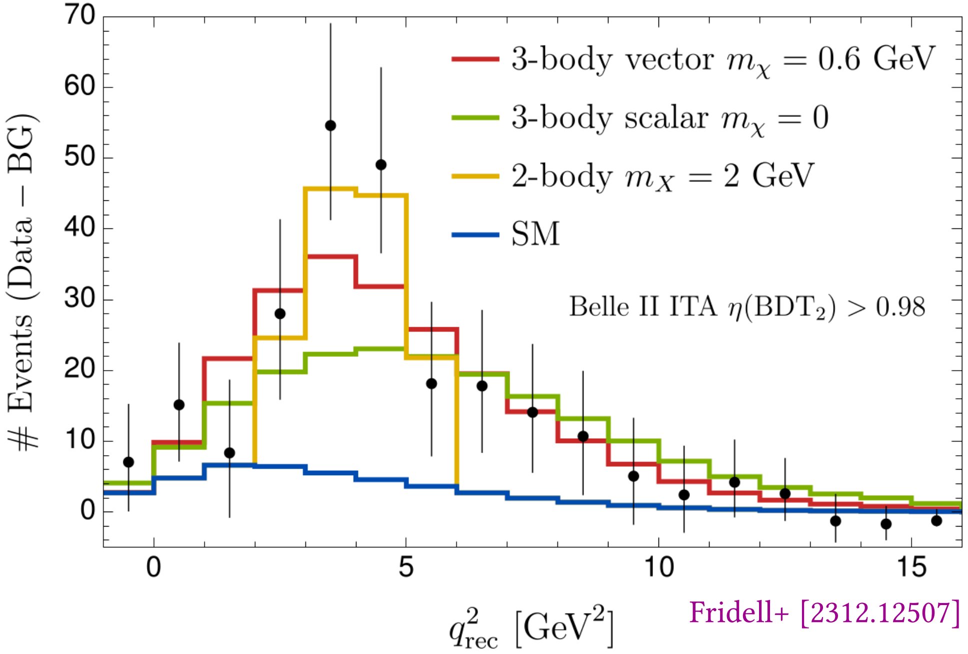


Gärtner+ [2402.08417]



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Light sterile neutrinos with vector operator

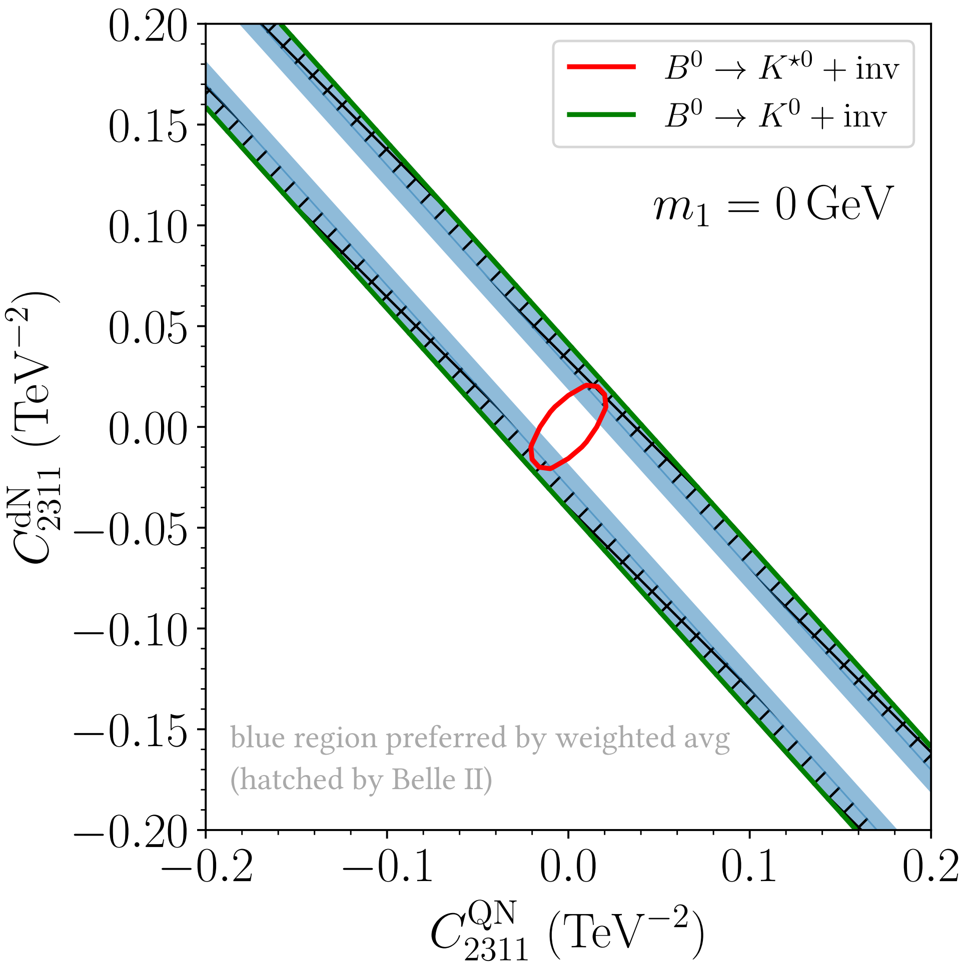
Felkl,Giri,Mohanta,MS [2309.02940]

νSMEFT operators at $\mu = 1$ TeV

$$\mathcal{L} = C^{\mathrm{QN}}\left(\overline{Q}\gamma_\mu Q\right)\left(\overline{N}\gamma^\mu N\right) + C^{\mathrm{dN}}\left(\overline{d}\gamma_\mu d\right)\left(\overline{N}\gamma^\mu N\right)$$

- $B \to K + \mathrm{inv}$ depends on *vector op.*
- $B \to K^* + \mathrm{inv}$ constrains *axial-vector op.*
  (see scenario $V^{(\prime)}$ above)

→ interference allows to avoid constraint



naive comparison of branching ratio, $\mathcal{B}(B^+ \to K^+ + \mathrm{inv}) = (2.4 \pm 0.7) \cdot 10^{-5}$ EPS 2023

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Felkl,Giri,Mohanta,MS [2309.02940] 3-body decay

νSMEFT operators at $\mu = 1$ TeV

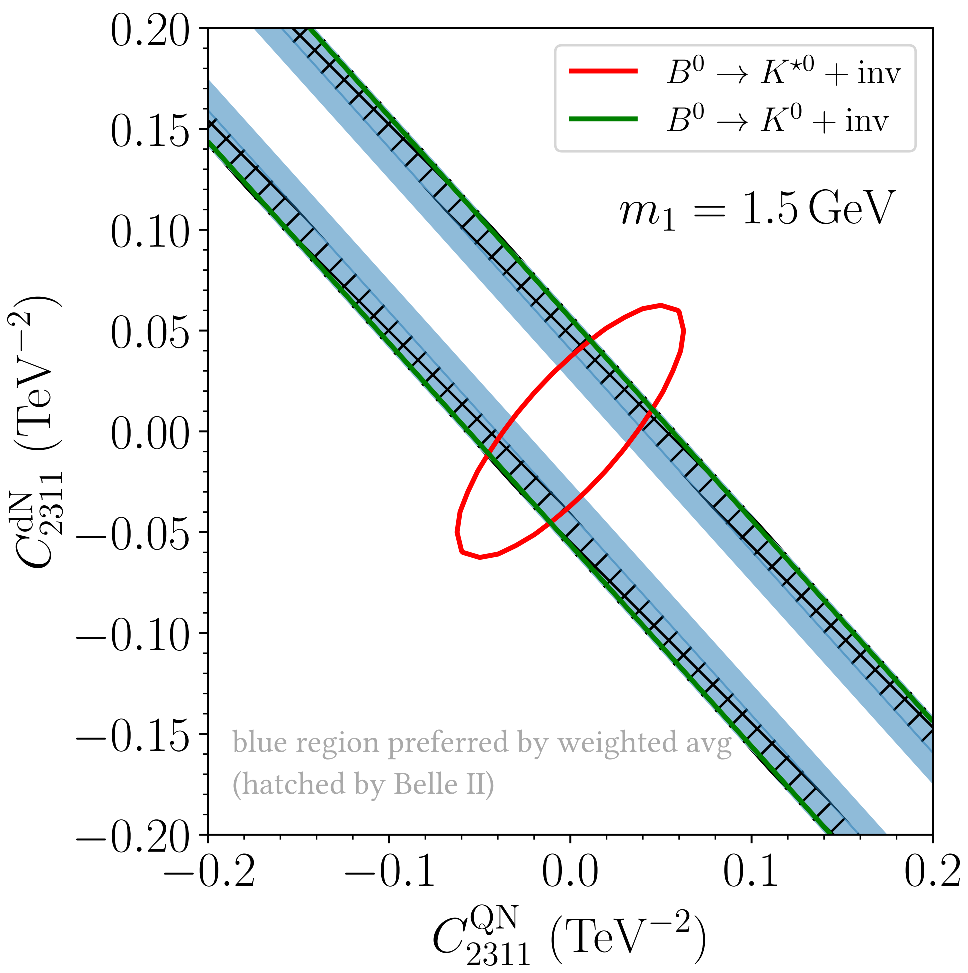
$$\mathcal{L} = C^{\mathrm{QN}}\left(\overline{Q}\gamma_\mu Q\right)\left(\overline{N}\gamma^\mu N\right) + C^{\mathrm{dN}}\left(\overline{d}\gamma_\mu d\right)\left(\overline{N}\gamma^\mu N\right)$$

- $B \to K + \mathrm{inv}$ depends on *vector op.*
- $B \to K^* + \mathrm{inv}$ constrains *axial-vector op.*
  (see scenario $V^{(\prime)}$ above)

$\to$ interference allows to avoid constraint

comparison to SMEFT

- no signal in $B \to K^{(*)}\tau\overline{\tau}$
- best fit for mass $m_1 \sim 0.6$ GeV
  Fridell+ [2312.12507]

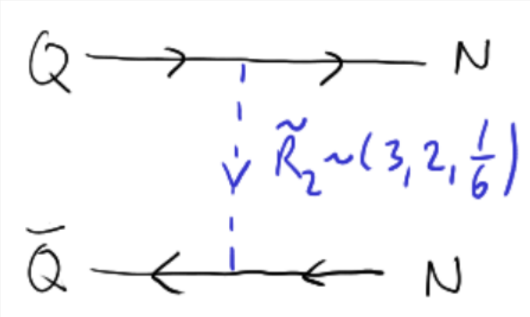


naive comparison of branching ratio, $\mathcal{B}(B^+ \to K^+ + \mathrm{inv}) = (2.4 \pm 0.7)\cdot 10^{-5}$ EPS 2023

UV completions of vector operator - leptoquarks

$\widetilde{R}_2 \sim \left(\mathbf{3}, \mathbf{2}, -\frac{1}{6}\right)$

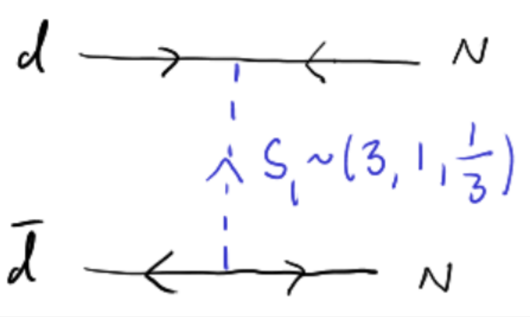
$$\overline{Q}\widetilde{R}_2 N \to \left(\overline{Q}\gamma_\mu Q\right)\left(\overline{N}\gamma^\mu N\right)$$



- also generates O^{Ld}
- $B_s - \overline{B_s}$ mixing only at 1-loop

$S_1 \sim \left(\mathbf{3}, \mathbf{1}, \frac{1}{3}\right)$

$$\overline{N^c} S_1 d \to \left(\overline{d}\gamma_\mu d\right)\left(\overline{N}\gamma^\mu N\right)$$



- also generates O^{eu}, $O^{\mathrm{LQ}(1,3)}$, $O^{\mathrm{LeQu}\ (1,3)}$, O^{LNQd}
- $B_s - \overline{B_s}$ mixing only at 1-loop

Scalar/tensor WET operators from D6 νSMEFT op

νSMEFT operators Liao+ [1612.04527]

$$\mathcal{L} \supset C^{\mathrm{LNQd}}\left(\overline{L}N\right)\varepsilon\left(\overline{Q}d\right) + C^{\mathrm{LNQdT}}\left(\overline{L}\sigma_{\mu\nu}N\right)\varepsilon\left(\overline{Q}\sigma^{\mu\nu}d\right) + \mathrm{h.c.}$$ Felkl+ [2309.02940]

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Matching to WET

$$\mathcal{C}^{\mathrm{SLL}}_{\nu d,\alpha\beta sb} = C^{\mathrm{LNQd}}_{\beta\alpha bs} \qquad \mathcal{C}^{\mathrm{TLL}}_{\nu d,\alpha\beta sb} = C^{\mathrm{LNQdT}}_{\beta\alpha bs} \qquad [\alpha = 4, \beta = 1, 2, 3]$$ Felkl+ [2309.02940]

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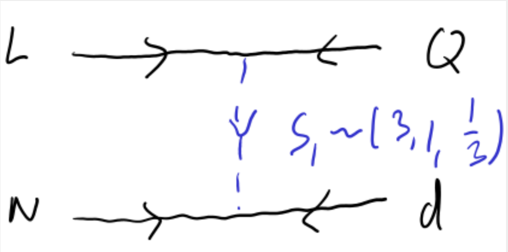
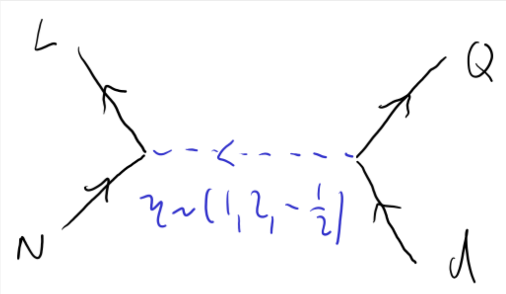
Examples for UV completions



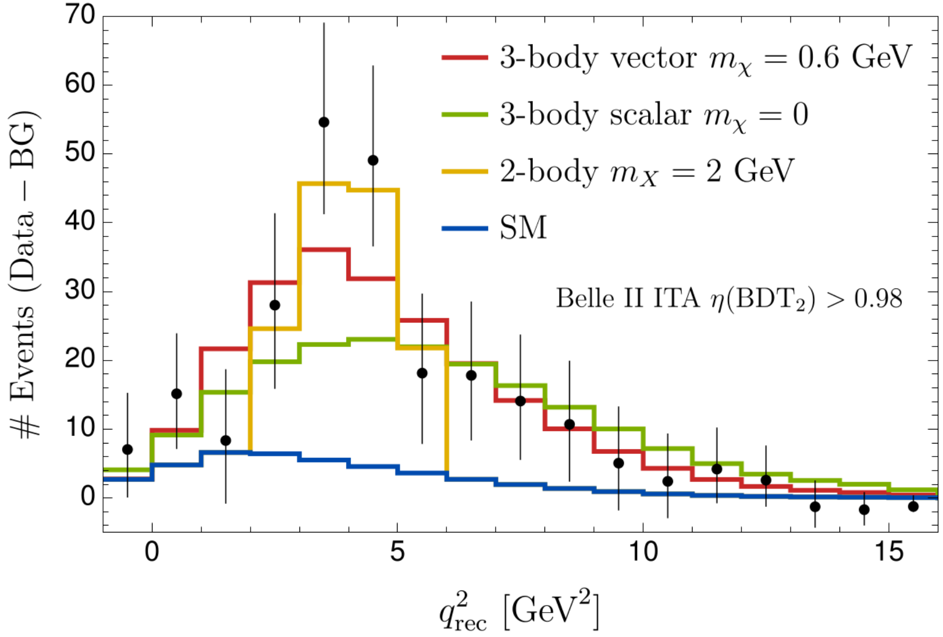


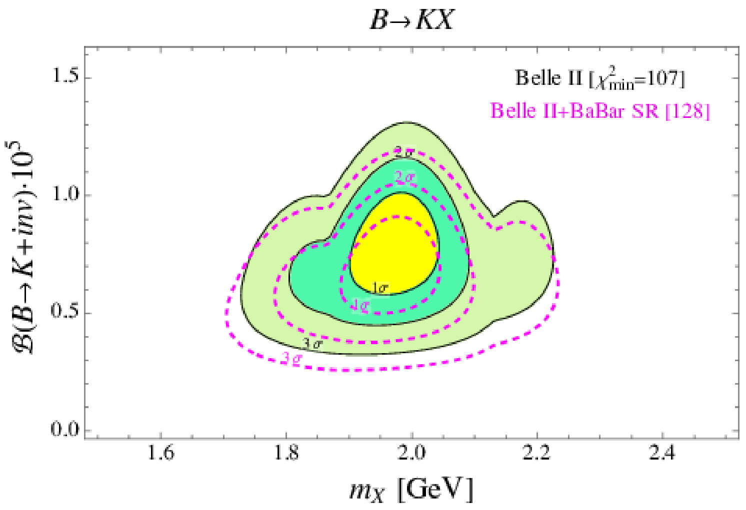
- S_1 leptoquark generates both O^{LNQd} and O^{LNQdT}
- EW doublet η generates O^{LNQd}
- alt. operator basis (Liao+ [1612.04527]): $O^{\mathrm{LNQdT}} = -4O^{\mathrm{LNQd}} - 8\left(\overline{L}d\right)\varepsilon\left(\overline{Q}N\right)$

2-body decay

Two-body decay provides good fit

Fridell+ [2312.12507]





