Interpreting BelleⅡ excess with light dark matter

Jongkuk Kim

jongkukkim@cau.ac.kr

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

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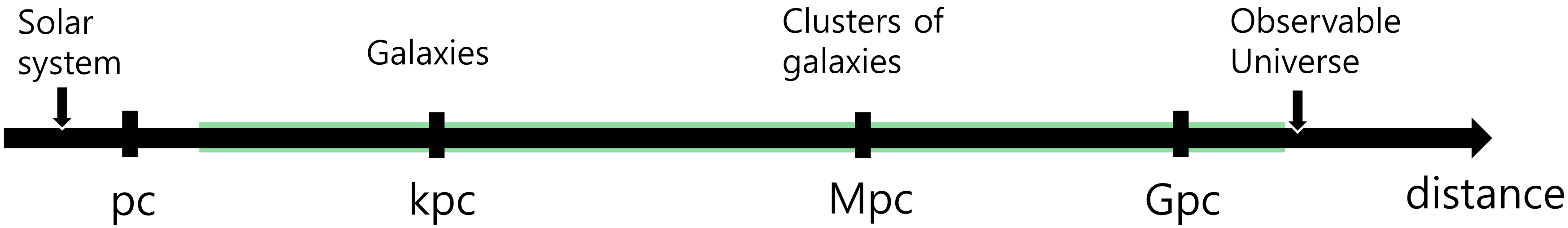
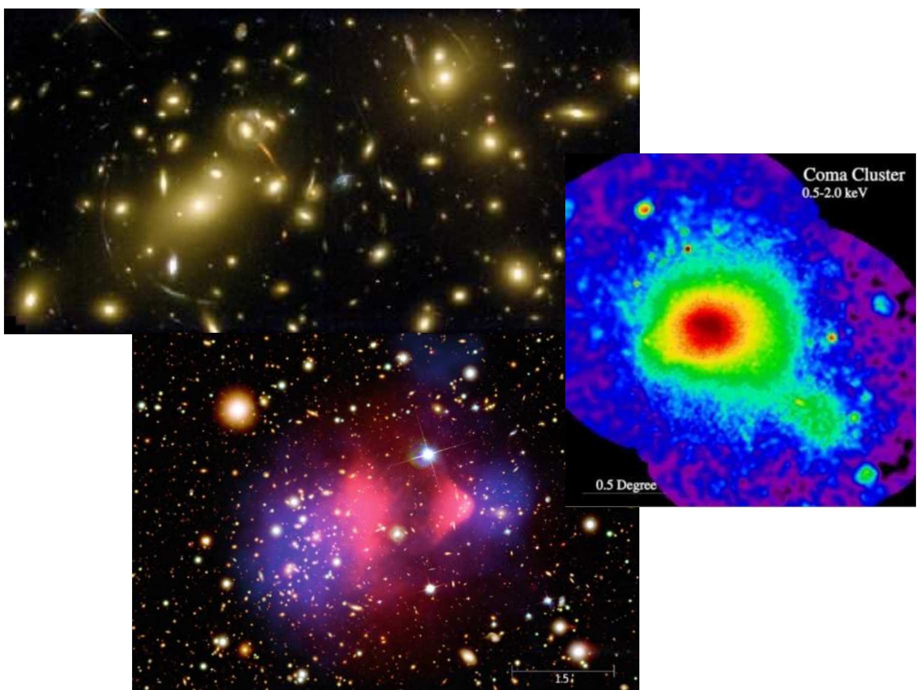
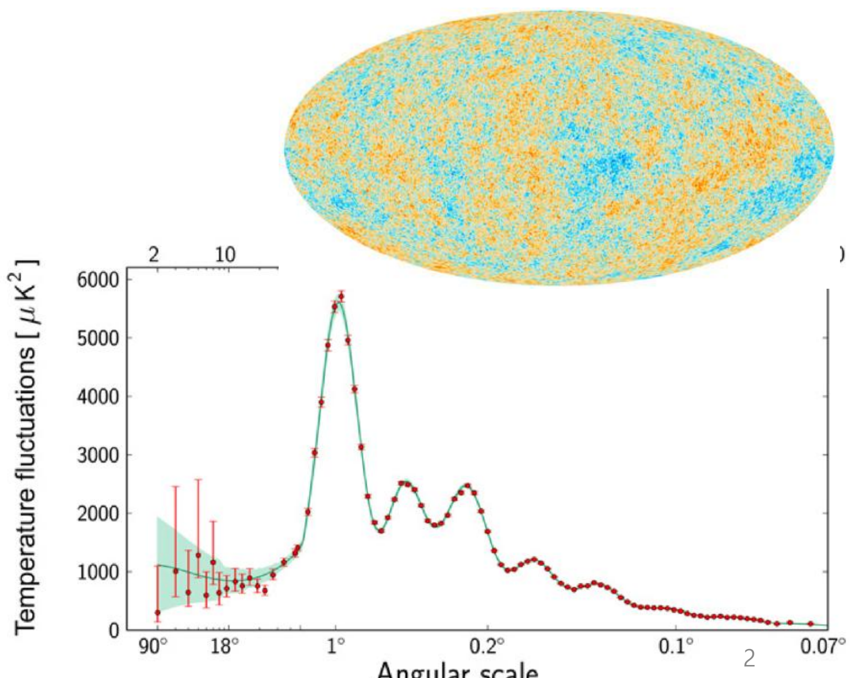
Evidences – Dark Matter

- There are undeniable evidences for dark matter in a wide range of distance scales

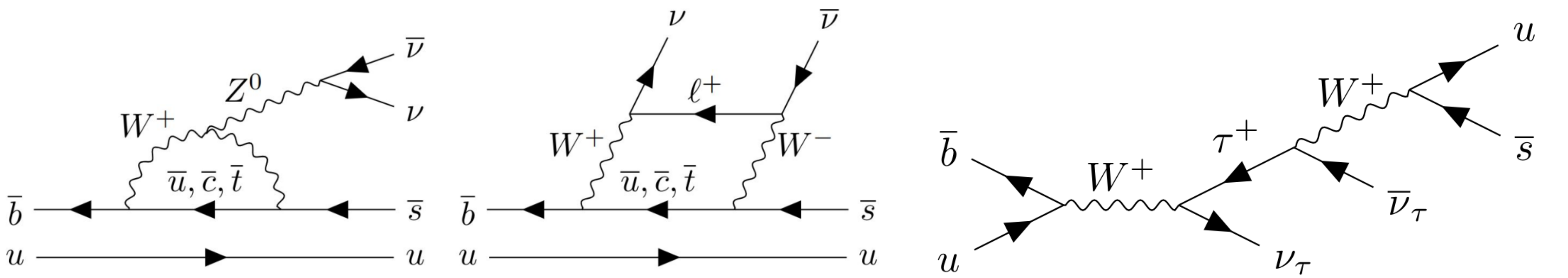






Measurement of $B^+ \to K^+\nu\bar{\nu}$

- 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**



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

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

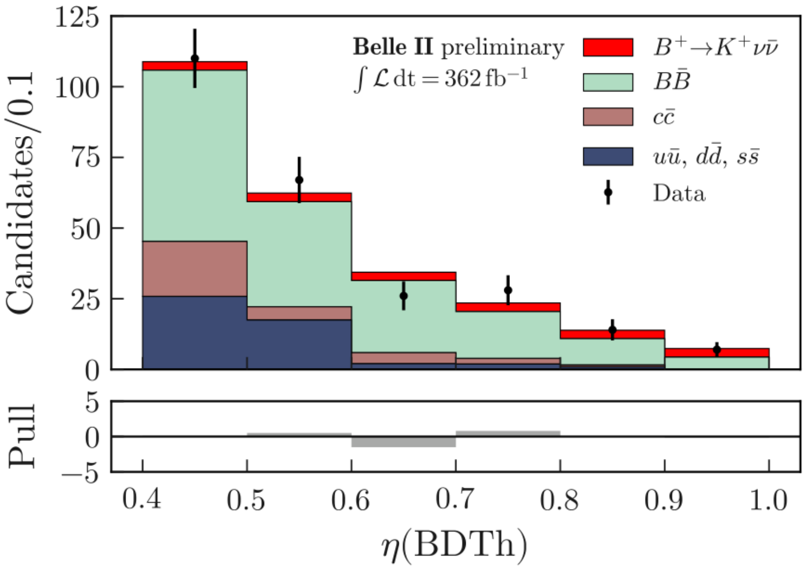
where $x_t = m_t^2/M_W^2$.

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

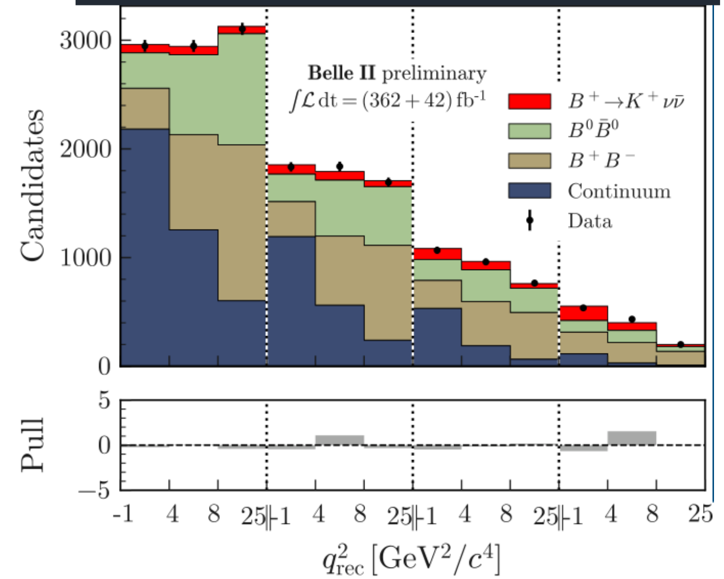
Belle II, 2311.14647

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

Hadronic tagging (HTA)



Inclusive tagging (ITA)

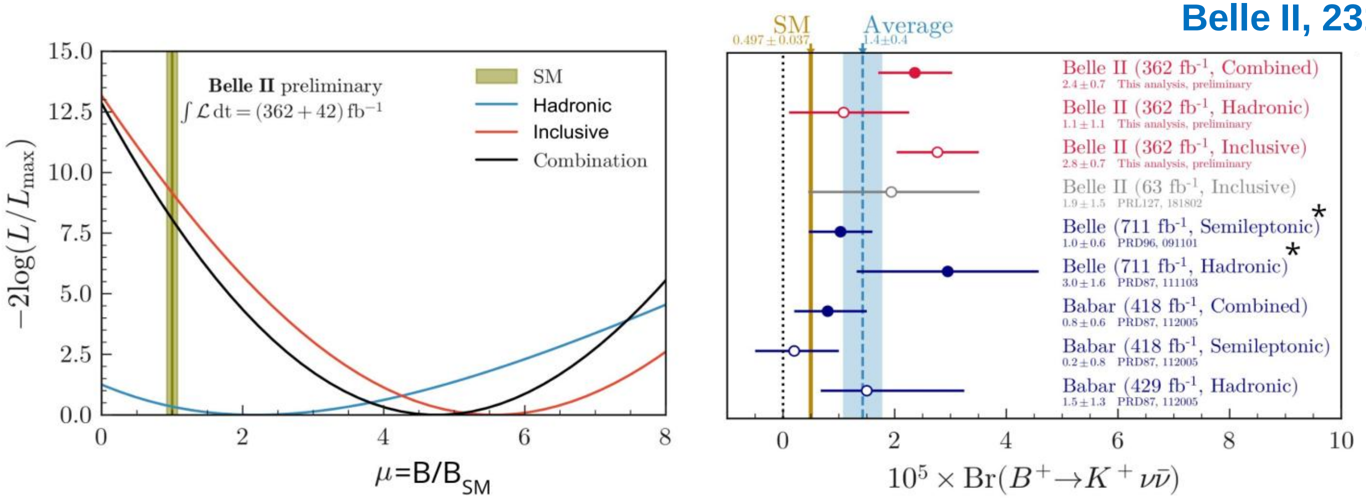


$$\mathscr{B}(B^+ \to K^+\nu\bar{\nu})_{\mathrm{HTA}} = (1.1^{+0.9+0.8}_{-0.8-0.5}) \times 10^{-5}$$

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

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 σ
  - 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: EFT-approach

X. He et al, 2309.12741

- Real/Complex scalar DM

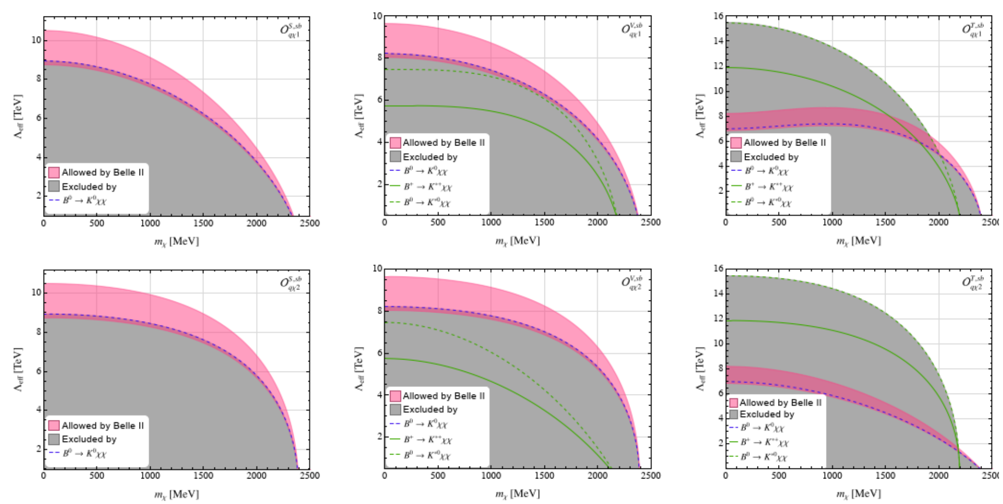
$$\mathcal{O}_{q\phi}^{S,sb} = (\bar{s}b)(\phi^\dagger\phi), \qquad \mathcal{O}_{q\phi}^{V,sb} = (\bar{s}\gamma^\mu b)(\phi^\dagger i\overleftrightarrow{\partial_\mu}\phi),\ (\times)$$

