$b \to s\nu\bar{\nu}$ decays: why, where and how?

Open Questions and Future Directions in Flavour Physics – MITP – 04/11/2024

Méril Reboud

Mostly based on:

- Amhis, Kenzie, MR, Wiederhold 2309.11353
- Gärtner, MR, *et al* 2402.08417

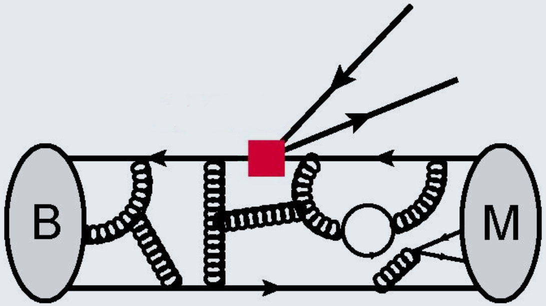
cnrs

EOS

IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

Theory primer

$$\mathcal{H}_{\text{eff}}^{sb\nu\nu} = -\frac{4G_F}{\sqrt{2}}\lambda_t \sum_i \mathcal{C}_i \mathcal{O}_i + \text{h.c.}$$



$$\mathcal{O}_L^{\nu_i,\nu_j} = \frac{e^2}{16\pi^2}\big(\bar{s}_L\gamma_\mu b_L\big)\big(\bar{\nu}_i\gamma^\mu(1-\gamma_5)\nu_j\big)$$

$$C_L^{\text{SM}} = -6.32(7)$$ @NLO QCD and NNLO EW [Buchalla, Buras '99; Misiak, Urban '99; Brod, Gorbahn, Stamou '10]

- Main message: b → s$\nu\bar{\nu}$ is boringly **clean**
- Neutrinos are the only current way of probing 3rd family leptons in FCNC
- I focus on b → s, but s → d has recently been probed via K → $\pi\nu\bar{\nu}$ [NA62 '24]

Branching ratios

$$\frac{d\mathcal{B}(B \to K \nu\bar{\nu})_{\rm SM}}{dq^2} = 3\,\tau_B\,|N_B|^2 |C_L^{\rm SM}|^2 |\lambda_t|^2 \rho_+^K\,,$$

$$N_{B_q} = \frac{G_F \alpha_{\rm em}}{16\pi^2}\sqrt{\frac{m_{B_q}}{3\pi}}$$

$$\frac{d\mathcal{B}(B \to K^* \nu\bar{\nu})_{\rm SM}}{dq^2} = 3\,\tau_B\,|N_B|^2 |C_L^{\rm SM}|^2 |\lambda_t|^2 (\rho_{A_1}^{K^*} + \rho_{A_{12}}^{K^*} + \rho_V^{K^*})\,,$$

$$\rho_+^K = \frac{\lambda^{3/2}}{m_B^4}\left(f_+^K(q^2)\right)^2,$$

$$\rho_V^{K^*} = \frac{2\,q^2\lambda^{3/2}}{(m_B + m_{K^*})m_B^4}\left(V^{K^*}(q^2)\right)^2,$$

$$\rho_{A_1}^{K^*} = \frac{2\,q^2\lambda^{1/2}(m_B + m_{K^*})^2}{m_B^4}\left(A_1^{K^*}(q^2)\right)^2,$$

$$\rho_{A_{12}}^{K^*} = \frac{64\,m_{K^*}^2\,\lambda^{1/2}}{m_B^2}\left(A_{12}^{K^*}(q^2)\right)^2,$$

Dominant sources of uncertainties:

- The CKM element $|\lambda_t|$
- The Wilson coefficient C_L
- The form-factors ρ^M

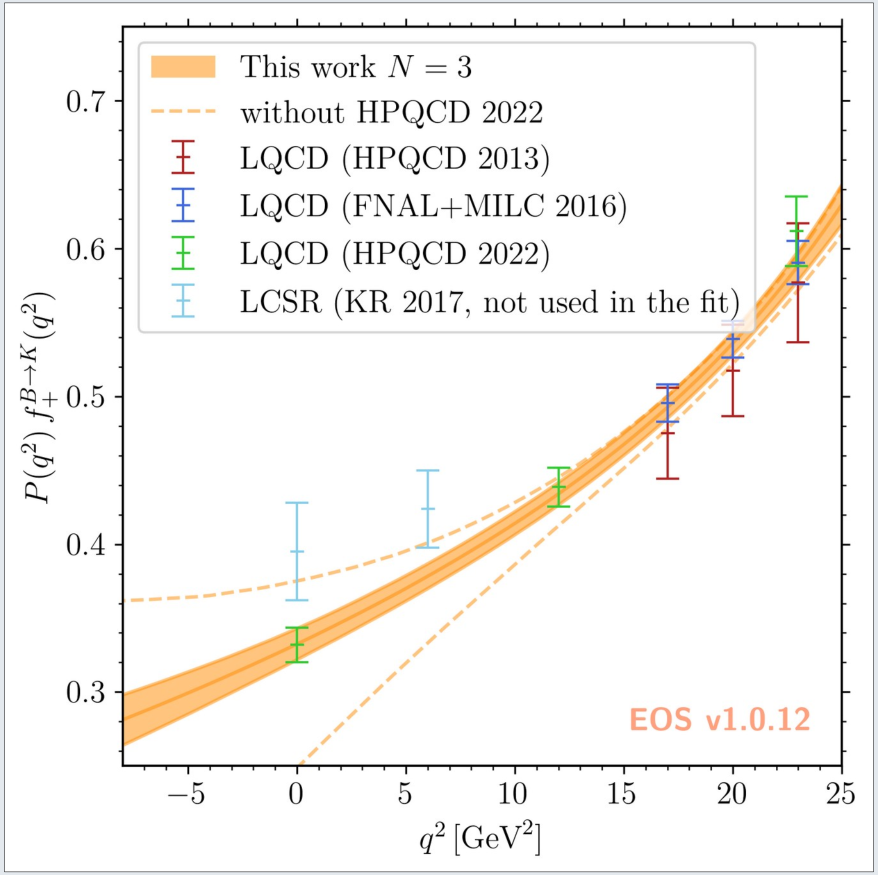
[Buras, Girrbach-Noe *et al* ‘14]

