Heavy QCD Axion at Belle II

PHENO 2022

Speaker: Vazha Loladze

arXiv:2102.04474 S. Chakraborty, M. Kraus, **V. L.** , T. Okui, K.Tobioka
arXiv:2108.10331 E. Bertholet, S. Chakraborty, **V. L.** , T. Okui, A. Soffer, K. Tobioka

Standard QCD Axion

- The compelling solution for **Strong CP** problem
- Pseudo nambu-goldstone boson of spontaneously broken **PQ** symmetry
- Very predictive! $\mathbf{m_a} = \frac{m_\pi f_\pi}{f_a}$

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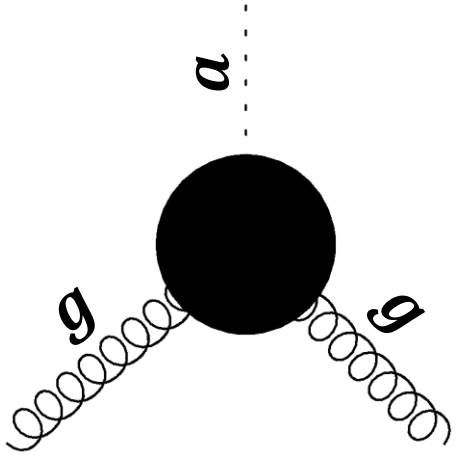
- For $f_a > 10$ TeV QG ruins PQ mechanism (Quality Problem)

Heavy QCD Axion

1. Is heavy m_a~GeV $\gg m_\pi f_\pi / f_a$=>
   large parameter space is experimentally allowed! (f_a <10 TeV allowed => **No QP!**)

2. Solves strong CP problem

3. The dominant coupling to SM



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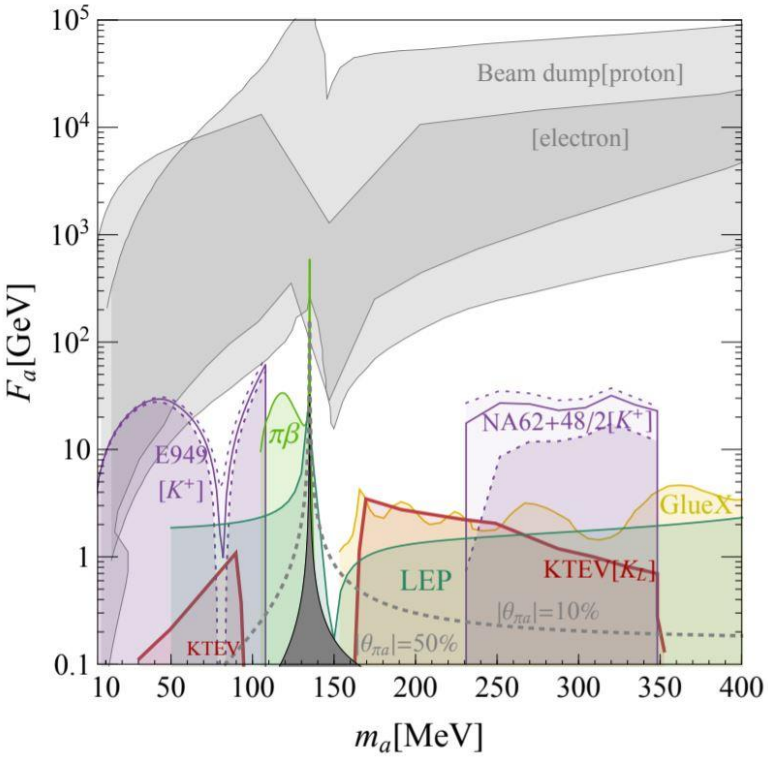
3. The dominant coupling to SM through gluons

Many models can reproduce this scenario:

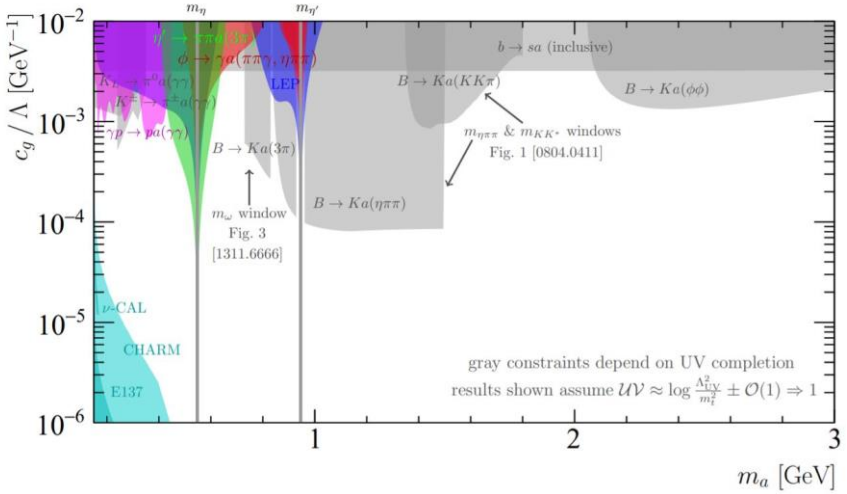
- **H. Fukuda, K. Harigaya, M. Ibe, T. T. Yanagida**
  arXiv: 1504.06084
- **P. Agrawal, K. Howe**
  arXiv: 1710.04213
- **P. Agrawal, G. Marques-Tavares, W. Xue**
  arXiv: 1708.05008
- **M.K. Gaillard, M.B. Gavela, R. Houtz, P. Quilez, R. del Rey**
  arXiv: 1805.06465
- **T. Gherghetta, V. V. Khoze, A. Pomarol, Y. Shirman**
  arXiv: 2001.05610
- **R.S. Gupta, V.V. Khoze, M. Spannowsky**
  arXiv: 2012.00017

