Belle II $B^+ \to K^+ \nu\bar{\nu}$ excess, muon g-2 illuminating light DM with Higgs portal

Pyungwon Ko (KIAS)

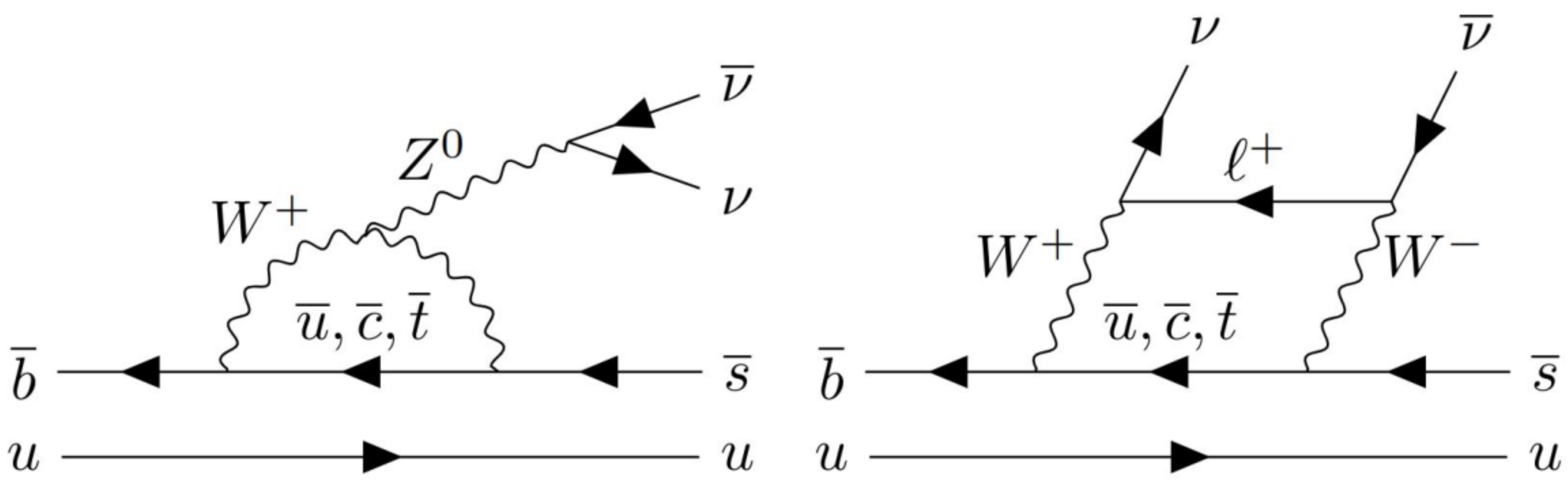
QCHSC2024, Aug 19 (2024)

Based on arXiv:2204.04889, arXiv:2401.10112

$B^+ \to K^+\nu\bar{\nu}$ in the SM

- 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



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

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

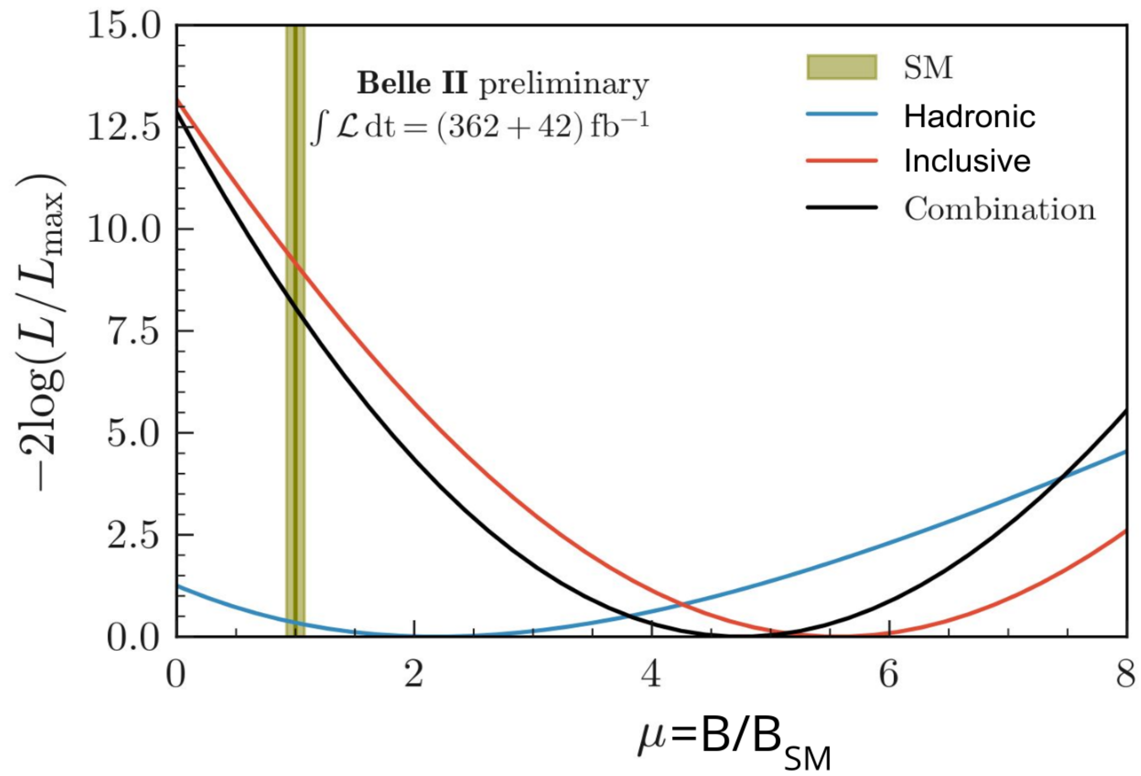
where $x_t = m_t^2/M_W^2$.

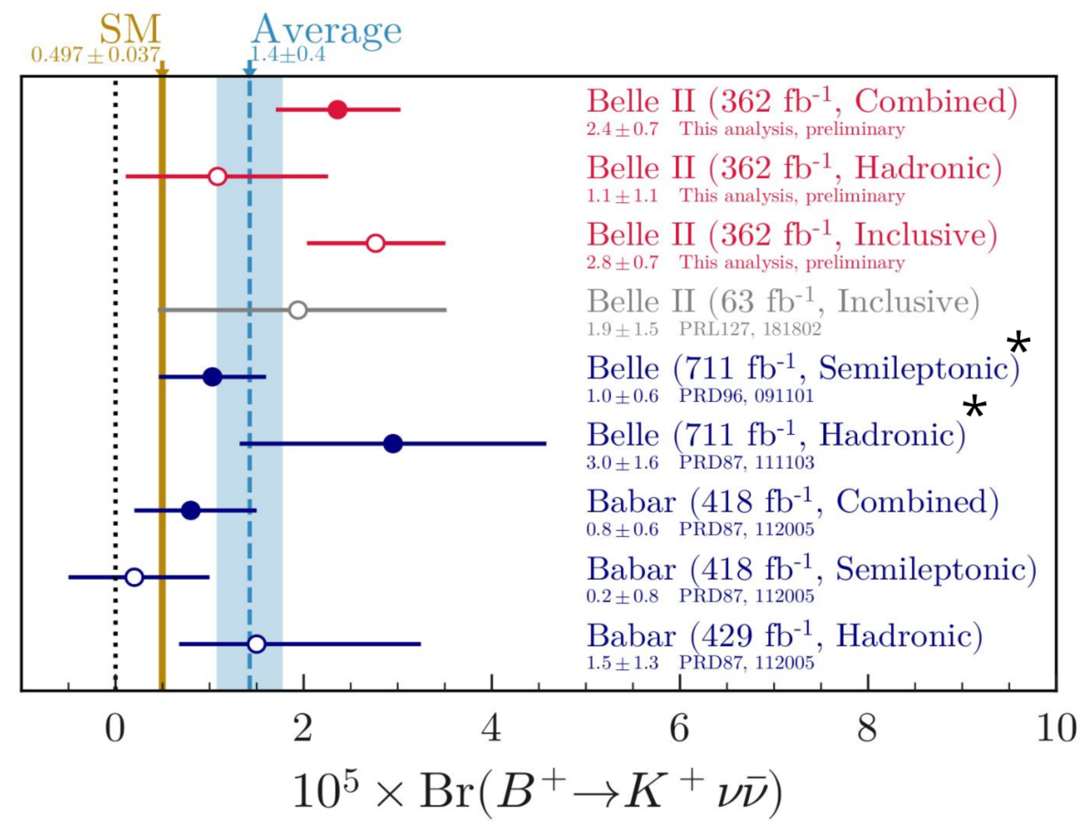
Measurement of $B^+ \to K^+\nu\bar{\nu}$

- 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 & BelleII)
  - Allow one to reconstruct inclusively the decay $B^+ \to K^+\nu\bar{\nu}$ from the charged kaon



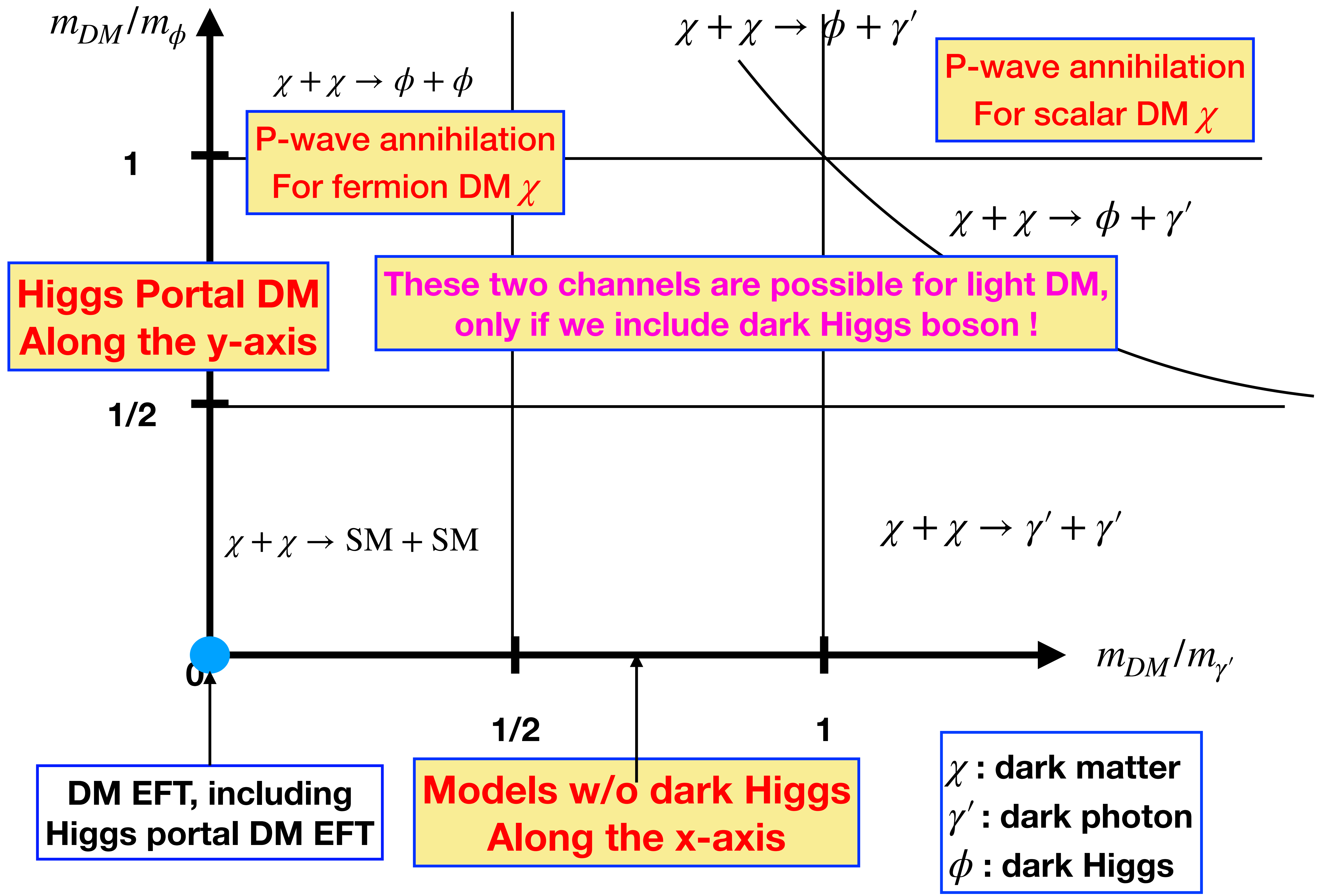


- $Br(B^+ \to K^+ \nu\bar{\nu}) = (2.4 \pm 0.7) \times 10^{-5}$
  - Significance of observation is 3.6σ
  - 2.8σ tension with the SM prediction
- $Br(B^+ \to K^+ E_{\text{miss}})_{NP} = (1.9 \pm 0.7) \times 10^{-5}$
- Indicate not only the presence of NP in the $b \to s\nu\bar{\nu}$ transitions but even the presence of new light states (particles in dark sector?)

Questions ?

