$B \to K +$ invisible as a probe for light physics

Michael Schmidt

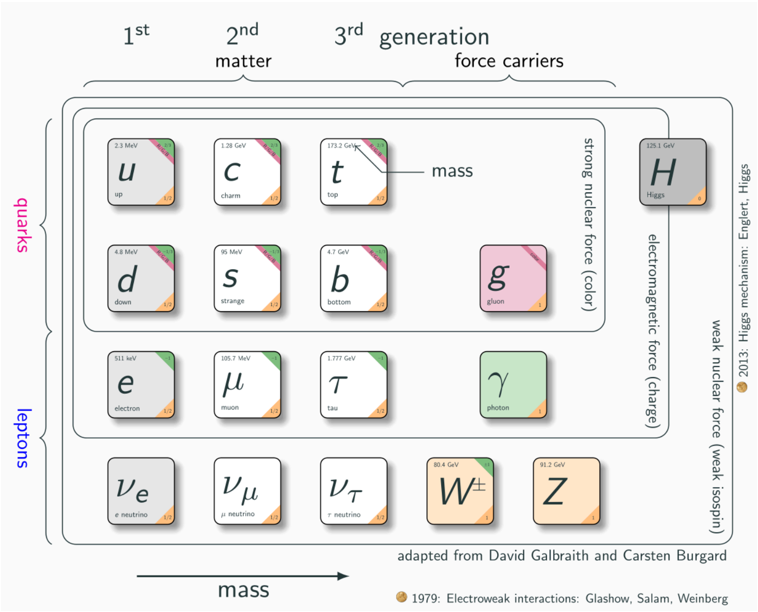
UNSW Sydney

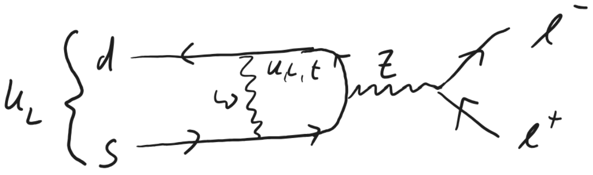
18 October 2024 @ PPC

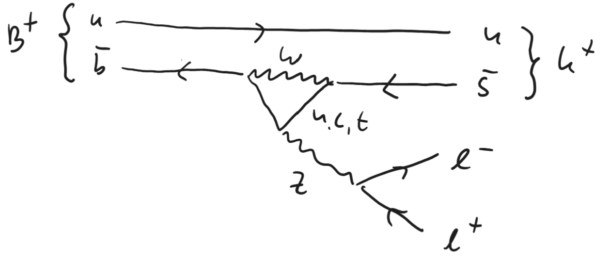
Introduction

Rare meson decays

- There are no tree-level flavour changing neutral currents (FCNC) in the Standard Model (SM)
- FCNC processes only occur at loop level. They are highly suppressed and are **rare processes**.
- Rare processes valuable probe for new physics (NP), because small NP contributions can be significant.
- Meson can be produced abundantly and thus allow for high statistics in searches for rare meson decays.
- (Semi-)leptonic decays provide clean exp. signatures







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- There are no tree-level flavour changing neutral currents (FCNC) in the Standard Model (SM)
- FCNC processes only occur at loop level. They are highly suppressed and are **rare processes**.
- Rare processes valuable probe for new physics (NP), because small NP contributions can be significant.
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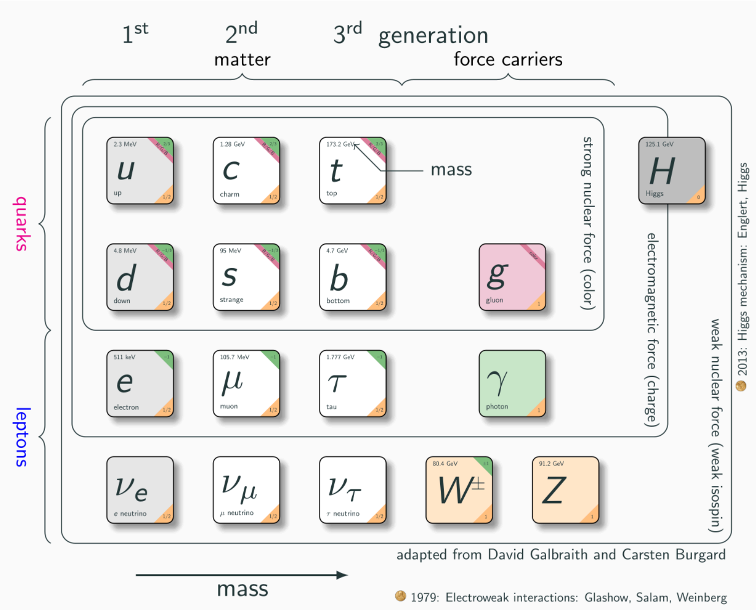
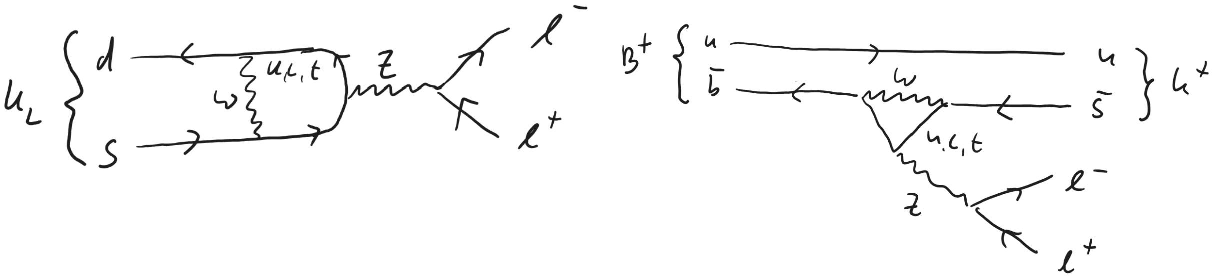
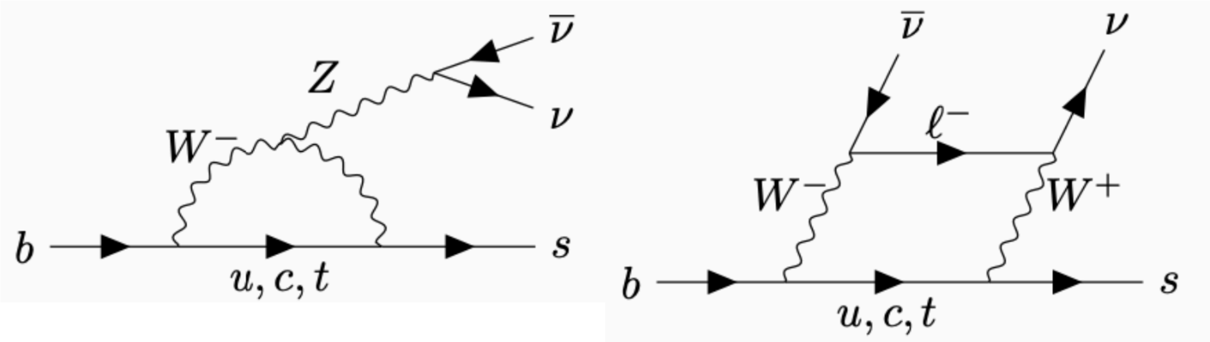




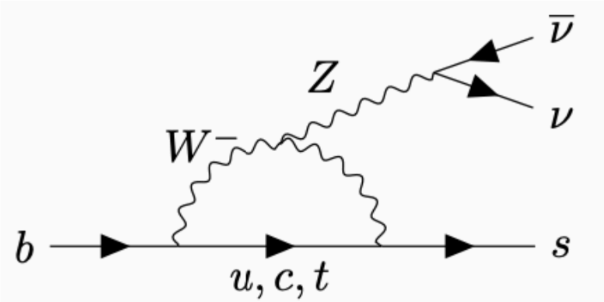
- K and B meson decays can be calculated reliably (compared to D mesons)
- many more B meson decay channels, since B is heavier

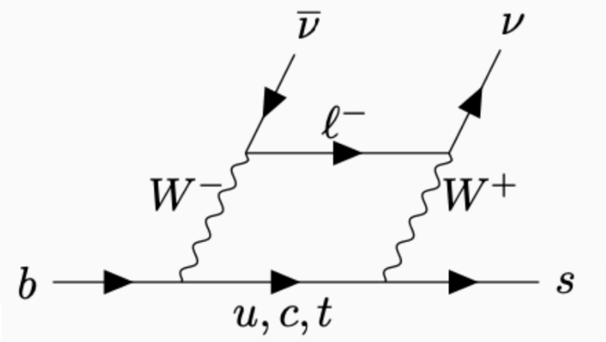
$B \to K + \text{invisible}$

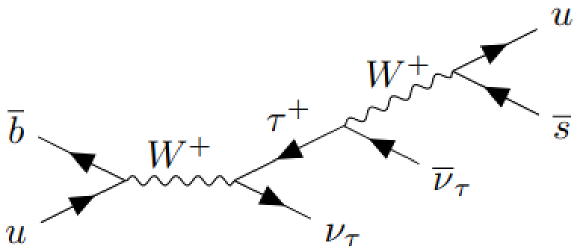


- SM loop, CKM and GIM suppressed: $\mathcal{A} \propto \frac{4G_F}{\sqrt{2}} \frac{\alpha}{4\pi} \sum_i V_{ib} V_{is}^* \frac{m_i^2}{m_W^2}$
- complete factorisation into hadronic and leptonic part
- sensitive to virtual corrections *and* **new light exotic final state**
- Belle II experiment expected to measure $B \to K^{(*)} \nu \overline{\nu}$ with $\mathcal{O}(10\%)$ precision
- Belle II already measured $B^+ \to K^+ + \text{invisible}$

