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

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22/7/2025

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

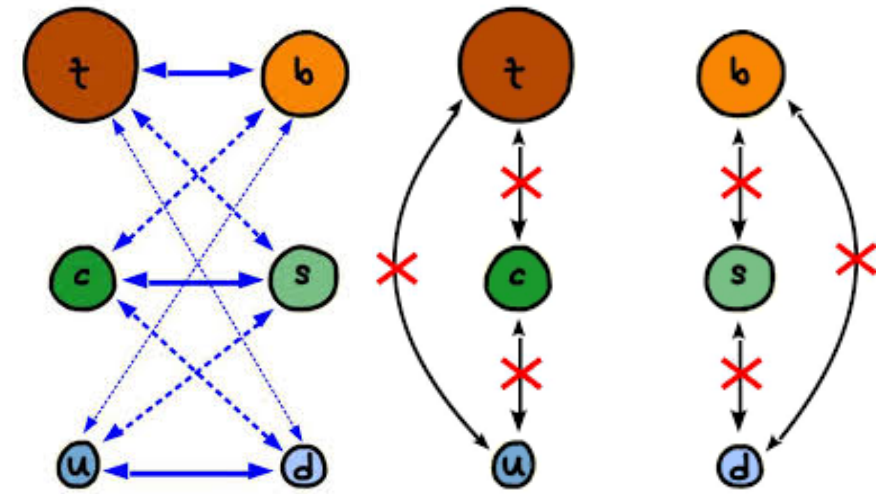
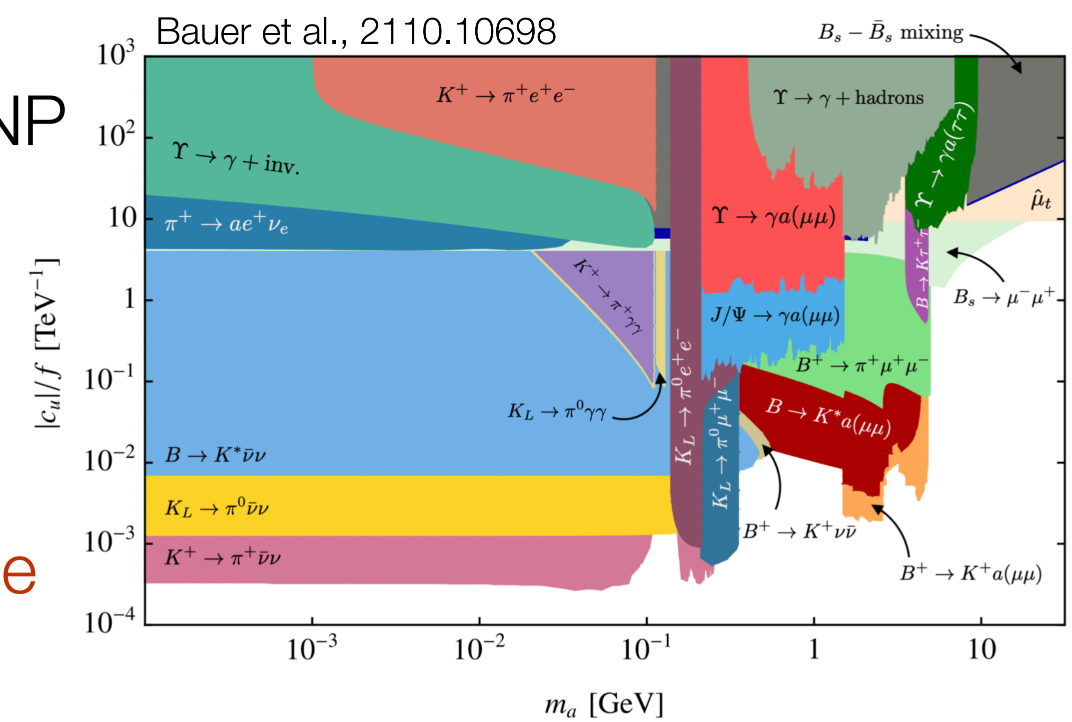


figure by
W. Altmannshofer

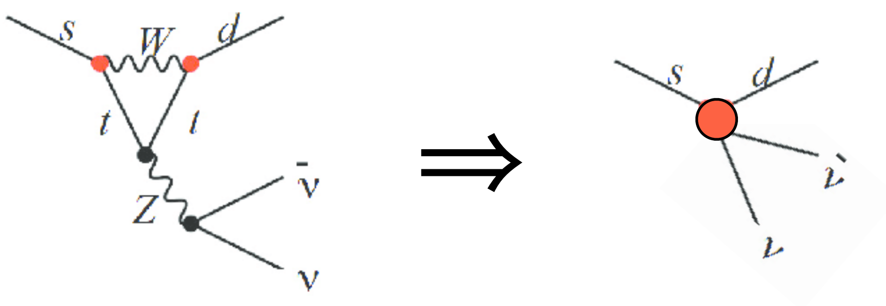
- Traditionally exhibit excellent sensitivity to heavy NP scales
    - Modes with missing energy can probe feebly interacting light NP
        - Potentially relate to cosmological DM puzzle



$b \to s+$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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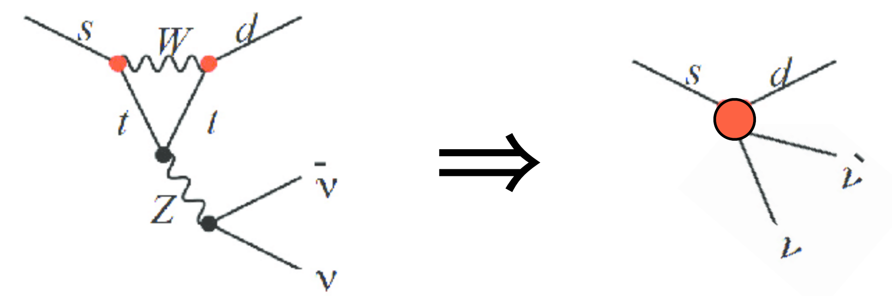
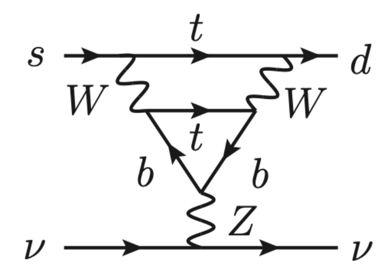
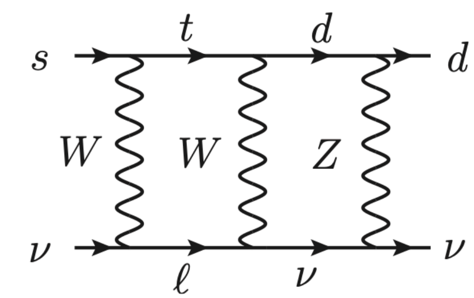
Buras et al., hep-ph/0508165
Brod, Gorbahn & Stamou, 1009.0947







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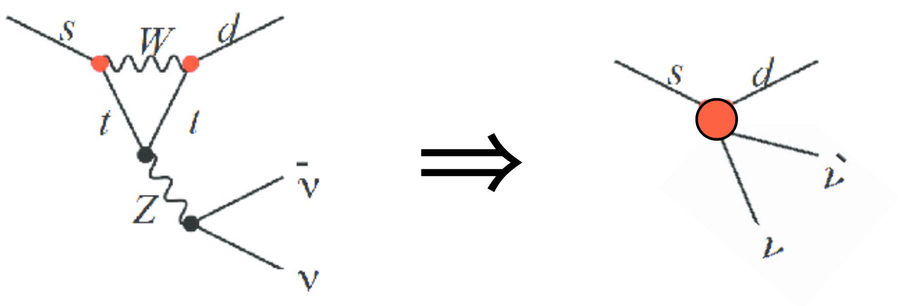