- Can we explain this mild excess in terms of new physics with light particles ?
- Light DM ? Something that decays mostly into neutrinos ?
- New light d.o.f. may have connections with other puzzles in particle physics and cosmology….
- Muon g-2, Hubble tension, etc.
- Answer : Yes, within $U(1)_{L_\mu - L_\tau}$ models with light complex scalar DM and light dark Higgs boson

Dark sector parameter space for a fixed m_{DM}



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

: Z' only vs. $Z' + \phi$

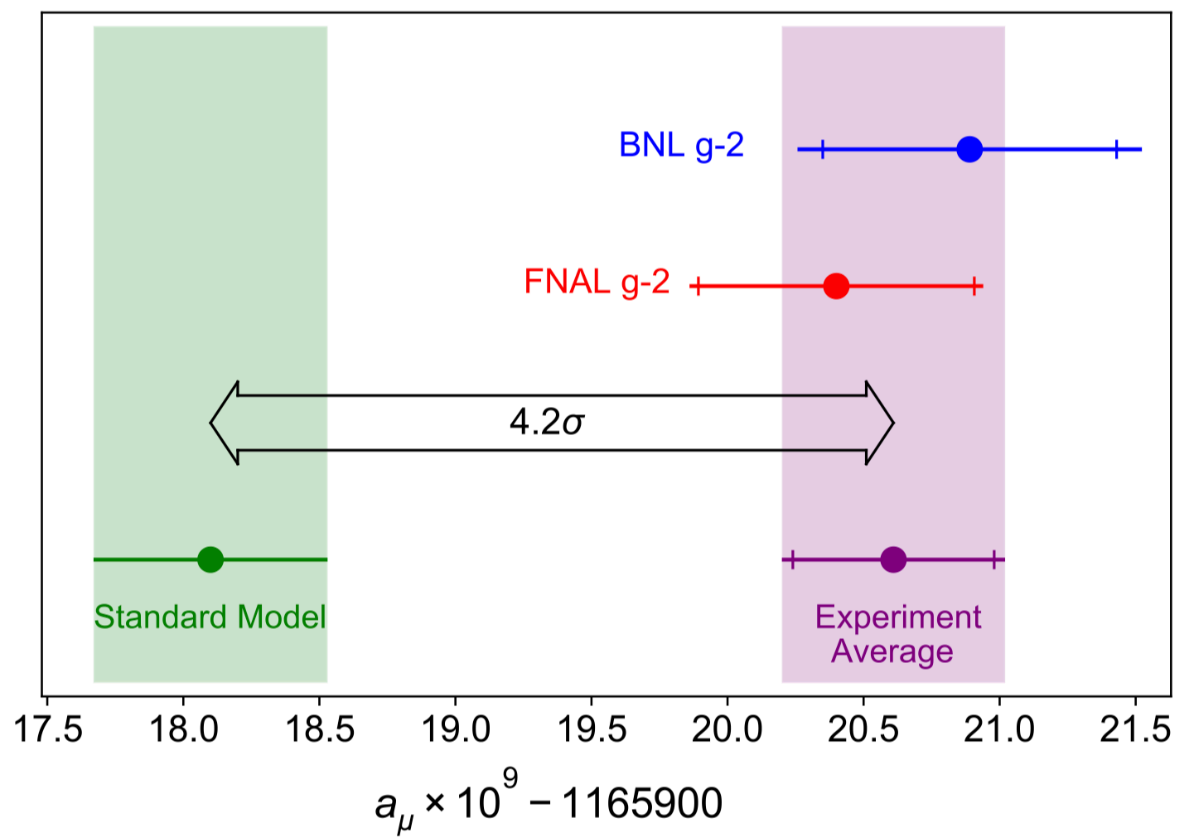
arXiv:2204.04889 [hep-ph]

With Seungwon Baek, Jongkuk Kim

SM+$U(1)_{L_\mu - L_\tau}$ gauge sym

- He, Josh, Lew, Volkas, PRD 43, 22; PRD 44, 2118 (1991)
- One of the anomaly free gauge groups without extension of fermion contents
- The simplest anomaly free U(1) extensions that couple to the SM fermions directly
- Can affect the muon g-2, PAMELA e^+ excess, (and B anomalies with extra fermions : Not covered in this talk)

Muon g-2



The Muon g-2 Collaboration, 2104.03281

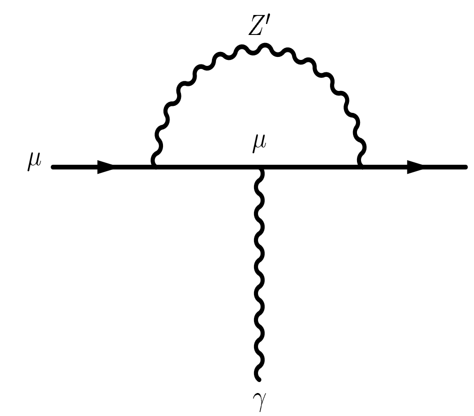
Excellent example for graduate students

- Relativistic E&M (spinning particle in EM fields)
- Special relativity (time dilation)
- (V-A) structure of charged weak interaction

Muon (g-2) in $U(1)_{\mu-\tau}$ Model

Baek, Deshpande, He, Ko : hep-ph/0104141
Baek, Ko : arXiv:0811.1646 [hep-ph]

$$
\begin{array}{llll}
L_L^e : & (1,2,-1)(0) & e_R : & (1,1,-2)(0) \\
L_L^\mu : & (1,2,-1)(2a) & \mu_R : & (1,1,-2)(2a) \\
L_L^\tau : & (1,2,-1)(-2a) & \mu_R : & (1,1,-2)(-2a).
\end{array}
$$



$$\Delta a_\mu = \frac{\alpha^{'}}{2\pi} \int_0^1 dx \frac{2m_\mu^2 x^2(1-x)}{x^2 m_\mu^2 + (1-x)M_{Z'}^2} \approx \frac{\alpha^{'}}{2\pi}\frac{2m_\mu^2}{3M_{Z'}^2}$$

$$Z^{'} \to \mu^+\mu^-, \tau^+\tau^-, \nu_\alpha\bar{\nu}_\alpha \ (\text{with } \alpha = \mu \text{ or } \tau), \ \psi_D\overline{\psi}_D$$

$$\Gamma(Z^{'} \to \mu^+\mu^-) = \Gamma(Z^{'} \to \tau^+\tau^-) = 2\Gamma(Z^{'} \to \nu_\mu\bar{\nu}_\mu) = 2\Gamma(Z^{'} \to \nu_\tau\bar{\nu}_\tau) = \Gamma(Z^{'} \to \psi_D\bar{\psi}_D)$$

if $M_{Z'} \gg m_\mu, m_\tau, M_{\rm DM}$. The total decay rate of $Z^{'}$ is approximately given by

$$\Gamma_{\rm tot}(Z^{'}) = \frac{\alpha^{'}}{3} M_{Z'} \times 4(3) \approx \frac{4(\text{or } 3)}{3} \text{ GeV} \left(\frac{\alpha^{'}}{10^{-2}}\right) \left(\frac{M_{Z'}}{100\text{GeV}}\right)$$

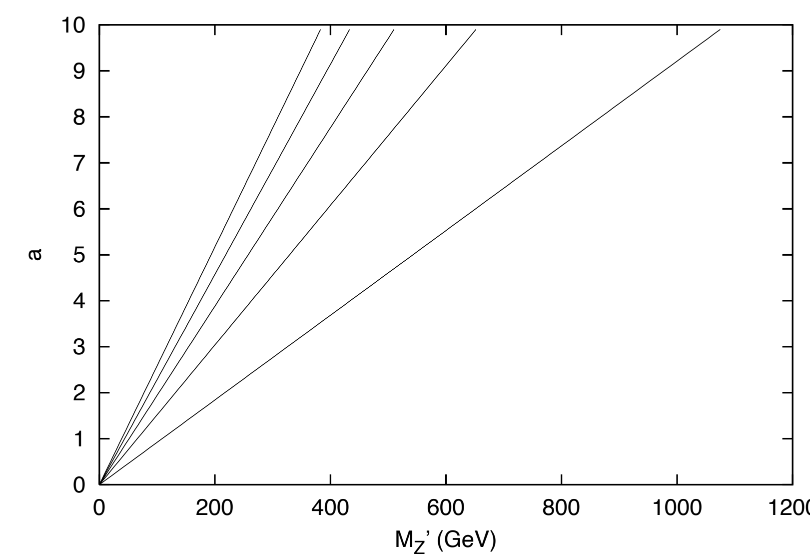


FIG. 2. Δa_μ on the a vs. $m_{Z'}$ plane in case b). The lines from left to right are for Δa_μ away from its central value at $+2\sigma, +1\sigma, 0, -1\sigma$ and -2σ, respectively.

$$
\begin{aligned}
q\bar{q} \ (\text{or } e^+e^-) &\to \gamma^*, Z^* \to \mu^+\mu^- Z^{'}, \tau^+\tau^- Z^{'} \\
&\to Z^* \to \nu_\mu\bar{\nu}_\mu Z^{'}, \nu_\tau\bar{\nu}_\tau Z^{'}
\end{aligned}
$$

Baek and Ko, arXiv:0811.1646, for PAMELA e^+ excess

$$\mathcal{L}_{\rm Model} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm New}$$

$$\mathcal{L}_{\rm New} = -\frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} + \overline{\psi_D} i D \cdot \gamma \psi_D - M_{\psi_D} \overline{\psi_D} \psi_D + D_\mu \phi^* D^\mu \phi - \lambda_\phi (\phi^* \phi)^2 - \mu_\phi^2 \phi^* \phi - \lambda_{H\phi} \phi^* \phi H^\dagger H.$$

Here we ignored kinetic mixing for simplicity

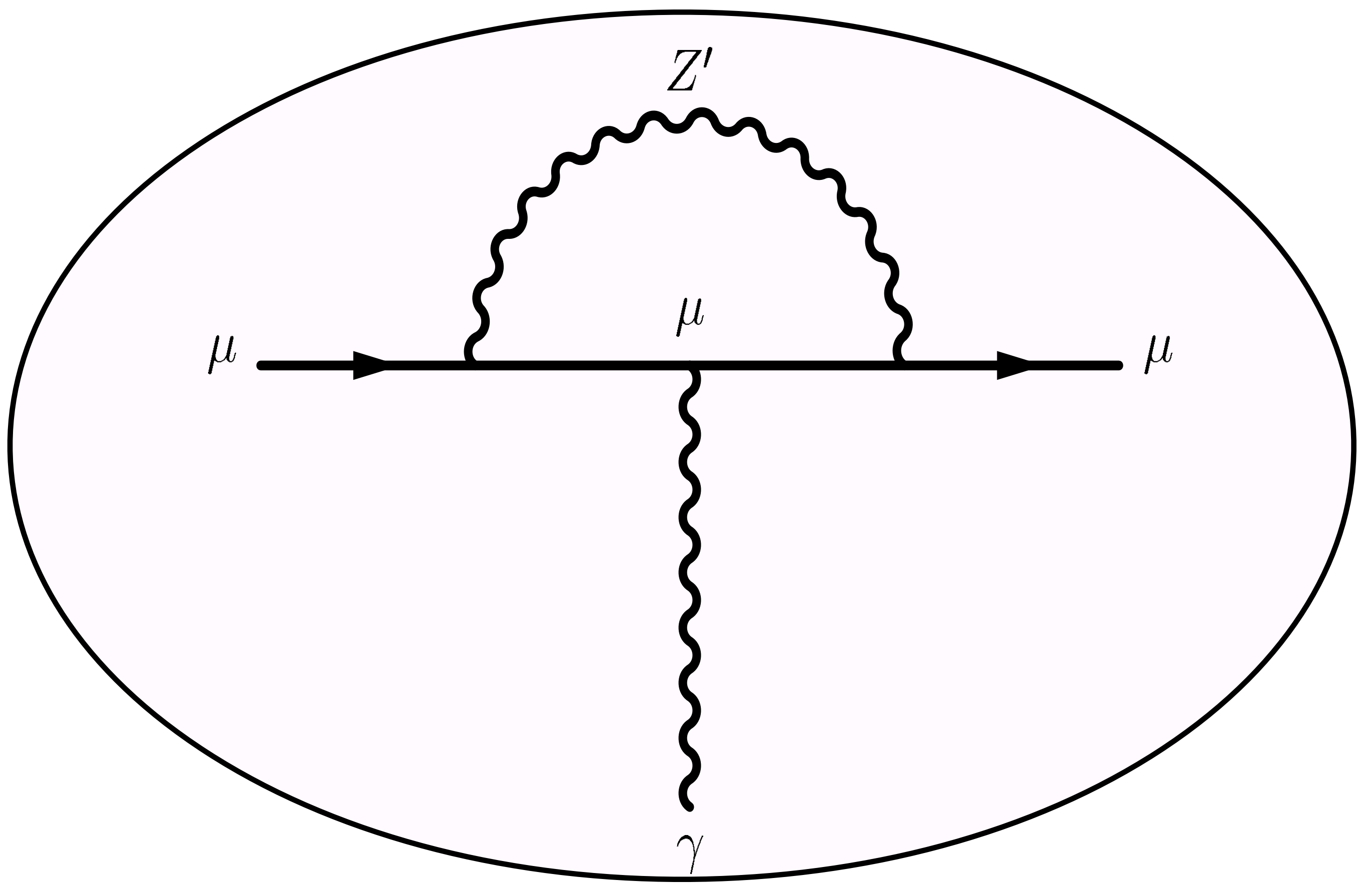
$$D_\mu = \partial_\mu + ieQA_\mu + i\frac{e}{s_W c_S}(I_3 - s_W^2 Q) Z_\mu + ig' Y' Z'_\mu$$

muon g-2, Leptophilc DM, Collider Signature

Muon (g-2)

Baek, Deshpande, He, Ko : hep-ph/0104141
Baek, Ko : arXiv:0811.1646 [hep-ph]

$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = (302 \pm 88) \times 10^{-11}.$$



$$\Delta a_\mu = \frac{\alpha'}{2\pi} \int_0^1 dx \frac{2 m_\mu^2 x^2 (1-x)}{x^2 m_\mu^2 + (1-x) M_{Z'}^2} \approx \frac{\alpha'}{2\pi} \frac{2 m_\mu^2}{3 M_{Z'}^2}$$

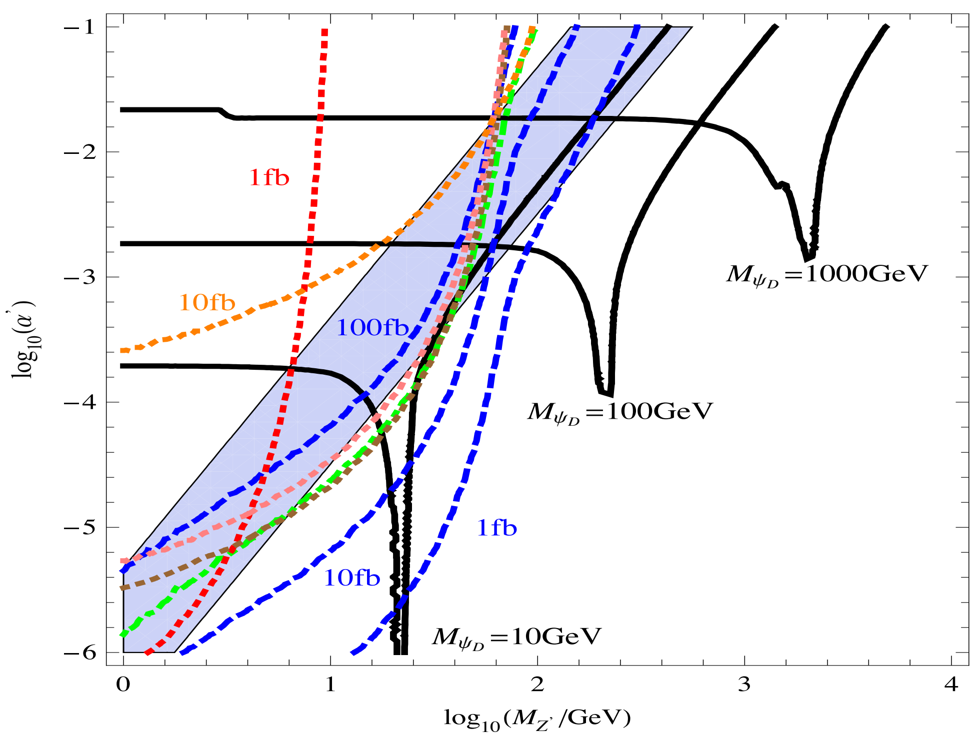


Figure 1: The relic density of CDM (black), the muon $(g-2)_\mu$ (blue band), the production cross section at B factories (1 fb, red dotted), Tevatron (10 fb, green dotdashed), LEP (10 fb, pink dotted), LEP2 (10 fb, orange dotted), LHC (1 fb, 10 fb, 100 fb, blue dashed) and the Z^0 decay width (2.5×10^{-6} GeV, brown dotted) in the $(\log_{10}\alpha', \log_{10} M_{Z'})$ plane. For the relic density, we show three contours with $\Omega h^2 = 0.106$ for $M_{\psi_D} = 10$ GeV, 100 GeV and 1000 GeV. The blue band is allowed by $\Delta a_\mu = (302 \pm 88)\times 10^{-11}$ within 3 σ.