$B \to K + \text{invisible}$







- SM loop, CKM and GIM suppressed: $\mathcal{A} \propto \frac{4G_F}{\sqrt{2}} \frac{\alpha}{4\pi} \sum_i V_{ib} V_{is}^* \frac{m_i^2}{m_W^2}$
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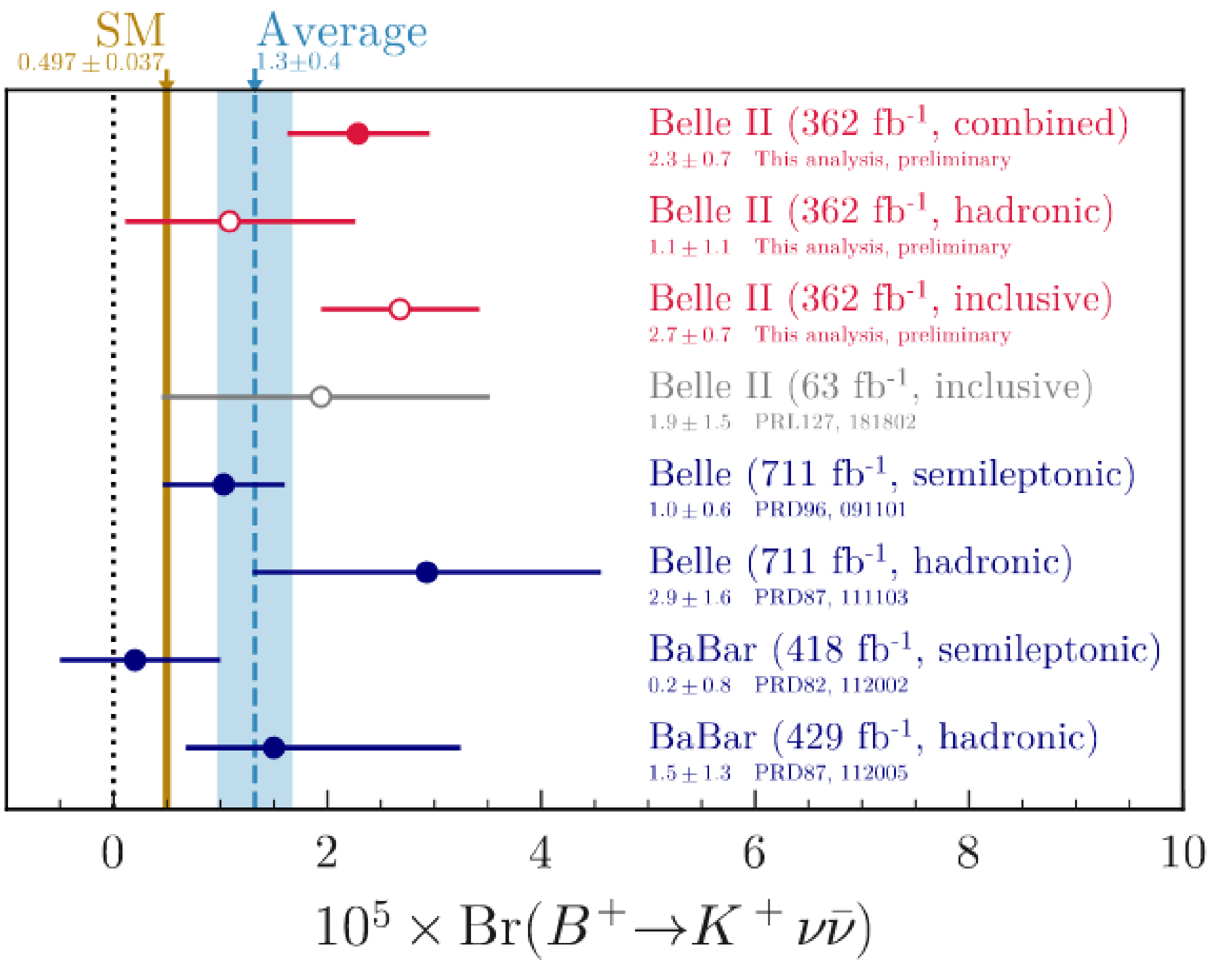
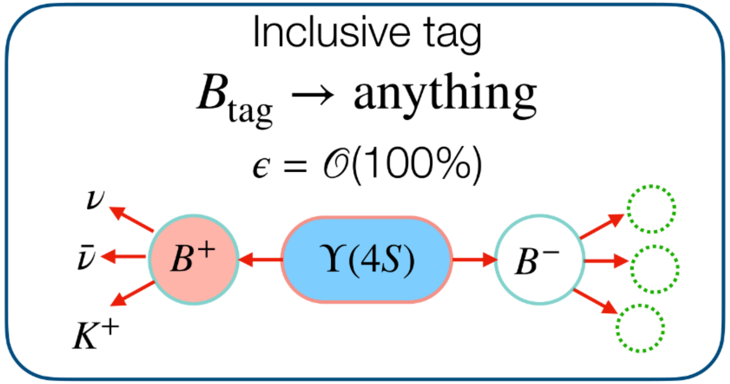
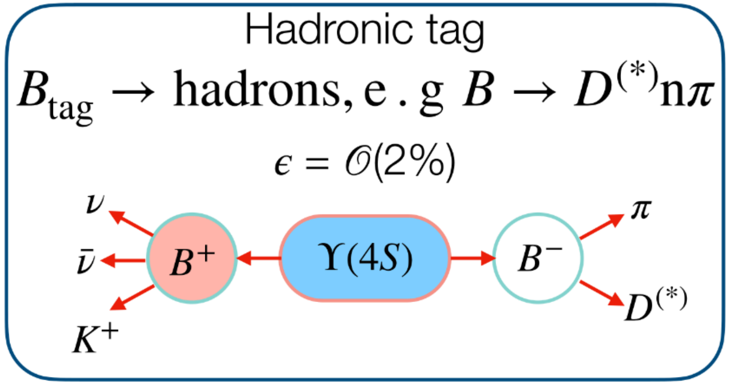
- sensitive to virtual corrections *and* **new light exotic final state**
- Belle II experiment expected to measure $B \to K^{(*)} \nu \overline{\nu}$ with $\mathcal{O}(10\%)$ precision
- Belle II already measured $B^+ \to K^+ + \text{invisible}$
- Tree level contribution to $B^+ \to K^+ \nu \overline{\nu}$ [Kamenik+ 0908.1174] treated as background

Current experimental result [Belle II 2311.14647]



