Jožef Stefan Institute

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

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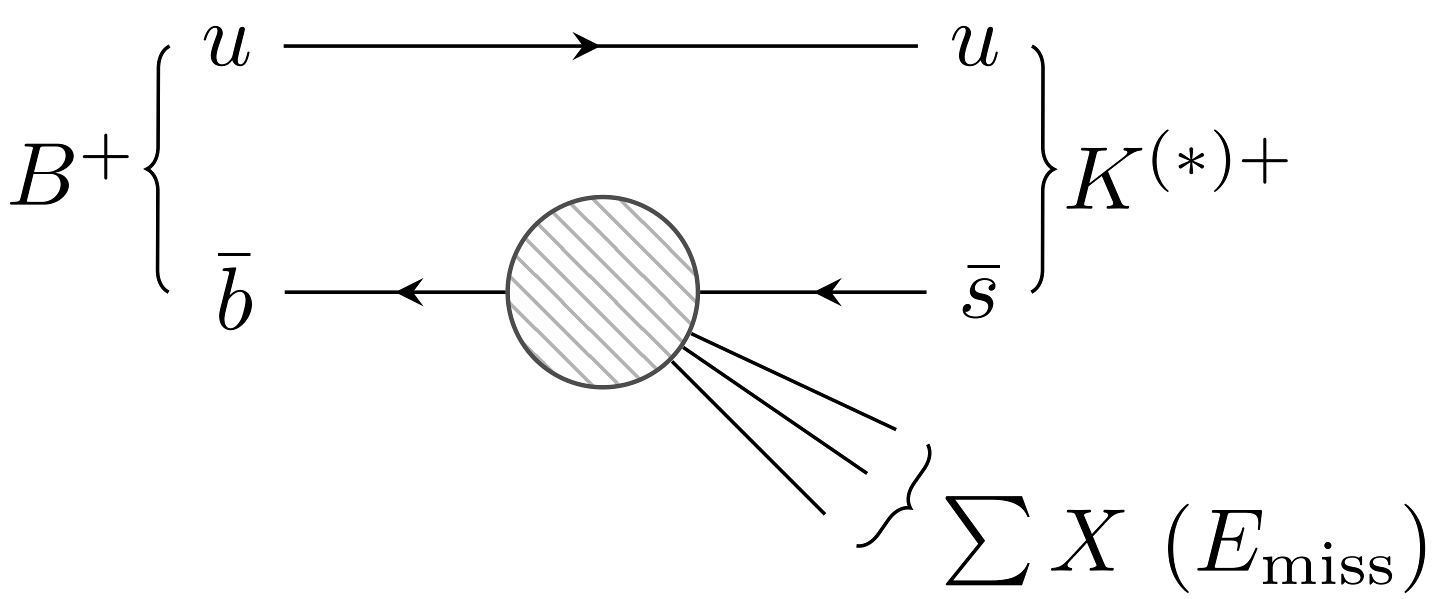
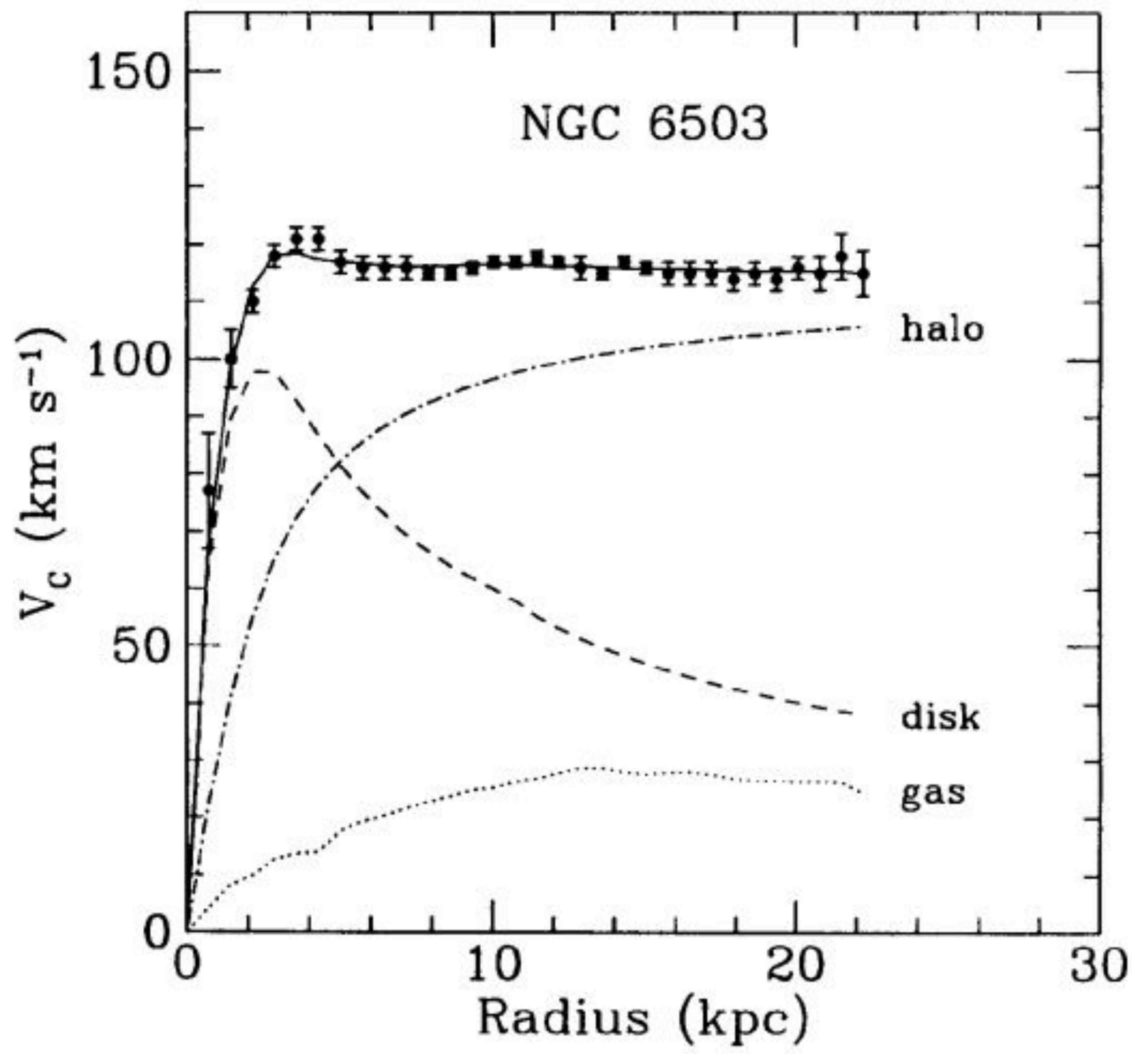
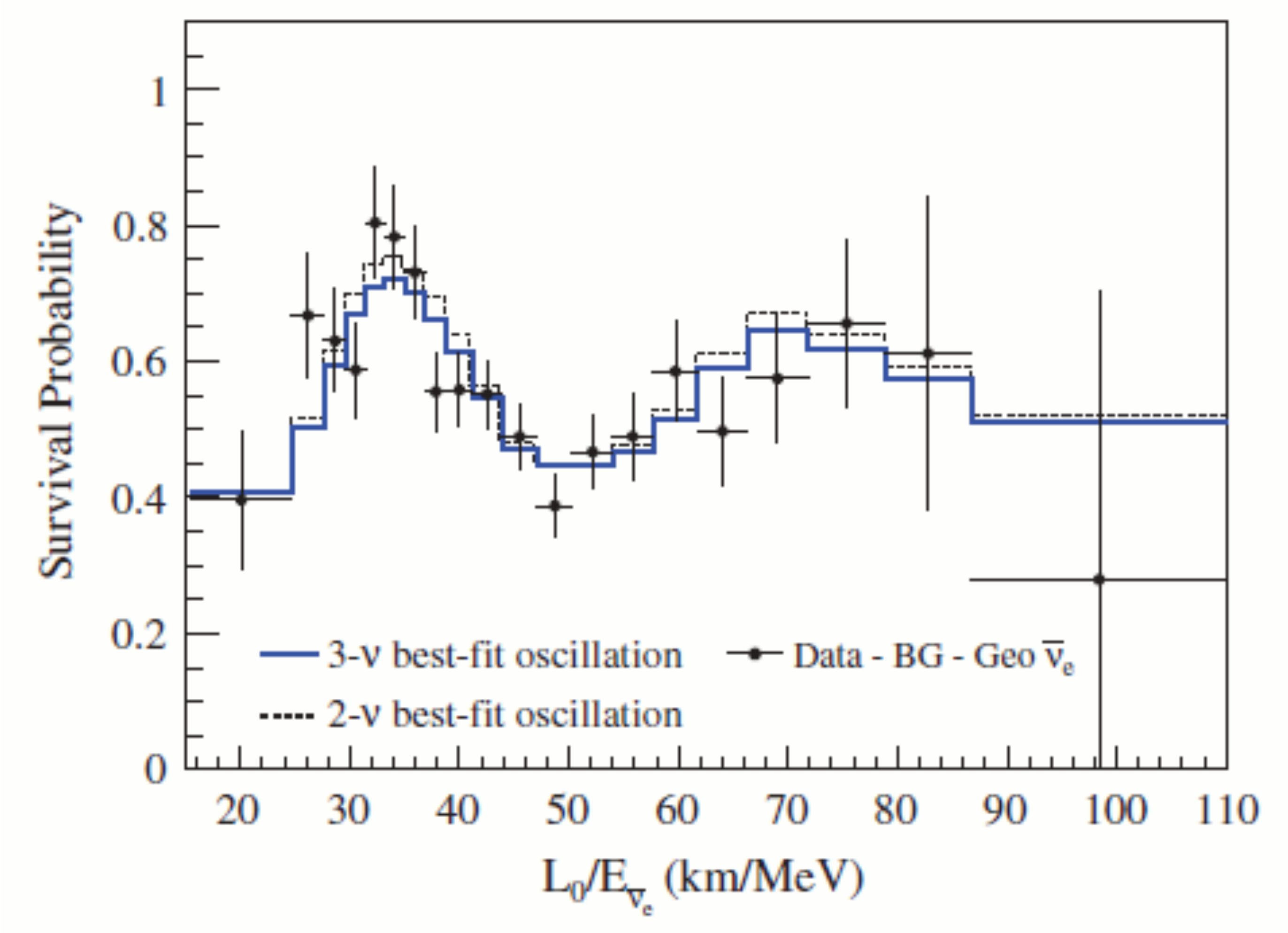
arXiv:2403.13887

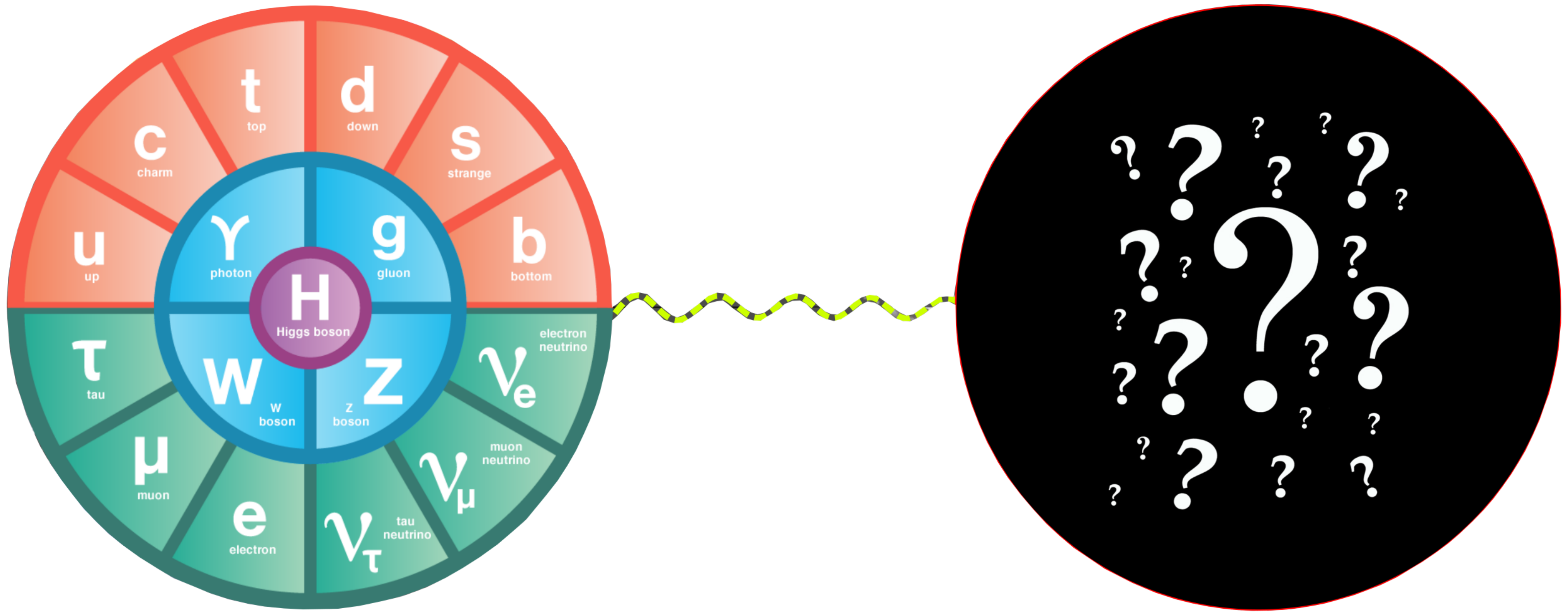


Light New Particles (where and why?)

Hidden Sectors







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Dark Matter

Neutrino Masses

Baryon Asymmetry

?

=

Hidden sector

[Graphic: Youngst@rs MITP Workshop]

Accessing a Hidden Sector

Vector Portal:

$$-\frac{1}{4}V_{\mu\nu}V^{\mu\nu} - \frac{\epsilon}{4}B_{\mu\nu}V^{\mu\nu} - m_V^2 V_\mu^\dagger V^\mu$$

[Rizzo, 18]

[Fabbrichesi, Gabrielli, Lanfranchi, 20]

[Caputo, Millar, O'Hare, Vitagliano, 21]

Higgs Portal:

$$(\partial_\mu\phi)(\partial^\mu\phi) - \mu'(H^\dagger H)\phi - \lambda'(H^\dagger H)\phi^\dagger\phi - V(\phi)$$

[Bird, Jackson, Kowalewski, Pospelov, 04]

[Arcadi, Djouadi, Kado, 21]

[Boiarska, Bondarenko, Boyarsky, Gorkavenko, Ovchynnikov, Sokolenko, 21]

Fermionic/Mixing Portal:

$$\bar{\psi}i\partial\!\!\!/\psi - \bar{L}Y_\nu\psi\tilde{H} - m_\psi\bar{\psi}\psi$$

[Atre, Han, Pascoli, Zhang, 09]

[Bondarenko, Boyarsky, Gorbunov, Ruchayskiy, 18]

[PDB, Deppisch, Dev, 19]

[Coloma, Fernandez-Martinez, Gonzalez-Lopez, Hernandez-Garcia, Pavlovic, 20]

Example: Right-Handed Neutrinos

Common to consider $\psi = N_R$. Because N_R is a SM gauge-singlet, only $U(1)_L$ forbids a mass term:

$$\mathcal{L} \supset \mathcal{L}_{\rm SM} + i\bar{N}_R \partial\!\!\!/ N_R - \left[\bar{L} Y_\nu N_R \tilde{H} + \frac{1}{2}\bar{N}_R^c M_R N_R + \text{h.c.}\right]$$

Then obtain an extended neutrino mass matrix

$$-\frac{1}{2}\begin{pmatrix}\bar{\nu}_L & \bar{N}_R^c\end{pmatrix}\begin{pmatrix}0 & M_D \\ M_D^T & M_R\end{pmatrix}\begin{pmatrix}\nu_L^c \\ N_R\end{pmatrix} + \text{h.c.}\,, \quad M_D = \frac{v}{\sqrt{2}}Y_\nu$$

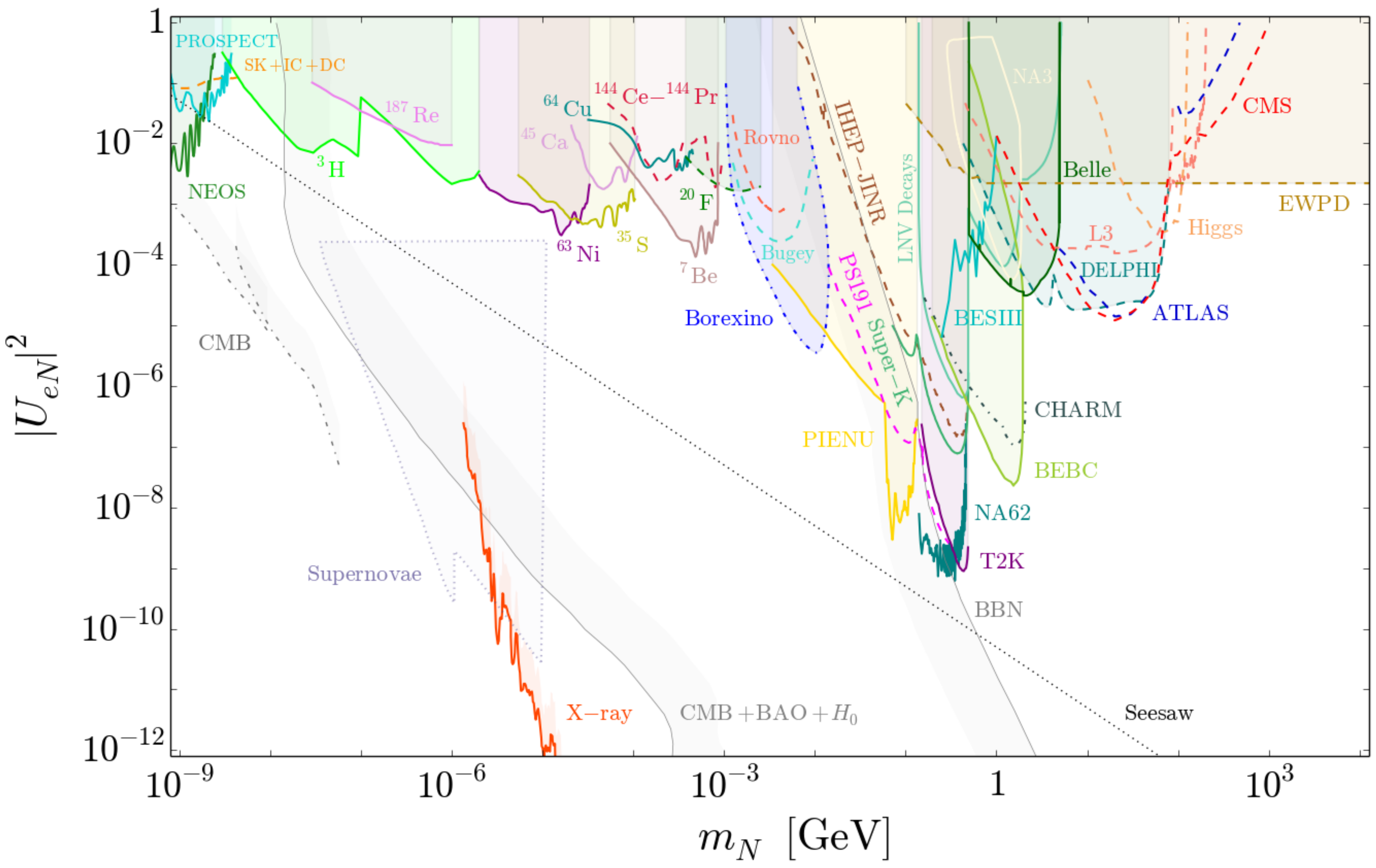
Diagonalise: Naturally generate the light neutrino masses if $M_D \ll M_R$ or $U(1)_L$ is approximately conserved

$$[M_\nu]_{\alpha\beta} = U_{\alpha i}U_{\beta i}m_i \approx -[M_D M_R^{-1} M_D^T]_{\alpha\beta} \qquad U_{\alpha N_i} = iU_{\alpha j}\mathcal{R}_{ji}\sqrt{\frac{m_j}{m_{N_i}}}$$

Example: Active-Sterile Mixing

Active-sterile mixing: heavy (Dirac or Majorana) states via charged and neutral currents

$$\mathcal{L} \supset \left[-\frac{g}{\sqrt{2}} U_{\alpha N_i} \bar{\ell}_\alpha \not{W} P_L N_i + \text{h.c.} \right] - \frac{g}{2c_W} \left[U_{\alpha N_i} \bar{\nu}_\alpha \not{Z} P_L N_i + U^*_{\alpha N_i} U_{\alpha N_j} \bar{N}_i \not{Z} P_L N_j \right]$$



[Atre, Han, Pascoli, Zhang, 09]

[Bondarenko, Boyarsky, Gorbunov, Ruchayskiy, 18]

[PDB, Deppisch, Dev, 19]

[Coloma et al., 20]

Beyond the Renormalisable: SMEFT + X

The scale of NP, Λ, is much above the scale of interest

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}+X} + \sum_i C_i^{(d)} \mathcal{O}_i^{(d)}$$

$$C_i^{(d)} \propto \Lambda^{4-d}$$

Λ

$E \ll \Lambda$

$SU(3)_c \times SU(2)_L \times U(1)_Y$ plus X (**SMEFT** + *X*)

X can only couple to invariant combinations of SM fields

$v = 246$ GeV

$E \ll m_W, m_Z, m_h, m_t$

$SU(3)_c \times U(1)_Q$ plus X (**LEFT/WET** + *X*)

Belle II and $B \to K\nu\bar{\nu}$

Flavour: A Window to the Hidden Sector?

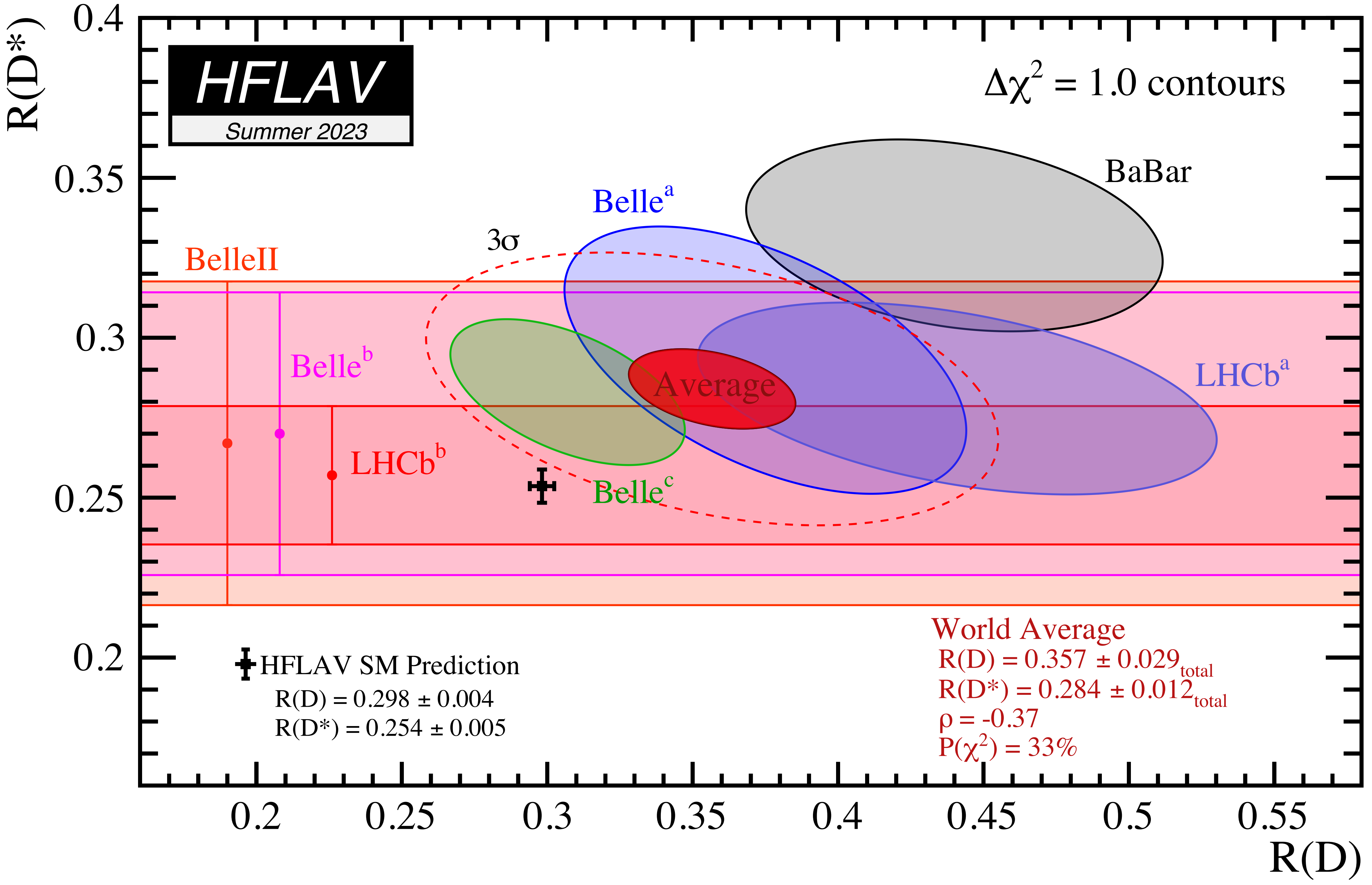
The so-called B anomalies have (mostly) persisted since the early 2010s and NP explanations have been explored

- The charged-current $b \to c\tau\nu$ ratios

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \to D^{(*)}\ell\bar{\nu})}$$

⇒3.2σ tension between BaBar, Belle, LHCb and SM prediction

⇒Points towards violation of lepton flavour universality (LFU)



- The neutral-current $b \to s\ell^+\ell^-$ ratios

$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}$$

⇒$R_{K^{(*)}}$ now in agreement with SM

⇒Anomalies persist in $B \to K\mu^+\mu^-$, P_5', $B \to \phi\mu^+\mu^-$

[Gubernari, Reboud, van Dyk, Virto, 22]

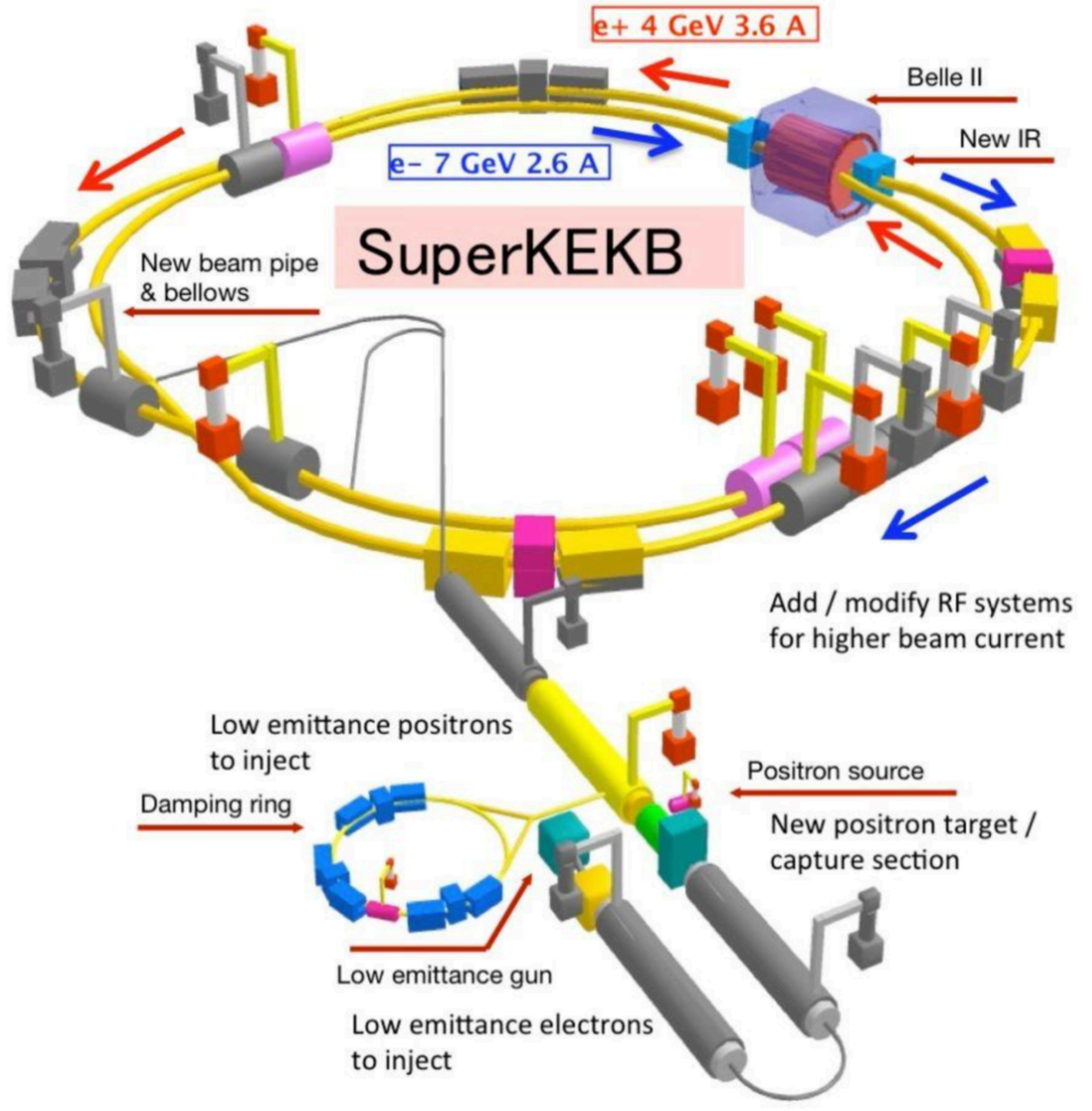
[Capdevila, Crivellin, Matias, 23]

Belle II Experiment

Belle II at SuperKEKB:

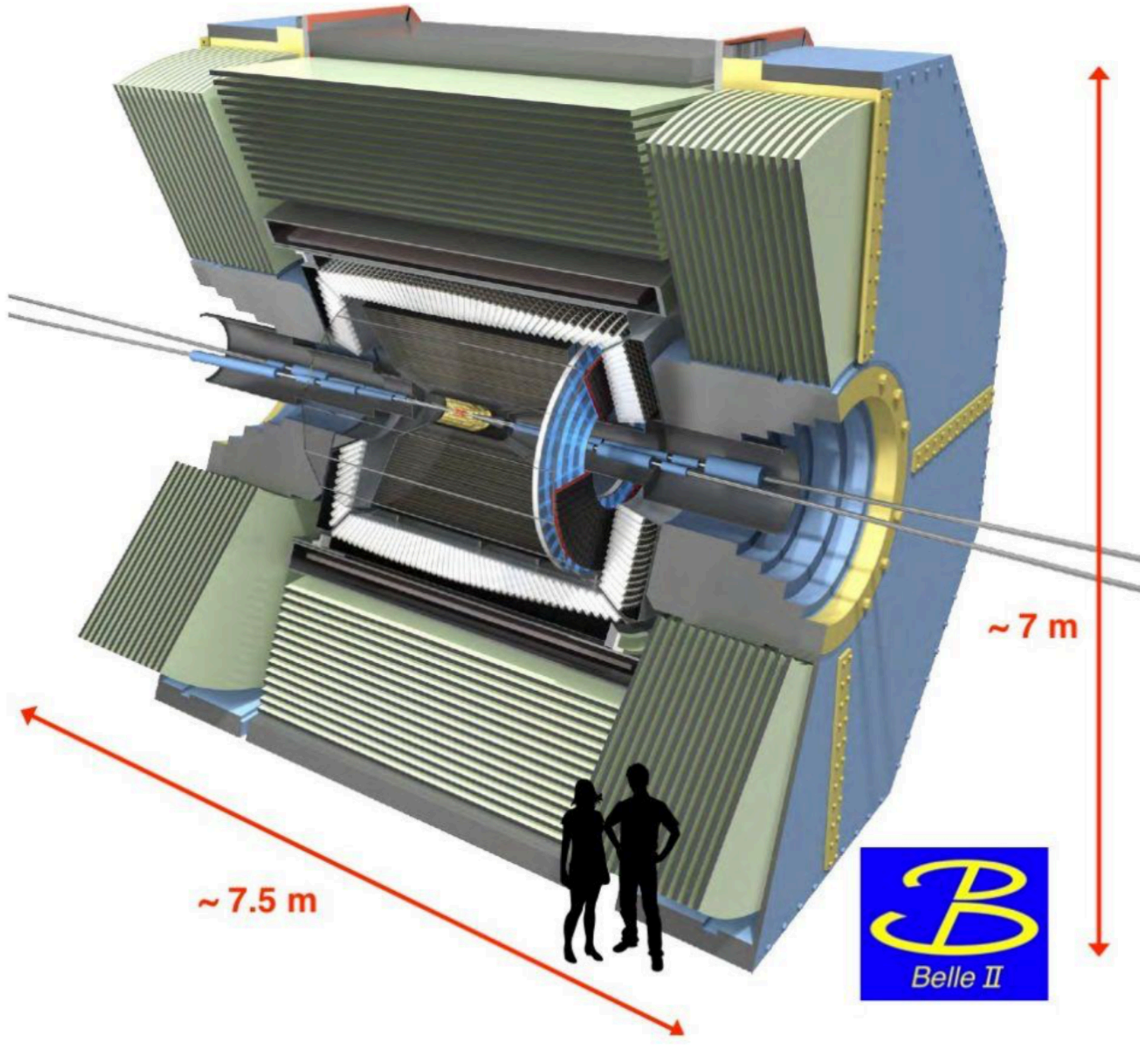
- e^+e^- collider operating at $\Upsilon(4S)$ resonance ($e^+e^- \to B^+B^-$)
- Integrated luminosity $\mathscr{L} = 362\ \mathrm{fb}^{-1}$
- Detector: Nearly 4π coverage, well suited for inclusive measurements

arxiv:2311.14647: Latest dedicated search for the rare decay $B \to K\nu\bar{\nu}$



Two methods in the search for $B \to K\nu\bar{\nu}$:

- Hadronic Tag Analysis (HTA): Explicit reconstruction via partner decay
- Inclusive Tag Analysis (ITA): *New* inclusive reconstruction method



Background for ITA

- $B^+B^-, B^0\bar{B}^0$ and continuum

BaBar Experiment

BaBar at SLAC:

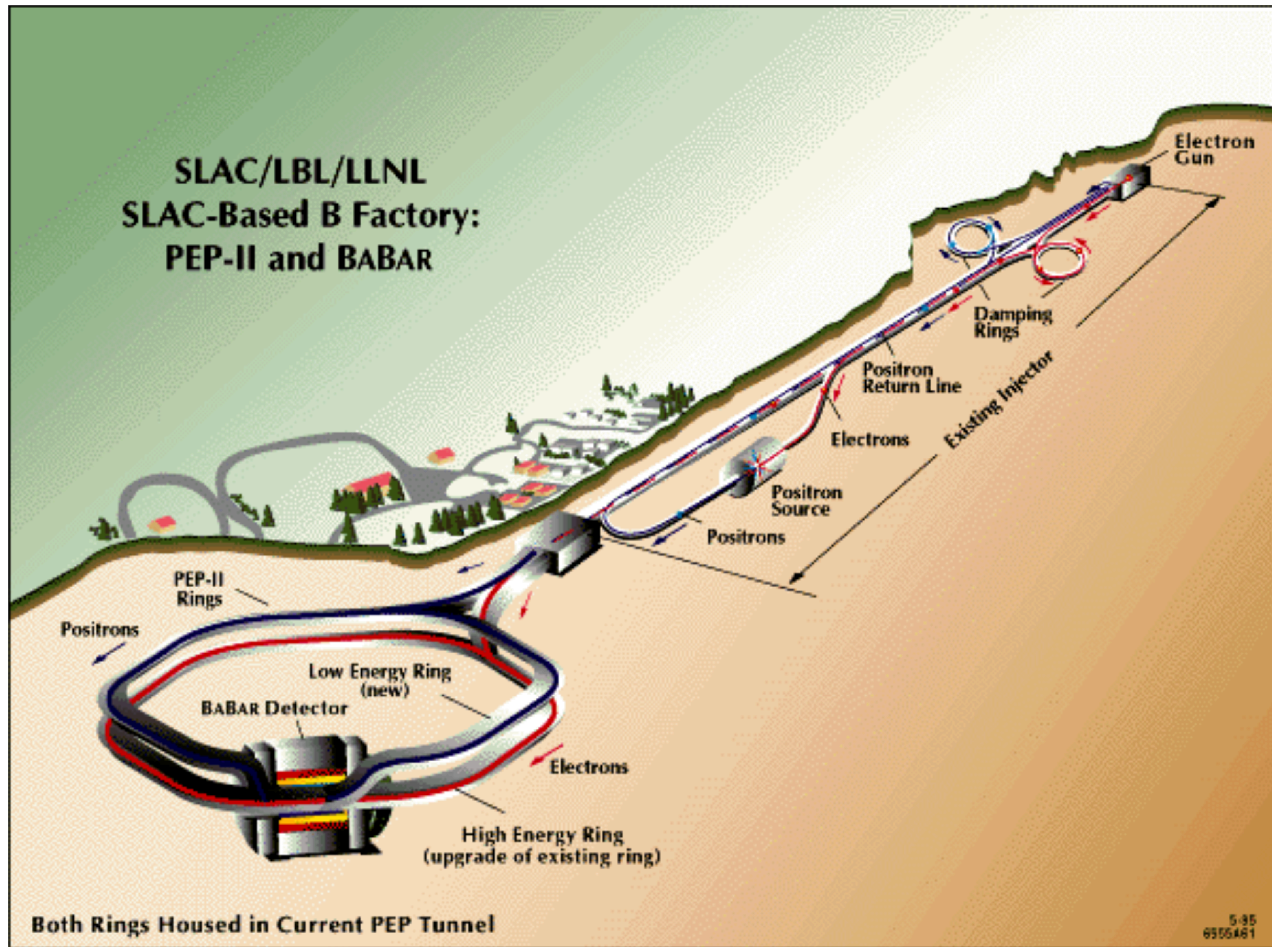
- e^+e^- collider operating at $\Upsilon(4S)$ resonance ($e^+e^- \to B^+B^-$)
- Integrated luminosity $\mathscr{L} = 429\ \mathrm{fb}^{-1}$