Existing Experimental Search

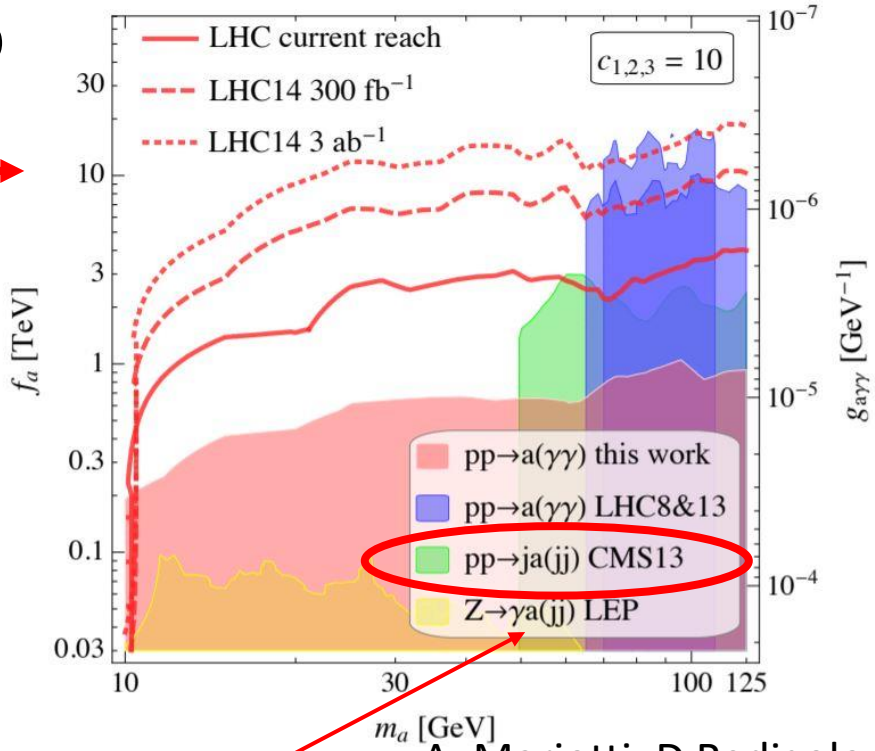


S. Gori, G. Perez,
K. Tobioka
arXiv: 2005.05170

Gap at few× 100 MeV to 50 GeV



D. Aloni, Y. Soreq, M.
Williams arXiv:1811.03474



Starts at 50 GeV

A. Mariotti, D.Redigolo,
F. Sala, K. Tobioka
arXiv: 1710.01743

m_a~GeV scale axion

$B \to K^{(*)} a$ - unique probe at $m_a \sim$ GeV:

1. **The correct mass!**

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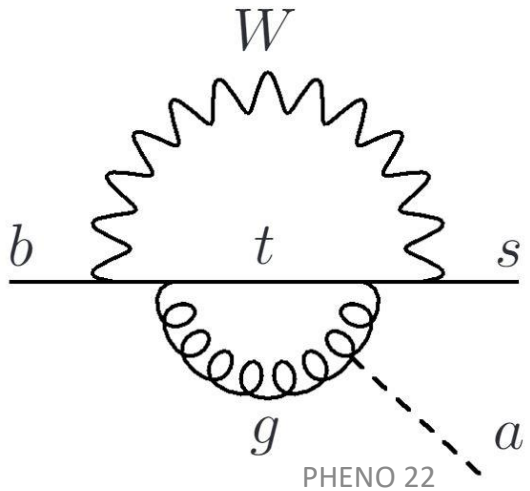
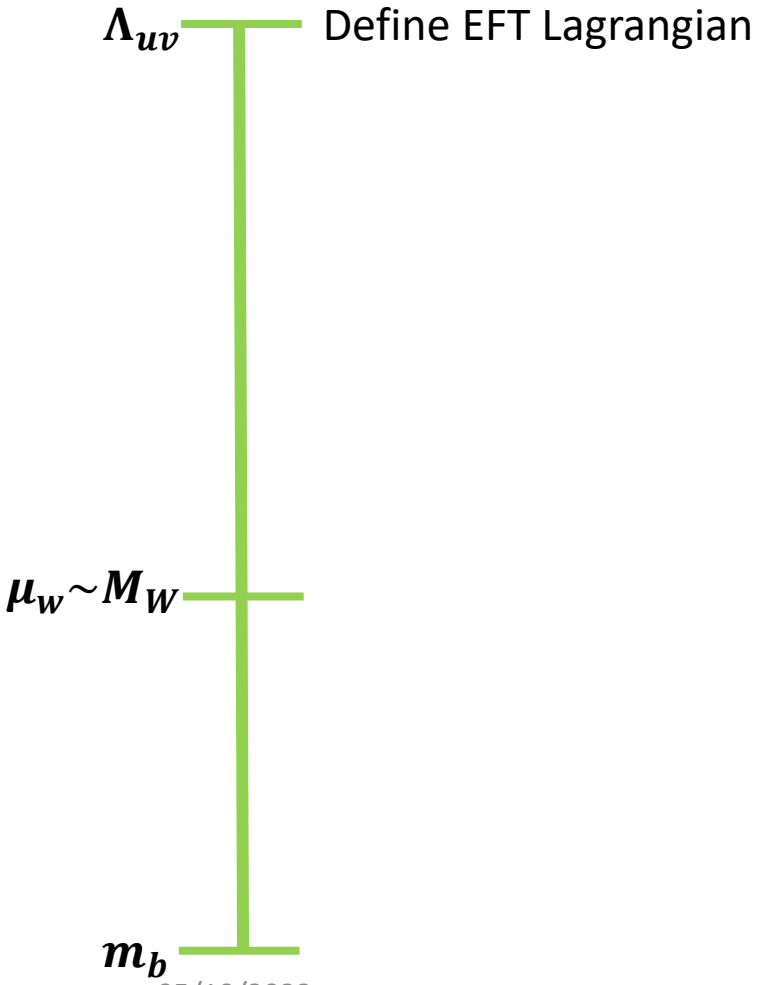
Leading order contribution to $B \to Ka$ comes at two loop level



