B→K+vv Excess and DM semi-annihilation

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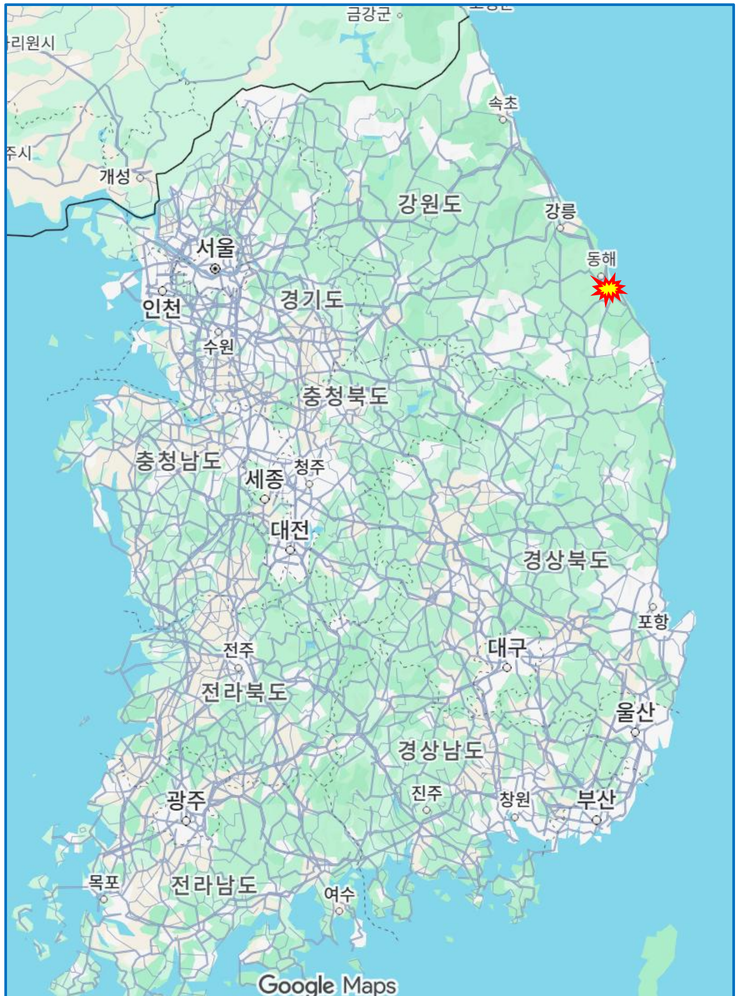
Based on

arXiv: 2511.20430 with Pyungwon Ko (KIAS)

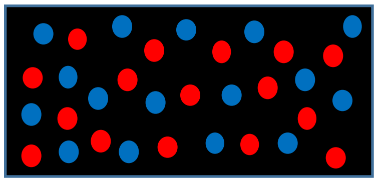
2026. 4. 26 (Sun)

Kangwon Natl. Univ. (Samcheok)

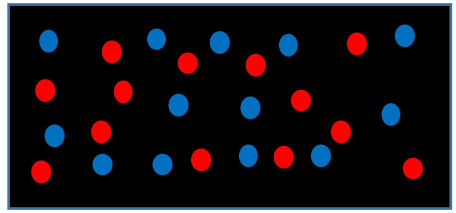
- A lot of tourist attractions



Thermal freeze-out Dark Matter



$T \gg M_{DM}$



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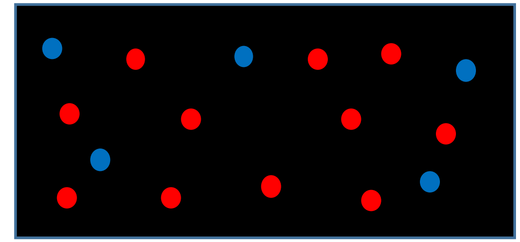
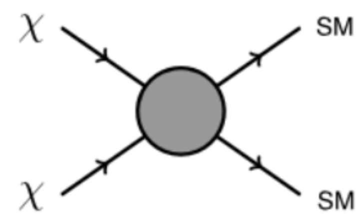
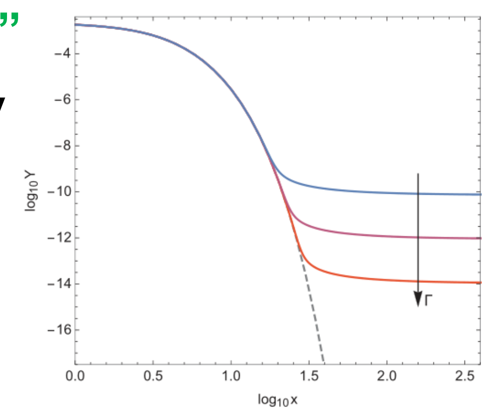


$T \ll M_{DM}$

- ● : Dark Matter
- ● : Standard Model

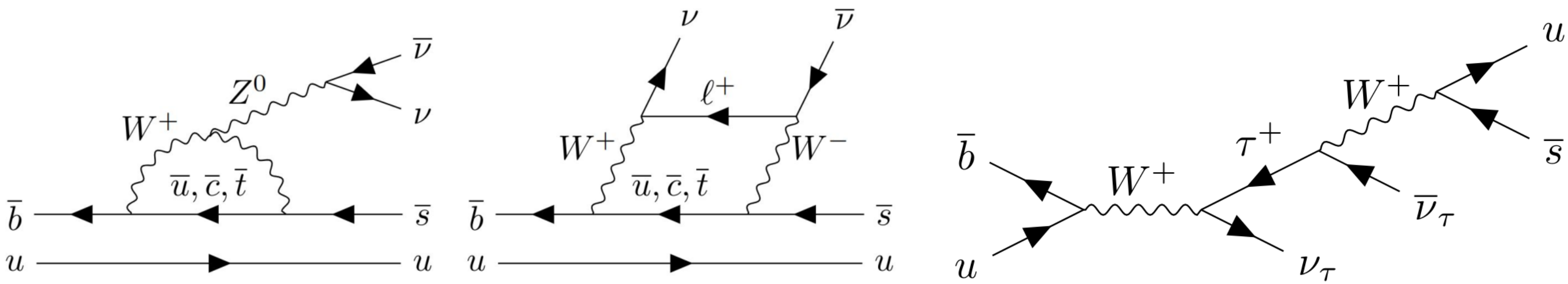


- Dark matter population in an expanding Universe
  - **Dark matter particles can no longer annihilate**
  - **The number of dark matter particles "freeze-out"**
- Standard calculation for WIMP DM relic density
  - The Boltzmann equation $\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma v \rangle \left(n_\chi^2 - n_{\text{eq}}^2 \right)$
- Relic density: $\Omega h^2 = 0.12 \rightarrow \langle \sigma v \rangle \sim 10^{-9} \text{GeV}^{-2}$



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

- The $B^+ \to K^+ \nu\bar{\nu}$ process is known with high accuracy in the SM:
  - $Br(B^+ \to K^+ \nu\bar{\nu}) = (5.58 \pm 0.37) \times 10^{-6}$ **HPQCD, PRD 2023**



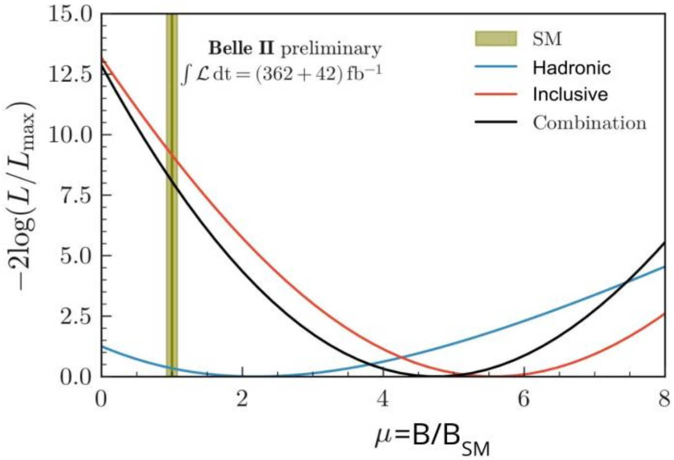
- $\mathcal{L}_{b\to s\nu\bar{\nu}} = -C_\nu \bar{s}_L \gamma^\mu b_L \bar{\nu}\gamma^\mu \nu$

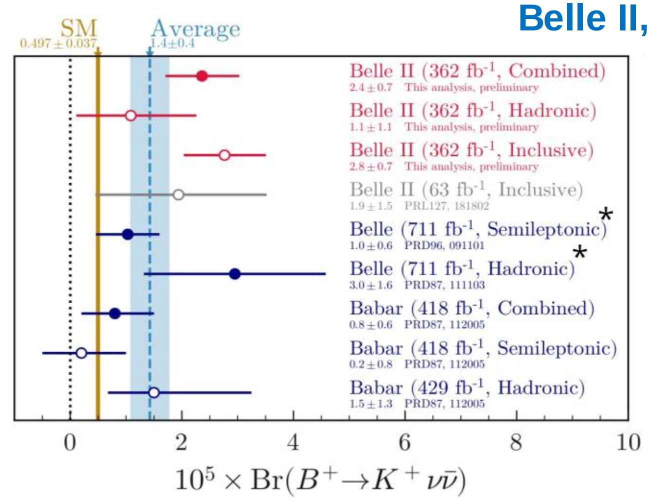
$$C_\nu = \frac{g_W^2}{M_W^2}\frac{g_W^2 V_{ts}^* V_{tb}}{16\pi^2}\left[\frac{x_t^2 + 2x_t}{8(x_t - 1)} + \frac{3x_t^2 - 6x_t}{8(x_t - 1)^2}\ln x_t\right],$$

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

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

Belle II, PRD 2024





- $Br(B^+ \to K^+\nu\bar{\nu})_{Exp} = (2.3 \pm 0.7) \times 10^{-5}$
  - 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)

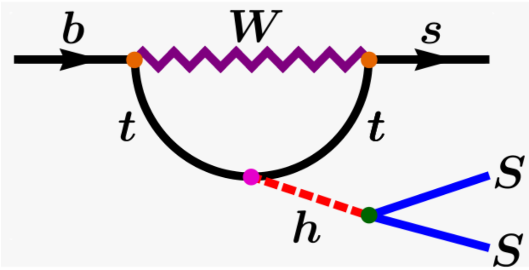
- $Br(B^+ \to K^+E_{\text{mis}})_{NP} = (1.8 \pm 0.7) \times 10^{-5}$
  - **Indirect NP effects**: The presence of heavy NP particles
  - **Direct NP effects**: the presence of new invisible particles

Solution: 3-body decay

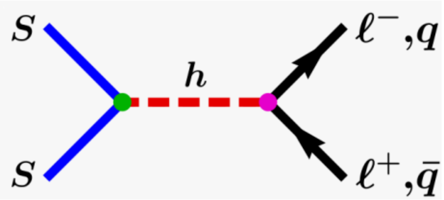
- Singlet light scalar DM ($m_s \leq 2.1\mathrm{GeV}$)

Bird et al, PRL 2004

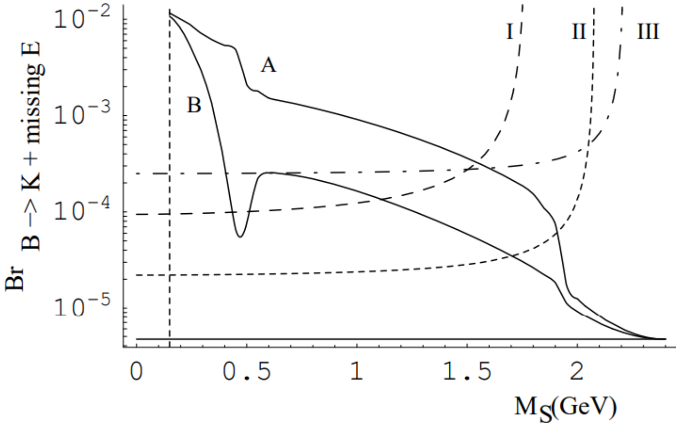
$$-\mathcal{L}_S = \frac{\lambda_S}{4} S^4 + \frac{m_0^2}{2} S^2 + \lambda S^2 H^\dagger H$$
$$= \frac{\lambda_S}{4} S^4 + \frac{1}{2}(m_0^2 + \lambda v_{EW}^2) S^2 + \boxed{\lambda v_{EW} S^2 h} + \frac{\lambda}{2} S^2 h^2,$$



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



  - 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).