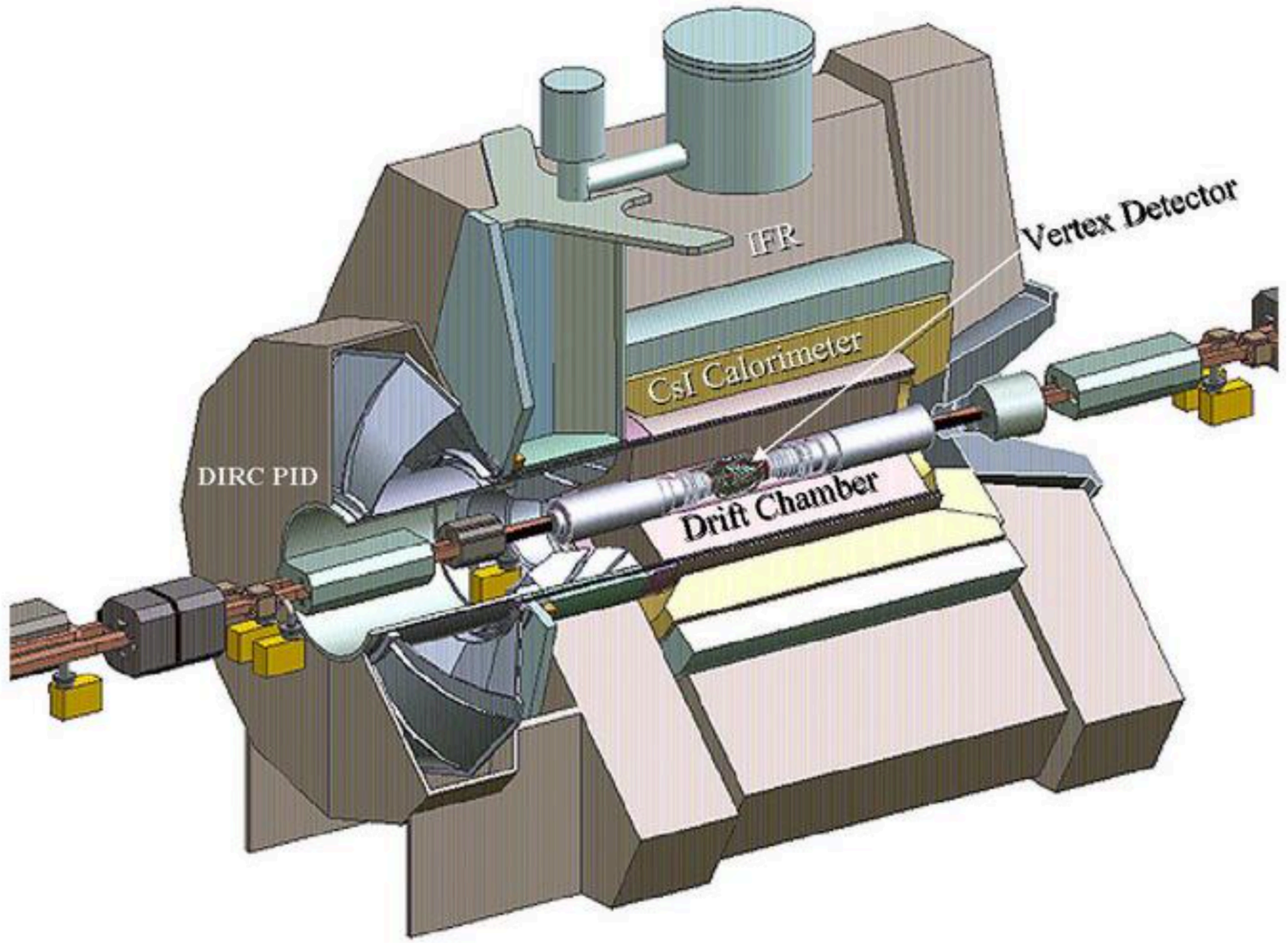
arXiv:1303.7465: Dedicated search for $B \to K^{(*)}\nu\bar{\nu}$

BaBar only used the hadronic tag method

Backgrounds classified as

- 'Peak' and 'combinatorial'





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

SM contribution described by:

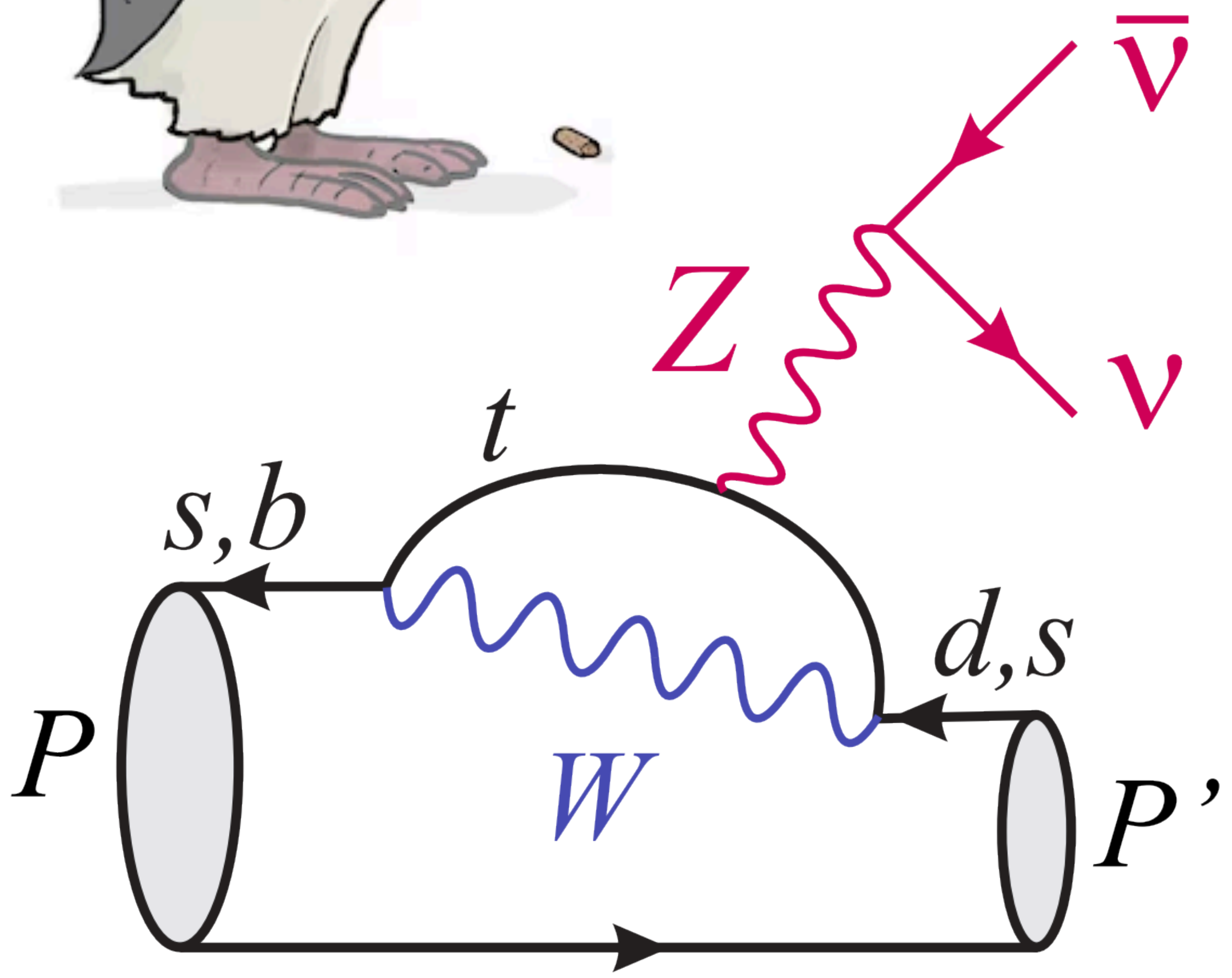
$$\mathcal{H}_{\rm eff}^{\rm SM} = -\frac{4G_F}{\sqrt{2}}\lambda_t C_L^{\rm SM}\mathcal{O}_L + {\rm h.c.}\,, \qquad \mathcal{O}_L = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_L b)(\bar{\nu}_\alpha\gamma^\mu(1-\gamma_5)\nu_\alpha)$$

$\lambda_t = V_{tb}V_{ts}^*$ and $C_L^{\rm SM} = -X_t/s_w^2$. ($X_t = 1.469 \pm 0.017$)

$$\frac{d\mathcal{B}(B^+\to K^+\nu\bar{\nu})}{dq^2} = \tau_{B^\pm}\frac{G_F^2\alpha^2\,|\lambda_t|^2\,X_t^2}{32\pi^5 s_w^4}\,|\vec{p}_{K^{(*)}}|\,q^2 f_{K^{(*)}}^2(q^2)$$

$$\mathcal{B}\left(B^+\to K^+\nu_\tau\bar{\nu}_\tau\right)\big|_{\rm LD} = (6.09\pm 0.53)\times 10^{-7}$$

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



[Kamenik, Smith, 12]
[Buras, Girrbach-Noe, Niehoff, Straub, 14]
[Parrott, Bouchard, Davies, 23]
[Bečirević, Piazza, Sumensari, 23]

Belle II and BaBar $B \to K\nu\bar{\nu}$ Measurements

Belle II measured $B^+ \to K^+ E_{\text{miss}}$ in both ITA and HTA analyses:

$$\mathcal{B}(B \to K E_{\text{miss}})\big|_{\text{ITA}} = (2.7 \pm 0.7) \times 10^{-5} \quad (2.9\sigma \text{ w.r.t. SM})$$

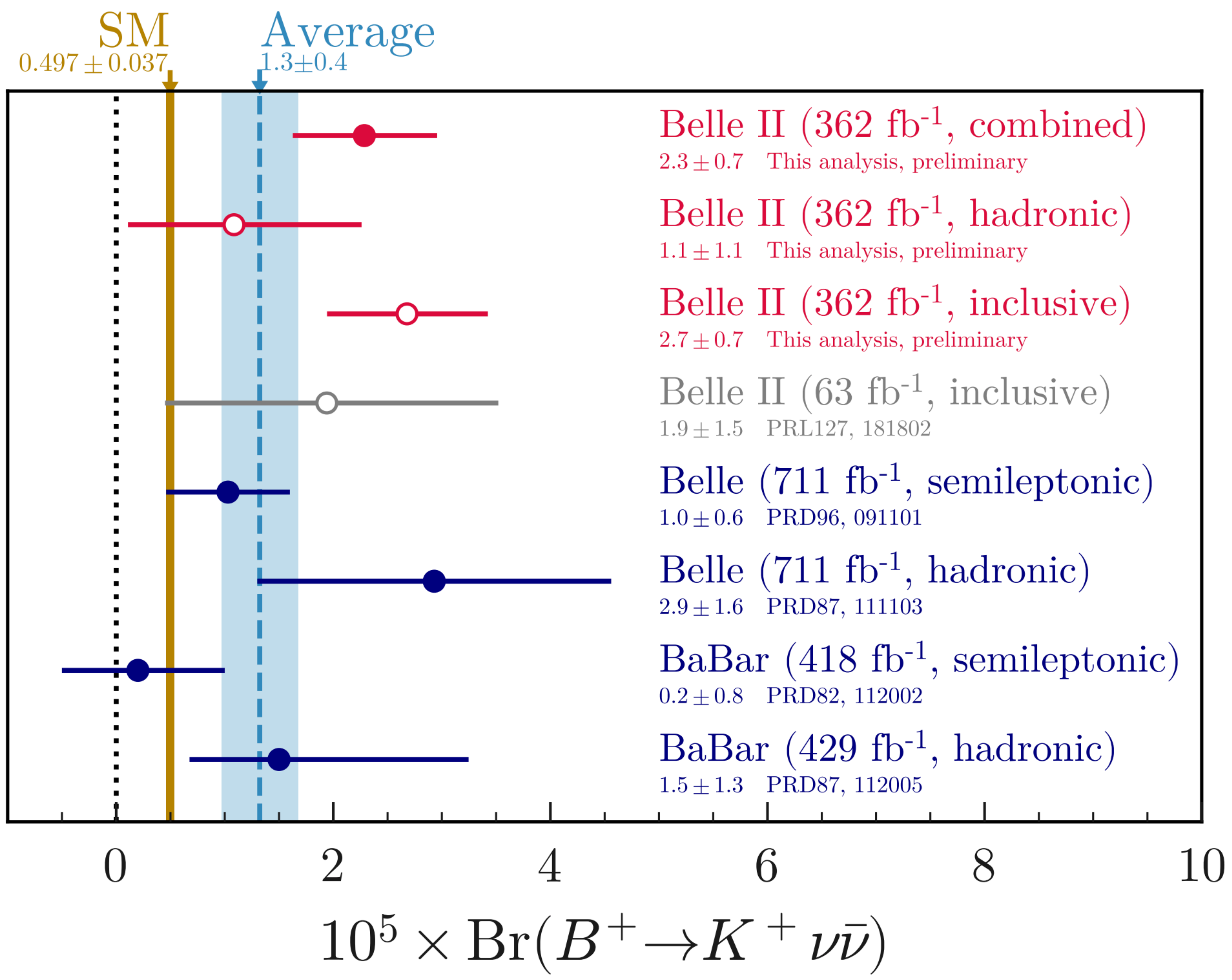
$$\mathcal{B}(B \to K E_{\text{miss}})\big|_{\text{HTA}} = (1.1 \pm 1.1) \times 10^{-5}$$

$$\mathcal{B}(B \to K E_{\text{miss}})\big|_{\text{comb}} = (2.3 \pm 0.7) \times 10^{-5}$$

BaBar placed the upper bounds

$$\mathcal{B}(B^+ \to K^+ E_{\text{miss}}) < 3.7 \times 10^{-5} \ (90\% \text{ CL})$$

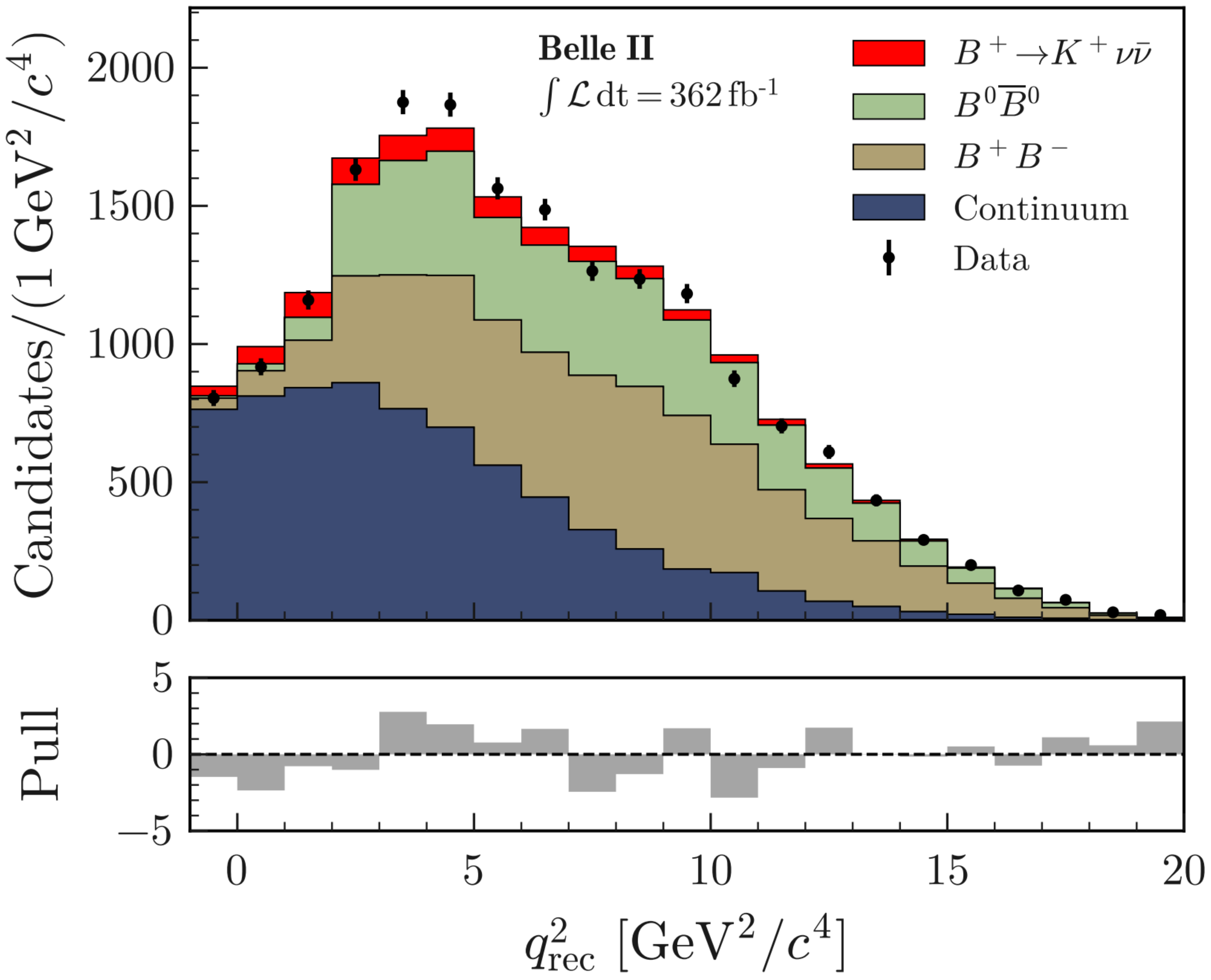
$$\mathcal{B}(B^0 \to K^{*0} E_{\text{miss}}) < 9.3 \times 10^{-5} \ (90\% \text{ CL})$$



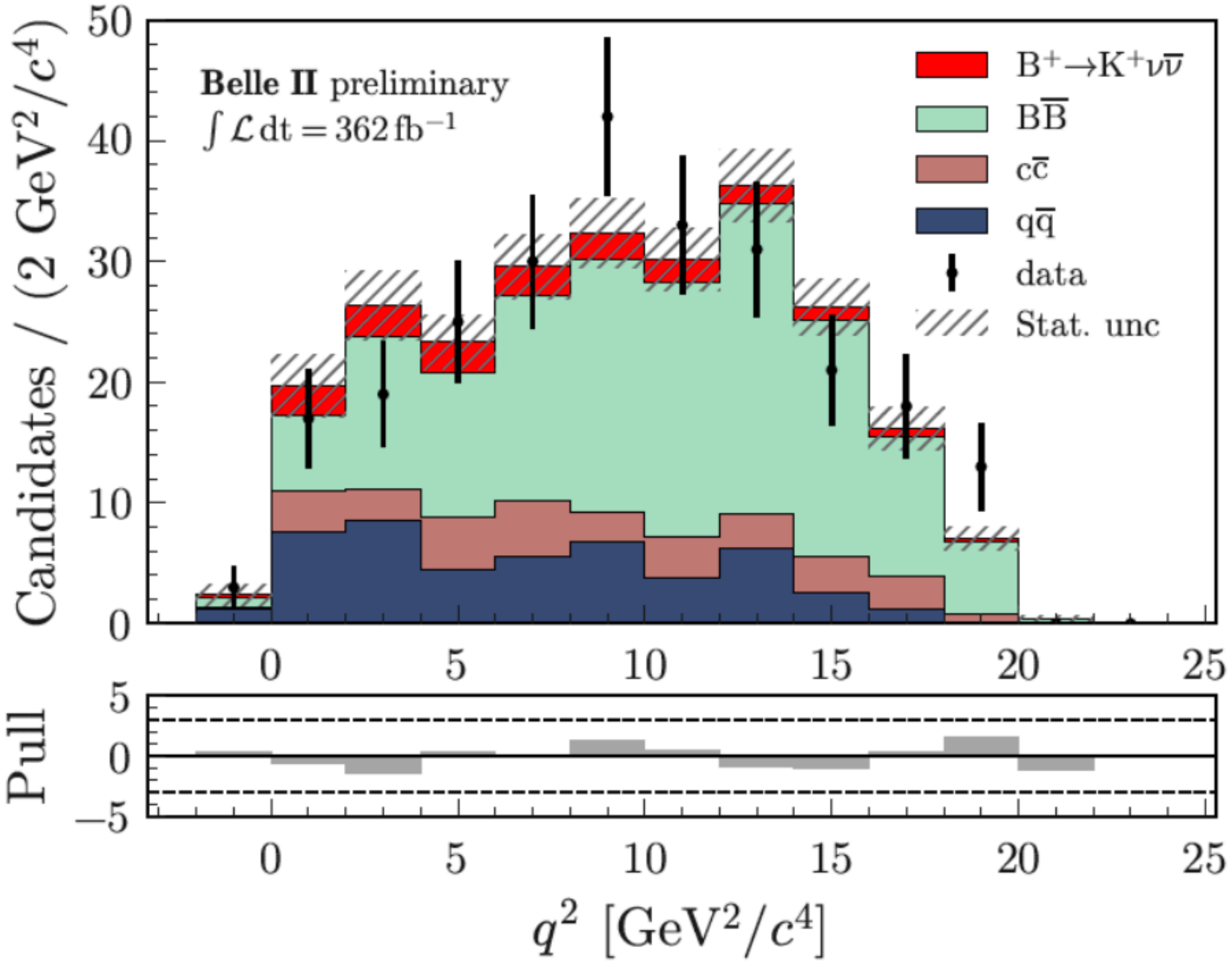
[Belle II Collaboration, 23]

Belle II and BaBar $B \to K\nu\bar{\nu}$ Measurements

Inclusive Tagging Analysis (**ITA**)



Hadronic Tagging Analysis (**HTA**)



[Belle II Collaboration, 23]

Aside: $K^+ \to \pi^+\nu\nu$ at NA62

Results in context

BNL E787/E949 experiment
[Phys.Rev.D 79 (2009) 092004]

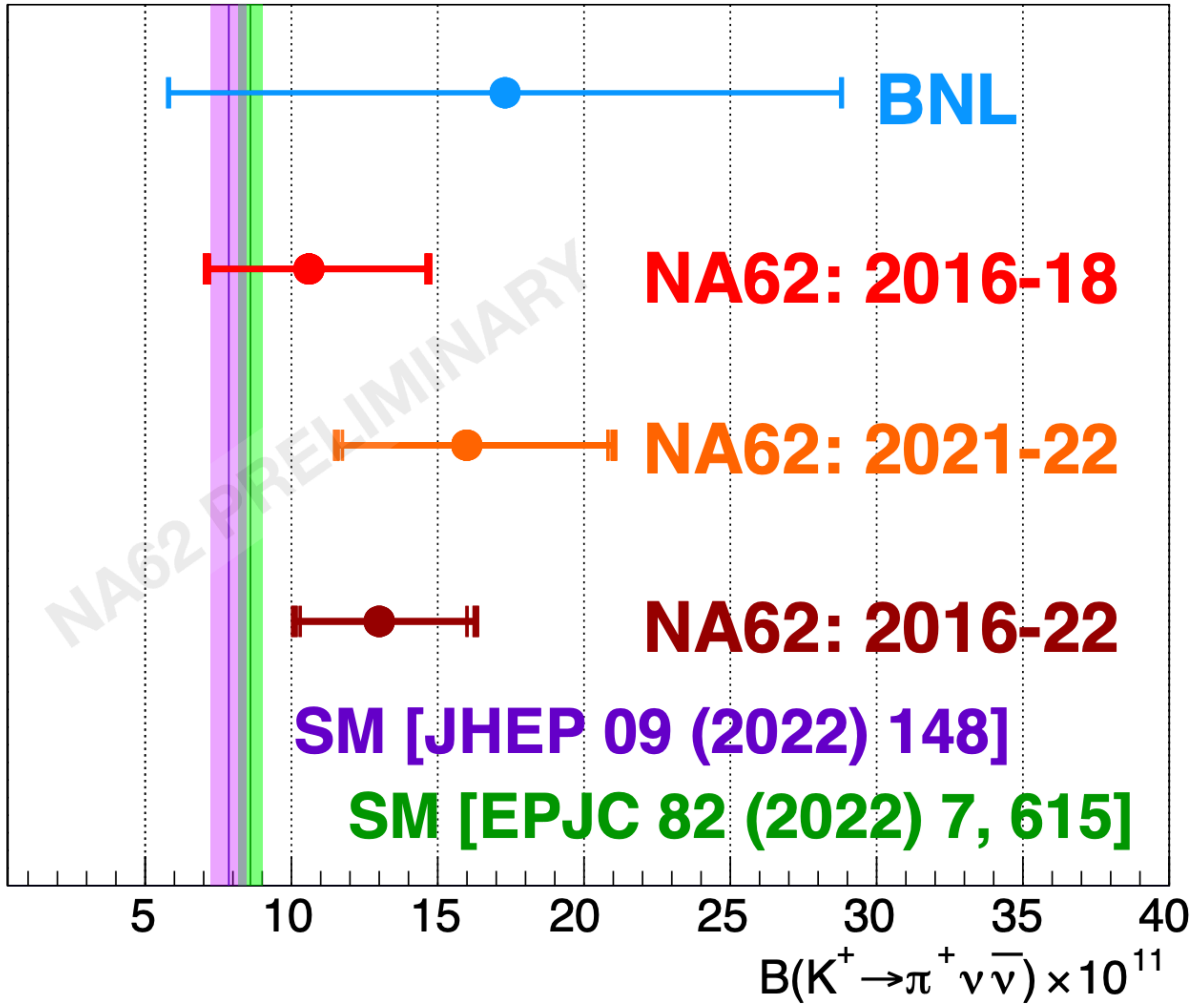
$$\mathcal{B}_{\pi\nu\bar{\nu}}^{16-18} = \left(10.6^{+4.1}_{-3.5}\right) \times 10^{-11}$$

[JHEP 06 (2021) 093]

$$\mathcal{B}_{\pi\nu\bar{\nu}}^{21-22} = \left(16.0^{+5.0}_{-4.5}\right) \times 10^{-11}$$

$$\mathcal{B}_{\pi\nu\bar{\nu}}^{16-22} = \left(13.0^{+3.3}_{-2.9}\right) \times 10^{-11}$$

- NA62 results are consistent
- Central value moved up (now 1.5—1.7σ above SM)
- Fractional uncertainty decreased: 40% to 25%
- Bkg-only hypothesis rejected with significance Z>5



Joel Swallow
CERN Seminar

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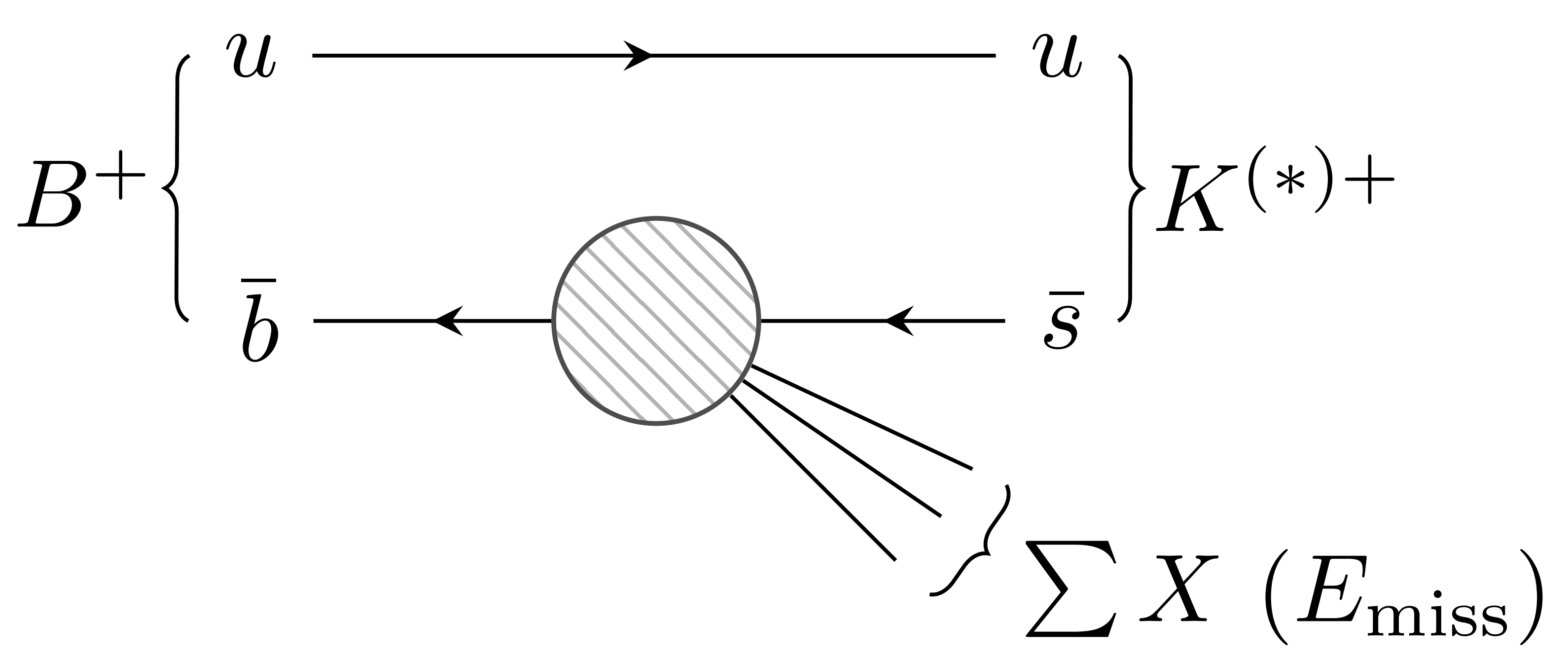
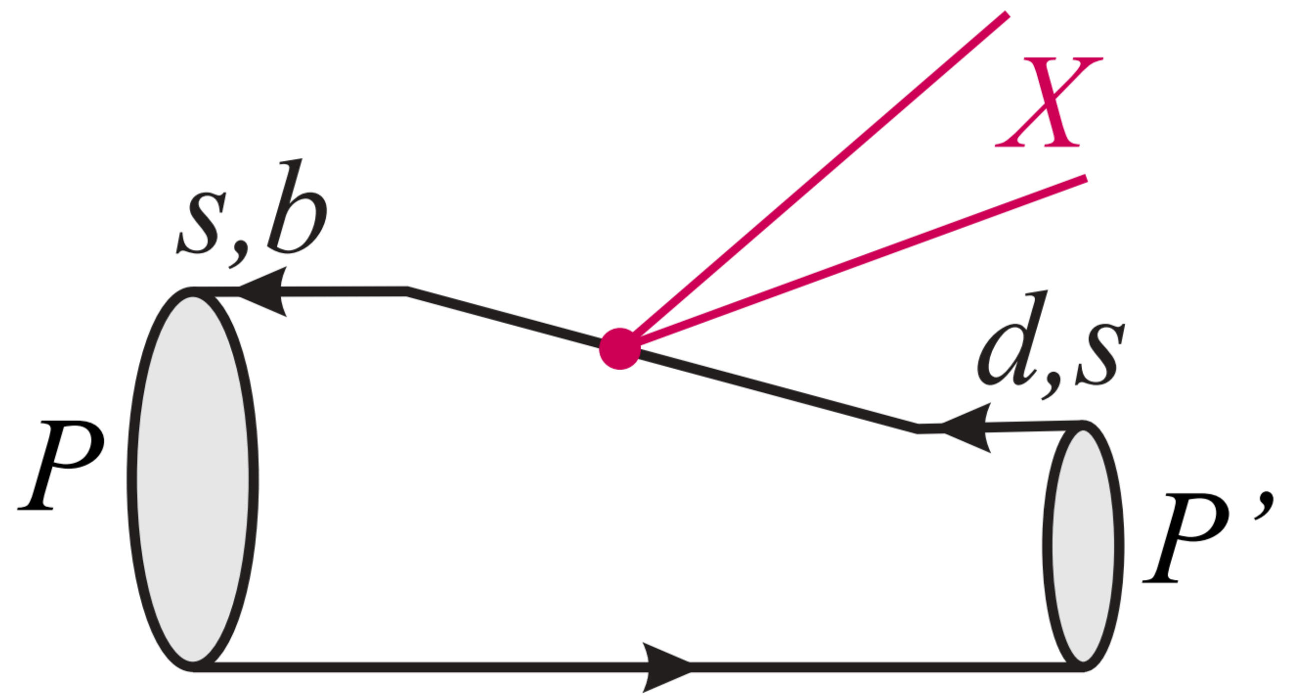
Generic NP Contribution



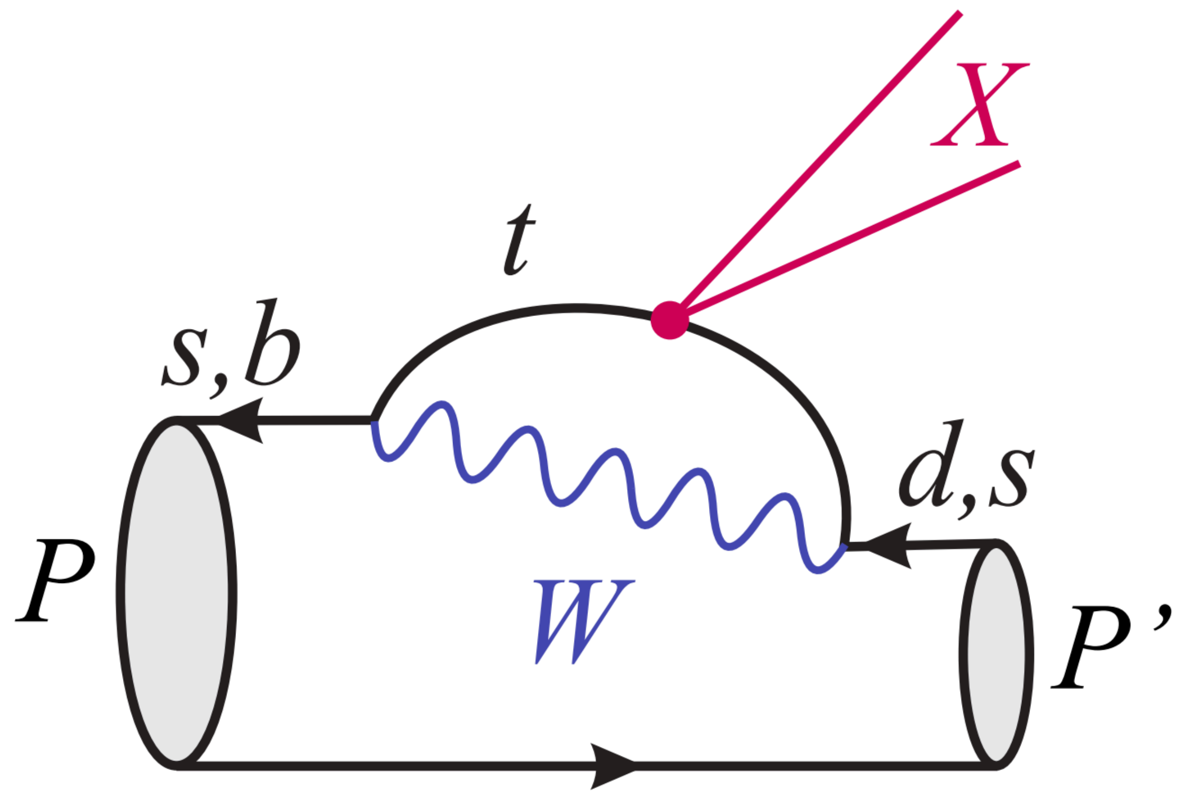
To **explain the Belle II excess**, other invisible states may be coupled to the flavour-changing quark current

Two options:

A) Flavour-changing heavy physics at Λ coupling *s* and *b* to X



B) Heavy physics at Λ couples *t* to *X*, FCNC comes from *W* exchange

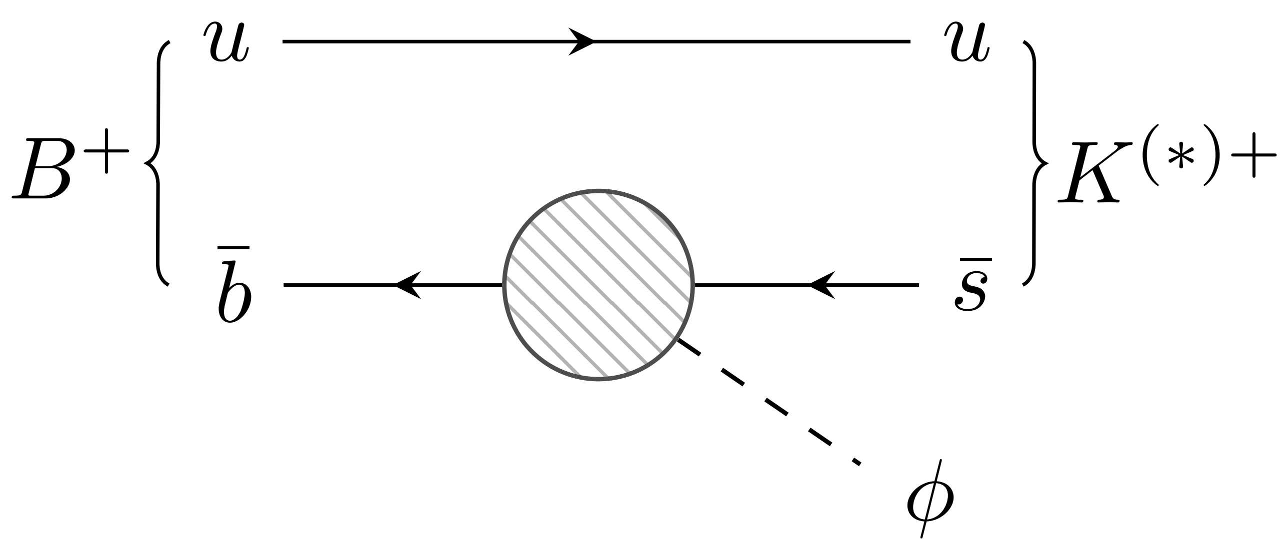


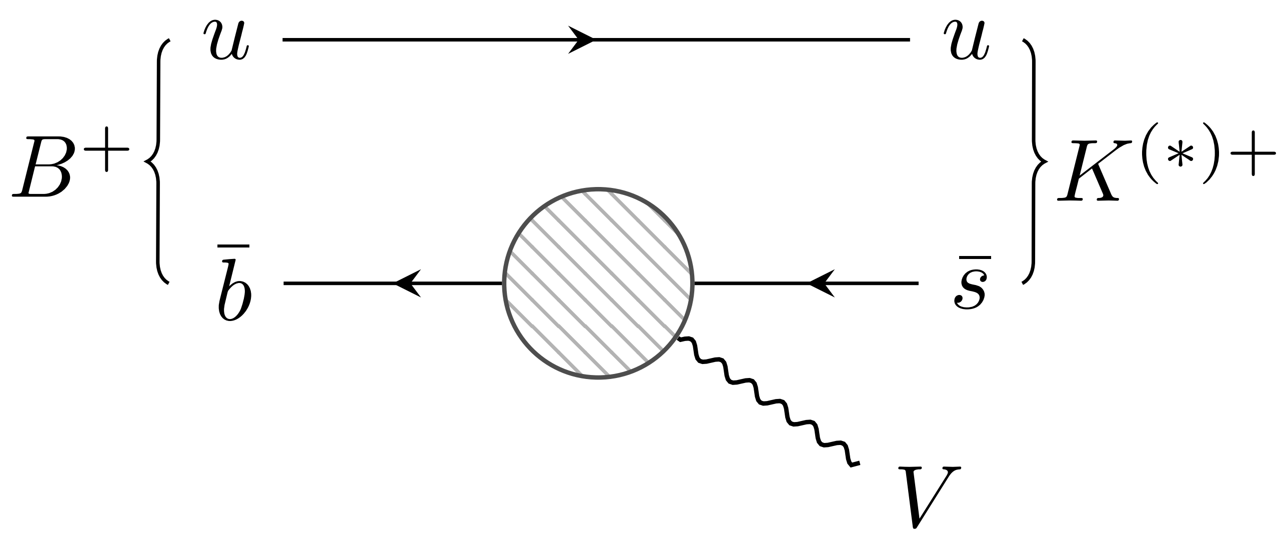
[Kamenik, Smith, 12]