EFT Framework for production

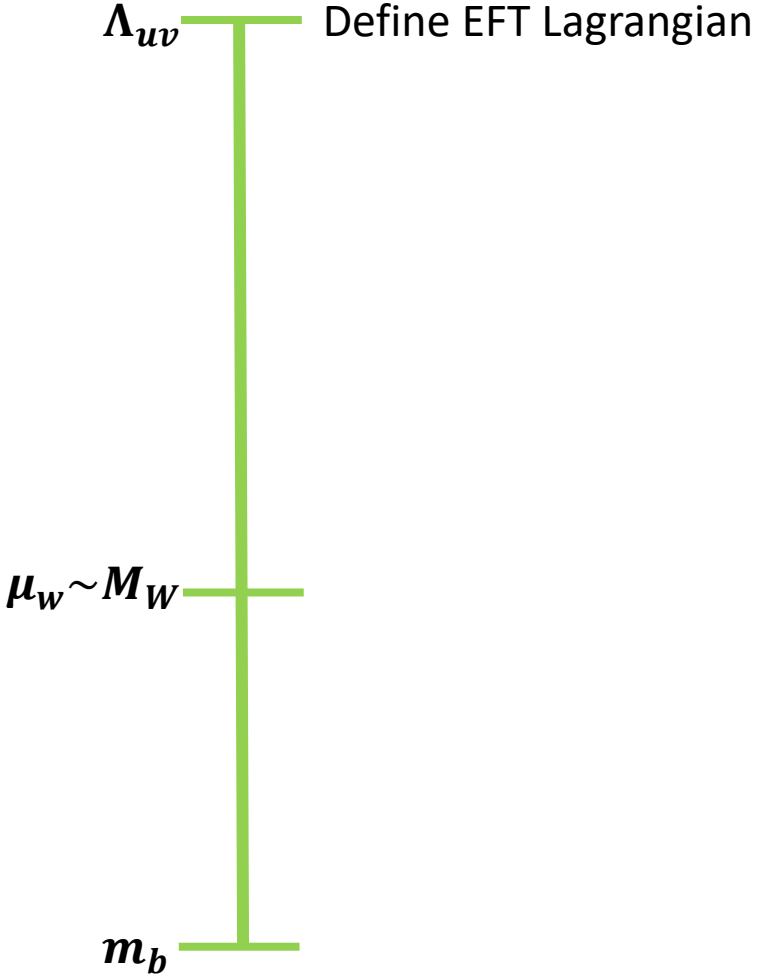


Define EFT Lagrangian

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{\alpha_s}{8\pi}\frac{a}{f_a} G^a_{\mu\nu}\tilde{G}^{a\mu\nu} + \frac{1}{2}\left(\partial_\mu a\right)^2 - \frac{m_a^2}{2}a^2$$

Dominant coupling to SM, **dim-5 operator**

EFT Framework for production



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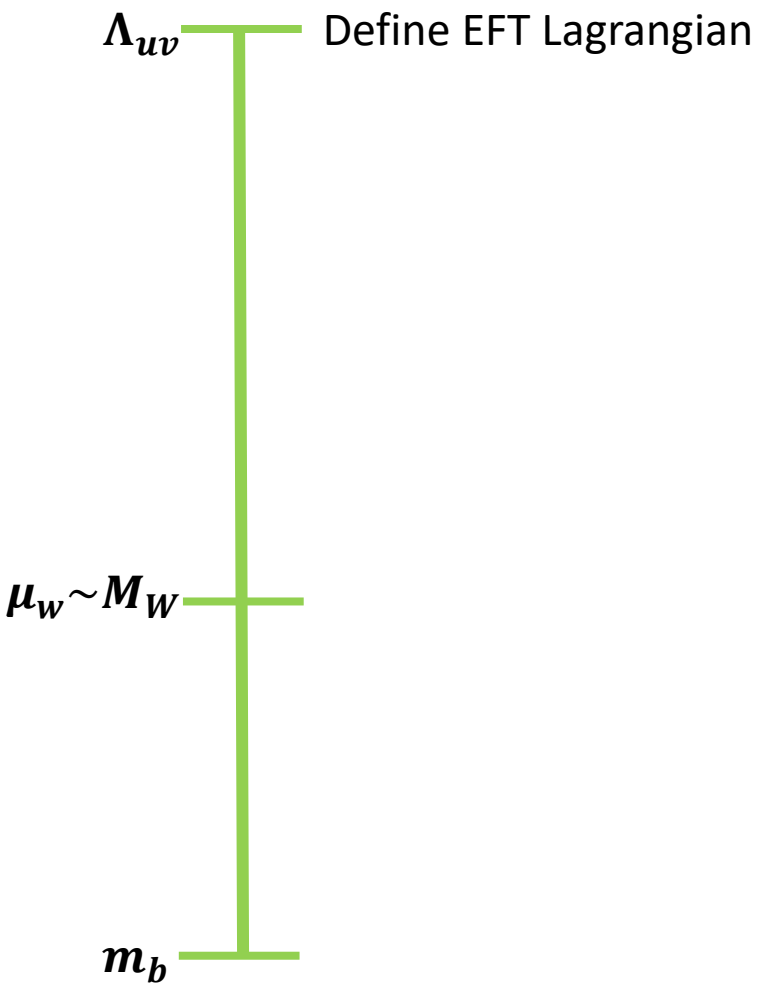
Other dim-5 operators to absorb divergences

EFT Framework for production



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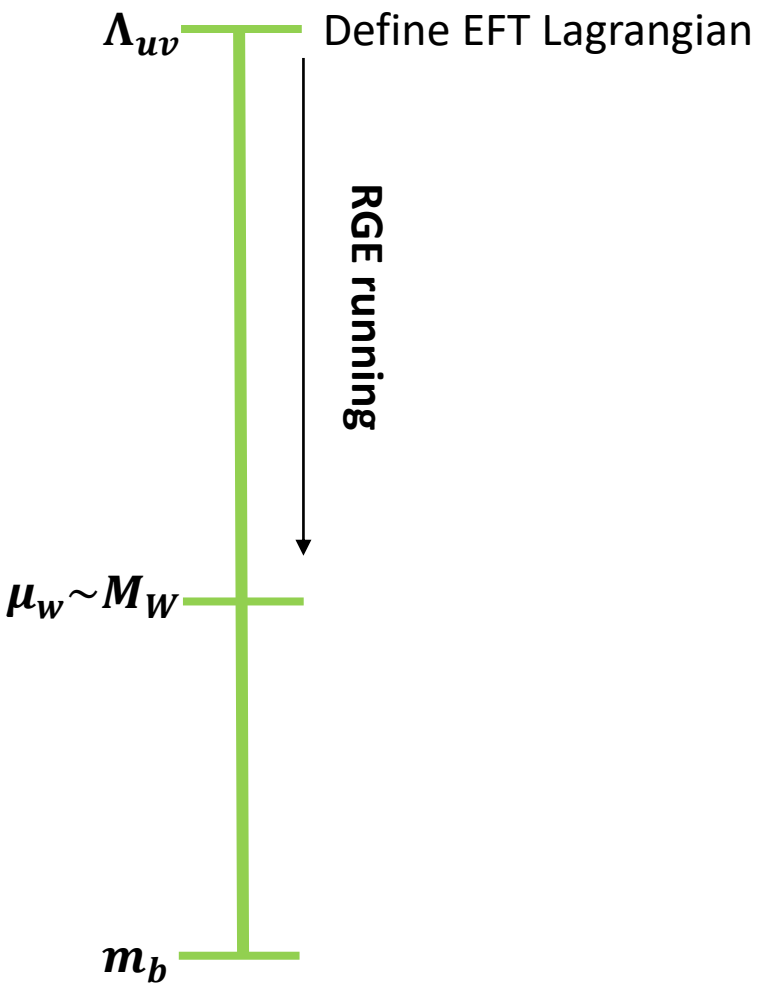
$$C_{qq}(\Lambda_{UV}) = A\,C_F\left(\frac{\alpha_s}{4\pi}\right)^2 \qquad C_{bs}(\Lambda_{UV}) = BC_F\left(\frac{\alpha_s}{4\pi}\right)^2\frac{\alpha_w}{4\pi}\sum_k V_{ik}V_{kj}^*\frac{m_k}{M_w}$$

