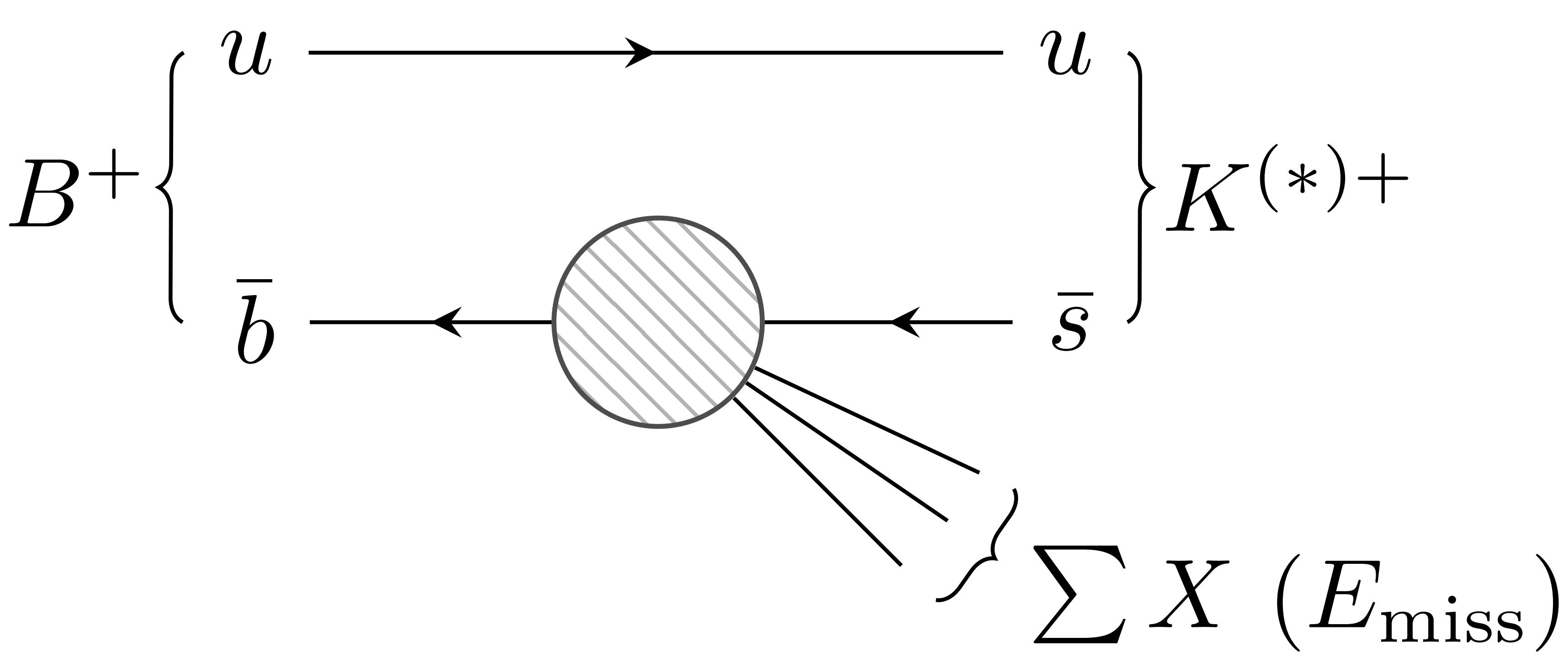
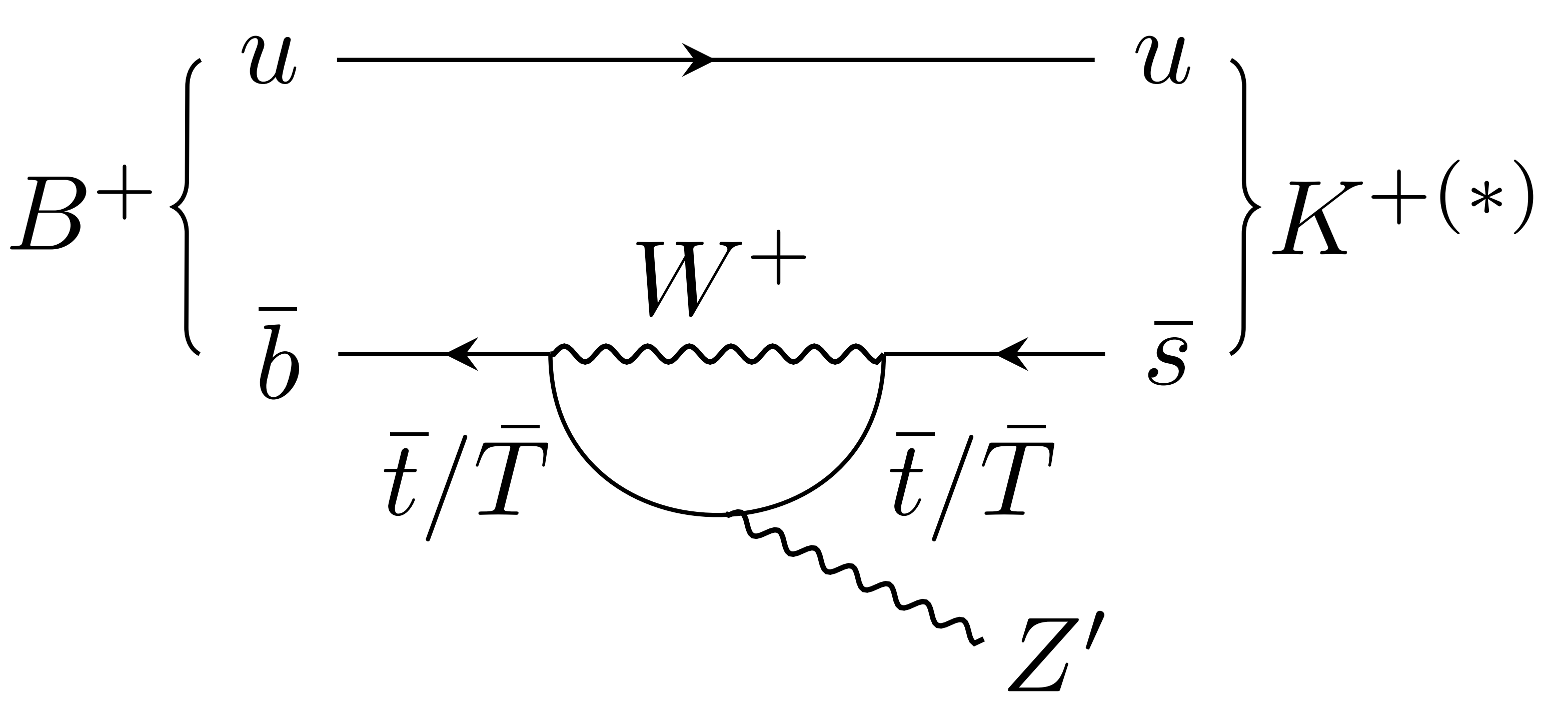




Hunting for a light Z' portal to the **dark side** at Belle II

Based on: arXiv:2403.13887, arXiv:2503.19025 with J. F. Kamenik, S. Fajfer and M. Novoa-Brunet
Ongoing work with J. F. Kamenik and M. Novoa-Brunet

BRDA 2025: Selected topics in (B)SM

Outline

Episode I

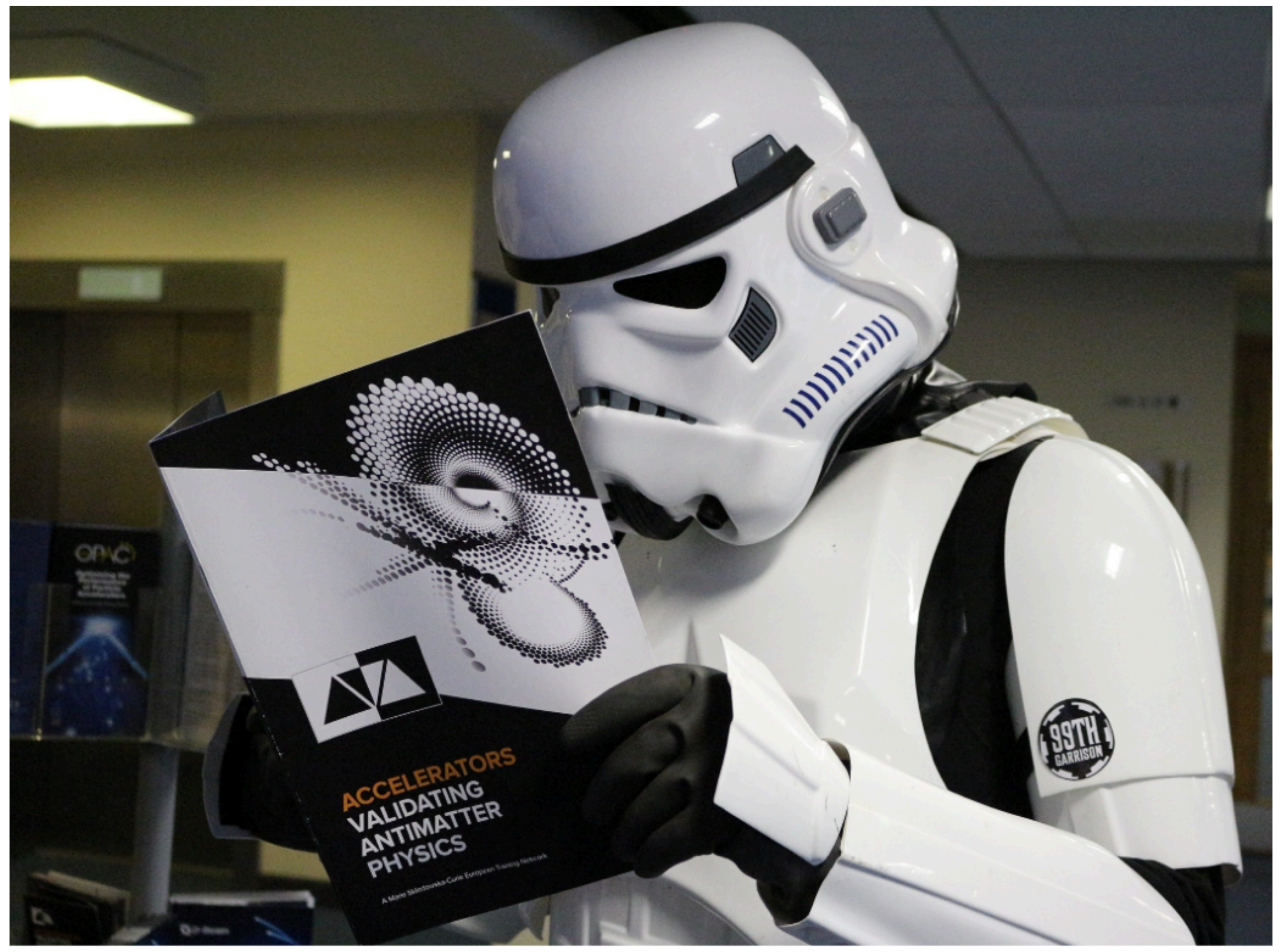
- Light NP interpretations of the Belle II $B^+ \to K^+\nu\bar{\nu}$ (E_{miss}) inclusive tagging analysis (ITA)
- Best-fit masses and couplings (including constraints from *BABAR* + LEP)

Episode II

- Impact of light NP scenarios on $B \to K^* E_{\text{miss}}$ observables

Episode III

- UV realisation of $B^+ \to K^+ X$ with $X = Z'$
- Constraints from theory and experiment
- Connection to dark matter (DM)

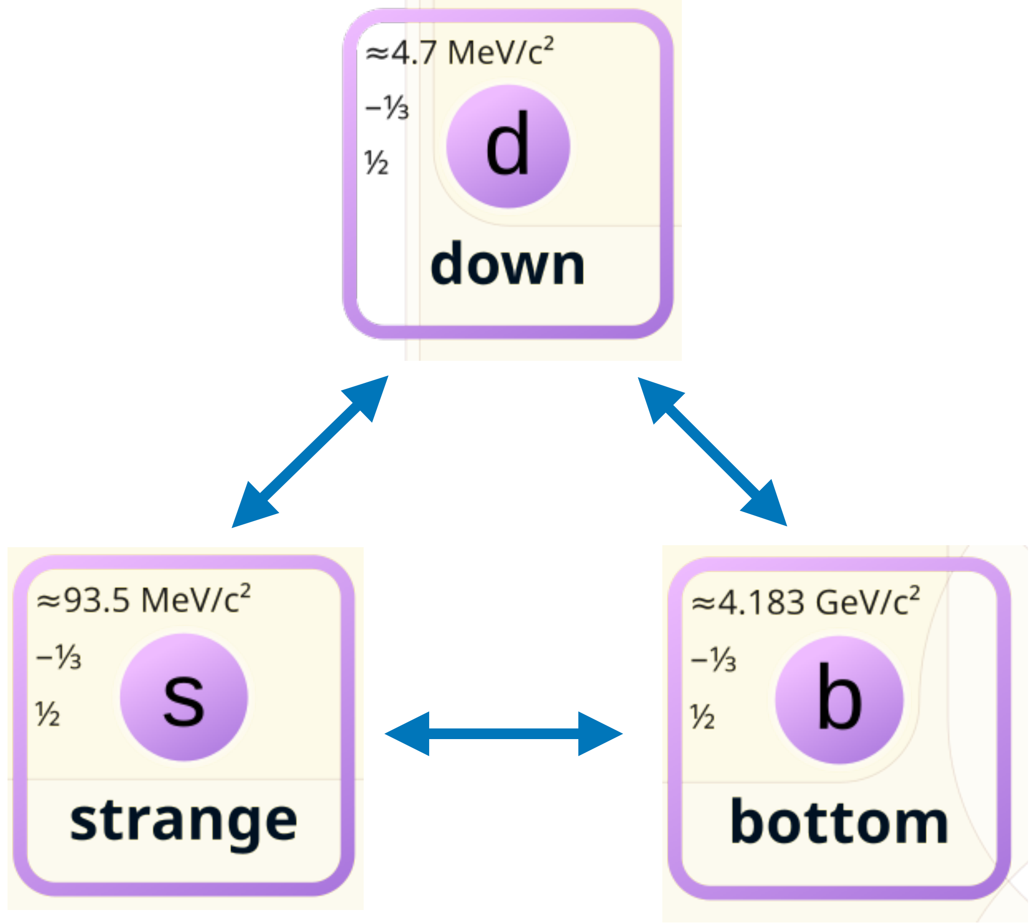


Episode I: Light new physics interpretations of $B^+ \to K^+ \nu \bar{\nu}$

Motivation

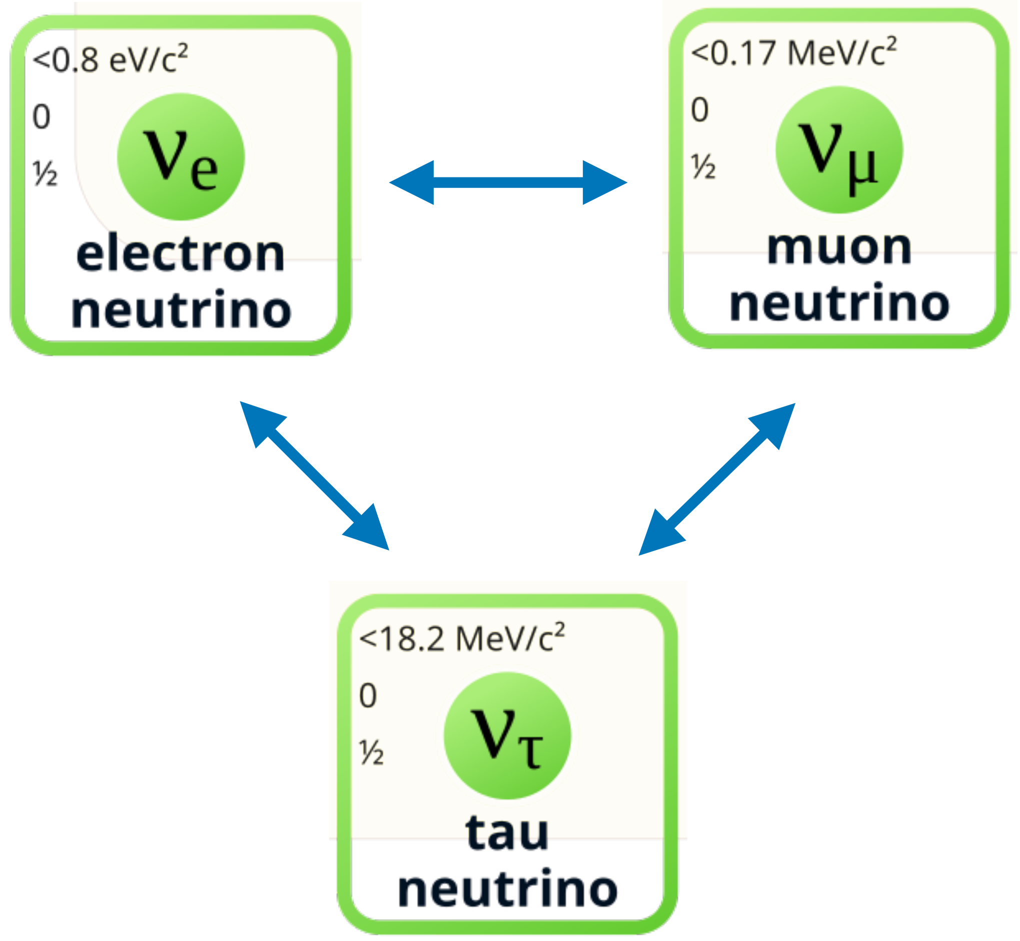
Study of Flavour Changing Neutral Currents (FCNCs) is highly motivated:

- Loop and CKM (i.e. GIM) suppressed in the SM
- *Powerful indirect probe of new physics* (related to flavour puzzle?)



Neutrino final states (or missing energy modes) are further compelling:

- Theoretically cleaner than charged lepton FCNCs
- However, experimentally more challenging
- If $E_{\text{miss}} =$ neutrinos, related to neutrino mass puzzle?
- If $E_{\text{miss}} \neq$ neutrinos, related to cosmological DM puzzle?



$B \to K\nu\bar{\nu}$ in the Standard Model

$$\boxed{\mathcal{B}(B^+ \to K^+\nu\bar{\nu})_{\text{SM}} = (5.58 \pm 0.37) \times 10^{-6}}$$

[Parrott et al. 2023]

Reviews: [Altmannshofer et al. 2009]
[Buras et al. 2014]

Factorisable short distance amplitude

$$\mathcal{A} \sim \sum_i C_i \langle \mathcal{O}_i \rangle \longrightarrow \boxed{\left.\frac{d\Gamma(B \to K\nu\bar{\nu})_{\text{SM}}}{dq^2}\right|_{\text{SD}} = \frac{|\vec{p}_K|^3}{64\pi^3}\left|C_{d\nu}^{V,LL}\right|^2 f_+^2(q^2)}$$

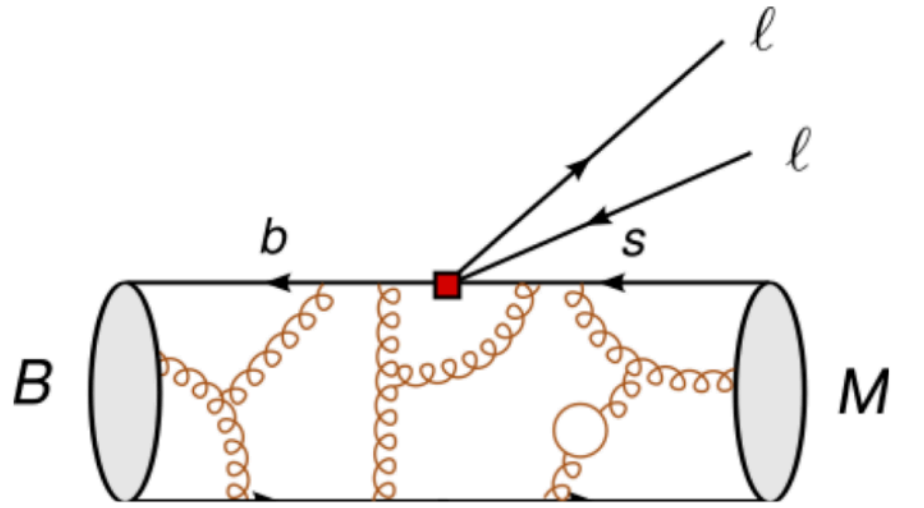
C_i : Wilson coefficient (WC) of weak effective theory (WET) operator

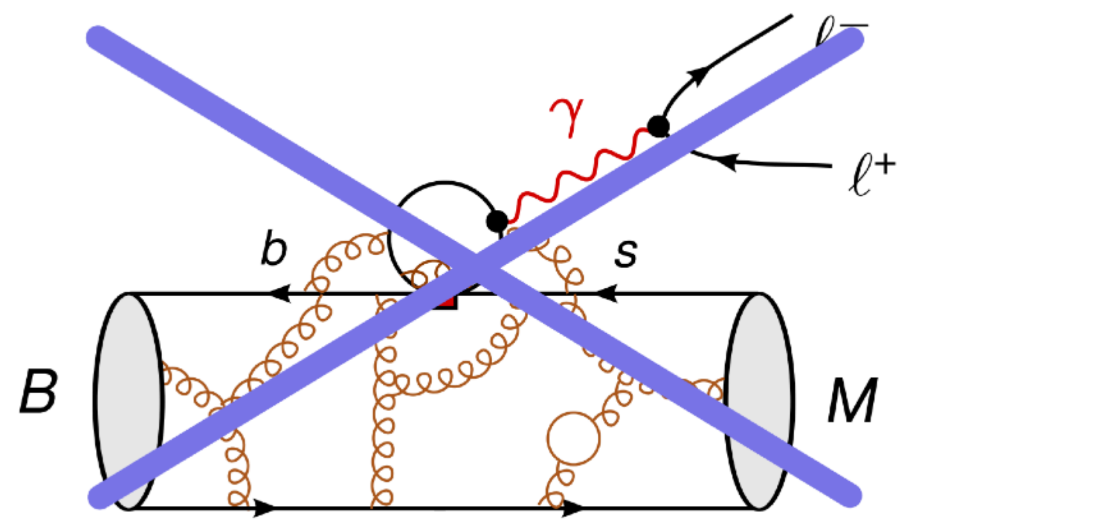
$$C_{d\nu}^{V,LL}(\bar{b}_L\gamma_\mu s_L)(\bar{\nu}_L\gamma^\mu\nu_L) \qquad C_{d\nu}^{V,LL} = \frac{4G_F V_{tb}V_{ts}^*}{\sqrt{2}}\frac{X_t}{s_w^2}\frac{\alpha(M_Z)}{2\pi}$$

$\langle \mathcal{O}_i \rangle$: Matrix elements written in terms of local form factors, evaluated non-perturbatively

$$\langle K|\,\bar{b}\gamma_\mu s\,|B\rangle = P_\mu f_+(q^2) + \frac{m_B^2 - m_K^2}{q^2} q_\mu \left[f_0(q^2) - f_+(q^2)\right]$$

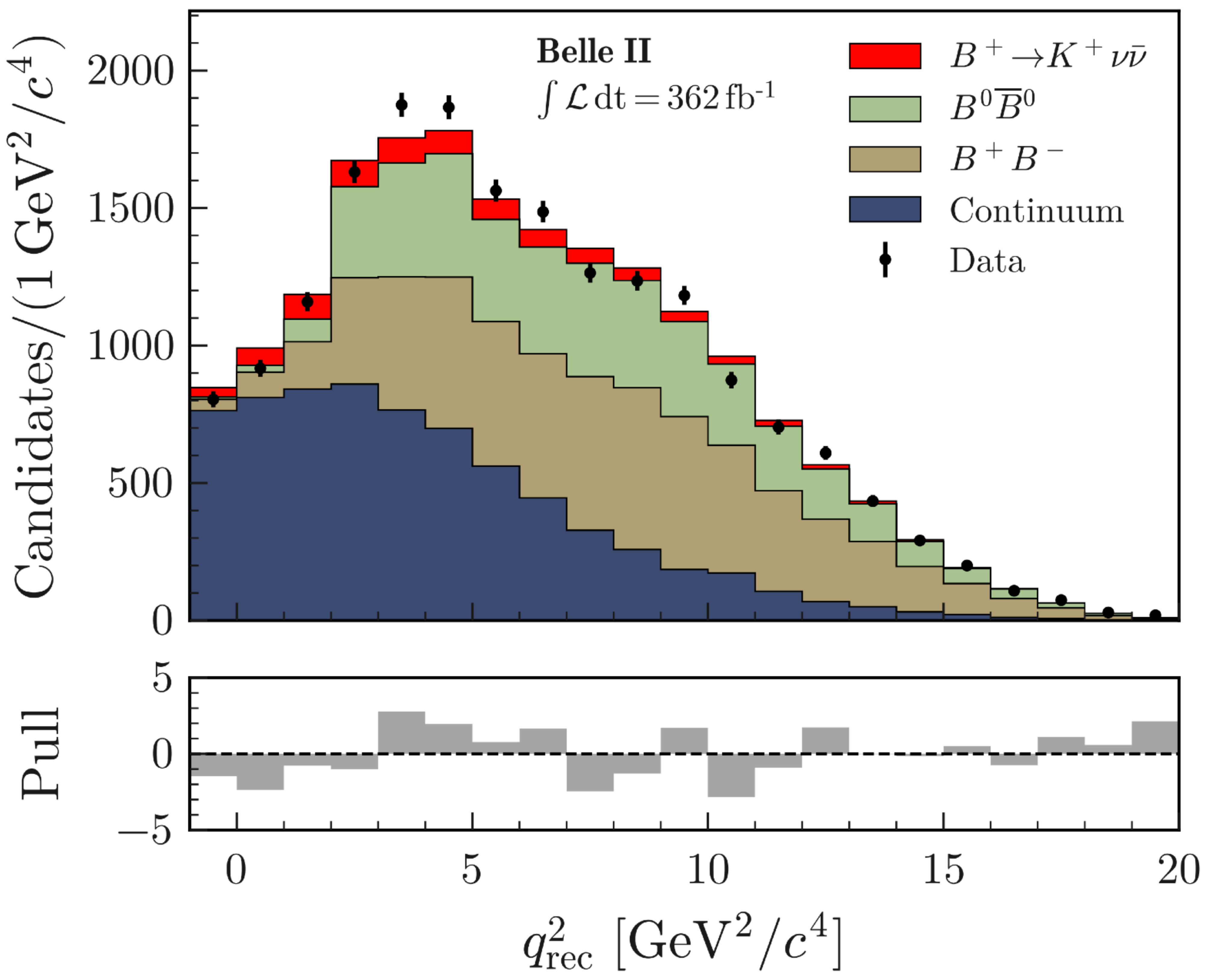
- Light-cone sum rules at low q^2
- Lattice QCD at high q^2



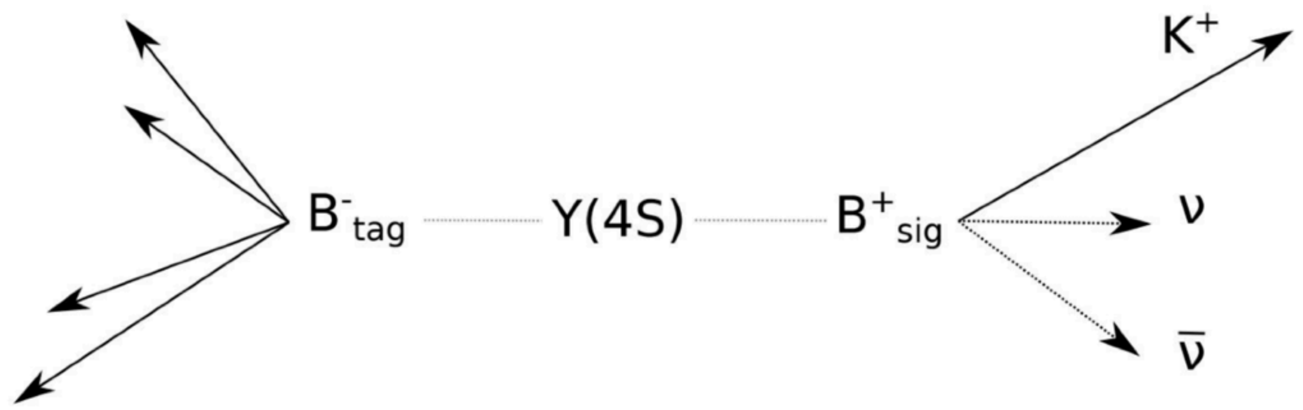


Belle II results

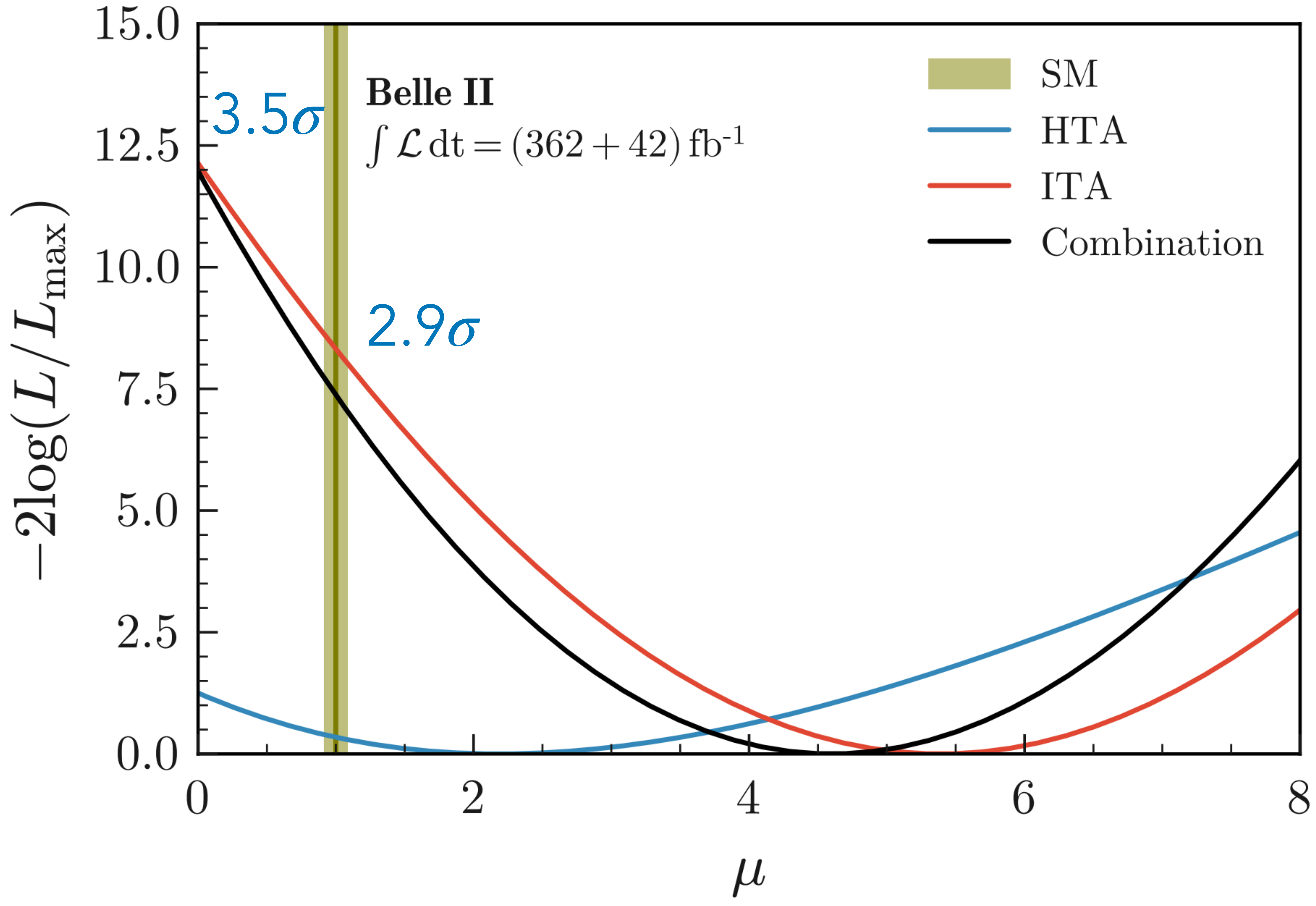
Full signal region, $\eta(\mathrm{BDT}_2) > 0.92$



$$\mu = \frac{\mathcal{B}(B^+ \to K^+\nu\bar{\nu})}{\mathcal{B}(B^+ \to K^+\nu\bar{\nu})\big|_{\mathrm{SM}}} = 5.4 \pm 1.0\ (\mathrm{stat}) \pm 1.1\ (\mathrm{syst})$$