Light New Physics: Field Content

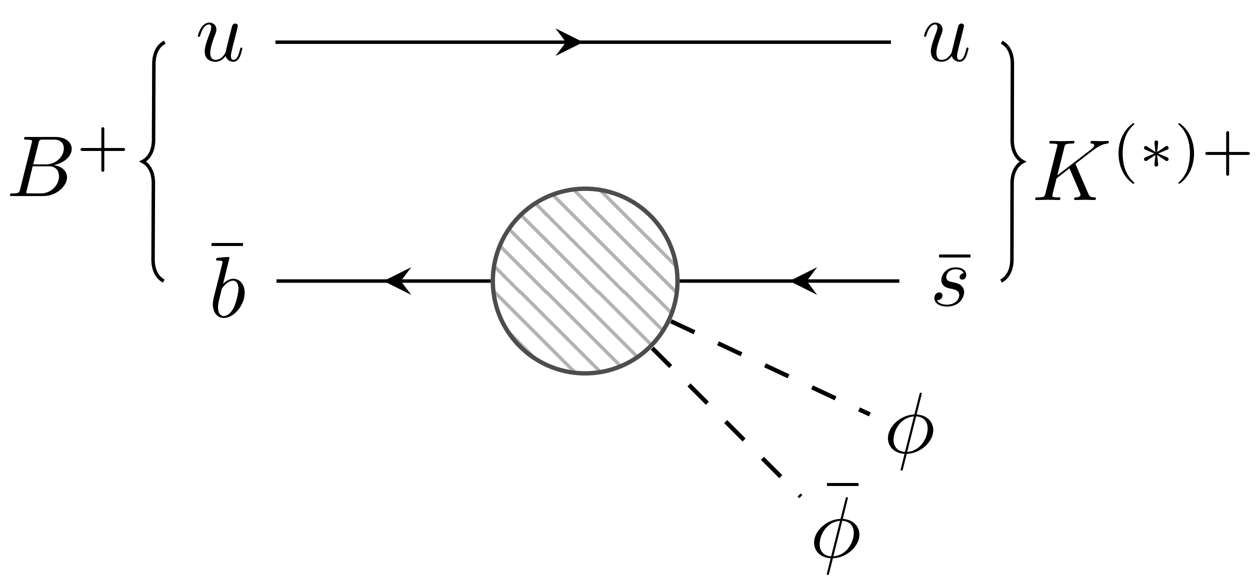
$$\sum X \in \{\phi, V, \phi\bar{\phi}, \psi\bar{\psi}, V\bar{V}, \Psi\bar{\Psi}\}$$

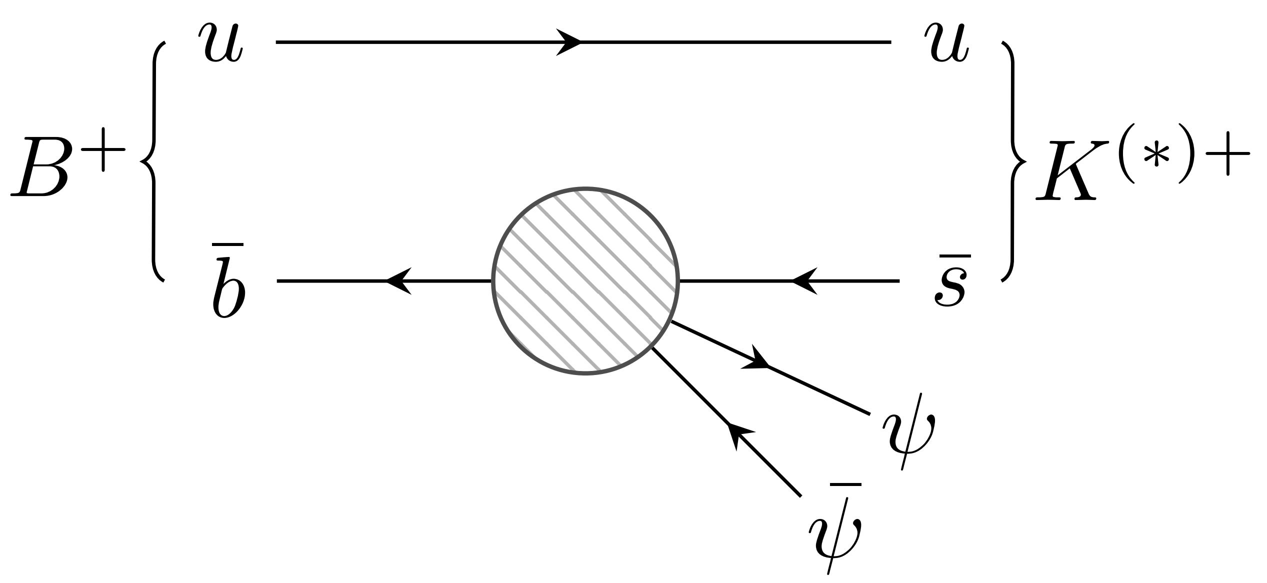
Two-body:

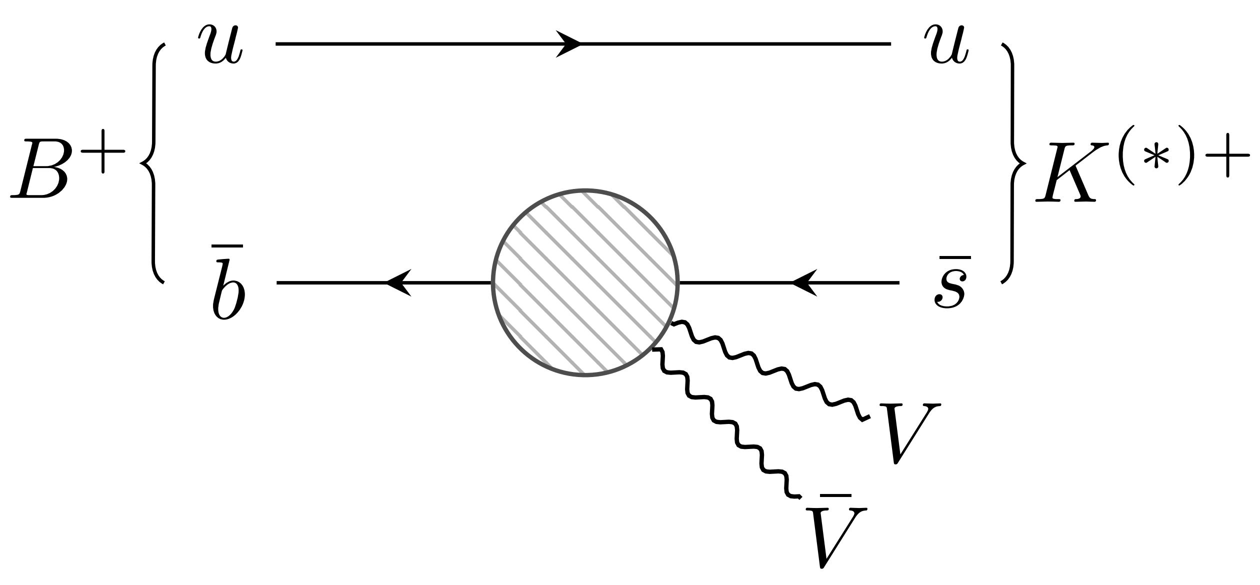


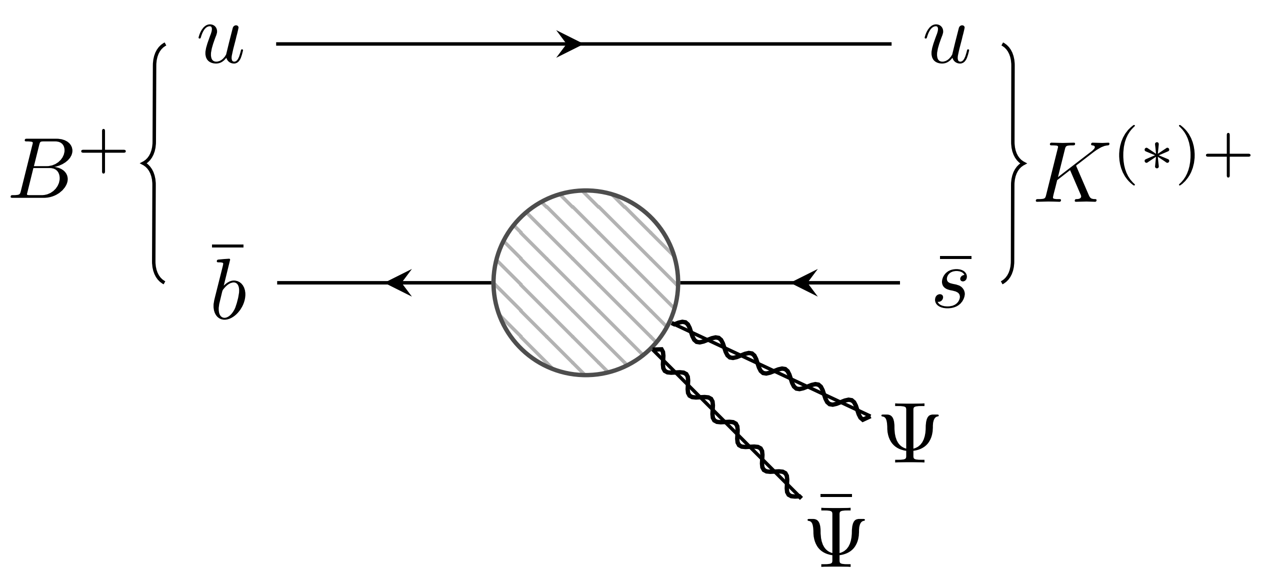


Three-body:

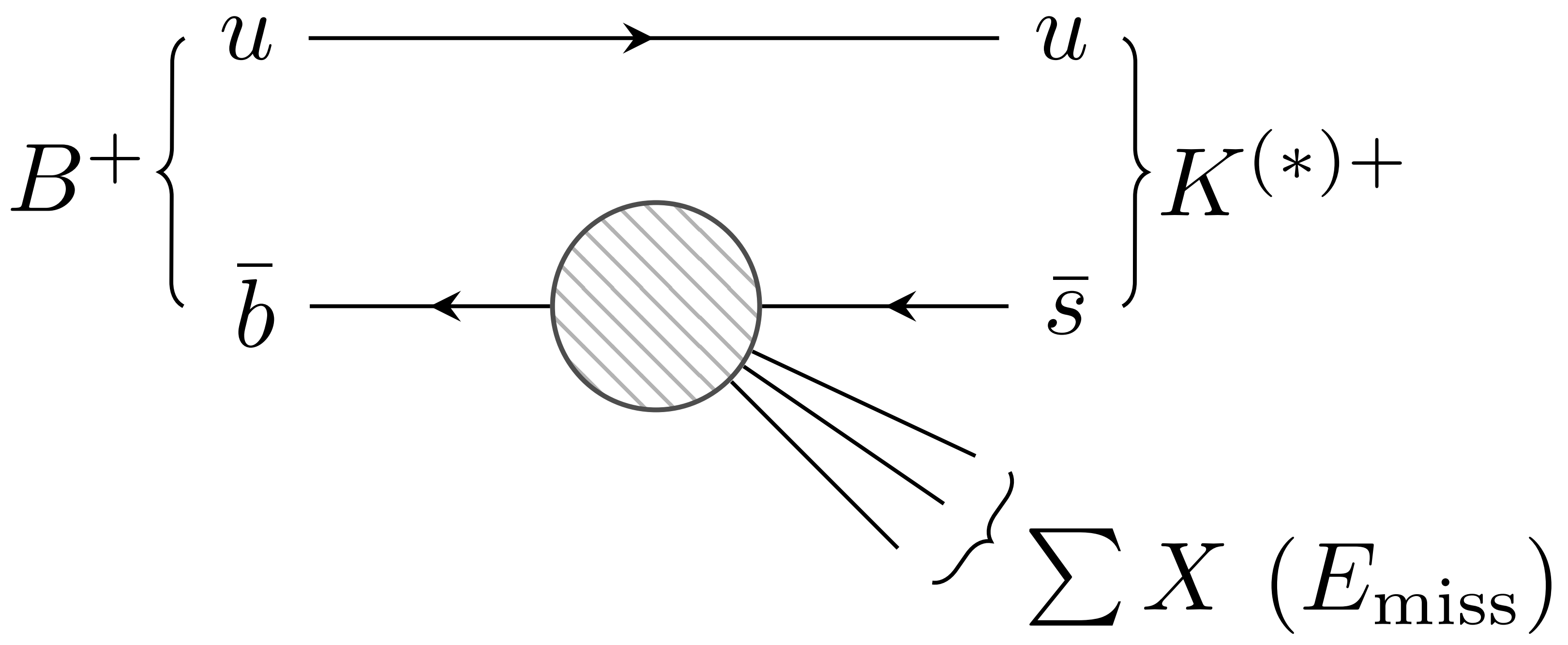








Couplings to Vector Quark Current



NP couplings to vector quark current:

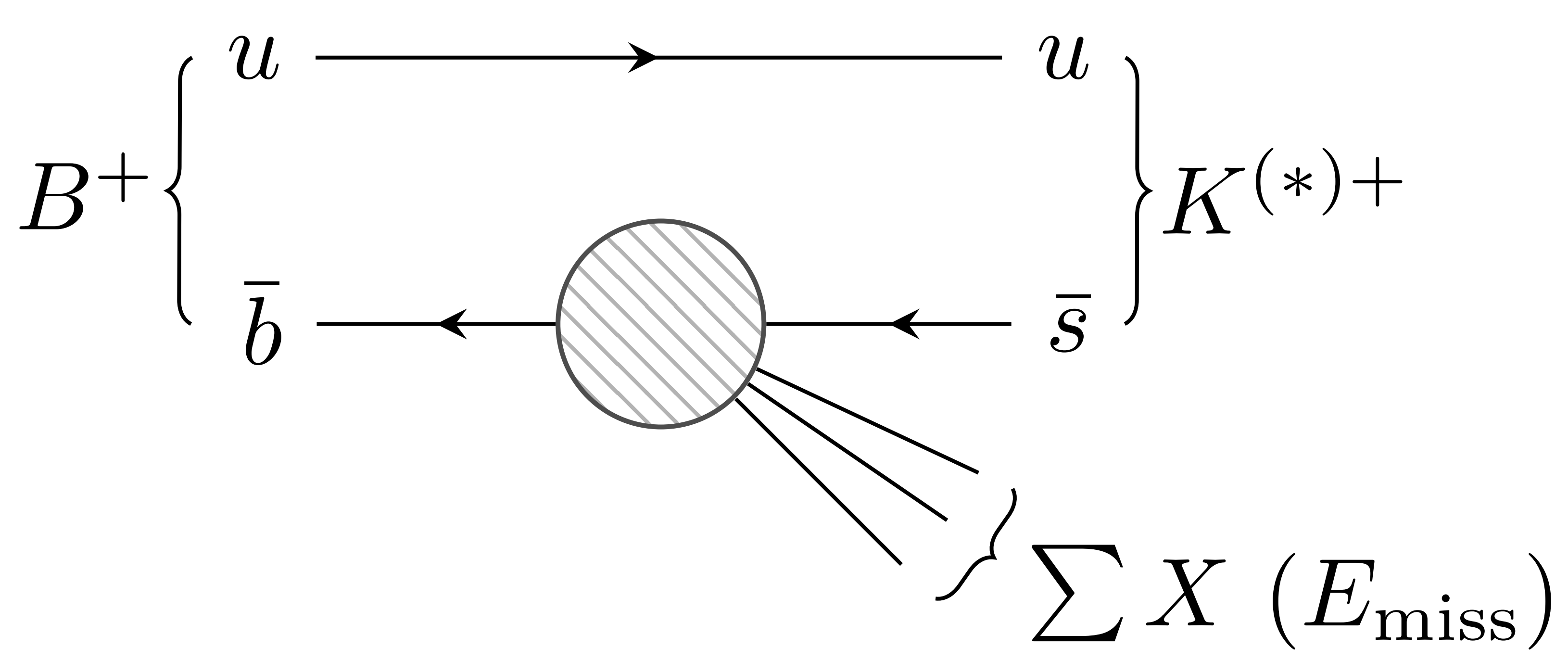
$$\mathcal{H}_{\text{eff}}^V \supset \bar{s}\gamma_\mu b \left[h_V V^\mu + \frac{g_{VV}}{\Lambda^2} i\phi^\dagger \overleftrightarrow{\partial}^\mu \phi + \frac{f_{VV}}{\Lambda^2} \bar{\psi}\gamma^\mu \psi + \frac{f_{VA}}{\Lambda^2} \bar{\psi}\gamma^\mu \gamma_5 \psi + \frac{F_{VV}}{\Lambda^2} \bar{\Psi}^\rho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

For axial-vector quark current: $\mathcal{H}_{\text{eff}}^A \quad (\bar{s}\gamma_\mu b) \to (\bar{s}\gamma_\mu \gamma_5 b) \qquad h_V \to h_A \,, \quad g_{VV} \to g_{AV} \,, \ldots$

$h_V \to 0$ if V_μ charged under dark gauge group

$g_{VV} \to 0$ for $\phi = \phi^\dagger$, $f_{XV} \to 0$ for $\psi = \psi^c$, $F_{XV} \to 0$ for $\Psi_\mu = \Psi_\mu^c$

Couplings to Scalar Quark Current



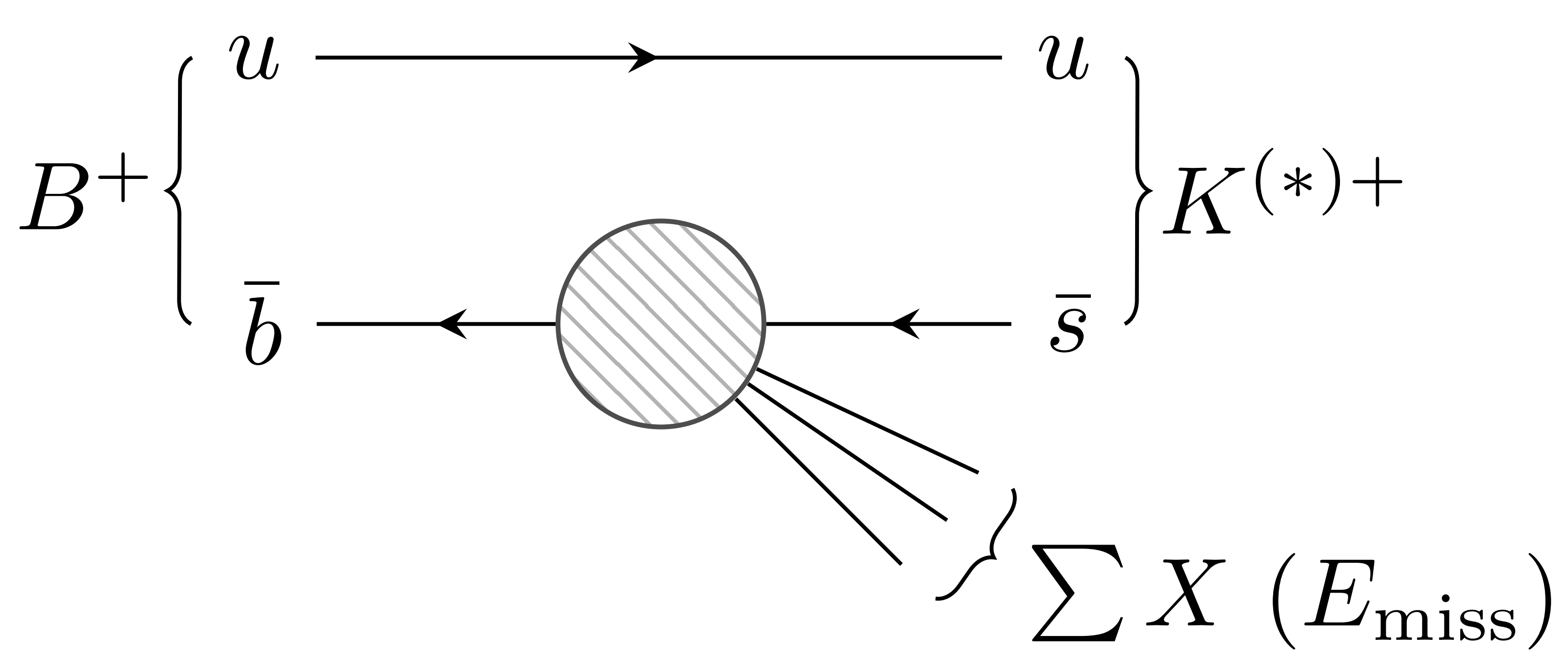
NP couplings to scalar quark current:

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

For pseudoscalar quark current: $\mathcal{H}_{\text{eff}}^{P}$ $(\bar{s}b) \to (\bar{s}\gamma_5 b)$ $g_S \to g_P\,, \quad f_{SS} \to f_{PS}\,, \ldots$

$g_S \to 0$ if ϕ charged under dark gauge group

Couplings to Tensor Quark Current



NP couplings to tensor quark current:

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

For axial-vector quark current: $\mathcal{H}_{\text{eff}}^{\tilde{T}}$ $\quad (\bar{s}\sigma_{\mu\nu}b) \to (\bar{s}\sigma_{\mu\nu}\gamma_5 b) \quad h_T \to h_{\tilde{T}}\,, \quad f_{TT} \to f_{\tilde{T}T}\,, \ldots$

$f_{XT} \to 0$ for $\psi = \psi^c$, $F_{XT} \to 0$ for $\Psi_\mu = \Psi_\mu^c$

NP Rates

The NP decay rates are computed as follows:

$$\Gamma(B \to K^{(*)}X) = \frac{|p_{K^{(*)}}|}{8\pi m_B^2} \left| \langle K^{(*)}X| \mathcal{H}_{\rm eff} |B\rangle \right|^2 \qquad \frac{\Gamma(B \to K^{(*)}X\bar{X})}{dq^2 ds'} = \frac{1}{256\pi^3 m_B^3} \left| \langle K^{(*)}X\bar{X}| \mathcal{H}_{\rm eff} |B\rangle \right|^2$$

With the factorisation

$$\langle K^{(*)}X(\bar{X})| \mathcal{H}_{\rm eff} |B\rangle = \langle K^{(*)}| \bar{s}\Gamma b |B\rangle \langle X(\bar{X})| \mathcal{H}'_{\rm eff} |0\rangle$$

↙

Hadronic form factors calculated on the **lattice** (high q^2) and with **light cone sum rules** (low q^2)

For the relevant form factors, we use the **BSZ parametrisation** of Gubernari, Reboud, van Dyk and Virto

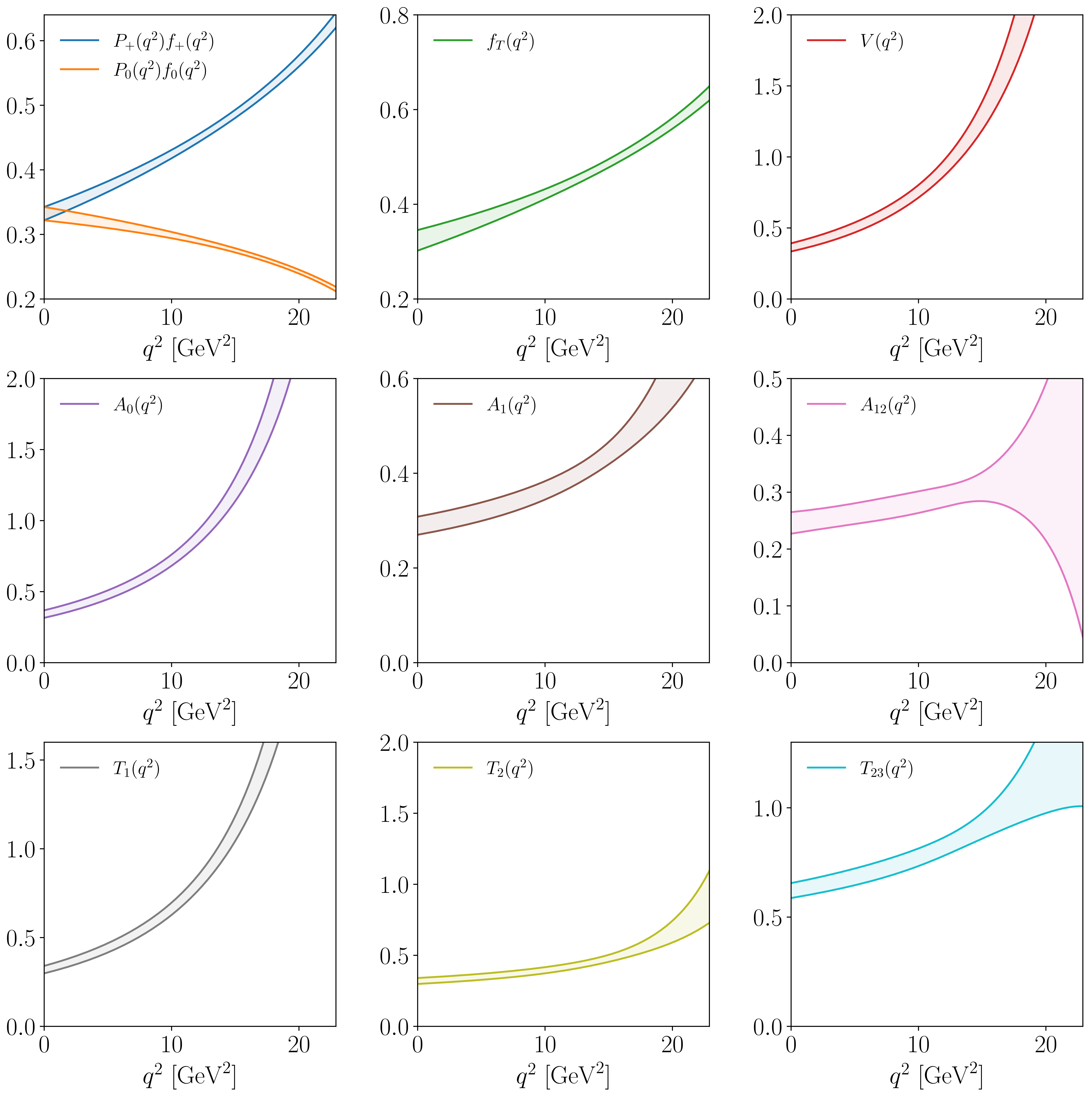
[Bharucha, Straub, Zwicky, 15]

[Gubernari, Reboud, van Dyk and Virto, 23]

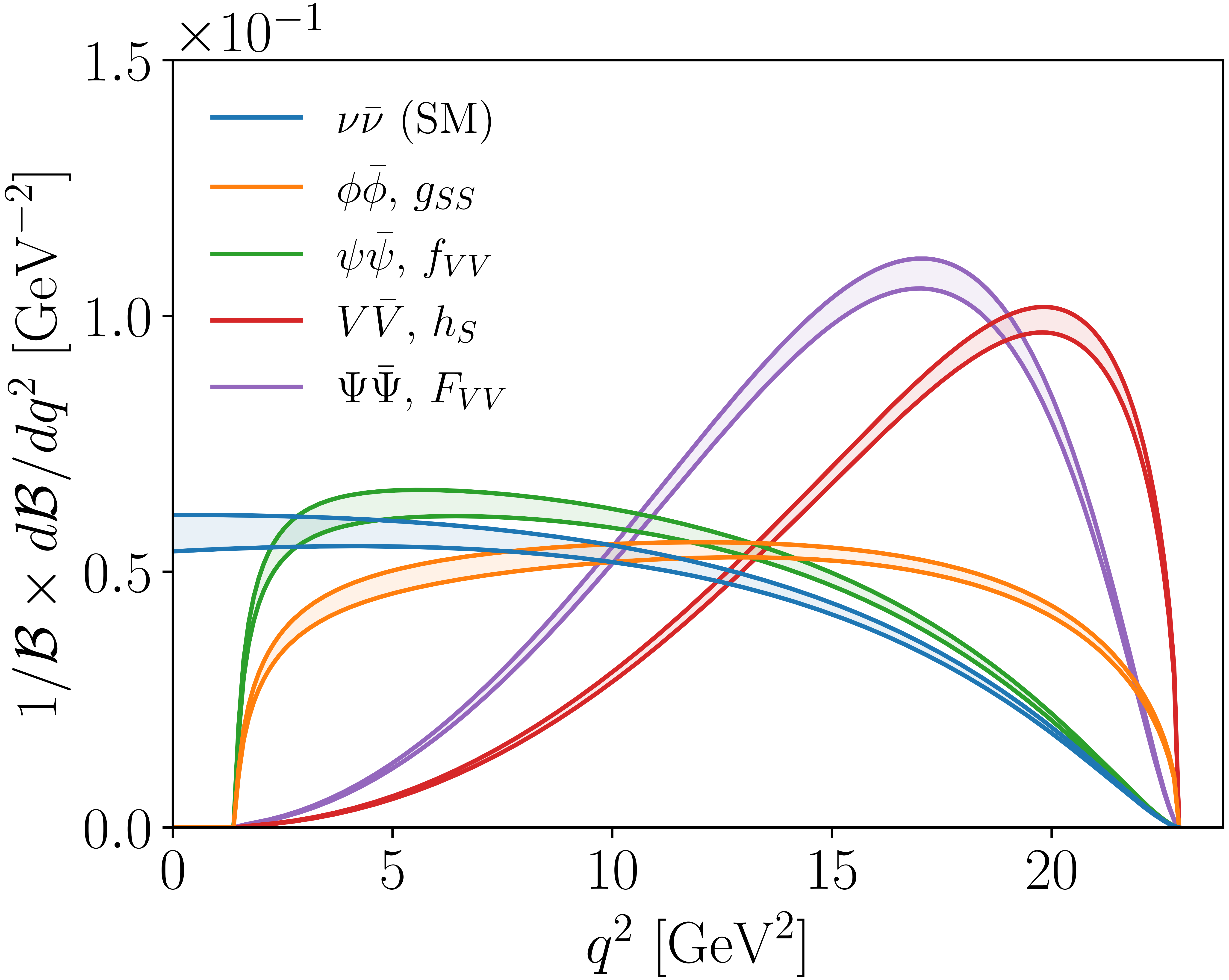
Form Factors

$B \to K : f_+, f_0$ and f_T

$B \to K^* : V, A_0 , A_1, A_{12}, T_1, T_2, T_{23}$



NP Rates



$\times 10^{-1}$
1.5
1.0
0.5
0.0
0
5
10
15
20
$1/\mathcal{B} \times d\mathcal{B}/dq^2$ [GeV^{-2}]
q^2 [GeV^2]
$\nu\bar{\nu}$ (SM)
$\phi\bar{\phi}$, g_{SS}
$\psi\bar{\psi}$, f_{VV}
$V\bar{V}$, h_S
$\Psi\bar{\Psi}$, F_{VV}

Belle II and BaBar Signal

Number of events in the reconstructed q^2:

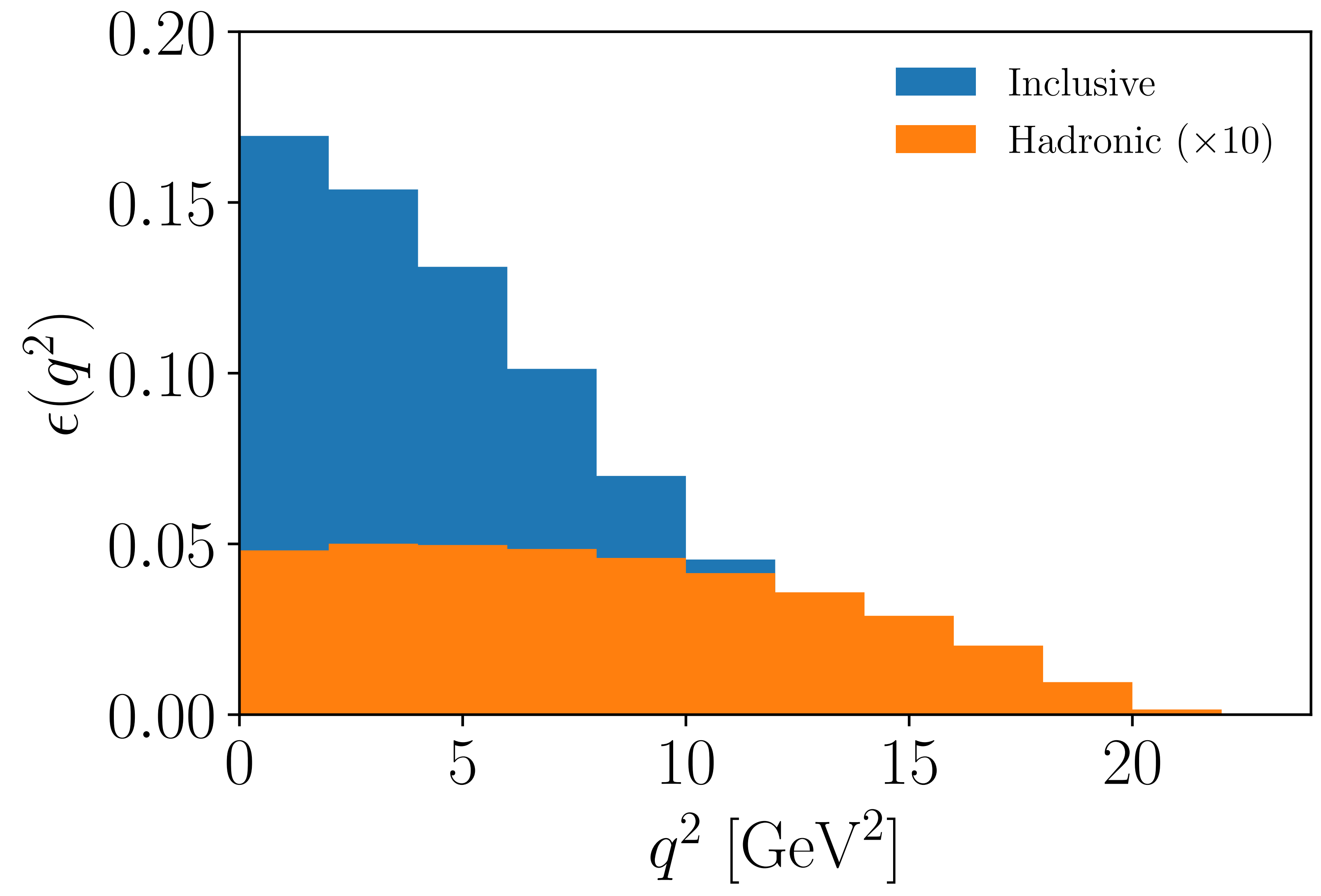
$$\frac{dN_{\mathrm{SM}(X)}}{dq^2_{\mathrm{rec}}} = N_B \int dq^2 f_{q^2_{\mathrm{rec}}}(q^2)\epsilon(q^2)\frac{d\mathcal{B}_{\mathrm{SM}(X)}}{dq^2}$$

