

# Signatures of Light New Particles in $B \rightarrow K^{(*)} E_{\text{miss}}$

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Based on: arXiv:2403.13887

Patrick Bolton, Svjetlana Fajfer, Jernej F. Kamenik, Martín Novoa-Brunet

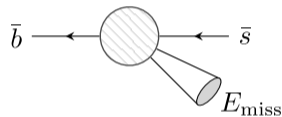
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Quirks in Quark Flavour Physics 2024



## Introduction

- We look at b-decays ( $b \rightarrow s$ ) with invisible final states
  - FCNC process
  - Loop suppressed in the SM (potential sensitivity to NP)
- Undetected particles (neutrinos) in the final state
  - Experimentally challenging compared to charged leptons
- Theoretically cleaner than charged lepton FCNC
  - Hadronic matrix elements (local form factors) are well understood
  - No non-local hadronic matrix elements involved
- Tension between Exp and SM (Belle II) at  $2.7\sigma$
- How can we explain this?
  - Heavy NP vs **New Light NP**
  - EFT approach for New Light Physics (Invisible Extended LEFT/SMEFT)

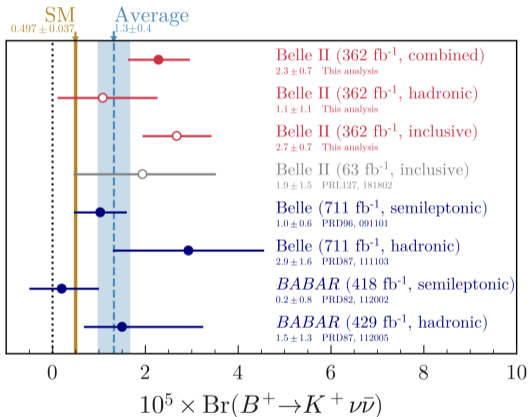


[A. Buras 2020; A. J. Buras et al. 2015]

[Bečirević et al. 2023; Gubernari et al. 2023; Athron et al. 2023]

## Experimental Status

- SM prediction:  $\mathcal{B}(B \rightarrow K\nu\bar{\nu}) = (5.58 \pm 0.37) \times 10^{-6}$   
 [Parrott et al. 2023]
- Recent Belle II measurement  
 $\mathcal{B}(B \rightarrow KE_{\text{miss}}) = (2.3 \pm 0.7) \times 10^{-5}$  [Adachi et al. 2023]
  - “New” inclusive tag (ITA) vs hadronic or semileptonic tags
  - Assuming  $\nu\bar{\nu} \Rightarrow E_{\text{miss}}$  tension of  $2.7\sigma$  w.r.t. SM



- Complementary bounds on  $b \rightarrow s\nu\bar{\nu}$

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$$\mathcal{B}(B \rightarrow KE_{\text{miss}}) = (2.3 \pm 0.7) \times 10^{-5} \quad [\text{Adachi et al. 2023}]$$

- “New” inclusive tag (ITA) vs hadronic or semileptonic tags
- Assuming  $\nu\bar{\nu} \Rightarrow E_{\text{miss}}$  tension of  $2.7\sigma$  w.r.t. SM
- $q^2$  distribution available
- $q^2$  approxed by  $q_{\text{rec}}^2$  since 4-momentum of tagged B meson not reconstructed in ITA

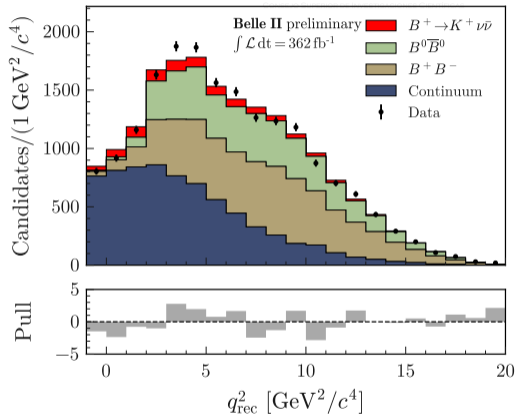
- Complementary bounds on  $b \rightarrow s\nu\bar{\nu}$  :