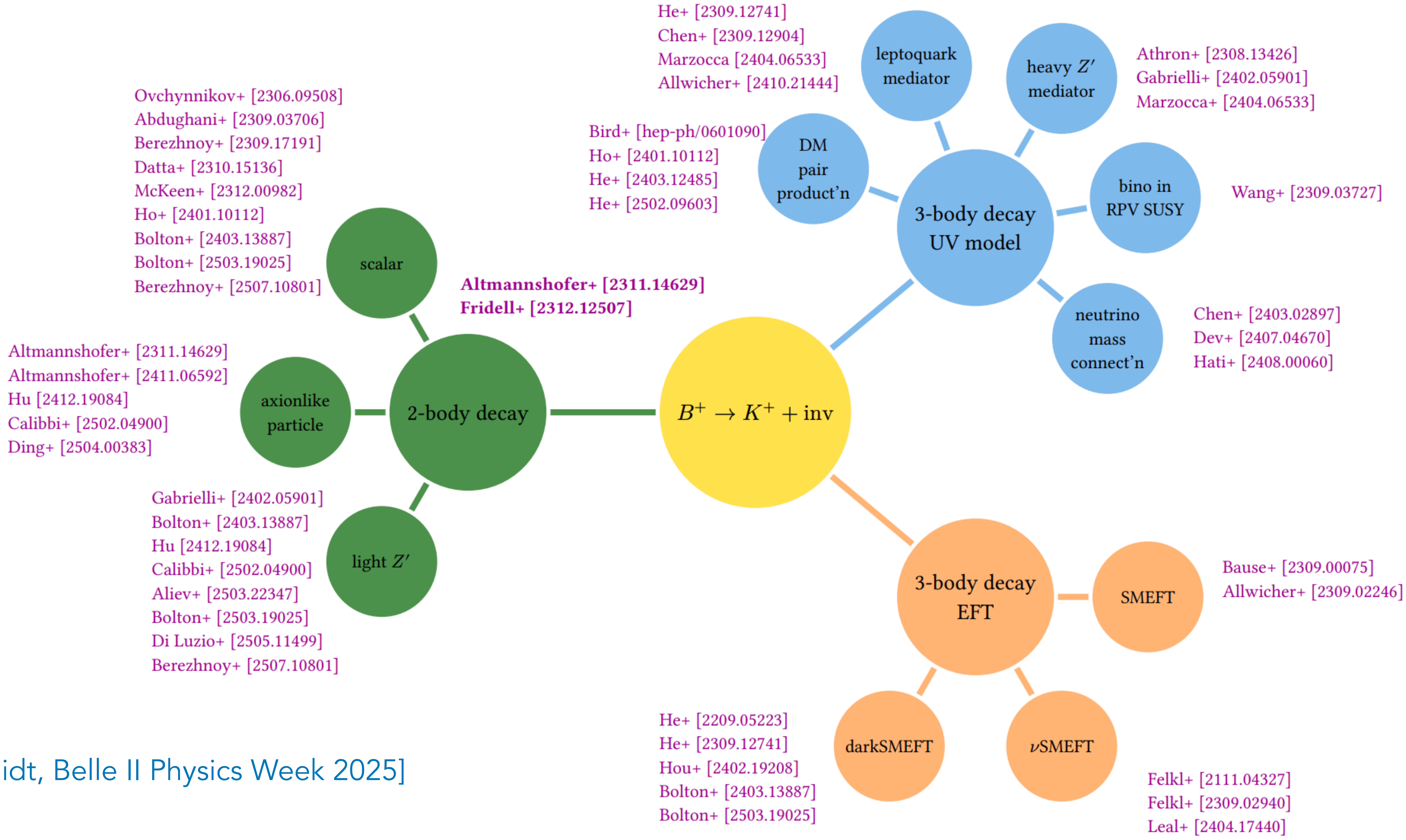


[Adachi et al. 2023]



Result assumes SM q^2 spectrum $\left.\frac{d\Gamma(B \to K\nu\bar{\nu})_{\mathrm{SM}}}{dq^2}\right|_{\mathrm{SD}}$

New physics interpretations: a survey



[M. Schmidt, Belle II Physics Week 2025]

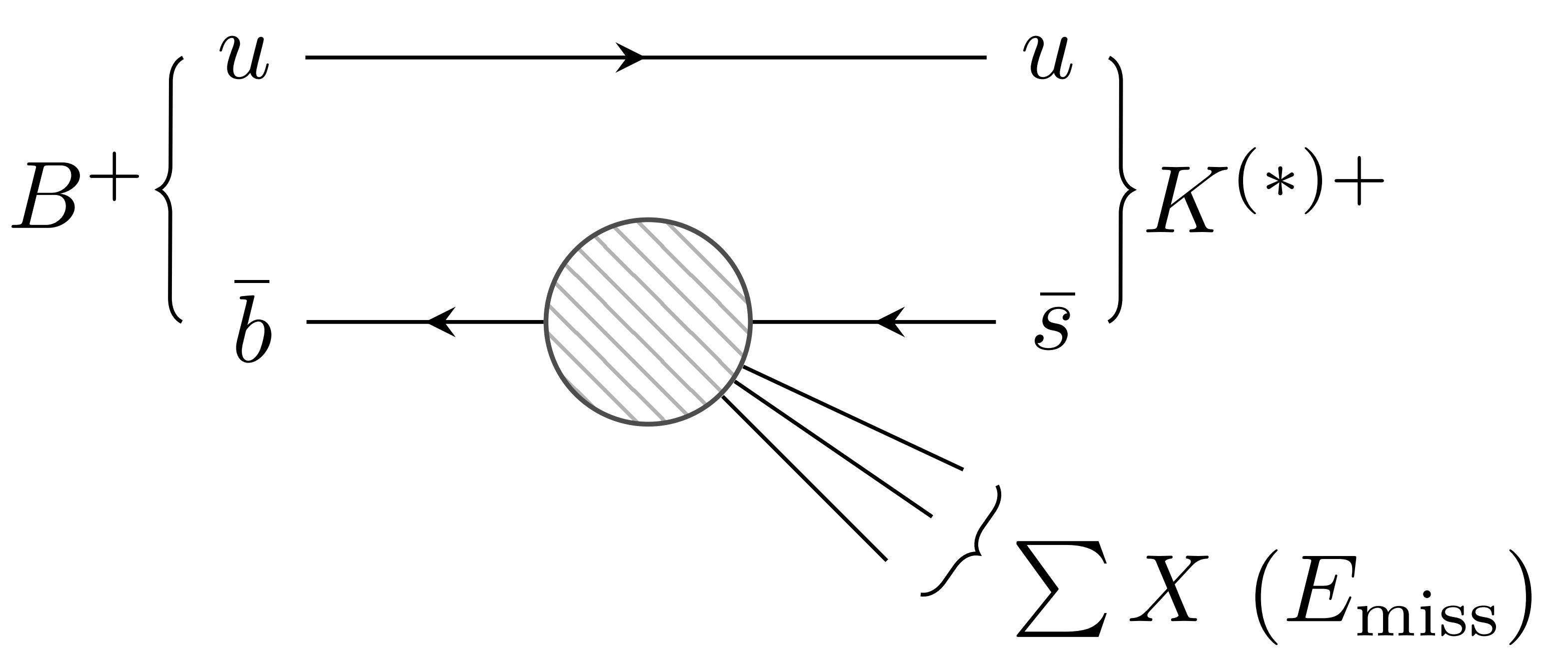
Light NP interpretations for $B^+ \to K^+ E_{\text{miss}}$

$$\mu = \frac{\mathcal{B}(B^+ \to K^+ \nu\bar{\nu})}{\mathcal{B}(B^+ \to K^+ \nu\bar{\nu})|_{\text{SM}}} = 5.4 \pm 1.0\ (\text{stat}) \pm 1.1\ (\text{syst}) \quad \text{(ITA)}$$

↓

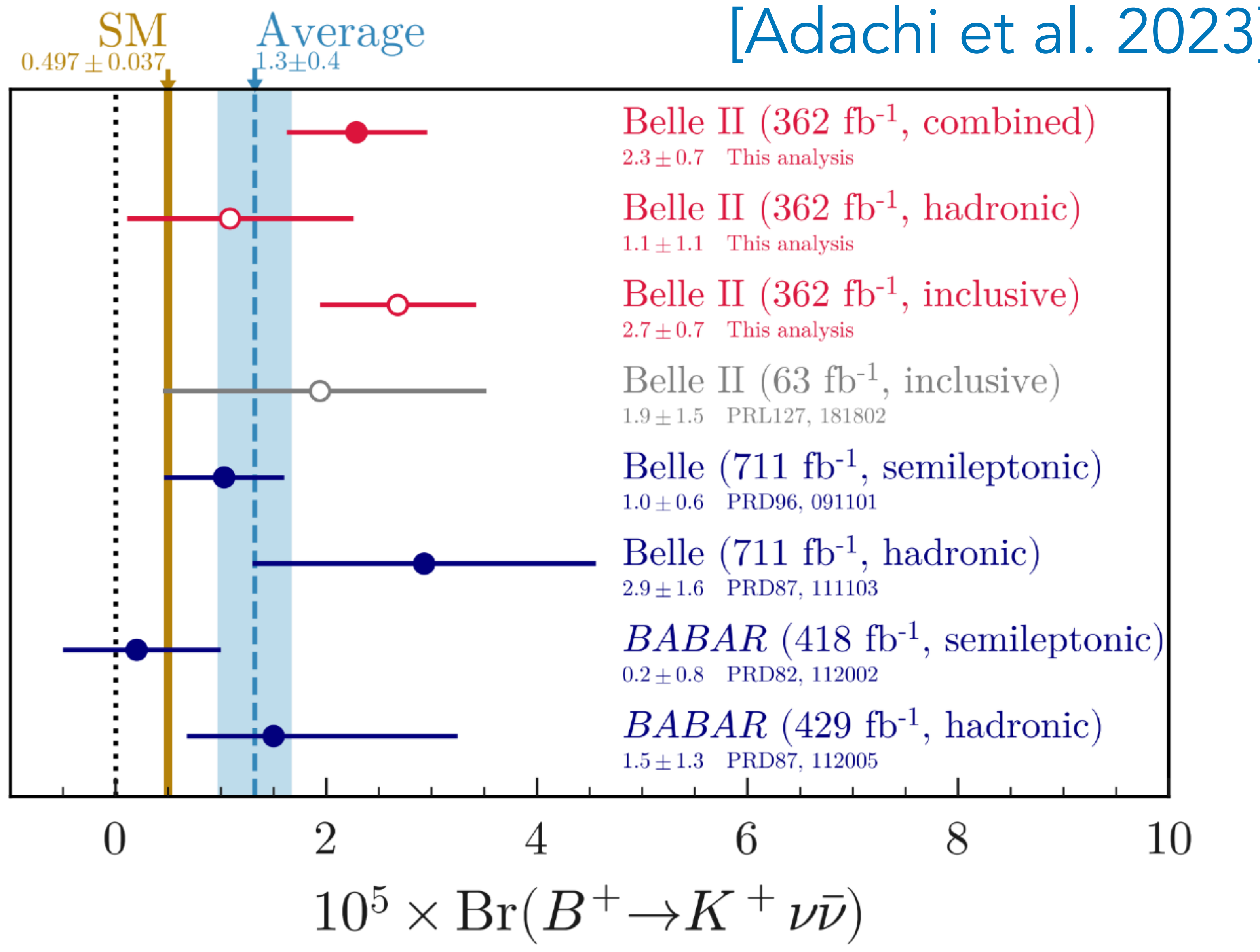
Parametric + form factor uncertainties well understood

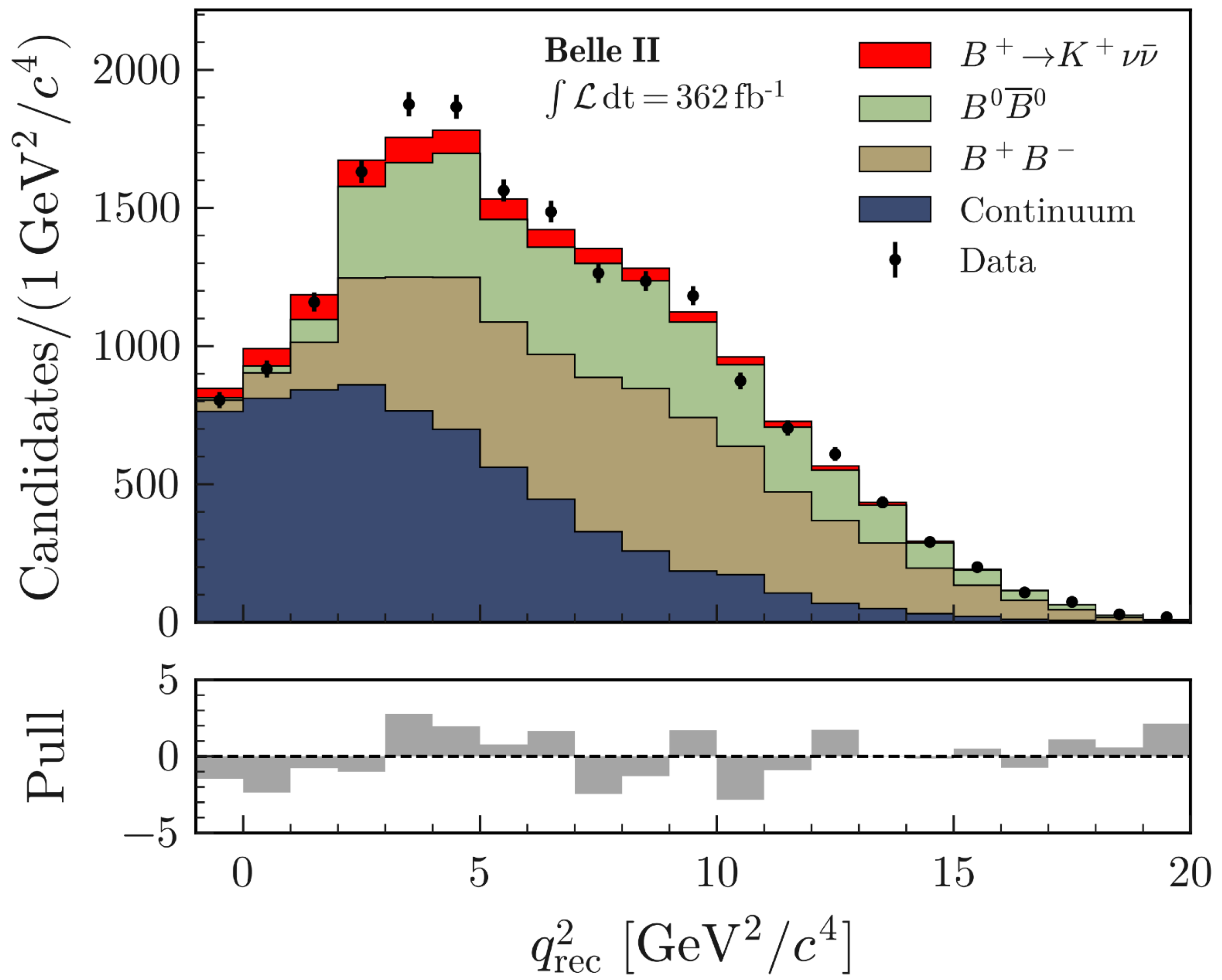
Interpret excess as E_{miss} = new light degrees of freedom



- Possible spin $J = \{0, 1/2, 1, 3/2\}$
- Distinct kinematic signatures due to spin, mass and multiplicity
- Intriguing possible connection to dark matter (DM)

[Adachi et al. 2023]



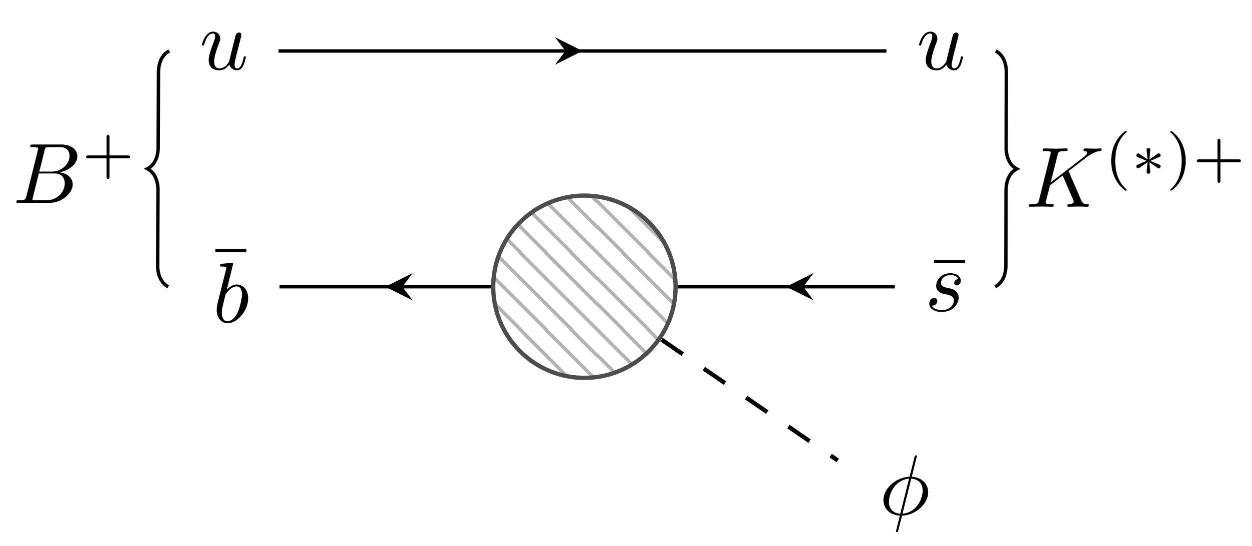


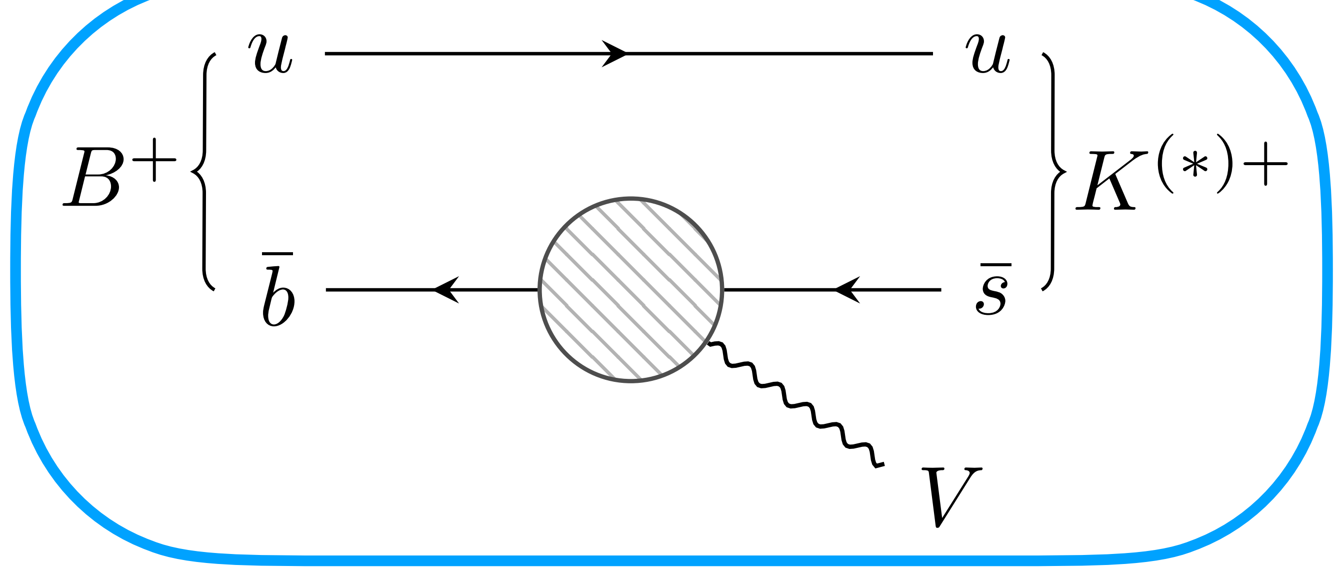
Light new physics scenarios

With generic $J = \{0, 1/2, 1, 3/2\}$ fields $X \in \{\phi, \psi, V_\mu, \Psi_\mu\}$, we may have

Two-body:

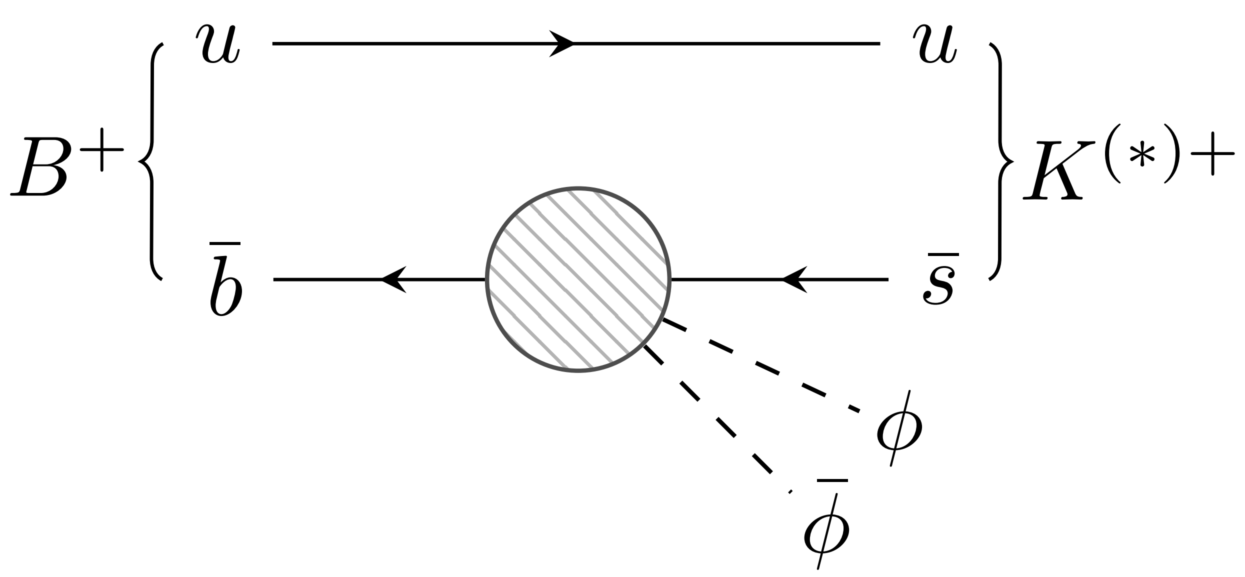
$B^+ \to K^+ X$

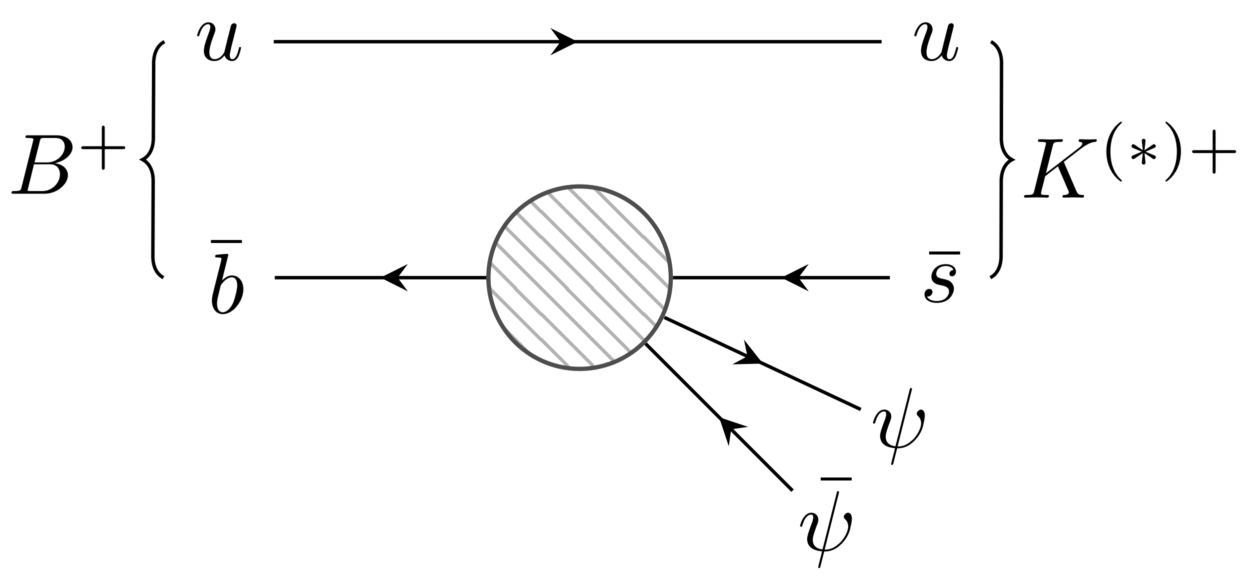


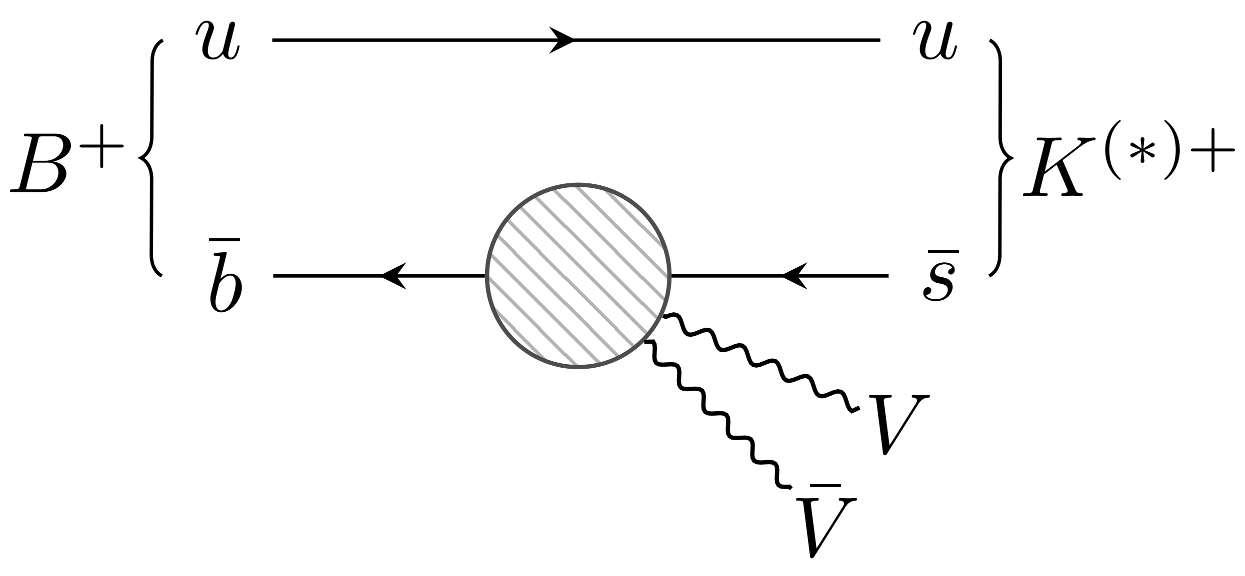


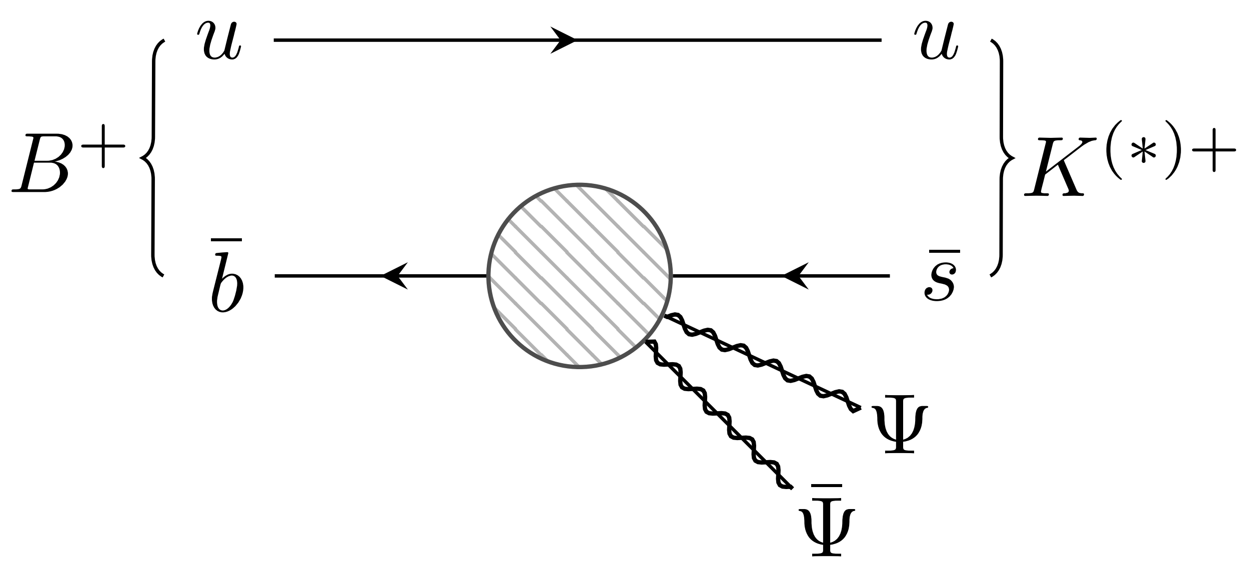
Three-body:

$B^+ \to K^+ X X$









Scenarios

Axion-like particle (ALP)

Light Z' (dark photon)

Heavy Neutral Lepton (connection to ν masses?)

Gravitino

Composite models

Effective couplings

New fields are assumed to have effective WET(+X) couplings to the $b \to s$ transition quark current

e.g. vector $b \to s$ current

$$\mathcal{H}_{\text{eff}}^{V(A)} \supset \bar{b}\gamma_\mu\gamma_5 s\Big[\underbrace{\frac{g_V}{\Lambda}\partial^\mu\phi + \frac{g_{VV}}{\Lambda^2}i\phi^\dagger\overleftrightarrow{\partial}^\mu\phi}_{\text{Spin-0}} + \underbrace{\frac{f_{VV}}{\Lambda^2}\bar{\psi}\gamma^\mu\psi + \frac{f_{VA}}{\Lambda^2}\bar{\psi}\gamma^\mu\gamma_5\psi}_{\text{Spin-1/2}} + \underbrace{h_V V^\mu}_{\text{Spin-1}} + \underbrace{\frac{F_{VV}}{\Lambda^2}\bar{\Psi}^\rho\gamma^\mu\Psi_\rho + \frac{F_{VA}}{\Lambda^2}\bar{\Psi}^\rho\gamma^\mu\gamma_5\Psi_\rho}_{\text{Spin-3/2}}\Big]$$

[Kamenik, Smith, 2011]

$$\langle K|\,\bar{b}\gamma_\mu s\,|B\rangle = P_\mu f_+(q^2) + \frac{m_B^2 - m_K^2}{q^2}q_\mu\Big[f_0(q^2) - f_+(q^2)\Big]$$

$$\langle K|\,\bar{b}\gamma_\mu\gamma_5 s\,|B\rangle = 0$$

- $B^+ \to K^+ E_{\text{miss}}$ is sensitive only to parity (P) even operators, use the 'parity' basis

$\Rightarrow$ Basis of operators using chiral quark fields more natural from UV (SMEFT) perspective

Effective couplings

Jožef Stefan Institute

Also WET(+X) couplings to scalar and tensor $b \to s$ current

$$\mathcal{H}_{\text{eff}}^{S(P)} \supset \bar{b}\gamma_5 s\Big[\underbrace{g_S\phi + \frac{g_{SS}}{\Lambda}\phi^\dagger\phi}_{\text{Spin-0}} + \underbrace{\frac{f_{SS}}{\Lambda^2}\bar{\psi}\psi + \frac{f_{SP}}{\Lambda^2}\bar{\psi}\gamma_5\psi}_{\text{Spin-1/2}} + \underbrace{\frac{h_S}{\Lambda}V_\mu^\dagger V^\mu}_{\text{Spin-1}} + \underbrace{\frac{F_{SS}}{\Lambda^2}\bar{\Psi}^\rho\Psi_\rho + \frac{F_{SP}}{\Lambda^2}\bar{\Psi}^\rho\gamma_5\Psi_\rho}_{\text{Spin-3/2}}\Big]$$

$$\mathcal{H}_{\text{eff}}^{T(\tilde{T})} \supset \bar{b}\sigma_{\mu\nu}\gamma_5 s\Big[\underbrace{\frac{f_{TT}}{\Lambda^2}\bar{\psi}\sigma^{\mu\nu}\psi}_{\text{Spin-1/2}} + \underbrace{\frac{h_T}{\Lambda}V^{\mu\nu}}_{\text{Spin-1}} + \underbrace{\frac{F_{TS}}{\Lambda^2}\bar{\Psi}^{[\mu}\Psi^{\nu]} + \frac{F_{TP}}{\Lambda^2}\bar{\Psi}^{[\mu}\gamma_5\Psi^{\nu]} + \frac{F_{TT}}{\Lambda^2}\bar{\Psi}^\rho\sigma^{\mu\nu}\Psi_\rho}_{\text{Spin-3/2}}\Big]$$

- Rates proportional $f_+(q^2)$, $f_0(q^2)$ and $f_T(q^2)$. All FFs taken from BSZ fit of [Gubernari et al. 2023]
- ψ may be unrelated to neutrinos (no $\bar{L}\tilde{H}\psi$ if ψ is charged under dark U(1) or odd under Z_2).