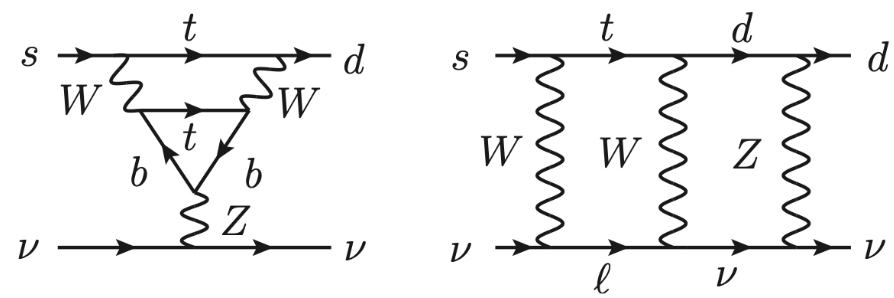

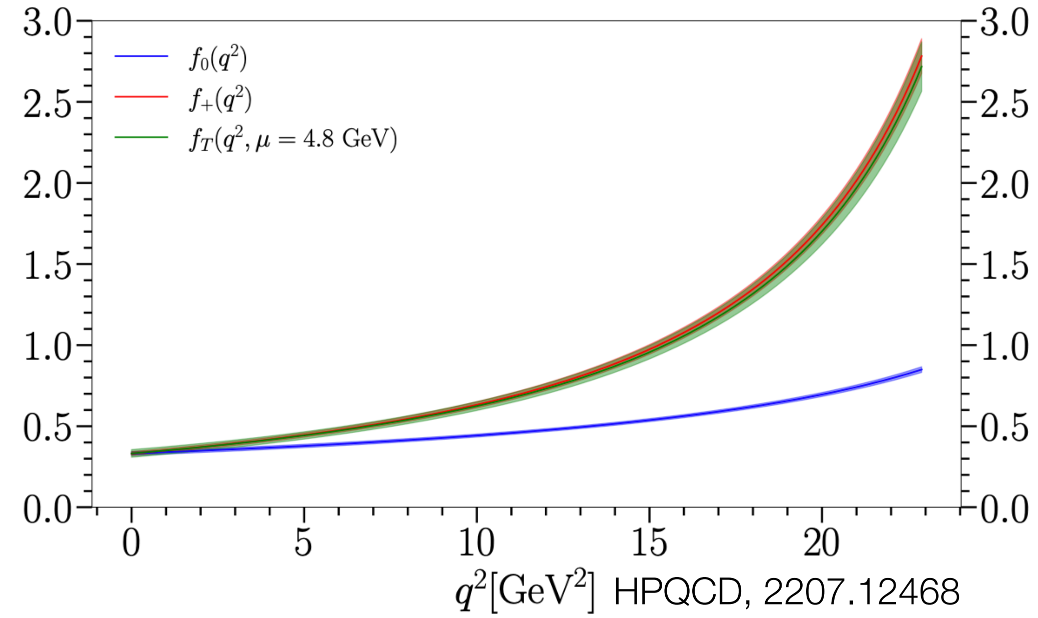

HPQCD, 2207.12468

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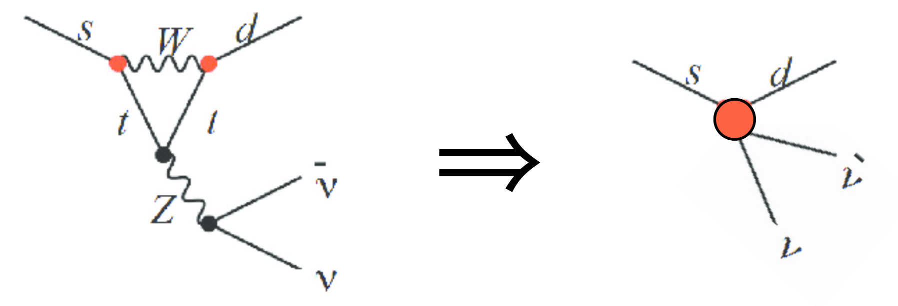
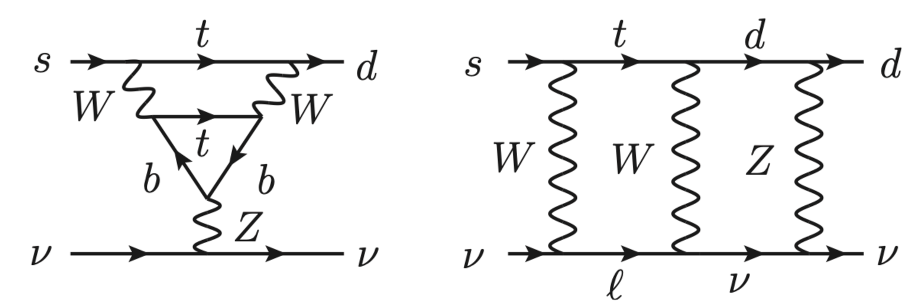




➡ Allow for precise predictions

Bolton et al., 2503.19025
see also Becirevic, Piazza, Sumensari, 2301.06990

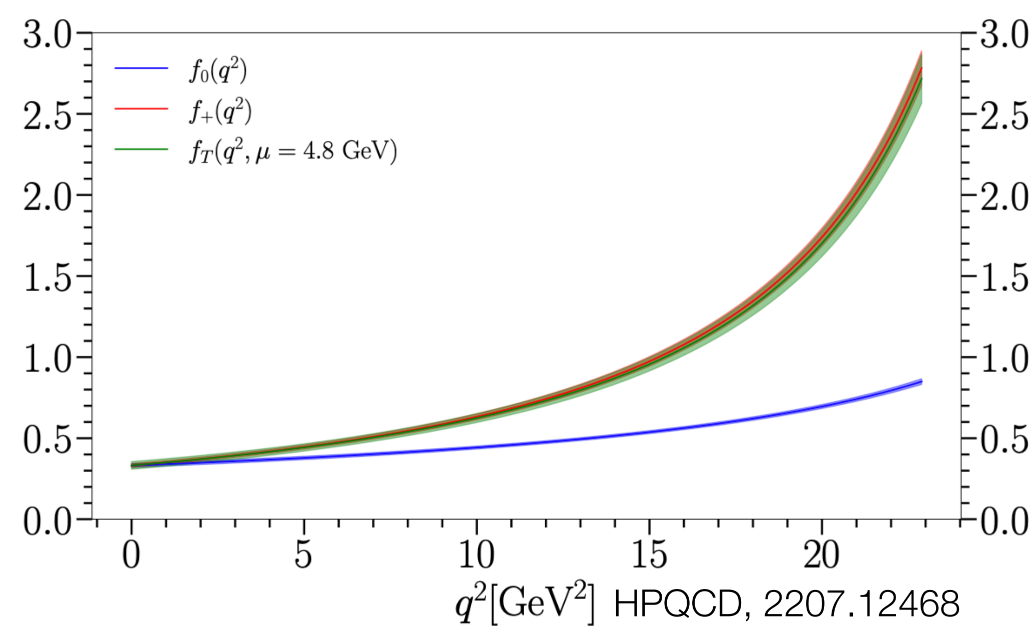
$$\mathcal{B}(B^+ \to K^+\nu\bar{\nu})_{\mathrm{SM}} = (4.90 \pm 0.17 \pm 0.25) \times 10^{-6}$$

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

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

$$\vdots$$

Bhattacharya, Grant & Petrov, 1809.04606



HPQCD, 2207.12468

Experimental situation

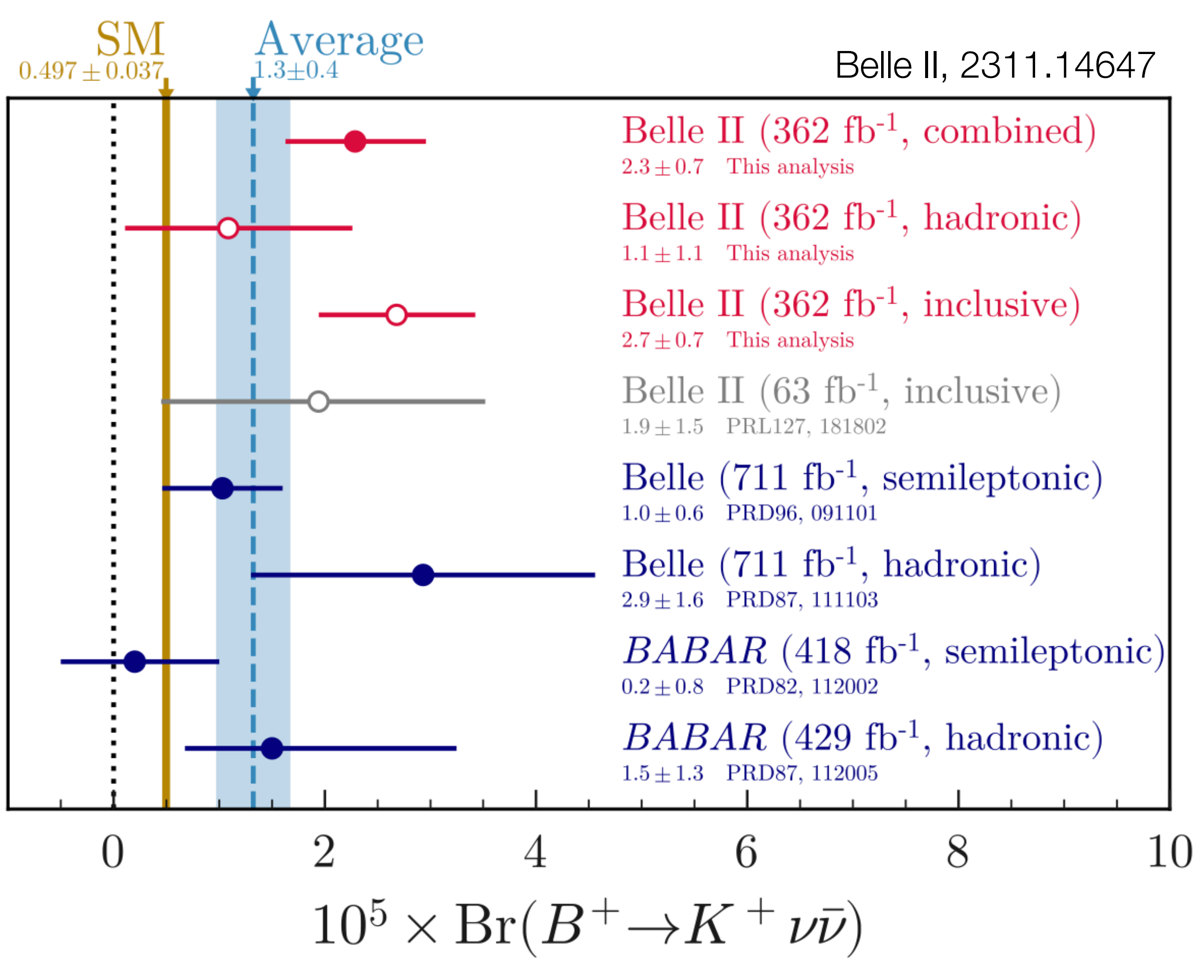
- Until recently exp. sensitivity (well) above SM expectations

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

Belle, 1702.03224 Alonso-Alvarez & Escudero, 2310.13043

- First signal evidence by Belle II in 2023

Belle II, 2311.14647



2.9σ or almost ×5 above SM

(×3 when averaged with previous measurements)

BSM interpretations of Belle II result

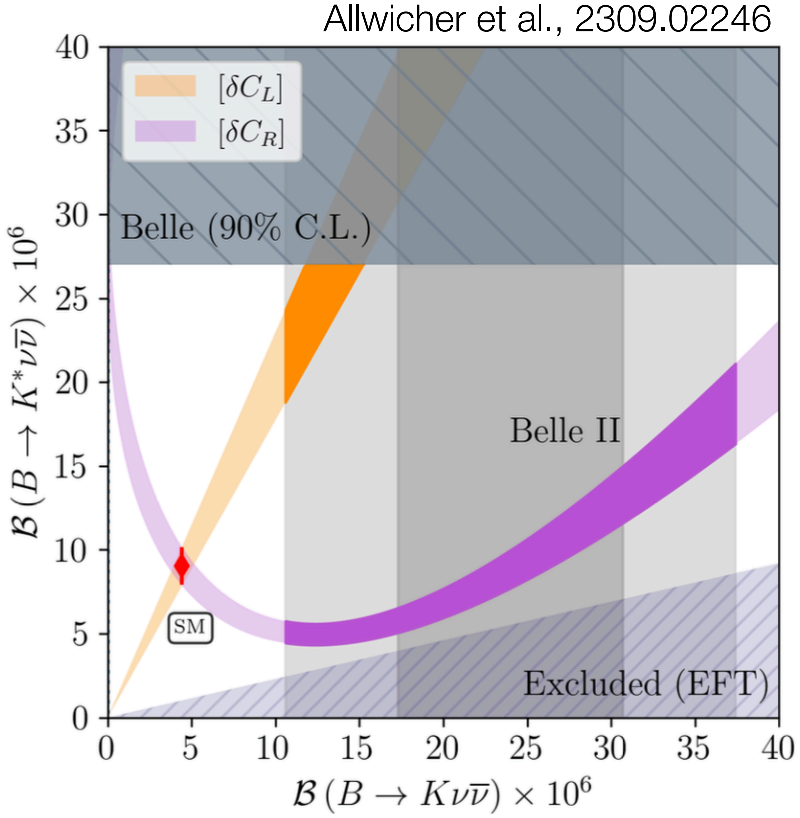
- Heavy NP can contribute to $b \to s\nu\bar{\nu}$ amplitudes   see e.g. Descotes-Genon et al., 2005.03734

