Belle II excess & Muon g-2 illuminating Light DM

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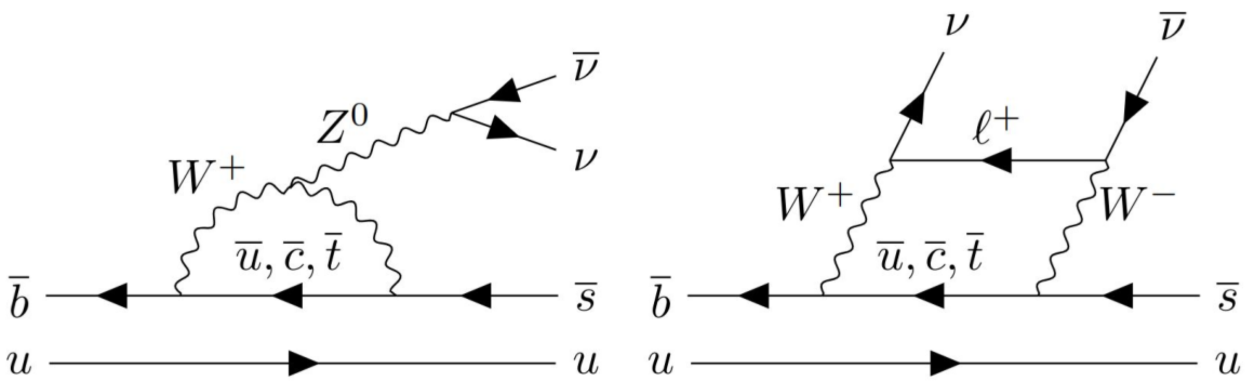
Based on

arXiv: 2401.10112

with Shu-Yu Ho (KIAS), Pyungwon Ko (KIAS)

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**



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

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

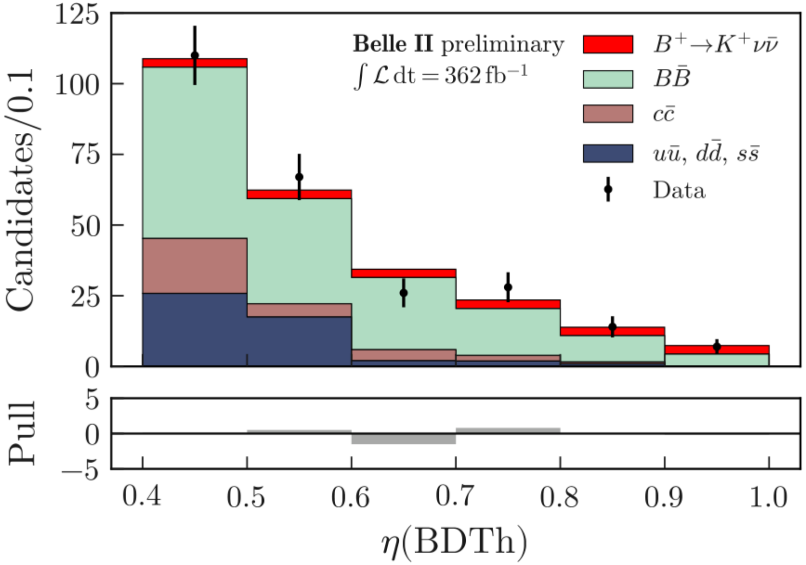
where $x_t = m_t^2/M_W^2$.

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

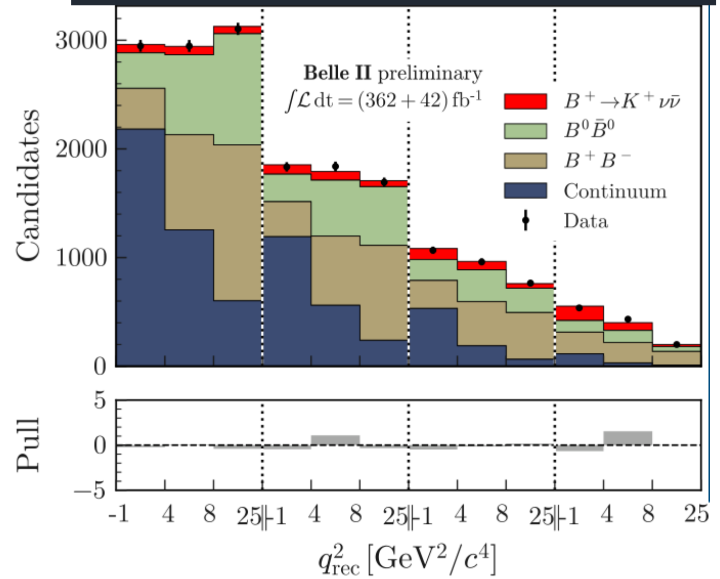
Belle-II, 2311.14647

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

Hadronic tagging (HTA)



Inclusive tagging (ITA)

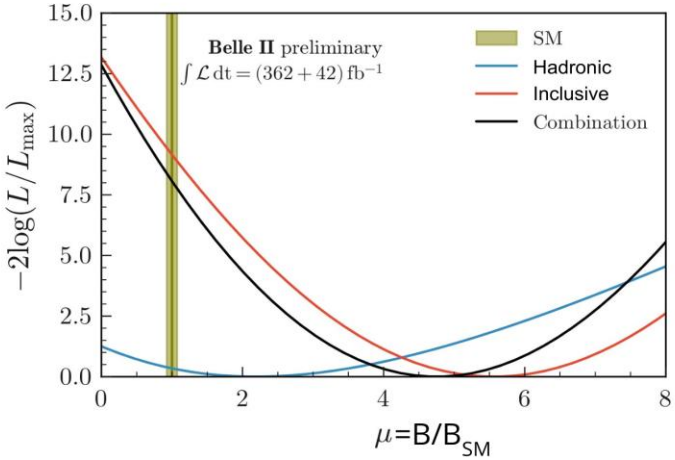


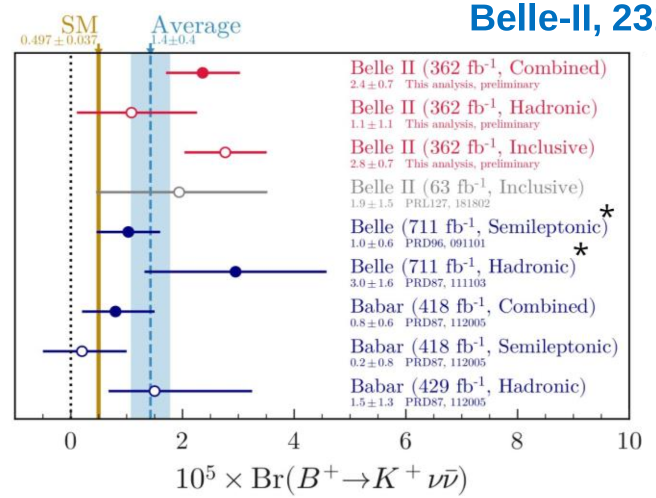
$$\mathscr{B}(B^+ \to K^+\nu\bar{\nu})_{\text{HTA}} = (1.1^{+0.9+0.8}_{-0.8-0.5}) \times 10^{-5}$$

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

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

Belle-II, 2311.14647

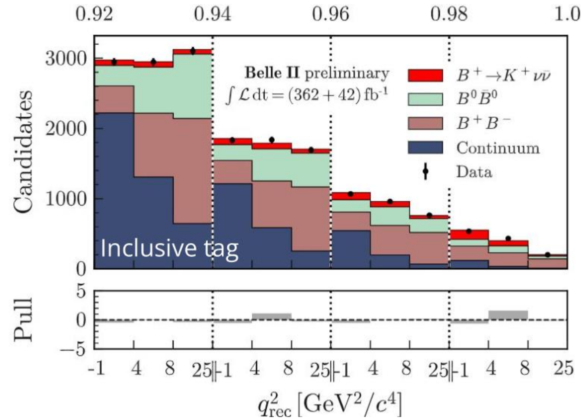


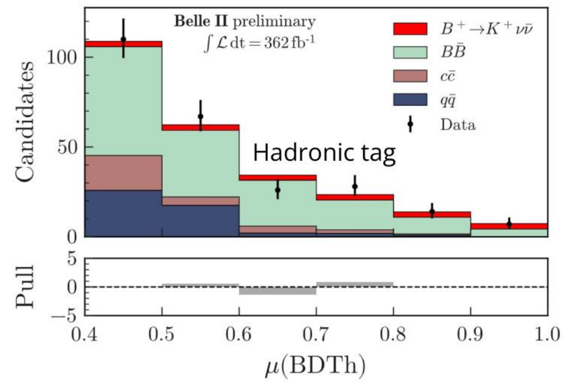


- $Br(B^+ \to K^+\nu\bar{\nu})_{Exp} = (2.3 \pm 0.7) \times 10^{-5}$
  - Prob(null signal from $B^+ \to K^+\nu\bar{\nu}$) $= 0.012\%$
  - ➔ Significance of observation: $3.5\ \sigma$
  - Prob$(B^+ \to K^+\nu\bar{\nu})_{SM} = 0.17\%$ (2.8σ tension with the SM prediction)

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

Solutions: 2- or 3-body decay

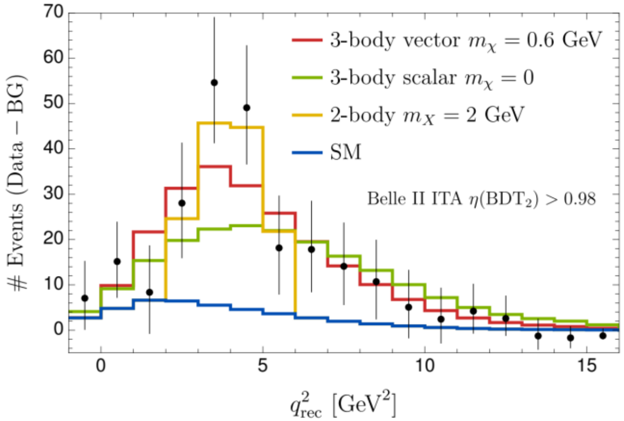


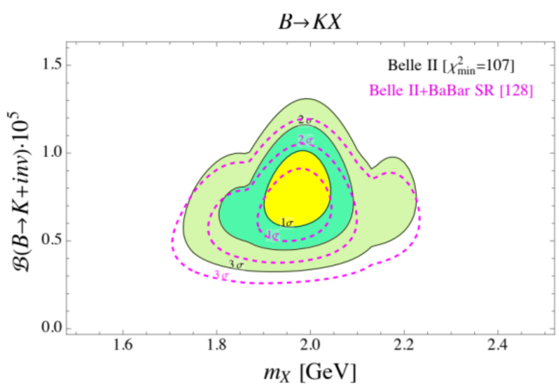


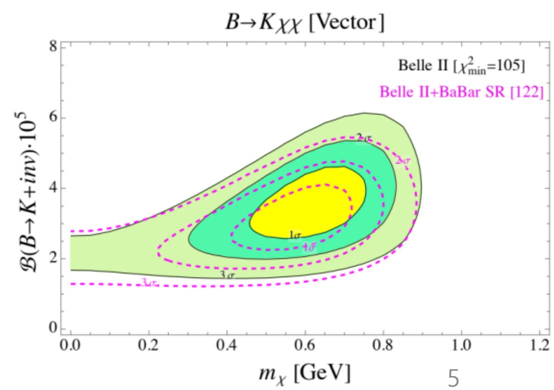
- Belle II provides information on the **q^2_{rec} spectrum**
  - q^2_{rec}: mass squared of the neutrino pair
  - A peak localized around $q^2_{rec} = 4\mathrm{GeV}^2$
  - Two-body decay $(B \to KX), m_X = 2\ \mathrm{GeV}$
  - Three-body decay $(B \to KXX), m_X < 0.6\ \mathrm{GeV}$

