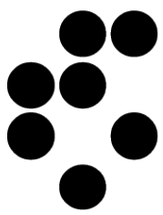
New light particles in $B \to K^{(*)}+$ invisible

Jernej F. Kamenik



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Motivation

- Rare decays of long-lived hadrons prospective probes of BSM
  - FCNC decays relate to flavour puzzle of SM & NP
  - Decays to neutrino final states potentially relate to neutrino mass puzzle of SM

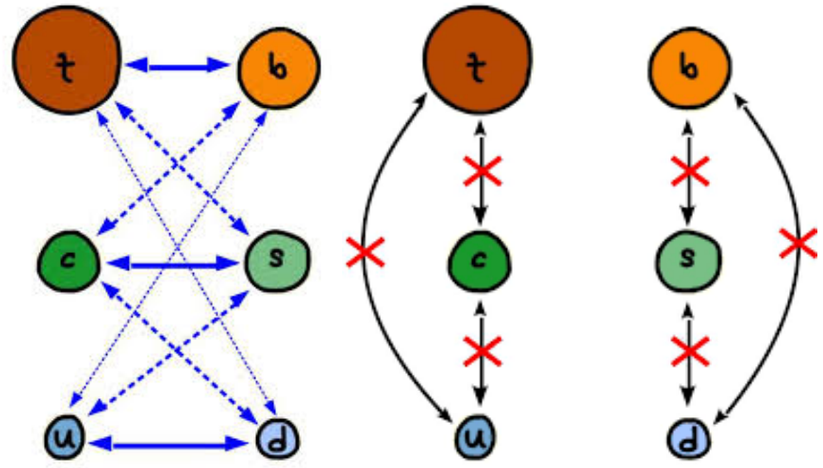
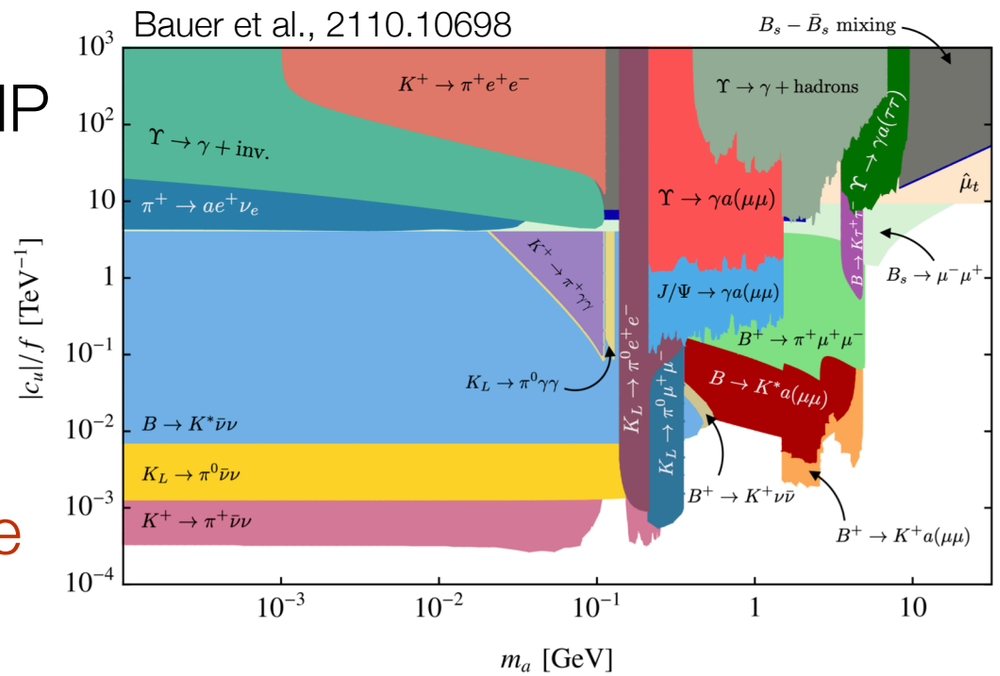


figure by W. Altmannshofer

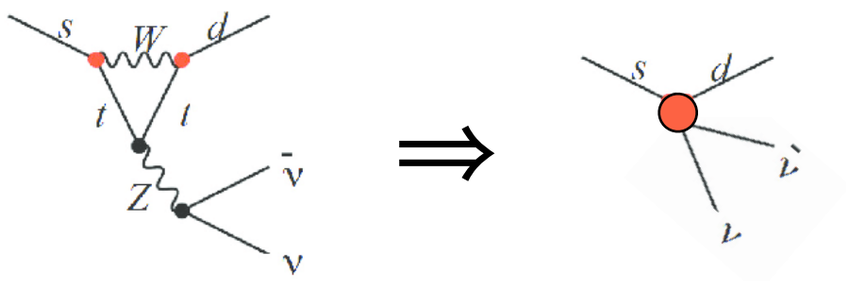
- Traditionally exhibit excellent sensitivity to heavy NP scales
  - Modes with missing energy can probe feebly interacting light NP
    - Potentially relate to cosmological DM puzzle



$b \to s$+invisible in SM

- SM contributions to $b \to s\nu\bar{\nu}, \nu\bar{\nu}\nu\bar{\nu}, \ldots$ dominated by factorizable contributions

$$\mathcal{M} \sim \sum_i C_i \times \langle \mathcal{O}_i \rangle$$



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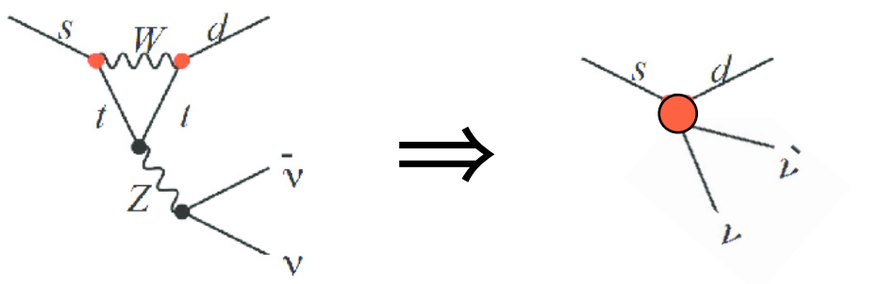
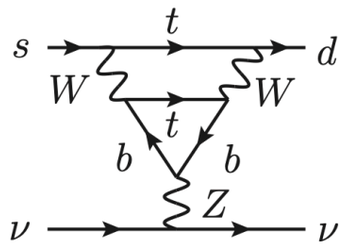
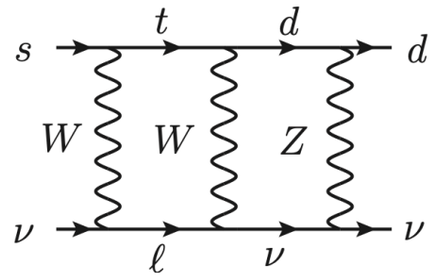
    Brod, Gorbahn & Stamou, 1009.0947