Two $B^+ \to K^+\nu\bar{\nu}$ analyses



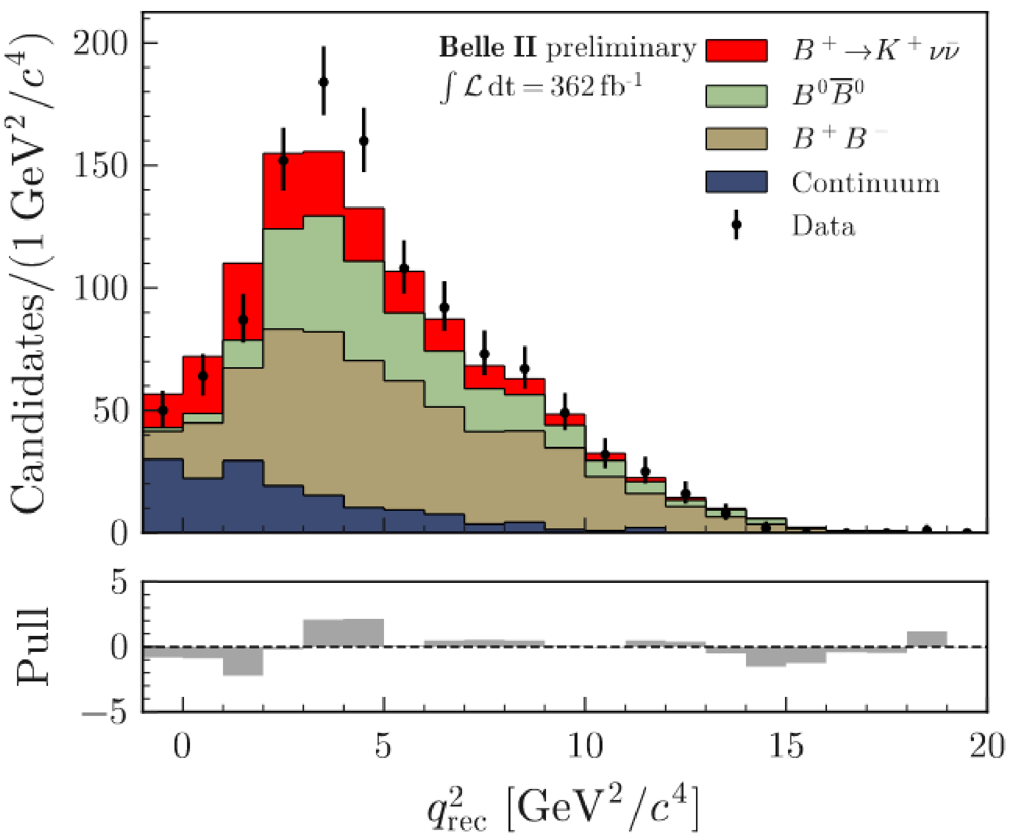


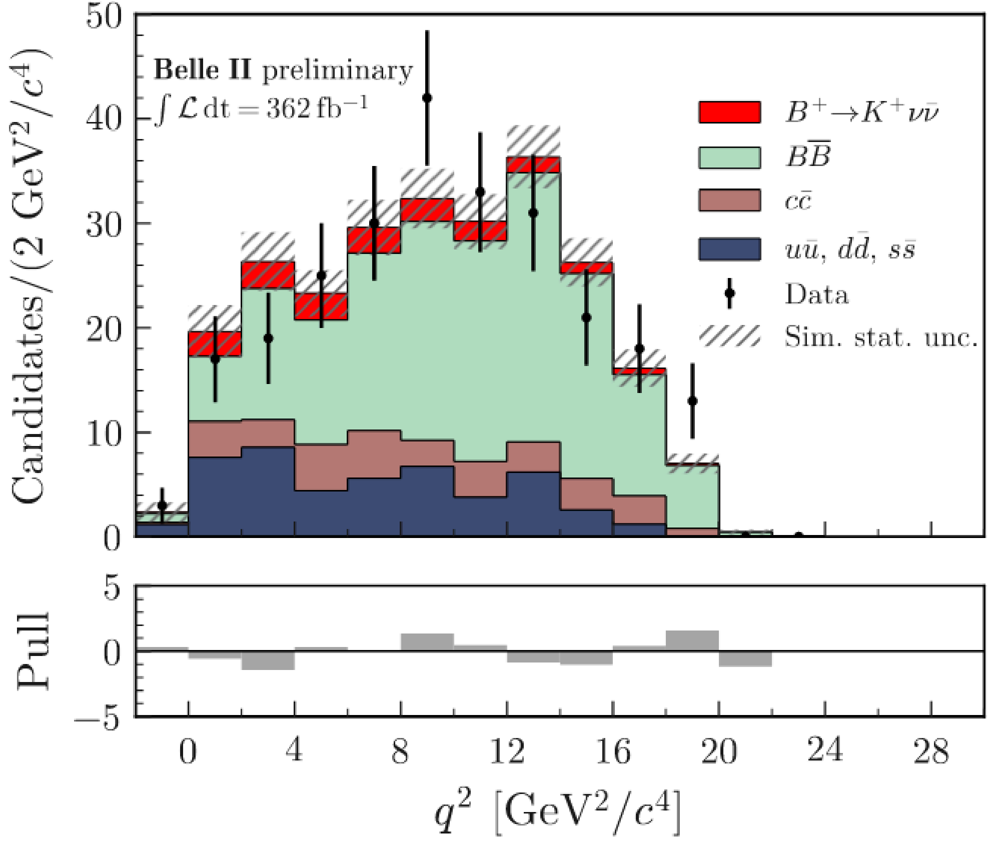
Weighted avg: $\mathcal{B}(B^+ \to K^+\nu\bar{\nu})_{\mathrm{SD}} = (1.3 \pm 0.4) \cdot 10^{-5}$

$\Upsilon(4S) \sim (b\bar{b}), B^+ \sim (u\bar{b}), K^+ \sim (u\bar{s})$

Current experimental result

[Belle II 2311.14647]





[2311.14648]

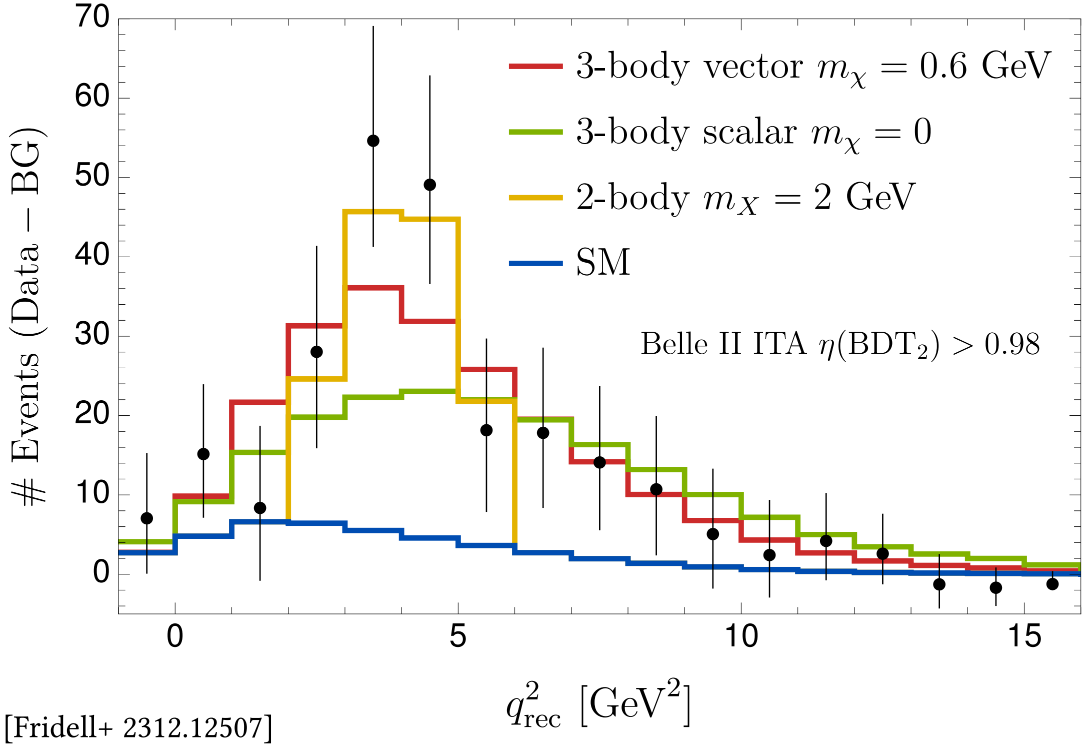
$$q^2_{\text{rec}} = q^2 + (E_B - m_B)^2 - 2\boldsymbol{p_K} \cdot \boldsymbol{p_B}$$

Belle II result

- ITA: excess for $q_{\text{rec}} \sim (3-5)\text{GeV}^2$
- HTA: no significant excess

Fits to data for different new physics

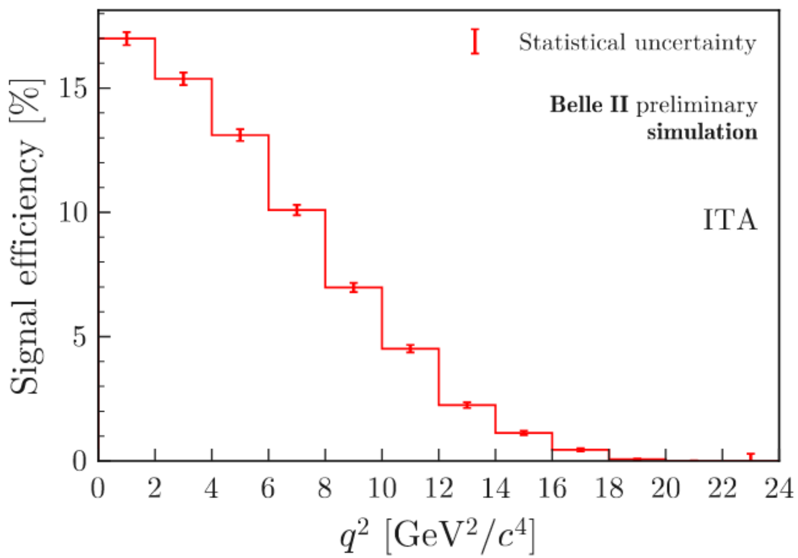
[Fridell+ 2312.12507]



[Fridell+ 2312.12507]

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

See also Altmannshofer+ 2311.14629 for 2-body decay explanation.



Fits of theory predictions to data

$\chi^2_{\mathrm{min}} - 100$	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

Observables

Observable	SM prediction LQCD+LCSR	current constraint	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$Br(B^+ \to K^+ \nu\bar{\nu})$	$(5.06 \pm 0.14 \pm 0.28) \times 10^{-6}$	$(1.3 \pm 0.4) \times 10^{-5}$	0.28(0.19)	0.11 (0.08)
$Br(B^0 \to K_S^0 \nu\bar{\nu})$	$(2.05 \pm 0.07 \pm 0.12) \times 10^{-6}$	$< 2.6 \times 10^{-5}$	1.31(0.87)	0.59(0.40)
$Br(B^+ \to K^{*+} \nu\bar{\nu})$	$(10.86 \pm 1.30 \pm 0.59) \times 10^{-6}$	$< 4.0 \times 10^{-5}$	1.06(0.75)	0.53(0.38)
$Br(B^0 \to K^{*0} \nu\bar{\nu})$	$(9.05 \pm 1.25 \pm 0.55) \times 10^{-6}$	$< 1.8 \times 10^{-5}$	0.60(0.40)	0.34(0.23)
$F_L(B^0 \to K^{*0} \nu\bar{\nu})$	0.49 ± 0.04			0.079
$F_L(B^+ \to K^{*+} \nu\bar{\nu})$	0.49 ± 0.04			0.077
$Br(B_s \to \text{inv})$		$< 5.9 \times 10^{-4}$	1.1×10^{-5}	
$Br(B \to X_s \nu\bar{\nu})$	$(2.7 \pm 0.2) \times 10^{-5}$	$< 6.4 \times 10^{-4}$	planned	

SM prediction: $B \to K^{(*)}\nu\bar{\nu}$ [Becirevic+ 2301.06990]; F_L [flavio 1810.08132]; $B \to X_s\nu\bar{\nu}$ [Altmannshofer+ 0902.0160] **constraints:** $B \to K^{(*)0}\nu\bar{\nu}$ [Belle 1702.03224]; $B^+ \to K^+\nu\bar{\nu}$ [Belle II 2311.14647]; $B^+ \to K^{*+}\nu\bar{\nu}$ [Belle 1303.3719]; $B \to X_s\nu\bar{\nu}$ [ALEPH hep-ex/0010022]; $B_s \to \text{inv}$ [Alonso-Alvarez+ 2310.13043] **projections:** [2207.06307, 1808.10567, private communication] F_L is longitudinal polarisation fraction of K^*

Light physics

Recent work on light physics explanations

Eur. Phys. J. C (2023) 83:1135
https://doi.org/10.1140/epjc/s10052-023-12326-9
THE EUROPEAN PHYSICAL JOURNAL C
Regular Article - Theoretical Physics

When energy goes missing: new physics in $b \to s\nu\nu$ with sterile neutrinos

Tobias Felkl[1], Anjan Giri[2], Rukmani Mohanta[3], Michael A. Schmidt[1,a]
[1] Sydney Consortium for Particle Physics and Cosmology, School of Physics, The University of New South Wales, Sydney, NSW 2052, Australia
[2] Department of Physics, IIT Hyderabad, Kandi 502285, India
[3] School of Physics, University of Hyderabad, Hyderabad 500046, India