Natural size for Wilson coefficients

EFT Framework for production



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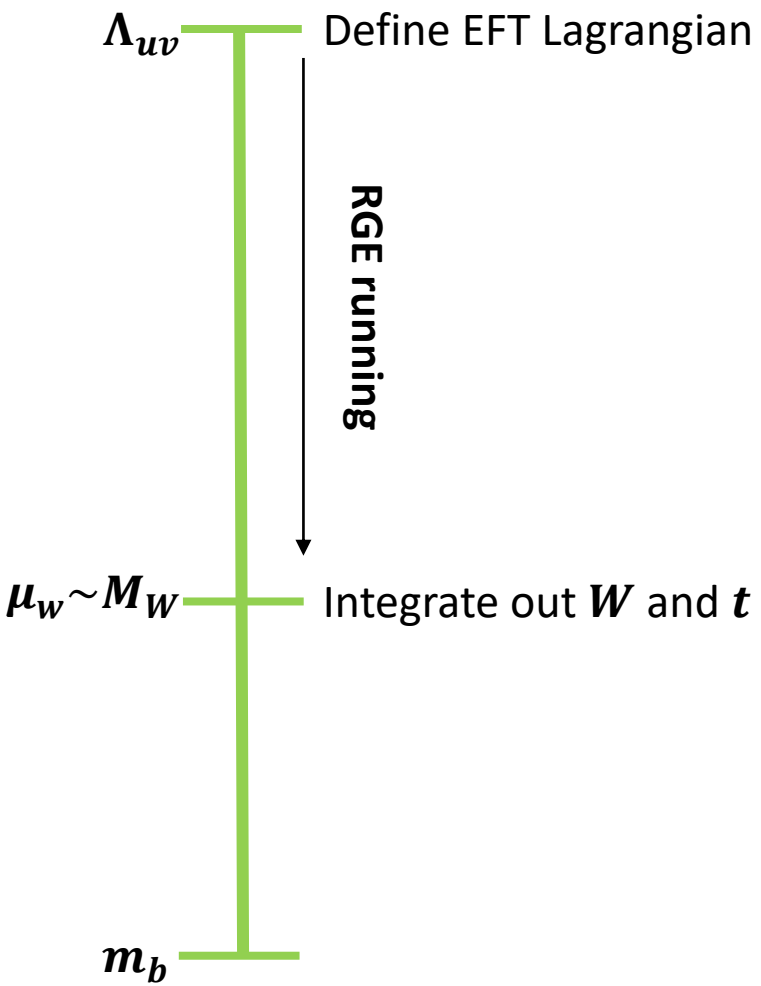

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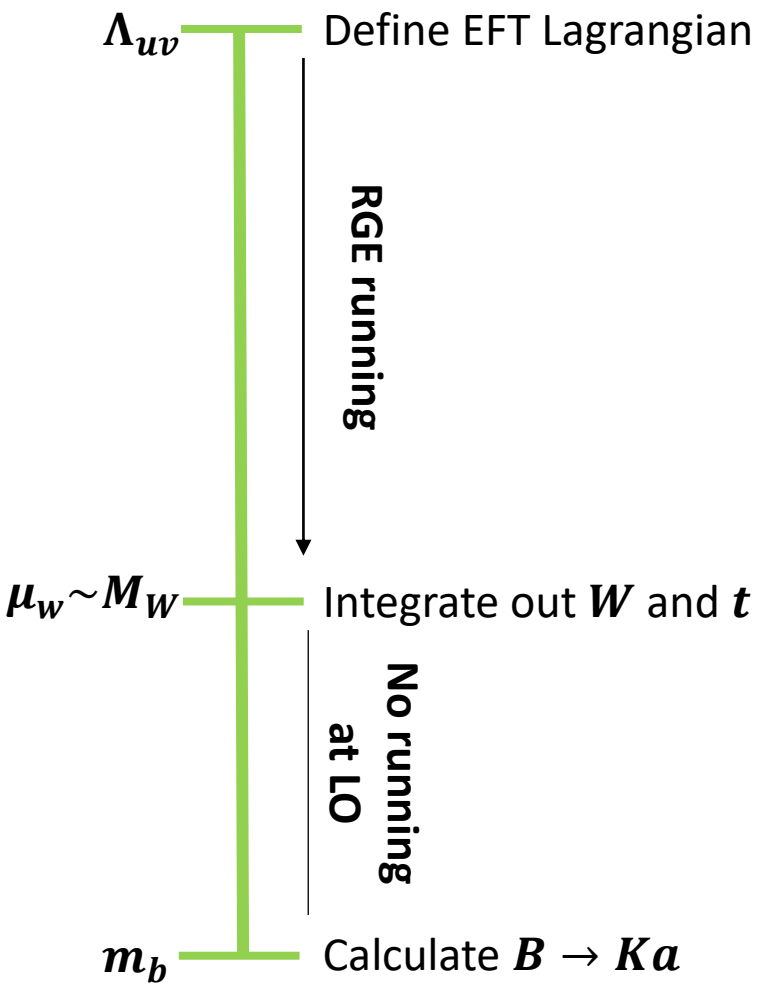

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Hadronic level cross section is calculated using **Light-Cone QCD Sum Rules**

