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

Based on: arXiv:2403.13887

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Introduction

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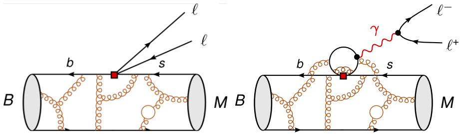
  - Form factors
  - Non-local contributions from $c\bar{c}$ loops



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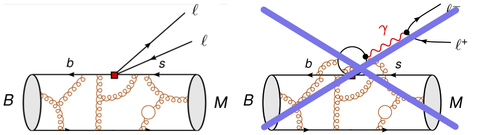
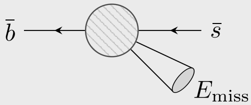


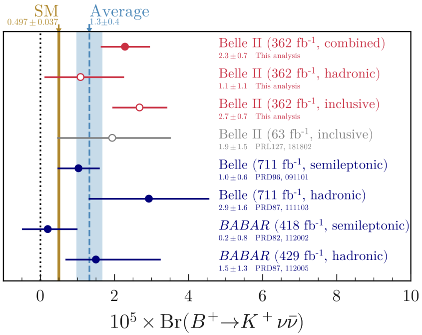
What about $b \to s\nu\bar{\nu}$

- Theoretically cleaner than charged lepton FCNC [A. Buras 2020; A. J. Buras et al. 2015]
  - Hadronic matrix elements (local form factors) are fairly well understood [Bečirević et al. 2023; Gubernari et al. 2023; Athron et al. 2023]
  - No non-local hadronic matrix elements involved
- Undetected particles (neutrinos) in the final state
  - You can only measure $b \to sE_{\text{miss}}$
  - Experimentally challenging compared to charged leptons



Experimental Status

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



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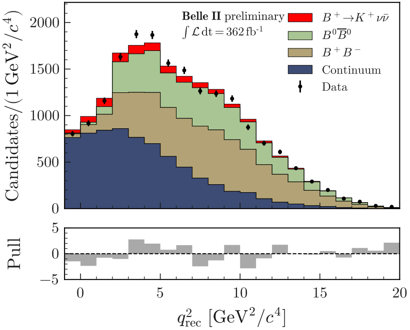
  - q^2 distribution available
  - q^2 approxed by q^2_{rec} since 4-momentum of tagged B meson not reconstructed in ITA



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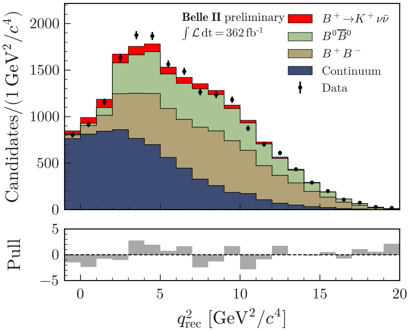

- Complementary bounds on $b \to s\nu\bar{\nu}$:
  - BaBar $\mathcal{B}(B \to K^* E_{\text{miss}}) < 11 \times 10^{-5}$ [Lees et al. 2013]
  - ALEPH Recast $\mathcal{B}(B_s \to E_{\text{miss}}) < 5.4 \times 10^{-4}$ (90% CL) [Alonso-Álvarez et al. 2023; Barate et al. 2001]
  - Other BaBar and Belle constraints on $\mathcal{B}(B \to K^{(*)} E_{\text{miss}})$ available however no q^2 distribution

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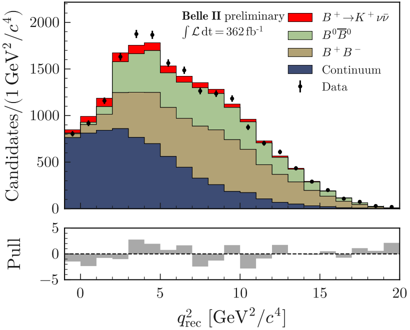

How can we explain this?

