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

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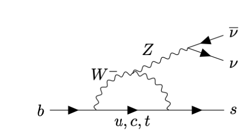
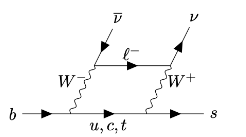
The University of New South Wales Sydney
Sydney-CPPC

based on work in collaboration with
Tobias Felkl and Sze-Lok Li JHEP 12 (2021) 118 [2111.04327]

Motivation

$B \to K^{(*)}\nu\nu$ is a rare process





SM: loop, CKM and GIM suppressed $\mathcal{A} \propto \frac{1}{16\pi^2} \sum_{i=u,c,t} V_{ib}^* V_{is} \frac{m_i^2}{m_W^2}$

$\Rightarrow$ **good place to search for New Physics**

- sensitive to virtual corrections and new exotic final states
- complete factorisation into hadronic and leptonic part
- Belle II is expected to measure with $\mathcal{O}(10\%)$ precision
- our work: establish sensitivity of Belle II
  - using full set of operators (vector, scalar, tensor)
  - including light sterile neutrinos (possibly massive)

Earlier work: Kim, Kim, Morozumi hep-ph/9905528; Aliev, Ozpineci, Savci hep-ph/0101066
Colango, De Fazio, Santorelli, Scrimieri hep-ph/9610297; Altmannshofer, Buras, Straub, Wick 0902.0160; Buras, Girrbach-Noe, Niehoff, Straub 1409.4557; ...

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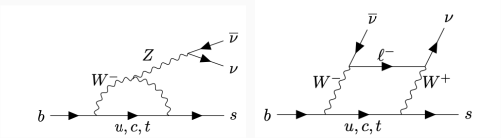

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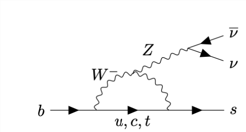

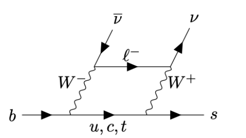

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Observables

Observable	SM prediction LQCD+LCSR	current constraint	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\text{Br}(B^0 \to K^0 \nu\bar{\nu})$	$(4.1 \pm 0.5) \times 10^{-6}$	$< 2.6 \times 10^{-5}$		
$\text{Br}(B^+ \to K^+ \nu\bar{\nu})$	$(4.4 \pm 0.7) \times 10^{-6}$	$< 1.6 \times 10^{-5}$	30%	11%
$\text{Br}(B^0 \to K^{*0} \nu\bar{\nu})$	$(9.5 \pm 0.9) \times 10^{-6}$	$< 1.8 \times 10^{-5}$	26%	9.6%
$\text{Br}(B^+ \to K^{*+} \nu\bar{\nu})$	$(10 \pm 1) \times 10^{-6}$	$< 4.0 \times 10^{-5}$	25%	9.3%
$F_L(B^0 \to K^{*0} \nu\bar{\nu})$	0.49 ± 0.04			0.079
$F_L(B^+ \to K^{*+} \nu\bar{\nu})$	0.49 ± 0.04			0.077
$\text{Br}(B \to X_s \nu\bar{\nu})$	$(2.7 \pm 0.2) \times 10^{-5}$	$< 6.4 \times 10^{-4}$		

constraints: $B \to K^{(*)0}\nu\nu$ 1702.03224, $B^+ \to K^+\nu\nu$ 1303.7465, $B^+ \to K^{*+}$ 1303.3716, $B \to X_s\nu\nu$ hep-ex/0010022; Projection: Belle II Physics book 1808.10567

F_L is longitudinal polarisation fraction of K^*

Form factors: LQCD + LCSR

- $B \to K$ Gubernari, Kokulu, van Dyk 1811.00983
- $B \to K^*$ Bharucha, Straub, Zwicky 1503.05534
  $+$ 10% to account for finite width Descotes-Genon, Khodjamirian, Virto 1908.02267

LEFT operator basis [Jenkins, Manohar, Stoffer 1711.05270]