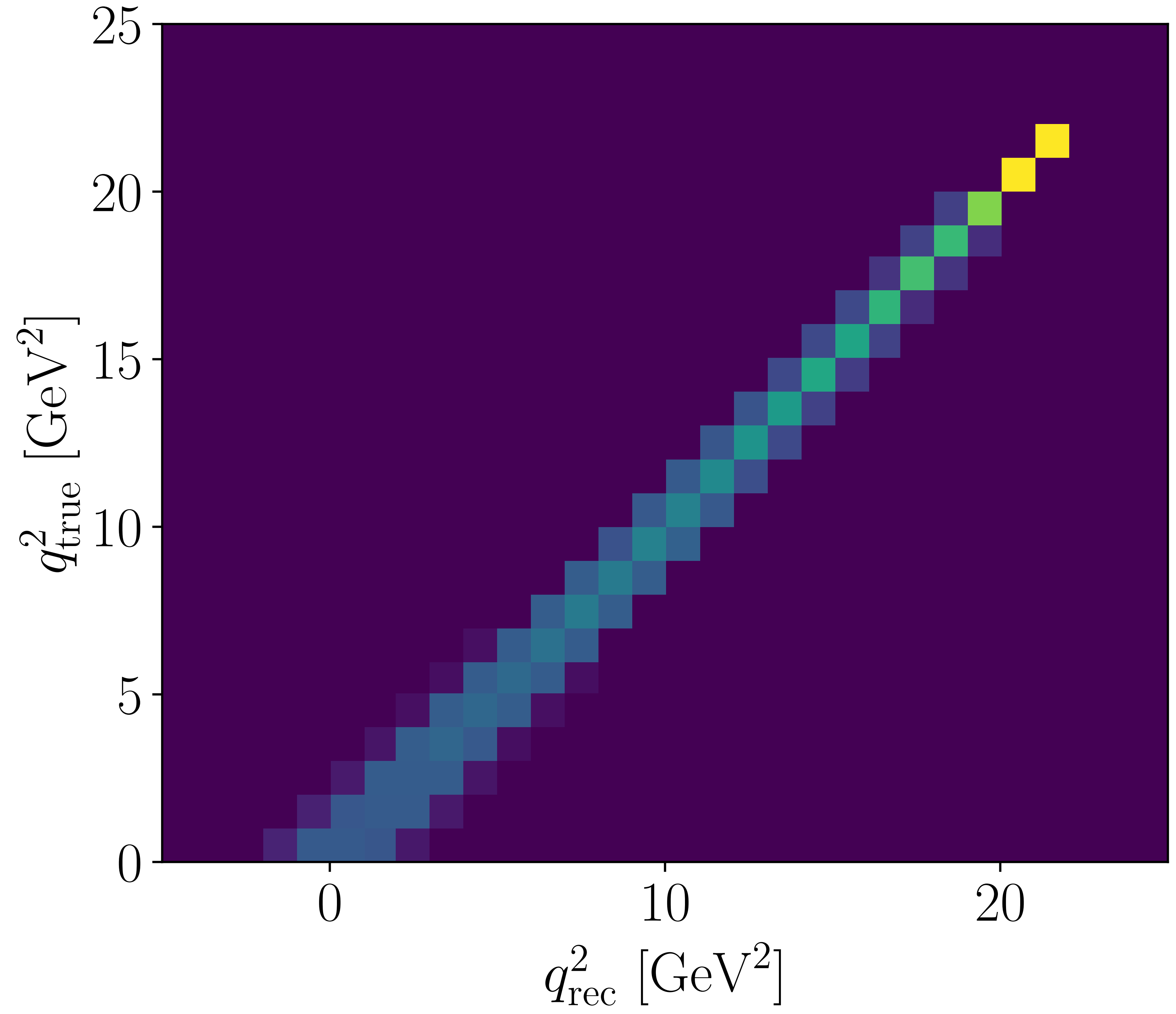
Number of $B^+B^-/B^0\bar{B}^0$ pairs

Smearing function accounting for $q^2_{\mathrm{true}} \to q^2_{\mathrm{rec}}$

Efficiency

SM or NP differential $B \to K^{(*)}E_{\mathrm{miss}}$ branching ratio





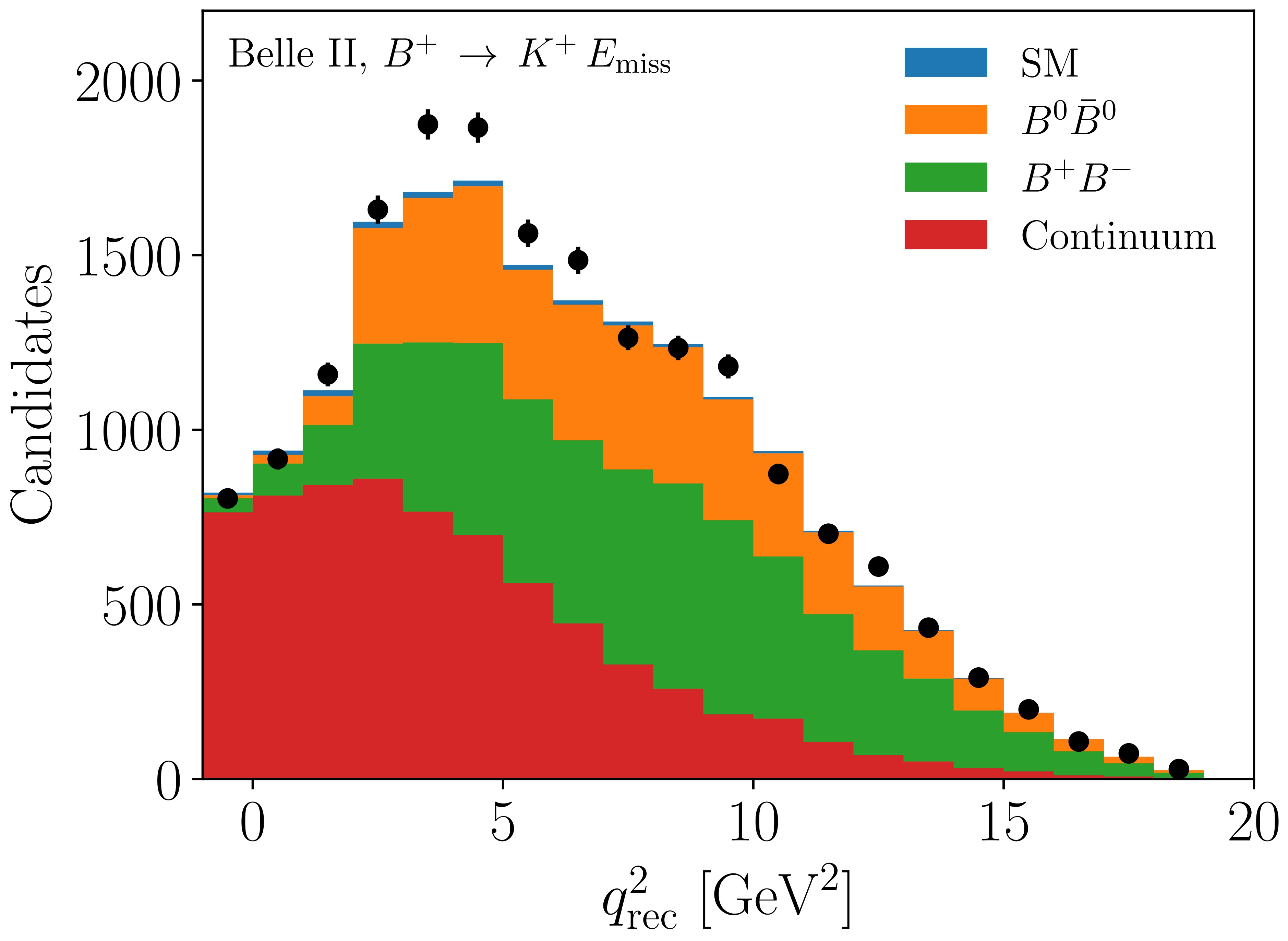
Constructing the Signal

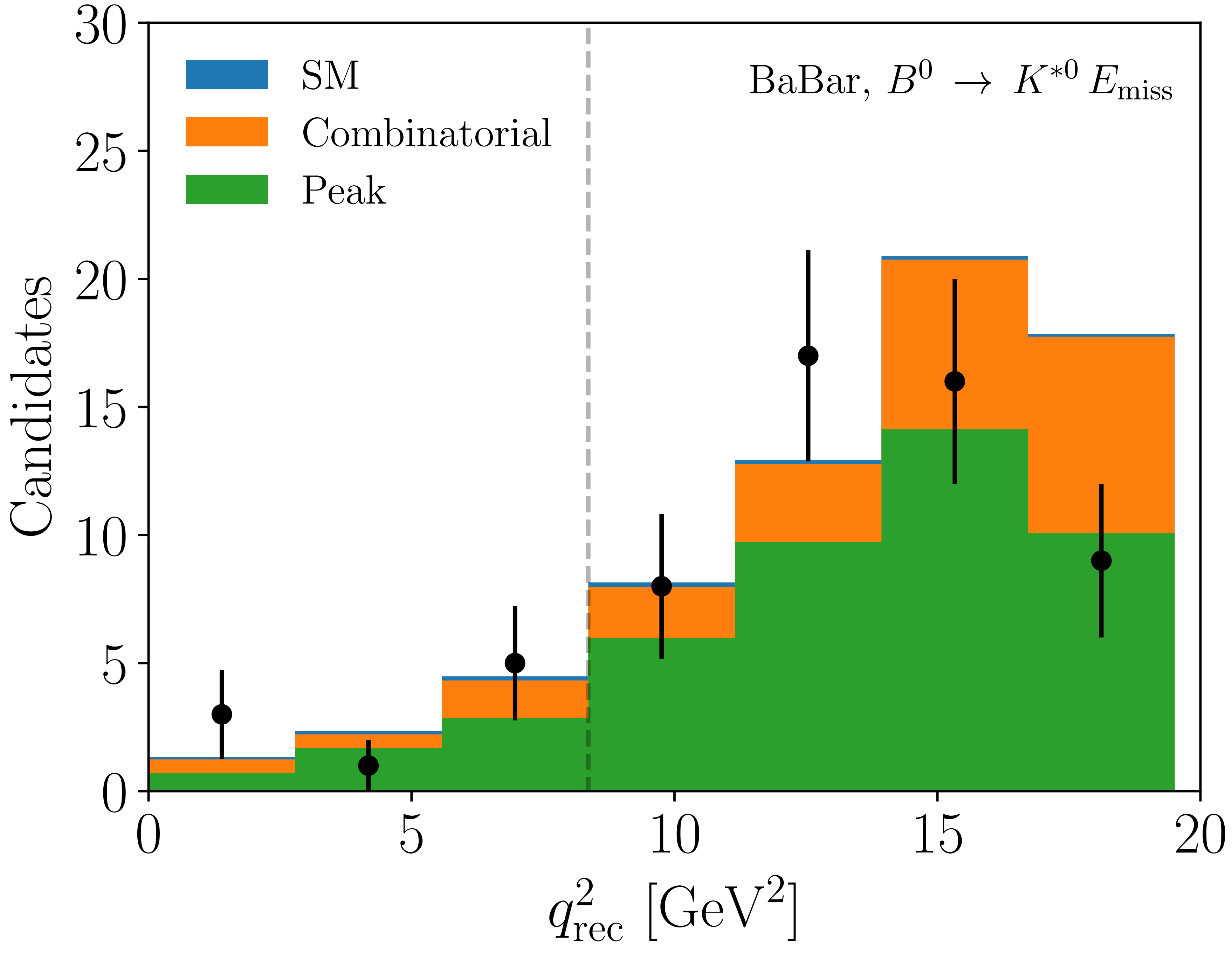
Number of events of events in each bin is then constructed as follows:

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

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

SM signal — NP signal — Backgrounds





Constructing a Likelihood

Nuisance parameters $\boldsymbol{\theta} = (\theta_i, \tau_b)$

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

SM signal strength

SM and NP nuisance parameters accounting for stat. and theory uncertainties

Bkg. nuisance parameters accounting for MC stat. uncertainties

Nuisance parameters for overall bkg. normalisation

Now we construct the binned likelihood:

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

Covariance (i.e. correlations between bins)
Found via Monte Carlo

Re-scaled SM Fit

To check our likelihood method:

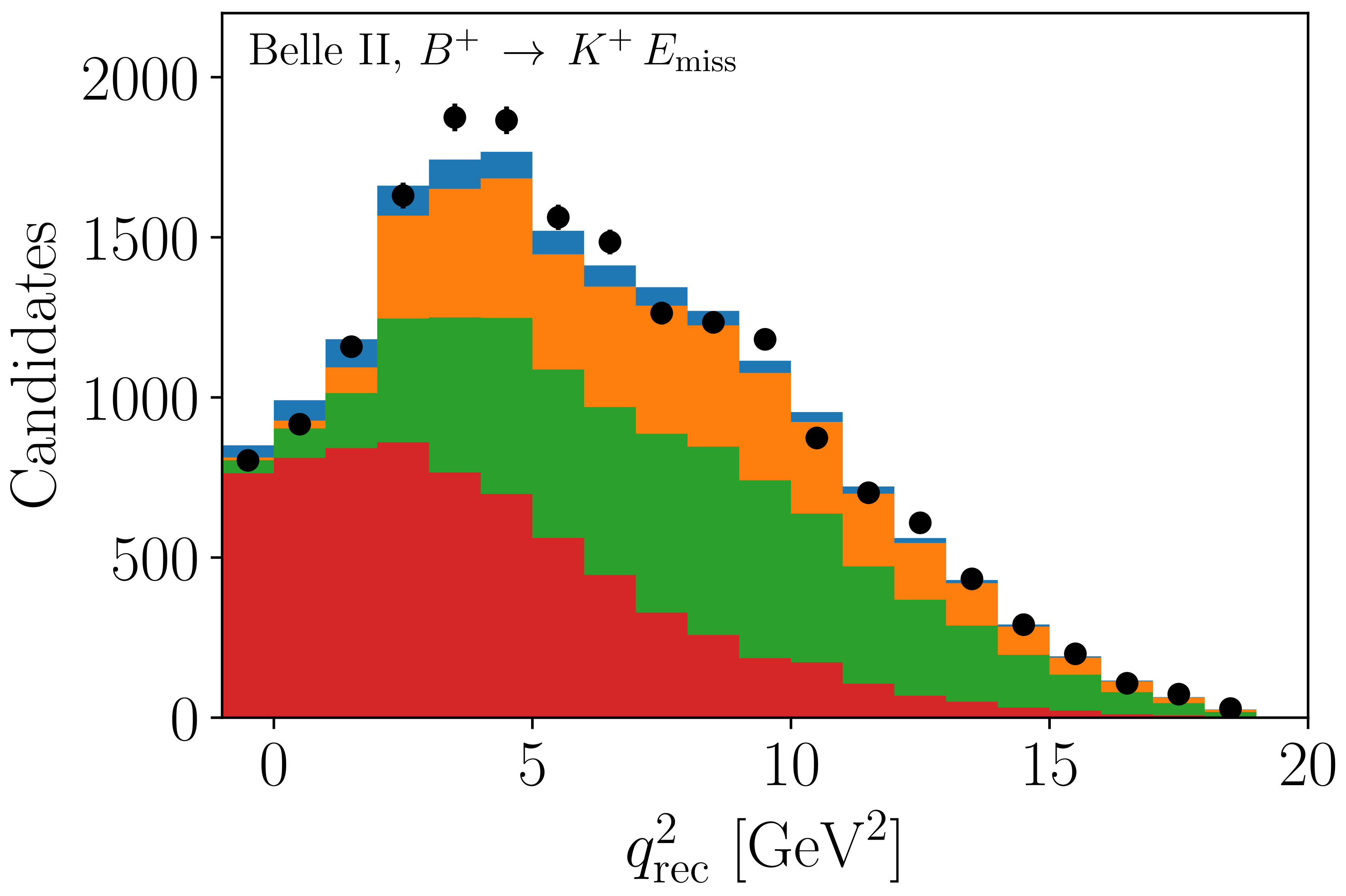
Set $s_X^i = 0$ and perform a fit varying SM signal strength μ

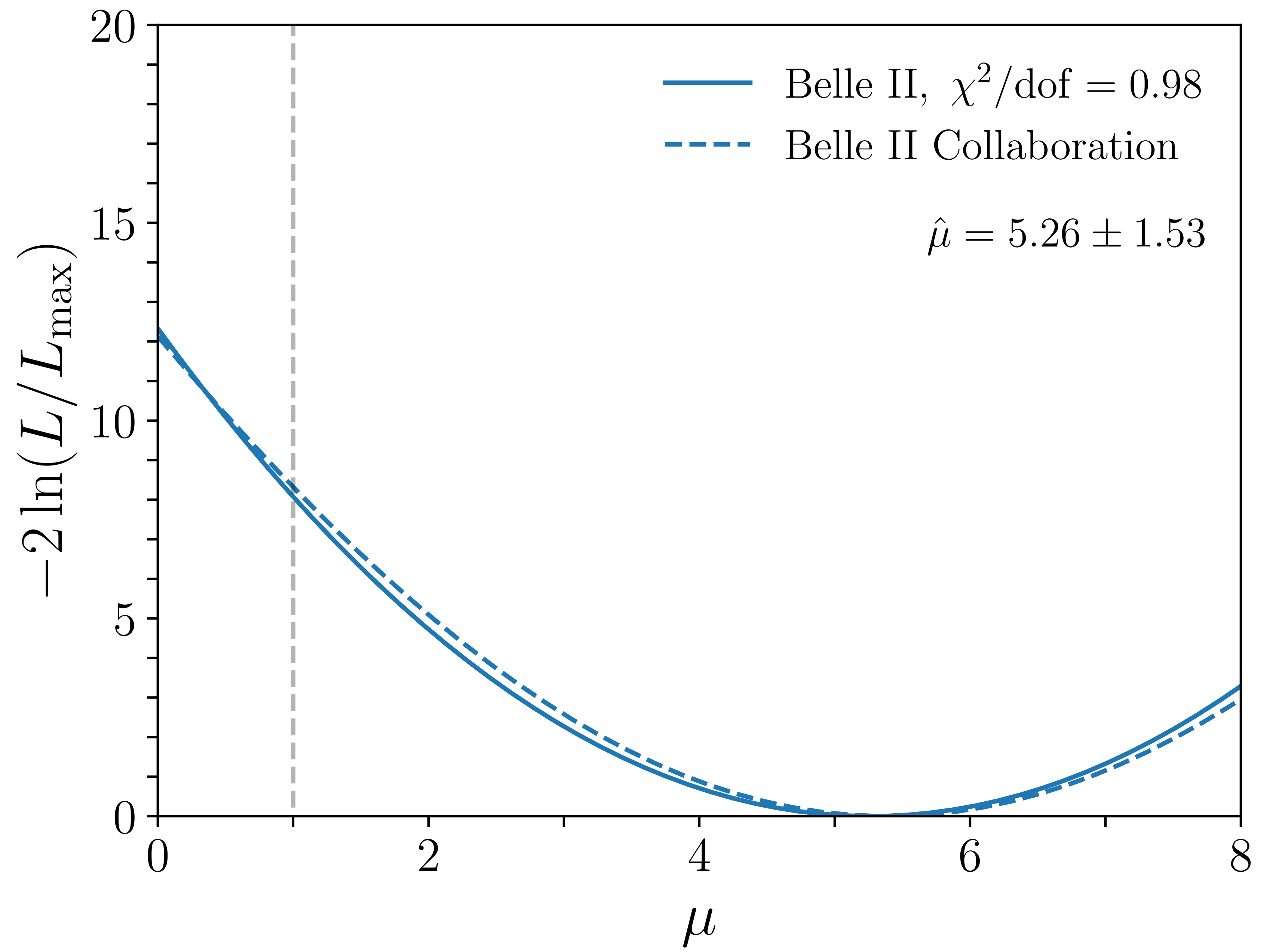
Find $(\hat{\mu}, \hat{\boldsymbol{\theta}})$ at the global minimum of the likelihood
$\Rightarrow$ In agreement with Belle II result $\hat{\mu} \approx 5.4$

Then profile over the likelihood

$$-2\ln \frac{L_{\mathrm{SM}}(\mu, \hat{\hat{\boldsymbol{\theta}}})}{L_{\mathrm{SM}}(\hat{\mu}, \hat{\boldsymbol{\theta}})}$$

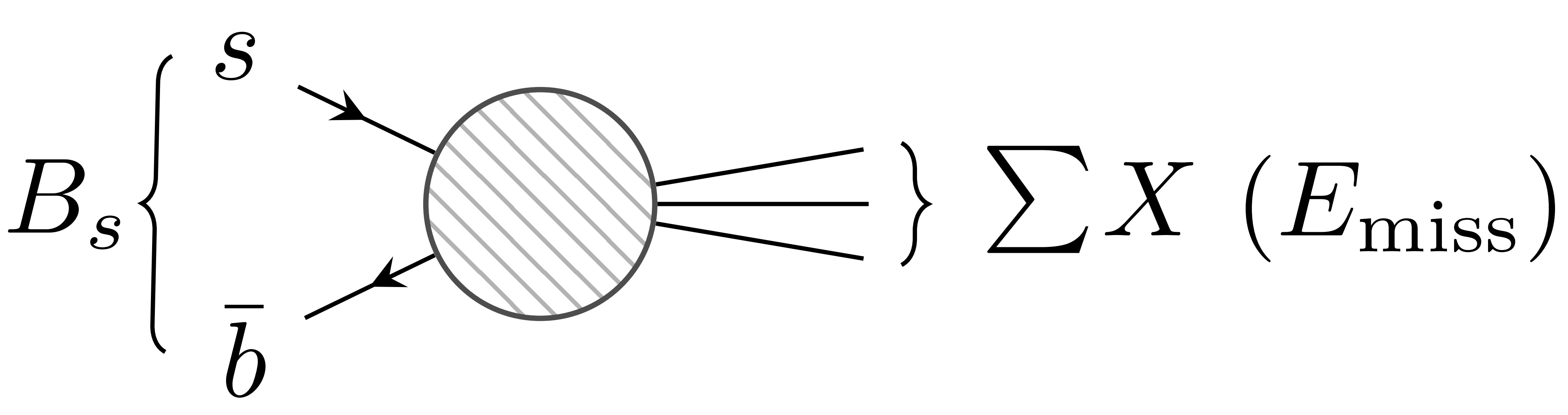
Fix σ_b to reproduce Belle II profile likelihood slope





[PDB, Fajfer, Kamenik, Novoa-Brunet, 24]

$B_s \to$ Invisible



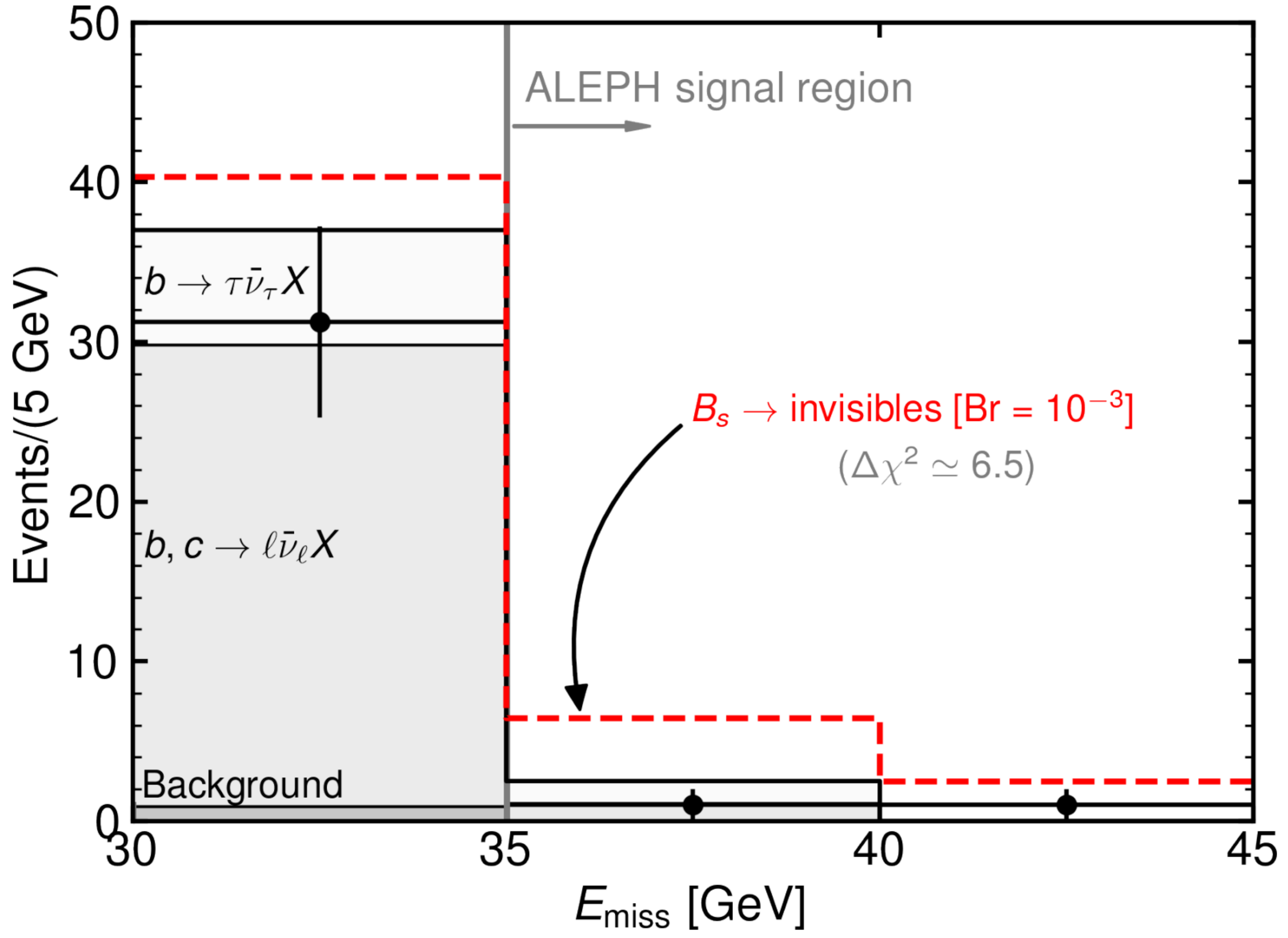
The NP operators contributing to three-body decays $B \to K^{(*)} E_{\text{miss}}$ also contribute to two-body $B_s \to E_{\text{miss}}$

No constraint on $B_s \to \nu\bar{\nu}$ has been set until recently

The ALEPH (LEP) search for $b \to \tau\bar{\nu}_\tau X$ can be recast onto the bound

$$\mathcal{B}(B_s \to \text{inv.}) < 5.4 \times 10^{-4} \ [90\% \ \text{CL}]$$

The constraint can be added to the global likelihood using a simple gaussian likelihood



[Alonso-Álvarez, Escudero, 23]

$B_s \to$ Invisible in the SM

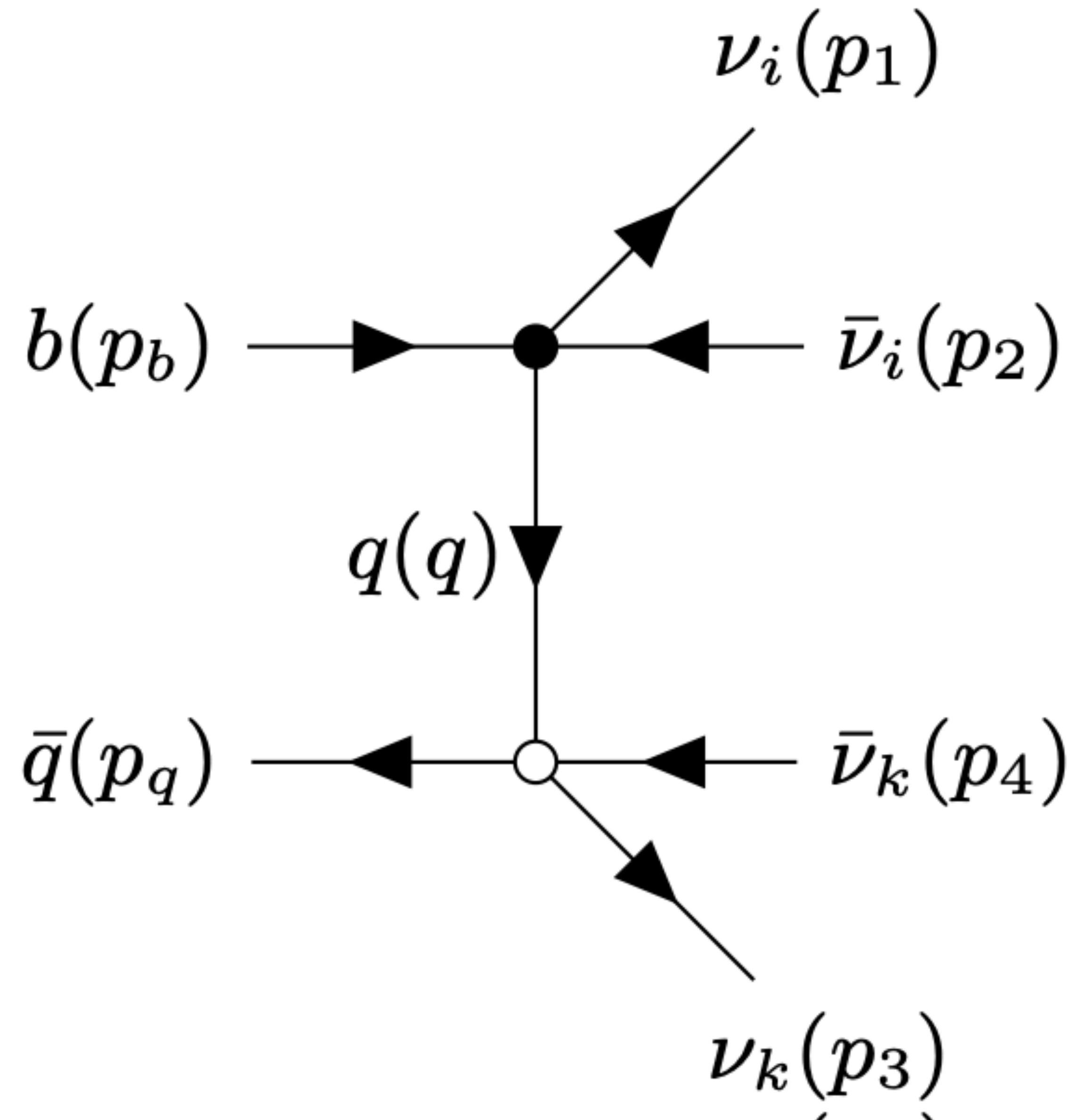
In the SM, the decay $B_s \to \nu\bar{\nu}$ is heavily suppressed:

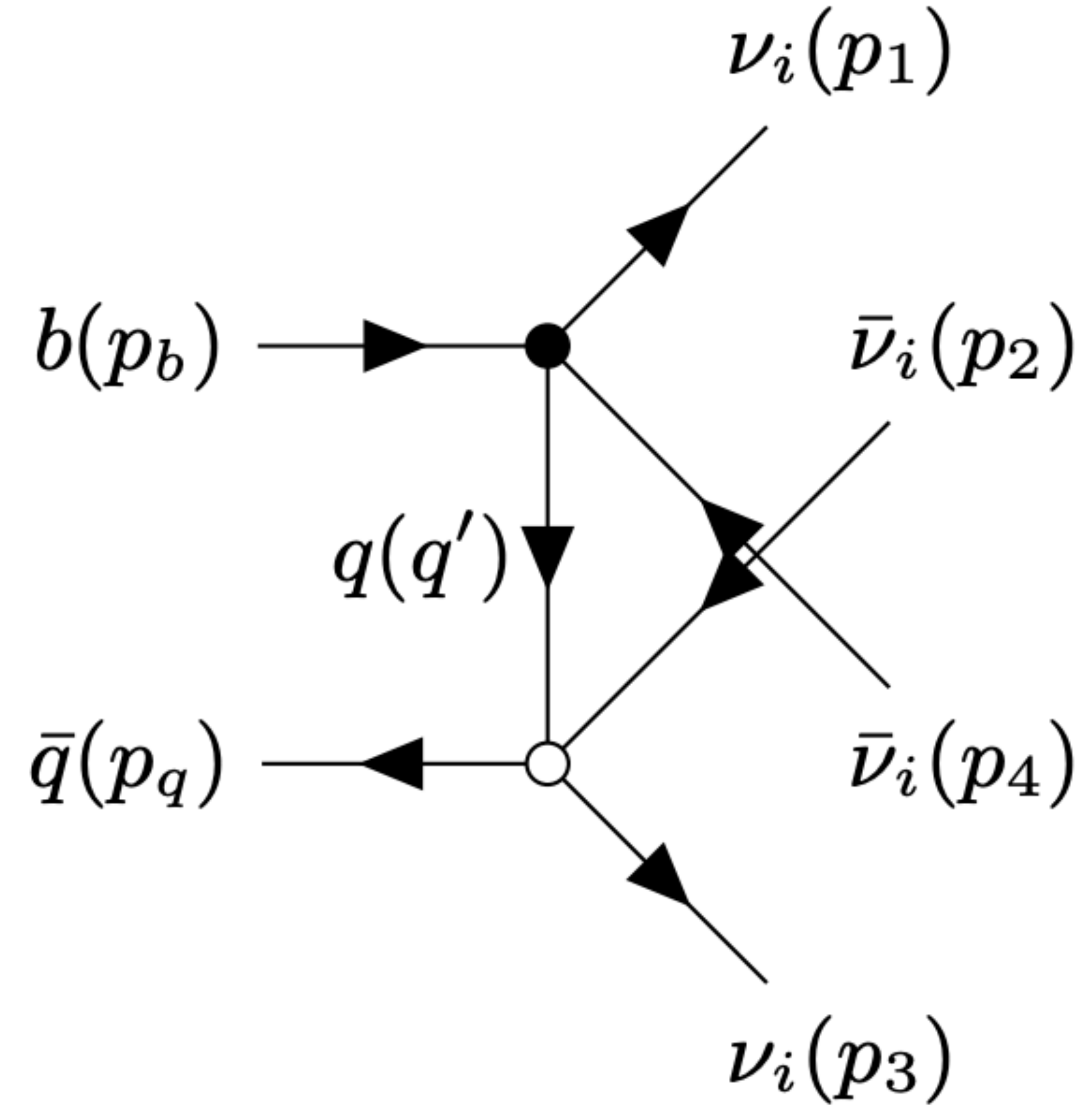
$$\mathcal{B}(B_s \to \nu\bar{\nu})\big|_{\mathrm{SM}} = \frac{G_F^2 \alpha^2 f_{B_q}^2 m_{B_s}^3}{16\pi^3 s_w^4 \Gamma_{B_s}} \left|V_{tb}V_{ts}^*\right|^2 X(x_t)^2 x_\nu^2 \sim 10^{-24}$$

While it has a smaller phase space, $B_s \to \nu\bar{\nu}\nu\bar{\nu}$ avoids helicity suppression

$$\mathcal{B}(B_s \to \nu\bar{\nu}\nu\bar{\nu})\big|_{\mathrm{SM}} = (5.48 \pm 0.8) \times 10^{-15}$$

Therefore promising avenue for NP searches





[Bhattacharya, Grant, Petrov, 19]

Results

NP Fit (Profile Likelihood)

1) To see what masses are implied by Belle II excess:

$$t_X = -2\ln\frac{L_{\mathrm{SM}+X}}{L_{\mathrm{SM}}}$$

Minimise $L_{\mathrm{SM+}X}$ with respect to NP couplings c_X and $\boldsymbol{\theta}$ with fixed m_X and $\mu = 1$

Minimise L_{SM} w.r.t. $\boldsymbol{\theta}$ with $\mu = 1$

2) To see what couplings are implied at the best-fit m_X

$$\hat{t}_X = t_X - t_X|_{\min}$$

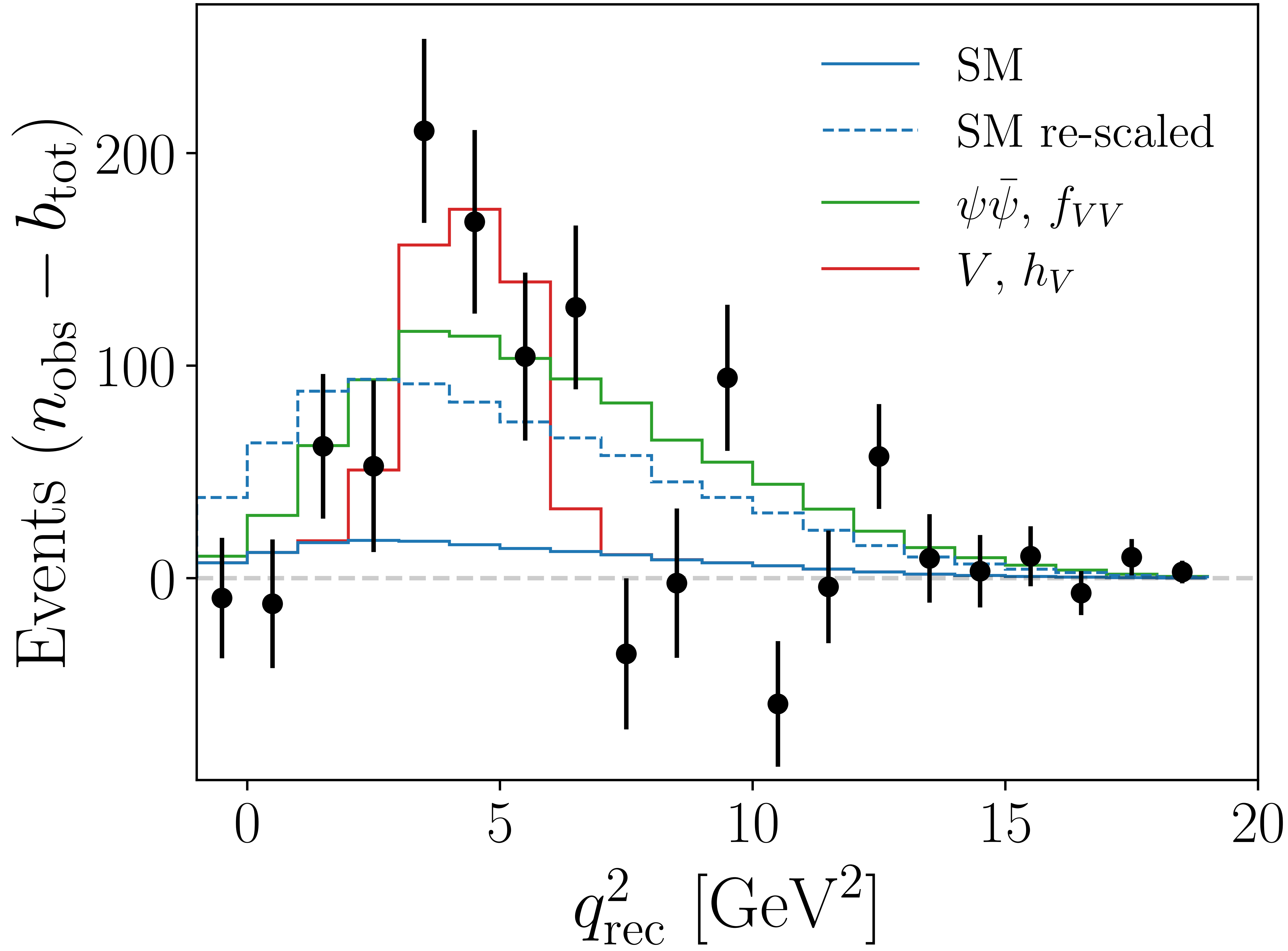
Minimised with respect to $\boldsymbol{\theta}$ for fixed c_X and $\mu = 1$

Minimised with respect to c_X and $\boldsymbol{\theta}$ for $\mu = 1$

[PDB, Fajfer, Kamenik, Novoa-Brunet, 24]