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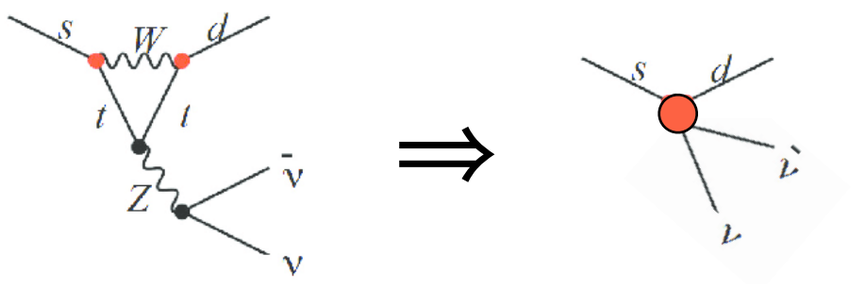
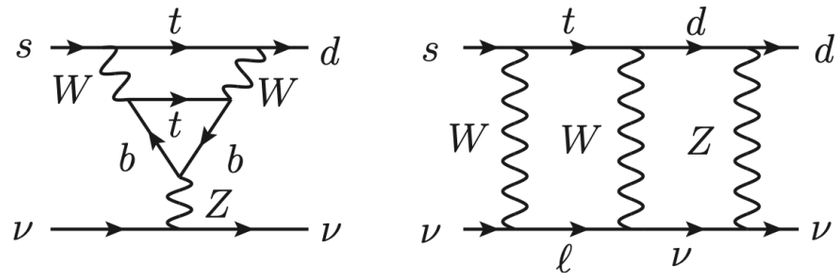
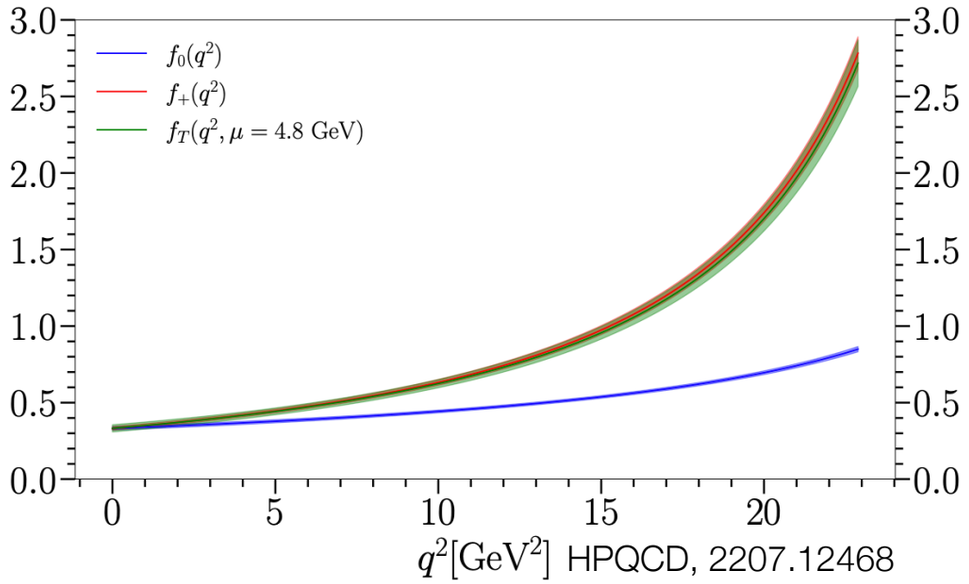
  - matrix elements of local operators can be computed e.g. using Lattice QCD







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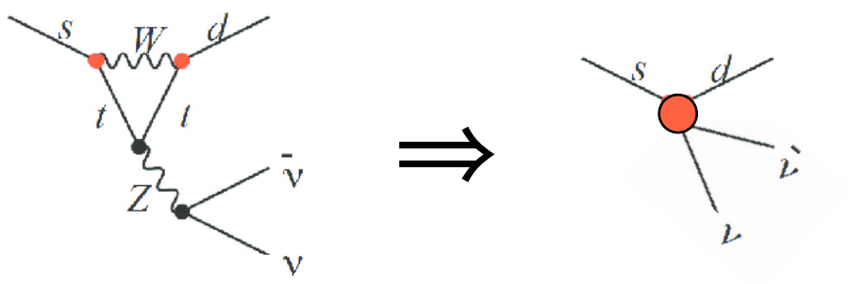
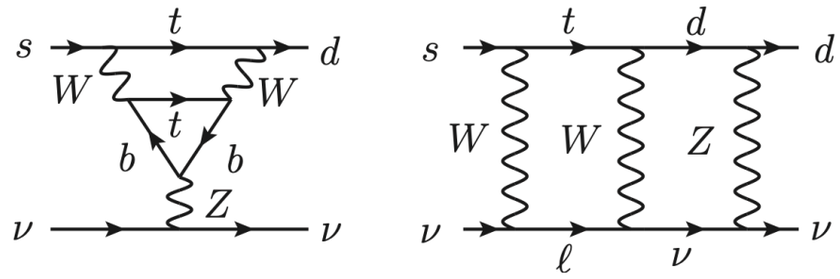




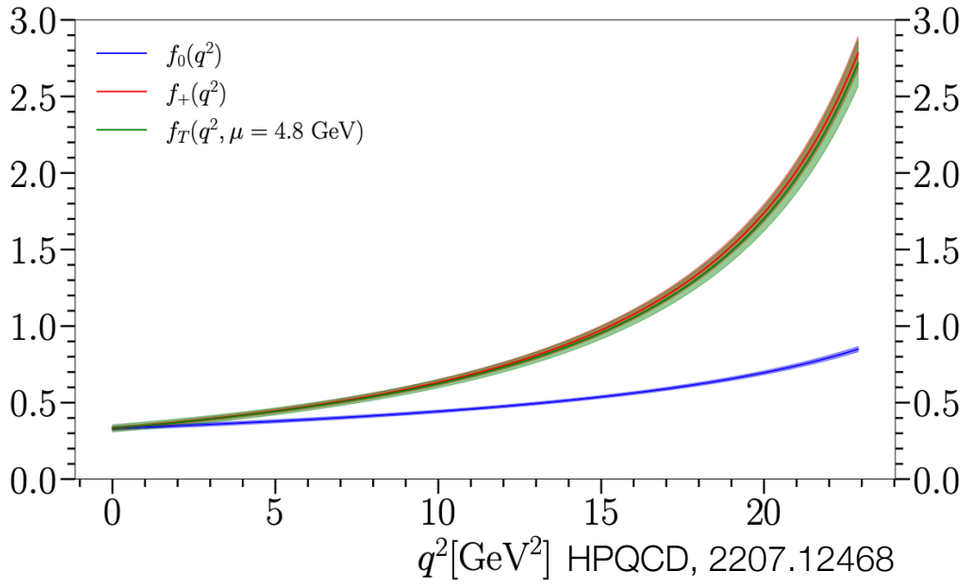
➡ Allow for precise predictions Bolton et al., 2503.19025 see also Becirevic, Piazza, Sumensari, 2301.06990

$$\mathcal{B}(B^+ \to K^+ \nu\bar{\nu})_{\rm SM} = (4.90 \pm 0.17 \pm 0.25) \times 10^{-6}$$

$$\mathcal{B}(B^0 \to K^{*0} \nu\bar{\nu})_{\rm SM} = (8.95 \pm 0.89 \pm 0.45) \times 10^{-6}$$

$$\mathcal{B}(B_s \to \nu\bar{\nu}\nu\bar{\nu})_{\rm SM} = (5.48 \pm 0.89) \times 10^{-15}$$

