HPNP2025

The 7th International Workshop on
"Higgs as a Probe of New Physics 2025"

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Interpreting Belle II excess with light dark matter

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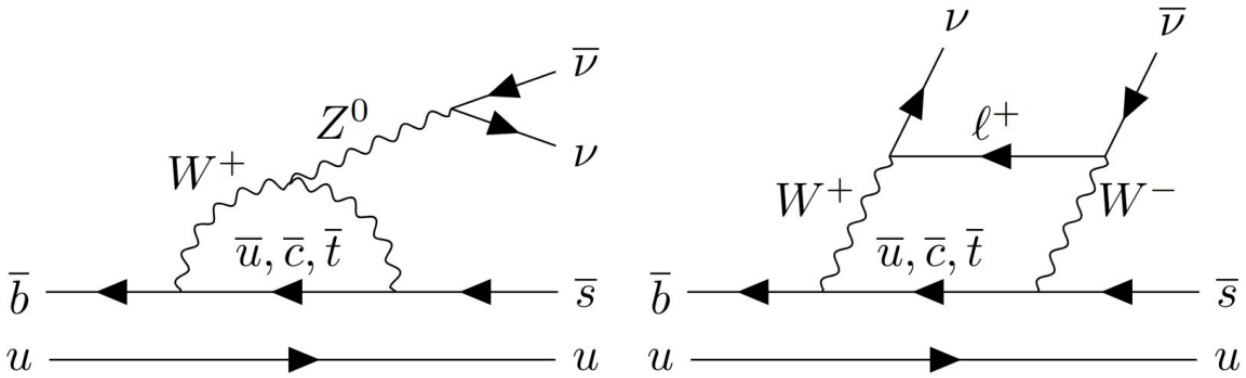
In collaboration with Shu-Yu Ho (Academia Sinica), Pyungwon Ko (KIAS)

2025. 6. 9 (Mon)

Measurement of $B^+ \to K^+ \nu\bar{\nu}$

- The $B^+ \to K^+ \nu\bar{\nu}$ process is known with high accuracy in the SM:
  - $Br(B^+ \to K^+ \nu\bar{\nu}) = (4.97 \pm 0.37) \times 10^{-6}$ **HPQCD, PRD 2023**



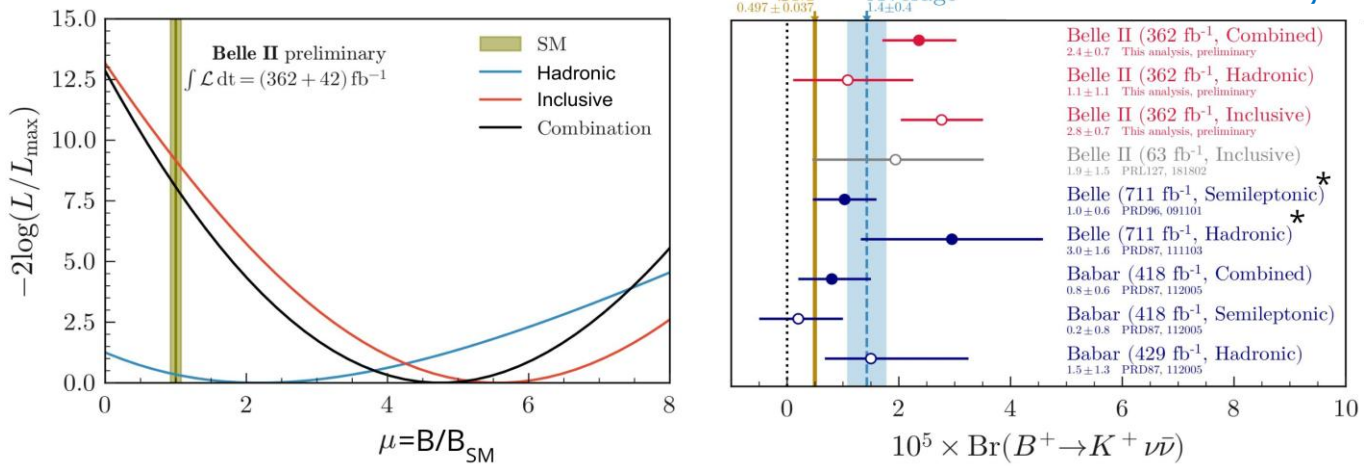
- $\mathcal{L}_{b\to s\nu\bar{\nu}} = -C_\nu \bar{s}_L \gamma^\mu b_L \bar{\nu}\gamma^\mu \nu$

$$C_\nu = \frac{g_W^2}{M_W^2} \frac{g_W^2 V_{ts}^* V_{tb}}{16\pi^2} \left[\frac{x_t^2 + 2x_t}{8(x_t - 1)} + \frac{3x_t^2 - 6x_t}{8(x_t - 1)^2} \ln x_t \right],$$

where $x_t = m_t^2 / M_W^2$.

Measurement of $B^+ \to K^+ \nu\bar{\nu}$

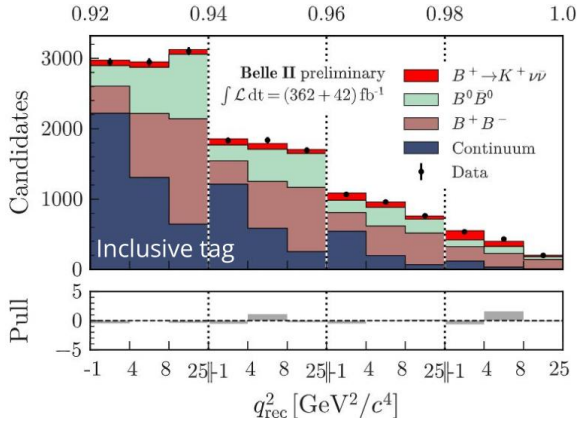
Belle-II, 2311.14647

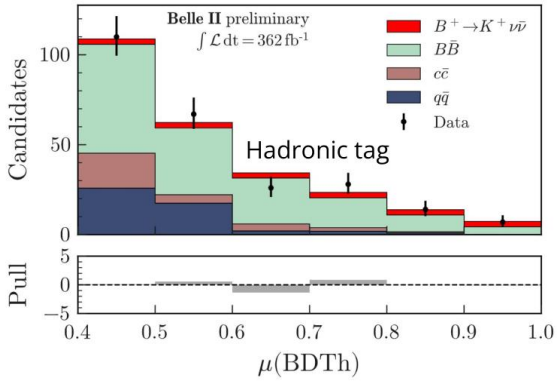


- $Br(B^+ \to K^+ \nu\bar{\nu})_{Exp} = (2.3 \pm 0.7) \times 10^{-5}$
  - Prob(null signal from $B^+ \to K^+ \nu\bar{\nu}$) $= 0.012\%$
  - ➔ Significance of observation: $3.5\,\sigma$
  - Prob$(B^+ \to K^+ \nu\bar{\nu})_{SM} = 0.17\%$ (2.8σ tension with the SM prediction)

- $Br(B^+ \to K^+ E_{\mathrm{mis}})_{NP} = (1.8 \pm 0.7) \times 10^{-5}$
  - **Indirect NP effects**: The presence of heavy NP particles
  - **Direct NP effects**: the presence of new invisible particles

Solutions: 2- or 3-body decay

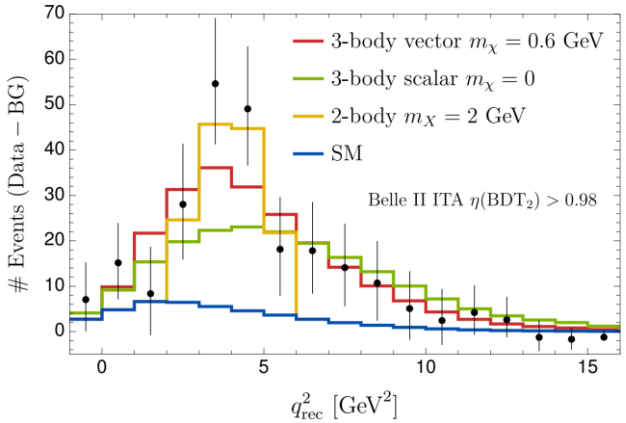


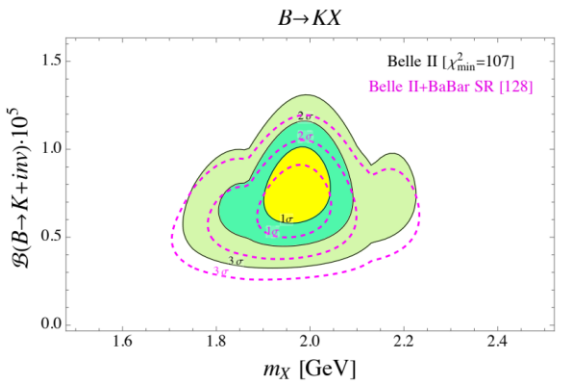


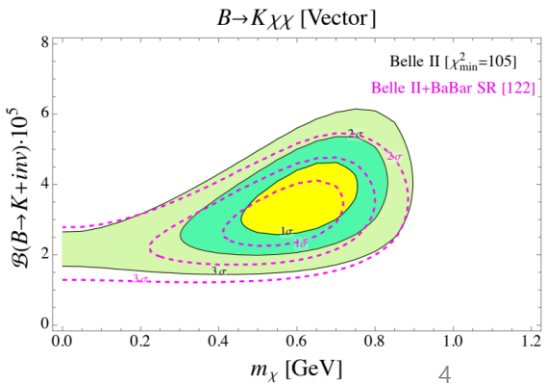
- Belle II provides information on the q^2_{rec} spectrum
  - q^2_{rec}: mass squared of the neutrino pair
  - A peak localized around $q^2_{rec} = 4\text{GeV}^2$
  - Two-body decay $(B \to KX), m_X = 2$ GeV
  - Three-body decay $(B \to KXX), m_X < 0.6$ GeV