$\Rightarrow$ We can consider scalar + tensor operators in $m_\psi \to 0$ limit with no neutrino mass/$0\nu\beta\beta$ bounds

New physics contributions to $B^+ \to K^+ E_{\rm miss}$

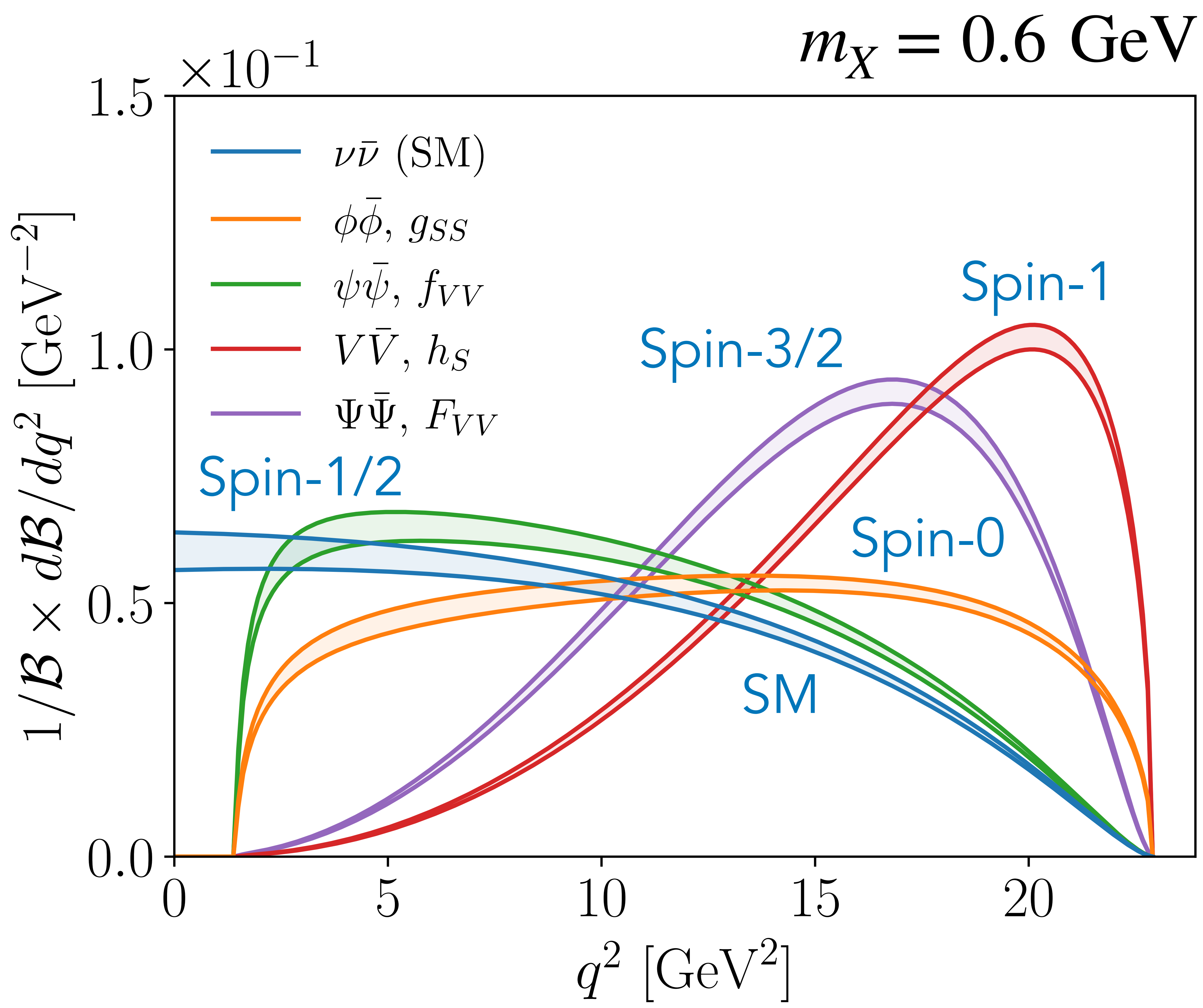
Two-body kinematics:

- q^2 fixed at mass of ϕ or V

Three-body kinematics:

- Smooth q^2 distribution
- Kinematic threshold at $q^2 = 4m_X^2$
- Different q^2 shapes for ϕ, ψ, V, Ψ

Unbiased NP interpretations require fit to reconstructed $q^2_{\rm rec}$ spectrum



[PDB, Fajfer, Kamenik, Novoa-Brunet 2024]

$\Rightarrow$ Belle II likelihood (reweighting method) now public

[Gärtner et al. 2024]

[Abumusabh et al. 2025]

Reinterpreting the Belle II ITA results

Before the Belle II likelihood release, our approach was to:

Construct differential event rate in the reconstructed q^2_{rec}:

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

Smearing of q^2_{rec} Detector efficiency

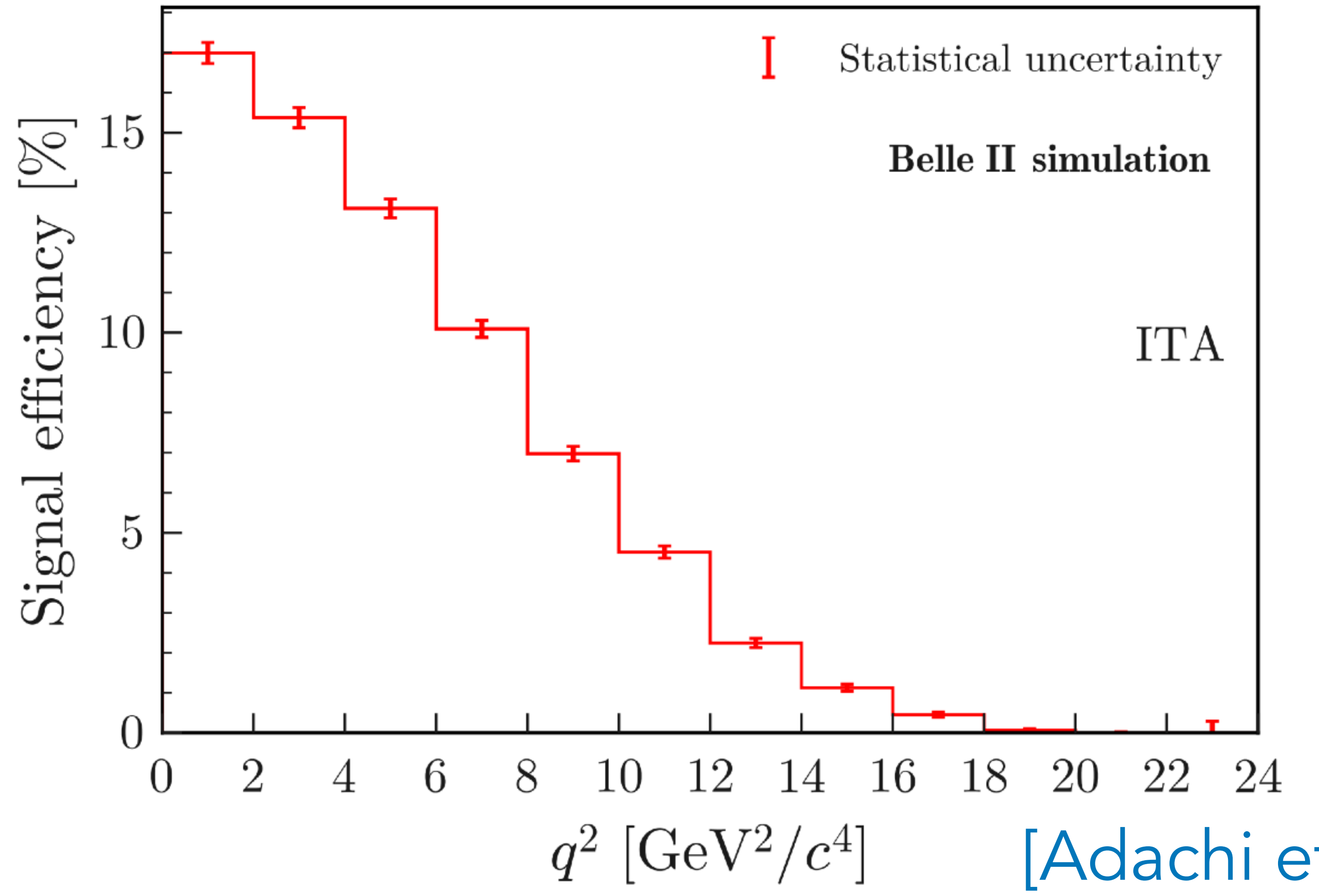
Construct total event count in bin i:

$$n_i = \mu(1+\theta_i^{\text{SM}})s_i^{\text{SM}} + (1+\theta_i^X)s_i^X + \sum_b \tau_b(1+\theta_i^b)b_i \,,$$

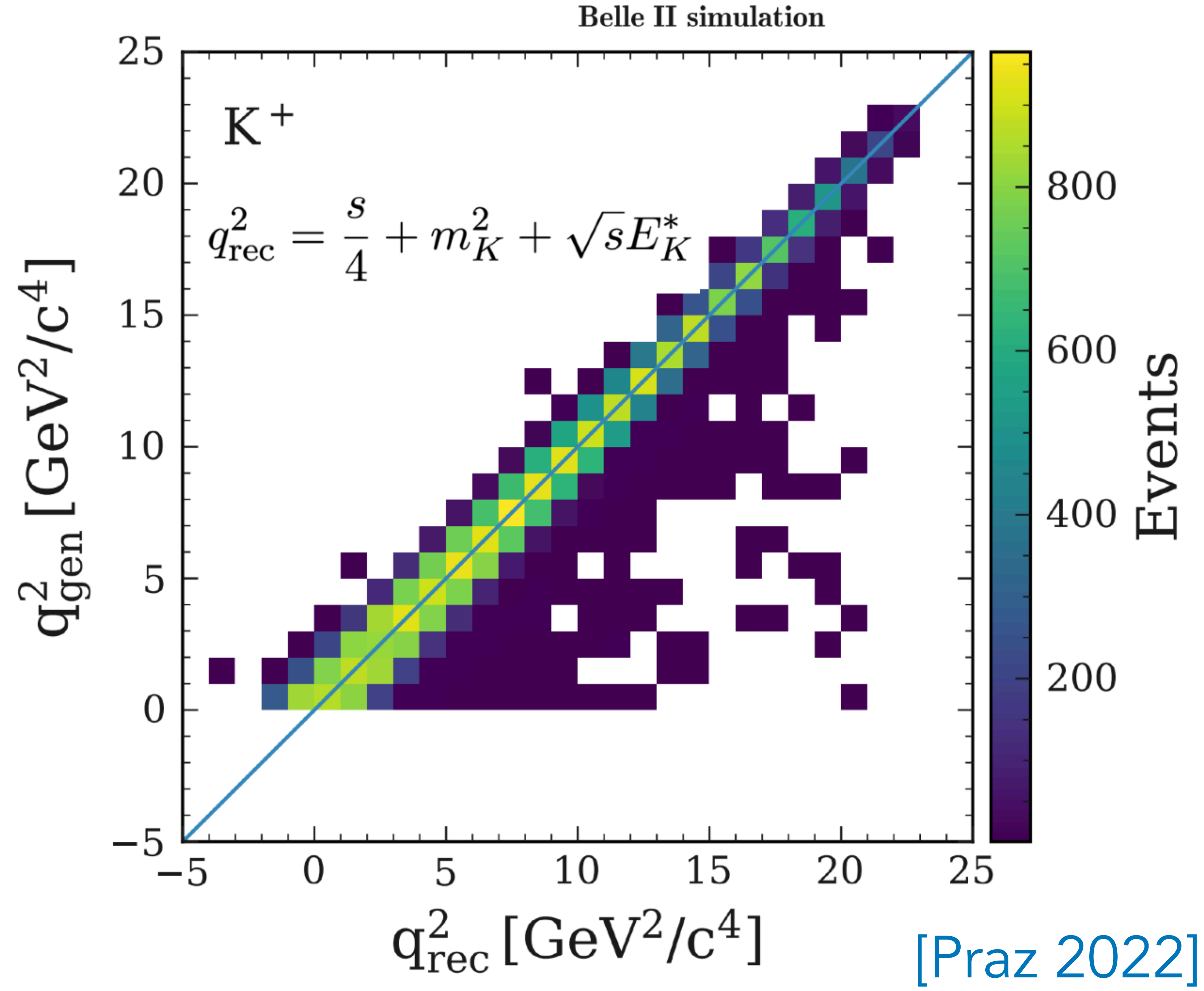
$$s_i^{\text{SM}(X)} = \int_{q_i^2}^{q_j^2} dq^2_{\text{rec}} \frac{dN_{\text{SM}(X)}}{dq^2_{\text{rec}}}$$

$b_i \Rightarrow B^+B^-$, $B^0\bar{B}^0$ and continuum bkgs.

Nuisance parameters: μ, θ_i and τ_b



[Adachi et al. 2023]



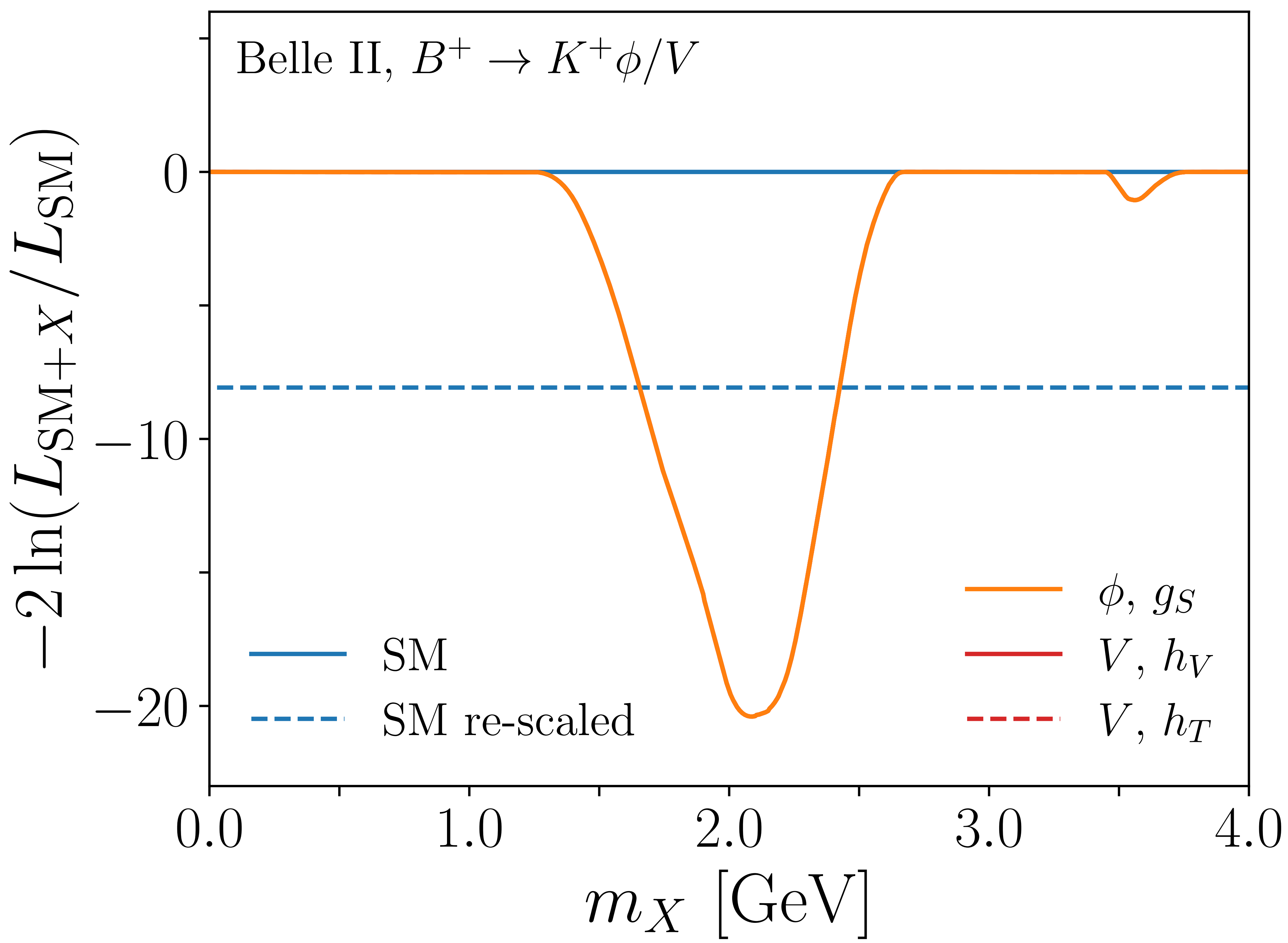
[Praz 2022]

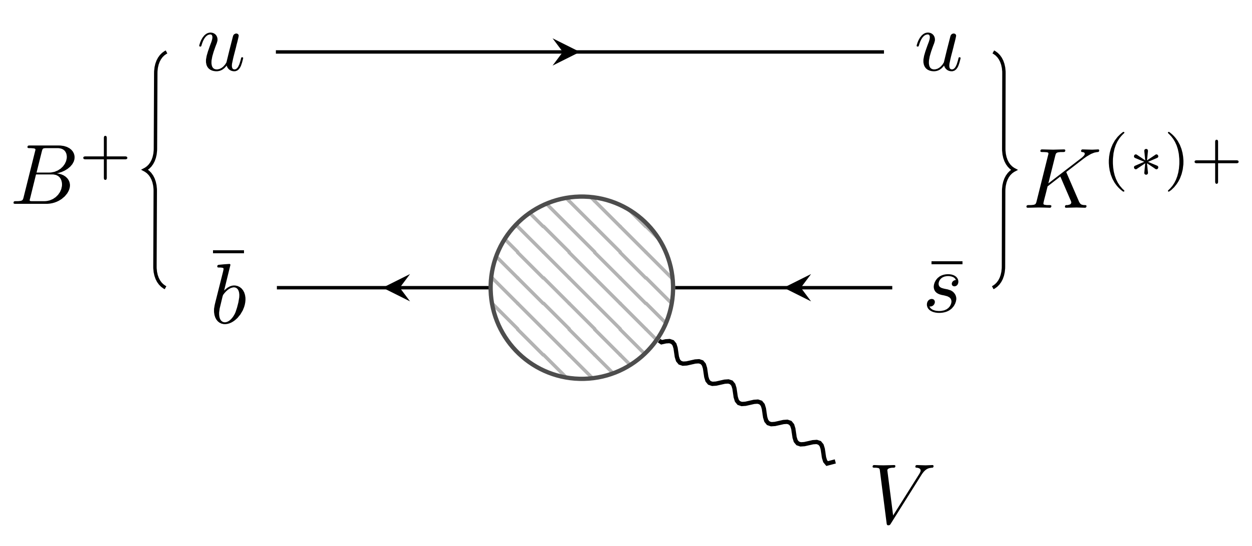
SM + NP signal hypothesis

Perform fit to the SM ($\mu = 1$) + NP for all effective couplings C_X

⇒ Vary light new particle mass m_X and profile over C_X and nuisance parameters

Two-body $B^+ \to K^+ X$





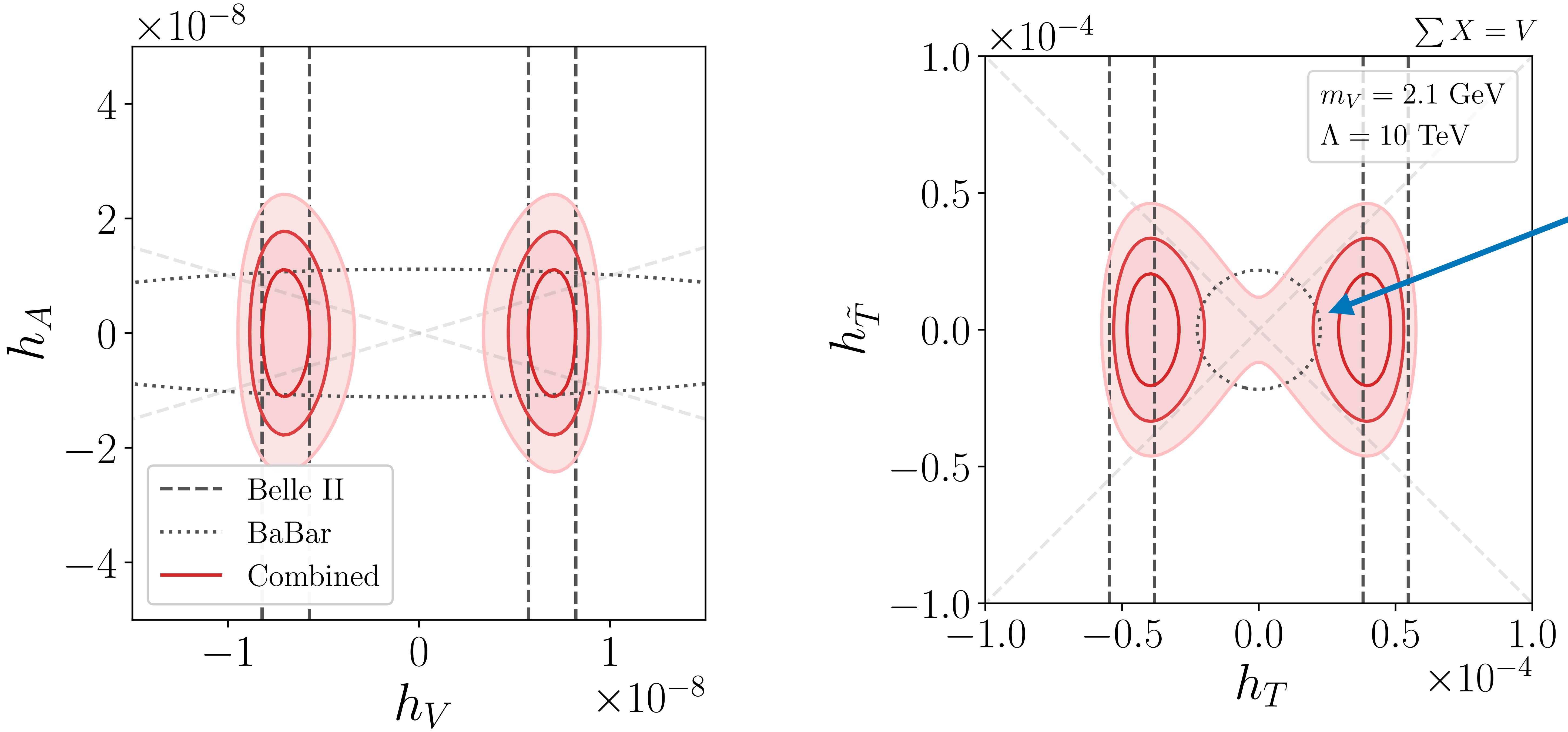
$$\boxed{m_{\phi/V} = (2.1 \pm 0.1)\ \mathrm{GeV}}$$

For three-body scenarios see:

[PDB, Fajfer, Kamenik, Novoa-Brunet 2024]

Vector boson (two-body) final state

Favoured vector and tensor couplings for the vector boson scenario



BABAR upper bound on $B \to K^* V$ in tension with favoured Belle II h_T coupling

$$h_V(\bar{b}\gamma_\mu s)V^\mu + h_A(\bar{b}\gamma_\mu\gamma_5 s)V^\mu$$

$$\frac{h_T}{\Lambda}(\bar{b}\sigma_{\mu\nu}s)V^{\mu\nu} + \frac{h_{\tilde{T}}}{\Lambda}(\bar{b}\sigma_{\mu\nu}\gamma_5 s)V^{\mu\nu}$$

See also: [Altmannshofer et al. 2023]
[Gabrielli et al. 2023]

Episode II: Implications for $B \to K^* E_{\mathrm{miss}}$

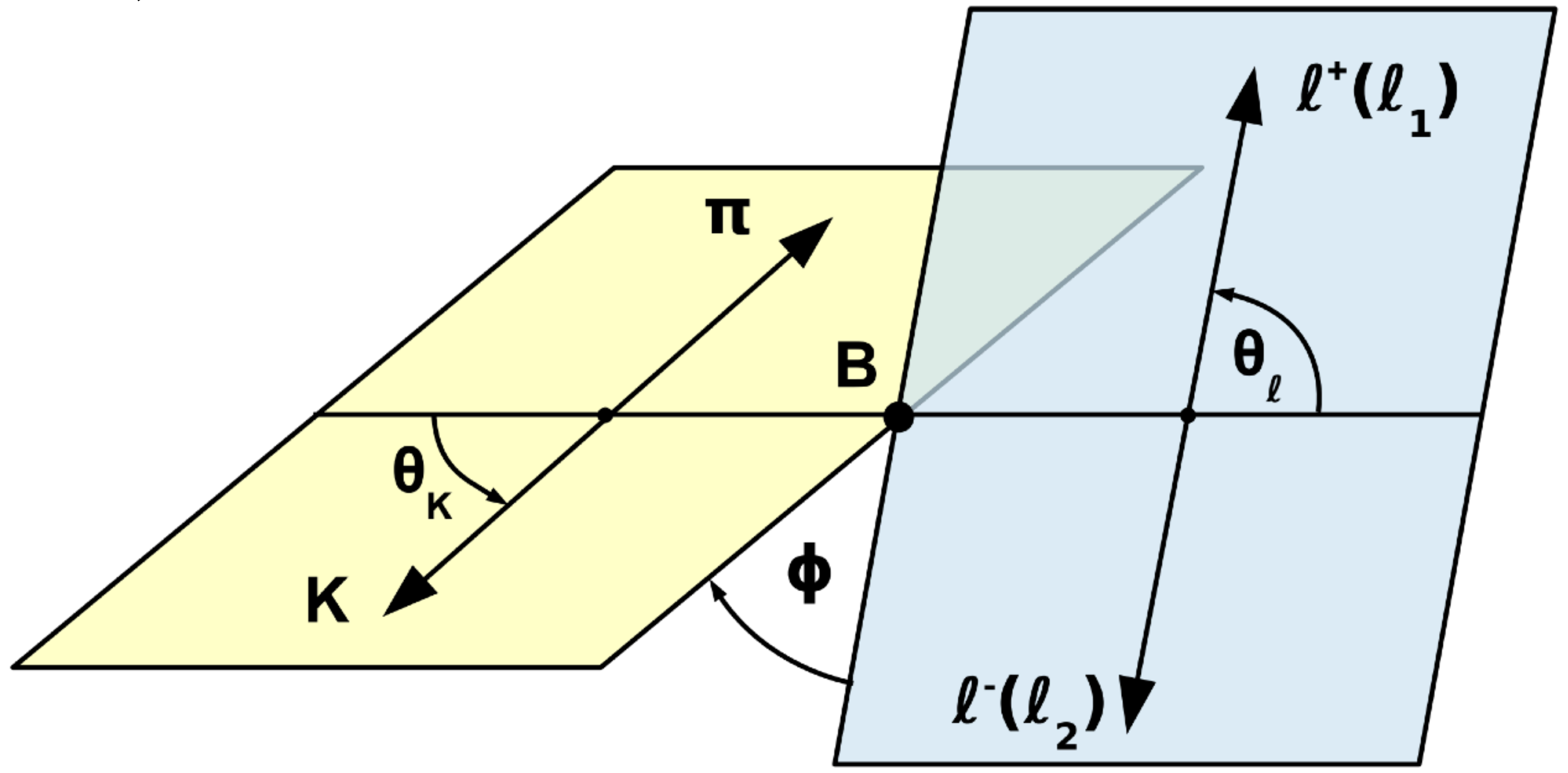
Implications for future measurements

With $\gtrsim 10\ \mathrm{ab}^{-1}$ of data, observation of $B \to K E_{\mathrm{miss}}$ and $B \to K^* E_{\mathrm{miss}}$ is possible

[Belle II Physics Book 2018]

⇒ $B \to K^*(\to K\pi) E_{\mathrm{miss}}$ is fully described by the differential rate

$$\frac{d^2\Gamma}{dq^2\, d\cos\theta_K} = \frac{1}{2}\frac{d\Gamma}{dq^2}\left(1 + (3F_L - 1)D^2_{0,0}\right) \qquad D^2_{0,0} = \frac{1}{2}(3\cos^2\theta_K - 1)$$



[Gratex et al. 2016]

Two observables:

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

⇒ F_L: longitudinal polarisation fraction of K^*

⇒ Integrated and differential (i.e. binned) forms of observables

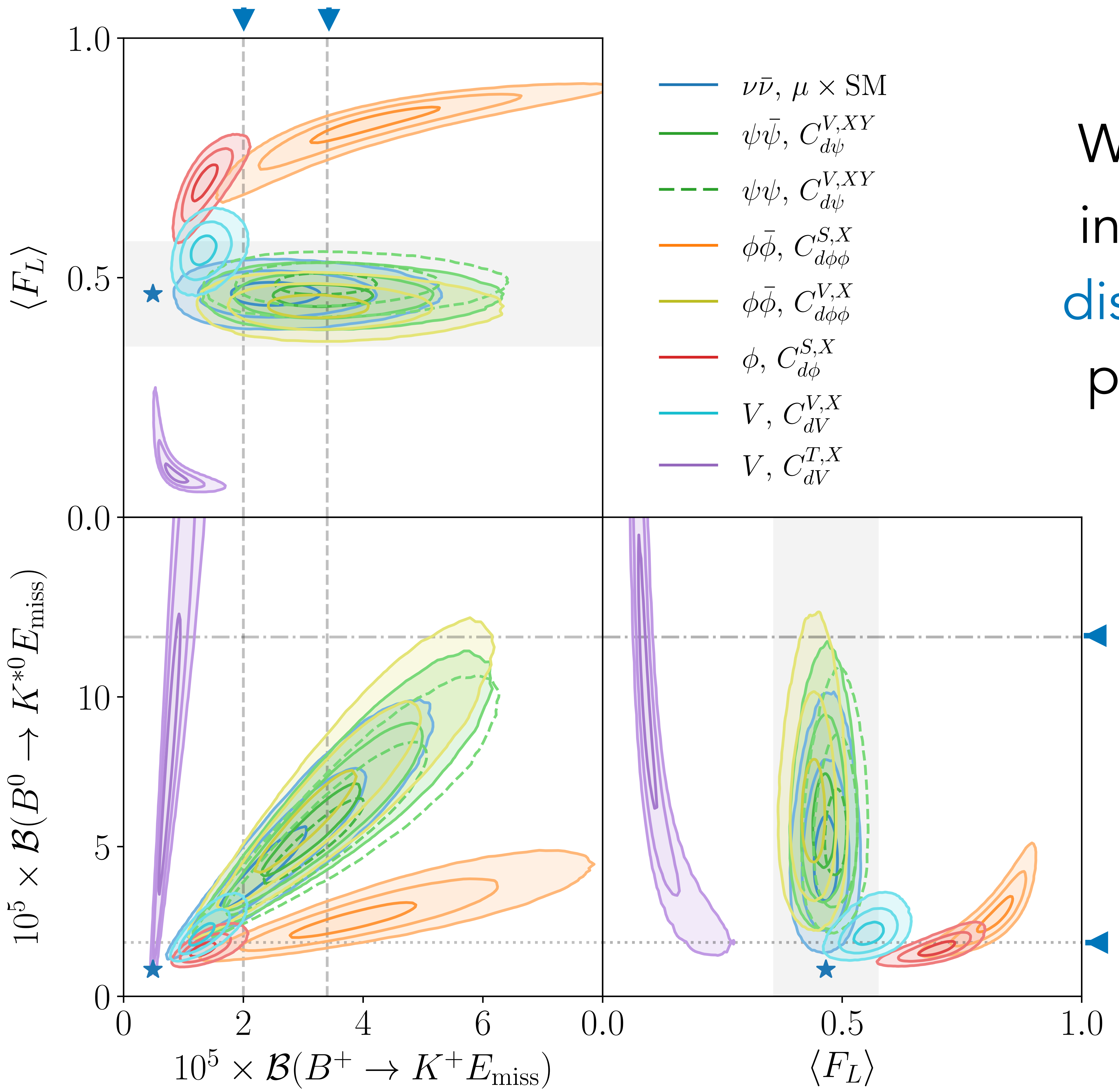
Implications for future measurements

Combined fit to Belle II, *BABAR* and ALEPH data

Chiral couplings maximise correlations

$$C_{dV}^{V,X}(\bar{b}\gamma_\mu P_X)sZ'^{\mu}$$

Belle II @ 68% CL (assuming SM) [Adachi et al. 2023]



BaBar @ 90% CL [Lees et al. 2013]

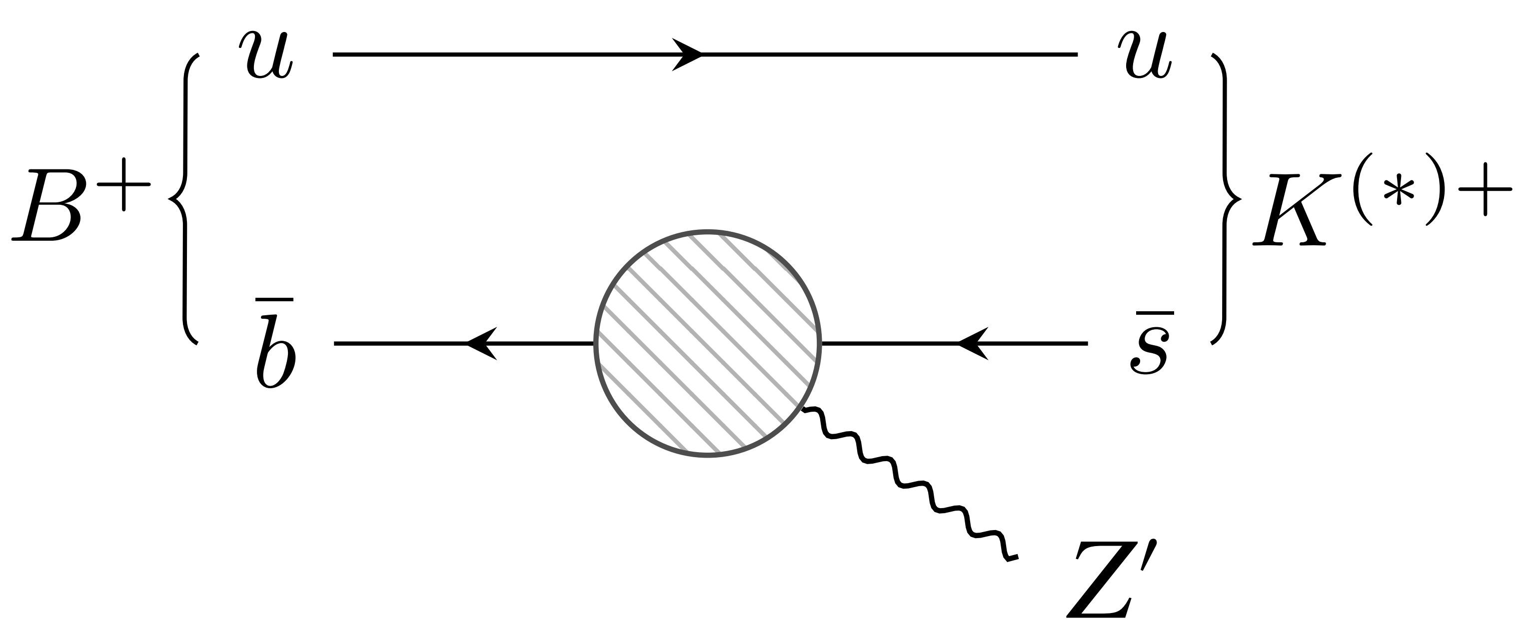
Belle @ 90% CL [Grygier, 2017]

With $\mathcal{O}(10\%)$ sensitivities to integrated BRs and F_L clear distinction of some scenarios possible (mostly two-body)

[PDB, Fajfer, Kamenik, Novoa-Brunet 2025]

Episode III: Light Z' portal to dark matter

Model building implications - light vector



The light vector with mass $\sim$ 2.1 GeV - a light Z′?