- Majorana/Dirac fermion DM

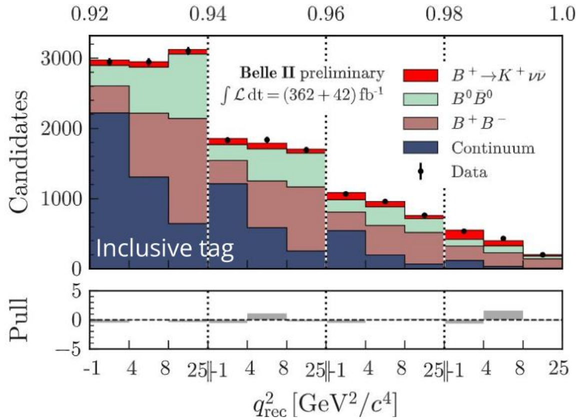
$$\begin{aligned}
\mathcal{O}_{q\chi1}^{S,sb} &= (\bar{s}b)(\bar{\chi}\chi), & \mathcal{O}_{q\chi2}^{S,sb} &= (\bar{s}b)(\bar{\chi}i\gamma_5\chi),\\
\mathcal{O}_{q\chi1}^{V,sb} &= (\bar{s}\gamma^\mu b)(\bar{\chi}\gamma_\mu\chi),\ (\times) & \mathcal{O}_{q\chi2}^{V,sb} &= (\bar{s}\gamma^\mu b)(\bar{\chi}\gamma_\mu\gamma_5\chi),\\
\mathcal{O}_{q\chi1}^{T,sb} &= (\bar{s}\sigma^{\mu\nu}b)(\bar{\chi}\sigma_{\mu\nu}\chi),\ (\times) & \mathcal{O}_{q\chi2}^{T,sb} &= (\bar{s}\sigma^{\mu\nu}b)(\bar{\chi}\sigma_{\mu\nu}\gamma_5\chi),\ (\times)
\end{aligned}$$

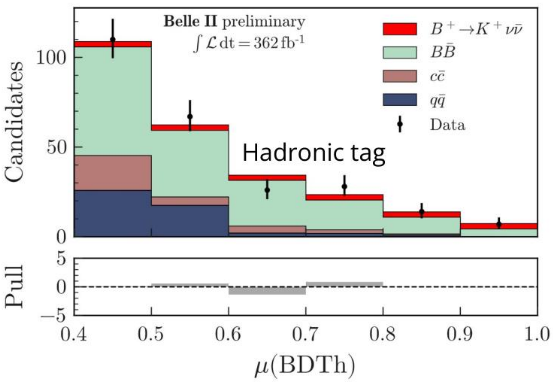
- Real/Complex vector DM

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



Solutions: 2- or 3-body decay

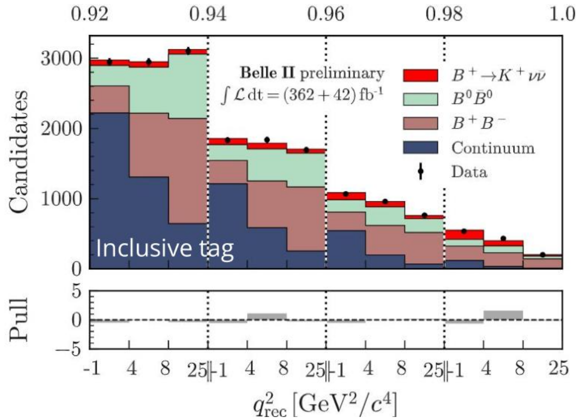


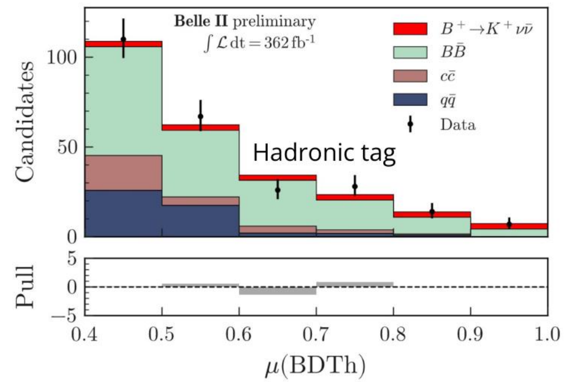


- Belle II provides information on the $\boldsymbol{q^2_{rec}}$ **spectrum**
  - q^2_{rec}: mass squared of the neutrino pair
  - A peak localized around $q^2_{rec} = 4\text{GeV}^2$
  - Two-body decay $(B \to KX), m_X = 2$ GeV

W. Altmannshofer et al, 2311.14629

Solutions: 2- or 3-body decay

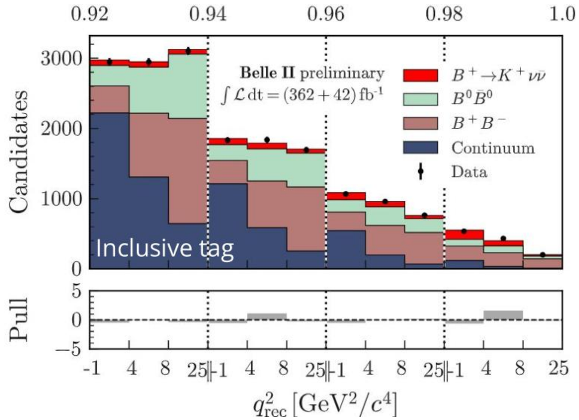


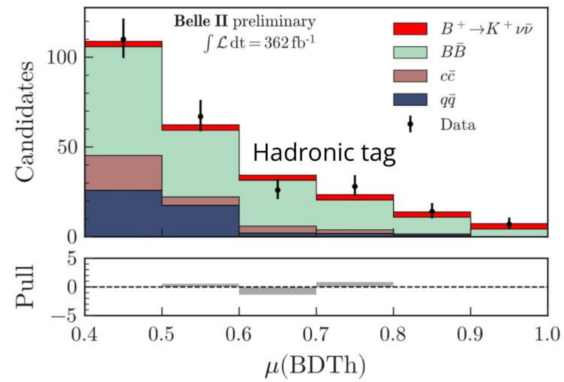


- Belle II provides information on the **q^2_{rec} spectrum**
  - q^2_{rec}: mass squared of the neutrino pair
  - A peak localized around $q^2_{rec} = 4\text{GeV}^2$
  - Two-body decay $(B \to KX), m_X = 2\ \text{GeV}$
  - 2.8σ tension under the assumption of heavy new physics
  - No excess was found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

W. Altmannshofer et al, 2311.14629

Solutions: 2- or 3-body decay

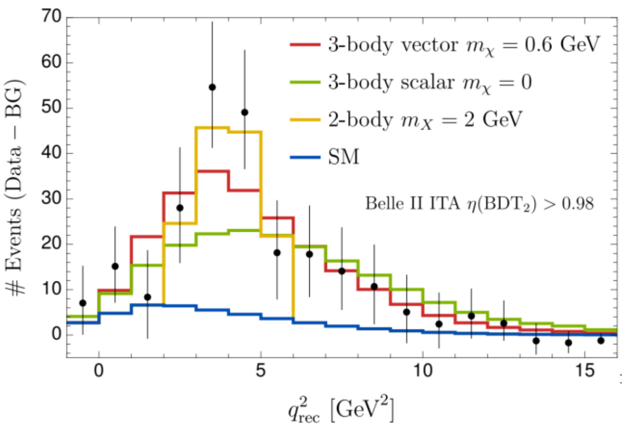


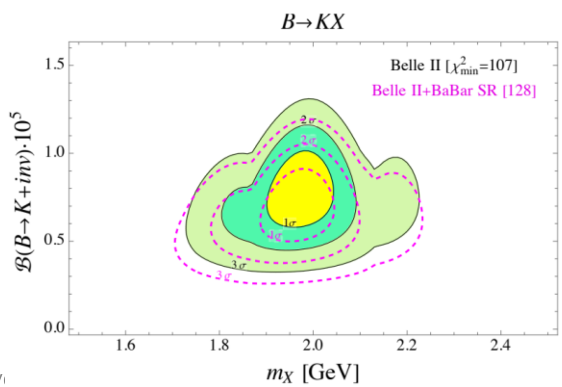


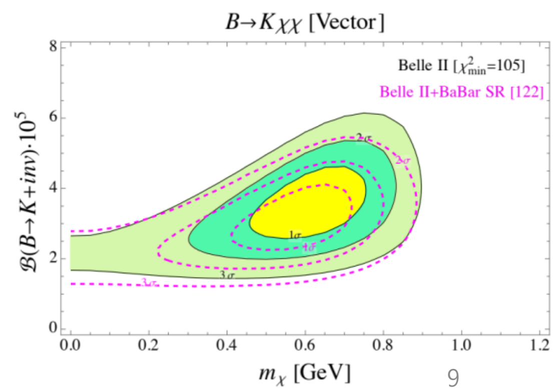
- Belle II provides information on the **q^2_{rec} spectrum**
  - q^2_{rec}: mass squared of the neutrino pair
  - A peak localized around $q^2_{rec} = 4\mathrm{GeV}^2$
  - Two-body decay $(B \to KX), m_X = 2\ \mathrm{GeV}$
  - Three-body decay $(B \to KXX), m_X < 0.6\ \mathrm{GeV}$

W. Altmannshofer et al, 2311.14629

K. Fridell et al, 2312.12507







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
  - $m_{Z'} = 2\text{GeV}$

W. Altmannshofer et al, 2311.14629

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

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

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

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

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

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

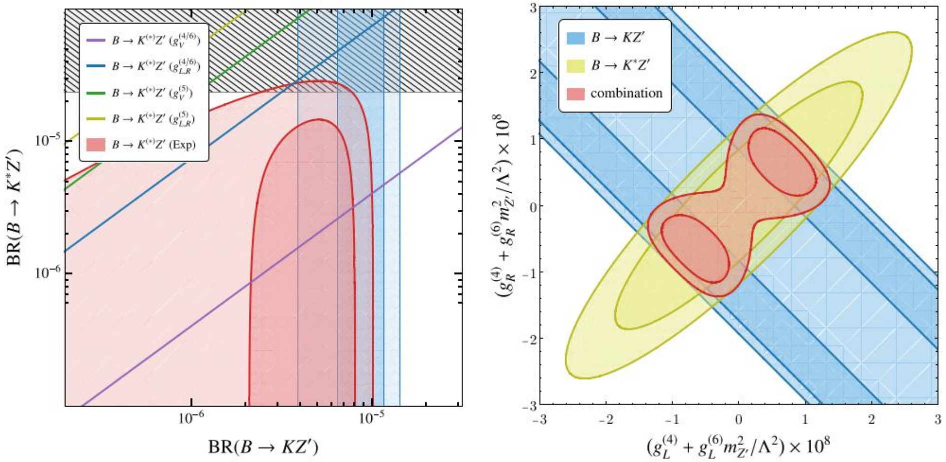


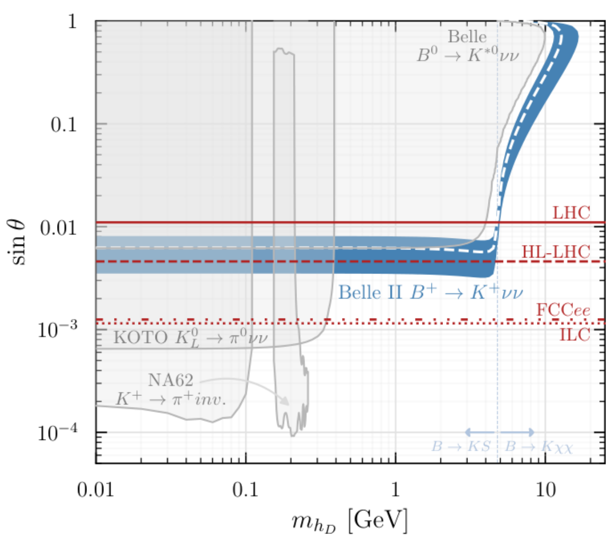
FIG. 2: *Left:* Correlations between $B \to KZ'$ and $B \to K^*Z'$ (colored lines) for the different $\bar s b Z'$ operators considered in this work. These are compared to the experimental data stemming from the combination of Belle-II, Babar and Belle measurements,which is represented by the red regions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

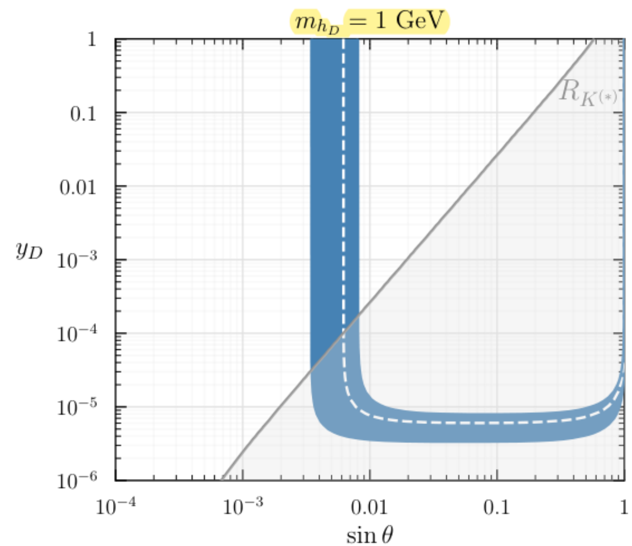
Solutions: 2- or 3-body decay

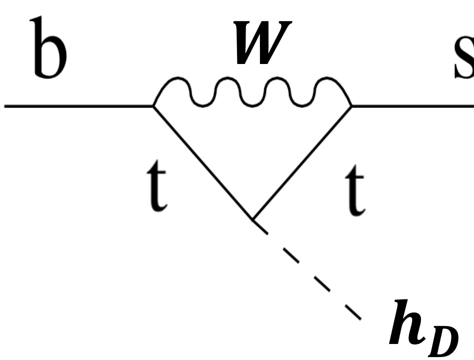
- Dark Higgs on-shell decay or three-body decay