The Decay $B \to K\nu\bar{\nu}$ at Belle II and a Massless Bino in R-parity-violating Supersymmetry

Herbert K. Dreiner,[1,*] Julian Y. Günther,[1,†] and Zeren Simon Wang[2,3,‡]

PHYSICAL REVIEW D 109, 075019 (2024)

Revisiting models that enhance $B^+ \to K^+\nu\bar{\nu}$ in light of the new Belle II measurement

Xiao-Gang He,[1,2,*] Xiao-Dong Ma,[3,4,†] and German Valencia[5,‡]

JHEP
PUBLISHED FOR SISSA BY SPRINGER
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PUBLISHED: July 18, 2024

Scalar dark matter explanation of the excess in the Belle II $B^+ \to K^+ +$ invisible measurement

Xiao-Gang He,[a] Xiao-Dong Ma,[b,c] Michael A. Schmidt,[d] German Valencia[e] and Raymond R. Volkas[f]

EPL, 145 (2024) 14001
doi: 10.1209/0295-5075/ad1d03
www.epljournal.org

$B \to K^*M_X$ vs. $B \to KM_X$ as a probe of a scalar mediator dark-matter scenario

ALEXANDER BEREZHNOY[1] and DMITRI MELIKHOV[1,2,3(a)]
[1] D. V. Skobeltsyn Institute of Nuclear Physics, M. V. Lomonosov Moscow State University 119991, Moscow, Russia
[2] Joint Institute for Nuclear Research - 141980 Dubna, Russia
[3] Faculty of Physics, University of Vienna - Boltzmanngasse 5, A-1090 Vienna, Austria

PHYSICAL REVIEW D 109, 075006 (2024)

Higgs portal interpretation of the Belle II $B^+ \to K^+\nu\nu$ measurement

David McKeen,[1,*] John N. Ng,[1,†] and Douglas Tuckler[1,2,‡]
[1] TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia V6T 2A3, Canada
[2] Department of Physics, Simon Fraser University, Burnaby, British Columbia V5A 1S6, Canada

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Recent $B^+ \to K^+\nu\bar{\nu}$ Excess and Muon $g-2$ Illuminating Light Dark Sector with Higgs Portal

Shu-Yu Ho,[*] Jongkuk Kim,[†] and Pyungwon Ko[‡]
Korea Institute for Advanced Study, Seoul 02455, Republic of Korea

High theory activity on light physics following recent Belle II measurement.

PHYSICAL REVIEW D 109, 075008 (2024)

Light new physics in $B \to K^{(*)}\nu\bar{\nu}$?

Wolfgang Altmannshofer[*]
Santa Cruz Institute for Particle Physics and Department of Physics, University of California, Santa Cruz, California 95064, USA
Andreas Crivellin[†]
Physik-Institut, Universität Zürich, Winterthurerstrasse 190, CH–8057 Zürich, Switzerland and Paul Scherrer Institut, CH–5232 Villigen PSI, Switzerland
Huw Haigh[‡] and Gianluca Inguglia[§]
Institute of High Energy Physics, 1050 Vienna, Austria
Jorge Martin Camalich[‖]
Instituto de Astrofísica de Canarias, C/ Vía Láctea, s/n E38205 - La Laguna, Tenerife, Spain and Universidad de La Laguna, Departamento de Astrofísica, La Laguna, Tenerife, Spain

PHYSICAL REVIEW D 109, 115006 (2024)

Decoding the $B \to K\nu\nu$ excess at Belle II: Kinematics, operators, and masses

Kåre Fridell,[1,2,*] Mitrajyoti Ghosh,[2,†] Takemichi Okui,[2,1,‡] and Kohsaku Tobioka[2,1,§]
[1] KEK Theory Center, Tsukuba, Ibaraki 305–0801, Japan
[2] Department of Physics, Florida State University, Tallahassee, Florida 32306-4350, USA

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PHYSICAL REVIEW D 110, 055001 (2024)

Signatures of light new particles in $B \to K^{(*)}E_{miss}$

Patrick D. Bolton[*]
Jožef Stefan Institute, Jamova 39, 1000 Ljubljana, Slovenia
Svjetlana Fajfer[†] and Jernej F. Kamenik[‡]
Jožef Stefan Institute, Jamova 39, 1000 Ljubljana, Slovenia and Faculty of Mathematics and Physics, University of Ljubljana, Jadranska 19, 1000 Ljubljana, Slovenia
Martín Novoa-Brunet[§]
Instituto de Física Corpuscular, Universitat de Valéncia—Consejo Superior de Investigaciones Científicas, Parc Científic, E-46980 Paterna, Valencia, Spain and Istituto Nazionale di Fisica Nucleare, Sezione di Bari, Via Orabona 4, 70126 Bari, Italy

Earlier work on light new physics

13 March 1997
PHYSICS LETTERS B
ELSEVIER
Physics Letters B 395 (1997) 339–344

Rare $B \to K^{(*)}\nu\bar{\nu}$ decays at B factories

P. Colangelo [a], F. De Fazio [a,b], P. Santorelli [c], E. Scrimieri [a,b]
[a] Istituto Nazionale di Fisica Nucleare, Sezione di Bari, Italy
[b] Dipartimento di Fisica, Università di Bari, Italy
[c] Istituto Nazionale di Fisica Nucleare, Sezione di Napoli, Italy

Received 31 October 1996; revised manuscript received 24 January 1997
Editor: R. Gatto

PHYSICAL REVIEW D, VOLUME 60, 094007

New physics effects in $B \to K^{(*)}\nu\nu$ decays

C. S. Kim* and Yeong Gyun Kim†
Department of Physics, Yonsei University, Seoul 120-749, Korea
T. Morozumi‡
Department of Physics, Hiroshima University, 739-8526 Higashi-Hiroshima, Japan

(Received 27 May 1999; published 1 October 1999)

This is a small selection of papers.

Let me know if I forgot to include your paper.

3 May 2001
PHYSICS LETTERS B
ELSEVIER
Physics Letters B 506 (2001) 77–84
www.elsevier.nl/locate/npe

Rare $B \to K^*\nu\bar{\nu}$ decay beyond standard model

T.M. Aliev, A. Özpineci, M. Savcı
Physics Department, Middle East Technical University, 06531 Ankara, Turkey

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A tale of invisibility: constraints on new physics in $b \to s\nu\nu$

Tobias Felkl, Sze Lok Li and Michael A. Schmidt
Sydney Consortium for Particle Physics and Cosmology,
School of Physics, The University of New South Wales,
Sydney, NSW 2052, Australia
E-mail: t.felkl@unsw.edu.au, szel10305@gmail.com,
m.schmidt@unsw.edu.au

Eur. Phys. J. C (2023) 83:791
https://doi.org/10.1140/epjc/s10052-023-11975-0
The European Physical Journal C
Regular Article - Theoretical Physics

Complementarity of $B \to K^{(*)}\mu\bar{\mu}$ and $B \to K^{(*)} + \text{inv}$ for searches of GeV-scale Higgs-like scalars

Maksym Ovchynnikov[1], Michael A. Schmidt[2,a], Thomas Schwetz[1]
[1] Institut für Astroteilchen Physik, Karlsruher Institut für Technologie (KIT), Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany
[2] Sydney Consortium for Particle Physics and Cosmology, School of Physics, The University of New South Wales, Sydney, NSW 2052, Australia

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Dark Matter Particle Production in $b \to s$ Transitions with Missing Energy

Chris Bird,[1] Paul Jackson,[1] Robert Kowalewski,[1] and Maxim Pospelov[1,2]
[1] Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, V8P 1A1, Canada
[2] Centre for Theoretical Physics, University of Sussex, Brighton BN1 9QJ, United Kingdom

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Published: April 6, 2009

New strategies for new physics search in $B \to K^*\nu\bar{\nu}$, $B \to K\nu\bar{\nu}$ and $B \to X_s\nu\bar{\nu}$ decays

Wolfgang Altmannshofer,[a] Andrzej J. Buras,[a,b] David M. Straub[a] and Michael Wick[a]
[a] Physik-Department, Technische Universität München,
James-Franck-Str., 85748 Garching, Germany
[b] TUM Institute for Advanced Study, Technische Universität München,
Arcisstr. 21, 80333 München, Germany
E-mail: wolfgang.altmannshofer@ph.tum.de, andrzej.buras@ph.tum.de,
david.straub@ph.tum.de, michael.wick@ph.tum.de