Many UV theory model building directions. Naturally interesting to connect with dark matter (DM)

e.g. unbroken U(1)′

$$B^+ \to K^+\gamma_D^* \to K^+X\bar{X}$$

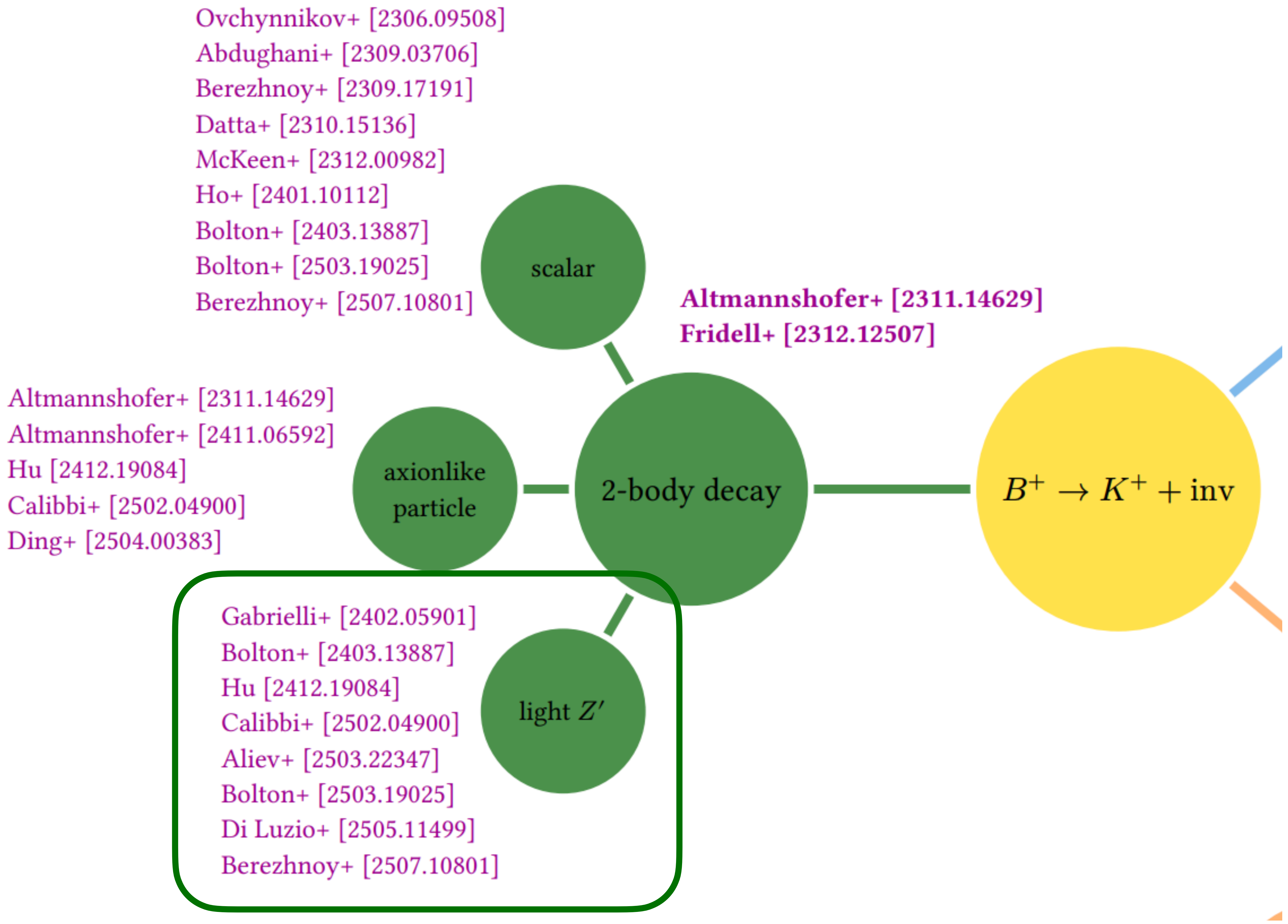
[Gabrielli et al. 24]

e.g. gauge anomalous $\mathrm{U}(1)_\tau$

⇒ Z′ couplings quarks one-loop via Wess-Zumino terms

$$B^+ \to K^+Z' \to K^+\nu\bar{\nu}$$

[di Luzio et al. 25]



[M. Schmidt, Belle II Physics Week 2025]

Minimal aligned U(1)′ model

[Kamenik, Soreq, Zupan, 2018]

Add Abelian gauge group U(1)′ with gauge field B'_μ with gauge coupling $\tilde{g}$, spontaneously broken

Add to SM field content T': Vector-like top partner (3,1,2/3,q')

Φ: Dark scalar (1,1,0,q') with vev $\tilde{v}$

$$\mathcal{L} \supset -\frac{1}{4}B'_{\mu\nu}B'^{\mu\nu} - \frac{\epsilon_B}{2}B_{\mu\nu}B'^{\mu\nu} + \left|D_\mu\Phi\right|^2 - V(H,\Phi)$$
$$+ \bar{T}'(i\not{D} - M_T)T' - \left[Y_T^r\bar{T}'\Phi u'_{Rr} + \mathrm{h.c.}\right],$$

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

Minimal aligned U(1)′ model

[Kamenik, Soreq, Zupan, 2018]

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

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

Rotate to gauge boson mass basis (at tree-level $B'_\mu = Z'_\mu$)

$$\Phi = \frac{1}{\sqrt{2}}(\tilde{v} + \phi + i\eta) \longrightarrow \mathcal{L} \supset -\frac{1}{2}M_{Z'}^2 Z'_\mu Z'^\mu \qquad M_{Z'} = \tilde{g}q'\tilde{v}$$

2.1 GeV for Belle II

Minimal aligned U(1)′ model

[Kamenik, Soreq, Zupan, 2018]

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$$\mathcal{L} \supset -\frac{1}{4}B'_{\mu\nu}B'^{\mu\nu} - \frac{\epsilon_B}{2}B_{\mu\nu}B'^{\mu\nu} + \left|D_\mu\Phi\right|^2 - V(H,\Phi)$$
$$+ \bar{T}'(i\not{D} - M_T)T' - \left[Y_T^r \bar{T}'\Phi u'_{Rr} + \text{h.c.}\right],$$

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

Rotate to up-type quark mass basis ⇒ top quark mixing with top partner T

$$\mathcal{L} \supset -\frac{1}{\sqrt{2}}\begin{pmatrix}\bar{t}'_L & \bar{T}'_L\end{pmatrix}\begin{pmatrix} vY_t & 0 \\ \tilde{v}Y_T^t & \sqrt{2}M_T\end{pmatrix}\begin{pmatrix} t'_R \\ T'_R\end{pmatrix} + \text{h.c.} \qquad \begin{pmatrix} t'_{L,R} \\ T'_{L,R}\end{pmatrix} = P_{L,R}\begin{pmatrix} c_{L,R} & s_{L,R} \\ -s_{L,R} & c_{L,R}\end{pmatrix}\begin{pmatrix} t_{L,R} \\ T_{L,R}\end{pmatrix}$$

Minimal aligned U(1)′ model

Add Abelian gauge group U(1)′ with gauge field B'_μ with gauge coupling $\tilde{g}$, spontaneously broken

Add to SM field content T': Vector-like top partner (3,1,2/3,q')

Φ: Dark scalar (1,1,0,q') with vev $\tilde{v}$

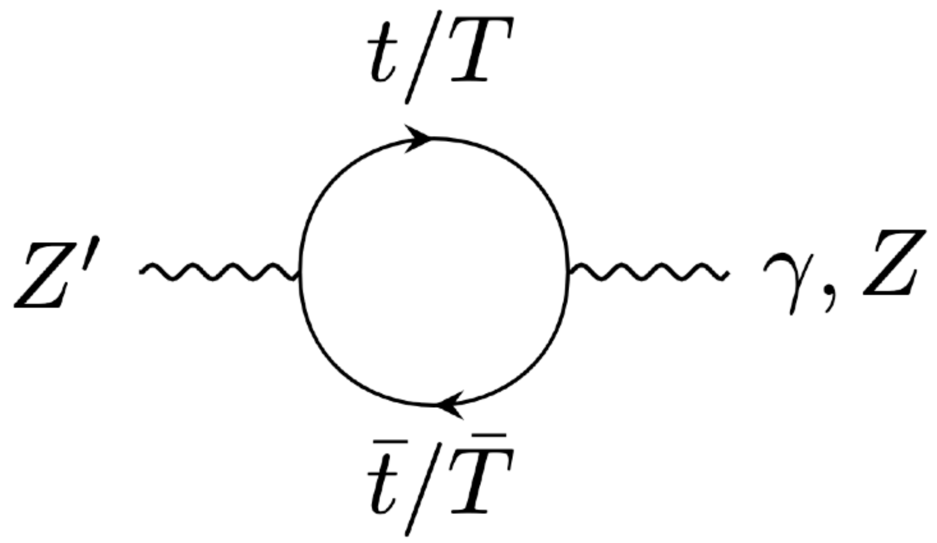
$$\mathcal{L} \supset -\frac{1}{4}B'_{\mu\nu}B'^{\mu\nu} - \frac{\epsilon_B}{2}B_{\mu\nu}B'^{\mu\nu} + \left|D_\mu\Phi\right|^2 - V(H,\Phi)$$
$$+\bar{T}'(i\not{D} - M_T)T' - \left[Y_T^r \bar{T}'\Phi u'_{Rr} + \text{h.c.}\right],$$

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

Other relevant effects: - Kinetic mixing between B' and B

- Mixing between ϕ and h

Kinetic and mass mixing



In the broken phase, kinetic and mass mixing is induced by T loops

$$\mathcal{L} \supset -\frac{\epsilon_A}{2} F_{\mu\nu} Z'^{\mu\nu} - \frac{\epsilon_Z}{2} Z_{\mu\nu} Z'^{\mu\nu}$$

$$\mathcal{L} \supset -M_{ZZ'}^2 Z_\mu Z'^\mu$$

$$\epsilon_A = \frac{e\tilde{g}q'}{12\pi^2}\left[(s_L^2 + s_R^2)\ln\frac{\Lambda^2}{m_t^2} + (c_L^2 + c_R^2)\ln\frac{\Lambda^2}{m_T^2}\right]$$

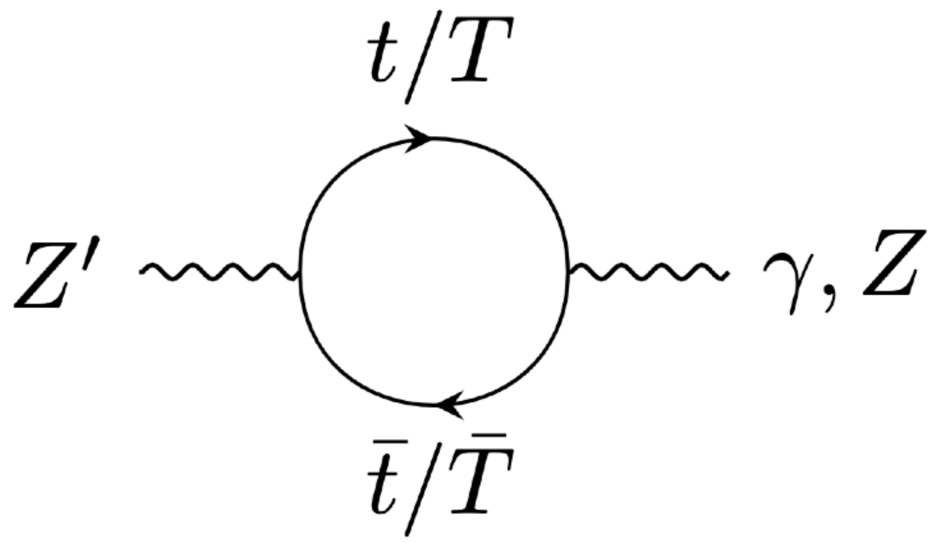
$$\epsilon_Z = -t_w \epsilon_A + \frac{g\tilde{g}q'}{16\pi^2 c_w} c_L^2 s_L^2 \left[\ln\frac{m_T^2}{m_t^2} - \frac{5}{3}\right]$$

$$\delta_Z = -\frac{3g\tilde{g}q'}{16\pi^2 c_w}\frac{m_T^2}{M_Z^2} s_L^2 \left[\ln\frac{m_T^2}{m_t^2} - \frac{3}{2}\right] \qquad (\delta_Z = M_{ZZ'}^2/M_Z^2)$$

Neutral gauge boson sector not canonically normalised!

$$\begin{pmatrix} A_\mu \\ Z_\mu \\ Z'_\mu \end{pmatrix} \to \begin{pmatrix} 1 & 0 & -\epsilon_A \\ 0 & 1 & -\delta_Z + x\epsilon_Z \\ 0 & \delta_Z - \epsilon_Z & 1 \end{pmatrix} \begin{pmatrix} A_\mu \\ Z_\mu \\ Z'_\mu \end{pmatrix} \qquad x = M_{Z'}^2/M_Z^2$$

Kinetic and mass mixing



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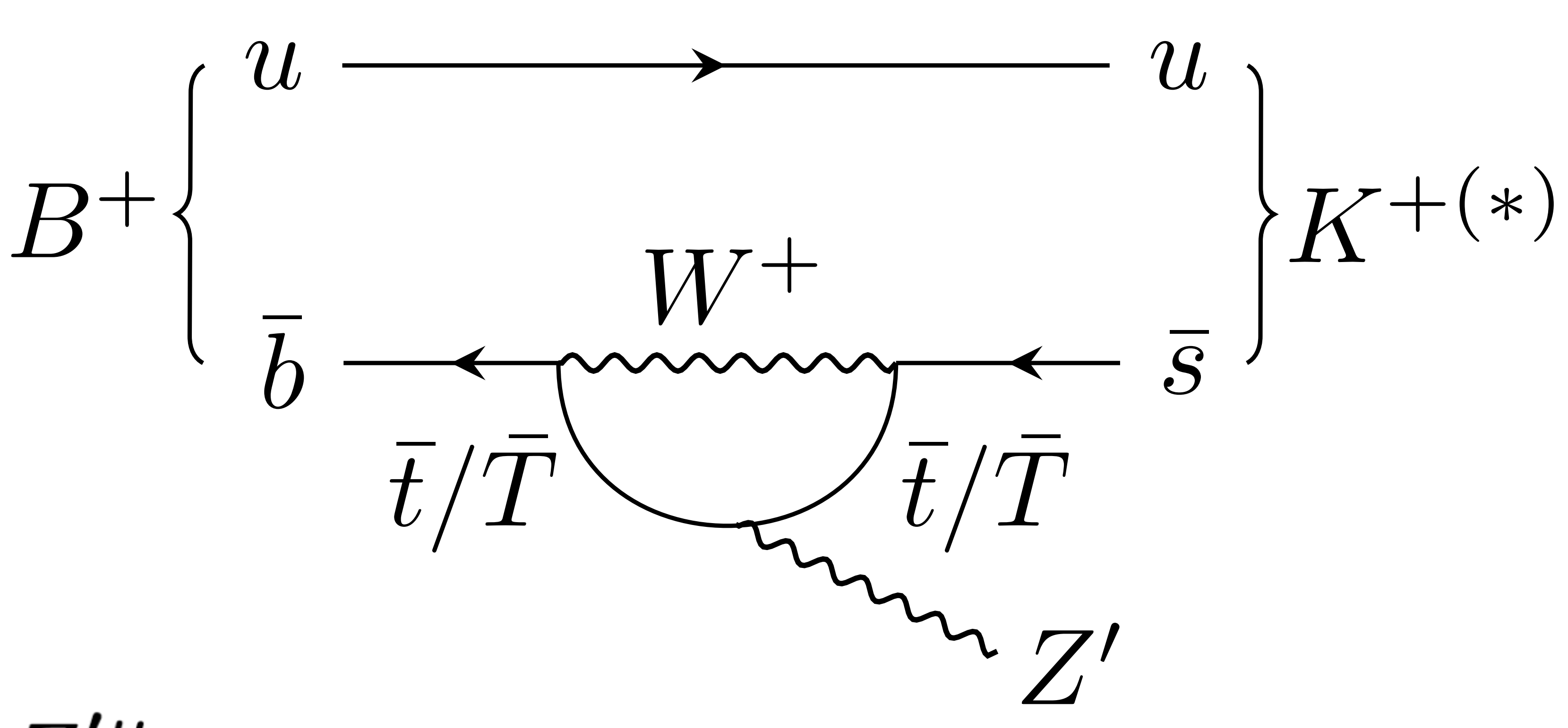
$\Rightarrow$ Z' inherits γ interactions (dark photon) or SM Z interactions (SM Z-like)

$\Rightarrow$ For $M_{Z'} = 2.1\ \mathrm{GeV}$, expect the decays $Z' \to \nu\bar{\nu}/e^+e^-/\mu^+\mu^-/\mathrm{hadr}$.

Z′ coupling to $b \to s$ transition



The model generates the WET operators:

$$\mathcal{H}_{\text{eff}} \supset \frac{4G_F}{\sqrt{2}} V_{ti}^* V_{tj} \frac{1}{16\pi^2} \sum_k C_k [\mathcal{O}_k]_{ij}$$

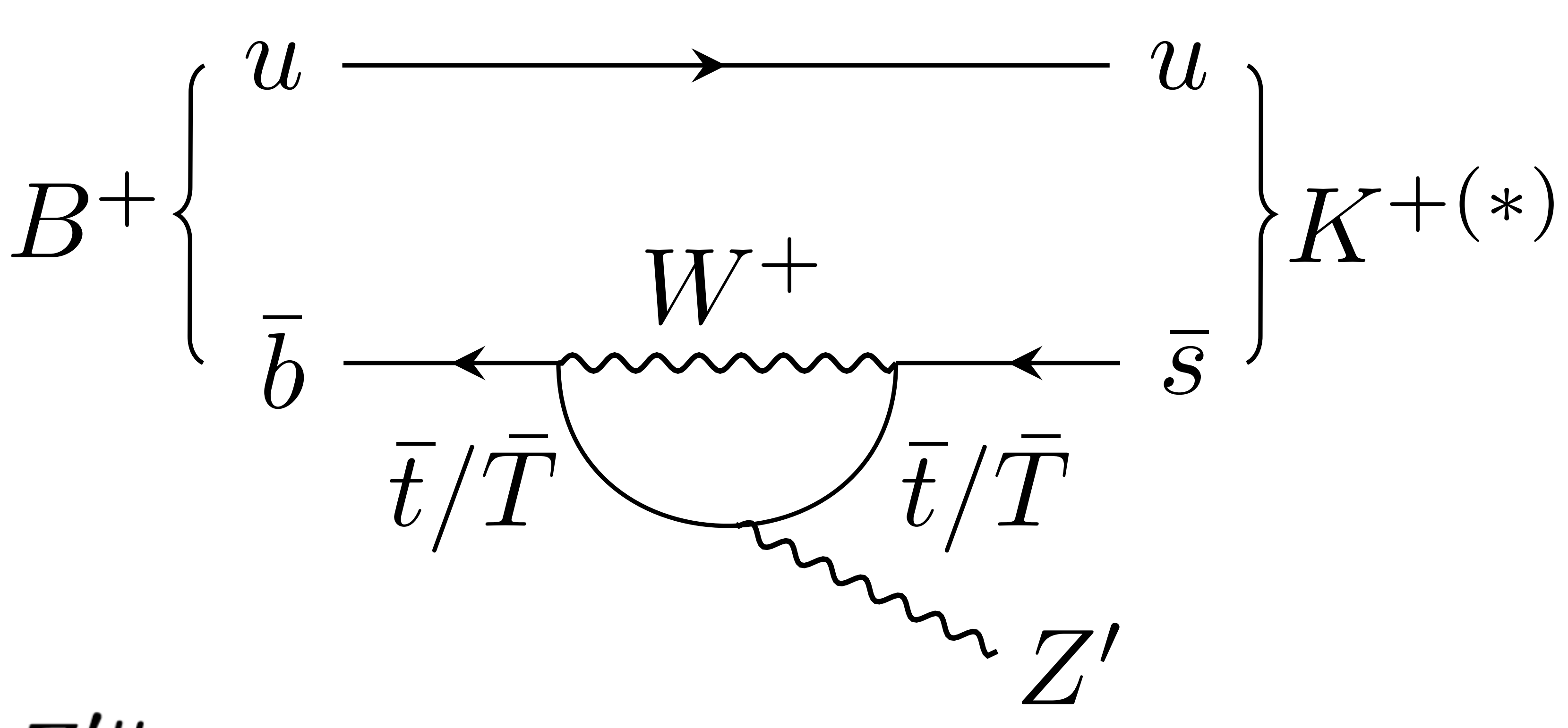
$$[\mathcal{O}_{dZ'}^{V,L(R)}]_{ij} = (\bar{d}_i \gamma_\mu P_{L(R)} d_j) Z'^\mu \,,$$
$$[\mathcal{O}_{dZ'}^{T,L}]_{ij} = m_i (\bar{d}_i \sigma_{\mu\nu} P_L d_j) Z'^{\mu\nu} \,,$$

The vector coupling $C_{dZ'}^{V,R}$ dominates over the dipole coupling $C_{dZ'}^{T,L}$

⇒ Naturally implements MFV U(2) flavour symmetry structure

$$C_{dZ'}^{V,L} = \frac{1}{2} m_t^2 \left\{ \tilde{g} q' s_R^2 \left[\ln \frac{m_T^2}{M_W^2} - 1 \right] - \frac{g}{c_w} \delta_Z X_t \right\}$$

Z′ coupling to $b \to s$ transition



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Direct coupling of Z' to t/T in loop

$Z - Z'$ kinetic and mass mixing.

Requires ϵ_A excluded by $Z' \to e^+e^-/\mu^+\mu^-$ at BaBar, BESIII + LHCb

Explanation of Belle II excess

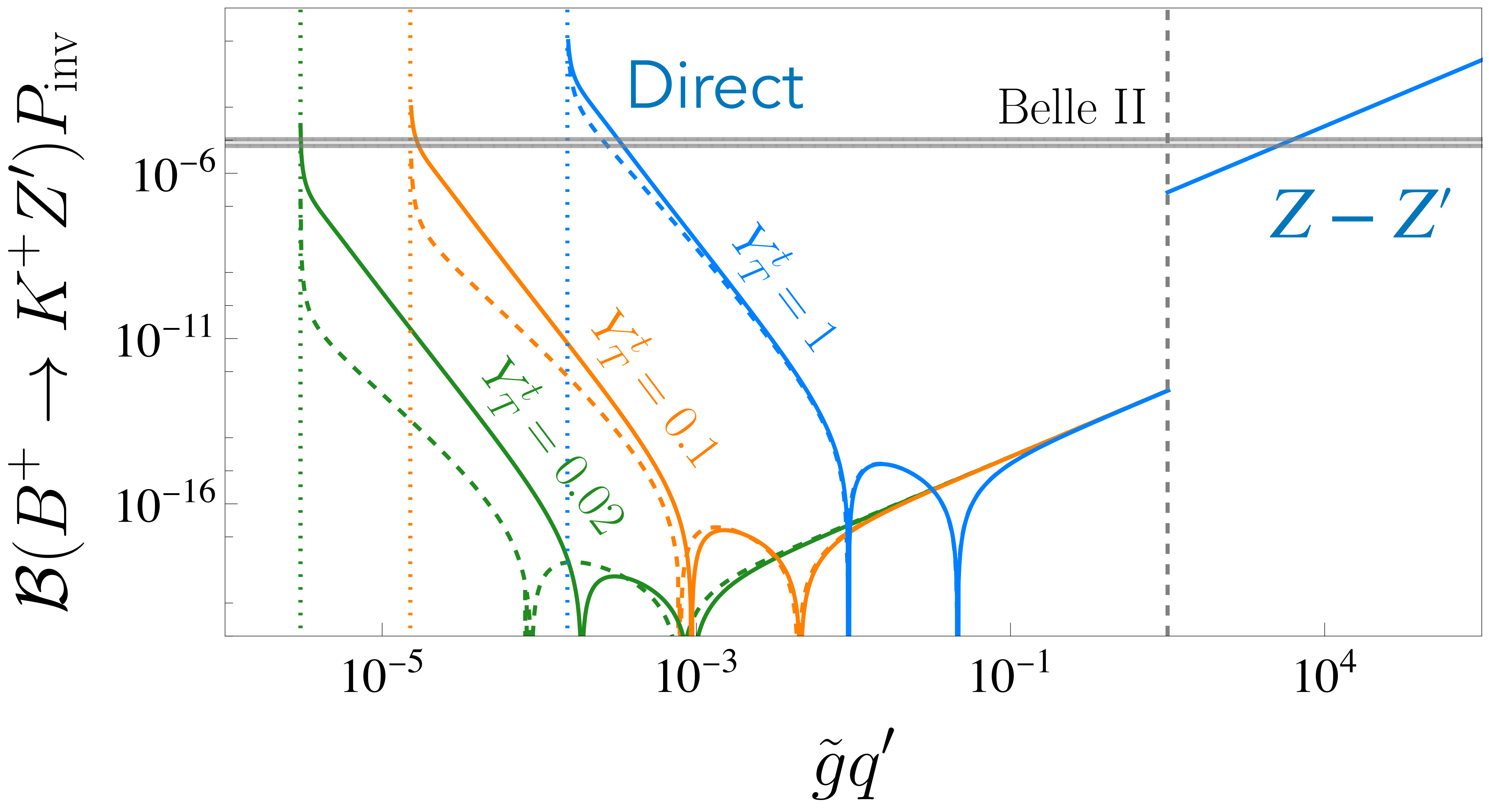
The Belle II excess is accommodated for

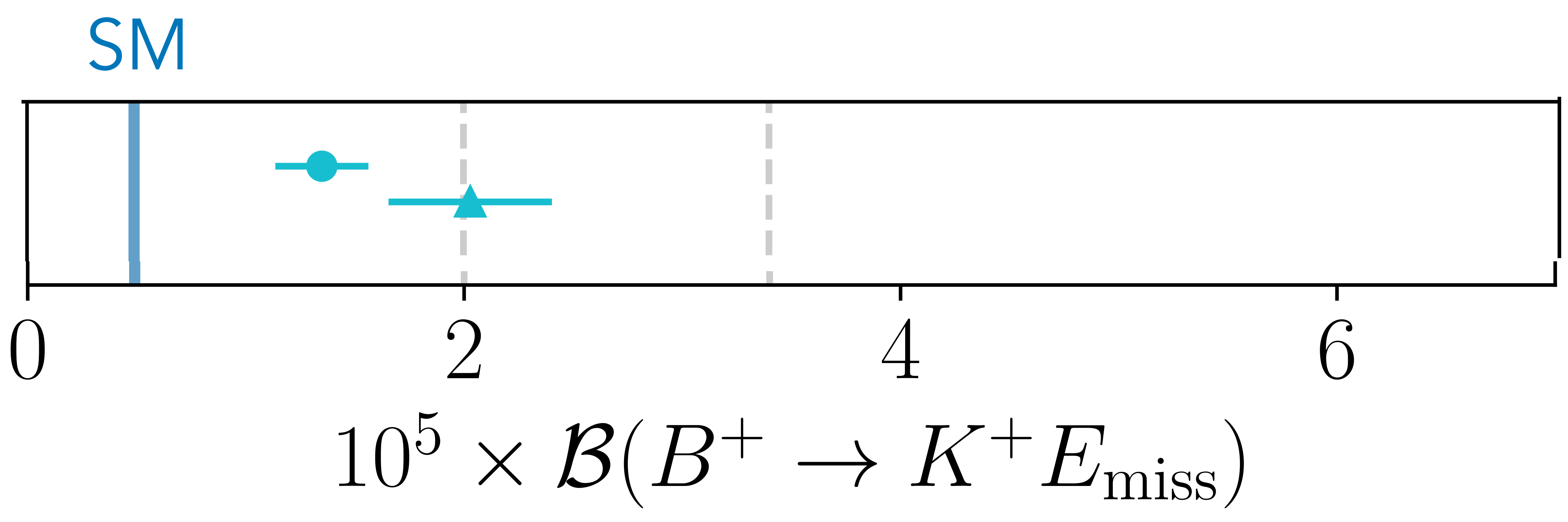
$$\mathcal{B}(B^+ \to K^+ Z')P_{\rm inv} = \mathcal{B}(B^+ \to K^+ V)|_{\rm exp}$$
$$= 8.6^{+2.2}_{-1.9} \times 10^{-6}$$

$$\mathcal{B}(B^+ \to K^+ Z') = \tau_{B^+} \frac{|\vec{p}_K|^3}{8\pi M_{Z'}^2} |C_{bs}|^2 f_+^2$$

$$P_{\rm inv} = P_{\rm out} + \left(1 - P_{\rm out}\right)\mathcal{B}(Z' \to \text{inv.})$$

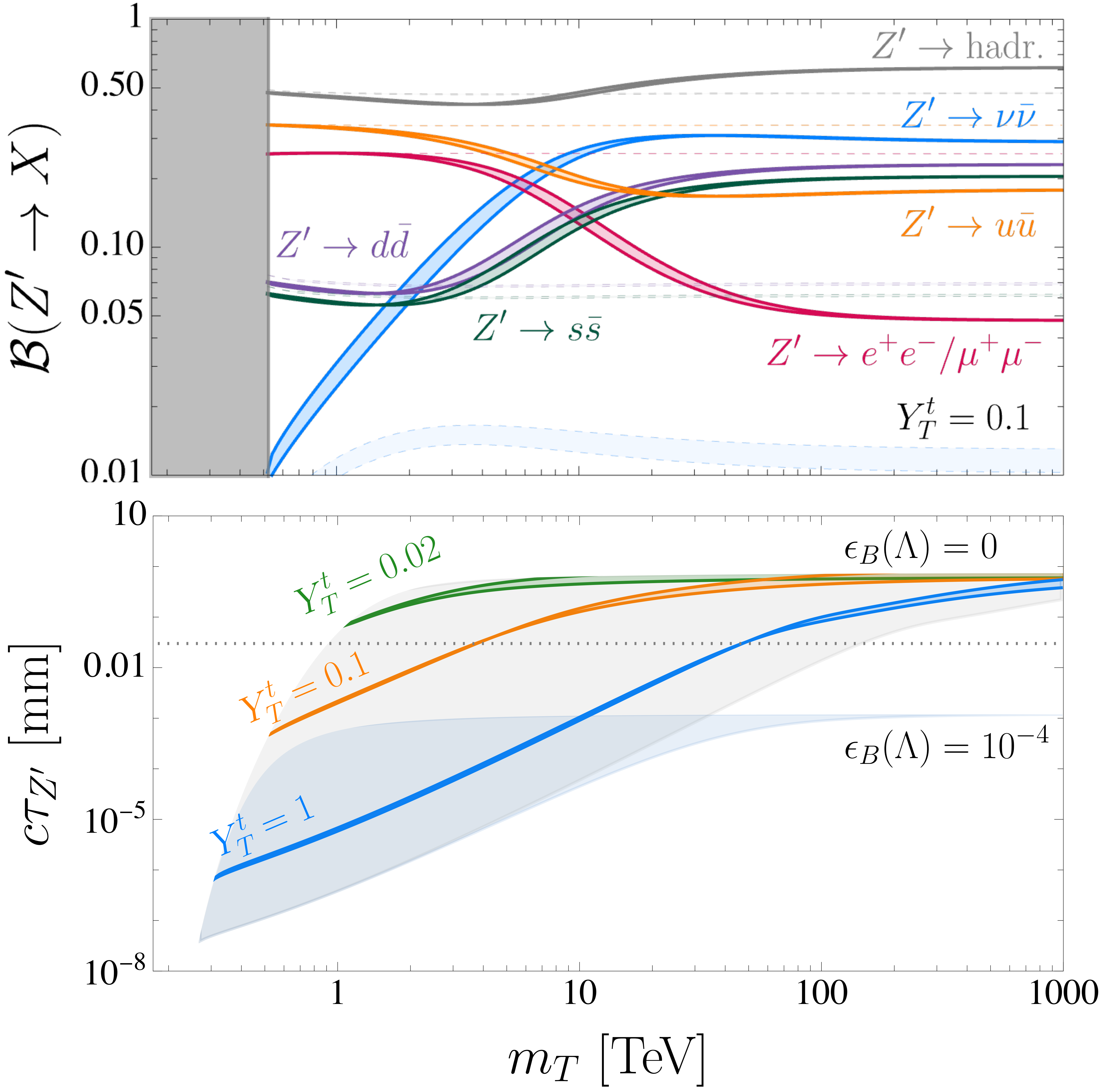
$$P_{\rm out} = \exp(-L/L_{Z'}) \quad L_{Z'} = \beta\gamma c\tau_{Z'}$$