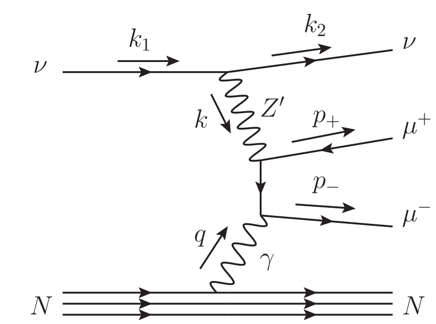


FIG. 1. The leading order contribution of the Z′ to neutrino trident production (another diagram with μ^+ and μ^- reversed i … in g'

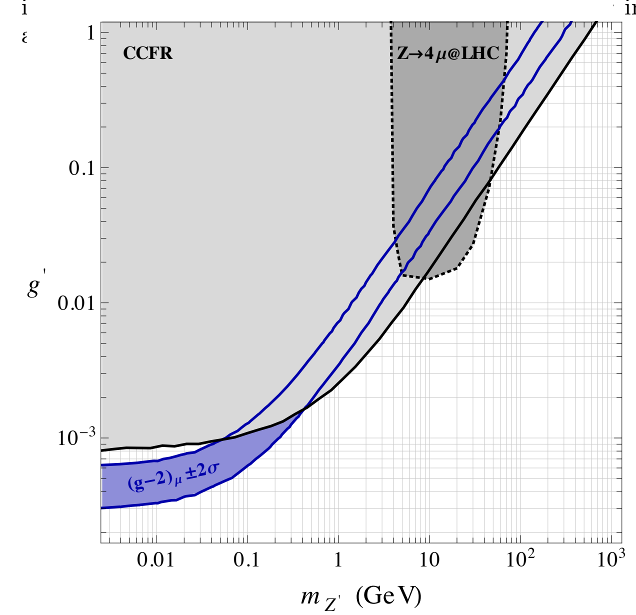


FIG. 2. Parameter space for the Z′ gauge boson. The light-grey area is excluded at 95% C.L. by the CCFR measurement of the neutrino trident cross-section. The grey region with the dotted contour is excluded by measurements of the SM

Seungwon Baek, Pyungwon Ko, arXiv:0811.1646, JCAP(2009) about PAMELA e^+ excess

Altmannshofer et al. arXiv:1406.2332 [hep-ph]

Neutrino trident puts strong constraints on this model

One can evade the neutrino trident constraint, if one introduces New fermions and generate muon g-2 at loop level w/ new fermions !

Z' Only

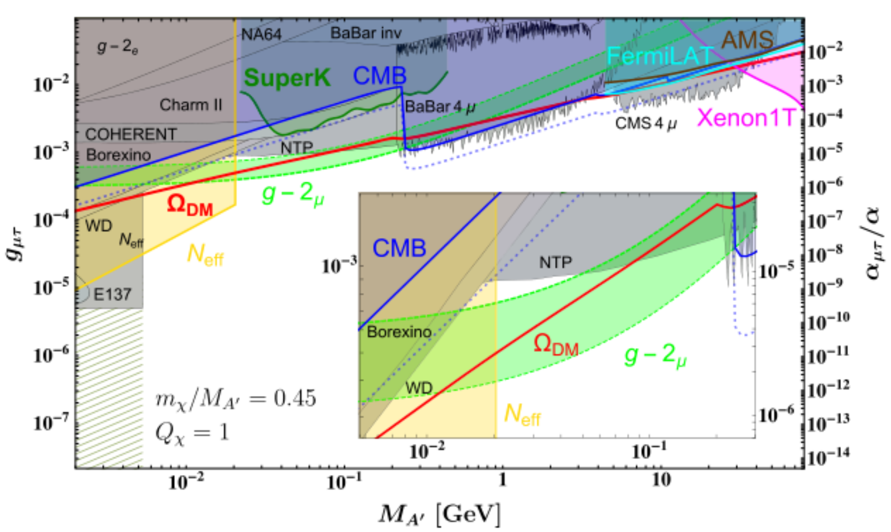
- Consider light Z' and $g_X \sim (\mathrm{a\ few}) \times 10^{-4}$ for the muon g-2. Then
- $\chi\bar{\chi} \to Z'^{*} \to f_{\mathrm{SM}}\bar{f}_{\mathrm{SM}}$: dominant annihilation channel
- $g_X \sim 10^{-4}$ is too small for $\chi\bar{\chi} \to Z'Z'$ to be effective for $\Omega_\chi h^2$
- $m_{Z'} \sim 2m_{\mathrm{DM}}$ with the s-channel Z' resonance for the correct relic density
- Many recent studies on this case:

- Asai, Okawa, Tsumura, 2011.03165
- Holst, Hooper, Krnjaic, 2107.09067
- Drees and Zhao, arXiv:2107.14528
- And some earlier papers

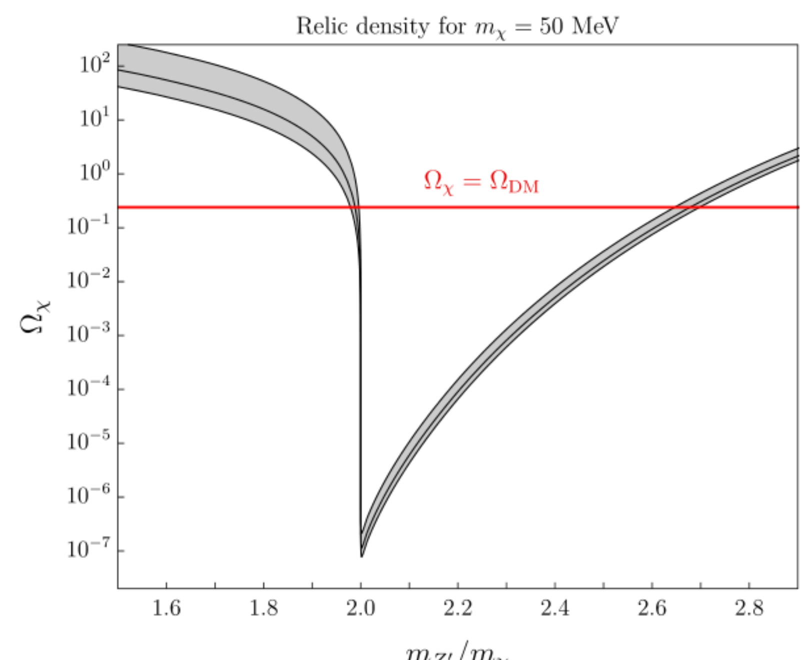
Leptophilic Z' model + DM

- $\chi\bar{\chi}(X\bar{X}) \to Z'^{*} \to \nu\bar{\nu}$: dominant annihilation channels
  - $M_{Z'} \sim 2M_{\chi}$ with the **s-channel Z' resonance** only gives the correct relic density

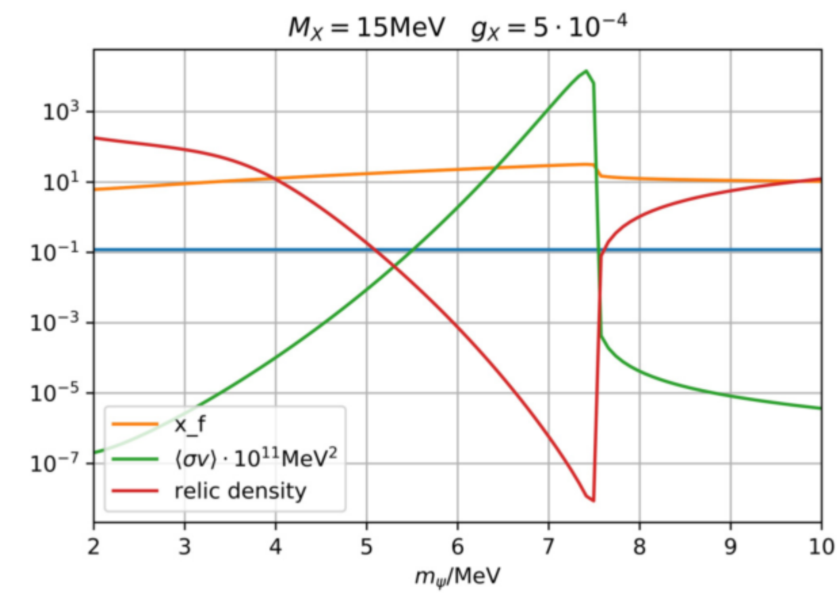
P. Foldenauer, PRD 2019



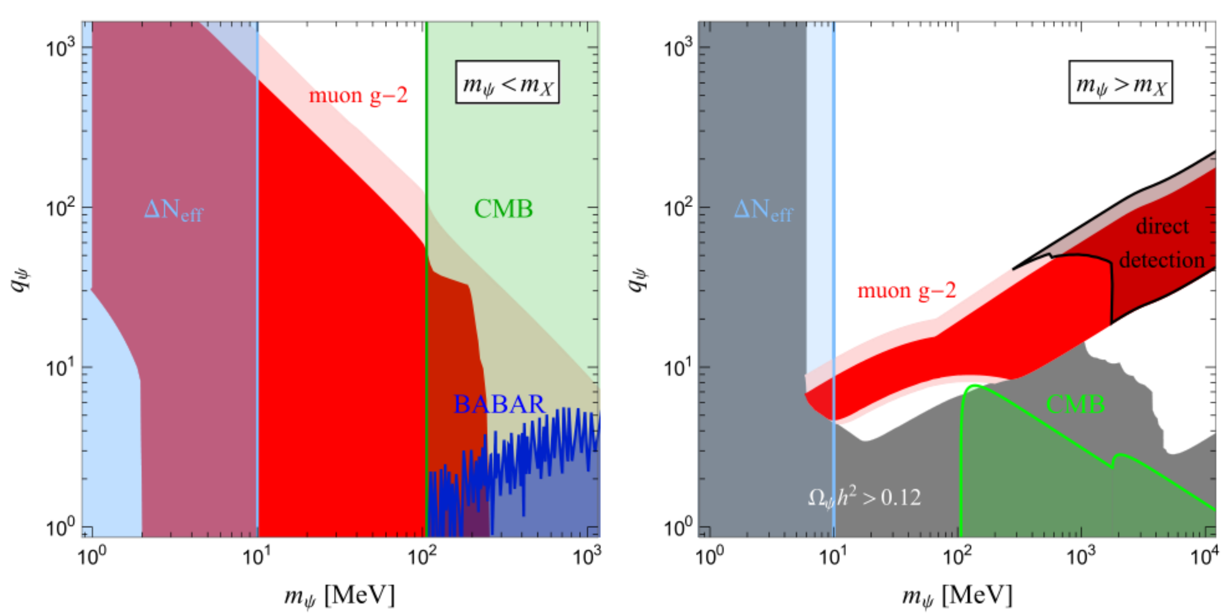
I. Holst. D. Hooper, G. Krnjaic, PRL 2022

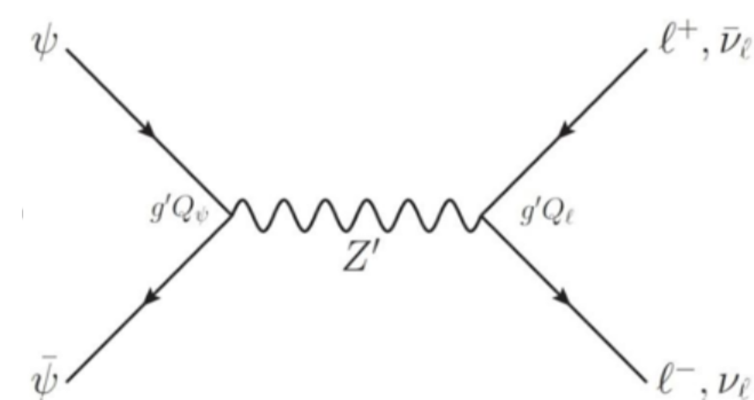


M. Drees, W. Zhao, PLB 2022



Asai, Okawa, Tsumura, JHEP 2021





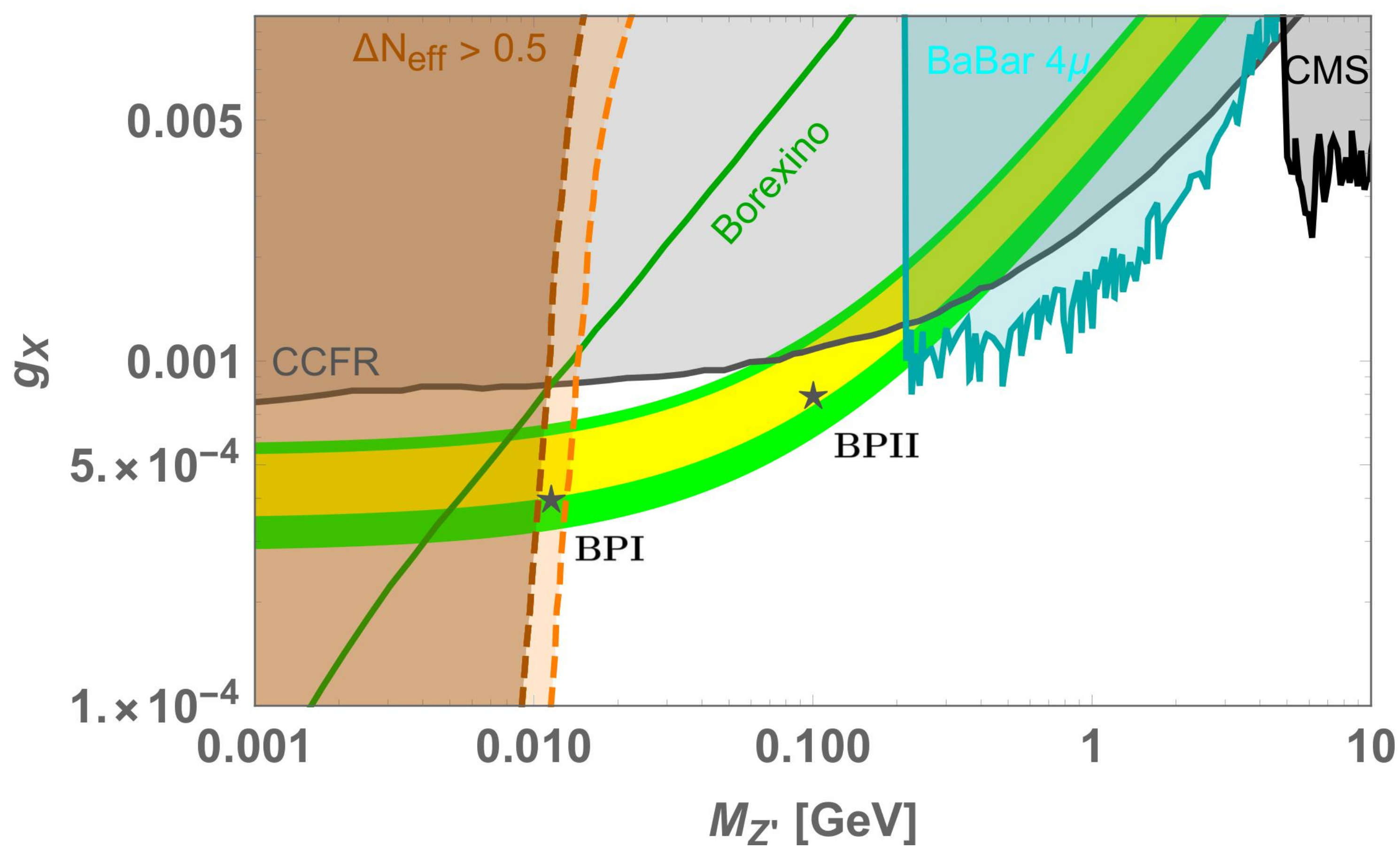


FIG. 1. Regions inside the yellow and Green shaded areas by the Δa_μ are allowed at 1σ and 2σ C.L.. Cyan, black, and orange regions are excluded by other experimental bounds. Above green solid line is ruled out by the Borexino experiment. Region inside the orange area can resolve the Hubble tension. We take two Benchmark Points (BP) $(M_{Z'}, g_X)$ as **BPI** $=(11.5\,\mathrm{MeV}, 4\times10^{-4})$ and **BPII** $= (100\,\mathrm{MeV}, 8\times10^{-4})$.