Form factors

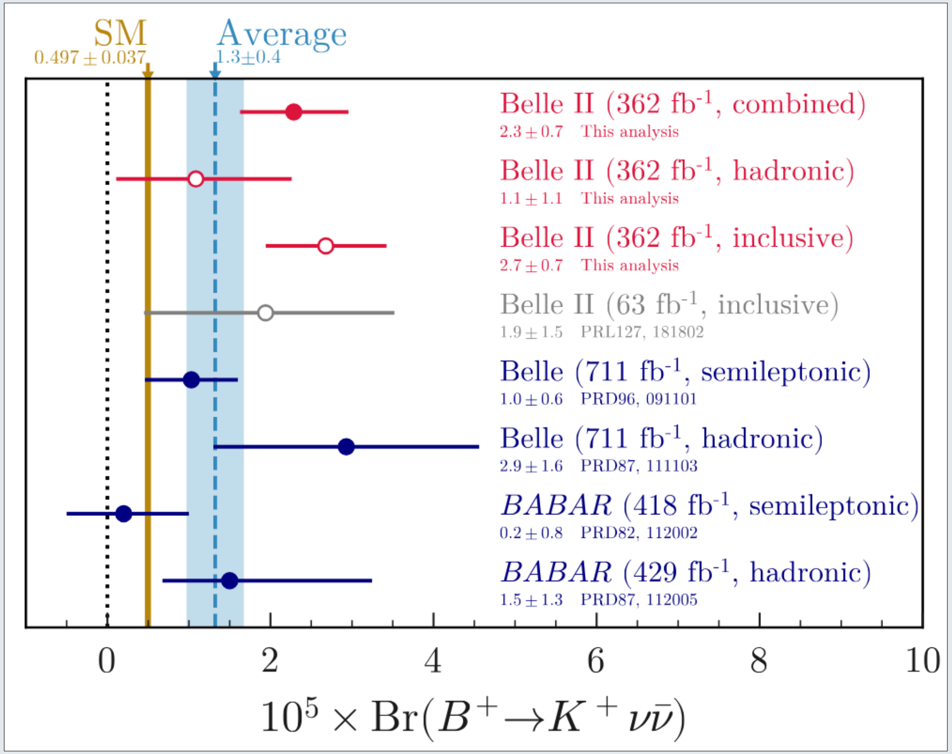
- State-of-the-art form-factor predictions [Boyd, Grinstein, Lebed '94; '97; Gubernari, MR *et al* '23]
  - Lattice QCD and LCSR estimates
  - Analyticity constraints
  - Dispersive bounds
  - Multi-channel analyses
- Investigate **tension between LQCD and LCSR**

$$r_{\mathrm{lh}} = \frac{\mathcal{B}(B \to K\nu\bar{\nu})_{\mathrm{low}-q^2}}{\mathcal{B}(B \to K\nu\bar{\nu})_{\mathrm{high}-q^2}}$$

→ Cancellation of normalization, CKM, WC (i.e. heavy NP!), experimental uncertainties, …
[Bečirević, Piazza, Sumensari '23]



Experimental status



[Belle II '23]

- Combined measurement shows

  3.5σ evidence over the background

  2.7σ 'tension' with SM prediction

- See Sally's talk for all the details

- This measurement is model-dependent, the signal is assumed to follow a **SM shape** (keep this in mind for later)

$$\mathscr{B}(B \to K^* \nu\bar{\nu}) < 2.7 \times 10^{-5},$$

@90% CL [Belle '17]

Slightly beyond the SM (only SM-like neutrinos)

- There is only one additional dim-6 operator that can be written with the SM fields

$$\mathcal{O}_R^{\nu_i\nu_j} = \frac{e^2}{(4\pi)^2}(\bar{s}_R\gamma_\mu b_R)(\bar{\nu}_i\gamma^\mu(1-\gamma_5)\nu_j)$$

- No additional theory uncertainties

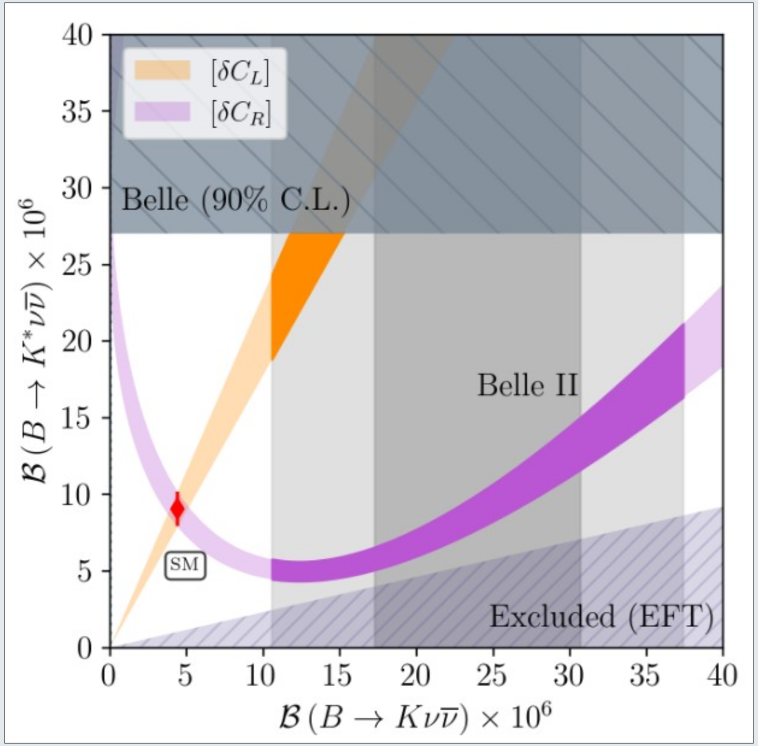
$$\frac{d\mathcal{B}(B \to K\, \nu\bar{\nu})}{dq^2} = 3\,\tau_B\, |N_B|^2|C_L + C_R|^2|\lambda_t|^2\rho_+^K \;,$$

$$\frac{d\mathcal{B}(B \to K^*\, \nu\bar{\nu})}{dq^2} = 3\,\tau_B|N_B|^2|\lambda_t|^2\left(|C_L - C_R|^2(\rho_{A_1}^{K^*} + \rho_{A_{12}}^{K^*}) + |C_L + C_R|^2\rho_V^{K^*}\right)$$

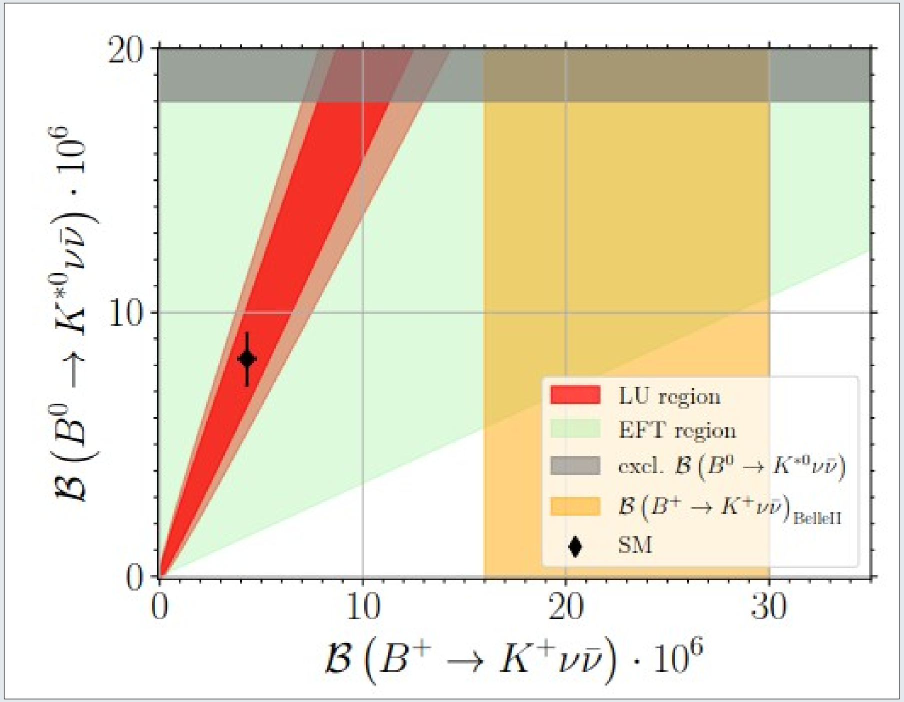
- Clear **blind direction** for pseudo-scalar kaon