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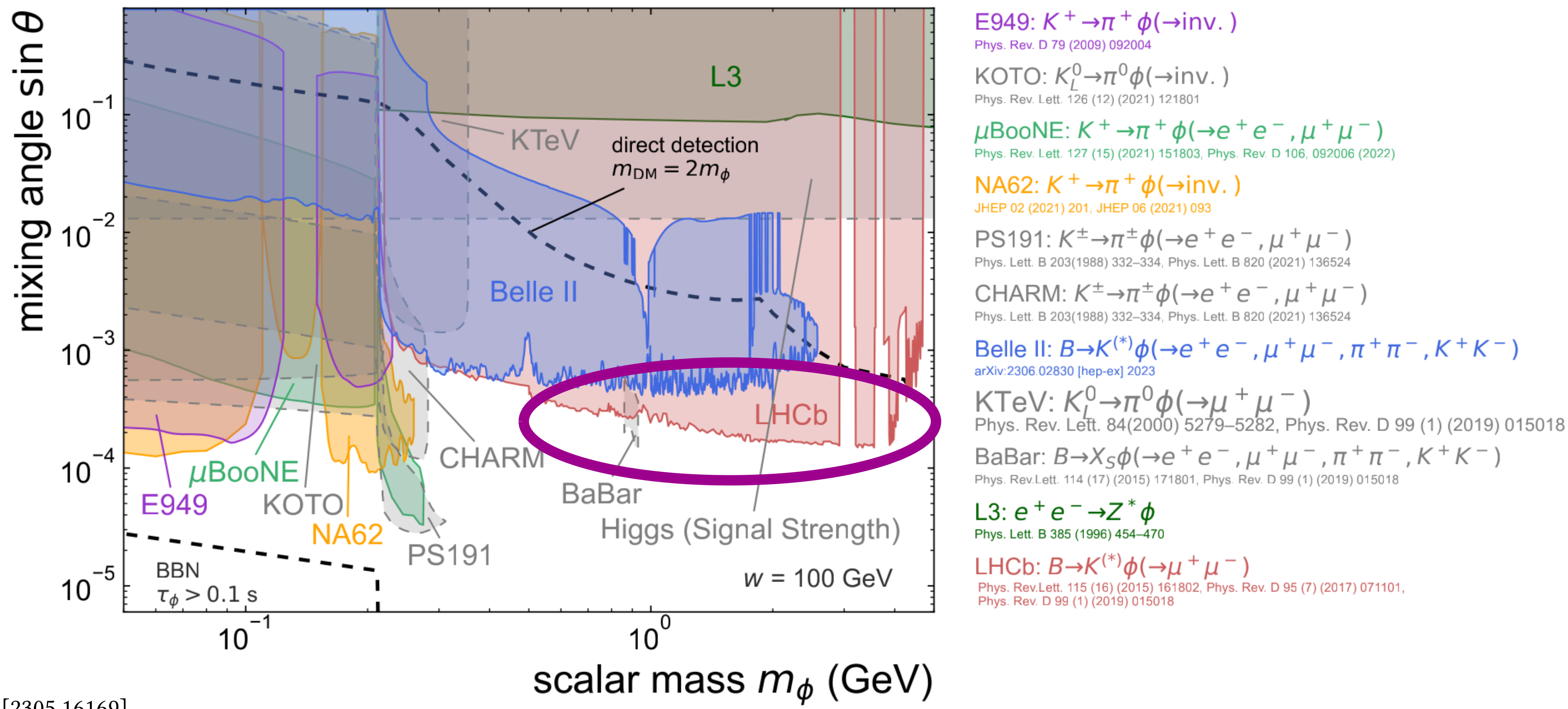
FCNC B and K meson decays with light bosonic Dark Matter

Xiao-Gang He,[a,b] Xiao-Dong Ma[a] and German Valencia[c]

Light scalar φ

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

Light GeV-scale Higgs-like scalar

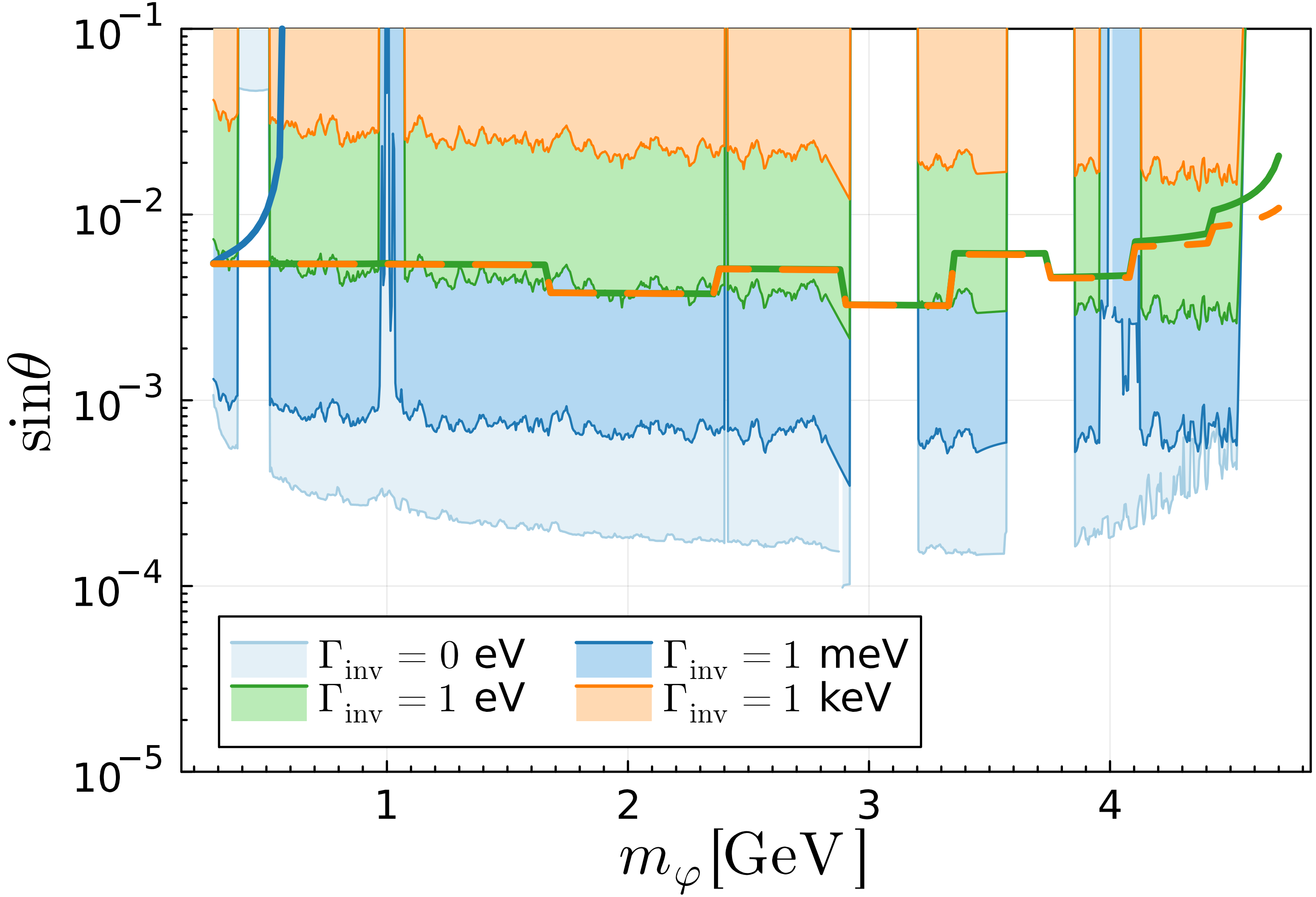


[2305.16169]

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

Light GeV-scale scalar

[Ovchynnikov, MS, Schwetz 2306.09508]



In presence of additional invisible decay width $\Gamma_{\rm inv}$, LHCb constraint is weakened

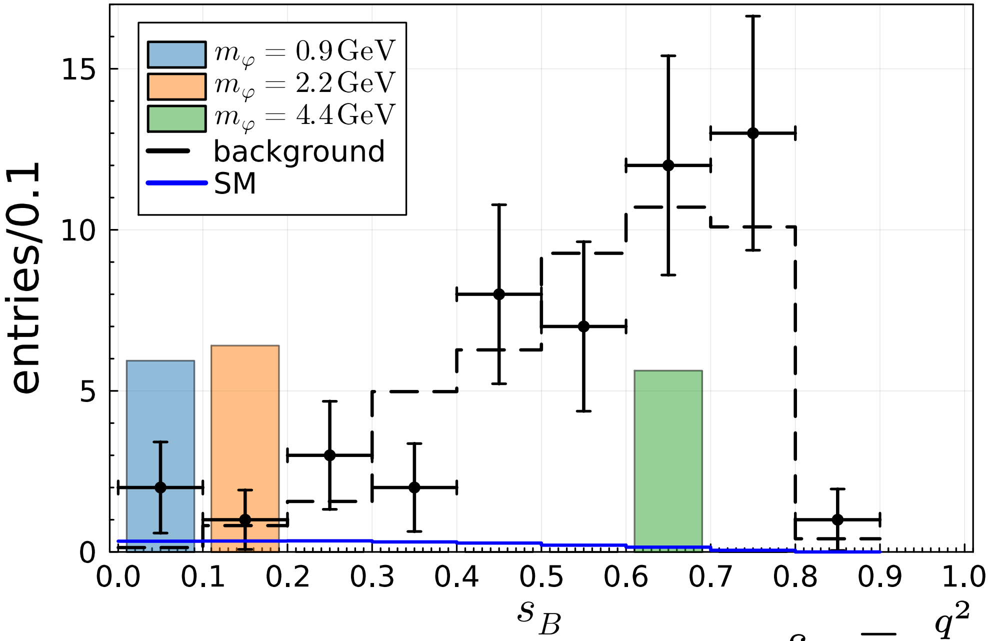
$B \to K +$ invisible provides a complementary probe which constrains this scenario.