W. Altmannshofer et al, 2311.14629

K. Fridell et al, 2312.12507

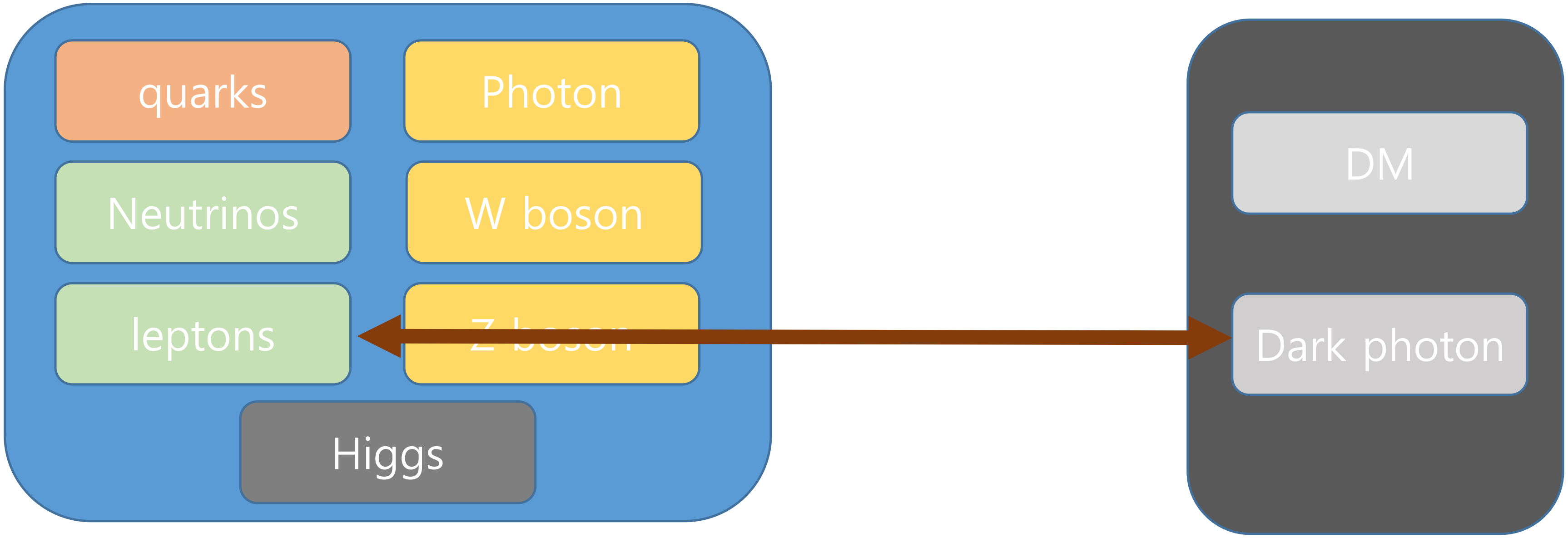






$U(1)_{L_\mu - L_\tau}$-charged DM model

- $U(1)_{dark} \equiv U(1)_{L_\mu - L_\tau}$

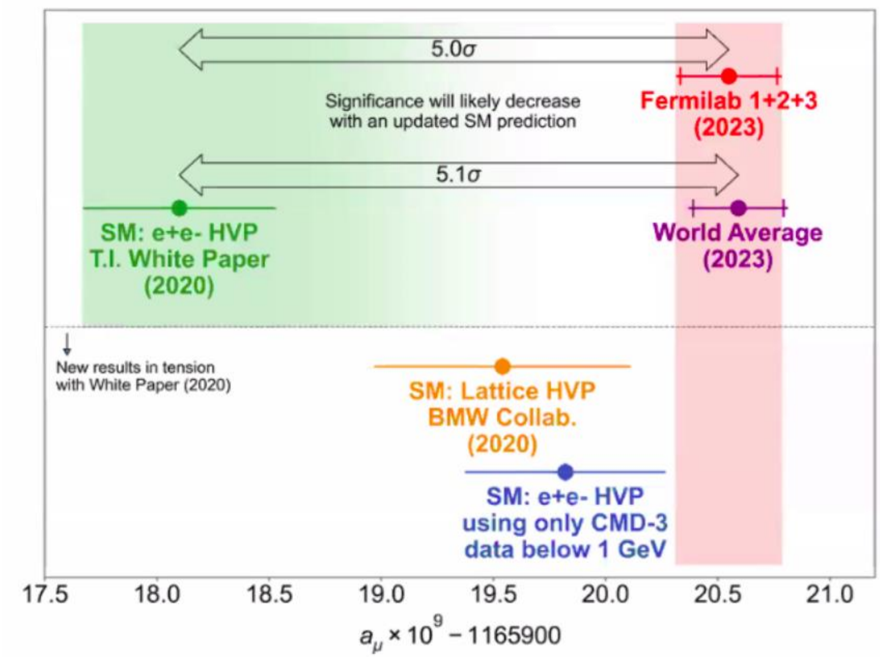


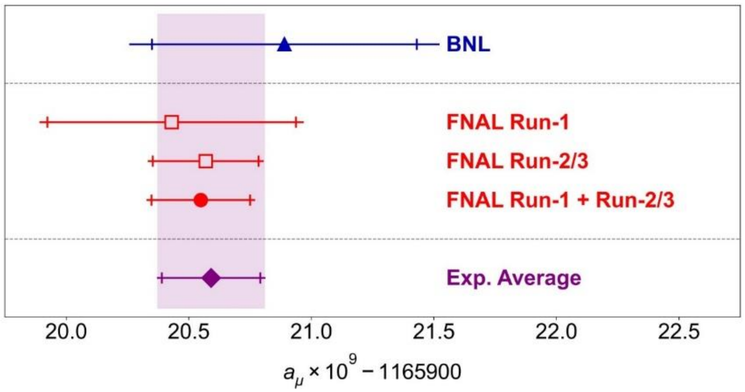
- Let's call Z', $U(1)_{L_\mu - L_\tau}$ gauge boson, dark photon since it couple to DM

Evidences – Muon g-2

Muon g-2 collaboration, PRL 2023

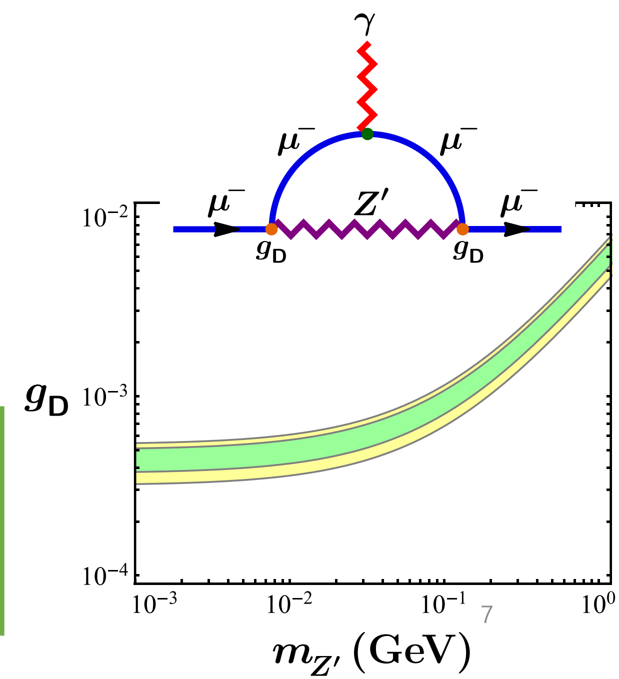
- Muon g-2 experiment improves the precision of their previous result by a factor of 2





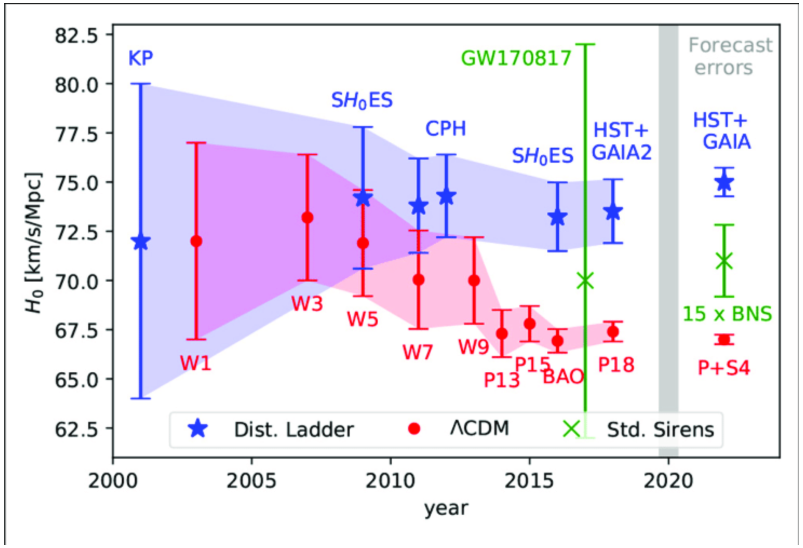
S. Baek, Deshpande, He, P. Ko, 2001
S. Beak, P. Ko, 2008
…

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

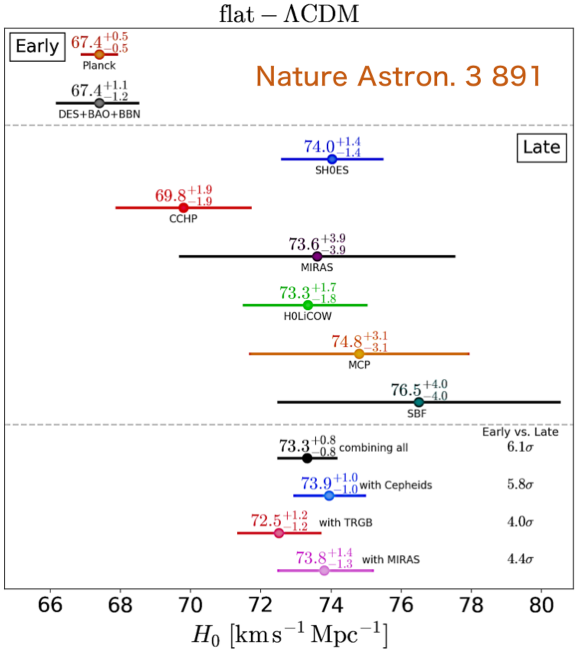


Evidences – Hubble tension

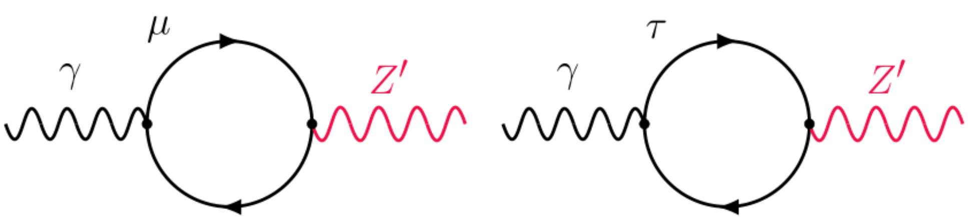
- Large difference between early and late H_0 measurement
  - Late-time: $H_0 = 73.2 \pm 1.3 \text{ kms}^{-1}\text{Mpc}^{-1}$
  - Early-time: $H_0 = 67.4 \pm 0.5 \text{ kms}^{-1}\text{Mpc}^{-1}$
- The discrepancy either arises because
  - Our distance measurements are incorrect (ΔG_N)
  - Cosmological model we use to fit all those distances is incorrect (ΔN_{eff})



P. Shah et al, AAR 2021



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

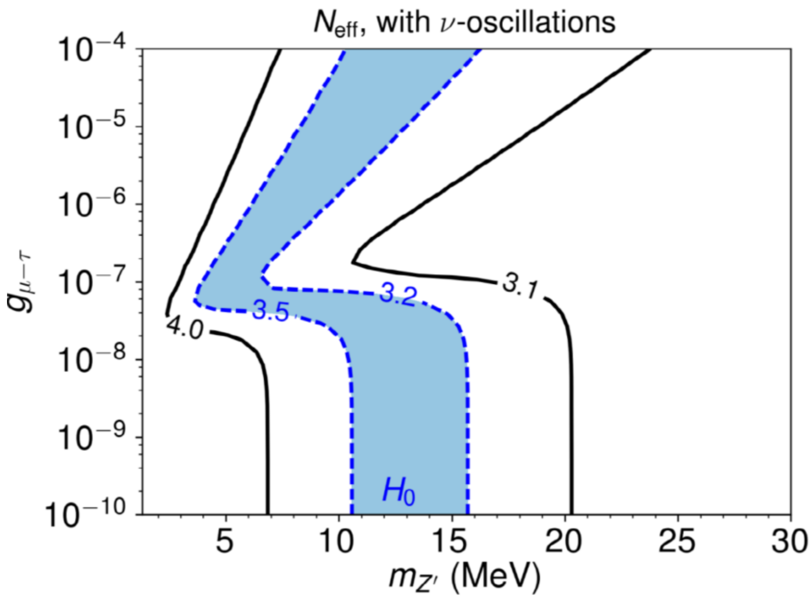
  - $\epsilon = -\frac{e g_{\mu-\tau}}{2\pi^2}\int_0^1 dx\, x(1-x)\log\left[\frac{m_\tau^2 - x(1-x)q^2}{m_\mu^2 - x(1-x)q^2}\right] \xrightarrow[m_\mu \gg q]{} -\frac{e g_{\mu-\tau}}{12\pi^2}\log\frac{m_\tau^2}{m_\mu^2} \simeq -\frac{g_{\mu-\tau}}{70}.$

