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

arXiv: 2309.12741

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2023/12/3

目录

研究背景

$\boldsymbol{B \to K^{(*)} \nu\bar{\nu}}$ 衰变过程是寻找超出标准模型新物理很好的探针，因为该过程在标准模型中的理论不确定性很小。

Belle II 实验测量值：

$$\mathcal{B}(B^+ \to K^+ \nu\bar{\nu})_{exp} = (2.4 \pm 0.7) \times 10^{-5}$$

SM 预测值：

2.8 σ

$$\mathcal{B}(B^+ \to K^+ \nu\bar{\nu})_{SM} = (4.43 \pm 0.31) \times 10^{-6}$$

[Submitted on 24 Nov 2023]

Evidence for $B^+ \to K^+\nu\bar{\nu}$ Decays

We search for the rare decay $B^+ \to K^+\nu\bar{\nu}$ in a $362\ \text{fb}^{-1}$ sample of electron-positron collisions at the $\Upsilon(4S)$ resonance collected with the Belle II detector at the SuperKEKB collider. We use the inclusive properties of the accompanying B meson in $\Upsilon(4S) \to B\bar{B}$ events to suppress background from other decays of the signal B candidate and light-quark pair production. We validate the measurement with an auxiliary analysis based on a conventional hadronic reconstruction of the accompanying B meson. For background suppression, we exploit distinct signal features using machine learning methods tuned with simulated data. The signal-reconstruction efficiency and background suppression are validated through various control channels. The branching fraction is extracted in a maximum likelihood fit. Our inclusive and hadronic analyses yield consistent results for the $B^+ \to K^+\nu\bar{\nu}$ branching fraction of $[2.7 \pm 0.5(\text{stat}) \pm 0.5(\text{syst})] \times 10^{-5}$ and $[1.1^{+0.9}_{-0.8}(\text{stat})^{+0.8}_{-0.5}(\text{syst})] \times 10^{-5}$, respectively. Combining the results, we determine the branching fraction of the decay $B^+ \to K^+\nu\bar{\nu}$ to be $[2.3 \pm 0.5(\text{stat})^{+0.5}_{-0.4}(\text{syst})] \times 10^{-5}$, providing the first evidence for this decay at 3.5 standard deviations. The combined result is 2.7 standard deviations above the standard model expectation.

Comments:	29 pages, 23 figures, to be submitted to PRD
Subjects:	**High Energy Physics - Experiment (hep-ex)**
Report number:	Belle II Preprint 2023-017, KEK Preprint 2023-35
Cite as:	arXiv:2311.14647 [hep-ex]

理论基础

LEFT（低能有效场理论）

$$\mathcal{H}_{\text{NP}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^{\star} \frac{e^2}{16\pi^2} \sum_{ij} \left(C_L^{ij} \mathcal{O}_L^{ij} + C_R^{ij} \mathcal{O}_R^{ij} + {C'_L}^{ij} {\mathcal{O}'_L}^{ij} + {C'_R}^{ij} {\mathcal{O}'_R}^{ij} \right) + \text{ h.c.}$$

相关有效算符：

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

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

理论基础

定义两个比值：

$$R_K^{\nu\nu} = \frac{\mathcal{B}(B^+ \to K^+\nu\bar{\nu})}{\mathcal{B}(B^+ \to K^+\nu\bar{\nu})_{\text{SM}}} = 5.4 \pm 1.6 \quad R_{K^*}^{\nu\nu} = \frac{\mathcal{B}(B \to K^*\nu\bar{\nu})}{\mathcal{B}(B \to K^*\nu\bar{\nu})_{\text{SM}}} \leq 2.7 \text{ or } 1.9$$

flavio 软件包分析结果：

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

$$R_{K^*}^{\nu\nu} \approx 1 + \mathrm{Re} \sum_i \left(-0.1\, C_L^{ii} + 0.07\, C_R^{ii}\right) + \sum_{ij} \left[0.008 \left({C_L^{ij}}^2 + {C_R^{ij}}^2 + {C_L'^{\,ij}}^2 + {C_R'^{\,ij}}^2\right) - 0.01 \left(C_L^{ij} C_R^{ij} + C_L'^{\,ij} C_R'^{\,ij}\right)\right]$$