W. Altmannshofer et al, 2311.14629

K. Fridell et al, 2312.12507



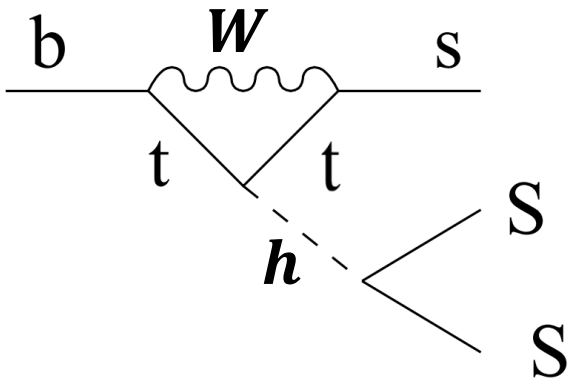




Solutions: 3-body decay

- Singlet scalar DM model ($m_s \leq 2.3\mathrm{GeV}$)

Bird et al, PRL 2004

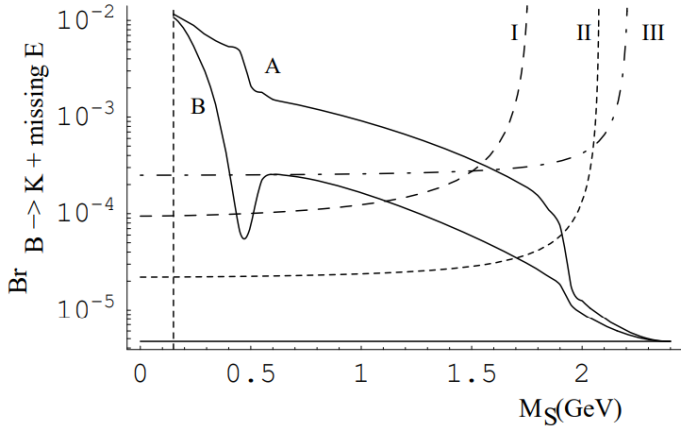


$$-\mathcal{L}_S = \frac{\lambda_S}{4}S^4 + \frac{m_0^2}{2}S^2 + \lambda S^2 H^\dagger H$$

$$= \frac{\lambda_S}{4}S^4 + \frac{1}{2}(m_0^2 + \lambda v_{EW}^2)S^2 + \boxed{\lambda v_{EW} S^2 h} + \frac{\lambda}{2}S^2 h^2,$$

- Belle $\Rightarrow$ $\frac{C_{DM}}{C_\nu} \simeq \frac{4.4\lambda M_W^2}{g_W^2 m_h^2}$
- Relic density: $\sigma_{\mathrm{ann}} v_{\mathrm{rel}} = \frac{8 v_{EW}^2 \lambda^2}{m_h^4} \left(\lim_{m_{\tilde{h}} \to 2m_S} m_{\tilde{h}}^{-1} \Gamma_{\tilde{h}X} \right).$

  - λ should be large to fit the relic as well as Belle II
  - $m_s \leq 1\mathrm{GeV}$ is already excluded by BABAR limits (2004 data).



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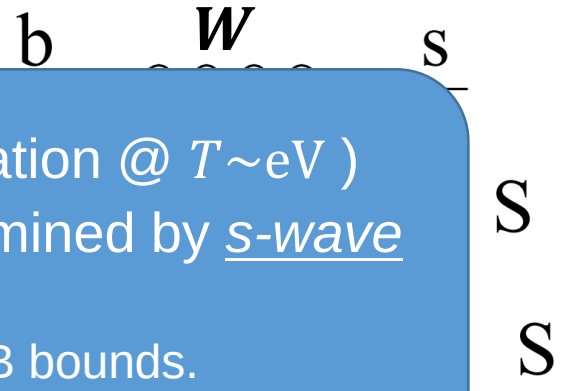

- For $m_\chi \lesssim 10\mathrm{GeV}$, CMB bound (DM annihilation @ $T \sim \mathrm{eV}$) excludes the thermal DM freeze-out determined by *s-wave* annihilation
- At that time, the authors did not consider the CMB bounds.
  This model does not work anymore.

- λ should be large to fit the relic as well as Belle II
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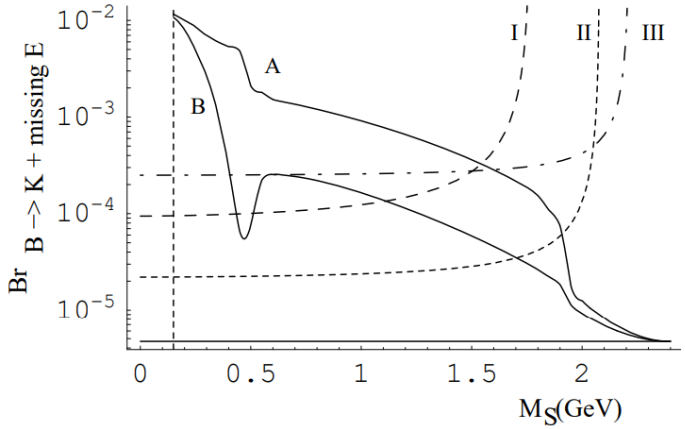
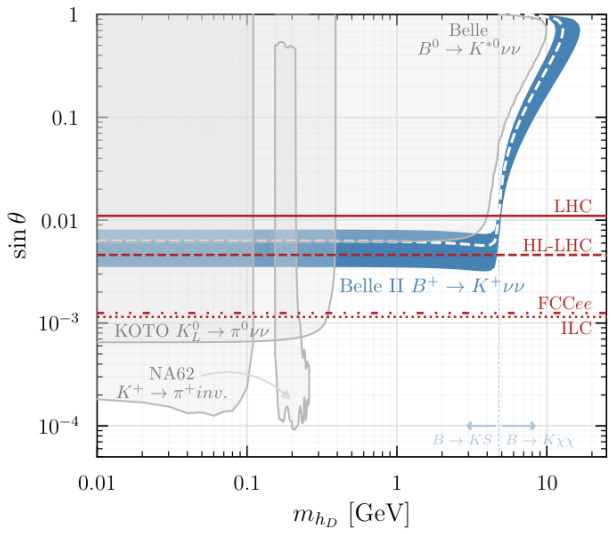


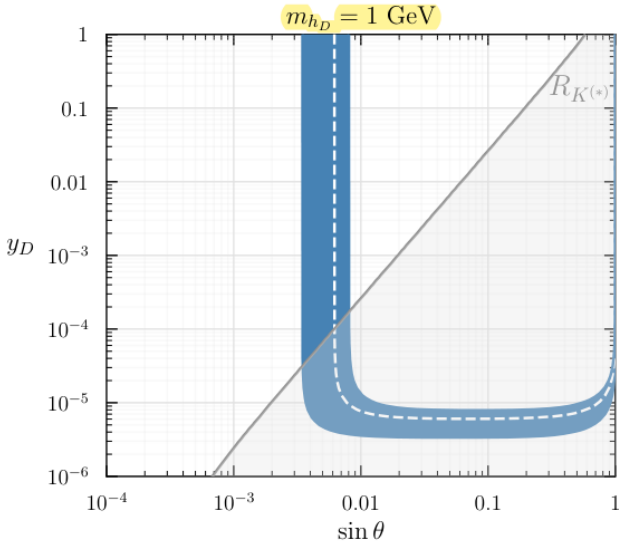
Solutions: 2- or 3-body decay

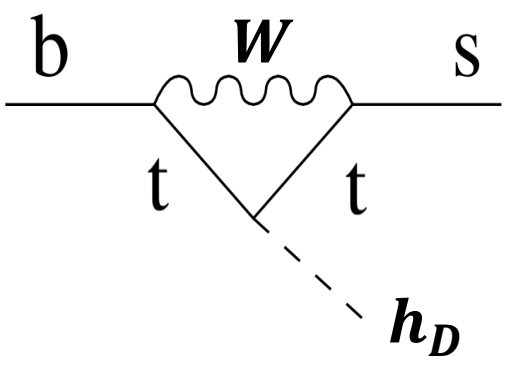
- Dark Higgs on-shell decay or three-body decay