arXiv: hep-ph/0412079, hep-ph/0406232, 0911.4938 ,1611.09355

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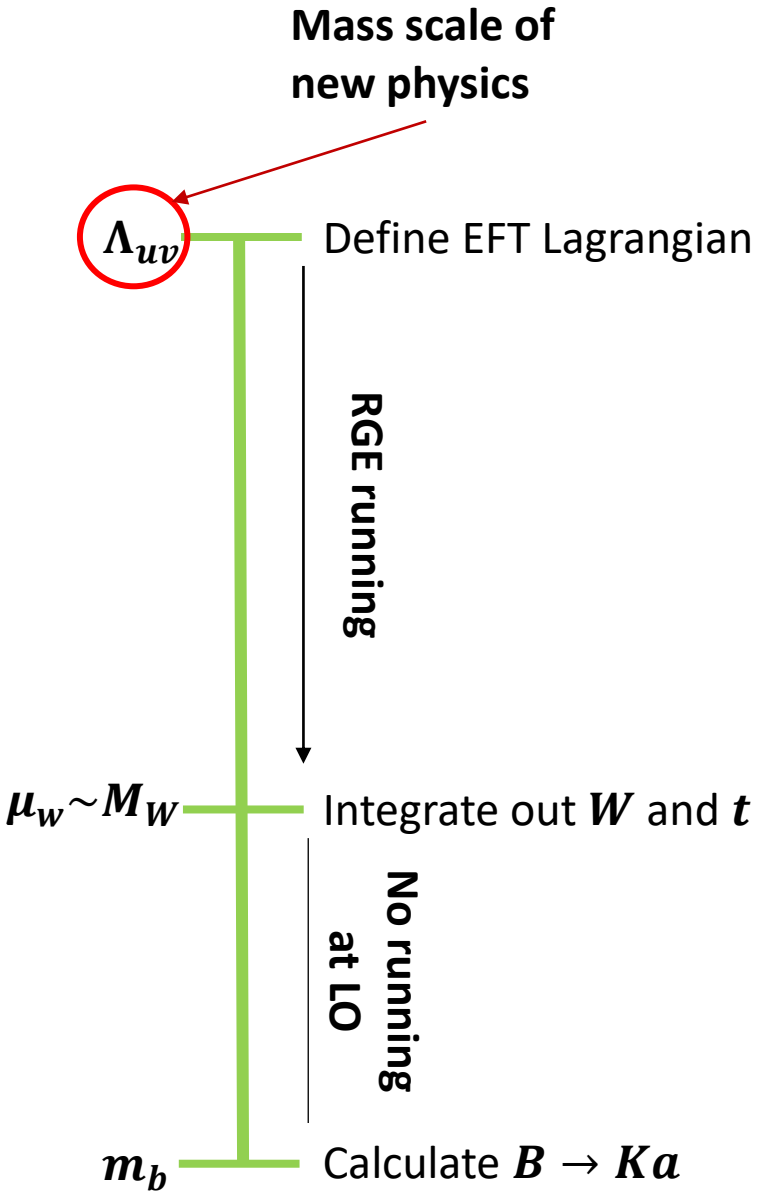

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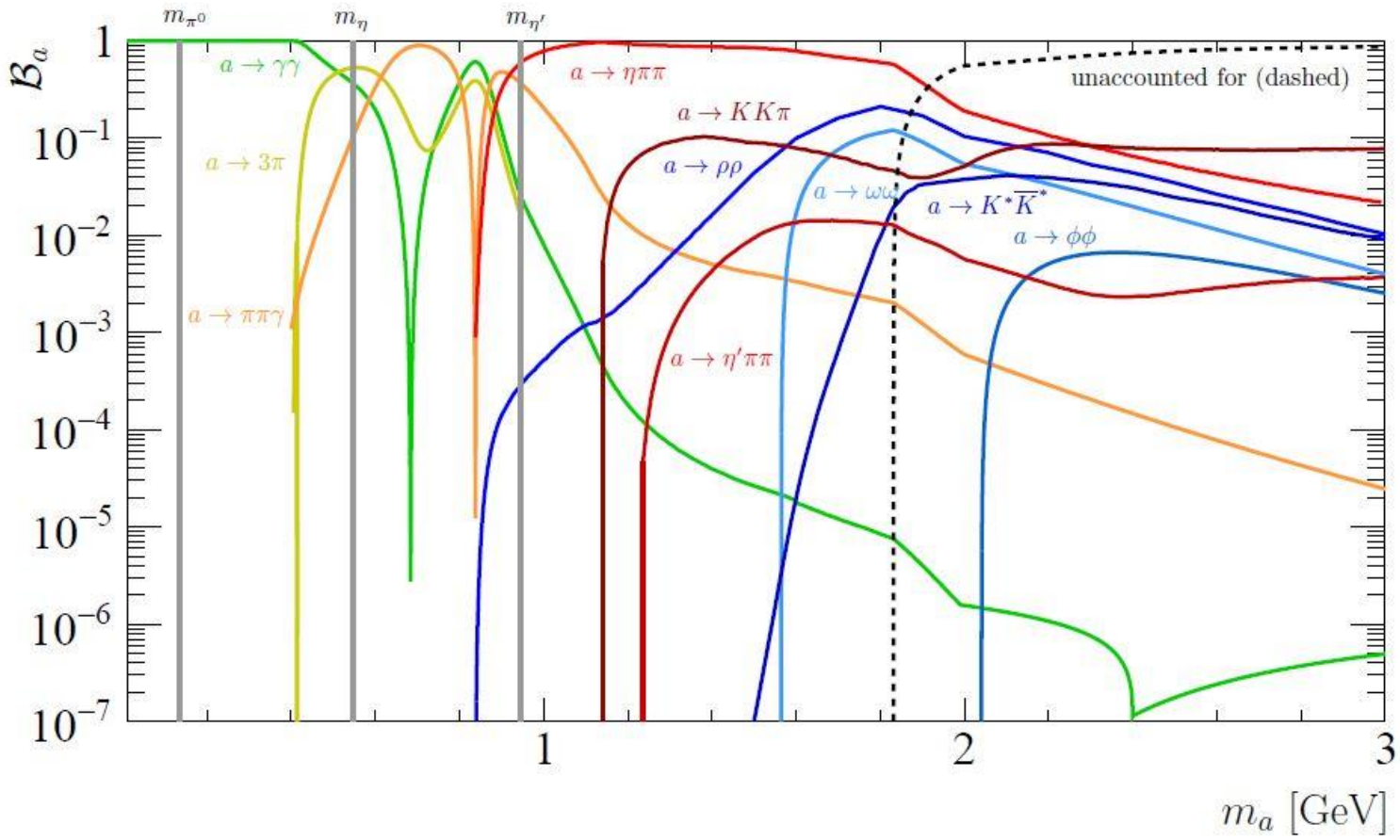
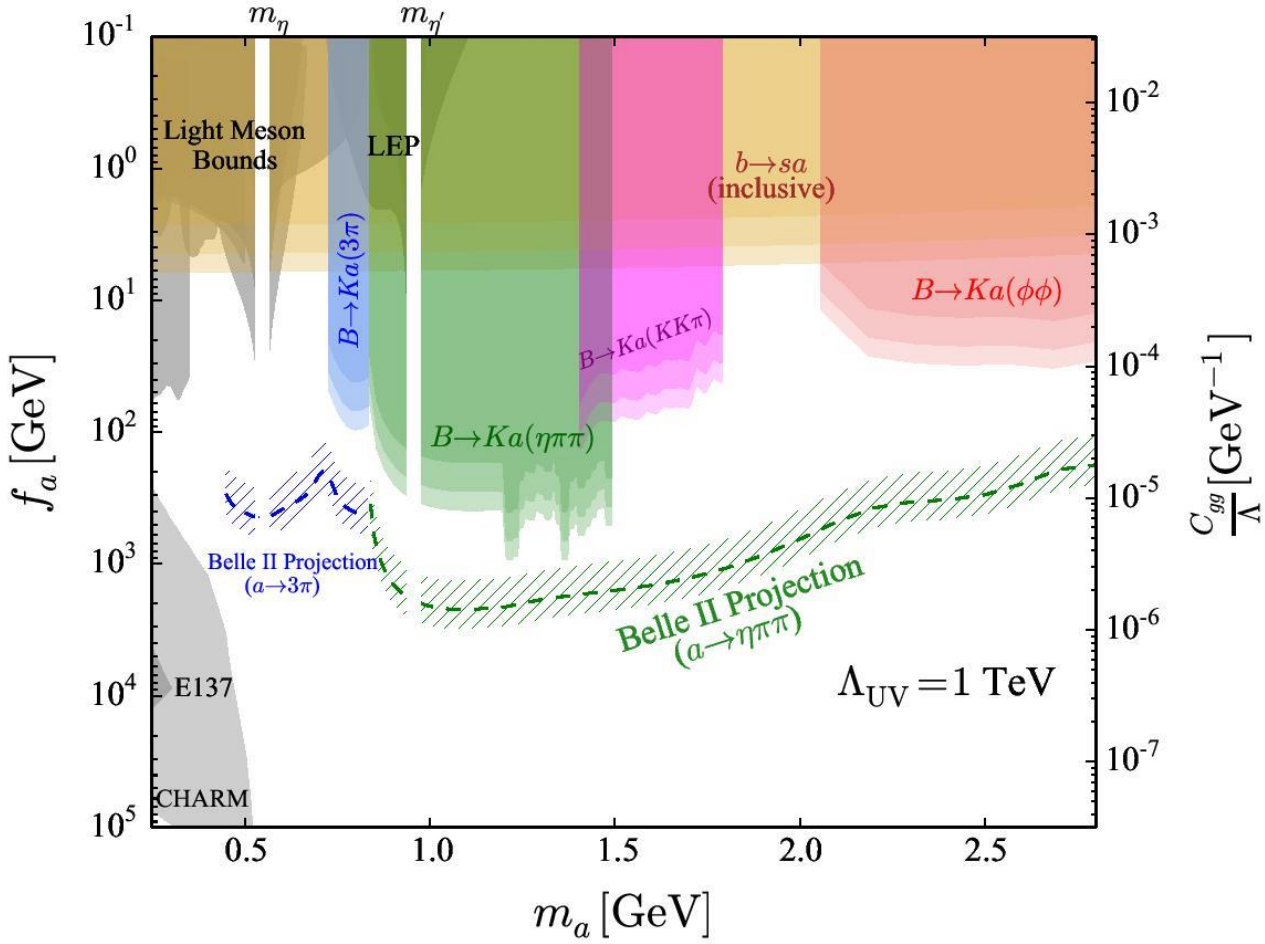
Exact structure of UV physics
Not very important!