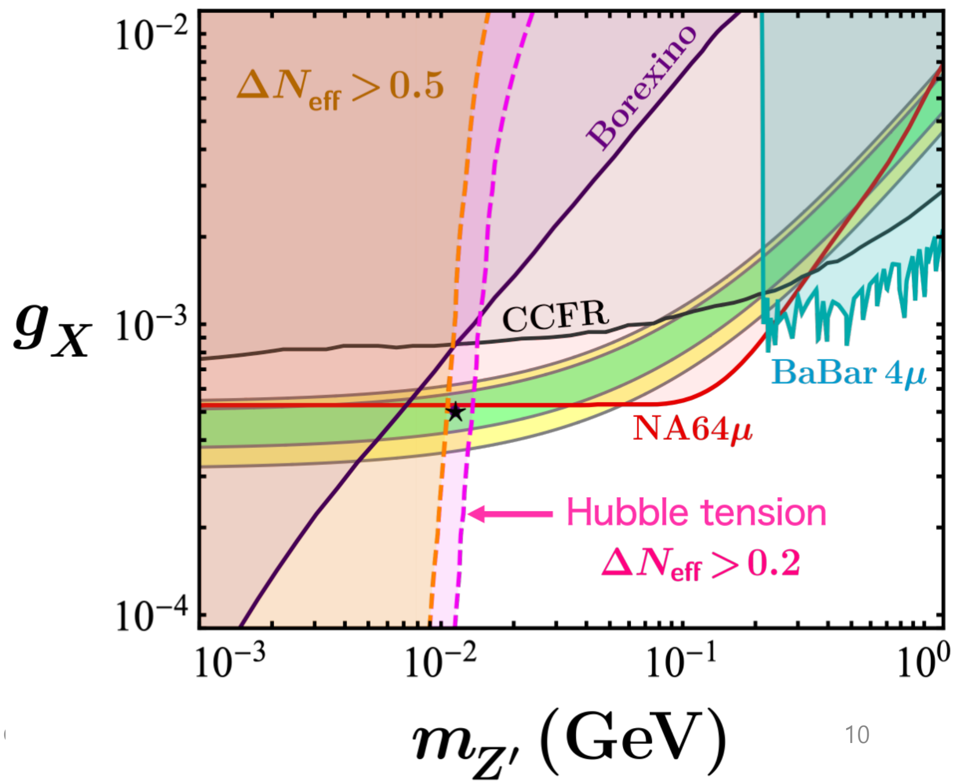
Gauged $U(1)_{L_\mu - L_\tau}$ Z' model

M. Escudero et al, JHEP 2019

- ***Hubble tension***
  - $\sim 10\mathrm{MeV}\ Z'$ 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
  - $0.2 < \Delta N_{\mathrm{eff}} < 0.5$

- BP : $m_{Z'} = 11.5\mathrm{MeV},\ g_X = 5 \times 10^{-4}$





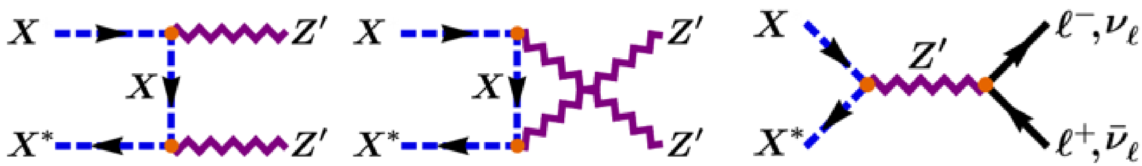
Can we find the integrated solution of Δa_μ, DM relic density, Hubble tension and $B^+ \to K^+ \nu\bar{\nu}$ at Belle II?

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

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

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

  - 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



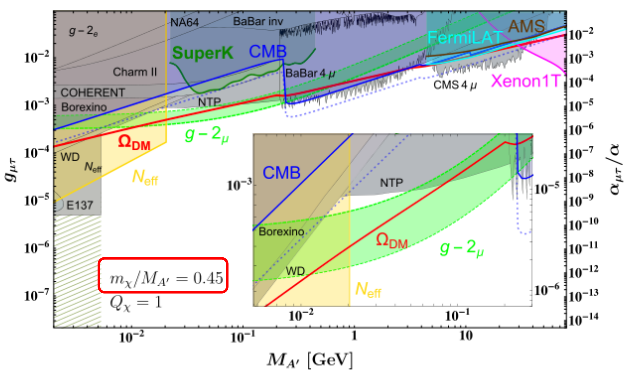
Only when $m_X > m_{Z'}$

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

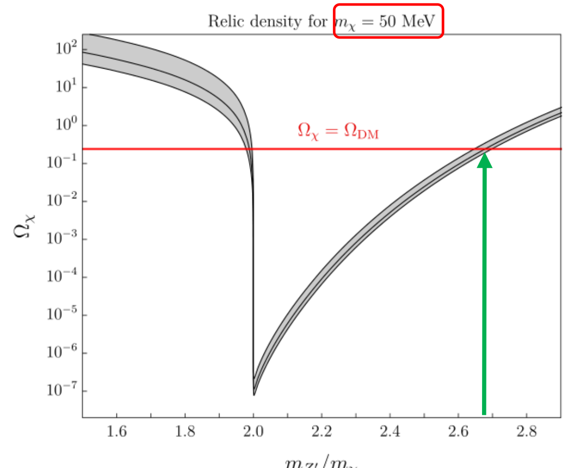
$U(1)_{L_\mu - L_\tau}$-charged DM model

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

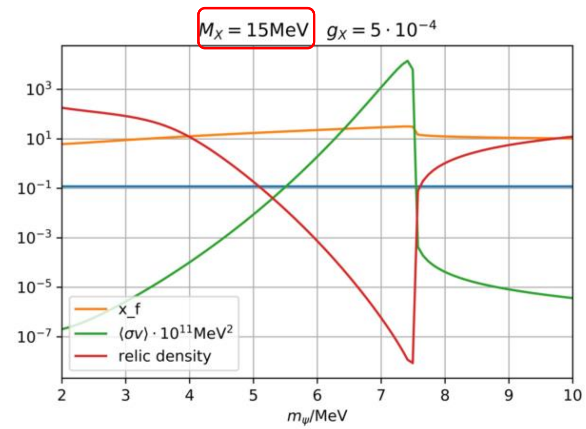
P. Foldenauer, PRD 2019



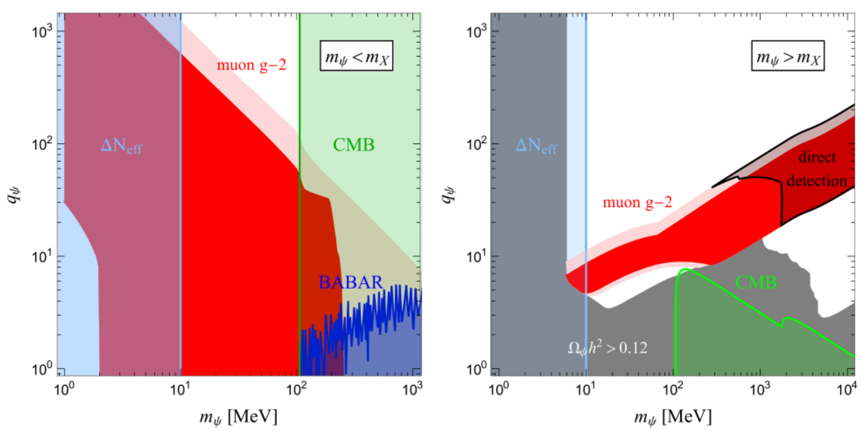
I. Holst, D. Hooper, G. Krnjaic, PRL 2022

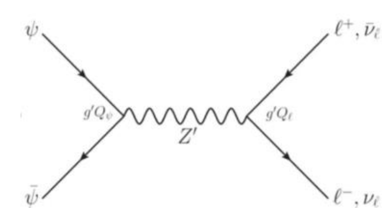


M. Drees, W. Zhao, PLB 2022



- 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: $\sigma_{\mathrm{el}}^{X-e} \simeq 10^{-45}\mathrm{cm}^2$

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

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  - $m_{Z'} \sim O(10)\text{MeV}, \& \; g_X \sim 10^{-4}$ is too small to get $\Omega h^2 = 0.12$
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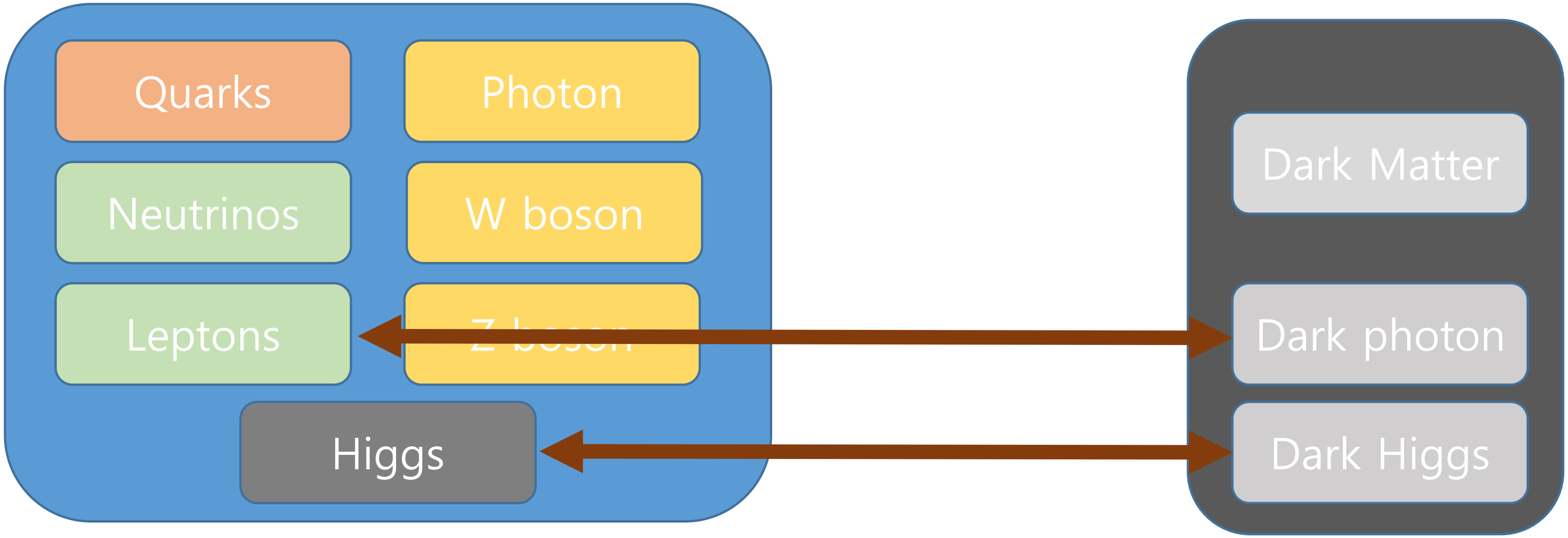
  - DM-electron scattering: $\sigma_{\text{el}}^{X-e} \simeq 10^{-45}\text{cm}^2$
- **BelleII excess**
  - $B \to KZ'$ (2-body decay)
    ➔ disfavored by q^2 spectrum
  - $B \to K\boldsymbol{XX}^\dagger$(3-body decay)
    ➔ suppressed by kinetic mixing and $g_X \sim 10^{-4}$

$U(1)_{L_\mu - L_\tau}$-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 $U(\not{1})_{L_\mu - L_\tau}$ breaking
- A new singlet scalar (**Dark Higgs**), which mixes with the SM Higgs

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

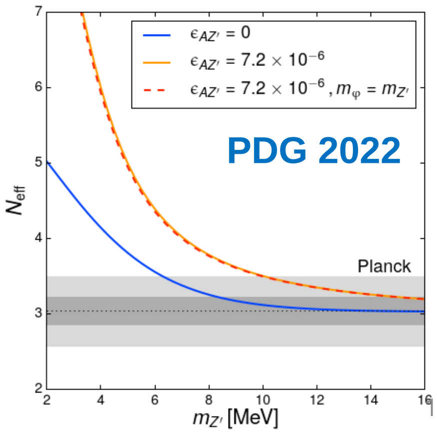
- Additional interactions with the dark Higgs