Express everything in terms of LH Weyl spinors $N_R \leftrightarrow \nu_L^c$

$$\mathcal{L} = \sum_{X=L,R} C_{\nu d}^{\mathrm{VLX}} \mathcal{O}_{\nu d}^{\mathrm{VLX}} + \left(\sum_{X=L,R} C_{\nu d}^{\mathrm{SLX}} \mathcal{O}_{\nu d}^{\mathrm{SLX}} + C_{\nu d}^{\mathrm{TLL}} \mathcal{O}_{\nu d}^{\mathrm{TLL}} + \mathrm{h.c.} \right)$$

$$\mathcal{O}_{\nu d}^{\mathrm{VLL}} = (\overline{\nu_L}\gamma_\mu \nu_L)(\overline{d_L}\gamma^\mu d_L) \qquad \mathcal{O}_{\nu d}^{\mathrm{VLR}} = (\overline{\nu_L}\gamma_\mu \nu_L)(\overline{d_R}\gamma^\mu d_R)$$

$$\mathcal{O}_{\nu d}^{\mathrm{SLL}} = (\overline{\nu_L^c} \nu_L)(\overline{d_R} d_L) \qquad \mathcal{O}_{\nu d}^{\mathrm{SLR}} = (\overline{\nu_L^c} \nu_L)(\overline{d_L} d_R)$$

$$\mathcal{O}_{\nu d}^{\mathrm{TLL}} = (\overline{\nu_L^c} \sigma_{\mu\nu} \nu_L)(\overline{d_R}\sigma^{\mu\nu} d_L)$$

- $C_{\nu d}^{\mathrm{SLX}}$ symmetric in neutrino flavour indices
- $C_{\nu d}^{\mathrm{TLL}}$ antisymmetric in neutrino flavour indices
- NP $C_{\nu d}^{\mathrm{VLX}}$ interfere with SM
  $C_{\nu d,\alpha\alpha sb}^{\mathrm{VLL,SM}} = -\frac{4G_F}{\sqrt{2}} \frac{\alpha}{2\pi} V_{ts}^* V_{tb} \left(\frac{X}{\sin^2\theta_W} \right)$ Brod, Gorbahn, Stamou 1009.0947
- ν dipole operators at 1-loop, strongly constrained, not included

Calculational details

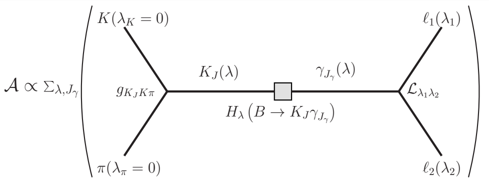
All Wilson coefficients defined at electroweak scale $\mu = m_Z$

$$C_{\nu d}^{\mathrm{VLX}}(m_B) = C_{\nu d}^{\mathrm{VLX}}(m_Z) \qquad X = L, R$$

$$C_{\nu d}^{\mathrm{SLX}}(m_B) = 1.370\, C_{\nu d}^{\mathrm{SLX}}(m_Z) \qquad m_B = 4.8\,\mathrm{GeV}$$

$$C_{\nu d}^{\mathrm{TLL}}(m_B) = 0.900\, C_{\nu d}^{\mathrm{TLL}}(m_Z)$$

$B \to K^{(*)}\nu\nu$: **helicity amplitudes** Gratrex, Hopfer, Zwicky 1506.03970



+ compared to transversity ampl. Altmannshofer, Ball, Bharucha, Buras, Straub 0811.1214

$B \to X_s\nu\nu$: **LO HQET calculation (=quark-level process)**

LO because unclear future prospects

compared to Altmannshofer, Buras, Straub, Wick 0902.0160 and `flavio` for limiting cases