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

: Z' only vs. $Z' + \phi$

cf: Let me call Z' , $U(1)_{L_\mu - L_\tau}$ gauge boson,
"dark photon", since it couples to DM

Models with Φ

TABLE I: $U(1)$ charge assignments of newly introduced particles and SM particles. The other SM particles are singlet.

Field	Z'_μ	$X(\chi)$	Φ	$L_\mu = (\nu_{L\mu}, \mu_L), \mu_R$	$L_\tau = (\nu_{L\tau}, \tau_L), \tau_R$
spin	1	0 (1/2)	0	1/2	1/2
$U(1)$ charge	0	$Q_X(Q_\chi)$	Q_Φ	+1	-1

We Consider Both Complex Scalar (X) and Dirac Fermion DM (χ)

- Physics depends on Q_Φ , Q_X and Q_χ
- $Q_\Phi = 2Q_{X(\chi)}$ and $3Q_X$ need special cares, since there are extra gauge invariant op's that break $U(1) \to Z_2$, Z_3 after $U(1)$ is spontaneously broken by nonzero VEV of Φ

Complex Scalar DM (generic with $Q_\Phi \neq Q_X, etc$)

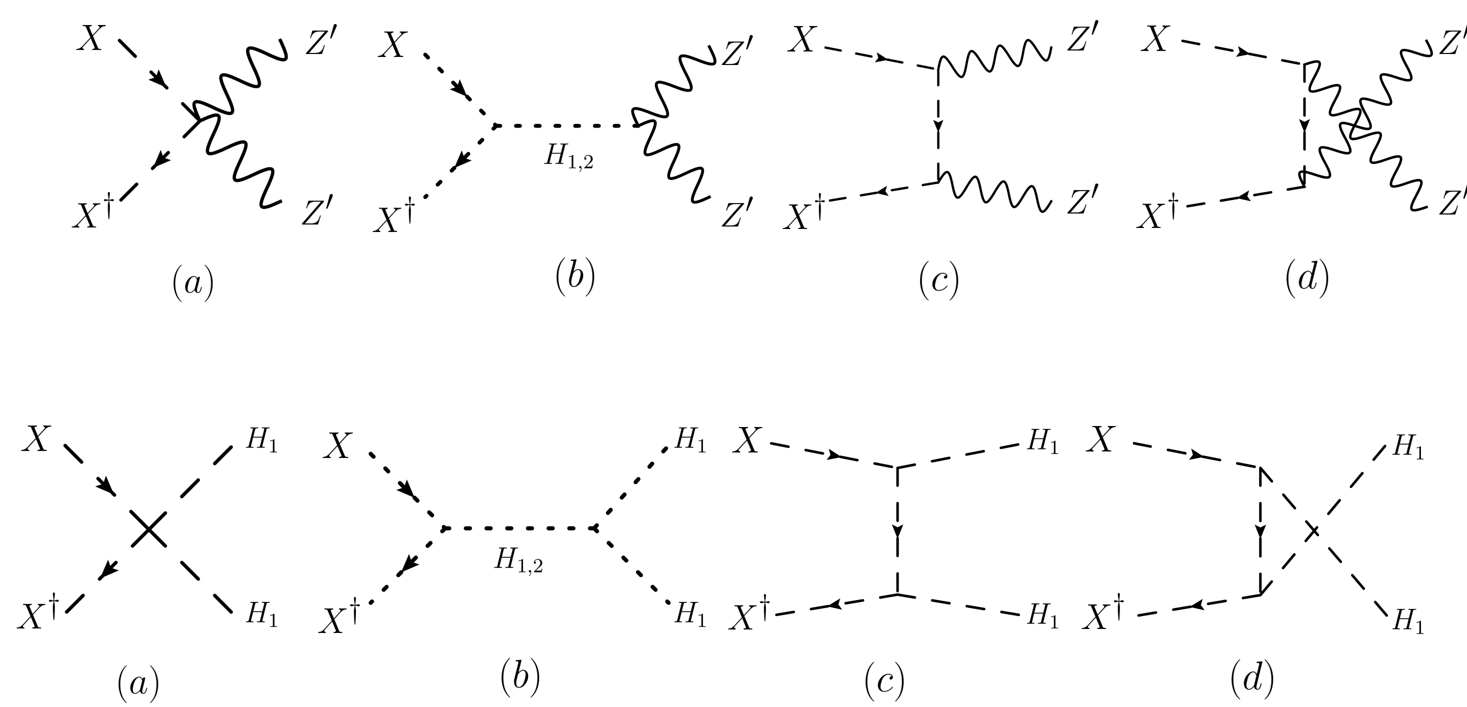


FIG. 2. (*Top*) Feynman diagrams for Complex scalar DM annihilating to a pair of Z' bosons. (*Bottom*) Feynman diagrams for Complex scalar DM annihilating to a pair of H_1 bosons.

$\boxed{H_2 \simeq H_{125} \text{ and } H_1 \simeq \phi \text{ (dark Higgs)}}$

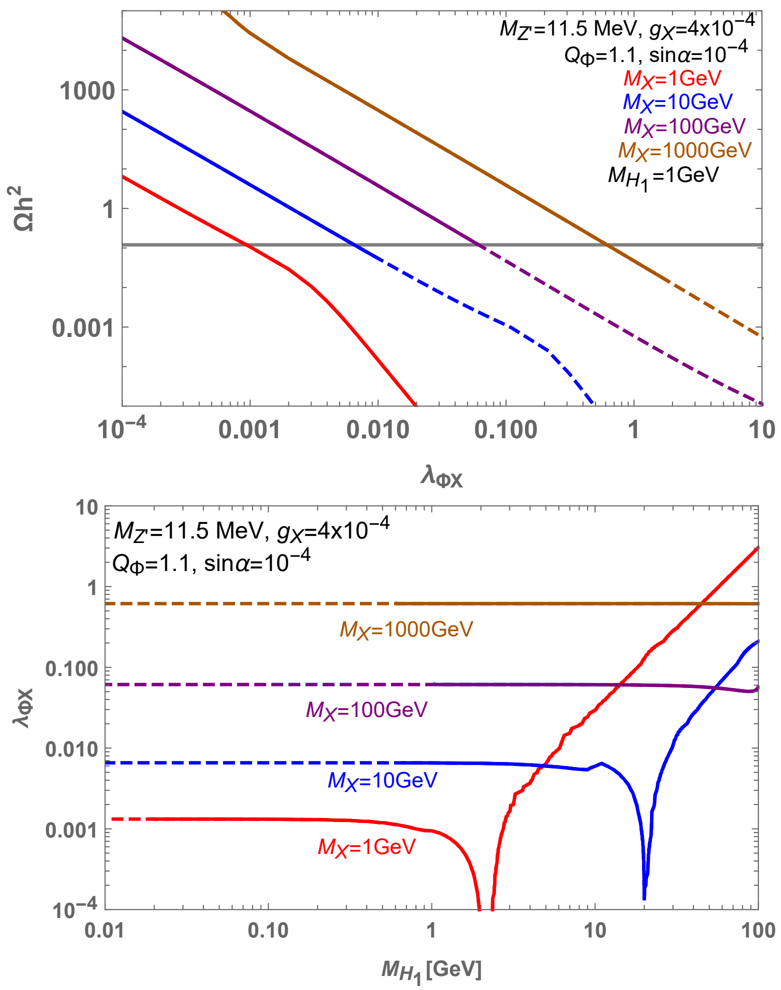


FIG. 3. *Top*: relic abundance of complex scalar DM as functions of $\lambda_{\Phi X}$ for [**BPI**] for $M_X = 1,\ 10, 100,\ 1000\text{GeV}$, respectively. We assumed $Q_\Phi = 1.1$, $M_{H_1} = 1\text{GeV}$, and $\sin\alpha = 10^{-4}$. Solid (Dashed) lines represent the region where bounds on DM direct detection are satisfied (ruled out). *Bottom*: the preferred parameter space in the $(M_{H_1}, \lambda_{\Phi X})$ plane for $\lambda_{HX} = 0$.

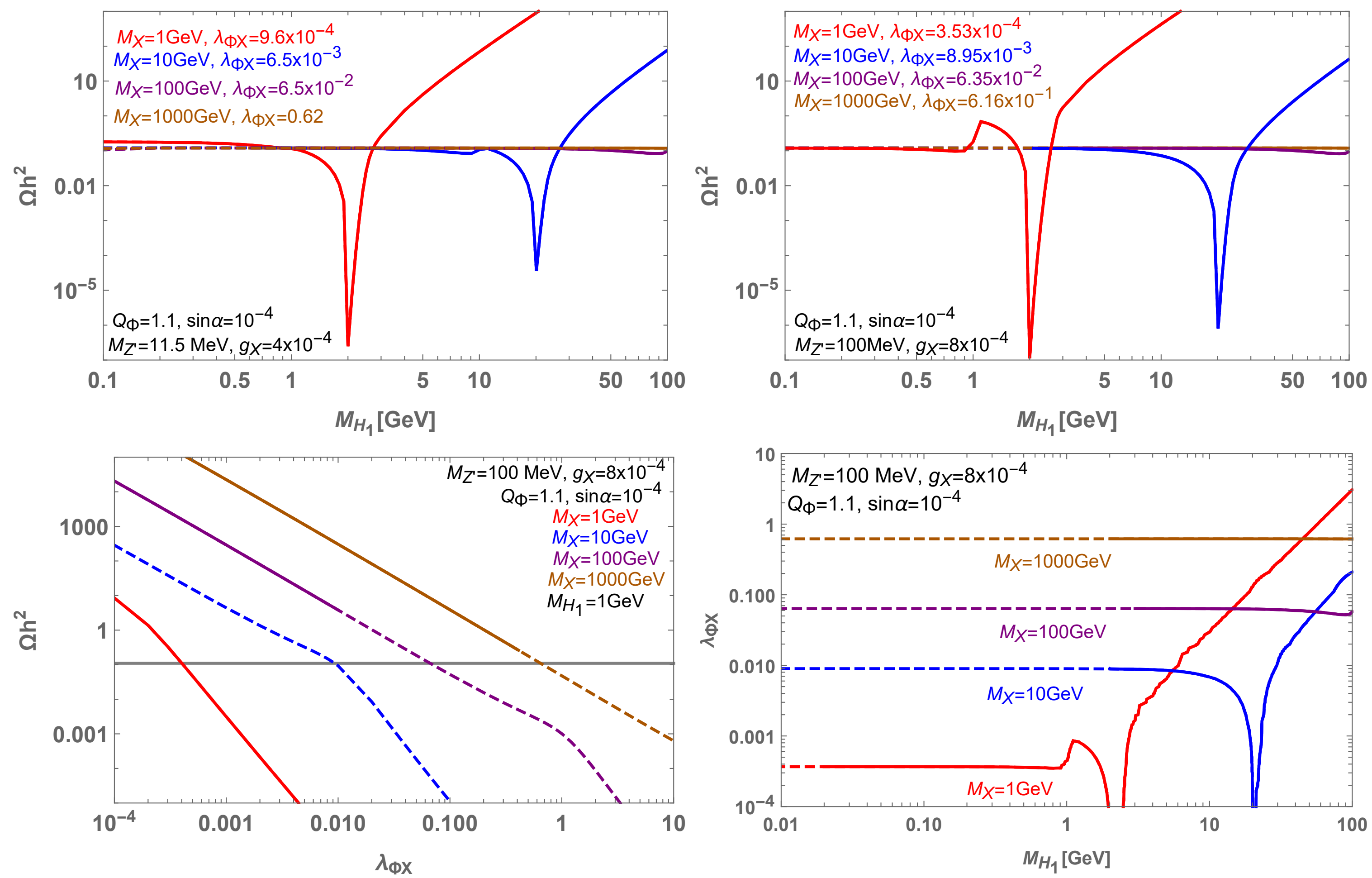


FIG. 7. The (*Top*) plots show the relic abundance of complex scalar DM for $Q_\Phi = 1.1$ as functions of dark Higgs mass M_{H_1} for [**BPI**] (*Left*) and [**BPII**] (*Right*). The (*Bottom*) plots show the relic density as functions of $\lambda_{\Phi X}$ (*Left*) and the preferred parameter space in the $(M_{H_1}, \lambda_{\Phi X})$ plane for $\lambda_{HX} = 0$ (*Right*) for [**BPII**] . We take four different DM masses, $M_X = 1,\ 10, 100,\ 1000\text{GeV}$, respectively. Solid (Dashed) lines represent the region where bounds on DM direct detection are satisfied (ruled out).