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

- **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



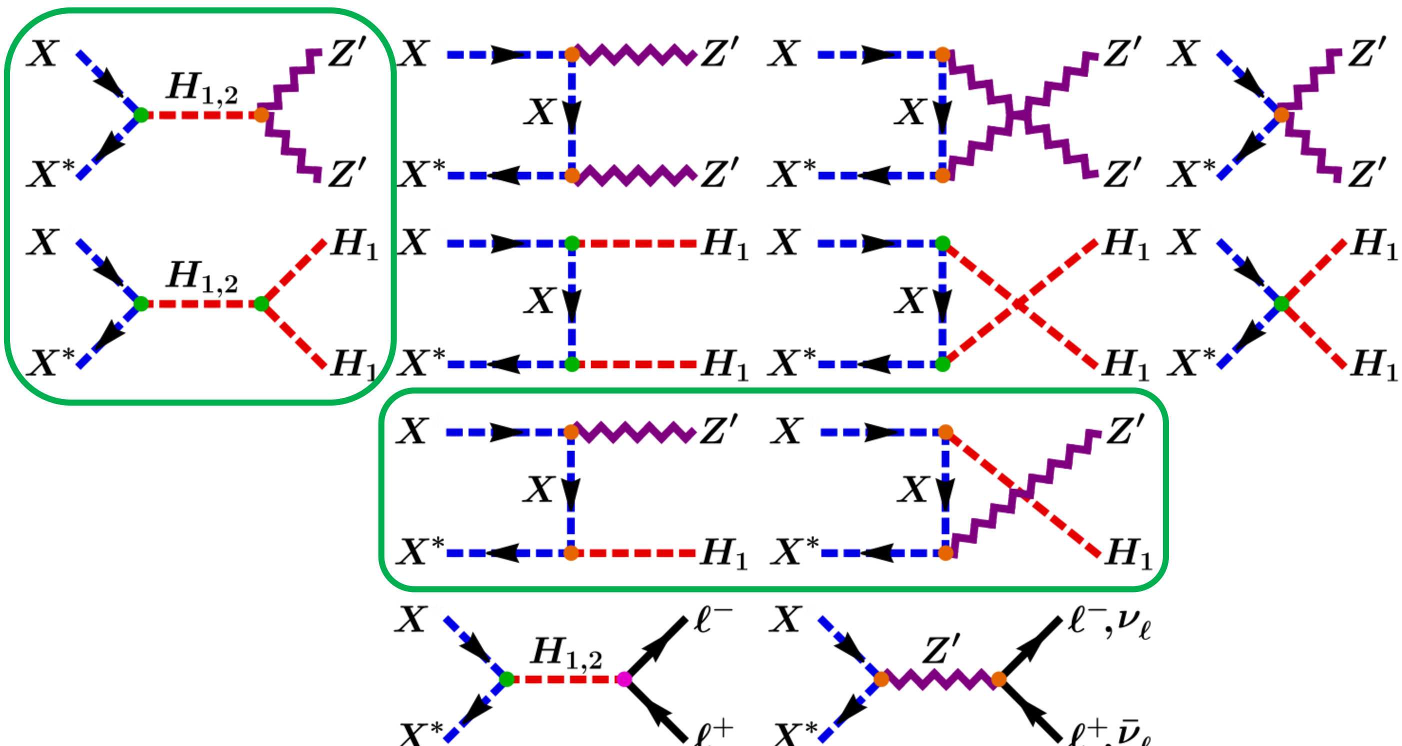
$U(1)_{L_\mu - L_\tau}$-charged DM + Dark Higgs

Baek, **JK**, Ko, 2204.04889

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

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

  - DM annihilation channels



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

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

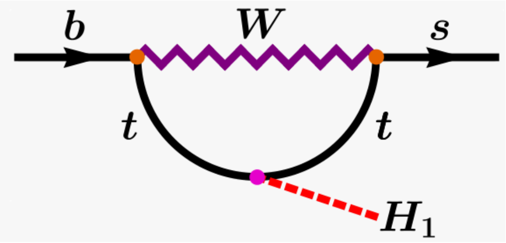
BelleII excess: 2- or 3-body decay

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

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

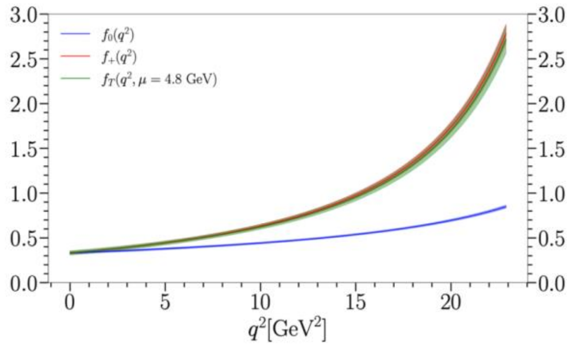
form factor

$\sin\theta \ll 1$



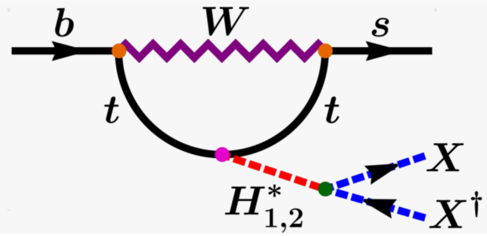
$$|\kappa_{cb}| \simeq 6.7 \times 10^{-6} \qquad \mathcal{K}(a,b,c) = a^2 + b^2 + c^2 - 2(ab + bc + ca)$$

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



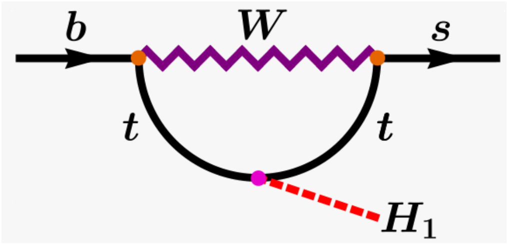
- When $m_{H_1} > m_B - m_K$, H_1 is off-shell → three-body decay

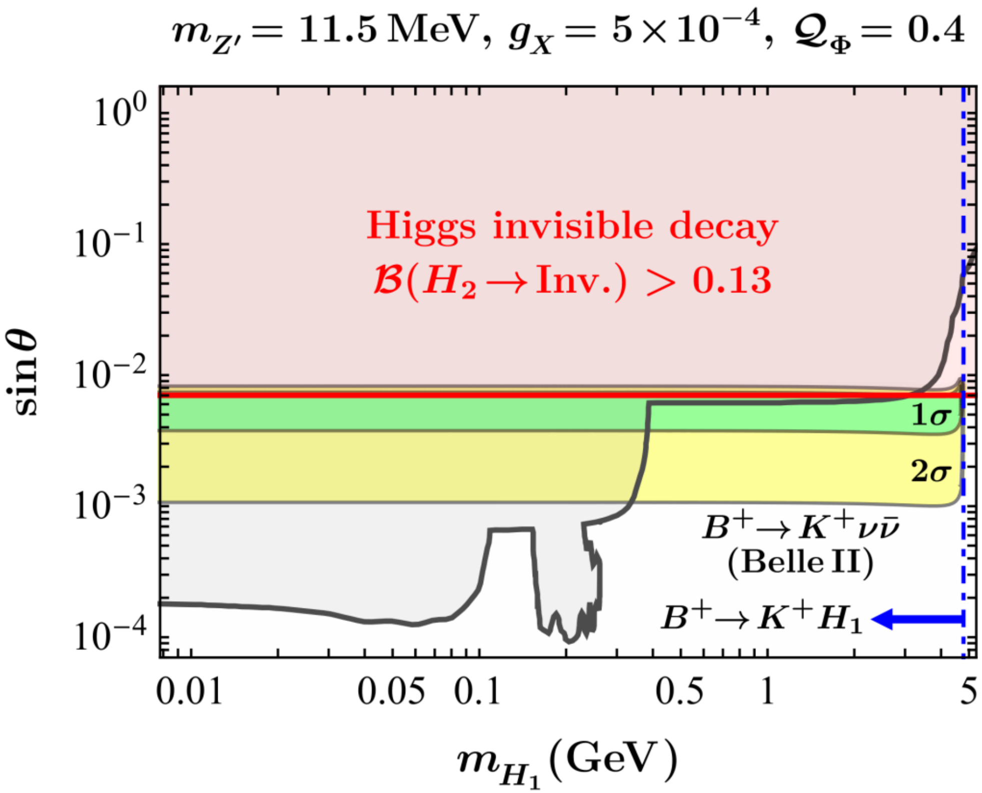
$$\Gamma_{B^+\to K^+XX^\dagger} \simeq \frac{\lambda_{\Phi X}^2 v_\Phi^2 |\kappa_{cb}|^2\sin^2\theta}{1024\pi^3 m_{B^+}^3}\left(\frac{m_{B^+}^2 - m_{K^+}^2}{m_b - m_s}\right)^2 (m_{H_1}^2 - m_{H_2}^2)^2 \times \int_{4m_X^2}^{(m_{B^+}-m_{K^+})^2} dq^2 \frac{\sqrt{1 - 4m_X^2/q^2}\sqrt{\mathcal{K}(m_{B^+}^2,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



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.

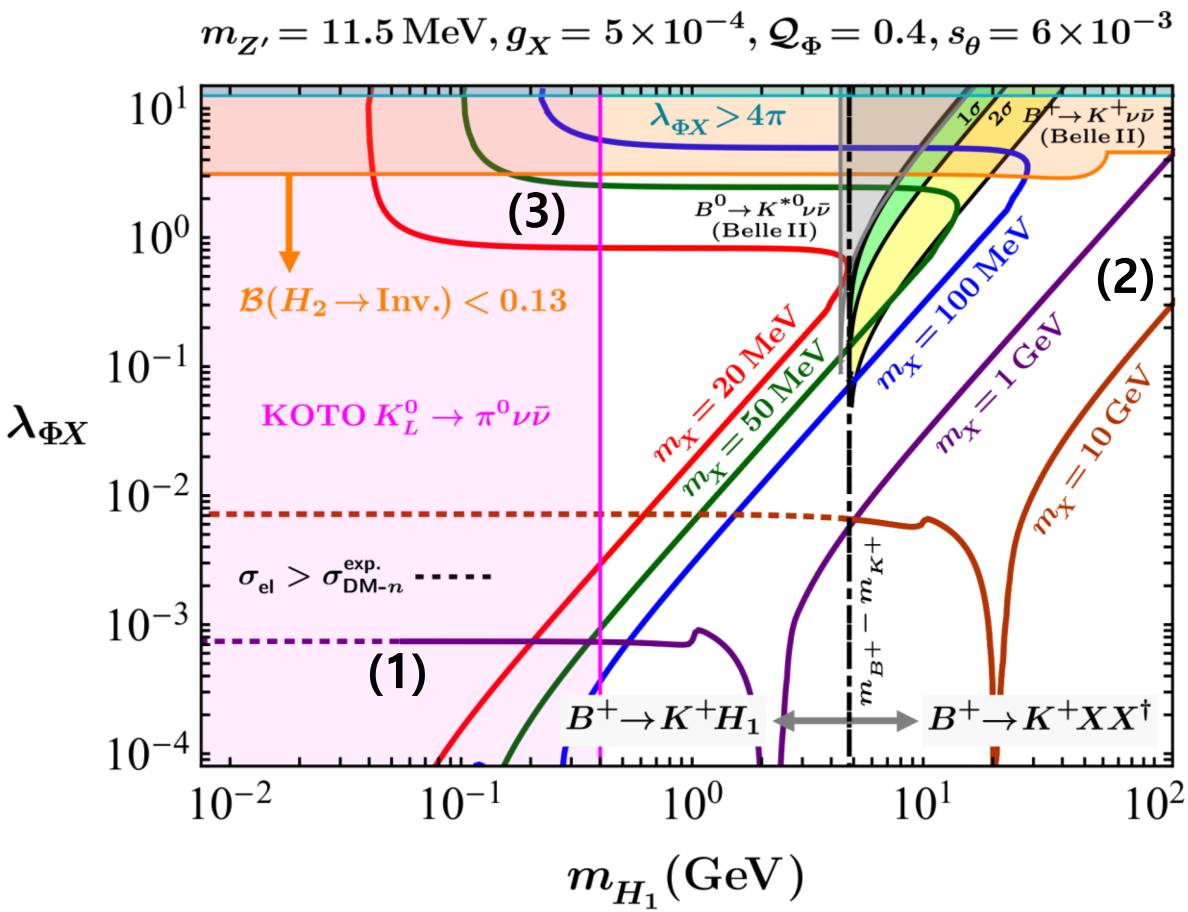


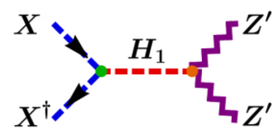


- H_1 decay process
  - $H_1 \to XX^\dagger, Z'Z', f\bar{f}$
- Allowed value
  - $10^{-3} \le \sin\theta \le 7\times10^{-3}$
  - take $\sin\theta = 6\times10^{-3}$

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: $m_X \lesssim 10$ GeV $(m_{H_1} < m_B - m_K)$
  - Three-body decay: $20\text{MeV} < m_X \lesssim 60\text{MeV}$ $(m_{H_1} > m_B - m_K)$