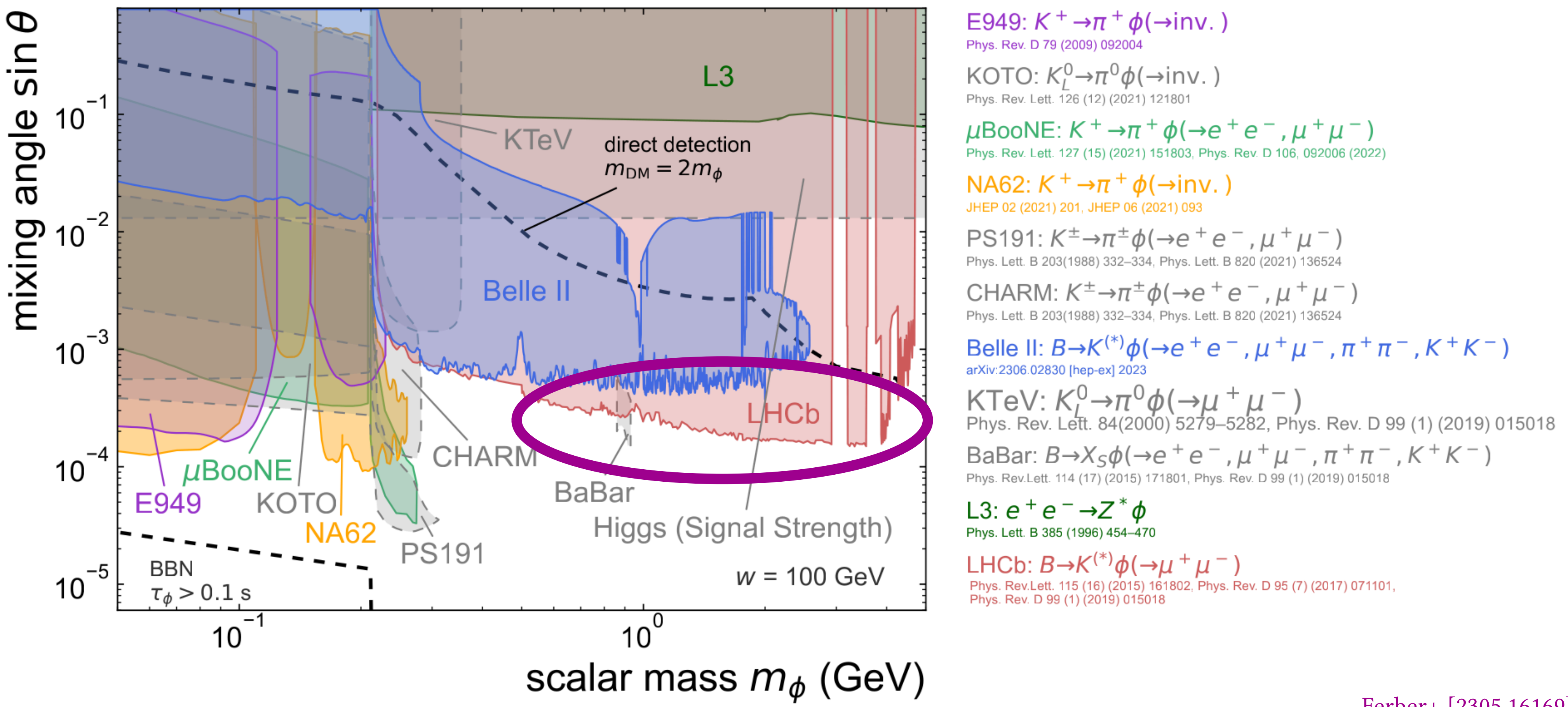
see also Altmannshofer+ [2311.14629]

$\chi^2_{\rm min} - 100$	2b	V	V′	S	T	SM
Belle II	**6.8**	15.2	**4.7**	15.1	11.9	44.6
+ BaBar SR	27.6	30.4	**22.1**	31.8	29.8	61.0
+ BaBar $s_B < 0.8$	**73.3**	78.8	**72.9**	90.2	86.9	106.7

Examples

- light Higgs-like scalar φ with $\varphi \to NN$
- long-lived axion-like particle (ALP)

Light Higgs-like scalar constraints



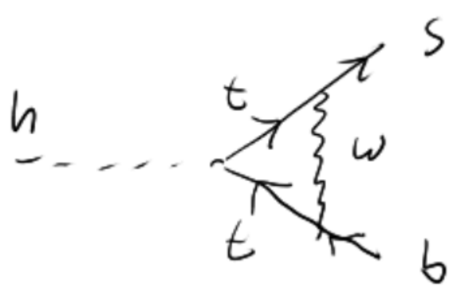
Ferber+ [2305.16169]

- two parameters: mass m_φ and mixing angle θ
- strongest constraint: LHCb displaced vertex search $B^+ \to K^+ \varphi(\to \mu\bar{\mu})$ LHCb [1612.07818]

Light Higgs-like scalar

Ovchynnikov, MS, Schwetz [2306.09508]

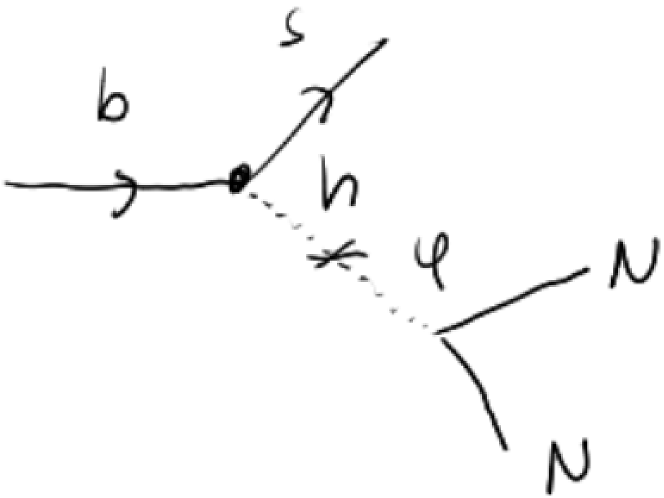
quark flavour-violating SM Higgs couplings

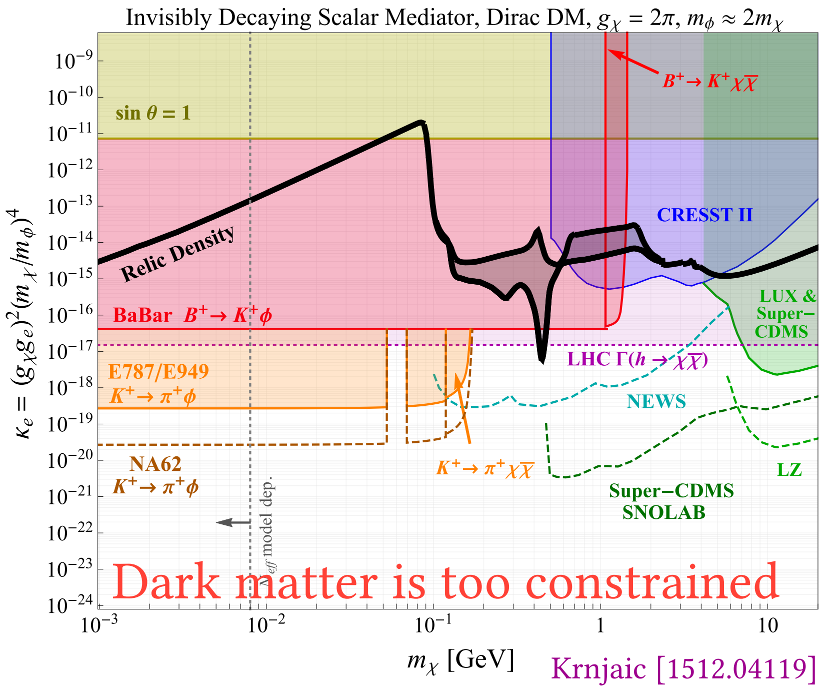


$$-\mathcal{L} = \kappa H^\dagger H \varphi^\dagger \varphi + \frac{1}{2}\varphi \overline{N^c} y_N N$$

short-lived scalar with large invisible width

- $\mathcal{B} \propto \kappa^2 y_N^\dagger y_N$
- need large Yukawa couplings y_N



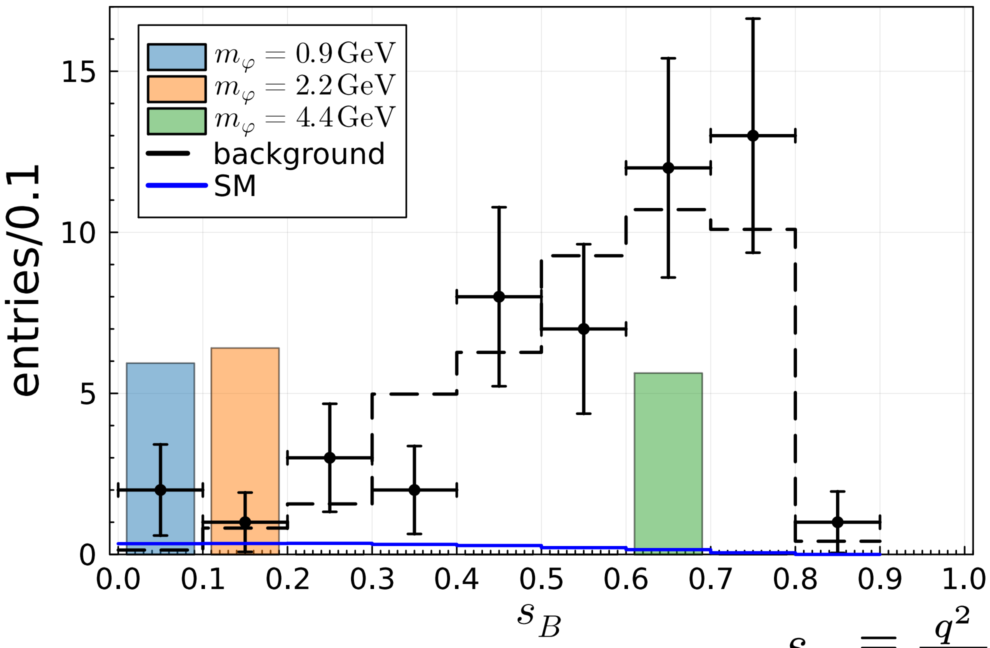


Krnjaic [1512.04119]

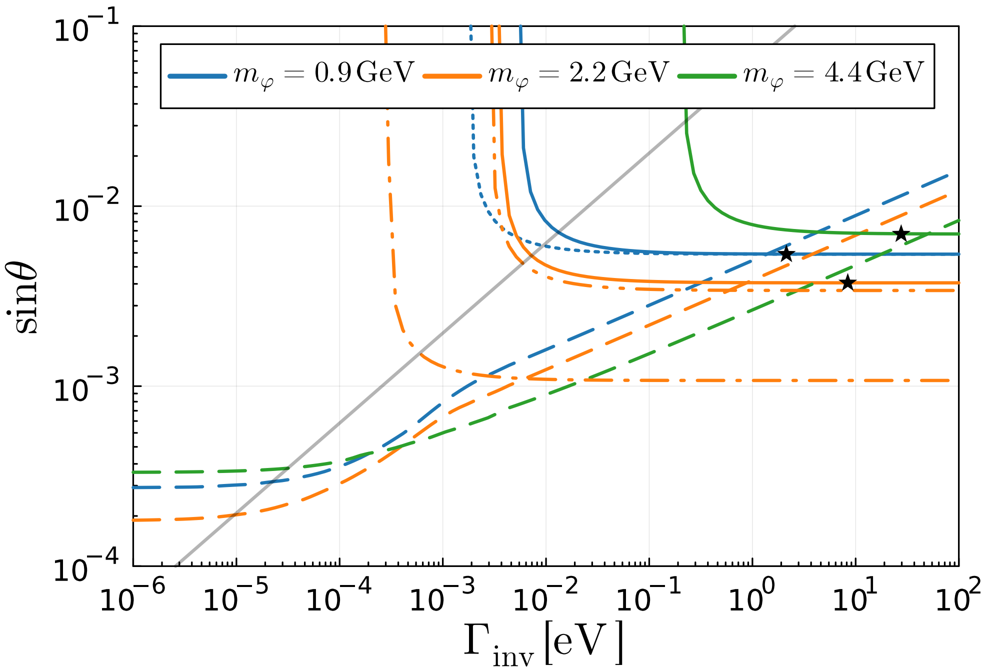
Higgs-like scalar

Ovchynnikov, MS, Schwetz [2306.09508]

- BaBar differential distribution
- 3 benchmark points with
  - masses 0.9, 2.2 and 4.4 GeV
  - $\Gamma_{\text{inv}} = 10$ eV and
  - $\sin\theta = 6 \cdot 10^{-3}$

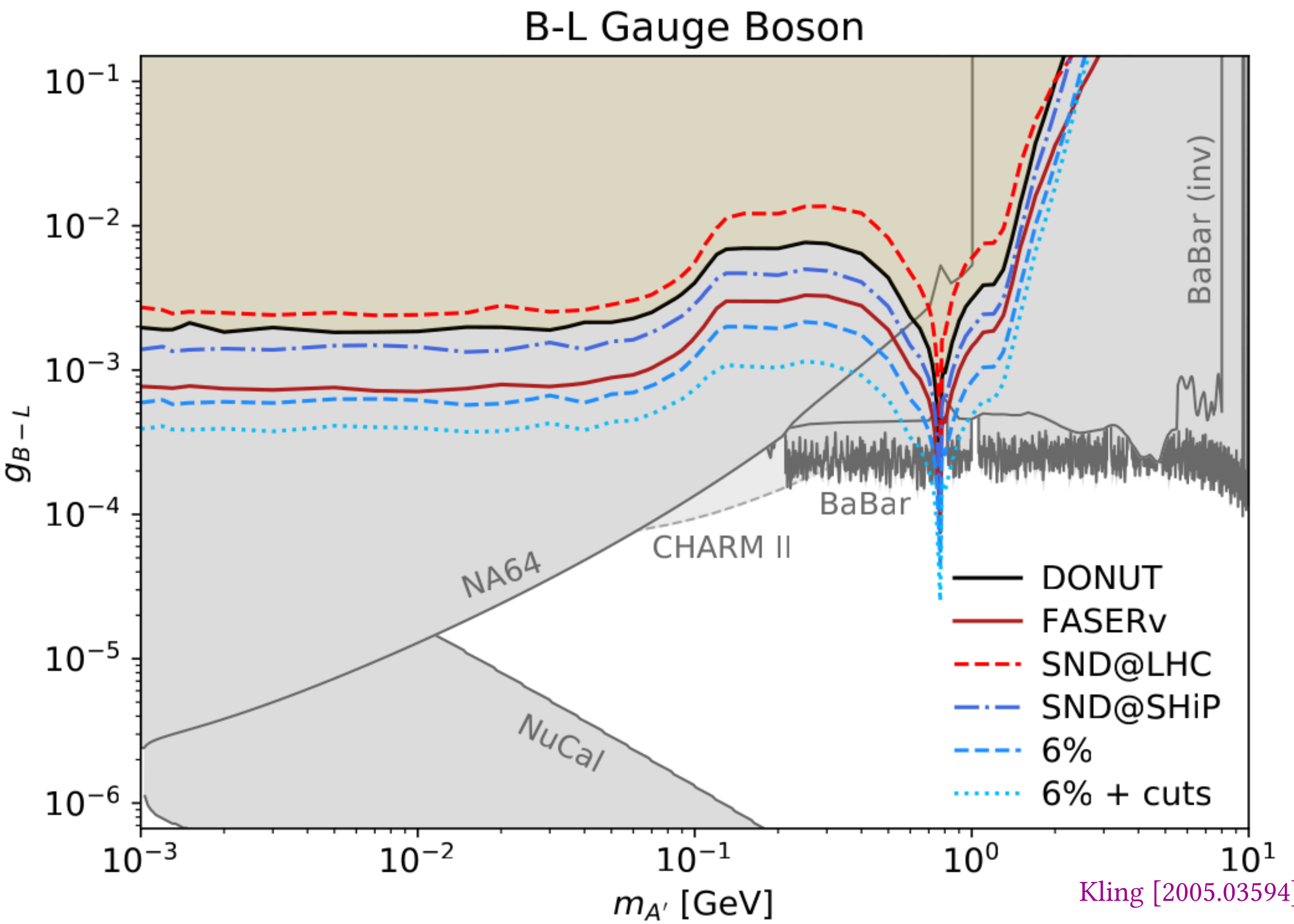


$$s_B \equiv \frac{q^2}{m_B^2}$$



- $B \to K + \text{inv.}$ constrains
  - $\sin(\theta)$ for $\Gamma_{\text{inv}} \gg \Gamma_{\text{vis}}$
  - Γ_{inv} for $\Gamma_{\text{inv}} \ll \Gamma_{\text{vis}}$
- $B \to K + \text{inv.}$ dominates for $\Gamma_{\text{inv}} \gtrsim 1$ eV

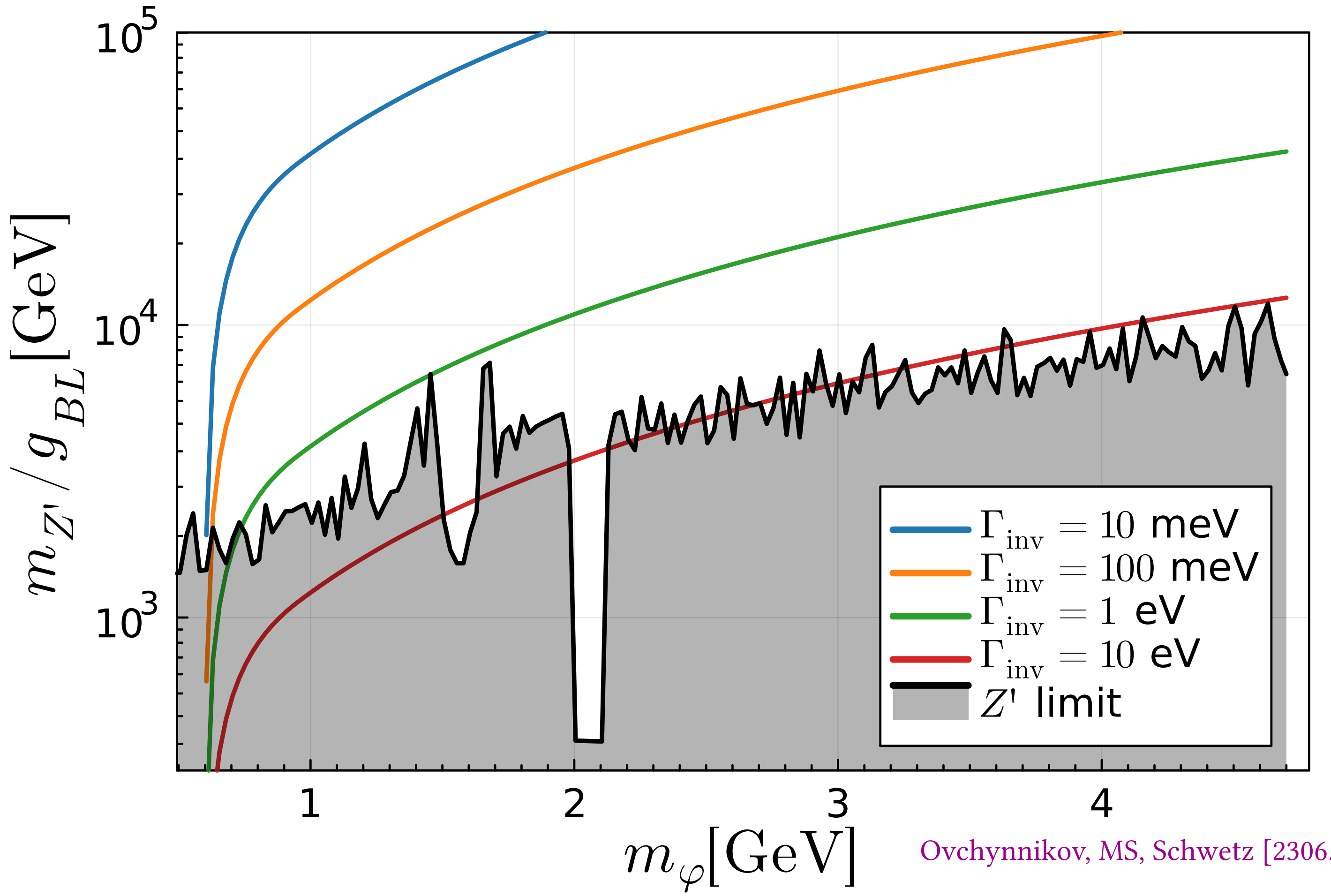
Other constraints



Kling [2005.03594]

