BelleII excess & Muon g-2 Illuminating Light DM Higgs portal

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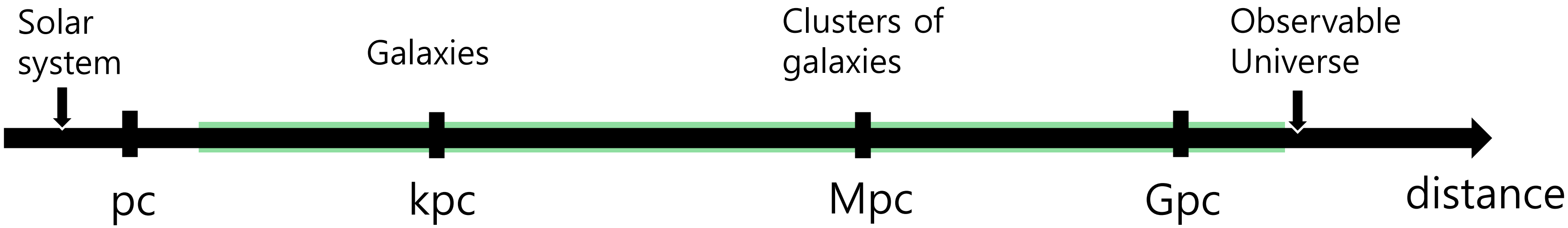
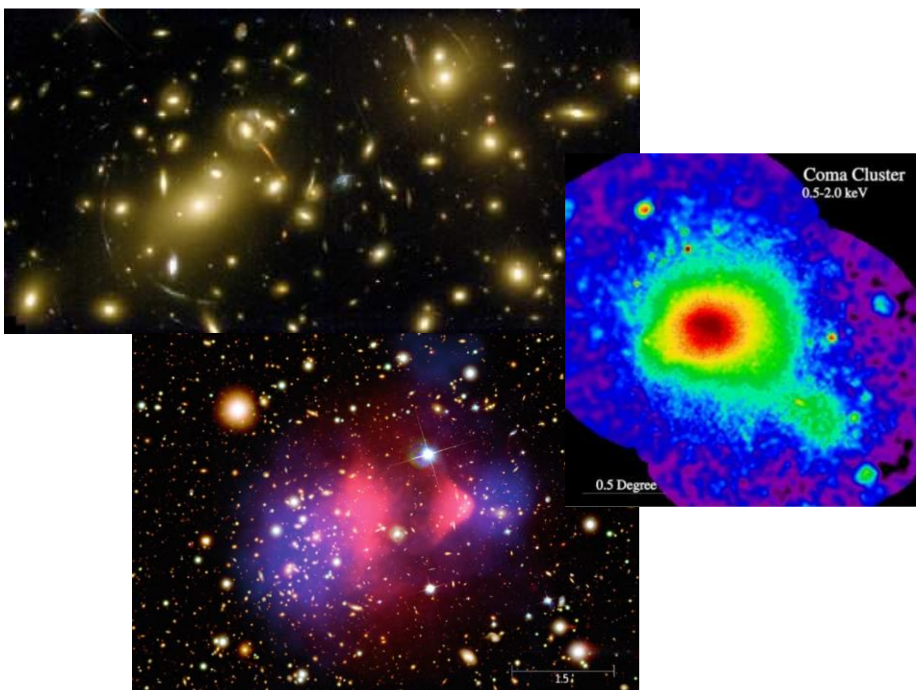
Based on arXiv: 2401.10112

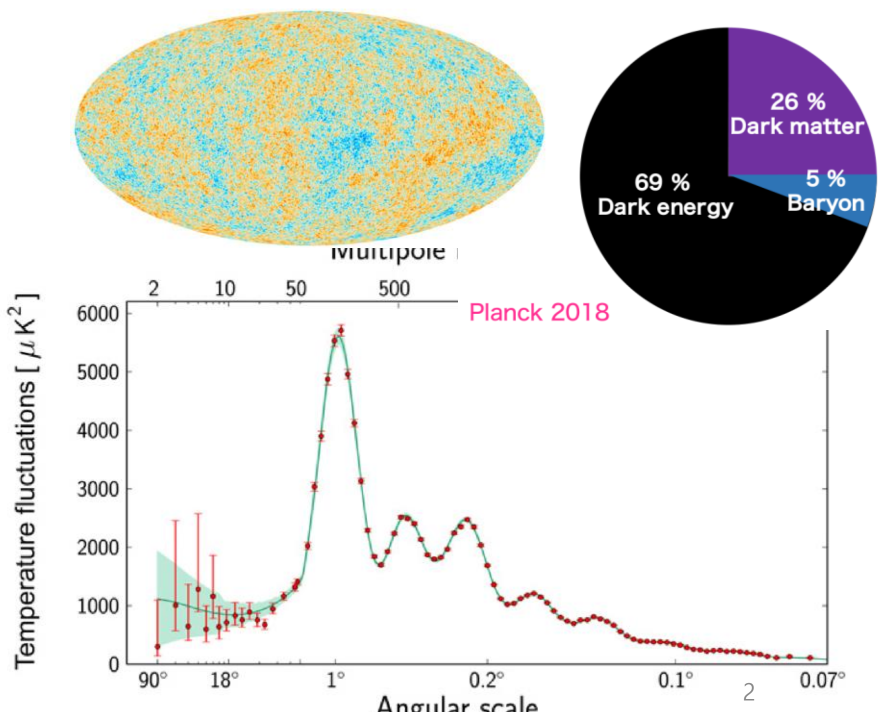
In collaboration with Shu-Yu Ho (KIAS), Pyungwon Ko (KIAS)

Evidences – Dark Matter

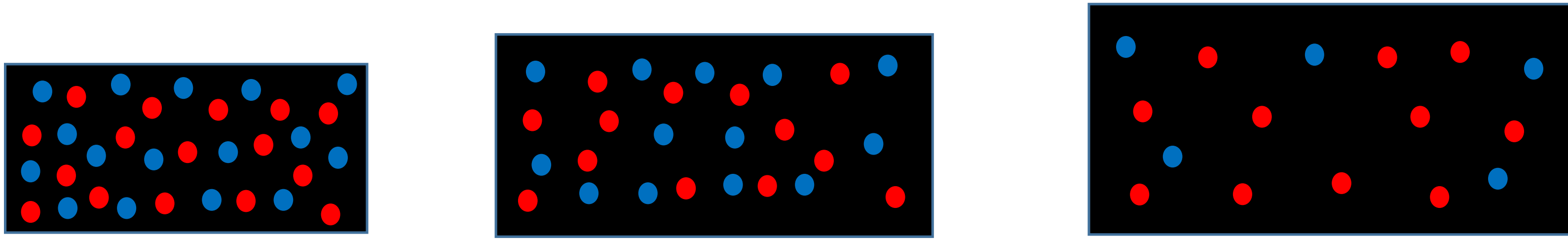
- There are undeniable evidences for dark matter in a wide range of distance scales





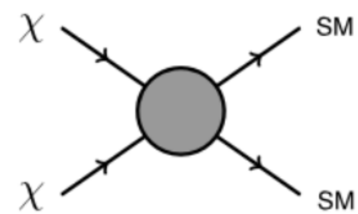


Evidences – Dark Matter

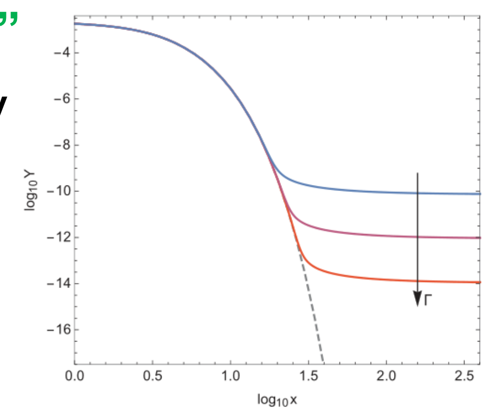


$T \gg M_{DM}$ $T \approx M_{DM}$ $T \ll M_{DM}$

- : Dark Matter
- : Standard Model



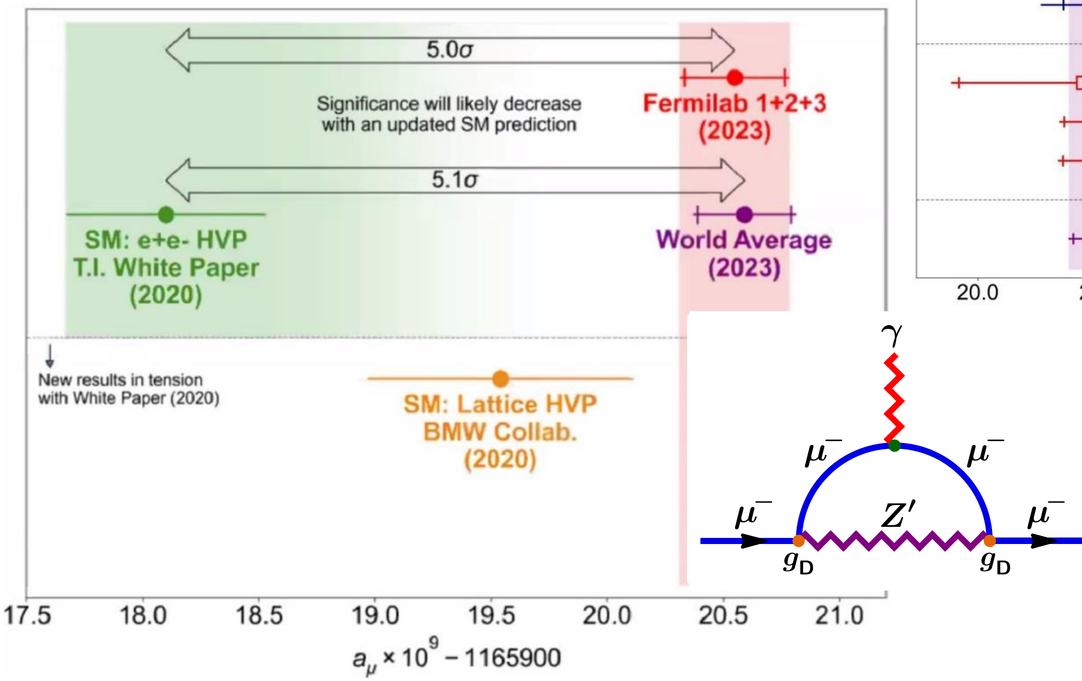
- Dark matter population in an expanding Universe
  - **Dark matter particles can no longer annihilate**
  - **The number of dark matter particles "freeze-out"**
- Standard calculation for WIMP DM relic density
  - The Boltzmann equation $\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle \left(n_\chi^2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

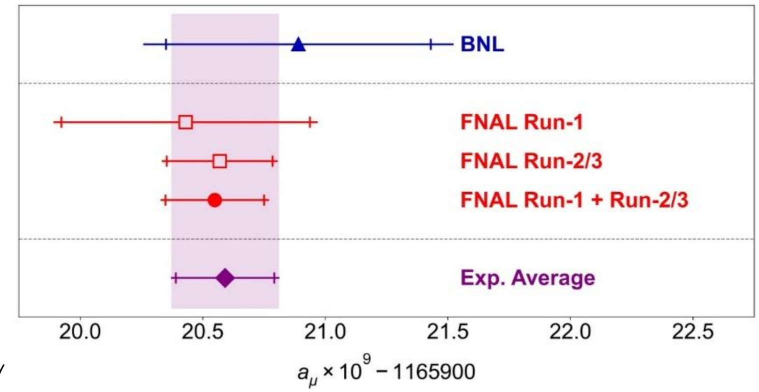


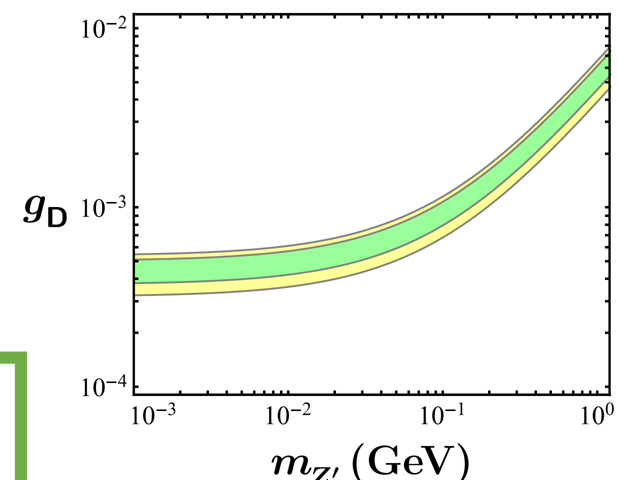
Evidences – muon g-2

Muon g-2 collaboration, PRL 2023

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







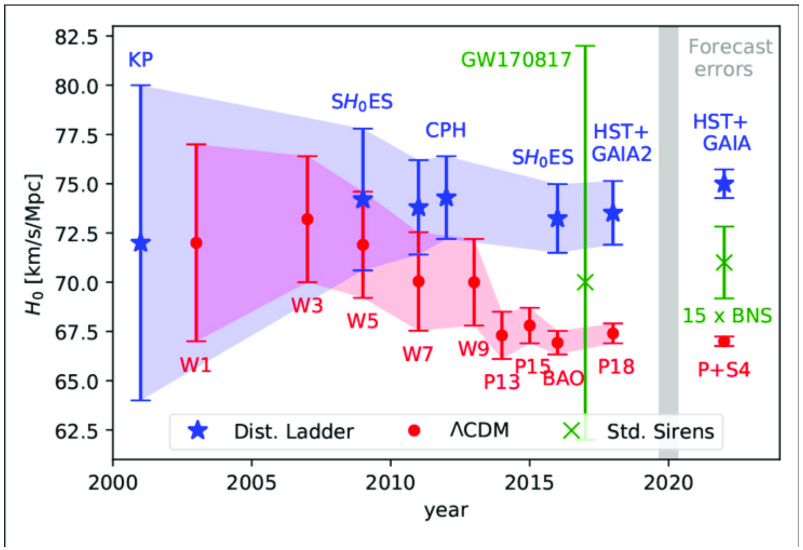
S. Baek, Deshpande, He, P. Ko, 2001
S. Beak, P. Ko, 2008
…

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

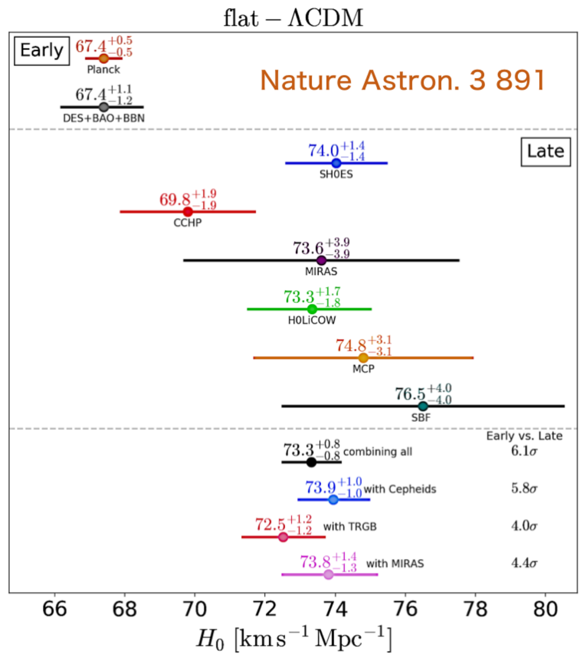
Evidences – Hubble tension

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

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

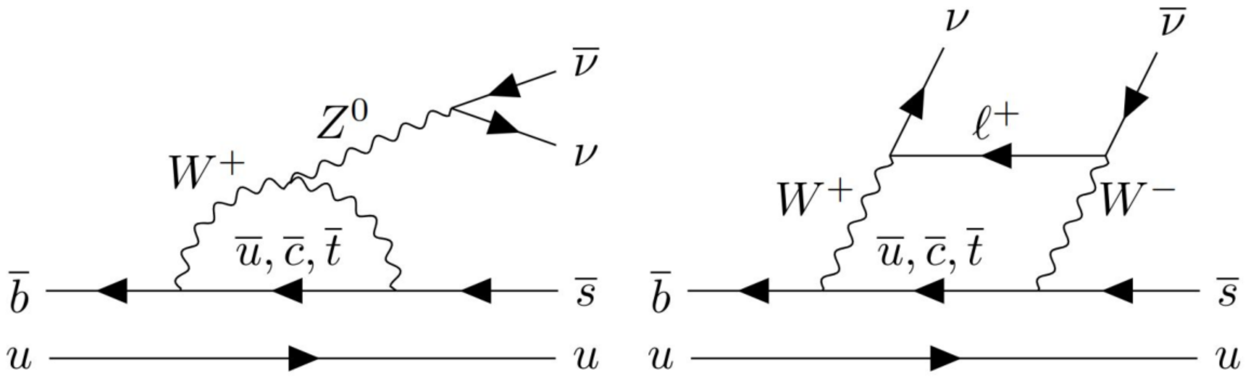


P. Shah et al, AAR 2021



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

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



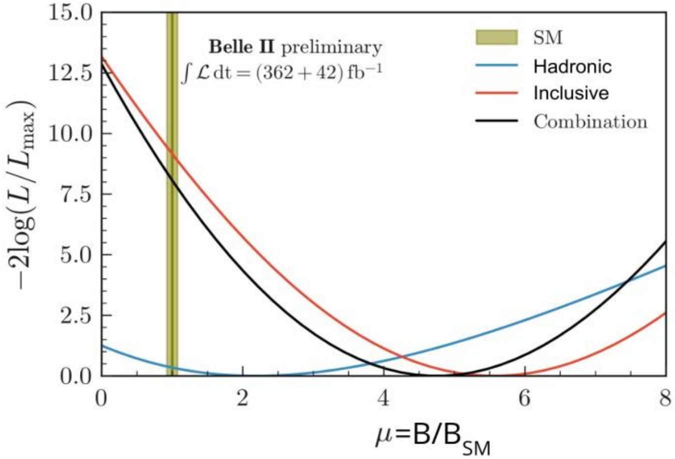
- $\mathcal{L}_{b\to s\nu\bar{\nu}} = -C_\nu \bar{s}_L \gamma^\mu b_L \bar{\nu}\gamma^\mu \nu$