- BaBar  $\mathcal{B}(B \rightarrow K^*E_{\text{miss}}) < 11 \times 10^{-5}$
- ALEPH Recast  $\mathcal{B}(B_s \rightarrow E_{\text{miss}}) < 5.4 \times 10^{-4}$  (90% CL)
- Other BaBar and Belle constraints on  $\mathcal{B}(B \rightarrow K^{(*)}E_{\text{miss}})$  available however no  $q^2$  distribution

[Lees et al. 2013]

[Alonso-Álvarez et al. 2023; Barate et al. 2001]

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## Theoretical Framework: Heavy NP EFT

- One approach: Heavy NP  $\Rightarrow$  LEFT/WET

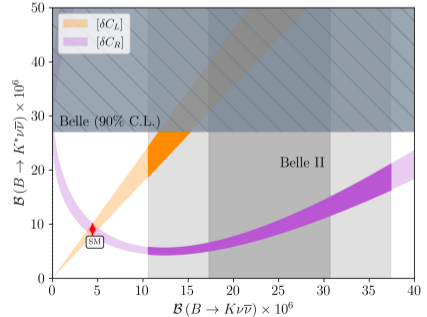
$$\mathcal{L}_{\text{eff}}^{b \rightarrow s\nu\nu} = \frac{4G_F}{\sqrt{2}} \lambda_t \sum_a C_a \mathcal{O}_a + \text{h.c.} \quad \mathcal{O}_{L(R)}^{\nu_i\nu_j} = \frac{e^2}{(4\pi)^2} (\bar{s}_{L(R)} \gamma_\mu b_{L(R)}) (\bar{\nu}_i \gamma^\mu (1 - \gamma_5) \nu_j)$$

- NP act as rescaling in  $B \rightarrow K$  (same form factor dependence)

$$\begin{aligned} \delta\mathcal{B}_{K^{(*)}}^{\nu\bar{\nu}} &= \sum_i \frac{2\text{Re}[C_L^{\text{SM}} (\delta C_L^{\nu_i\nu_i} + \delta C_R^{\nu_i\nu_i})]}{3|C_L^{\text{SM}}|^2} \\ &+ \sum_{i,j} \frac{|\delta C_L^{\nu_i\nu_j} + \delta C_R^{\nu_i\nu_j}|^2}{3|C_L^{\text{SM}}|^2} \\ &- \eta_{K^{(*)}} \sum_{i,j} \frac{\text{Re}[\delta C_R^{\nu_i\nu_j} (C_L^{\text{SM}} \delta_{ij} + \delta C_L^{\nu_i\nu_j})]}{3|C_L^{\text{SM}}|^2}, \end{aligned}$$

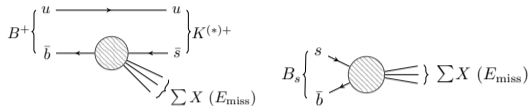
$$\eta_K = 0 \text{ and } \eta_{K^*} = 3.33(7)$$

- No anomalous effects on  $q^2$  spectrum
- What about light NP?



[Allwicher et al. 2024]

## Theoretical Framework: Invisible Extended SMEFT



- Consider additional invisible final states ( $\sum X$ )
  - One or two particle final states (avoid phase space suppression)
- $X \in \{\phi, \psi, V_\mu, \Psi_\mu\}$  massive particles of spin  $J = \{0, 1/2, 1, 3/2\}$

$$\sum X \in \{\phi, V, \phi\bar{\phi}, \psi\bar{\psi}, V\bar{V}, \Psi\bar{\Psi}\}$$