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

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

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

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

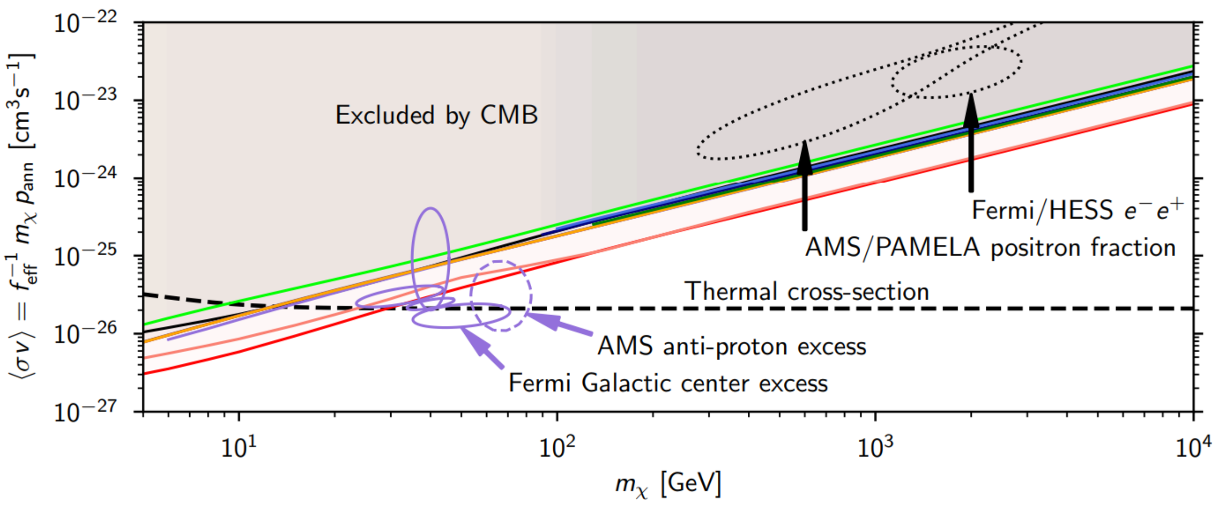
$$\Rightarrow \langle \sigma v \rangle \propto \frac{m_X^2}{\lambda_{\Phi X}^2 v_\Phi^4} \Rightarrow \lambda_{\Phi X} \simeq \text{const.}$$

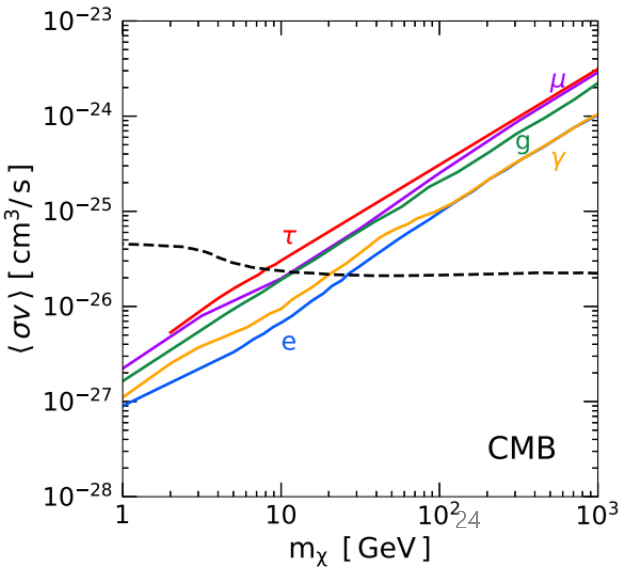
CMB constraints

- 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.

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

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





CMB constraints

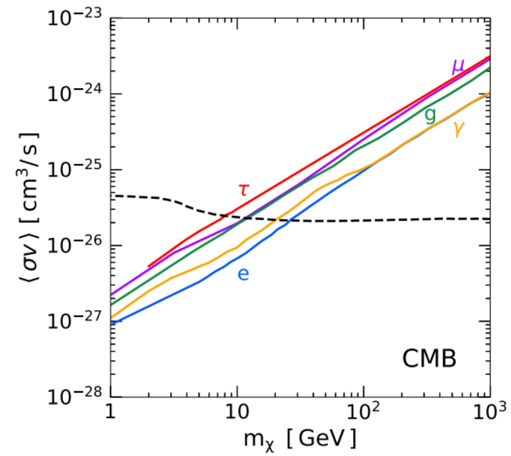
- For $m_X \lesssim 20\mathrm{GeV}$, CMB bound (DM annihilation @ $T \sim \mathrm{eV}$) excludes the thermal DM freeze-out determined by <u>*s-wave*</u> annihilation
  - DM annihilation should be mainly in **p-wave**
  - …

p-wave

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

s-wave

- 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
- H_1 decay



CMB constraints

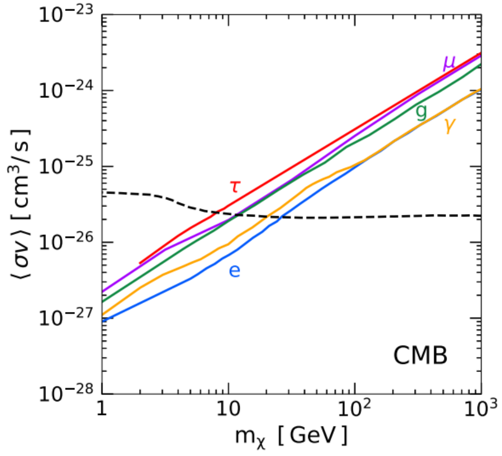
- For $m_X \lesssim 20\mathrm{GeV}$, CMB bound (DM annihilation @ $T \sim \mathrm{eV}$) excludes the thermal DM freeze-out determined by *s-wave* annihilation
  - DM annihilation should be mainly in **p-wave**
  - …

p-wave

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

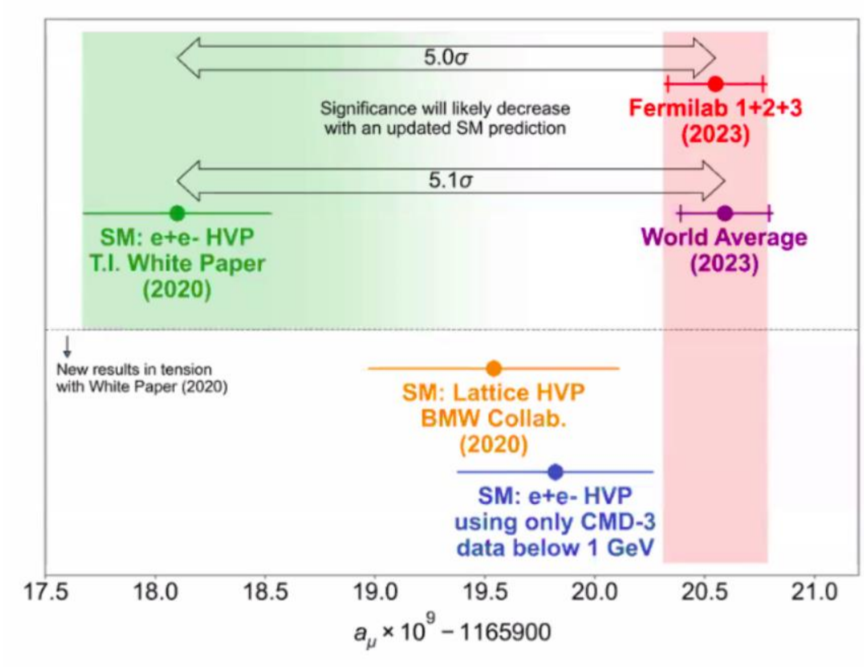
s-wave

- Dominant DM annihilation channel
  - $XX^\dagger \to Z'Z', H_1 H_1$: **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 & $\sin\theta$)

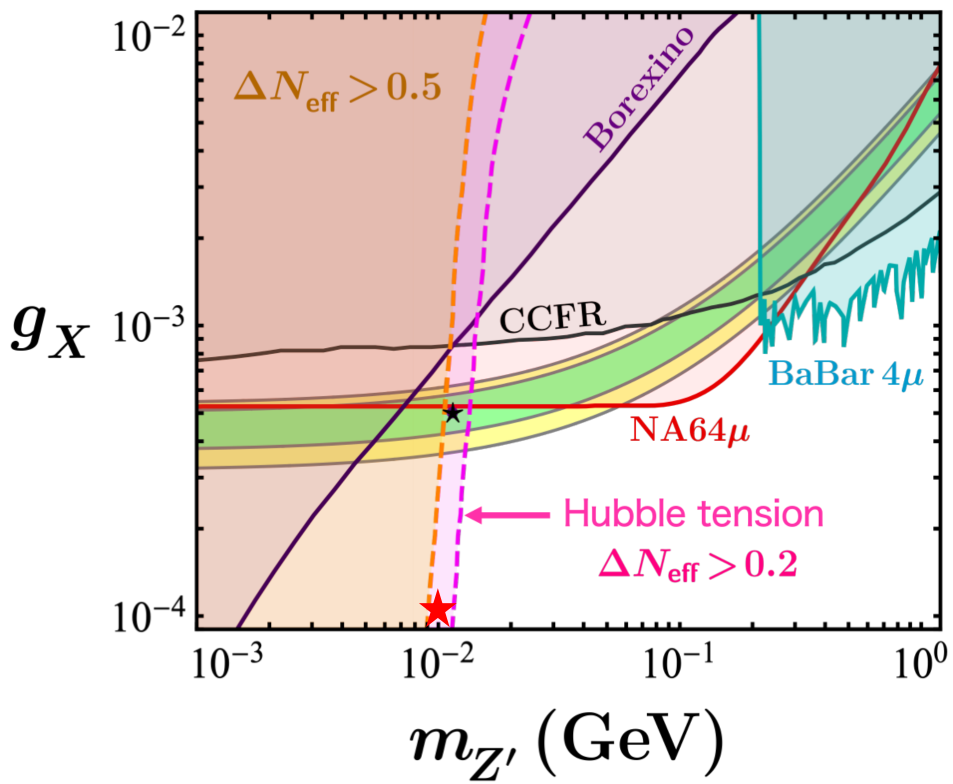


Evidences – Muon g-2

- ***Muon g-2 experimental data from CMD-3 & BMW***
  - consistent with the combined experimental data from BNL and Fermilab muon g−2.

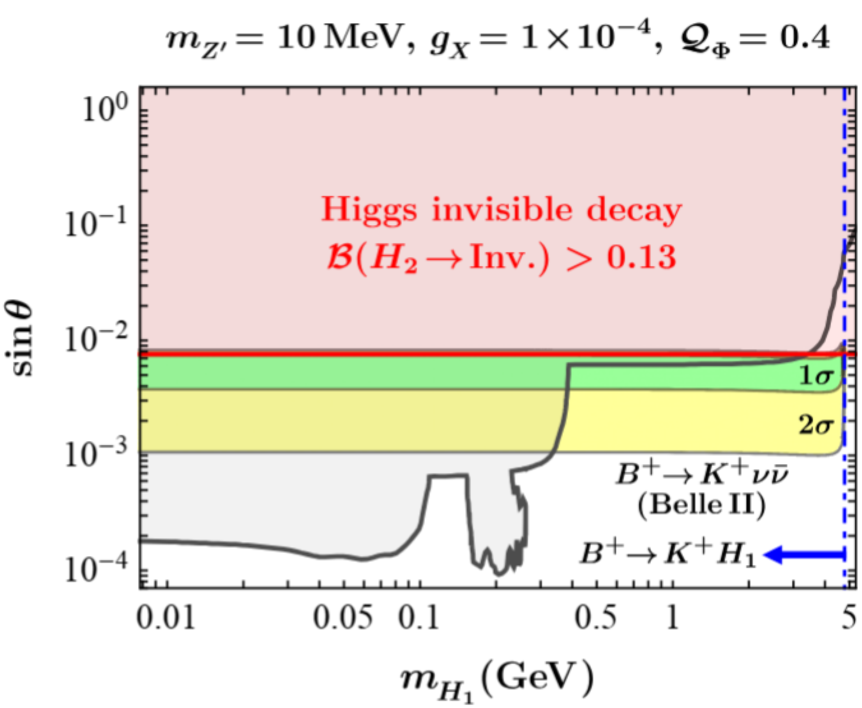


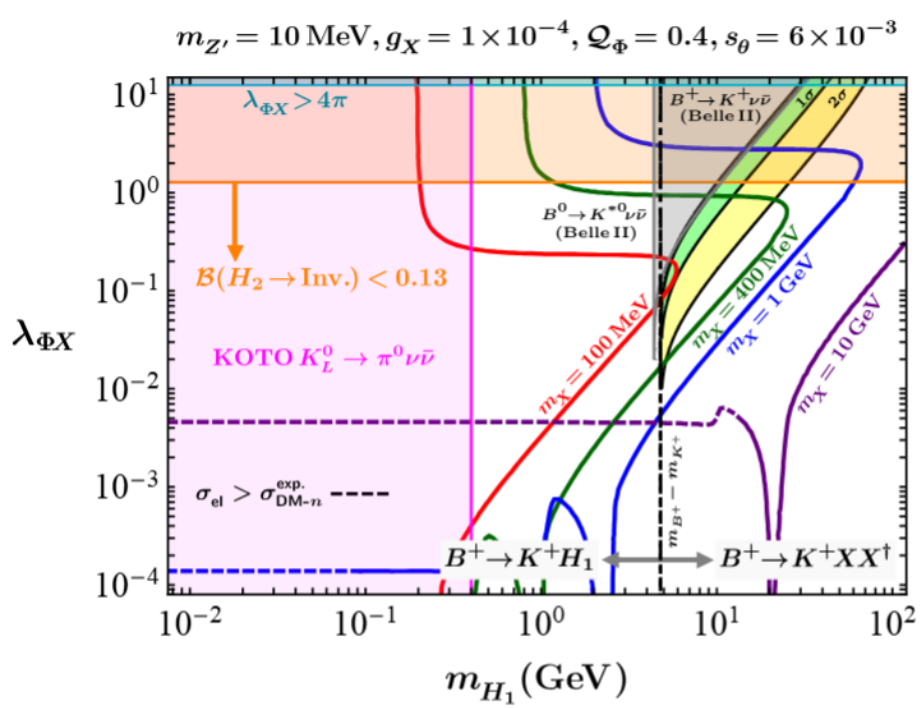
- New BP : $m_{Z'} = 10\text{MeV}$, $g_X = 10^{-4}$