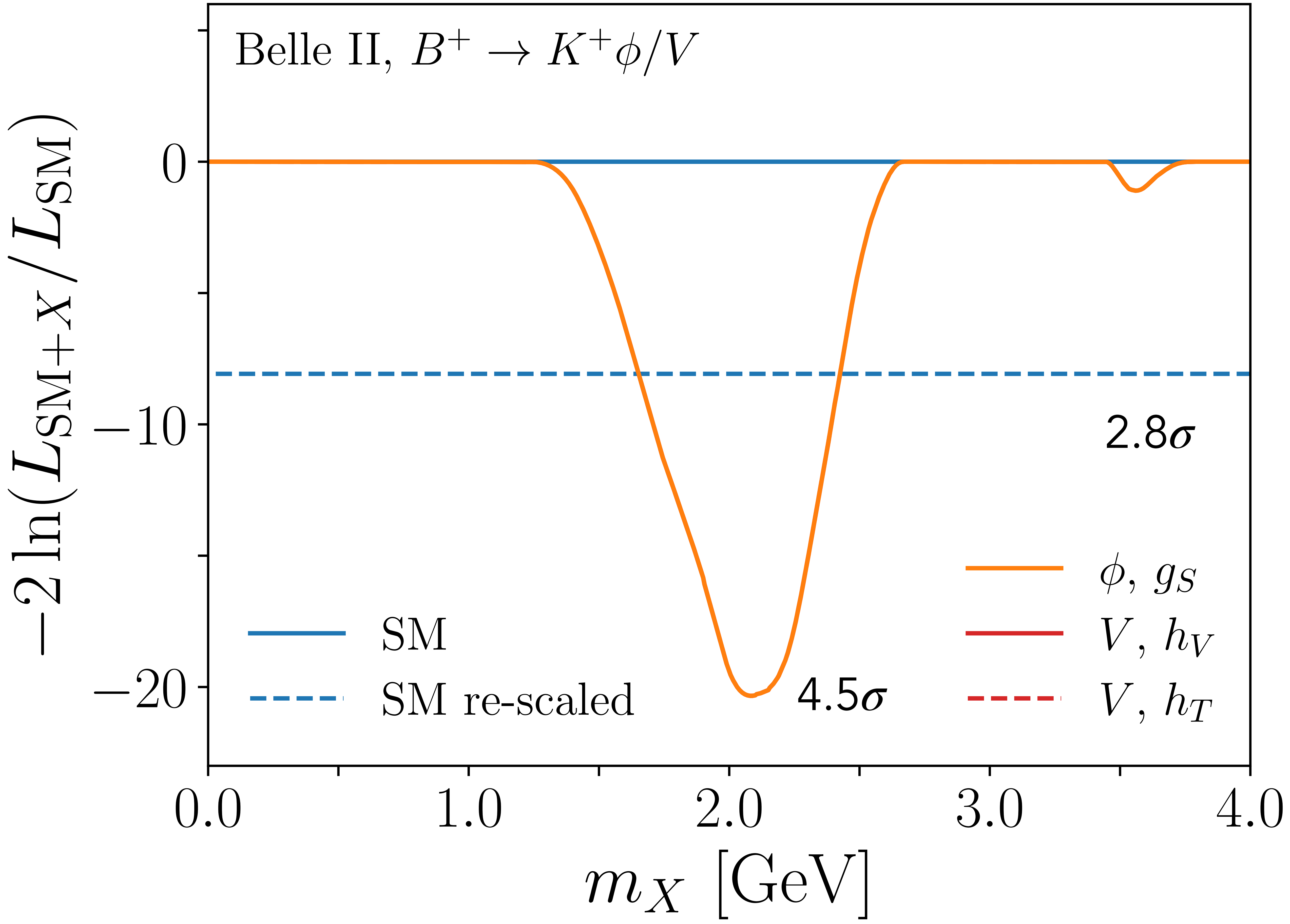
Results

Example fits to the Belle II data: Vector two-body and fermion three-body scenarios

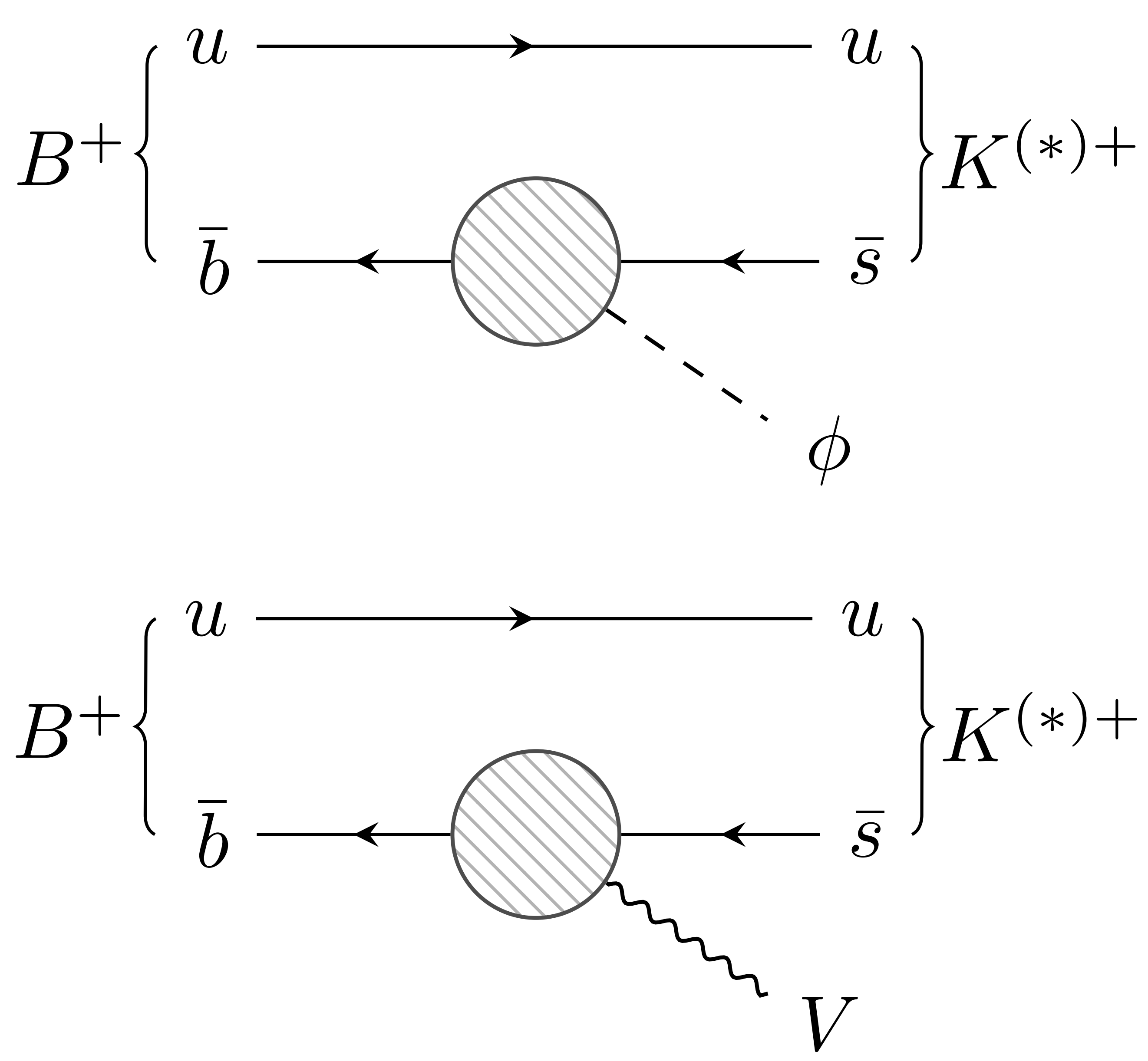


[PDB, Fajfer, Kamenik, Novoa-Brunet, 24]

Two-body Scenarios: Masses

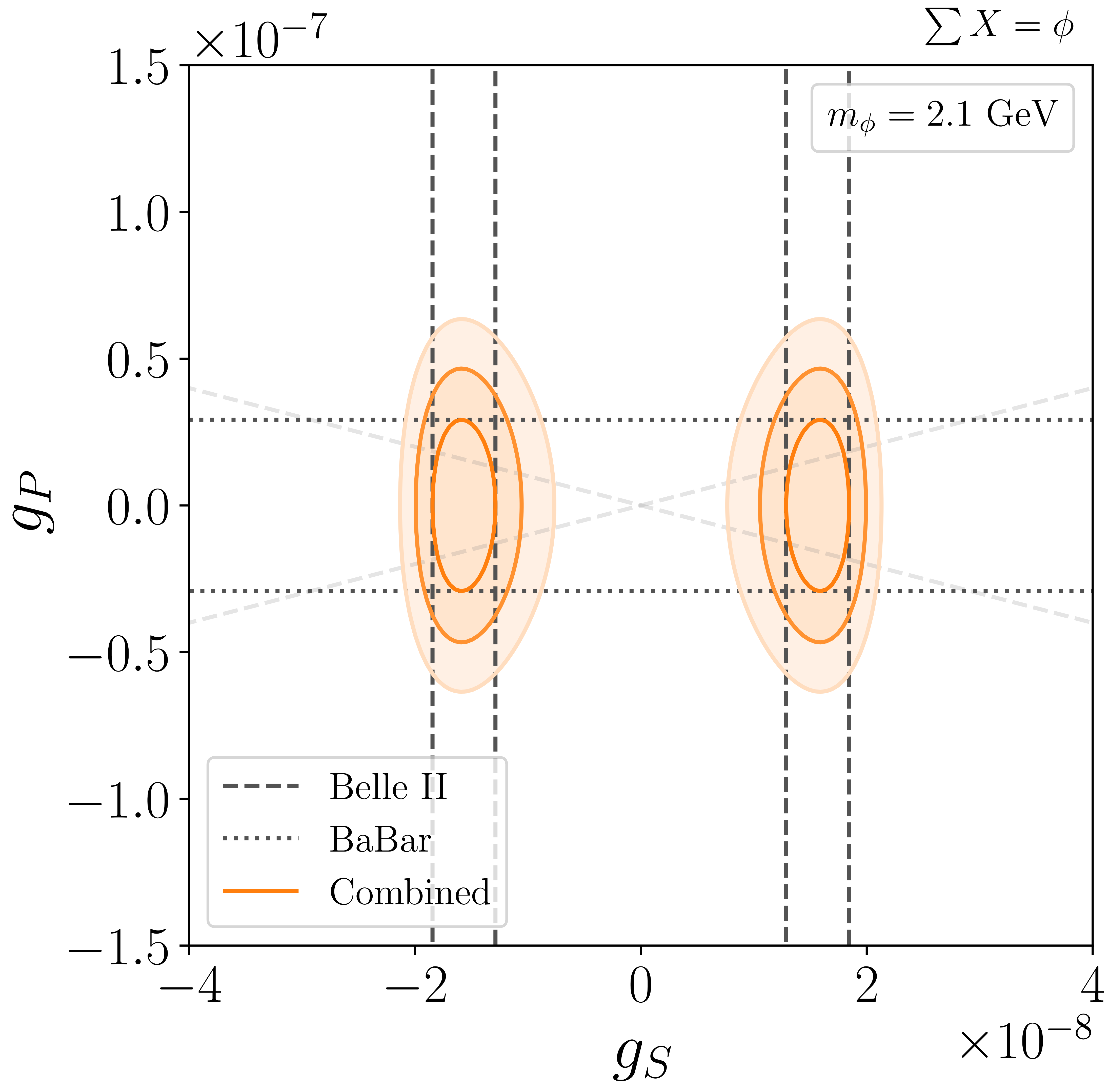


$$m_{\phi/V} = (2.1 \pm 0.1)\ \mathrm{GeV}$$



[PDB, Fajfer, Kamenik, Novoa-Brunet, 24]

Two-body Scenarios: Scalar Couplings



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

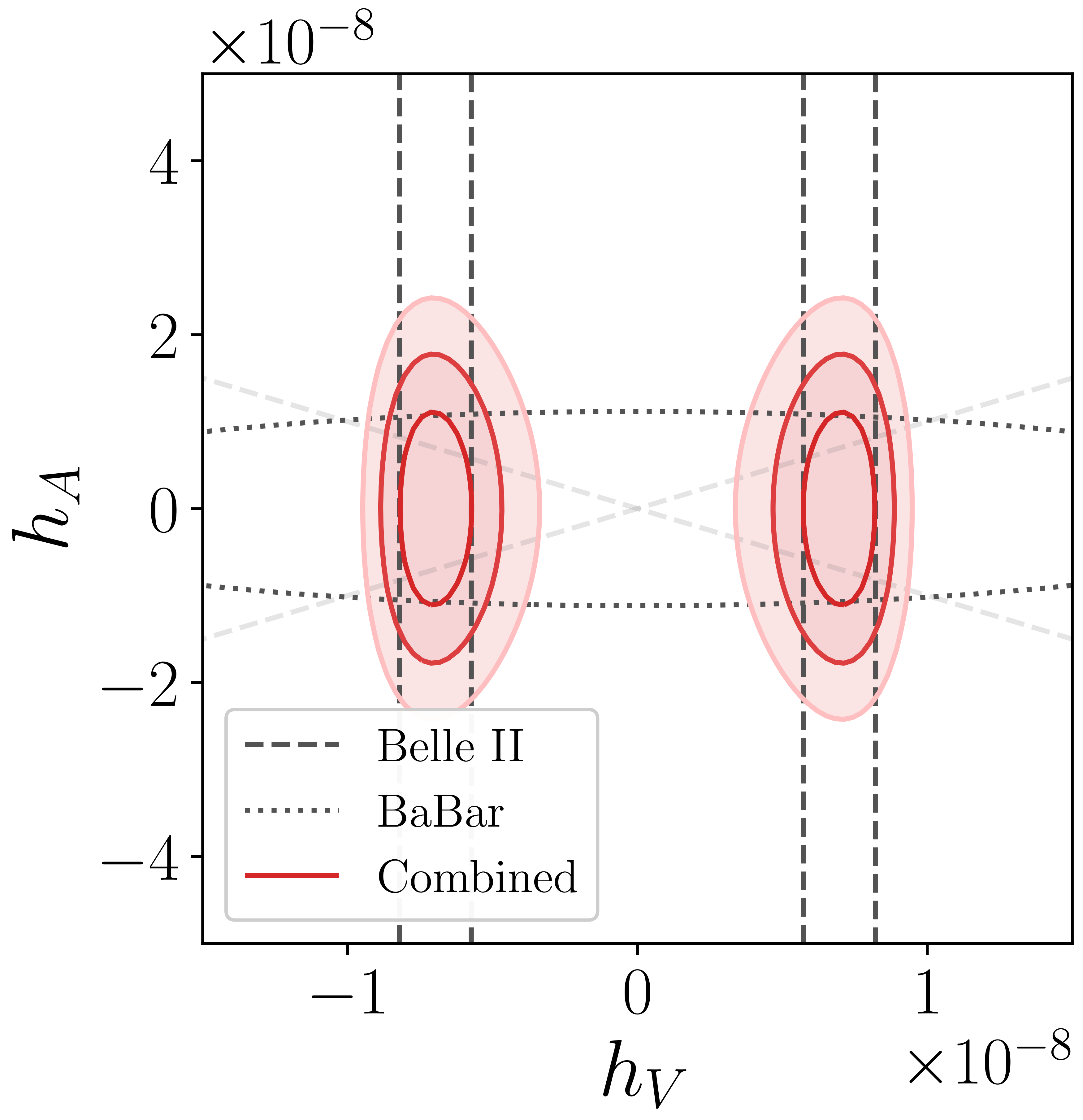
$$\frac{g_V}{\Lambda}(\bar{s}\gamma_\mu b)\partial^\mu\phi + \frac{g_A}{\Lambda}(\bar{s}\gamma_\mu\gamma_5 b)\partial^\mu\phi$$

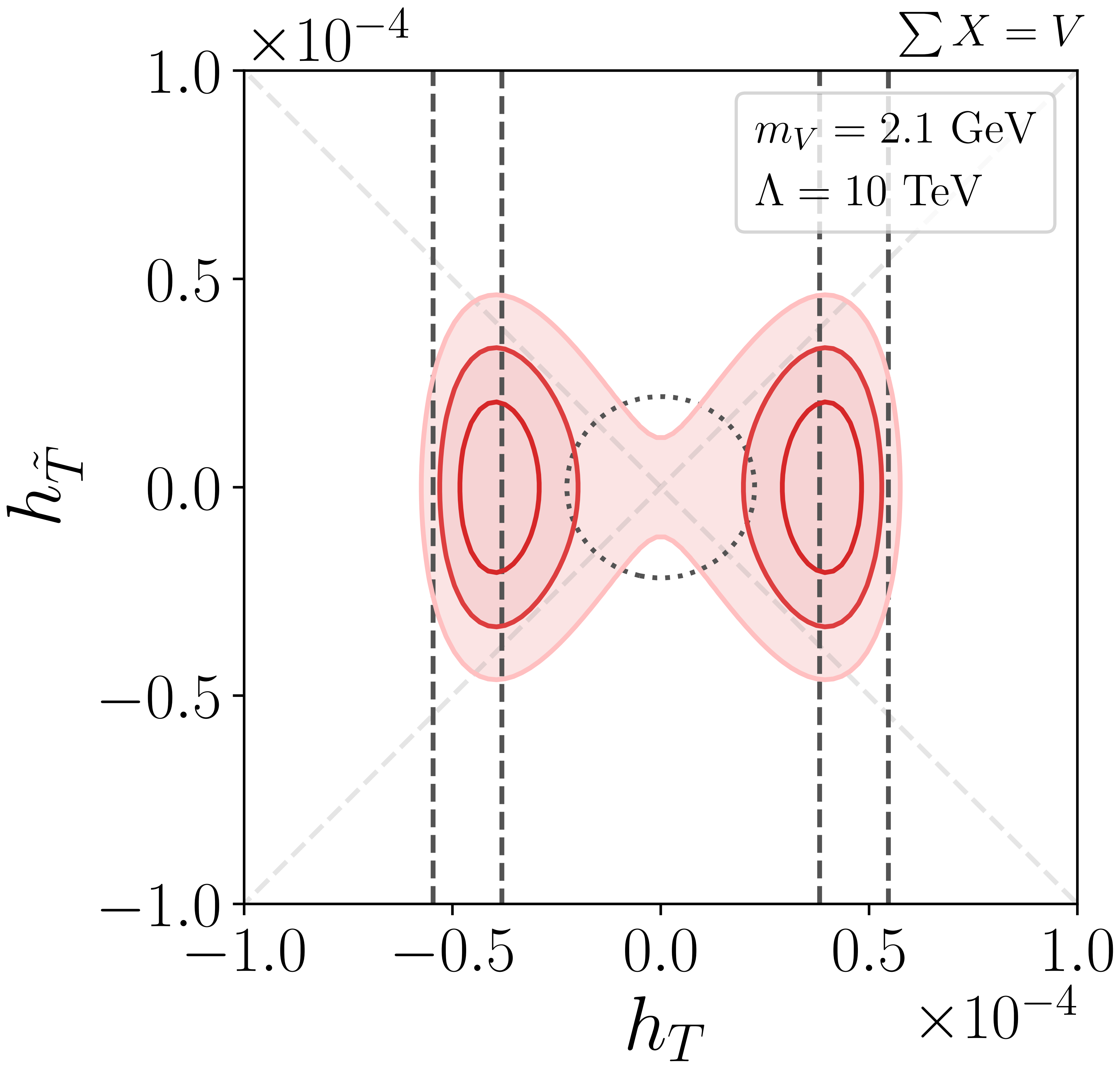
[PDB, Fajfer, Kamenik, Novoa-Brunet, 24]

Two-body Scenarios: Vector Couplings

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

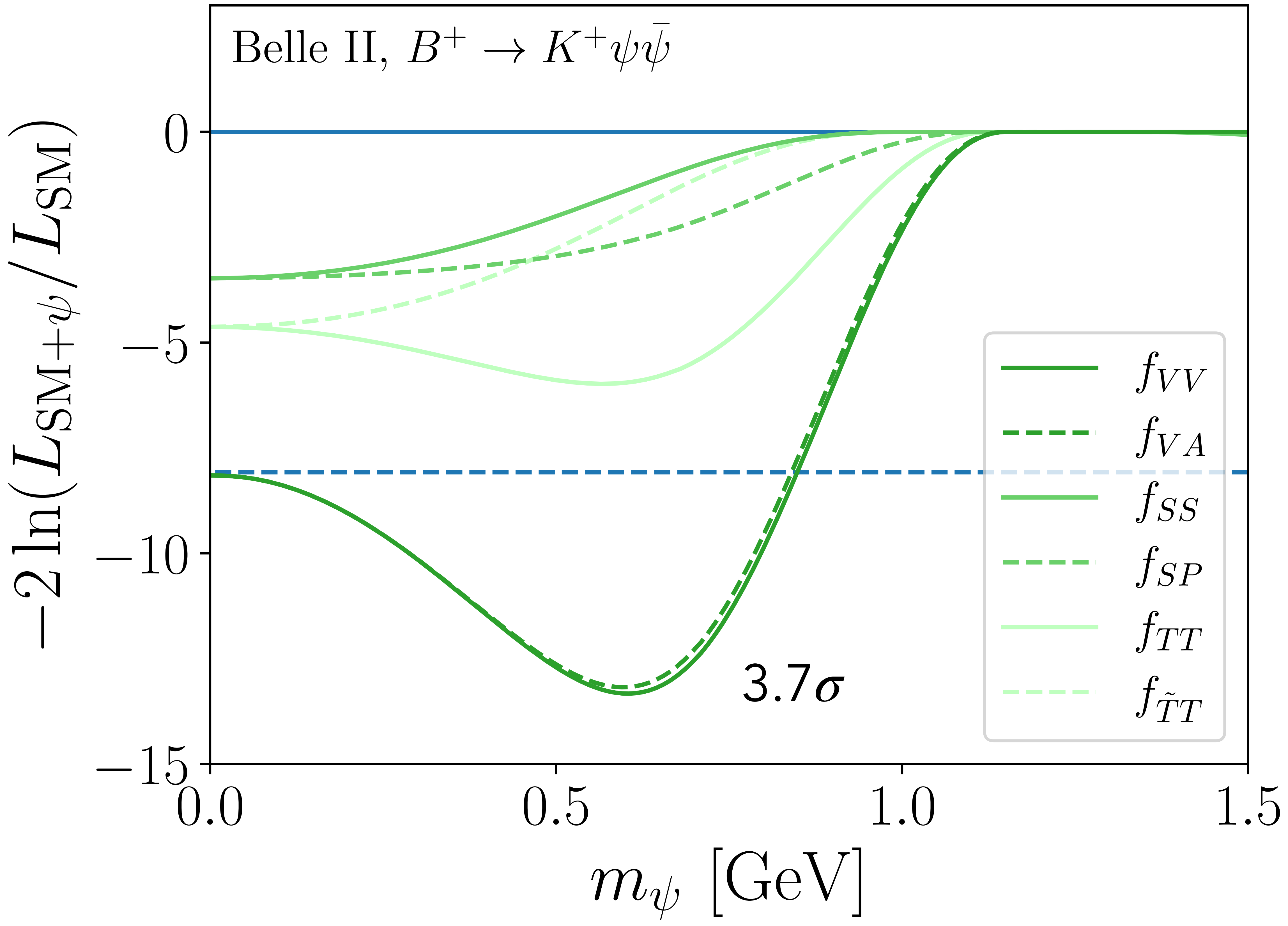
$$\frac{h_T}{\Lambda}(\bar{s}\sigma_{\mu\nu}b)V^{\mu\nu} + \frac{h_{\tilde{T}}}{\Lambda}(\bar{s}\sigma_{\mu\nu}\gamma_5 b)V^{\mu\nu}$$



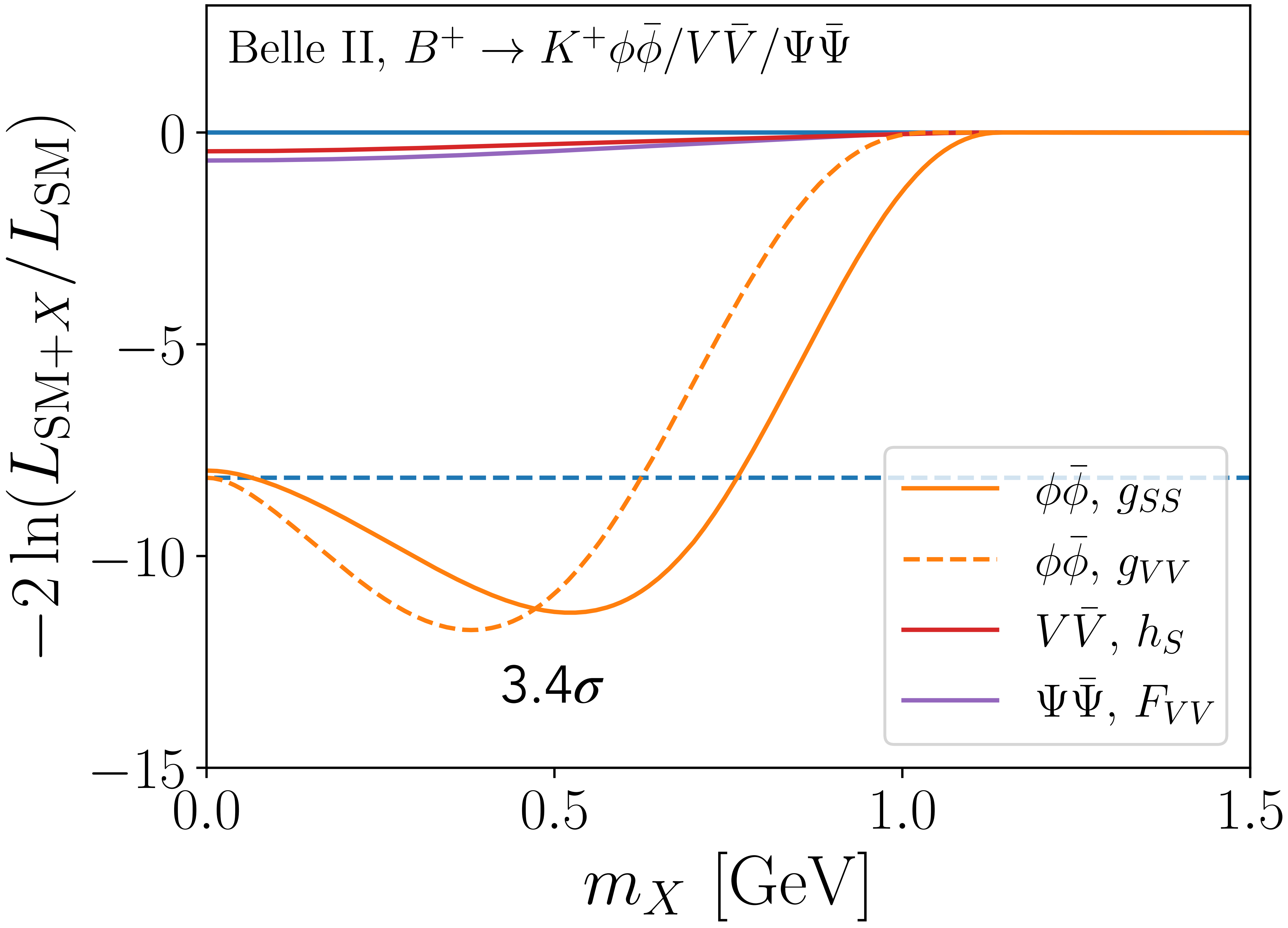


[PDB, Fajfer, Kamenik, Novoa-Brunet, 24]

Three-body Scenarios: Masses



$$m_\psi = 0.60^{+0.11}_{-0.14}\ \mathrm{GeV}$$



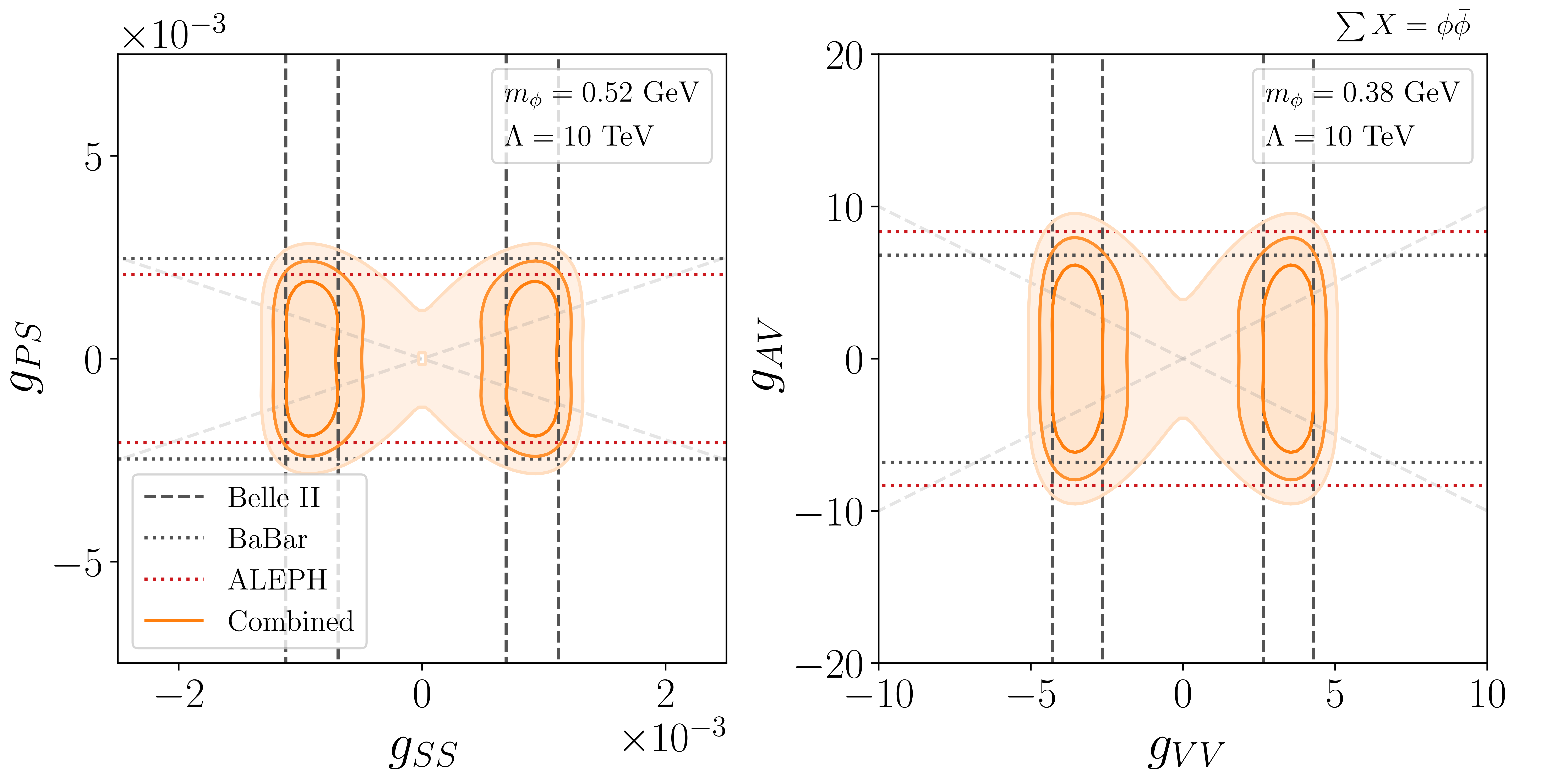
$$m_\phi = 0.38^{+0.13}_{-0.15}\ \mathrm{GeV} \quad m_\phi = 0.52^{+0.11}_{-0.14}\ \mathrm{GeV}$$

[PDB, Fajfer, Kamenik, Novoa-Brunet, 24]

Three-body Scenarios: Scalar Couplings

$$\frac{g_{SS}}{\Lambda}(\bar{s}b)(\phi^\dagger\phi) + \frac{g_{PS}}{\Lambda}(\bar{s}\gamma_5 b)(\phi^\dagger\phi)$$

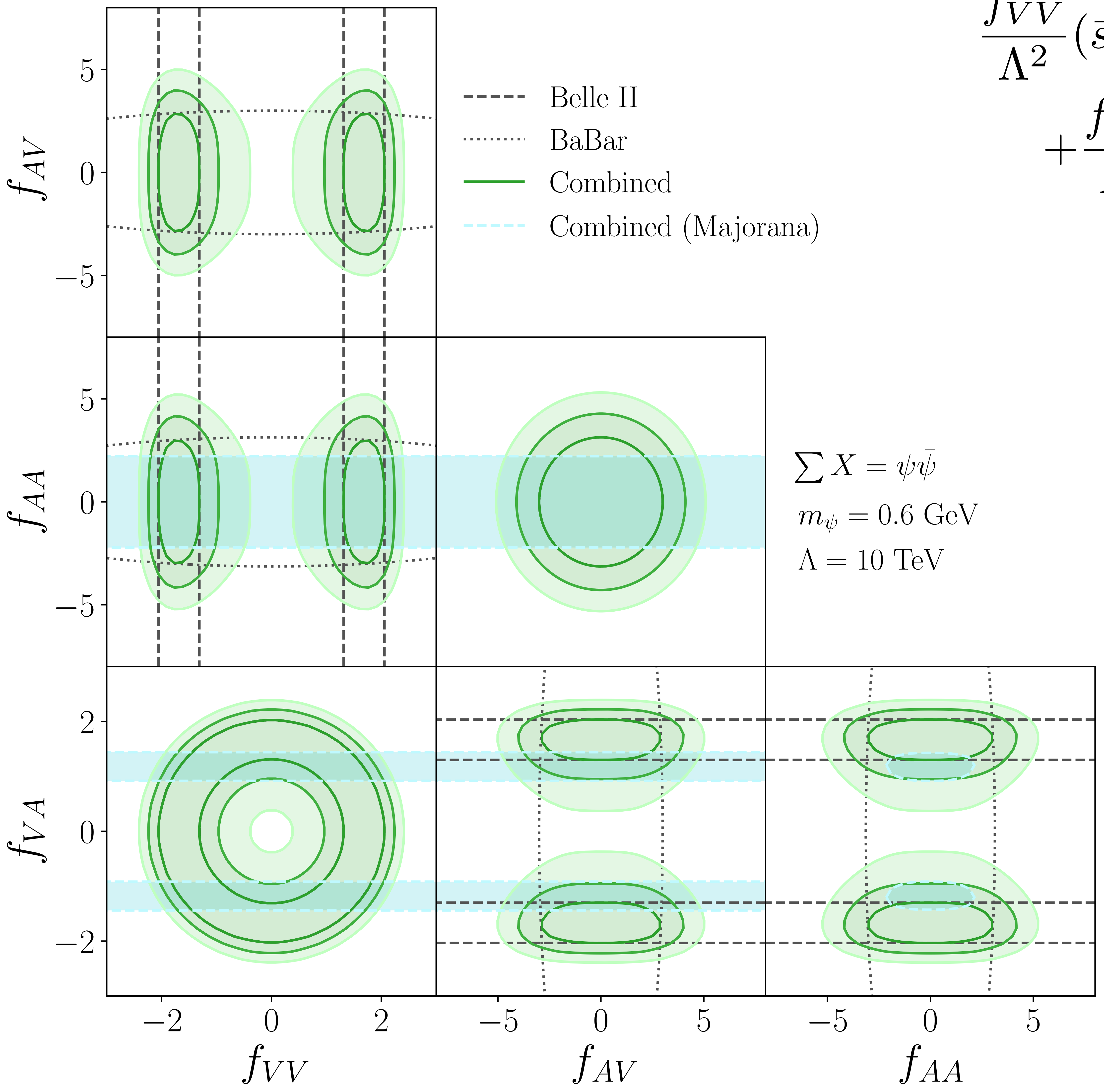
$$\frac{g_{VV}}{\Lambda^2}(\bar{s}\gamma_\mu b)(i\phi^\dagger \overleftrightarrow{\partial}^\mu \phi) + \frac{g_{AV}}{\Lambda^2}(\bar{s}\gamma_\mu\gamma_5 b)(i\phi^\dagger \overleftrightarrow{\partial}^\mu \phi)$$



[PDB, Fajfer, Kamenik, Novoa-Brunet, 24]

Three-body Scenarios: Fermion Couplings

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



[PDB, Fajfer, Kamenik, Novoa-Brunet, 24]

Conclusions

Conclusions

Belle II result: $\mathcal{B}(B \to K E_{\text{miss}}) = (2.3 \pm 0.7) \times 10^{-5}$ vs. $\mathcal{B}\left(B^+ \to K^+ \nu\bar{\nu}\right)\big|_{\text{SM}} = (5.58 \pm 0.37) \times 10^{-6}$

Find **viable scenarios** to explain excess: Full binned likelihood fit w. Belle II (ITA), BaBar and ALEPH data

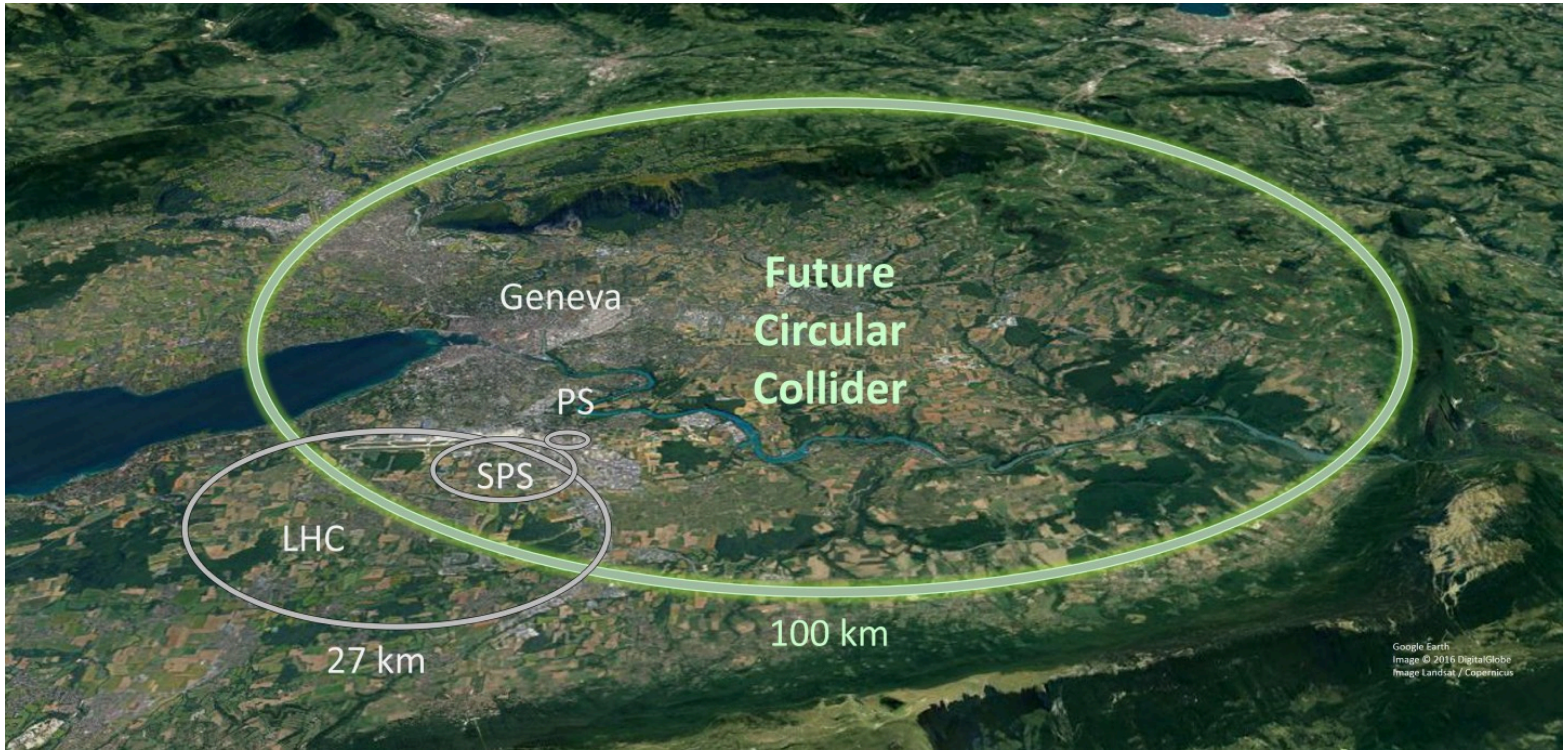
- Two body decay with scalar or vector (4.5σ) $m_{\phi/V} = (2.1 \pm 0.1)$ GeV
- Three body with scalars (3.4σ) or fermions (3.7σ) $m_\psi = 0.60^{+0.11}_{-0.14}$ GeV $m_\phi = 0.38^{+0.13}_{-0.15}$ GeV$\big/ m_\phi = 0.52^{+0.11}_{-0.14}$ GeV

Much theory activity: we are in good agreement with previous works

While the excess may be an unknown background on inclusive Belle II method (ITA):

- Exploring NP scenarios which may solve other outstanding SM issues (e.g. dark matter)
- Upcoming data will verify $B \to KE_{\text{miss}}$ and perform the first measurement of $B \to K^{(*)}E_{\text{miss}}$

Future Prospects?