CMB constraints

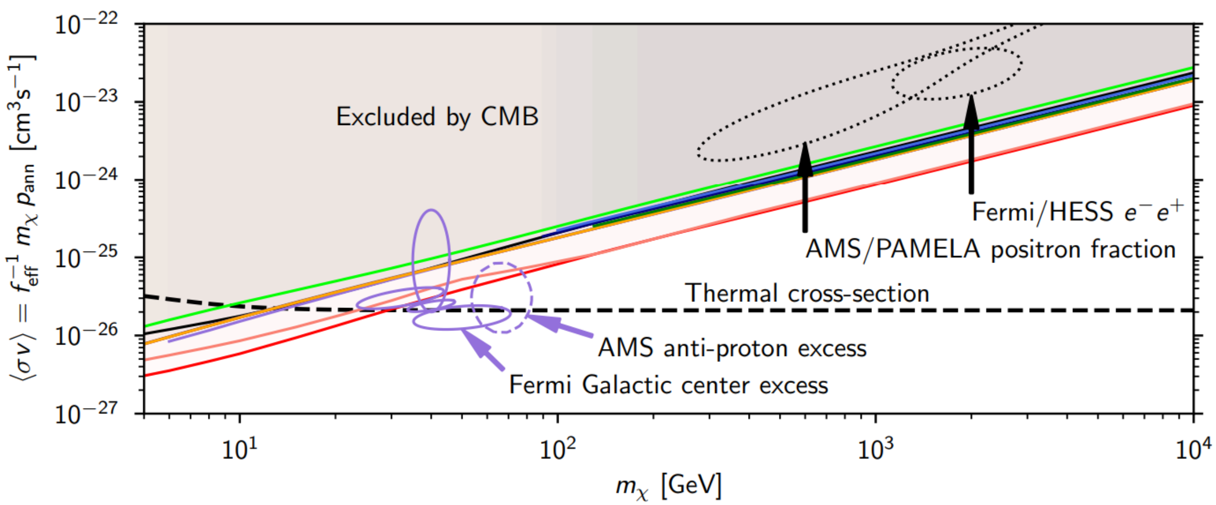
- Any injection of ionizing particles modifies the ionization history of hydrogen and helium gas, perturbing CMB anisotropies
  - DM annihilations to the charged SM particles
- Measurements of these anisotropies provide robust constraints on production of ionizing particles from DM annihilation products.

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

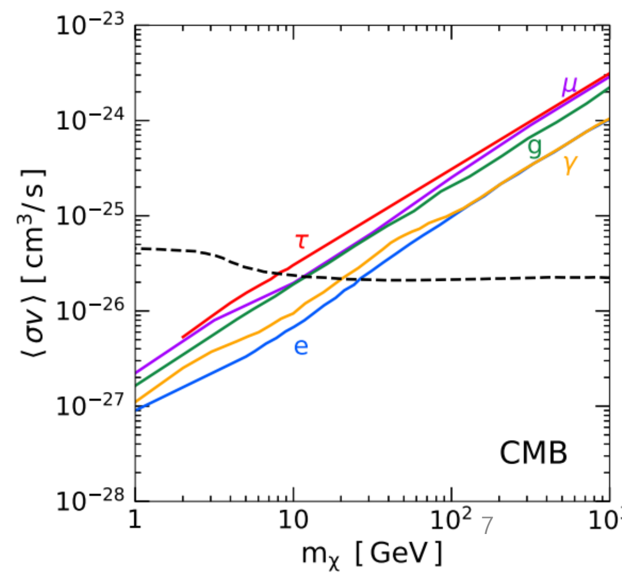
p-wave

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

s-wave



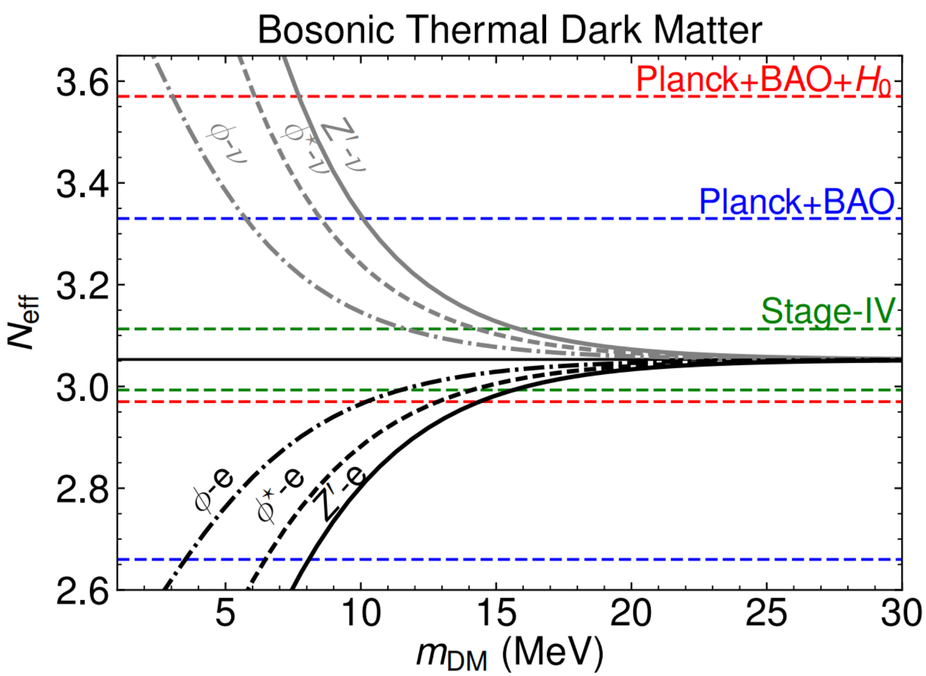
Planck 2018,
R. K. Leane et al, PRD 2018

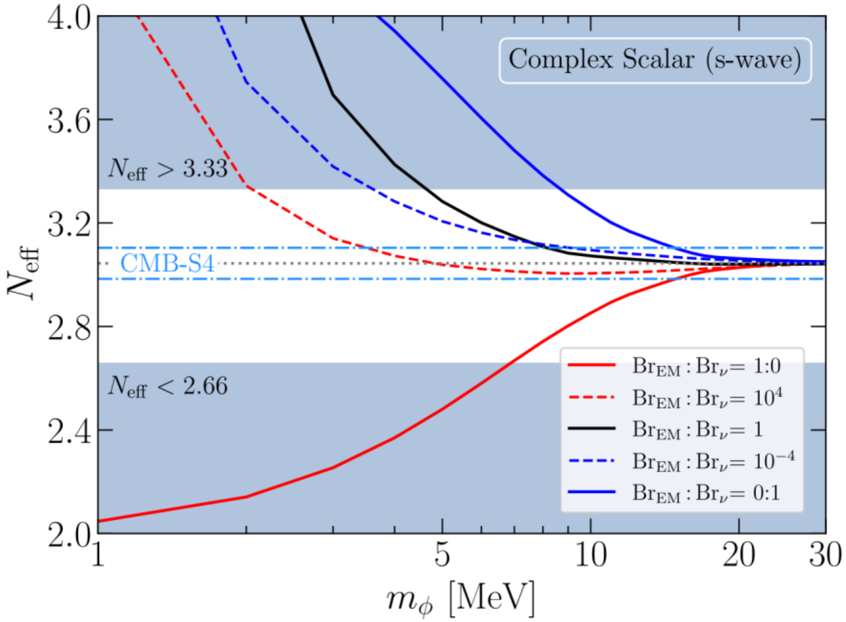


CMB constraints

- DM dominantly annihilates to neutrinos
- **WIMPs of $m \leq 20$ MeV** will generically alter neutrino decoupling and hence impact ΔN_{eff}

M. Escudero, JCAP 2019
X. Chu et al, PRD 2024





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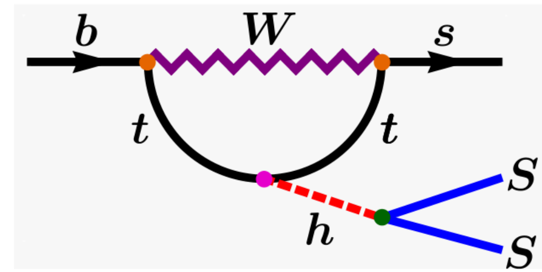
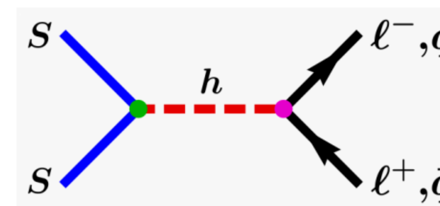


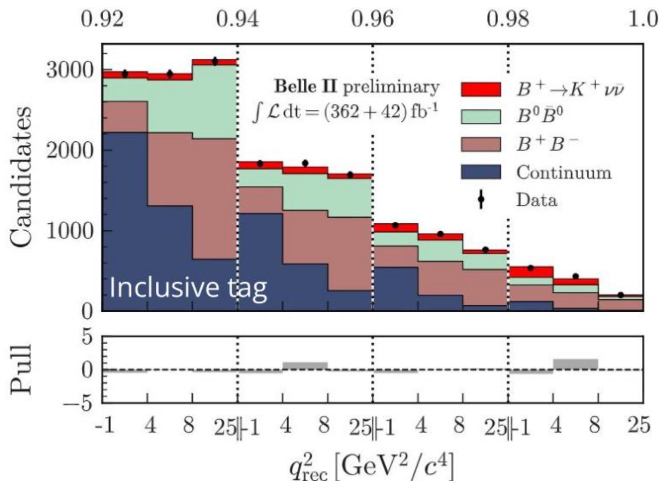
- Belle ⇨ $\frac{C_{DM}}{C_\nu} \simeq \frac{4.4 \lambda M_W^2}{g_W^2 m_h^2}$
- Relic density: $\sigma_{\mathrm{ann}} v_{\mathrm{rel}} = \frac{8 v_{EW}^2 \lambda^2}{m_h^4} \left(\lim_{m_{\tilde{h}} \to 2 m_S} m_{\tilde{h}}^{-1} \Gamma_{\tilde{h}X} \right).$