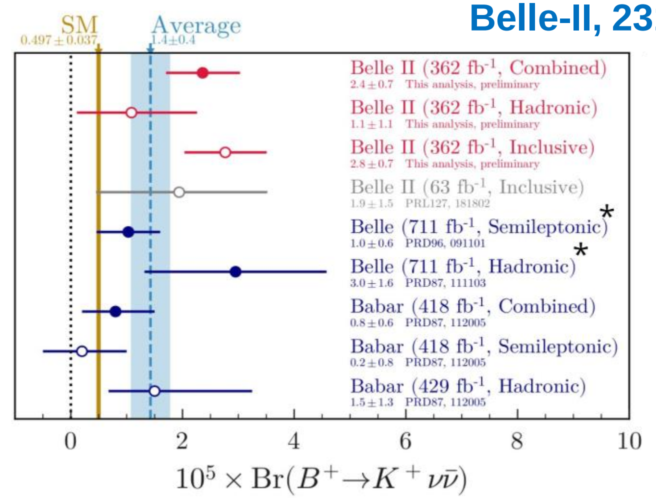
$$C_\nu = \frac{g_W^2}{M_W^2}\frac{g_W^2 V_{ts}^* V_{tb}}{16\pi^2}\left[\frac{x_t^2 + 2x_t}{8(x_t - 1)} + \frac{3x_t^2 - 6x_t}{8(x_t - 1)^2}\ln x_t\right],$$

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

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

Belle-II, 2311.14647





- $Br(B^+ \to K^+ \nu\bar{\nu})_{Exp} = (2.3 \pm 0.7) \times 10^{-5}$
  - Significance of observation is 3.6σ
  - 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

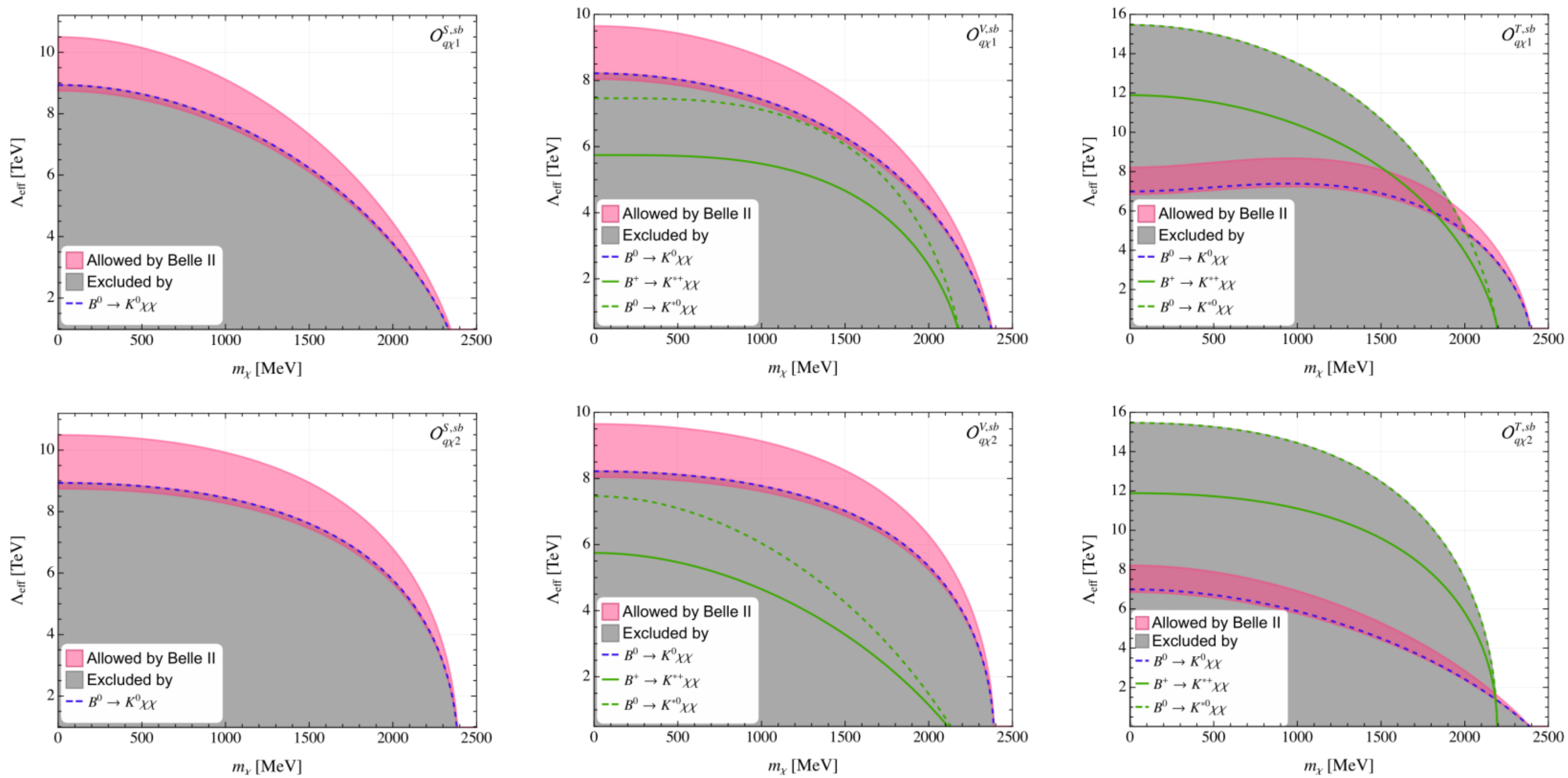
X. He et al, 2309.12741

- Interactions between DM and quarks

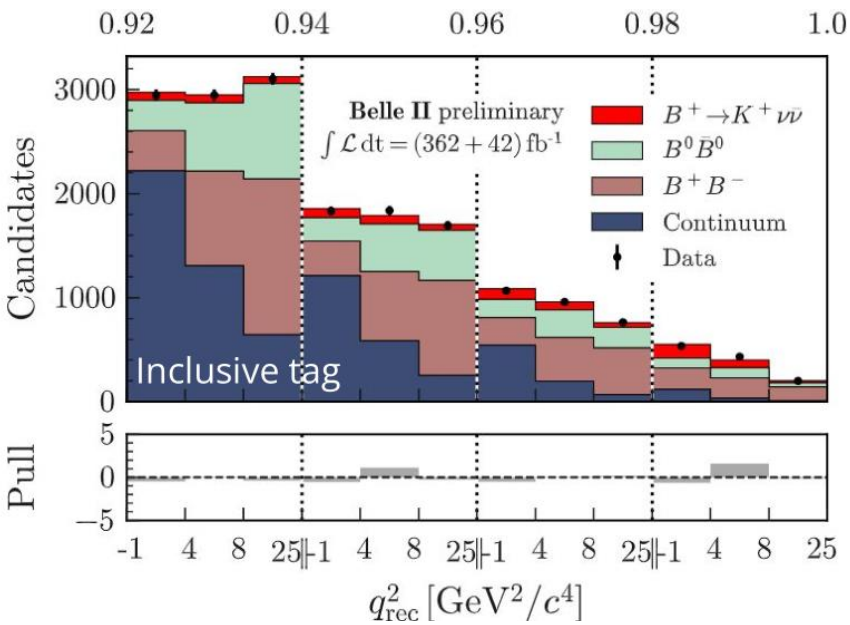
$$\mathcal{O}^{S,sb}_{q\chi1} = (\overline{s}b)(\overline{\chi}\chi), \qquad \mathcal{O}^{S,sb}_{q\chi2} = (\overline{s}b)(\overline{\chi}i\gamma_5\chi),$$

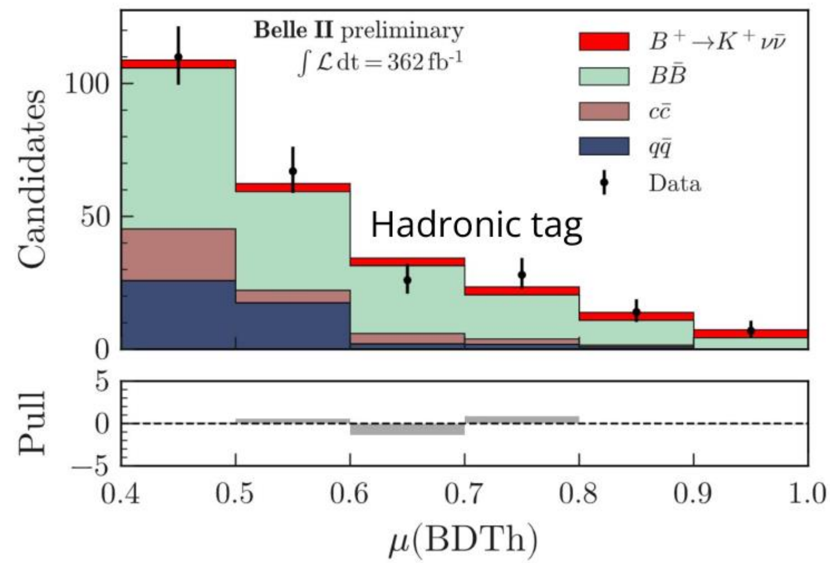
$$\mathcal{O}^{V,sb}_{q\chi1} = (\overline{s}\gamma^{\mu}b)(\overline{\chi}\gamma_{\mu}\chi), \ (\times) \qquad \mathcal{O}^{V,sb}_{q\chi2} = (\overline{s}\gamma^{\mu}b)(\overline{\chi}\gamma_{\mu}\gamma_5\chi),$$

$$\mathcal{O}^{T,sb}_{q\chi1} = (\overline{s}\sigma^{\mu\nu}b)(\overline{\chi}\sigma_{\mu\nu}\chi), \ (\times) \qquad \mathcal{O}^{T,sb}_{q\chi2} = (\overline{s}\sigma^{\mu\nu}b)(\overline{\chi}\sigma_{\mu\nu}\gamma_5\chi), \ (\times)$$



Solutions: 2-body decay





- Belle II provides information on the q^2 spectrum
  - A peak localized around $q^2 = 4\text{GeV}^2$

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

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

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

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

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

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

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

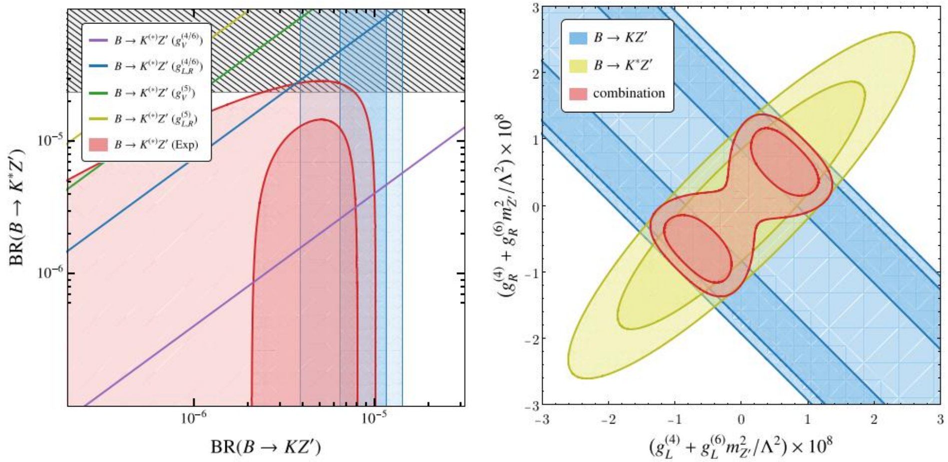


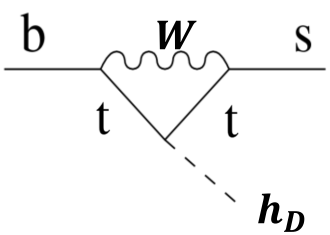
FIG. 2: *Left:* Correlations between $B \to KZ'$ and $B \to K^*Z'$ (colored lines) for the different $\bar{s}bZ'$ operators considered in this work. These are compared to the experimental data stemming from the combination of Belle-II, Babar and Belle measurements,which is represented by the red regions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

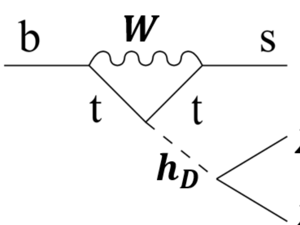
Solutions: 2- or 3-body decay

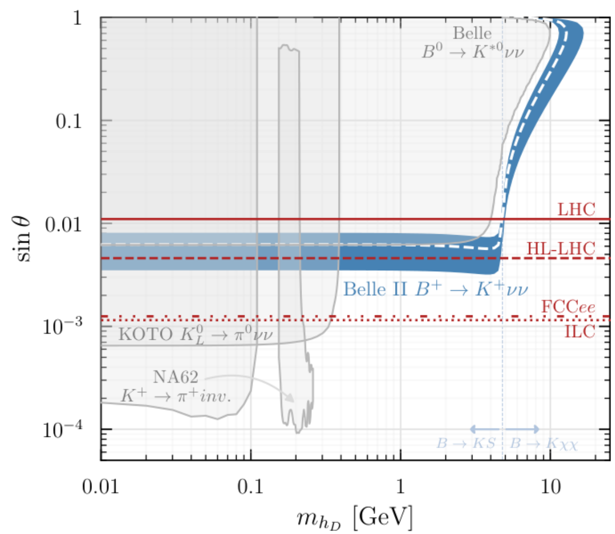
- Dark Higgs on-shell decay or three-body decay