Particle production (10^9)	B^0 / $\overline{B}^0$	B^+ / B^-	B_s^0 / $\overline{B}_s^0$	Λ_b / $\overline{\Lambda}_b$	$c\bar{c}$	τ^-/τ^+
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-ee	300	300	80	80	600	150

Thank you for your attention!

Bonus

EFT + X Example: SMEFT + N_R

For the SMEFT extended with N_R, plethora of operators of internet phenomenologically

For example, so-called *dipole* portal

$$\mathcal{L} \supset d_{LB} \bar{L} \sigma_{\mu\nu} N_R \tilde{H} B^{\mu\nu}$$

Interesting phenomenology:

- Neutrino upscattering (CEνNS)
- Collider and beam dump (LLPs)
- Supernovae

$\psi^2 H^2$		$\psi^2 H^2 D$		ψ^4	
$\mathcal{O}_W$	$(\bar{l}_\alpha \tilde{H})(\tilde{H}^T l^c_\beta)$	$\mathcal{O}^{(1)}_{Hl}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_\alpha \gamma^\mu l_\beta)$	$\mathcal{O}_{ll}$	$(\bar{l}_\alpha \gamma_\mu l_\beta)(\bar{l}_\gamma \gamma^\mu l_\delta)$
$\mathcal{O}_N$	$(\bar{N}^c_{Rs} N_{Rt})(H^\dagger H)$	$\mathcal{O}^{(3)}_{Hl}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{l}_\alpha \tau^I \gamma^\mu l_\beta)$	$\mathcal{O}_{le}$	$(\bar{l}_\alpha \gamma_\mu l_\beta)(\bar{e}_{R\gamma} \gamma^\mu e_{R\delta})$
$\psi^2 H^3$		$\mathcal{O}_{He}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_{R\alpha} \gamma^\mu e_{R\beta})$	$\mathcal{O}_{lNle}$	$(\bar{l}_\alpha N_{Rt}) \epsilon (\bar{l}_\beta e_{R\gamma})$
$\mathcal{O}_{lNH}$	$(\bar{l}_\alpha N_{Rt}) \tilde{H} (H^\dagger H)$	$\mathcal{O}_{HN}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{N}_{Rs} \gamma^\mu N_{Rt})$	$\mathcal{O}_{lN}$	$(\bar{l}_\alpha \gamma_\mu l_\beta)(\bar{N}_{Rs} \gamma^\mu N_{Rt})$
				$\mathcal{O}_{eN}$	$(\bar{e}_{R\alpha} \gamma_\mu e_{R\beta})(\bar{N}_{Rs} \gamma^\mu N_{Rt})$

$\psi^2 H^4$		$\psi^4 H$	
$\mathcal{O}_{lH}$	$(\bar{l}_\alpha \tilde{H})(\tilde{H}^T l^c_\beta)(H^\dagger H)$	$\mathcal{O}_{llleH}$	$(\bar{l}_\alpha e_{R\beta}) \epsilon (\bar{l}_\gamma l^c_\delta) \tilde{H}$
$\mathcal{O}_{NH}$	$(\bar{N}^c_{Rs} N_{Rt})(H^\dagger H)^2$	$\mathcal{O}_{lNlH}$	$(\bar{l}_\alpha \gamma_\mu l_\beta)(\bar{l}^c_\gamma \gamma^\mu N_{Rt}) \tilde{H}^*$
$\psi^2 H^3 D$		$\mathcal{O}_{eNlH}$	$(\bar{e}_{R\alpha} \gamma_\mu e_{R\beta})(\bar{l}^c_\gamma \gamma^\mu N_{Rt}) \tilde{H}^*$
$\mathcal{O}_{Nl1}$	$(\bar{l}^c_\alpha \gamma_\mu N_{Rt}) \epsilon (i D^\mu H)(H^\dagger H)$	$\mathcal{O}_{lNeH}$	$(\bar{l}_\alpha N_{Rs})(\bar{N}^c_{Rt} e_{R\beta}) \tilde{H}$
$\mathcal{O}_{Nl2}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}^c_\alpha \gamma^\mu N_{Rt}) \tilde{H}^*$	$\mathcal{O}_{elNH}$	$H^\dagger (\bar{e}_{R\alpha} l_\beta)(\bar{N}^c_{Rs} N_{Rt})$

[Magill, Plestid, Pospelov, Tsai, 18]

[Beltrán, Cepedello, Hirsch, 23]

[Fridell, Gráf, Hati, Harz, 23]

[Fernández-Martínez, González-López, Hernández-García, Hostert, López-Pavón, 23]

Chiral Basis

The couplings we use (g_S, f_{VV}, h_P etc.) are in the 'parity basis' of the WET + X

Keep in mind that these are matched onto SMEFT + X with SM fields Q, d, u, L, e

$$\frac{C_{d\phi}^{S,L}}{\Lambda}\bar{d}_R H^\dagger q\phi\,, \quad \frac{C_{d\phi}^{S,R}}{\Lambda}\bar{q} H d_R\phi \quad \Rightarrow \quad g_S(\bar{s}b)\phi, \quad g_P(s\gamma_5 b)\phi$$

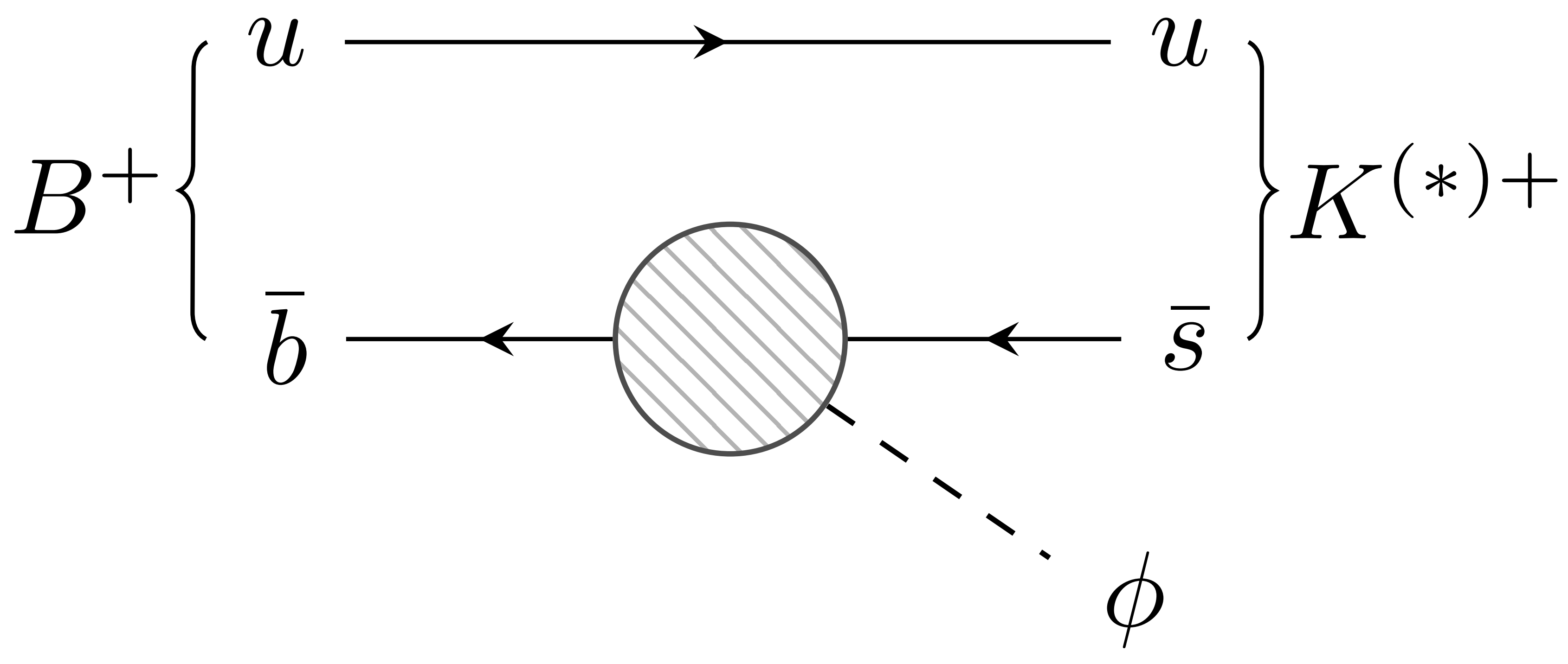
Matching looks something like:

$$\begin{pmatrix} g_S \\ g_P \end{pmatrix} = \frac{1}{2}\begin{pmatrix} 1 & 1 \\ -1 & 1 \end{pmatrix} \frac{v}{\sqrt{2}\Lambda} \begin{pmatrix} C_{d\phi}^{S,L} \\ C_{d\phi}^{S,R} \end{pmatrix}$$

Two-body Decay Rates: Scalar

$$\Gamma(B \to K\phi) = \frac{|g_S|^2}{8\pi} \frac{|\vec{p}_K|\, m_B^2 \delta_K^2}{(m_b - m_s)^2} f_0^2(m_\phi^2)$$

$$\Gamma(B \to K^*\phi) = \frac{|g_P|^2}{2\pi} \frac{|\vec{p}_{K^*}|^3}{(m_b + m_s)^2} A_0^2(m_\phi^2)$$



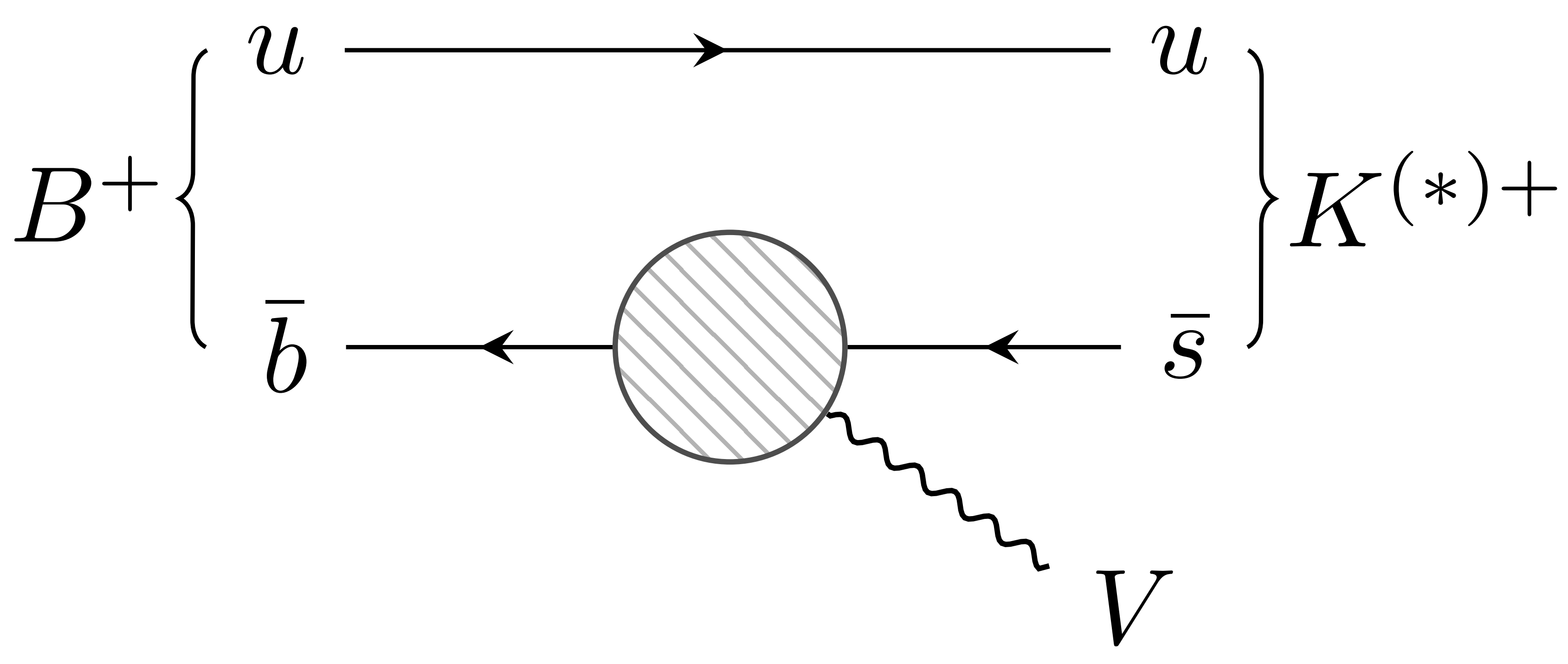
$$\delta_{K^{(*)}} = 1 - \frac{m_{K^{(*)}}^2}{m_B^2} \qquad |\vec{p}_{K^{(*)}}| = \frac{\lambda^{1/2}(m_B^2, m_\phi^2, m_{K^{(*)}}^2)}{2m_B}$$

$$\lambda(x,y,z) = (x - y - z)^2 - 4yz$$

Two-body Decay Rates: Vector

$$\Gamma(B \to KV) = \frac{|\vec{p}_K|}{2\pi}\left[|h_V|^2 \frac{|\vec{p}_K|^2}{m_V^2} f_+^2(m_V^2) + 4|h_T|^2 \frac{|\vec{p}_K|^2}{\Lambda^2}\frac{m_V^2}{(m_B+m_K)^2} f_T^2(m_V^2) - 4\,\Re[h_V h_T^*]\frac{|\vec{p}_K|^2}{(m_B+m_K)\Lambda} f_+(m_V^2) f_T(m_V^2)\right]$$

$$\Gamma(B \to K^*V) = \frac{|\vec{p}_{K^*}|}{2\pi}\left[2|h_V|^2 \frac{|\vec{p}_{K^*}|^2}{(m_B+m_{K^*})^2} V^2(m_V^2) + |h_A|^2\left(\frac{(m_B+m_{K^*})^2}{2m_B^2}A_1^2(m_V^2) + \frac{16m_{K^*}^2}{m_V^2}A_{12}^2(m_V^2)\right) + 8|h_T|^2\frac{|p_{K^*}|^2}{\Lambda^2}T_1^2(m_V^2) + 2|h_{\tilde{T}}|^2\frac{m_V^2}{\Lambda^2}\left(\frac{m_B^2\delta_{K^*}^2}{m_V^2}T_2^2(m_V^2) + \frac{8m_{K^*}^2}{(m_B+m_{K^*})^2}T_{23}^2(m_V^2)\right) + 8\,\Re[h_V h_T^*]\frac{|\vec{p}_{K^*}|^2}{(m_B+m_{K^*})\Lambda}V(m_V^2)T_1(m_V^2) + 2\,\Re[h_A h_{\tilde{T}}^*]\frac{m_B+m_{K^*}}{\Lambda}\left(\delta_{K^*}A_1(m_V^2)T_2(m_V^2) + \frac{16m_{K^*}^2}{(m_B+m_{K^*})^2}A_{12}(m_V^2)T_{23}(m_V^2)\right)\right]$$

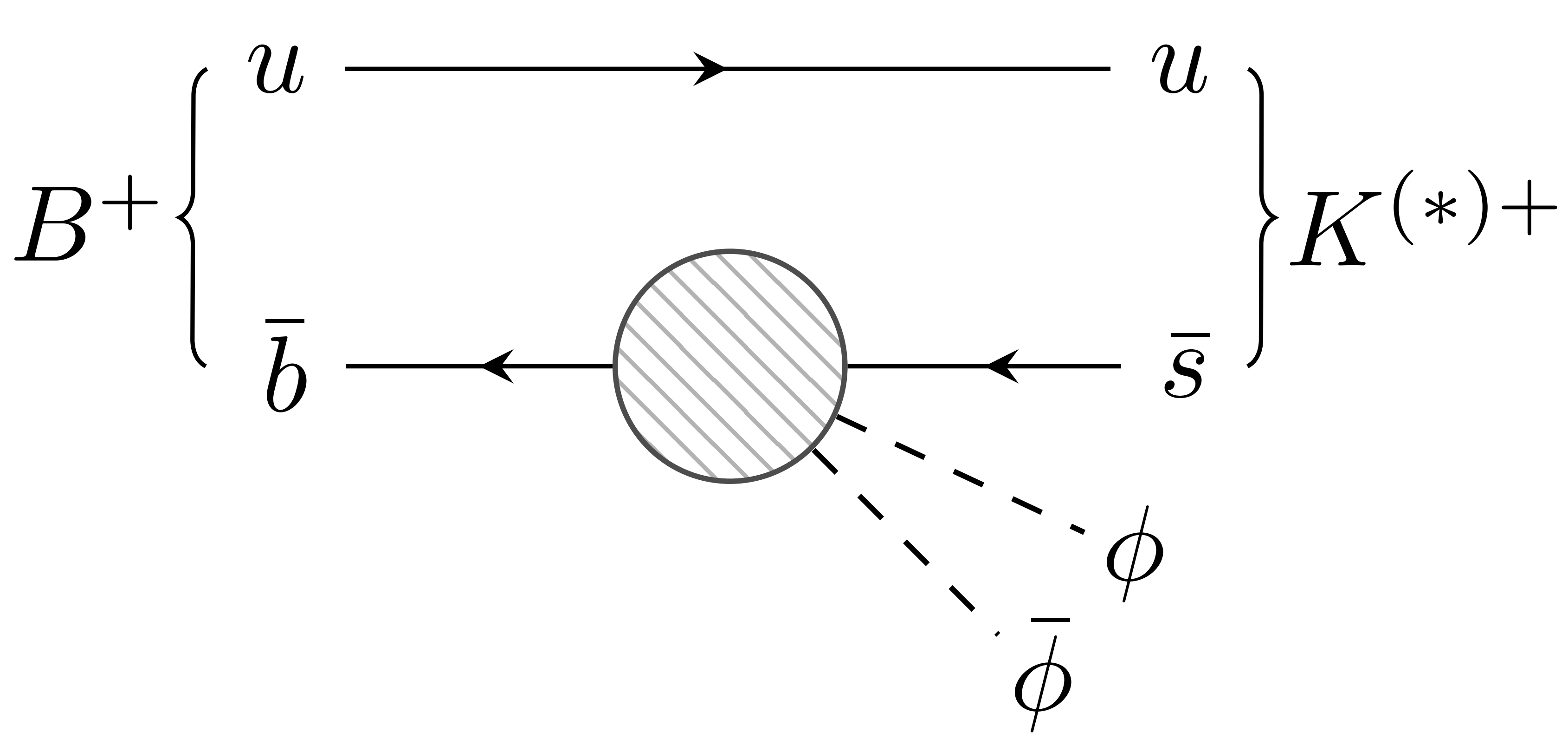


$$|\vec{p}_{K^{(*)}}| = \frac{\lambda^{1/2}(m_B^2, m_V^2, m_{K^{(*)}}^2)}{2m_B}$$

Three-body Decay Rates: Scalar

$$\frac{d\Gamma(B \to K\phi\bar{\phi})}{dq^2} = \frac{\beta_\phi}{96\pi^3}\frac{|\vec{p}_K|}{\Lambda^2}\left[\frac{3}{4}|g_{SS}|^2\frac{m_B^2\delta_K^2}{(m_b - m_s)^2}f_0^2(q^2) + |g_{VV}|^2\frac{|\vec{p}_K|^2}{\Lambda^2}\beta_\phi^2 f_+^2(q^2)\right]$$

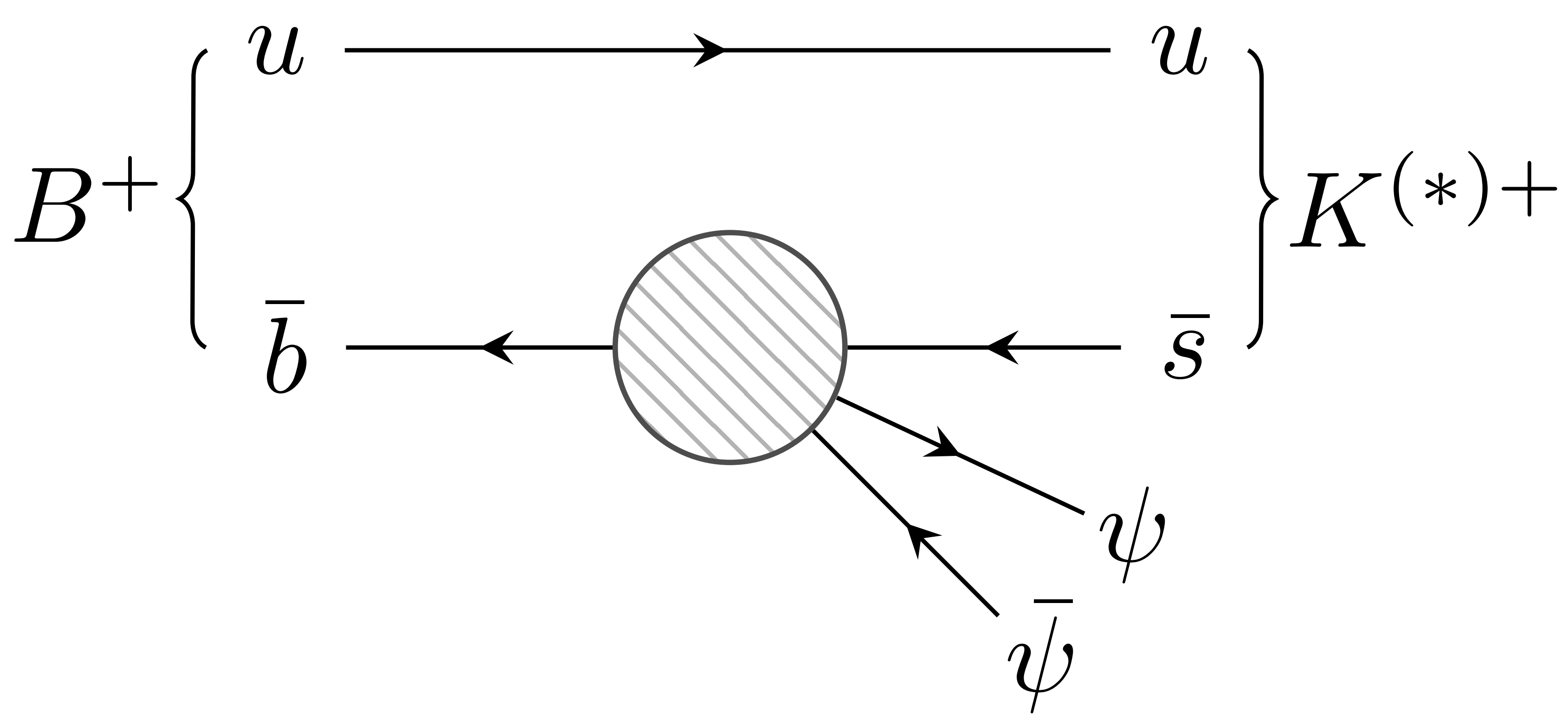
$$\frac{d\Gamma(B \to K^*\phi\bar{\phi})}{dq^2} = \frac{\beta_\phi}{96\pi^3}\frac{|\vec{p}_{K^*}|}{\Lambda^2}\Bigg[3|g_{PS}|^2\frac{|\vec{p}_{K^*}|^2}{(m_b + m_s)^2}A_0^2(q^2) + |g_{AV}|^2\frac{q^2}{\Lambda^2}\beta_\phi^2\left(\frac{(m_B + m_{K^*})^2}{2m_B^2}A_1^2(q^2) + \frac{16m_{K^*}^2}{q^2}A_{12}^2(q^2)\right)\Bigg]$$



$$|\vec{p}_{K^{(*)}}| = \frac{\lambda^{1/2}(m_B^2, q^2, m_{K^{(*)}}^2)}{2m_B}$$

Three-body Decay Rates: Fermion

$$\frac{d\Gamma(B \to K\psi\bar{\psi})}{dq^2} = \frac{\beta_\psi}{24\pi^3}\frac{|\vec{p}_K|q^2}{\Lambda^4}$$
$$\times \Bigg[\bigg(\Big(|f_{VV}|^2\beta_\psi'^2 + |f_{VA}|^2\beta_\psi^2\Big)f_+(q^2) + 12\,\Re\big[f_{VV}f_{TT}^*\big]\frac{m_\psi}{m_B+m_K}f_T(q^2)\bigg)\frac{|\vec{p}_K|^2}{q^2}f_+(q^2)$$
$$+\frac{3}{8}\bigg(4|f_{VA}|^2\frac{m_\psi^2(m_b-m_s)^2}{q^4} + |f_{SS}|^2\beta_\psi^2 + |f_{SP}|^2 + 4\,\Re\big[f_{VA}f_{SP}^*\big]\frac{m_\psi(m_b-m_s)}{q^2}\bigg)\frac{m_B^2\delta_K^2}{(m_b-m_s)^2}f_0^2(q^2)$$
$$+2\Big(|f_{TT}|^2\beta_\psi''^2 + |f_{\tilde{T}T}|^2\beta_\psi^2\Big)\frac{|\vec{p}_K|^2}{(m_B+m_K)^2}f_T^2(q^2)\Bigg]$$

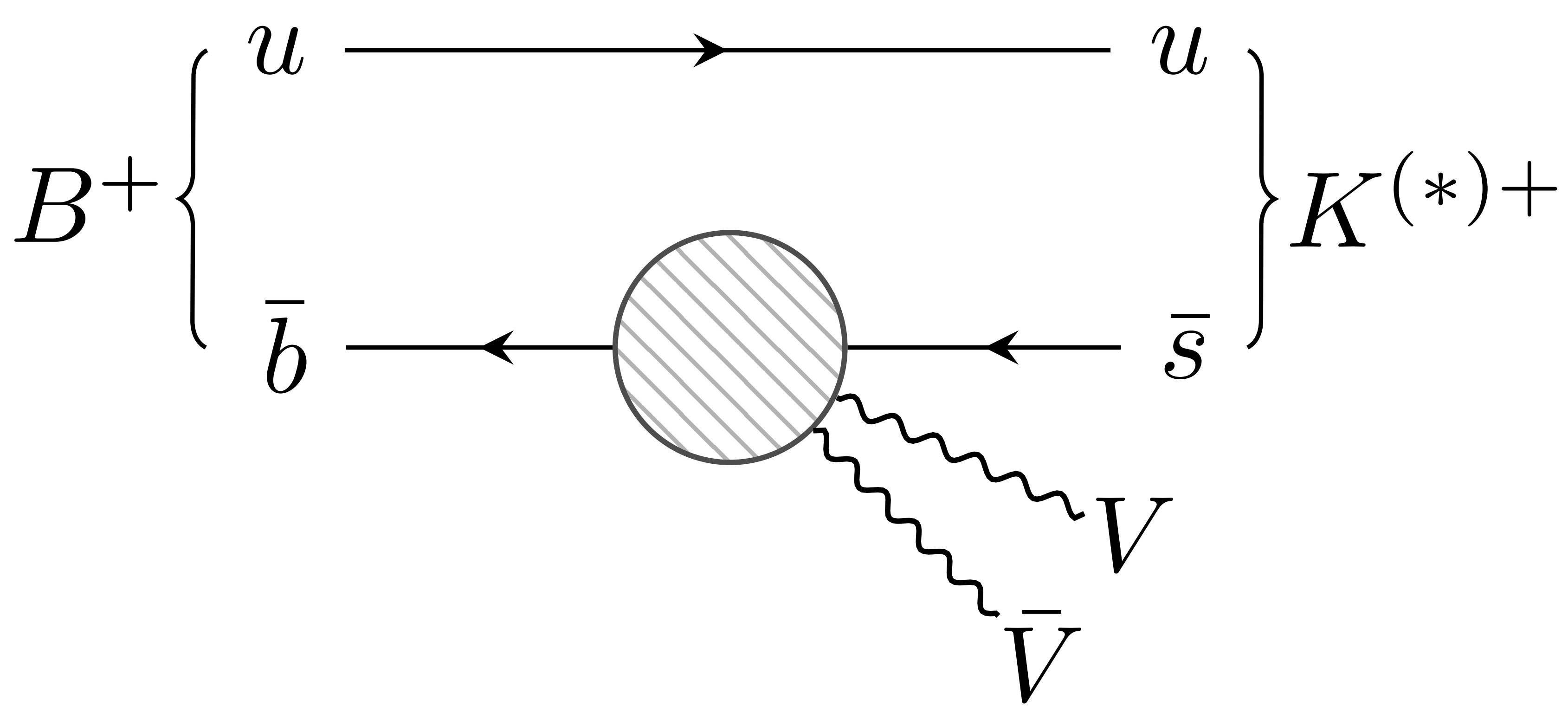


For $B \to K^*\psi\bar{\psi}$, see Appendix B of arXiv:2403.13887

$$\beta_X = \sqrt{1 - \frac{4m_X^2}{q^2}} \qquad |\vec{p}_{K^{(*)}}| = \frac{\lambda^{1/2}(m_B^2, q^2, m_{K^{(*)}}^2)}{2m_B}$$

Three-body Decay Rates: Vector

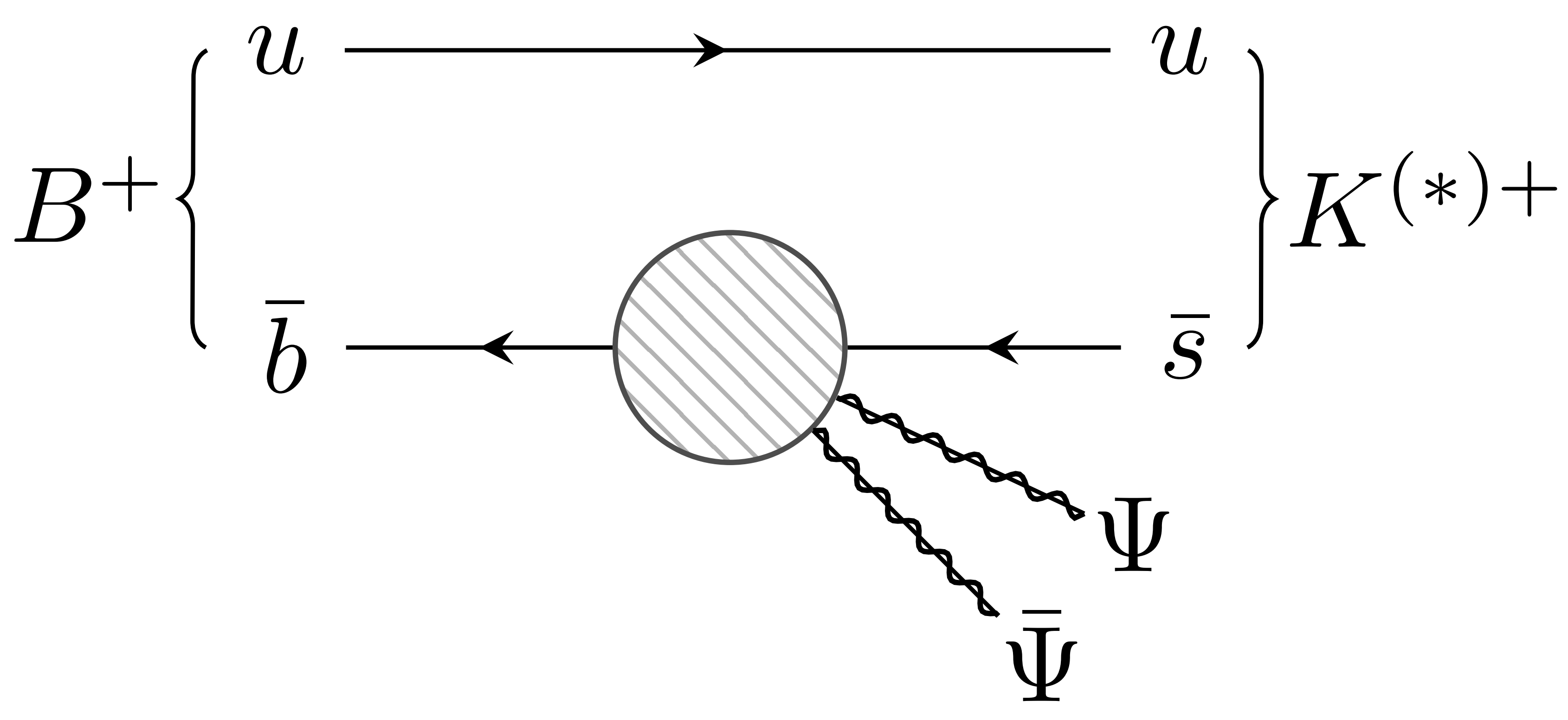
$$\frac{d\Gamma(B \to KV\bar{V})}{dq^2} = \frac{\beta_V |h_S|^2}{512\pi^3} \frac{|\vec{p}_K| q^4}{m_V^2 \Lambda^2} \mathcal{J}_V \frac{m_B^2 \delta_K^2}{(m_b - m_s)^2} f_0^2(q^2)$$