- Heavy NP vs Light NP
- EFT approach for Light New Physics (Invisible Extended LEFT/SMEFT)

Theoretical Framework: Heavy NP EFT (Check O. Sumensari's Talk)

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

[Allwicher et al. 2024; Rosauro-Alcaraz et al. 2024]

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

- No anomalous effects on q^2 spectrum
- NP act as rescaling in $B \to K$ (same form factor dependence)

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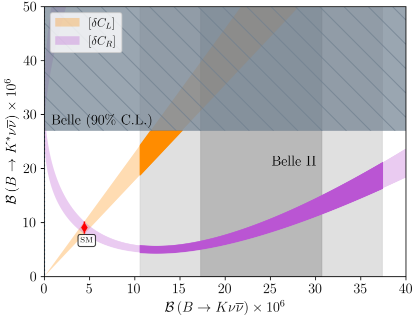
- Combined constrains adding $B \to K^*$ prefer right handed currents

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

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



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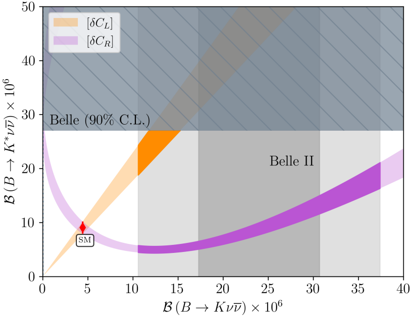
- Combined constrains adding $B\to K^*$ prefer right handed currents
  - Right handed curents $\Rightarrow$ $b\to s\ell^+\ell^-$ and $b\to s\nu\nu$ are correlated in SMEFT

$$\mathcal{L}_{\text{SMEFT}}^{(6)} \supset [\mathcal{C}_{ld}]_{ij}\ (\bar{s}_R\gamma^\mu b_R)\left[(\overline{\nu}_{Li}\gamma_\mu\nu_{Lj}) + (\overline{e}_{Li}\gamma_\mu e_{Lj})\right]$$

  - Constrains from $b\to s\mu^+\mu^-$ require LFUV (NP only on τ and ν_τ)



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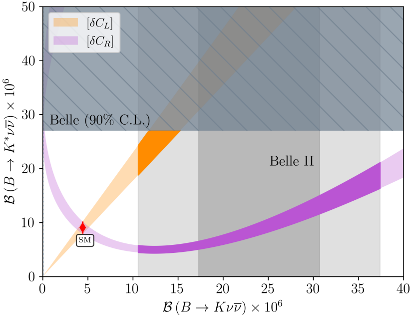
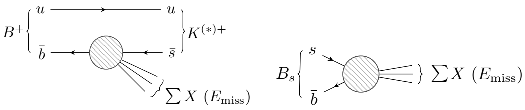
  - Constrains from $b \to s\mu^+\mu^-$ require LFUV (NP only on τ and ν_τ)
- What about light NP?



[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

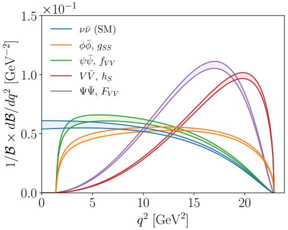
- B decays $\Rightarrow$ LEFT/WET (EW and top integrated out)

LEFT (parity basis)

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

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

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



- The P-odd quark currents:
  - $V \to A$ and $\bar{s}\gamma_\mu b \to \bar{s}\gamma_\mu\gamma_5 b$
  - $S \to P$ and $\bar{s}b \to \bar{s}\gamma_5 b$
  - $T \to \tilde{T}$ and $\bar{s}\sigma_{\mu\nu}b \to \bar{s}\sigma_{\mu\nu}\gamma_5 b$
- 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^2_{rec}

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

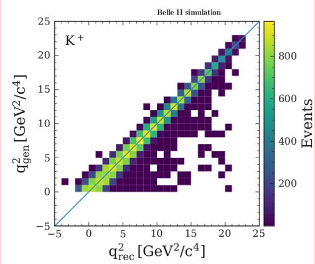
  - N_B : number of BB pairs
  - $f_{q^2_{\text{rec}}}(q^2)$: smearing of q^2_{rec}
  - $\epsilon(q^2)$: detector efficiency