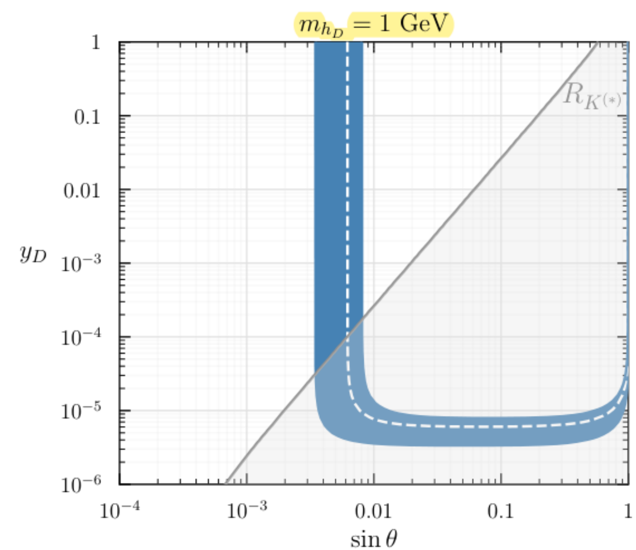
D. McKeen et al, 2312.00982

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



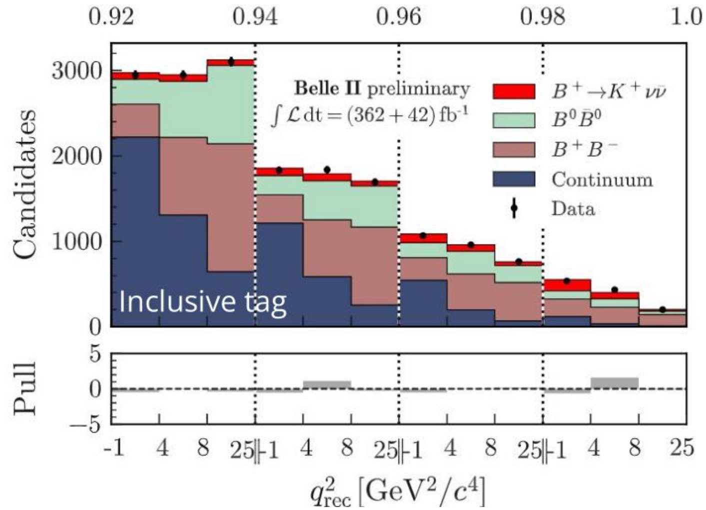


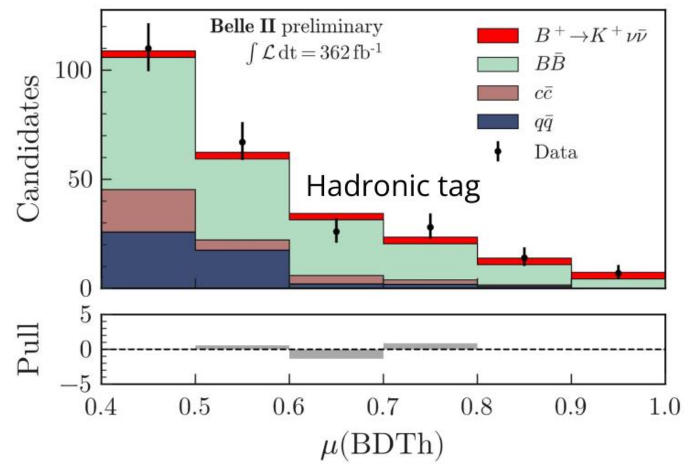




- **Extremely large relic density**
  - $\Omega h^2 \simeq 10^{20} \left(\frac{10^{-4}}{y_D}\right)^2 \left(\frac{\sin\theta}{10^{-3}}\right)^2 \left(\frac{m_\chi}{100\,\mathrm{MeV}}\right)^2 \left(\frac{1\,\mathrm{GeV}}{m_{H_1}}\right)^2$: overclose the Universe
  - Either introduce a new DM annihilation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

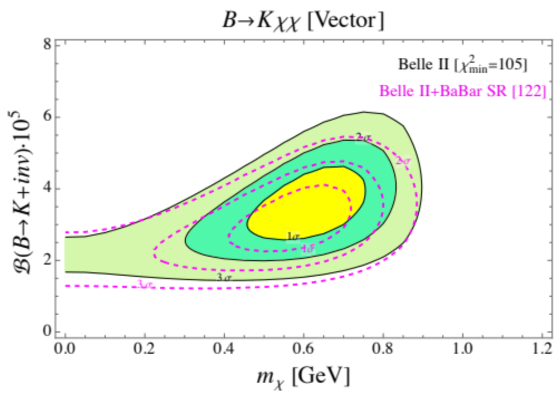
Solutions: 2- or 3-body decay

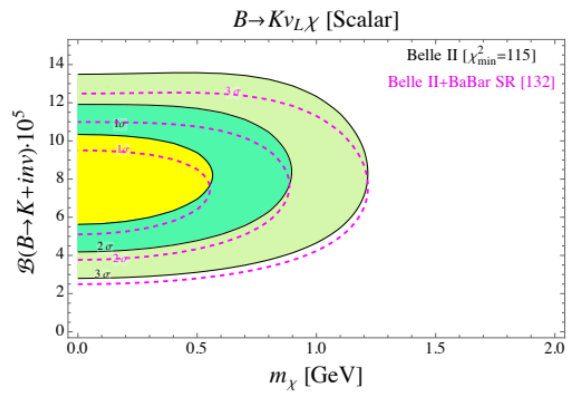




- Belle II provides information on the q^2 spectrum
  - A peak localized around $q^2 = 4\mathrm{GeV}^2$
  - ➔ Three-body decay $(B \to KXX), m_X < 0.6$ GeV

K. Fridell et al, 2312.12507

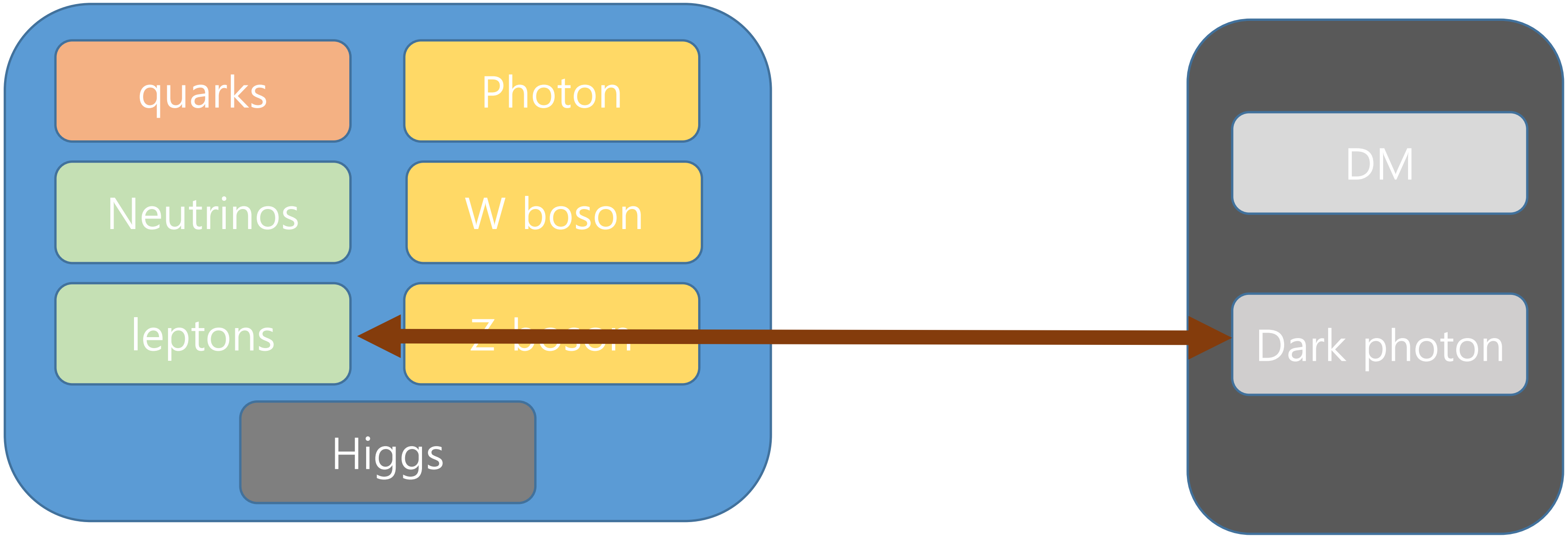




Can we find the integrated solution of Δa_μ, DM relic density, Hubble tension and $B^+ \to K^+ \nu\bar{\nu}$ at Belle II?

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

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



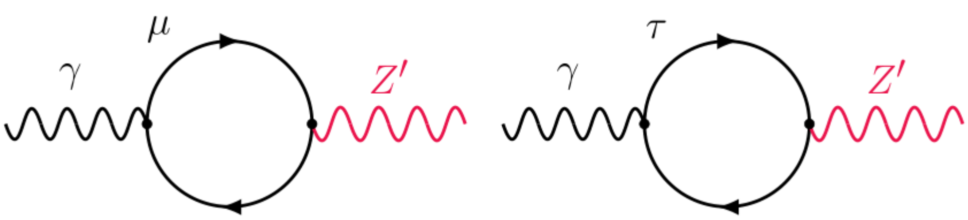
- Let's call Z', $U(1)_{L_\mu - L_\tau}$ gauge boson, dark photon since it couple to DM

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
  - 

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

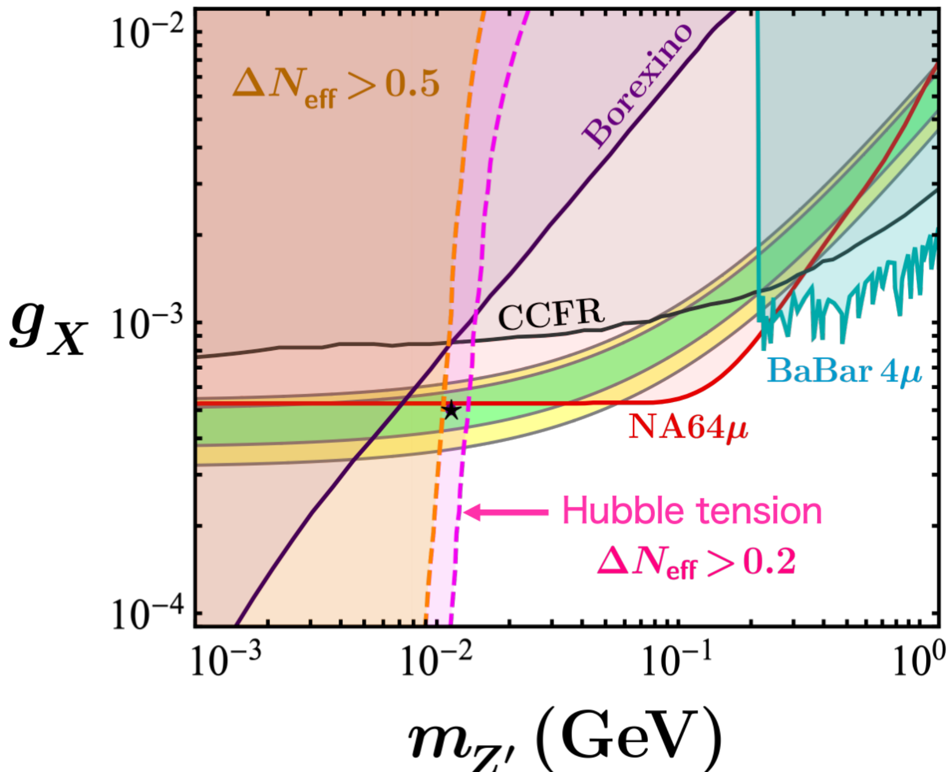
Gauged $U(1)_{L_\mu - L_\tau}$ Z' model

- ***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
  - Delay the process of neutrino decoupling
  - $0.2 < \Delta N_{\mathrm{eff}}$: substantially relaxes the tension

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

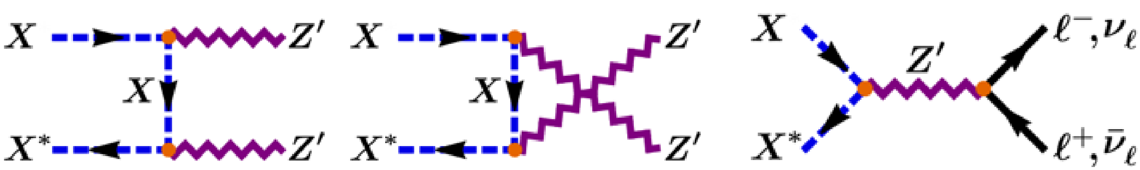


$U(1)_{L_\mu - L_\tau}$-charged DM model

- Conventional $U(1)_{L_\mu - L_\tau}$-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 by hand or Stueckelberg mechanism



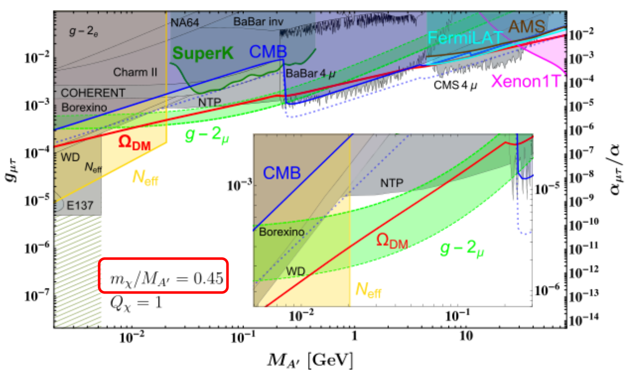
Only when $m_X > m_{Z'}$

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

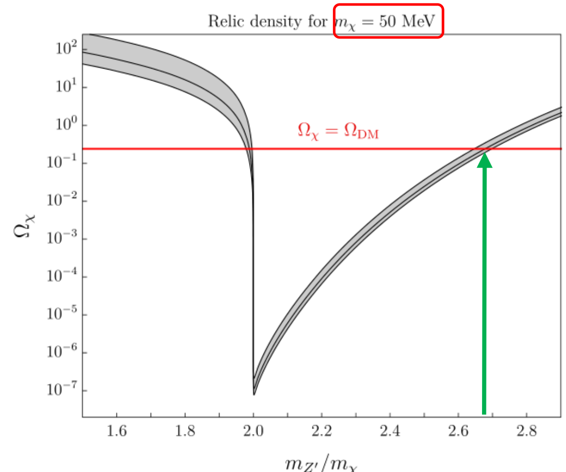
$U(1)_{L_\mu - L_\tau}$-charged DM model

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

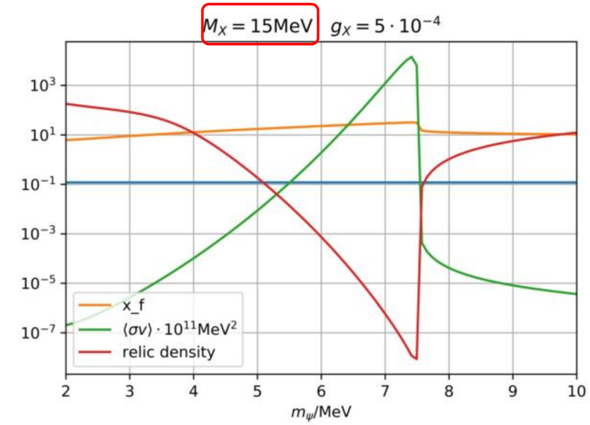
P. Foldenauer, PRD 2019



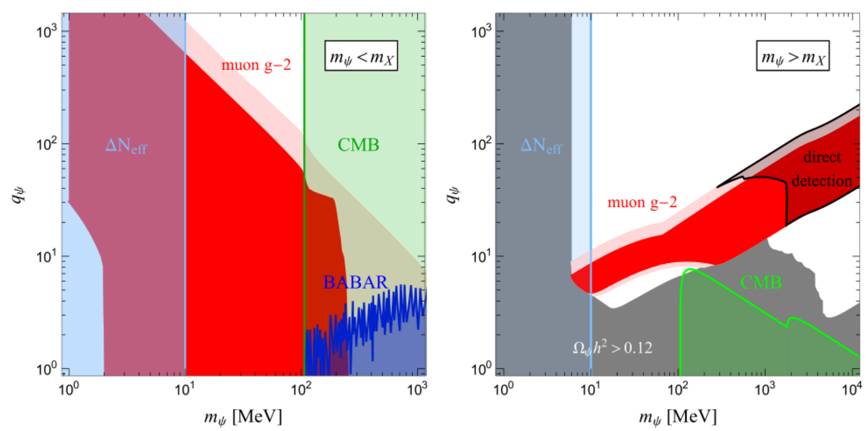
I. Holst, D. Hooper, G. Krnjaic, PRL 2022

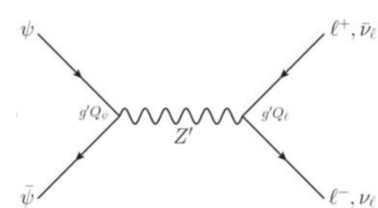


M. Drees, W. Zhao, PLB 2022



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





-29)