$$|\vec{p}_{K^{(*)}}| = \frac{\lambda^{1/2}(m_B^2, q^2, m_{K^{(*)}}^2)}{2m_B}$$

Three-body Decay Rates: Spin 3/2

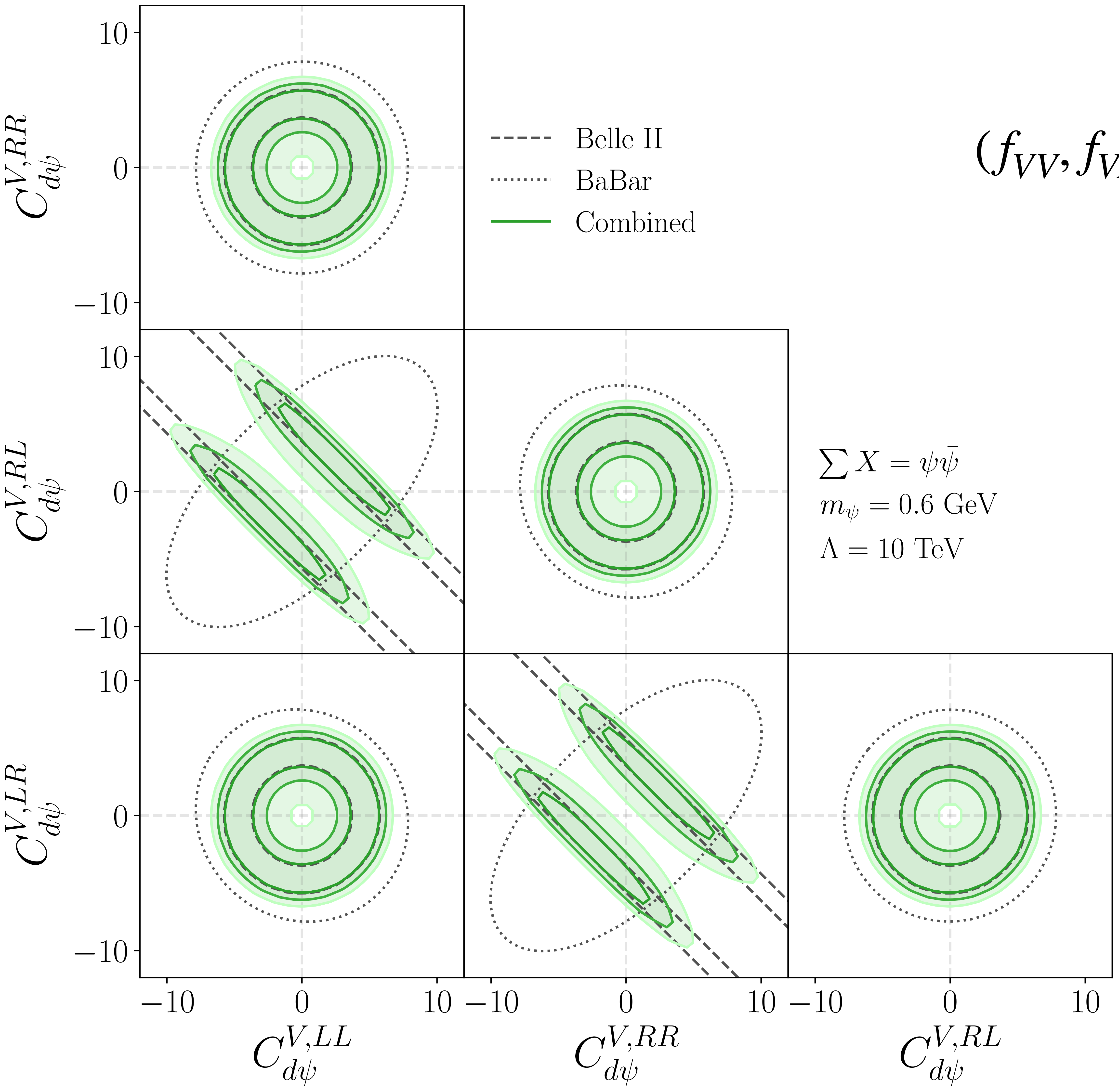
$$\frac{d\Gamma(B\to K\Psi\bar{\Psi})}{dq^2} = \frac{\beta_\Psi}{216\pi^3}\frac{|\vec{p}_K|q^6}{m_\Psi^4\Lambda^4}$$
$$\times\Bigg[\Bigg(\Big(|F_{VV}|^2\mathcal{J}_{VV}+|F_{VA}|^2\beta_\Psi^2\mathcal{J}_{VA}\Big)f_+(q^2)$$
$$+2\,\Re\Big[F_{VV}\Big(6F^*_{TT}\mathcal{J}_{VV,TT}+2F^*_{TS}\beta_\Psi^4+F^*_{\tilde{T}P}\mathcal{J}_{VV,\tilde{T}P}\Big)\Big]\frac{m_\Psi}{m_B+m_K}f_T(q^2)\Bigg)\frac{|\vec{p}_K|^2}{q^2}f_+(q^2)$$
$$+\frac{3}{8}\Bigg(|F_{VA}|^2(1-\beta_\Psi^2)\mathcal{J}_\Psi\frac{(m_b-m_s)^2}{q^2}$$
$$+|F_{SS}|^2\beta_\Psi^2\mathcal{J}'_\Psi+|F_{SP}|^2\mathcal{J}_\Psi+4\,\Re\big[F_{VA}F^*_{SP}\big]\mathcal{J}_\Psi\frac{m_\Psi(m_b-m_s)}{q^2}\Bigg)\frac{m_B^2\delta_K^2}{(m_b-m_s)^2}f_0^2(q^2)$$
$$+2\Bigg(|F_{TT}|^2\mathcal{J}_{TT}+\frac{1}{4}|F_{TS}|^2\beta_\Psi^4\mathcal{J}_{TS}+\frac{1}{4}|F_{TP}|^2\beta_\Psi^2\mathcal{J}_{TP}$$
$$+|F_{\tilde{T}T}|^2\beta_\Psi^2\mathcal{J}_\Psi+\frac{3}{16}|F_{\tilde{T}S}|^2\beta_\Psi^2(1-\beta_\Psi^2)\mathcal{J}_{\tilde{T}S}+\frac{5}{16}|F_{\tilde{T}P}|^2\beta'^2_\Psi(1-\beta_\Psi^2)$$
$$+\Re\Bigg[F_{TT}\Bigg(F^*_{TS}\beta_\Psi^4\mathcal{J}_{TT,TS}+\frac{5}{4}F^*_{\tilde{T}P}\beta'^2_\Psi(1-\beta_\Psi^2)\Bigg)-\frac{1}{2}F_{TP}F^*_{\tilde{T}S}\beta_\Psi^2(1-\beta_\Psi^2)$$
$$+F_{\tilde{T}T}\Bigg(F^*_{TP}\beta_\Psi^2\mathcal{J}_{\tilde{T}T,TP}-\frac{1}{4}F^*_{\tilde{T}S}\beta_\Psi^2(1-\beta_\Psi^2)\mathcal{J}_{\tilde{T}T,\tilde{T}S}\Bigg)\Bigg]\Bigg)\frac{|\vec{p}_K|^2}{(m_B+m_K)^2}f_T^2(q^2)\Bigg],$$



$$|\vec{p}_{K^{(*)}}| = \frac{\lambda^{1/2}(m_B^2, q^2, m_{K^{(*)}}^2)}{2m_B}$$

For definition of $\mathcal{J}_X$ factors, see Appendix B of arXiv:2403.13887

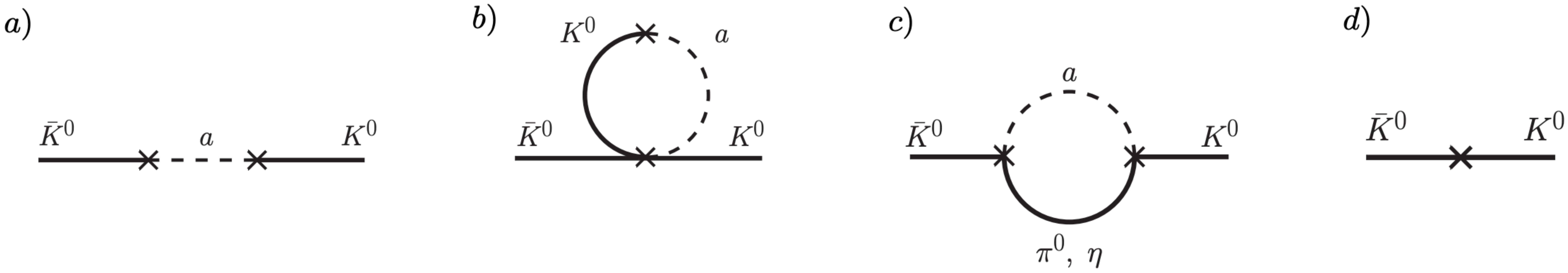
Fermion Constraints in Chiral Basis



$$(f_{VV}, f_{VA}, f_{AV}, f_{AA}) \Rightarrow (C_{d\psi}^{V,LL}, C_{d\psi}^{V,LR}, C_{d\psi}^{V,RL}, C_{d\psi}^{V,RR})$$

$B_s \to \bar{B}_s$ Mixing

Neutral meson mixing can be induced by the scalar ϕ

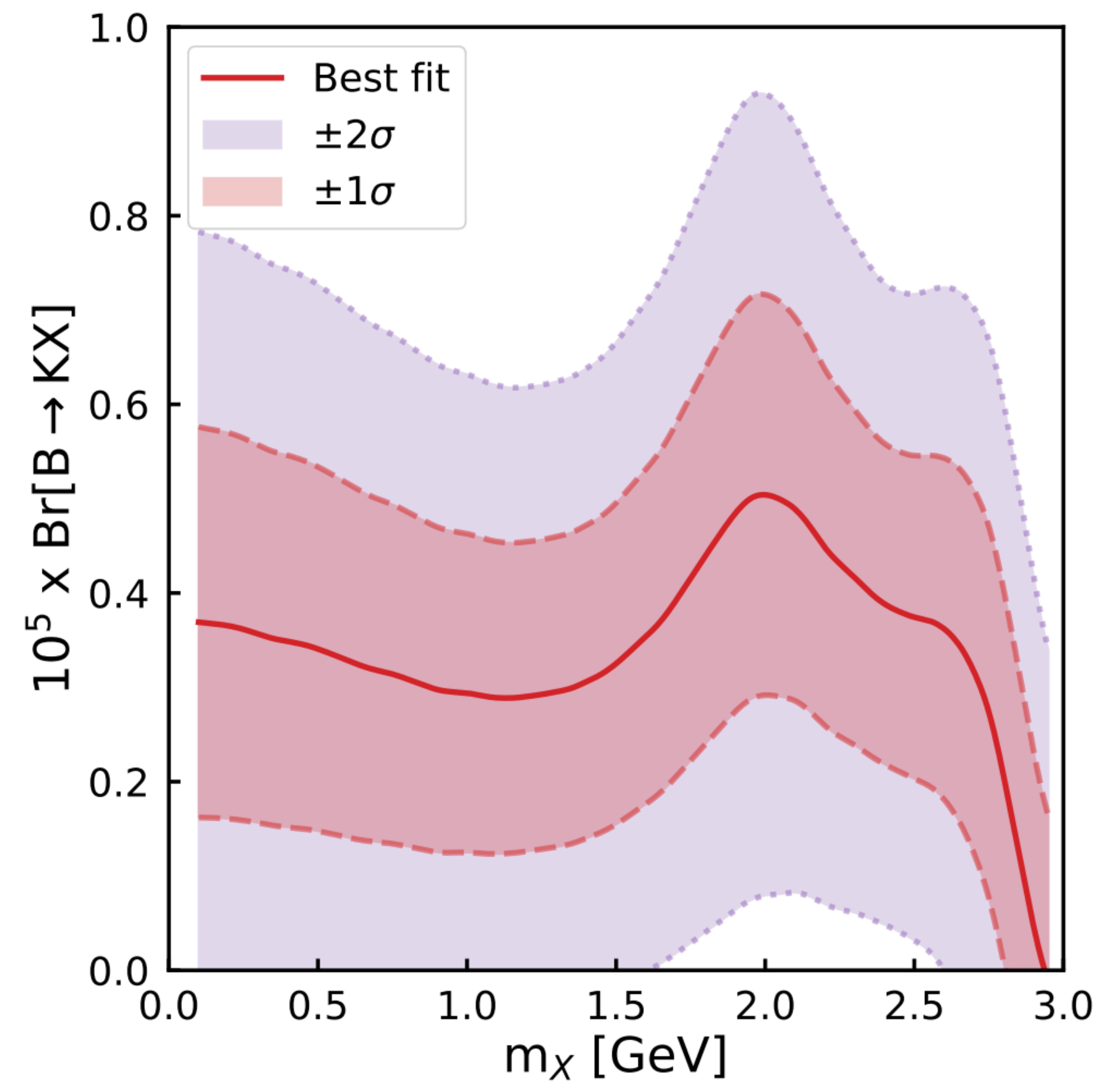


$$|g_S| = m_b \frac{|g_V|}{\Lambda} \lesssim 10^{-5}$$

[Camalich, Pospelov, Vuong, Ziegler, Zupan, 20]

Comparison with other Analyses

Comparison: Invisible Scalar(s)



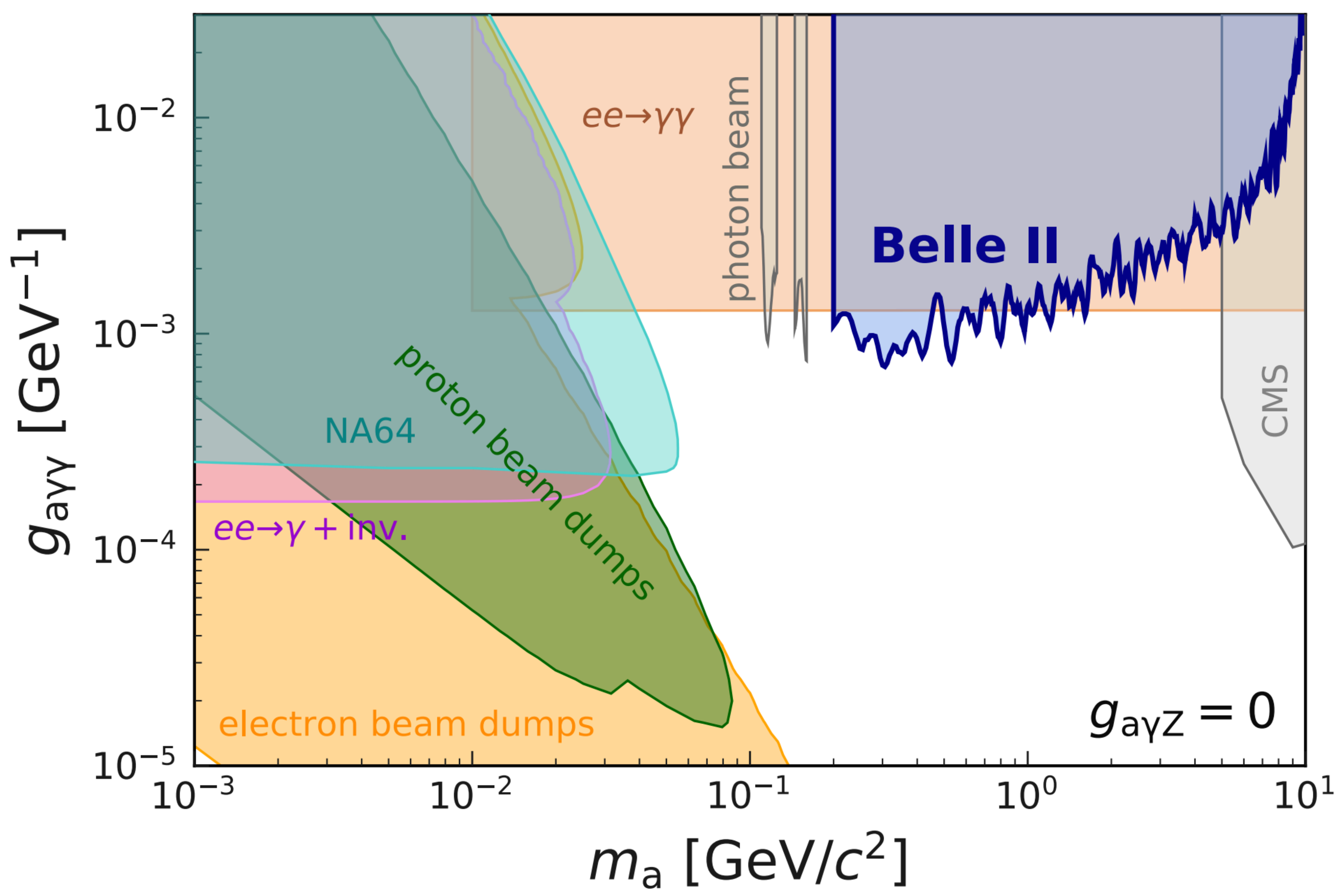
An axion-like particle (ALP) has been considered via the couplings

$$\mathcal{H}_{\text{eff}} \supset \bar{s}\gamma_\nu(g_V + g_A\gamma_5)b\frac{\partial^\mu a}{2f}$$

These couplings are directly related to g_S and g_P

Result of their fit is also $m_a \sim 2$ GeV

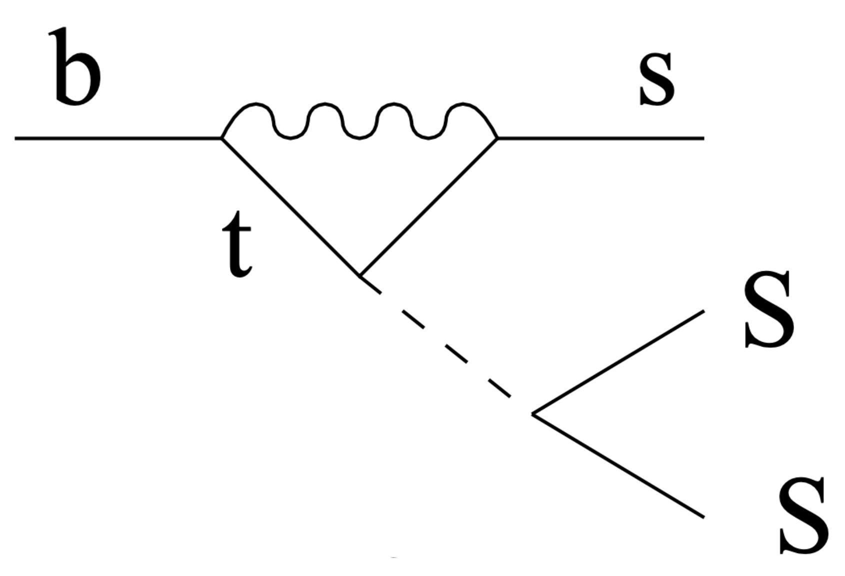
Aside: Belle II has also looked for ALPS via $e^+e^- \to \gamma a$



[Altmannshofer, Crivellin, Haigh, Inguglia, Camalich, 24]

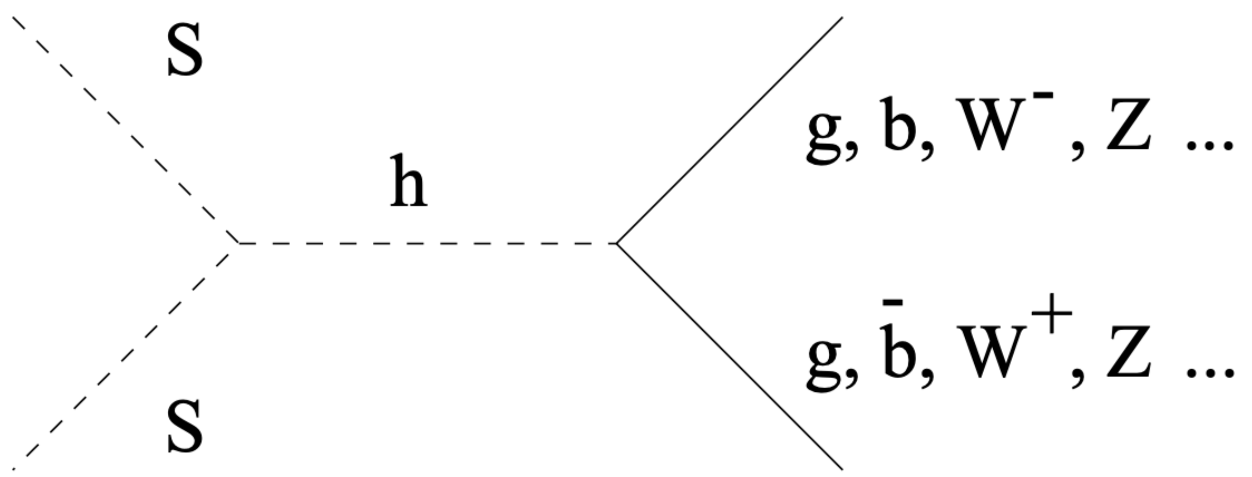
Comparison: Invisible Scalar(s)

The scalar ϕ via Higgs portal has been considered before as a DM candidate:



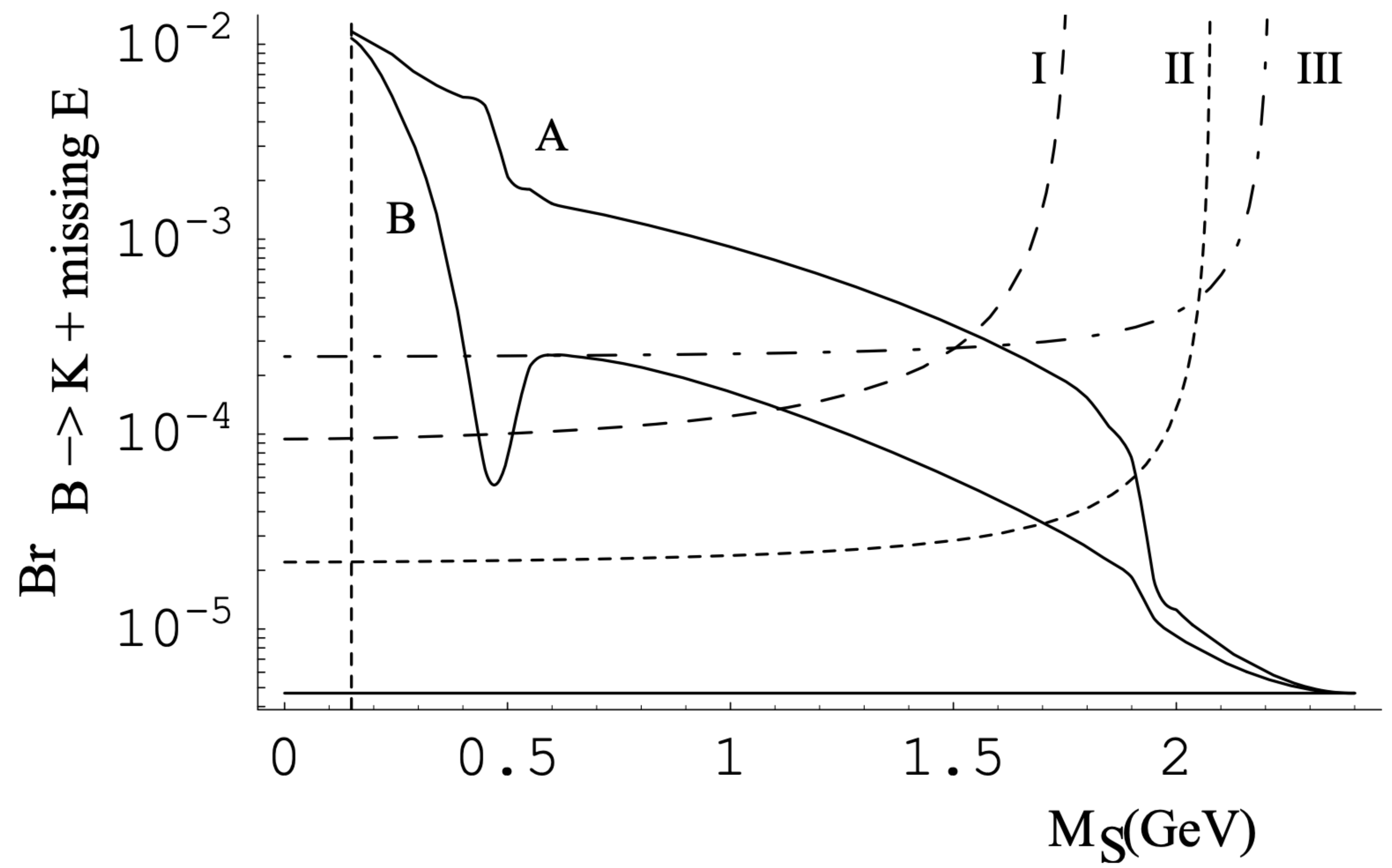
$$\mathcal{H}_{\rm eff}^{S} \supset \frac{1}{2} C^{S,R}_{d\phi\phi} m_b (\bar{s} P_R b) \phi^2$$

$$C^{S,R}_{d\phi\phi} = \frac{\lambda'}{m_h^2} \frac{3 g^2 V_{ts}^* V_{tb}}{32\pi^2} \frac{m_t^2}{m_W^2}$$



$$\Omega_{\rm DM} h^2 = \frac{\left(1.07 \times 10^9\right)}{g_*^{1/2} M_{\rm Pl} {\rm GeV} \langle \sigma v_{\rm rel} \rangle} \frac{m_\phi}{T_f}$$

$$\mathcal{B}(h \to {\rm inv.}) < 0.107 \text{ (90\% CL)}$$

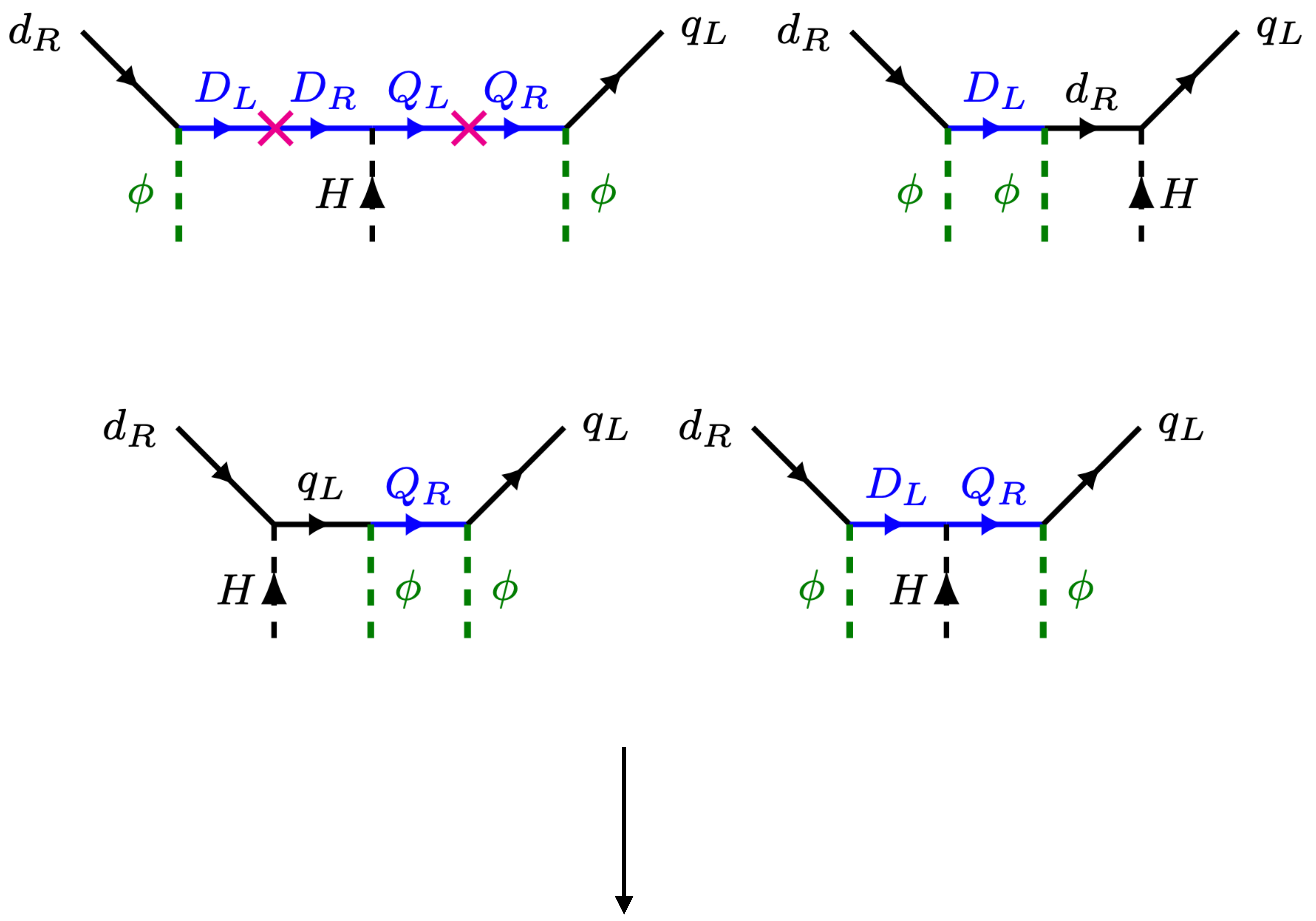


[Burgess, Pospelov, ter Veldhuis, 01]

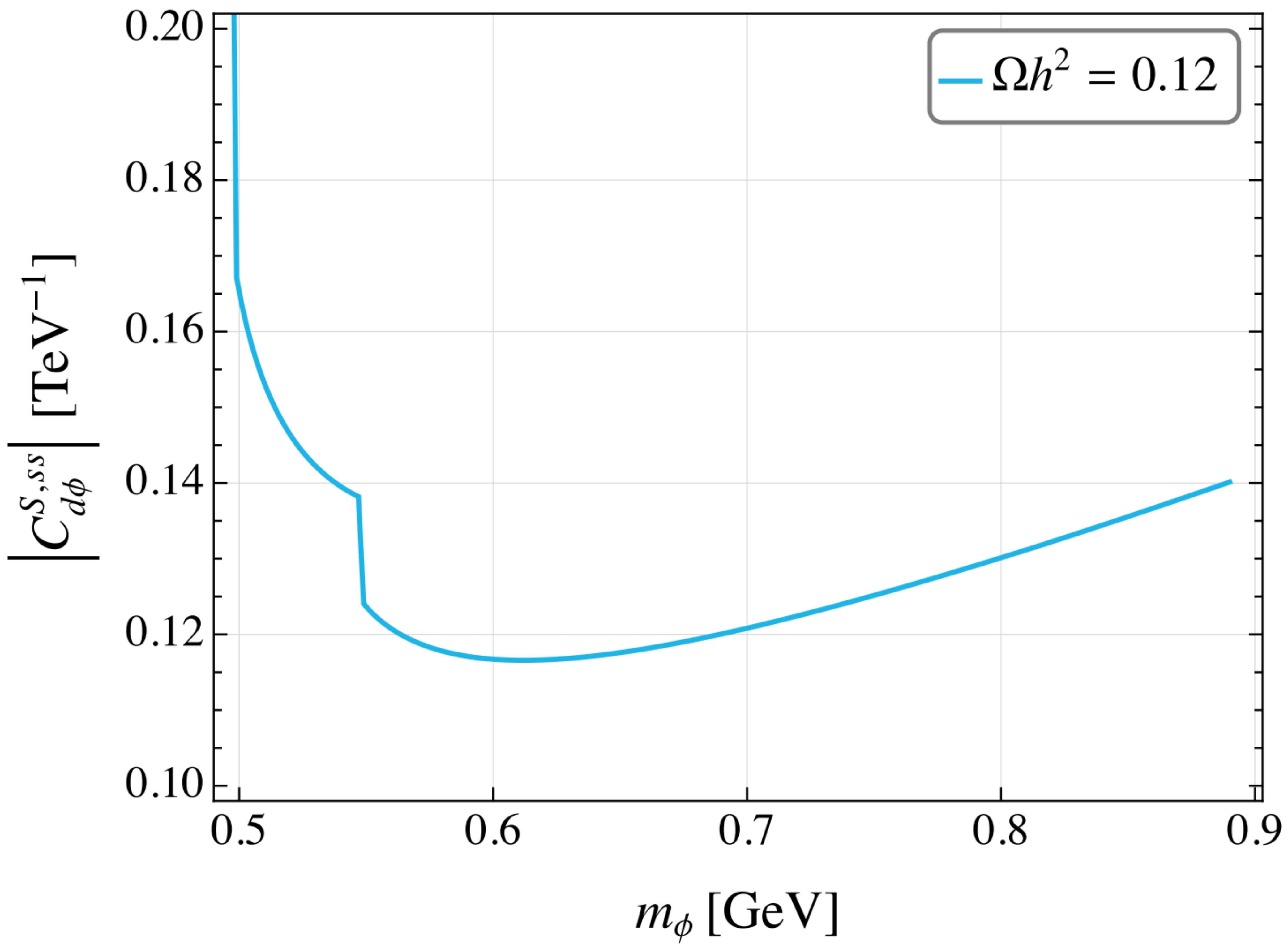
[Bird, Jackson, Kowalewski, Pospelov, 04]

Comparison: Invisible Scalar(s)

The scalar ϕ via another UV model: $Q \sim (\mathbf{3}, \mathbf{2}, 1/6)$ $D \sim (\mathbf{3}, \mathbf{1}, -1/3)$



$$C^{S,L(R)}_{d\phi\phi}\,,\ C^{S,L(R)}_{u\phi\phi}$$



[He, Ma, Schmidt, Valencia, Volkas, 24]

Comparison: Invisible Fermion(s)

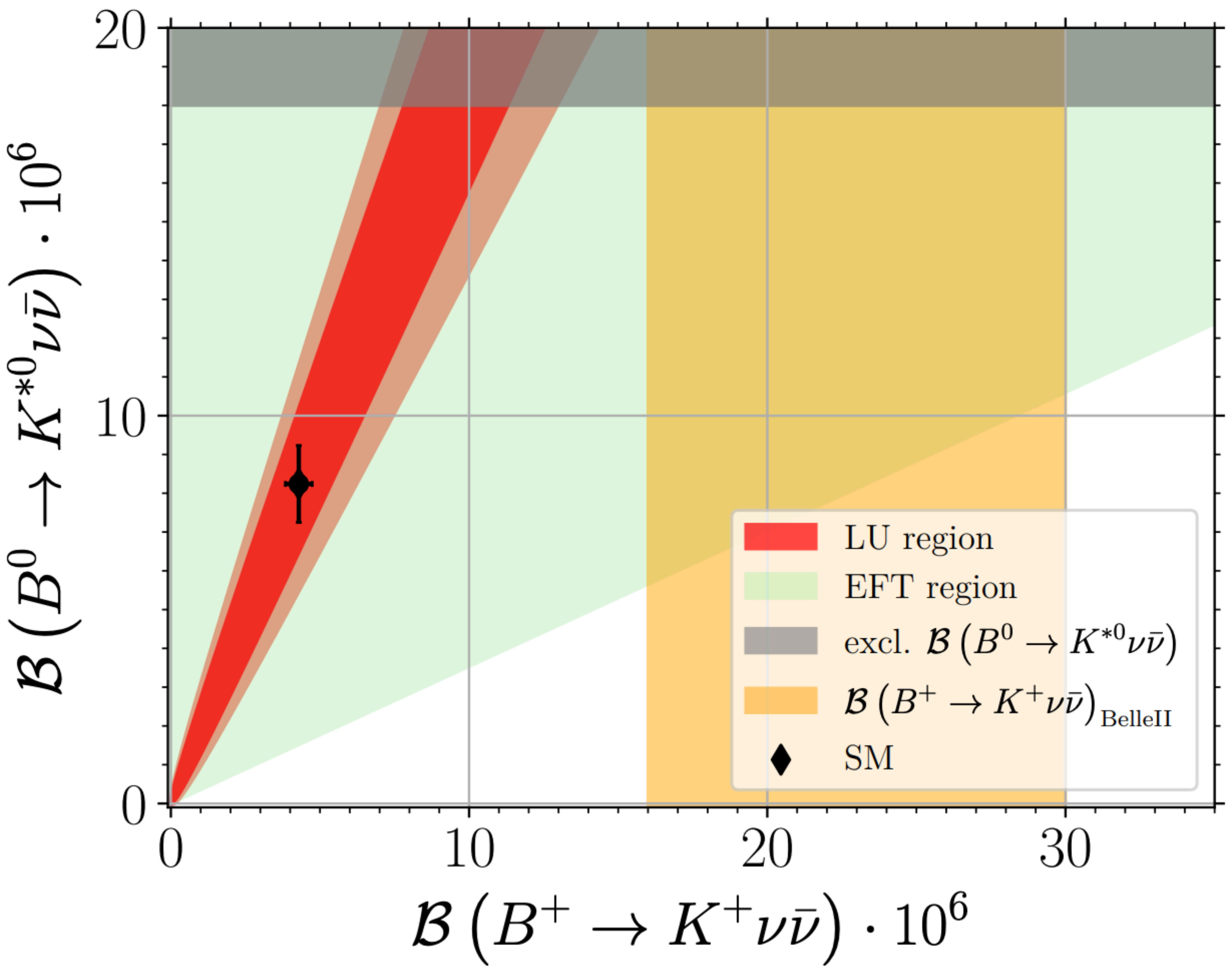
The invisible fermion scenario includes the (massless) SM neutrinos ($m_\psi = 0$) via:

$$\mathcal{H}_{\text{eff}}^{\nu\nu} \supset C_{d\nu}^{V,LL}(\bar{s}\gamma_\mu P_L b)(\bar{\nu}_L \gamma^\mu \nu_L) + \supset C_{d\nu}^{V,RL}(\bar{s}\gamma_\mu P_R b)(\bar{\nu}_L \gamma^\mu \nu_L) + \text{h.c.}$$

Two possibilities: 1) Lepton flavour universal or 2) non-universal

1) Belle II and BaBar: Large contribution needed from $C_{d\nu}^{V,RL}$
$\Rightarrow$ Constrained by $B \to K^{(*)+}\mu^+\mu^-$ and $B_s \to \mu^+\mu^-$

2) LFU favoured with $C_{d\nu}^{V,XL}$ for ν_τ



[Bause, Gisbert, Hiller, 23]

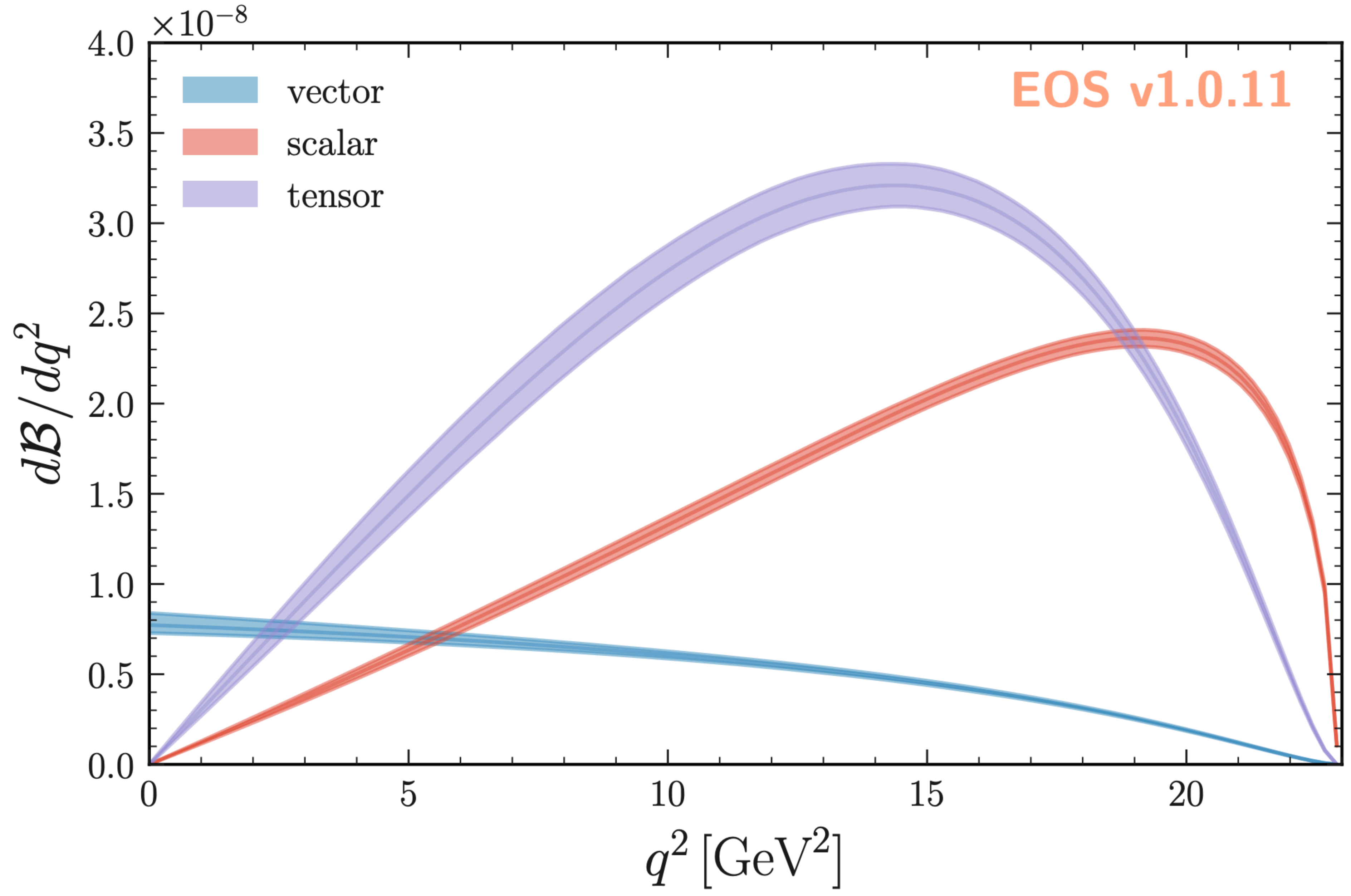
[Athron, Martinez, Sierra, 23]