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

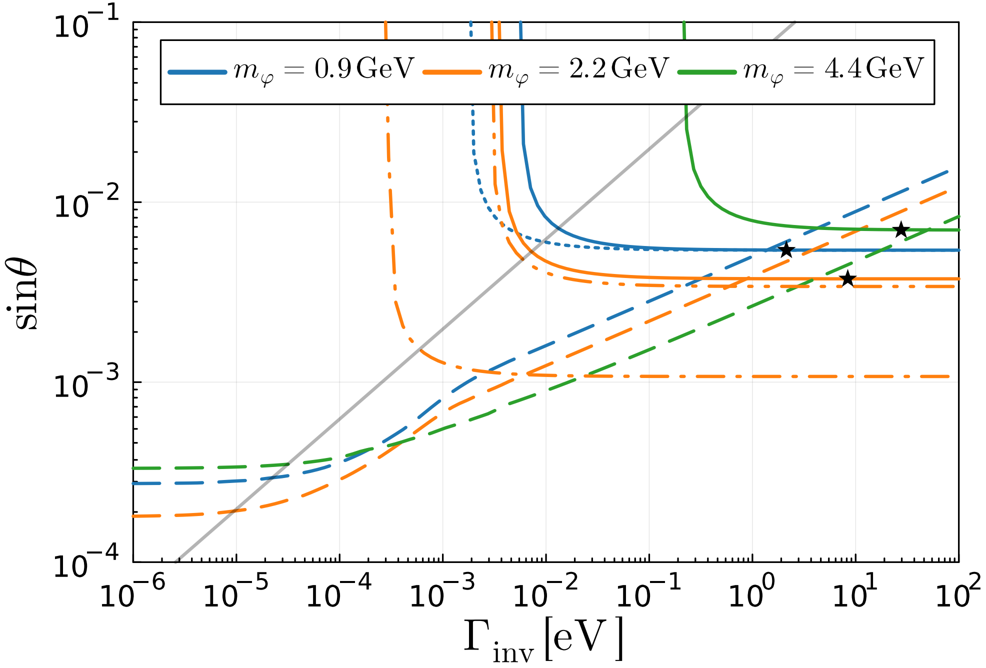
Light GeV-scale scalar

[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

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

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

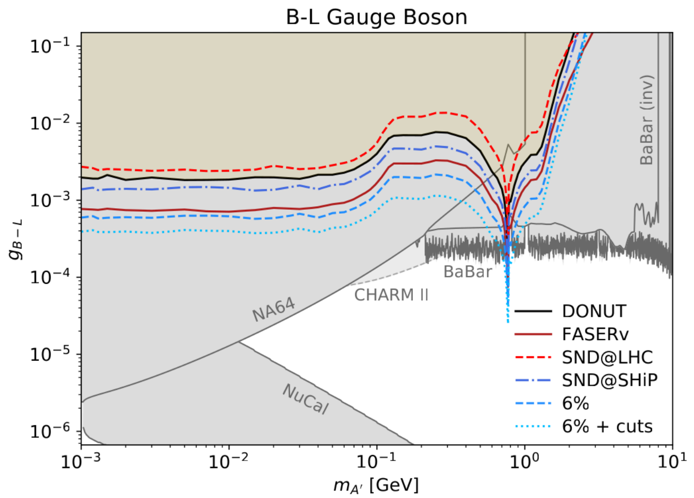
Invisible decays to heavy neutral leptons

real scalar coupled to sterile neutrinos

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

Invisible Higgs decay constrains

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



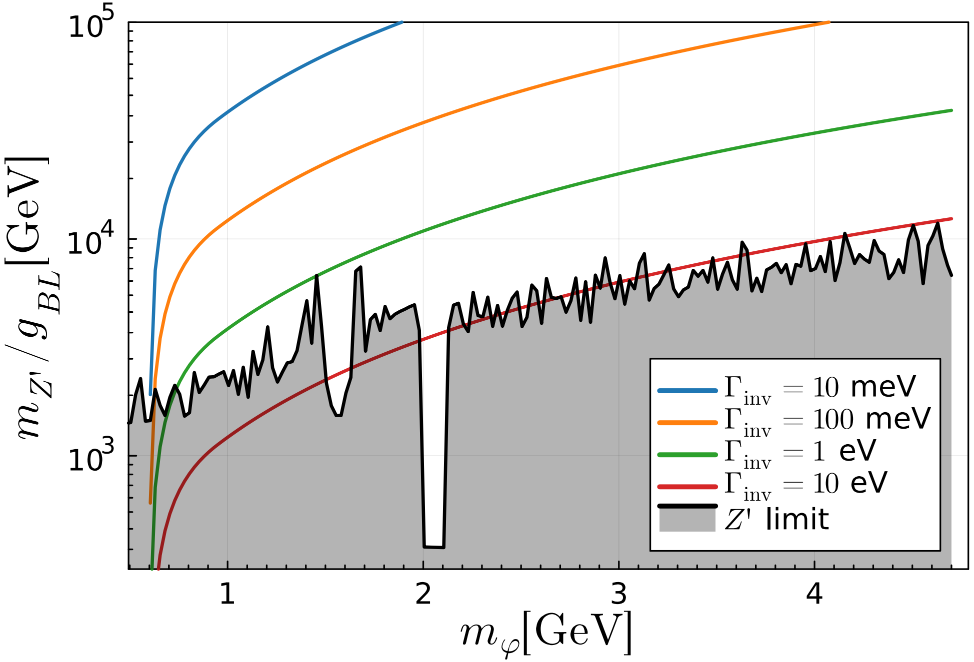
[2005.03594]

$\Longrightarrow$

$B - L$ 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, $g_{\rm BL}$



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

Light sterile neutrinos N

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

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

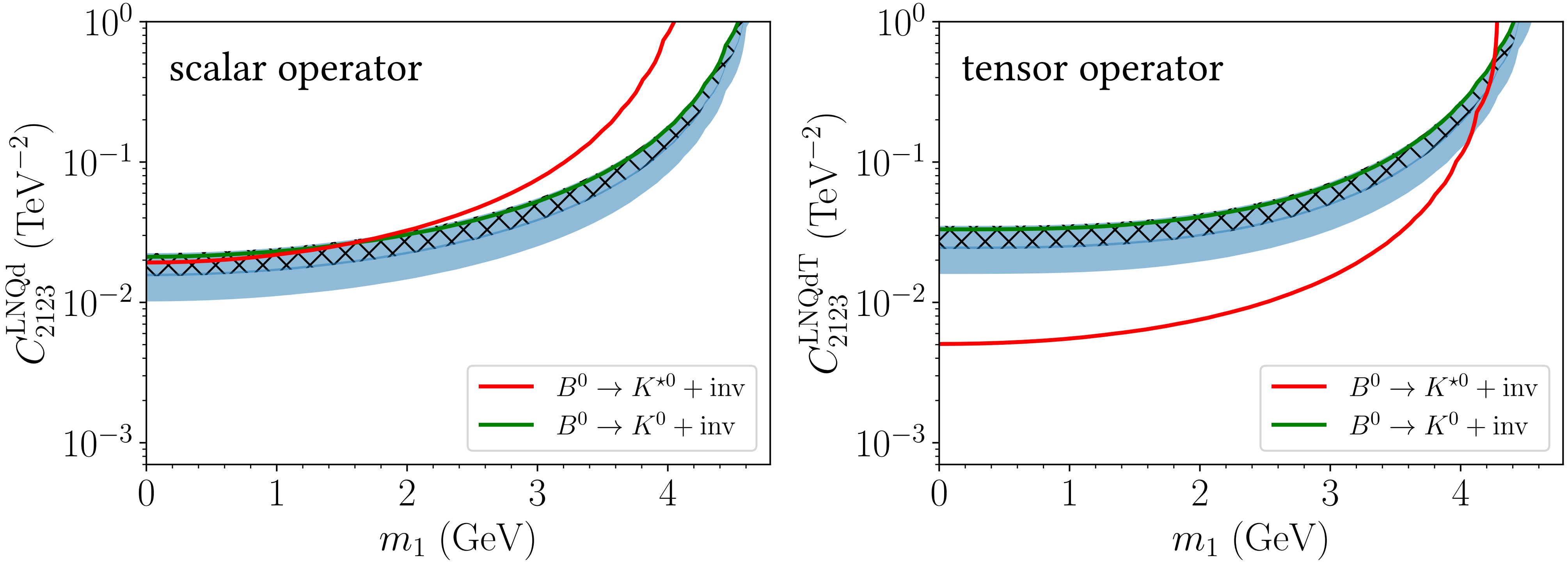
Light sterile neutrinos

[Felkl,Giri,Mohanta,MS 2309.02940]

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

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 $B \to K^* + \mathrm{inv}$

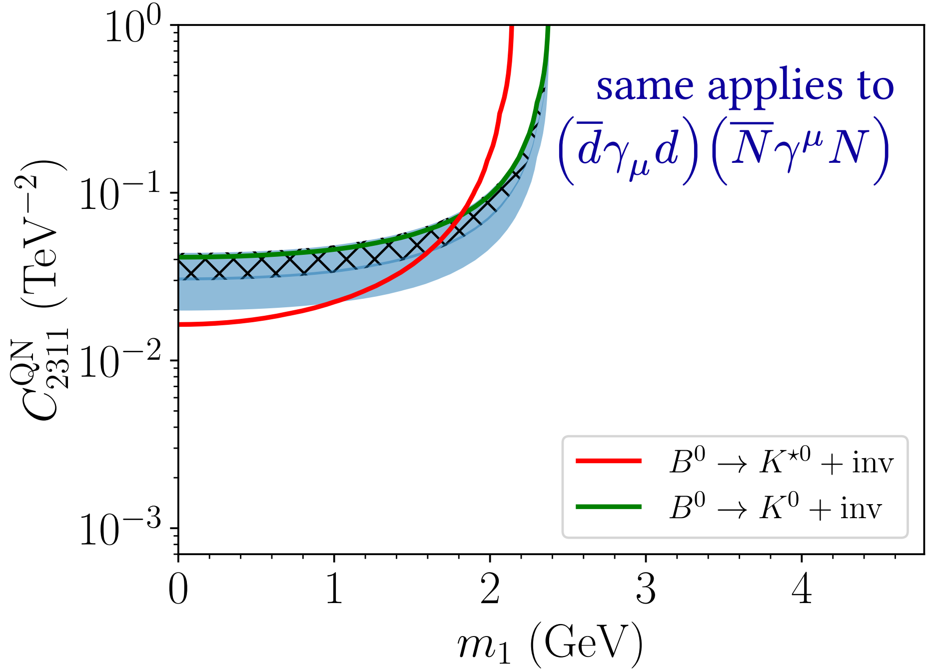


blue region preferred by weighted avg (hatched by Belle II), experimental constraints - dashed, theory prediction - solid