Slightly beyond the SM (only SM-like neutrinos)

- Left-handed currents alone cannot account for the current tension



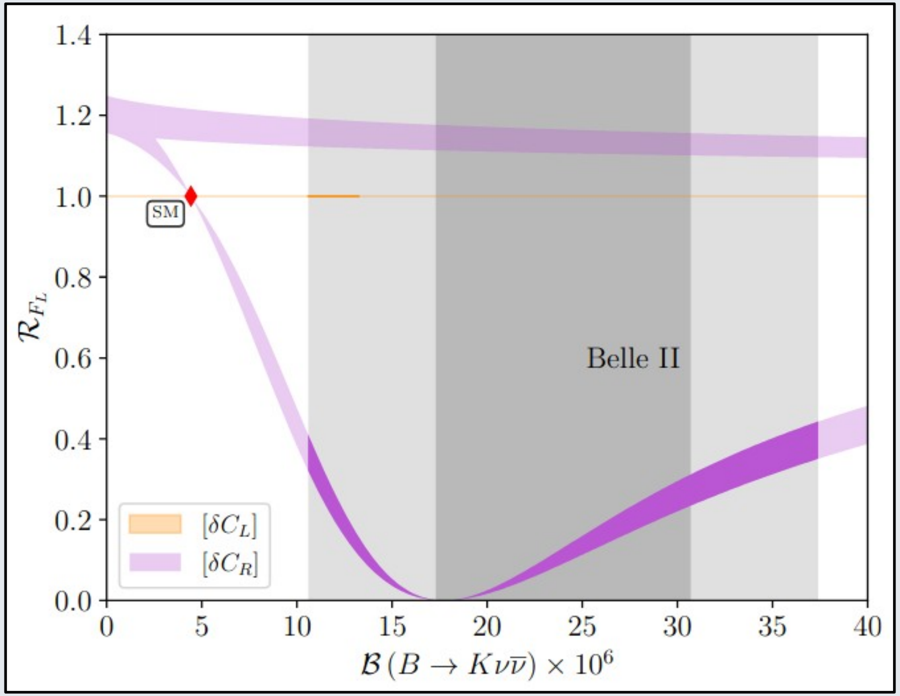
[Bečirević, Piazza, Sumensari ‘23]



[Bause, Gisbert, Hiller ‘23]

Other observables (1)

- With a bit more data, one can measure more involved observables such as:
  - Longitudinal fraction [Buras, Girrbach-Noe *et al* ‘14; Altmannshofer, Buras *et al* ‘09…]



$$F_L(B \to K^* \nu\bar{\nu})_{\rm SM} = \frac{\rho^{K^*}_{A_{12}}}{\rho^{K^*}_{A_1} + \rho^{K^*}_{A_{12}} + \rho^{K^*}_{V}}$$

$$F_L(B \to K^* \nu\bar{\nu}) = \frac{|C_L - C_R|^2 \rho^{K^*}_{A_{12}}}{|C_L - C_R|^2(\rho^{K^*}_{A_1} + \rho^{K^*}_{A_{12}}) + |C_L + C_R|^2 \rho^{K^*}_{V}}$$

Other observables (2)

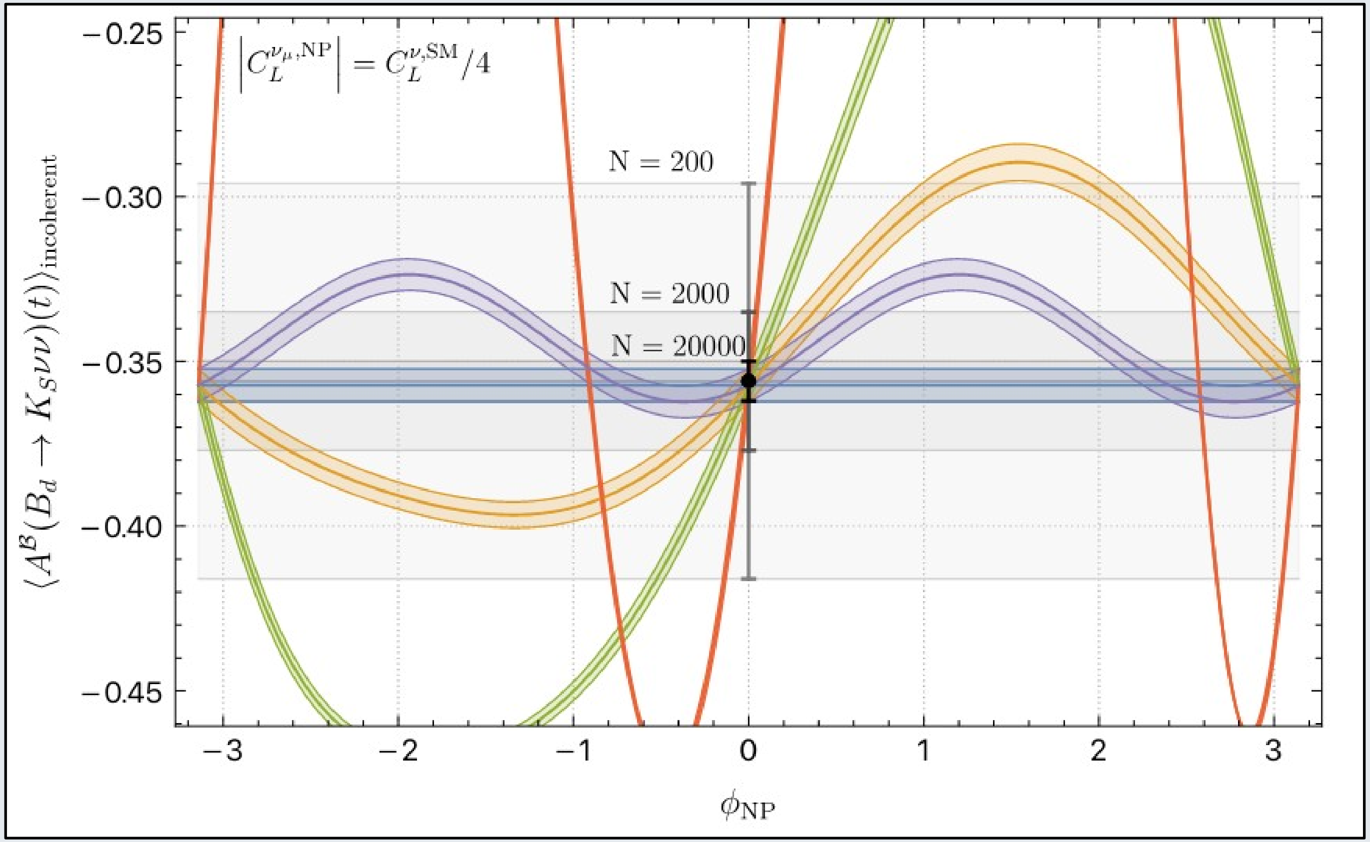
- With a bit more data, one can measure more involved observables such as:
  - Longitudinal fraction [Buras, Girrbach-Noe *et al* ‘14; Altmannshofer, Buras *et al* ‘09…]
  - (mixing induced) CP-asymmetries [Descotes-Genon, Fajfer *et al* ‘22]