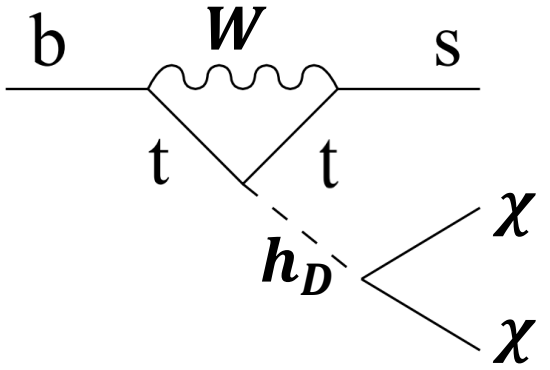
McKeen et al, 2312.00982

$$\mathcal{L}_{\rm DM} = y_D \phi \bar{\chi} \chi$$





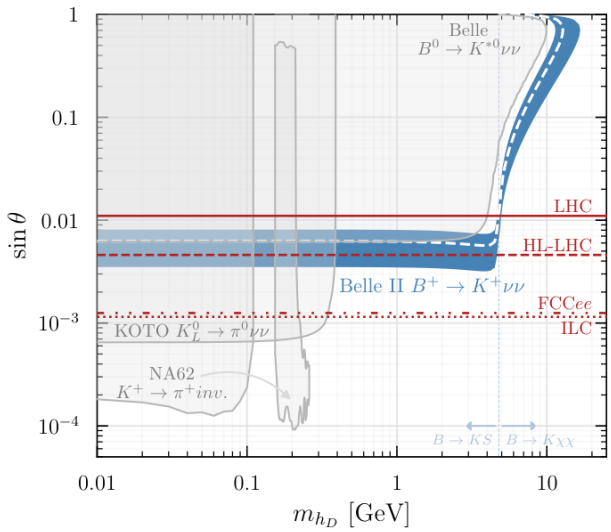


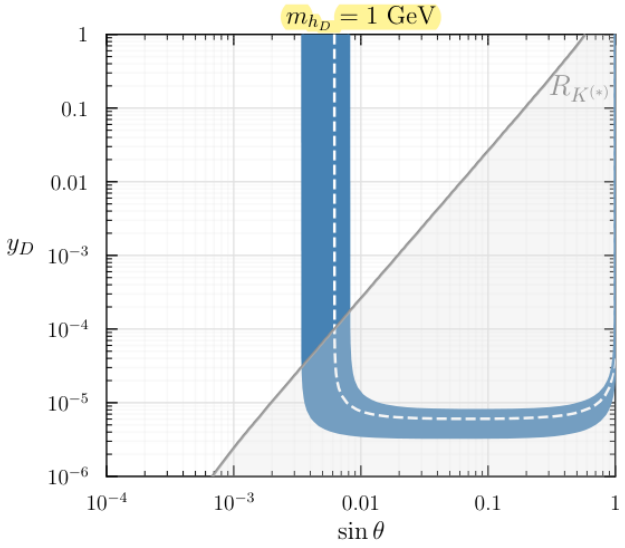


Solutions: 2- or 3-body decay

- Dark Higgs on-shell decay or three-body decay **McKeen et al, 2312.00982**

$$\mathcal{L}_{\rm DM} = y_D \phi \bar{\chi} \chi$$

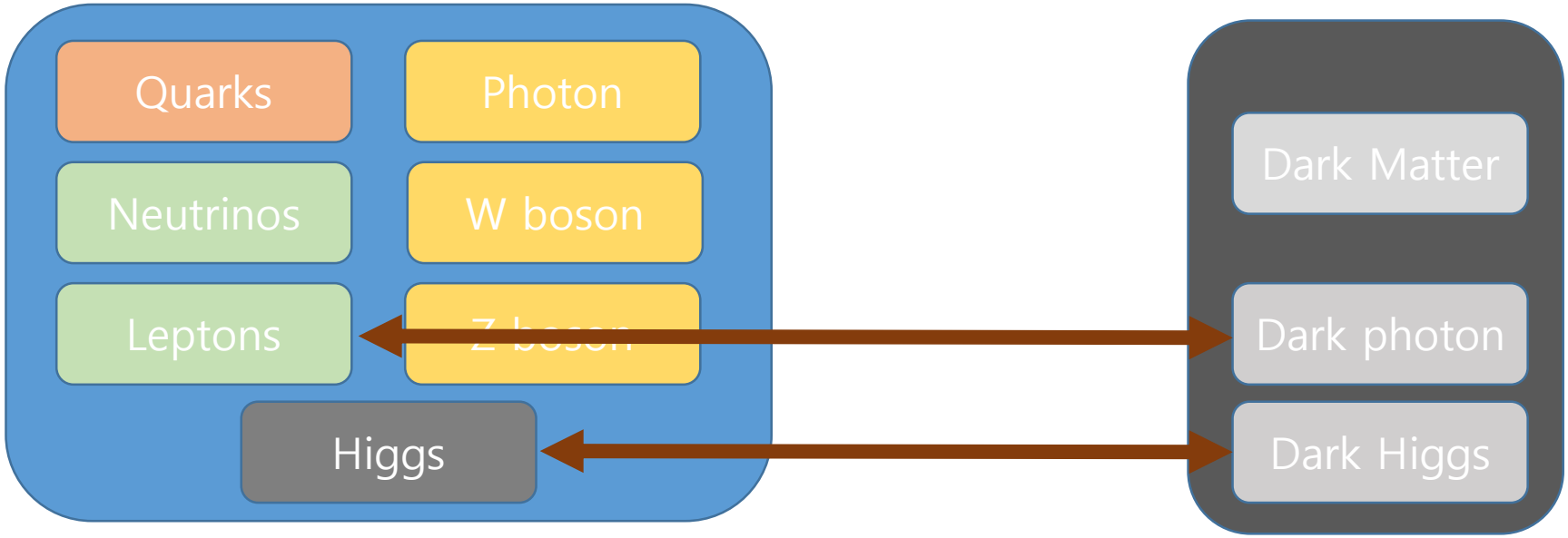




- **Extremely large relic density**
  - $\Omega h^2 \simeq 10^{20} \left(\frac{10^{-4}}{y_D}\right)^2 \left(\frac{\sin\theta}{10^{-3}}\right)^2 \left(\frac{m_\chi}{100\,\mathrm{MeV}}\right)^2 \left(\frac{1\,\mathrm{GeV}}{m_{H_1}}\right)^2$: overclose the Universe
  - Either introduce a new DM annihilation or allow DM to decay
  - In that sense, **fermion DM does not work…**

$U(1)_{L_\mu - L_\tau}$-charged DM + Dark Higgs

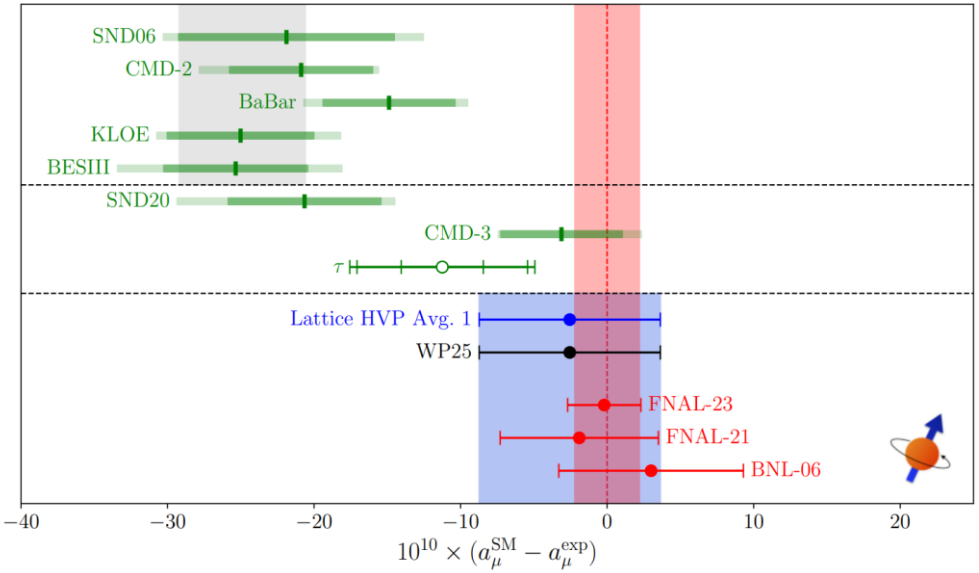
- $U(1)_{dark} \equiv U(1)_{L_\mu - L_\tau}$
  - Let's call Z',$U(1)_{L_\mu - L_\tau}$ gauge boson, dark photon since it couple to DM

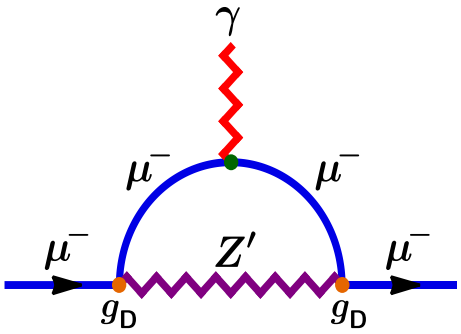


- **UV complete** $U(1)_{L_\mu - L_\tau}$-charged **scalar** DM model
- Dark photon Z' gets massive through $U(1)_{L_\mu - L_\tau}$ breaking
- A new singlet scalar (**Dark Higgs**), which mixes with the SM Higgs

Muon g-2 bound

- Muon g-2 experiment improves the precision of their previous result by a factor of 2
  - $\Delta a_\mu = 26(66) \times 10^{-11}$ **arXiv: 2505.21476**





S. Baek, Deshpande, He, P. Ko, 2001
S. Beak, P. Ko, 2008
…

$$\Delta a_\mu = \frac{g_x^2}{4\pi^2} \int_0^1 dx \frac{m_\mu^2 x^2 (1-x)}{x^2 m_\mu^2 + (1-x) m_{Z'}^2}$$