$\vdots$ Bhattacharya, Grant & Petrov, 1809.04606



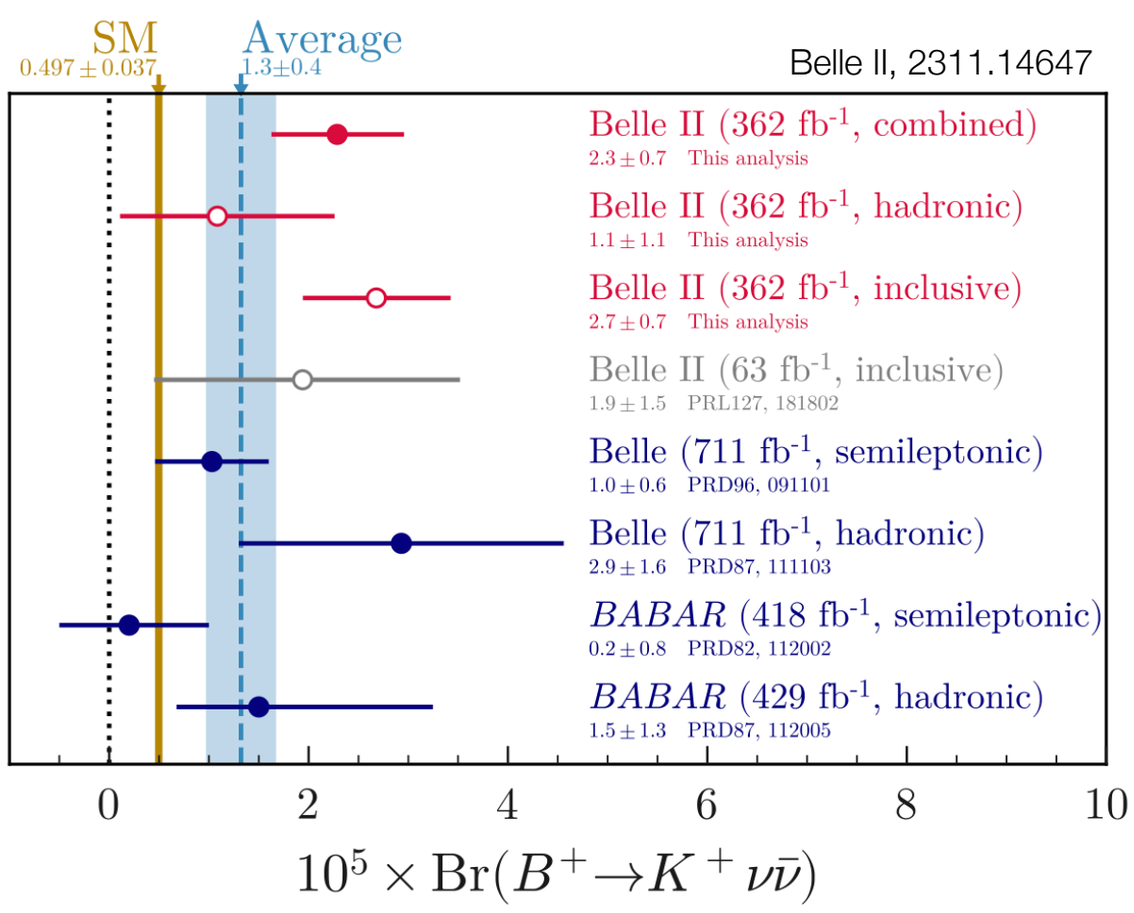
Experimental situation

- Until recently exp. sensitivity (well) above SM expectations

$$\mathcal{B}(B^0 \to K^{*0} E_{\rm miss}) < 1.8 \times 10^{-5} \qquad \mathcal{B}(B_s \to E_{\rm miss}) < 5.6 \times 10^{-4}$$

Belle, 1702.03224 Alonso-Alvarez & Escudero, 2310.13043

- First signal evidence by Belle II in 2023 see talk by Stefkova



2.9σ or almost ×5 above SM

(×3 when averaged with previous measurements)

BSM interpretations of Belle II result

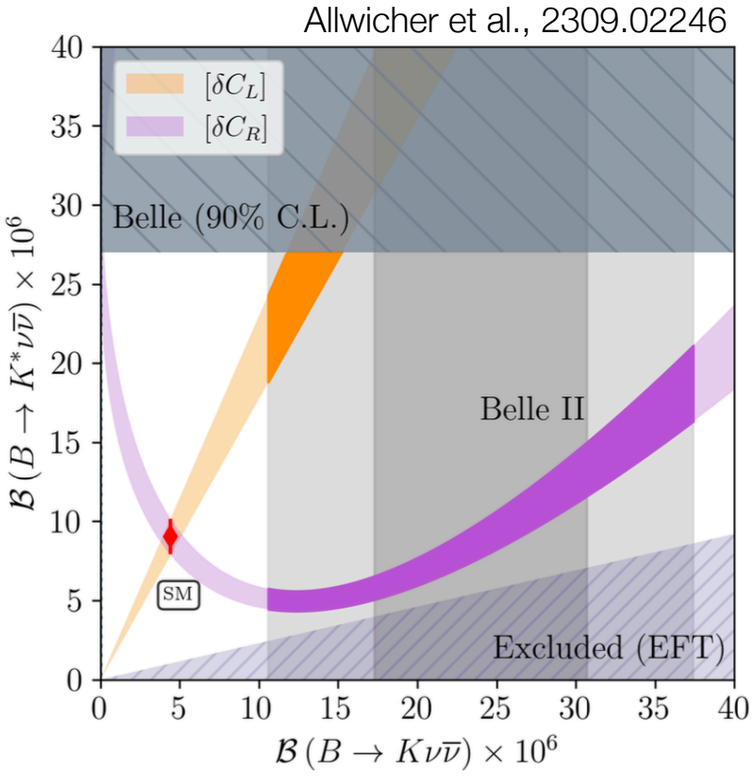
- Heavy NP can contribute to $b \to s\nu\bar{\nu}$ amplitudes see e.g. Descotes-Genon et al., 2005.03734