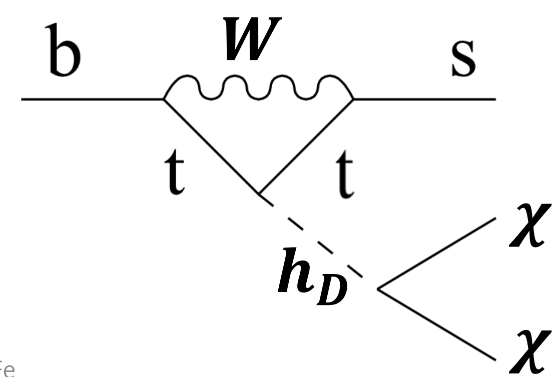
McKeen et al, 2312.00982

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





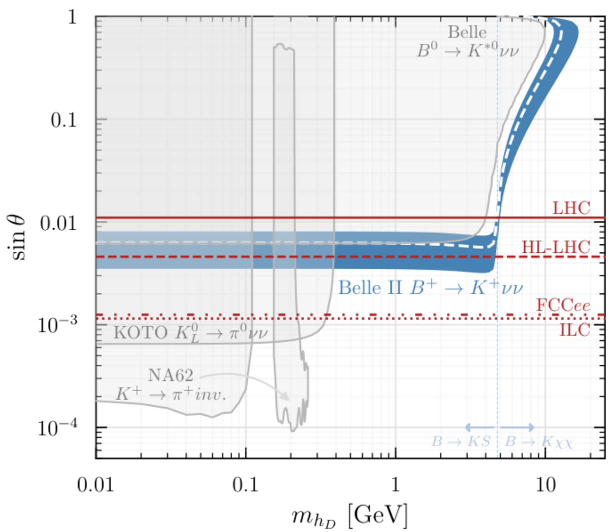


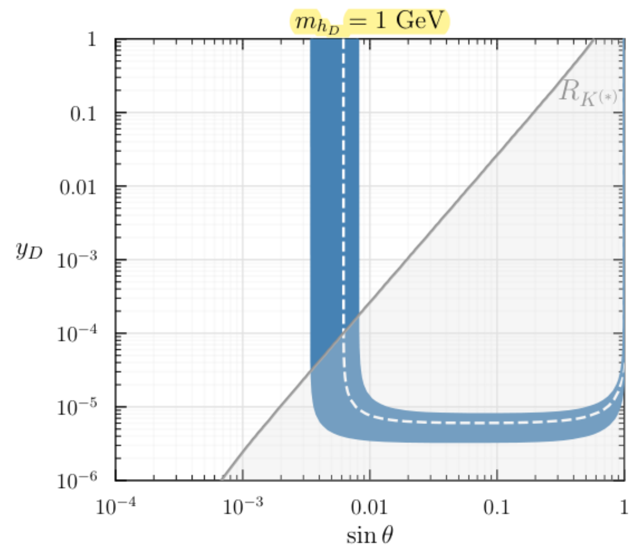


Solutions: 2- or 3-body decay

- 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…**

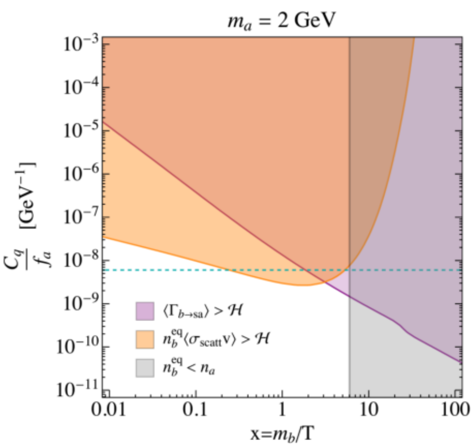
Solutions: 2-body decay

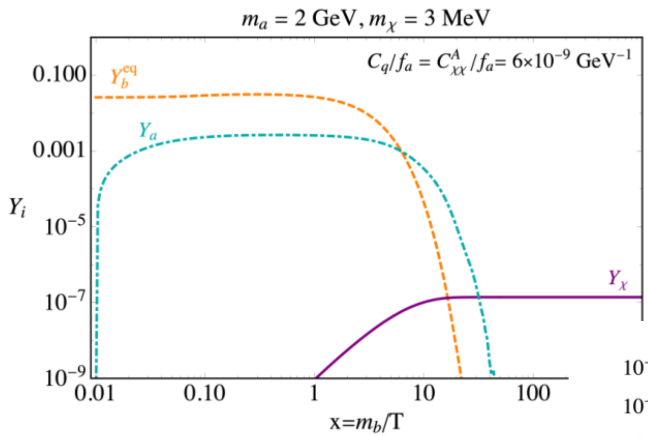
- ALP portal

Lorenzo Calibbi et al, 2502.04900

$$\mathcal{L}_{aff} = \frac{\partial_\mu a}{2f_a}\bar{f}_i\gamma^\mu\left(C^V_{f_if_j} + C^A_{f_if_j}\gamma_5\right)f_j \quad + \mathcal{L}_{a\chi\chi} = \frac{\partial_\mu a}{2f_a}\bar{\chi}C^A_{\chi\chi}\gamma^\mu\gamma_5\chi$$

- DM **freeze-in** production: $\Gamma(b\to sa), \sigma\left(b\bar{b}\to ag\right), \sigma(bg\to ba)$





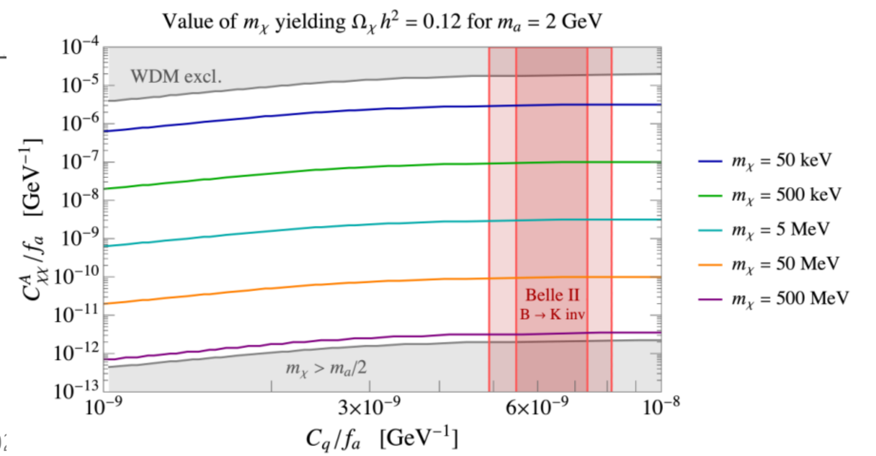
$$\mathrm{BR}(a\to gg)\simeq 93\%\,,\quad \mathrm{BR}(a\to s\bar{s})\simeq 7\%\,,\quad \mathrm{BR}(a\to\gamma\gamma)\simeq 2\times10^{-5}\,, \tag{17}$$

which is consistent with the results in Ref. [45]. The decay into DM is subdominant for $m_\chi \ll m_a$:

$$\mathrm{BR}(a\to\chi\bar{\chi})\simeq 2.6\times10^{-6}\times\left(\frac{C^A_{\chi\chi}}{C_q}\right)^2\left(\frac{m_\chi}{1\,\mathrm{MeV}}\right)^2. \tag{18}$$

The resulting ALP decay length is

$$c\tau_a \simeq 65\,\mathrm{m}\times\left(\frac{10^8\,\mathrm{GeV}}{f_a/C_q}\right)^2. \tag{19}$$



Solutions: 2-body decay

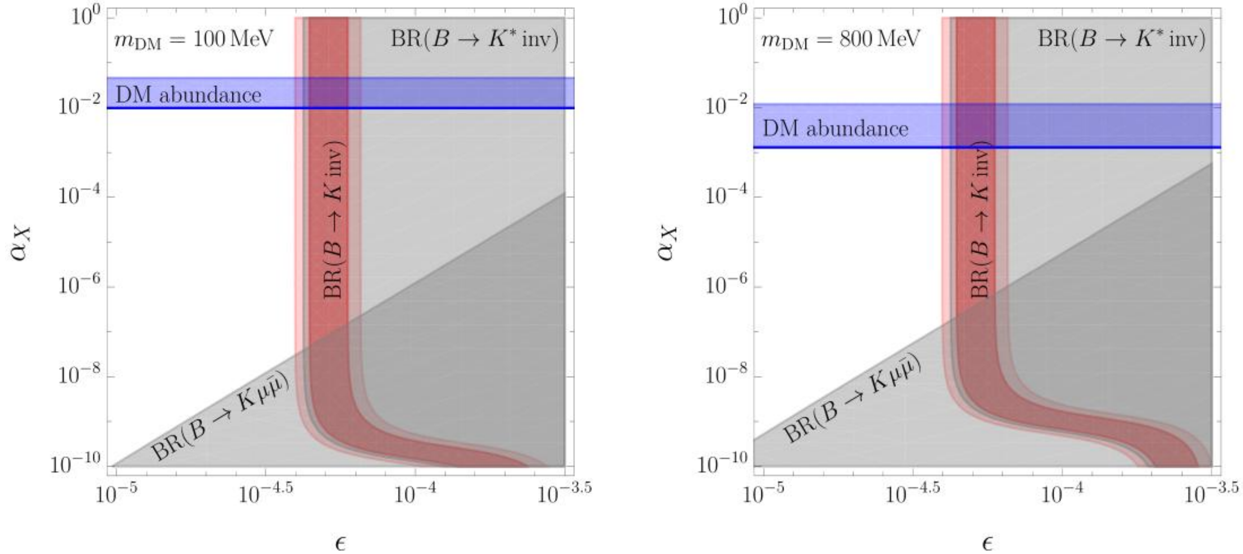
- Dark Photon portal through kinetic mixing **Lorenzo Calibbi et al, 2502.04900**

$$\mathcal{L} \supset \frac{1}{2}\overline{\psi}(i\partial\!\!\!/ - m_R)\psi + \frac{g_X}{2}\overline{\psi}X\!\!\!/\gamma_5\psi - \frac{y_R}{2\sqrt{2}}\overline{\psi}\psi\varphi - \frac{y_R}{2\sqrt{2}}\overline{\psi}i\gamma_5\psi a$$

- BelleII excess (B → K + Dark Photon with 2GeV)
  - The partial decay widths for decays to SM particles: suppressed by kinetic mixing
  - The partial width for decays of the dark photon to DMs: **Not** suppressed by the kinetic mixing
- DM freeze-out production
  - The relevant process is the DM annihilation into dark Higgs bosons, $\psi\psi \rightarrow \varphi\varphi$, which subsequently decay to SM particles
  - The annihilation process is **p-wave** suppressed
  - To satisfy BBN constraints, we require the dark Higgs lifetime to be shorter than $\tau\varphi \lesssim 0.1$ s → $m_\varphi > 4\,\mathrm{MeV}$
  - Relic density: $\Omega_\psi h^2 \approx 0.1 \times \left(\frac{0.5\,\mathrm{GeV}}{m_{\mathrm{DM}}}\right)^2 \left(\frac{0.002}{\alpha_X}\right)^2$

Solutions: 2-body decay

Lorenzo Calibbi et al, 2502.04900



solid blue line corresponds to a dark Higgs with mass $m_\varphi = 4$ MeV and the blue shaded region displays the range $m_\varphi \in [4\,\text{MeV}, m_{\rm DM}]$.

- DM scattering off a Xenon nucleus: five orders of magnitude below the DM direct detection limit
- DM self-interaction cross section

$$\frac{\sigma_{\rm SI}}{m_{\rm DM}} = \frac{16\pi\alpha_X^2 v_{\rm DM}^2}{m_X^3} \frac{x_{\rm DM}(3 - 20x_{\rm DM}^2 + 40x_{\rm DM}^4)}{(1 - 4x_{\rm DM}^2)^2}$$

$$\approx 1.1 \times 10^{-14} \left(\frac{\alpha_X}{10^{-2}}\right)^2 \left(\frac{v}{10^3\,\text{km/s}}\right)^2 \frac{x_{\rm DM}(3 - 20x_{\rm DM}^2 + 40x_{\rm DM}^4)}{(1 - 4x_{\rm DM}^2)^2} \frac{\text{cm}^2}{\text{g}}$$

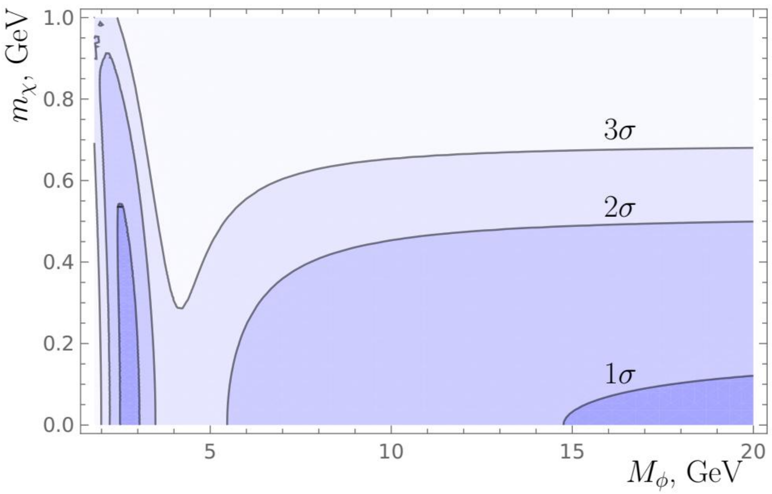
Solutions: 2- or 3-body decay

- $B \to (K, K^*)\chi\bar{\chi}$ decays via a scalar mediator

A. Berezhnoyet al, 2502.14313

$$\mathcal{L}_{\text{int}} = -\frac{y m_t}{v}\phi\,\bar{t}t - \kappa\phi\bar{\chi}\chi$$

$$\mathcal{L}_{b\to s\phi} = g_{b\to s\phi}\,\phi\,\bar{s}_L b_R + \text{h.c.}, \qquad g_{b\to s\phi} = \frac{y m_b}{v}\frac{3\sqrt{2}G_F m_t^2 V_{ts}^* V_{tb}}{16\pi^2}.$$



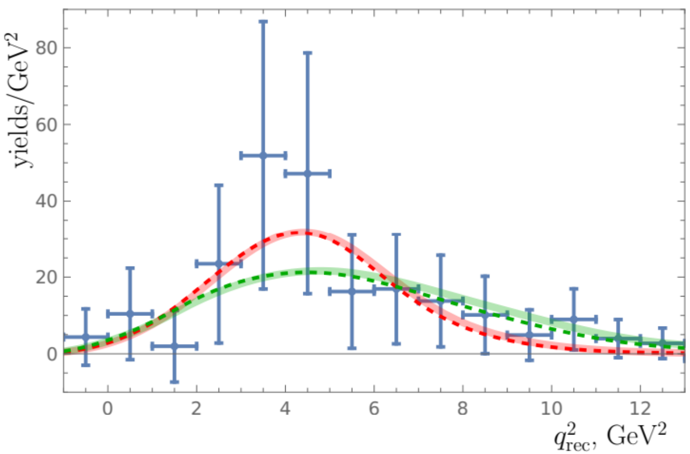
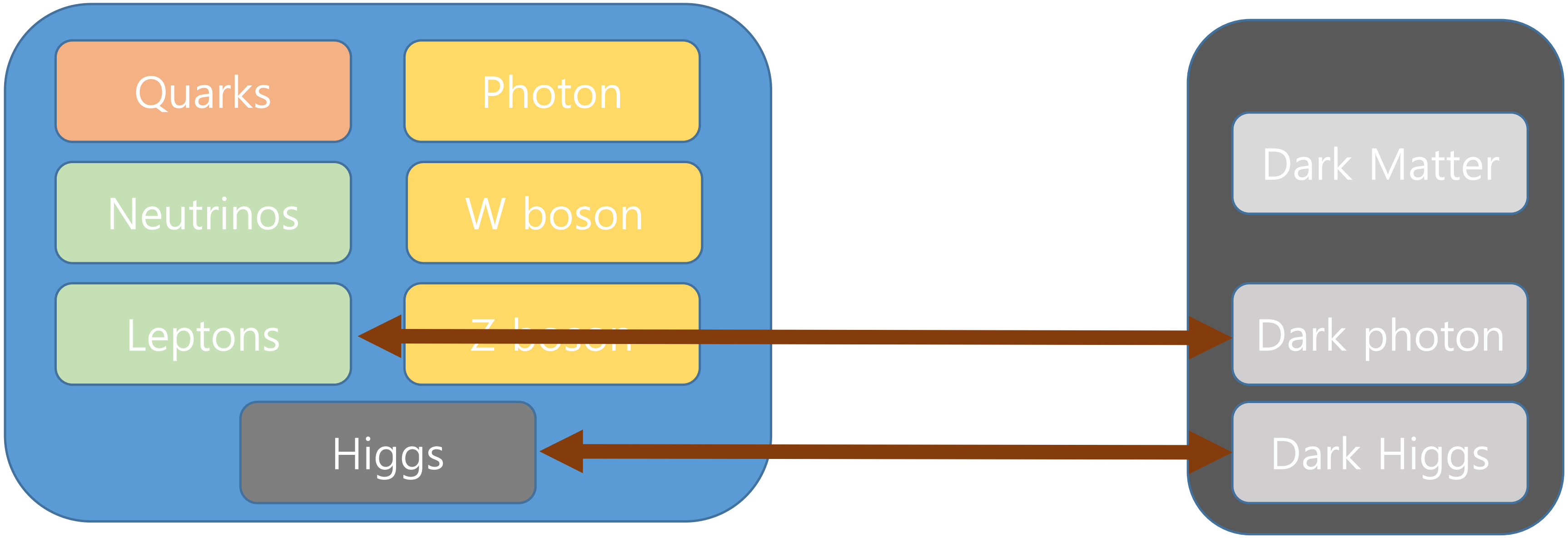


Figure 2: The Belle II data on the decay $B \to KM_X$ fitted by the DM model considered for different parameter values: $M_\phi = 2.8$ GeV, $\Gamma^0_\phi = 2.8$ GeV and $m_\chi = 0$ GeV (red solid curve); $M_\phi = 20$ GeV, $\Gamma^0_\phi = 0$ GeV and $m_\chi = 0$ GeV (green solid curve). The corresponding predictions for $B \to K^* M_X$ are also shown, assuming the same detection efficiency (red dashed and green dashed curves). Only excess events over the SM expectations are shown.