DM mass : much wider range than $m_{Z'} \sim 2m_{\rm DM}$
due to dark Higgs boson contributions

Complex Scalar DM: $U(1)_{L_\mu - L_\tau} \to Z_2$ $(Q_\Phi = 2Q_X)$

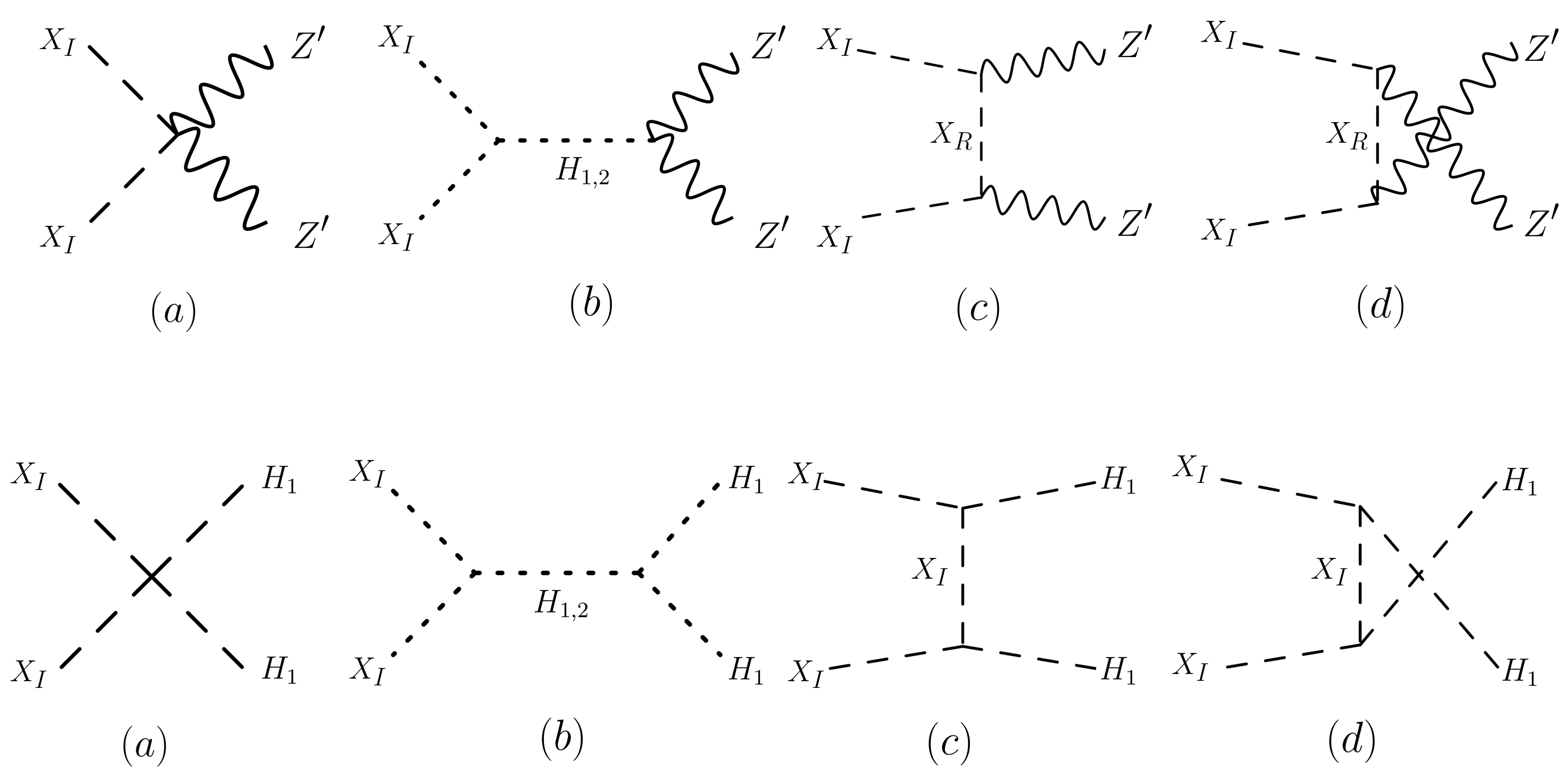


FIG. 8. (*Top*) Feynman diagrams for local Z_2 scalar DM annihilatiing to a pair of Z' bosons. (*Bottom*) Feynman diagrams for local Z_2 scalar DM annihilatiing to a pair of H_1 bosons, which is mostly dark Higgs-like.

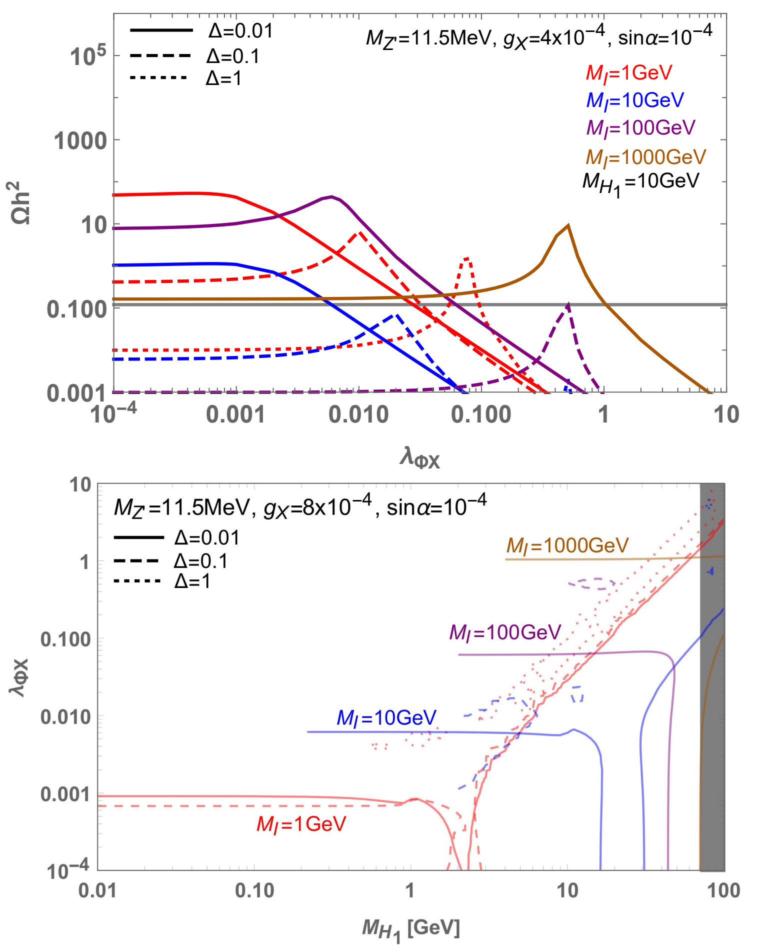


FIG. 4. *Top*: Relic abundance of local Z_2 scalar DM as functions of $\lambda_{\Phi X}$ for [**BPI**] and different values of mass splittings (Δ). We take $\lambda_{HX} = 0$, $M_{H_1} = 10$GeV, and $s_\alpha = 10^{-4}$. All the curves satisfy the DM direct detection bound. *Bottom*: The preferred parameter space in the $(M_{H_1}, \lambda_{\Phi X})$ plane for different values of Δ. The gray area is excluded by the perturbative condition.

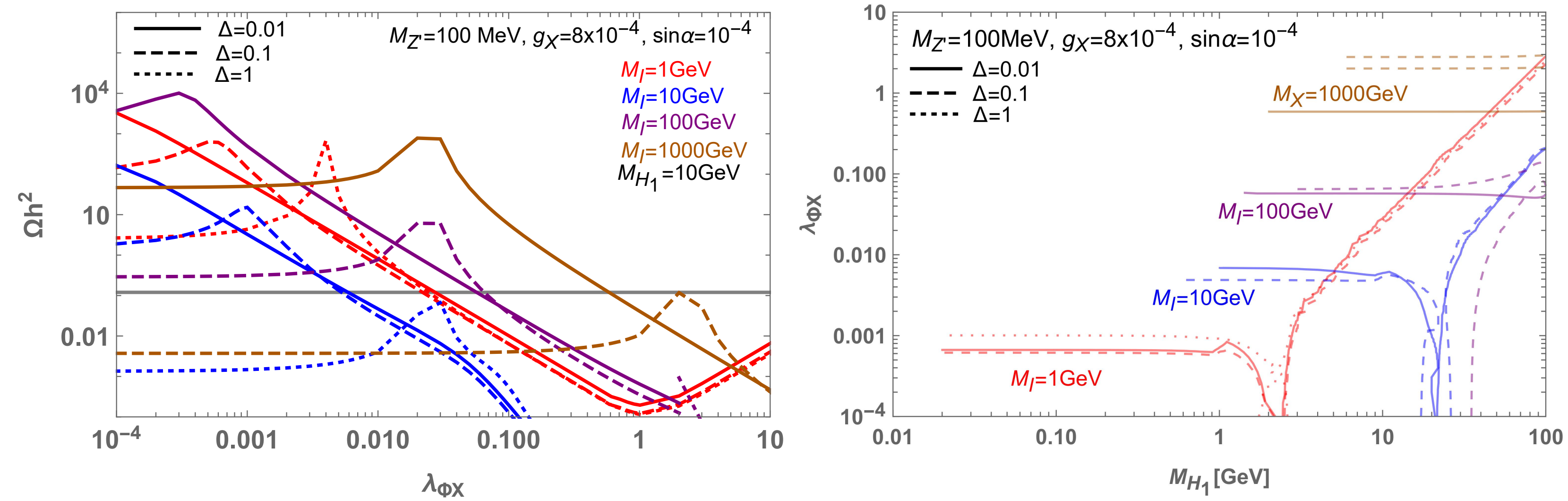


FIG. 9. (*Left*) Relic abundance of local Z_2 scalar DM in case of [**BPII**]. We take $\lambda_{HX} = 0$, $M_{H_1} = 10$GeV, and $s_\alpha = 10^{-4}$. All the lines satisfy the DM direct detection bound. (*Right*) Relic abundance of local Z_2 scalar DM in the $(M_{H_1}, \lambda_{\Phi X})$ plane.

DM mass : much wider range than $m_{Z'} \sim 2m_{\mathrm{DM}}$
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Dirac fermion DM:
$U(1)_{L_\mu - L_\tau} \to Z_2 \; (Q_\Phi = 2Q_\chi)$

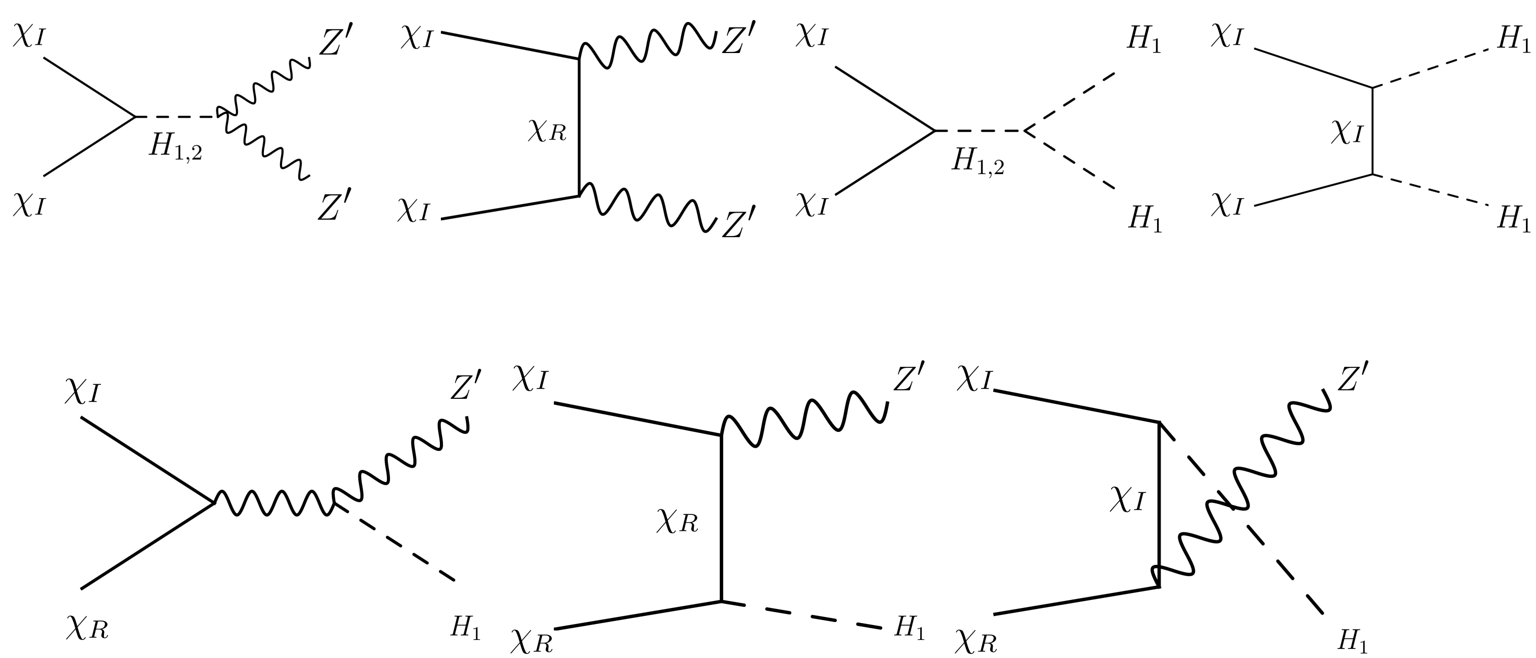

FIG. 5. Feynman diagrams of local Z_2 fermion DM (co-)annihilating into a pair of Z' bosons and H_1 bosons (*Top*), and $Z' + H_1$ (*Bottom*).

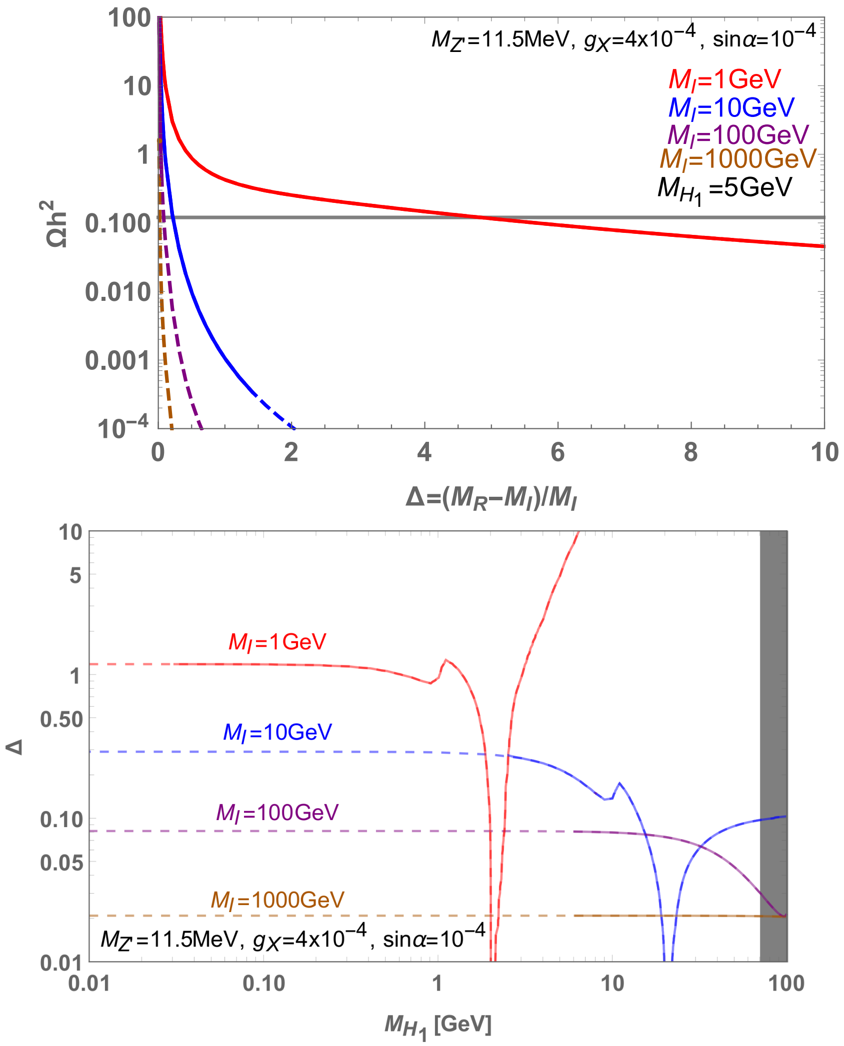

FIG. 6. *Top*: Dark matter relic density as functions of mass splitting Δ for [**BPI**] and for different values of DM mass, $M_I = 1, 10, 100, 1000$GeV. Solid (Dashed) lines denote the region where bounds on DM direct detection are satisfied (ruled out). *Bottom*: Preferred parameter space in the (M_{H_1}, Δ) plane for different DM masses. The gray region is ruled out by the perturbativity condition on λ_Φ.