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

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

- Existing exp. upper bounds then imply non-trivial NP EFT operator structure

Allwicher et al., 2309.02246



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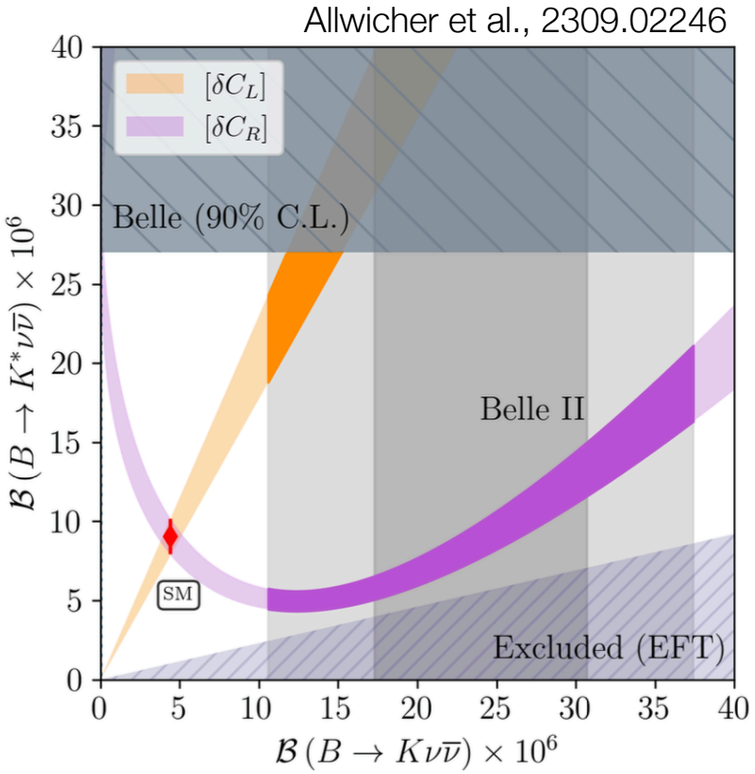


$\Rightarrow$

- Above EW scale, NP ops. need to respect SM gauge invariance

$$[\mathcal{O}_{lq}^{(1)}]_{ijkl} = (\overline{L}_i\gamma^\mu L_j)(\overline{Q}_k\gamma_\mu Q_l)\,,$$

$$[\mathcal{O}_{lq}^{(3)}]_{ijkl} = (\overline{L}_i\gamma^\mu\tau^I L_j)(\overline{Q}_k\tau^I\gamma_\mu Q_l)\,,$$

$$[\mathcal{O}_{ld}]_{ijkl} = (\overline{L}_i\gamma^\mu L_j)(\overline{d}_{kR}\gamma_\mu d_{lR})\,,$$

$\Rightarrow B \to K^{(*)}\ell^+\ell^-,\ B_s \to \mu^+\mu^-$ measurements exclude sizable $\nu_e\bar{\nu}_e,\ \nu_\mu\bar{\nu}_\mu$ contributions

Bause, Gisbert & Hiller, 2309.00075

$\Rightarrow$ Possible relation to charged current B decays: constraints inconsistent with simultaneous explanation of $R_{D^{(*)}}$

Extending SM with new invisible particles

- New d.o.f.s, if neutral under SM gauge symmetry, can also be light, must be included in low energy (SM)EFT J.F.K. & Smith, 1111.6402

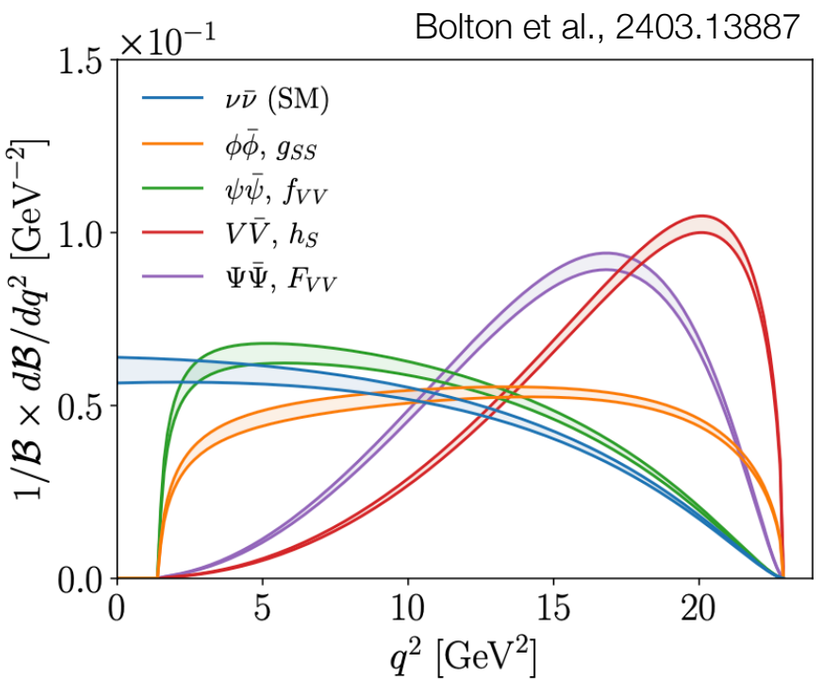
$$\mathcal{H}_{mat} = \frac{c_{RL}^{IJ}}{\Lambda^n} H^\dagger \bar{D}^I Q^J \times X + \frac{c_{LR}^{IJ}}{\Lambda^n} H \bar{Q}^I D^J \times X + \frac{c_{LL}^{IJ}}{\Lambda^n} \bar{Q}^I Q^J \times X + \frac{c_{RR}^{IJ}}{\Lambda^n} \bar{D}^I D^J \times X$$

  - relevant spin (0, 1/2, 1, 3/2) candidates $X \in \{\phi, V, \phi\bar{\phi}, \psi\bar{\psi}, V\bar{V}, \Psi\bar{\Psi}\}$

$$\Rightarrow \quad (\bar{b}\gamma_\mu P_X s)\left[C_{dV}^{V,X} V^\mu + \frac{C_{d\phi}^{V,X}}{\Lambda}\partial^\mu\phi + \frac{C_{d\phi\phi}^{V,X}}{\Lambda^2} i\phi^* \overleftrightarrow{\partial^\mu} \phi + \frac{C_{d\psi}^{V,XY}}{\Lambda^2}(\bar{\psi}\gamma^\mu P_Y \psi)\right]$$
$$+(\bar{b}P_X s)\frac{v}{\sqrt{2}}\left[\frac{C_{d\phi}^{S,X}}{\Lambda}\phi + \frac{C_{d\phi\phi}^{S,X}}{\Lambda^2}|\phi|^2\right] + \dots$$