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

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

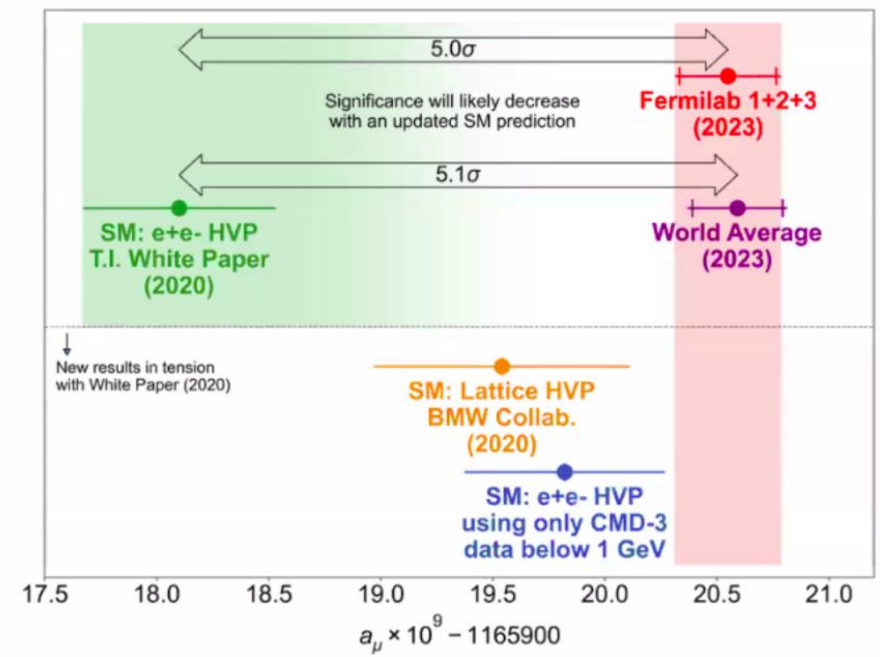


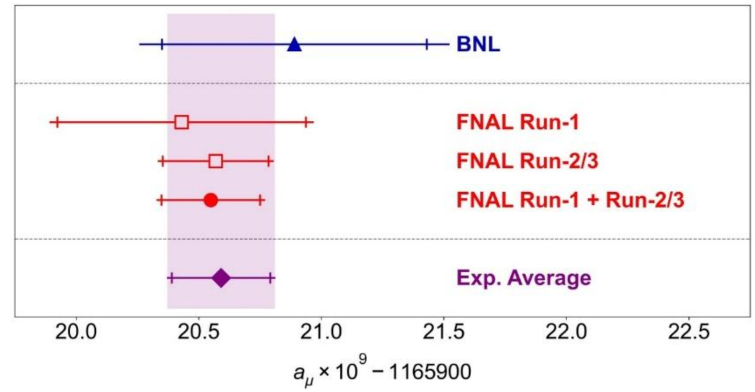
- **UV complete** $U(1)_{L_\mu - L_\tau}$-charged **scalar** DM model
- Dark photon Z' gets massive through $U(\cancel{1})_{L_\mu - L_\tau}$ breaking
- A new singlet scalar (**Dark Higgs**), which mixes with the SM Higgs

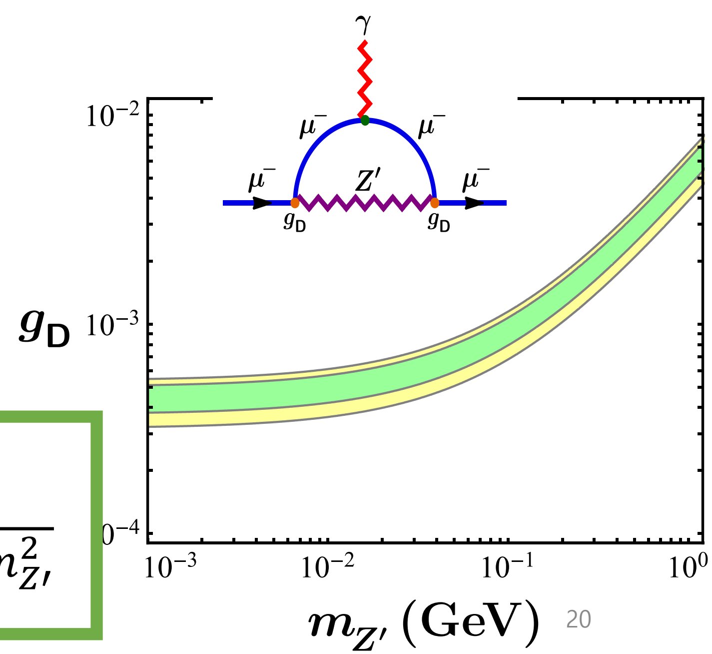
Evidences – Muon g-2

Muon g-2 collaboration, PRL 2023

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







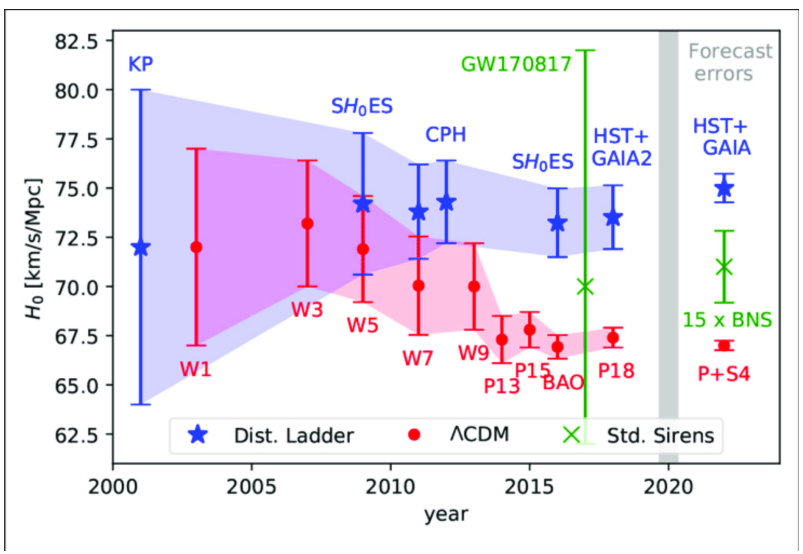
S. Baek, Deshpande, He, P. Ko, 2001
S. Beak, P. Ko, 2008
…

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

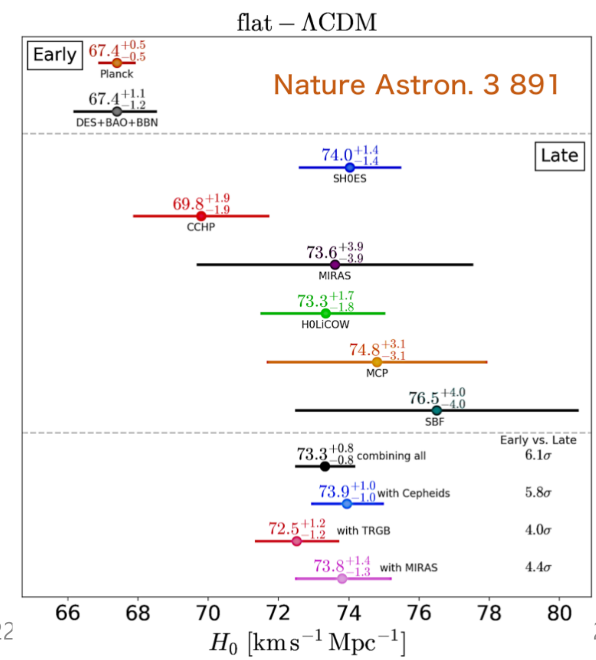
Evidences – Hubble tension

- 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})

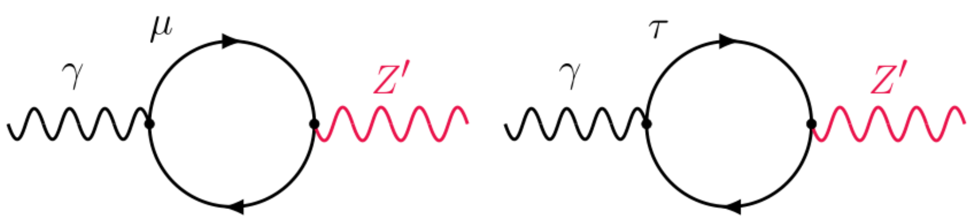


P. Shah et al, AAR 2021



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
  - 

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

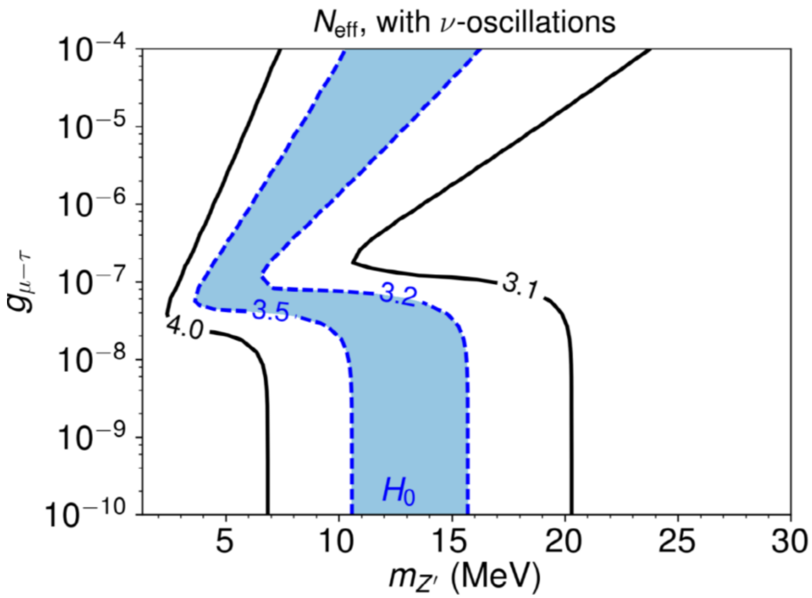
Gauged $U(1)_{L_\mu - L_\tau}$ Z' model

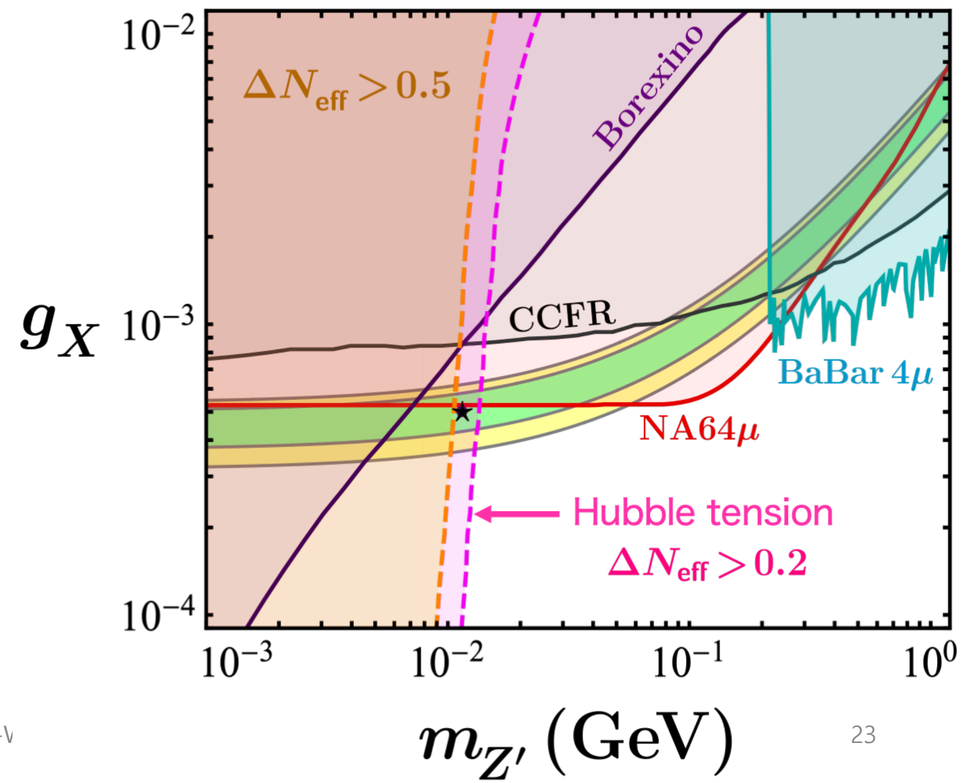
- ***Hubble tension***

M. Escudero et al, JHEP 2019

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





$U(1)_{L_\mu - L_\tau}$-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: $\boxed{m_{Z'} = g_X |Q_\Phi| v_\Phi}$