This can be used to constrain the scale of the $B-L$ VEV: $v_{\text{B-L}} = \frac{m_{Z'}}{2} g_{\text{BL}}$

Other constraints



Ovchynnikov, MS, Schwetz [2306.09508]

two degenerate HNL with $M_N = \max\left(\frac{m_\varphi}{\sqrt{10}}, 0.3\ \text{GeV}\right)$ and $m_{Z'} \gtrsim \frac{m_\varphi}{2}$. This choice maximizes $\Gamma_{\rm inv}$

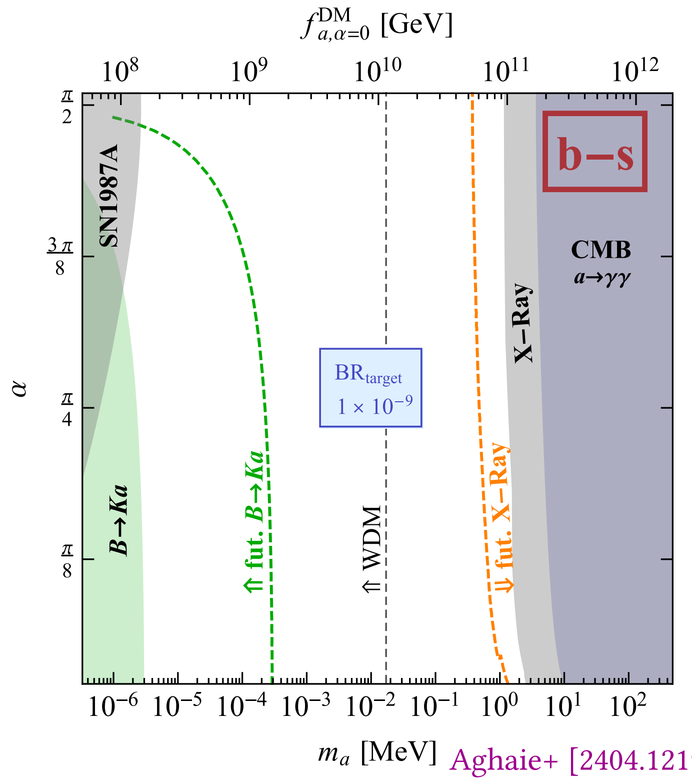
Axion-like particle explanation

- Light axion-like particles (ALPs) are well motivated extension of the SM
- Vanilla QCD axion models (KSVZ, DFSZ) have flavour universal couplings
- Flavour off-diagonal couplings present in models of flavour

Froggatt, Nielsen (1979) Wilczek (1982) Ema [1612.05492] Calibbi+ [1612.08040]

$$\mathcal{L} = \frac{\partial_\mu a}{2 f_a} \overline{f_i} \gamma^\mu \left(C^V_{f_i f_j} + C^A_{f_i f_j} \gamma_5 \right) f_j$$

- ALP may be able to explain excess Altmannshofer+ [2311.14629]
- 2 GeV ALP cannot be DM see e.g. Aghaie+ [2404.12199]



Aghaie+ [2404.12199]

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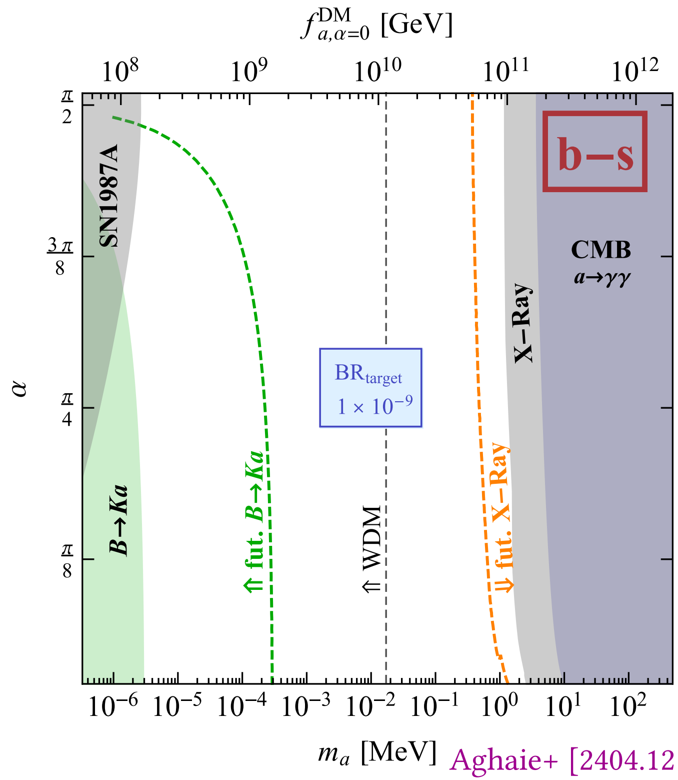
- 2 GeV ALP cannot be DM see e.g. Aghaie+ [2404.12199]
- Simple extension Calibbi, Li, Mukherjee, MS [2502.04900]

Fermionic DM with 2 GeV ALP mediator

$$\mathcal{L} = \frac{\partial_\mu a}{2 f_a} \overline{\chi} C^A_{\chi\chi} \gamma^\mu \gamma_5 \chi$$



Aghaie+ [2404.12199]

ALP - B meson decays

Calibbi, Li, Mukherjee, MS [2502.04900]

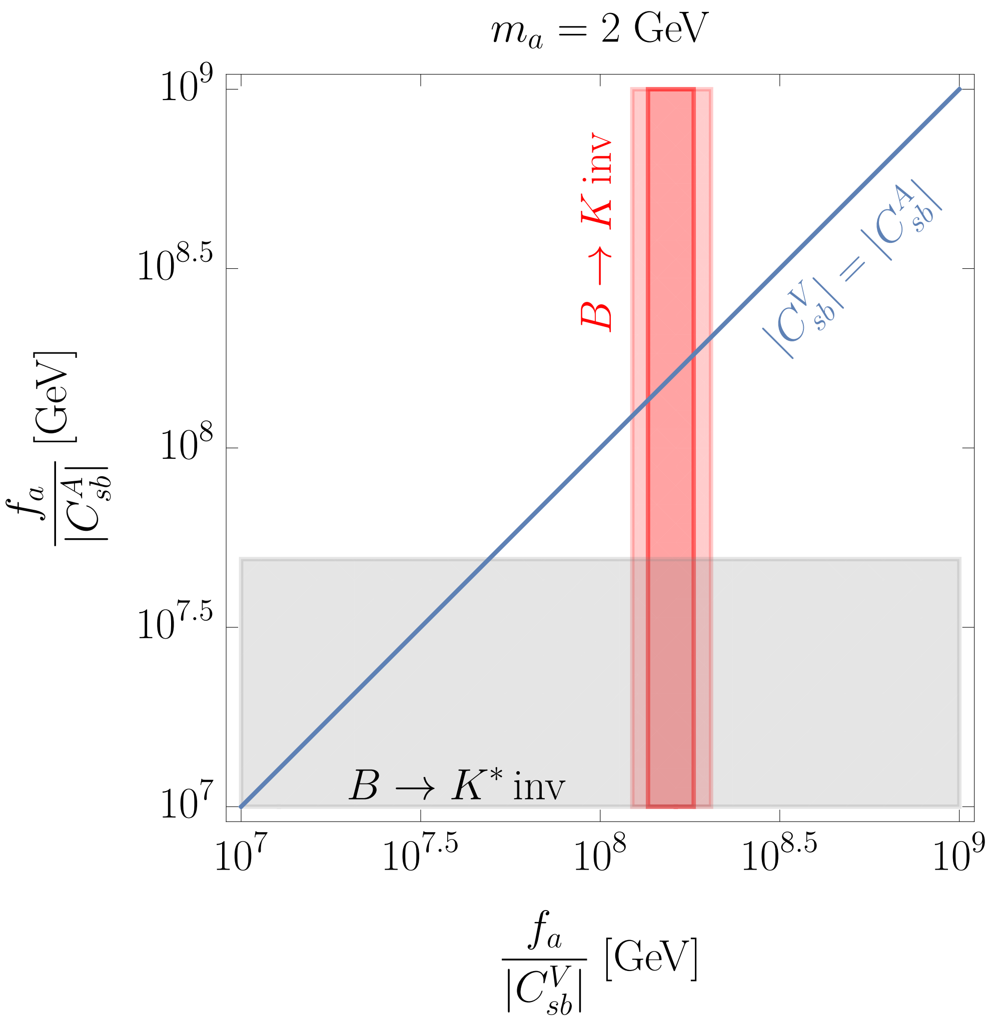
$$\mathrm{BR}(B \to K a) \propto \frac{\tau_B m_B^3}{64\pi} \frac{|C_{sb}^V|^2}{f_a^2} \, |f_0(m_a^2)|^2$$

$$\mathrm{BR}(B \to K^* a) \propto \frac{\tau_B m_B^3}{64\pi} \frac{|C_{sb}^A|^2}{f_a^2} \, |A_0(m_a^2)|^2$$

- decay rates to Ka and K^*a depend on different couplings $C_{sb}^{V/A}$
- ALP coupling to RH or LH fermions has $|C_{sb}^V| = |C_{sb}^A|$ and is able to explain excess
- Universal quark couplings $C_q \equiv C_{qq'}^{V/A}$

$$\mathrm{BR}(a \to gg) \approx 93\%, \quad \mathrm{BR}(a \to s\bar{s}) \approx 7\%$$

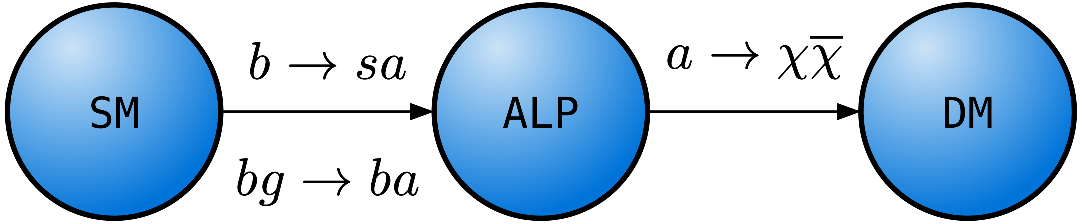
- decay length $c\tau_a \approx 65\mathrm{m}\left(\frac{10^8 \text{ GeV}}{f_a/C_q}\right)^2$

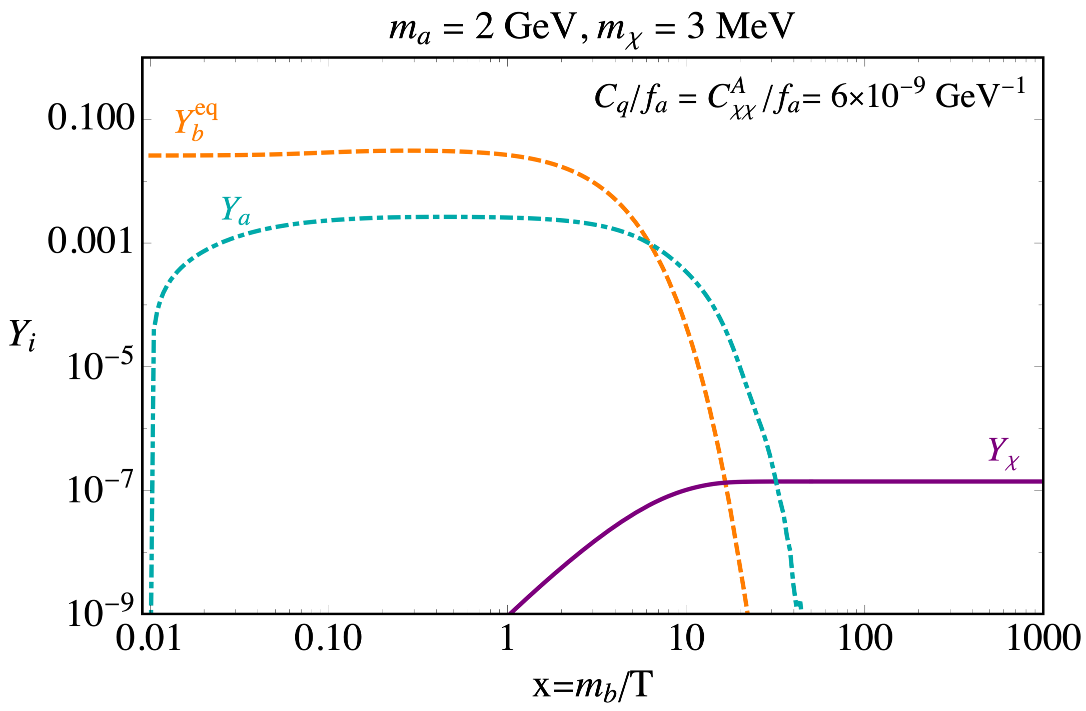


DM freeze-in production - ALP mediator

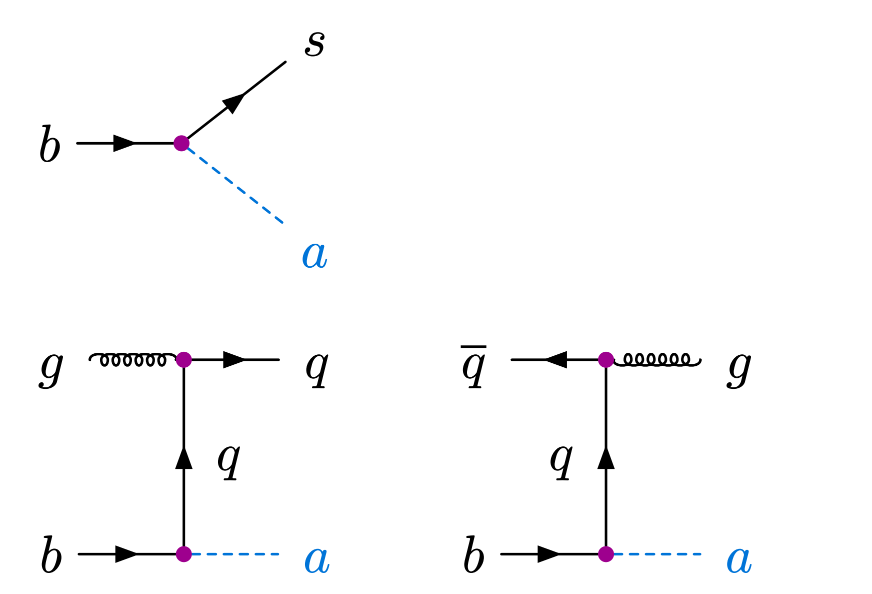
Calibbi, Li, Mukherjee, MS [2502.04900]

2-body decay





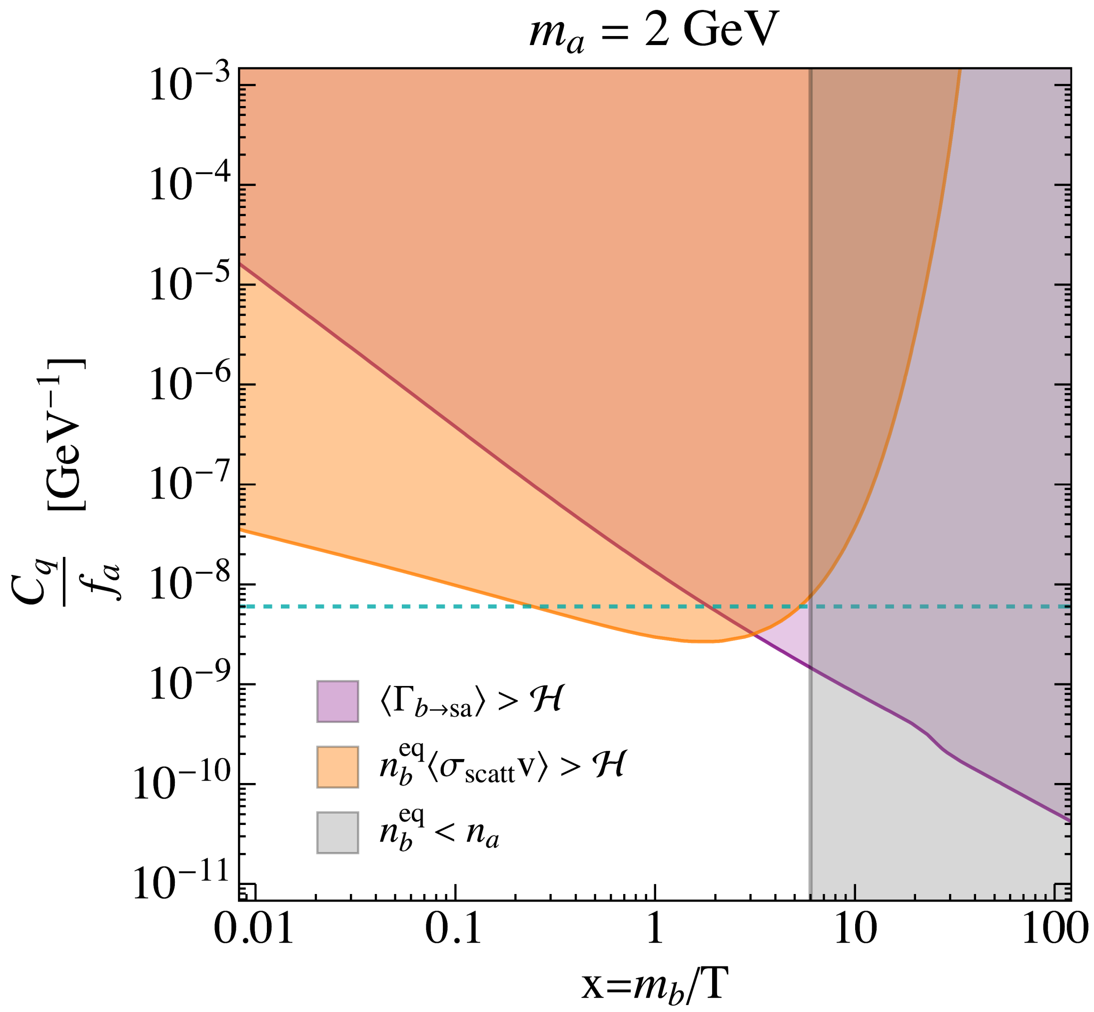
ALP production Aghaie+ [2404.12199]