- If long-lived, X can mimic missing energy of SM neutrinos

- Distinct kinematic signatures due to spin, mass, multiplicity



Reinterpreting Belle II results

- Experimental acceptance & efficiency uneven across decay phase-space

$$\frac{dN}{dq^2_{\rm rec}} = N_{B\bar{B}} \int dq^2 f_{q^2_{\rm rec}}(q^2)\epsilon(q^2)\frac{d\mathcal{B}}{dq^2}$$

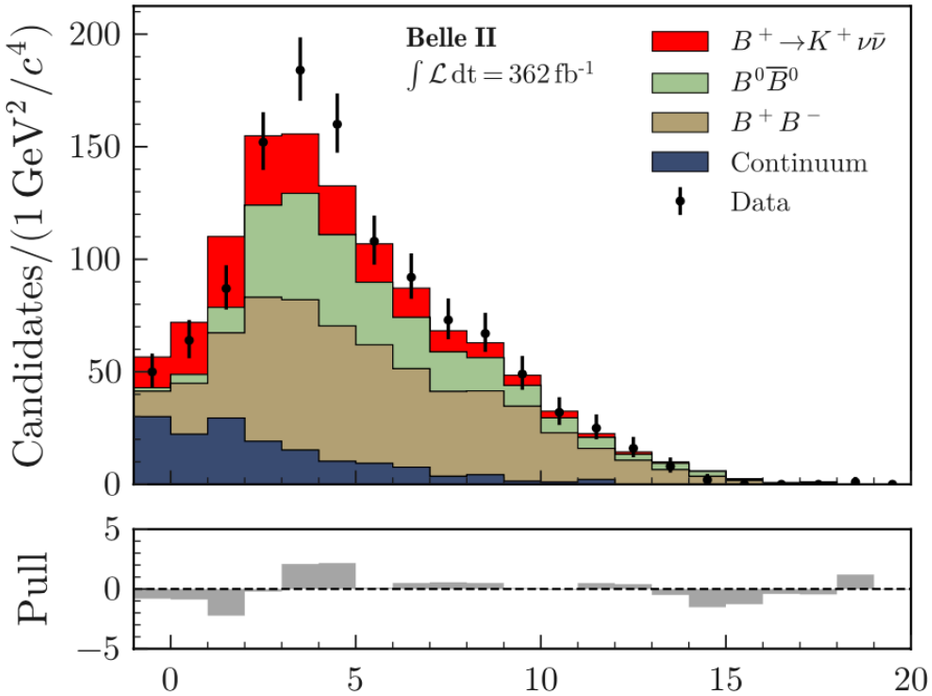
  - ➡ Integrated Br interpretations of measurement are model dependent!

- Unbiased NP interpretations require fit to reconstructed spectrum

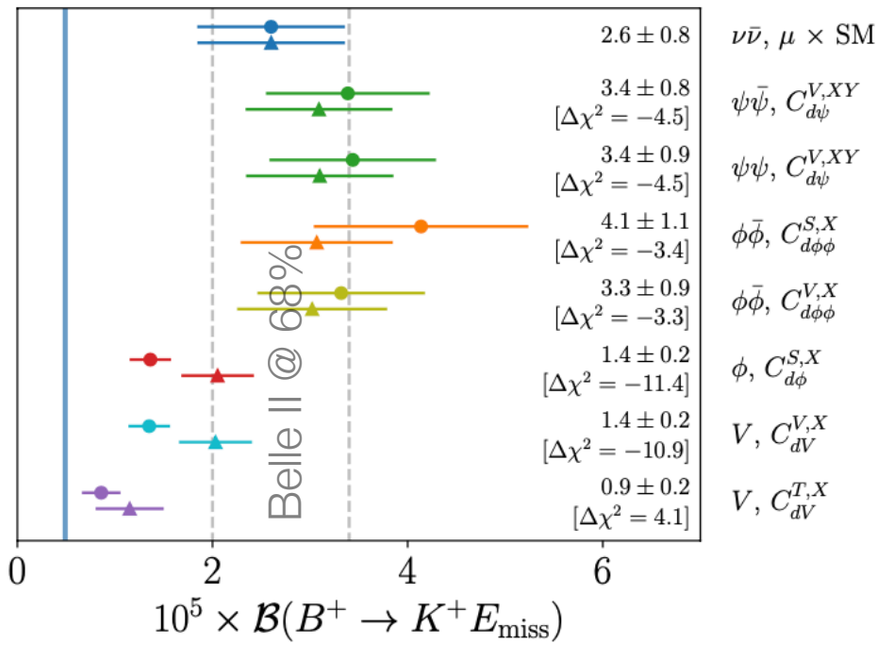
$$L_{\rm SM+X} = \prod_i^{N_{\rm bins}} \text{Poiss}\left[n^i_{\rm obs}, n^i_{\rm exp}(\mu, m_X, c_X, \boldsymbol{\theta}_x, \tau_b)\right] \mathcal{N}(\boldsymbol{\theta}^x; \Sigma^x)$$

  - ➡ Better discrimination among NP scenarios - some are preferred compared to rescaled SM

Belle II, 2311.14647



Bolton et al., 2503.19025



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  - ➡ Potential to infer masses & multiplicities of new particles

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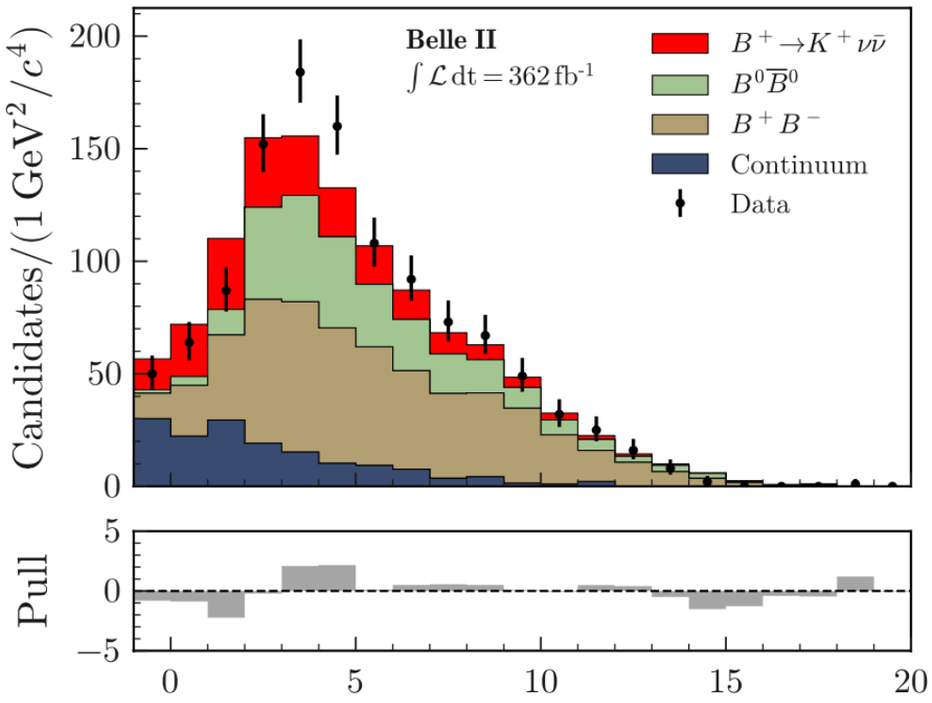