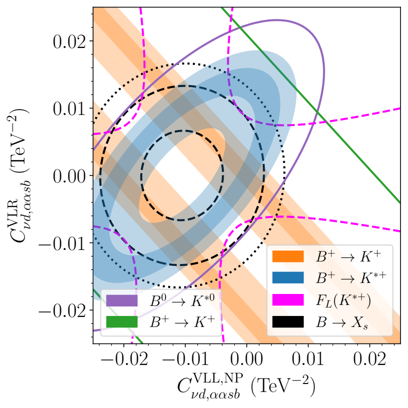
One operator with massless neutrinos

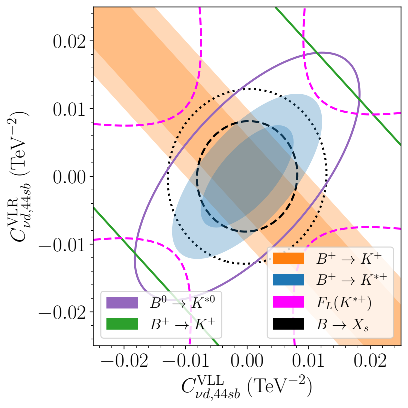
	Current Bound			Future Sensitivity (50 ab^{-1})		
Operator	Value [TeV^{-2}]	NP scale [TeV]	Observable	Value [TeV^{-2}]	NP scale [TeV]	Observable
$\mathcal{O}^{\text{VLL,NP}}_{\nu d,\alpha\alpha sb}$	0.028	6	$B \to K^*\nu\nu$	0.023	7	$B \to K^{(*)}\nu\nu$
$\mathcal{O}^{\text{VLR}}_{\nu d,\alpha\alpha sb}$	0.021	7	$B \to K\nu\nu$	0.002	25	$B \to K^{(*)}\nu\nu$
$\mathcal{O}^{\text{VLL}}_{\nu d,\gamma\delta sb}$	0.014	9	$B \to K^*\nu\nu$	0.006	13	$B \to K^{(*)}\nu\nu$
$\mathcal{O}^{\text{SLL}}_{\nu d,\gamma\gamma sb}$	0.012	10	$B \to K^{(*)}\nu\nu$	0.002	25	$B \to K\nu\nu$
$\mathcal{O}^{\text{SLL}}_{\nu d,\gamma\delta sb}$	0.009	10	$B \to K^{(*)}\nu\nu$	0.002	25	$B \to K\nu\nu$
$\mathcal{O}^{\text{TLL}}_{\nu d,\gamma\delta sb}$	0.002	25	$B \to K^*\nu\nu$	0.0009	35	$B \to K^*\nu\nu$

$\alpha \in \{1, 2, 3\}$ and $\gamma \neq \delta$ arbitrary

$$\Lambda_{\text{NP}} = \frac{1}{\sqrt{|C^{XLY}_{\nu d}|}}$$

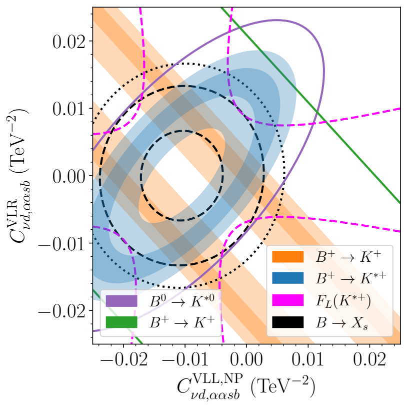
Two operators with massless neutrinos – vector

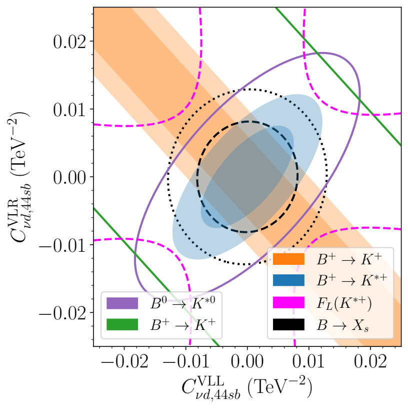




- Current constraints solid purple and green lines
- Viable light (dark) regions if SM predictions are confirmed by Belle II with 5(50) ab^{-1}
- Black dotted (dashed) $B \to X_s \nu\nu$ with 50% (20%) precision

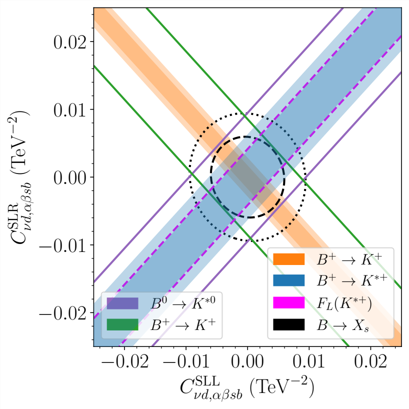
Two operators with massless neutrinos – vector

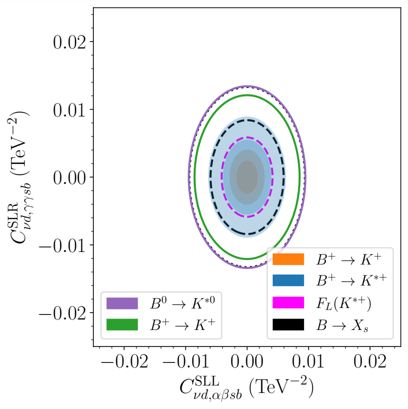




- Straight bands $\mathcal{A} \propto |C^{\mathrm{VLL}}_{\nu d,\alpha\alpha sb} + C^{\mathrm{VLR}}_{\nu d,\alpha\alpha sb}|^2 \to$ exact cancellation
- Ellipses: $\mathcal{A} \propto A(q^2)|C^{\mathrm{VLL}}_{\nu d,\alpha\alpha sb} + C^{VLR}_{\nu d,\alpha\alpha sb}|^2 + B(q^2)|C^{\mathrm{VLL}}_{\nu d,\alpha\alpha sb} - C^{VLR}_{\nu d,\alpha\alpha sb}|^2$
- Four viable regions $(0,0)$, $(0,-2)|C^{\mathrm{VLL,SM}}_{\nu d,\alpha\alpha sb}|$, $(-1,\pm1)|C^{\mathrm{VLL,SM}}_{\nu d,\alpha\alpha sb}|$
- No destructive interference $\to$ centre of viable region excluded