- 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

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

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

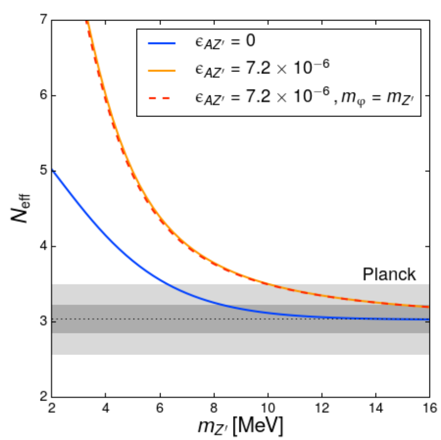
- Additional interactions with the dark Higgs

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

- **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



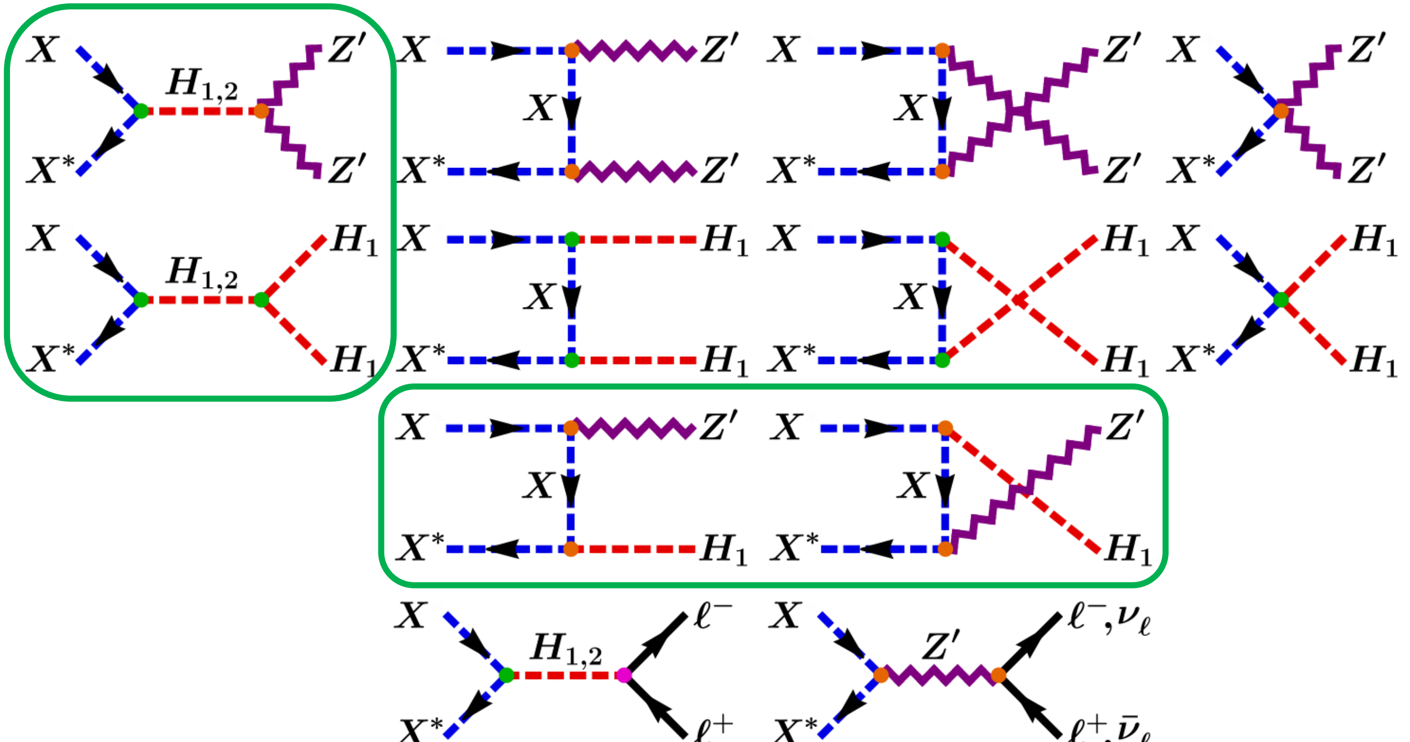
$U(1)_{L_\mu - L_\tau}$-charged DM + Dark Higgs

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

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

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

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

$$\sigma_{\text{el}}^{X\text{-}n} \simeq \frac{\mu_n^2}{\pi} \frac{e^2 g_X^2 Z^2 \epsilon^2}{A^2 m_{Z'}^4}$$

BelleII excess: 2- or 3-body decay

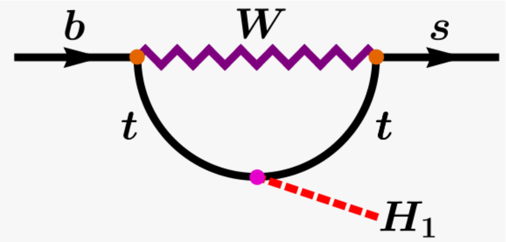
- When $m_{H_1} < m_B - m_K$, H_1 is on-shell

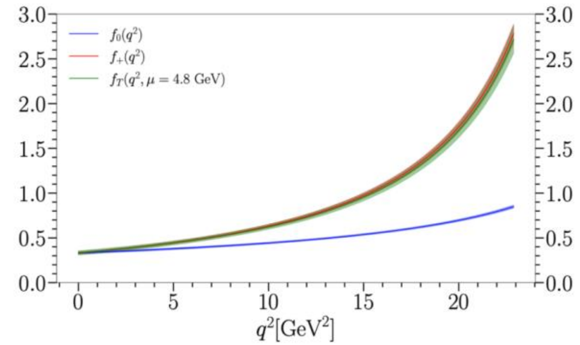
$$\Gamma_{B^+\to K^+H_1} \simeq \frac{|\kappa_{cb}|^2\sin^2\theta}{64\pi m_{B^+}^3}\left(\frac{m_{B^+}^2 - m_{K^+}^2}{m_b - m_s}\right)^2 \left[f_0(m_{H_1}^2)\right]^2 \times \sqrt{\mathcal{K}(m_{B^+}^2, m_{K^+}^2, m_{H_1}^2)}$$

form factor

$\sin\theta \ll 1$

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

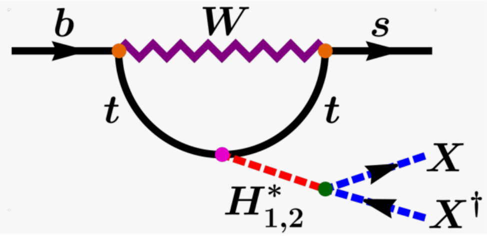




W. G. Parrott, C. Bouchard & C. T. H. Davies, ORD 2023

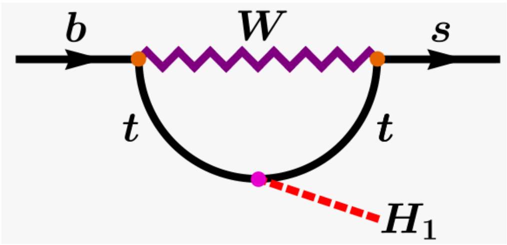
- When $m_{H_1} > m_B - m_K$, H_1 is off-shell → three-body decay

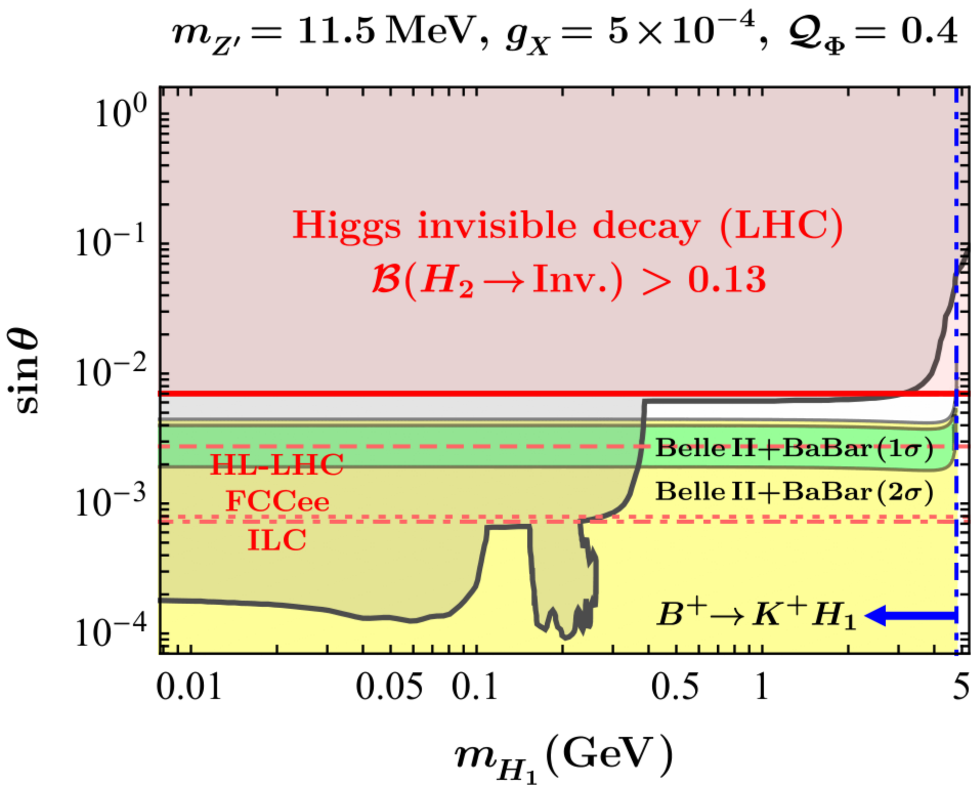
$$\Gamma_{B^+\to K^+XX^\dagger} \simeq \frac{\lambda_{\Phi X}^2 v_\Phi^2 |\kappa_{cb}|^2\sin^2\theta}{1024\pi^3 m_{B^+}^3}\left(\frac{m_{B^+}^2 - m_{K^+}^2}{m_b - m_s}\right)^2 (m_{H_1}^2 - m_{H_2}^2)^2 \times \int_{4m_X^2}^{(m_{B^+} - m_{K^+})^2} dq^2 \frac{\sqrt{1 - 4m_X^2/q^2}\sqrt{\mathcal{K}(m_{B^+}^2,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



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.



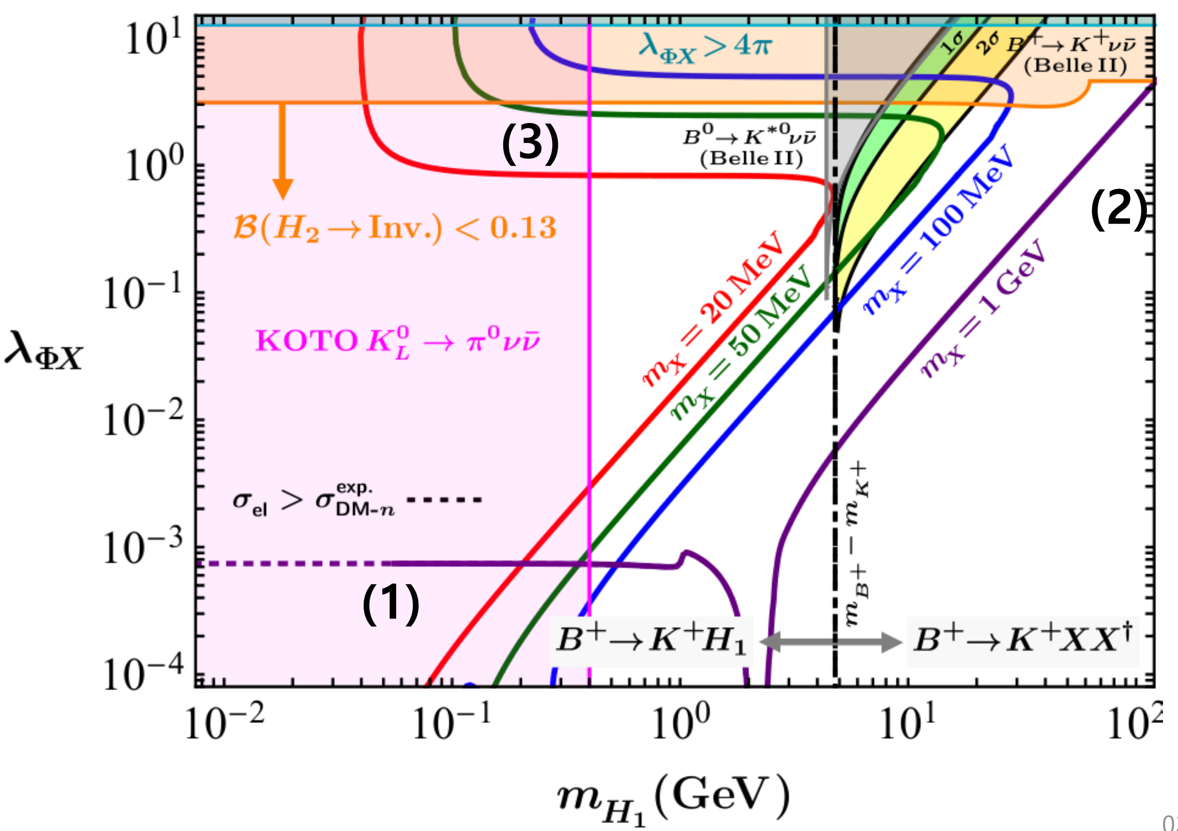


- H_1 decay process
  - $H_1 \to XX^\dagger, Z'Z', f\bar{f}$
- Allowed value
  - $10^{-3} \leq \sin\theta \leq 5\times10^{-3}$
  - take $\sin\theta = 6\times10^{-3}$

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: $m_X \lesssim 1.2\ \mathrm{GeV}\ (m_{H_1} < m_B - m_K)$
  - Three-body decay: $20\mathrm{MeV} < m_X \lesssim 60\mathrm{MeV}\ (m_{H_1} > m_B - m_K)$

$m_{Z'} = 11.5\,\mathrm{MeV},\ g_X = 5\times10^{-4},\ \mathcal{Q}_\Phi = 0.4,\ s_\theta = 6\times10^{-3}$



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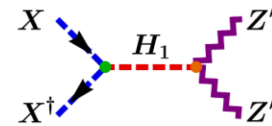