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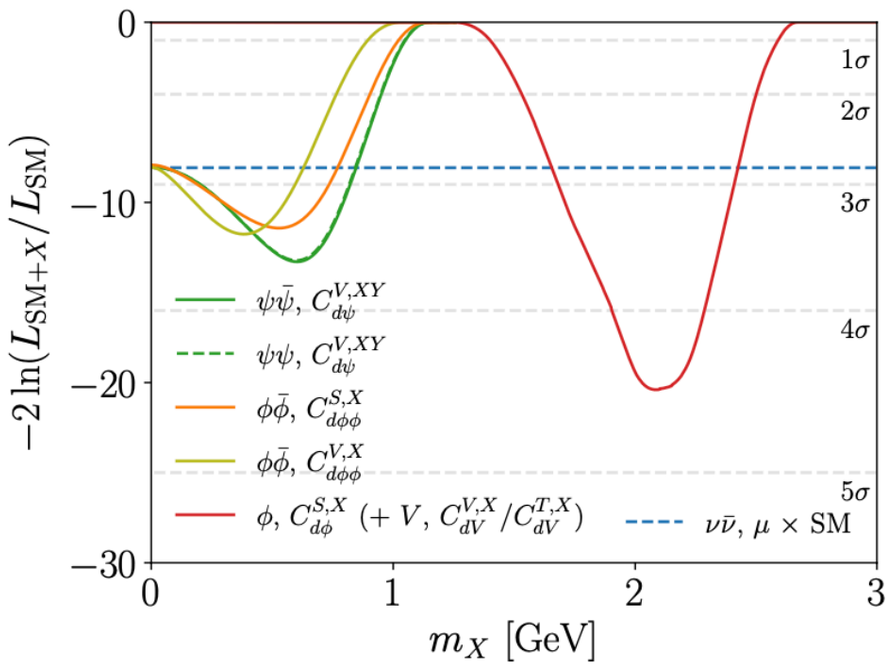
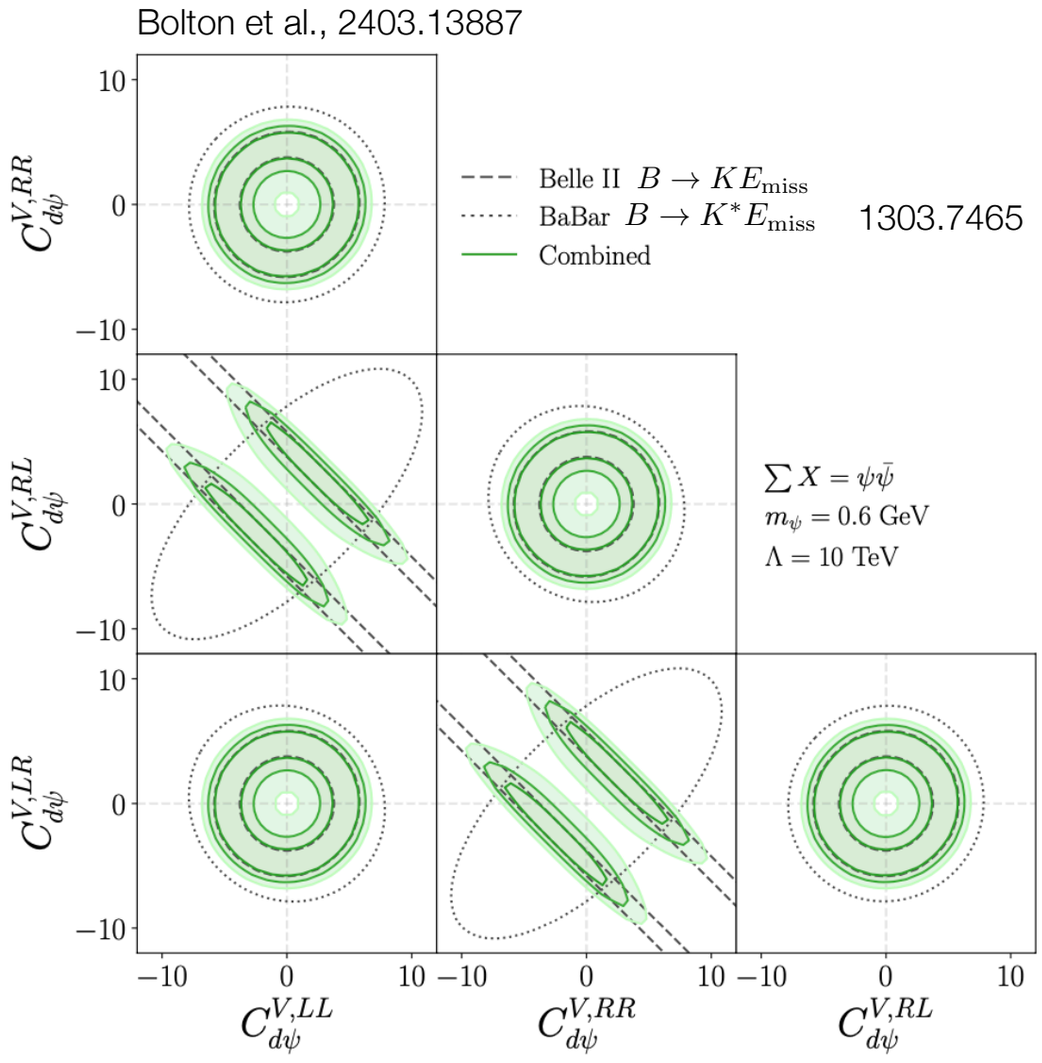


Implications of/for other measurements

- $B \to K^* E_{\rm miss}$ offers richer phenomenology
  - sensitive to both parity-even and -odd operators