    → gives a **clean access to the phase of the WC** (many cancellations)

    → e.g. for $B^0 \to K_S \nu\nu$, this gives direct access to:

$$\mathrm{Im}[e^{-2i\beta}(V_{tb}V_{ts}^*)^2(C_L^\nu + C_R^\nu)^2]$$

$B^0 \to K_S \nu\bar{\nu}$ direct CP asymmetry



Rule of thumb:

- Belle II 50 ab^{-1}
  → N = 200
- FCC-ee Tera Z
  → N > 20k

Colors:

- Blue (flat) → SM
- Other → benchmark BSM models

[Descotes-Genon, Fajfer *et al* ‘22]

Other observables (3)

- With a bit more data, one can measure more involved observables such as:
  - Longitudinal fraction [Buras, Girrbach-Noe *et al* ‘14; Altmannshofer, Buras *et al* ‘09…]
  - (mixing induced) CP-asymmetries [Descotes-Genon, Fajfer et al ‘22]
  - ν/ℓ ratio [Bečirević, Piazza, Sumensari ‘23]:

$$\mathcal{R}_K^{(\nu/l)}[1.1,6]\Big|_{\rm SM} = 7.58 \pm 0.04 \qquad \mathcal{R}_{K^*}^{(\nu/l)}[1.1,6]\Big|_{\rm SM} = 8.6 \pm 0.3$$

Summed over the three ν and ℓ = e, μ
(minimalist implementation of the charm-loops…)

BSM analysis

- As discussed, the B → Kνν analysis assumes the **SM kinematics**.
- In general, such analyses require theory inputs for the form-factors:
  - For fully reconstructed final-state, the uncertainty assigned to form-factors is **usually small** (but has to be checked!)
  - For partially reconstructed final-state, this can be a **large source of uncertainties**
- In the case of B → Kνν, switching on **scalar or tensor WC** changes the kinematics completely, as they involve other form-factors!
- Sometimes overlooked in the literature.

$$\frac{d\Gamma}{dq^2} = 3\left(\frac{4G_F}{\sqrt{2}}\frac{\alpha}{2\pi}\right)^2 \left|V_{ts}^* V_{tb}\right|^2 \frac{\sqrt{\lambda_{BK}}q^2}{(4\pi)^3 M_B^3} \times \left[\frac{\lambda_{BK}}{24q^2}\left|f_+(q^2)\right|^2 \left|C_{\rm VL}+C_{\rm VR}\right|^2 + \frac{\left(M_B^2-M_K^2\right)^2}{8\left(m_b-m_s\right)^2}\left|f_0(q^2)\right|^2\left|C_{\rm SL}+C_{\rm SR}\right|^2 + \frac{2\lambda_{BK}}{3\left(M_B+M_K\right)^2}\left|f_T(q^2)\right|^2\left|C_{\rm TL}\right|^2\right],$$

Reinterpretation

- Several techniques have been developed:
  - **Full reinterpretation**: new MC samples are created based on an alternative model [CheckMate; MadAnalysis5; RECAST]
  - **Simplified reinterpretation**: assumes the kinematic distribution to be weakly impacted by BSM physics [SModels]
  - **Reweighting**: Use the existing simulation but reweight the distributions according to a new model [HAMMER; Gärtner, MR *et al* '24]
- The choice of the tool completely depends on the experimental analysis

→ **Compromise** between the needs and the computational cost

Our reinterpretation framework in a nutshell

Updated model
(WCs, resonances...)

Nuisance parameters
(form factors, CKM entries...)

- Analytic implementation
- Plotting framework
- Bayesian analysis (model sampling, ...)
- Discretisation (correlated uncertainties, ...)

EOS

Updated signal
or background
distributions σ_1

Model
likelihood

Analysis framework

Efficiency maps

Signal benchmark
MC distributions σ_0

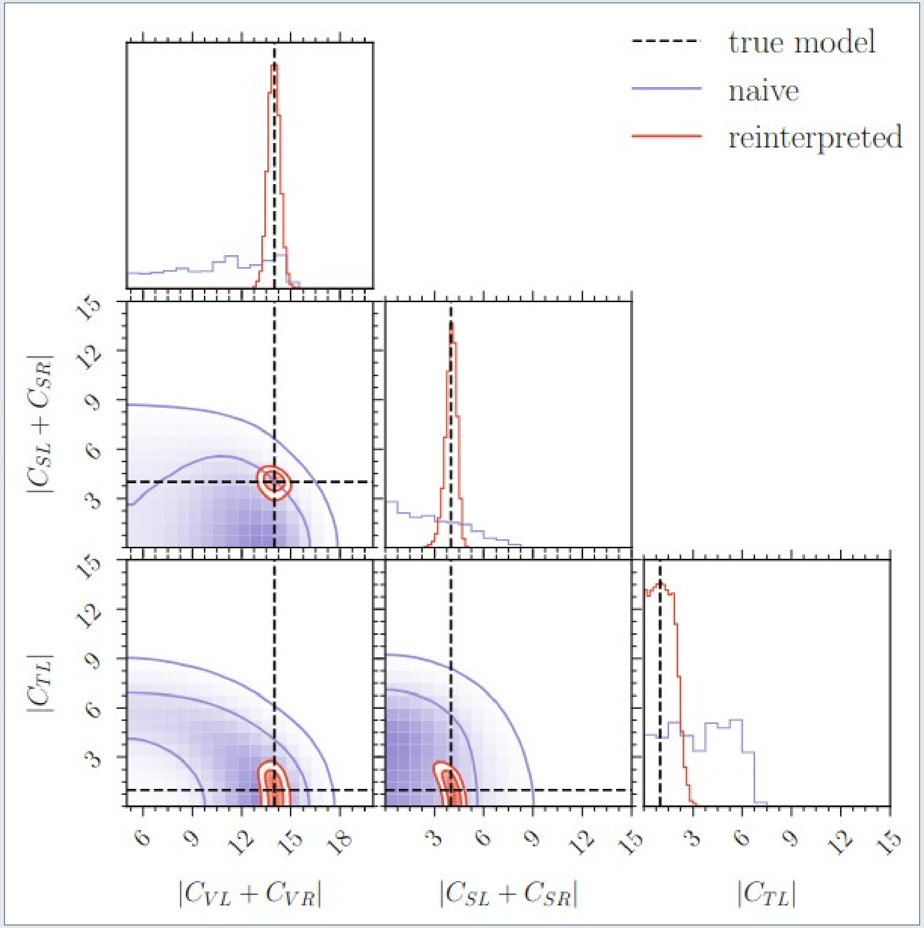
Experimental datapoints
and background shapes

pyhf [Feickert, Heinrich *et al* '21; '24]