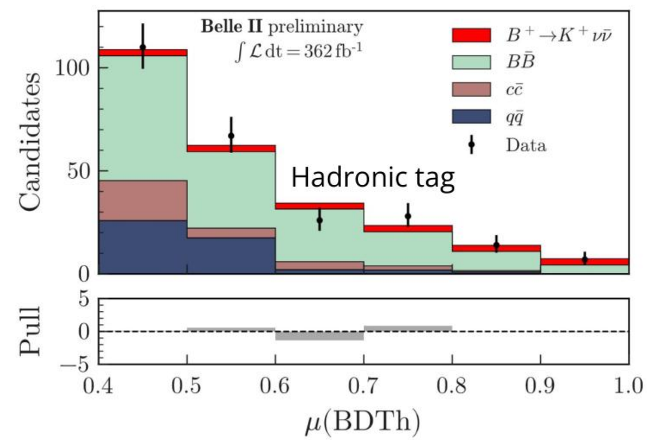


  - λ should be large to fit the relic as well as Belle II
  - $m_s \leq 1\mathrm{GeV}$ is already excluded by BABAR limits (2004 data).

- For $m_\chi \lesssim 20\mathrm{GeV}$, CMB bound (DM annihilation @ $T \sim \mathrm{eV}$) excludes the thermal DM freeze-out determined by *s-wave* annihilation
- **This model does not work anymore.**

Alternative solution: 2-body decay





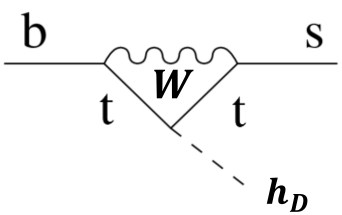
- Belle II provides information on the **q^2_{rec} spectrum**
  - q^2_{rec}: mass squared of the neutrino pair
  - A peak localized around $q^2_{rec} = 4\text{GeV}^2$
  - Two-body decay $(B \to KX), m_X = 2\ \text{GeV}$ **W. Altmannshofer et al, PRD 2024**
  - 2.8σ tension under the assumption of heavy new physics
  - No excess was found in the BaBar measurements of $B \to K^*\nu\bar{\nu}$
  - A global analysis of the BelleII and BaBar data leads to $\text{B}r(B \to KX) = (5.1 \pm 2.1) \times 10^{-6}$ with a reduced significane of $\approx \mathbf{2.4\sigma}$

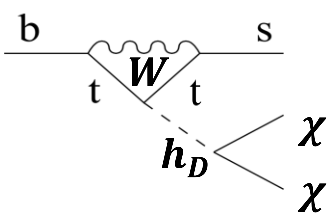
Solution: 2- or 3-body decay

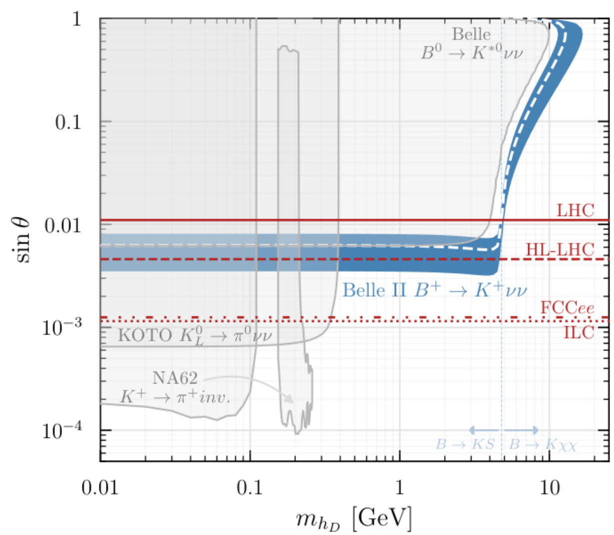
- Dark Higgs on-shell decay or three-body decay

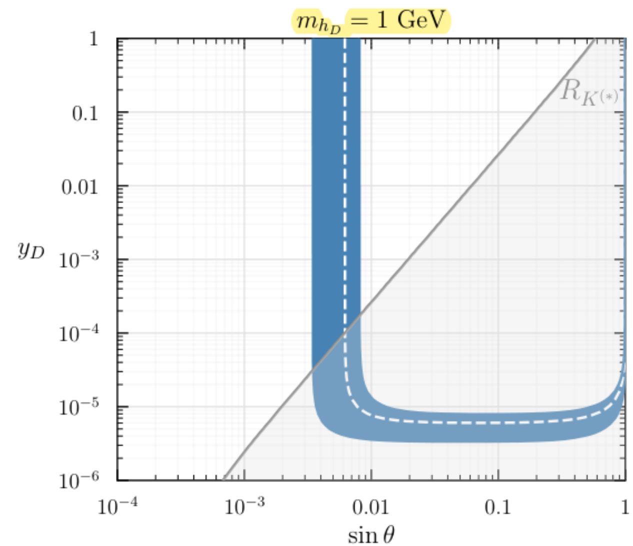
McKeen et al, PRD 2024

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









- **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, **fermionic DM does not work**

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McKeen et al, PRD 2024

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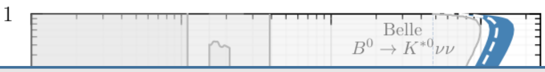
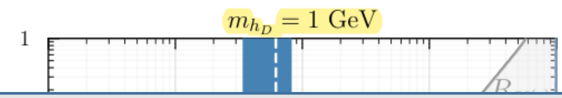




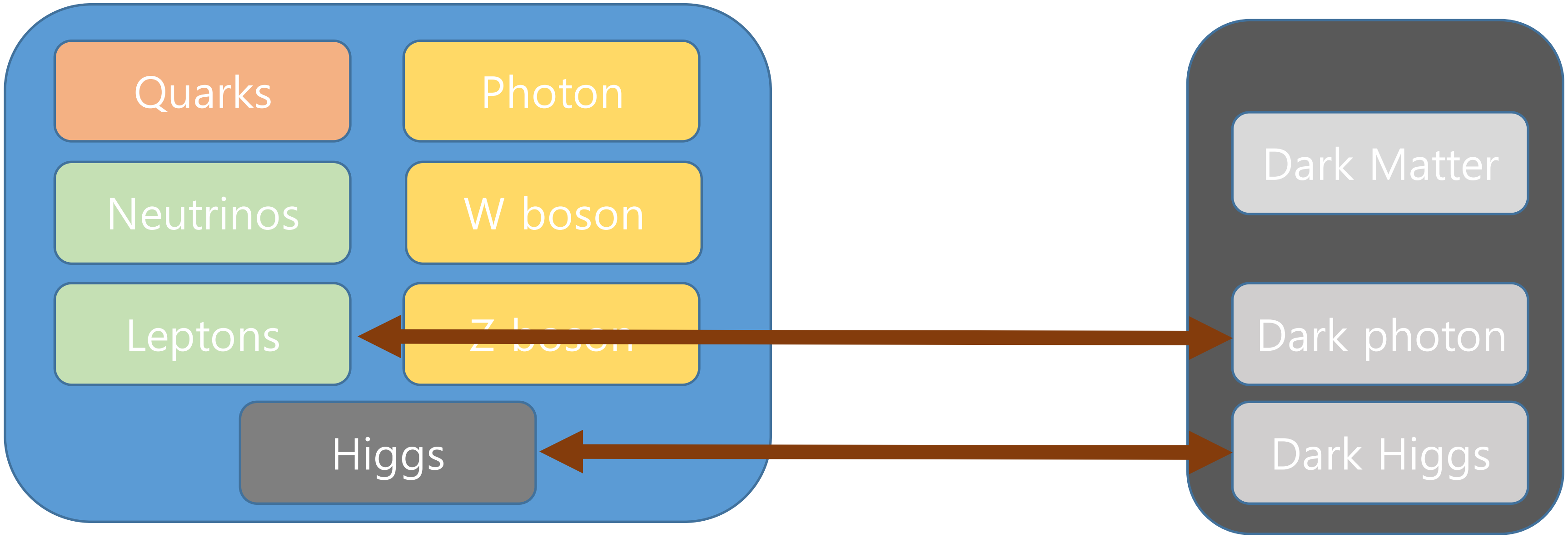
- **Fermionic DM seems to be disfavored.**
  → Could scalar DM with a dark Higgs provide a viable alternative?

- **How can one evade the CMB constraints?**

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

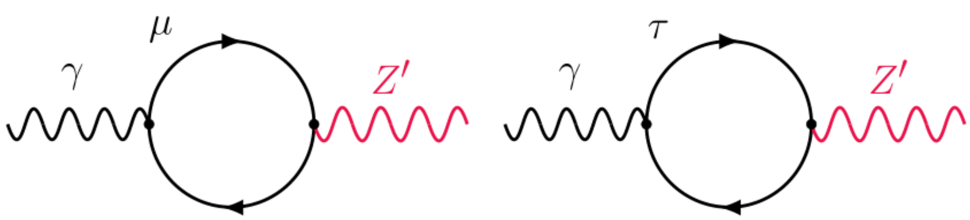
$U(1)_{L_\mu - L_\tau}$-charged DM + Dark Higgs

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



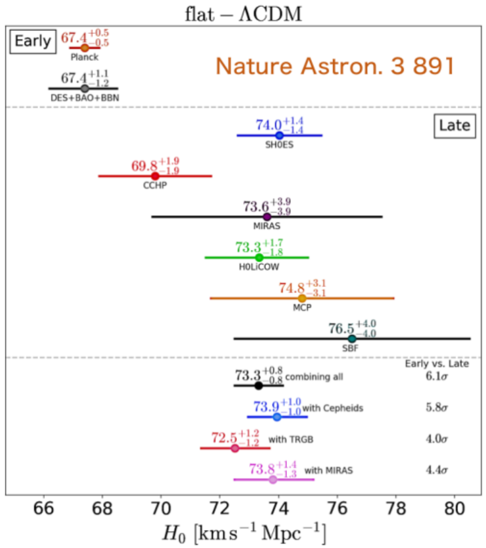
- **UV complete** $U(1)_{L_\mu - L_\tau}$-charged **scalar** DM model
- Dark photon Z' gets massive through $U(1)_{L_\mu - L_\tau}$ breaking
- A new singlet scalar (**Dark Higgs**), which mixes with the SM Higgs