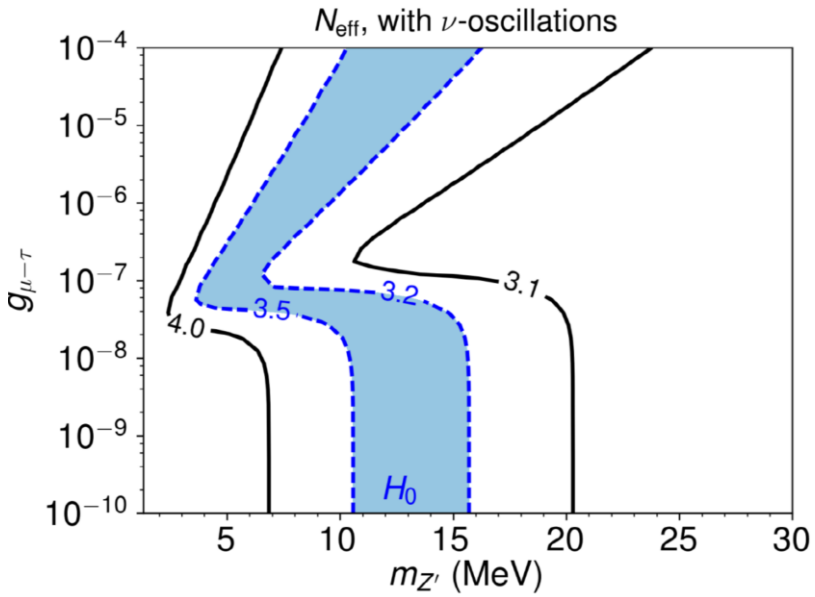
Gauged $U(1)_{L_\mu - L_\tau}$ Z' model

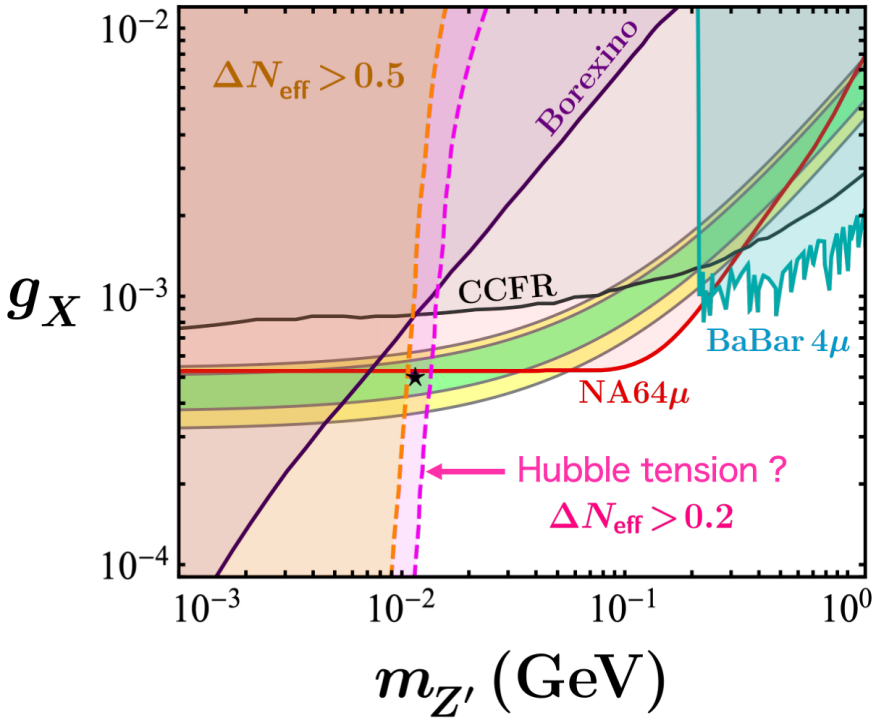
- ***Hubble tension***

M. Escudero et al, JHEP 2019

  - $\sim 10\text{MeV}$ Z' reached thermal equilibrium in the early Universe and decays, heating the neutrino population.
  - The expansion rate of the universe departed from the predictions of standard ΛCDM cosmology at early times
  - $0.2 < \Delta N_{\text{eff}} < 0.5$

- BP : $m_{Z'} = 10\text{MeV}$, $g_X = 10^{-4}$





$U(1)_{L_\mu - L_\tau}$-charged DM + Dark Higgs

- After electroweak and $U(1)_{L_\mu - L_\tau}$ symmetry breaking

$$\mathcal{H} = \frac{1}{\sqrt{2}}(0 \;\; v_H + h)^\intercal \;, \;\; \Phi = \frac{1}{\sqrt{2}}(v_\Phi + \phi)$$

- Dark photon Z' gets massive: $m_{Z'} = g_X |Q_\Phi| v_\Phi$

- Two CP-even neutral scalar bosons mix each other due to non-zero of $\lambda_{H\Phi}$

$$H_1 = \phi \cos\theta - h \sin\theta \;, \;\; H_2 = \phi \sin\theta + h \cos\theta$$

dark Higgs boson — SM-like Higgs boson — mixing angle

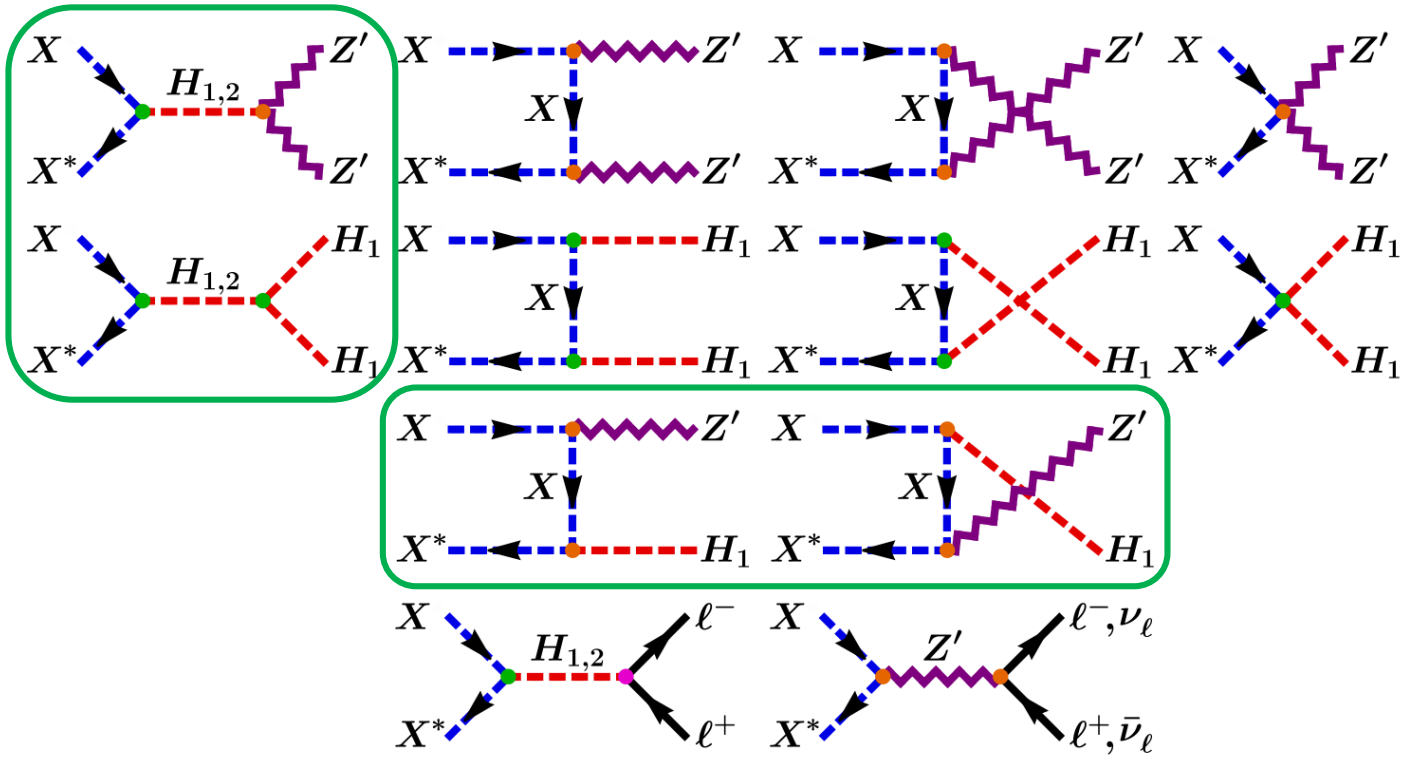
$$m_{H_1} < m_{H_2} \simeq 125\,\text{GeV}$$

$U(1)_{L_\mu - L_\tau}$-charged DM + Dark Higgs

- UV-complete $U(1)_{L_\mu - L_\tau}$-charged scalar DM model Baek, **JK**, Ko, 2204.04889

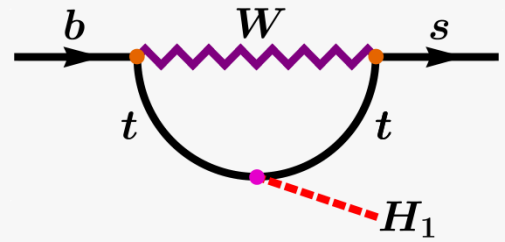
$$\mathcal{L}_{\rm DM} = |D_\mu X|^2 - m_X^2 |X|^2 - \lambda_{\Phi X} |X|^2 \left(|\Phi|^2 - \frac{v_\Phi^2}{2} \right)$$