- Singlet under the SM gauge group  $SU(3)_c \times SU(2)_L \times U(1)_Y$  (can be charged under dark gauge or global symmetry)
  - Leads to only interactions involving gauge-invariant combinations of SM fields
- Interactions through renormalizable dim-4 operators (portals) or higher-dimensional effective operators (mediated by heavy NP)

$$\mathcal{L} = \underbrace{\mathcal{L}_{\text{SM}+X}}_{\text{dim}=4} + \sum_i \underbrace{C_i^{(d)} \mathcal{O}_i^{(d)}}_{\text{dim}>4}$$

## Theoretical Framework: Invisible Extended LEFT/WET

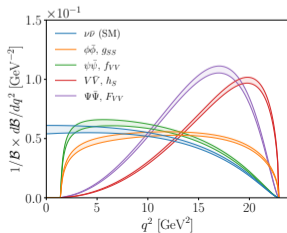
- $B$  decays  $\Rightarrow$  LEFT/WET (EW and top integrated out)

### LEFT (parity basis)

$$\mathcal{H}_{\text{eff}}^S \supset \bar{s}b \left[ g_S \phi + \frac{g_{SS}}{\Lambda} \phi^\dagger \phi + \frac{h_S}{\Lambda} V_\mu^\dagger V^\mu + \frac{f_{SS}}{\Lambda^2} \bar{\psi} \psi + \frac{f_{SP}}{\Lambda^2} \bar{\psi} \gamma_5 \psi + \frac{F_{SS}}{\Lambda^2} \bar{\Psi}^\rho \Psi_\rho + \frac{F_{SP}}{\Lambda^2} \bar{\Psi}^\rho \gamma_5 \Psi_\rho \right]$$

$$\mathcal{H}_{\text{eff}}^V \supset \bar{s} \gamma_\mu b \left[ h_V V^\mu + \frac{g_{VV}}{\Lambda^2} i \phi^\dagger \overleftrightarrow{\partial}^\mu \phi + \frac{f_{VV}}{\Lambda^2} \bar{\psi} \gamma^\mu \psi + \frac{f_{VA}}{\Lambda^2} \bar{\psi} \gamma^\mu \gamma_5 \psi + \frac{F_{VV}}{\Lambda^2} \bar{\Psi}^\rho \gamma^\mu \Psi_\rho + \frac{F_{VA}}{\Lambda^2} \bar{\Psi}^\rho \gamma^\mu \gamma_5 \Psi_\rho \right]$$

$$\mathcal{H}_{\text{eff}}^T \supset \bar{s} \sigma_{\mu\nu} b \left[ \frac{h_T}{\Lambda} V^{\mu\nu} + \frac{f_{TT}}{\Lambda^2} \bar{\psi} \sigma^{\mu\nu} \psi + \frac{F_{TT}}{\Lambda^2} \bar{\Psi}^\rho \sigma^{\mu\nu} \Psi_\rho + \frac{F_{TS}}{\Lambda^2} \bar{\Psi}^{\rho[\mu} \Psi^{\nu]} + \frac{F_{TP}}{\Lambda^2} \bar{\Psi}^{\rho[\mu} \gamma_5 \Psi^{\nu]} \right]$$



- The  $P$ -odd quark currents:
  - $V \rightarrow A$  and  $\bar{s} \gamma_\mu b \rightarrow \bar{s} \gamma_\mu \gamma_5 b$
  - $S \rightarrow P$  and  $\bar{s} b \rightarrow \bar{s} \gamma_5 b$
  - $T \rightarrow \tilde{T}$  and  $\bar{s} \sigma_{\mu\nu} b \rightarrow \bar{s} \sigma_{\mu\nu} \gamma_5 b$
- New light states generate different  $q^2$ -distributions depending on spin, mass and coupling.