Two operators with massless neutrinos – scalar





Interference for $B \to K^{(*)}\nu\nu$

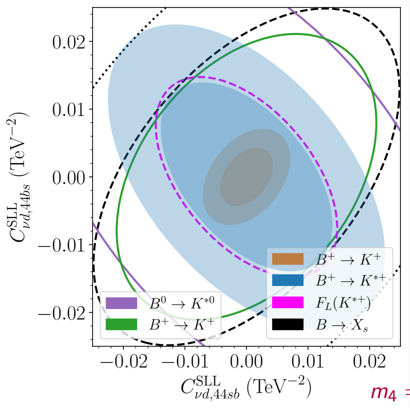
$$\mathcal{A} \propto |C^{\mathrm{SLL}}_{\nu d,\alpha\beta sb} \pm C^{\mathrm{SLR}}_{\nu d,\alpha\beta sb}|^2$$

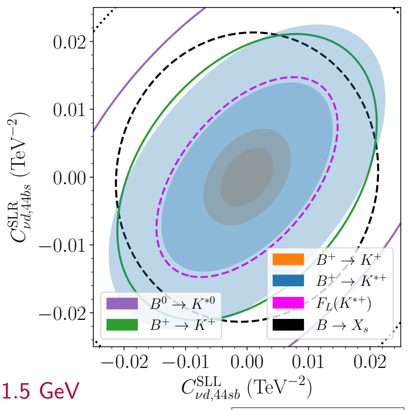
$$\alpha \neq \beta$$

no interference due to different neutrinos in final state

$$\alpha \neq \beta \neq \gamma$$

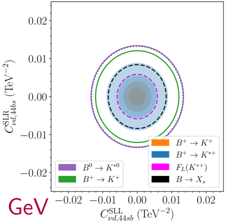
Massive neutrinos – interference





$m_4 = 1.5$ GeV

- interference between $\mathcal{O}^{SLX}_{\nu d,\alpha\beta sb}$ and $\mathcal{O}^{SLX\dagger}_{\nu d,\alpha\beta bs}$ for massive neutrinos
- $B \to K^* \nu\nu$: distinction between operators with same/opposite chirality



$m_4 = 0$ GeV

$B^+ \to K^+\nu\nu$ – current status

Simple weighted average of Belle II, Belle, BaBar

$\mathrm{BR}_{\mathrm{avg}} = (11 \pm 4) \times 10^{-6} > \mathrm{BR}_{\mathrm{SM}} = (4.4 \pm 0.7) \times 10^{-6}$ see Belle II 2104.12624

	$\mathcal{O}^{\mathrm{VLL}}_{\nu d,44sb}$	$\mathcal{O}^{\mathrm{SLL}}_{\nu d,44sb}$	$\mathcal{O}^{\mathrm{SLL}}_{\nu d,34sb}$	$\mathcal{O}^{\mathrm{TLL}}_{\nu d,34sb}$	Bound	SM
WC (10^{-3} TeV^{-2})	$22.3^{+5.97}_{-8.31}$	$9.12^{+2.44}_{-3.40}$	$6.45^{+1.72}_{-2.40}$	$9.33^{+2.50}_{-3.48}$		
$\mathrm{Br}(B^0 \to K^{*0}\nu\nu)/10^{-5}$	2.89 ± 1.05	1.45 ± 0.18		13.5 ± 7.5	1.8	1.16 ± 0.11
$\mathrm{Br}(B^+ \to K^{*+}\nu\nu)/10^{-5}$	3.11 ± 1.13	1.57 ± 0.20		14.6 ± 8.1	4.0	1.24 ± 0.12
$\mathrm{Br}(B \to X_s\nu\nu)/10^{-4}$	1.01 ± 0.37	0.494 ± 0.055		4.57 ± 2.53	6.4	0.27 ± 0.02