Axion decay



D. Aloni, Y. Soreq, M. Williams arXiv:1811.03474

B meson decay



S. Chakraborty, M. Kraus, **V. L.**, T. Okui, K.Tobioka arXiv:2102.04474

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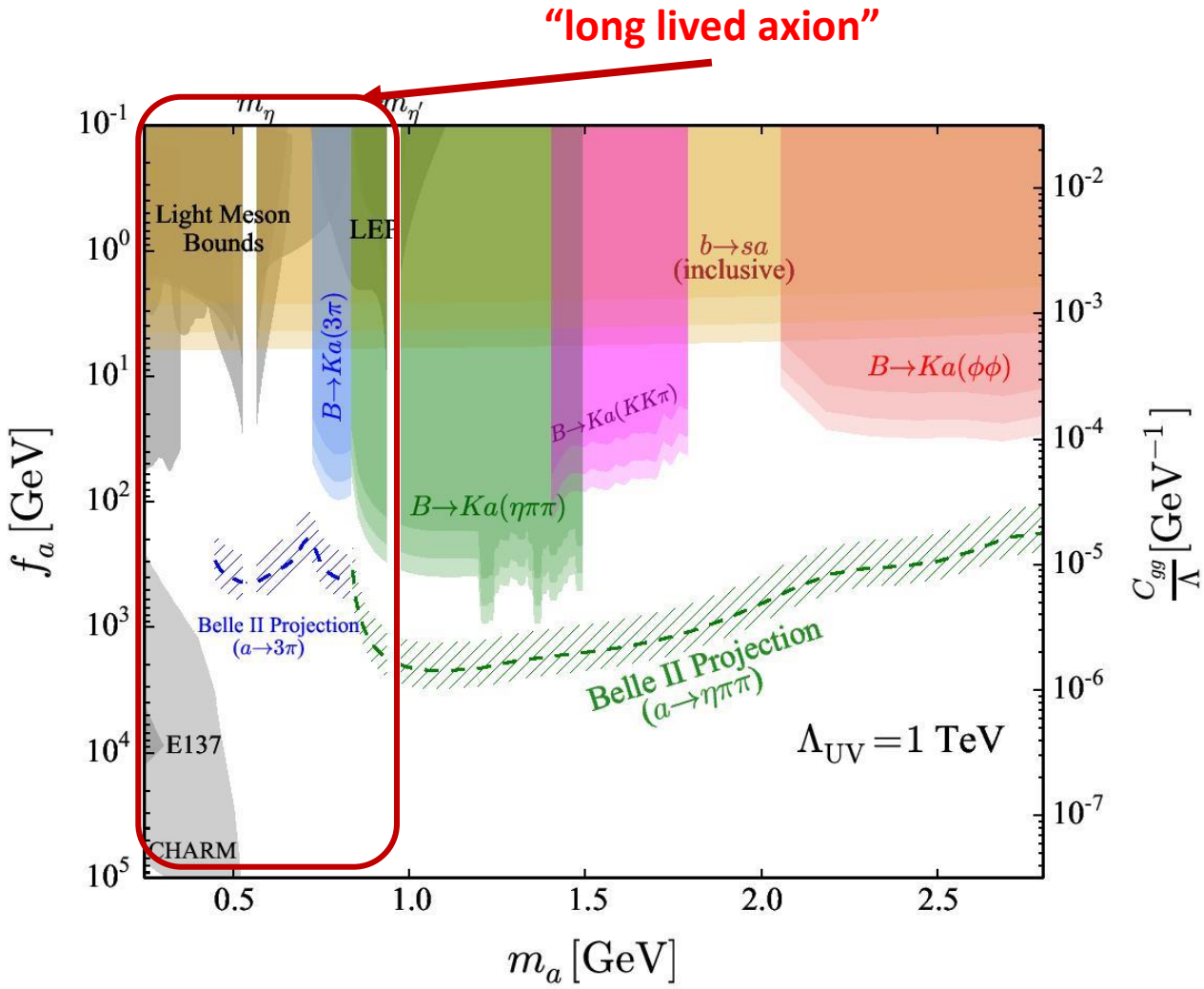