新物理模型

新物理模型

- Leptoquark 模型
- 轻的惰性中微子
- 轻暗物质粒子（不可见轻粒子）*

Leptoquark 模型

标量与矢量 Leptoquark：

$$S_0^\dagger = S_0^{1/3} : (\bar{3}, 1, 1/3) \,, \qquad \tilde{S}_{1/2}^\dagger = \left(\tilde{S}_{1/2}^{-1/3}, \tilde{S}_{1/2}^{2/3} \right) : (3, 2, 1/6)$$

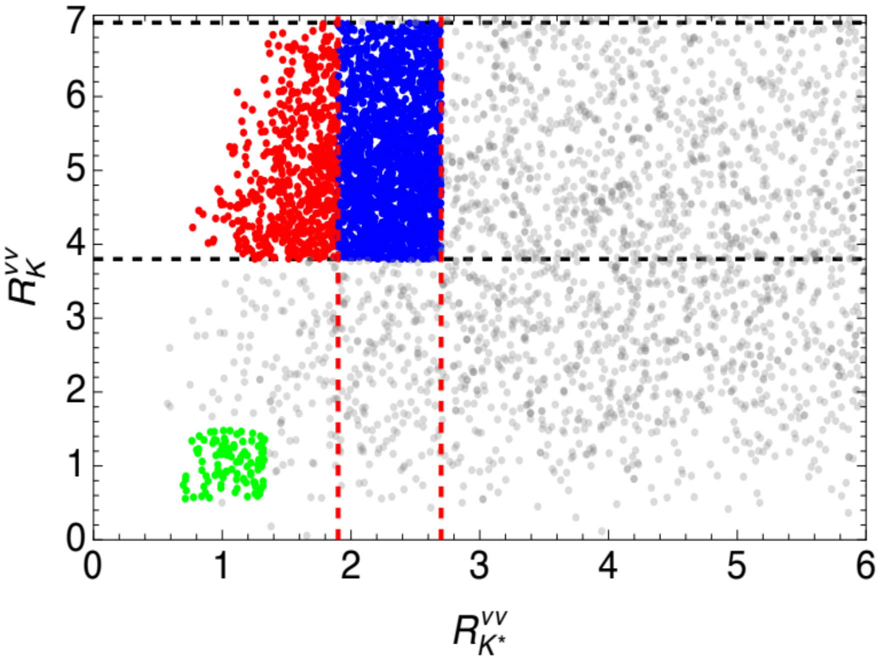
$$\vec{\tau} \cdot \vec{S}_1^\dagger = \begin{pmatrix} S_1^{1/3} & \sqrt{2} S_1^{4/3} \\ \sqrt{2} S_1^{-2/3} & -S_1^{1/3} \end{pmatrix} : (\bar{3}, 3, 1/3)$$

$$V_{1/2}^\dagger = \left(V_{1/2}^{1/3}, V_{1/2}^{4/3} \right) : (\bar{3}, 2, 5/6) \qquad \vec{\tau} \cdot \vec{V}_1^\dagger = \begin{pmatrix} V_1^{2/3} & \sqrt{2} V_1^{5/3} \\ \sqrt{2} V_1^{-1/3} & -V_1^{2/3} \end{pmatrix} : (3, 3, 2/3)$$