    ⇒ existing constraints on chiral (SMEFT+X) operators

Bolton et al., 2403.13887



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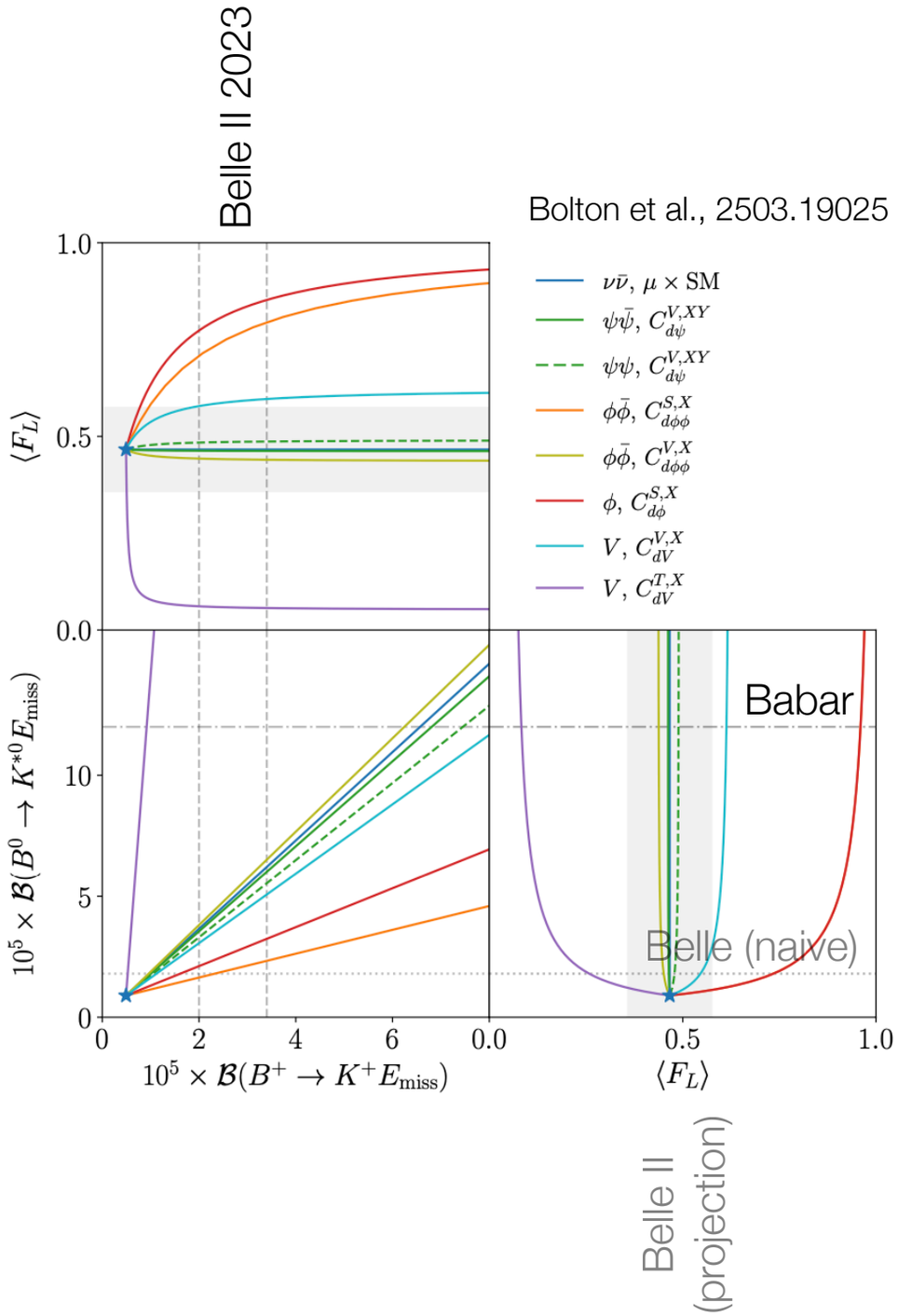
  - two distinguishable K* polarization states

$$\frac{d\Gamma}{dq^2} = \frac{d\Gamma_T}{dq^2} + \frac{d\Gamma_L}{dq^2}\,, \qquad F_L = \frac{d\Gamma_L}{dq^2} \Big/ \frac{d\Gamma}{dq^2}$$

⇒ nontrivial correlations between rates



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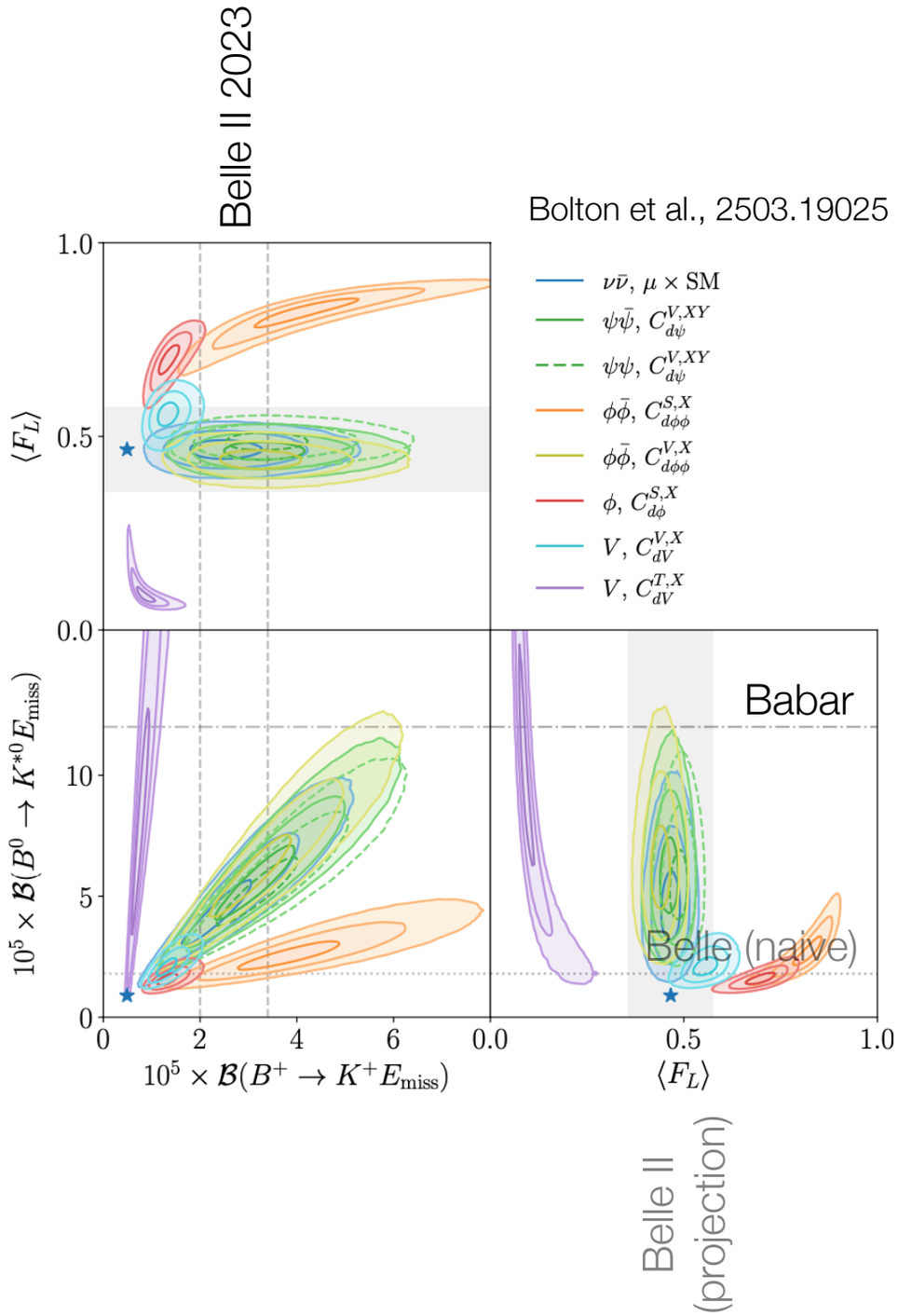