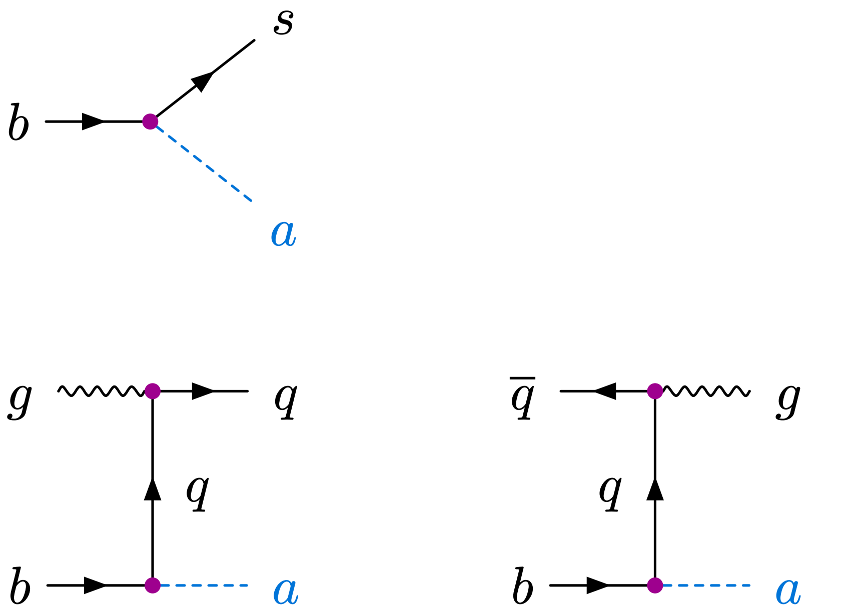


- ALP reaches thermal equilibrium through decay and scattering processes
- χ DM frozen in through ALP decays

DM freeze-in production - ALP mediator

Calibbi, Li, Mukherjee, MS [2502.04900]



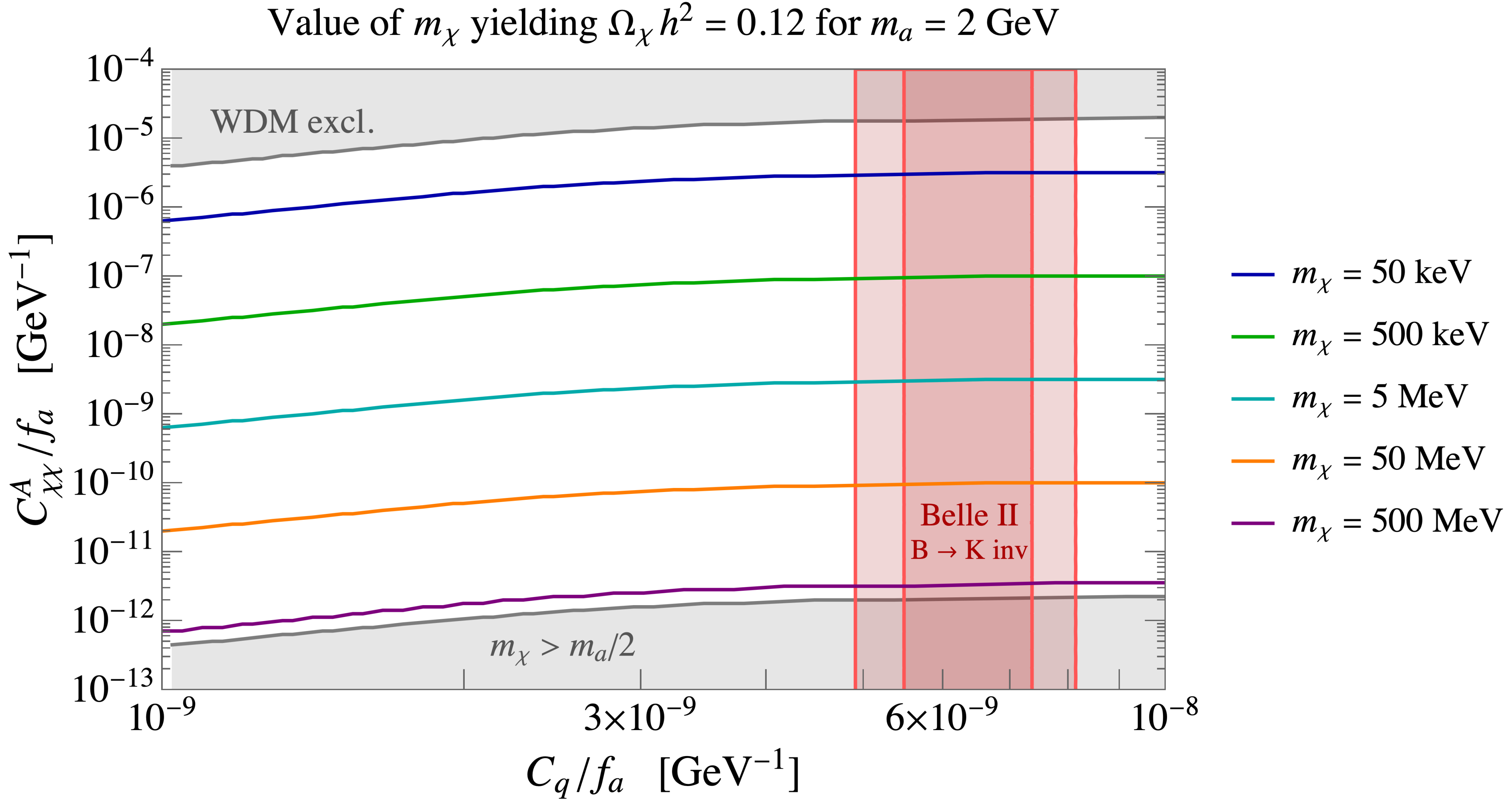


$$\frac{\Omega_\chi}{0.1} \approx \left(\frac{m_\chi}{3\ \mathrm{MeV}}\right)^3 \left(\frac{1.7\times 10^8\ \mathrm{GeV}}{f_a/\,|C^A_{\chi\chi}|}\right)^2$$

$$\frac{\mathrm{BR}(B\to Ka)}{1.7\times 10^{-5}} \approx \left(\frac{1.7\times 10^8\ \mathrm{GeV}}{f_a/C^V_{sb}}\right)^2$$

Viable parameter space

Calibbi, Li, Mukherjee, MS [2502.04900]



Take-home messages

3-body decay

NP scale $\Lambda_{\text{NP}} \sim \mathcal{O}(1-10)$ TeV
✓ connections to DM and ν possible
q^2 distribution $\rightarrow$ Lorentz structure

dark Z' with freeze-out DM

✗ dark photon excluded
$\rightarrow$ additional Z mixing required
✓ highly predictive

ALP with freeze-in DM

NP scale $\Lambda_{\text{NP}} \sim \mathcal{O}(10^5)$ TeV
✓ similarly sized ALP couplings
✗ DM difficult to test

light Higgs and sterile neutrinos

✓ highly predictive
✗ some tuning required
$\rightarrow$ testable using Z' and scalar searches

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- Excess is quite large $\rightarrow$ some model building required
- Even if excess goes away $b \rightarrow s + \text{inv}$ will provide important information on new physics.
- Lesson from neutrino physics: nature does not necessarily follow our expectations
  - We have to remain open-minded and critical.

Take-home messages

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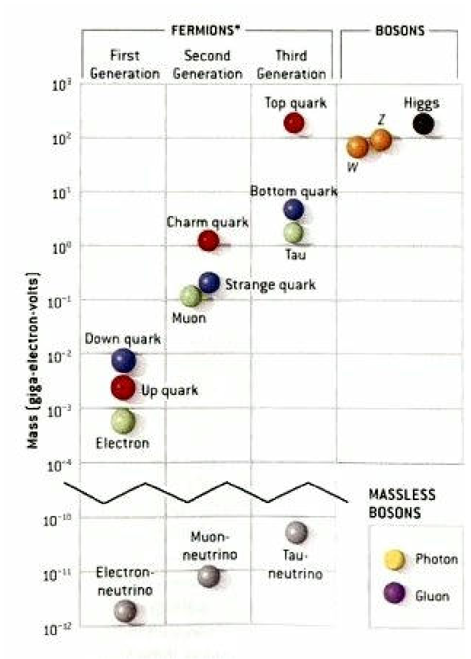
ありがと! Thank you!

Backup slides

Effective field theory

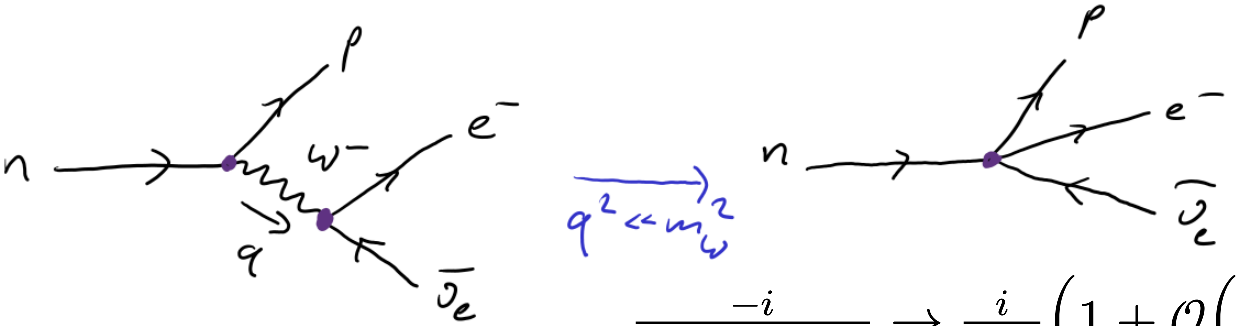
The description of physics at low energies (large distances) does **not** depend on dynamics at high energies (short distances) to good approximation.

- hydrogen orbitals and energy levels
- Fermi's theory of beta decay



  - top quark, Higgs and W and Z bosons are heavy
  - at low energies described by contact interactions

$$\mathcal{L}_{4F} = -2\sqrt{2}G_F(\overline{p}\gamma^\mu P_L n)(\overline{e}\gamma_\mu P_L \nu_e)$$

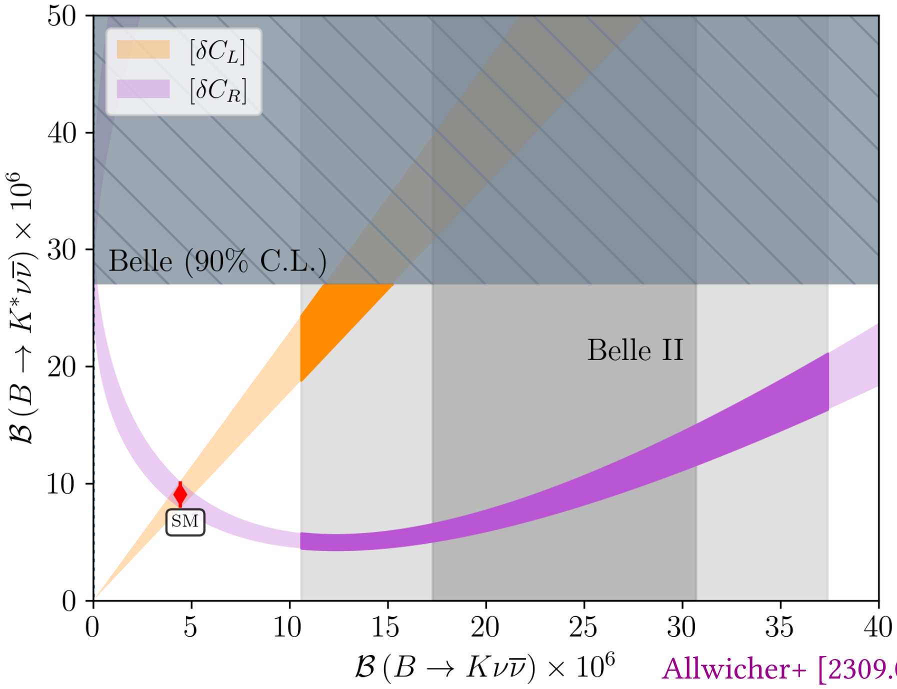


$$\frac{-i}{q^2 - m_W^2 + i0_+} \to \frac{i}{m_W^2}\left(1 + \mathcal{O}\left(\frac{q^2}{m_W^2}\right)\right)$$

Weak effective theory (WET)

Weak effective theory $\Lambda \gg m_b$:

$$\mathcal{L}_6 = 4\sqrt{2} G_F V_{ts}^* V_{tb} \frac{\alpha}{4\pi} \sum_i C_i O_i + \text{h.c.}$$



Allwicher+ [2309.02246]

Assuming lepton number conservation with *only* LH neutrinos ν_i

Relevant dimension-6 operators: $\mathcal{O}_{\mathrm{L,R}} = \left(\bar{\nu}_i \gamma^\mu P_{\mathrm{L}} \nu_j\right)\left(\bar{s}\gamma_\mu P_{\mathrm{L,R}} b\right)$

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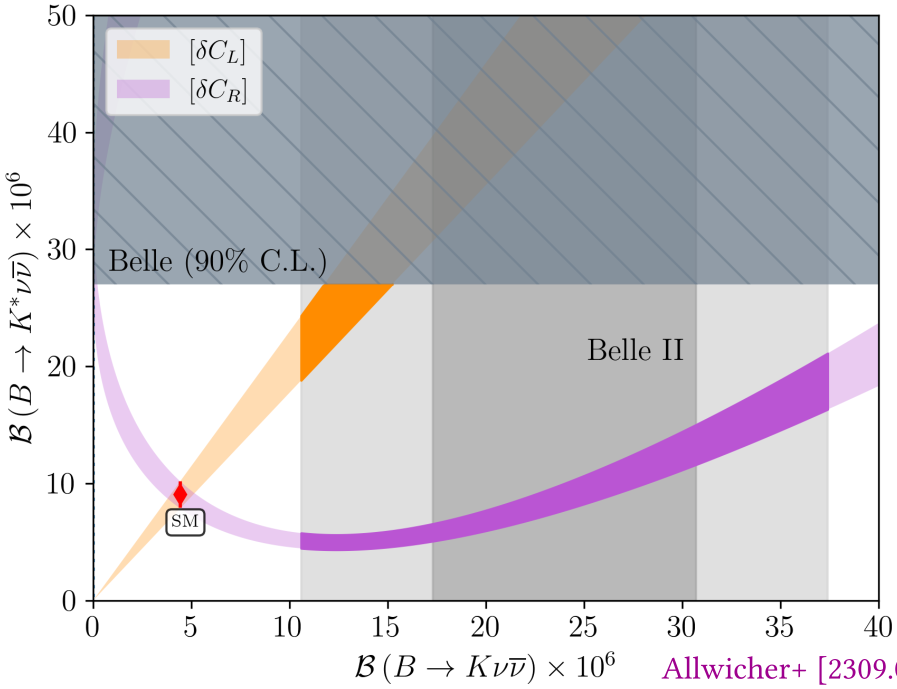

Allwicher+ [2309.02246]

- Is there a realization in SM effective field theory?
- Any realization within a UV model?