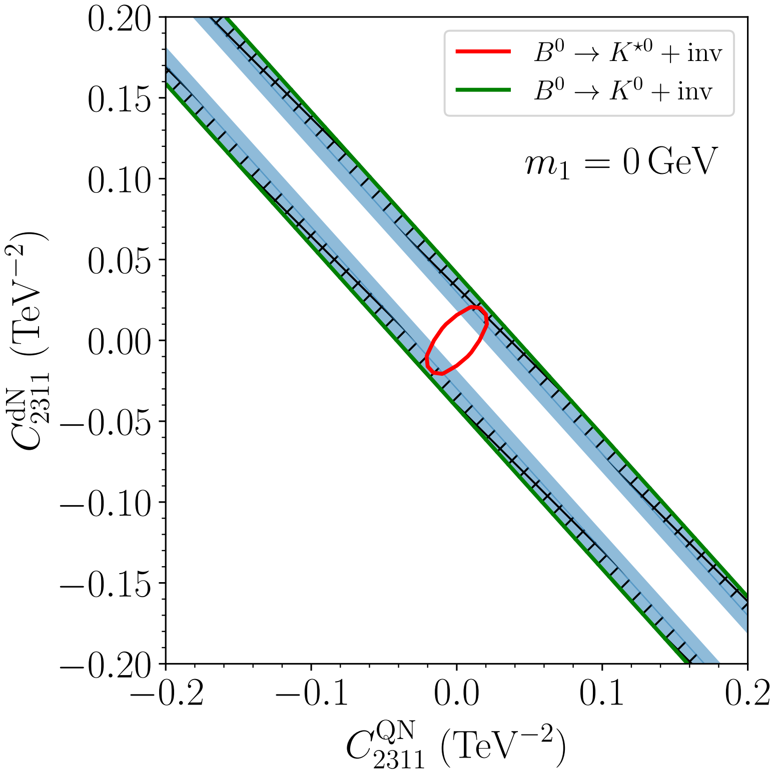
Light sterile neutrinos [Felkl,Giri,Mohanta,MS 2309.02940]

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

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



$\mathcal{B}(B^+ \to K^+ + \text{inv}) = (2.4 \pm 0.7) \cdot 10^{-5}$ [EPS 2023]



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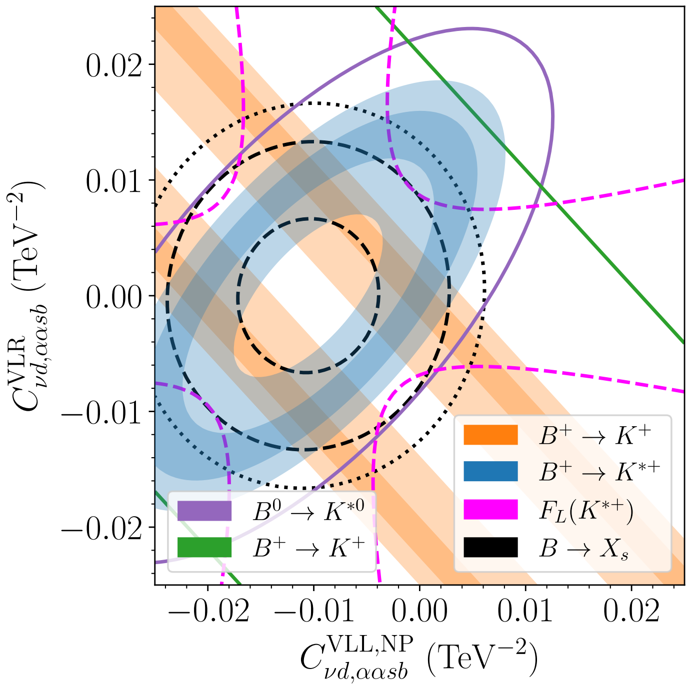
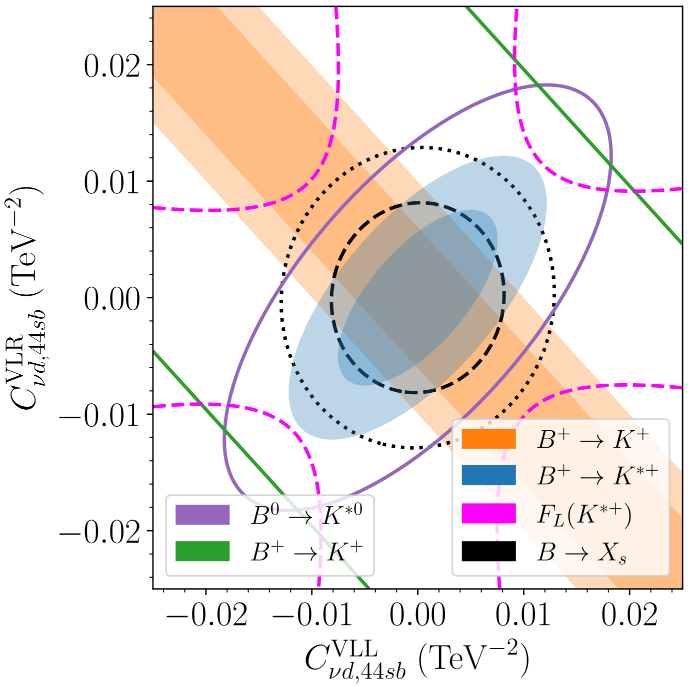
Complementarity

[Felkl, Li, MS 2111.04327]





LEFT operators

$$\mathcal{O}^{\mathrm{VLX}}_{\nu d,\alpha\alpha sb} =$$

$$(\overline{\nu_\alpha}\gamma_\mu P_L \nu_\alpha)(\bar{s}\gamma^\mu P_{L,R} b)$$

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

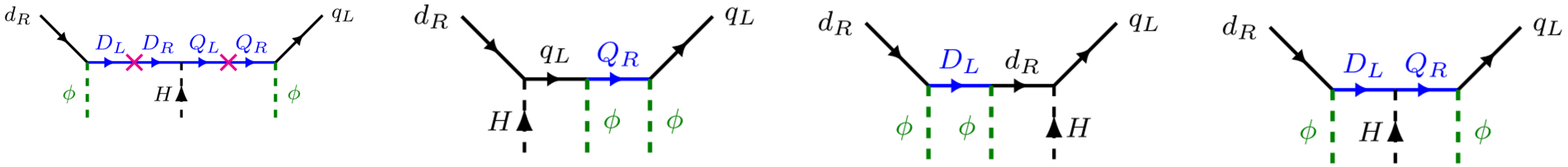
Light dark matter

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

Light scalar dark matter

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

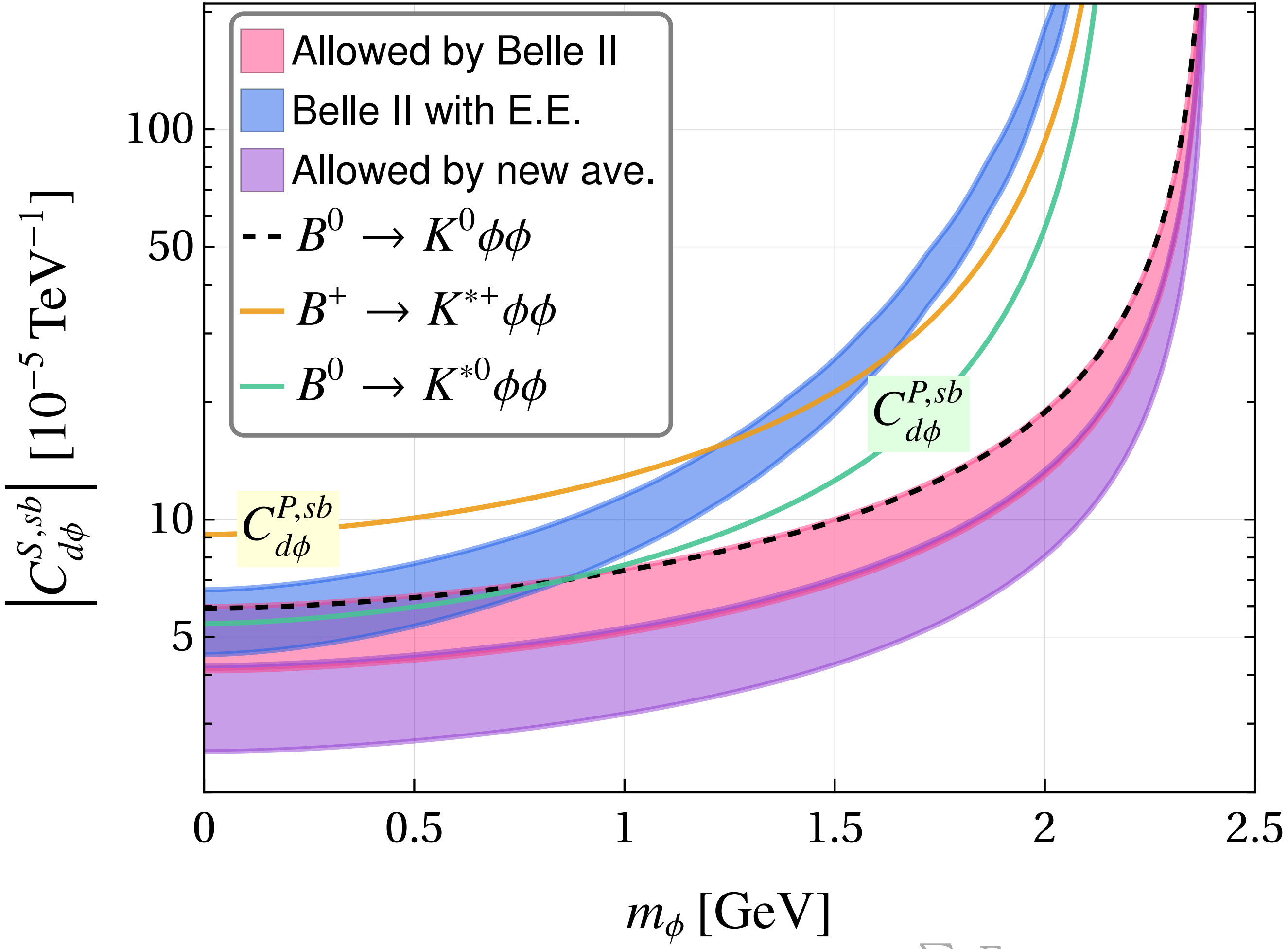
- Real scalar $\varphi \sim (\mathbf{1},\mathbf{1},0)\_$
- Scalar operator $\mathcal{O}_{q\varphi}^{S,sb} = \frac{1}{2}(\bar{s}b)\varphi^2$ viable explanation for $B^+ \to K^+\nu\bar{\nu}$ with $\Lambda \sim O(10\text{ PeV})$ [Ma+ 2309.12741]
- UV completion: Introduce vector-like quarks $Q \sim \left(\mathbf{3},\mathbf{2},\frac{1}{6}\right)\_$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