$m_X^2 \gg m_{Z'}^2$

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

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

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

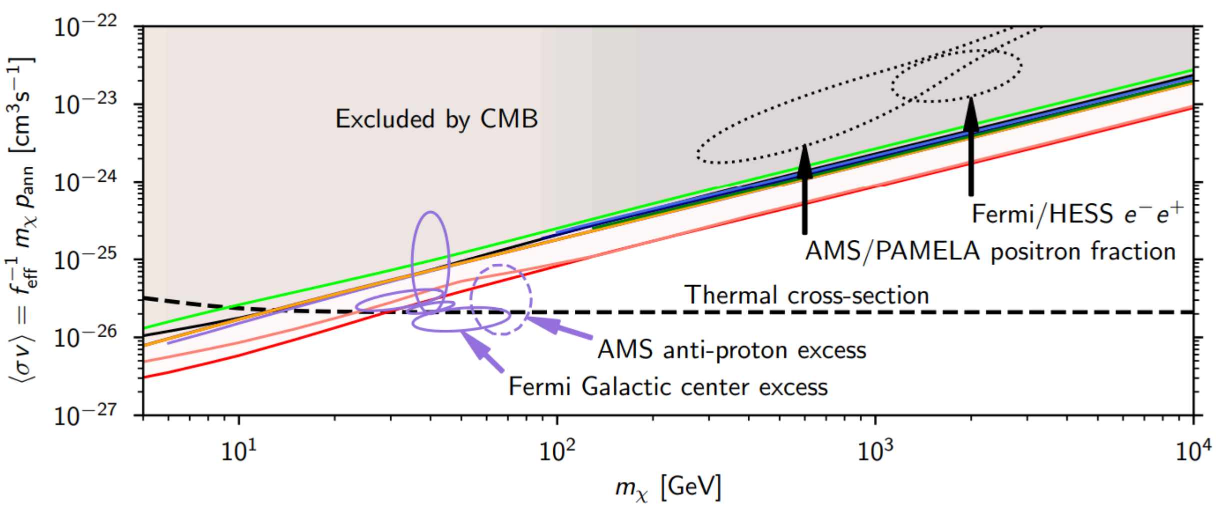
$$\Rightarrow \langle\sigma v\rangle \propto \frac{m_X^2}{\lambda_{\Phi X}^2 v_\Phi^4} \Rightarrow \lambda_{\Phi X} \simeq \text{const.}$$

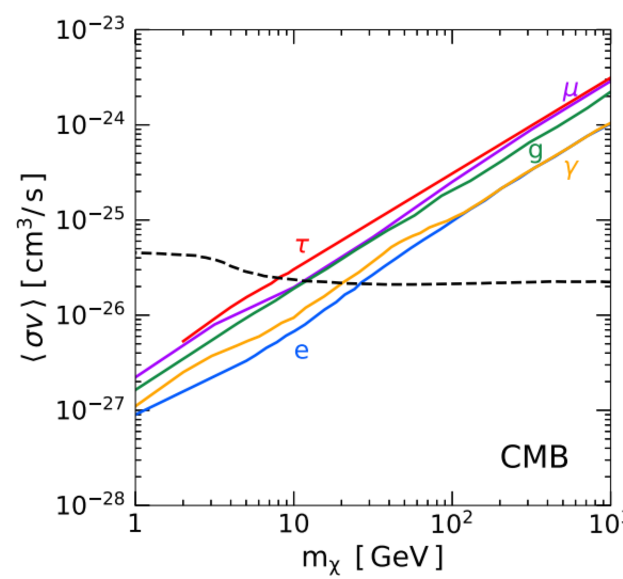
CMB constraints

- 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.

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

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



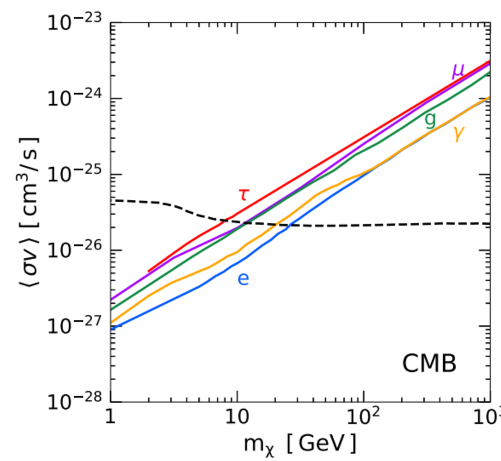


CMB constraints

- 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**
  - …

$$\sigma v = \underset{\text{s-wave}}{a} + \overset{\text{p-wave}}{b} v^2 + O(v^4)$$

- 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

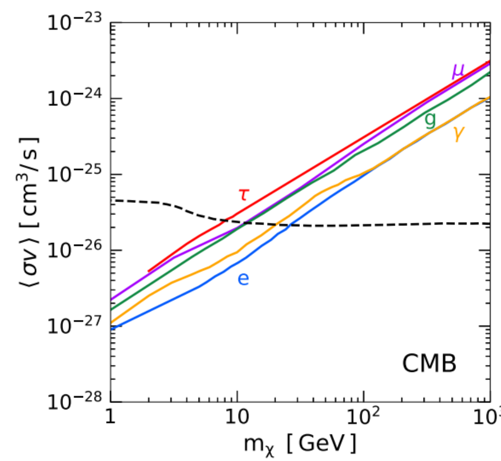
- For $m_X \lesssim 20\mathrm{GeV}$, CMB bound (DM annihilation @ $T \sim \mathrm{eV}$) excludes the thermal DM freeze-out determined by <u>*s-wave*</u> annihilation
    - DM annihilation should be mainly in **p-wave**
    - …

p-wave

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

s-wave

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



CMB constraints

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

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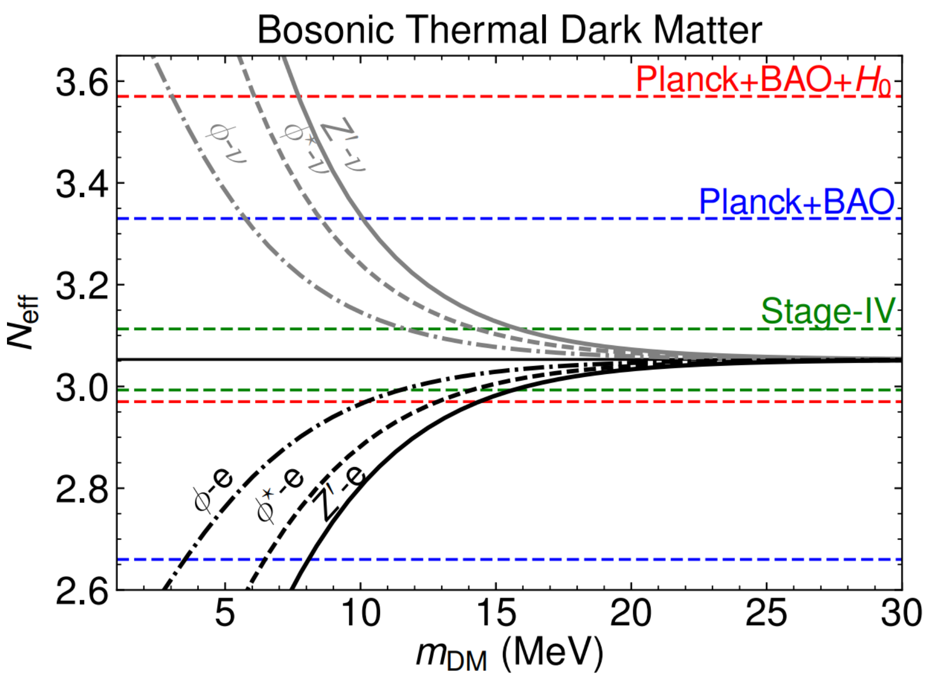
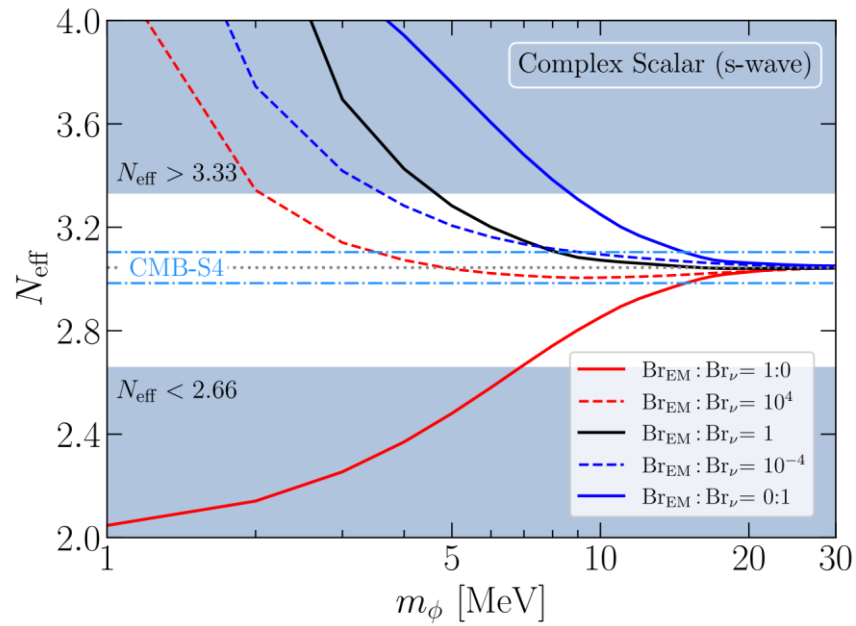
M. Escudero, 1812.05605
X. Chu et al, 2310.06611





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

Conclusions

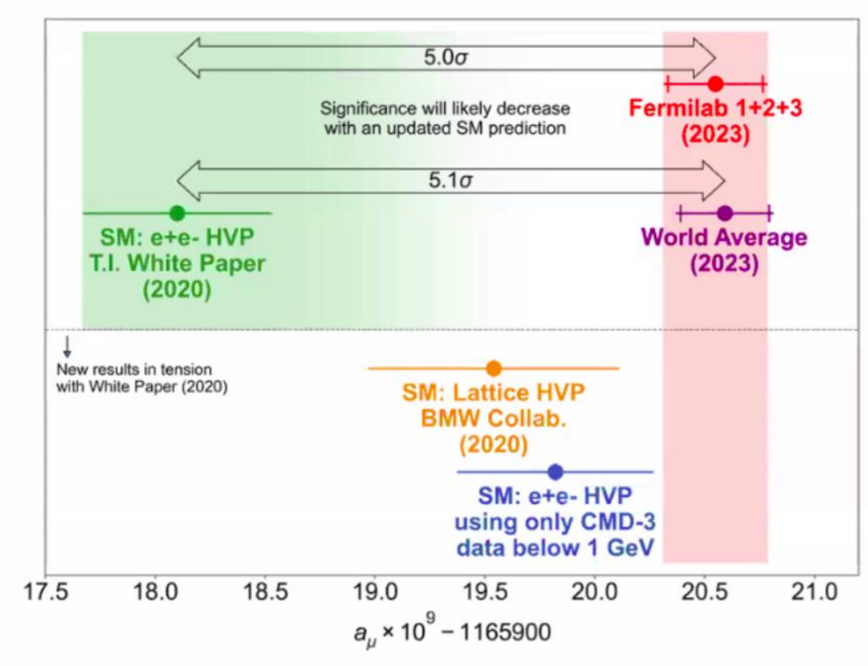
- BelleII data shows a excess of $B^+ \to K^+ \nu\bar{\nu}$ over the SM prediction
- Th pa
- CN ations int
- We can accommodate the muon g-2 and subsequently relax the tension in the Hubble constant with extra radiation

Thank you very much

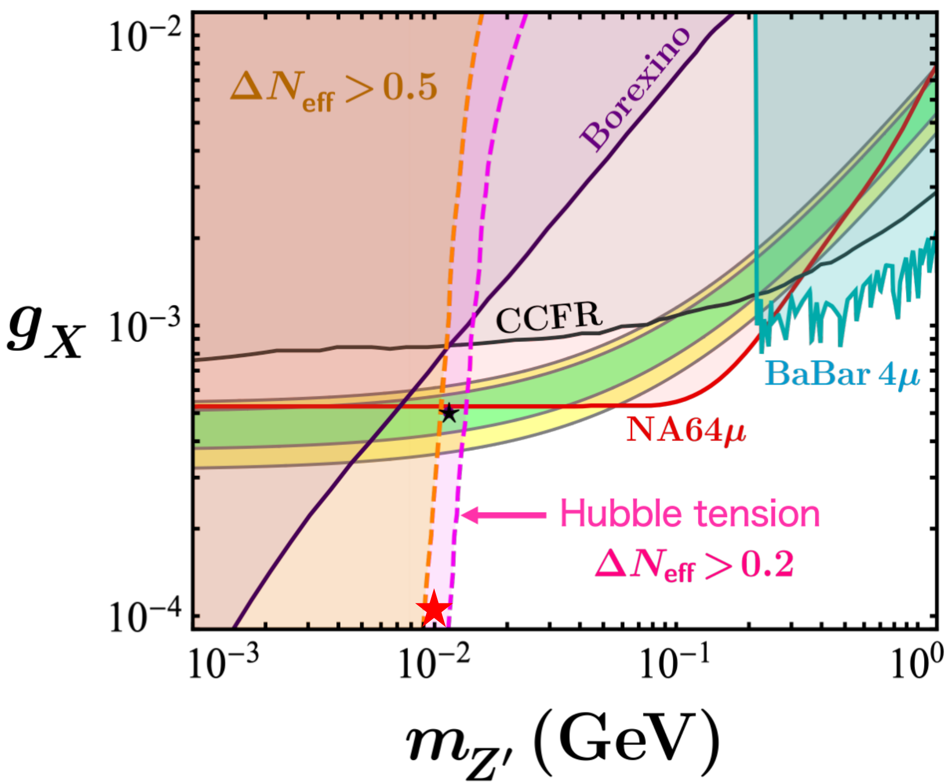
Back-up Slides

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.