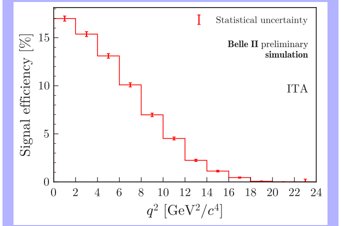
- SM (X) signal for i-bin

$$s^i_{\text{SM}(X)} = \int_{q^2_{\text{rec},i}}^{q^2_{\text{rec},i+1}} dq^2_{\text{rec}} \, \frac{dN_{\text{SM}(X)}}{dq^2_{\text{rec}}}$$

- Important experimental input, recasting is not trivial
  - Collaborations should provide methods of recasting (for instance reweigthing methods)

[Gärtner et al. 2024]





Likelihood Reconstruction

- Total expected event count in i-bin

$$n^i_{\text{exp}} = \mu \left(1 + \theta^i_{\text{SM}}\right) s^i_{\text{SM}} + \left(1 + \theta^i_X\right) s^i_X(m_X, c_X) + \sum_b \tau_b (1 + \theta^i_b) b^i$$

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

Full combined likelihood

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

Likelihood Reconstruction: Bin Correlations

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

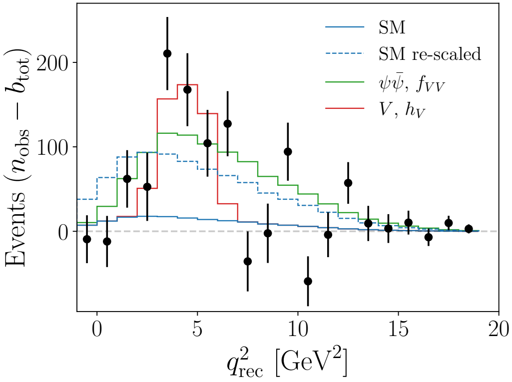
Correlation treatment

- Correlations relevant since q^2 smearing introduces correlations among q^2_{rec} bins
- Σ_{SM}: obtained through Monte-Carlo simulation of SM Signal
  - We include uncertainties on efficiency and form factors
- Σ_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
- Σ_b: SD obtained from MC statistical uncertainties, while correlations, are estimated by re-scaling SM correlations.

Signal Hypotheses / Best Fit Points

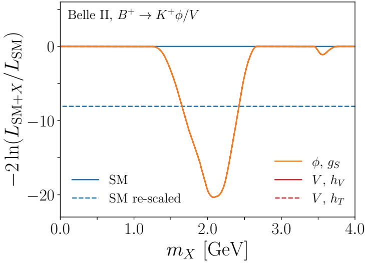
- Three types of signal hypothesis:
  1. SM ($\mu = 1$ and $s^i_X = 0$)
  2. Re-scaled SM (μ is a free nuisance parameter and $s^i_X = 0$)
  3. SM + NP ($\mu = 1$ and $s^i_X \neq 0$) considering separately each NP final state $\sum X$ and its possible couplings c_X.

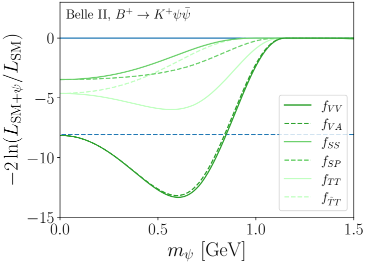
- First two hypotheses :
  - Crosscheck of Recast
  - Benchmark for NP
- We fit only Belle II data for bfp and 1D data
- Best two- and three-body decays
  - $B^+ \to K^+ V$
    - $m_V = 2.1$ GeV
    - $h_V = 7.1 \times 10^{-9}$
    - $\text{pull}_{\text{SM}} = 4.5\sigma$
  - $B^+ \to K^+ \bar{\psi}\psi$
    - $m_\psi = 0.6$ GeV
    - $f_{VV}/\Lambda^2 = 1.7 \times 10^{-2}$ TeV^{-2}
    - $\text{pull}_{\text{SM}} = 3.7\sigma$