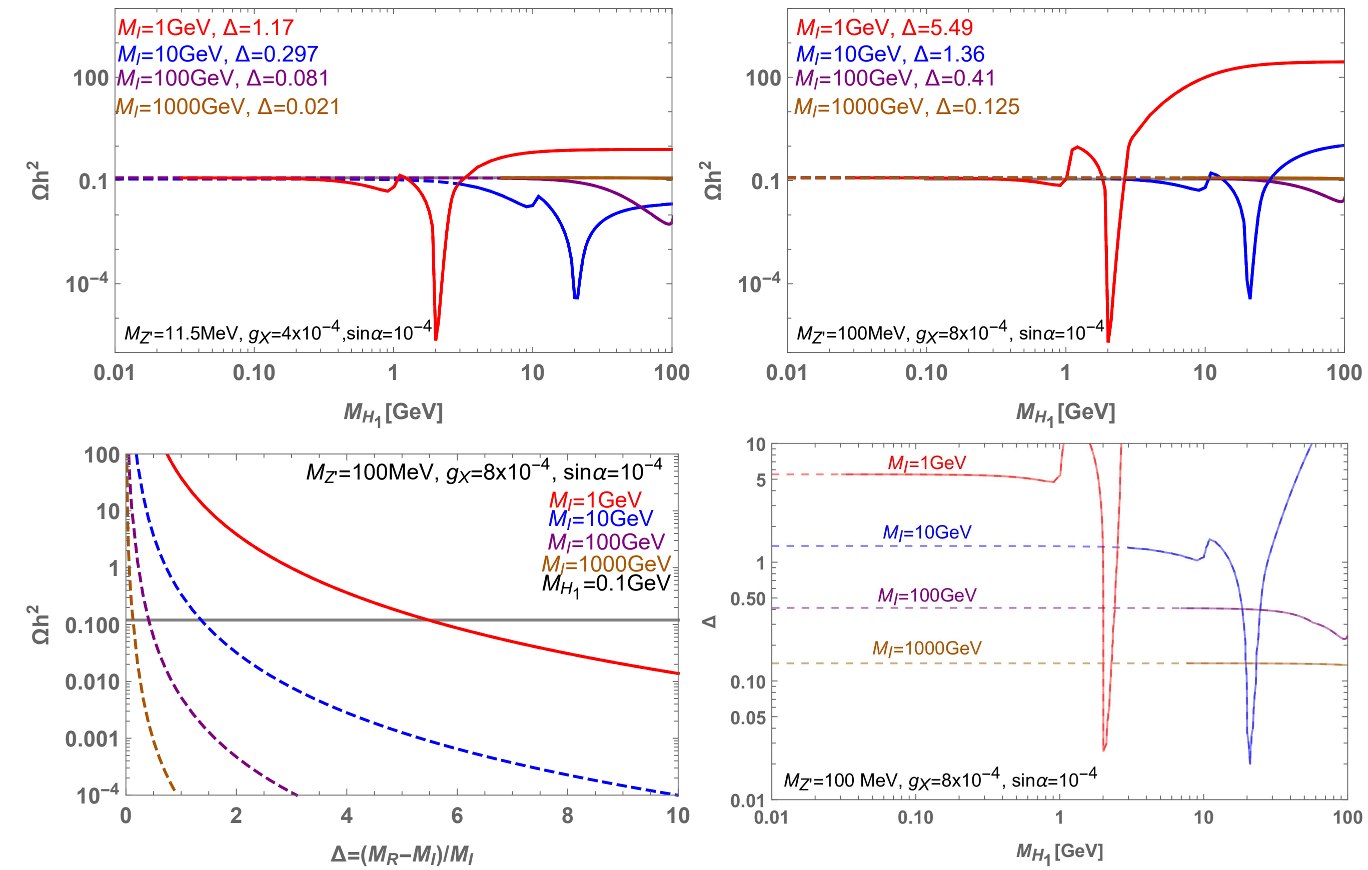

FIG. 11. (*Top*) Dark matter relic density as functions of dark Higgs mass M_{H_1} for [**BPI**] (*Left*) and [**BPII**] (*Right*) (*Bottom-Left*) Dark matter relic density as functions of Δ for [**BPII**], and *(Bottom-right)* Preferred parameter region in the (Δ, M_{H_1}) plane. Solid (Dashed) lines denote the region where bounds on DM direct detection are satisfied (ruled out).

DM mass : much wider range than $m_{Z'} \sim 2m_{\rm DM}$ due to dark Higgs boson contributions

Summary of this part

- DM physics with massive dark photon can not be complete without including dark gauge symmetry breaking mechanism, e.g. dark Higgs field ϕ, which have been largely ignored by DM community (or some ways other than dark Higgs to provide dark photon mass)

- Many examples show the importance of ϕ in DM phenomenology, astroparticle physics and cosmology

- Once ϕ is included, can accommodate the muon g-2 and thermal DM without the s-channel resonance condition $m_{Z'} \sim 2m_{\rm DM}$

- $m_{\rm DM}$: essentially free, whereas $m_{Z'} \sim O(10 - 100)$ MeV and $g_X \sim O(10^{-4})$ can explain the muon (g-2)

On Recent Belle II data on $B^+ \to K^+ \nu \bar{\nu}$

arXiv:2401.10112

With Shu-Yu Ho, Jongkuk Kim

$B^+ \to K^+\nu\bar{\nu}$ in the SM

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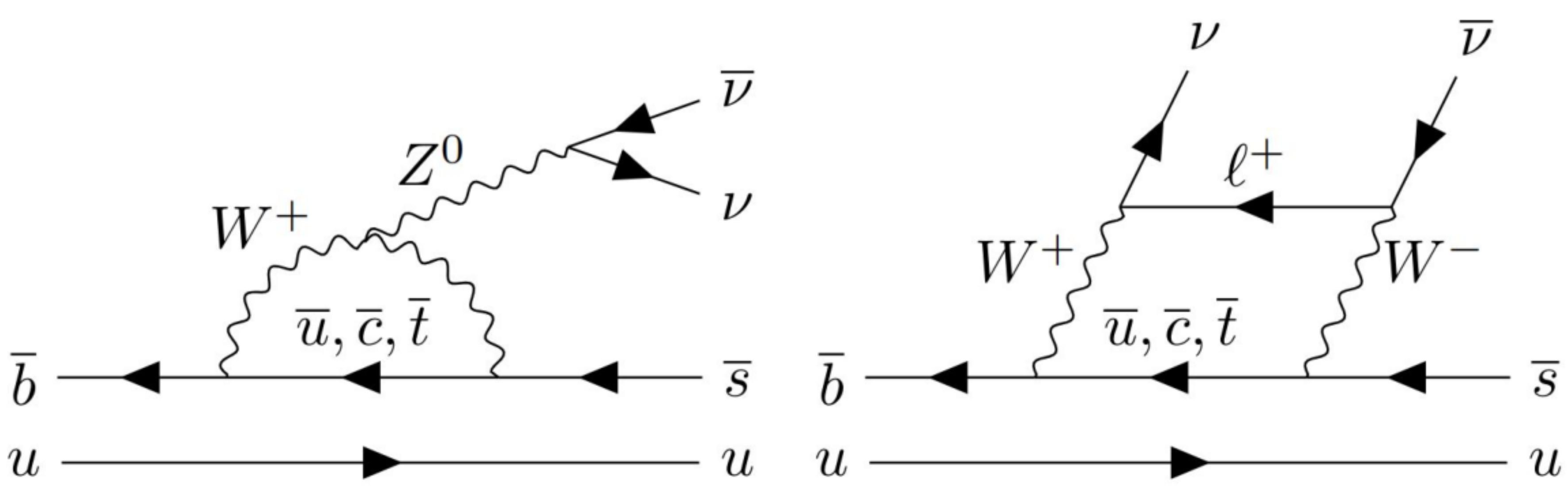
HPQCD, PRD 2023



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

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

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

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

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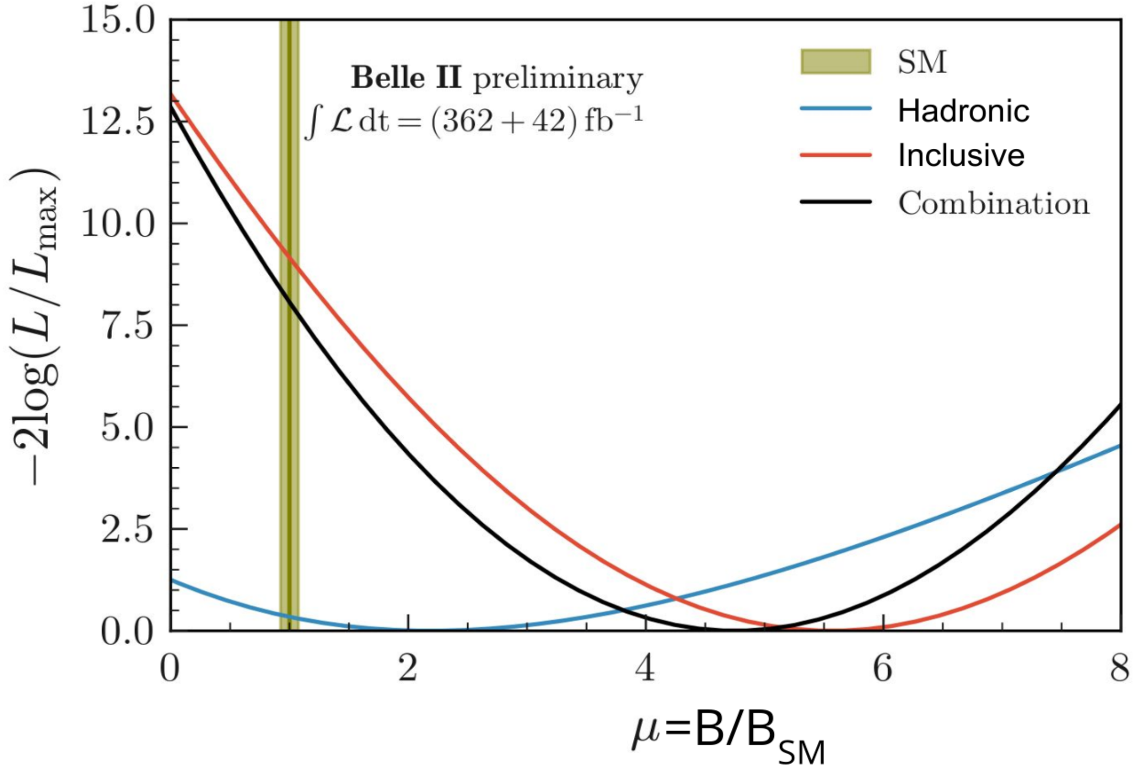
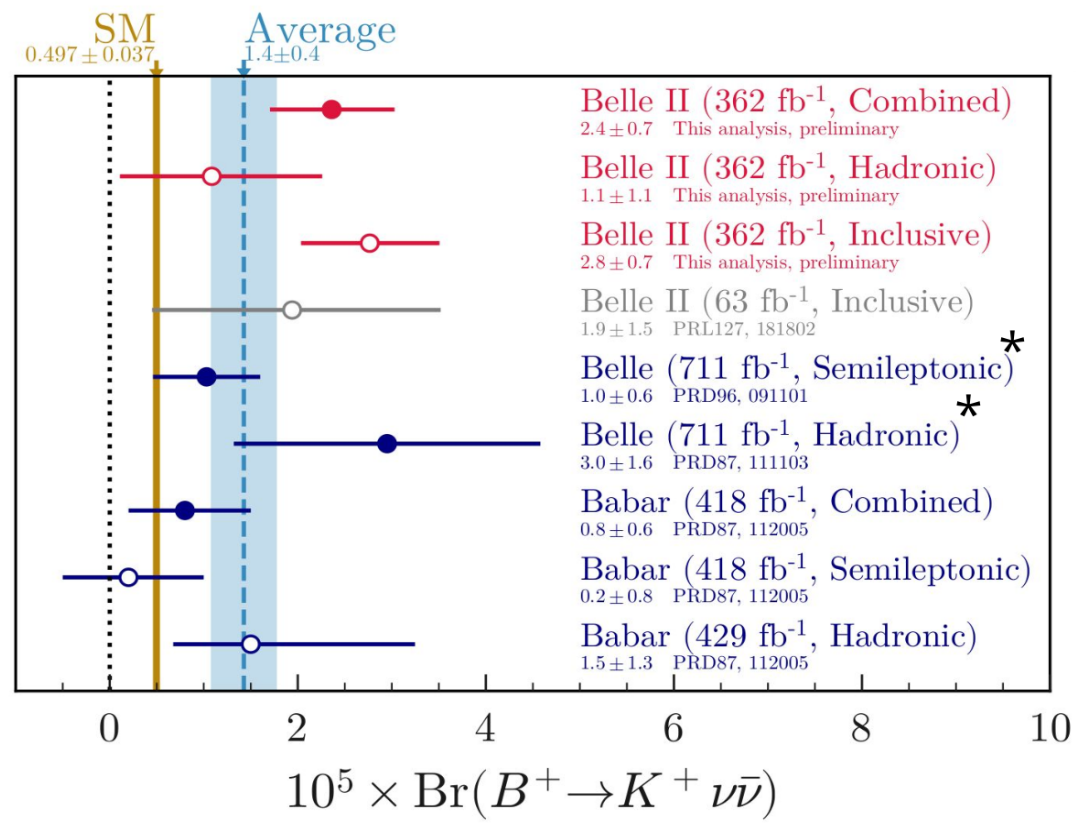
- Inclusive tag analysis (Belle & BelleII)
  - Allow one to reconstruct inclusively the decay $B^+ \to K^+\nu\bar{\nu}$ from the charged kaon





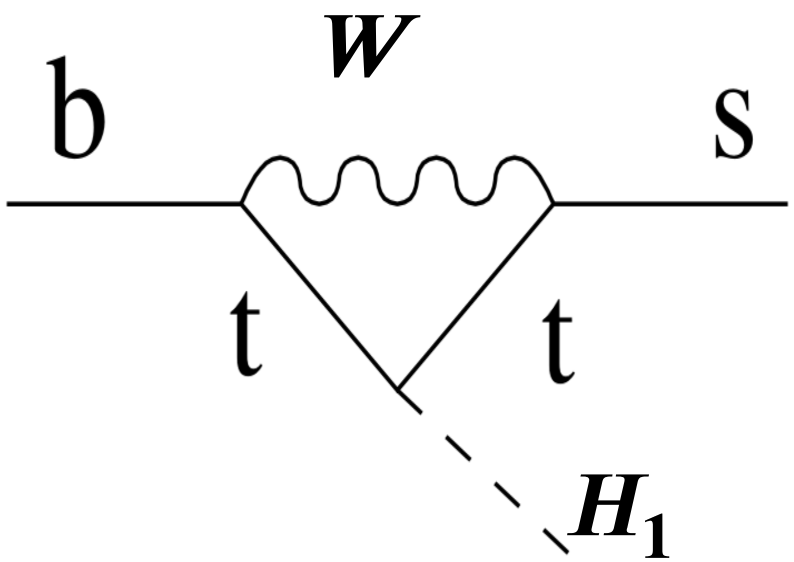
- $Br(B^+ \to K^+ \nu\bar{\nu}) = (2.4 \pm 0.7) \times 10^{-5}$
  - Significance of observation is 3.6σ
  - 2.8σ tension with the SM prediction
- $Br(B^+ \to K^+ E_{\text{miss}})_{NP} = (1.9 \pm 0.7) \times 10^{-5}$
- Indicate not only the presence of NP in the $b \to s\nu\bar{\nu}$ transitions but even the presence of new light states (particles in dark sector?)