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

- $g_X \sim 10^{-4}$ is too small to get $\Omega h^2 = 0.12$
- $m_{Z'} \sim 2m_X$ with the s-channel Z' resonance
- Dark Photon mass is generated by Stueckelberg mechanism
- Only sub-GeV **DM** available
- No direct detection bound
- BelleII excess → $B \to KZ'$ (2body decay. Disfavored by q^2 spectrum)

$,\nu_\ell$

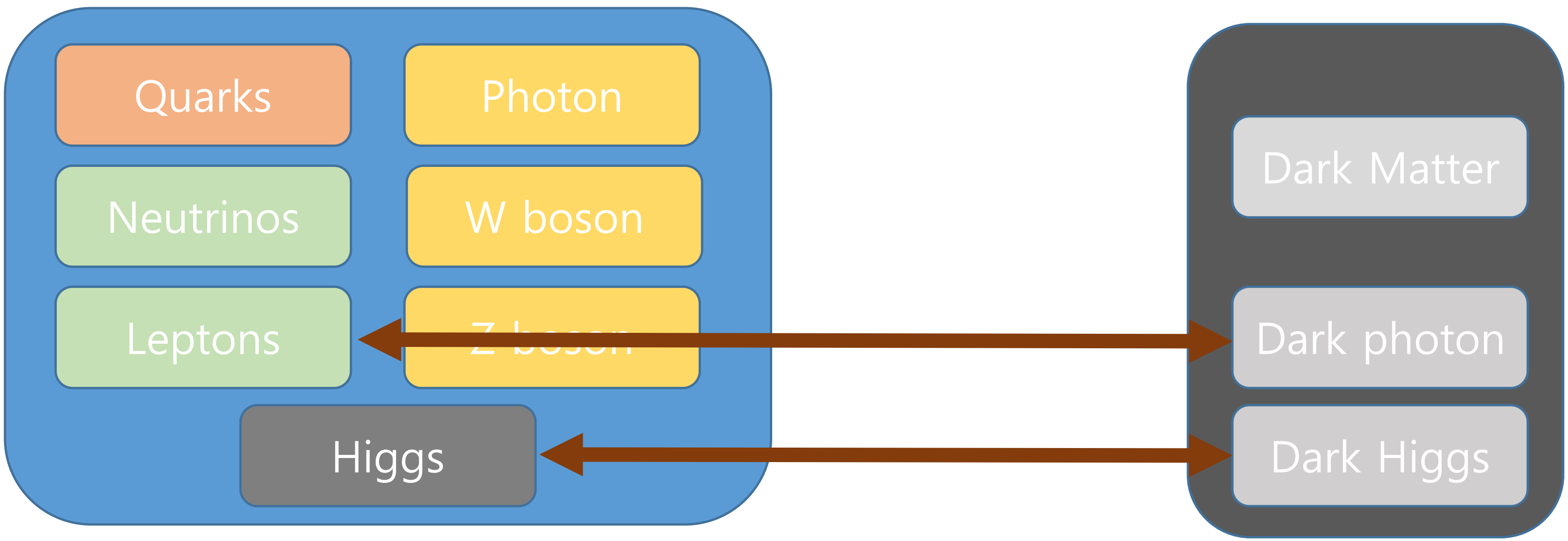
$,\bar{\nu}_\ell$

Tight correlation between DM mass and Z' mass

$$m_{Z'} \sim 2m_X$$

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

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

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

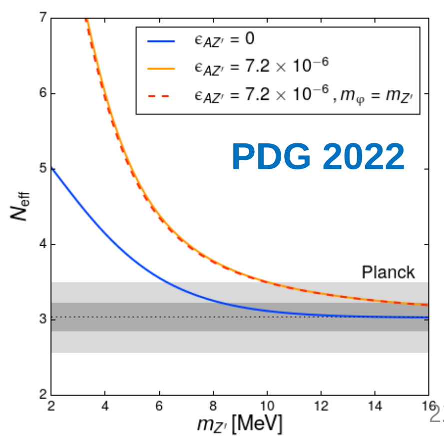
- Additional interactions with the dark Higgs

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

- **The SM-like Higgs invisible decay**
  - $\boldsymbol{H_2 \to H_1 H_1, Z' Z', X X^\dagger}$
  - 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



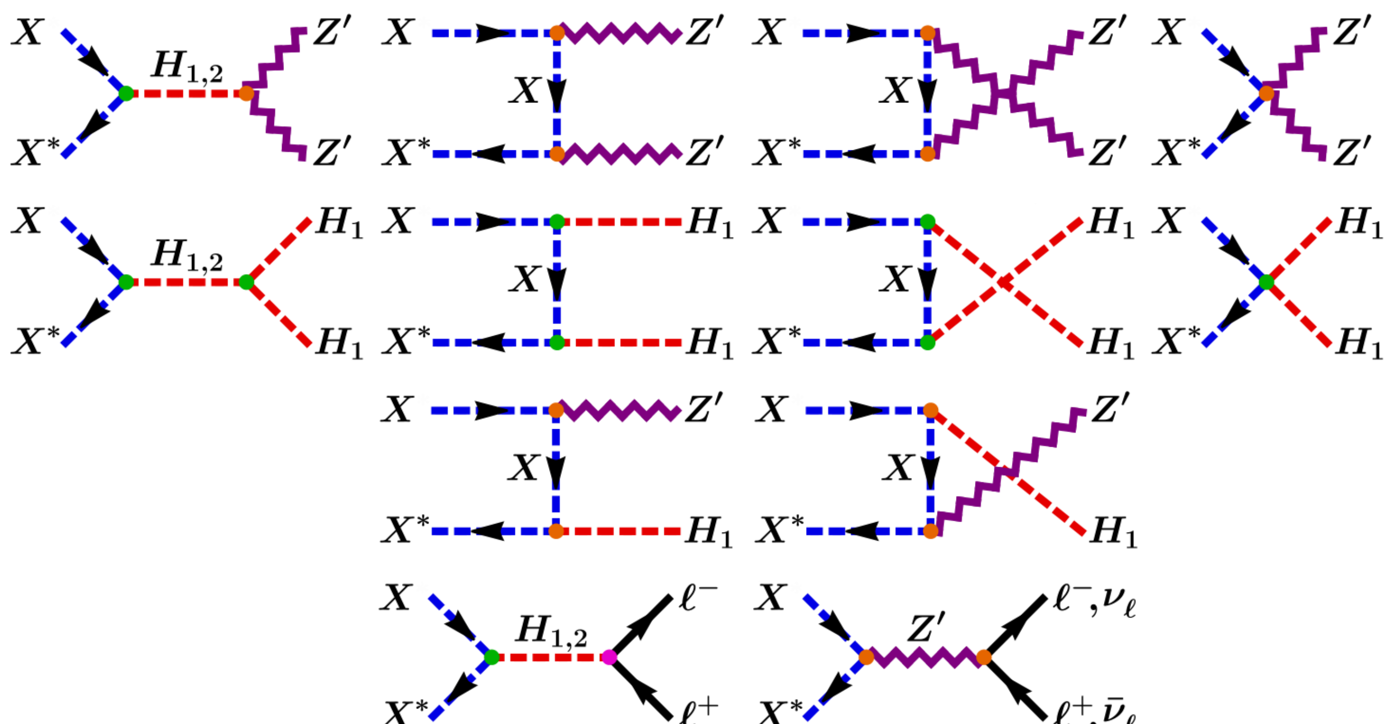
$U(1)_{L_\mu - L_\tau}$-charged DM + Dark Higgs

Baek, **JK**, Ko, 2204.04889

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

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

- Free parameters: $\{m_{Z'}, g_X, \sin\theta, m_X, m_{H_1}, Q_\Phi, \lambda_{\Phi X}\}$



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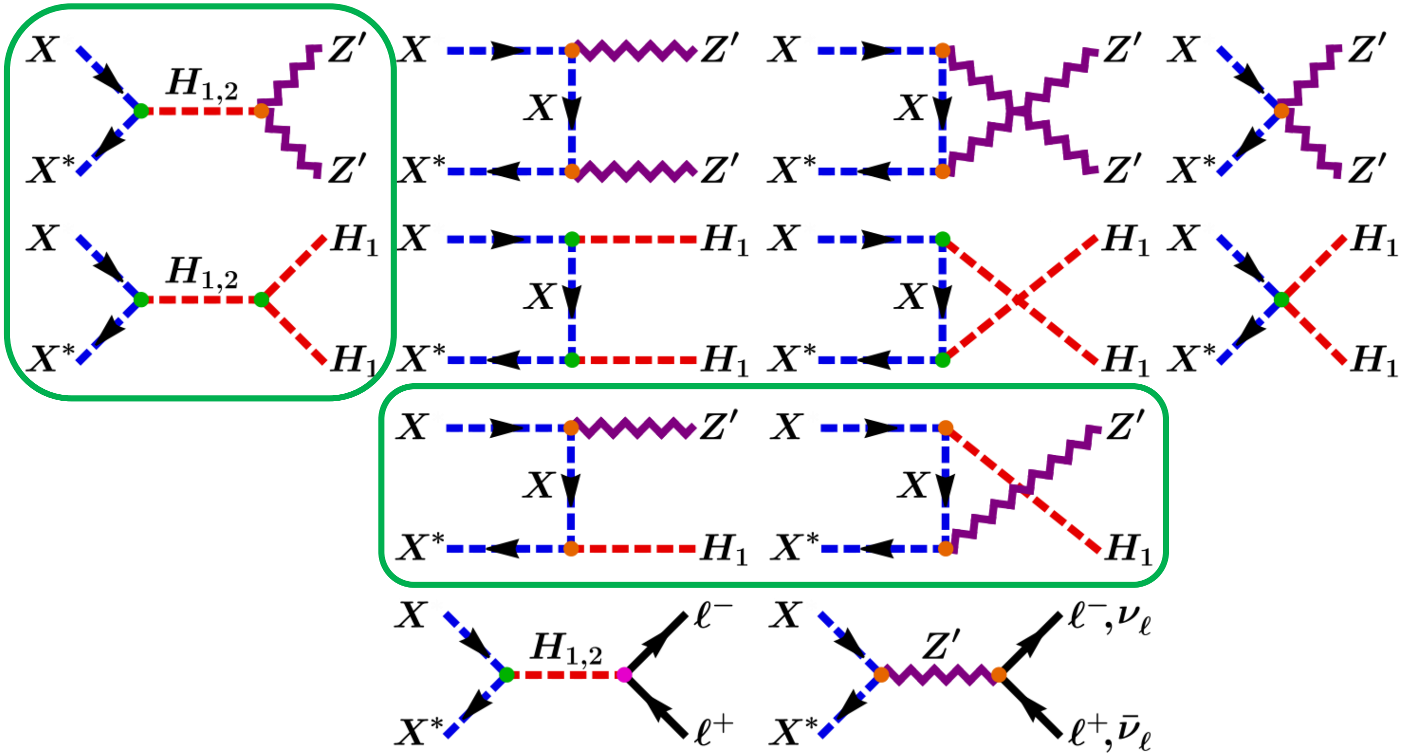


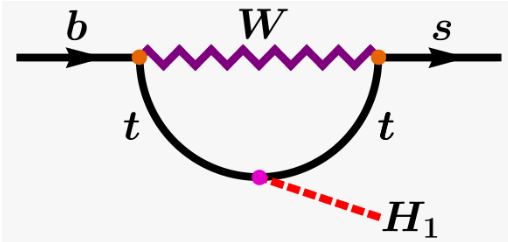
BelleII excess: 2-body decay

- 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

$\sin\theta \ll 1$

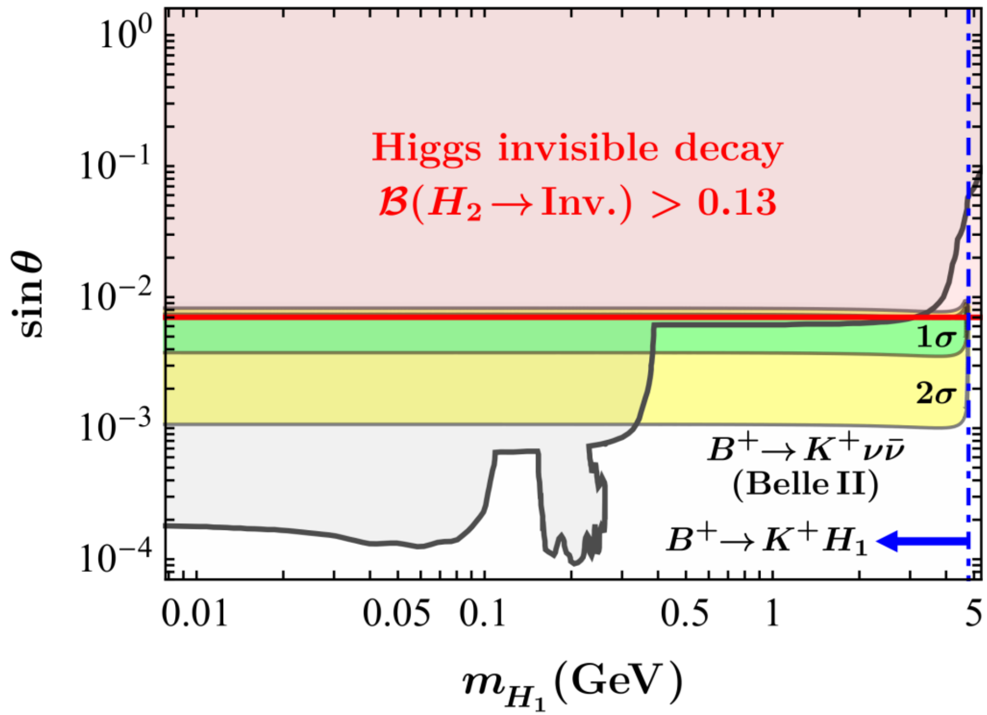


- H_1 decay process
  - $H_1 \to XX^\dagger, Z'Z', f\bar{f}$

- Allowed value
  - $10^{-3} \leq \sin\theta \leq 7\times 10^{-3}$

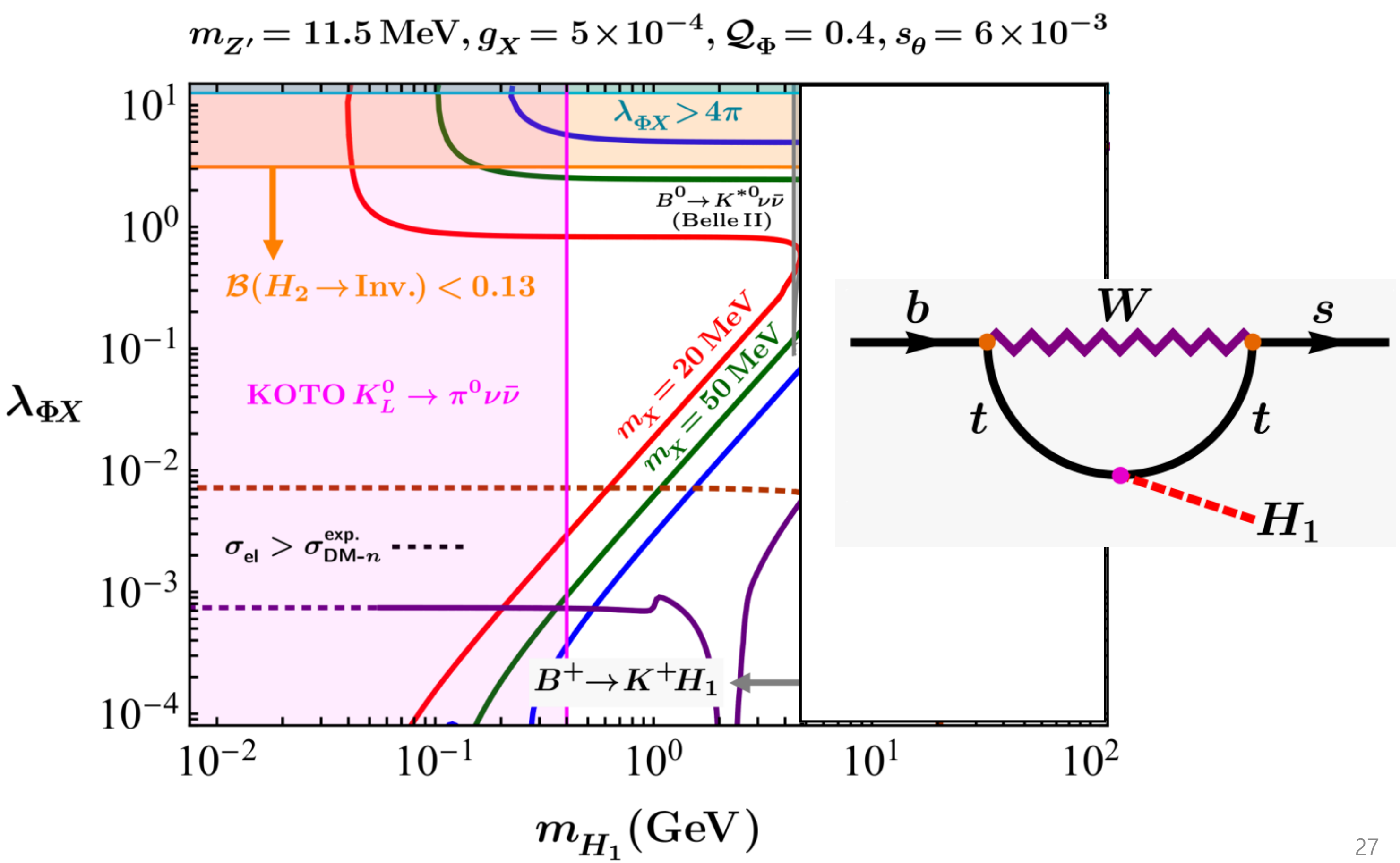
- Our numerical input:
  - $\sin\theta = 6\times 10^{-3}$