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

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

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

Allwicher et al., 2309.02246



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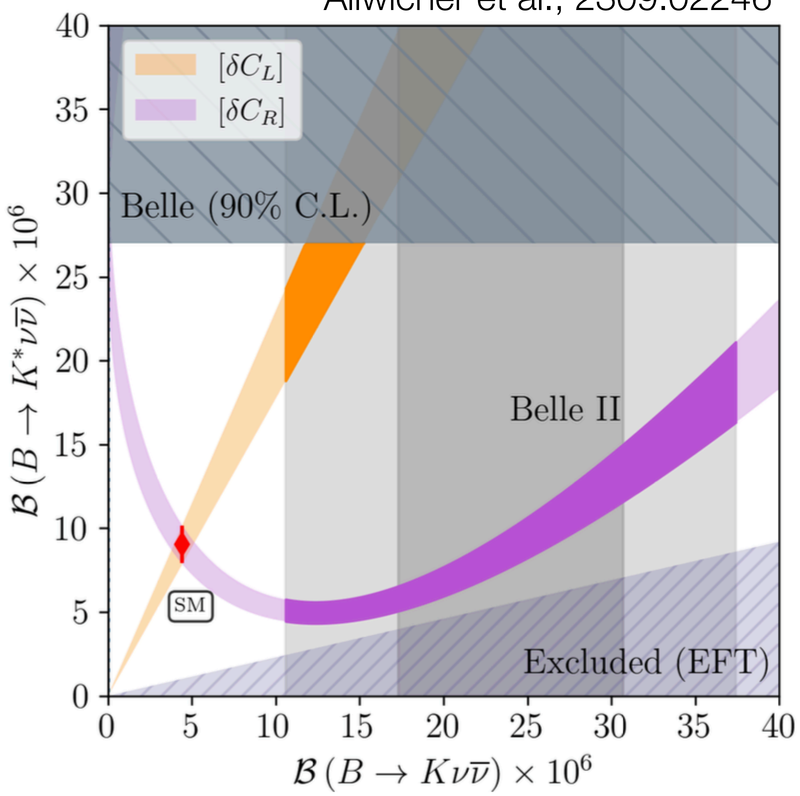


$\Rightarrow$

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

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

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

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

$\Rightarrow B \to K^{(*)}\ell^+\ell^-,\ B_s \to \mu^+\mu^-$ 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

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

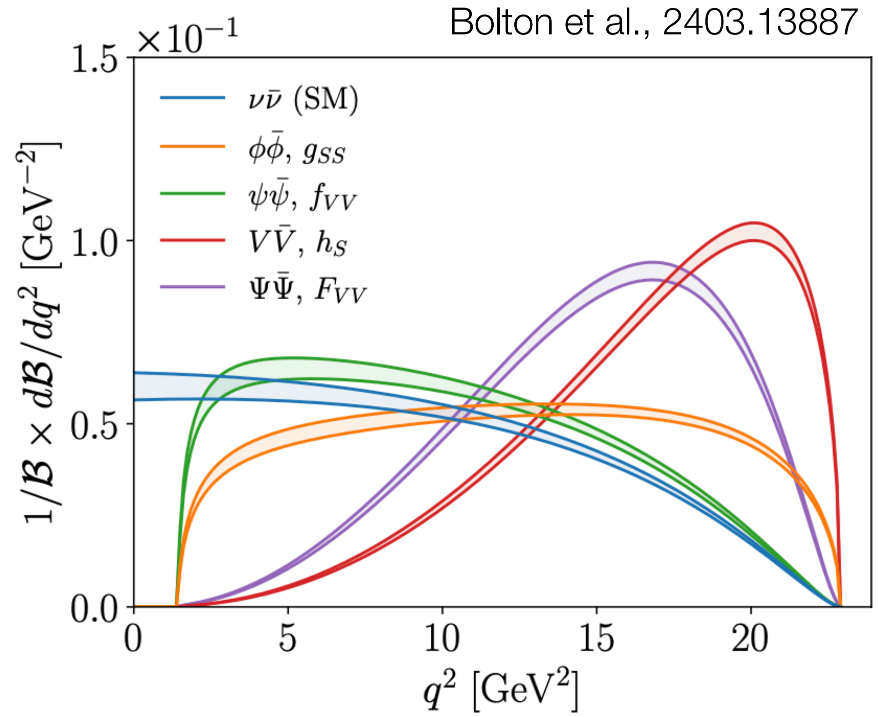
  - relevant spin (0, 1/2, 1, 3/2) candidates $X \in \{\phi, V, \phi\bar{\phi}, \psi\bar{\psi}, V\bar{V}, \Psi\bar{\Psi}\}$

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

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

- Distinct kinematic signatures due to spin, mass, multiplicity

Bolton et al., 2403.13887



Reinterpreting Belle II results

- Experimental acceptance & efficiency uneven across decay phase-space

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

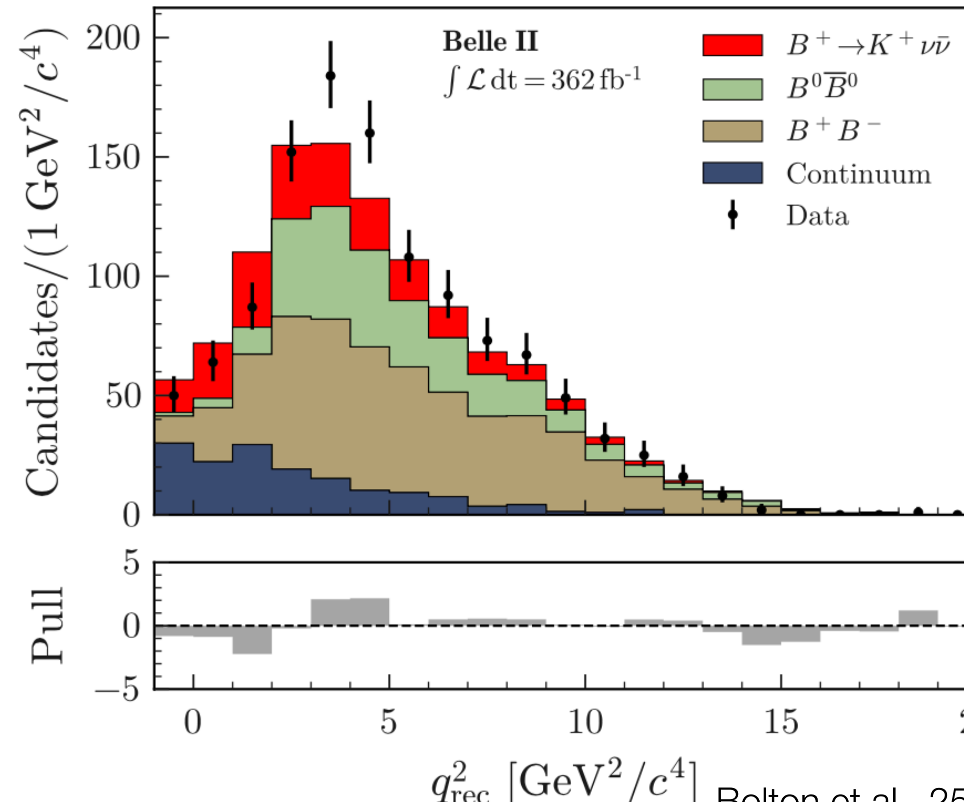
➡ Integrated Br interpretations of measurement are model dependent!

- Unbiased NP interpretations require fit to reconstructed spectrum

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

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

Belle II, 2311.14647



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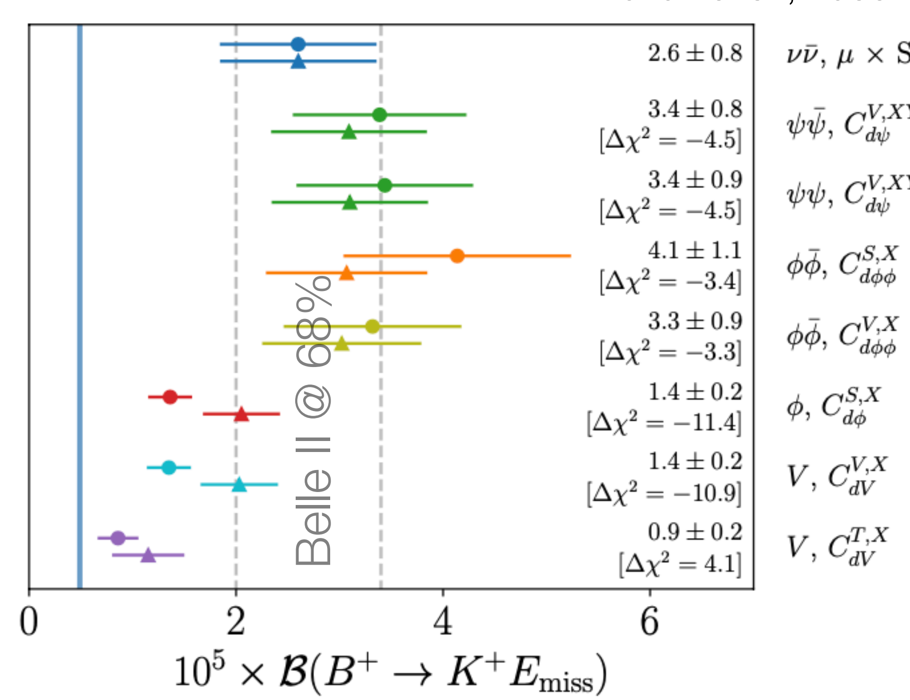