## Likelihood Reconstruction

- We determine the distribution of Belle II and BaBar events in the reconstructed momentum transfer,  $q_{\text{rec}}^2$

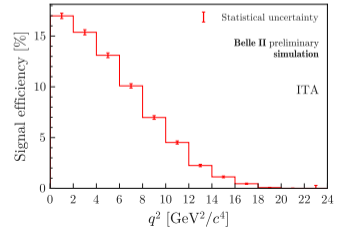
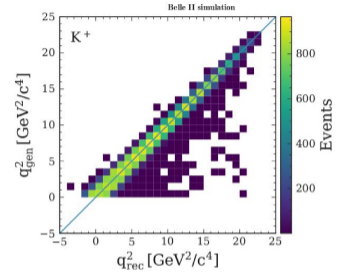
$$\frac{dN_{\text{SM}(X)}}{dq_{\text{rec}}^2} = N_B \int dq^2 f_{q_{\text{rec}}^2}(q^2) \epsilon(q^2) \frac{d\mathcal{B}_{\text{SM}(X)}}{dq^2}$$

- $N_B$  : number of  $BB$  pairs
- $f_{q_{\text{rec}}^2}(q^2)$  : smearing of  $q_{\text{rec}}^2$
- $\epsilon(q^2)$  : detector efficiency

- SM ( $X$ ) signal for  $i$ -bin

$$s_{\text{SM}(X)}^i = \int_{q_{\text{rec},i}^2}^{q_{\text{rec},i+1}^2} dq_{\text{rec}}^2 \frac{dN_{\text{SM}(X)}}{dq_{\text{rec}}^2}$$

- Important experimental input, recasting is not trivial
  - Collaborations should provide methods of recasting [Gärtner et al. 2024]





## Likelihood Reconstruction

- Total expected event count in  $i$ -bin

$$n_{\text{exp}}^i = \mu \left(1 + \theta_{\text{SM}}^i\right) s_{\text{SM}}^i + \left(1 + \theta_X^i\right) s_X^i(m_X, c_X) + \sum_b \tau_b \left(1 + \theta_b^i\right) b^i$$

- $\mu$  signal strength parameter (SM rescaling)
- $s_{\text{SM}(X)}^i$  Expected SM(NP) signals (NP depends on mass  $m_X$  and coupling  $c_X$ )
- $b^i$  Expected background signal for the background  $b$
- $\tau_b$  Overall background normalisation for the background  $b$
- $\theta_x$  Nuisance parameters for Monte-Carlo / theory uncertainties

## Full combined likelihood

$$L_{\text{SM}+X} = \prod_i^{N_{\text{bins}}} \text{Pois} \left[ n_{\text{obs}}^i, n_{\text{exp}}^i(\mu, m_X, c_X, \theta_x, \tau_b) \right] \times \prod_{x=\text{SM}, X, b} \mathcal{N}(\theta_x; \mathbf{0}, \Sigma_x) \times \prod_b \mathcal{N}(\tau_b; 0, \sigma_b^2)$$

## Likelihood Reconstruction: Bin Correlations

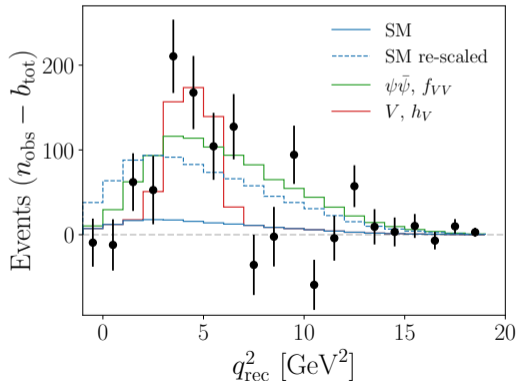
$$L_{SM+X} = \prod_i^{N_{\text{bins}}} \text{Poiss} \left[ n_{\text{obs}}^i, n_{\text{exp}}^i(\mu, m_X, c_X, \boldsymbol{\theta}_x, \tau_b) \right] \times \prod_{x=\text{SM}, X, b} \mathcal{N}(\boldsymbol{\theta}_x; \mathbf{0}, \Sigma_x) \times \prod_b \mathcal{N}(\tau_b; 0, \sigma_b^2)$$