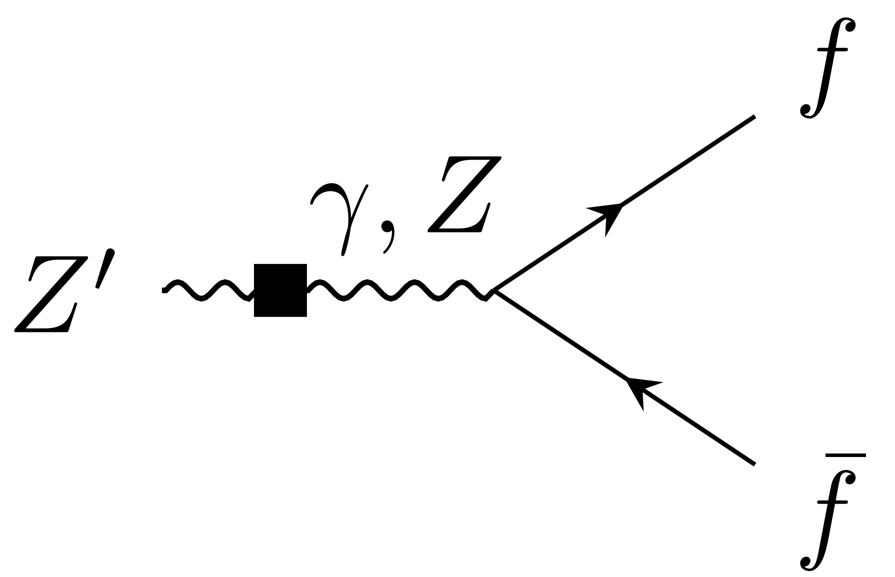


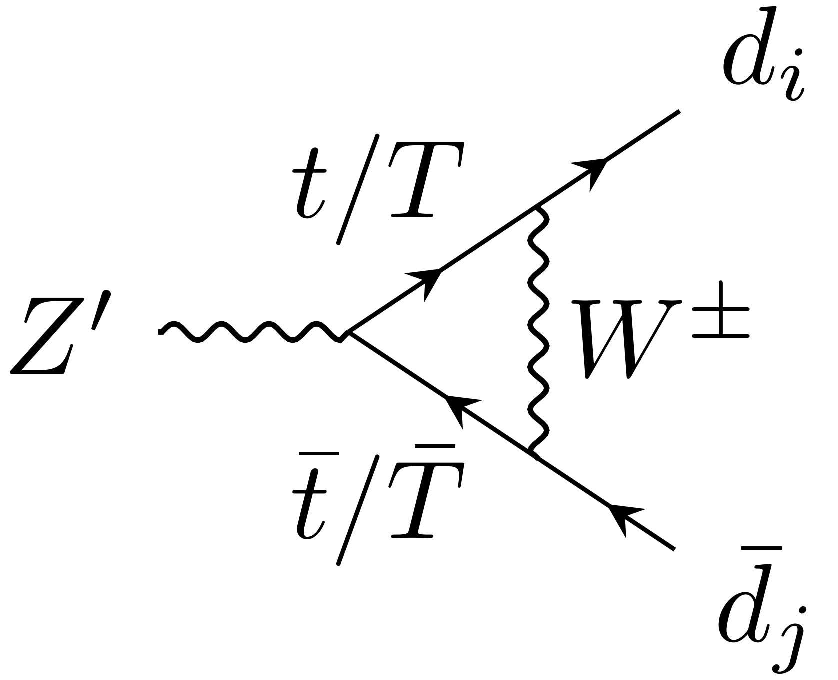


Z′ decays

If the Belle II excess is satisfied, predictions for branching ratios and lifetime

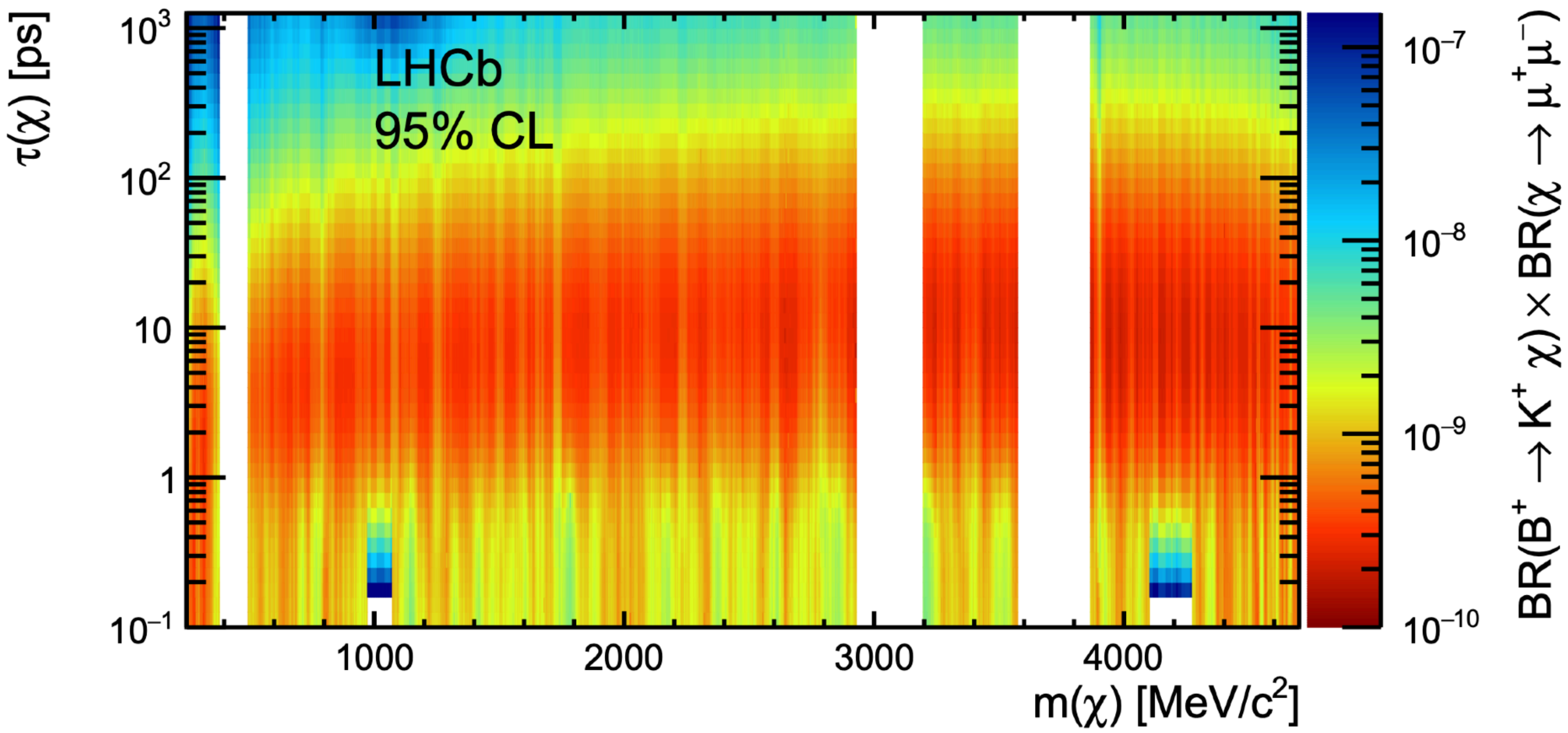






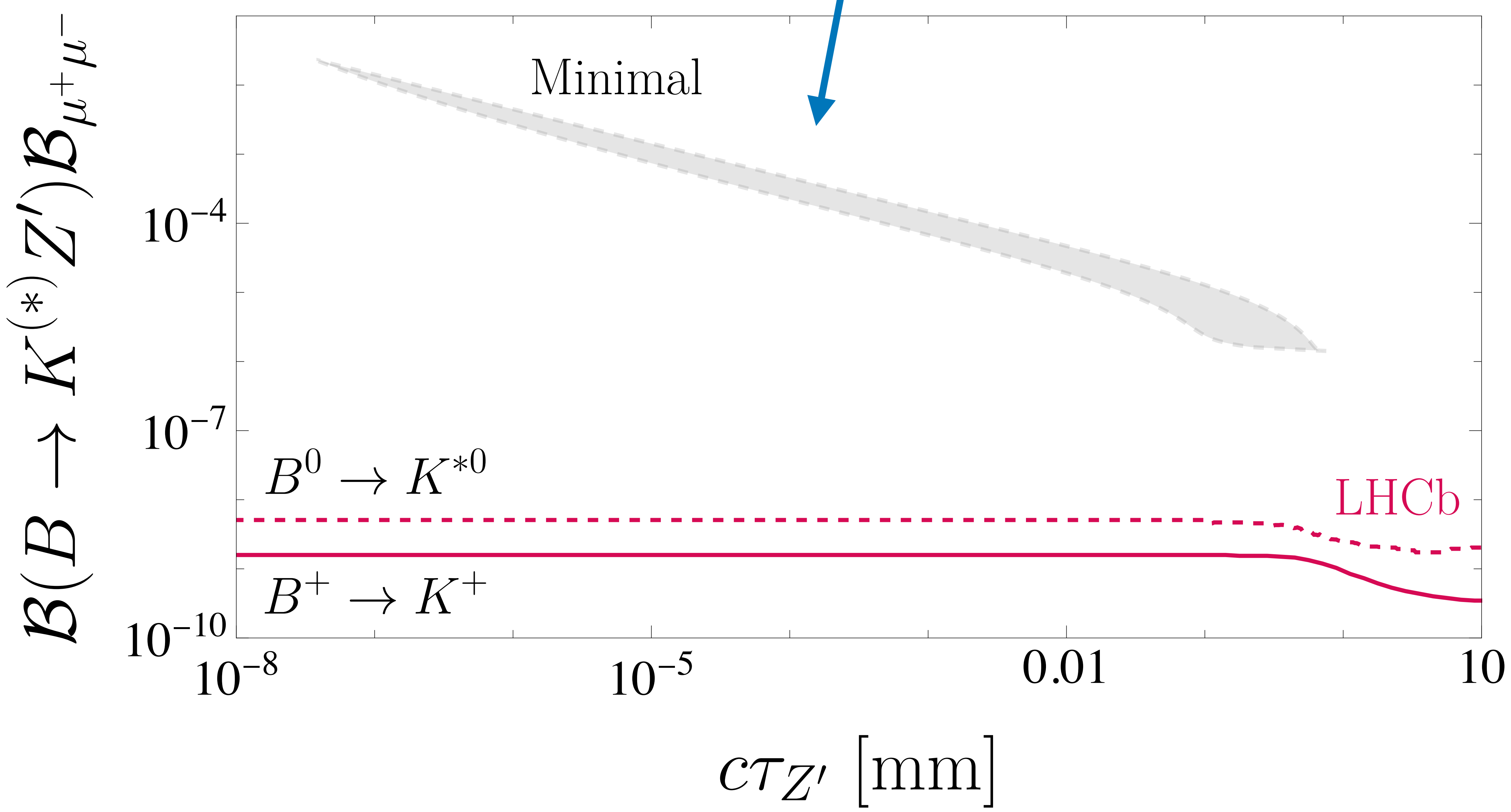
LHCb bounds

Strong constraints from displaced dimuon, $B \to K^{(*)}X(\to \mu^+\mu^-)$, searches at LHCb



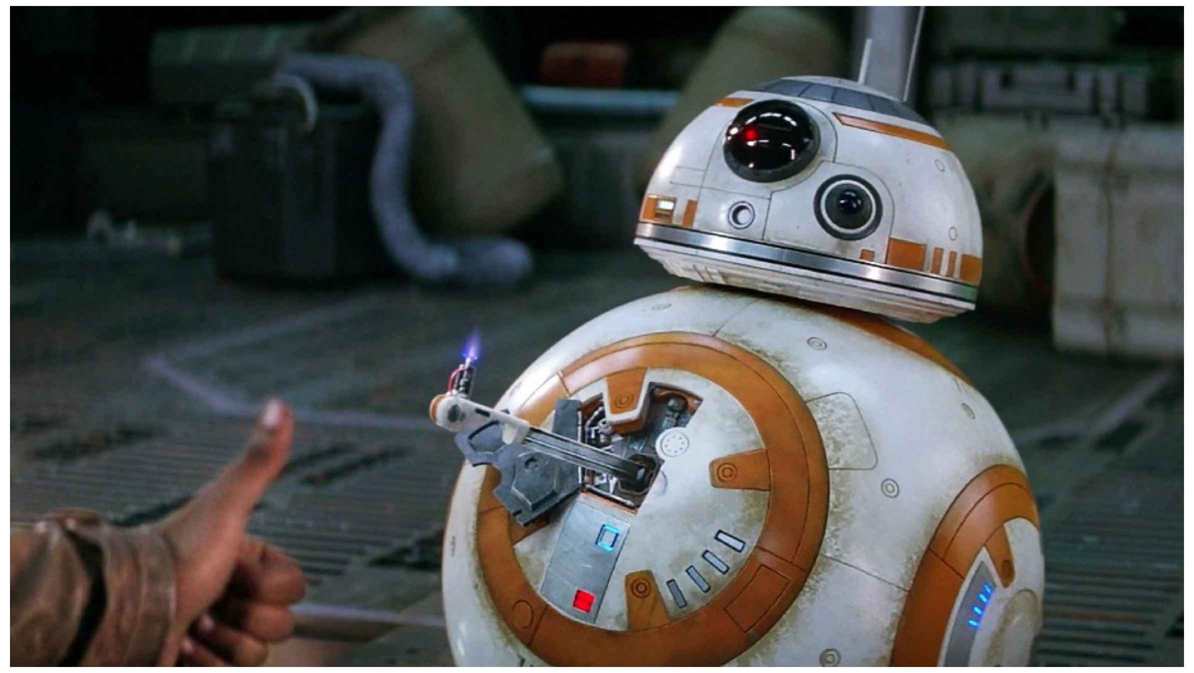
[LHCb, 2015]

Minimal model completely excluded



Conclusion: the light Z' must have additional invisible decay modes to non-SM states

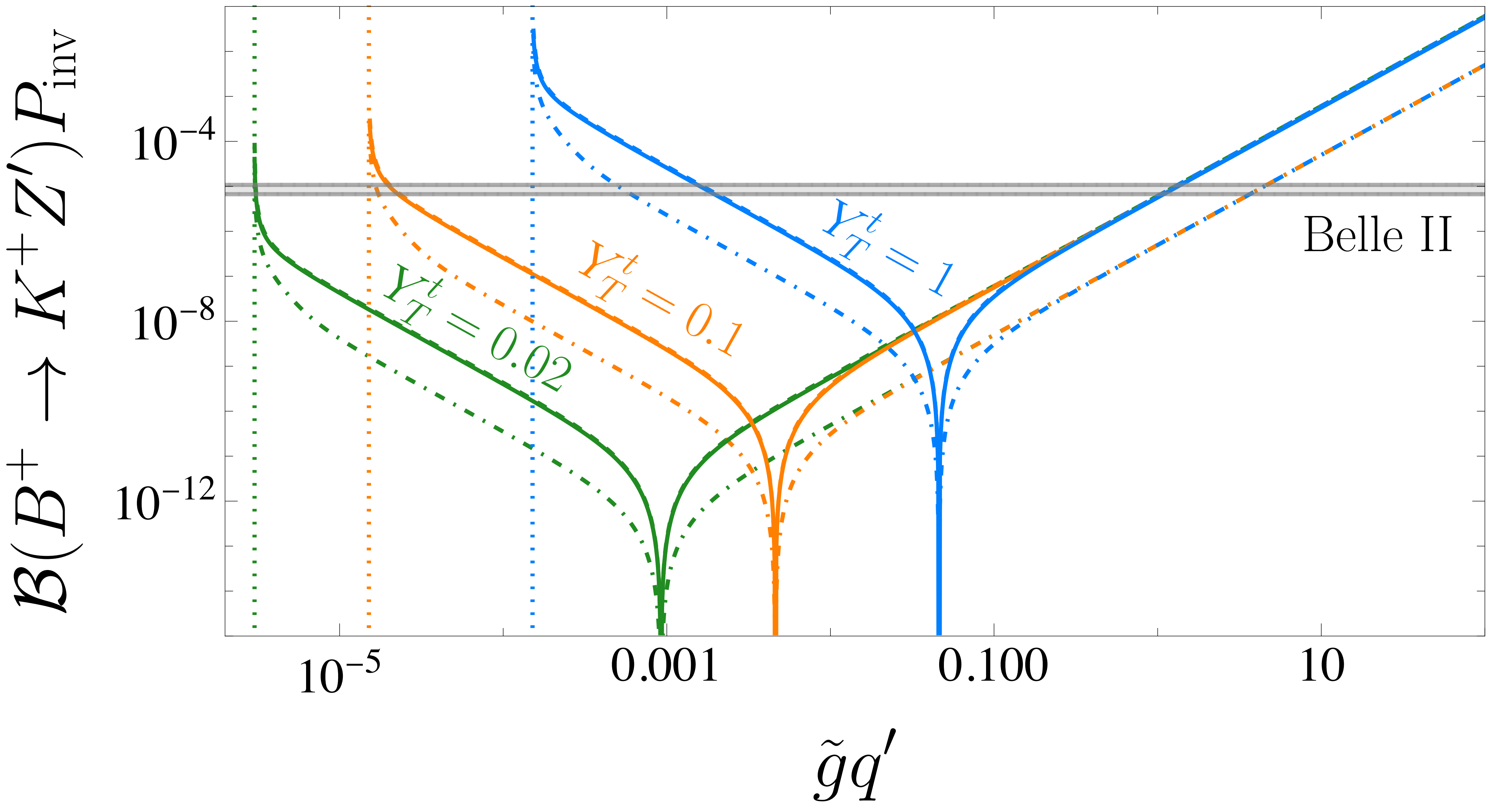
Dark fermion final state

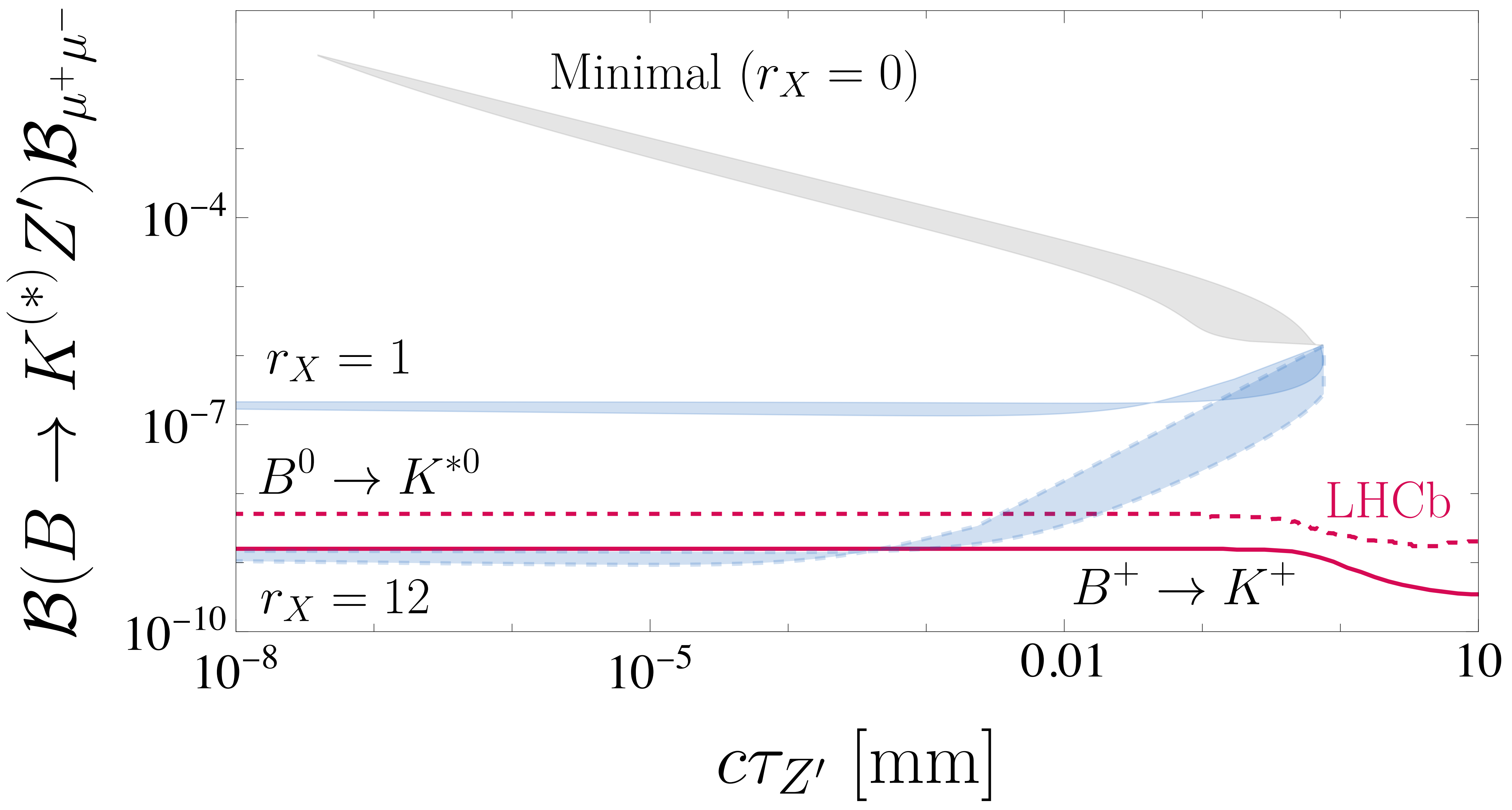


We therefore consider the vector-like fermion $X(1,1,0,q'_X)$

$$\mathcal{L} \supset \bar{X}(i\not{D} - m_X)X$$

The decay $Z' \to X\bar{X}$ occurs at tree-level. For $r_X \equiv q'_X/q' \gtrsim 12$, evade LHCb bounds





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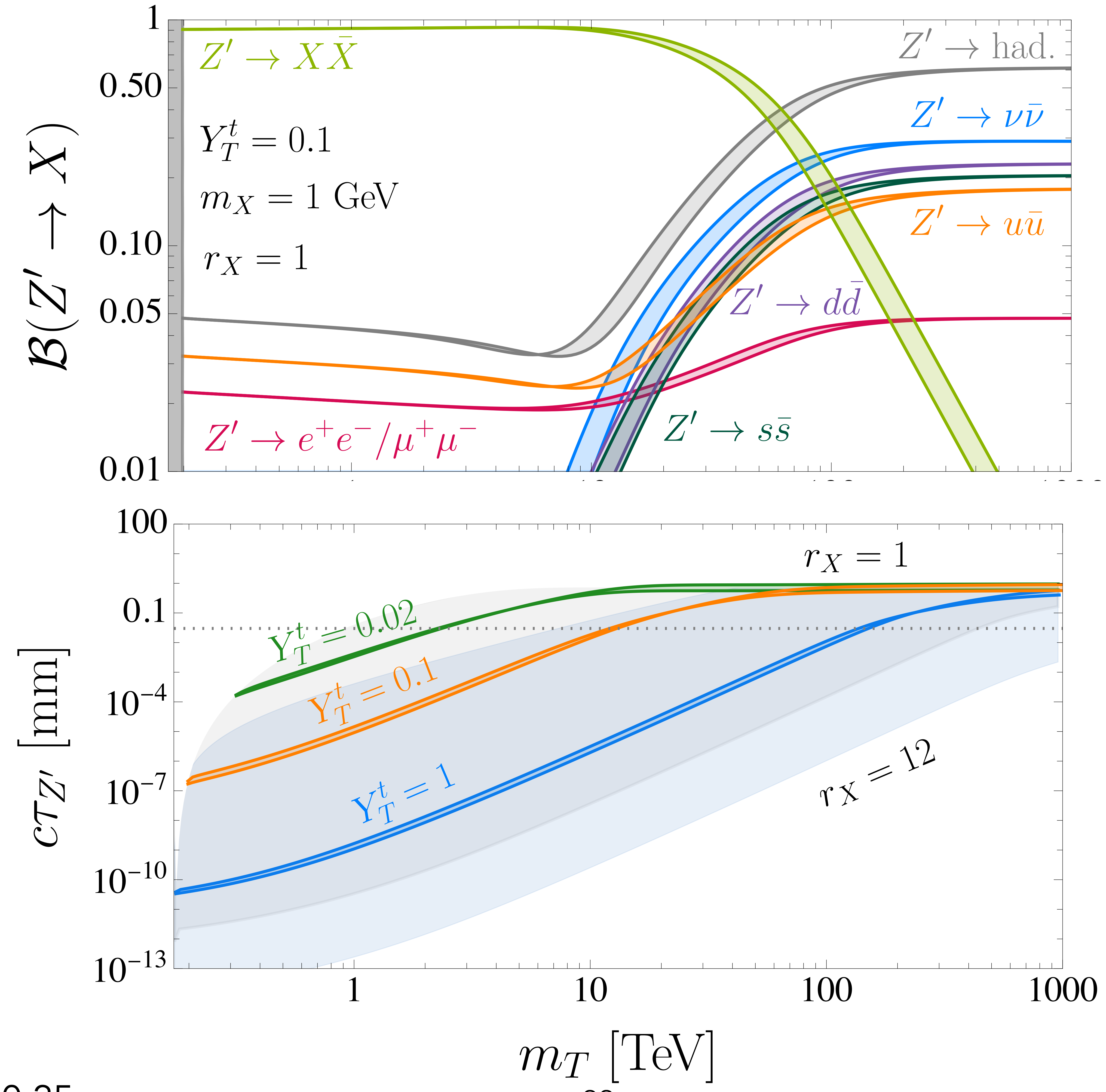
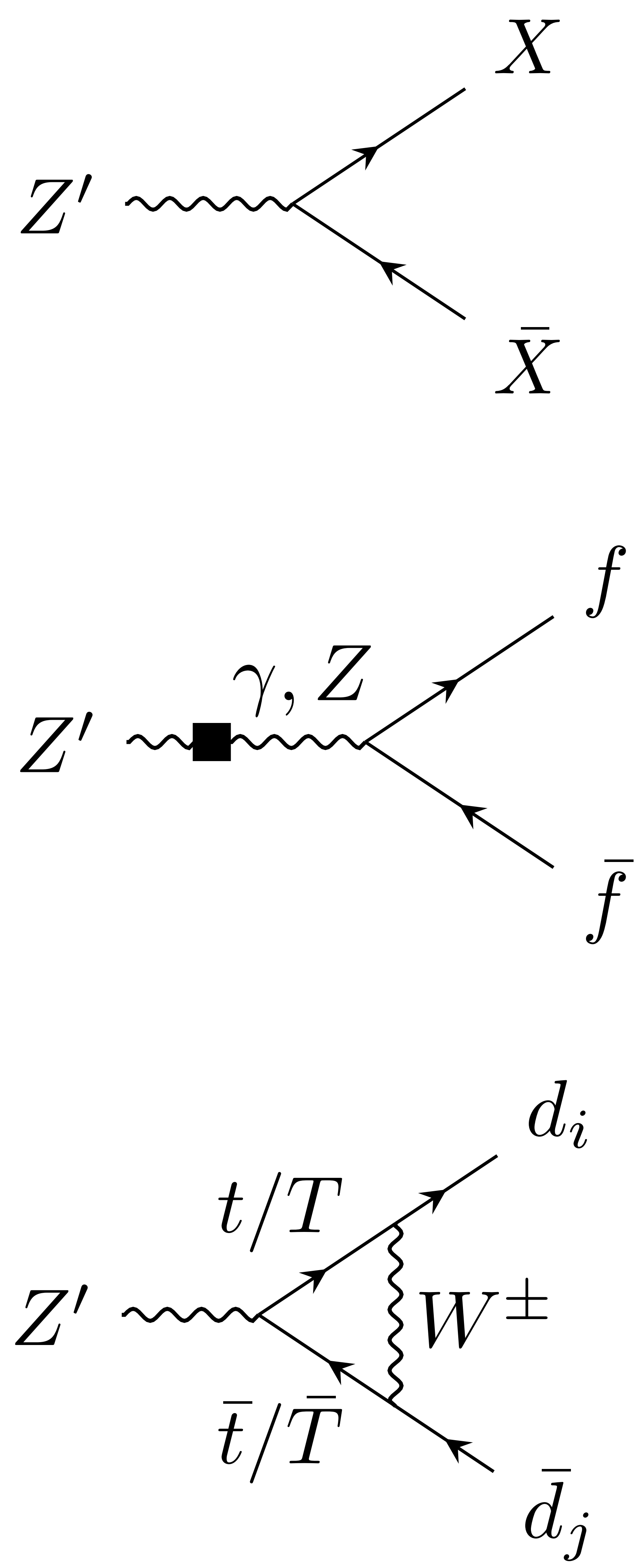
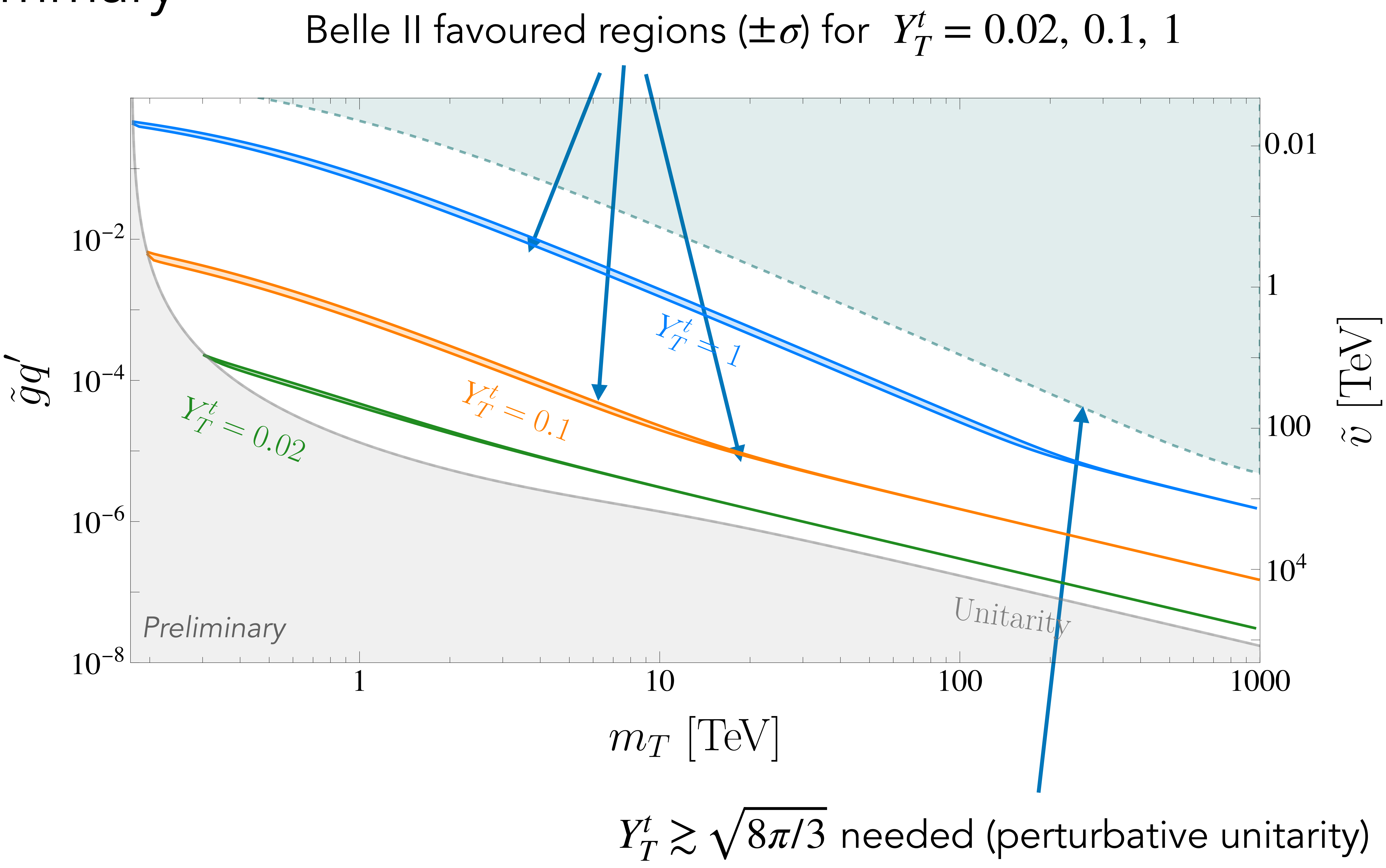