$m_{Z'} = 11.5\,\mathrm{MeV},\ g_X = 5\times 10^{-4},\ \mathcal{Q}_\Phi = 0.4$



BelleII excess : 2-body decay

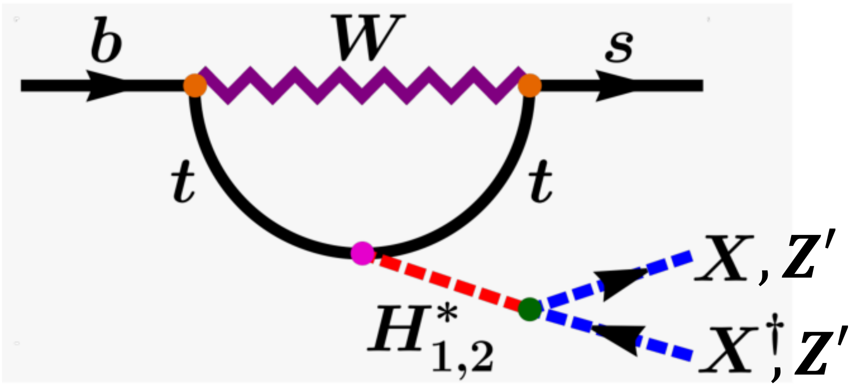
- When $m_{H_1} < m_B - m_K$, H_1 is on-shell
  - Two-body decay: $m_X \lesssim 10$ GeV $(m_{H_1} < m_B - m_K)$



BelleII excess : 3-body decay

- When $m_{H_1} > m_B - m_K > 2m_X$, H_1 is off-shell → three-body decay

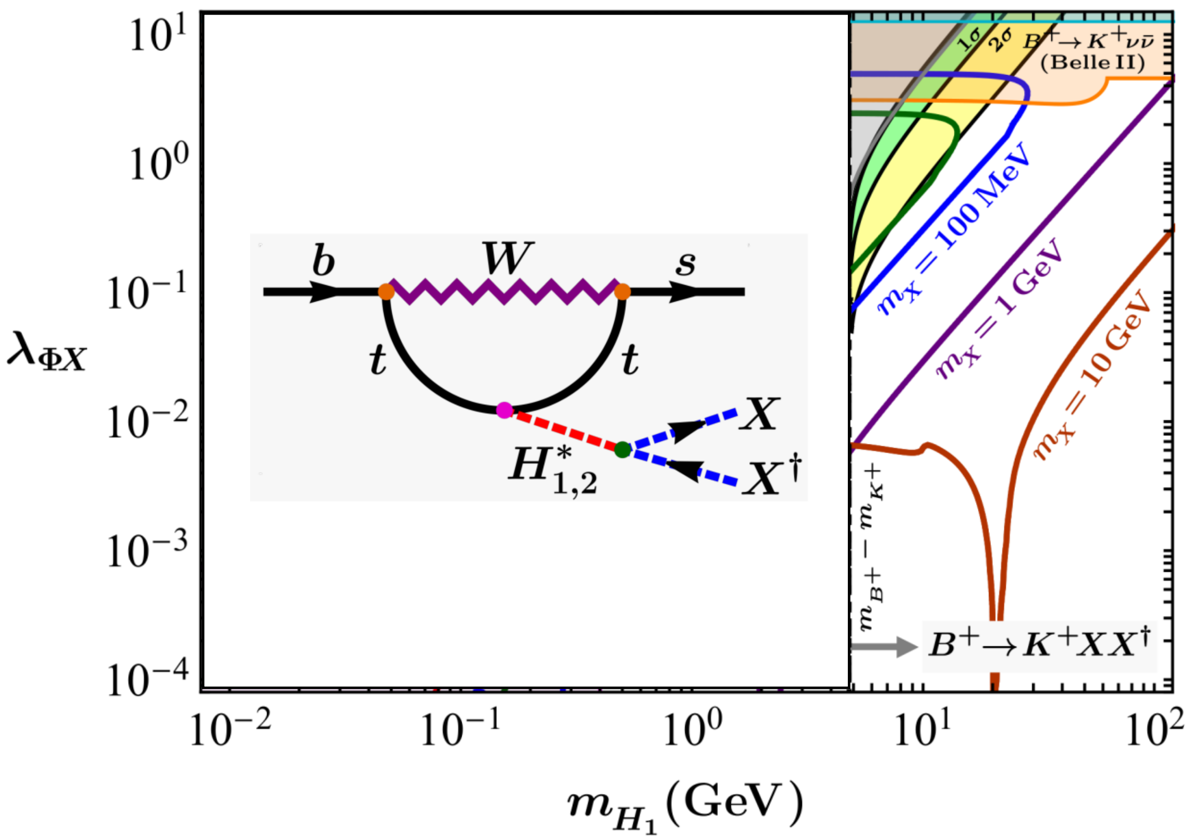
$$\Gamma_{B^+\to K^+XX^\dagger} \simeq \frac{\lambda_{\Phi X}^2 v_\Phi^2 |\kappa_{cb}|^2 \sin^2\theta}{1024\pi^3 m_{B^+}^3} \left(\frac{m_{B^+}^2 - m_{K^+}^2}{m_b - m_s}\right)^2 (m_{H_1}^2 - m_{H_2}^2)^2$$
$$\times \int_{4m_X^2}^{(m_{B^+}-m_{K^+})^2} \mathrm{d}q^2 \, \frac{\sqrt{1 - 4m_X^2/q^2}\sqrt{\mathcal{K}(m_{B^+}^2,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



BelleII excess : 3-body decay

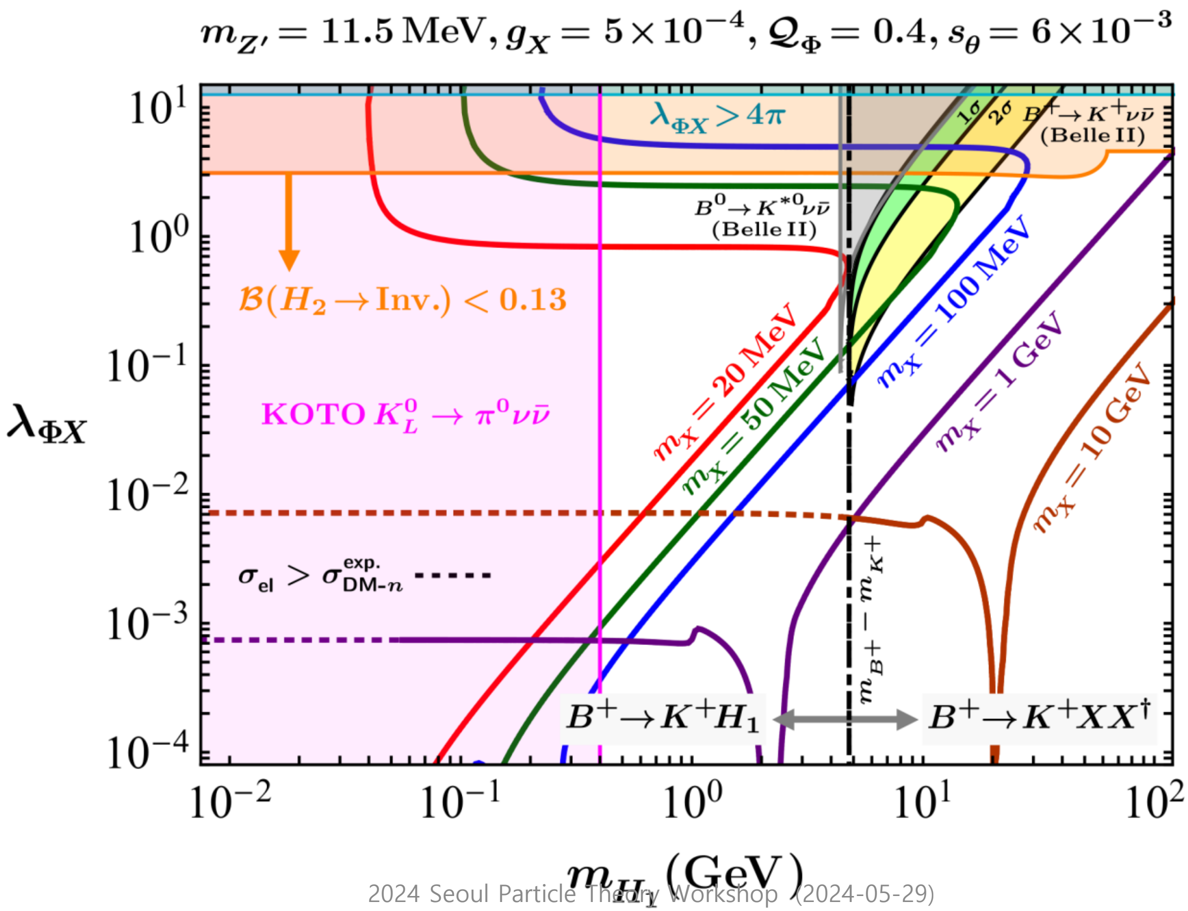
- When $m_{H_1} > m_B - m_K$, H_1 is off-shell → three-body decay
  - Three-body decay: $20\text{MeV} < m_X \lesssim 60\text{MeV}\ (m_{H_1} > m_B - m_K)$

$m_{Z'} = 11.5\,\text{MeV}, g_X = 5\times 10^{-4}, \mathcal{Q}_\Phi = 0.4, s_\theta = 6\times 10^{-3}$



BelleII excess : 2- or 3-body decay

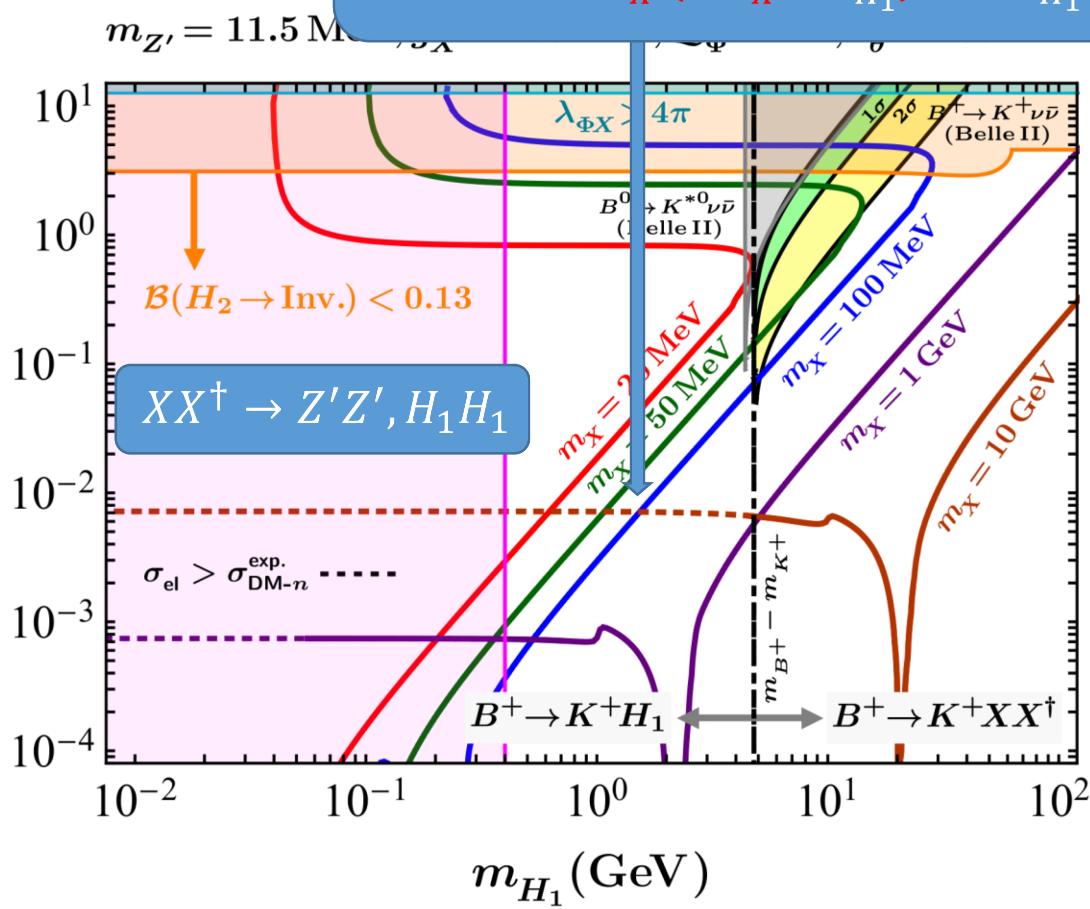
- When $m_{H_1} > (<)\ m_B - m_K$, H_1 is off(on)-shell → 3(2)-body decay
  - Two-body decay: $m_X \lesssim 10\ \mathrm{GeV}\ (m_{H_1} < m_B - m_K)$
  - Three-body decay: $20\mathrm{MeV} < m_X \lesssim 60\mathrm{MeV}\ (m_{H_1} > m_B - m_K)$



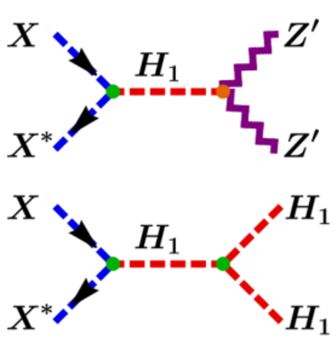
BelleII excess : 2- or 3-body decay

- When $m_{H_1} > (<)\ m_B - m_K$, H_1 is off(on)-shell → 3(2)-body decay
  - Two-body decay: m_X
  - Three-body decay: 20

$$\sigma v \simeq \frac{\lambda_{\Phi X}^2}{16\pi m_X^2}\frac{4m_X^4 - 4m_X^2 m_{Z'}^2 + 3m_{Z'}^4}{(4m_X^2 - m_{H_1}^2)^2 + m_{H_1}^2\Gamma_{H_1}^2}\sqrt{1-\frac{m_{Z'}^2}{m_X^2}}$$