### Correlation treatment

- Correlations relevant since  $q^2$  smearing introduces correlations among  $q_{\text{rec}}^2$  bins
- $\Sigma_{\text{SM}}$ : obtained through Monte-Carlo simulation of SM Signal
  - We include uncertainties on efficiency and form factors
- $\Sigma_X$ : Similar to SM but we neglect correlations between bins
  - Speeds up calculation
  - We check that it doesn't have an impact in the minimum
- $\Sigma_b$ : SD obtained from MC statistical uncertainties, while correlations, are estimated by re-scaling SM correlations.

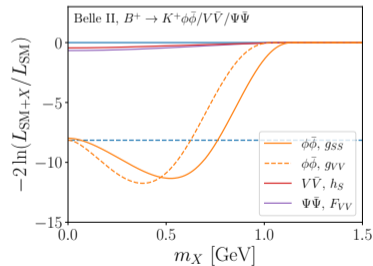
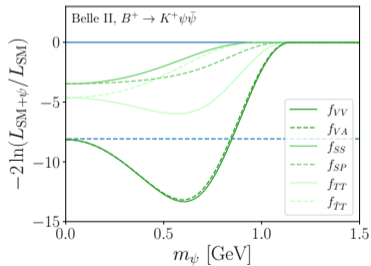
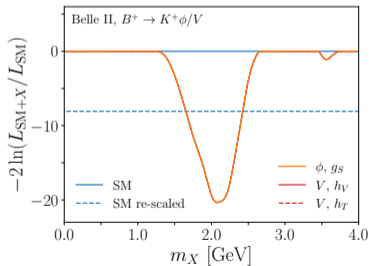
## Signal Hypotheses / Best Fit Points

- Three types of signal hypothesis:
  1. SM ( $\mu = 1$  and  $s_X^i = 0$ )
  2. Re-scaled SM ( $\mu$  is a free nuisance parameter and  $s_X^i = 0$ )
  3. SM + NP ( $\mu = 1$  and  $s_X^i \neq 0$ ) considering separately each NP final state  $\sum X$  and its possible couplings  $c_X$ .
- First two hypotheses :
  - Crosscheck of Recast
  - Benchmark for NP
- We fit only Belle II data for bfp and 1D data
- Best two- and three-body decays
  - $B^+ \rightarrow K^+ V$ 
    - »  $m_V = 2.1$  GeV
    - »  $h_V = 7.1 \times 10^{-9}$
    - »  $\text{pull}_{\text{SM}} = 4.5\sigma$
  - $B^+ \rightarrow K^+ \bar{\psi}\psi$ 
    - »  $m_\psi = 0.6$  GeV
    - »  $f_{VV}/\Lambda^2 = 1.7 \times 10^{-2} \text{ TeV}^{-2}$
    - »  $\text{pull}_{\text{SM}} = 3.7\sigma$



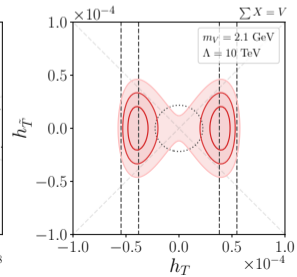
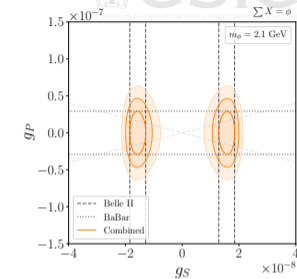
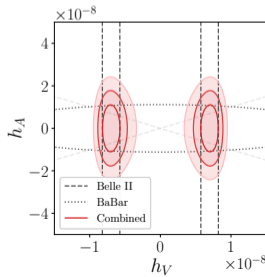
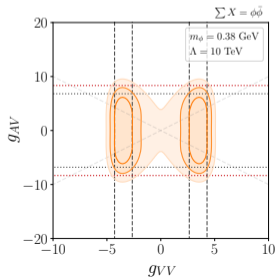
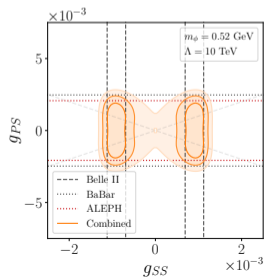
## Profile Likelihoods - mass