相关 Wilson 系数：

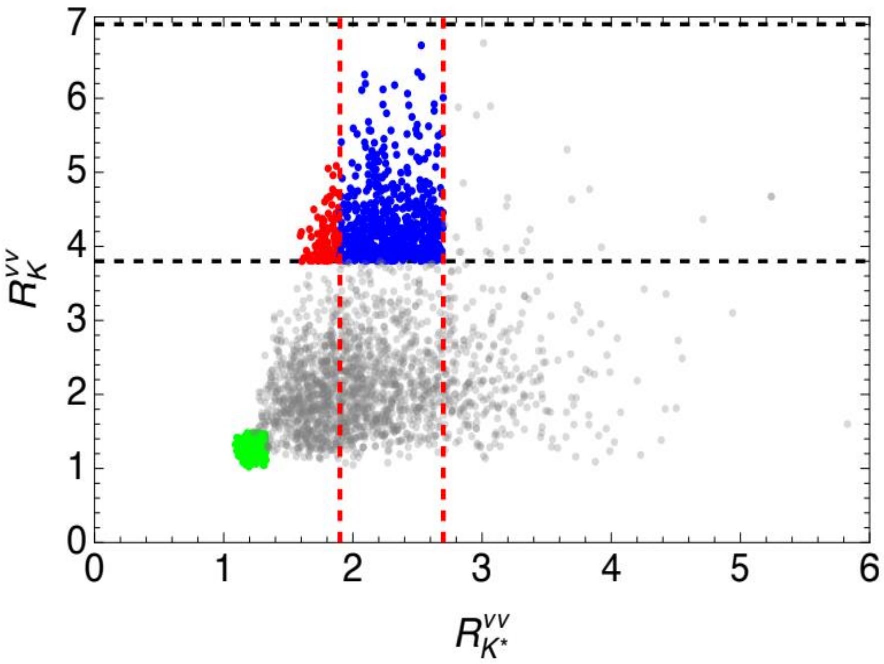
$$C_R^{ij} = C_{9'}^{ij} = -C_{10'}^{ij} = \frac{\pi}{\sqrt{2} \alpha G_F V_{tb} V_{ts}^*} \left(-\frac{\lambda_{L\tilde{S}_{1/2}}^{2j} \lambda_{L\tilde{S}_{1/2}}^{*3i}}{2 m_{S_{1/2}}^2} + \frac{\lambda_{LV_{1/2}}^{3j} \lambda_{LV_{1/2}}^{*2i}}{m_{V_{1/2}}^2} \right)$$