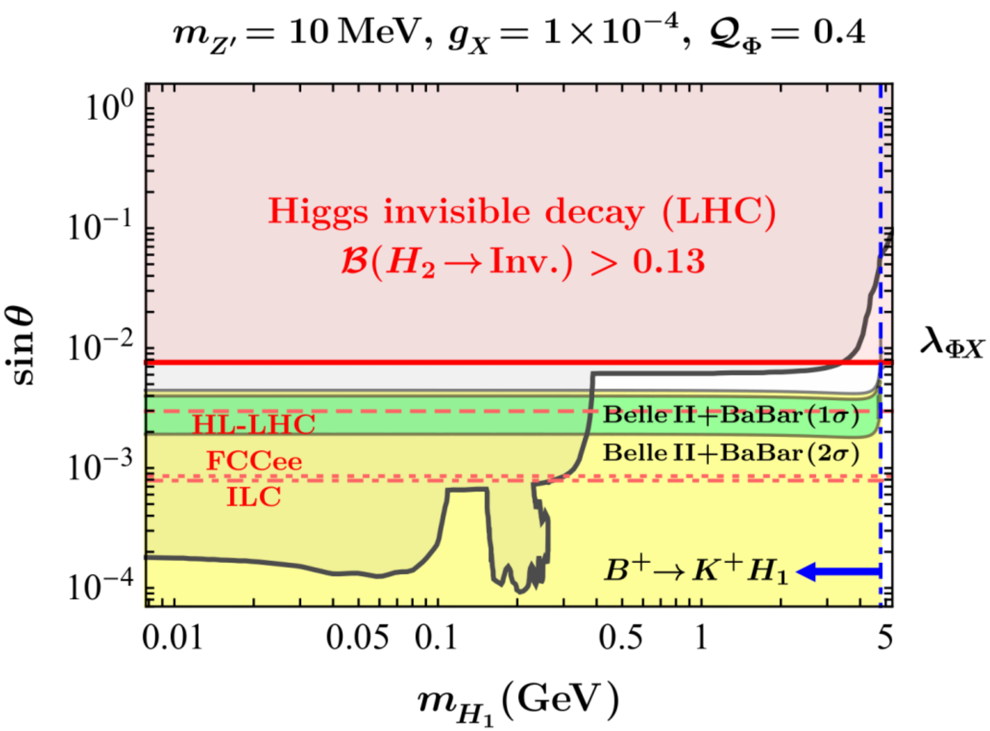


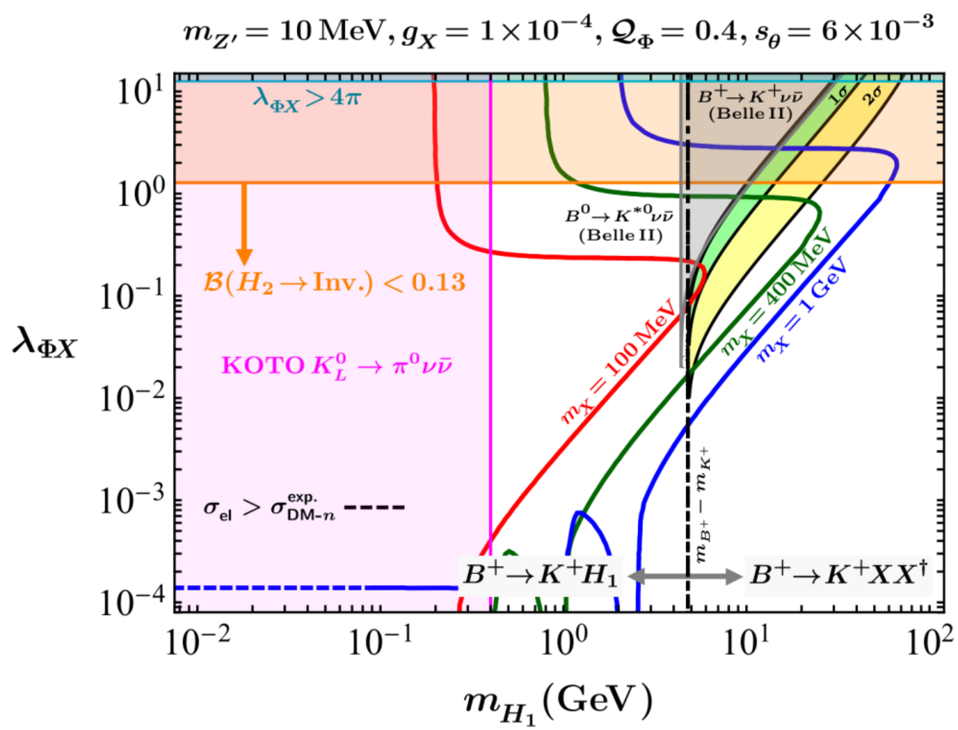
- New BP : $m_{Z'} = 10\text{MeV}$, $g_X = 10^{-4}$



BelleII excess : 2- or 3-body decay

- $m_{Z'} = 10\text{MeV},\ g_X = 10^{-4}$ ($\boxed{m_{Z'} = g_X|Q_\Phi|v_\Phi}$ → Larger v_Φ)
  - Hubble tension can be relaxed
  - $\Delta a_\mu = 10^{-10}$ **(BMW & CMD-3 collaboration)**
  - **Belle II** (2-body decay): $m_X \lesssim 1.2\ \text{GeV}\ (m_{H_1} < m_B - m_K)$
  - **Belle II** (3-body decay): $\sim 90\text{MeV} < m_X \lesssim 450\text{MeV}\ (m_{H_1} > m_B - m_K)$





Evidences – Dark Matter

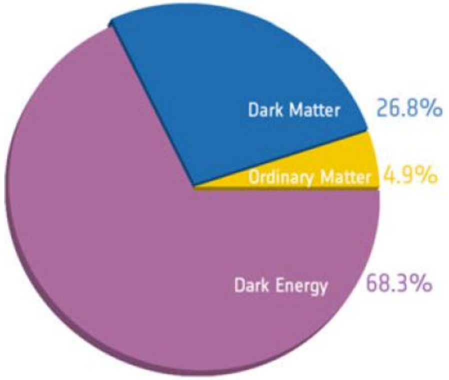
- **Dark Matter as a particle must be**
  - **Non-baryonic**
  - **Massive**
  - **Have existed from early Universe up to now**
    - **Stable or lifetime longer than the age of Universe → new symmetry**

  - **Dark : No electromagnetic interaction → EM charge singlet**

  - **27% of the present energy density of the Universe → $\boldsymbol{\Omega h^2 = 0.12}$**

    Planck 2018

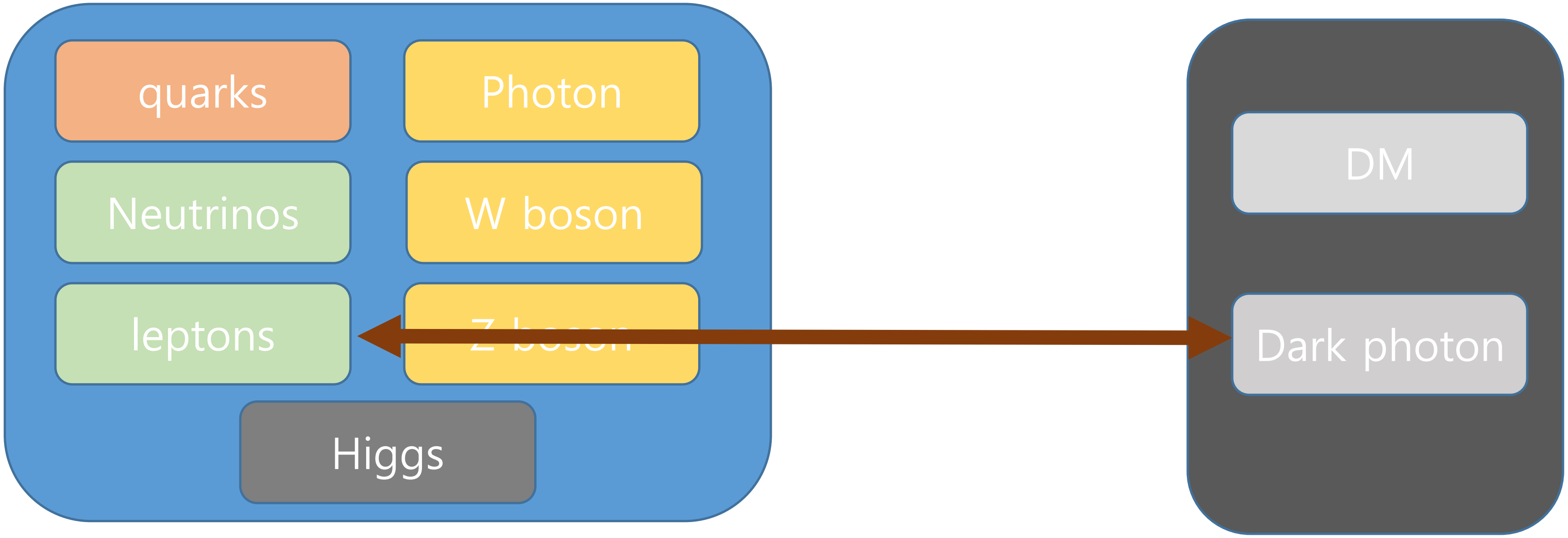
  - **Cold : non-relativistic at the time of formation of the first structures**



- **Cold Dark Matter**
  - **Weakly Interacting Massive Particle**

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

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



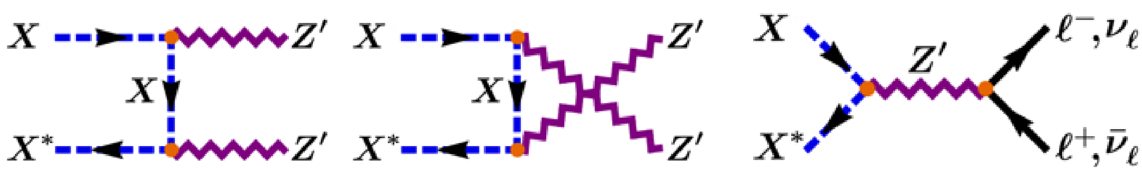
- Let's call Z', $U(1)_{L_\mu - L_\tau}$ gauge boson, dark photon since it couple to DM

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

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

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

  - 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



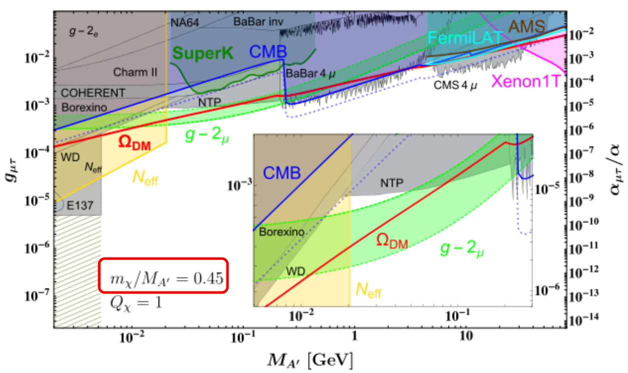
Only when $m_X > m_{Z'}$

- 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

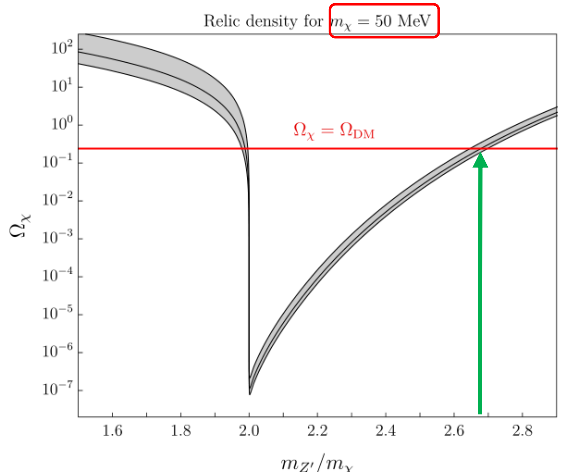
$U(1)_{L_\mu - L_\tau}$-charged DM model

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

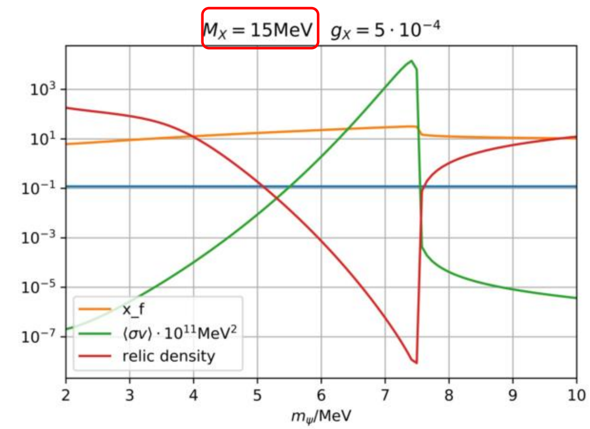
P. Foldenauer, PRD 2019



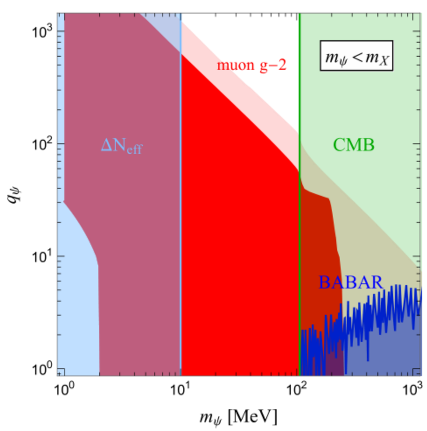
I. Holst, D. Hooper, G. Krnjaic, PRL 2022

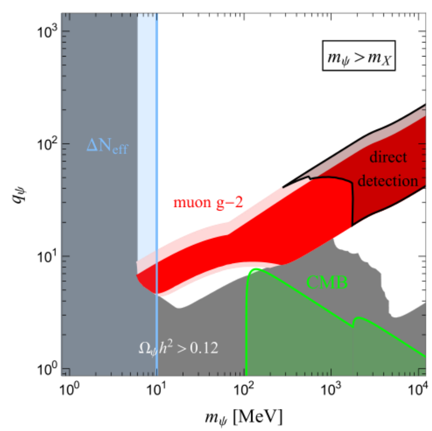


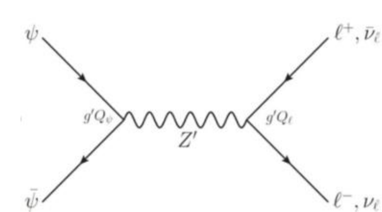
M. Drees, W. Zhao, PLB 2022



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







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

- **Muon g-2**
  - $m_{Z'} \sim O(10)\text{MeV}, \&\ g_X \sim 10^{-4}$ 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: $\sigma_{\text{el}}^{X-p} \simeq 10^{-46}\text{cm}^2$
  - DM-electron scattering: $\sigma_{\text{el}}^{X-e} \simeq 10^{-45}\text{cm}^2$

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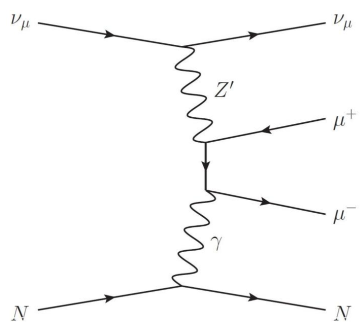
- **BelleII excess**
  - $B \to KZ'$ (2-body decay)
    ➔ disfavored by q^2 spectrum
  - $B \to K\boldsymbol{XX}^\dagger$(3-body decay)
    ➔ suppressed by kinetic mixing and $g_X \sim 10^{-4}$

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



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

- $\boldsymbol{\Delta N_{\rm eff}}$ **M. Escudero et al, JHEP 2019**
  - Z' will reheat the neutrino gas, resulting in a higher expansion rate
  - Increase the effective number of neutrinos $N_{\rm eff}$
  - $\boldsymbol{\Delta N_{\rm eff} < 0.5}$