BelleII excess : 2- or 3-body decay

- $m_{Z'} = 10\text{MeV}, g_X = 10^{-4}$ ($m_{Z'} = g_X|Q_\Phi|v_\Phi$ → Larger v_Φ)
  - Hubble tension can be relaxed
  - $\Delta a_\mu = 10^{-10}$ **(BMW & CMD-3 collaboration)**
  - **Belle II** (2-body decay): $m_X \lesssim 8\text{ GeV}$ ($m_{H_1} < m_B - m_K$)
  - **Belle II** (3-body decay): $\sim 90\text{MeV} < m_X \lesssim 450\text{MeV}$ ($m_{H_1} > m_B - m_K$)





Conclusions

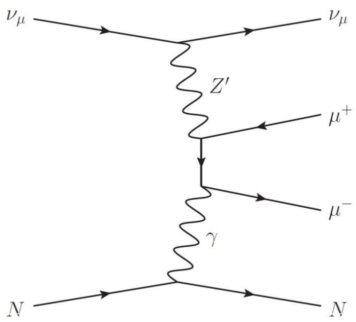
- BelleII data shows a excess of $B^+ \to K^+ \nu\bar{\nu}$ over the SM prediction
- This excess can be interpreted as $B^+ \to K^+ +$ dark sector particles
- CMB constraints can be evaded because DM pair annihilations into $H_1 H_1, H_1 Z', Z'Z'$, all of which are invisible
- We can accommodate the muon g-2 and subsequently relax the tension in the Hubble constant with extra radiation


Thank you
very much

Back-up Slides

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 $1\text{MeV} \le m_{Z'} \le 1\text{GeV}$

- 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}
  - $\Delta N_{\text{eff}} < \mathbf{0.5}$
- ***BOREXINO*** — R. Harnik et al, JCAP 2012
  - $\nu - e$ scattering

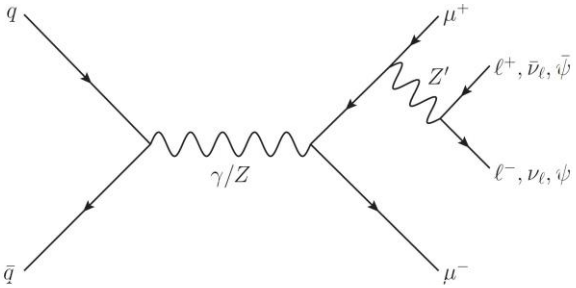
BaBar, LHC 4μ channels

BaBar Collaboration, PRD 2016

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

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



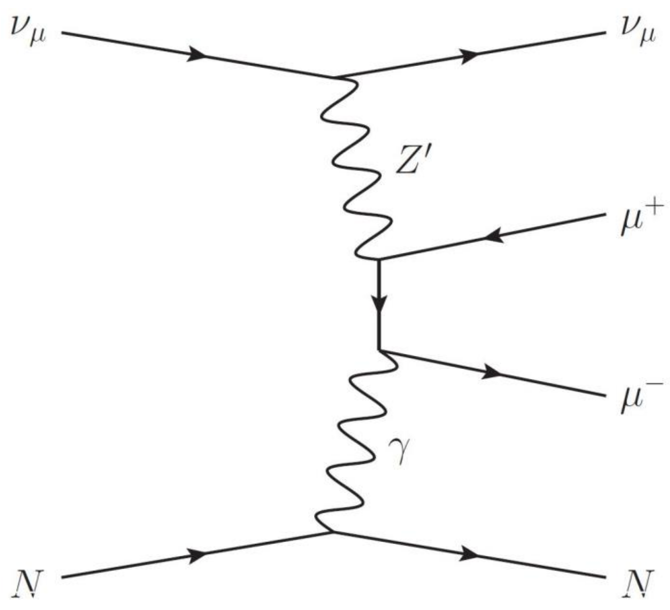
- Final states
  - two pair of charged-leptons
  - A pair of charged-lepton plus missing energy

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

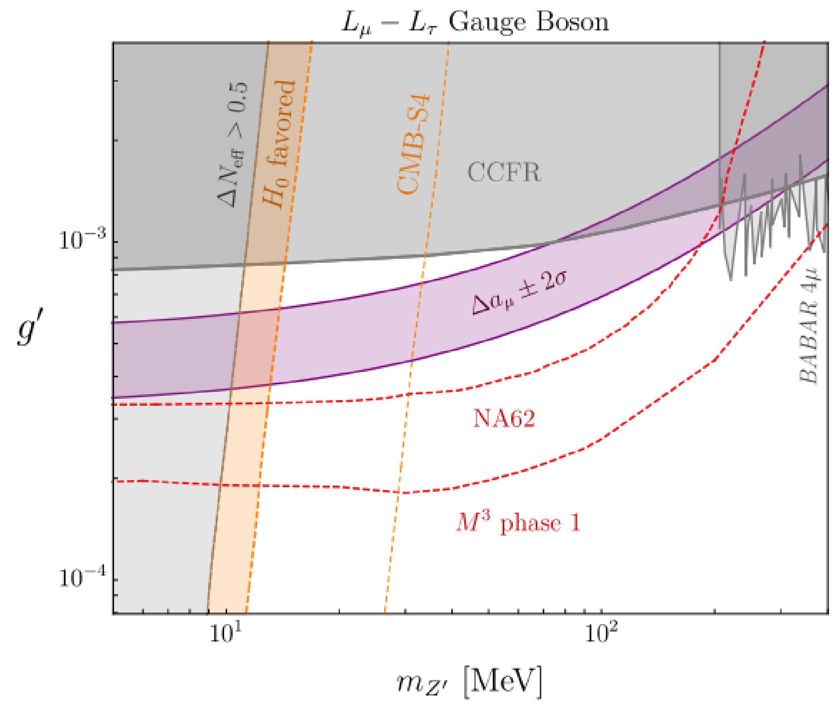
$$\alpha_{B-L}^2 \to \begin{cases} \left[\sum_{i,j=1}^{3} f_i \,|(U^\dagger Q_{\mu e} U)_{ij}|^2\right]^{1/2} \alpha_{\mu e}^2 \,, & \text{for} \quad \mathrm{U}(1)_{L_\mu - L_e} \,, \\ \left[\sum_{i,j=1}^{3} f_i \,|(U^\dagger Q_{e\tau} U)_{ij}|^2\right]^{1/2} \alpha_{e\tau}^2 \,, & \text{for} \quad \mathrm{U}(1)_{L_e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

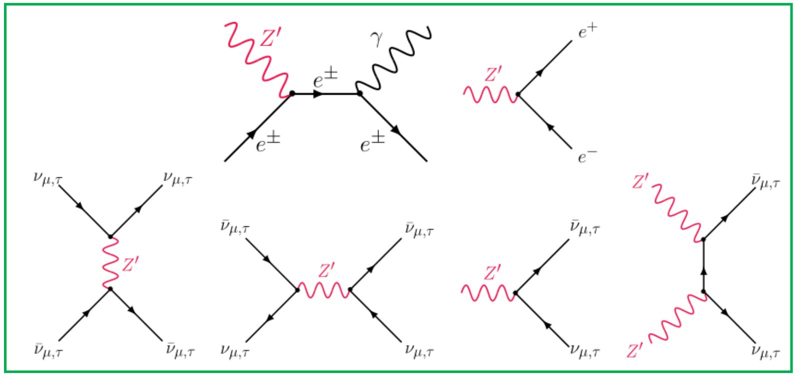
$$Q_{\mu\tau} = \mathrm{diag}(0, 1, -1)$$

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





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

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

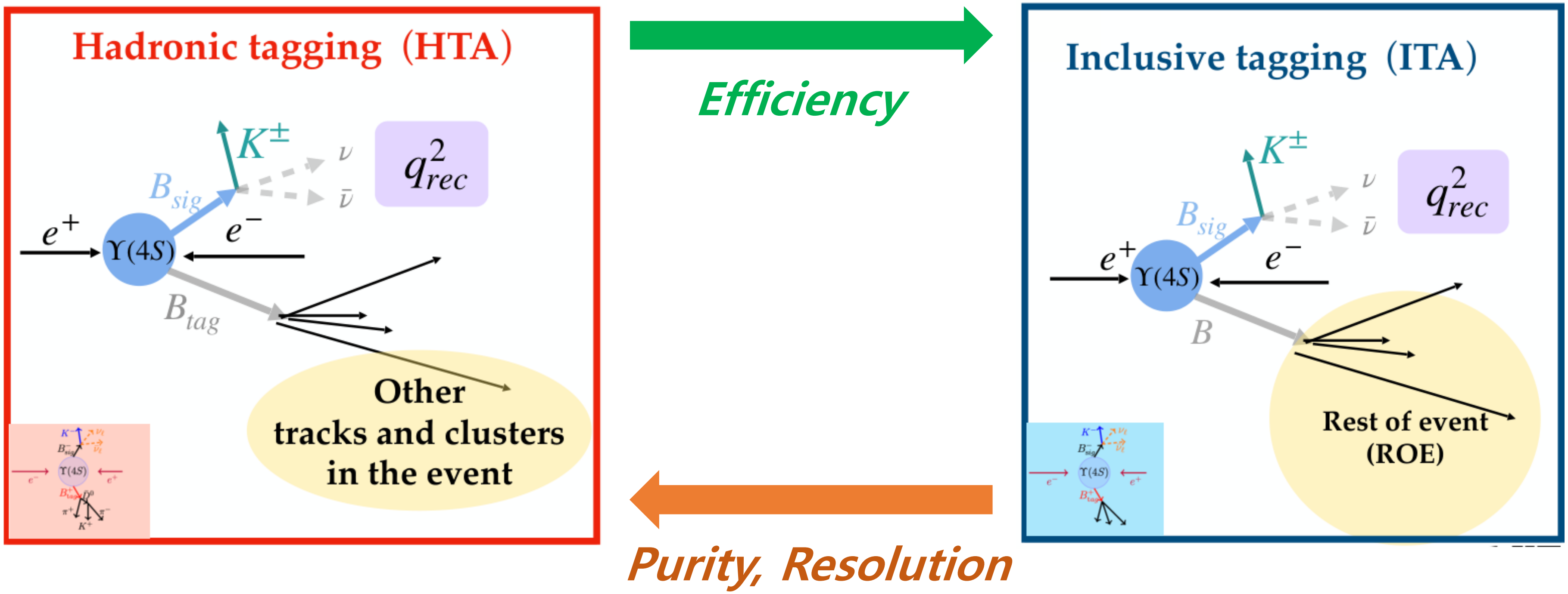
$$\mathcal{L} \supset \mathcal{L}_{\rm SM} - \frac{1}{4} Z'_{\alpha\beta} Z'^{\alpha\beta} + \underline{\frac{1}{2} m_{Z'}^2 Z'_\alpha Z'^\alpha} + i\bar{\chi}\gamma^\alpha \partial_\alpha \chi - m_\chi \bar{\chi}\chi$$
$$+ g_X Q_\chi Z'_\alpha \bar{\chi}\gamma^\alpha \chi + g_X Z'_\alpha \sum Q_\ell \bar{\ell}\gamma^\alpha \ell$$

  - Dark Photon Z' plays a role of messenger particle between DM and the SM leptons
  - Dark Photon mass is generated by hand or Stueckelberg mechanism