$XX^\dagger \to Z'Z', H_1H_1$

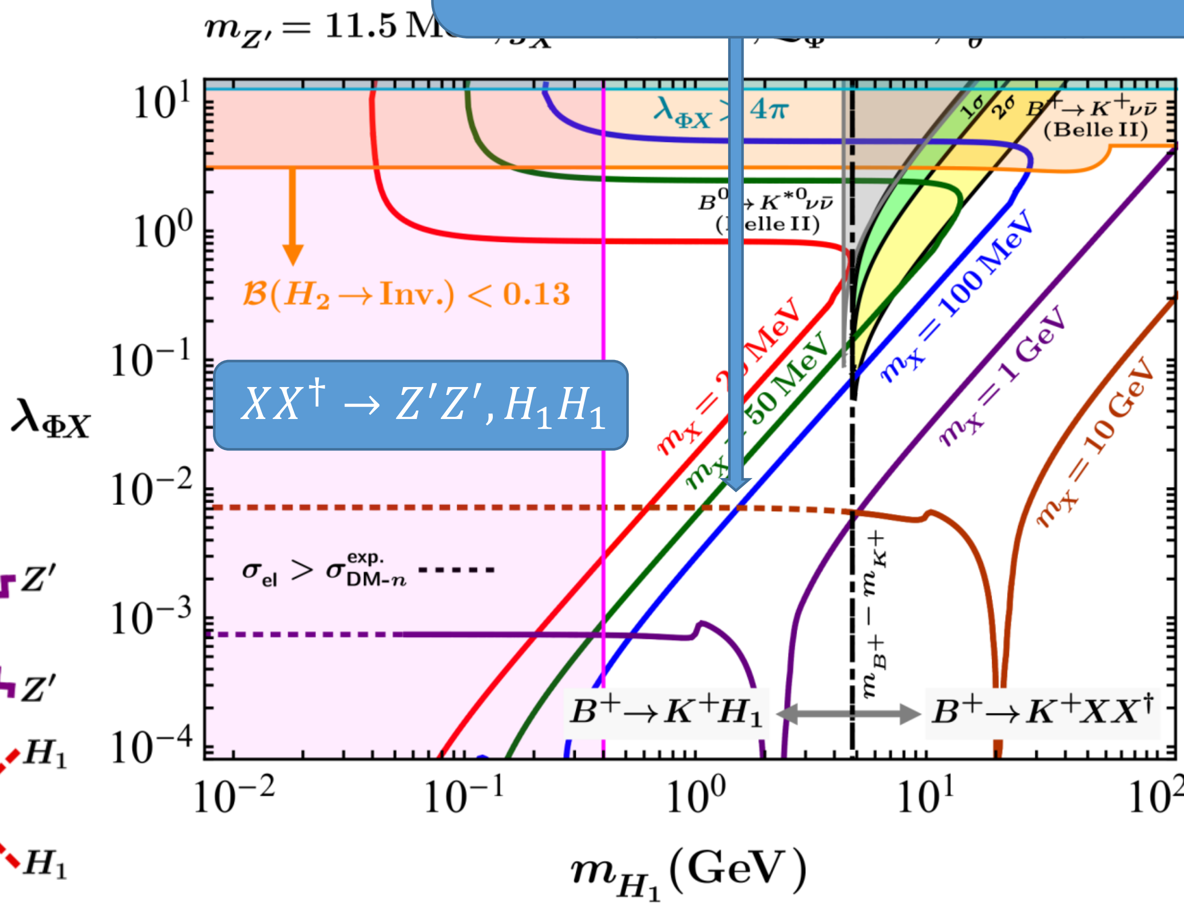


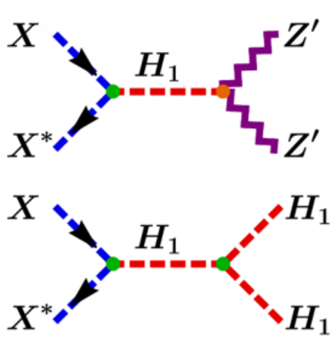
BelleII excess : 2- or 3-body decay

- When $m_{H_1} > (<)\ m_B - m_K$, H_1 is off(on)-shell → 3(2)-body decay
  - Two-body decay: m_X ...
  - Three-body decay: 20...

$$\sigma v \propto \frac{\lambda_{\Phi X}^2}{m_X^2} \Longrightarrow \lambda_{\Phi X} \simeq const.$$

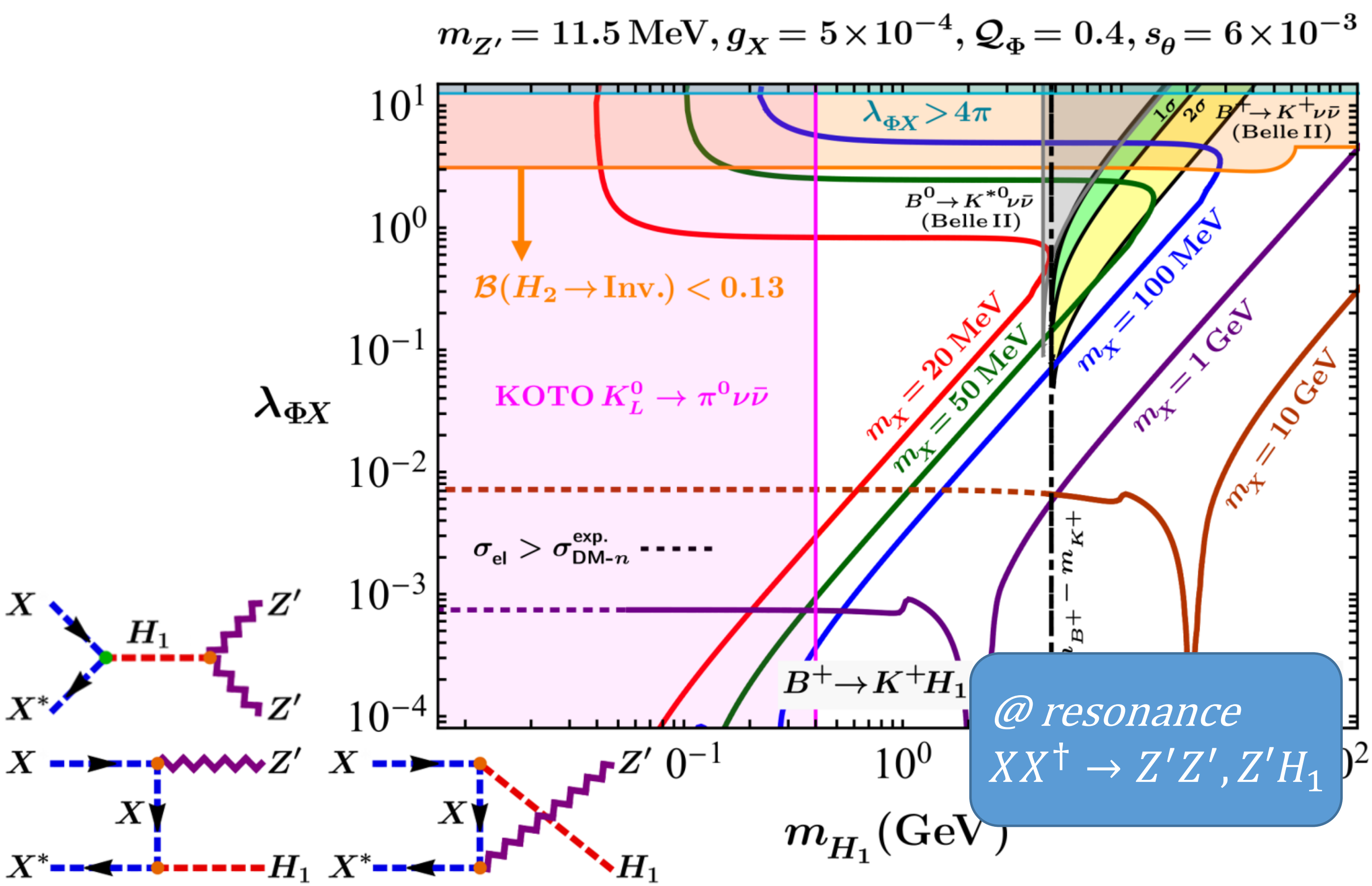
$XX^\dagger \to Z'Z', H_1 H_1$





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

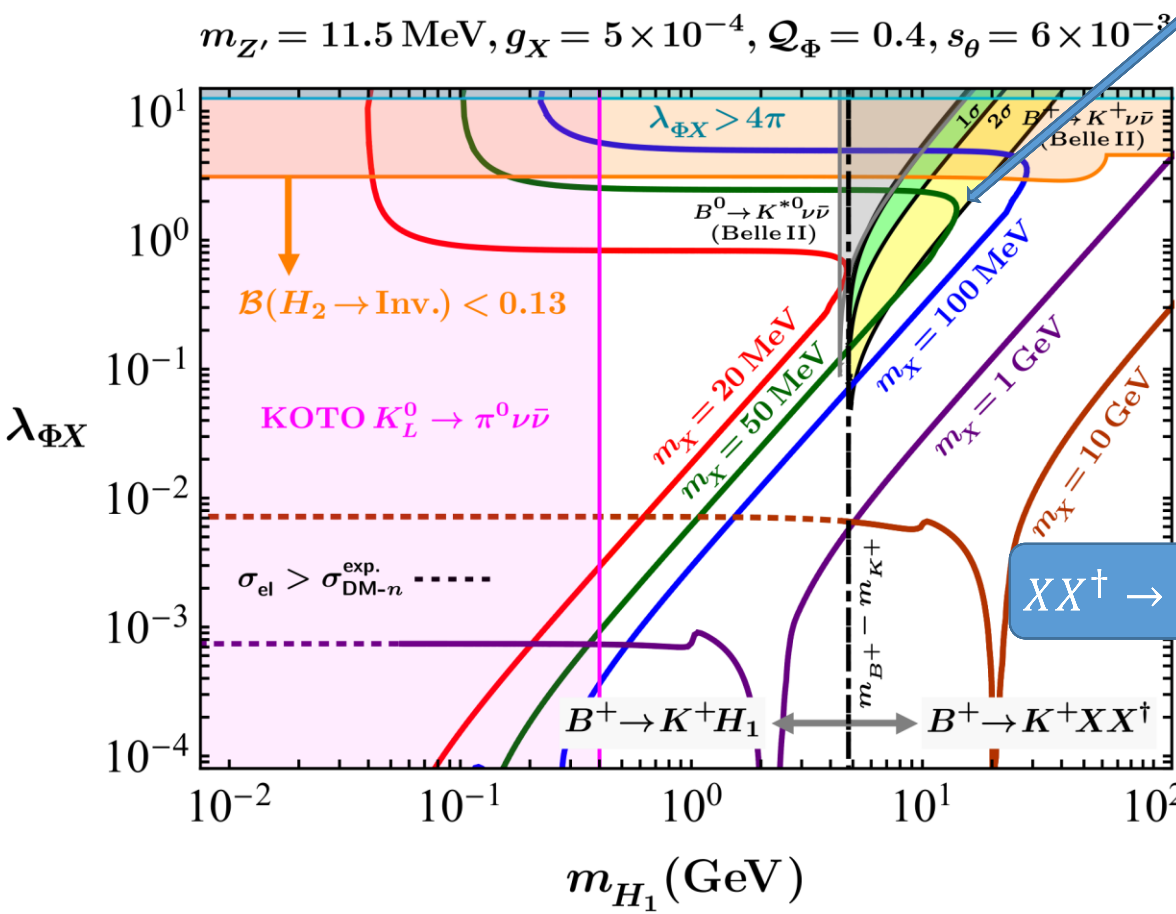


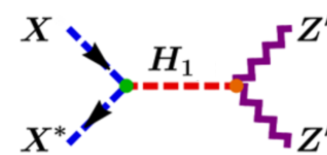
@ resonance
$XX^\dagger \to Z'Z', Z'H_1$

BelleII excess : 2- or 3-body decay

- When $m_{H_1} > (<)\ m_B - m$
  - Two-body decay: $m_X \lesssim 1$
  - Three-body decay: $20\mathrm{MeV}$

$$\sigma v \simeq \frac{\lambda_{\Phi X}^2}{16\pi m_X^2} \frac{4m_X^4 - 4m_X^2 m_{Z'}^2 + 3m_{Z'}^4}{(4m_X^2 - m_{H_1}^2)^2 + m_{H_1}^2 \Gamma_{H_1}^2} \sqrt{1 - \frac{m_{Z'}^2}{m_X^2}}$$



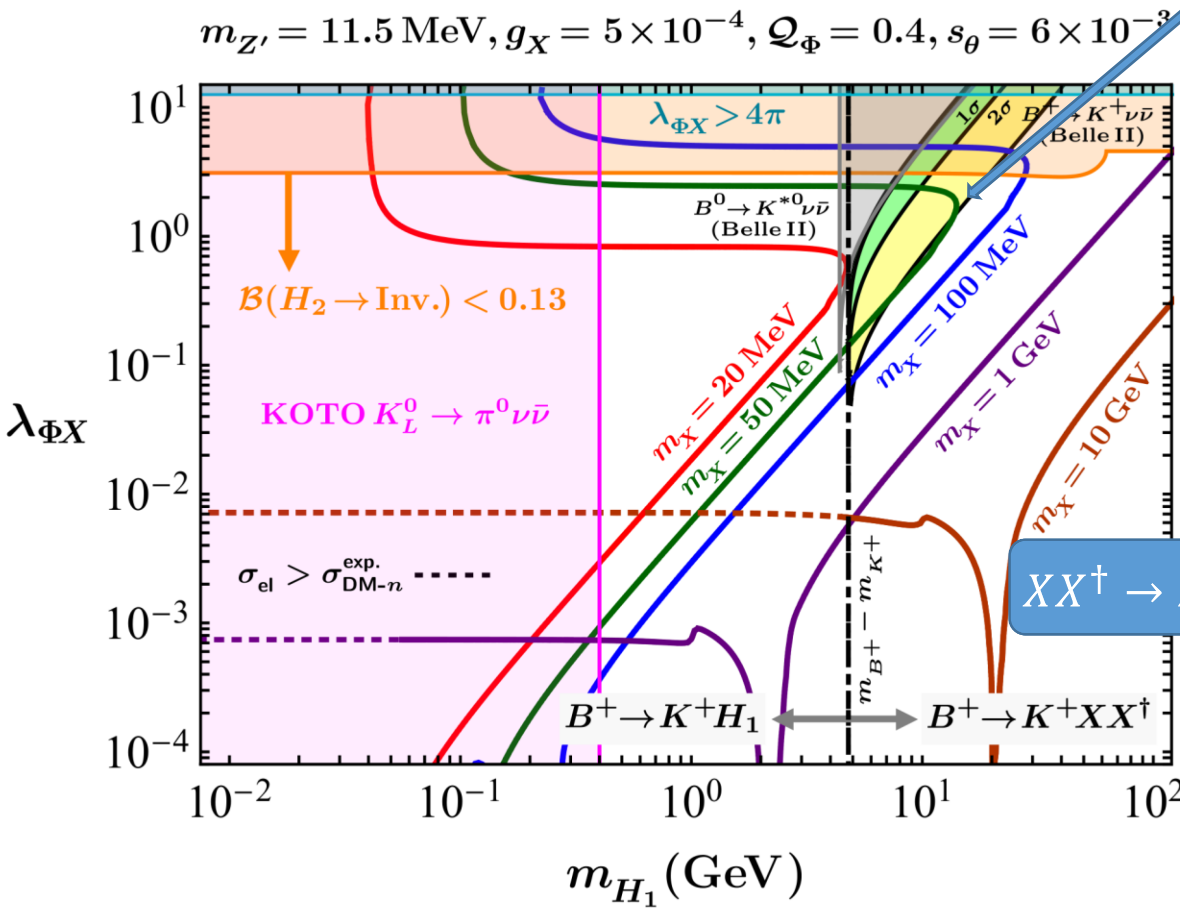


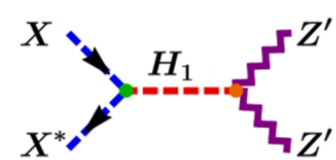
$XX^\dagger \to Z'Z'$

BelleII excess : 2- or 3-body decay

- When $m_{H_1} > (<)\ m_B - m$
  - Two-body decay: $m_X \lesssim 1$
  - Three-body decay: $20\mathrm{Me}$