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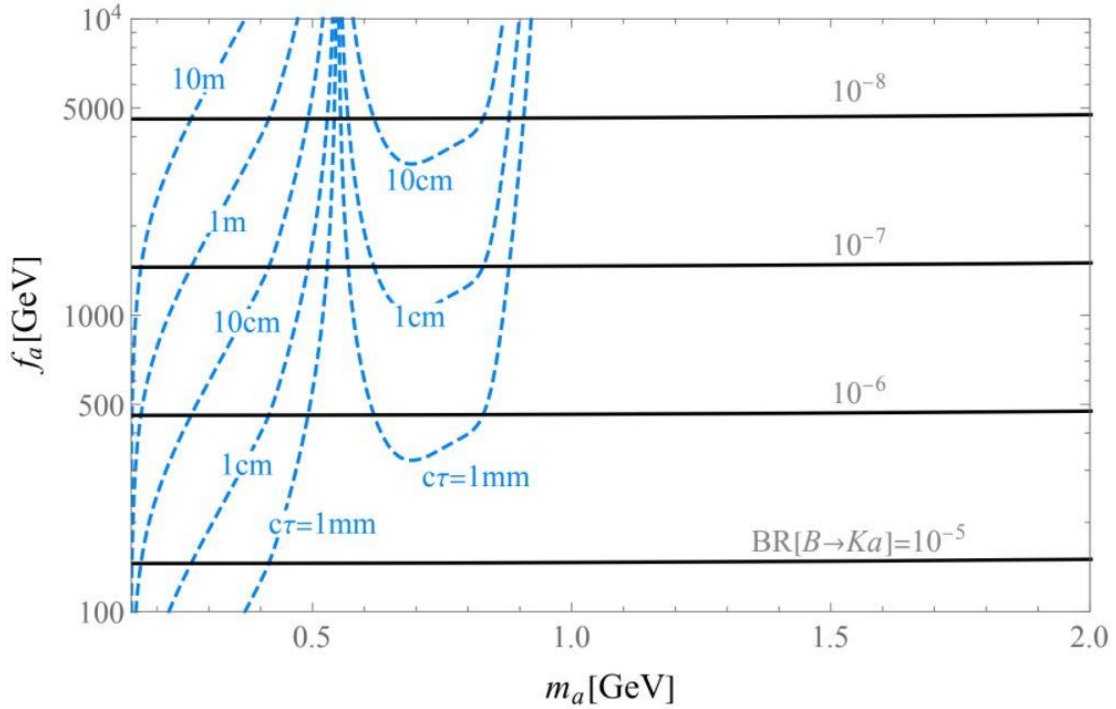
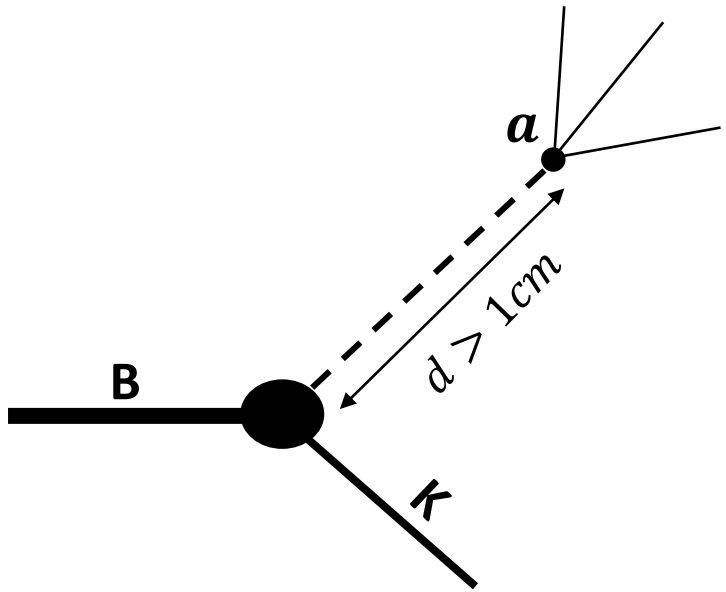
Long Lived Heavy QCD Axion at Belle II

displaced decay of axion





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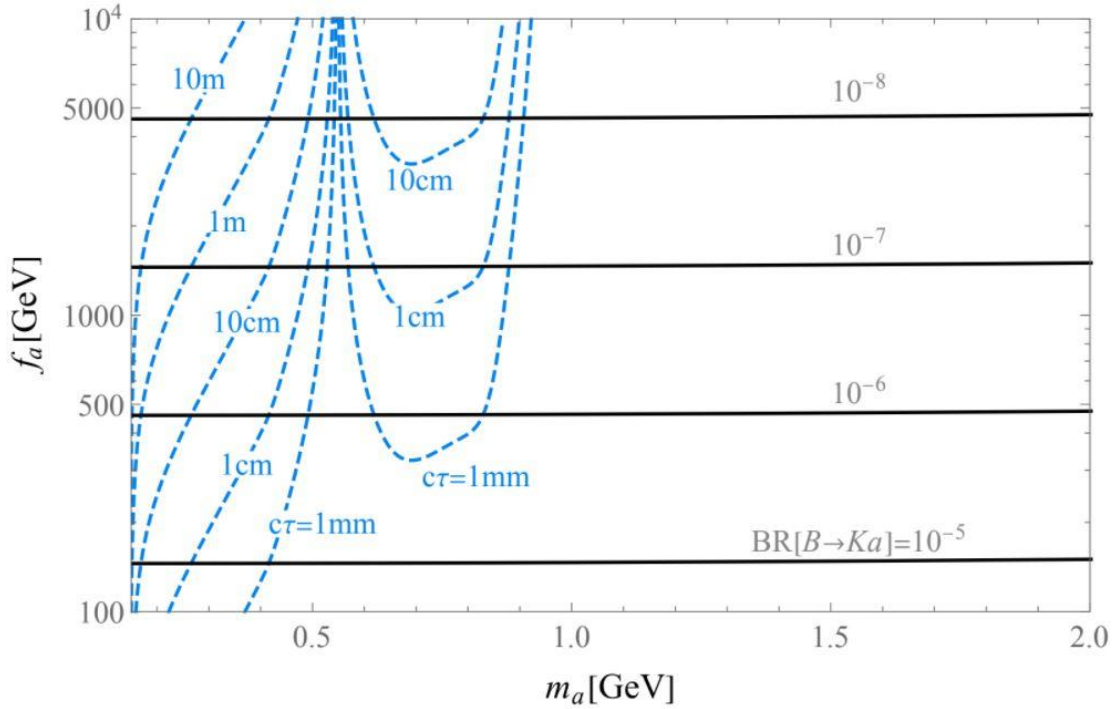