数值分析



Leptoquark 模型

C_L^{ij} , C_R^{ij}



轻的惰性中微子模型

C'^{ij}_L , C'^{ij}_R

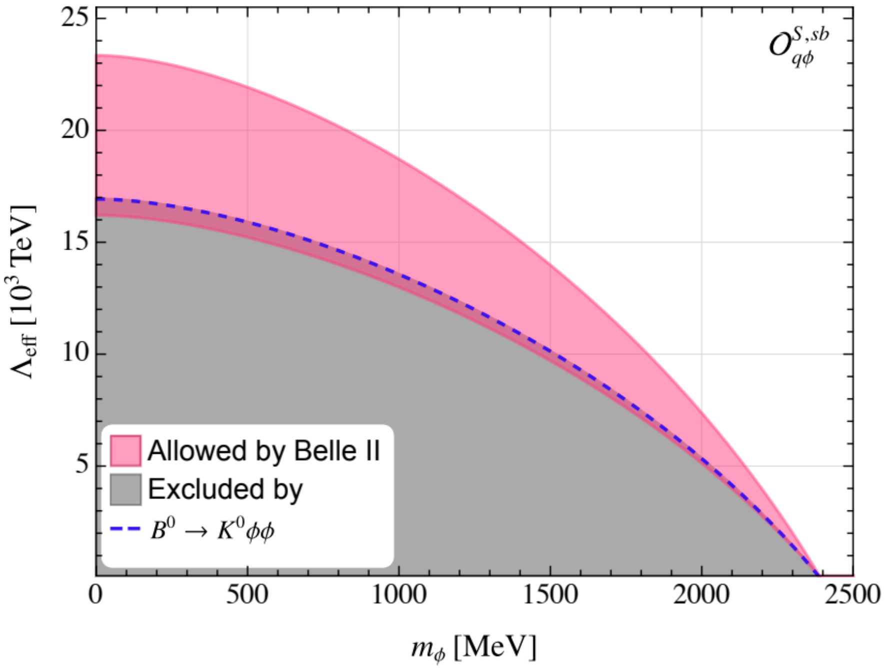
轻暗物质粒子（不可见轻粒子）

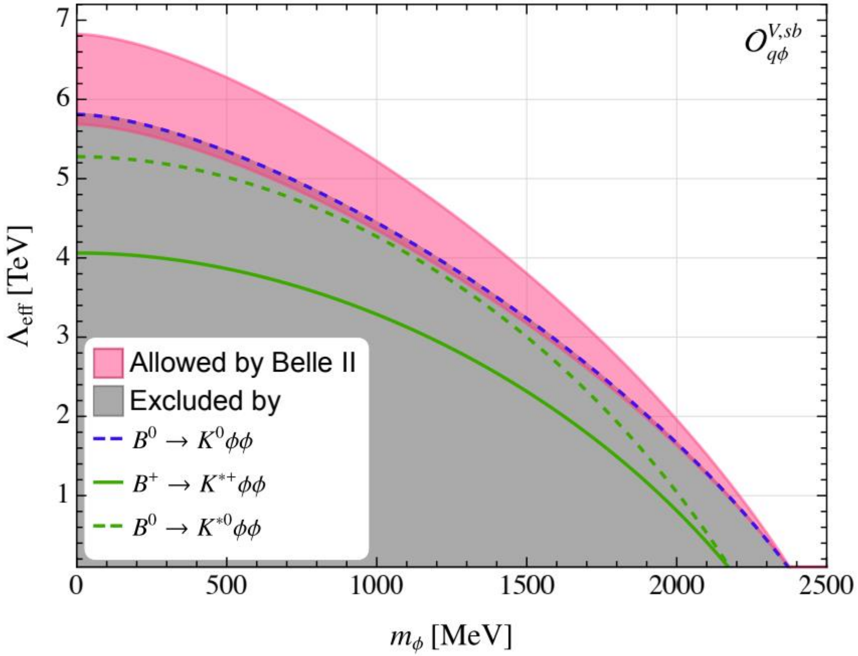
- 轻暗物质粒子
  - 标量暗物质粒子
  - 费米暗物质粒子
  - 矢量暗物质粒子

标量暗物质粒子

相关有效算符：

$$\mathcal{O}_{q\phi}^{S,sb} = (\bar{s}b)(\phi^\dagger\phi) \qquad \mathcal{O}_{q\phi}^{V,sb} = (\bar{s}\gamma^\mu b)(\phi^\dagger i\overleftrightarrow{\partial_\mu}\phi),\ (\times)$$