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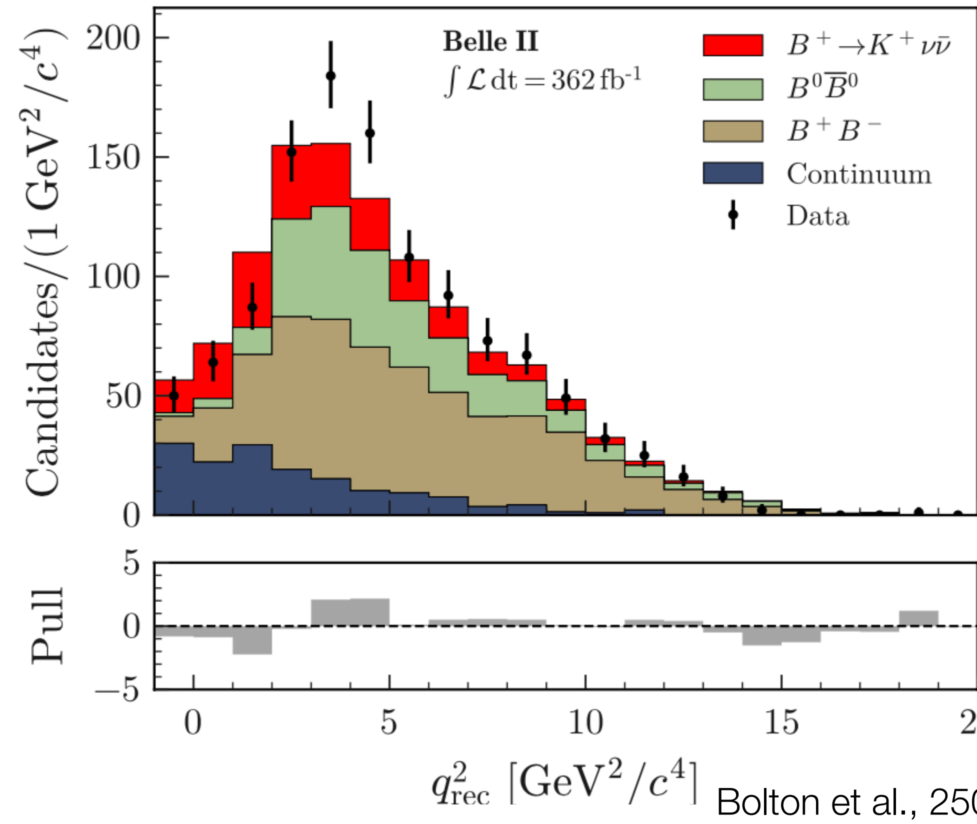
  ➡ Potential to infer masses & multiplicities of new particles

Belle II, 2311.14647



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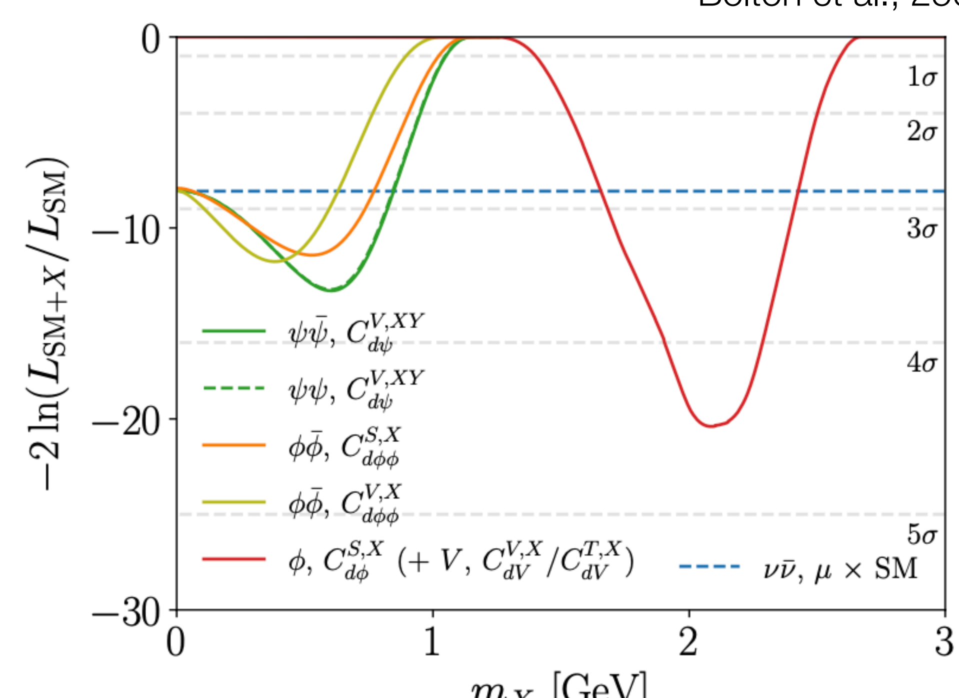

Implications of/for other measurements

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

    $\Rightarrow$ existing constraints on chiral (SMEFT+X) operators

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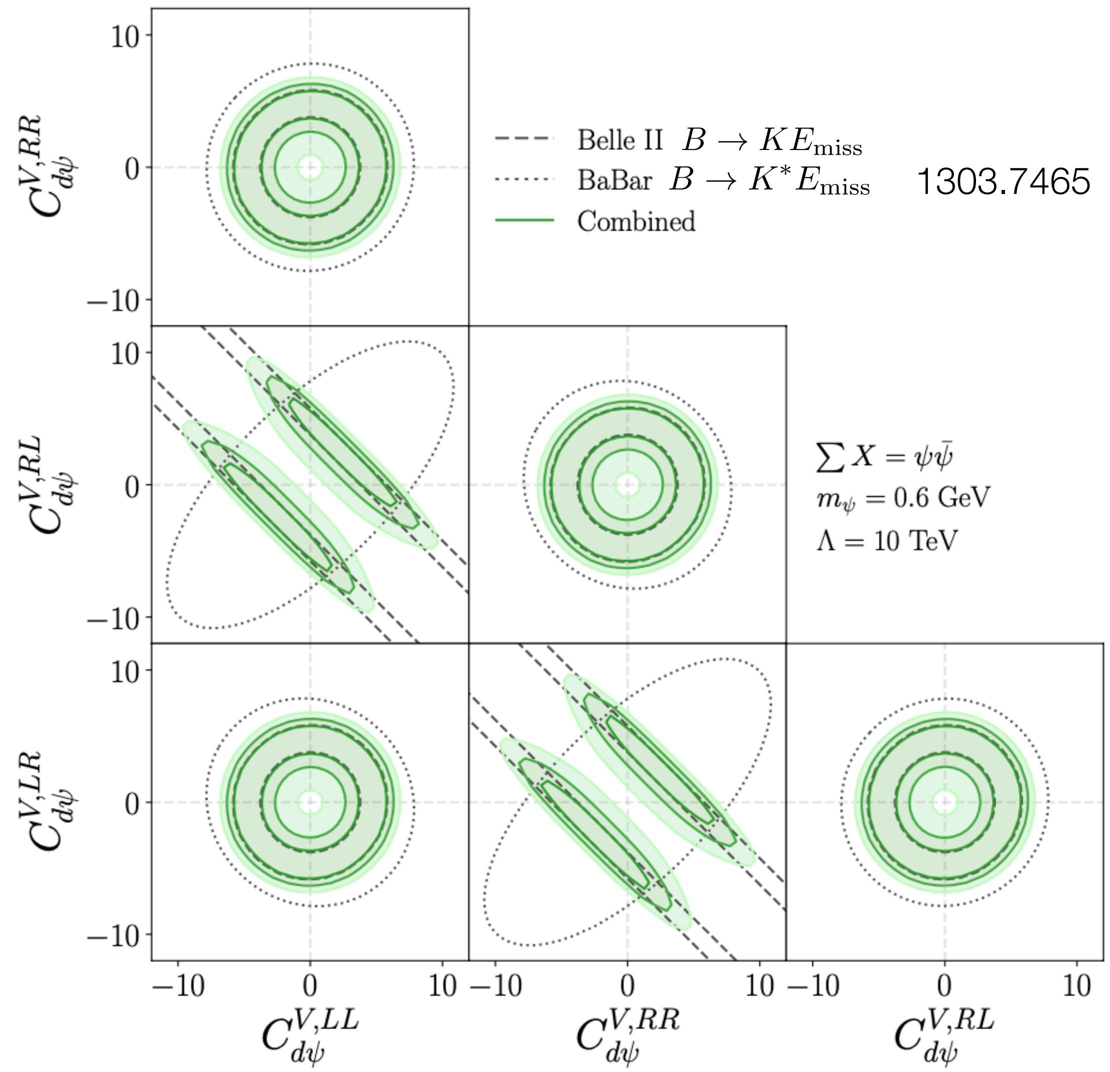

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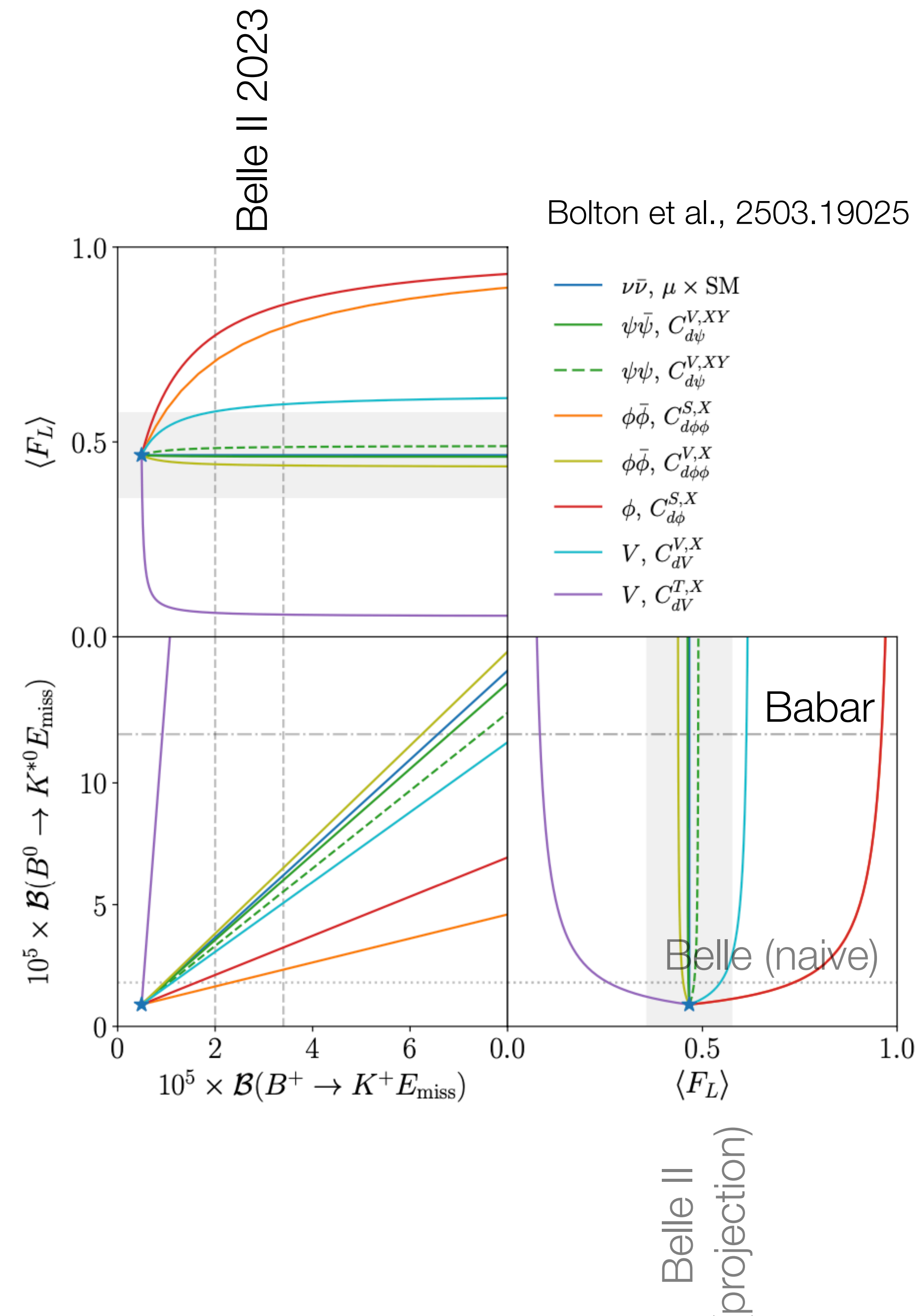
  - two distinguishable K* polarization states