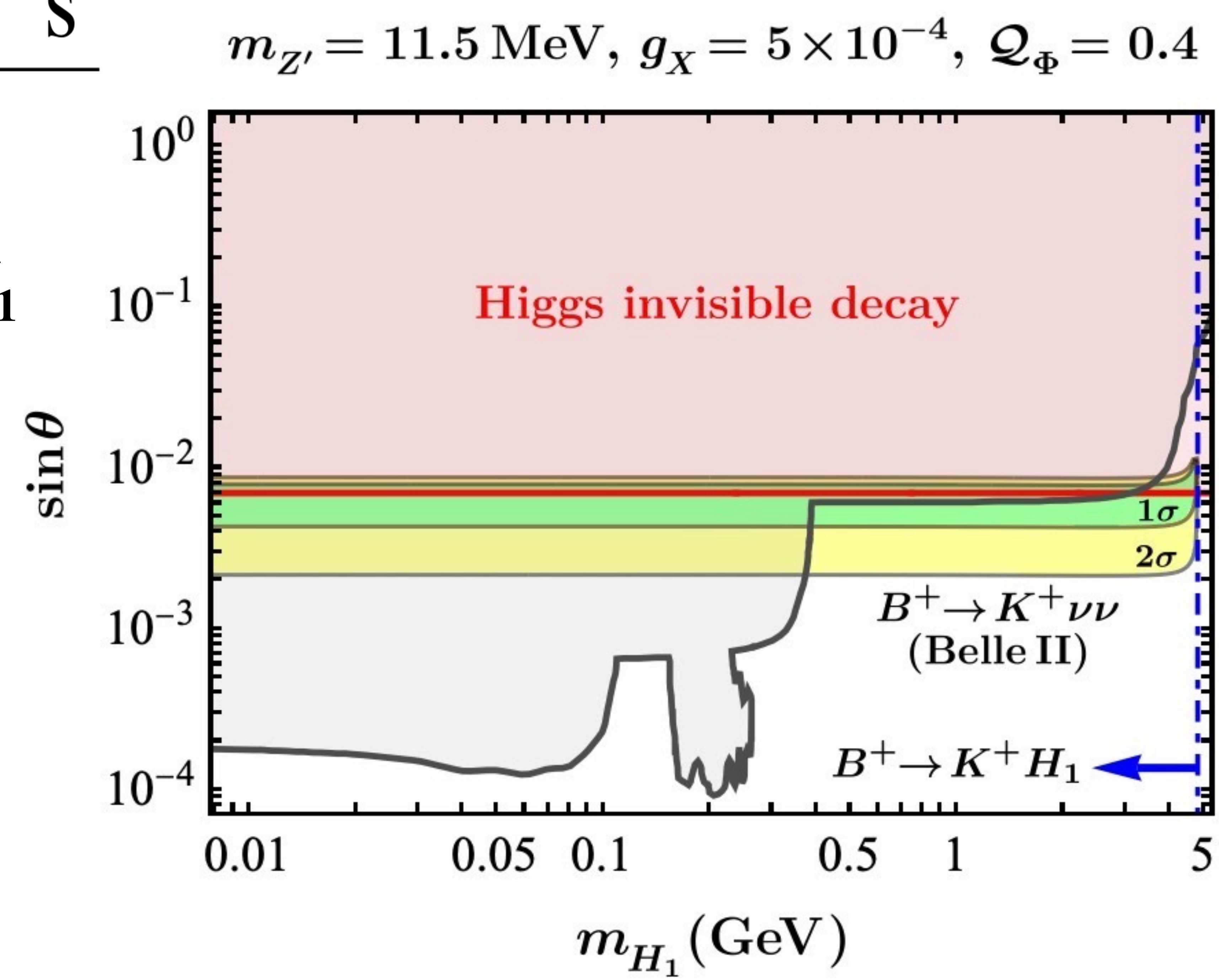
CMB constraints

- Dominant DM annihilation channel
  - Before resonance, $XX^* \to Z'Z', h_1 h_1$
  - Near resonance, $XX^* \to Z'h_1$
  - After resonance, $XX^* \to Z'Z'$
- h_1 dominantly decays into a pair of either Z' or DM (kinematically open when $m_{h_1} > 2m_X$)
- We can avoid the stringent CMB bound thanks to invisible decay of both h_1 and Z'

Belle II anomaly: two-body decay

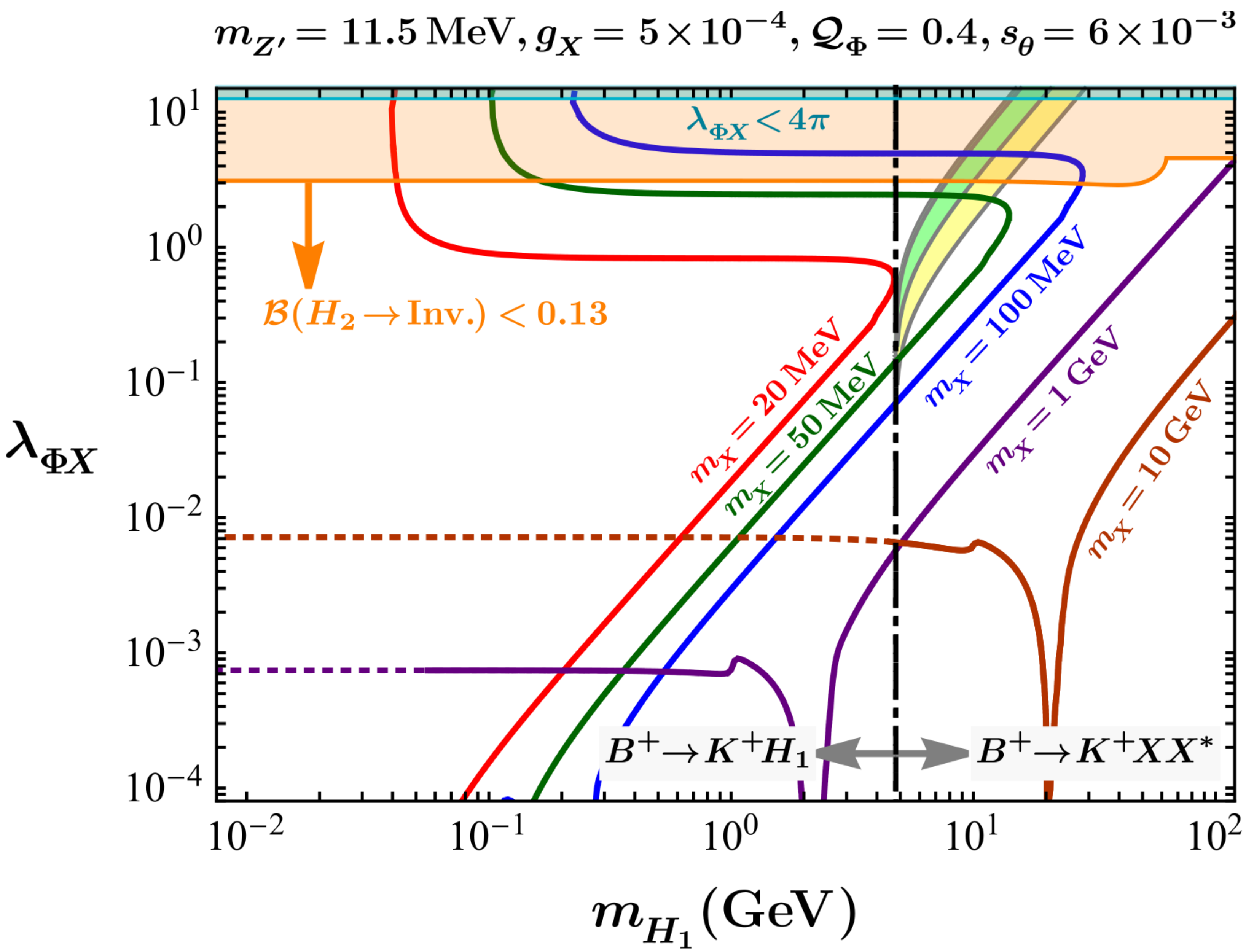
- When $m_{H_1} < m_B - m_K$, two-body decay
-





Belle II anomaly: three-body decay

- When $m_{H_1} > m_B - m_K$, H_2 is off-shell → three-body decay
  - Two-body decay: $m_X \lesssim 6.5\text{GeV}\ (m_{H_1} = 2\text{GeV})$
  - Three-body decay: $20\text{MeV} < m_X \lesssim 60\text{MeV}\ (m_{H_1} > m_B - m_K)$



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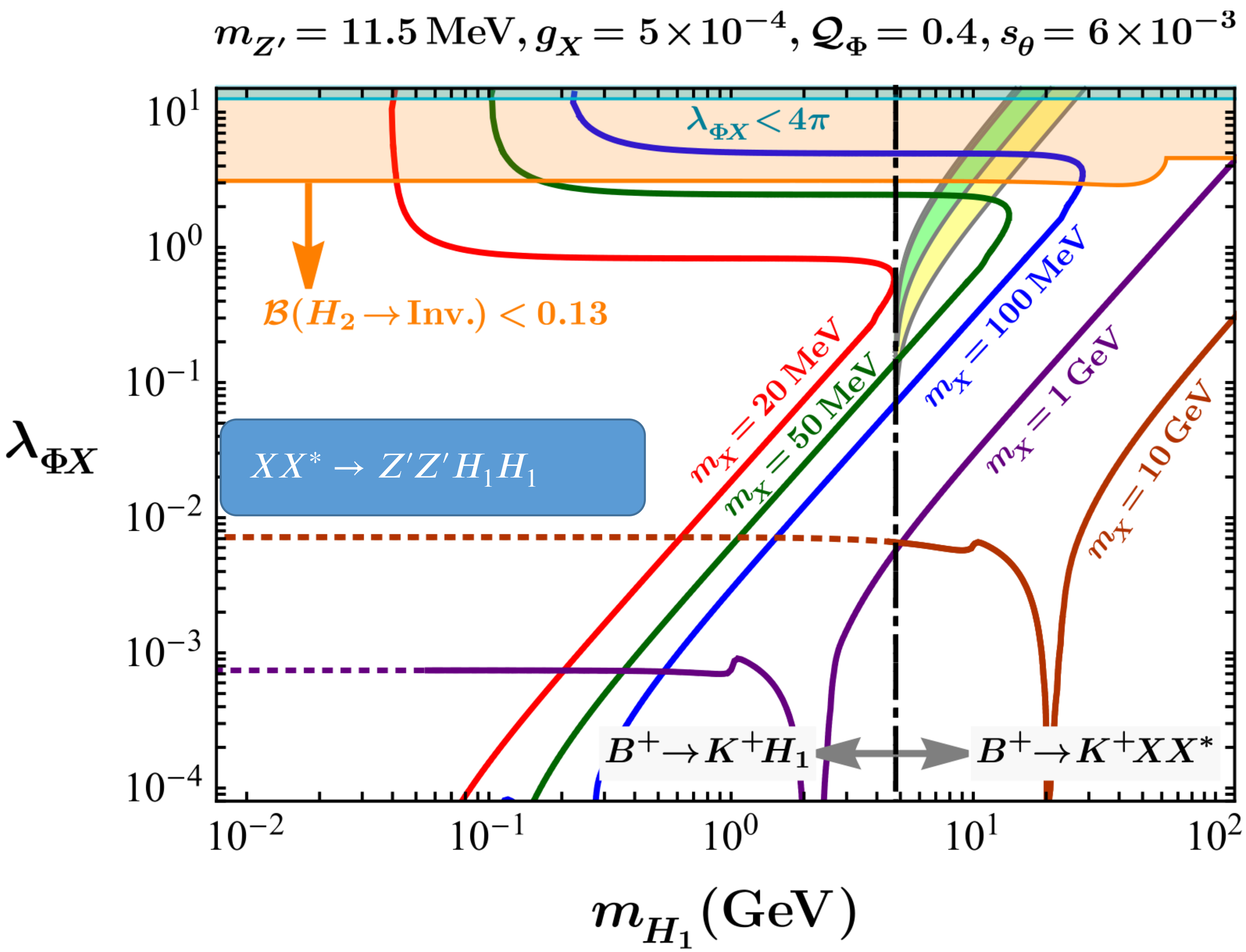

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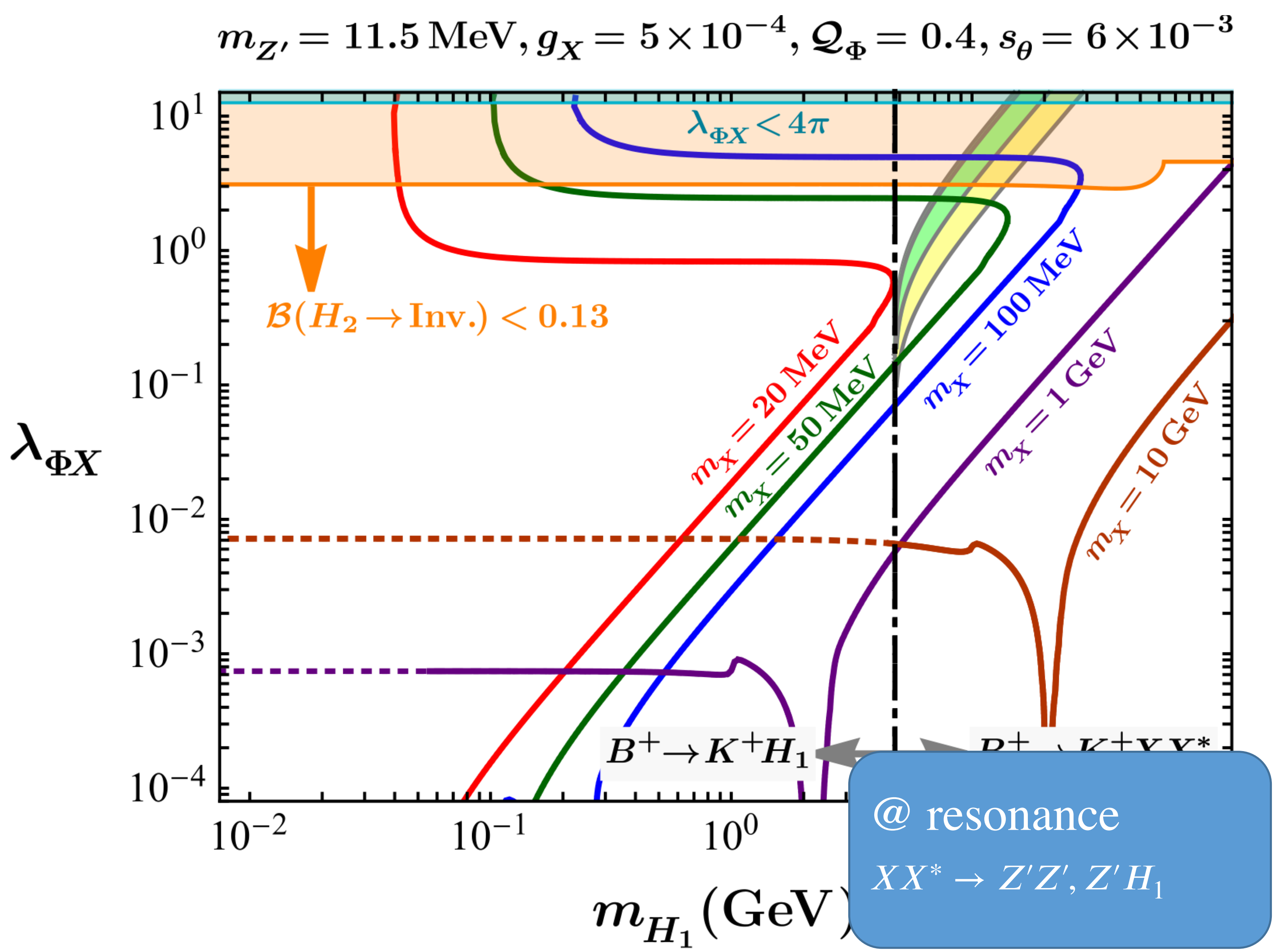