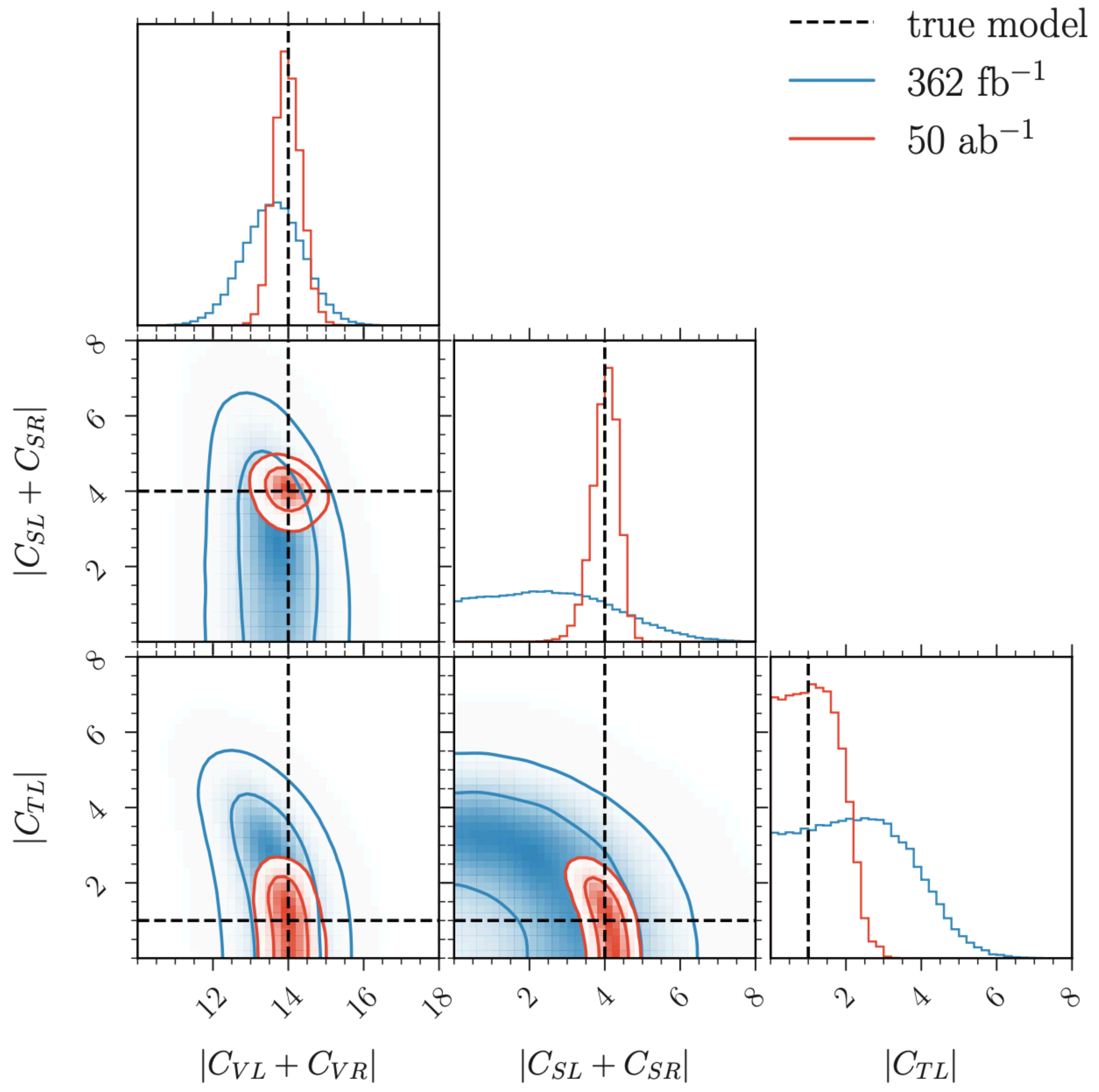
[Allwicher, Bečirević, Piazza, Rosauro-Alcaraz, Sumensari, 23]

Comparison: Invisible Fermion(s)

Massive SM neutrinos ($m_\psi \lesssim 1$ eV) via

$$\mathcal{H}_{\text{eff}}^{\nu\nu} \supset C_{d\nu}^{V,XL}(\bar{s}\gamma_\mu P_X b)(\bar{\nu}_L\gamma^\mu \nu_L) + C_{d\nu}^{S,XL}(\bar{s}P_X b)(\bar{\nu}_L^c \nu_L) + C_{d\nu}^{T,LL}(\bar{s}_R\sigma_{\mu\nu}b_L)(\bar{\nu}_L^c\sigma^{\mu\nu}\nu_L) + \text{h.c.}$$





Problem: Large corrections to m_ν

[Fridell, Graf, Harz, Hati, 24]

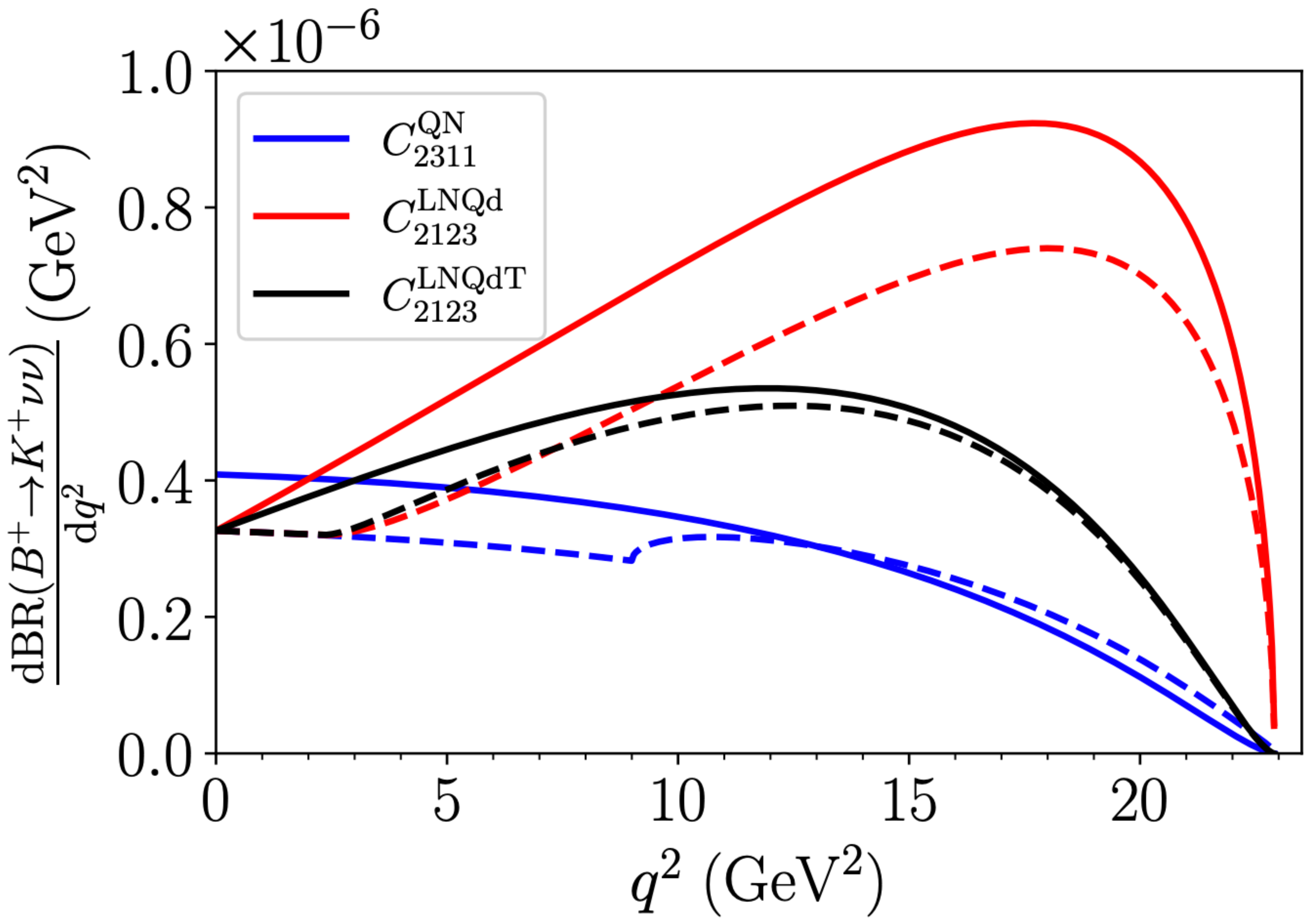
[Gärtner et al., 24]

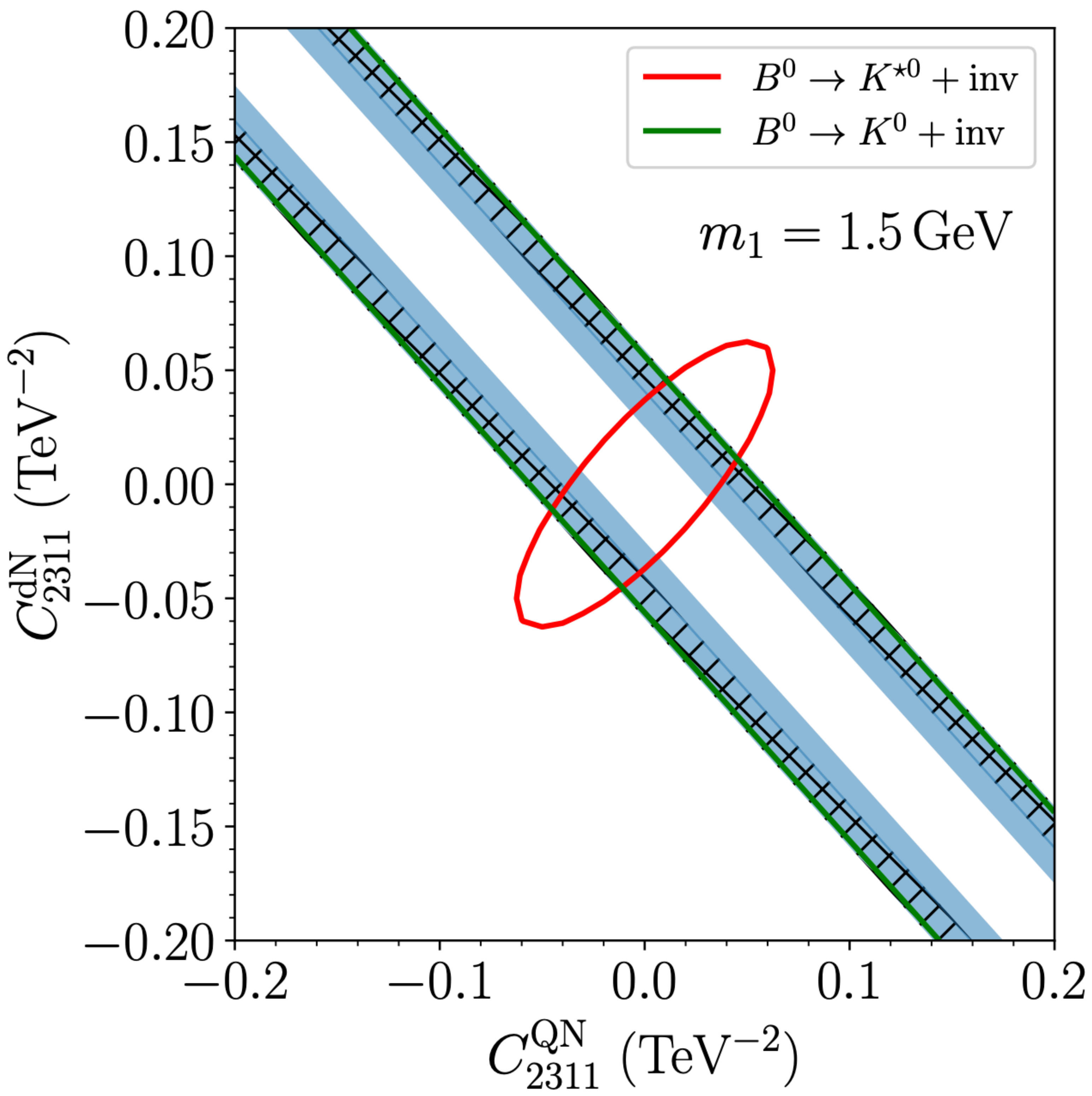
Comparison: Invisible Fermion(s)

Massive SM neutrinos plus N_R in EFT picture

$$\mathcal{H}_{\text{eff}}^{\nu\nu} \supset C_{d\nu}^{V,XL}(\bar{s}\gamma_\mu P_X b)(\bar{\nu}_L\gamma^\mu \nu_L) + C_{d\nu}^{S,XL}(\bar{s}P_X b)(\bar{\nu}_L^c \nu_L) + C_{d\nu}^{T,LL}(\bar{s}_R\sigma_{\mu\nu} b_L)(\bar{\nu}_L^c \sigma^{\mu\nu}\nu_L) + \text{h.c.}$$

Now with $\nu_{L\alpha} = N^c_{R(\alpha-3)}$ for $\alpha > 3$





[Felkl, Li, Schmidt, 21]

[Felkl, Giri, Mohanta, Schmidt, 23]

Comparison: Invisible Vector(s)

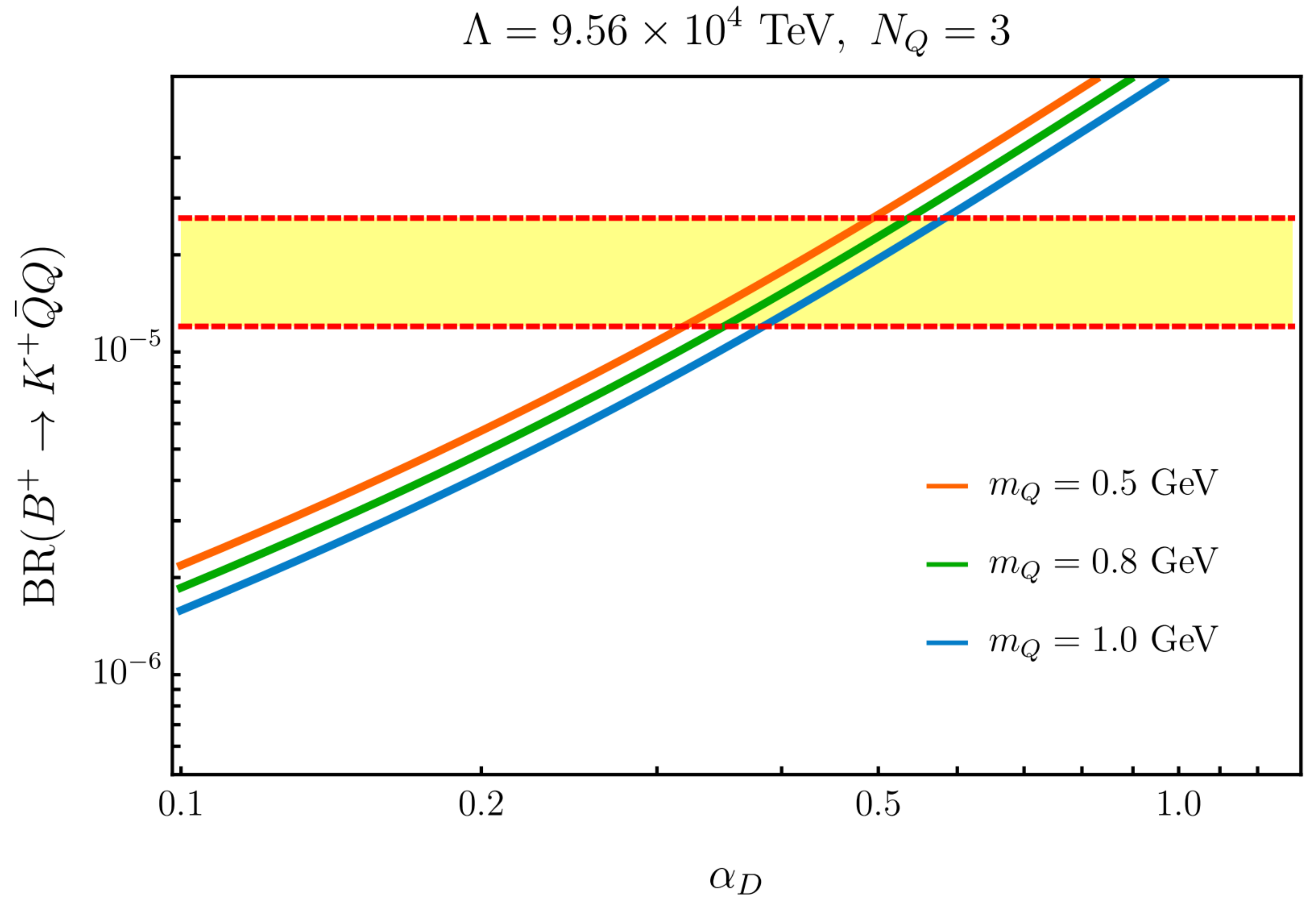
Massless dark photon ($V = \gamma_D$) via dipole operator has been considered $\mathcal{H}^T_{\rm eff} \supset \frac{h_T}{\Lambda}(\bar{s}\sigma_{\mu\nu}b)V^{\mu\nu} + \text{h.c.}$

The rate for $B \to K\gamma_D$ vanishes (but not $B \to K^*\gamma_D$) due to angular momentum conservation

$$\Gamma(B \to KV) = \frac{2|\vec{p}_K|^3}{\pi\Lambda^2}|h_T|^2 \frac{m_V^2}{(m_B + m_K)^2} f_T^2(m_V^2)$$

Consider γ_D coupling to dark fermions Q:

Fit to Belle II $m_Q \sim 0.6$ GeV

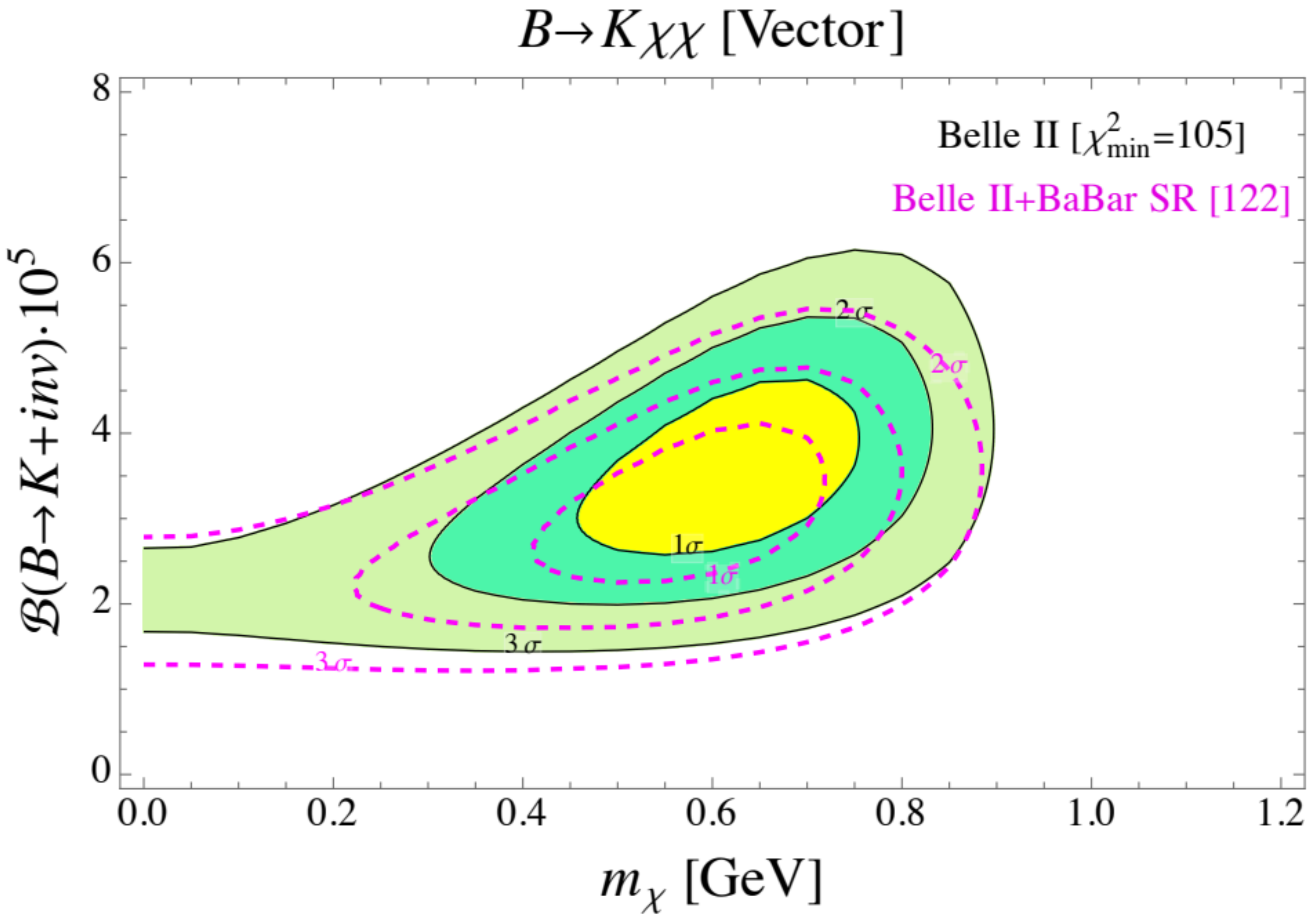


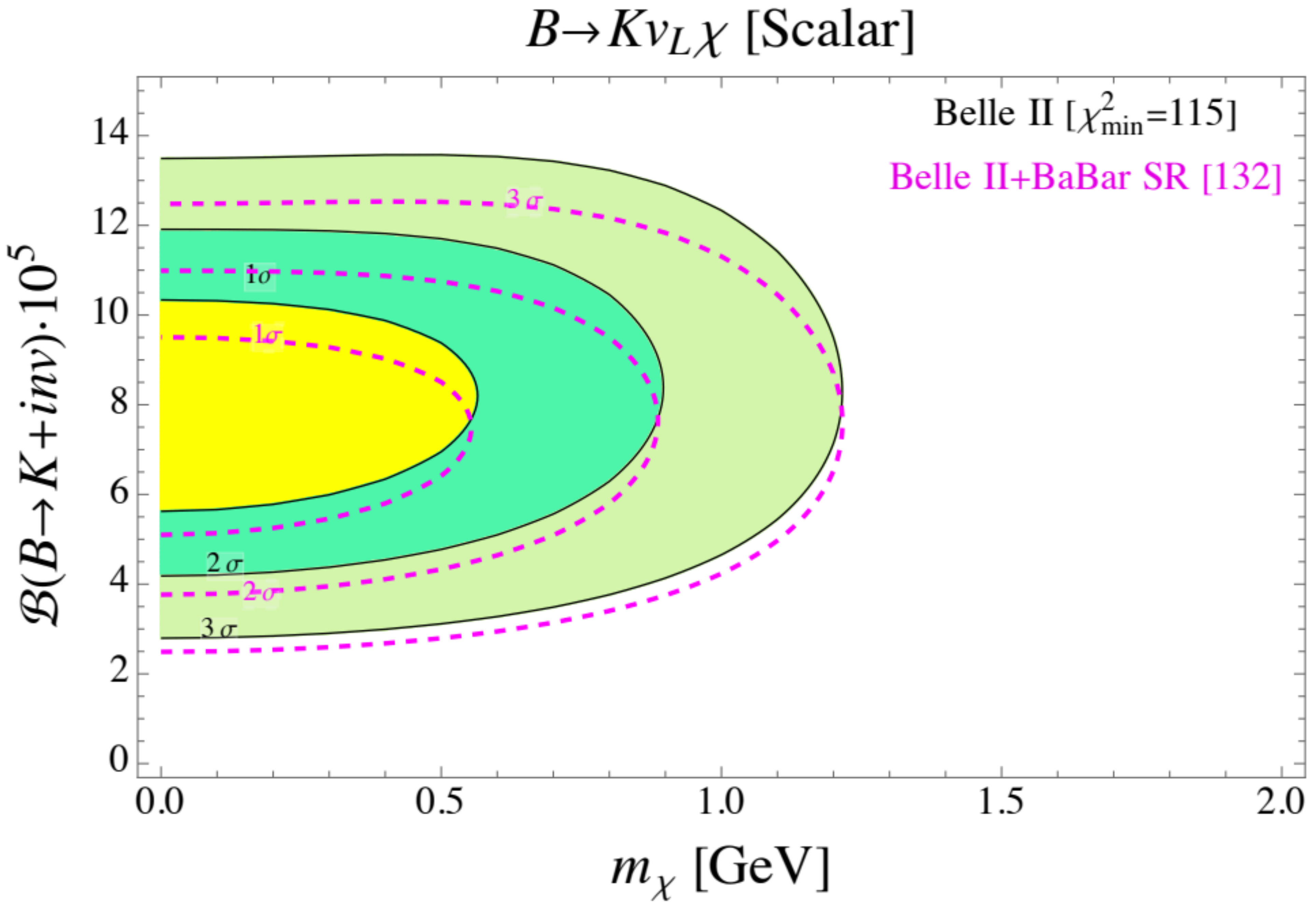
[Gabrielli, Marzola, Müürsepp, Raidal, 24]

Comparison: Invisible Fermion(s)

Other results for generic fermions ψ:

Fridell, Ghosh, Okui and Tobioka perform a binned fit using only $B \to K\nu\bar{\nu}$ Belle II and BaBar data:
$\Rightarrow$ Only couplings that do not contribute to $B \to K^*\nu\bar{\nu}$





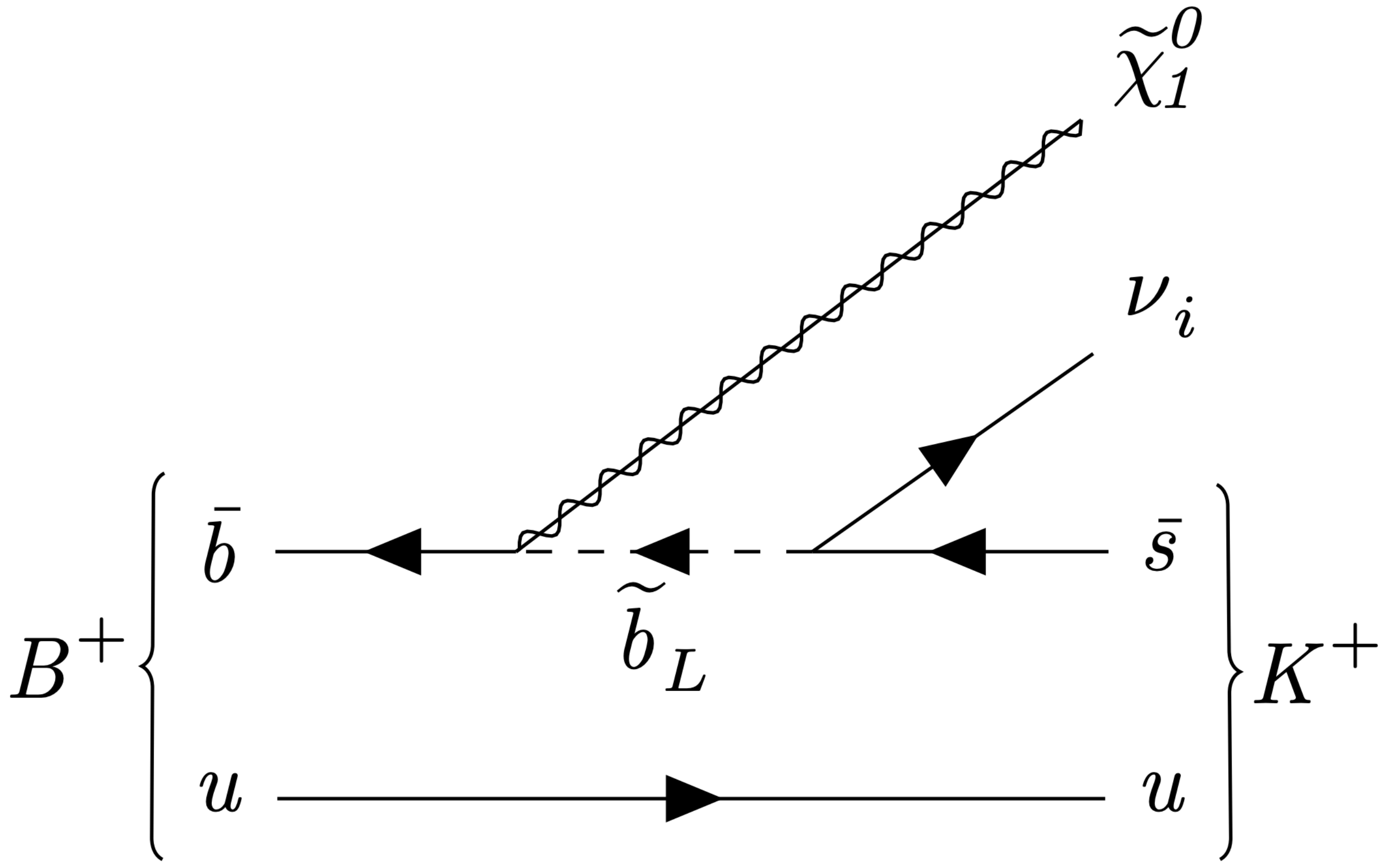
[Fridell, Ghosh, Okui, Tobioka, 24]

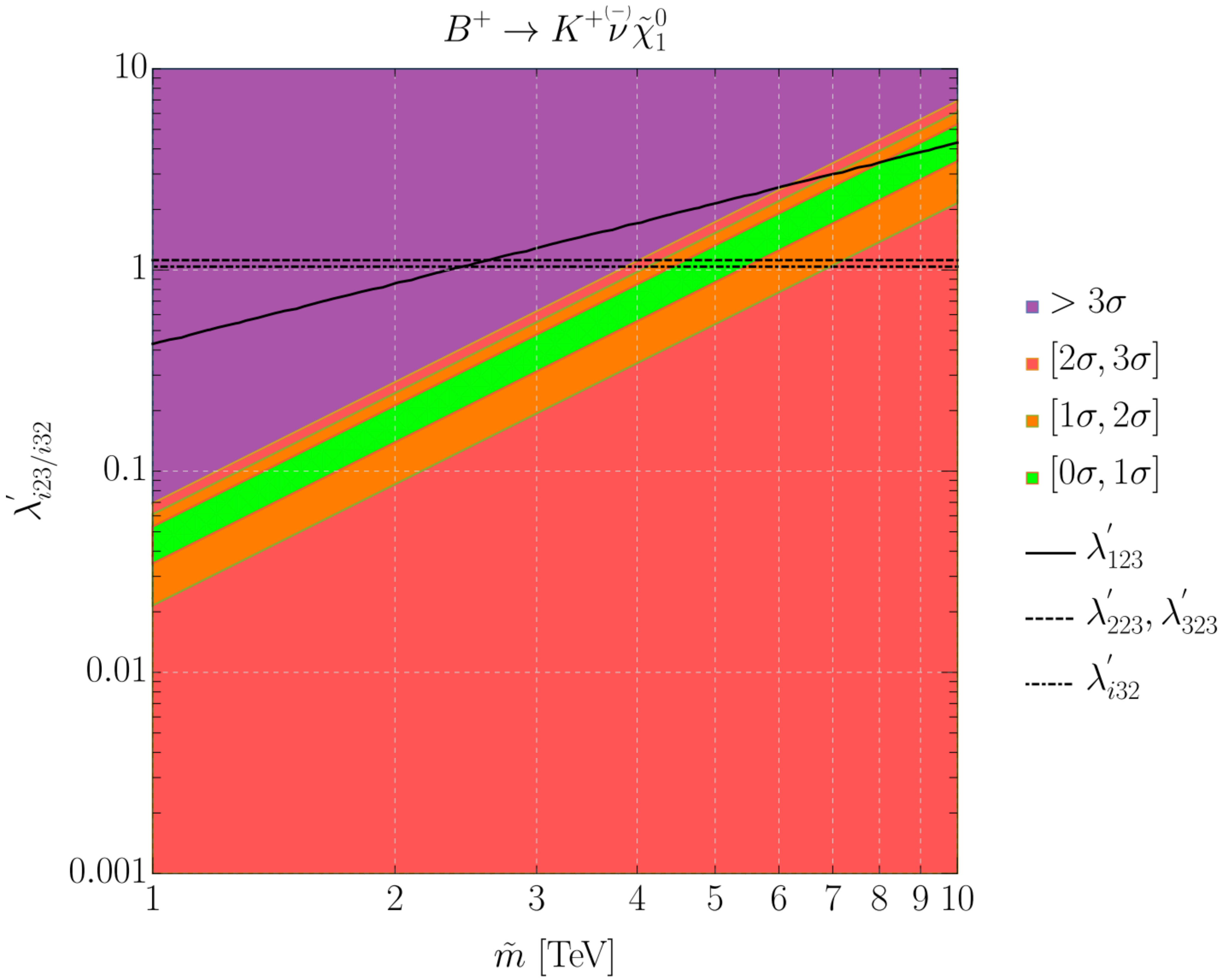
Comparison: Invisible Fermion(s)

Other results for generic fermions ψ:

Massless bino in *R*-parity violating (RPV) supersymmetry: $B \to K\nu\tilde{\chi}_1^0$

$$W_{\Delta L\neq 0} = \lambda'_{ijk} L_i Q_j \bar{D}_k$$

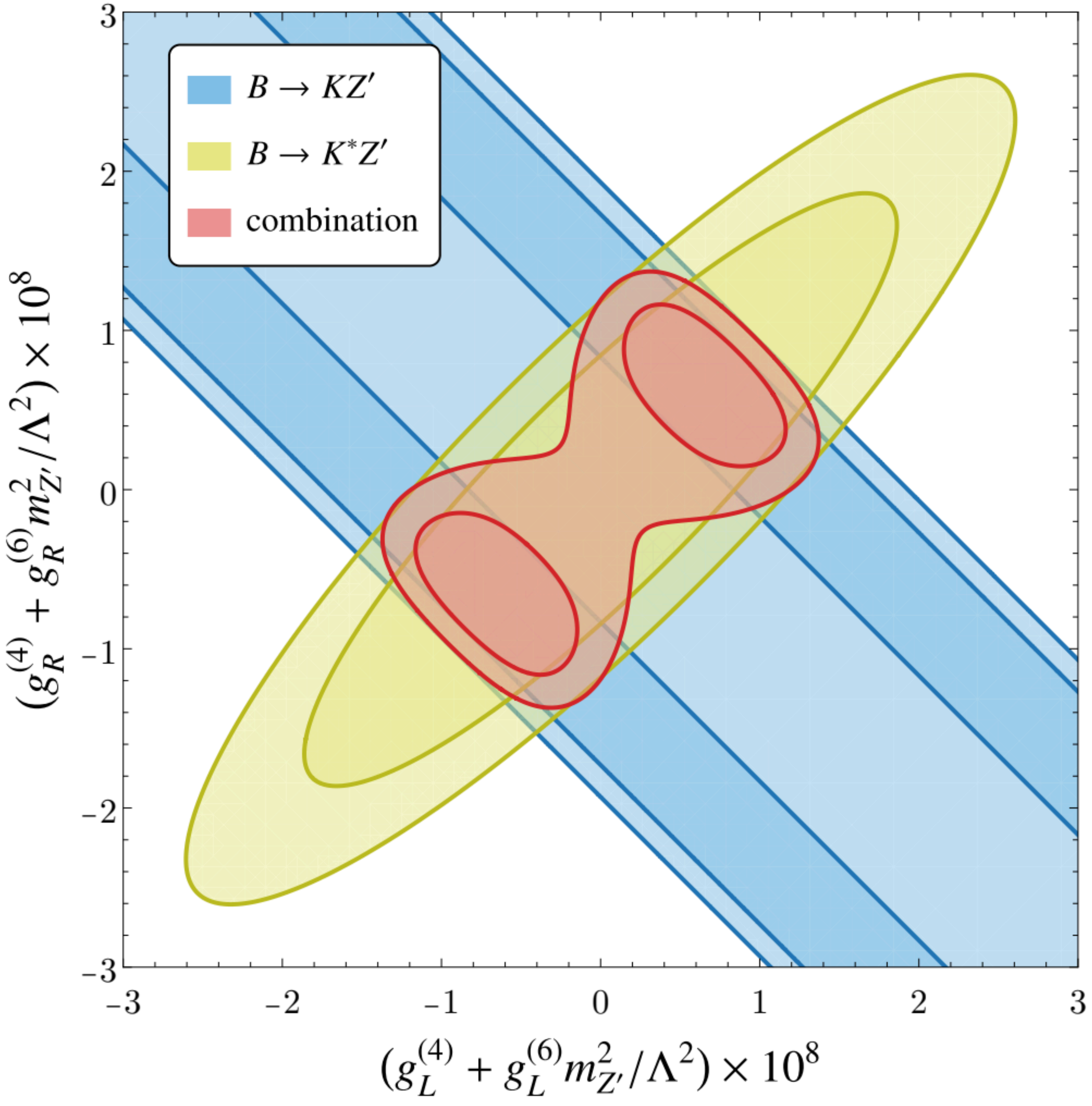




[Dreiner, Günther, Wang 24]

Comparison: Invisible Vector(s)

A massive vector boson ($V = Z'$) has also been considered



Conversion between couplings:

$$g_{V(A)}^{(4)} = 2h_{V(A)}$$

[Altmannshofer, Crivellin, Haigh, Inguglia, Camalich, 24]