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

$\Rightarrow$ nontrivial correlations between rates



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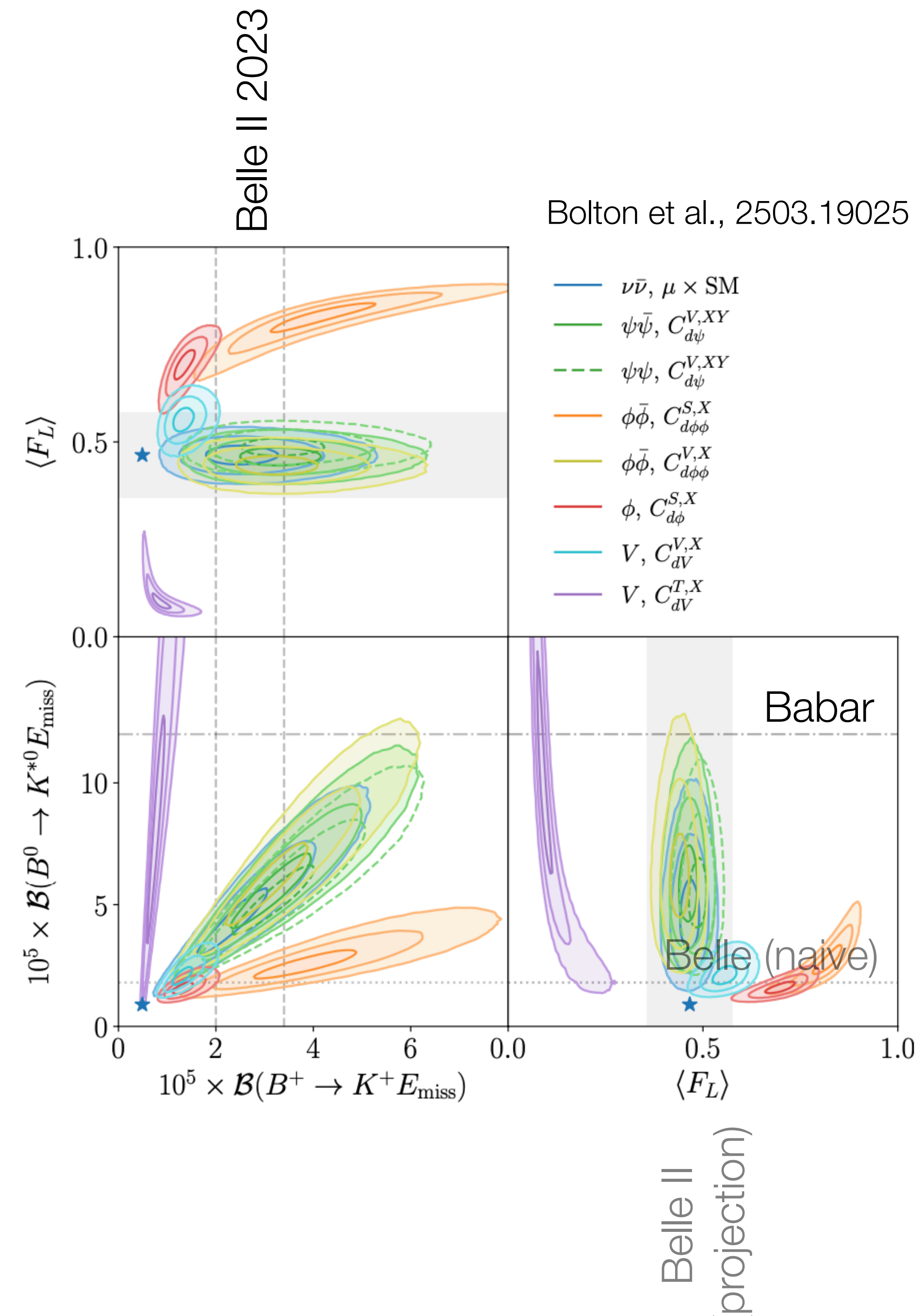

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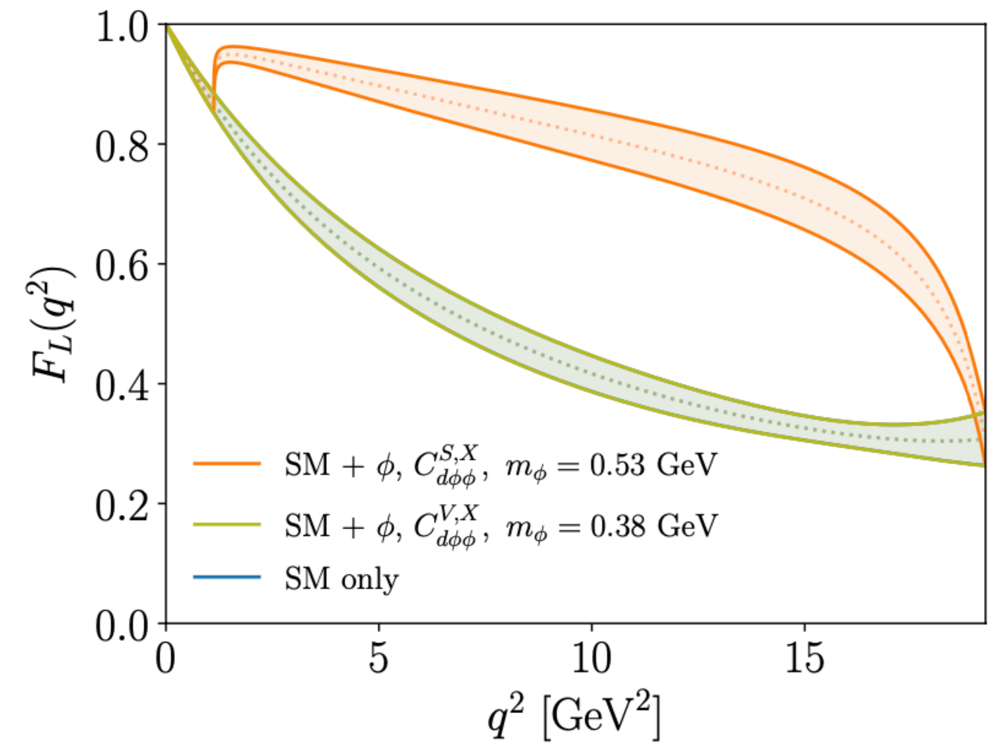
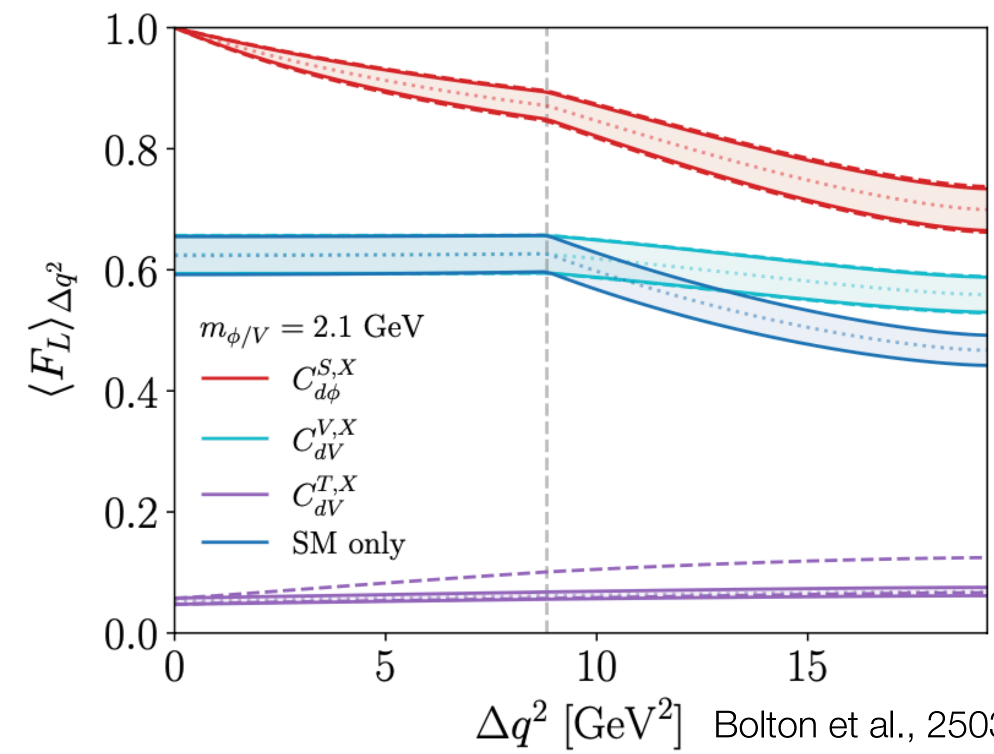
- Projected Belle II statistics could allow for differential measurements, e.g.