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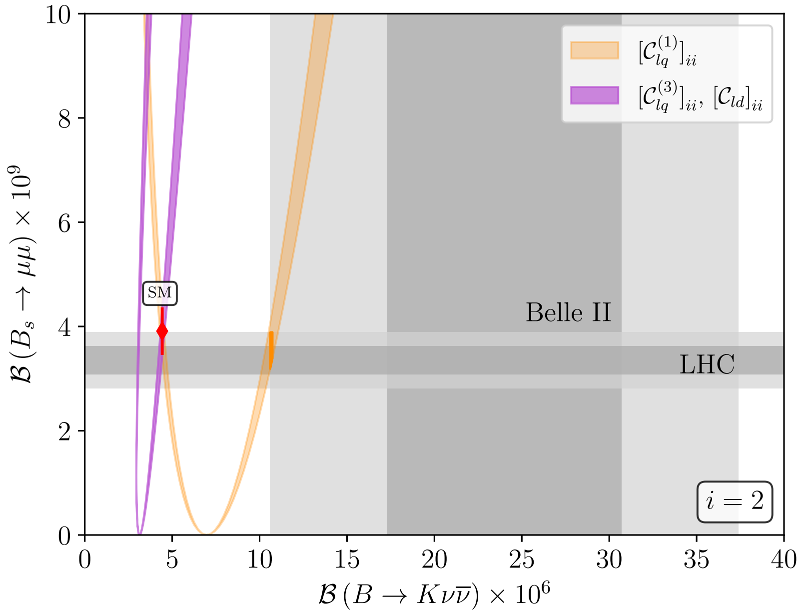
SM effective theory (SMEFT)

relevant SMEFT operators

$$\mathcal{O}_{lq}^{(1)} = \left(\overline{L}\gamma_\mu L\right)\left(\overline{Q}\gamma^\mu Q\right) \quad \mathcal{O}_{lq}^{(3)} = \left(\overline{L}\gamma_\mu \tau^I L\right)\left(\overline{Q}\gamma^\mu \tau^I Q\right) \quad \mathcal{O}_{ld} = \left(\overline{L}\gamma_\mu L\right)\left(\overline{d}\gamma^\mu d\right)$$

$$\mathcal{O}_{Hq}^{(1)} = \left(H^\dagger \overleftrightarrow{D}_\mu H\right)\left(\overline{Q}\gamma^\mu Q\right) \quad \mathcal{O}_{Hq}^{(3)} = \left(H^\dagger \overleftrightarrow{D}_\mu \tau^I H\right)\left(\overline{Q}\gamma^\mu \tau^I Q\right) \quad \mathcal{O}_{Hd} = \left(H^\dagger \overleftrightarrow{D}_\mu H\right)\left(\overline{d}\gamma^\mu d\right)$$

- necessarily couplings to LH charged leptons



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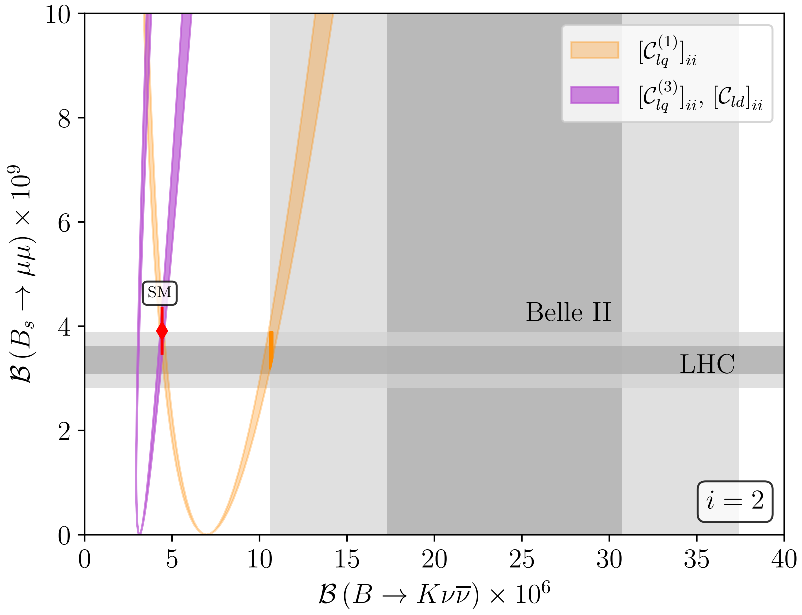
- necessarily couplings to LH charged leptons
- strong constraint from $B_s \to \mu\overline{\mu}$



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SM effective theory (SMEFT)

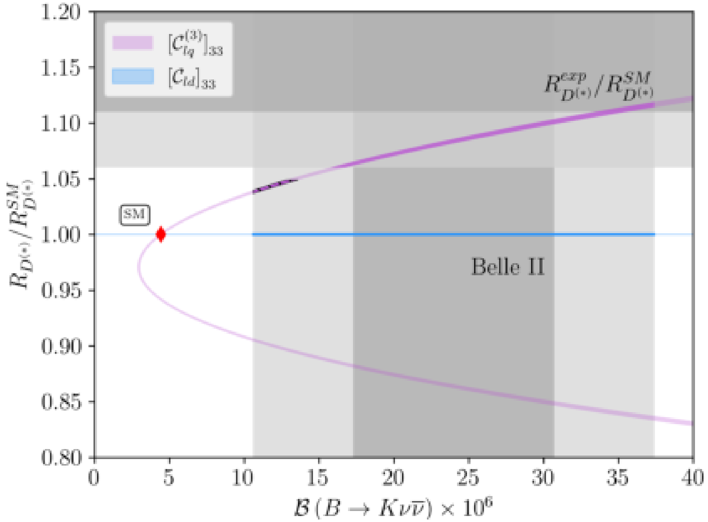
relevant SMEFT operators

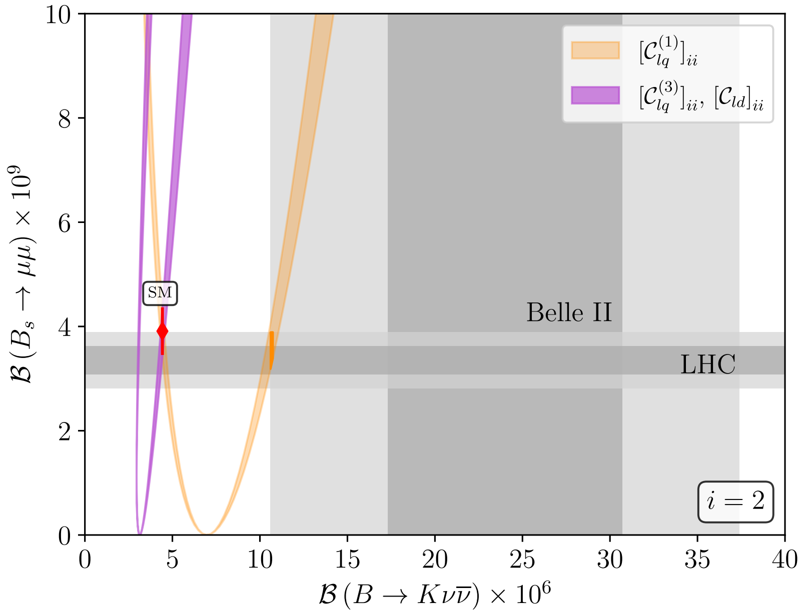
$$\mathcal{O}_{lq}^{(1)} = \left(\overline{L}\gamma_\mu L\right)\left(\overline{Q}\gamma^\mu Q\right) \quad \mathcal{O}_{lq}^{(3)} = \left(\overline{L}\gamma_\mu \tau^I L\right)\left(\overline{Q}\gamma^\mu \tau^I Q\right) \quad \mathcal{O}_{ld} = \left(\overline{L}\gamma_\mu L\right)\left(\overline{d}\gamma^\mu d\right)$$

$$\mathcal{O}_{Hq}^{(1)} = \left(H^\dagger \overleftrightarrow{D}_\mu H\right)\left(\overline{Q}\gamma^\mu Q\right) \quad \mathcal{O}_{Hq}^{(3)} = \left(H^\dagger \overleftrightarrow{D}_\mu \tau^I H\right)\left(\overline{Q}\gamma^\mu \tau^I Q\right) \quad \mathcal{O}_{Hd} = \left(H^\dagger \overleftrightarrow{D}_\mu H\right)\left(\overline{d}\gamma^\mu d\right)$$

- necessarily couplings to LH charged leptons
- strong constraint from $B_s \to \mu\overline{\mu}$
- τ flavour scenario

✓ SMEFT e.g. $[C_{ld}]_{33}$





Allwicher+ [2309.02246]

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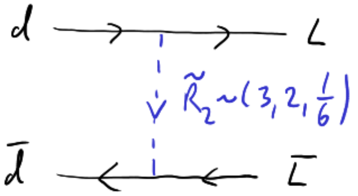
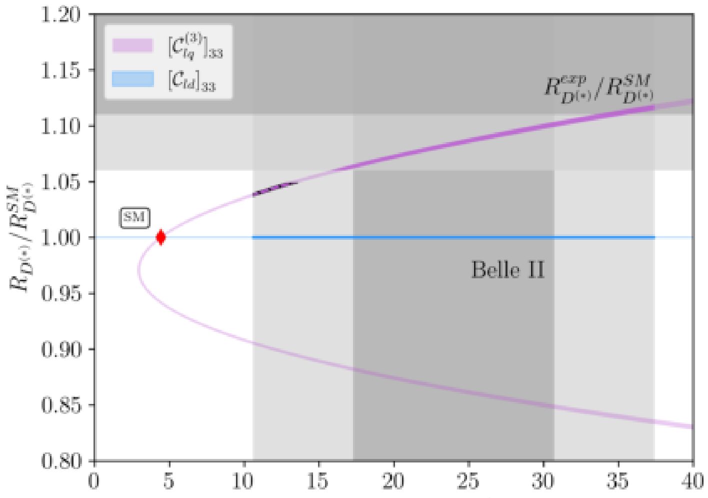
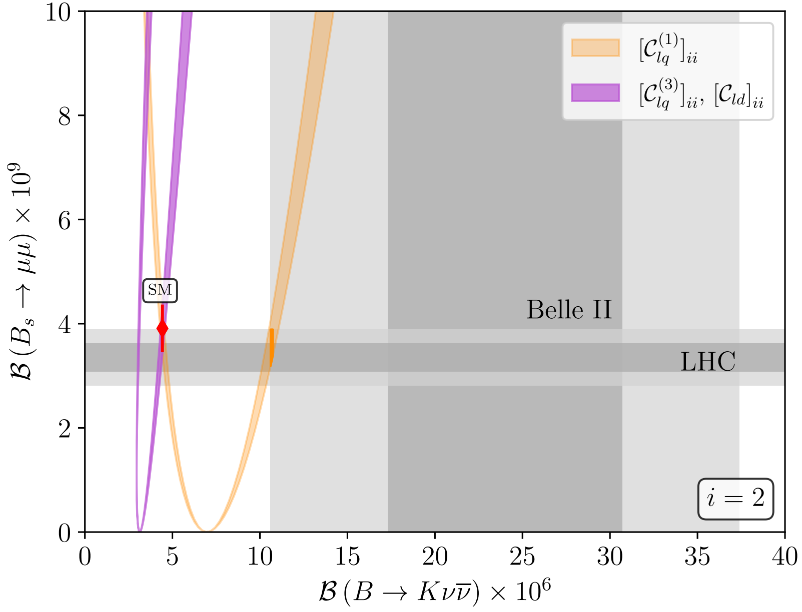


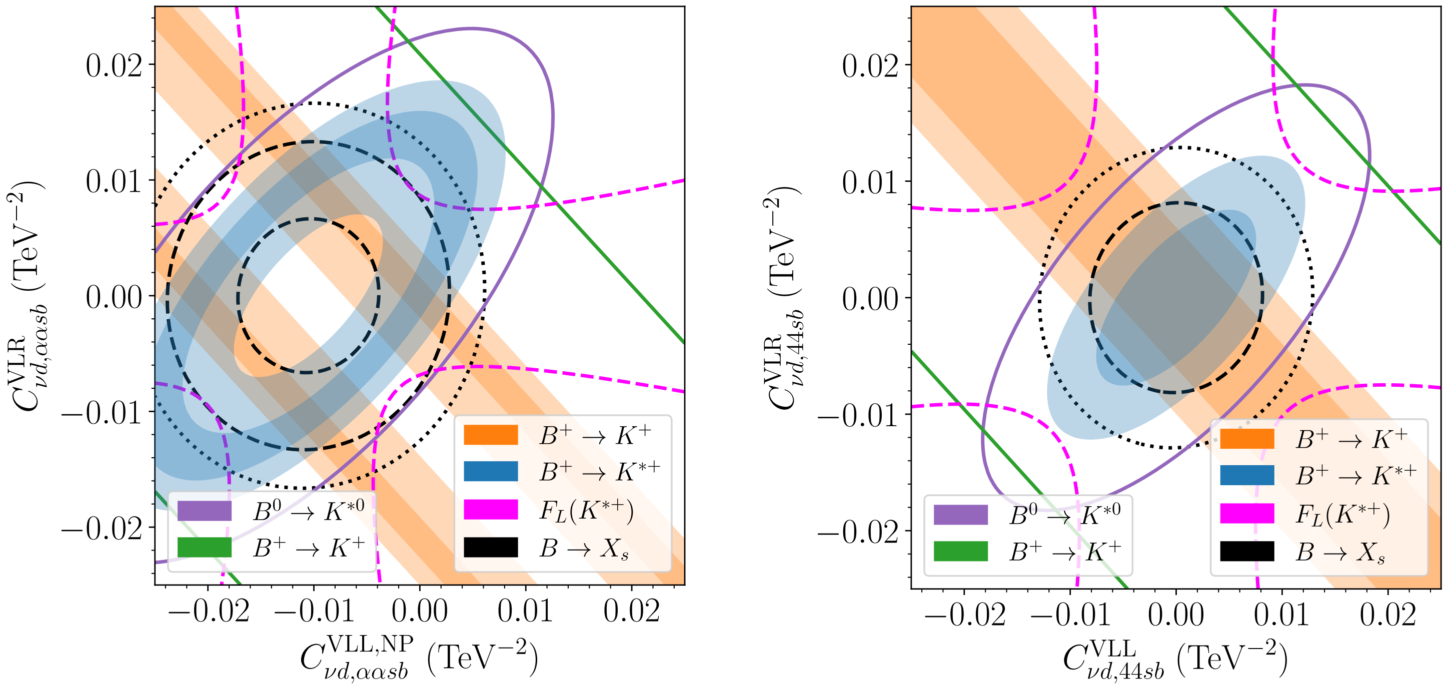
✓ UV completion





Allwicher+ [2309.02246]

Complementarity   Felkl, Li, MS [2111.04327]



LEFT operators

$$\mathcal{O}^{\rm VLX}_{\nu d,\alpha\alpha sb} = (\overline{\nu_\alpha}\gamma_\mu P_L \nu_\alpha)(\overline{s}\gamma^\mu P_{L,R} b)$$

- current constraints solid purple and green lines
- viable light (dark) regions if SM confirmed by Belle II with 5(50)ab^{-1}
- black dotted (dashed) $B \to X_s \nu\nu$ with 50% (20%) precision

Different observables provide complementary probes

- Straight bands $\mathcal{A} \propto |C^{\rm VLL}_{\nu d,\alpha\alpha sb} + C^{\rm VLR}_{\nu d,\alpha\alpha sb}|^2$
- Ellipses: $\mathcal{A} \propto A(q^2)|C^{\rm VLL}_{\nu d,\alpha\alpha sb} + C^{\rm VLR}_{\nu d,\alpha\alpha sb}|^2 + B(q^2)|C^{\rm VLL}_{\nu d,\alpha\alpha sb} - C^{\rm VLR}_{\nu d,\alpha\alpha sb}|^2$

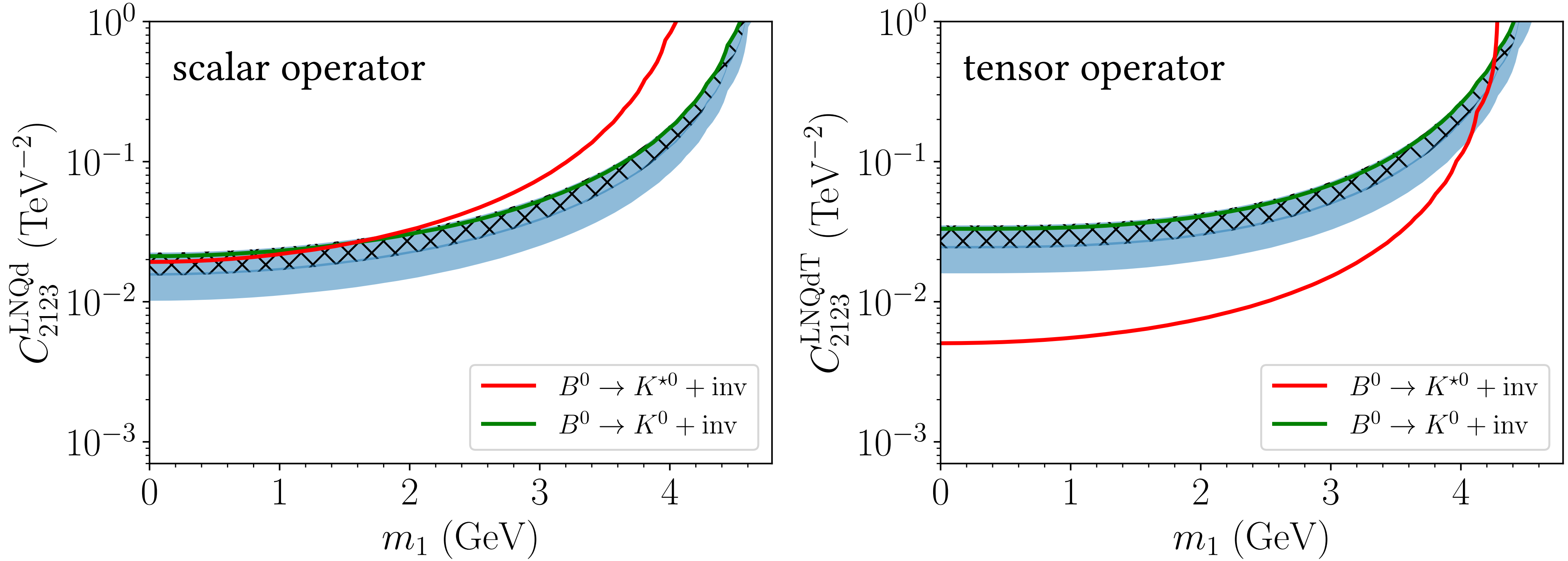
Complementarity

Felkl, Li, MS [2111.04327]

$$\mathcal{L} = C^{\mathrm{LNQd}}\left(\overline{L}^{\alpha} N\right)\varepsilon_{\alpha\beta}\left(\overline{Q}^{\beta} d\right)$$
$$+C^{\mathrm{LNQdT}}\left(\overline{L}^{\alpha}\sigma_{\mu\nu} N\right)\varepsilon_{\alpha\beta}\left(\overline{Q}^{\beta}\varepsilon^{\mu\nu} d\right)$$

Wilson coeff. defined at $\mu = 1$ TeV

- $\mathcal{B}(B^+ \to K^+ + \mathrm{inv}) = (2.4 \pm 0.7)\cdot 10^{-5}$ EPS 2023
- naive comparison of branching ratio
- *scalar operator* not constrained by $B \to K^* + \mathrm{inv}$
- *tensor operator* strongly constrained by $B \to K^* + \mathrm{inv}$