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: $\hat{\mathcal{Q}}_{\mathrm{L}_\mu - \mathrm{L}_\tau}(\nu_\mu, \nu_\tau, \mu, \tau) = (1, -1, 1, -1)$
- No kinetic mixing between Z' and B @ high-energy
  - Kinetic mixing is generated through
  - 

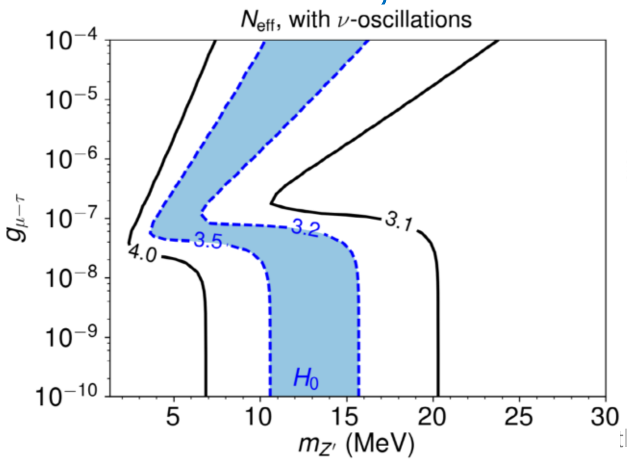
  - $\epsilon = -\frac{e g_{\mu-\tau}}{2\pi^2} \int_0^1 dx\, x(1-x) \log\left[\frac{m_\tau^2 - x(1-x)q^2}{m_\mu^2 - x(1-x)q^2}\right] \xrightarrow[m_\mu \gg q]{} -\frac{e g_{\mu-\tau}}{12\pi^2} \log\frac{m_\tau^2}{m_\mu^2} \simeq -\frac{g_{\mu-\tau}}{70}.$

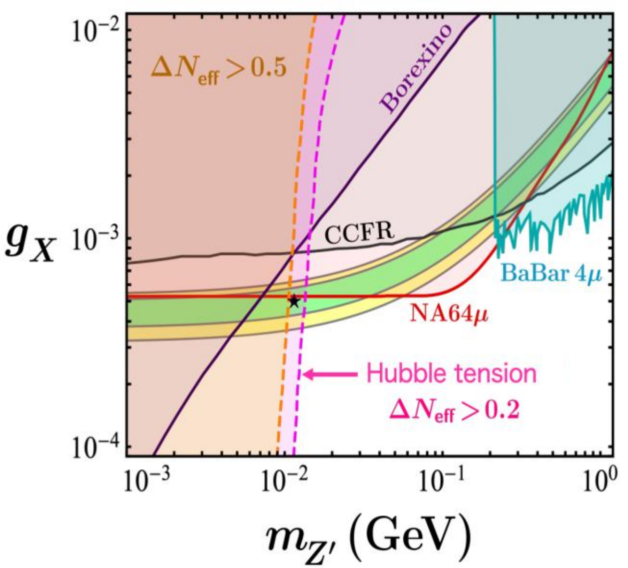
Hubble tension



- Large difference between early and late H_0
  - Late-time: $H_0 = 73.2 \pm 1.3 \ \mathrm{kms^{-1}Mpc^{-1}}$
  - Early-time: $H_0 = 67.4 \pm 0.5 \ \mathrm{kms^{-1}Mpc^{-1}}$
- Increasing $\Delta \mathrm{N_{eff}}$
  - $\sim 10 \mathrm{MeV} \ Z'$ 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
  - $0.2 < \Delta N_{\mathrm{eff}} < 0.5$

M. Escudero et al, JHEP 2019





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

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

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

- 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 (H_1), SM-like Higgs boson (H_2), mixing angle (θ)

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

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

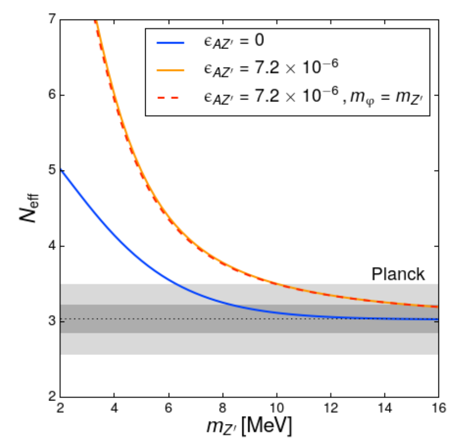
- Additional interactions with the dark Higgs
  - Dark Higgs kinetic term & potential

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

- **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

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

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



Local Z_3 scalar DM model

Baek, **JK**, Ko, 2204.04889

- Local Z_3 scalar DM model
  - $Q_X =, 1\ Q_\Phi = 3$
  - **Belle II excess**: 2-body decay ($B^+ \to K^+ H_1$)

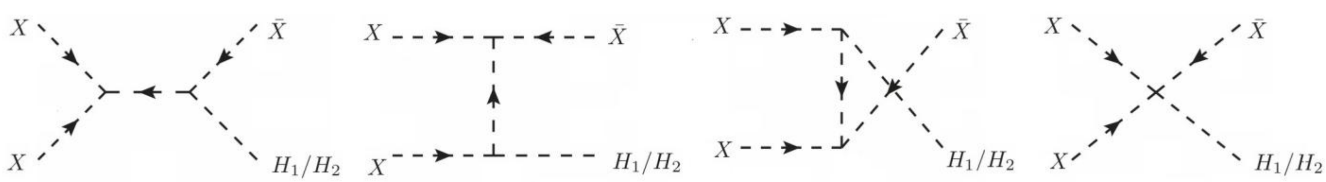
$$\mathcal{L}_{\rm DM} = D^\mu X^\dagger D_\mu X - m_X^2 X^\dagger X - \lambda_{\Phi X} X^\dagger X \left(\Phi^\dagger \Phi - \frac{v_\Phi^2}{2} \right) + \lambda_3 \left(X^3 \Phi^\dagger + {\rm H.c.} \right)$$

- Boltzmann equation

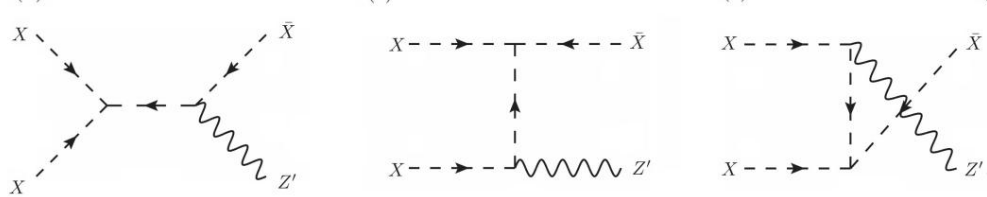
$$\frac{dY_X}{dx} = - \frac{s(x) \langle \sigma v \rangle_{X\bar{X} \to {\rm SM}}}{H(x)} \left(Y_X^2 - (Y_X^{\rm eq})^2 \right) + \frac{1}{2} \frac{s(x) \langle \sigma v \rangle_{XX \to \bar{X} Y}}{H(x)} \left(Y_X^2 - Y_X Y_X^{\rm eq} \right)$$

- Semi-annihilation DM channels

- **Semi-annihilation**



(a) (b) (c) (d)



(a) (b) (c)

CMB constraints

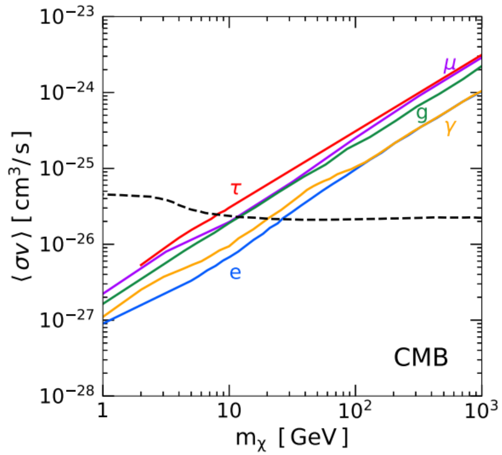
- For $m_X \lesssim 20\text{GeV}$, CMB bound (DM annihilation @ $T \sim \text{eV}$) excludes the thermal DM freeze-out determined by <u>*s-wave*</u> annihilation
  - DM annihilation should be mainly in **p-wave**
  - DM dominantly annihilates to neutrinos ($m_X \geq 20\text{MeV}$)

- 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

p-wave

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

s-wave



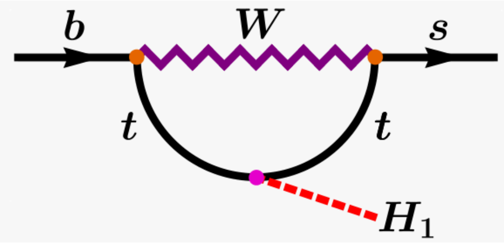
Belle II excess: 2-body decay

- When $m_{H_1} = 2\text{GeV}$, 2-body decay occurs

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

form factor

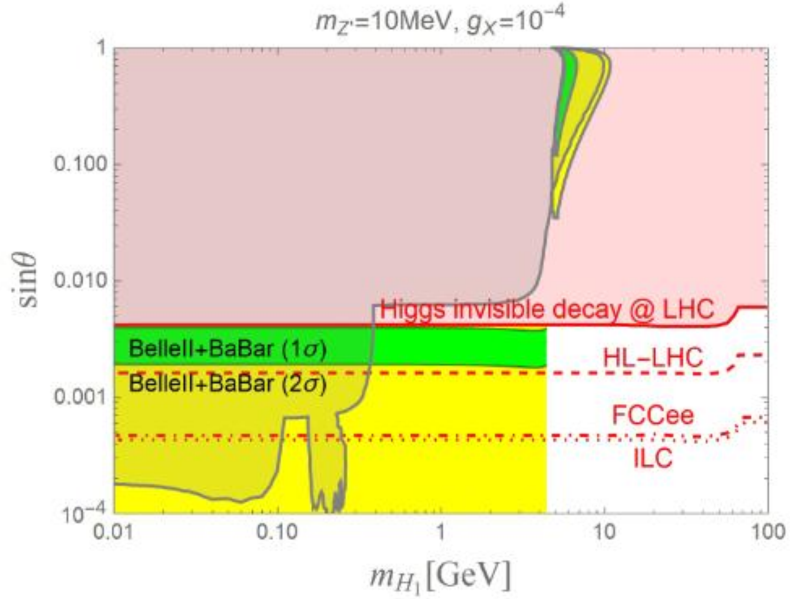
$\sin\theta \ll 1$

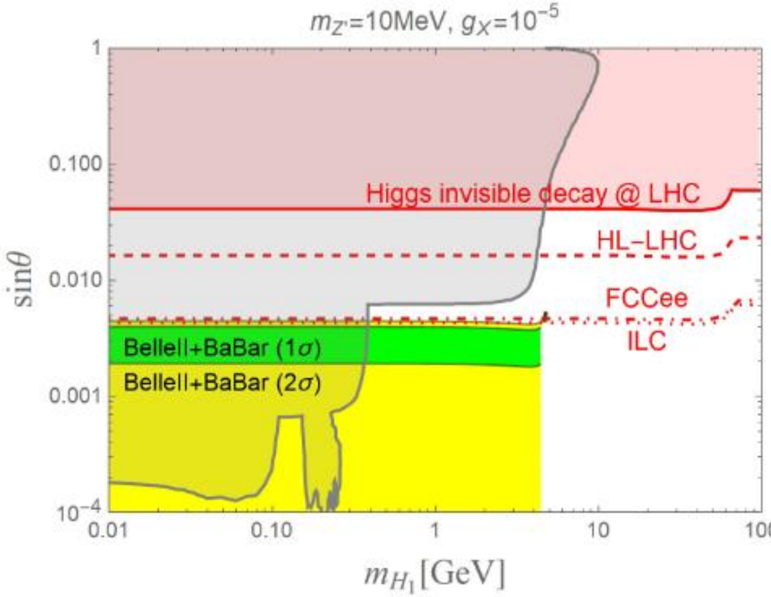


$$|\kappa_{cb}| \simeq 6.7\times 10^{-6} \qquad \mathcal{K}(a,b,c) = a^2+b^2+c^2-2(ab+bc+ca)$$