Constraints summary

Belle II can be accommodated everywhere above the gray region



Constraints summary

Perturbative unitarity in scalar sector

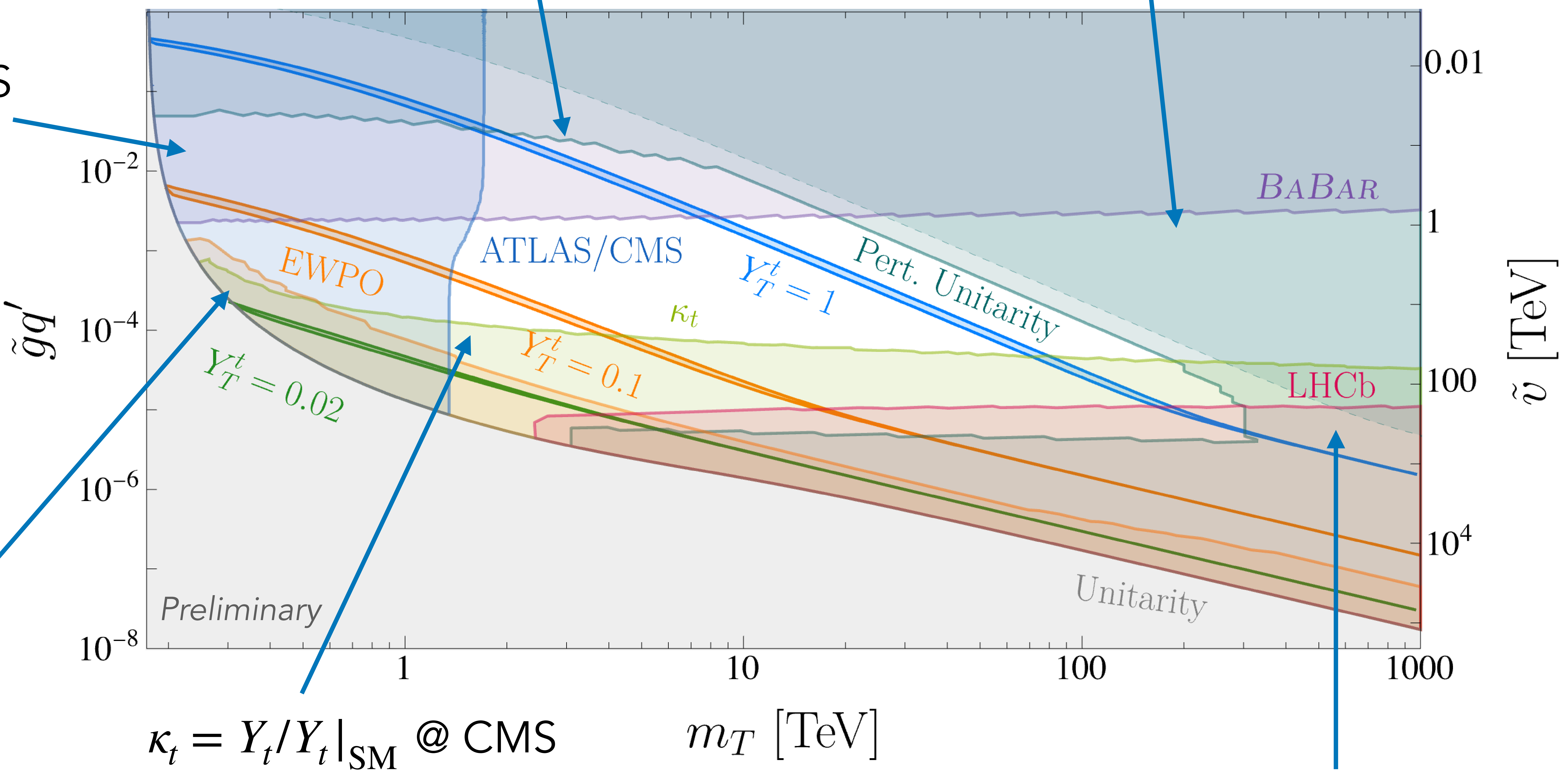
$e^+e^- \to \gamma + \text{inv}$ @ *BABAR*

[Lees, 2017]

$pp \to T\bar{T}$ @ ATLAS, CMS

$T \to tZ', bW^+, tZ, tH$

[ATLAS, 2024]



$$\rho = \frac{M_W^2}{M_Z^2 c_w^2} \approx 1 + \alpha T$$

(EW precision)

$\kappa_t = Y_t / Y_t|_{\text{SM}}$ @ CMS

[CMS, 2021]

$B \to K\mu^+\mu^-$ @ LHCb

[LHCb, 2015]

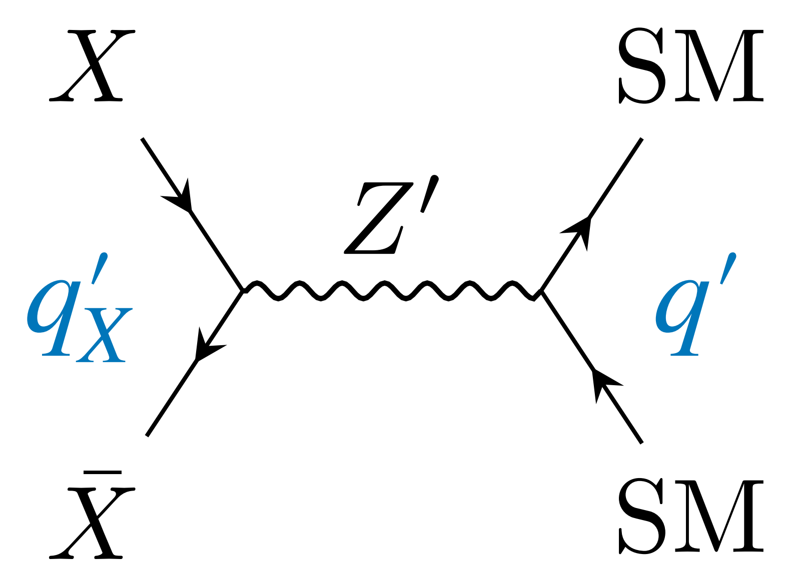
Honourable mentions: $Z \to X\bar{X}$ @ LEP, $(g-2)_\mu$, atomic parity violation in ${}^{133}_{78}\text{Cs}$

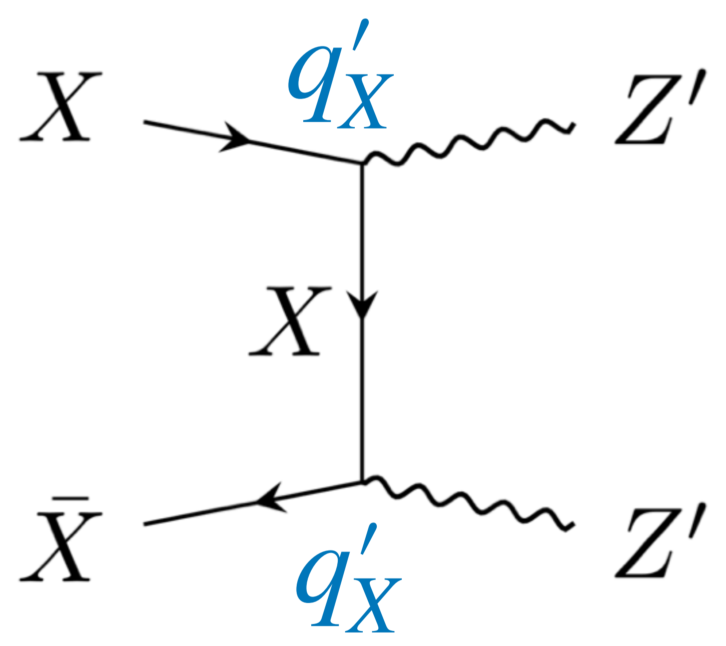
Dark matter

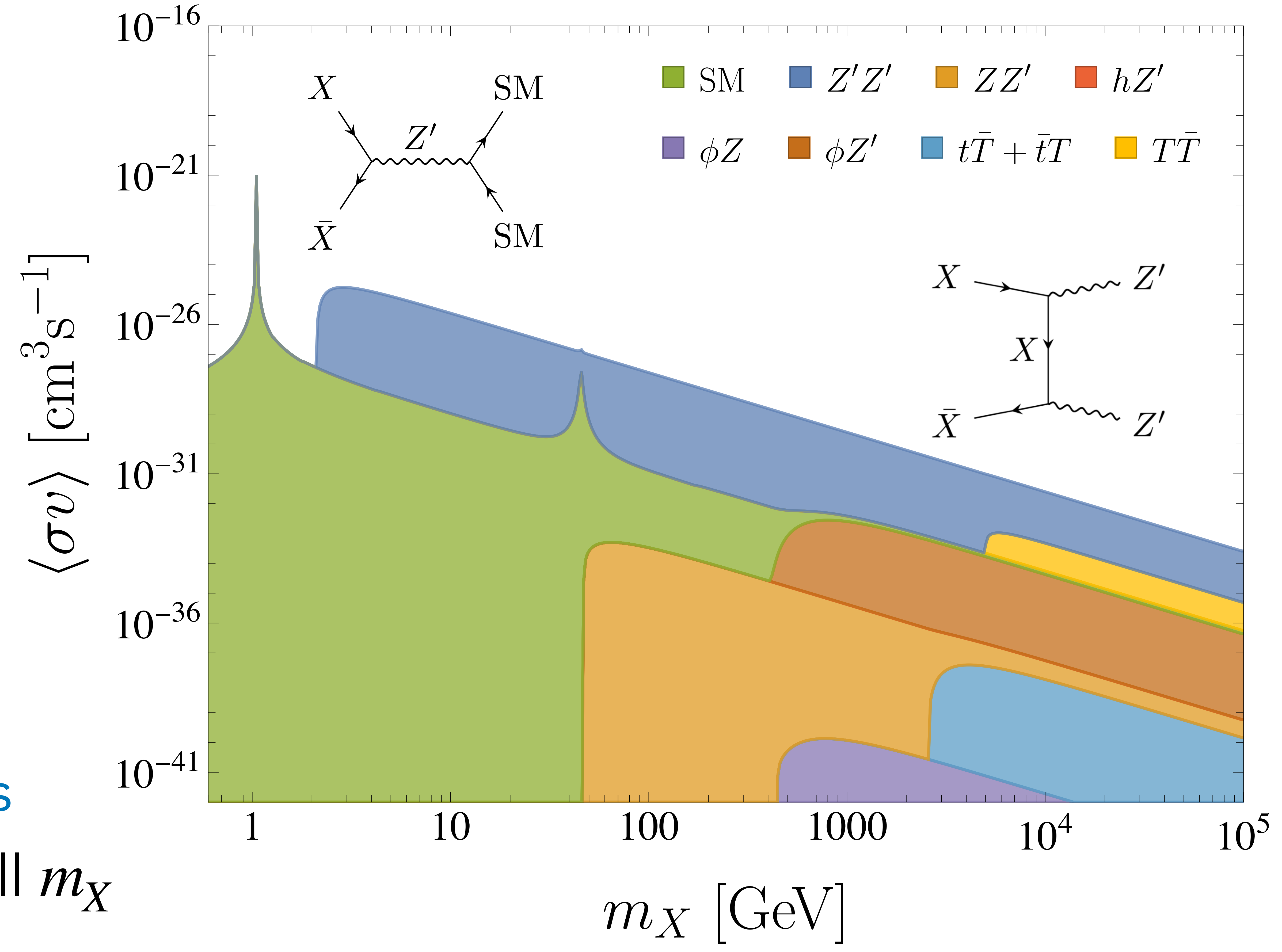
Would need an additional light state for Belle II excess i.e extended dark sector

Thermal freeze-out with s-wave dominated X annihilation cross section

Light X: $X\bar{X} \to \mathrm{SM}$ Heavy X: $X\bar{X} \to Z'Z'$





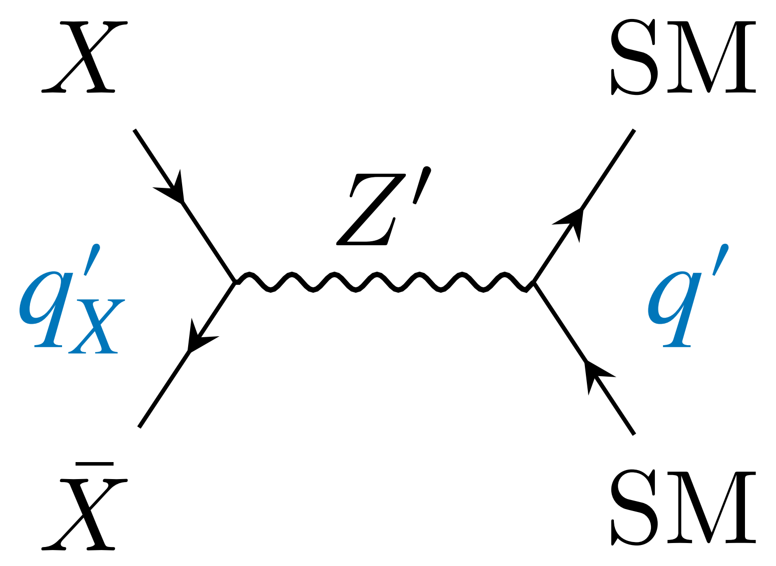


Relic abundance Ω_X calculated using MicrOMEGAs

$\Omega_X = \Omega_{\mathrm{DM}} = 0.12 \pm 0.001$ (Planck) is possible for all m_X

$\Rightarrow$ Much of the parameter space excluded by direct and indirect detection

Light dark matter



Standard freeze-out of dark matter below 10 GeV excluded by CMB

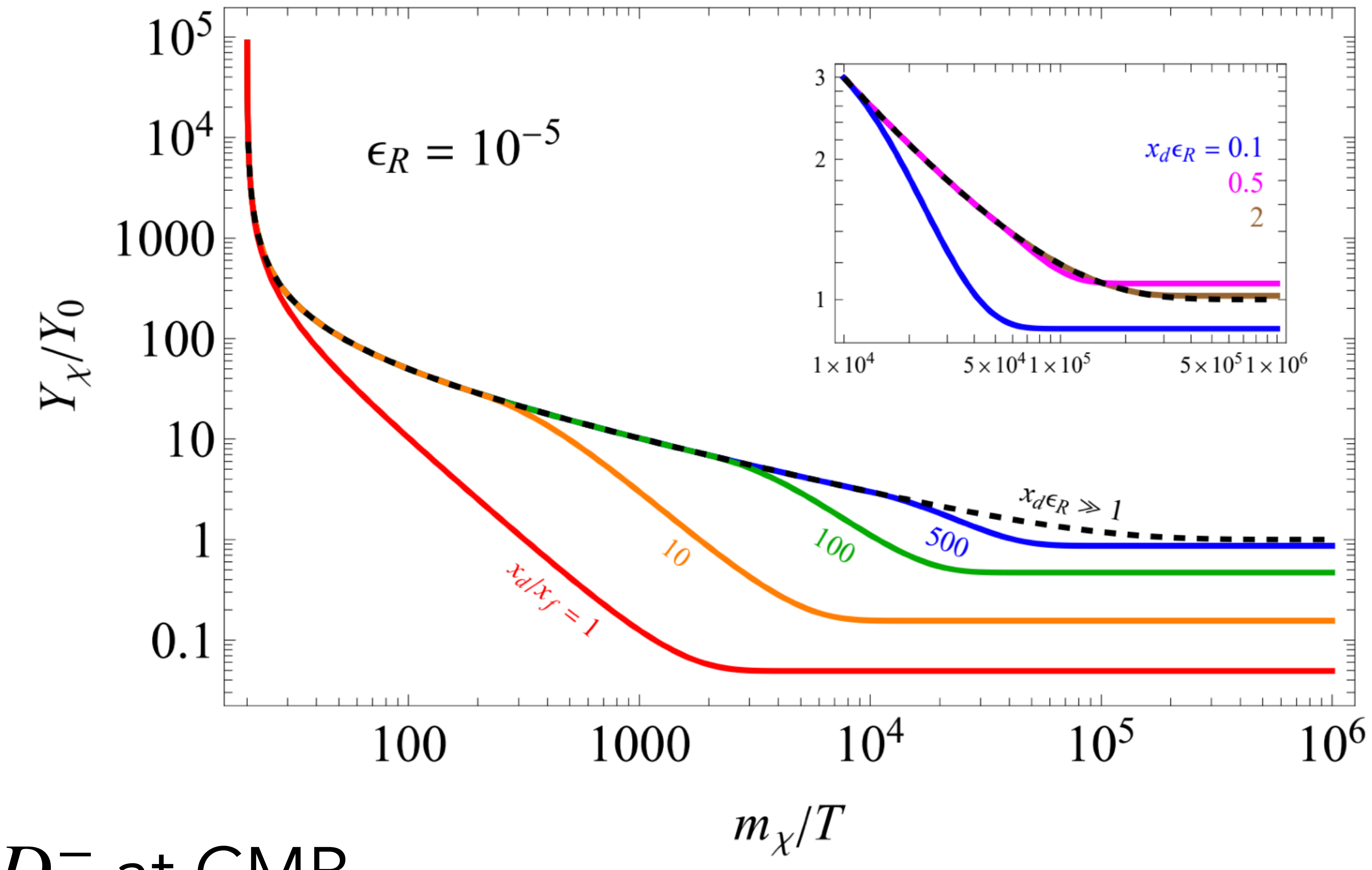
But resonant enhancement (Breit-Wigner) of $\langle \sigma v \rangle$ for $2m_X \sim M_{Z'}$,

Dynamics depends on $\epsilon = (M_{Z'}^2 - 4m_X^2)/4m_X^2$

$\Rightarrow$ For $\epsilon \ll 1$, kinetic equilibrium not met and Ω_X evolves after decoupling (belated freeze-out)

[Belanger et al. 25]

$\Rightarrow$ We consider $\epsilon > 0.1$, using thermal freeze out implemented in MicrOMEGAs



Planck constrains energy injection from $\mathrm{DM} \to e^+, \gamma, \nu, \bar{p}, D^-$ at CMB

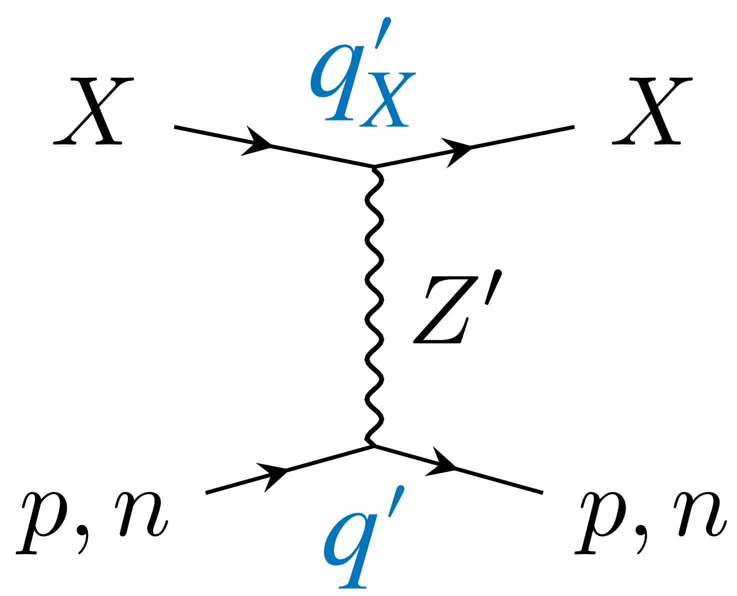
$\Rightarrow$ Resonance suppresses $\langle \sigma v \rangle$ at CMB

Light dark matter

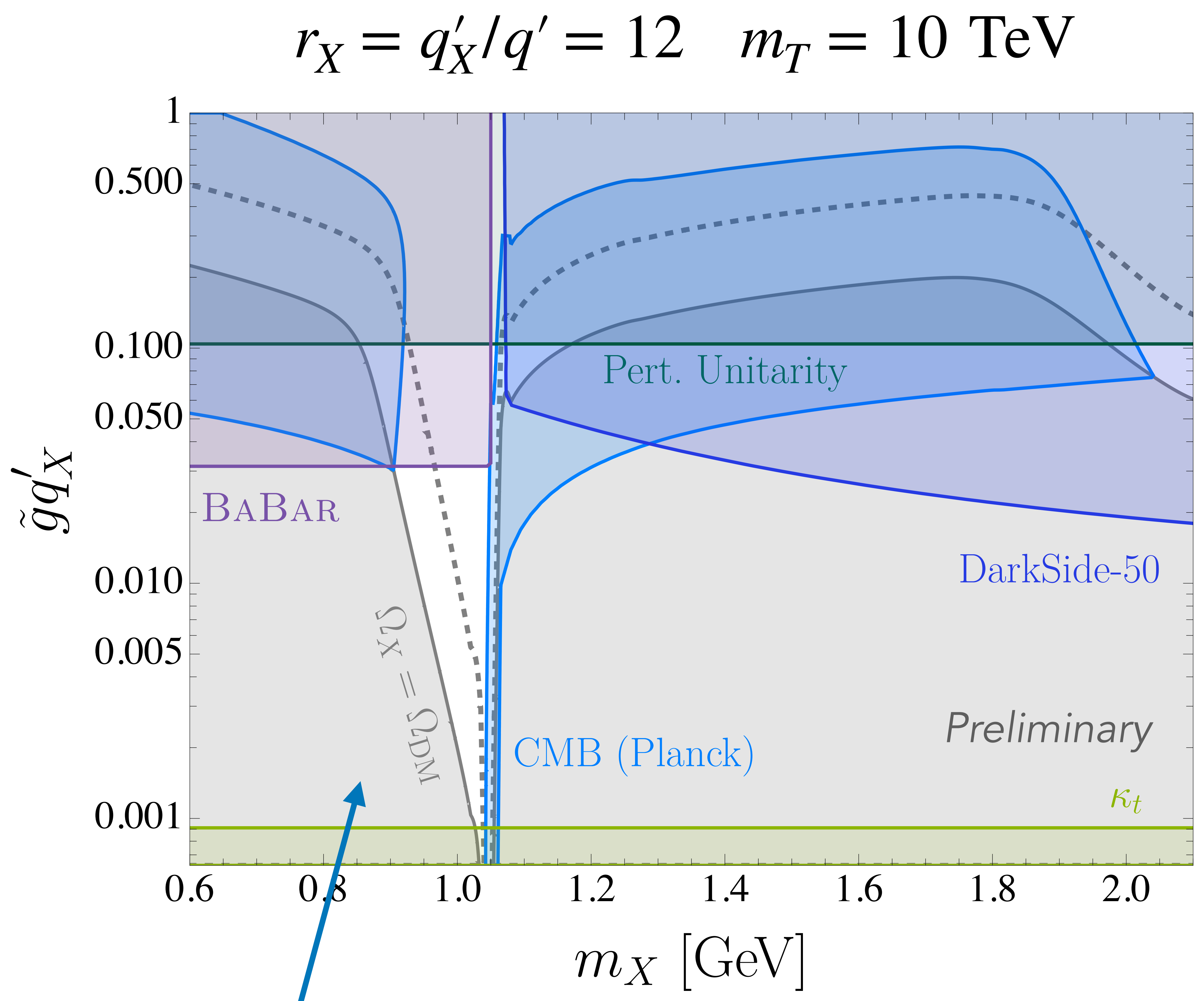
Planck CMB constraint:

$$P_{\mathrm{ann}} = \sum_j \frac{f_j^{\mathrm{eff}} \langle \sigma \rangle_i}{m_X} \left(\frac{\Omega_X}{\Omega_{\mathrm{DM}}} \right)^2 < 3.2 \times 10^{-28} \frac{\mathrm{cm}^3}{s\mathrm{GeV}}$$

Direct detection constraints from DarkSide-50 also constraints Z' mediated scattering



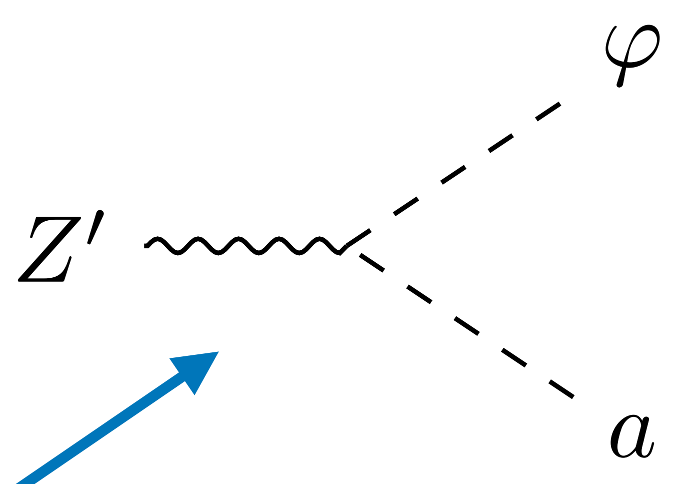
$0.9\ \mathrm{GeV} \lesssim m_X \lesssim 1\ \mathrm{GeV}$ gives correct Ω_X and evades bounds from direct and indirect detection



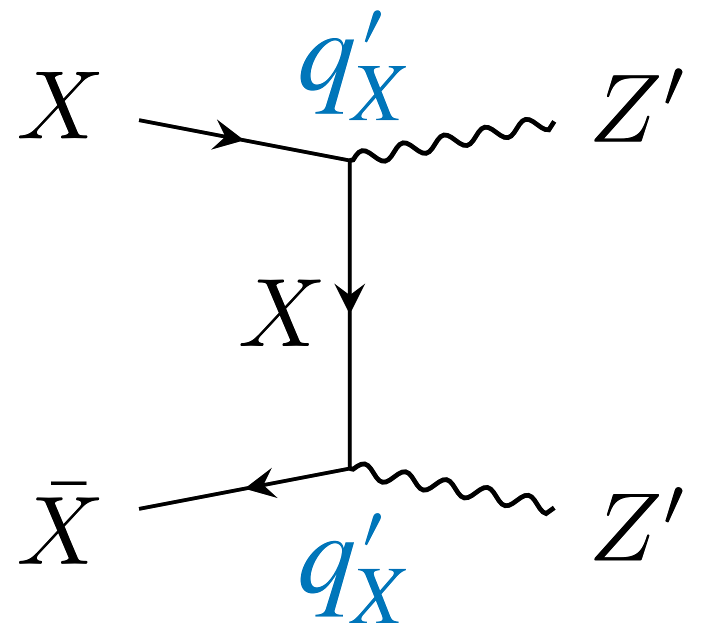
Viable window

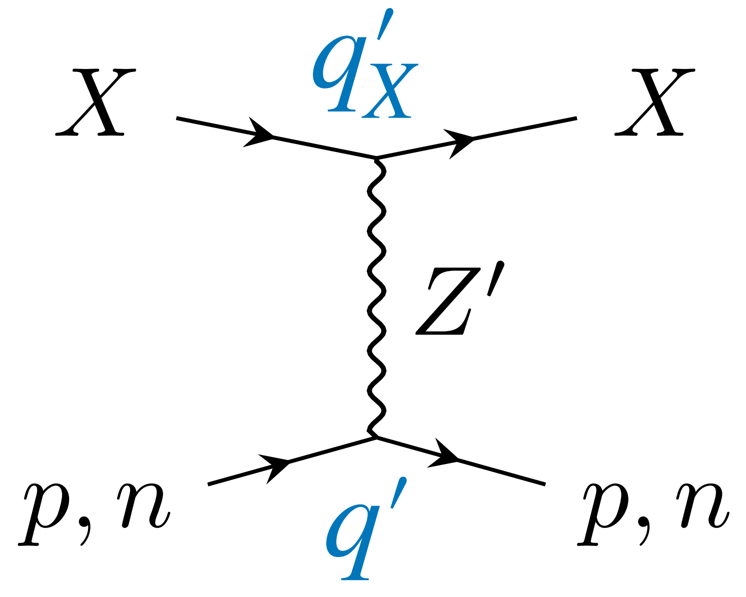
Traditional WIMP dark matter

For heavier DM ($2m_X > M_{Z'}$), we need additional Z' decay modes to explain Belle II result



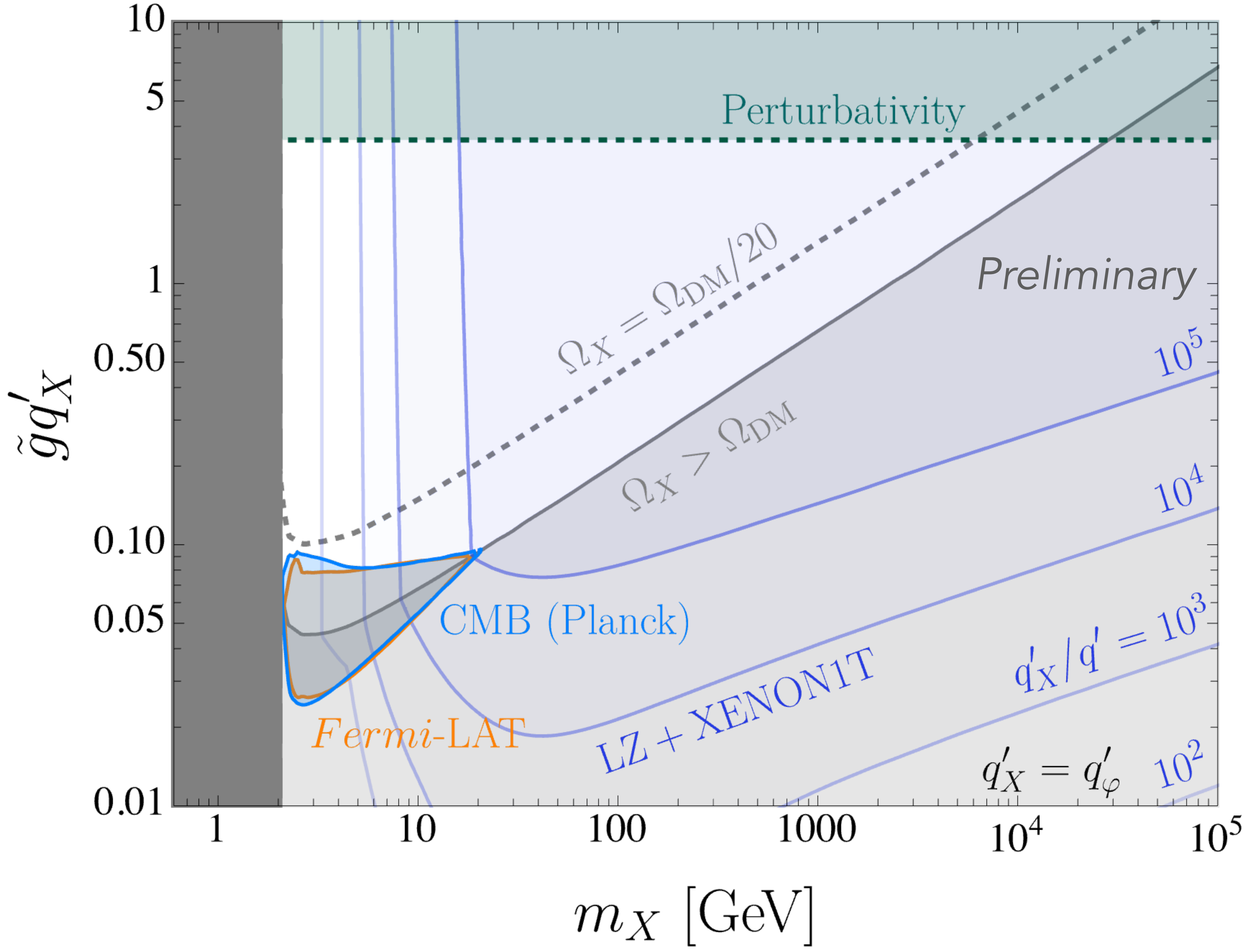
$\Rightarrow$ Assume extra fields charged under U(1)′, e.g. a scalar $\Phi' = \frac{1}{\sqrt{2}}(\tilde{v}_\varphi + \varphi + ia)$





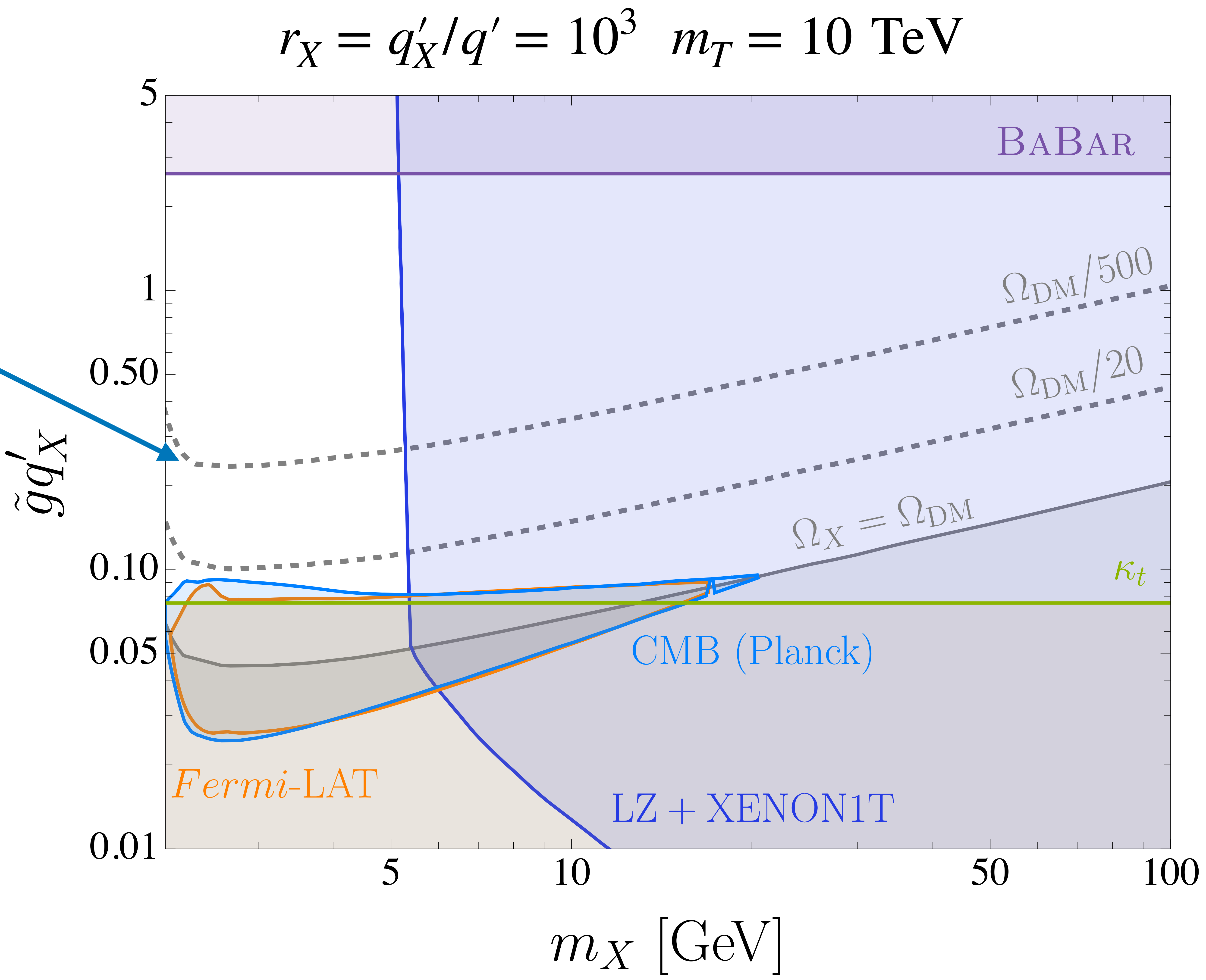
But we need $q'_X \gg q'$ to avoid stringent bounds from LZ + XENON1T

$\Rightarrow$ But this limit is also excluded by $\kappa_t = Y_t / Y_t^{\mathrm{SM}}$



Traditional WIMP dark matter

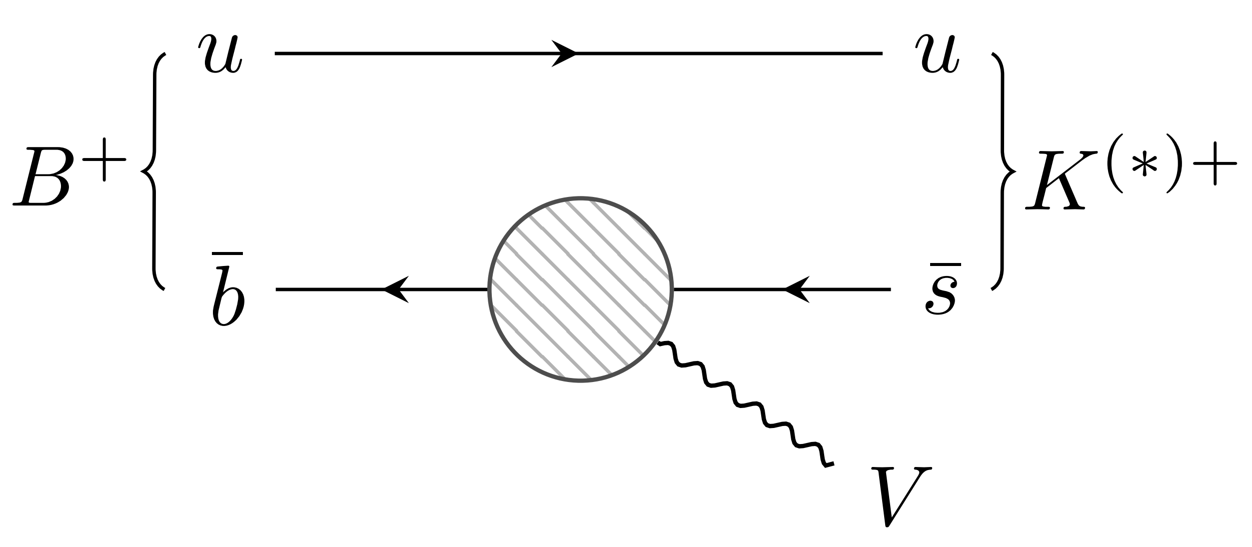
Heavy fermion X can be some, but not all of the dark matter



Conclusions

Light NP interpretation of current Belle II $B^+ \to K^+ \nu\bar{\nu}$ ITA data

- Two-body decays with scalar or vector (4.5σ), m_X ~ 2 GeV



[PDB, Fajfer, Kamenik, Novoa-Brunet 2024 + 2025]

Await future Belle II measurements of $B \to K^{(*)} E_{\text{miss}}$ to exclude and/or discriminate scenarios

- Model-agnostic inference essential, supported by recent release of Belle II likelihood

[Abumusabh et al. 2025]

The minimal aligned U(1)' model is predictive and tightly constrained

- Z' with mass 2.1 GeV, coupled to light dark fermion, can give $B \to K E_{\text{miss}}$ and avoid other bounds
- DM with $m_X \sim 0.9 - 1$ GeV can provide all of the required DM, $\Omega_X = \Omega_{\text{DM}}$

Thank you for your attention!