- New parameters: $\{g_X, m_{Z'}, m_\chi, Q_\chi\}$
- Consider Z' boson only & **$g_X \sim (3-5) \times 10^{-4}$ for the muon g-2**
  - $\chi\bar{\chi}(X\bar{X}) \to f_{SM}\bar{f}_{SM}$: dominant annihilation channels
  - $g_X \sim 10^{-4}$ is too small to get $\Omega_\chi h^2 = 0.12$

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

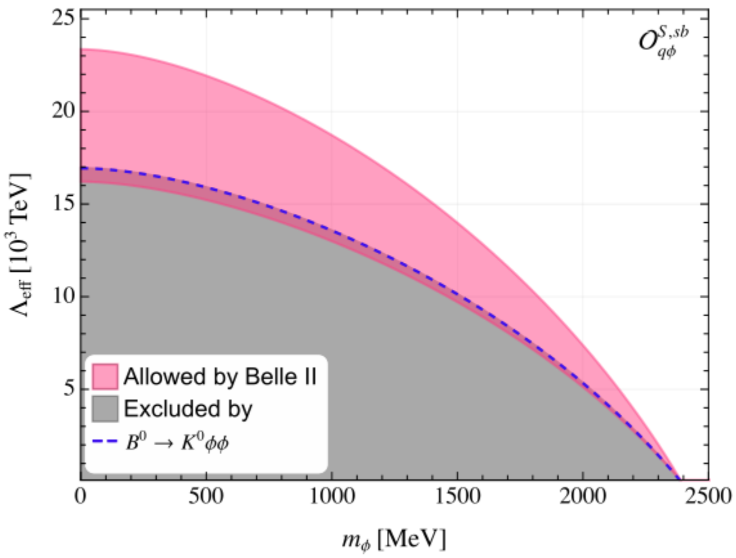
Solutions: EFT-approach

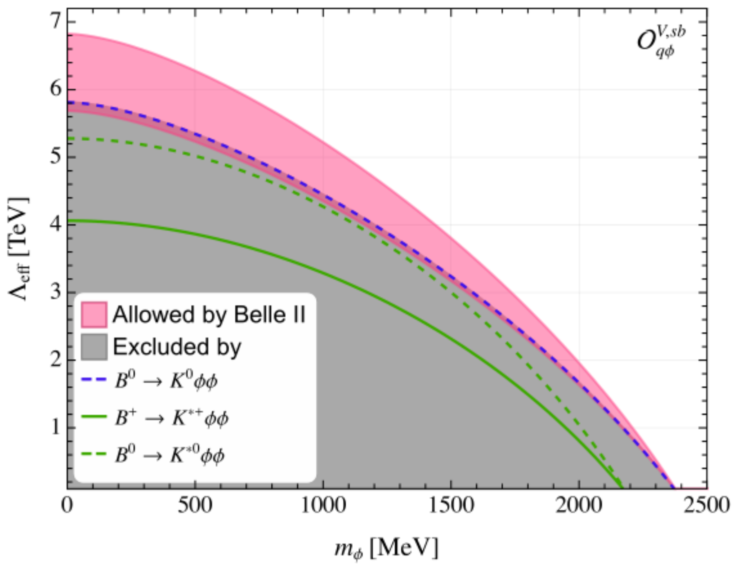
- Real/Complex scalar DM

X. He et al, 2309.12741

$$\mathcal{O}_{q\phi}^{S,sb} = (\bar{s}b)(\phi^\dagger\phi),$$

$$\mathcal{O}_{q\phi}^{V,sb} = (\bar{s}\gamma^\mu b)(\phi^\dagger i \overleftrightarrow{\partial_\mu}\phi),\ (\times)$$



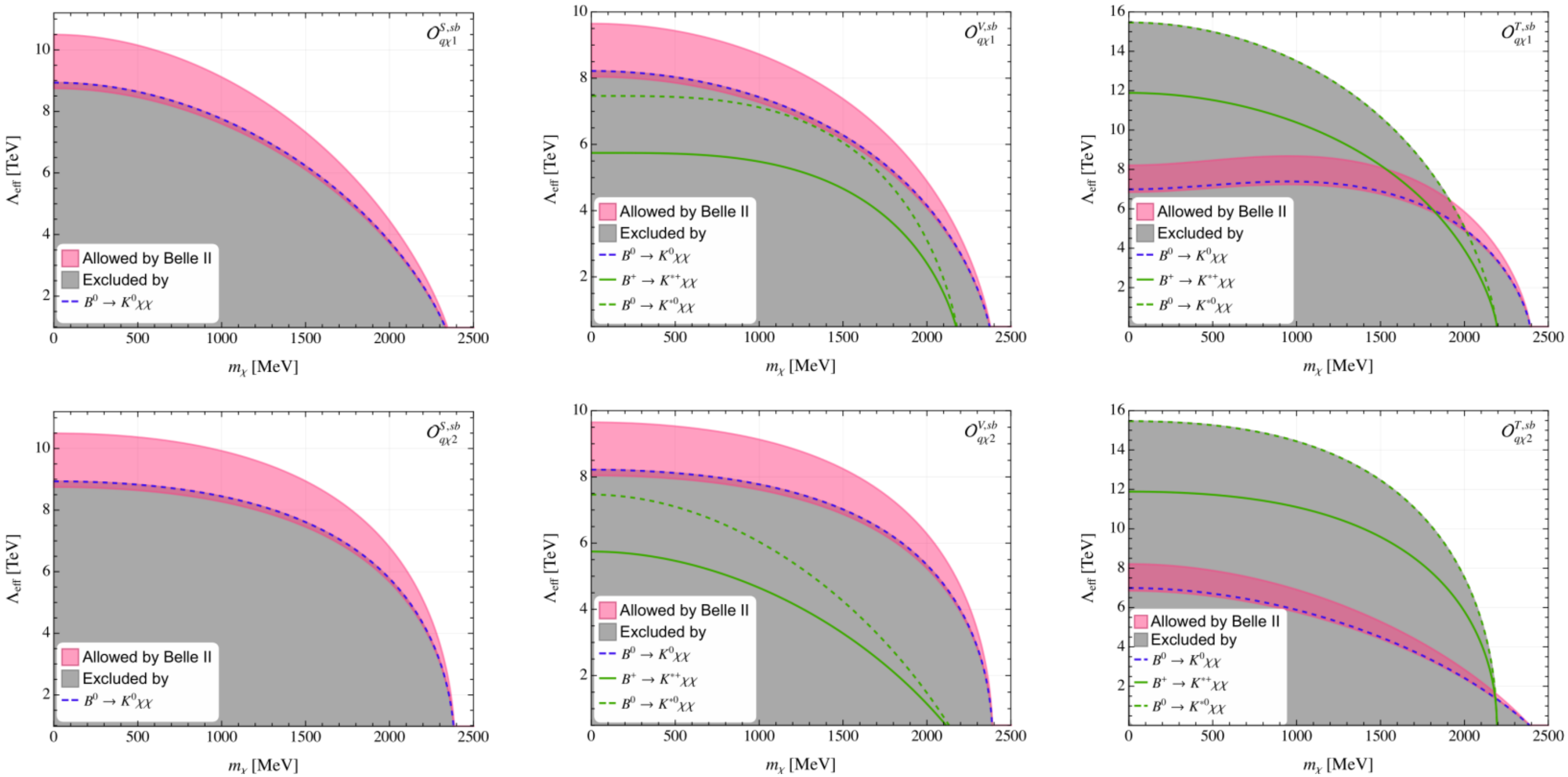


Solutions: EFT-approach

X. He et al, 2309.12741

- Majorana/Dirac fermion DM

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

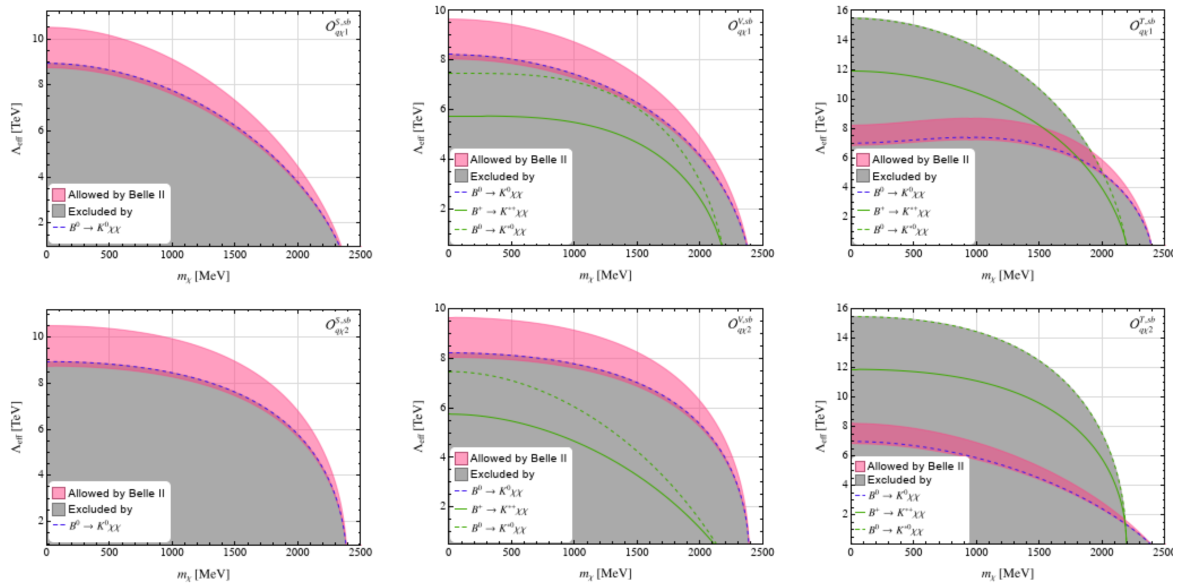


Solutions: EFT-approach

- Real/Complex vector DM

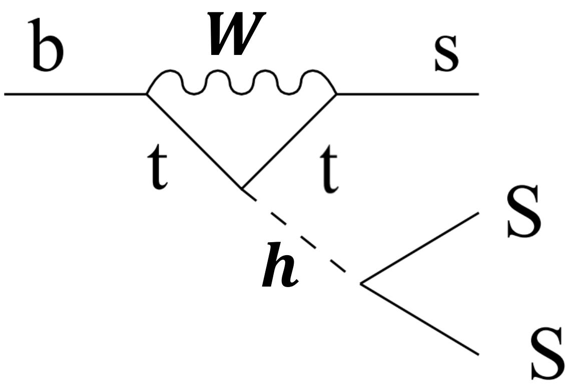
X. He et al, 2309.12741

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



Solutions: 3-body decay

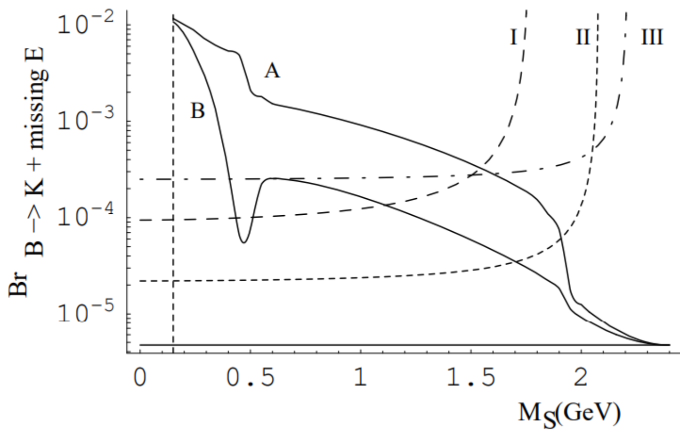
Bird et al, PRL 2004



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

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

- Belle ⇒ $\frac{C_{DM}}{C_\nu} \simeq \frac{4.4\lambda M_W^2}{g_W^2 m_h^2}$
- Relic density: $\sigma_{\text{ann}} v_{\text{rel}} = \frac{8 v_{EW}^2 \lambda^2}{m_h^4}\left(\lim_{m_{\tilde{h}} \to 2m_S} m_{\tilde{h}}^{-1}\Gamma_{\tilde{h}X}\right).$
  - λ should be large to fit the relic as well as Belle II
  - $m_s \leq 1\text{GeV}$ is already excluded by BABAR limits (2004 data).