- Weights $w_z = \frac{\sigma_{1,z}}{\sigma_{0,z}} = \frac{\int_{\text{bin } z} dz' \; \sigma_1(z')}{\int_{\text{bin } z} dz' \; \sigma_0(z')}$
- Fit framework (MCMC sampling with **Bayesian pyhf** [Feickert, Heinrich, Horstmann '23])

Concrete examples (1)

- Comparison between the posterior of a WC analysis with and without reinterpreting the data:
  - 2 blind directions are due to the decay ($C_{VL} - C_{VR}$, $C_{SL} - C_{SR}$)
  - Reinterpreting the data increases the sensitivity drastically
- The plot is a 50 ab^{-1} projection of the B → Kνν analysis [Gärtner, MR *et al* '24]

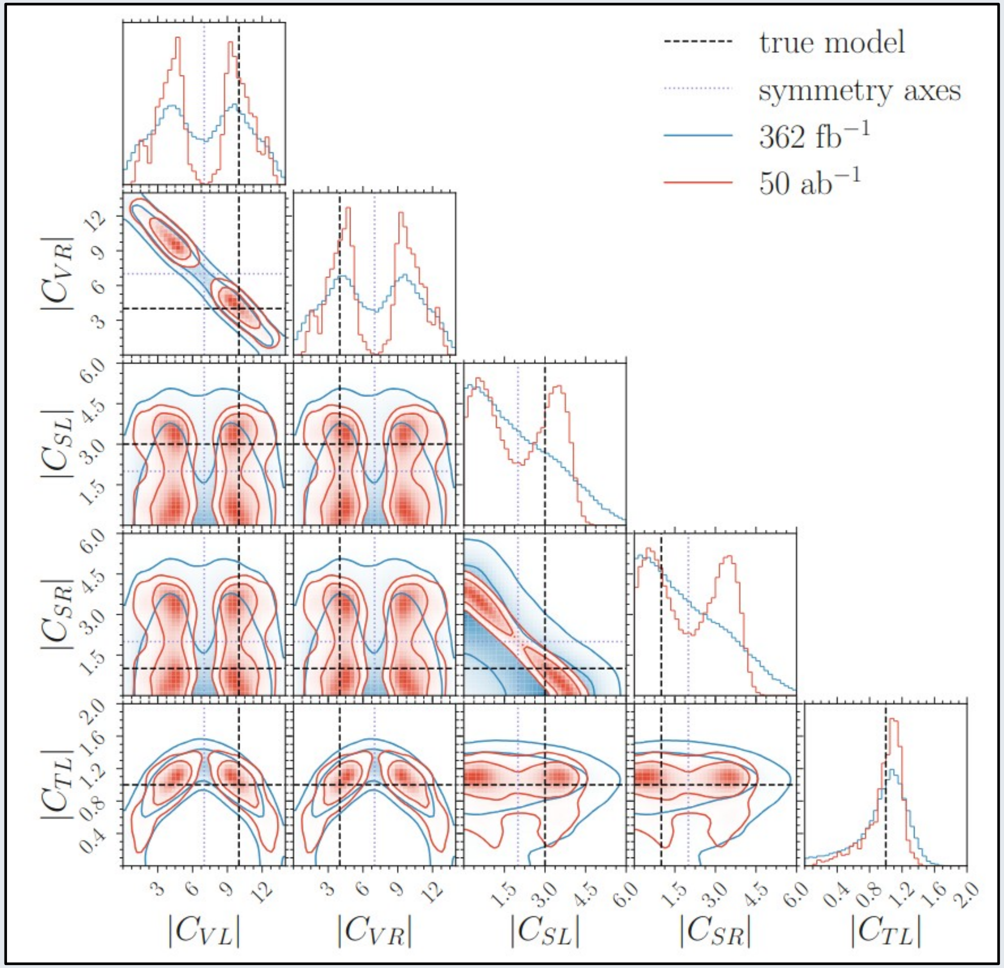


Concrete examples (2)

- This framework can easily be generalized to a **combined analysis** of $B \to K \nu\bar{\nu}$ and $B \to K^* \nu\bar{\nu}$ branching ratios

- Symmetry axes will prevent from an unambiguous WC determination
$\to$ angular analyses will be needed

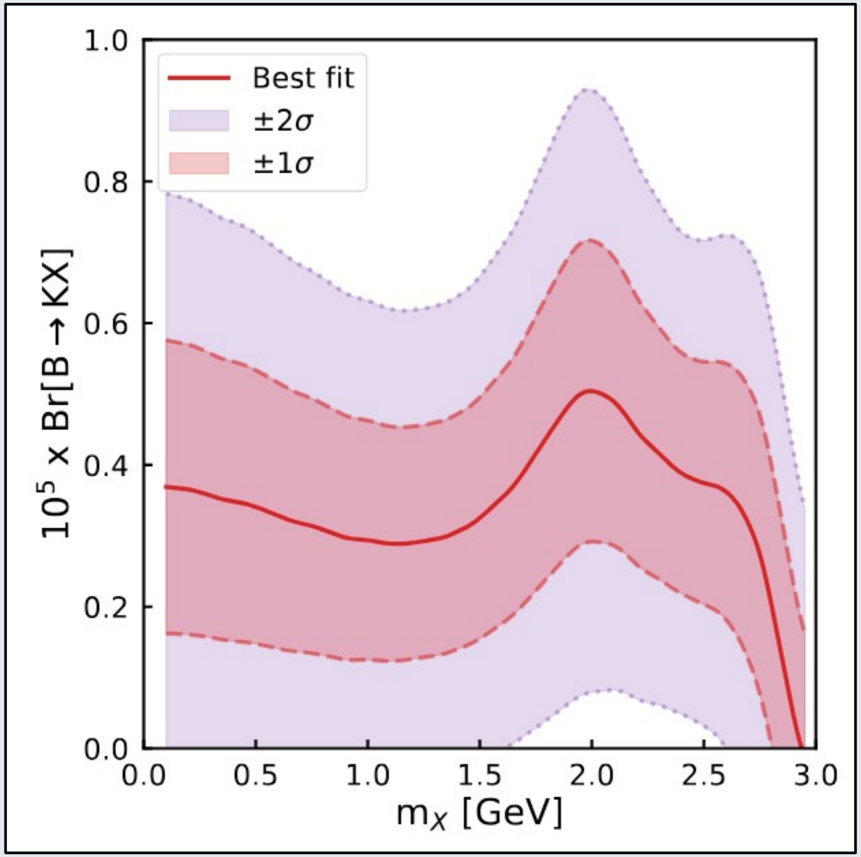
- Current luminosity vs full Belle II dataset differs mostly in the scalar sector