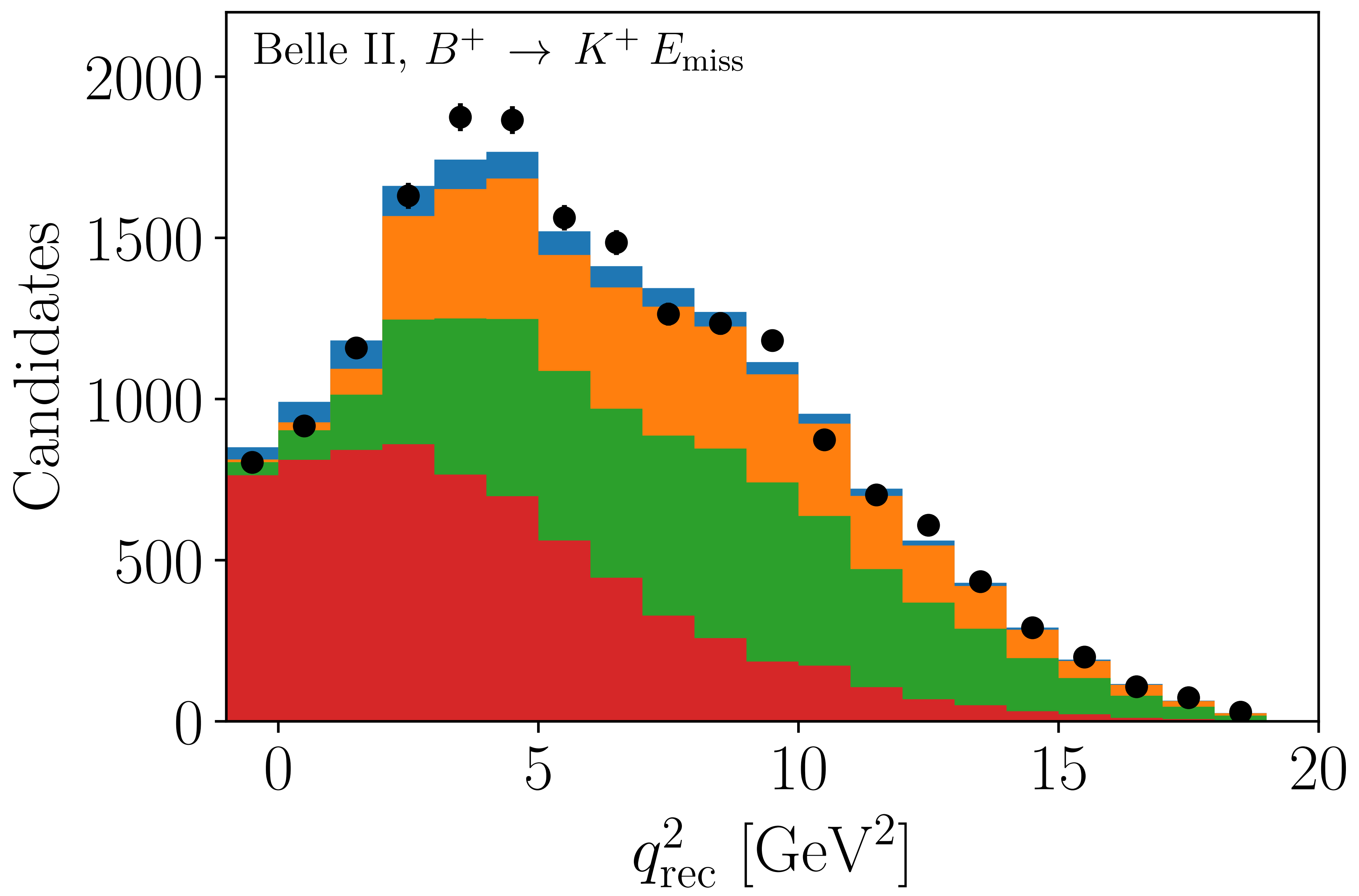
Backup

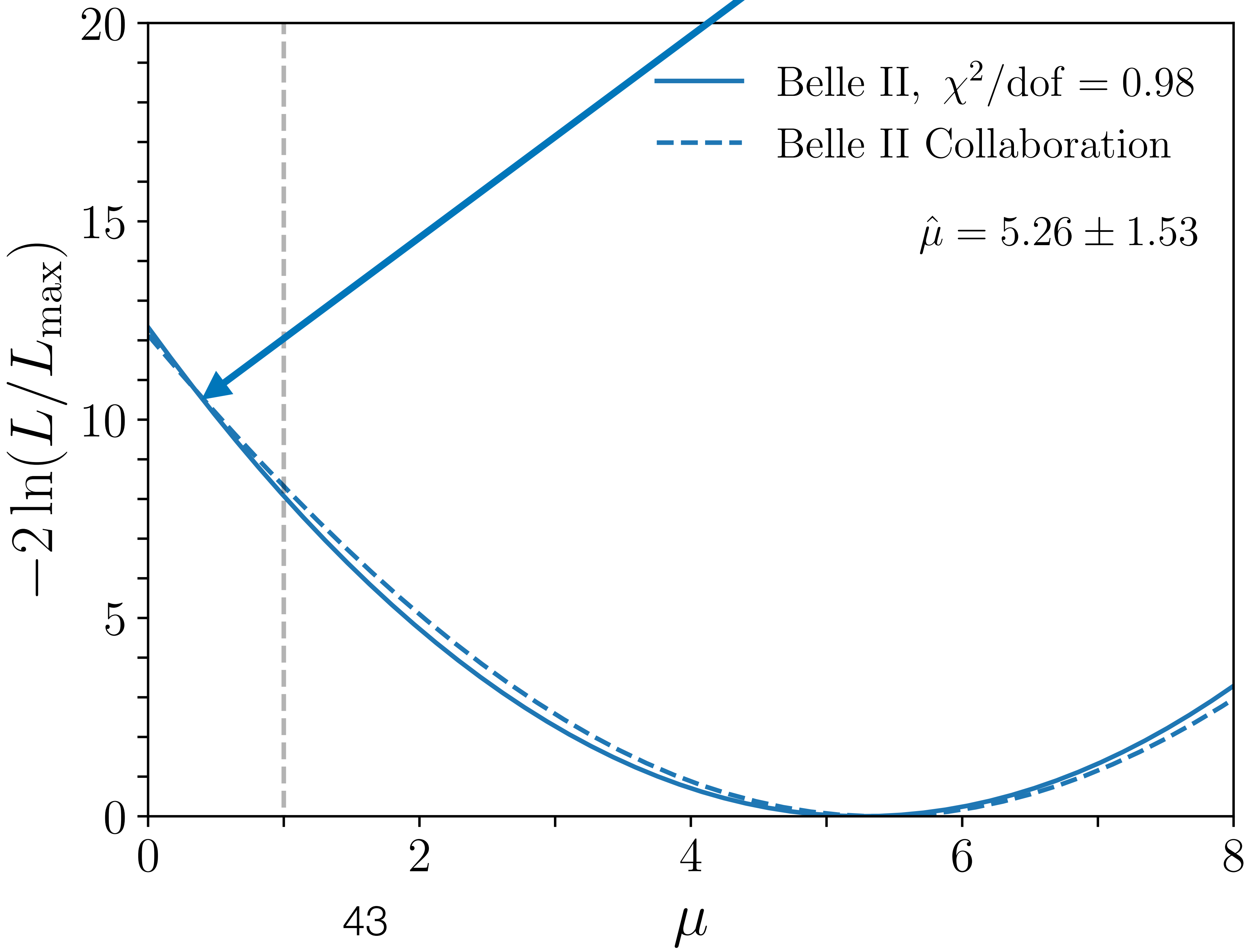
Reinterpreting the Belle II ITA Results

Construct binned likelihood: $L_{\mathrm{SM}+X}^{\text{Belle II}} = \prod_{i,x,b} P\left(n_i^{\mathrm{obs}}, n_i\right) \mathcal{N}\left(\boldsymbol{\theta}^x; \Sigma^x\right) \mathcal{N}\left(\tau_b; \sigma_b^2\right)$ $\quad x = \mathrm{SM}, X, b$

Σ^x : Covariances accounting for signal theory uncertainties and background MC statistical errors for ITA

σ_b : Overall background normalisation uncertainty, fixed to obtain agreement with Belle II profile likelihood





[Adachi et al. 2023]

n_i^{obs} : $\eta(\mathrm{BDT}_2) > 0.92$ q^2_{rec} data

Fit varying μ and θ, assuming SM only

Favoured Scenarios

Viable scenarios (better fit w.r.t to the re-scaled SM):

Two-body:

$$B \to K\phi \text{ or } B \to KV \text{ with } m_{\phi/V} = (2.1 \pm 0.1)\ \text{GeV}$$

Three-body:

$B \to K\psi\bar{\psi}$ for vector couplings with $m_\psi = 0.60^{+0.11}_{-0.14}$ GeV

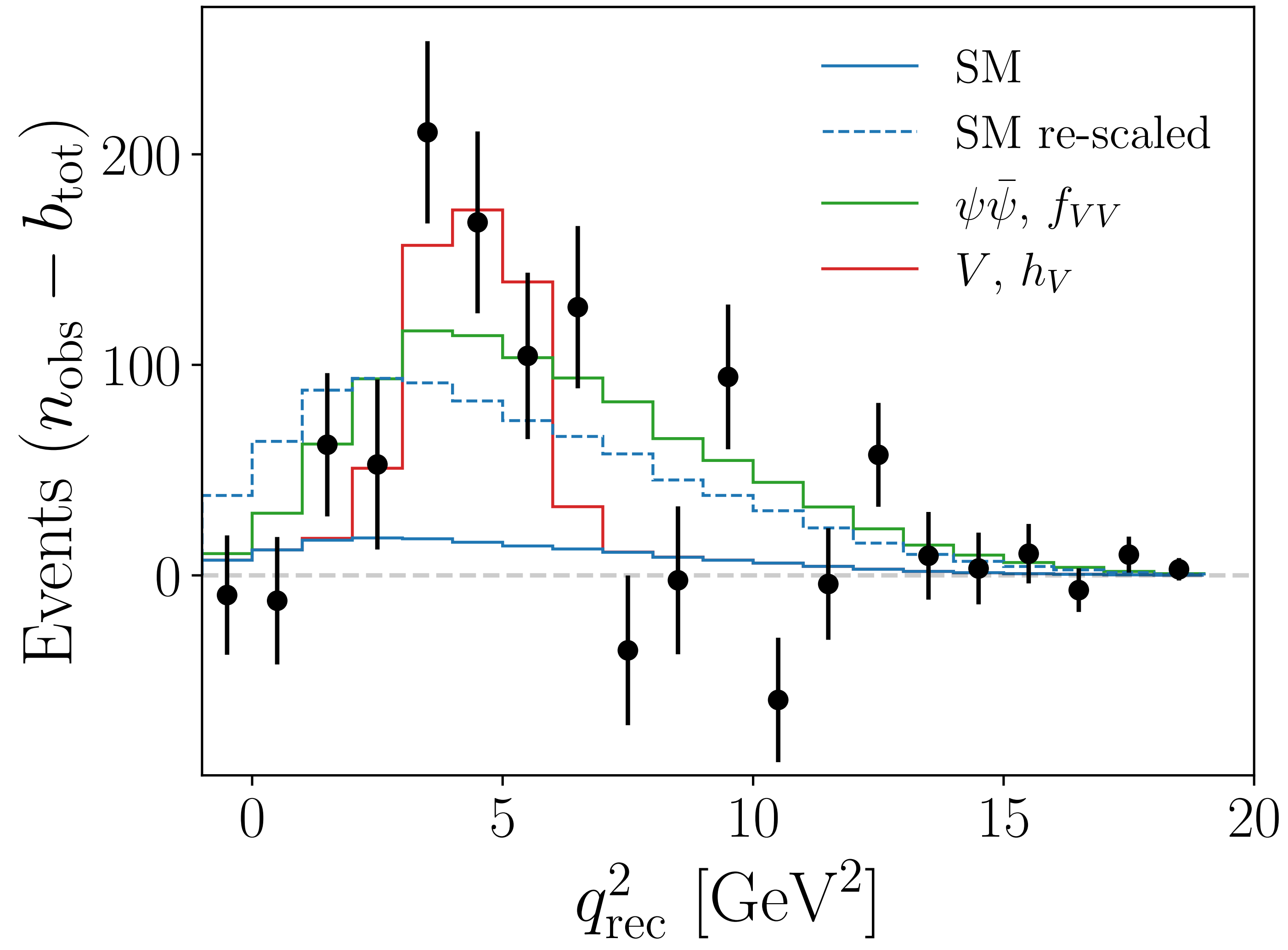
$B \to K\phi\bar{\phi}$ for vector couplings with $m_\phi = 0.38^{+0.13}_{-0.15}$ GeV

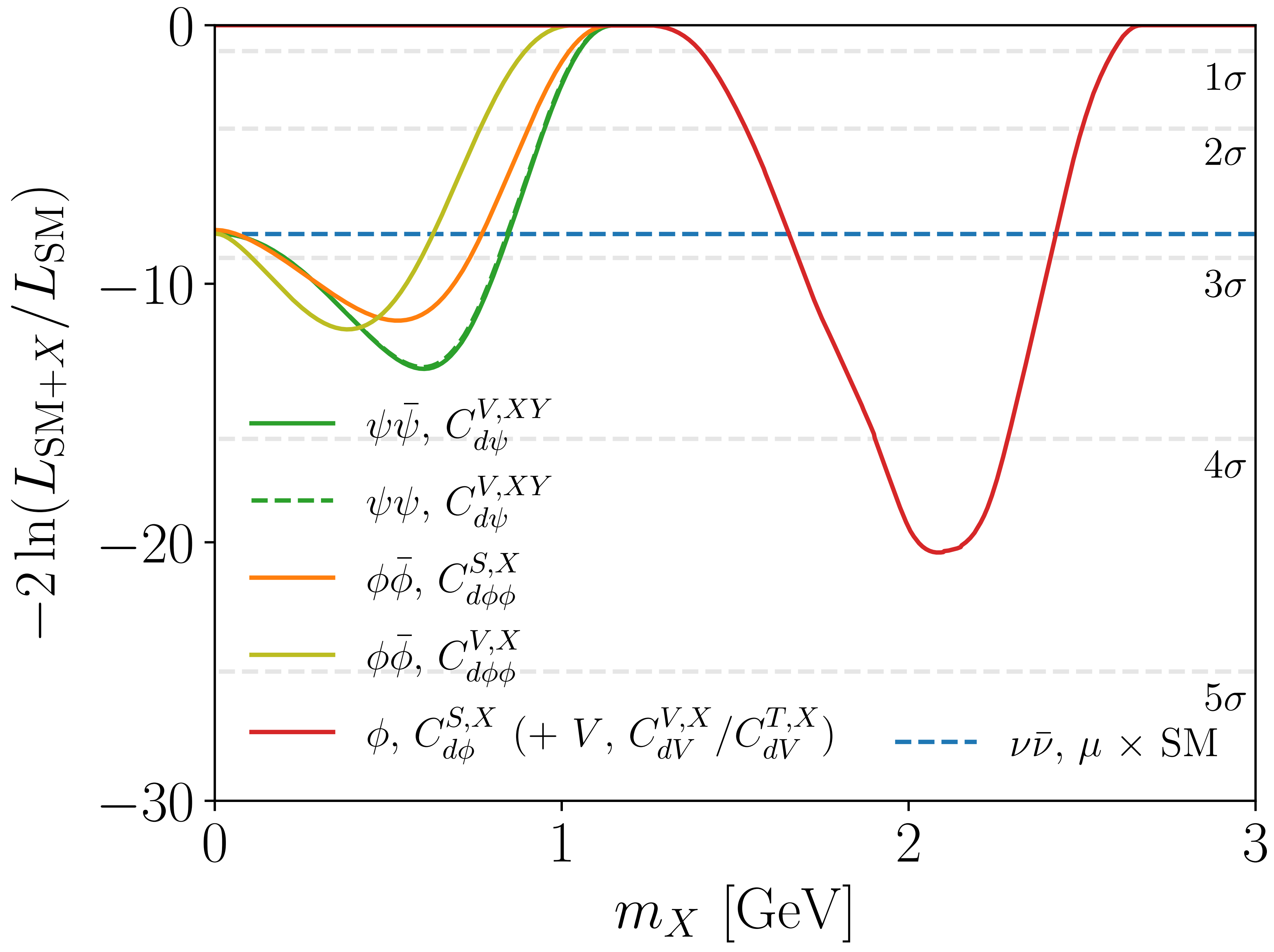
scalar couplings with $m_\phi = 0.52^{+0.11}_{-0.14}$ GeV

Non-viable scenarios (worse fit w.r.t to the re-scaled SM:

- $B \to K\psi\bar{\psi}$ for scalar and tensor couplings
- $B \to KVV/\Psi\bar{\Psi}$ for all couplings

$\Rightarrow$ Kinetics cannot accommodate excess at $q^2_{\text{rec}} \sim 4$ GeV^2





Scalar Boson (Two-body) Scenario

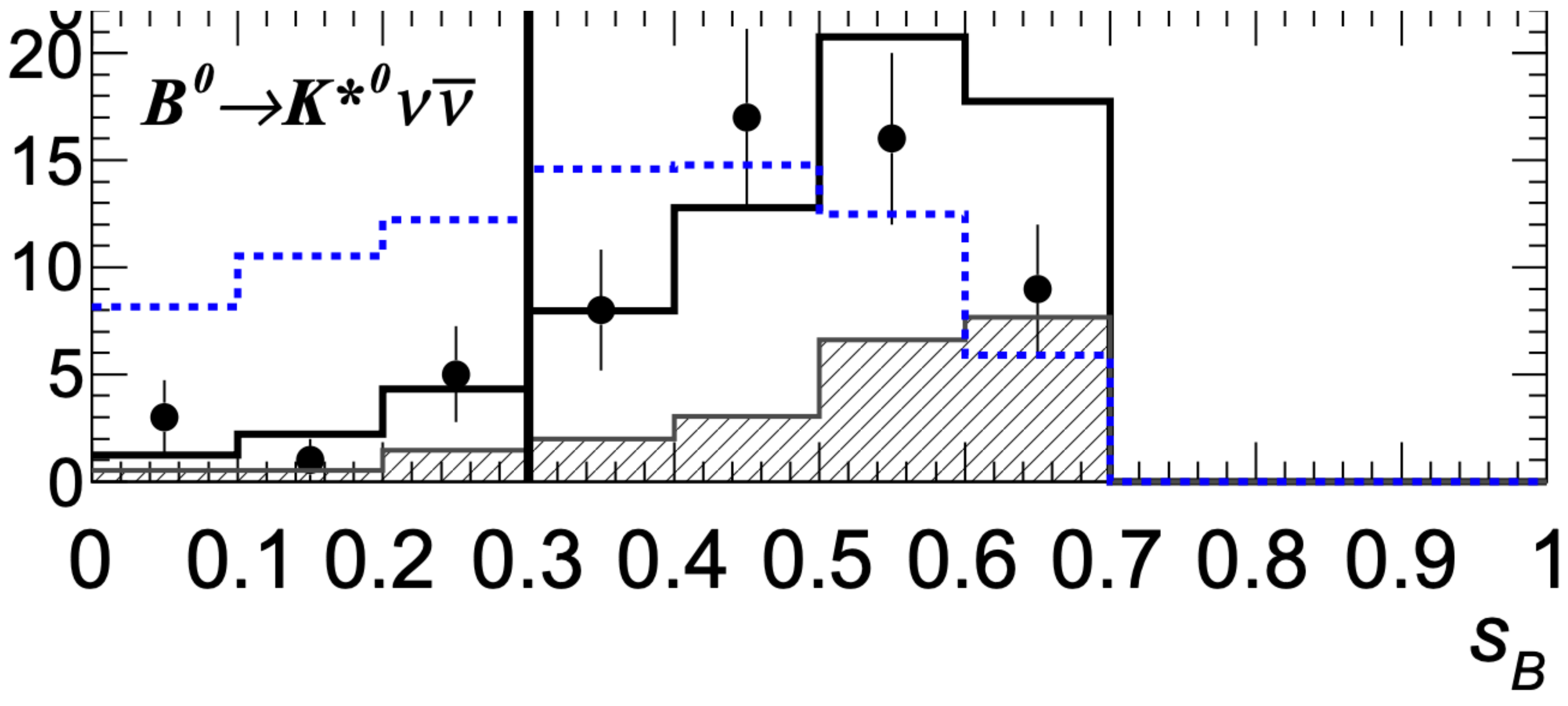
Next, we investigate the favoured couplings for the best-fit scalar mass values $\Rightarrow$ profile likelihood

We allow *P* even and *P* odd couplings,

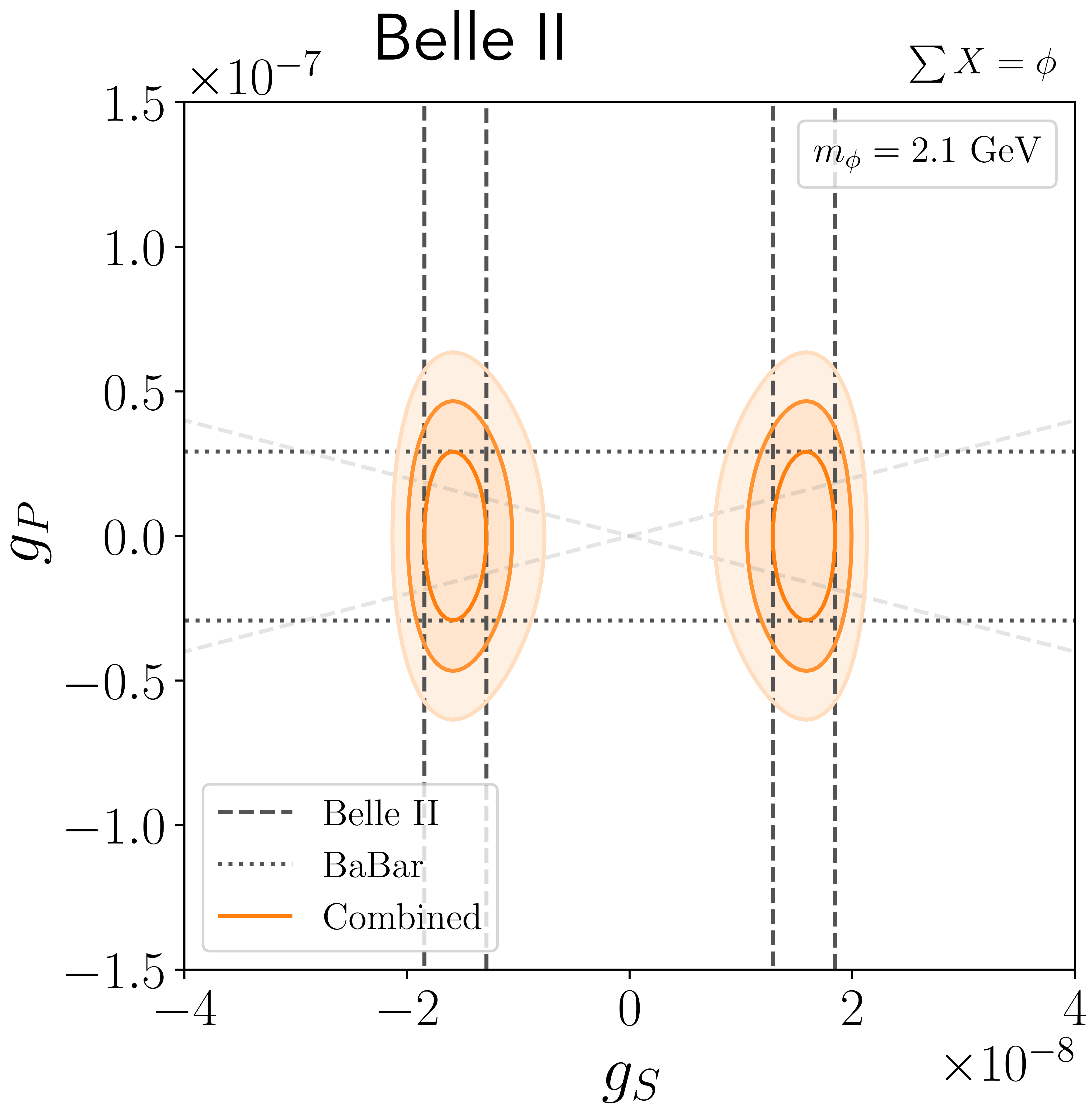
$$g_S(\bar{b}s)\phi + g_P(\bar{b}\gamma_5 s)\phi$$

P odd couplings can be constrained by the *BABAR* $B \to K^* E_{\text{miss}}$ upper bound (most recent q^2 distribution):

$$\mathcal{B}(B \to K^* E_{\text{miss}}) < 11 \times 10^{-5}$$



[Lees et al. 2013]

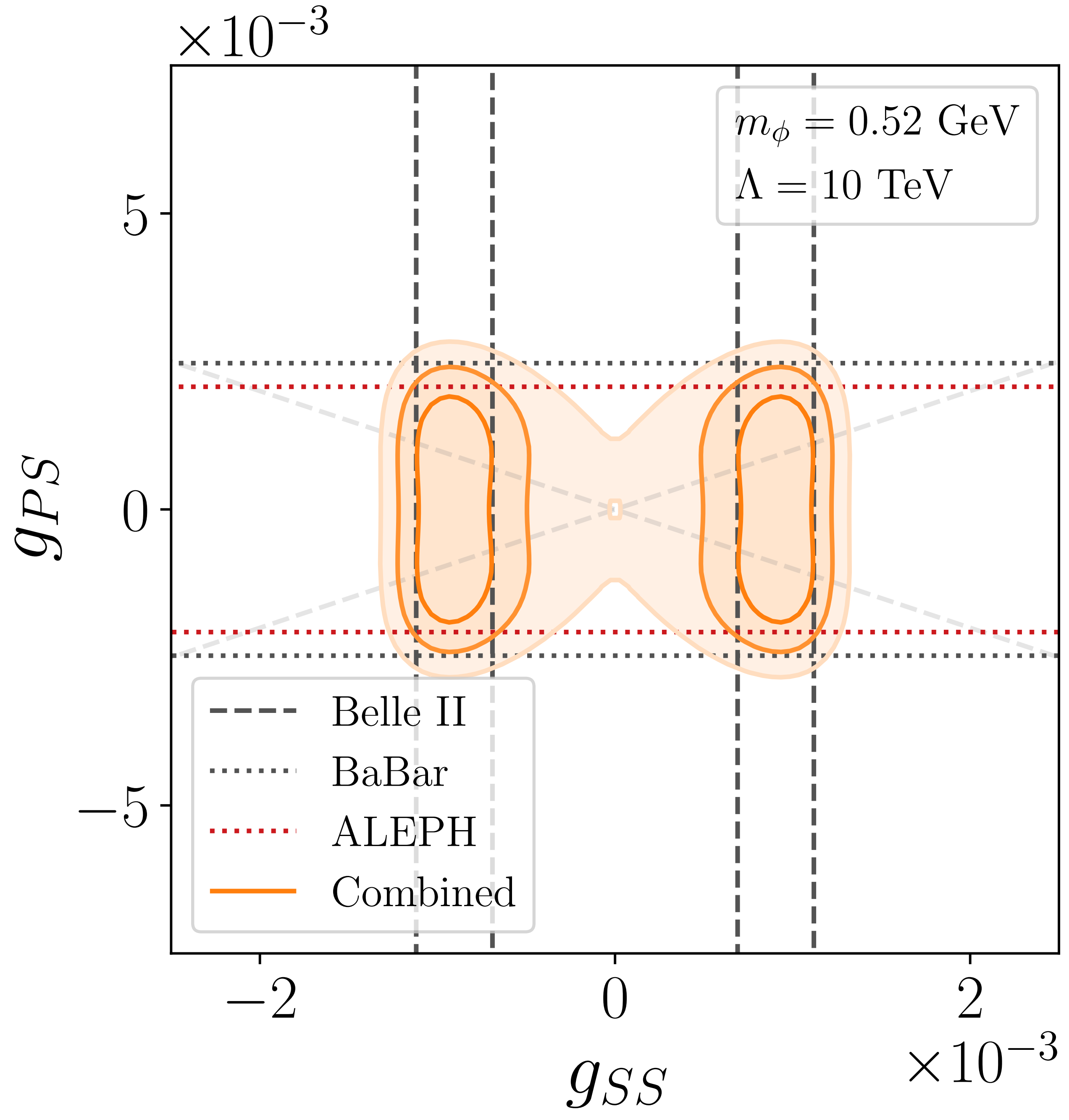


BABAR

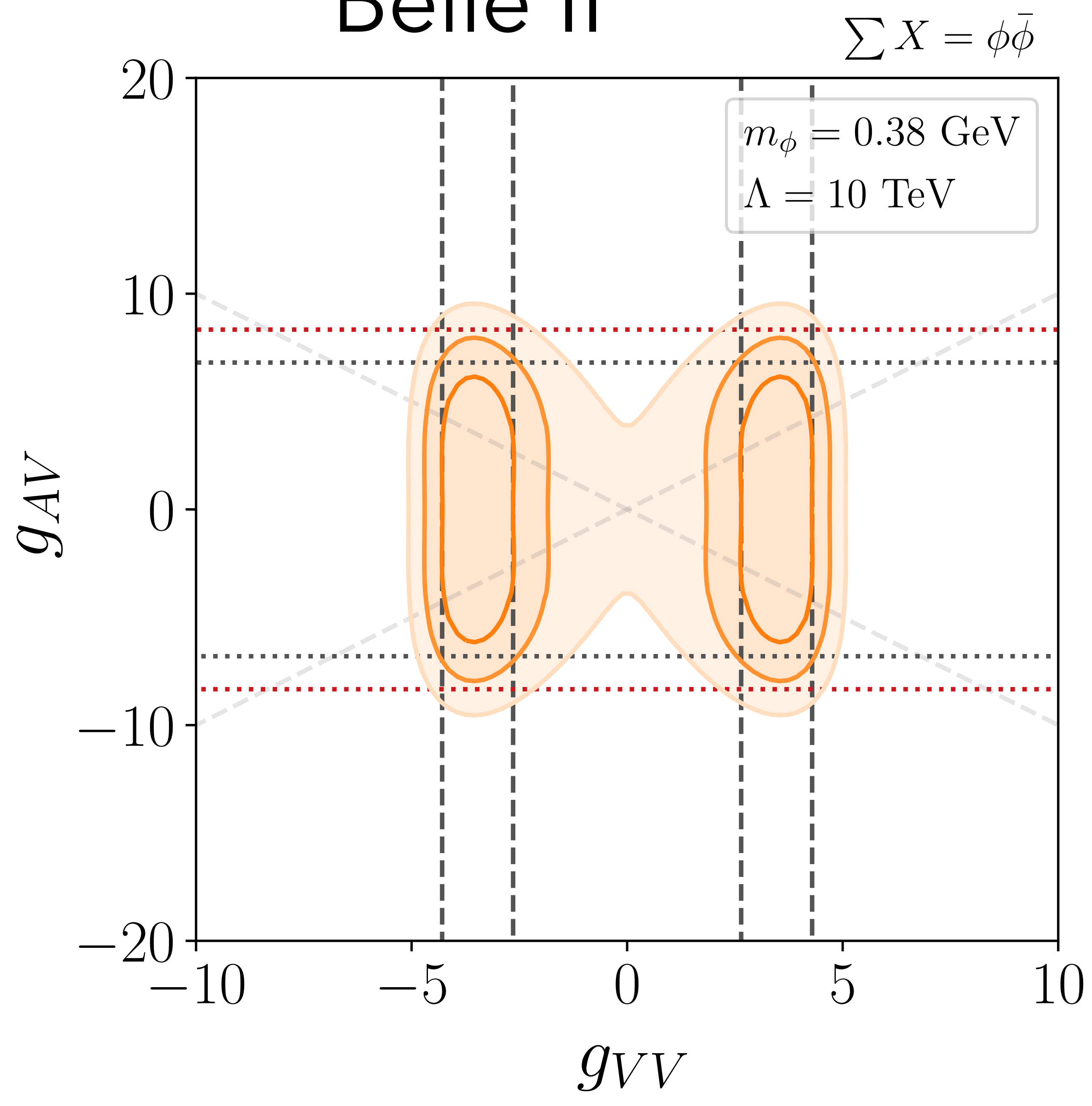
See also: [Altmannshofer et al. 2023]
[McKeen et al. 2023]
[Hati et al. 2024]