- DM annihilation channels

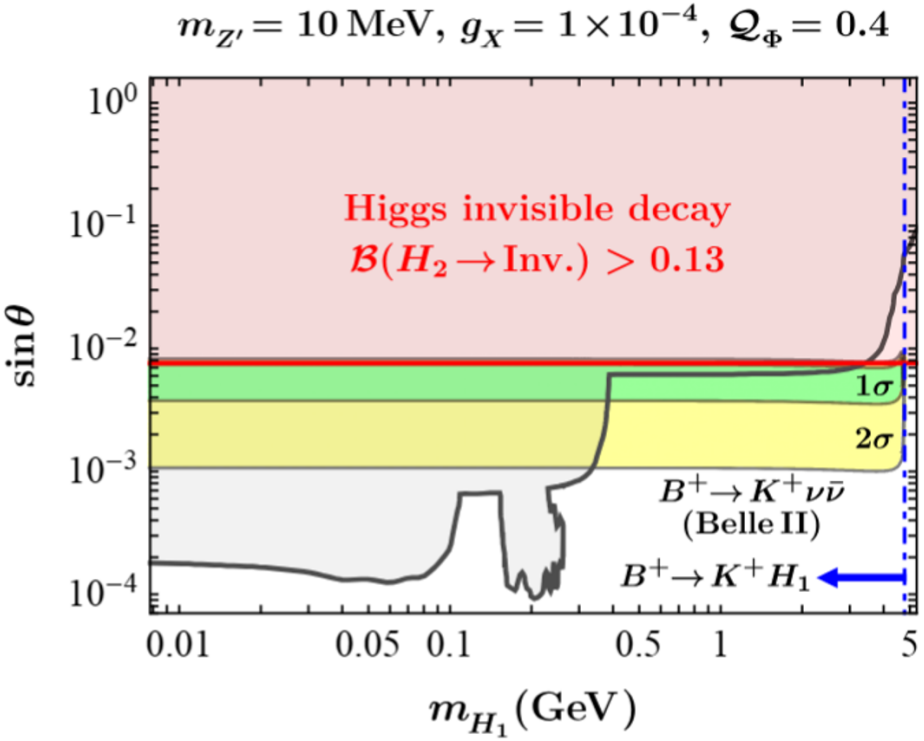


BelleII excess: 2-body decay

- When $m_{H_1} < m_B - m_K$, H_1 is on-shell
- The gray shaded area is excluded by BelleII $B^0 \to K^{*0}\nu\bar{\nu}$, KOTO $K_L^0 \to \pi^0\nu\bar{\nu}$ & NA62 $K^+ \to \pi^+$+ inv.

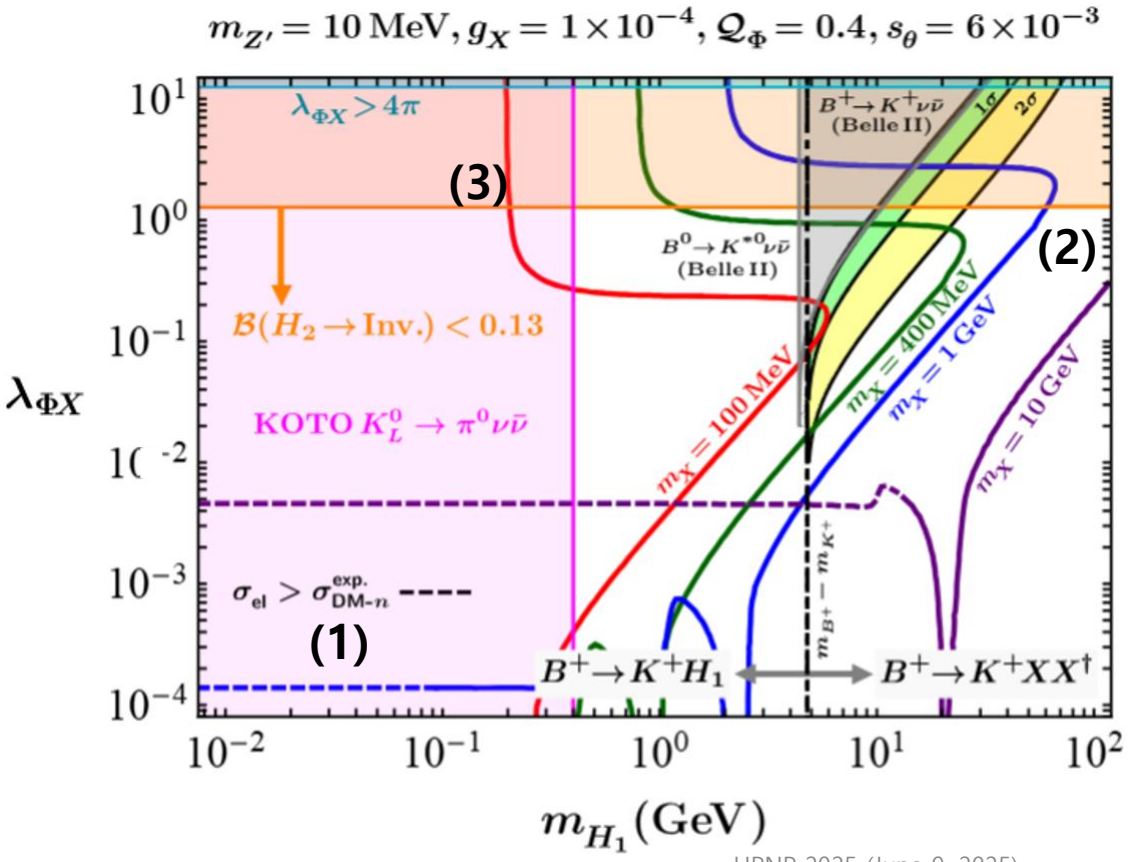


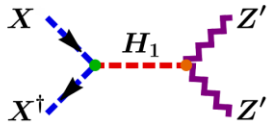
- H_1 decay process
  - $H_1 \to \boldsymbol{X X^\dagger}, \boldsymbol{Z' Z'}, f\bar{f}$
- Allowed value
  - $10^{-3} \leq \sin\theta \leq 7 \times 10^{-3}$
  - take $\sin\theta = 6 \times 10^{-3}$



BelleII excess : 2- or 3-body decay

- When $m_{H_1} > (<)\, m_B - m_K$, H_1 is off(on)-shell → 3(2)-body decay
  - Two-body decay: $m_X \lesssim 8\ \mathrm{GeV}\ (m_{H_1} < m_B - m_K)$
  - Three-body decay: $\sim 90\mathrm{MeV} < m_X \lesssim 450\mathrm{MeV}\ (m_{H_1} > m_B - m_K)$





$m_X^2 \gg m_{Z'}^2$

$$\langle\sigma v\rangle \propto \frac{\lambda_{\Phi X}^2 m_X^2}{(m_{H_1}^2 - 4m_X^2)^2 + \Gamma_{H_1}^2 m_{H_1}^2}$$

$$\Gamma_{H_1}^2 m_{H_1}^2 \propto \lambda_{\Phi X}^4 v_\Phi^4 \sqrt{1 - 4m_X^2/m_{H_1}^2}$$

(1) $\lambda_{\Phi X} \ll 1$ & $m_X^2 \gg m_{H_1}^2$

$$\Rightarrow \langle\sigma v\rangle \propto \frac{\lambda_{\Phi X}^2}{m_X^2} \Rightarrow \lambda_{\Phi X} \simeq \text{const.}$$

(2) $\lambda_{\Phi X} \ll 1$ & $m_{H_1}^2 \gg m_X^2$

$$\Rightarrow \langle\sigma v\rangle \propto \frac{\lambda_{\Phi X}^2 m_X^2}{m_{H_1}^4} \Rightarrow \lambda_{\Phi X} \propto m_{H_1}^2$$

(3) $\lambda_{\Phi X} \gg 1$ & $m_{H_1}^2 \gg m_X^2$

$$\Rightarrow \langle\sigma v\rangle \propto \frac{m_X^2}{\lambda_{\Phi X}^2 v_\Phi^4} \Rightarrow \lambda_{\Phi X} \simeq \text{const.}$$

CMB constraints

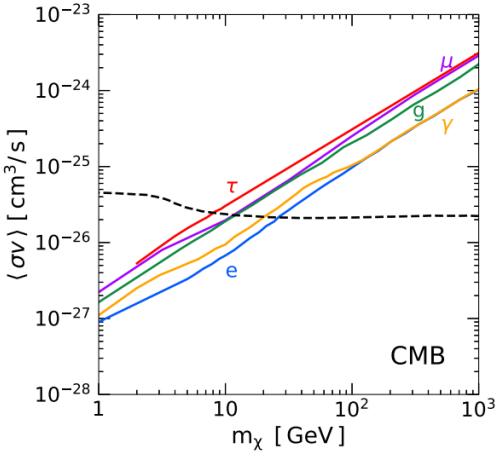
- For $m_X \lesssim 20\mathrm{GeV}$, CMB bound (DM annihilation @ $T \sim \mathrm{eV}$) excludes the thermal DM freeze-out determined by *s-wave* annihilation
  - DM annihilation should be mainly in **p-wave**
  - …

$$\sigma v = a + b v^2 + O(v^4)$$

p-wave (the $b v^2$ term)

s-wave (the a term)

- Dominant DM annihilation channel
  - $XX^\dagger \to Z'Z', H_1H_1$: **s-wave** annihilation
  - $XX^\dagger \to Z'H_1$: **p-wave** annihilation
- Z' decay
  - A pair of ν
- H_1 decay
  - A pair of DM (open when $m_{H_1} > 2m_X$)
  - A pair of Z' ($Z' \to \nu\nu$)
  - SM particles (suppressed due to small Yukawa coupling & $\sin\theta$)