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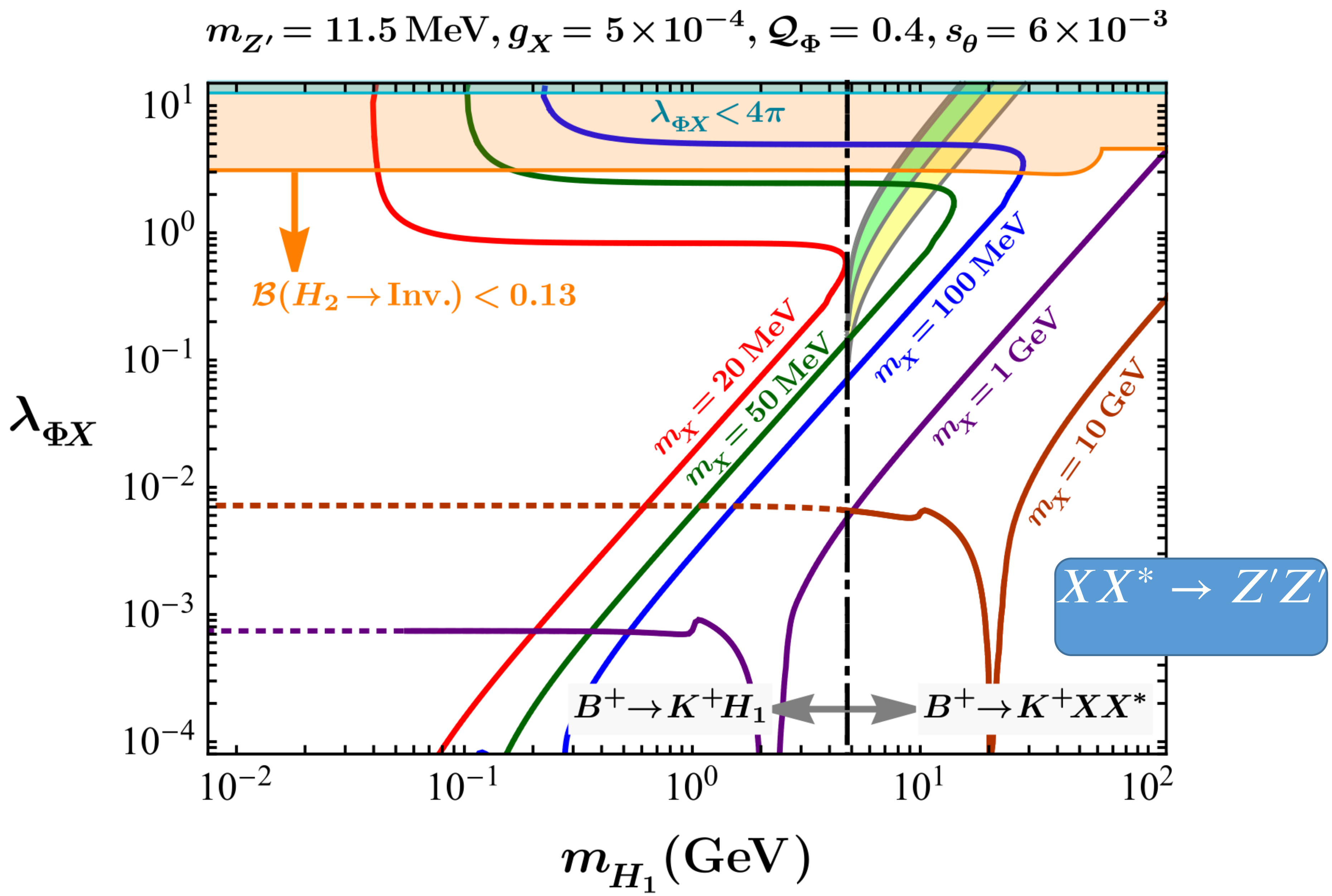

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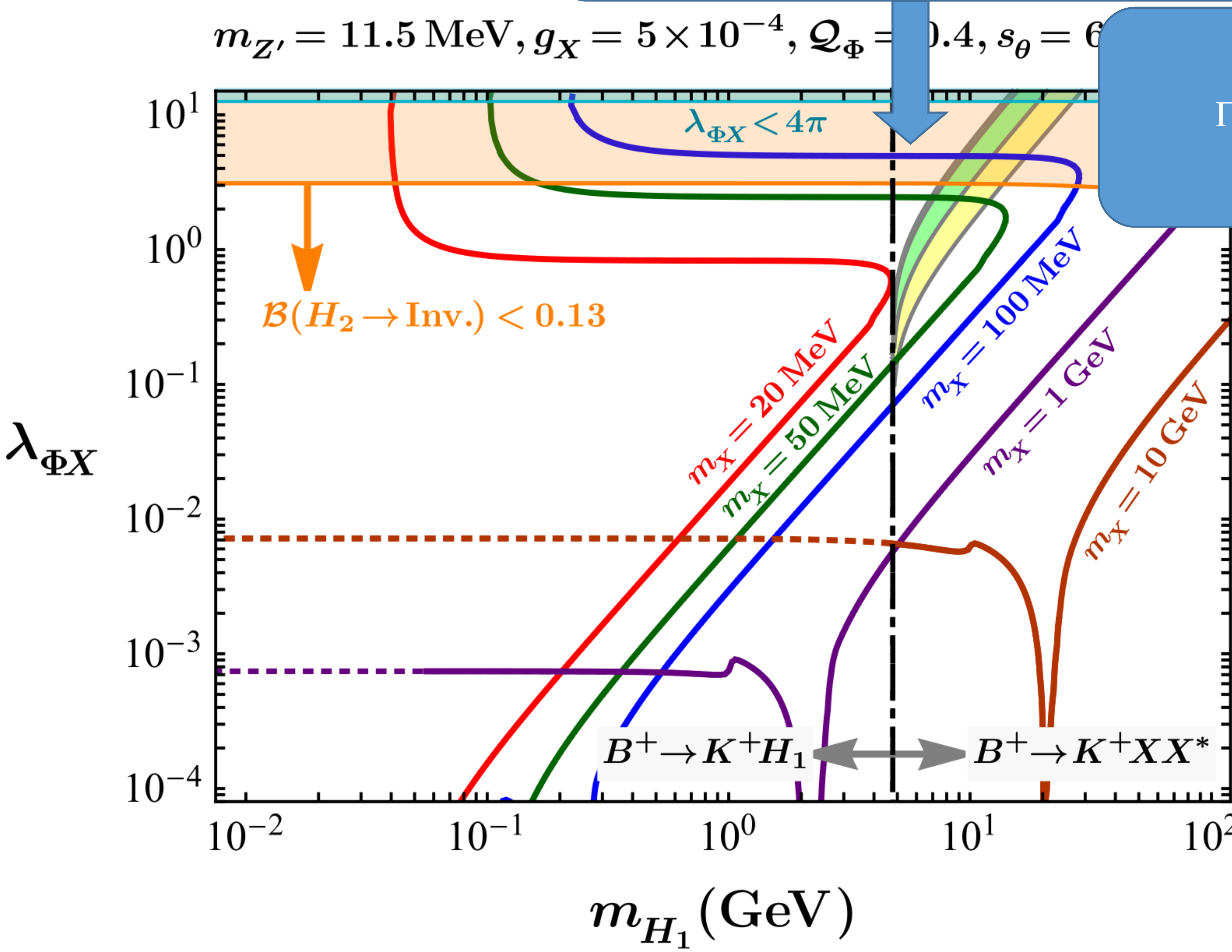
$$\sigma v \simeq \frac{\lambda_{\Phi X}^2}{16\pi m_X^2}\frac{4m_X^4 - 4m_X^2 m_{Z'}^2 + 3m_{Z'}^4}{(4m_X^2 - m_{H_1}^2)^2 + m_{H_1}^2\Gamma_{H_1}^2}\sqrt{1-\frac{m_{Z'}^2}{m_X^2}}$$

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



Belle II anomaly: three-body decay

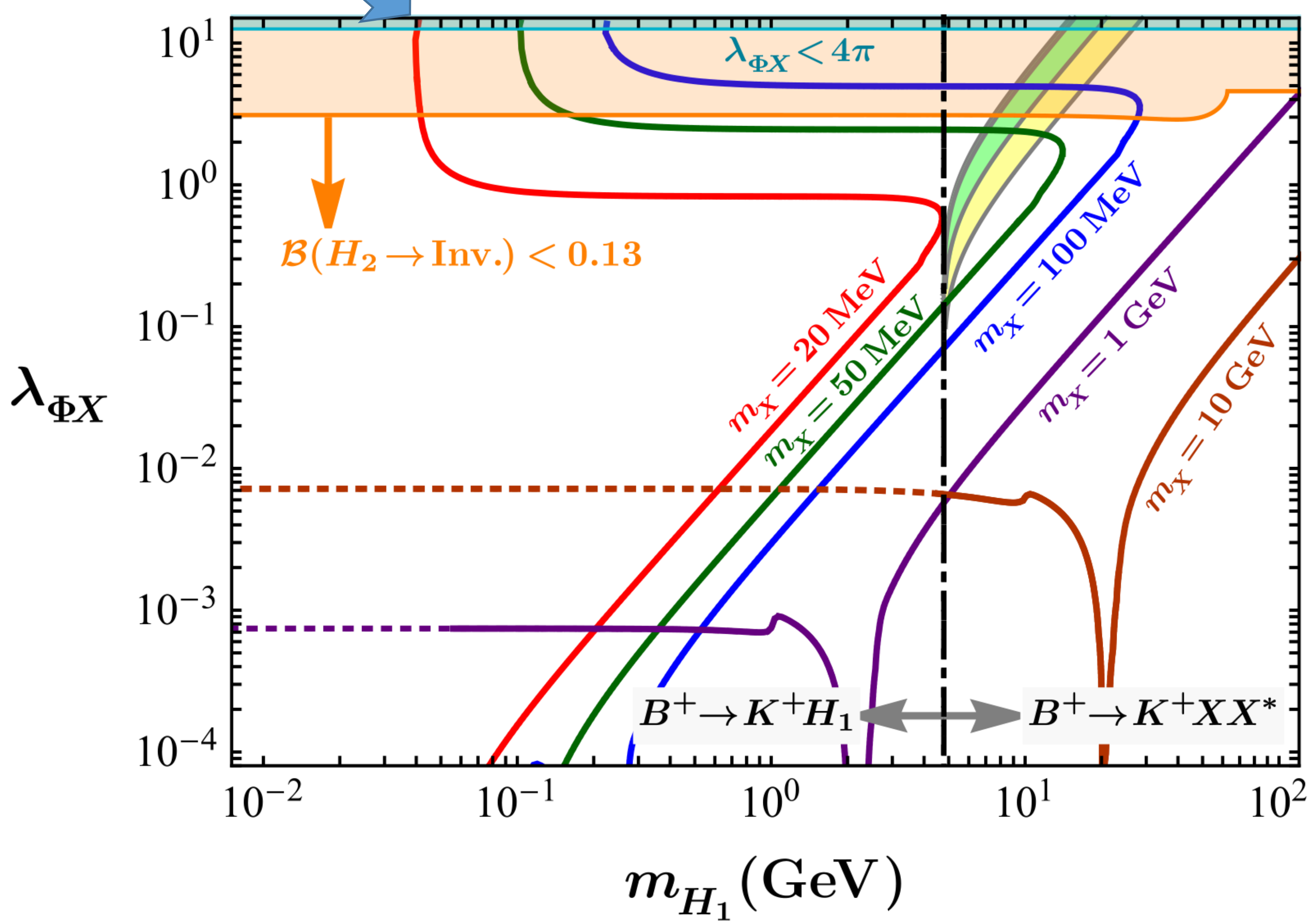
$$\Gamma_{H_1} = \frac{\lambda_{\Phi X}^2 v_\Phi^2}{16\pi\, m_{H_1}} \sqrt{1 - \frac{4m_X^2}{m_{H_1}^2}} \quad \sigma v \propto \frac{\lambda_{\Phi X}^2}{m_{H_1}^2 \Gamma_{H_1}^2}$$

Phase-space suppression

ee-body decay

$_B - m_K)$

$m_{Z'}$ = 1.5 MeV, $g_X = 5\times 10$, $Q_\Phi = 0.4$, $s_\theta = 6\times 10^{-3}$



Conclusion

- Belle II data shows a mild excess of $B^+ \to K^+ \nu\bar{\nu}$ over the SM prediction

- This mild excess can be interpreted as $B^+ \to K^+$ + dark sector particles through a dark Higgs portal: a pair of scalar DM, a pair of Z' decaying into a pair of neutrinos, both of which are invisibles in $U(1)_{L_\mu - L_\tau}$ models with complex scalar DM

- Can accommodate the muon g-2, and relax the tension in the Hubble parameter with extra dark radiation

Back Up

Local dark gauge symmetry

- Better to use local gauge symmetry for DM stability
  (Baek,Ko,Park,arXiv:1303.4280)

- Success of the Standard Model of Particle Physics lies in “local gauge symmetry” without imposing any internal global symmetries
- Electron stability : U(1)em gauge invariance, electric charge conservation, massless photon
- Proton longevity : baryon # is an accidental sym of the SM
- No gauge singlets in the SM ; all the SM fermions chiral

- Dark sector with (excited) dark matter, dark radiation and force mediators might have the same structure as the SM
- “(Chiral) dark gauge theories without any global sym”
- Origin of DM stability/longevity from dark gauge sym, and not from dark global symmetries, as in the SM
- Just like the SM (conservative)

In QFT,

- DM could be absolutely stable due to unbroken local gauge symmetry (DM with local Z_2, Z_3 etc.) or topology (hidden sector monopole + vector DM + dark radiation)
- Longevity of DM could be due to some accidental symmetries (Strongly interacting hidden sector (DQCD), dark pions and dark baryons : Ko et al (2007))
- Kinematically long-lived if DM is very light (axion, sterile ν_s , etc..)