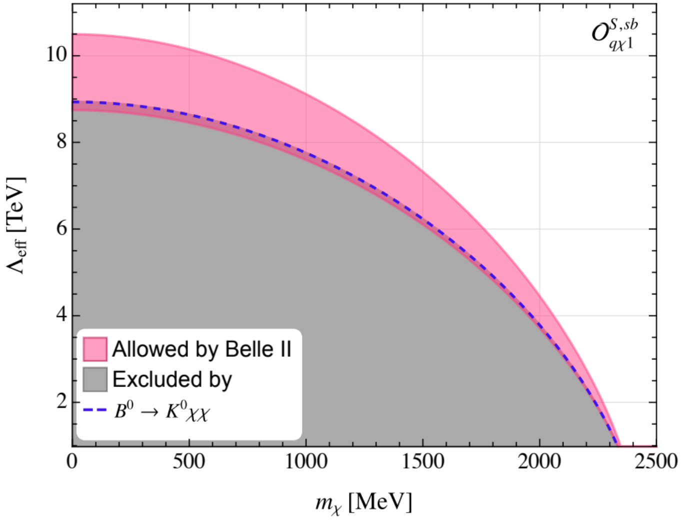


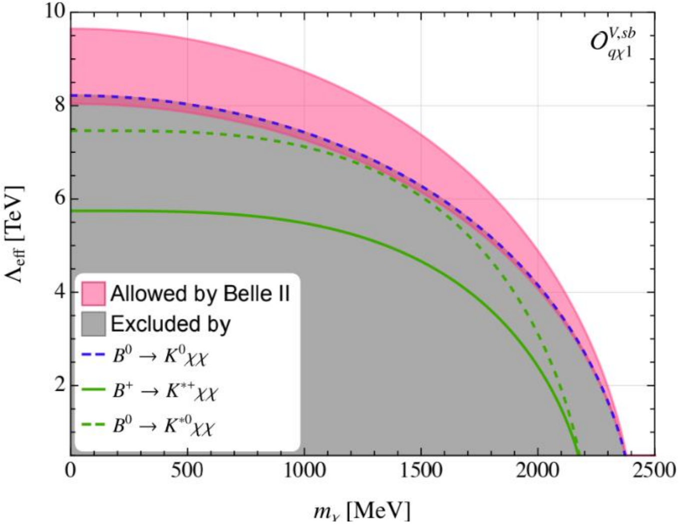
费米暗物质粒子

相关有效算符：

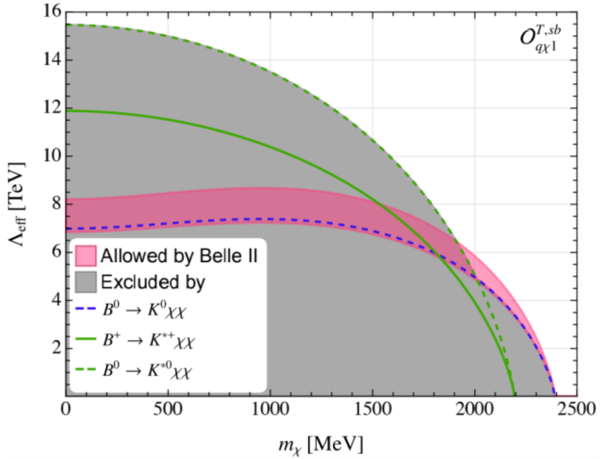
$$\mathcal{O}_{q\chi 1}^{S,sb} = (\bar{s}b)(\bar{\chi}\chi),$$
$$\mathcal{O}_{q\chi 1}^{V,sb} = (\bar{s}\gamma^{\mu}b)(\bar{\chi}\gamma_{\mu}\chi), \ (\times)$$
$$\mathcal{O}_{q\chi 1}^{T,sb} = (\bar{s}\sigma^{\mu\nu}b)(\bar{\chi}\sigma_{\mu\nu}\chi), \ (\times)$$

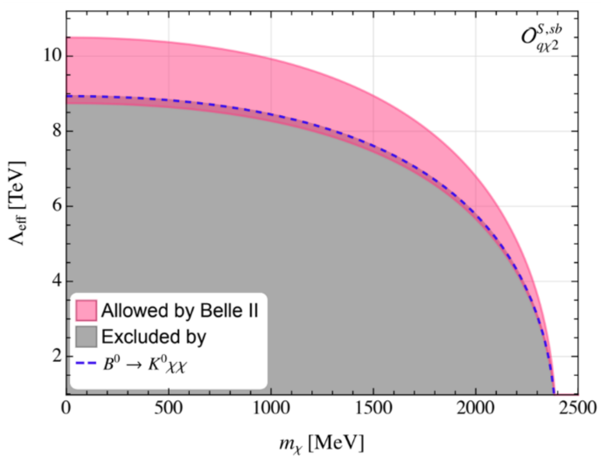
$$\mathcal{O}_{q\chi 2}^{S,sb} = (\bar{s}b)(\bar{\chi}i\gamma_5\chi),$$
$$\mathcal{O}_{q\chi 2}^{V,sb} = (\bar{s}\gamma^{\mu}b)(\bar{\chi}\gamma_{\mu}\gamma_5\chi),$$
$$\mathcal{O}_{q\chi 2}^{T,sb} = (\bar{s}\sigma^{\mu\nu}b)(\bar{\chi}\sigma_{\mu\nu}\gamma_5\chi), \ (\times)$$