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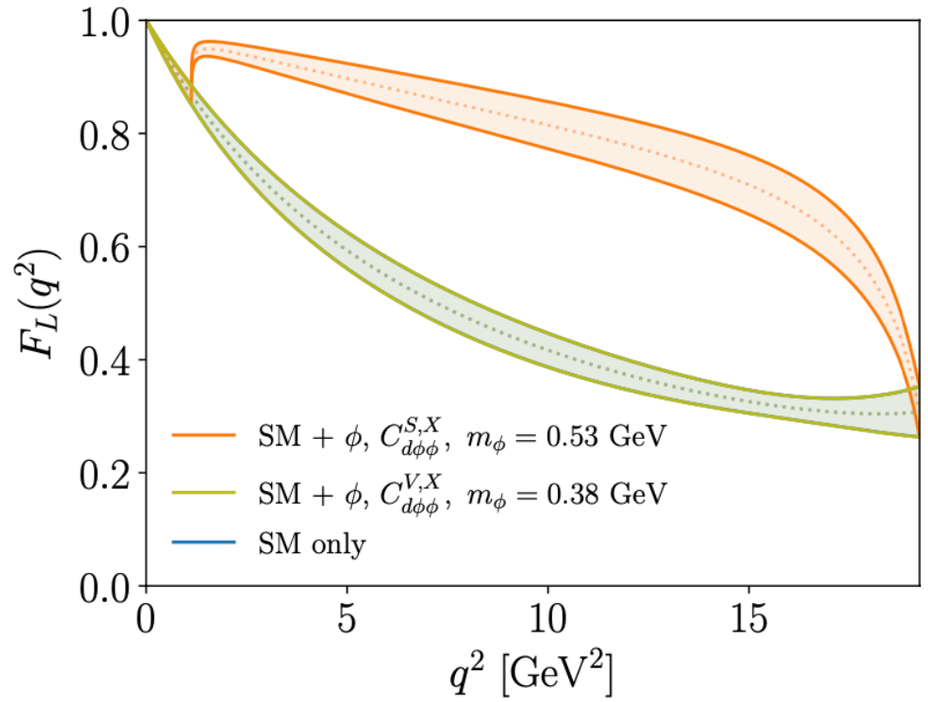
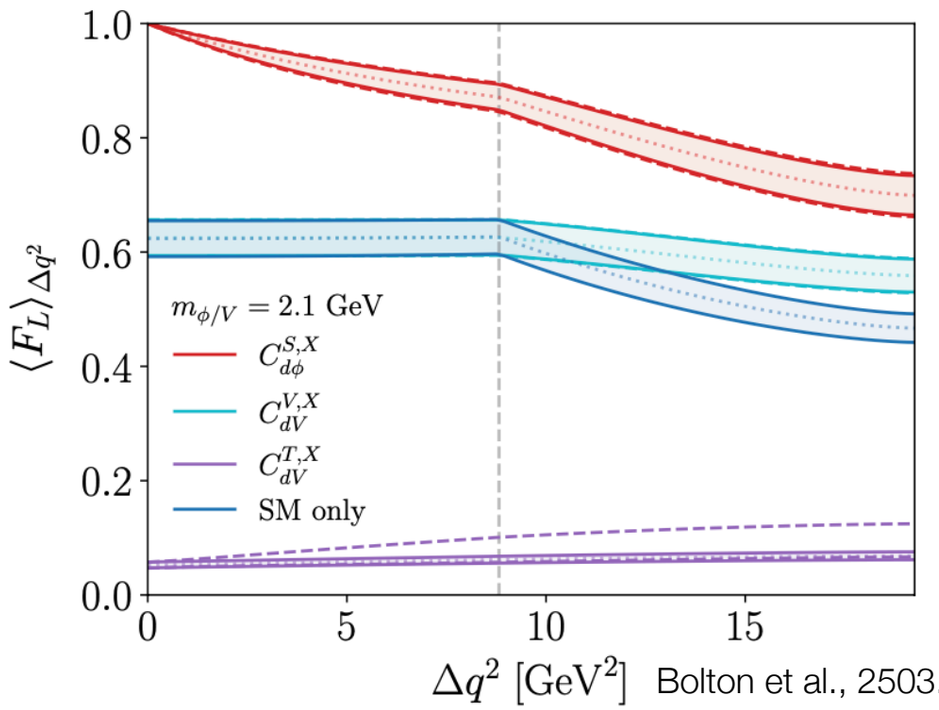
- Projected Belle II statistics could allow for differential measurements, e.g.

$$\langle F_L \rangle_{\Delta q^2} = \left(\int_{q_i^2}^{q_j^2} dq^2 \frac{d\Gamma_L}{dq^2} \right) \Big/ \left(\int_{q_i^2}^{q_j^2} dq^2 \frac{d\Gamma}{dq^2} \right)$$

see also, Buras, Harz & Mojahed, 2405.06742
Hu, 2412.19084





Bolton et al., 2503.19025

Conclusions

- Rare processes are excellent probes of NP
  - $q_i \to q_j E_{\rm miss}$ well predicted in SM, can probe heavy NP (indirectly) and light invisible NP (directly)
- Intriguing current experimental situation could indicate presence of new (sub) GeV-mass particles!
- Important implications for model building (DM, neutrino mass, …)

see e.g. Altmannshofer et al., 2311.14629 — Felkl et al., 2309.02940 — He et al., 2403.12485
Berezhnoy & Melikhov, 2309.17191 — McKeen, Ng & Tuckler, 2312.00982 — Hati et al., 2408.00060
Abdughani & Reyimuaji, 2309.03706 — Ho, Kim & Ko, 2401.10112 — Becirevic et al., 2410.23257
…

- Belle II sensitivity to $B \to K^* E_{\rm miss}$ should discriminate between scenarios
- Gives emphasis to related phenomenology
  - in existing exp. like NA62, KOTO, BESIII - $K \to \pi E_{\rm miss}, \; D^0 \to \pi^0 E_{\rm miss}$
  - at future facilities like FCC-ee/CEPC - $\Lambda_b \to \Lambda E_{\rm miss}\,, \; B_s \to (\phi) E_{\rm miss}\,, \; \ldots$

Amhis et al., 2309.11353
Li et al., 2201.07374