  - Dark Higgs decay process: $Br(H_1 \to Z'Z') \approx 1,\ Br(Z' \to \nu\bar{\nu}) \approx 1$

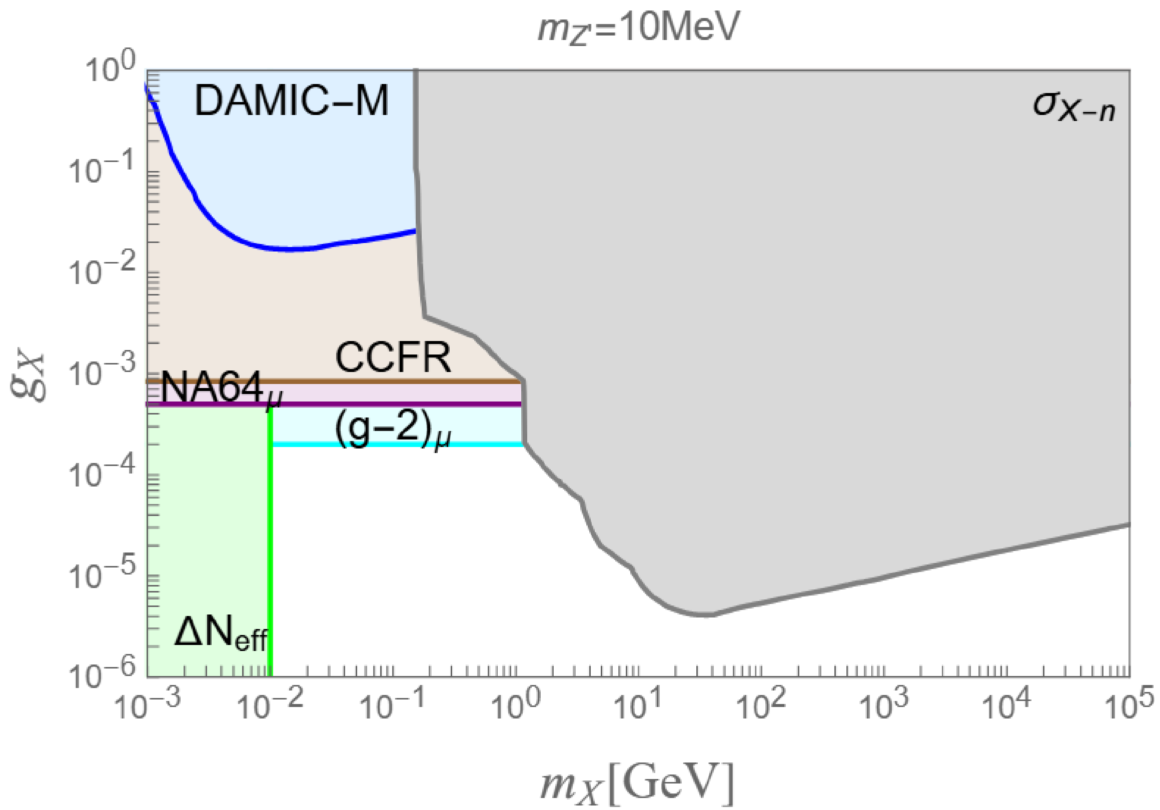
- Local Z_3 scalar DM model





Local Z_3 scalar DM model

- DAMIC-M: DM-electron elastic scattering
- DM-nucleon elastic scattering
- CCFR: neutrino trident production
- NA64: $\mu N \to \mu N Z', Z' \to \nu\bar{\nu}$
- Muon g-2
- ΔN_{eff}

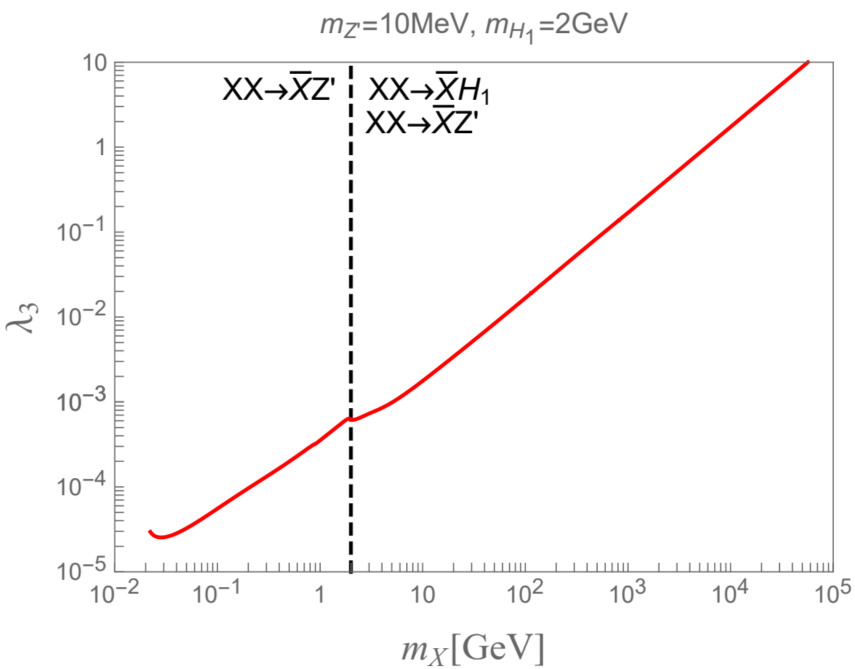


Local Z_3 scalar DM model

- Semi-annihilation:
  - Cross section is independent of the choice of v_ϕ

$$\langle\sigma v\rangle_{XX\to\bar{X}Z'} = \langle\sigma v\rangle_{XX\to\bar{X}H_1} = \frac{27}{64\pi}\frac{\lambda_3^2}{m_X^2}$$

- CMB bound
  - Dark Higgs, Z' predominantly decays into neutrinos



Conclusions

- BelleII data shows a excess of $B^+ \to K^+\nu\bar{\nu}$ over the SM prediction
- This excess can be interpreted as $B^+ \to K^+ +$ light dark sector particle (2-body decay)
- CMB constraints can be evaded because of semi-annihilations
- We can subsequently relax the tension in the Hubble constant with extra radiation

Thank you very much

arXiv: 2511.20430

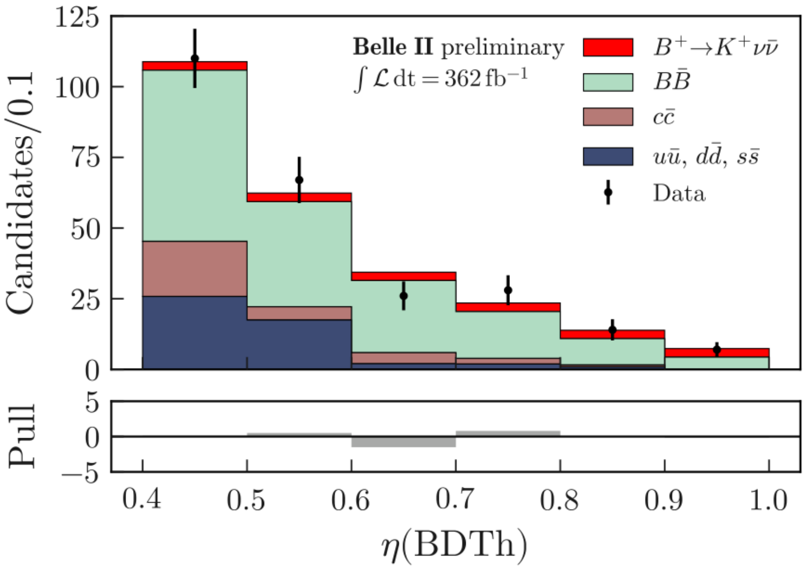
Back-up Slides

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

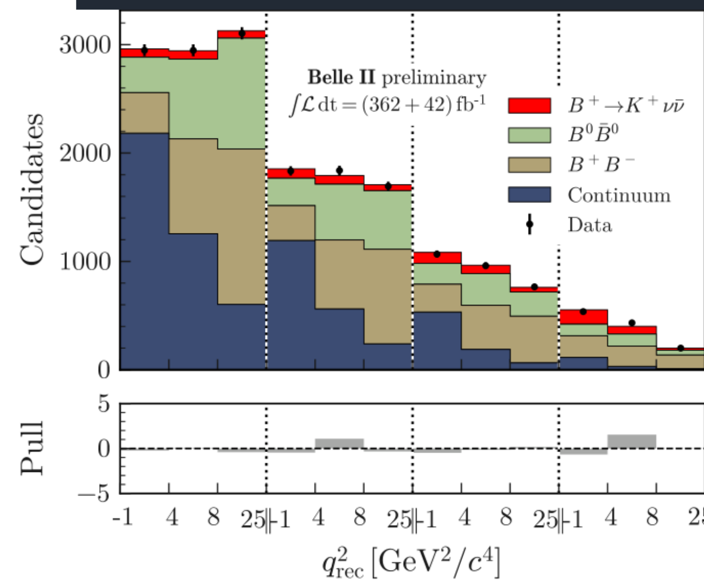
Belle II, PRD 2024

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

Hadronic tagging (HTA)



Inclusive tagging (ITA)