Scalar Boson (Three-body) Scenario

Favoured scalar and vector couplings for the scalar boson three-body scenario



Belle II



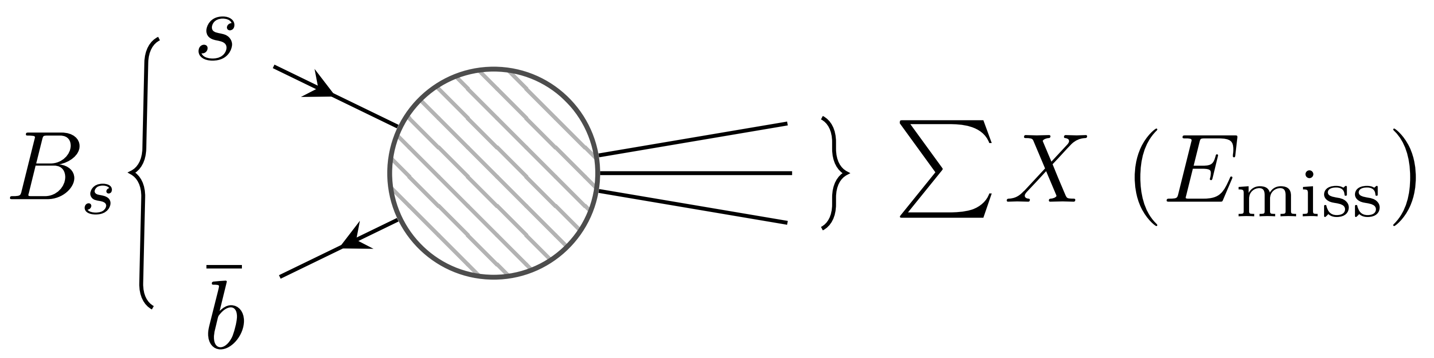
BABAR

ALEPH

$B_s \to \phi\phi$ upper bound from recent ALEPH recast

$$\mathcal{B}(B_s \to E_{\text{miss}}) < 5.4 \times 10^{-4}$$

[Alonso-Álvarez, Escudero 2023]



$$\frac{g_{SS}}{\Lambda}(\bar{b}s)\phi\phi + \frac{g_{PS}}{\Lambda}(\bar{b}\gamma_5 s)\phi\phi \qquad \frac{g_{VV}}{\Lambda^2}(\bar{b}\gamma_\mu s)(i\phi^* \overleftrightarrow{\partial}^\mu \phi) + \frac{g_{AV}}{\Lambda^2}(\bar{b}\gamma_\mu\gamma_5 s)(i\phi^* \overleftrightarrow{\partial}^\mu \phi)$$

See also: [Bird et al. 2004]
[He et al. 2024]

Effective Couplings - Chiral Basis

Given the NP explanations of the Belle II excess, what is expected for $B \to K^* E_{\text{miss}}$?

$\Rightarrow$ We consider the chiral basis to maximise correlations between $B \to K E_{\text{miss}}$ and $B \to K^* E_{\text{miss}}$

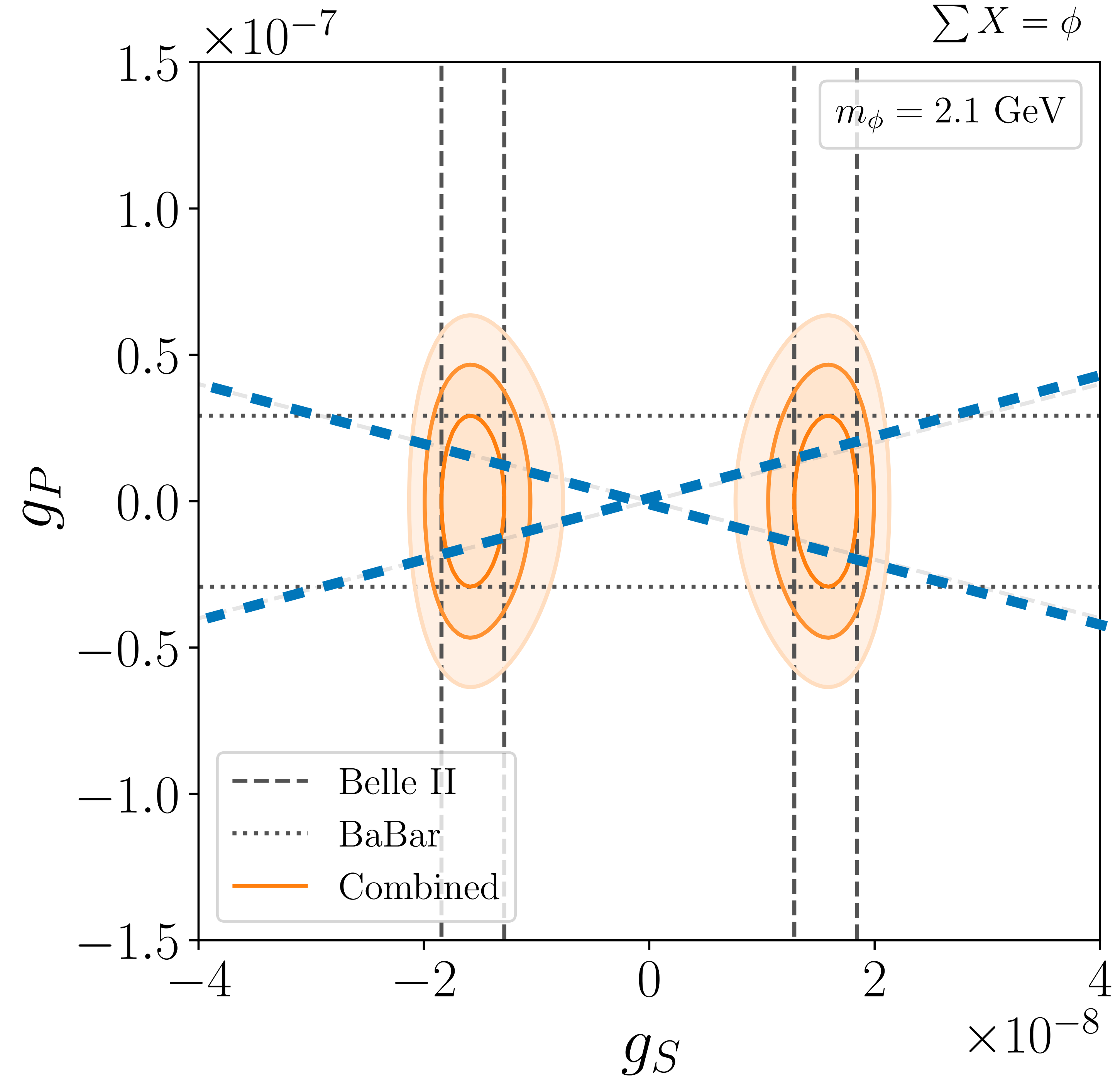
$$\mathcal{H}_{\text{eff}}^{V,L(R)} \supset C_i(\bar{b}\gamma_\mu P_{L(R)} s) \times \left[\text{light fields}\right]$$

$$\mathcal{H}_{\text{eff}}^{S,L(R)} \supset C_i(\bar{b} P_{L(R)} s) \times \left[\text{light fields}\right]$$

$$\mathcal{H}_{\text{eff}}^{T,L(R)} \supset C_i(\bar{b}\sigma_{\mu\nu} P_{L(R)} s) \times \left[\text{light fields}\right]$$

e.g.

$$\frac{v}{\sqrt{2}} C_{d\phi}^{S,L} = g_S - g_P \qquad \frac{v}{\sqrt{2}} C_{d\phi}^{S,R} = g_S + g_P$$



$$C_{d\phi}^{S,L} = 0$$

$$C_{d\phi}^{S,R} = 0$$

$\Rightarrow$ Add factors of Higgs vev expected from SM-invariant EFT

$$\bar{Q}Hd \to \frac{v}{\sqrt{2}} \bar{b}_L s_R$$

Fermion Scenario

Favoured vector couplings for the fermion scenario

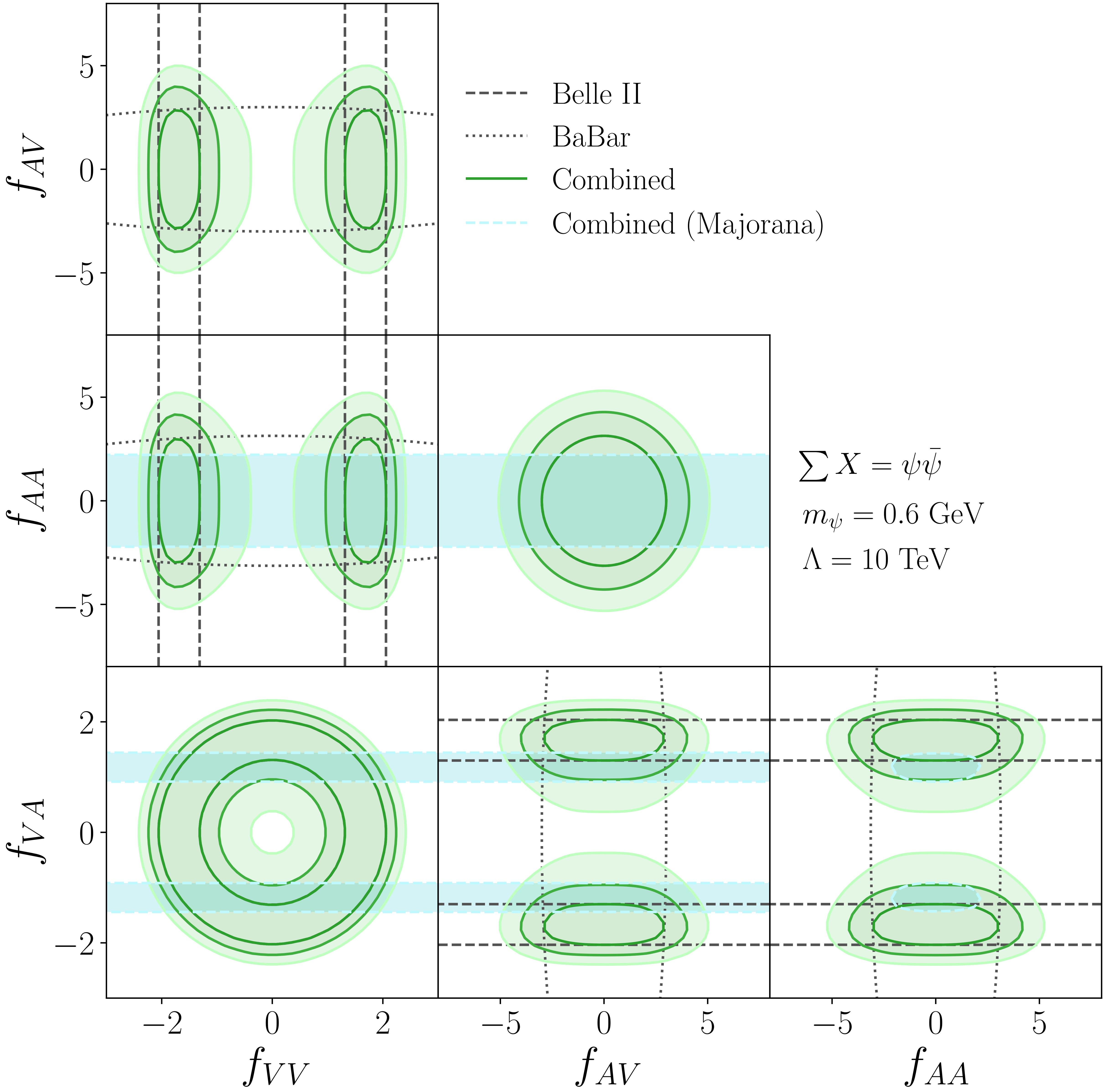
$$\frac{f_{VV}}{\Lambda^2}(\bar{b}\gamma_\mu s)(\bar{\psi}\gamma^\mu\psi) + \frac{f_{VA}}{\Lambda^2}(\bar{b}\gamma_\mu s)(\bar{\psi}\gamma^\mu\gamma_5\psi)$$
$$+ \frac{f_{AV}}{\Lambda^2}(\bar{b}\gamma_\mu\gamma_5 s)(\bar{\psi}\gamma^\mu\psi) + \frac{f_{AA}}{\Lambda^2}(\bar{b}\gamma_\mu\gamma_5 s)(\bar{\psi}\gamma^\mu\gamma_5\psi)$$

We consider Dirac and Majorana ψ

$\Rightarrow f_{VV}$ and f_{AV} vanish for Majorana ψ: $\bar{\psi}\gamma_\mu\psi = 0$

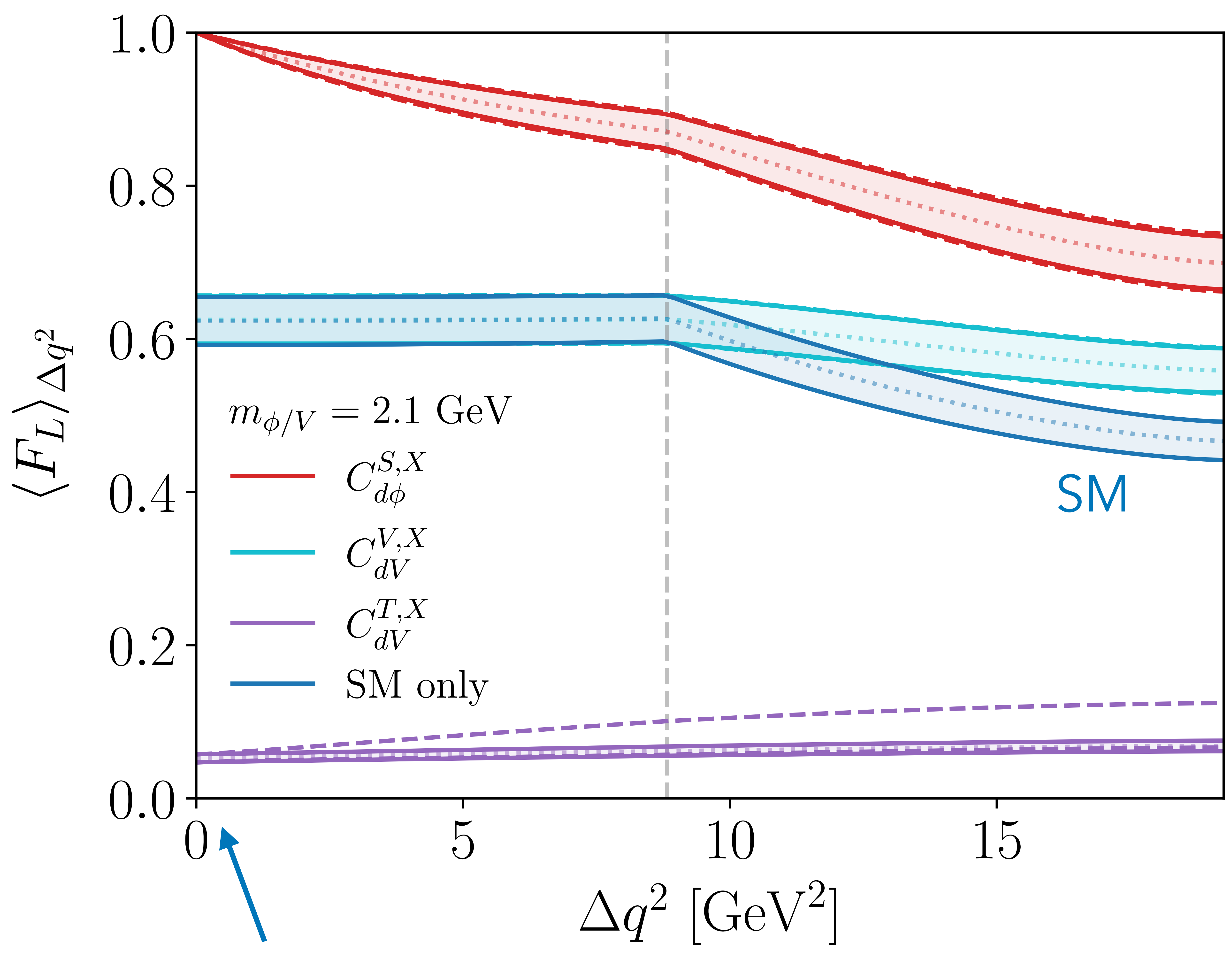
Only other relevant constraint (on P odd) operators from $B \to K^*\psi\bar{\psi}$

$B_s \to \psi\bar{\psi}$ is helicity suppressed



See also: [Fridell et al. 2024]

Implications for Future Measurements



Width of q^2 bin centred on m_X^2

Deviations in F_L for two-body scenarios can benefit from either:

a) Measuring F_L around $q^2 = m_X^2$ peak

b) Integrating over whole q^2 range

Binned F_L:

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

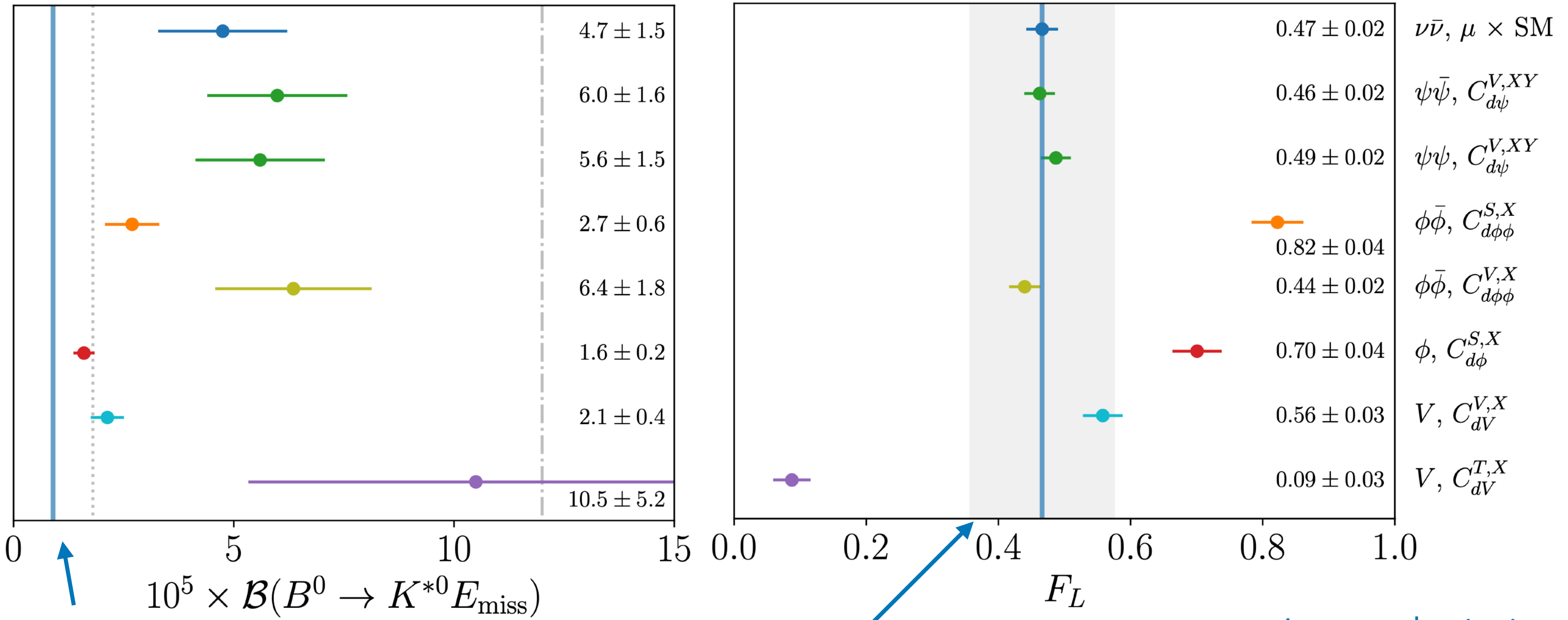
[PDB, Fajfer, Kamenik, Novoa-Brunet 2025]

Implications for Future Measurements

Predictions for integrated observables, e.g. $\langle F_L \rangle = \int dq^2 F_L(q^2)$

[PDB, Fajfer, Kamenik, Novoa-Brunet 2025]

SM



SM

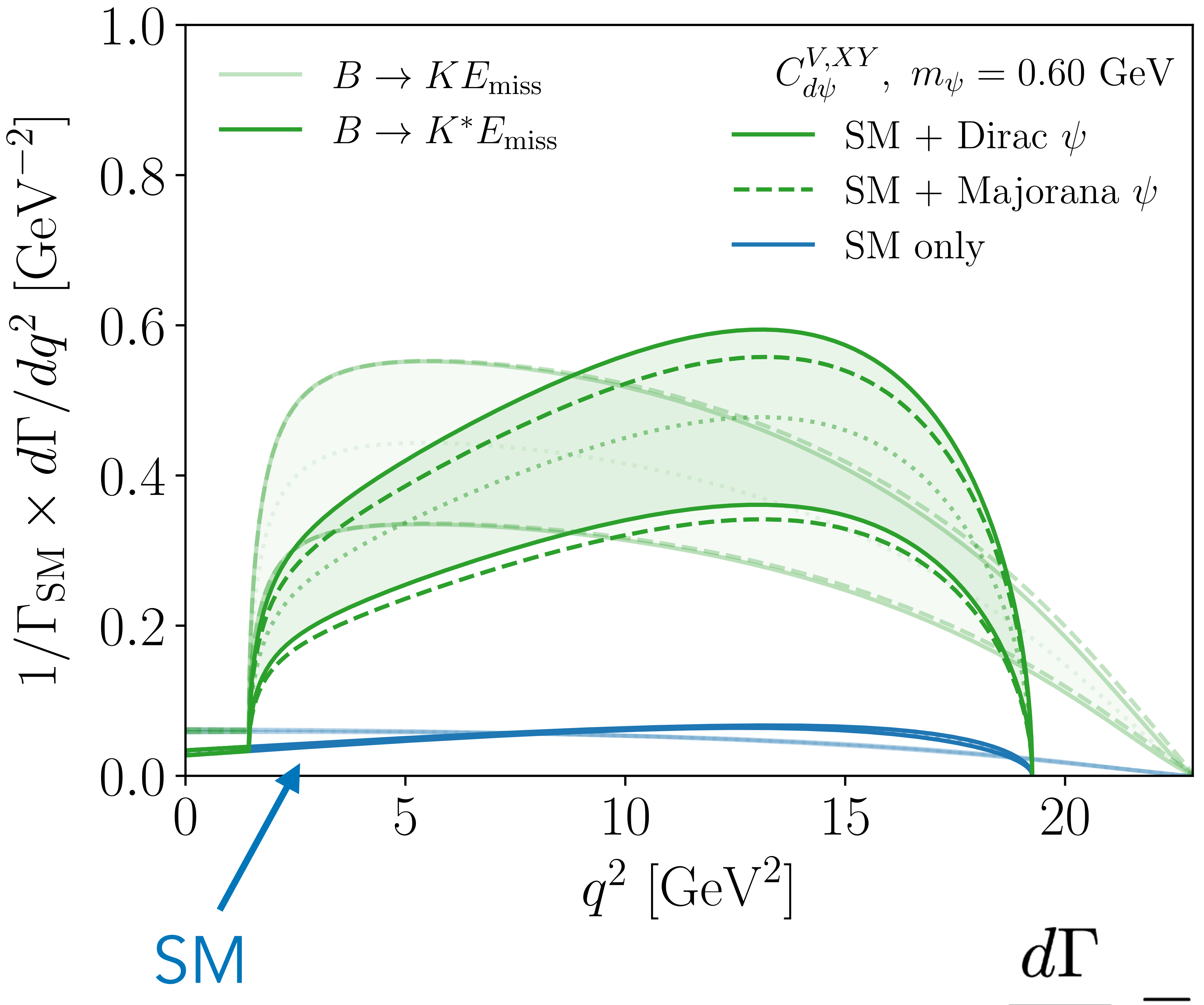
Belle II sensitivity

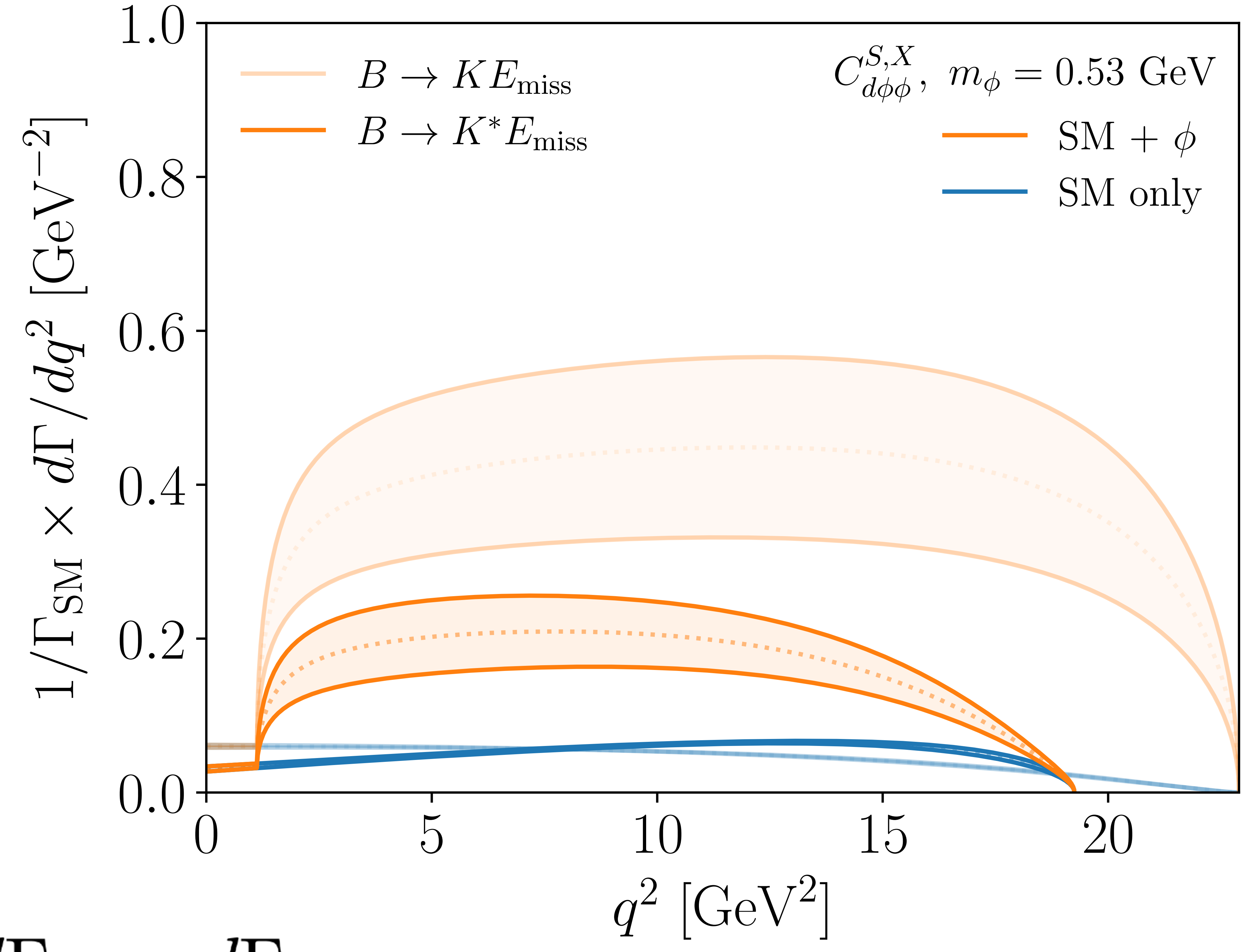
Large deviations from SM in some viable scenarios

Implications for Future Measurements

Differential (binned) observables, e.g. branching fractions:

⇒ For chiral couplings, large $\mathscr{B}(B \to K^* E_{\text{miss}})$ is expected for large $\mathscr{B}(B \to K E_{\text{miss}})$





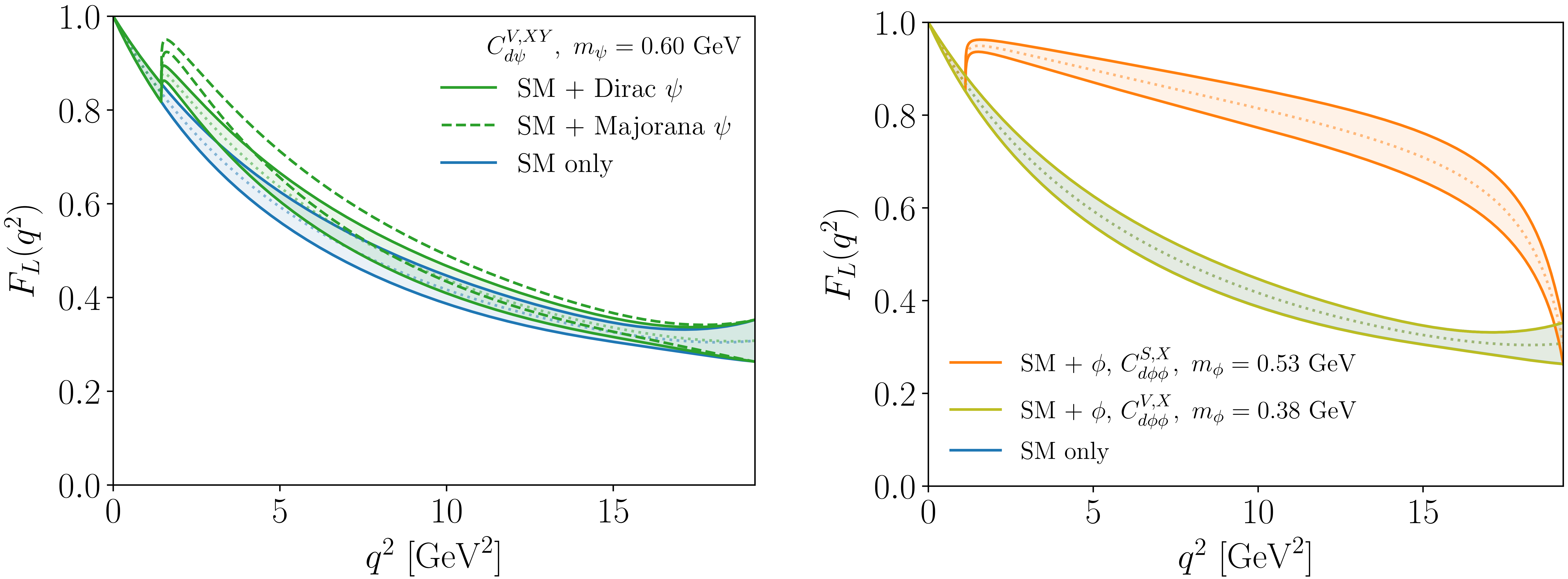
$$\frac{d\Gamma}{dq^2} = \frac{d\Gamma_T}{dq^2} + \frac{d\Gamma_L}{dq^2}$$

[PDB, Fajfer, Kamenik, Novoa-Brunet 2025]

Implications for Future Measurements

Differential (binned) observables, e.g. $F_L(q^2)$

⇒ Further discrimination (e.g. around NP thresholds) for the three-body scenarios



$$F_L = \frac{d\Gamma_L}{dq^2} \Big/ \frac{d\Gamma}{dq^2}$$

[PDB, Fajfer, Kamenik, Novoa-Brunet 2025]