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

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





Bolton et al., 2503.19025

Example BSM

Bolton et al., 2508.XXXXX

- gauged & higgsed $U(1)\,'$

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}B'_{\mu\nu}B'^{\mu\nu} - \frac{\epsilon_B}{2}B_{\mu\nu}B'^{\mu\nu} + \left|D_\mu\Phi\right|^2 - V(H,\Phi)\,,$$

  - minimally coupled to SM quarks via $T\,'$-t mass mixing

$$+\,\bar{T}'(i\not{D} - M_T)T' - \left[Y_T^t\bar{T}'\Phi t'_R + \text{h.c.}\right]$$

  - possibly mediating SM-DM (X) interactions

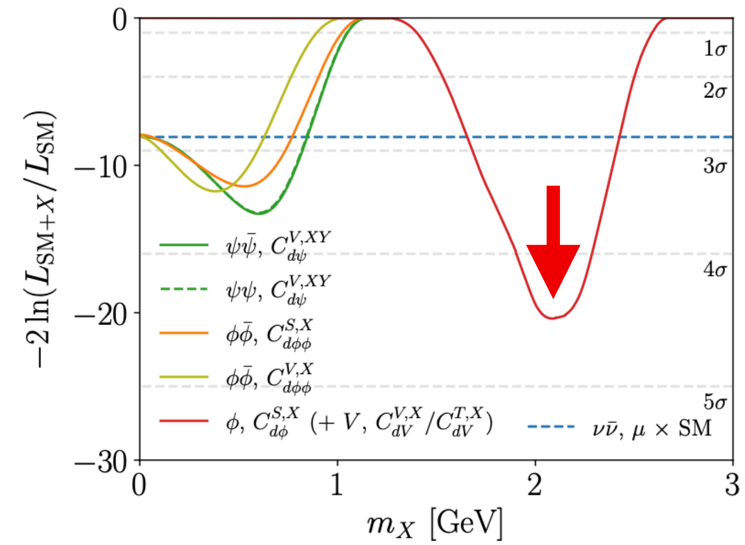
$$+\,\bar{X}(i\not{D} - m_X)X$$

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
Φ	$\mathbf{1}$	$\mathbf{1}$	0	q'
T'	$\mathbf{3}$	$\mathbf{1}$	$2/3$	q'
X	$\mathbf{1}$	$\mathbf{1}$	0	q'_X

Spectrum & interactions

$$V(H,\Phi) = -\tilde{\mu}^2|\Phi|^2 + \tilde{\lambda}|\Phi|^4 + \lambda'|\Phi|^2(H^\dagger H)$$

- Scalar potential breaks $U(1)'$ orthogonally to SM: $\Phi = (\tilde{v} + \phi')/\sqrt{2}$
  - No tree-level Z-Z' mixing: $M_{Z'} = \tilde{g}q'\tilde{v} \simeq 2.1\,\mathrm{GeV}$
- T'-t mass mixing modifies $W,\ Z$ couplings to top quark,



$$-\frac{g}{\sqrt{2}}\left[V_{ti}(c_L\bar{t} + s_L\bar{T})\gamma_\mu P_L d_i W^{+\mu} + \mathrm{h.c.}\right]$$

- induces $U(1)'$ charge $-\tilde{g}q'\left[(-s_L\bar{t} + c_L\bar{T})\gamma_\mu P_L(-s_L t + c_L T) + (L \leftrightarrow R)\right]Z'^\mu$

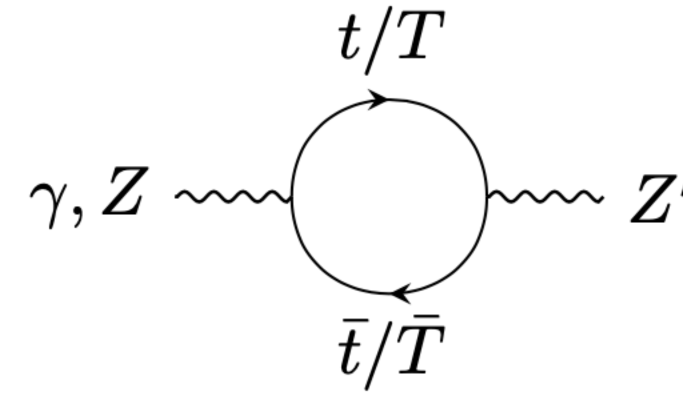
$$\tan 2\theta_L = \frac{v\tilde{v}Y_t Y_T^t}{M_T^2 + (\tilde{v}Y_T^t)^2/2 - (vY_t)^2/2}\,,$$

$$\tan 2\theta_R = \frac{\sqrt{2}\tilde{v}Y_T^t M_T}{M_T^2 - (\tilde{v}Y_T^t)^2/2 - (vY_t)^2/2}\,,$$

Radiative corrections

- Z' - Z/γ mixing
  - assuming $\varepsilon_B = 0$ in UV (Λ)

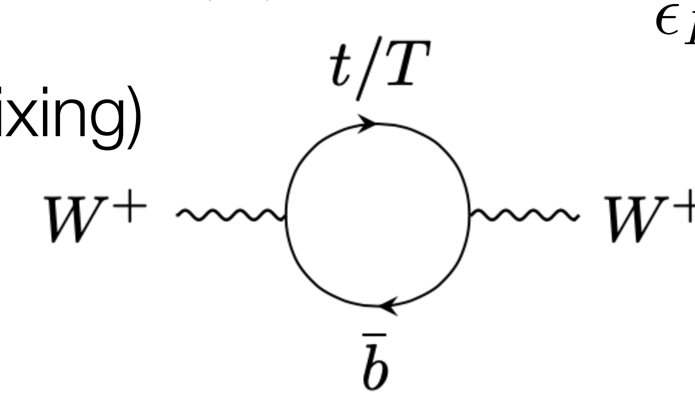
    $s^2_{L,R} \ll 1$



$$\epsilon_A = -\frac{\epsilon_Z}{t_w} = \frac{e\tilde{g}q'}{6\pi^2}\ln\frac{\Lambda^2}{m_T^2} = 3\times 10^{-3}\left(\frac{\tilde{g}q'}{10^{-2}}\right)\left(\frac{\ln\Lambda^2/m_T^2}{55.3}\right)$$

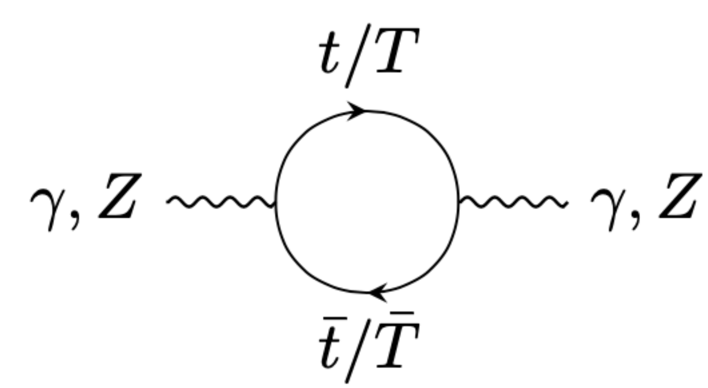
  - can be further suppressed/fine-tuned against $\varepsilon_B(\Lambda)$: $\delta = \dfrac{\epsilon_B(m_W) - \epsilon_B(\Lambda)}{\epsilon_B(m_W)}$

- Contributions to EWPOs (neglecting Z' - Z/γ mixing)



$$T = \frac{3}{8\pi s_w^2}\frac{m_t^2}{M_W^2}s_L^2\left[\ln\frac{m_T^2}{m_t^2} - 1\right],$$

$$S = \frac{1}{3\pi}s_L^2\left[\ln\frac{m_T^2}{m_t^2} - \frac{5}{2}\right], \quad U = \frac{5}{6\pi}s_L^2$$

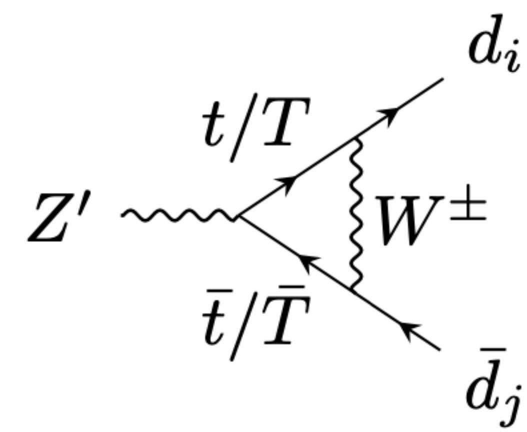


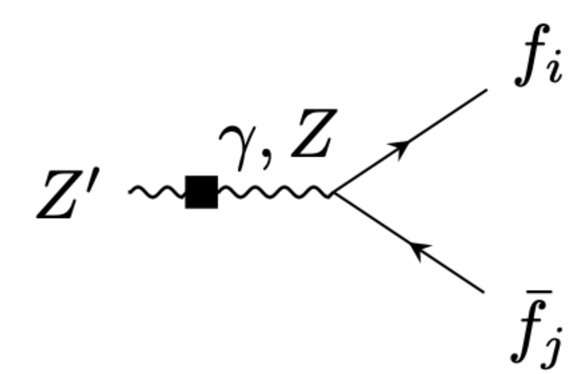
  - sensitivity to $m_T,\ s_L$

Z' couplings to SM fermions

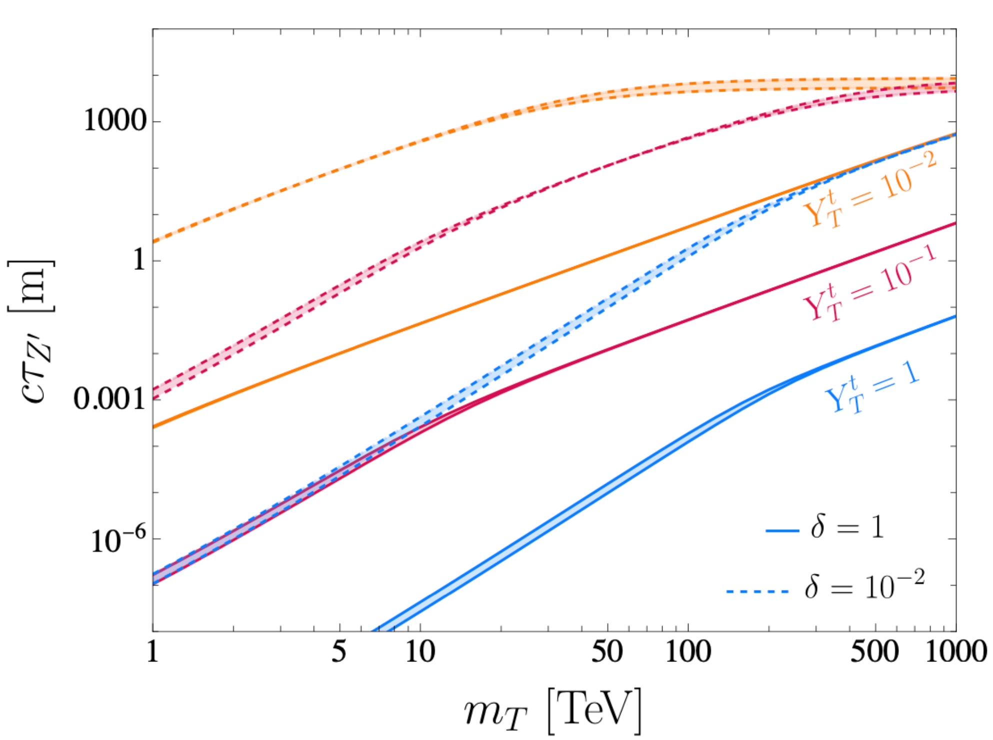
- Below EWSB scale:

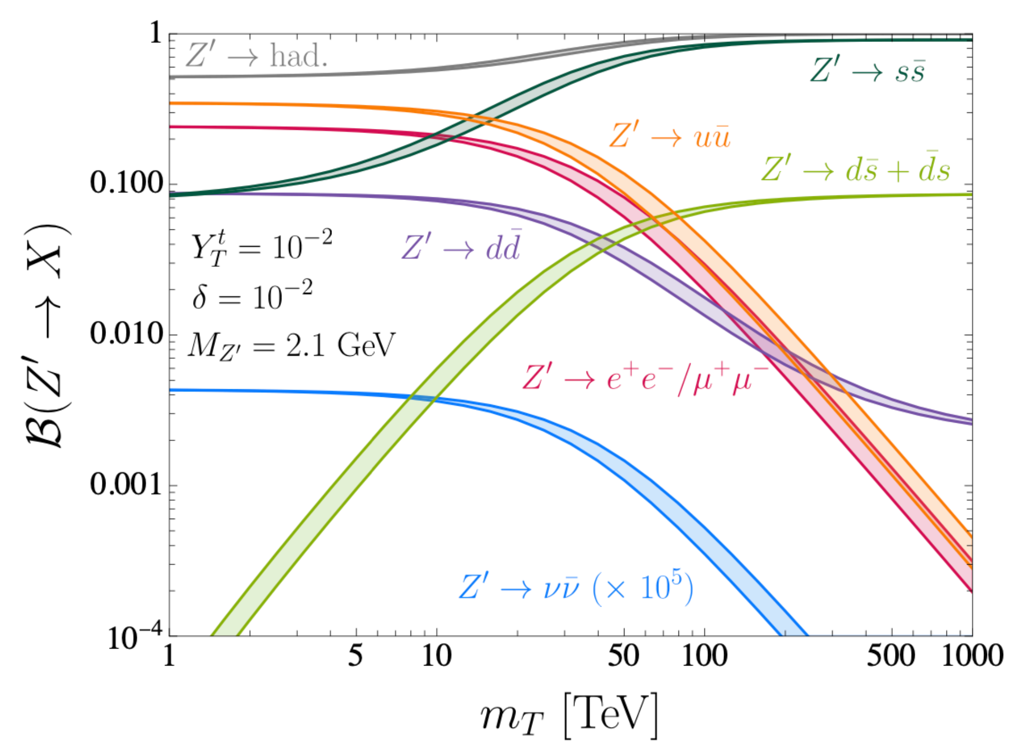
$$\mathcal{H}_{\text{eff}} \supset \frac{4G_F}{\sqrt{2}} V_{ti}^* V_{tj} \frac{\tilde{g}q'}{16\pi^2} m_T m_t \bar{d}_i \gamma_\mu P_L d_j Z'^\mu$$





  - U(2) / MFV -like flavour patterns
  - Accommodating Belle II result via $b \to sZ'$ implies $\tilde{g}q' \gtrsim 9.5 \times 10^{-7} \left(\frac{10\ \text{TeV}}{m_T} \right)$
    - Lower bound saturated if all Z' escape / decay invisibly

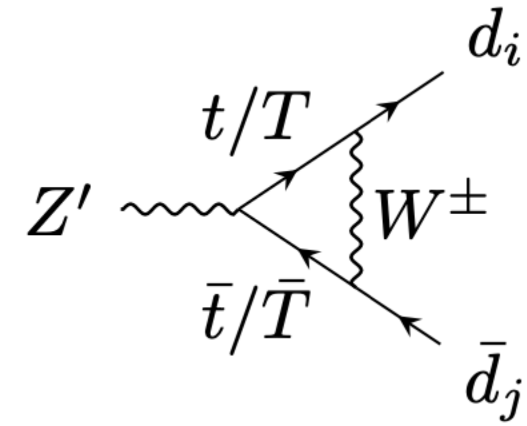


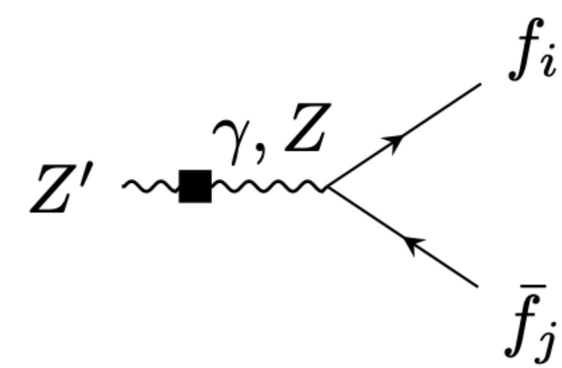


Z' couplings to SM fermions

- Below EWSB scale:

$$\mathcal{H}_{\rm eff} \supset \frac{4G_F}{\sqrt{2}} V_{ti}^* V_{tj} \frac{\tilde{g}q'}{16\pi^2} \, m_T m_t \bar{d}_i \gamma_\mu P_L d_j Z'^\mu$$

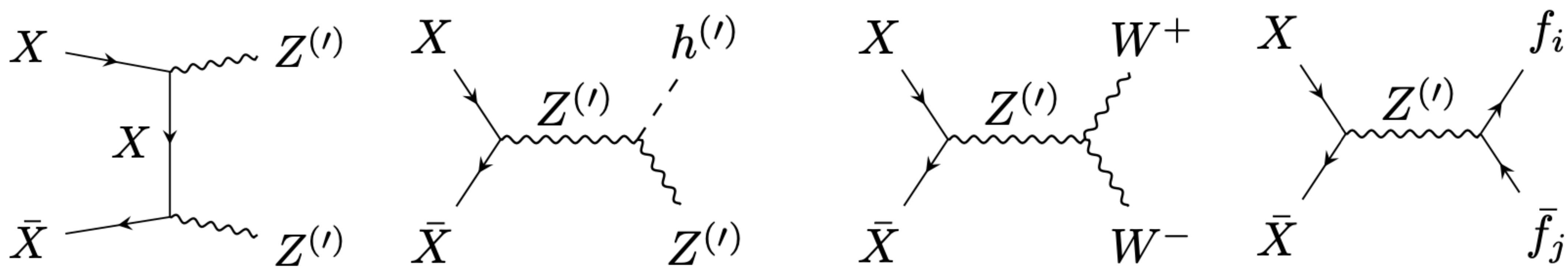




  - U(2) / MFV -like flavour patterns
  - Accommodating Belle II result via $b \to sZ'$ implies $\tilde{g}q' \gtrsim 9.5 \times 10^{-7} \left(\frac{10 \text{ TeV}}{m_T}\right)$
    - Lower bound saturated if all Z' escape / decay invisibly
    - Prediction of $b \to dZ'$ mediated $B \to \rho/\pi E_{\rm miss}$
    - $K \to \pi Z'$ kinematically forbidden

DM phenomenology

- SM-neutral U(1)$'$ charged fermions can be cosmologically stable
  - can form thermal relics in early universe



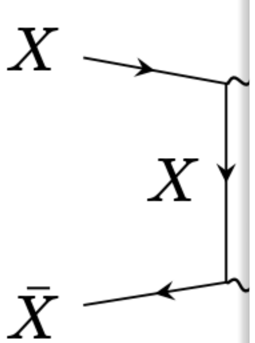
  - in interesting region ($M_X > M_{Z'}$) freeze-out dominated by t-channel annihilation into Z'

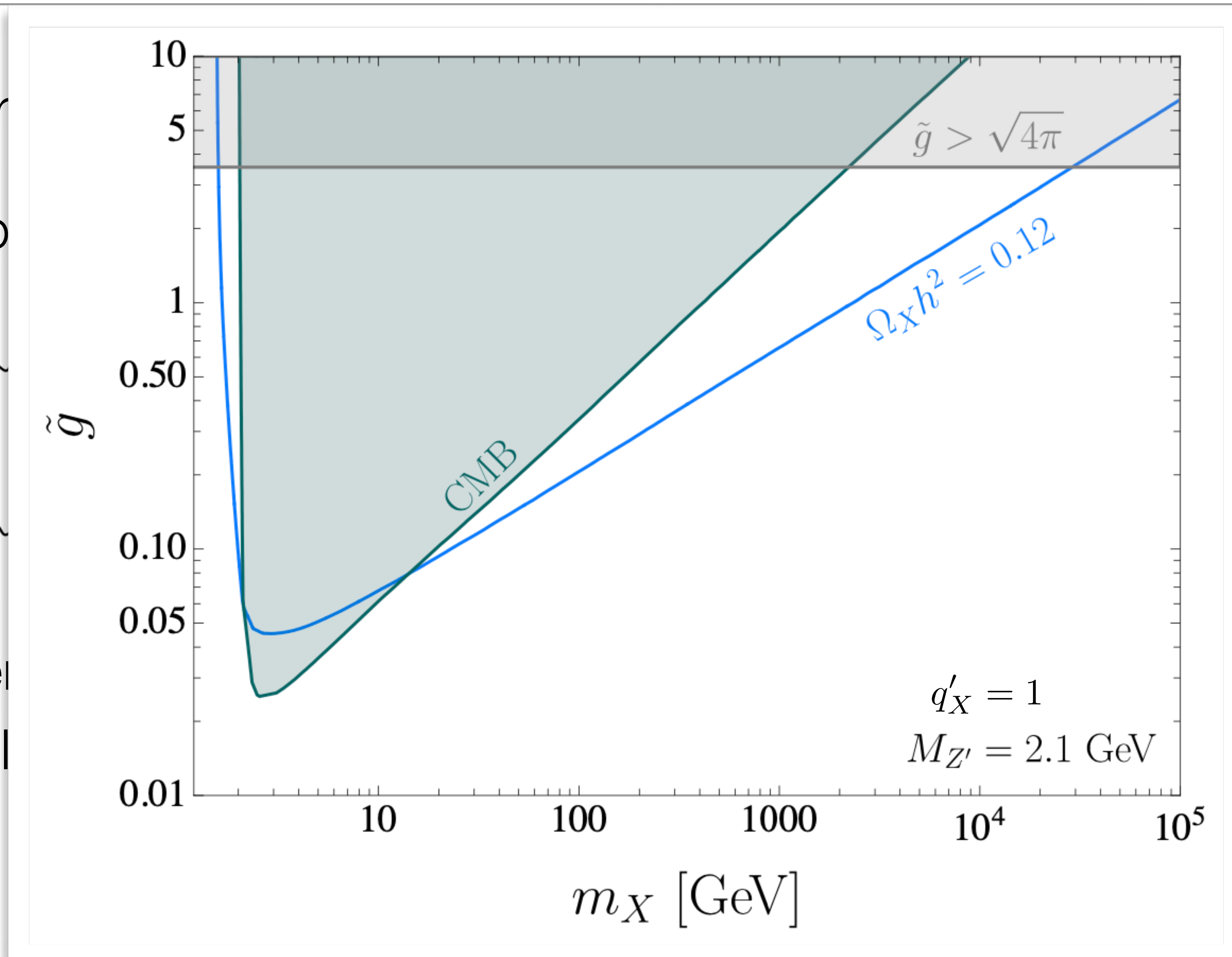
$$\frac{\Omega_X}{\Omega_{\rm DM}} \approx \left(\frac{m_X}{10\ \rm GeV}\right)^2 \left(\frac{0.07}{\tilde{g}q'_X}\right)^4$$