Conclusions

- BelleII data shows a excess of $B^+ \to K^+ \nu\bar{\nu}$ over the SM prediction
- This excess can be interpreted as $B^+ \to K^+ +$ dark sector particles
- CMB constraints can be evaded because DM pair annihilations into $H_1 H_1, H_1 Z', Z'Z'$, all of which are invisible
- We can subsequently relax the tension in the Hubble constant with extra radiation

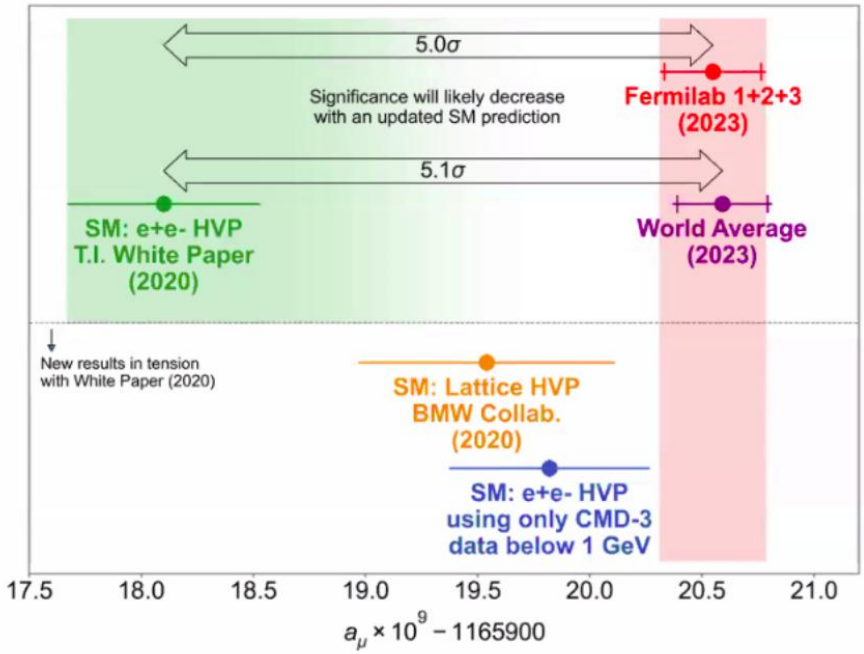
Thank you very much

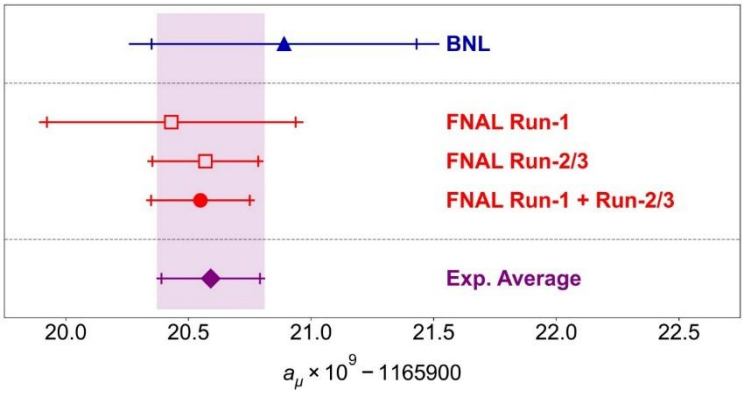
Back-up Slides

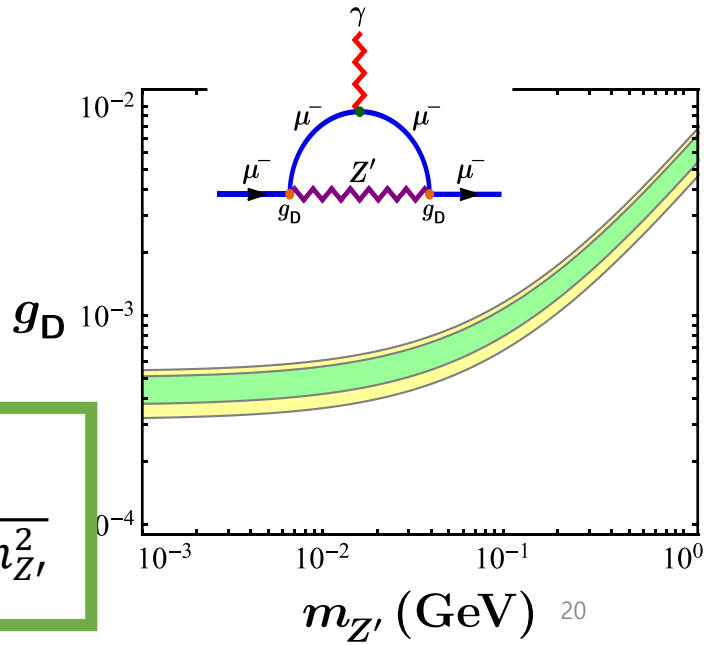
Evidences – Muon g-2

Muon g-2 collaboration, PRL 2023

- Muon g-2 experiment improves the precision of their previous result by a factor of 2







S. Baek, Deshpande, He, P. Ko, 2001
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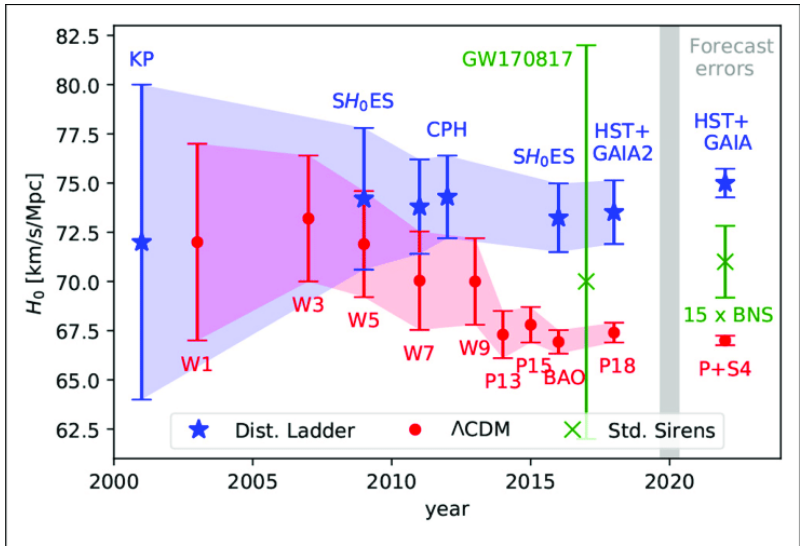
$$\Delta a_\mu = \frac{g_x^2}{4\pi^2}\int_0^1 dx \frac{m_\mu^2 x^2(1-x)}{x^2 m_\mu^2 + (1-x)m_{Z'}^2}$$

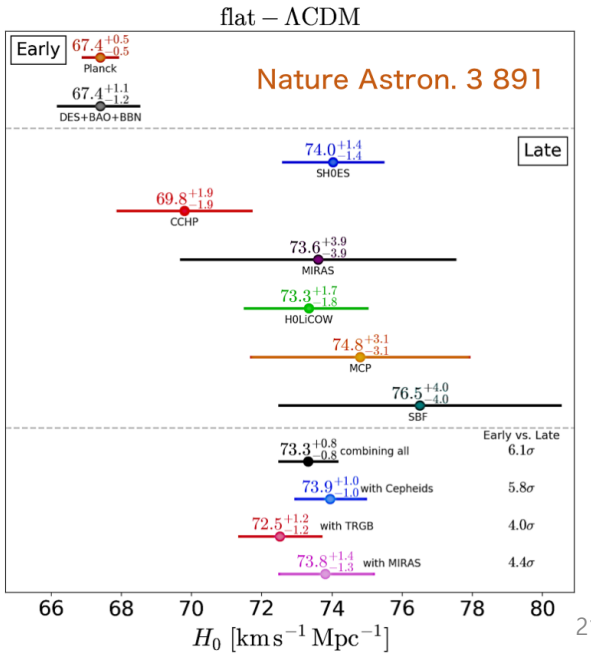
Evidences – Hubble tension

- Large difference between early and late H_0 measurement
  - Late-time: $H_0 = 73.2 \pm 1.3\ \mathrm{kms^{-1}Mpc^{-1}}$
  - Early-time: $H_0 = 67.4 \pm 0.5\ \mathrm{kms^{-1}Mpc^{-1}}$

- The discrepancy either arises because
  - Our distance measurements are incorrect (ΔG_N)
  - Cosmological model we use to fit all those distances is incorrect (ΔN_{eff})