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

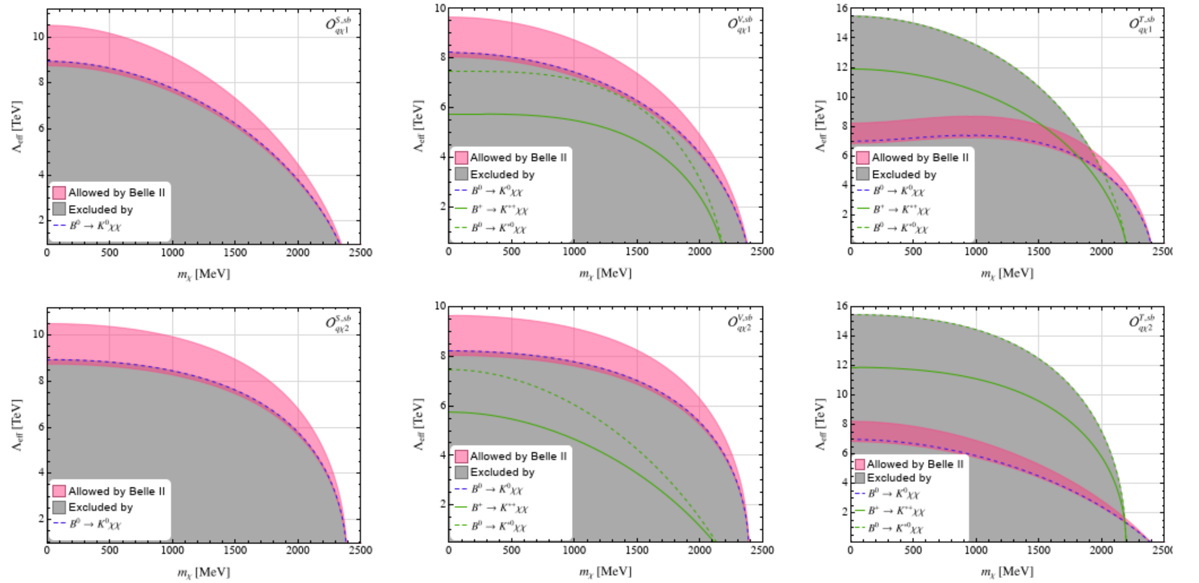
$$\mathscr{B}(B^+ \to K^+\nu\bar{\nu})_{\mathrm{ITA}} = (2.7 \pm 0.5 \pm 0.5) \times 10^{-5}$$

Solution: 3-body decay

- Real/Complex vector DM

X. He et al, PRD 2024

$$\mathcal{O}^{S,sb}_{qX} = (\bar{s}b)(X^\dagger_\mu X^\mu),$$
$$\mathcal{O}^{T,sb}_{qX1} = \frac{i}{2}(\bar{s}\sigma^{\mu\nu}b)(X^\dagger_\mu X_\nu - X^\dagger_\nu X_\mu),\ (\times)$$
$$\mathcal{O}^{T,sb}_{qX2} = \frac{1}{2}(\bar{s}\sigma^{\mu\nu}\gamma_5 b)(X^\dagger_\mu X_\nu - X^\dagger_\nu X_\mu),\ (\times)$$
$$\mathcal{O}^{V,sb}_{qX2} = (\bar{s}\gamma_\mu b)\partial_\nu(X^{\mu\dagger}X^\nu + X^{\nu\dagger}X^\mu),$$
$$\mathcal{O}^{V,sb}_{qX3} = (\bar{s}\gamma_\mu b)(X^\dagger_\rho \overleftrightarrow{\partial_\nu} X_\sigma)\epsilon^{\mu\nu\rho\sigma},$$
$$\mathcal{O}^{V,sb}_{qX4} = (\bar{s}\gamma^\mu b)(X^\dagger_\nu i\overleftrightarrow{\partial_\mu} X^\nu),\ (\times)$$
$$\mathcal{O}^{V,sb}_{qX5} = (\bar{s}\gamma_\mu b)i\partial_\nu(X^{\mu\dagger}X^\nu - X^{\nu\dagger}X^\mu),\ (\times)$$
$$\mathcal{O}^{V,sb}_{qX6} = (\bar{s}\gamma_\mu b)i\partial_\nu(X^\dagger_\rho X_\sigma)\epsilon^{\mu\nu\rho\sigma}.\ (\times)$$



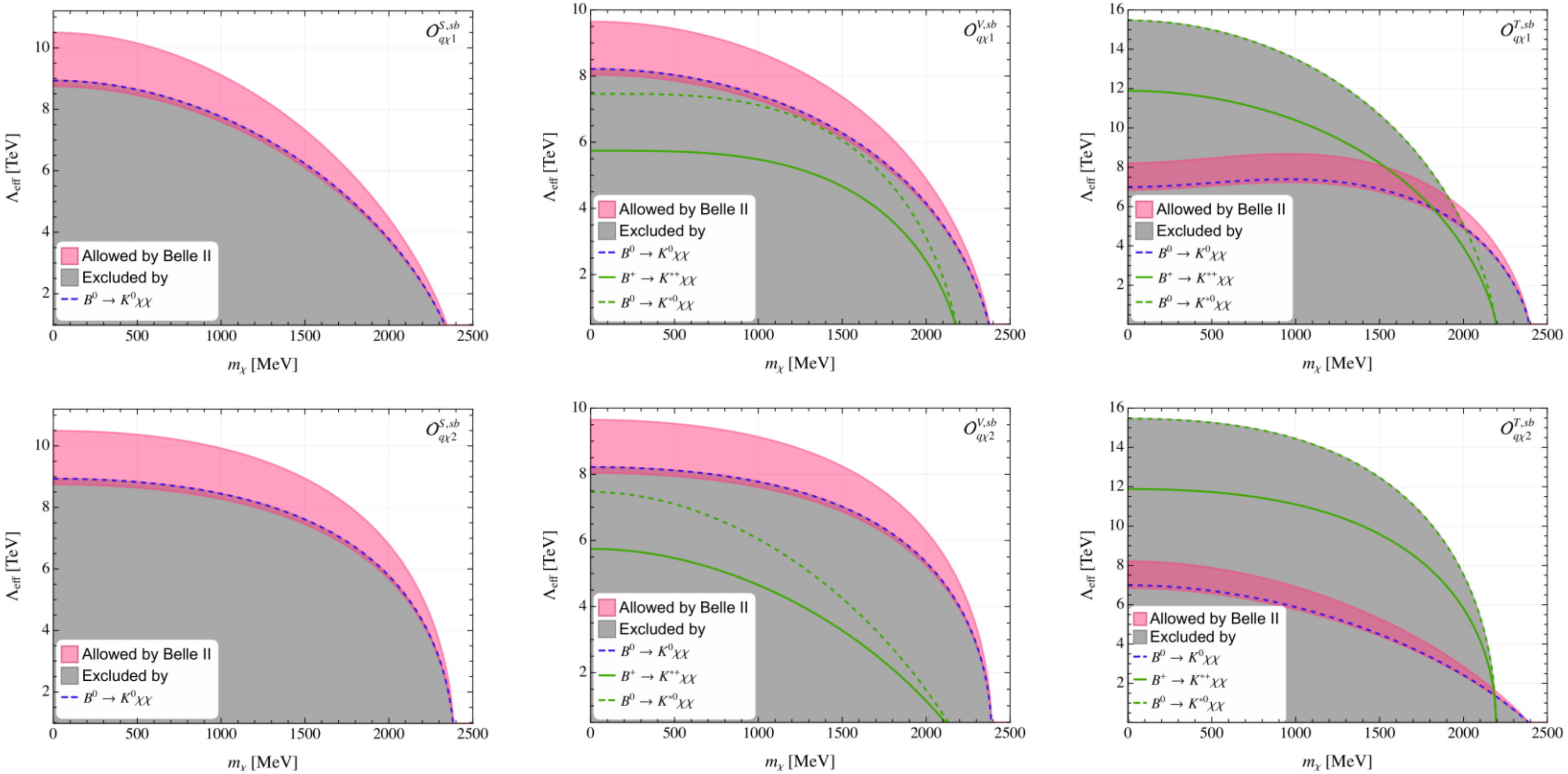
- DM annihilates to a pair of the SM quarks
  - Required large Λ → small self-annihilation cross section

Solution: 3-body decay

- Majorana/Dirac fermion DM

X. He et al, PRD 2024

$$\mathcal{O}^{S,sb}_{q\chi 1} = (\bar{s}b)(\bar{\chi}\chi), \qquad \mathcal{O}^{S,sb}_{q\chi 2} = (\bar{s}b)(\bar{\chi}i\gamma_5\chi),$$
$$\mathcal{O}^{V,sb}_{q\chi 1} = (\bar{s}\gamma^\mu b)(\bar{\chi}\gamma_\mu\chi),\ (\times) \qquad \mathcal{O}^{V,sb}_{q\chi 2} = (\bar{s}\gamma^\mu b)(\bar{\chi}\gamma_\mu\gamma_5\chi),$$
$$\mathcal{O}^{T,sb}_{q\chi 1} = (\bar{s}\sigma^{\mu\nu} b)(\bar{\chi}\sigma_{\mu\nu}\chi),\ (\times) \qquad \mathcal{O}^{T,sb}_{q\chi 2} = (\bar{s}\sigma^{\mu\nu} b)(\bar{\chi}\sigma_{\mu\nu}\gamma_5\chi),\ (\times)$$



Solution: 3-body decay

- Vector DM

X. He et al, PRD 2024

$$\mathcal{O}^{S,sb}_{qX} = (\bar{s}b)(X^{\dagger}_{\mu}X^{\mu}),$$

$$\mathcal{O}^{T,sb}_{qX1} = \frac{i}{2}(\bar{s}\sigma^{\mu\nu}b)(X^{\dagger}_{\mu}X_{\nu} - X^{\dagger}_{\nu}X_{\mu}),\ (\times)$$

$$\mathcal{O}^{T,sb}_{qX2} = \frac{1}{2}(\bar{s}\sigma^{\mu\nu}\gamma_5 b)(X^{\dagger}_{\mu}X_{\nu} - X^{\dagger}_{\nu}X_{\mu}),\ (\times)$$