[Gärtner, MR *et al* '24]

Light new physics

- The Belle II $B \to K\nu\bar{\nu}$ results shows a slight excess for $q^2 \sim 4$ GeV^2, motivating a **light new physics** interpretation, $B \to KX$ [Altmannshofer, Crivellin *et al* '23]
  - A **bump search** is performed assuming a Gaussian signal with experimental width only
  - **pyhf** is used with the maximal amount of experimental information → would require a fully reinterpreted analysis [Belle II (Gärtner), w.i.p.]
  - Current data favors $m_X \sim 2$ GeV



Future of $b \to s\nu\nu$

- $q_i \to q_j \nu\bar{\nu}$ are very promising transitions but remain an experimental challenge
- As far as $b \to s\nu\bar{\nu}$ is concerned, only $B \to K^{(*)} \nu\bar{\nu}$ decays are currently measurable
- A *tera-Z* run at FCC-ee, if it is build, would however open **many possibilities**:
  - (10^{12} Z bosons) x ($Br(Z \to b\bar{b}) = 0.15$) = lot of *b* hadrons*! ("LEP in a minute")
  - All of this in a **clean environment**
  - With many interaction points (as opposed to a linear design).

* But also *c* hadrons: $Br(Z \to c\bar{c} = 0.12)$

Future of $b \to s\nu\nu$

- Future e^+e^- (CEPC, FCCee) will give access to many $b \to s\nu\nu$ modes
- Let's focus on **charged 4-body modes** (for the tracking)

Decay mode	$\mathcal{B}/\lvert\lambda_t\rvert^2\,[10^{-3}]$	$\mathcal{B}\,[10^{-6}]$
$B^0 \to K^0_S \nu\bar{\nu}$	1.33 ± 0.04	2.02 ± 0.12
$B^0 \to K^{*0} \nu\bar{\nu}$	5.13 ± 0.51	7.93 ± 0.89
$B^0_s \to \phi \nu\bar{\nu}$	6.31 ± 0.67	9.74 ± 1.15
$\Lambda^0_b \to \Lambda \nu\bar{\nu}$	5.55 ± 0.56	8.57 ± 0.97

[Amhis, MR *et al* '23]

With current form-factor uncertainties

FCCee analysis (briefly)

- **We generated** 4 signal MC samples as well as background (inclusive $Z \to b\bar{b}$, $Z \to c\bar{c}$, $Z \to q\bar{q}$) samples
  - We assumed an IDEA detector design
  - The kinematic is generated via weights from the generated phase-space-only events and EOS predictions (LQCD + LCSR)
- **We developed** 4 dedicated analyses
  - Assumption: perfect vertex seeding and perfect PID
  - 2-step BDT optimization
- **We studied** few (inclusive) backgrounds

[Amhis, MR *et al* ‘23]

Results

- Final results for the K* and φ modes:

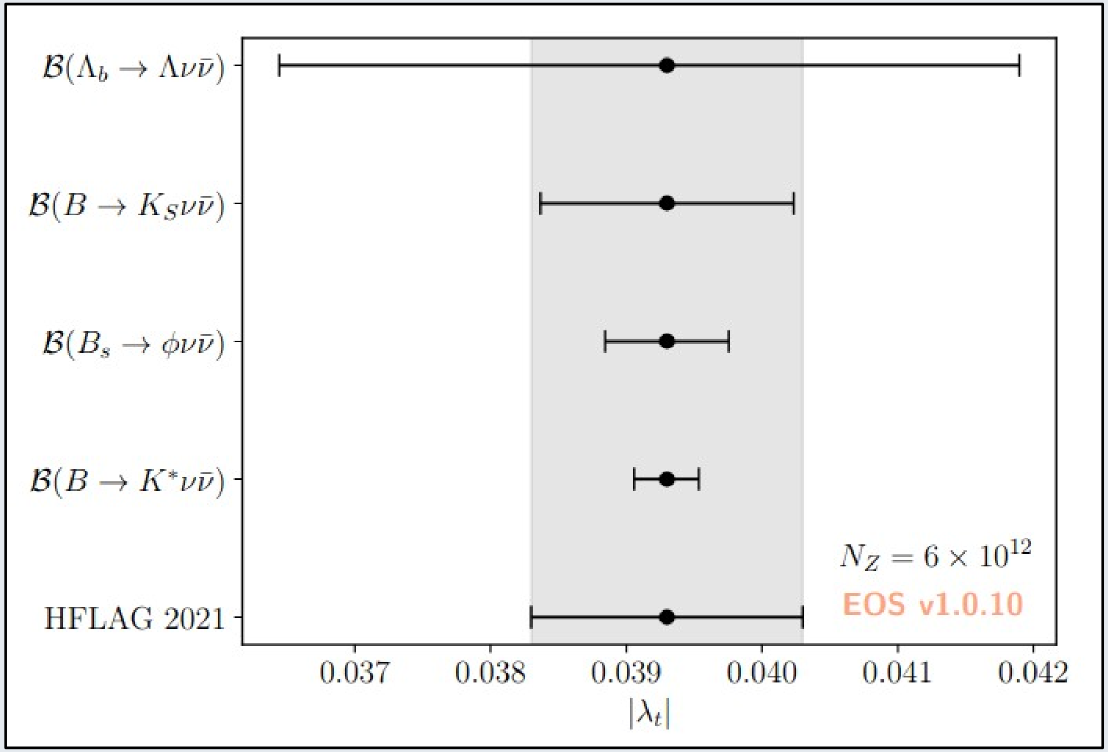
Mode	N_S	N_B	ϵ^s	$\epsilon^{b\bar{b}}$	$\epsilon^{c\bar{c}}$	$\epsilon^{q\bar{q}}$	S/B	$\sqrt{S+B}/S$
$B^0 \to K^{*0}\nu\bar{\nu}$	231 K	1.27 M	3.7%	$\mathcal{O}(10^{-7})$	$\mathcal{O}(10^{-9})$	$\mathcal{O}(10^{-9})$	0.17	0.53%
$B_s^0 \to \phi\nu\bar{\nu}$	61 K	0.48 M	7.4%	$\mathcal{O}(10^{-7})$	$\mathcal{O}(10^{-9})$	$\mathcal{O}(10^{-9})$	0.13	1.20%

- The reconstruction of K_S and Λ were not fully available and the results come from extrapolations: σ(K_S) = 3.37%, σ(Λ) = 9.86%, with purities of 4% and 1.5% respectively

- Rough comparison to the current Belle II sensitivity for the B → Kνν (different analyses), ε(ITA) ~ 5 – 10%, ε(HTA) ~ 0.3 – 0.5%, with a purity of 5% in the signal region