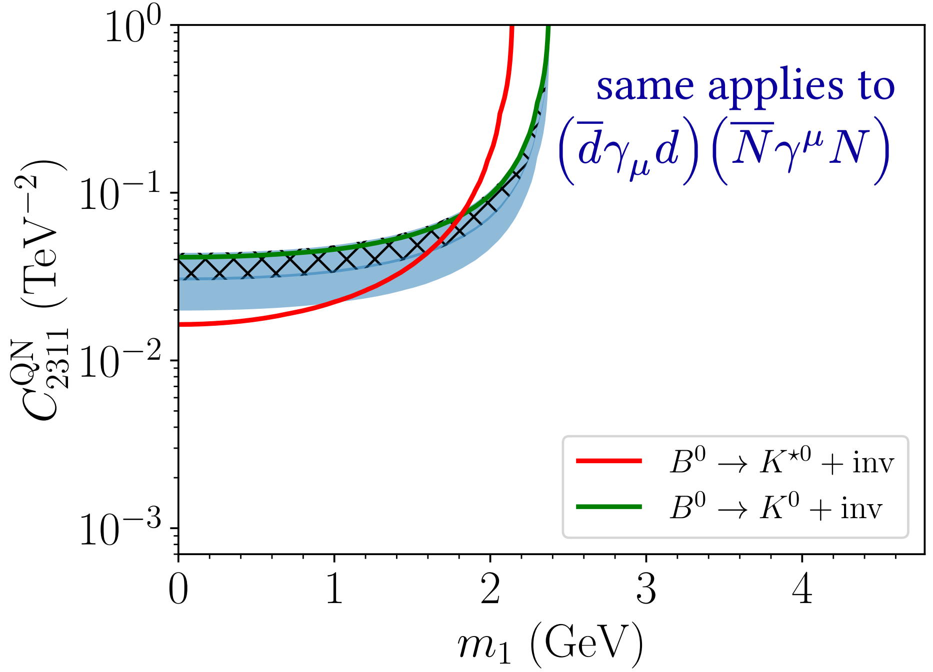


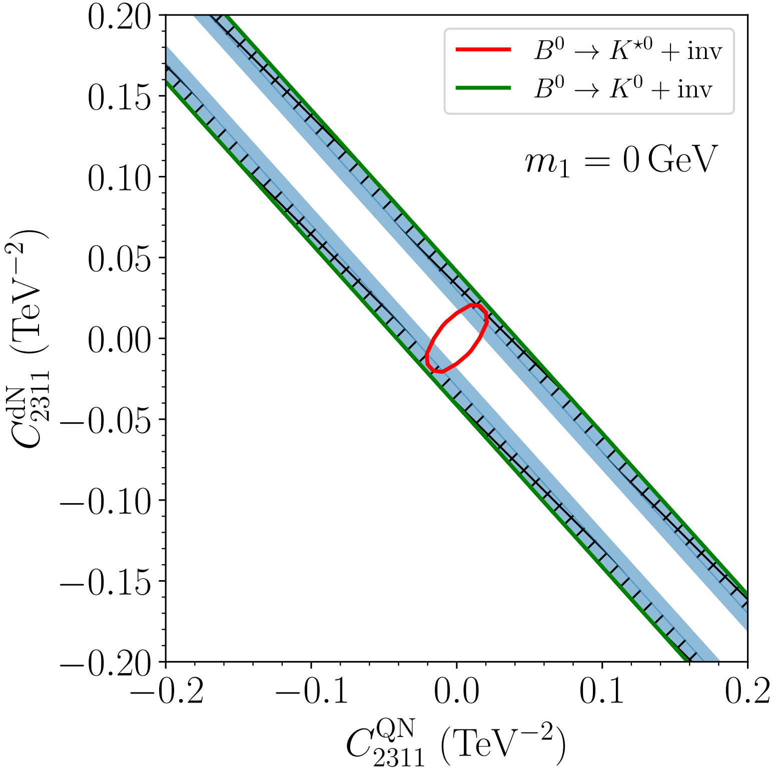
blue region preferred by weighted avg (hatched by Belle II), experimental constraints - dashed, theory prediction - solid

Complementarity Felkl, Li, MS [2111.04327]

$$\mathcal{L} = C^{\mathrm{QN}}\left(\overline{Q}\gamma_\mu Q\right)\left(\overline{N}\gamma^\mu N\right) + C^{\mathrm{dN}}\left(\overline{d}\gamma_\mu d\right)\left(\overline{N}\gamma^\mu N\right)$$

- Wilson coefficients defined at $\mu = 1$ TeV
- naive comparison of branching ratio
- $B \to K^* + \mathrm{inv}$ constrains *chiral vector operator* at low mass, $\to$ interference allows to avoid constraint





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blue region preferred by weighted avg (hatched by Belle II),
experimental constraints - dashed,
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UV completions of sterile neutrino operators

UV completion of scalar operator – electroweak doublet $\eta \sim \left(\mathbf{1}, \mathbf{2}, -\frac{1}{2}\right)$

$$\overline{L}N\eta + \overline{Q}\tilde{\eta}d \to \left(\overline{L}N\right)\left(\overline{Q}d\right) + \left(\overline{L}\gamma_\mu L\right)\left(\overline{N}\gamma^\mu N\right) + \left(\overline{Q}\gamma_\mu Q\right)\left(\overline{d}\gamma^\mu d\right)$$

constraints from

- $B_s - \overline{B_s}$ mixing
- lepton flavour universality in $\ell_i \to \ell_j +$ invisible

UV completion of vector operator – leptoquarks

$\widetilde{R}_2 \sim \left(\mathbf{3}, \mathbf{2}, -\frac{1}{6}\right)$

$$\overline{Q}\widetilde{R}_2 N \to \left(\overline{Q}\gamma_\mu Q\right)\left(\overline{N}\gamma^\mu N\right)$$

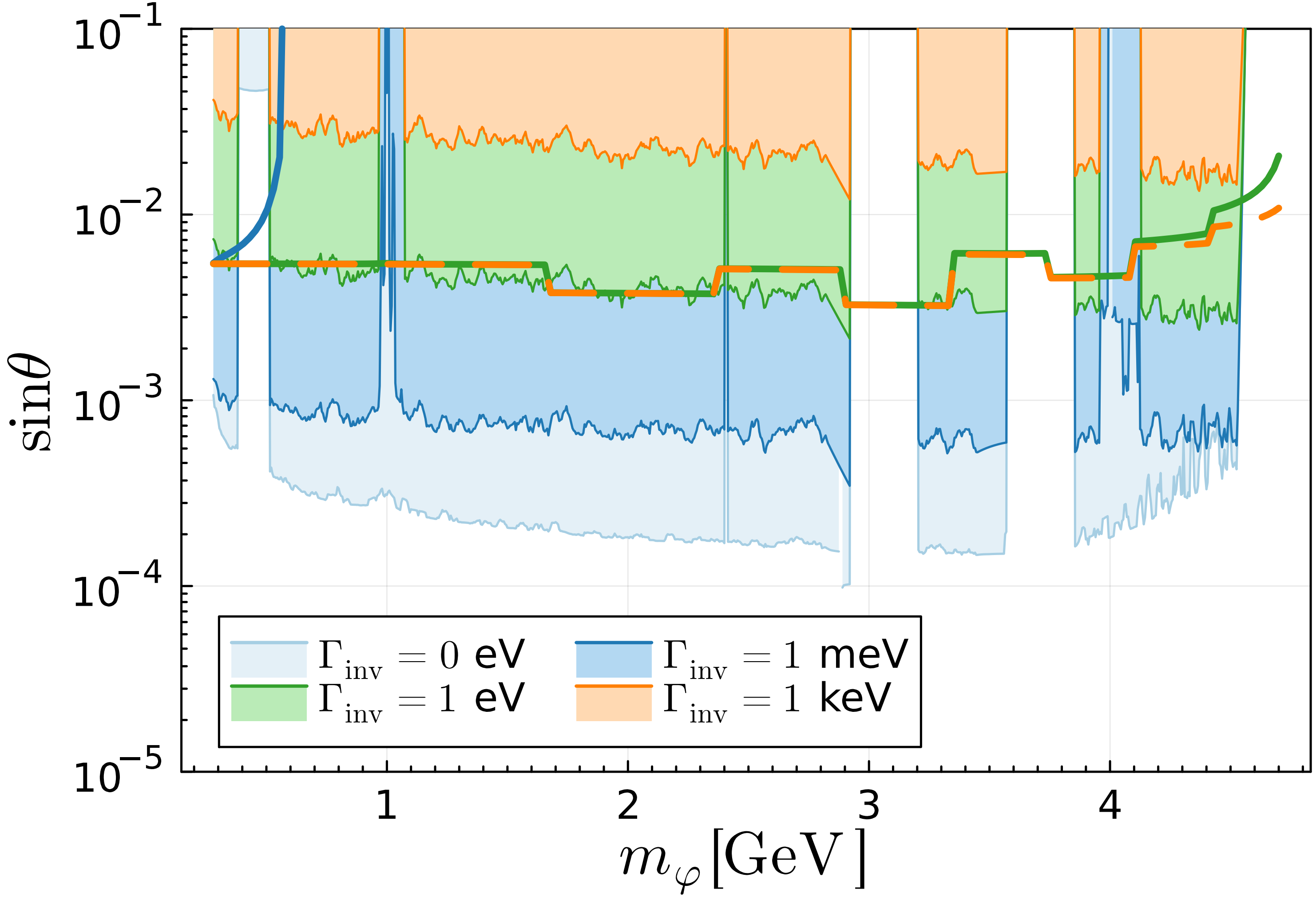
- could generate $\mathcal{O}^{Ld}$
- $B_s - \overline{B_s}$ mixing only at 1-loop

$S_1 \sim \left(\mathbf{3}, \mathbf{1}, \frac{1}{3}\right)$

$$\overline{N^c}S_1 d \to \left(\overline{d}\gamma_\mu d\right)\left(\overline{N}\gamma^\mu N\right)$$

- could generate $\mathcal{O}^{\mathrm{eu}}$, $\mathcal{O}^{\mathrm{LQ}(1,3)}$, $\mathcal{O}^{\mathrm{LeQu}\,(1,3)}$
- $B_s - \overline{B_s}$ mixing only at 1-loop

Higgs-like scalar Ovchynnikov, MS, Schwetz [2306.09508]



LHCb constraint is weakened for new invisible width $\Gamma_{\rm inv}$

$B \to K +$ invisible provides a complementary probe which constrains this scenario.

requires $\Gamma_{\rm inv} \gtrsim 1$ eV

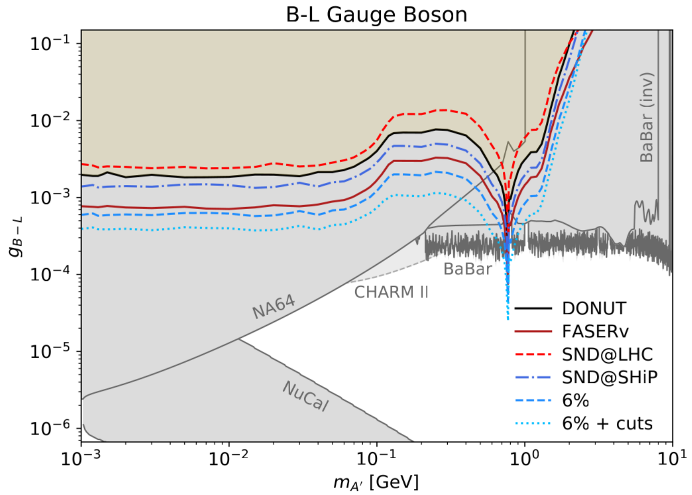
Invisible decays to heavy neutral leptons

real scalar coupled to sterile neutrinos

$$\mathcal{L} = -\frac{1}{2}\overline{N^c}(\mu_N + y_N\varphi)N$$

Invisible Higgs decay constrains

$$\Gamma(\varphi \to NN) \lesssim 0.06 \left(\frac{10^{-2}}{\sin\theta}\right)^2 m_\varphi$$



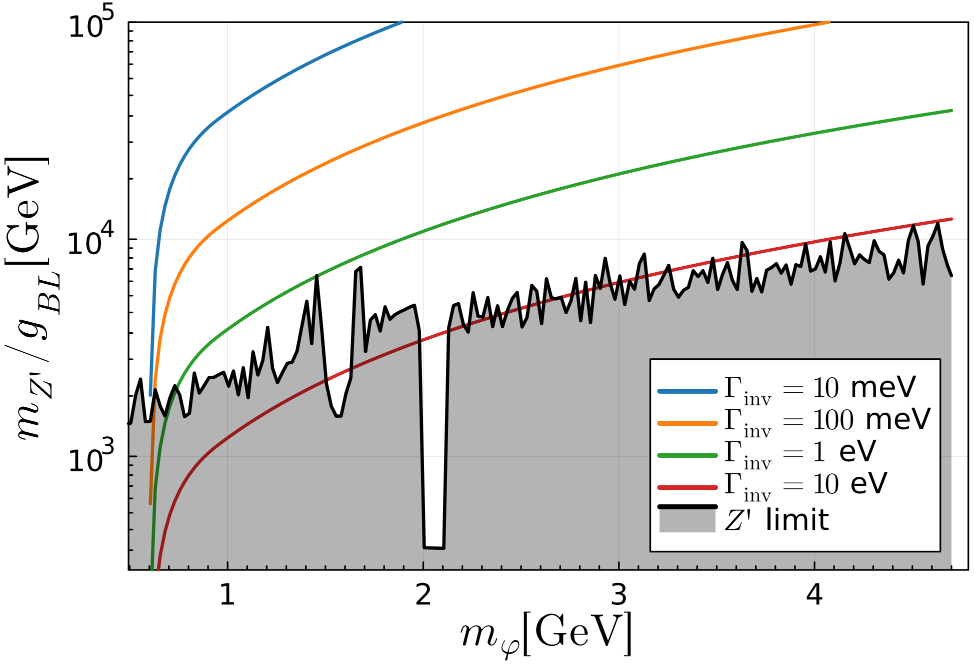
Kling [2005.03594]

$\Longrightarrow$

$B-L$ model

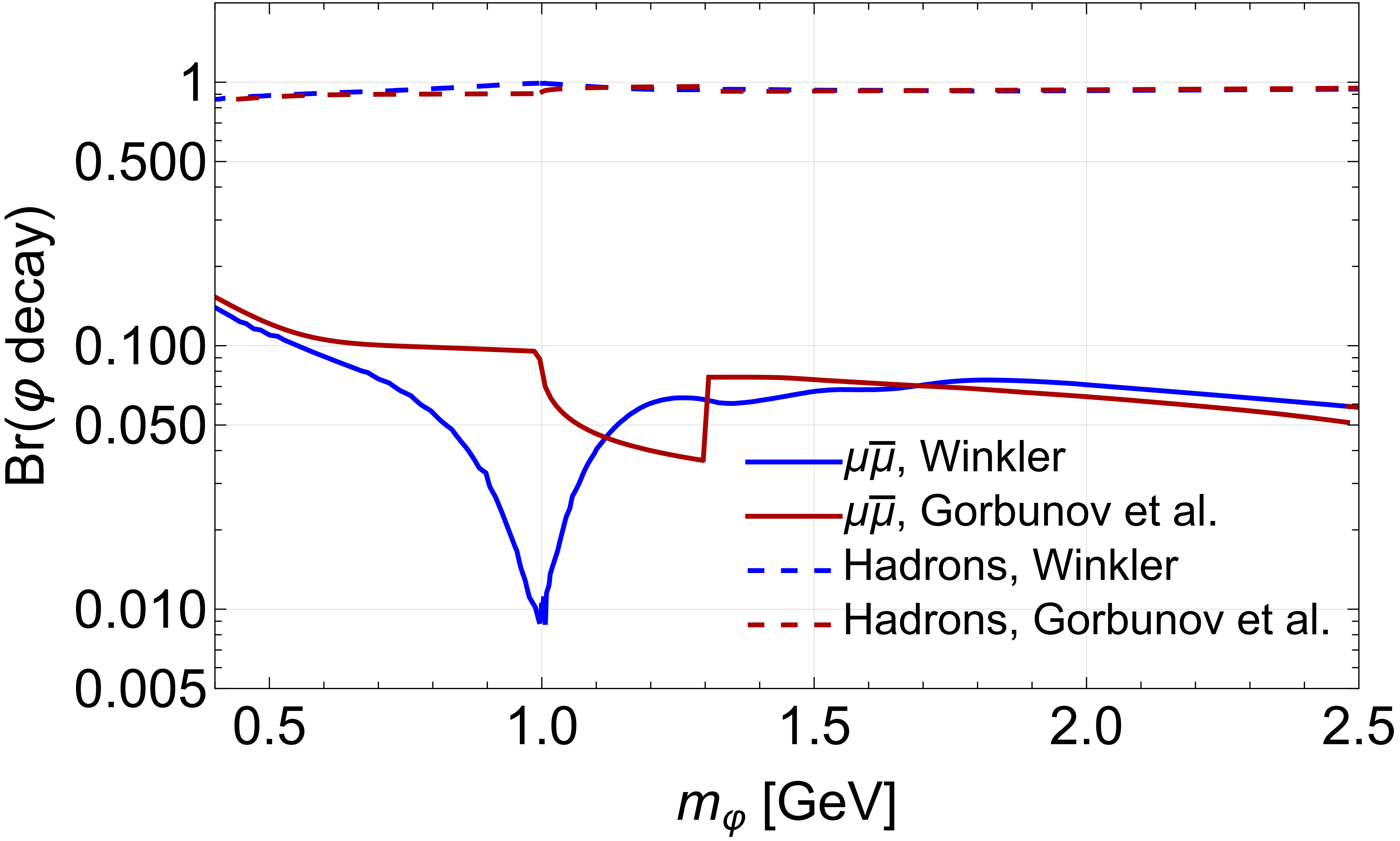
$$\mathcal{L} = -\frac{1}{2}\overline{N^c}y_N\varphi N \;\to\; M_N = y_N\frac{v_\varphi}{\sqrt{2}}$$

Four free parameters: M_N, $m_{Z'}$, m_φ, $g_{\rm BL}$



$$M_N = \max\left(\frac{m_\varphi}{\sqrt{10}}, 0.3\text{ GeV}\right)$$

Branching ratio uncertainty



Dark photon Calibbi, Li, Mukherjee, MS [2502.04900]

- minimal dark photon scenario
  - dark photon X^μ
  - dark Higgs ϕ with $U(1)_{\text{dark}}$ charge 2
  - vector-like dark fermion χ with $U(1)_{\text{dark}}$ charge 1
- coupling to SM fermions parameterised in terms of kinetic mixing ε and $Z - X$ mixing ε_Z

$$\mathcal{L}_{X\text{SM}} = \left(e\varepsilon J_\mu^{\text{em}} + \frac{g}{2c_w}\varepsilon_Z J_\mu^{\text{NC}} \right) X^\mu$$