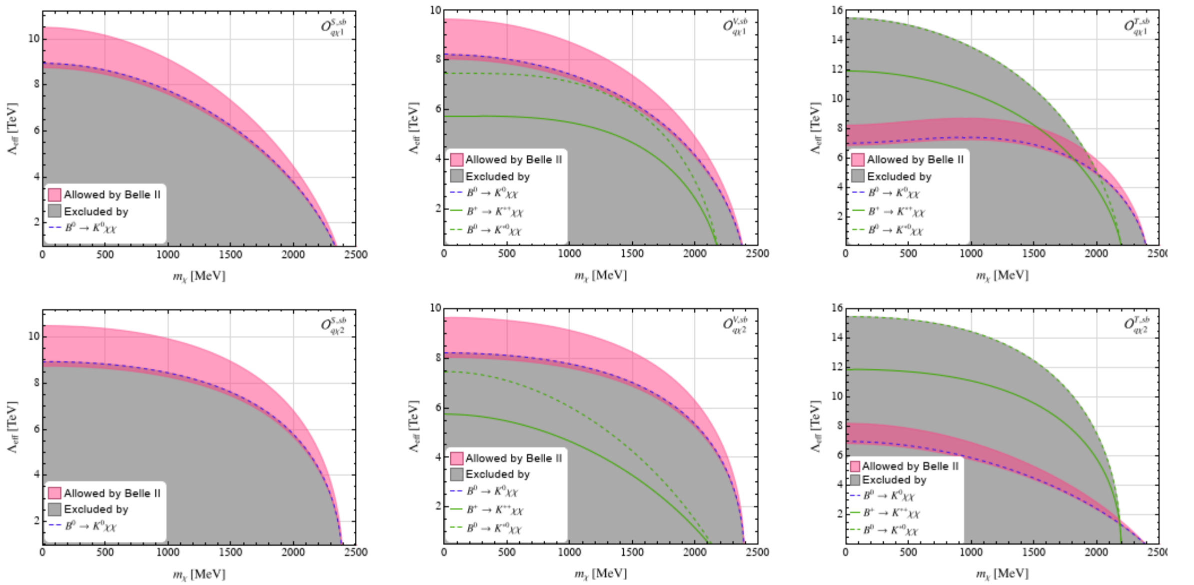
$$\mathcal{O}^{V,sb}_{qX2} = (\bar{s}\gamma_{\mu}b)\partial_{\nu}(X^{\mu\dagger}X^{\nu} + X^{\nu\dagger}X^{\mu}),$$

$$\mathcal{O}^{V,sb}_{qX3} = (\bar{s}\gamma_{\mu}b)(X^{\dagger}_{\rho}\overleftrightarrow{\partial}_{\nu}X_{\sigma})\epsilon^{\mu\nu\rho\sigma},$$

$$\mathcal{O}^{V,sb}_{qX4} = (\bar{s}\gamma^{\mu}b)(X^{\dagger}_{\nu}i\overleftrightarrow{\partial}_{\mu}X^{\nu}),\ (\times)$$

$$\mathcal{O}^{V,sb}_{qX5} = (\bar{s}\gamma_{\mu}b)i\partial_{\nu}(X^{\mu\dagger}X^{\nu} - X^{\nu\dagger}X^{\mu}),\ (\times)$$

$$\mathcal{O}^{V,sb}_{qX6} = (\bar{s}\gamma_{\mu}b)i\partial_{\nu}(X^{\dagger}_{\rho}X_{\sigma})\epsilon^{\mu\nu\rho\sigma}.\ (\times)$$



Alternative solution: 2-body decay

W. Altmannshofer et al, PRD 2024

- Light particle X
  - Light neutral vector boson Z'
  - Flavoured axions and ALPs

- Light → on-shell: $m_X < m_B - m_K$: $m_X = 2\ \mathrm{GeV}$
- Undetected particle X is stable, long-lived or decays invisibly
  - Couplings to electrons, muons, and light quarks should be absent or sufficiently small

- For $B \to K^* \nu\bar{\nu}$, only BaBar data is available, there is no excess seen
  - Use the $B \to K^* \nu\bar{\nu}$ measurements of BaBar to set an upper limit on $\mathrm{Br}(B \to K^* \nu\bar{\nu})$

Alternative solution: 2-body decay

- $B \to KZ'$ decay rate
  - $m_{Z'} = 2\text{GeV}$

W. Altmannshofer et al, PRD 2024

Including couplings up to dimension 6, the interaction Lagrangian is [47]

$$\mathcal{L}_{Z'} \supset \left\{ g_L^{(4)} Z'_\mu (\bar{s}\gamma^\mu P_L b) + \frac{g_L^{(5)}}{\Lambda} Z'_{\mu\nu} (\bar{s}\sigma^{\mu\nu} P_R b) + \frac{g_L^{(6)}}{\Lambda^2} \partial^\nu Z'_{\mu\nu} (\bar{s}\gamma^\mu P_L b) \ + \ \text{h.c.} \right\} \ + \ \{L \leftrightarrow R\}, \quad (2)$$

$$g_V^{(d)} = g_R^{(d)} + g_L^{(d)} \text{ and } g_A^{(d)} = g_R^{(d)} - g_L^{(d)}.$$

$$\Gamma^{(4)}_{B\to KZ'} = \frac{|g_V^{(4)}|^2}{64\pi} \frac{m_B^3}{m_{Z'}^2} \lambda^{\frac{3}{2}} f_+ \,,$$

$$\Gamma^{(5)}_{B\to KZ'} = \frac{|g_V^{(5)}|^2}{16\pi} \frac{m_B m_{Z'}^2}{\Lambda^2} \left(1 + \frac{m_K}{m_B}\right)^{-2} \lambda^{\frac{3}{2}} f_T \,,$$

$$\Gamma^{(6)}_{B\to KZ'} = \frac{|g_V^{(6)}|^2}{64\pi} \frac{m_B^3 m_{Z'}^2}{\Lambda^4} \lambda^{\frac{3}{2}} f_+ \,,$$

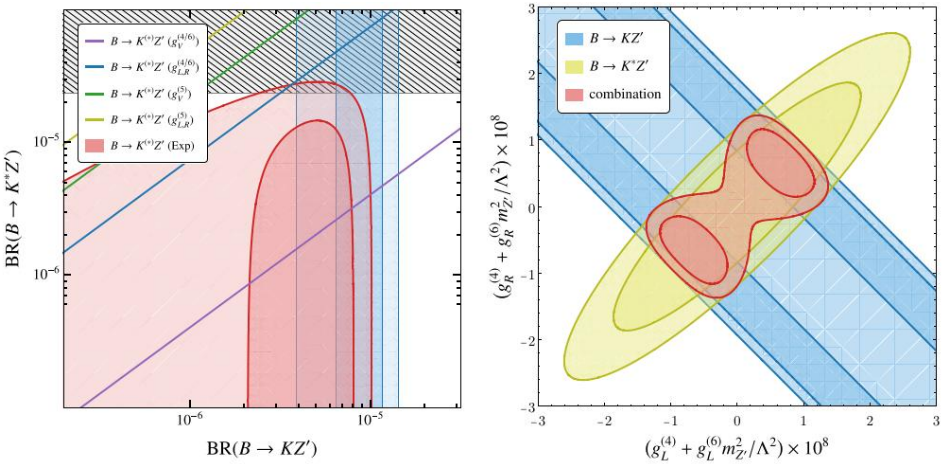


FIG. 2: *Left:* Correlations between $B \to KZ'$ and $B \to K^*Z'$ (colored lines) for the different $\bar{s}bZ'$ operators considered in this work. These are compared to the experimental data stemming from the combination of Belle-II, Babar and Belle measurements,which is represented by the red regions correspondingto $\Delta\chi^2 = 2.3$ and $\Delta\chi^2 = 6.18$. Belle's upper limit (hatched region at 2σ) and the new Belle II measurement (blue vertical band at 1σ and 2σ). *Right:* preferred regions in the $g_L - g_R$ plane. One can see that (approximately) vectorial couplings of the order of 10^{-8} are suggested by current data.

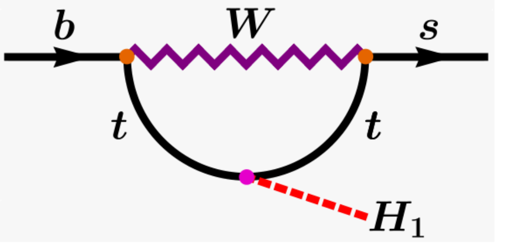
BelleII excess: 2- or 3-body decay

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

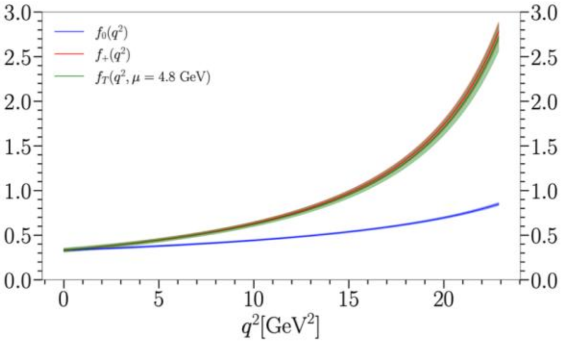
$$\Gamma_{B^+\to K^+H_1} \simeq \frac{|\kappa_{cb}|^2 \sin^2\theta}{64\pi m_{B^+}^3}\left(\frac{m_{B^+}^2 - m_{K^+}^2}{m_b - m_s}\right)^2 \left[f_0(m_{H_1}^2)\right]^2 \times \sqrt{\mathcal{K}(m_{B^+}^2, m_{K^+}^2, m_{H_1}^2)}$$

form factor

$\sin\theta \ll 1$



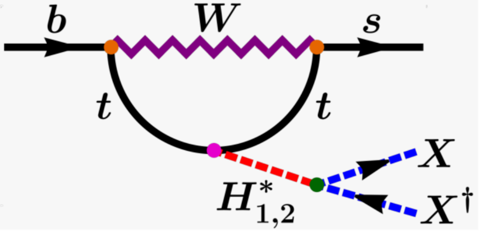
$$|\kappa_{cb}| \simeq 6.7 \times 10^{-6} \qquad \mathcal{K}(a,b,c) = a^2 + b^2 + c^2 - 2(ab + bc + ca)$$



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

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

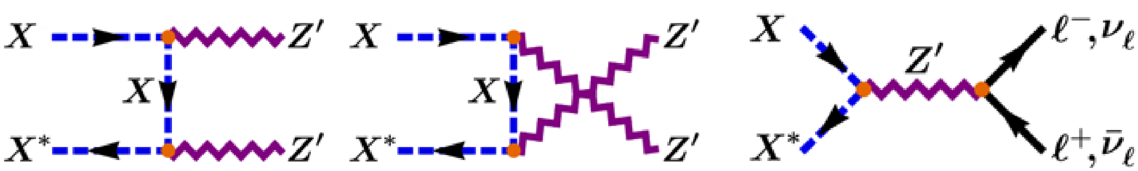


$U(1)_{L_\mu - L_\tau}$-charged DM model

- $U(1)_{L_\mu - L_\tau}$-charged scalar DM model

$$\mathcal{L}_{\rm int} = i g_X Z'_\mu \left(X^* \partial^\mu X - X \partial^\mu X^*\right) + g_X Z'_\alpha \sum Q_\ell \bar{\ell} \gamma^\alpha \ell$$

  - Free parameters: $\{m_{Z'}, g_X, m_X, Q_X\}$
  - Dark Photon Z' plays a role of messenger particle between DM and the SM leptons
  - Dark Photon mass is generated Proca or Stueckelberg mechanism



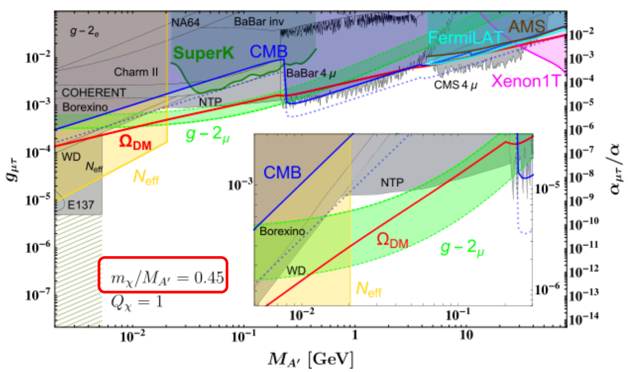
Only when $m_X > m_{Z'}$

- Consider Z' boson only & $g_X \sim (3-5) \times 10^{-4}$ **for the muon g-2**
  - $X\bar{X} \to f_{SM}\bar{f}_{SM}$: dominant annihilation channels