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





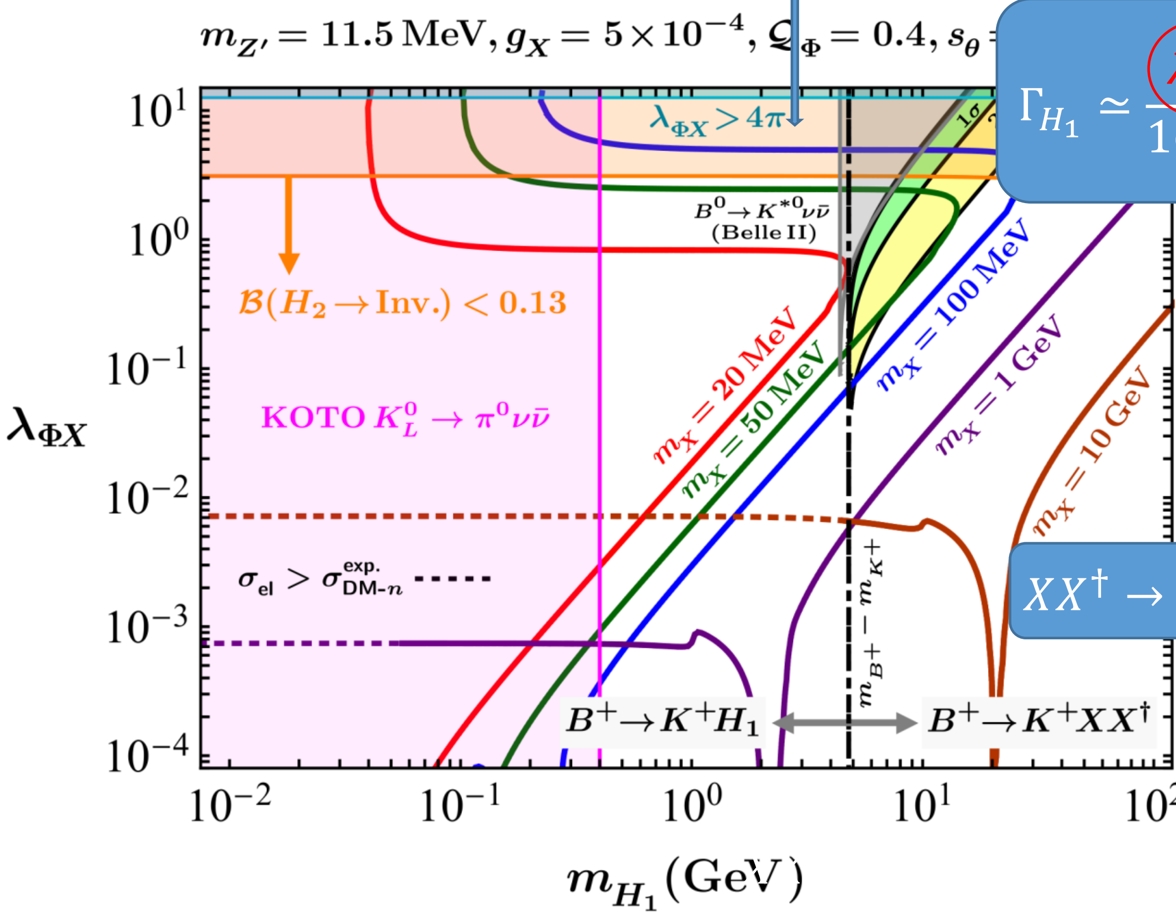
$XX^\dagger \to Z'Z'$

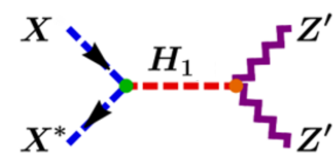
BelleII excess : 2- or 3-body decay

- When $m_{H_1} > (<)\ m_B - m$
  - Two-body decay: $m_X \lesssim 1$
  - Three-body decay: 20Me

$$\sigma v \simeq \frac{\lambda_{\Phi X}^2}{16\pi m_X^2}\frac{4m_X^4 - 4m_X^2 m_{Z'}^2 + 3m_{Z'}^4}{(4m_X^2 - m_{H_1}^2)^2 + m_{H_1}^2\Gamma_{H_1}^2}\sqrt{1-\frac{m_{Z'}^2}{m_X^2}}$$

$$\Gamma_{H_1} \simeq \frac{\lambda_{\Phi X}^2 v_\Phi^2}{16\pi\, m_{H_1}}\sqrt{1-\frac{4m_X^2}{m_{H_1}^2}}$$





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- When $m_{H_1} > (<)\ m_B - m$
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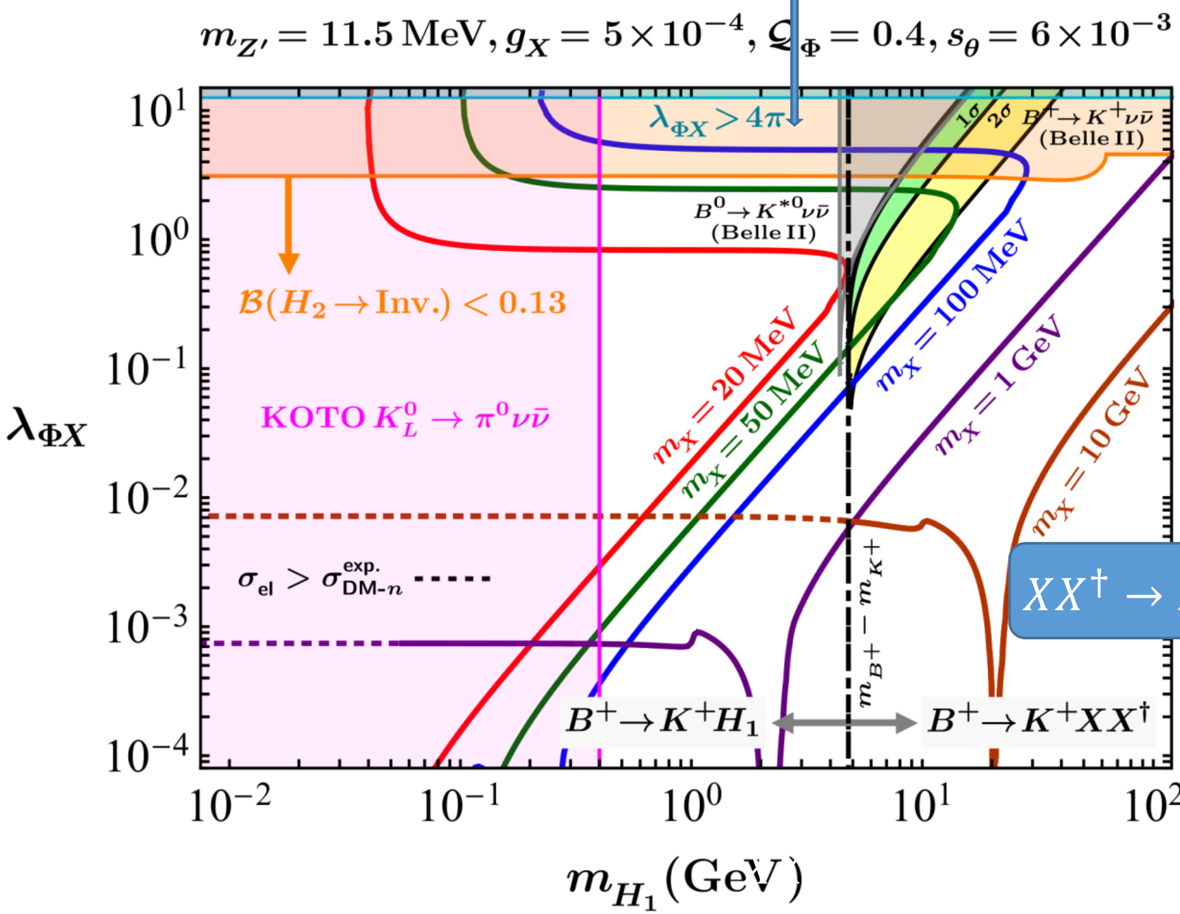
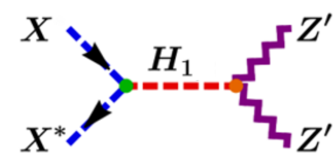




$XX^\dagger \to Z'Z'$

BelleII excess : 2- or 3-body decay

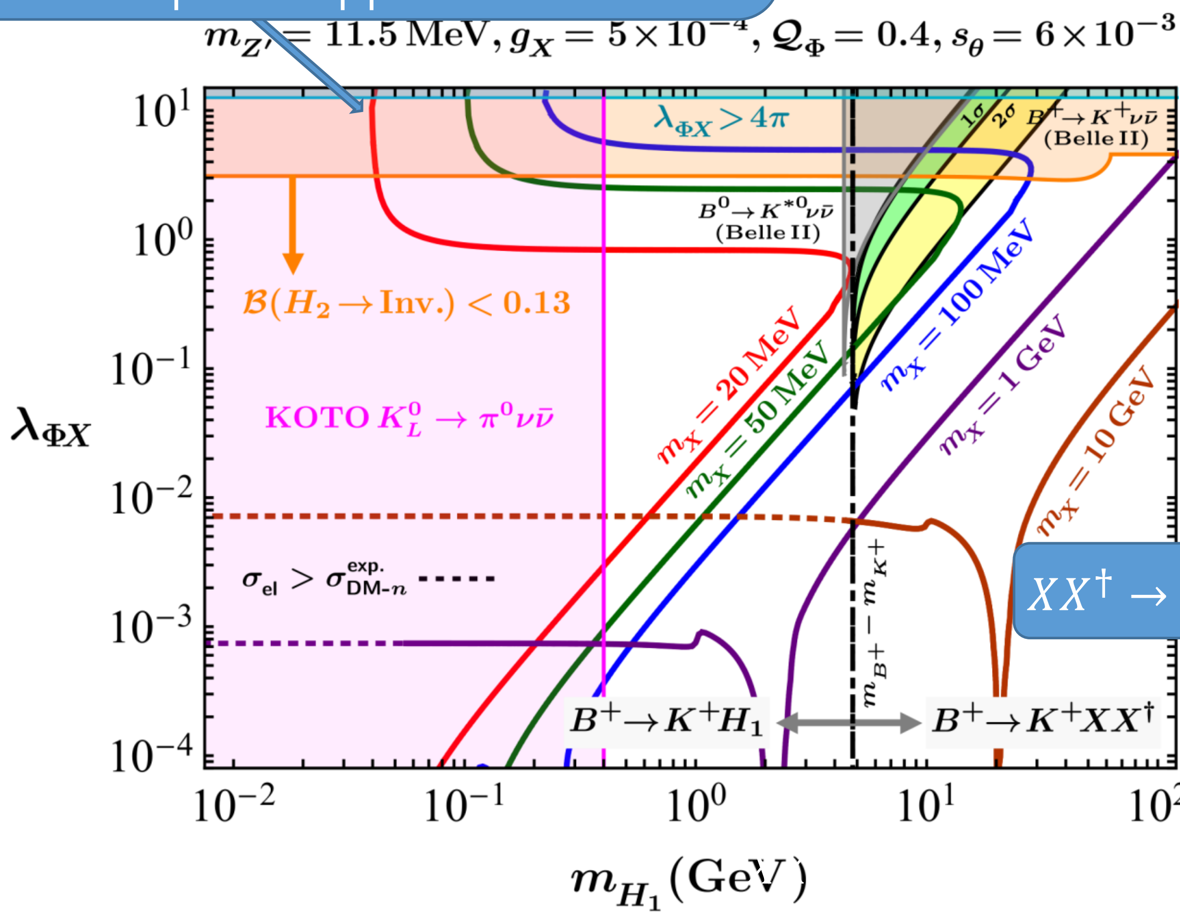
(on)-shell → 3(2)-body decay

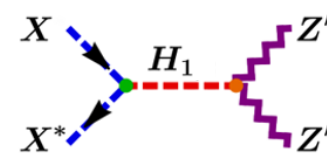
$m_B - m_K)$

eV ($m_{H_1} > m_B - m_K$)

$$\Gamma_{H_1} = \frac{\lambda_{\Phi X}^2 v_\Phi^2}{16\pi\, m_{H_1}} \sqrt{1 - \frac{4m_X^2}{m_{H_1}^2}} \quad \& \ \sigma v \propto \frac{\lambda_{\Phi X}^2}{m_{H_1}^2 \Gamma_{H_1}^2}$$

Phase-space suppression





$XX^\dagger \to Z'Z'$

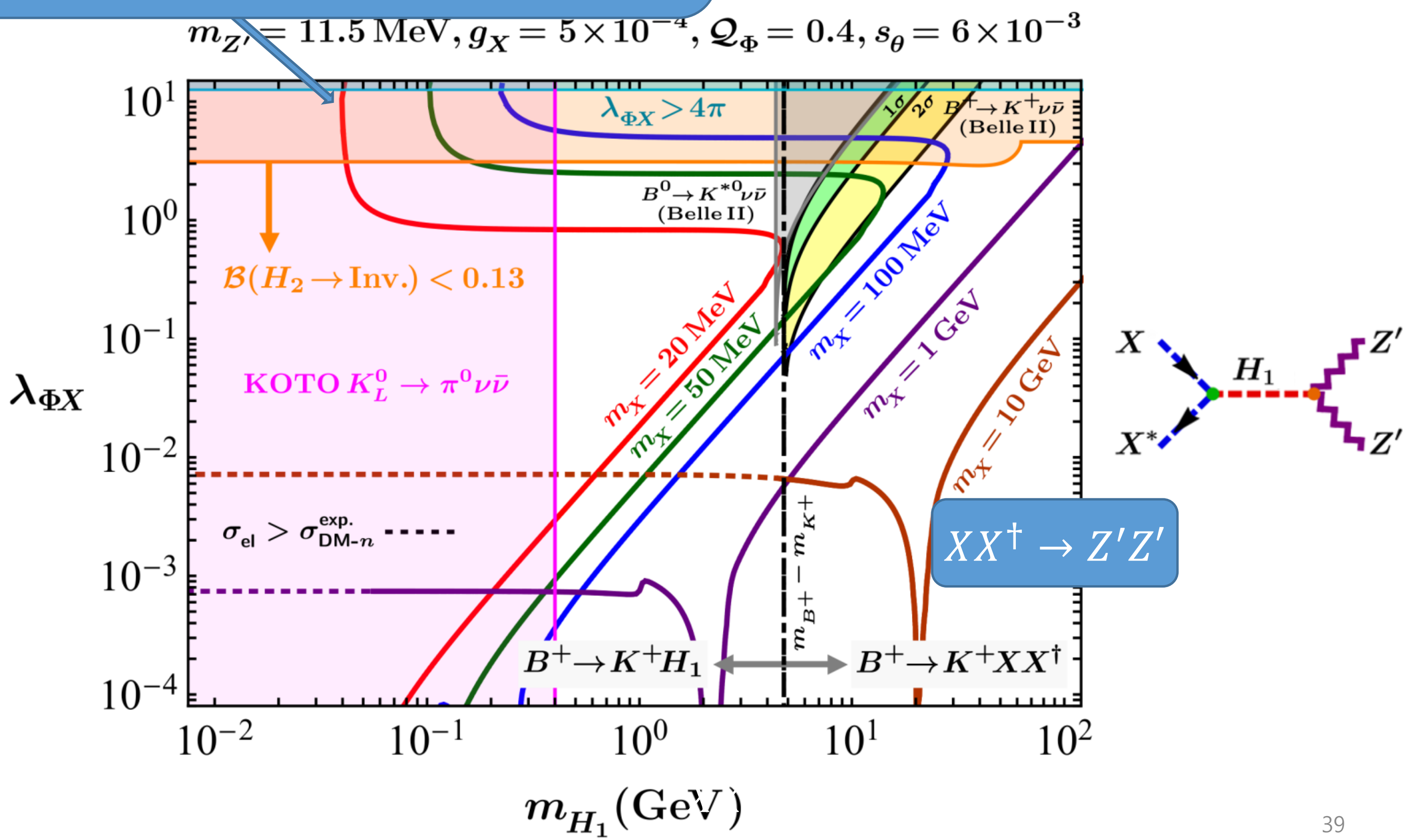
BelleII excess : 2- or 3-body decay

$$\sigma v \propto \frac{m_X^2}{\lambda_{\Phi X}^2 v_\Phi^4 \sqrt{1-\frac{4m_X^2}{m_{H_1}^2}}} \Longrightarrow \lambda_{\Phi X} \uparrow$$

(on)-shell → 3(2)-body decay

$m_B - m_K)$

eV ($m_{H_1} > m_B - m_K$)



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

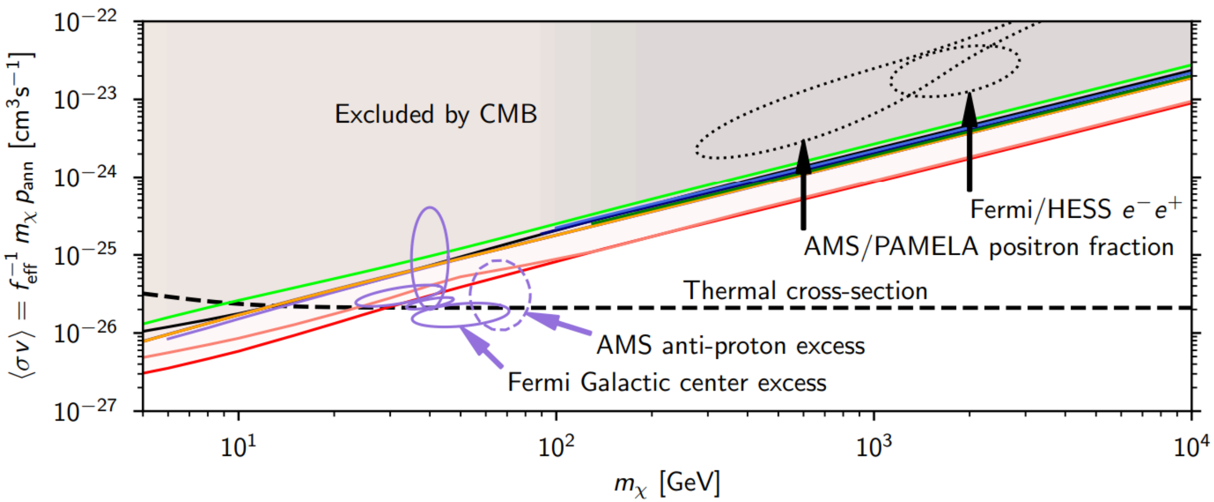
- Measurements of these anisotropies provide robust constraints on production of ionizing particles from DM annihilation products.