- Dark fermion $\mathcal{L}_\chi = \overline{\chi}(i\not{D} - m_D)\chi - \phi\overline{\chi^c}(y_L P_L + y_R P_R)\chi$
- Yukawa coupling $\rightarrow$ Majorana mass term $m_{R/L} = y_{R/L} v_\phi/\sqrt{2}$

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Simplified scenario: DM candidate $\psi \approx \chi_R$ with $0 \approx m_D \ll m_R \ll m_X \ll m_L$,

$$\mathcal{L}_{\text{dark}} = \frac{1}{2}\overline{\psi}(i\not{\partial} - m_R)\psi + \frac{g_X}{2}\overline{\psi}\not{X}\psi - \frac{m_R}{2}\overline{\psi}\left(\frac{\varphi}{v_\phi} + i\frac{a}{v_\phi}\gamma_5 \right)\psi$$

$B \to KX$

$$\mathcal{L} = \left(e\varepsilon J_\mu^{\text{em}} + \frac{g}{2c_w}\varepsilon_Z J_\mu^{\text{NC}} \right) X^\mu + \frac{g_X}{2}\bar{\psi}\not{X}\psi + \ldots$$

$$\text{BR}(B \to KX) \propto \frac{|\varepsilon_Z|^2 \; m_B \tau_B \; |f_+(m_X)|^2}{64\pi}$$

$$\text{BR}(B \to K^* X) \propto \frac{|\varepsilon_Z|^2 \; m_B \tau_B \sum_h |\tilde{H}_h|^2}{64\pi}$$

- $\text{BR}(B \to K^* X) \approx 1.9 \; \text{BR}(B \to KX)$

$B \to KX$

$$\mathcal{L} = \left(e\varepsilon J_\mu^{\mathrm{em}} + \frac{g}{2c_w} \varepsilon_Z J_\mu^{\mathrm{NC}} \right) X^\mu + \frac{g_X}{2} \bar{\psi} \not{X} \psi + \ldots$$

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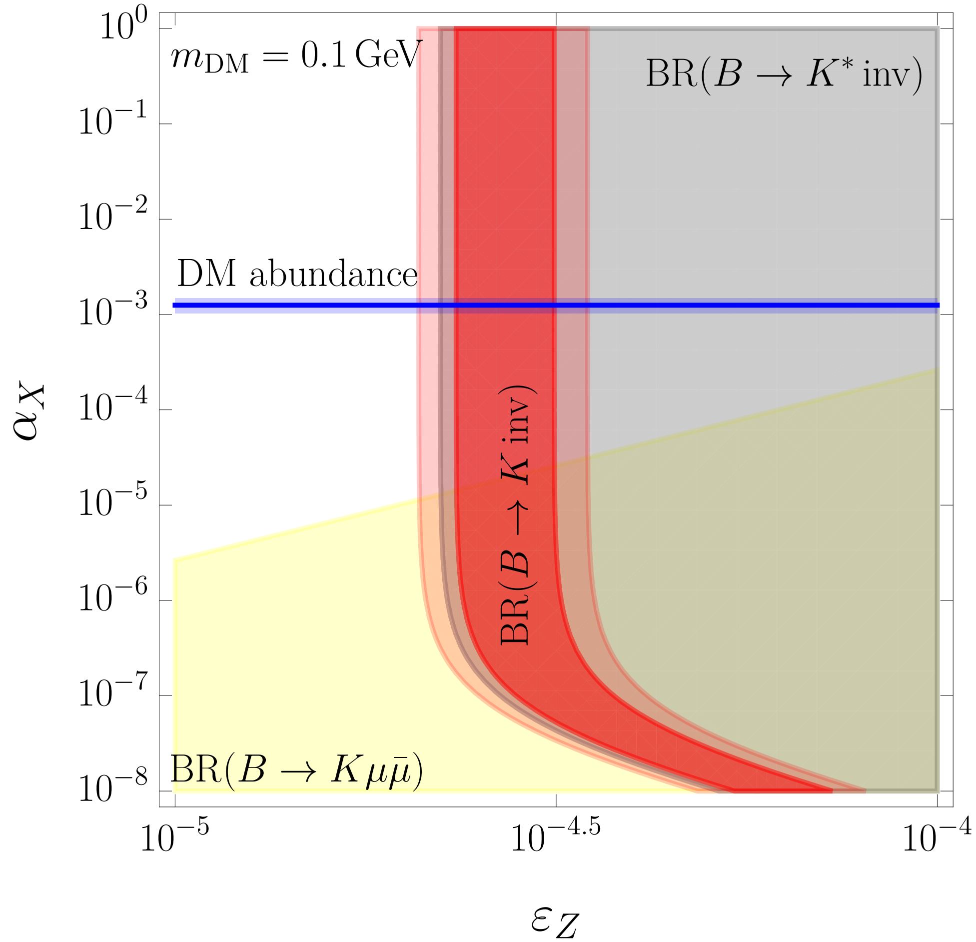
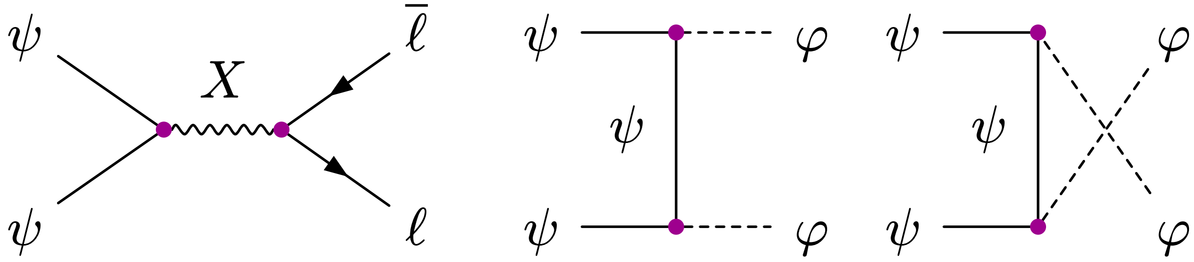
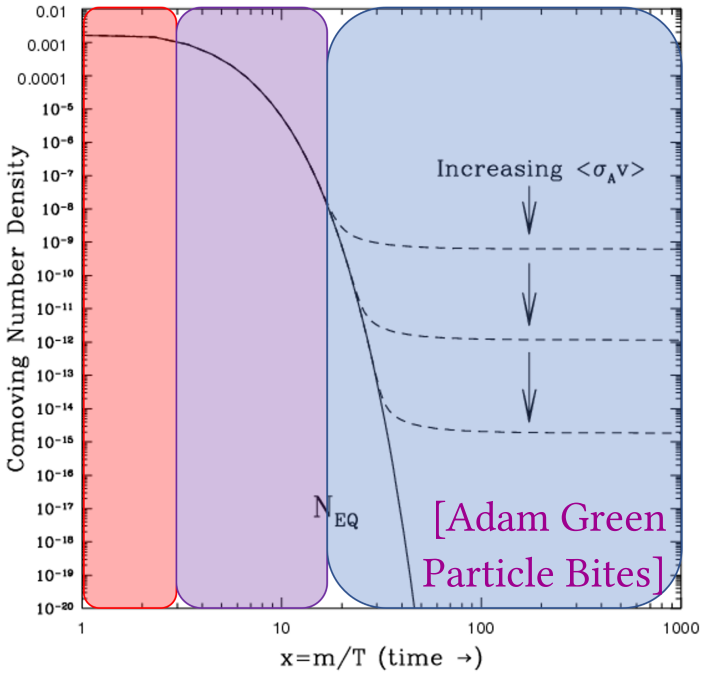
- $\mathrm{BR}(B \to K^* X) \approx 1.9\ \mathrm{BR}(B \to KX)$
- X short-lived: $c\tau_X = 11 \left(\frac{2 \times 10^{-5}}{\varepsilon} \right)^2 \mu m$
- $B \to K^{(*)} \mu\bar{\mu}$ LHCb [1403.8044] constrains ε_Z
  - need large invisible BR: $X \to \psi\psi$



DM relic abundance: freeze-out

DM annihilation channels





- annihilation to $\ell\bar{\ell}$ suppressed

Ferber+ [2305.16169]

see also NA62 [2412.12015]

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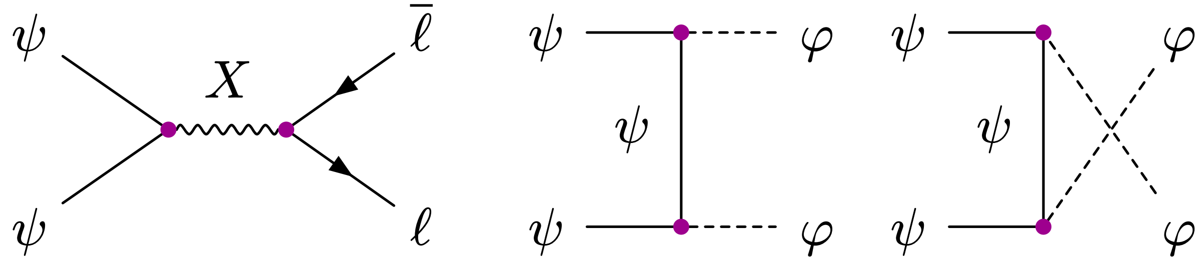
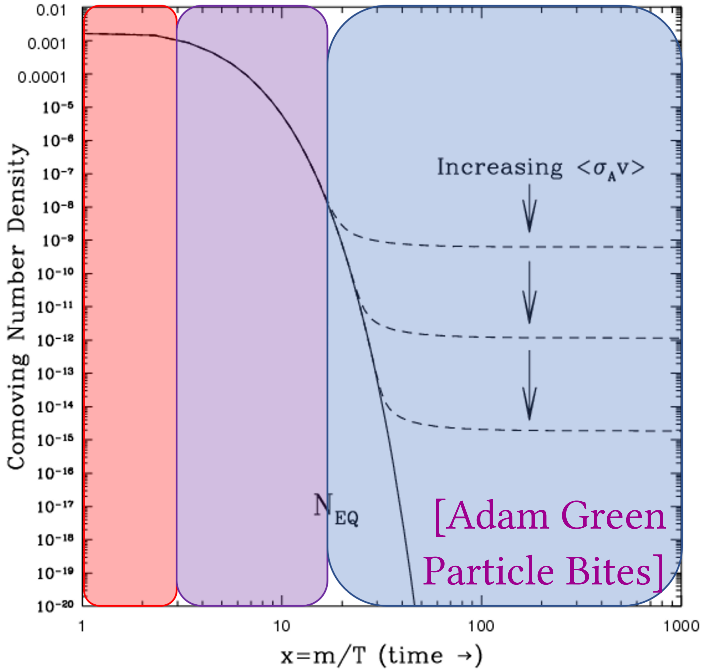
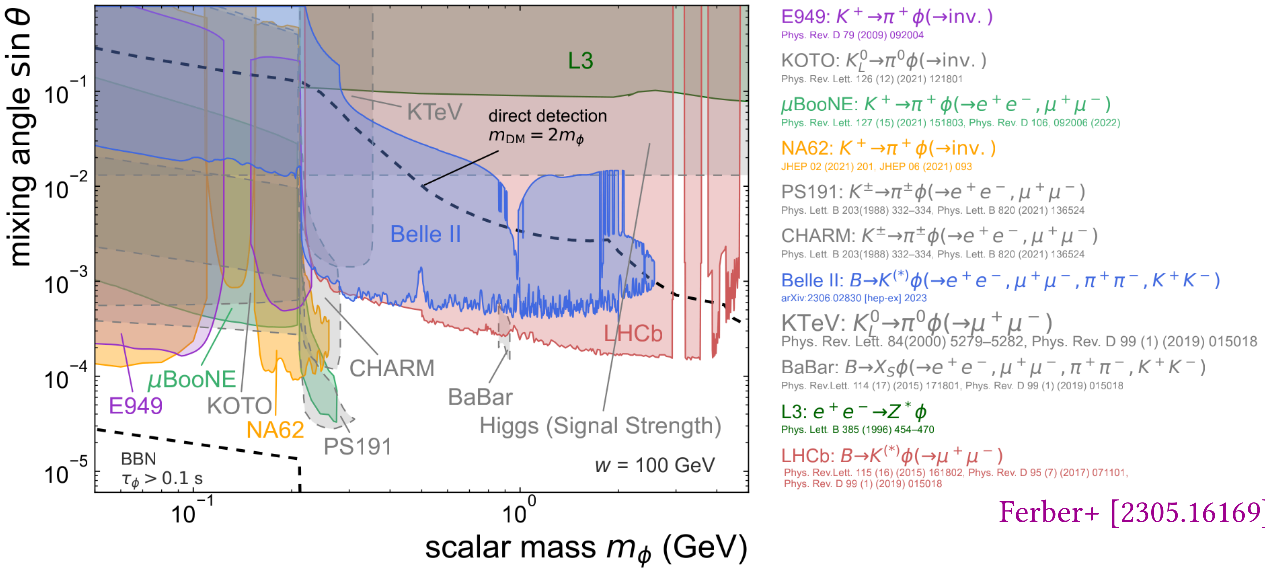


- annihilation to $\ell\bar{\ell}$ suppressed
- BBN: $\tau_\varphi \lesssim 0.1s$
- $K^+ \to \pi^+ + \text{inv} : \sin\theta \lesssim 1.3 \times 10^{-4}$
- light dark Higgs: $m_\varphi \gtrsim 4$ MeV





Ferber+ [2305.16169]

see also NA62 [2412.12015]

Other constraints

dark matter constraints

✓ DM-nucleon scattering

$$\frac{\sigma_N}{\mathrm{cm}^2} \approx 7 \times 10^{-40} \left(\frac{\varepsilon}{8.4 \times 10^{-4}}\right)^2 \frac{\alpha_X}{10^{-3}} \left(\frac{m_{\mathrm{DM}}}{\mathrm{GeV}}\right)^2$$

satisfies current constraint

$$\sigma_N \lesssim 2 \times 10^{-39} \text{ at } m_{\mathrm{DM}} = 1 \text{ GeV}$$

✓ DM-electron scattering

$$\sigma_e \sim 10^{-52} \mathrm{cm}^2$$

✓ DM self-interaction

$$\frac{\sigma_{\mathrm{SI}}}{m_{\mathrm{DM}}} \sim 10^{-15}$$

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constraints on kinetic mixing

dark photon: fixed relationship

$$\varepsilon_Z = 2\varepsilon t_w \left(\frac{m_X^2}{m_Z^2} - \varepsilon t_w\right)$$

$e^+e^- \to \gamma X(\to \text{invisible})$ BaBar [1702.03327]

✗ $\varepsilon < 8.3 \times 10^{-4} \quad \Rightarrow \quad \varepsilon_Z < 4 \times 10^{-8}$

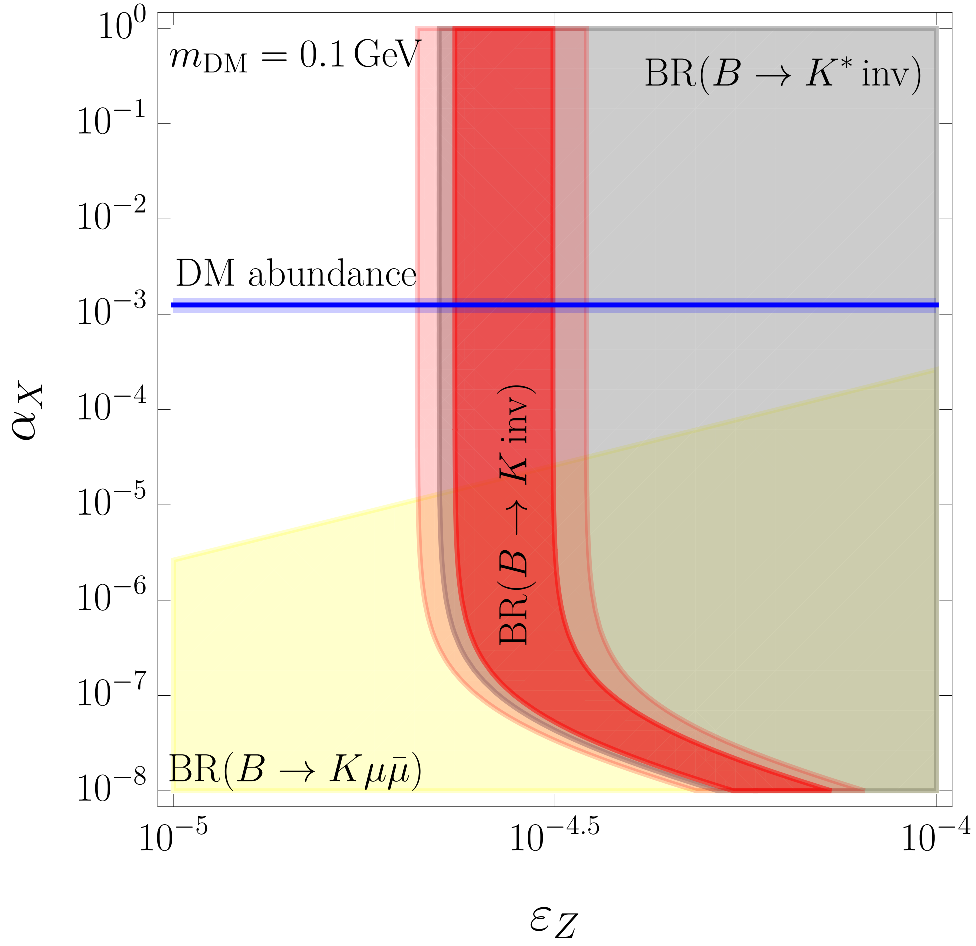
✓ solution:

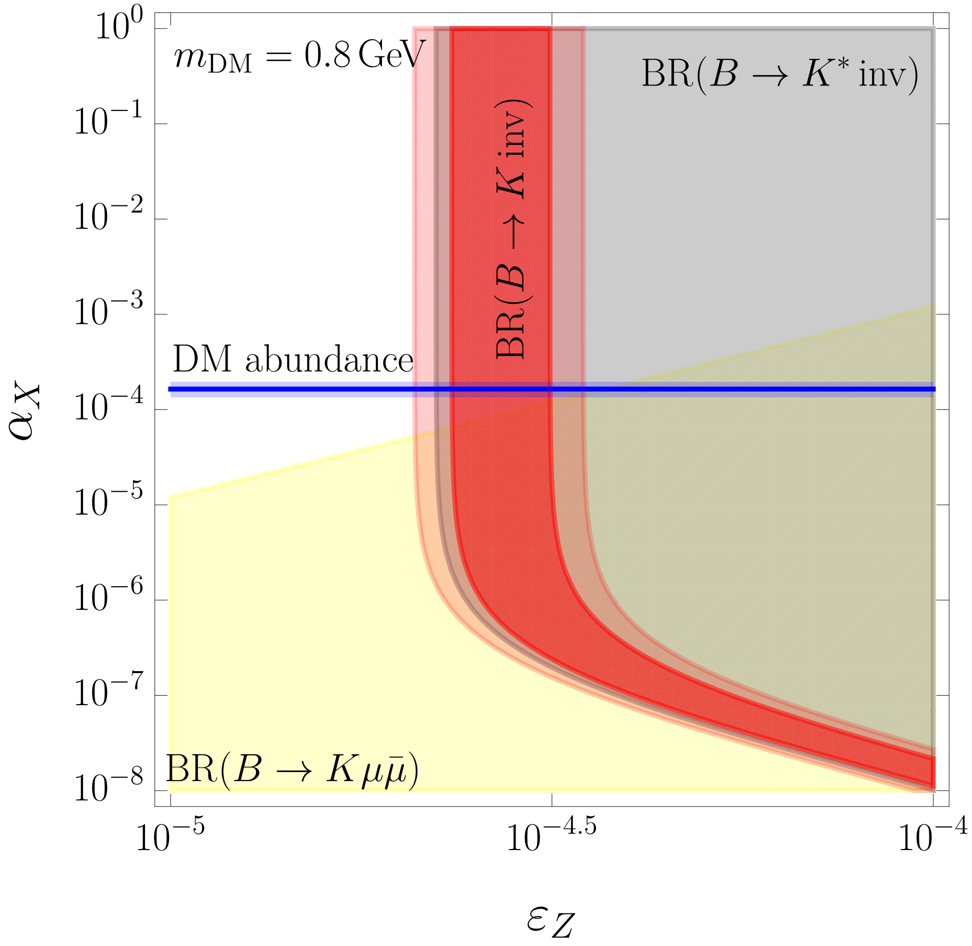
additional Higgs doublet with $U(1)_{\mathrm{dark}}$ charge introduces new $X - Z$ mixing

$$\to \quad \varepsilon_Z = \frac{m_X}{m_Z}\delta \quad \text{with} \quad \delta \sim 10^{-3}$$

Davoudiasl+ [1203.2947]

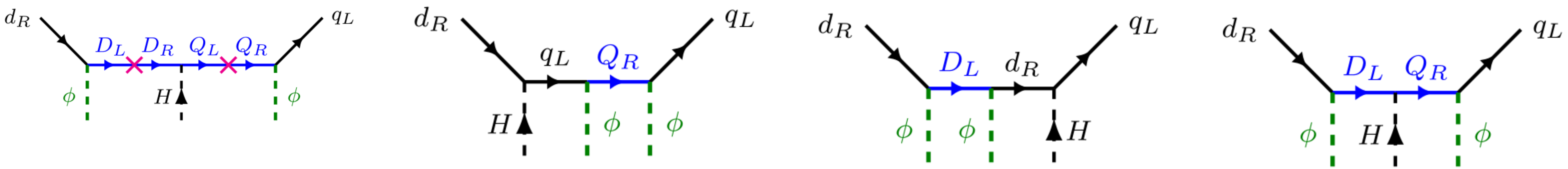
Viable parameter space





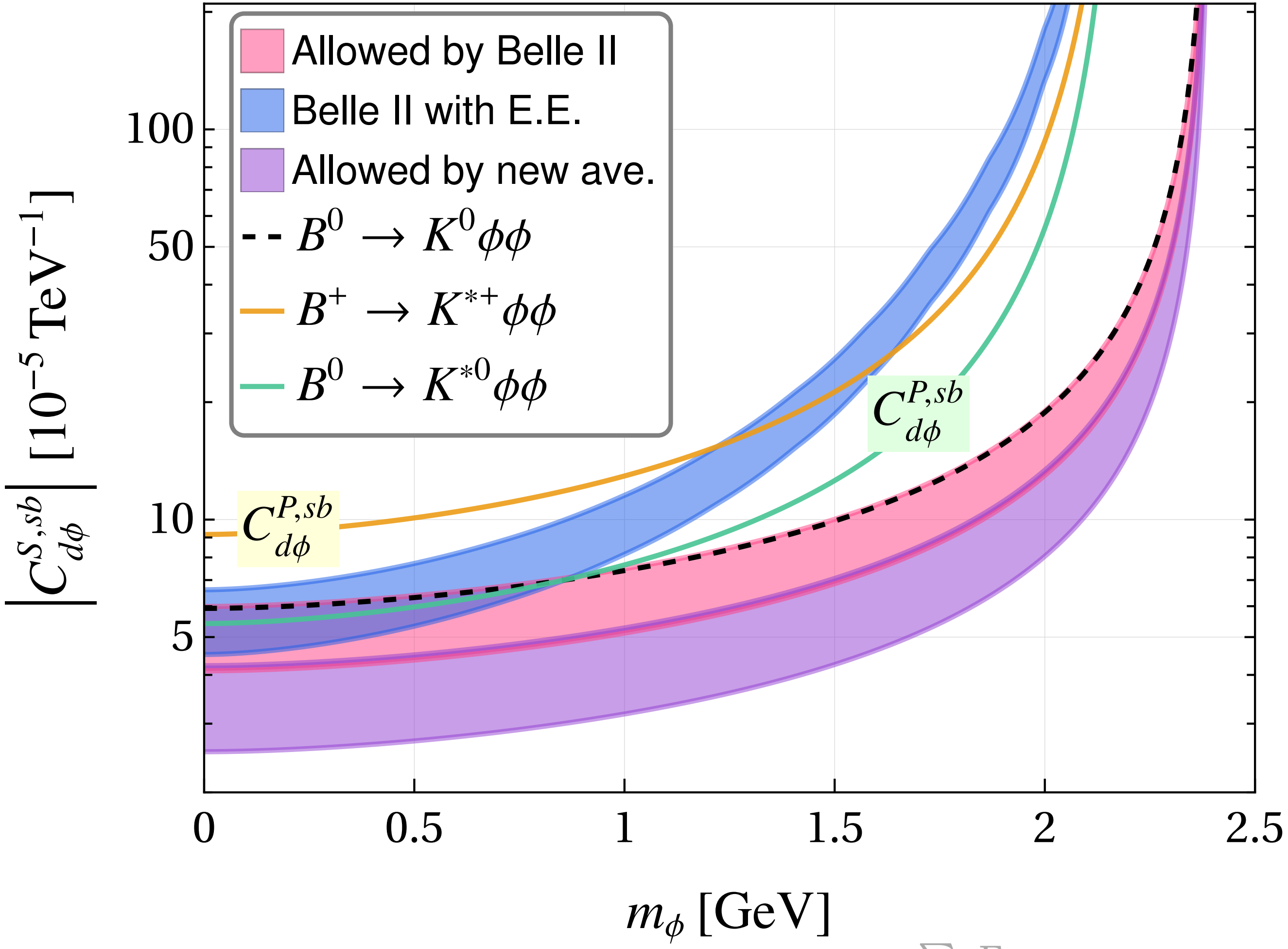
Scalar DM He, Ma, MS, Valencia, Volkas [2403.12485]

- Real scalar $\varphi \sim (\mathbf{1},\mathbf{1},0)_{-}$
- Scalar operator $\mathcal{O}_{q\varphi}^{S,sb} = \frac{1}{2}(\overline{s}b)\varphi^2$ viable explanation for $B^+ \to K^+ \nu\overline{\nu}$ with $\Lambda \sim O(10\ \text{PeV})$ Ma+ [2309.12741]
- UV completion: Introduce vector-like quarks $Q \sim \left(\mathbf{3},\mathbf{2},\frac{1}{6}\right)_{-}$ and $D \sim \left(\mathbf{3},\mathbf{1},-\frac{1}{3}\right)_{-}$



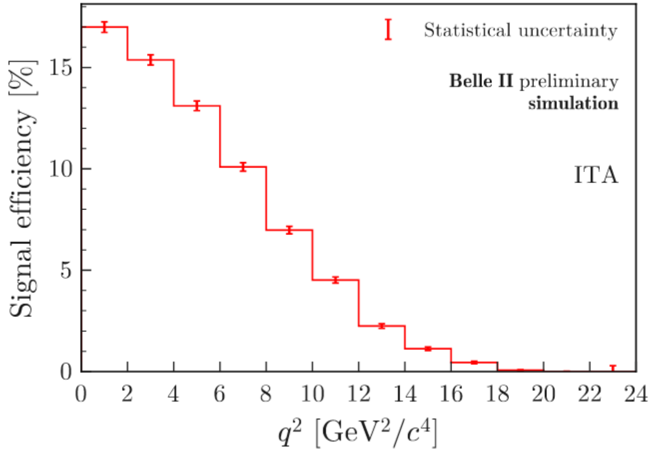
- SMEFT $\mathcal{L} \simeq \frac{y_q y_d y_1}{m_Q m_D}(\overline{q_L} d_R H)\varphi^2$
- LEFT $C_{q\varphi}^{S(P),sb} \simeq \left(y_q^2 y_d^3 y_1 \pm y_q^{3*} y_d^{2*} y_1^*\right)\frac{v\,\mathcal{O}_{q\varphi}^{S(P),sb}}{\sqrt{2} m_Q m_D}$ with $\mathcal{O}_{q\varphi}^{S(P),sb} = \frac{1}{2}(\overline{s}(\gamma_5)b)\varphi^2$
- $C_{q\varphi}^{S,sb}$ and $C_{q\varphi}^{P,sb}$ are independent

Scalar DM He, Ma, MS, Valencia, Volkas [2403.12485]



$$\mathcal{O}^{S(P),sb}_{q\varphi} = \frac{1}{2}(\bar{s}(\gamma_5)b)\varphi^2$$

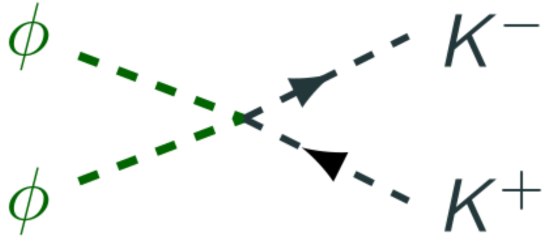
- $C^{S,sb}_{q\varphi}$ and $C^{P,sb}_{q\varphi}$ are independent
- Branching ratios $B \to K\varphi\varphi$ and $B \to K^*\varphi\varphi$ are independent

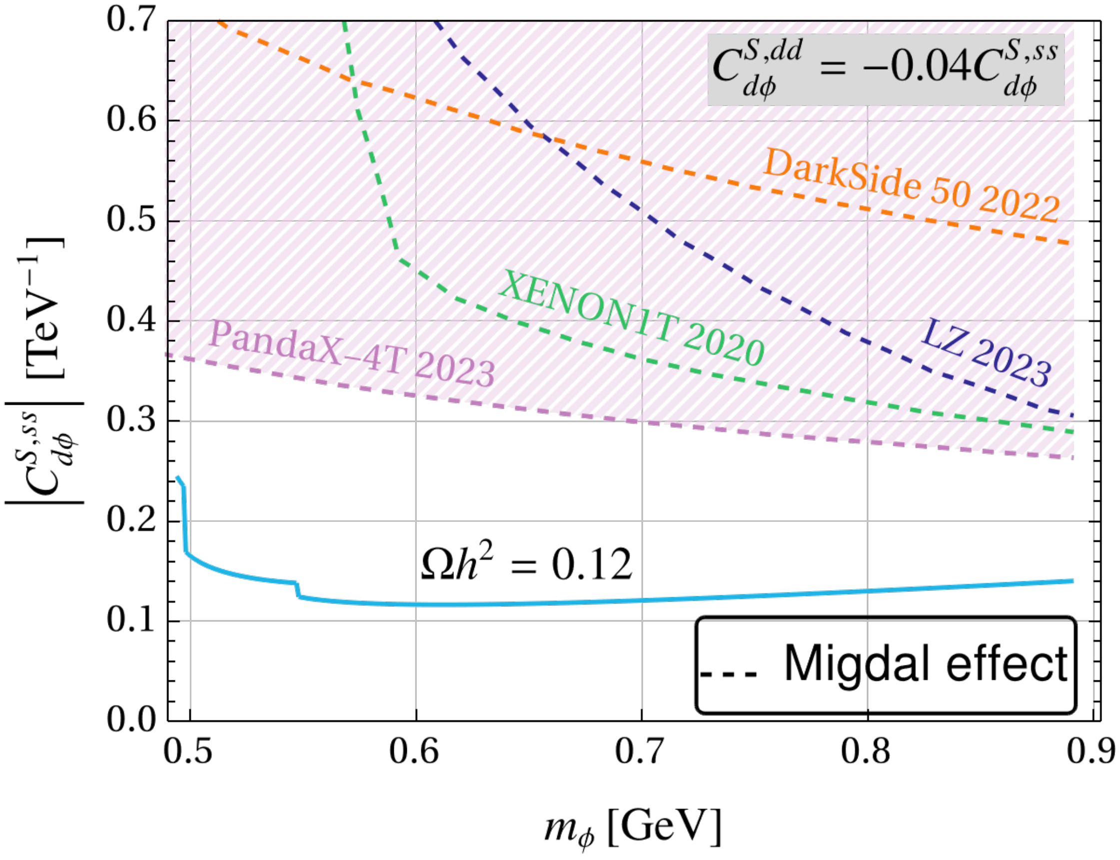


Rescaling w/ signal efficiency ε: $\omega(m) = \frac{\sum_i \Gamma_{i,\mathrm{SM}}\varepsilon_i}{\sum_i \Gamma_{i,\,\mathrm{NP}}(m)\varepsilon_i}$ (blue)

Scalar DM He, Ma, MS, Valencia, Volkas [2403.12485]

- dark matter abundance set by annihilation to light mesons
- preferred DM mass range, 500 MeV $< m_\varphi <$ 900 MeV





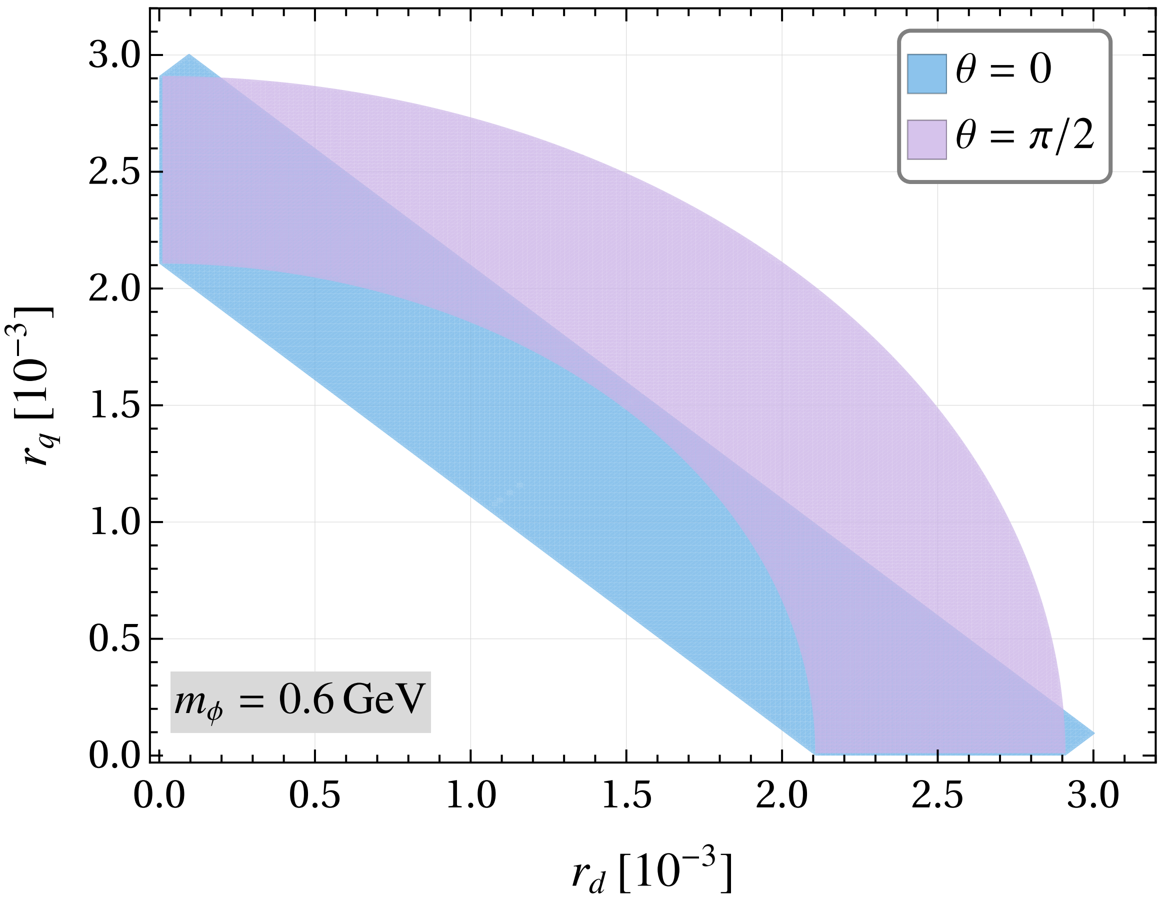
- Migdal effect allows to test DM
- PandaX-4T constrains Wilson coeff's

$$-0.07 \lesssim \frac{C^{S,dd}_{d\varphi}}{C^{S,ss}_{d\varphi}} \lesssim -0.02$$

- Model will be further constrained by next generation DM direct detection experiments.

Scalar DM He, Ma, MS, Valencia, Volkas [2403.12485]

Wilson coefficients parametrized by $|C_{d\varphi}^{S(P),sb}| \approx \frac{1}{2}\,|C_{d\varphi}^{S,ss}|\,\sqrt{r_d^2 + r_q^2 \pm 2 r_d r_q \cos\theta}$



with ratios $r_x \equiv \frac{|y_x^b|}{|y_x^s|}$

DM abundance $\frac{m_{Q,D}}{y} \sim 1.5$ TeV

$B^+ \to K^+ + \text{inv}$: $r_{q,d} \sim \mathcal{O}(10^{-3})$

direct searches

- searches for vector-like quarks don't apply due Z_2
- monojet constraints

Roy, MS, Valencia [2509.14869]