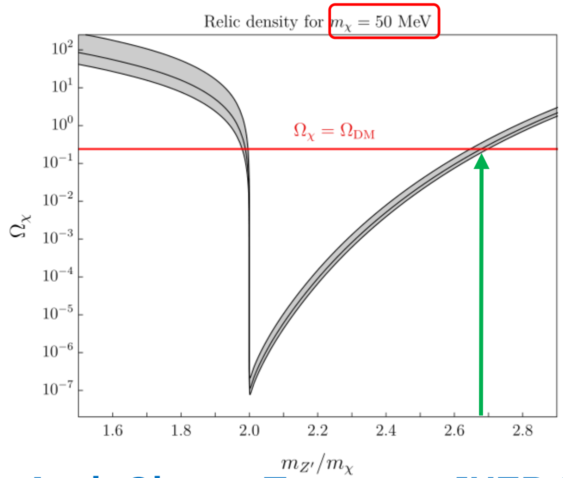
$U(1)_{L_\mu - L_\tau}$-charged DM model

- $XX^\dagger \to Z'^* \to \nu\bar{\nu}$: dominant annihilation channels
  - $m_{Z'} \sim 2m_X$ with the **s-channel Z' resonance** only gives the correct relic density

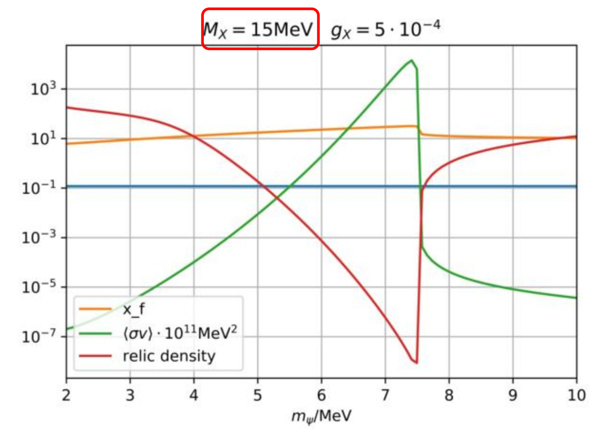
P. Foldenauer, PRD 2019



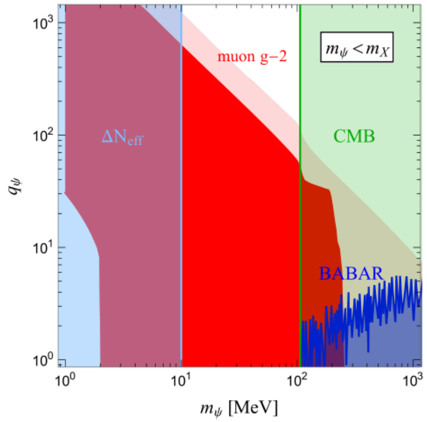
I. Holst, D. Hooper, G. Krnjaic, PRL 2022

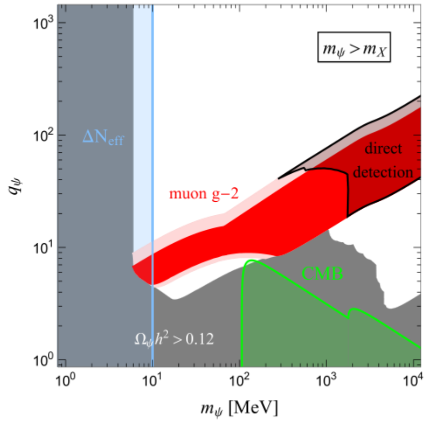


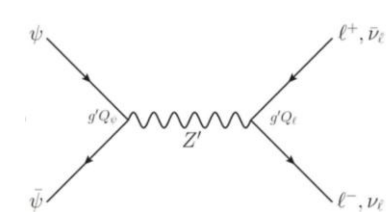
M. Drees, W. Zhao, PLB 2022



- Large DM charges **Asai, Okawa, Tsumura, JHEP 2021**





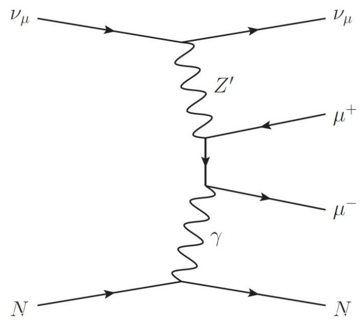


$U(1)_{L_\mu - L_\tau}$-charged DM model

- **Muon g-2**
  - $m_{Z'} \sim O(10)\mathrm{MeV}, \&\ g_X \sim 10^{-4}$ is too small to get $\Omega h^2 = 0.12$
  - $m_{Z'} \sim 2m_X$ with the s-channel Z' resonance
  - Only sub-GeV **DM** available
  - Tight correlation between DM mass and $\boldsymbol{Z'}$ mass
- No DM direct detection bound
  - DM-nucleon scattering: $\sigma_{\mathrm{el}}^{X-p} \simeq 10^{-46}\mathrm{cm}^2$
  - DM-electron scattering: $\sigma_{\mathrm{el}}^{X-e} \simeq 10^{-45}\mathrm{cm}^2$
- **BelleII excess**
  - $B \to KZ'$ (2-body decay)
    ➔ disfavored by q^2 spectrum
  - $B \to K\boldsymbol{X}\boldsymbol{X}^\dagger$(3-body decay)
    ➔ suppressed by kinetic mixing and $g_X \sim 10^{-4}$

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

- ***Neutrino trident production*** **W. Altmannshofer et al, PRL 2014**
  - Production of a muon pair from the scattering of a muon neutrino with heavy nuclei
  - $R_{\text{CCFR}} \equiv \frac{\sigma_{\text{CCFR}}}{\sigma_{\text{SM}}} = 0.82 \pm 0.28.$



- ***NA64*** **Y. Andreev, 2401.01708**
  - $\mu^- N \to \mu^- N Z', (Z' \to \text{inv.})$
  - Upper limit on g_X for $1\text{MeV} \leq m_{Z'} \leq 1\text{GeV}$

- ΔN_{eff} **M. Escudero et al, JHEP 2019**
  - Z' will reheat the neutrino gas, resulting in a higher expansion rate
  - Increase the effective number of neutrinos N_{eff}
  - $\mathbf{\Delta N_{\text{eff}} < 0.5}$
- ***BOREXINO*** **R. Harnik et al, JCAP 2012**
  - $\nu - e$ scattering

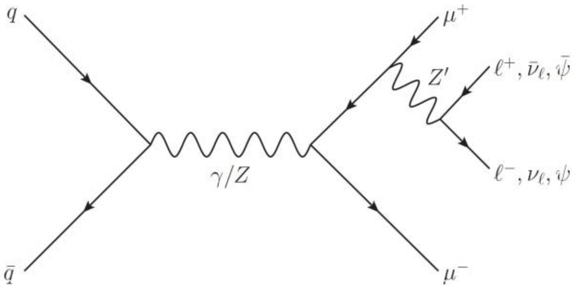
BaBar, LHC 4μ channels

BaBar Collaboration, PRD 2016

- $e^+e^- \to \mu^+\mu^- Z',\ Z' \to \mu^+\mu^-$
  - Upper limit on g_X for $200\mathrm{MeV} \le M_{Z'} \le 10\mathrm{GeV}$

CMS Collaboration, PLB 2019

- The lowest order Z' production process at collider
  - Produce a charged lepton pair through Drell-Yan process
  - Z' is radiated from one of leptons



- Final states
  - two pair of charged-leptons
  - A pair of charged-lepton plus missing energy

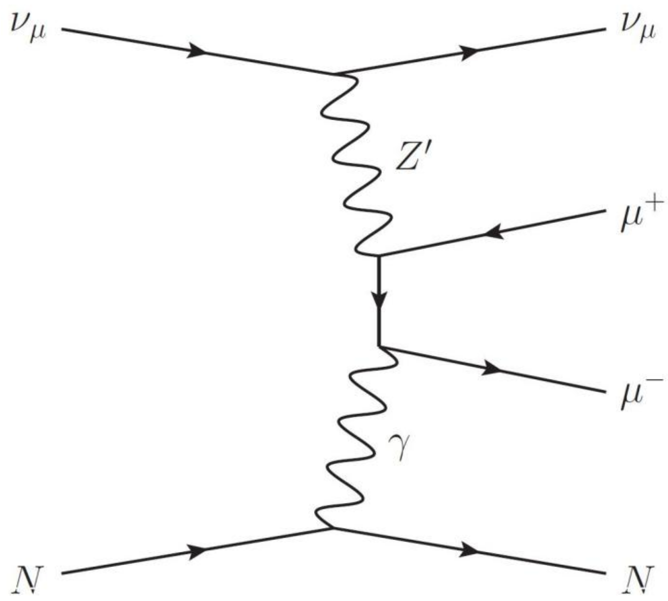
Neutrino trident production

- Production of a muon pair from the scattering of a muon neutrino with heavy nuclei

  - $R_{\rm CCFR} \equiv \frac{\sigma_{\rm CCFR}}{\sigma_{\rm SM}} = 0.82 \pm 0.28.$

W. Altmannshofer et al, PRL 2014

- The leading order Z' contribution:



Borexino: $\nu - e$ scattering

- Borexino is a liquid scintillator experiment measuring solar neutrino scattering off electron
  - Probe non-standard interactions between neutrinos and target
  - Limits from Borexino for the $U(1)_{B-L}$ gauge boson have been derived.

R. Harnik et al, JCAP 2012

- Rescale the constraints on $U(1)_{B-L}$ boson as

$$\alpha_{B-L}^2 \to \begin{cases} \left[\sum_{i,j=1}^3 f_i \, |(U^\dagger Q_{\mu e} U)_{ij}|^2\right]^{1/2} \alpha_{\mu e}^2 \,, & \text{for} \quad \mathrm{U}(1)_{L_\mu - L_e} \,, \\ \left[\sum_{i,j=1}^3 f_i \, |(U^\dagger Q_{e\tau} U)_{ij}|^2\right]^{1/2} \alpha_{e\tau}^2 \,, & \text{for} \quad \mathrm{U}(1)_{L_e - L_\tau} \,, \\ \left[\sum_{i,j=1}^3 f_i \, |(U^\dagger Q_{\mu\tau} U)_{ij}|^2\right]^{1/2} \alpha \, \alpha_{\mu\tau} \, \epsilon_{\mu\tau}(q^2) \,, & \text{for} \quad \mathrm{U}(1)_{L_\mu - L_\tau} \,, \end{cases}$$

$$Q_{\mu\tau} = \mathrm{diag}(0, 1, -1)$$

CMB & Hubble tension

M. Escudero et al, JHEP 2019

- Z' will reheat the neutrino gas
  - Resulting in a higher expansion rate
  - Increase the effective number of neutrinos N_{eff}
- Taking into account kinetic mixing