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

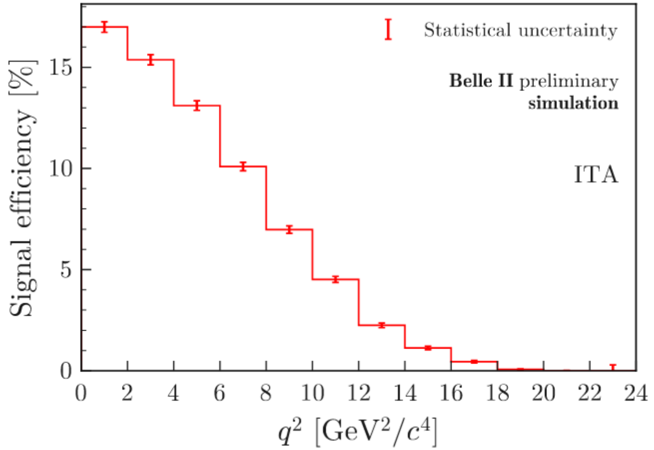
Light scalar dark matter

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



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

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

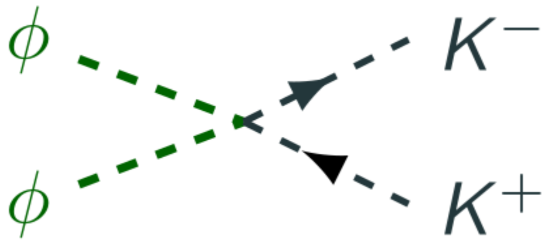


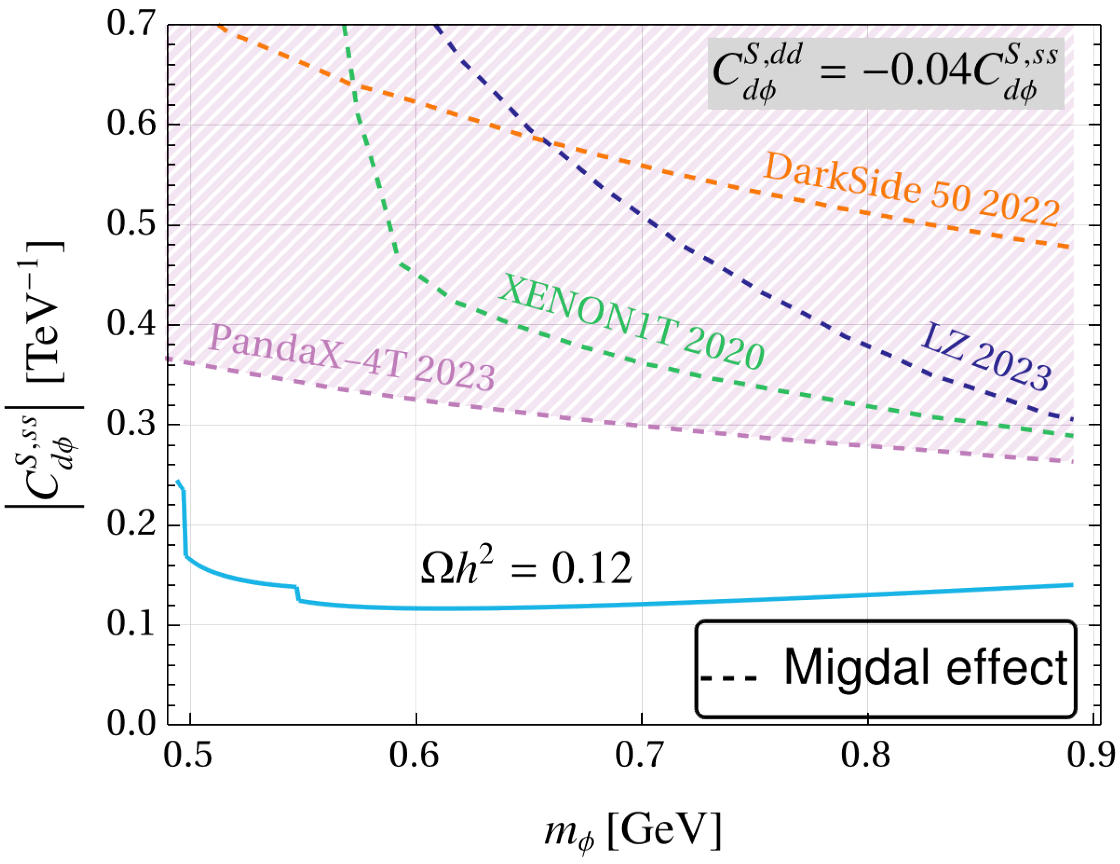
Rescaling w/ signal efficiency ε: $\omega(m) = \frac{\sum_i \Gamma_{i,\mathrm{SM}}\varepsilon_i}{\sum_i \Gamma_{i,\,\mathrm{NP}}(m)\varepsilon_i}$ (blue)

Light scalar dark matter

[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

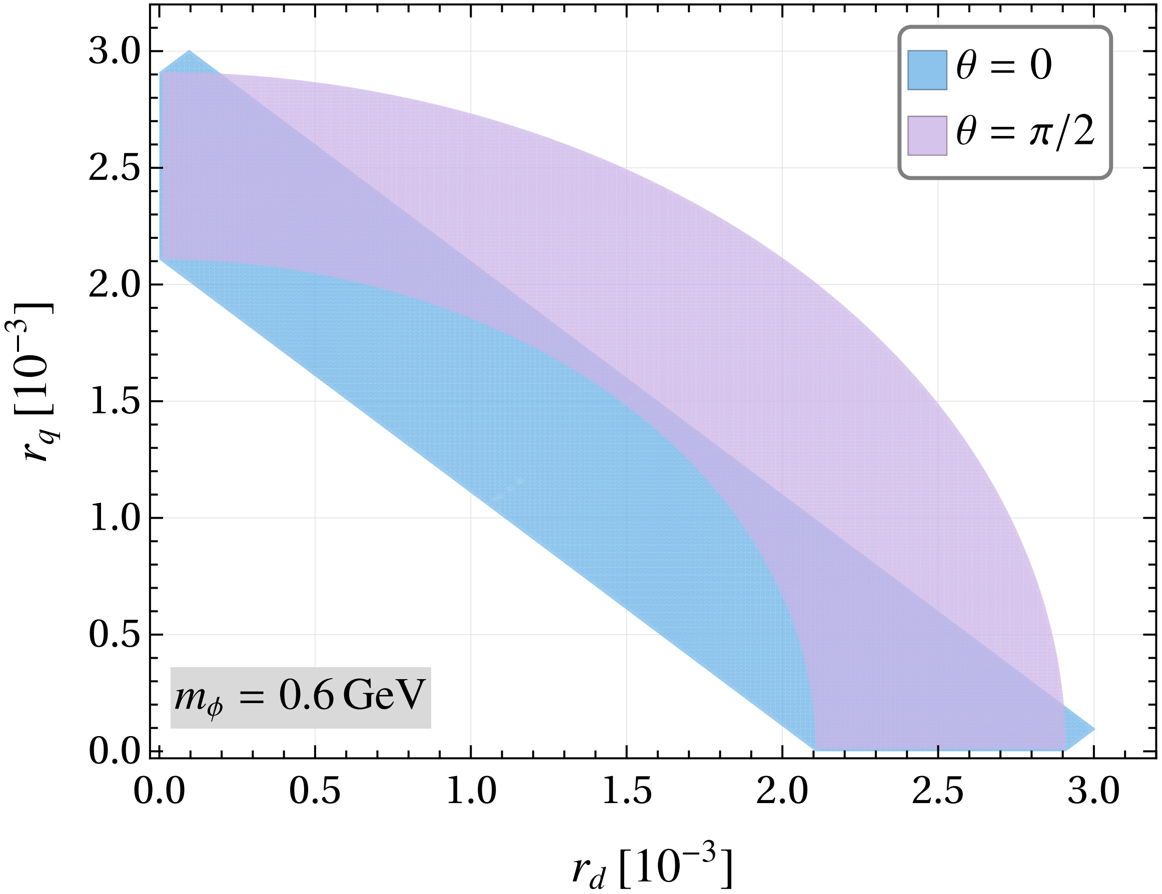
$$-0.07 \lesssim \frac{C^{S,dd}_{d\varphi}}{C^{S,ss}_{d\varphi}} \lesssim -0.02$$

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

Light scalar dark matter

[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

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

LHC may probe vector-like quarks

current searches don't apply due Z_2

$\to$ expect senstivity of $\mathcal{O}(2\ \text{TeV})$

work in progress

Take-away messages

- Viable DM and sterile neutrino explanations of excess in $B^+ \to \text{inv}$ for $\Lambda_{\text{NP}} \sim \mathcal{O}(1-10)$ TeV

- $B \to K +$ invisible is a new probe for GeV-scale new physics

- This is the first measurement...
  We can look forward to further interesting results from $B \to K +$ invisible:
  - other branching ratio measurements $B \to K^{(*)}$ +invisible
  - more details on missing invariant mass distribution

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Thank you!

Appendix

UV completions of sterile neutrino operators

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

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

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

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

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

- 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

Branching ratio uncertainty