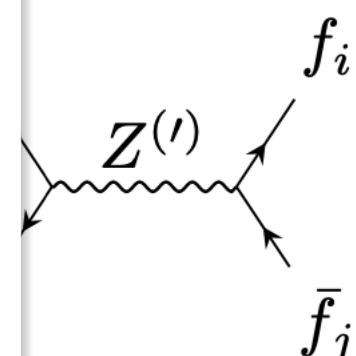
    - suppressed/decoupled effects in DM direct detection experiments
    - dominant constraints from CMB distortions Slatyer, 1506.03811

DM phenomenology

- SM-neutr
  - can fo





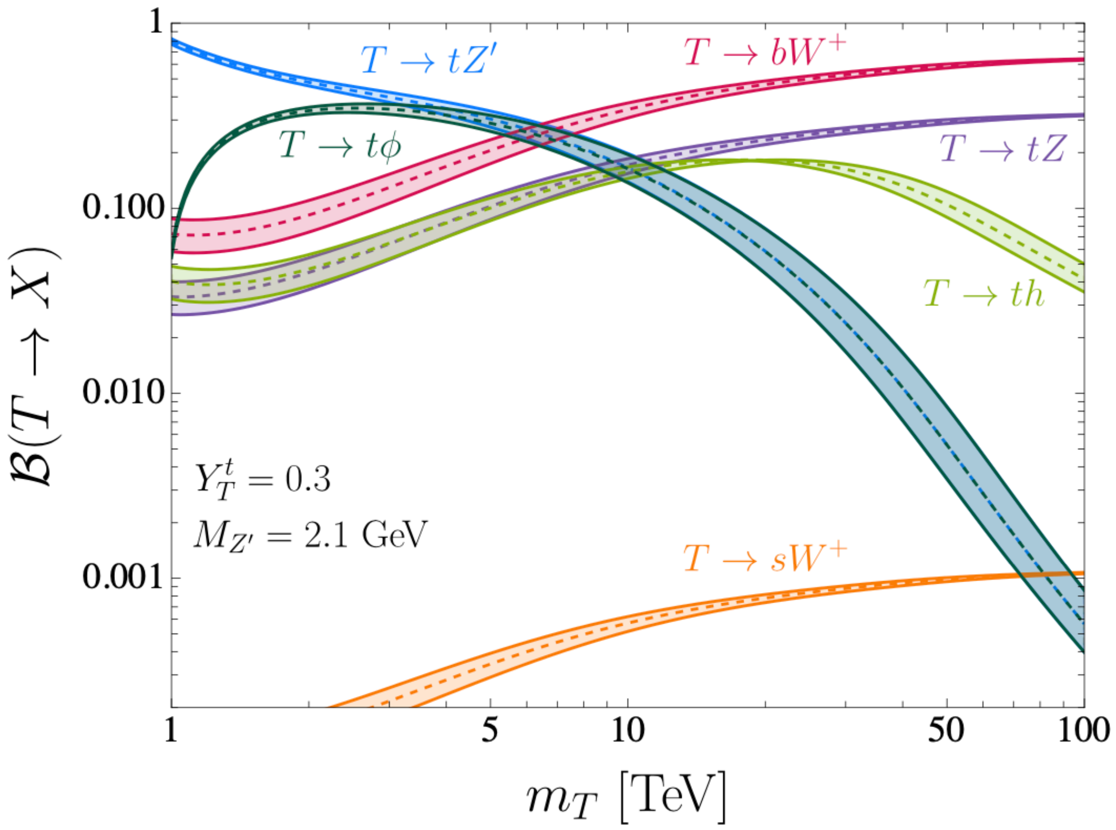


  - in inte chanel annihil
    - suppressed/decoupled effects in DM direct detection experiments
    - dominant constraints from CMB distortions Slatyer, 1506.03811

$$M_X \gtrsim 20\ GeV\,, \quad \tilde{g} q'_X \gtrsim 0.08$$

Collider searches

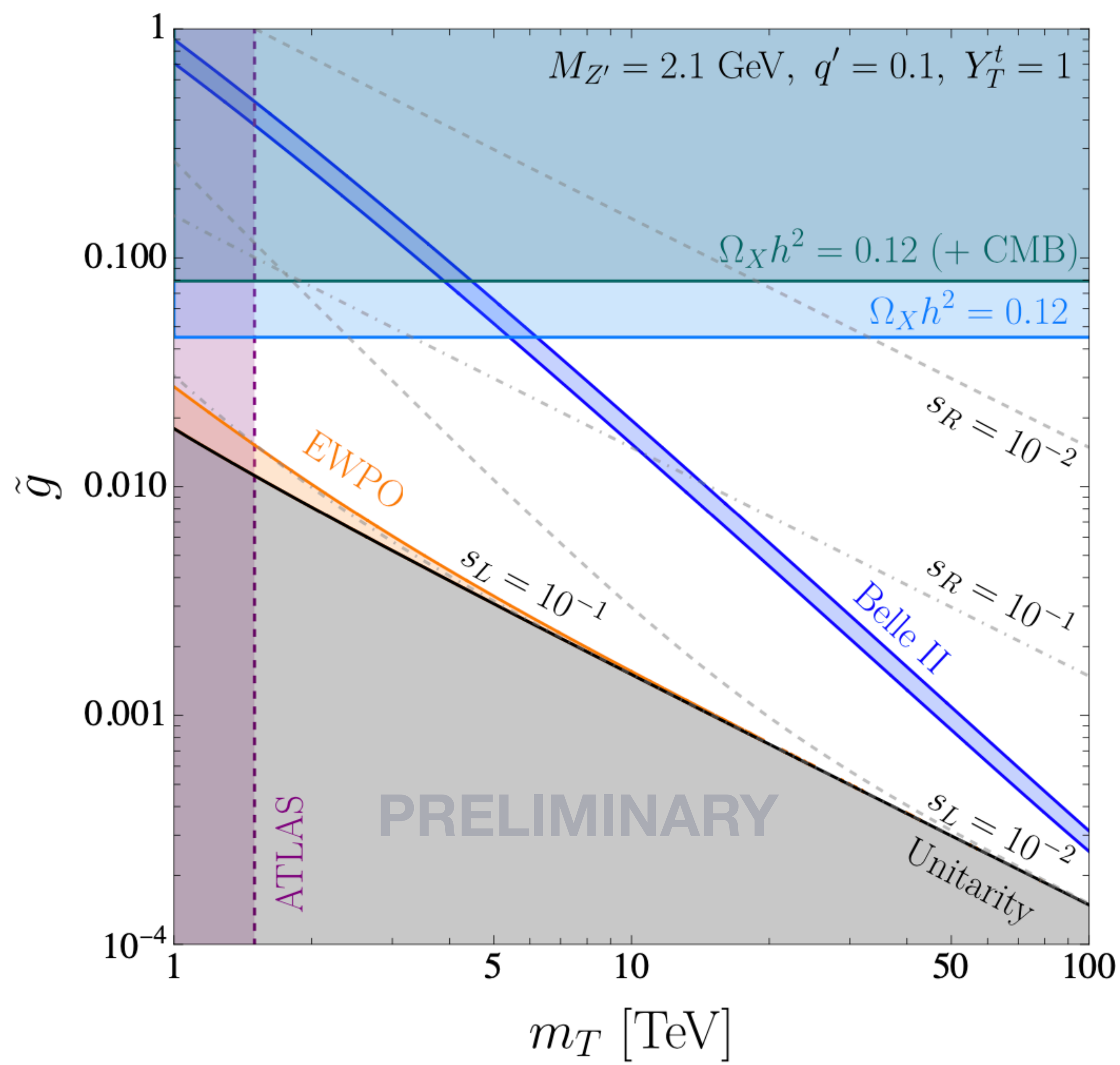
- VL top partner (*T*) can be QCD pair produced at LHC
  - presence of light Z' (and potentially ϕ) modifies search signatures
  - reduced sensitivity of standard VL quark searches i.e. ATLAS, 2401.17165
  - novel signature of $t\bar{t} + E_{\rm miss}$ i.e. ATLAS, 2401.13430



Summary

Bolton et al., 2508.XXXXX

- Model can simultaneously account for Belle II result, accommodate DM
- Effects correlated with VL top partner parameters $(m_T,\, Y_T^t)$
  - m_T cannot be decoupled!
- Combined explanations imply a hierarchy of U(1)$'$ charges $q' \ll q'_X$
- Z - Z' mixing constraints might require O(10^{-2}) cancellations in kinetic mixing



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
        - Simple U(1)$'$ example connecting to DM, VL quark searches
    - 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