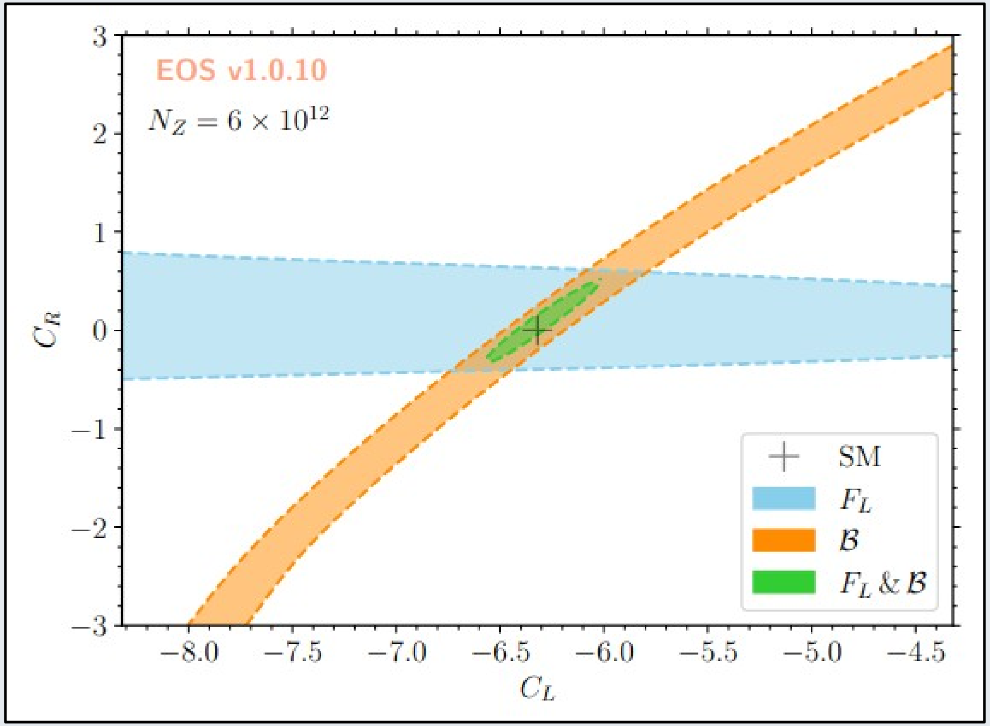
Future phenomenology of $b \to s\nu\nu$

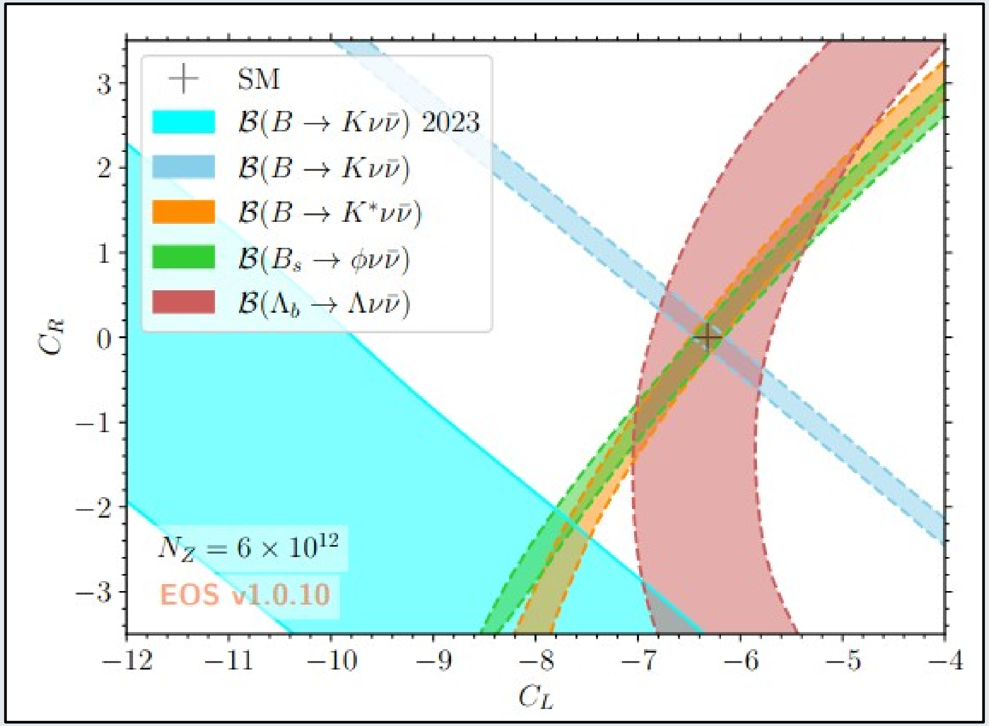
- Assuming these efficiency, we would get clean access to $|\lambda_t|$:



Future phenomenology of b → sνν

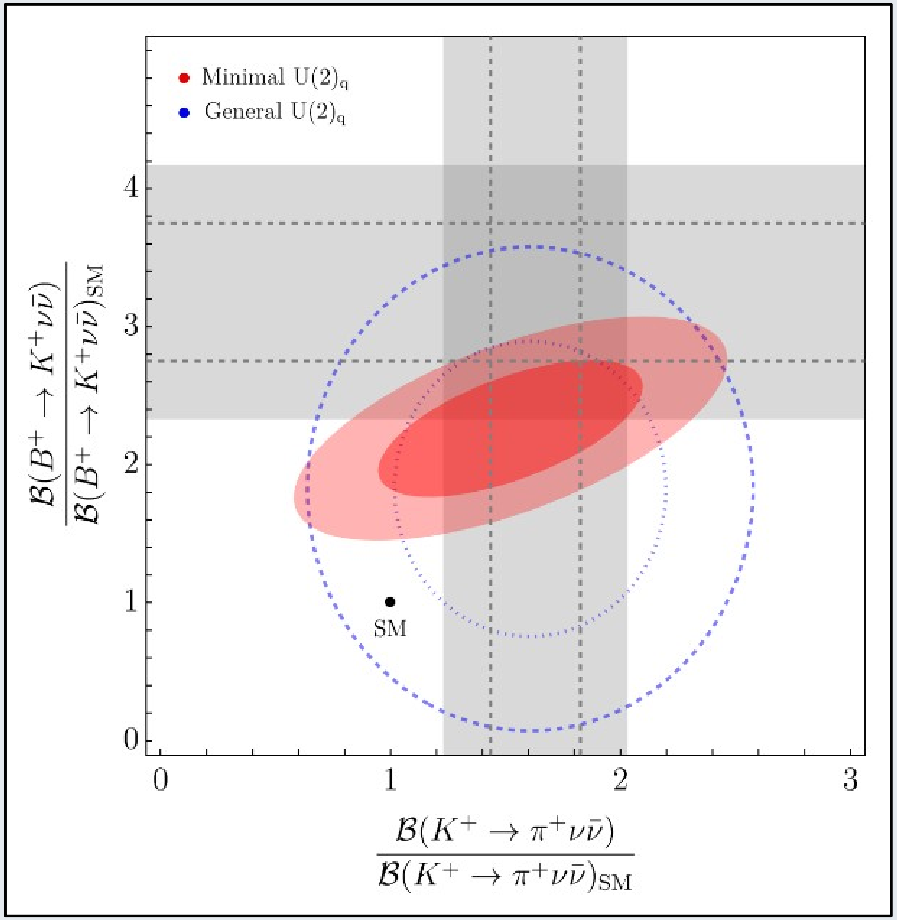
- Assuming these efficiency, we would get clean access to the WET WCs:





Beyond b → sνν

- K → πνν̄ recently measured [NA62 ‘24]
  - Allows to disantangle NP scenarios [Buras, Harz, Mojahed ‘24]
  - Possibility of combined analysis with a flavour structure [Allwicher, Bordone *et al* ‘24]
- Combined analysis in the (ν)SMEFT framework and impact for b → cℓν [Allwicher, Bečirević *et al*; Leal, Rosauro-Alcaraz; Bernlochner, Fedele, *et al*; Datta, Kumar *et al*; Bečirević, Fajfer, *et al*, Marzocca, Nardecchia *et al*; Hou, Li *et al*; Chen, Xu *et al*] (All ‘24, I hope I didn’t forget any groups)



Conclusions

- $b \to s\nu\bar{\nu}$ decays offer plenty of **extremely clean observables**, opening many opportunities for future phenomenology analyses of
  - (B)SM parameters: CKM elements, WET/SMEFT coefficients…
  - QCD effects: form-factors, QCD penguins…
- This comes with the price of **high experimental challenges**
  - At the level of the measurements: missing energy, vertexing…
  - At the level of the interpretation: model-dependent analyses that need to be reinterpreted
- Belle II will already offer a **first set of measurements**, the rest will have to wait for **future colliders**

Back-up slides

More observables (for FCC-ee)

$$\frac{d\mathcal{B}(B^0 \to K_S^0 \nu\bar\nu)_{\rm SM}}{dq^2} = 3\,\tau_{B^0} |N_{B^0}|^2 |C_L^{\rm SM}|^2 |\lambda_t|^2 \rho_+^{K_S^0}\,,$$

$$\frac{d\mathcal{B}(B^0 \to K^{*0} \nu\bar\nu)_{\rm SM}}{dq^2} = 3\,\tau_{B^0} |N_{B^0}|^2 |C_L^{\rm SM}|^2 |\lambda_t|^2 (\rho_{A_1}^{K^{*0}} + \rho_{A_{12}}^{K^{*0}} + \rho_V^{K^{*0}})\,,$$

$$\frac{d\mathcal{B}(B_s^0 \to \phi \nu\bar\nu)_{\rm SM}}{dq^2} = 3\,\tau_{B_s^0} |N_{B_s^0}|^2 |C_L^{\rm SM}|^2 |\lambda_t|^2 (\rho_{A_1}^{\phi} + \rho_{A_{12}}^{\phi} + \rho_V^{\phi})\,,$$

$$\frac{d\mathcal{B}(\Lambda_b^0 \to \Lambda \nu\bar\nu)_{\rm SM}}{dq^2} = 3\,\tau_{\Lambda_b^0} |N_{\Lambda_b^0}|^2 |C_L^{\rm SM}|^2 |\lambda_t|^2 (\rho^\Lambda_{f_\perp^V} + \rho^\Lambda_{f_\perp^A} + \rho^\Lambda_{f_0^V} + \rho^\Lambda_{f_0^A})\,,$$

$$\rho_+^{K_S^0} = \frac{\lambda^{3/2}}{2 m_{B^0}^4} \left(f_+^K(q^2)\right)^2,$$

$$\rho_V^{K^{*0}} = \frac{2\,q^2 \lambda^{3/2}}{(m_{B^0} + m_{K^{*0}}) m_{B^0}^4} \left(V^{K^*}(q^2)\right)^2,$$

$$\rho_{A_1}^{K^{*0}} = \frac{2\,q^2 \lambda^{1/2} (m_{B^0} + m_{K^{*0}})^2}{m_{B^0}^4} \left(A_1^{K^*}(q^2)\right)^2,$$

$$\rho_{A_{12}}^{K^{*0}} = \frac{64\, m_{K^{*0}}^2 \lambda^{1/2}}{m_{B^0}^2} \left(A_{12}^{K^*}(q^2)\right)^2,$$

$$\rho^\Lambda_{f_\perp^{V/A}} = \frac{32\,q^2 \lambda^{1/2} ((m_{\Lambda_b^0} \mp m_\Lambda)^2 - q^2)}{m_{\Lambda_b^0}^4} \left(f_\perp^{V/A}(q^2)\right)^2,$$

$$\rho^\Lambda_{f_0^{V/A}} = \frac{16\,\lambda^{1/2} (m_{\Lambda_b^0} \pm m_\Lambda)^2 ((m_{\Lambda_b^0} \mp m_\Lambda)^2 - q^2)}{m_{\Lambda_b^0}^4} \left(f_0^{V/A}(q^2)\right)^2,$$

$$F_L(B^0 \to K^{*0} \nu\bar\nu)_{\rm SM} = \frac{\rho_{A_{12}}^{K^{*0}}}{\rho_{A_1}^{K^{*0}} + \rho_{A_{12}}^{K^{*0}} + \rho_V^{K^{*0}}}\,,$$

$$F_L(B_s^0 \to \phi \nu\bar\nu)_{\rm SM} = \frac{\rho_{A_{12}}^{\phi}}{\rho_{A_1}^{\phi} + \rho_{A_{12}}^{\phi} + \rho_V^{\phi}}\,.$$

$$F_L(\Lambda_b^0 \to \Lambda \nu\bar\nu)_{\rm SM} = \frac{\rho^\Lambda_{f_0^V} + \rho^\Lambda_{f_0^A}}{\rho^\Lambda_{f_\perp^V} + \rho^\Lambda_{f_\perp^A} + \rho^\Lambda_{f_0^V} + \rho^\Lambda_{f_0^A}}\,,$$

$$A_{\rm FB}^\Lambda(\Lambda_b^0 \to \Lambda \nu\bar\nu)_{\rm SM} = \frac{\alpha}{2} \frac{\tilde\rho_\perp^\Lambda + \tilde\rho_0^\Lambda}{\rho^\Lambda_{f_\perp^V} + \rho^\Lambda_{f_\perp^A} + \rho^\Lambda_{f_0^V} + \rho^\Lambda_{f_0^A}}\,,$$

$$\tilde\rho_\perp^\Lambda = \frac{32\,q^2 \lambda^{1/2} ((m_{\Lambda_b^0} \mp m_\Lambda)^2 - q^2)}{m_{\Lambda_b^0}^4} f_\perp^V(q^2) f_\perp^A(q^2),$$

$$\tilde\rho_0^\Lambda = \frac{16\,\lambda^{1/2} (m_{\Lambda_b^0} \pm m_\Lambda)^2 ((m_{\Lambda_b^0} \mp m_\Lambda)^2 - q^2)}{m_{\Lambda_b^0}^4} f_0^V(q^2) f_0^A(q^2).$$

$$N_{B_q} = \frac{G_F \alpha_{\rm em}}{16\pi^2} \sqrt{\frac{m_{B_q}}{3\pi}}$$