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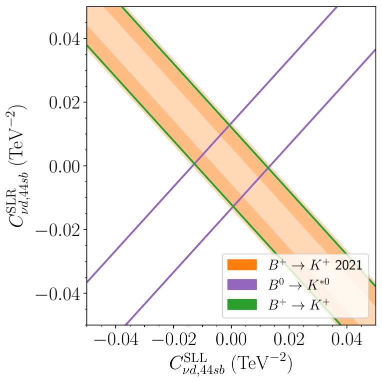
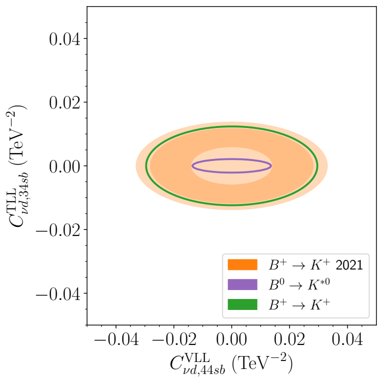




Summary and conclusions

$B \to K\nu\nu$, $B \to K^*\nu\nu$ **(and** $B \to X_s\nu\nu$**)**
interesting probes for new physics

flavour independent
$\Rightarrow$ **sensitive to** ν_τ **flavour and sterile** ν

observables are complementary:
allow to distinguish Lorentz structures

The Dark Side of the Universe

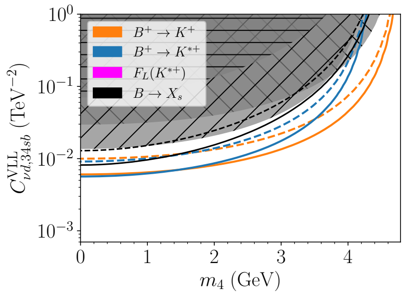
DSU2022

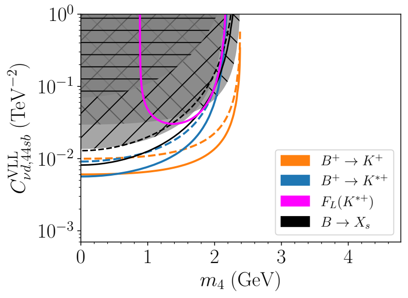
5-9 December 2022

https://indico.cern.ch/event/1107937

Backup slides

Massive neutrinos





- $\backslash\backslash$ (//)[−] hatching: current bounds on $B \to K^0(K^{*0})[X_s]\nu\nu$
- dashed (solid) lines: future reach for $5(50)\mathrm{ab}^{-1}$
- weaker bounds for heavier masses ← phase space suppression
- $B \to K\nu\nu$ more stringent for large masses (vector)
- $B \to K\nu\nu$ always most stringent (scalar)

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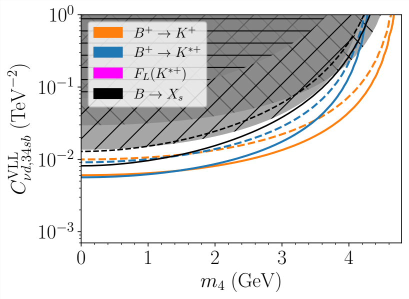

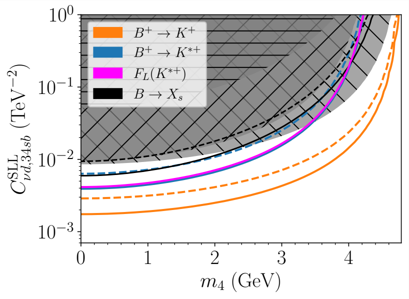

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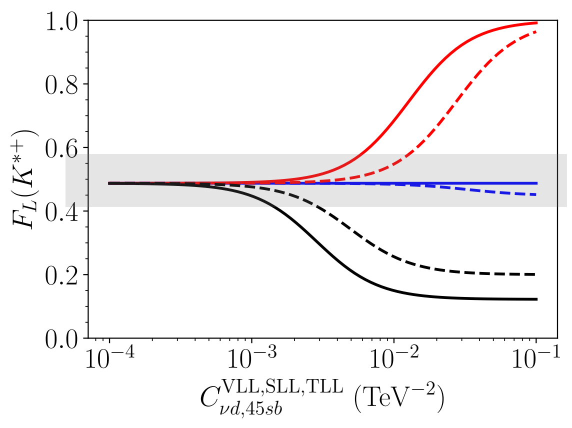
Massive neutrinos – F_L



- solid (dashed) lines for $m_{4,5} = 0(1.5)$ GeV
- gray indicates future reach centred on SM prediction
- sharp distinction between scalar, vector and tensor operators