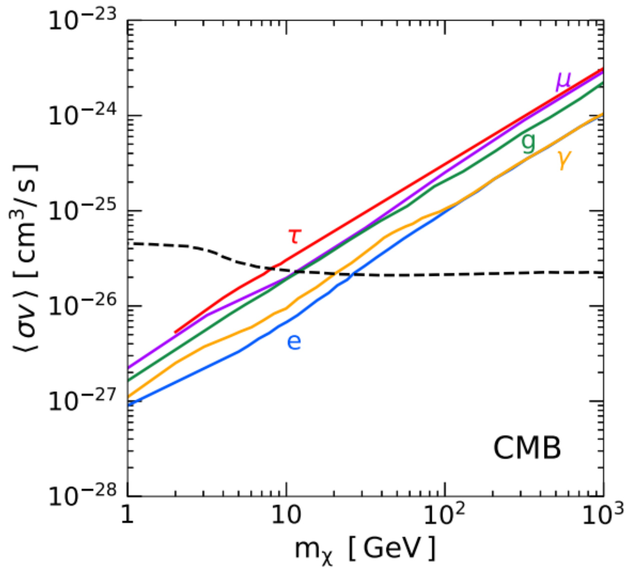
$$\langle \sigma v \rangle \leqslant \frac{4.1 \times 10^{-28}\,\mathrm{cm}^3\,\mathrm{sec}^{-1}}{f_{\mathrm{eff}}} \left(\frac{m_{\mathrm{DM}}}{\mathrm{GeV}} \right)$$

CMB constraints

- For $m_\chi \lesssim 20\text{GeV}$, CMB bound (DM annihilation @ $T\sim\text{eV}$) excludes the thermal DM freeze-out determined by *s-wave* annihilation
  - DM annihilation should be mainly in **p-wave**
  - **Forbidden** DM channel
  - Asymmetric DM

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





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

CMB constraints

- 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 ($m_{Z'} = 11.5$MeV, $g_X = 5 \times 10^{-4}$)

- H_1 decays
  - A pair of DM (open when $m_{H_1} > 2m_X$)
  - A pair of Z'
  - SM particles

CMB constraints

- 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 ($m_{Z'} = 11.5$MeV, $g_X = 5 \times 10^{-4}$)
  - Br($Z' \to e^+e^-$) $\simeq 10^{-5}$ due to smallness of kinetic mixing ($\epsilon \equiv -g_X/70$)

- H_1 decays
  - 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 & $\sin\theta$)

- We can naturally avoid the stringent CMB bound thanks to invisible decay of both H_1 and Z'

Conclusions

- New physics beyond the Standard Model shows up through 80% dark matter

- We shows the importance of the dark Higgs in DM phenomenology via Muon g-2 anomaly, BelleII excess

- We found the dark Higgs boson mass,

(KOTO) $0.4\text{GeV} \leq m_{H_1} \leq 10\text{GeV}$ ($B \to K\nu\nu$ excess)

the complex scalar DM mass,

(ΔN_{eff}) $10\text{MeV} \leq m_X \leq 10\text{GeV}$ ($B \to K\nu\nu$ excess + Direct detection)

and the dark photon mass

$m_{Z'} \sim 10\text{MeV}, g_X \sim 5 \times 10^{-4}$ (Muon g-2 anomaly)

Conclusions

- New physics beyond the Standard Model shows up through 80% dark matter

Thank you very much

- W… ph…
- W…

the complex scalar DM mass;

($\Delta N_{\rm eff}$) $10\text{MeV} \le m_X \le 10\text{GeV}$ ($B \to K\nu\nu$ excess + Direct detection)

and the dark photon mass

$m_{Z'} \sim 10\text{MeV},\ g_X \sim 5 \times 10^{-4}$ (Muon g-2 anomaly)

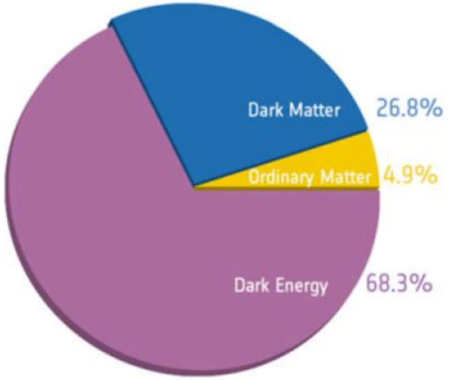
Back-up Slides

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 → $\Omega h^2 = 0.12$**

Planck 2018

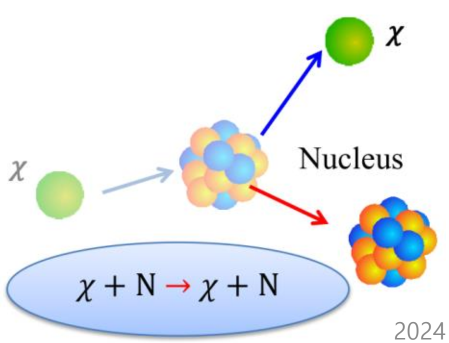
  - **Cold : non-relativistic at the time of formation of the first structures**



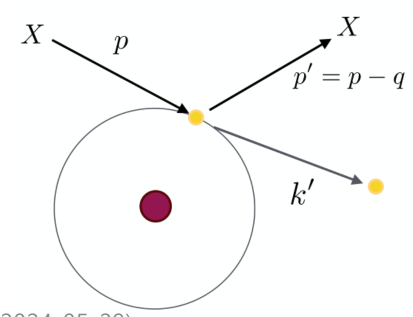
- **Cold Dark Matter**
  - **Weakly Interacting Massive Particle**

Thermal freeze-out DM Detection

- General idea:
  - The Earth is moving through dark matter medium. Or, from our point of view, there is a flux of dark matter particles going through the Earth
  - Once in a while a dark matter particle will interact with a nucleus or electron
  - The nucleus gains momentum and recoils. The existence of dark matter can then be inferred if there is a significant excess in the number of recoils compared to the expected recoils induced by natural radioactivity in the detector
- Try to observe recoil energy coming from DM scattering process
  - Nuclear Recoil (NR)
    - $E_R = 1\sim100\text{keV}$

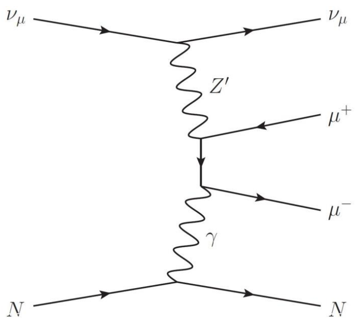


Electronic Recoil (ER)
- Ionization



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



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

- 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}
  - $\Delta N_{\mathrm{eff}} < \mathbf{0.5}$

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

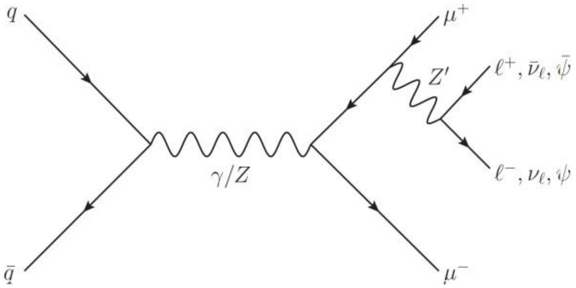
BaBar, LHC 4μ channels

BaBar Collaboration, PRD 2016

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

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



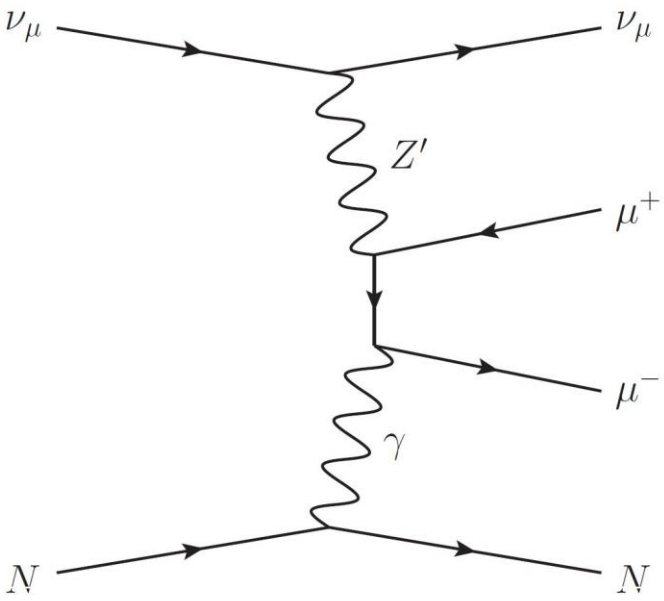
- Final states
  - two pair of charged-leptons
  - A pair of charged-lepton plus missing energy

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

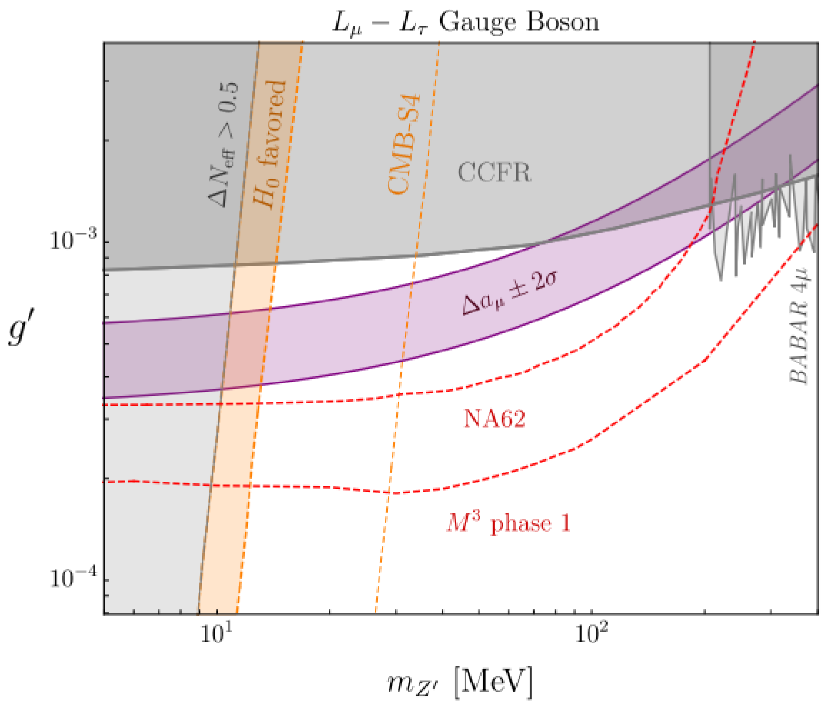
$$\alpha_{B-L}^2 \to \begin{cases} \left[\sum_{i,j=1}^3 f_i \, |(U^\dagger Q_{\mu e} U)_{ij}|^2\right]^{1/2} \alpha_{\mu e}^2 \,, & \text{for} \quad \mathrm{U}(1)_{L_\mu - L_e} \,, \\ \left[\sum_{i,j=1}^3 f_i \, |(U^\dagger Q_{e\tau} U)_{ij}|^2\right]^{1/2} \alpha_{e\tau}^2 \,, & \text{for} \quad \mathrm{U}(1)_{L_e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

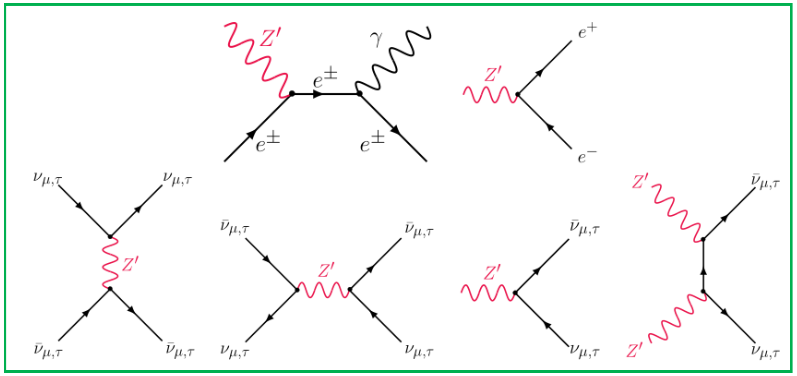
$$Q_{\mu\tau} = \mathrm{diag}(0, 1, -1)$$

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

- Challenges in reconstructing the events
  - Searches for $B \to K^{(*)}\nu\bar{\nu}$ have only been performed at the B factories Belle and BaBar

- Using the same techniques in Belle, BaBar
  - Semileptonic tagged analyses
  - Hadronic-tagged analyses

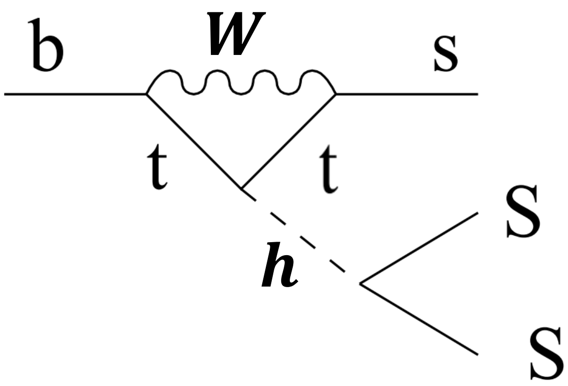
- Inclusive tag analysis (Belle & Belle II)
  - Allow one to reconstruct inclusively the decay $B^+ \to K^+\nu\bar{\nu}$ from the charged kaon

Solutions: 3-body decay

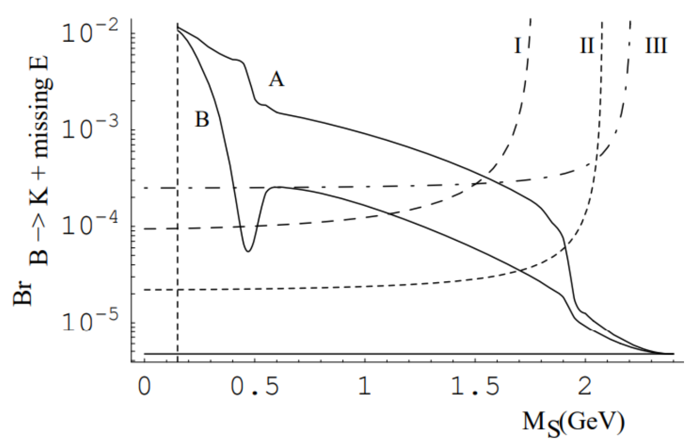
Bird et al, PRL 2004

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

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



- 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).



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- For $m_\chi \lesssim 10\text{GeV}$, CMB bound (DM annihilation @ $T \sim \text{eV}$) 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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- $m_s \leq 1\text{GeV}$ is already excluded by BABAR limits (2004 data).