- ***BOREXINO*** **R. Harnik et al, JCAP 2012**
  - $\nu - e$ scattering

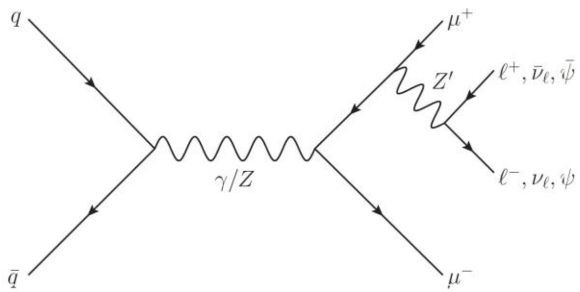
BaBar, LHC 4μ channels

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

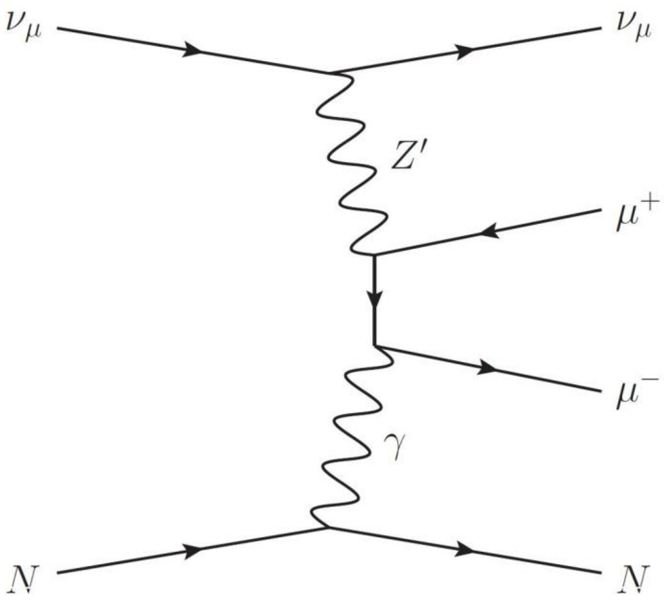
Neutrino trident production

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

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

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

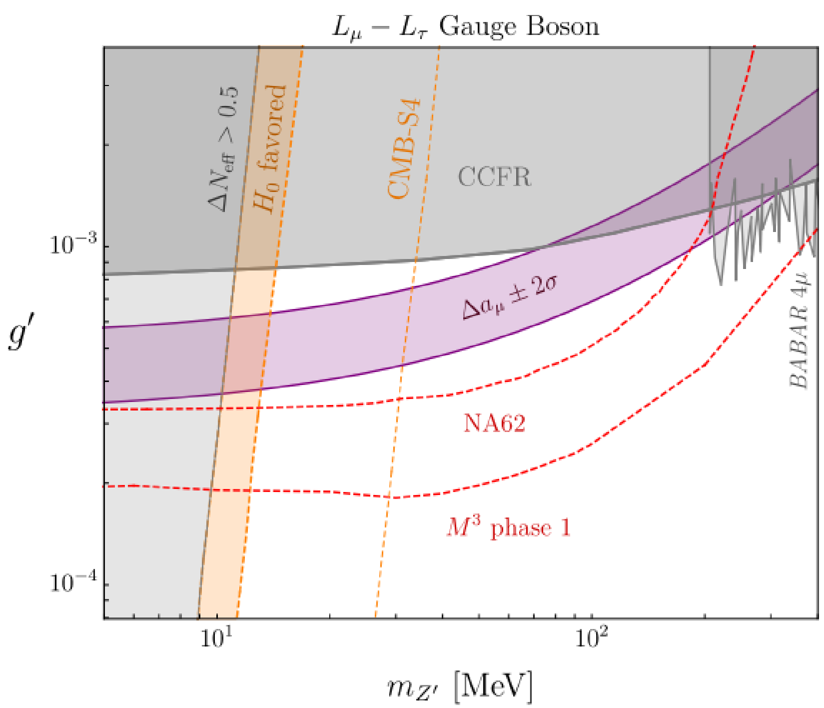
$$\alpha_{B-L}^2 \to \begin{cases} \left[\sum_{i,j=1}^3 f_i \, |(U^\dagger Q_{\mu e} U)_{ij}|^2\right]^{1/2} \alpha_{\mu e}^2 \,, & \text{for} \quad \mathrm{U}(1)_{L_\mu - L_e} \,, \\ \left[\sum_{i,j=1}^3 f_i \, |(U^\dagger Q_{e\tau} U)_{ij}|^2\right]^{1/2} \alpha_{e\tau}^2 \,, & \text{for} \quad \mathrm{U}(1)_{L_e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

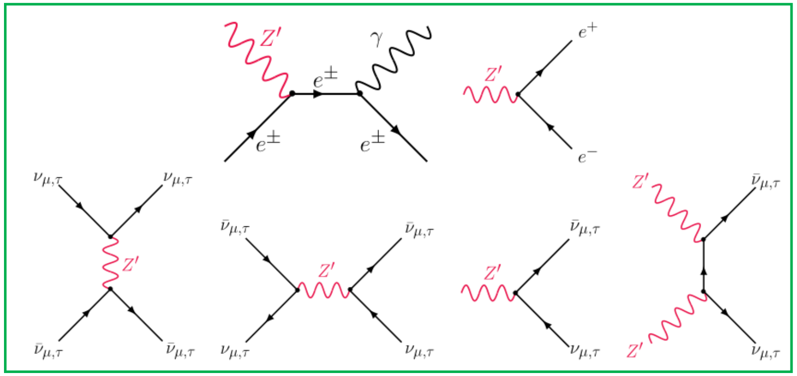
$$Q_{\mu\tau} = \mathrm{diag}(0, 1, -1)$$

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

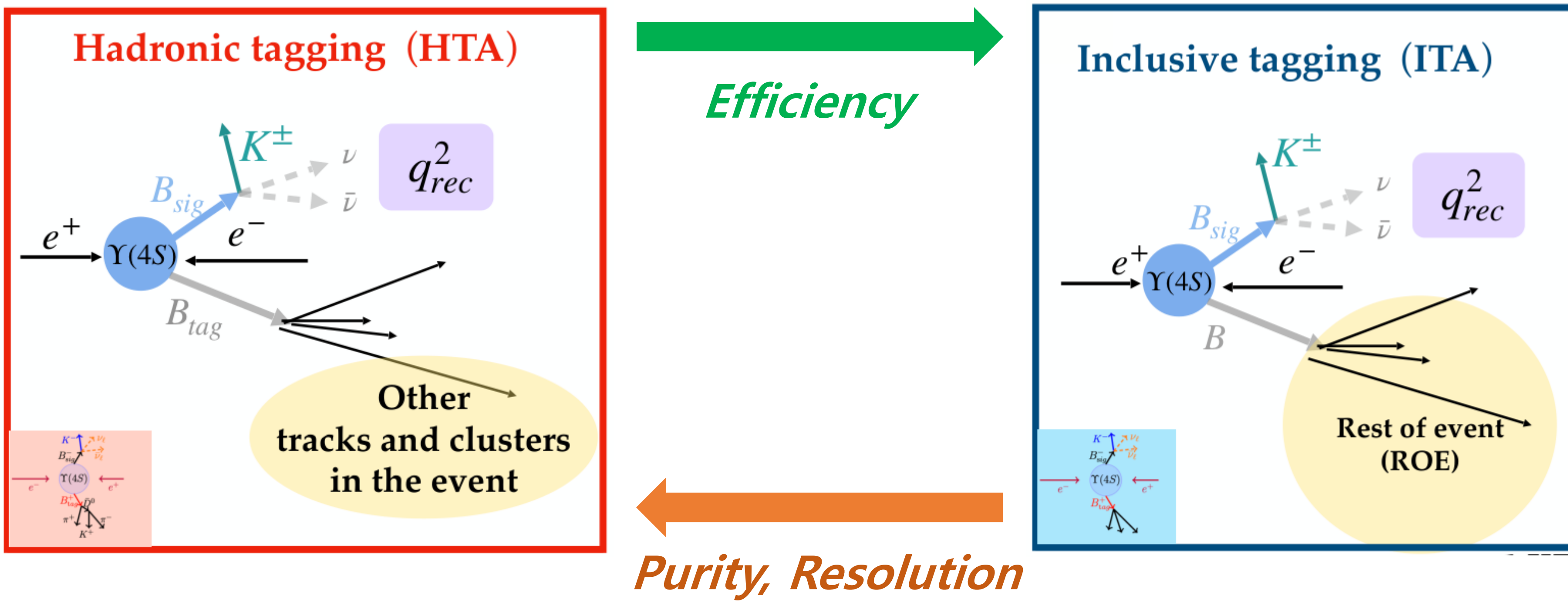
$$\mathcal{L} \supset \mathcal{L}_{\rm SM} - \frac{1}{4} Z'_{\alpha\beta} Z'^{\alpha\beta} + \underline{\frac{1}{2} m_{Z'}^2 Z'_\alpha Z'^\alpha} + i\bar{\chi}\gamma^\alpha \partial_\alpha \chi - m_\chi \bar{\chi}\chi$$
$$+ g_X Q_\chi Z'_\alpha \bar{\chi}\gamma^\alpha \chi + g_X Z'_\alpha \sum Q_\ell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

  - 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



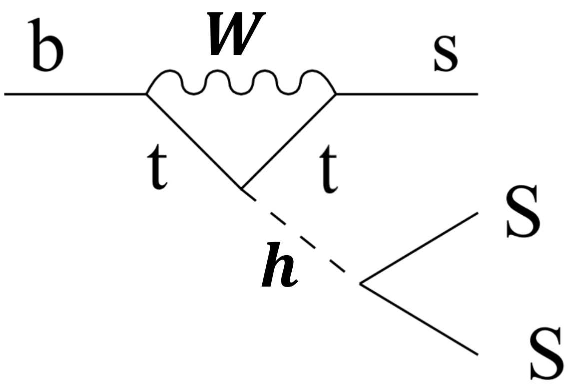
- q^2_{rec}: mass squared of the neutrino pair
- Inclusive tagging: It allows one to reconstruct inclusively the decay $B^+ \to K^+\nu\bar{\nu}$ from the charged kaon

Solutions: 3-body decay

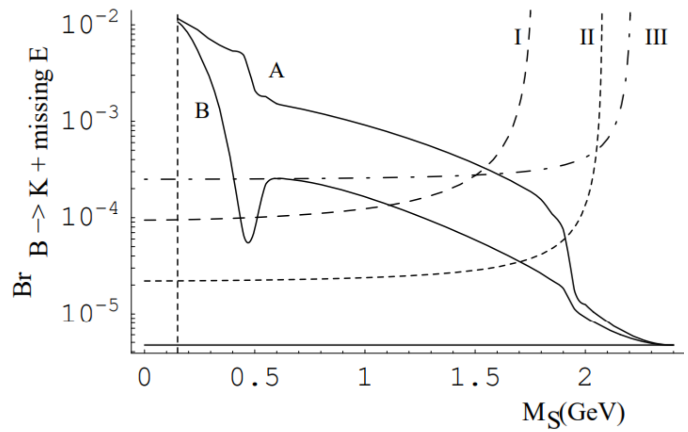
Bird et al, PRL 2004

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

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



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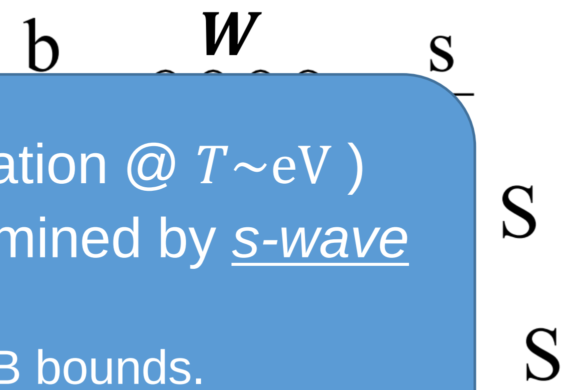

- For $m_\chi \lesssim 10\mathrm{GeV}$, CMB bound (DM annihilation @ $T \sim \mathrm{eV}$) excludes the thermal DM freeze-out determined by *s-wave* annihilation
- At that time, the authors did not consider the CMB bounds.

  This model does not work anymore.

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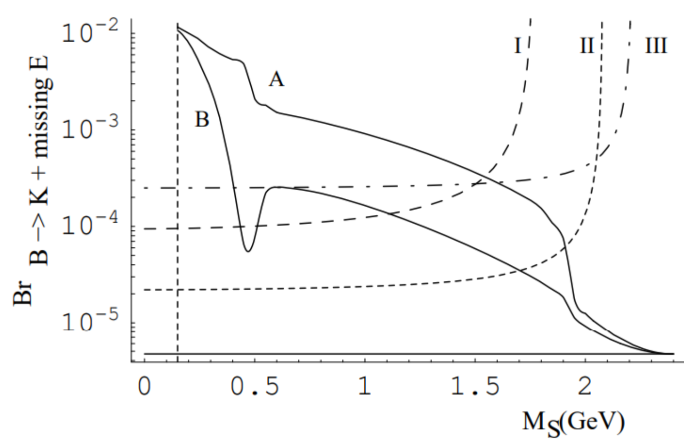
- $m_s \leq 1\mathrm{GeV}$ is already excluded by BABAR limits (2004 data).

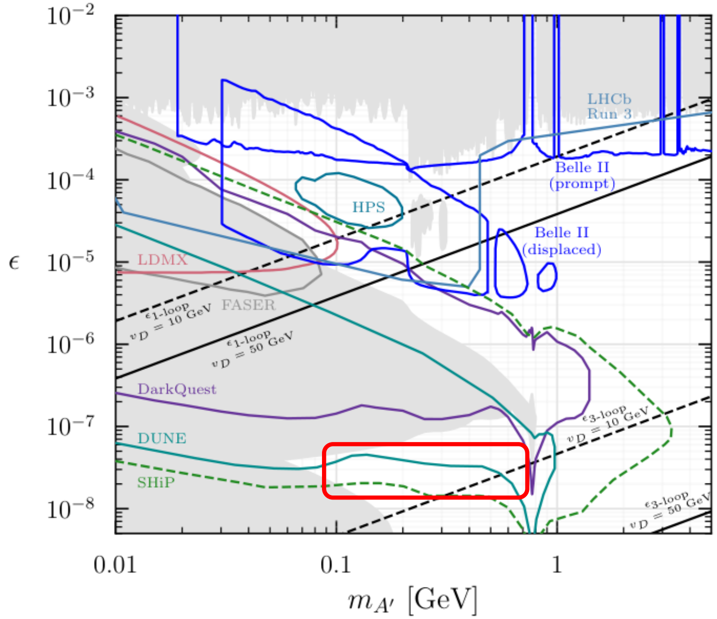


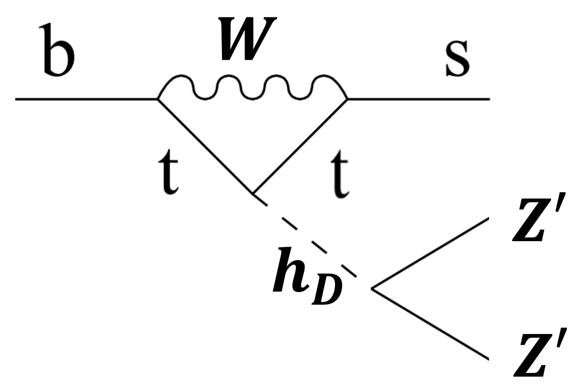
Solutions: 3-body decay

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 $10^{-6} \lesssim \epsilon \lesssim 10^{-4}$.