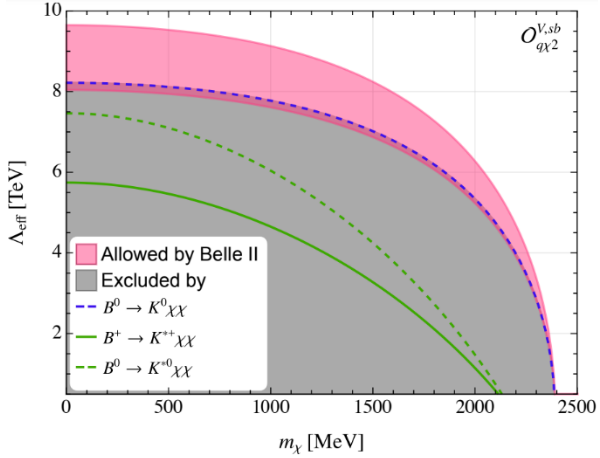


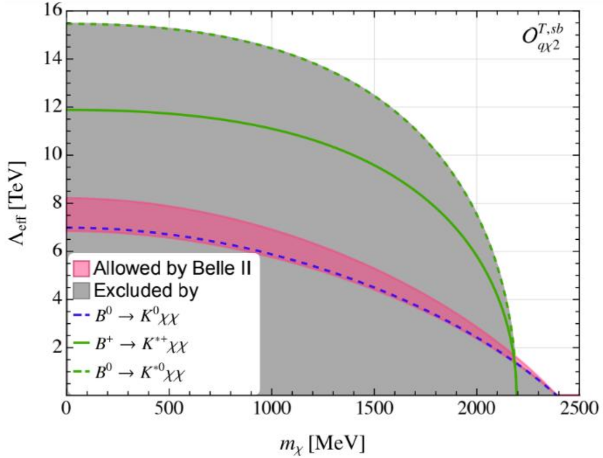


费米暗物质粒子


$O^{T,sb}_{q\chi 1}$
$\Lambda_{\rm eff}$ [TeV]
m_χ [MeV]
Allowed by Belle II
Excluded by
$B^0 \to K^0 \chi\chi$
$B^+ \to K^{*+} \chi\chi$
$B^0 \to K^{*0} \chi\chi$


$O^{S,sb}_{q\chi 2}$
$\Lambda_{\rm eff}$ [TeV]
m_χ [MeV]
Allowed by Belle II
Excluded by
$B^0 \to K^0 \chi\chi$


$O^{V,sb}_{q\chi 2}$
$\Lambda_{\rm eff}$ [TeV]
m_χ [MeV]
Allowed by Belle II
Excluded by
$B^0 \to K^0 \chi\chi$
$B^+ \to K^{*+} \chi\chi$
$B^0 \to K^{*0} \chi\chi$


$O^{T,sb}_{q\chi 2}$
$\Lambda_{\rm eff}$ [TeV]
m_χ [MeV]
Allowed by Belle II
Excluded by
$B^0 \to K^0 \chi\chi$
$B^+ \to K^{*+} \chi\chi$
$B^0 \to K^{*0} \chi\chi$

矢量暗物质粒子

相关有效算符：

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

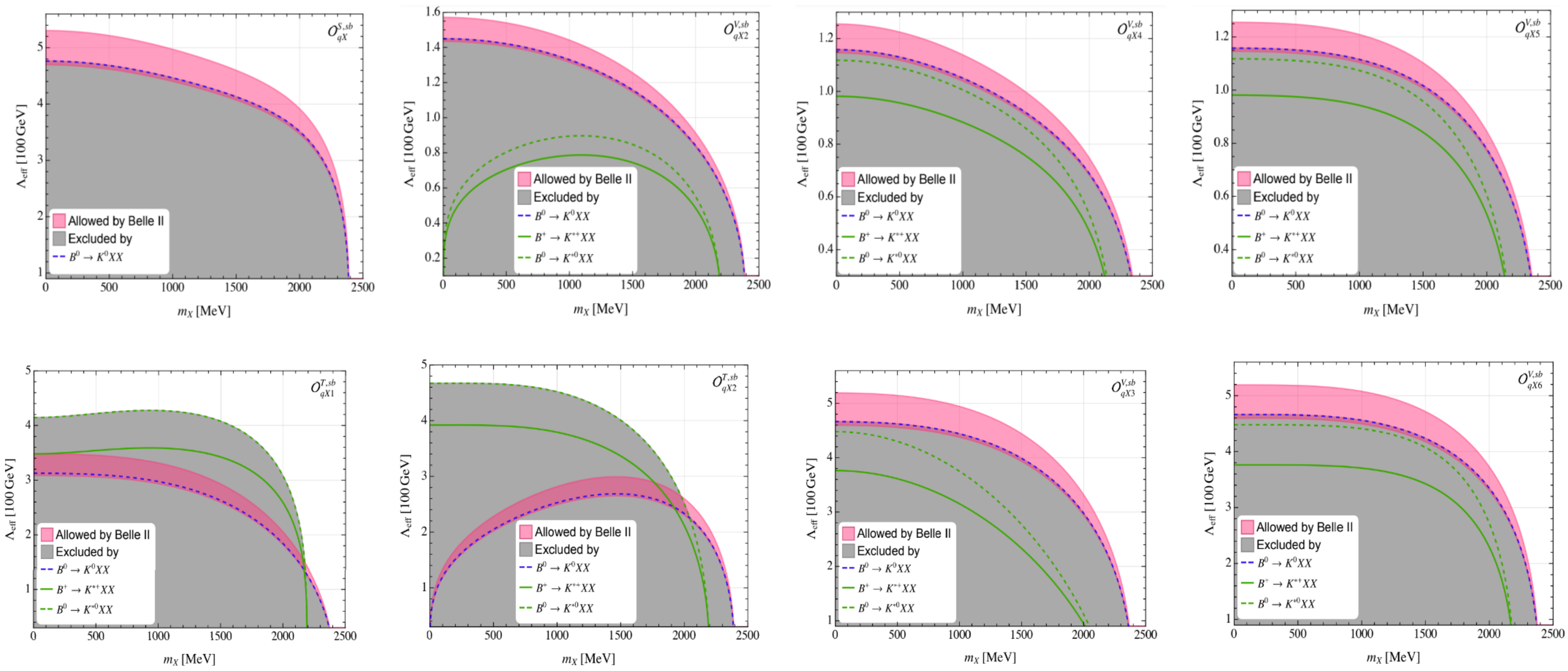
$$\mathcal{O}_{qX3}^{V,sb} = (\bar{s}\gamma_\mu b)(X_\rho^\dagger \overleftrightarrow{\partial_\nu} X_\sigma)\epsilon^{\mu\nu\rho\sigma}$$