P. Shah et al, AAR 2021

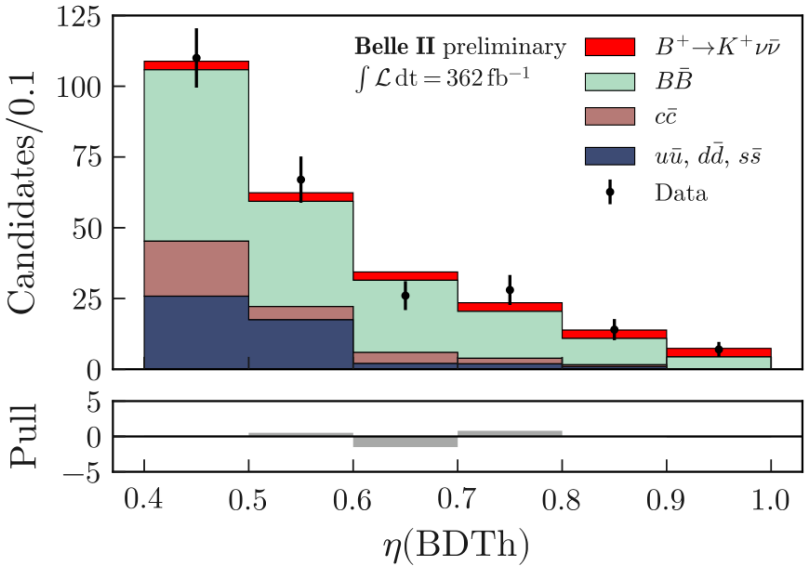


Measurement of $B^+ \to K^+ \nu\bar{\nu}$

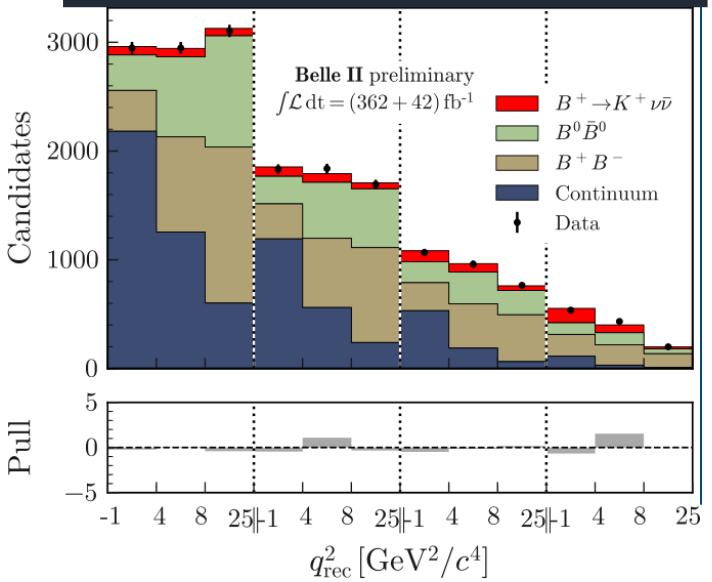
Belle-II, 2311.14647

- **Two ways** of tagging
  - HTA: Better resolution, purity
  - ITA: Better efficiency

Hadronic tagging (HTA)



Inclusive tagging (ITA)

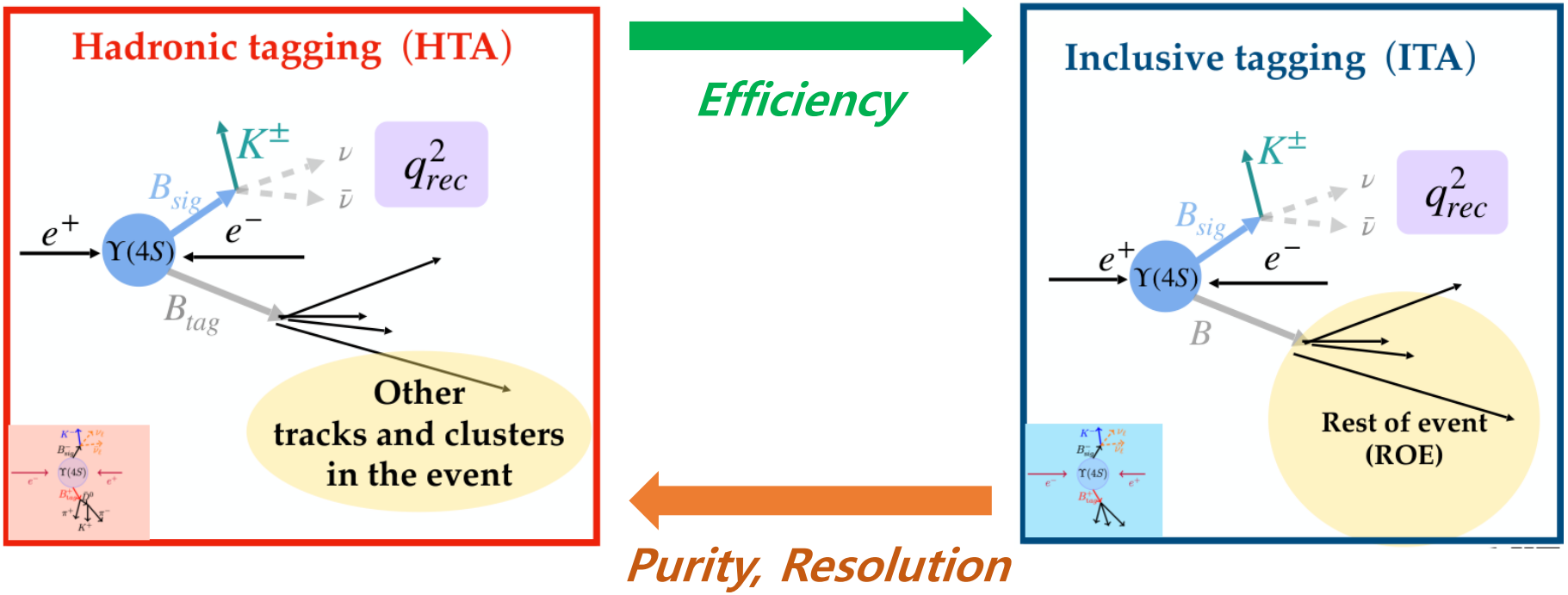


$$\mathcal{B}(B^+ \to K^+ \nu\bar{\nu})_{\text{HTA}} = (1.1^{+0.9+0.8}_{-0.8-0.5}) \times 10^{-5}$$

$$\mathcal{B}(B^+ \to K^+ \nu\bar{\nu})_{\text{ITA}} = (2.7 \pm 0.5 \pm 0.5) \times 10^{-5}$$

Measurement of $B^+ \to K^+ \nu\bar{\nu}$

- Two ways of tagging

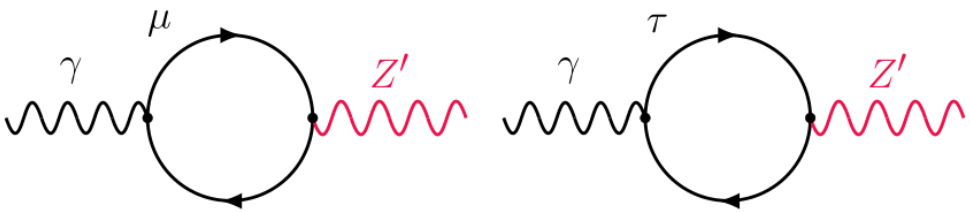


- q^2_{rec}: mass squared of the neutrino pair
- Inclusive tagging: It allows one to reconstruct inclusively the decay $B^+ \to K^+ \nu\bar{\nu}$ from the charged kaon

Gauged $U(1)_{L_\mu - L_\tau}$ Z' model

- Gauge one of the differences of two lepton-flavor numbers
  - $L_e - L_\mu, L_\mu - L_\tau, L_e - L_\tau$: anomaly free without extension of fermion contents **X. G. He et al, PRD 1991**
  - Symmetry including L_e is strongly constrained
  - Charge assignments: $\widehat{\mathcal{Q}}_{\mathsf{L}_\mu - \mathsf{L}_\tau}(\nu_\mu, \nu_\tau, \mu, \tau) = (1, -1, 1, -1)$

- No kinetic mixing between Z' and B @ high-energy
  - Kinetic mixing is generated through



- $\epsilon = -\frac{e g_{\mu-\tau}}{2\pi^2} \int_0^1 dx\, x(1-x) \log\left[\frac{m_\tau^2 - x(1-x)q^2}{m_\mu^2 - x(1-x)q^2}\right] \xrightarrow[m_\mu \gg q]{} -\frac{e g_{\mu-\tau}}{12\pi^2} \log\frac{m_\tau^2}{m_\mu^2} \simeq -\frac{g_{\mu-\tau}}{70}.$

$U(1)_{L_\mu - L_\tau}$-charged DM + Dark Higgs

Baek, **JK**, Ko, 2204.04889

- Thermal WIMP DM relic density

$$\Omega_{\rm WIMP}\hat{h}^2 = 2\Omega_X\hat{h}^2 \simeq \frac{1.75\times 10^{-10}{\rm GeV}^{-2}x_f}{\sqrt{g_*}\langle\sigma v\rangle}$$

- DM direct detection
  - $U(1)_{L_\mu - L_\tau}$ DM model without dark Higgs boson, DM-nucleon/electron scattering is highly suppressed: $\sigma_{\rm el}^{X-p} \simeq 10^{-46}{\rm cm}^2, \sigma_{\rm el}^{X-e} \simeq 10^{-51}{\rm cm}^2$
  - We can have a sizable DM-nucleon scattering due to the dark Higgs boson exchange

$$\sigma_{\rm el} \simeq \frac{4\mu_n^2 f_n^2 \lambda_{\Phi X}^2 \sin^2\theta}{\pi}\left(\frac{m_n}{m_X}\right)^2\left(\frac{v_\Phi}{v_H}\right)^2\left(\frac{1}{m_{H_1}^2}-\frac{1}{m_{H_2}^2}\right)^2$$