Solutions: 3-body decay

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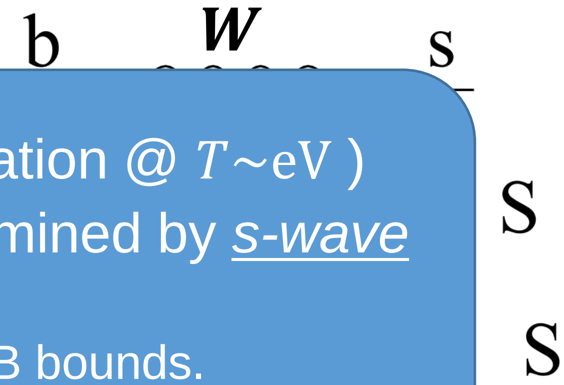
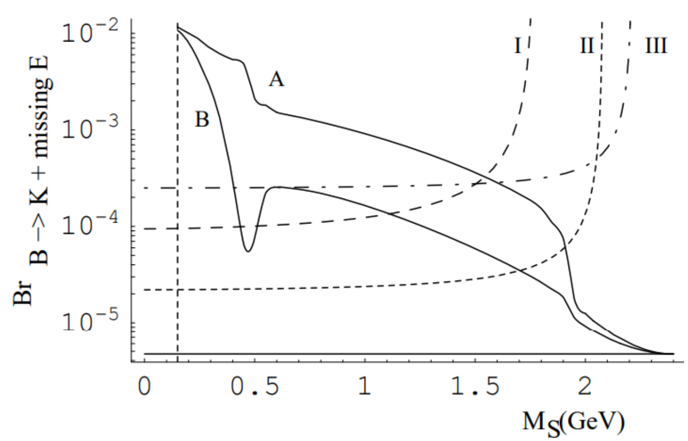


- For $m_\chi \lesssim 10\mathrm{GeV}$, CMB bound (DM annihilation @ $T \sim \mathrm{eV}$) excludes the thermal DM freeze-out determined by *s-wave* annihilation
- At that time, the authors did not consider the CMB bounds.

  This model does not work anymore.

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



Solutions: 2-body decay

W. Altmannshofer et al, 2311.14629

- 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 $\mathrm{Br}(B \to K^* \nu\bar{\nu})$

Solutions: 2-body decay

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

W. Altmannshofer et al, 2311.14629

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

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

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

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

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

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

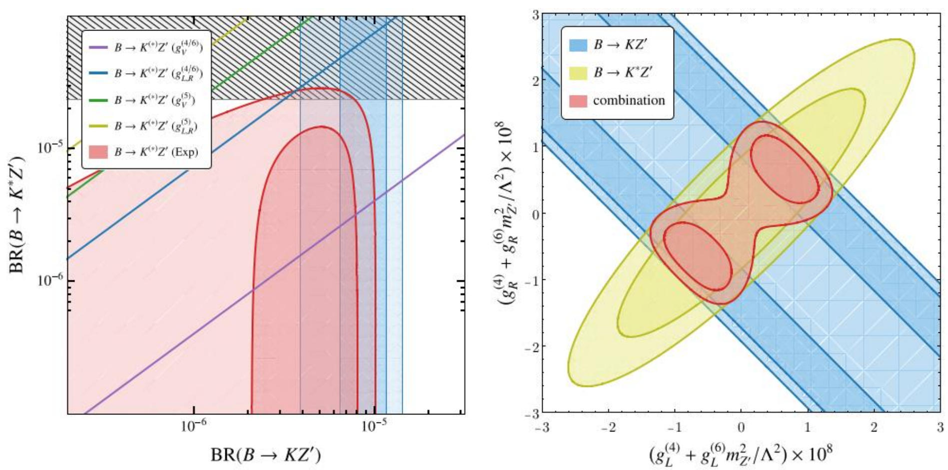


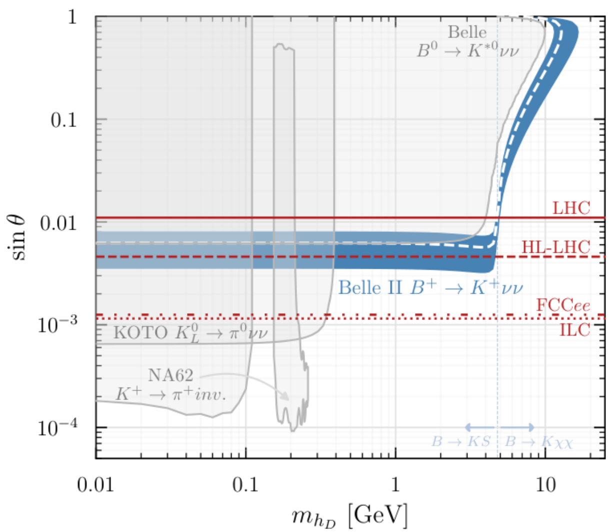
FIG. 2: *Left:* Correlations between $B \to KZ'$ and $B \to K^*Z'$ (colored lines) for the different $\bar s bZ'$ operators considered in this work. These are compared to the experimental data stemming from the combination of Belle-II, Babar and Belle measurements,which is represented by the red regions 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.

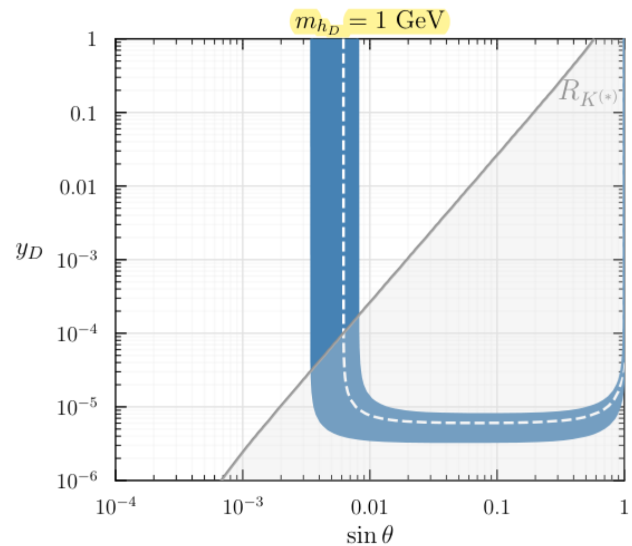
Solutions: 2- or 3-body decay

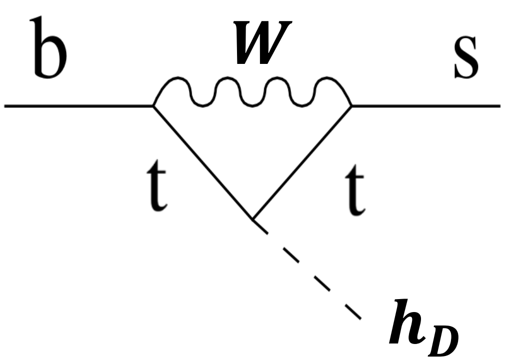
- Dark Higgs on-shell decay or three-body decay

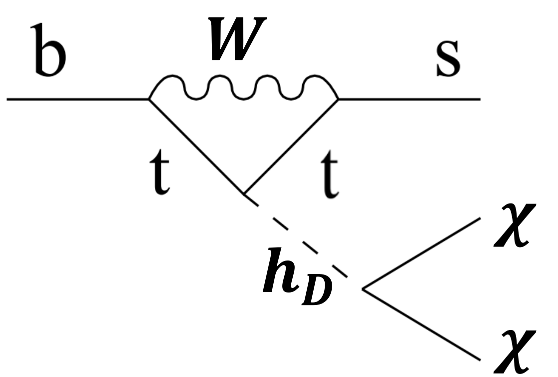
McKeen et al, 2312.00982

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









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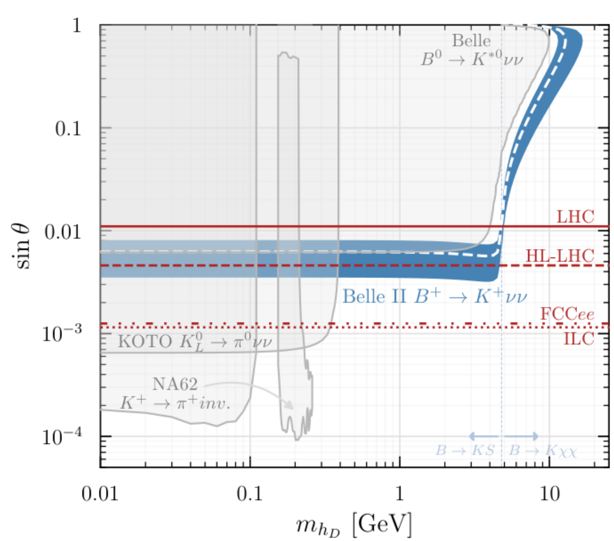
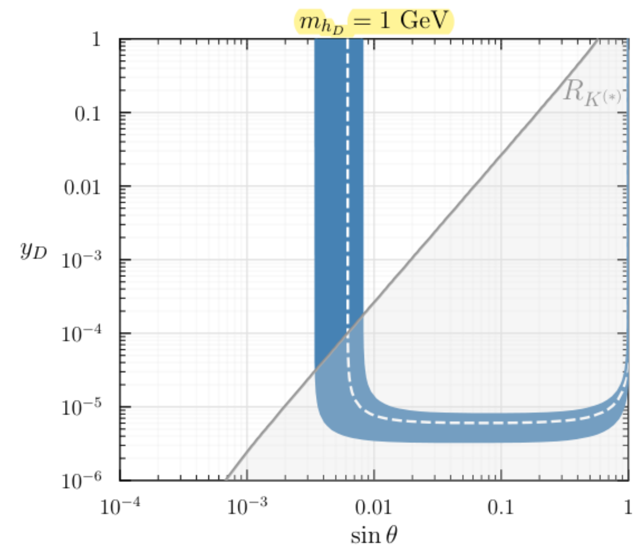
McKeen et al, 2312.00982

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





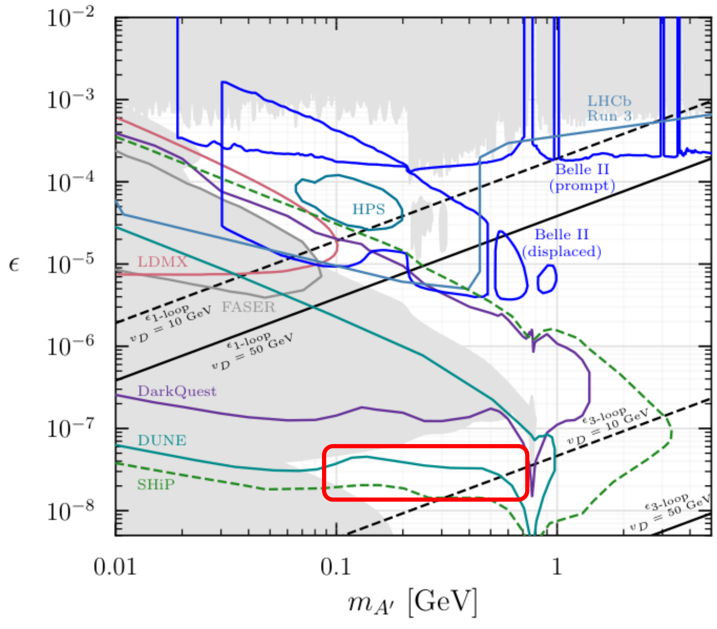
- **Extremely large relic density**
  - $\Omega h^2 \simeq 10^{20} \left(\frac{10^{-4}}{y_D}\right)^2 \left(\frac{\sin\theta}{10^{-3}}\right)^2 \left(\frac{m_\chi}{100\,\text{MeV}}\right)^2 \left(\frac{1\,\text{GeV}}{m_{H_1}}\right)^2$: overclose the Universe
  - Either introduce a new DM annihilation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

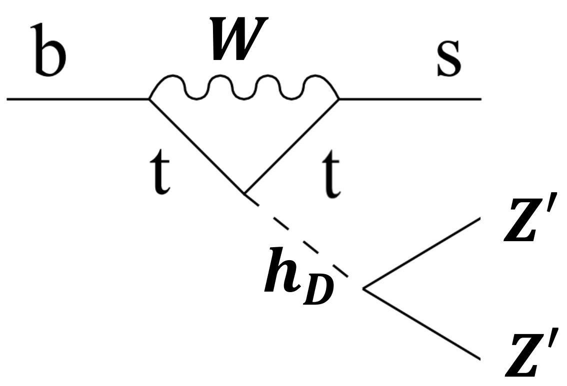
Solutions: 3-body decay

McKeen et al, 2312.00982

- Dark Higgs decays to dark Photon
  - Dark Photon can be long-lived → appear missing energy at BelleII
  - $\mathcal{L} \supset g_D^2 v_D A'_\mu A'^\mu (-h \sin\theta + h_D \cos\theta)$

- Two-regions for sub-GeV dark photon that unconstrained by existing experimental searches:





1. $m_{A_D} \gtrsim 100$ MeV with $10^{-8} \lesssim \epsilon \lesssim 10^{-7}$
2. $m_{A_D} \gtrsim 50$ MeV with $10^{-6} \lesssim \epsilon \lesssim 10^{-4}$.