$$\mathcal{O}_{qX1}^{T,sb} = \frac{i}{2}(\bar{s}\sigma^{\mu\nu}b)(X_\mu^\dagger X_\nu - X_\nu^\dagger X_\mu), \ (\times) \qquad \mathcal{O}_{qX4}^{V,sb} = (\bar{s}\gamma^\mu b)(X_\nu^\dagger i\overleftrightarrow{\partial_\mu} X^\nu), \ (\times)$$

$$\mathcal{O}_{qX2}^{T,sb} = \frac{1}{2}(\bar{s}\sigma^{\mu\nu}\gamma_5 b)(X_\mu^\dagger X_\nu - X_\nu^\dagger X_\mu), \ (\times) \quad \mathcal{O}_{qX5}^{V,sb} = (\bar{s}\gamma_\mu b)i\partial_\nu(X^{\mu\dagger}X^\nu - X^{\nu\dagger}X^\mu), \ (\times)$$

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

矢量暗物质粒子


$O_{qX}^{S,sb}$
$O_{qX2}^{V,sb}$
$O_{qX4}^{V,sb}$
$O_{qX5}^{V,sb}$
$O_{qX1}^{T,sb}$
$O_{qX2}^{T,sb}$
$O_{qX3}^{V,sb}$
$O_{qX6}^{V,sb}$
Allowed by Belle II
Excluded by
$B^0 \to K^0 XX$
$B^+ \to K^{*+} XX$
$B^0 \to K^{*0} XX$
$\Lambda_{\rm eff}$ [100 GeV]
m_X [MeV]

总结

- 本文基于 $\boldsymbol{B}^+ \to \boldsymbol{K}^+ \boldsymbol{v}\bar{\boldsymbol{v}}$ 衰变过程的最新实验测量结果，考察了三种可能的新物理模型解释。
- 在 Leptoquark 模型中，仅有 $\tilde{S}_{1/2}$ 和 $\tilde{V}_{1/2}$ 两个 Leptoquark 夸克可以解释该过程的超出现象。同样，轻惰性中微子模型同样可以解释该过程的超出现象。
- 在轻暗物质模型中，标量、费米和矢量轻暗物质粒子均可以很好的解释 Belle II 实验最新结果的超出现象。

未来计划

- 掌握分析物理唯象过程的程序包 flavio
- 探究暗物质在低能高亮度的对撞机中的可能信号
- 考察对撞机实验对轻暗物质模型参数空间的限制

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汇报完毕 谢谢大家