$U(1)_{L_\mu - L_\tau}$-charged DM + Dark Higgs

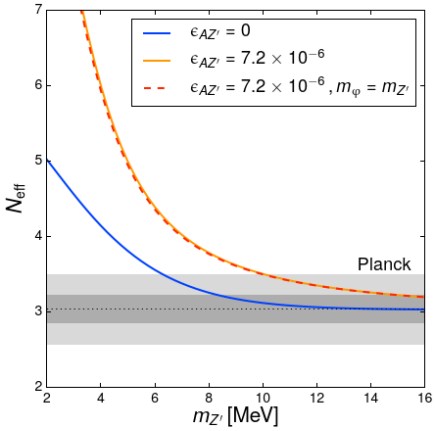
- Additional interactions with the dark Higgs

$$\mathcal{L}_\phi \supset \frac{1}{2} g_X^2 Q_\Phi^2 Z'^\mu Z'_\mu \phi^2 + g_X^2 Q_\Phi^2 v_\Phi Z'^\mu Z'_\mu \phi - \lambda_\Phi v_\Phi \phi^3 - \lambda_H v_H h^3 - \frac{\lambda_{\Phi H}}{2} v_\Phi \phi h^2 - \frac{\lambda_{\Phi H}}{2} v_H \phi^2 h$$

- **The SM-like Higgs invisible decay**
  - $\boldsymbol{H_2 \to H_1 H_1, Z'Z', XX^\dagger}$
  - SM Higgs mainly decays into dark photon and dark Higgs

$$\Gamma_{H_2 \to H_1 H_1} \simeq \Gamma_{H_2 \to Z'Z'} \propto \frac{\sin^2\theta\, m_{H_2}^3}{v_\Phi^2} \gg \Gamma_{H_2 \to XX^\dagger} \propto \frac{\sin^2\theta\, \lambda_{\Phi X}^2 v_\Phi^2}{m_{H_2}}$$

- $\mathrm{Br}(H_2 \to \mathrm{inv.}) = \dfrac{\Gamma_{H_2}^{ZZ^* \to 4\nu} + \Gamma_{H_2}^{H_1 H_1} + \Gamma_{H_2}^{Z'Z'} + \Gamma_{H_2}^{XX^\dagger}}{\Gamma_{H_2}^{SM} + \Gamma_{H_2}^{H_1 H_1} + \Gamma_{H_2}^{Z'Z'} + \Gamma_{H_2}^{XX^\dagger}} < 13\%$
- $sin\theta \leq 0.01$ to satisfy the Higgs invisible decay

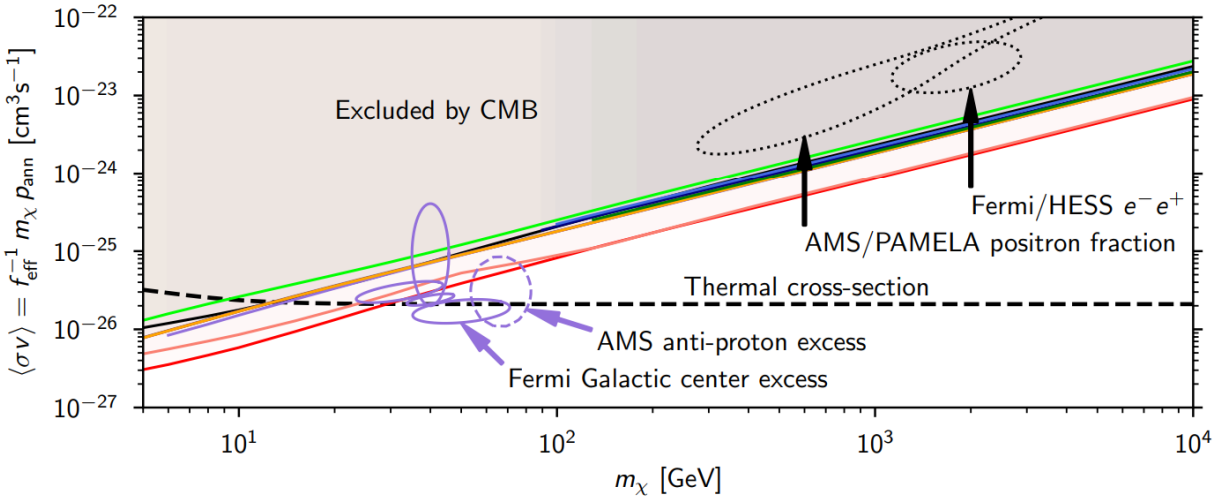


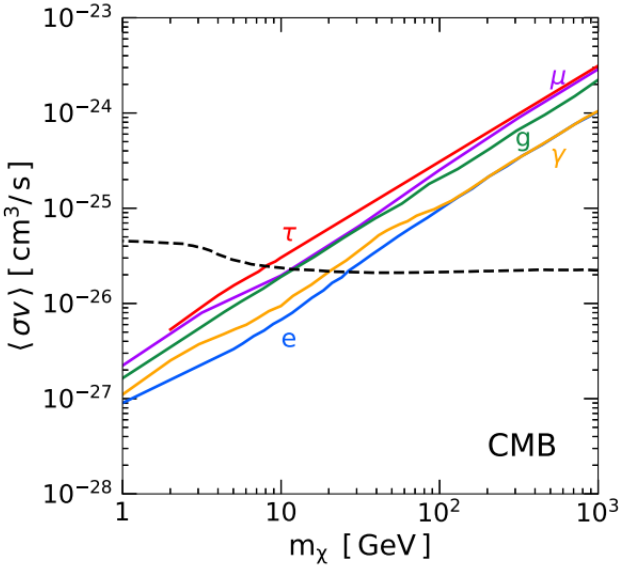
CMB constraints

- Any injection of ionizing particles modifies the ionization history of hydrogen and helium gas, perturbing CMB anisotropies
  - DM annihilations to the charged SM particles
- Measurements of these anisotropies provide robust constraints on production of ionizing particles from DM annihilation products.

$$\langle \sigma v \rangle \leqslant \frac{4.1 \times 10^{-28}\,\mathrm{cm^3\,sec^{-1}}}{f_{\mathrm{eff}}} \left(\frac{m_{\mathrm{DM}}}{\mathrm{GeV}} \right)$$

Planck 2018,
R. K. Leane et al, PRD 2018





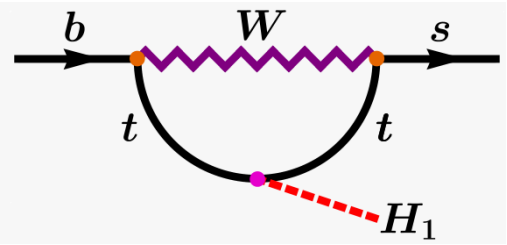
BelleII excess: 2- or 3-body decay

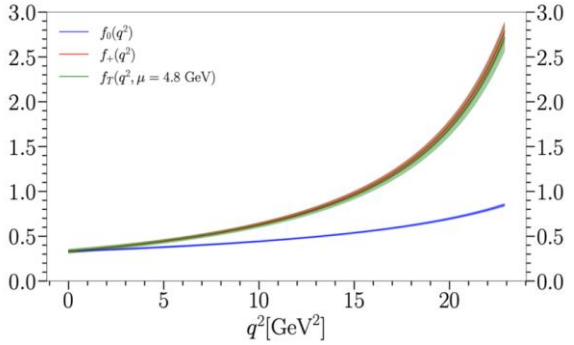
- When $m_{H_1} < m_B - m_K$, H_1 is on-shell

$$\Gamma_{B^+\to K^+H_1} \simeq \frac{|\kappa_{cb}|^2 \sin^2\theta}{64\pi m_{B^+}^3}\left(\frac{m_{B^+}^2 - m_{K^+}^2}{m_b - m_s}\right)^2 \left[f_0(m_{H_1}^2)\right]^2 \times \sqrt{\mathcal{K}(m_{B^+}^2, m_{K^+}^2, m_{H_1}^2)} \qquad \sin\theta \ll 1$$

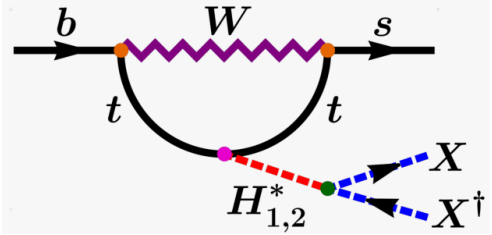
form factor

$$|\kappa_{cb}| \simeq 6.7 \times 10^{-6} \qquad \mathcal{K}(a,b,c) = a^2 + b^2 + c^2 - 2(ab + bc + ca)$$





W. G. Parrott, C. Bouchard & C. T. H. Davies, ORD 2023

- When $m_{H_1} > m_B - m_K$, H_1 is off-shell → three-body decay

$$\Gamma_{B^+\to K^+XX^\dagger} \simeq \frac{\lambda_{\Phi X}^2 v_\Phi^2 |\kappa_{cb}|^2 \sin^2\theta}{1024\pi^3 m_{B^+}^3}\left(\frac{m_{B^+}^2 - m_{K^+}^2}{m_b - m_s}\right)^2 (m_{H_1}^2 - m_{H_2}^2)^2 \times \int_{4m_X^2}^{(m_{B^+}-m_{K^+})^2} dq^2 \frac{\sqrt{1-4m_X^2/q^2}\sqrt{\mathcal{K}(m_{B^+}^2, m_{K^+}^2, q^2)}\left[f_0(q^2)\right]^2}{(q^2 - m_{H_1}^2)^2(q^2 - m_{H_2}^2)^2}$$