- We profile over mass using only Belle II data
- The two-body decay likelihood ( $B \rightarrow K$ ) is independent of the nature of the light NP state and the coupling
- Three-body decays:
  - Scalar boson  $\phi$  ( $g_{SS}, g_{VV}$ )
  - Spin 1/2 Fermion  $\psi$  ( $f_{VV}, f_{VA}$ )



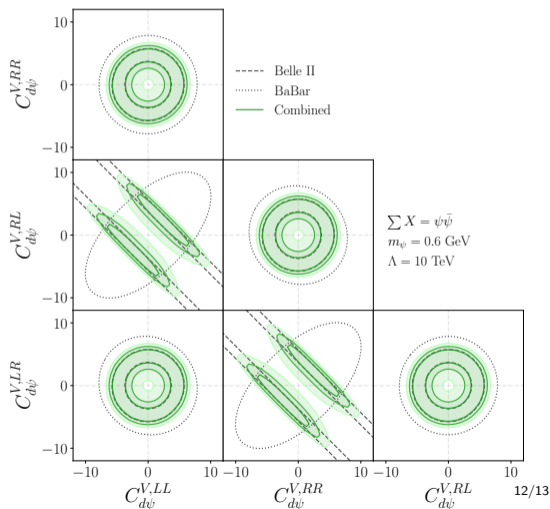
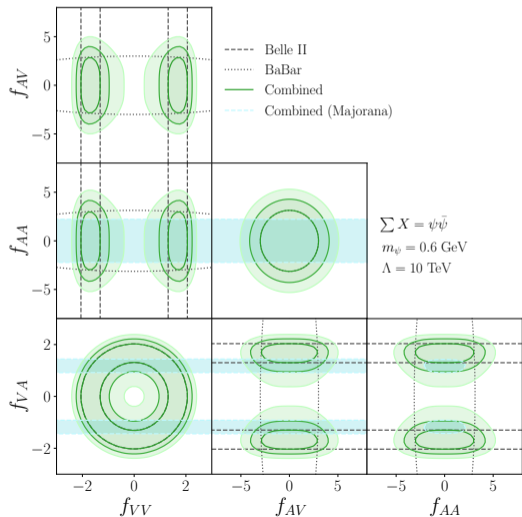
## 2D Profile Likelihoods - couplings

- Allowed values for 2d combinations of couplings (parity vs chiral bases)
- ALEPH  $B_s \rightarrow E_{\text{miss}}$  constrains relevant for new scalar  $X = \phi\bar{\phi}$
- $B \rightarrow K$  and  $B \rightarrow K^*$  orthogonal in parity basis except for tensor couplings for  $X = V$



## 2D Profile Likelihoods - couplings: Parity vs Chiral

- Orthogonality of constraints is basis dependent



- Invisible Extended EFT provides a systematic way of considering light NP with minimal assumptions
  - Can be matched to specific models
- New light states provide a better description of the shape of data than SM rescaling
  - Significance of up to  $4.5\sigma$
  - Heavy NP acts similarly to rescaling SM when looking only at  $B \rightarrow K$  branching
  - When including  $B \rightarrow K^*$  different chiral structures
- Look for missing backgrounds with a similar signature to best fit points? ( $\phi\bar{\phi}$  close to kaon mass)
- Recasting not trivial and important information is lost from the analysis
  - Collaborations could provide easily recastable results

[Gärtner et al. 2024]

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