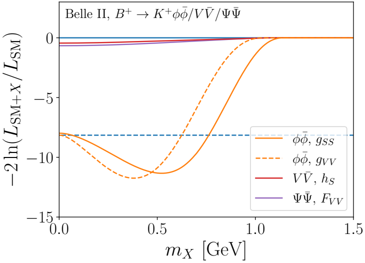


Profile Likelihoods - mass

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

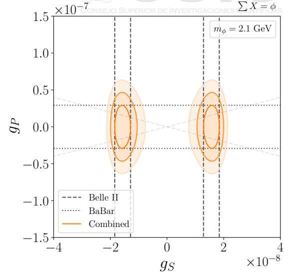


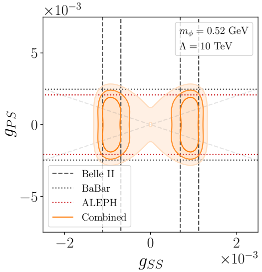


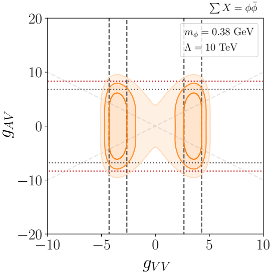


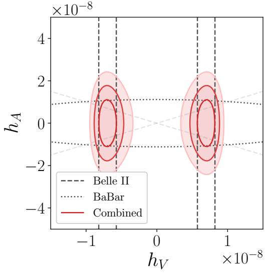
2D Profile Likelihoods - couplings

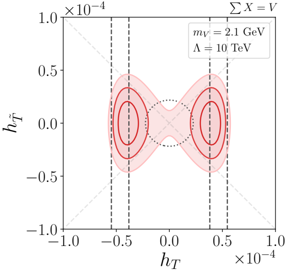
- Allowed values for 2d combinations of couplings (parity vs chiral bases)
- ALEPH $B_s \to E_{\text{miss}}$ constrains relevant for new scalar $X = \phi\bar{\phi}$
- $B \to K$ and $B \to K^*$ orthogonal in parity basis except for tensor couplings for $X = V$





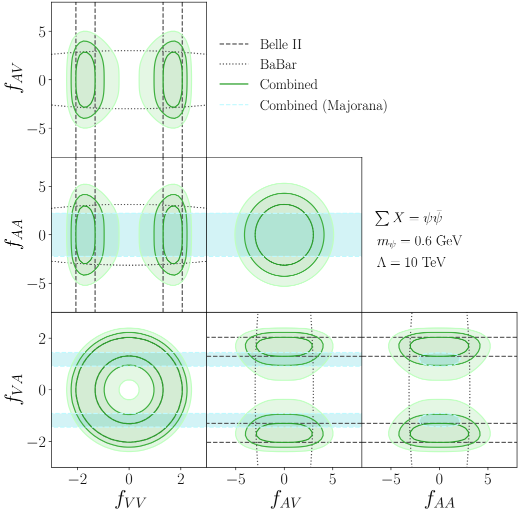


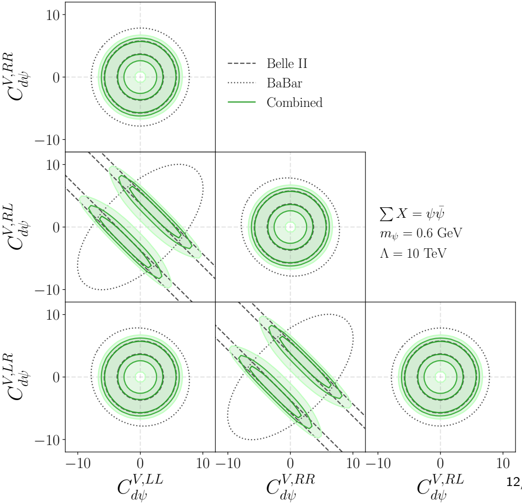




2D Profile Likelihoods - couplings: Parity vs Chiral

- Orthogonality of constraints is basis dependent





Outlook

- Invisible Extended EFT provides a systematic way of considering light NP with minimal assumptions
  - Can be matched to specific models
- New light final states provide a better description of the shape of data than SM rescaling and Heavy NP
  - Significance of up to 4.5σ
  - Heavy NP acts similarly to rescaling SM when looking only at $B \to K$ branching
  - When including $B \to K^*$ 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 can be lost from the analysis
  - It is fundamental that collaborations provide "recastable" results (e.g. reweigthing methods) [Gärtner et al. 2024]

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