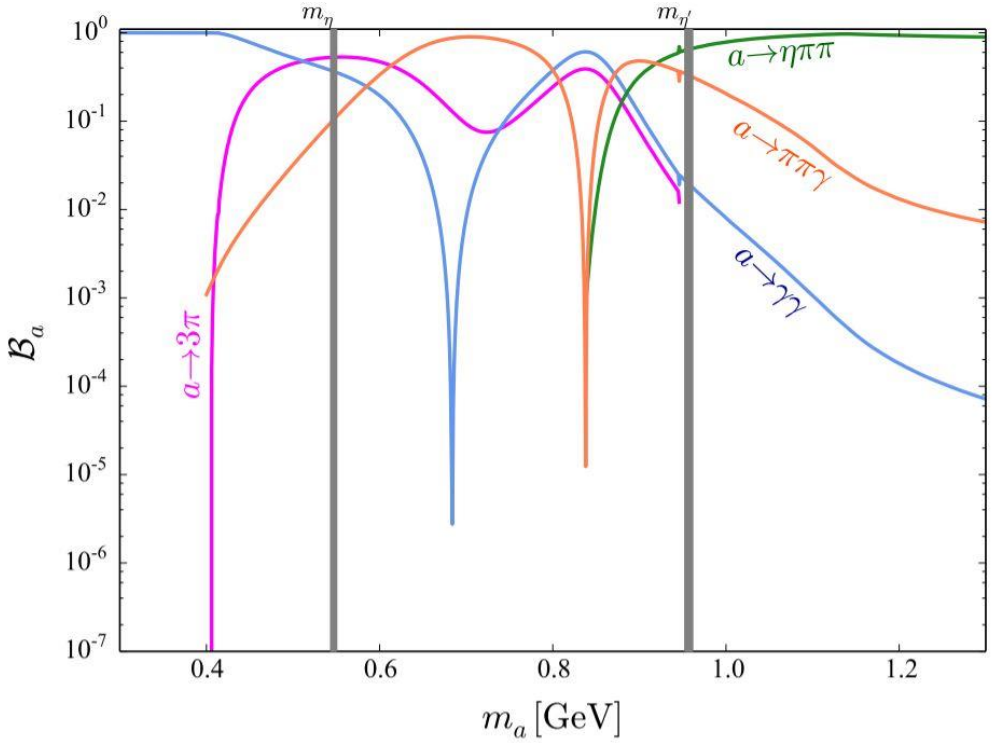

D. Aloni, Y. Soreq, M. Williams
arXiv:1811.03474

$a \to 3\pi$

- Signal: **B**$\to K a\left(\to \pi^0\pi^+\pi^-\right)$
- **We can resolve displaced vertex!**

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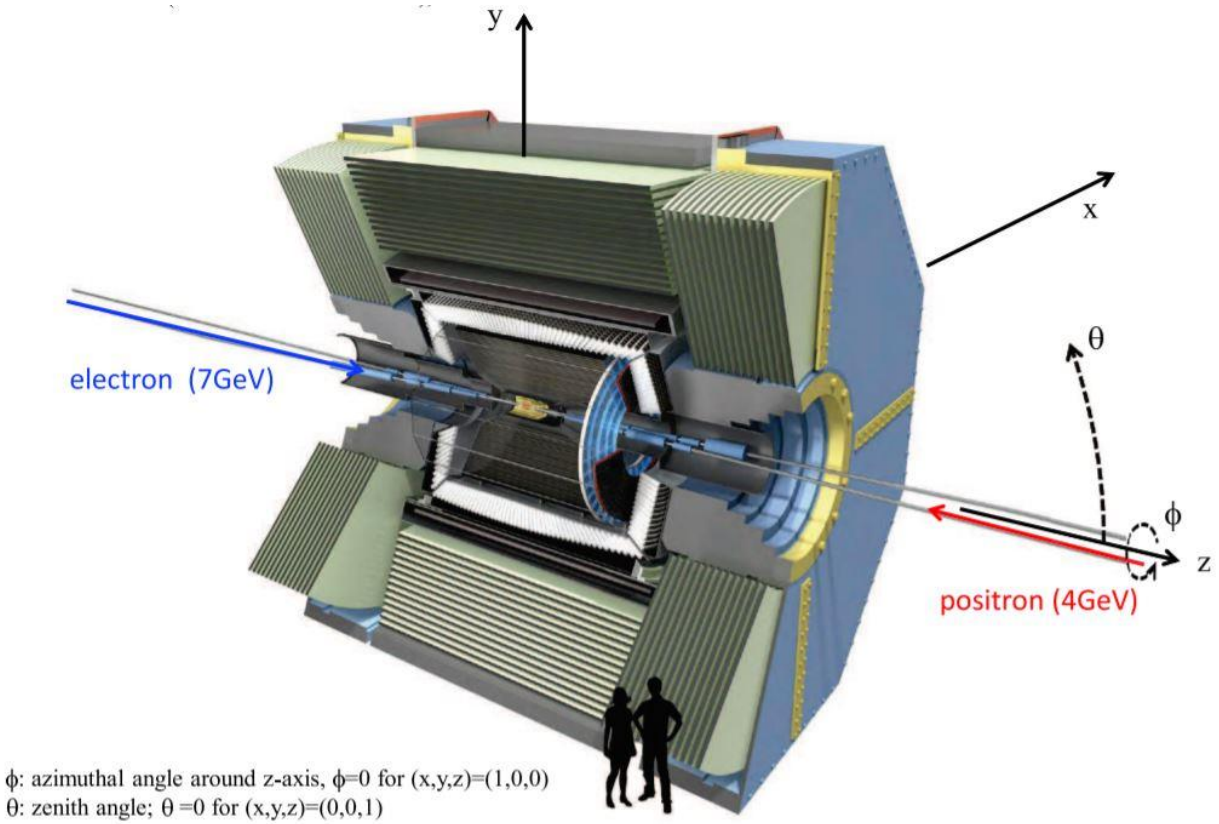
- **We can resolve displaced vertex!**
- **DV cut:**

Fiducial volume

$-40 < z < 120$ cm

$1 < r < 80$ cm $\quad (r = \sqrt{x^2 + y^2})$



$a \to 3\pi$

- **Background:**

1. **B**$\to K\eta\left(\to \pi^0\pi^+\pi^-\right)$ **suppressed by DV cut** $\Rightarrow N_B \approx 0$
2. **B** $\to K\omega\left(\to \pi^0\pi^+\pi^-\right)$ **suppressed by DV cut** $\Rightarrow N_B \approx 0$
3. **B** $\to KK^{*0}(892)\left(\to \pi^0 K_s(\to \pi^+\pi^-)\right)$ **suppressed by** $m_{\pi^+\pi^-} = m_{K_s}$ **cut** $\Rightarrow N_B \approx 0$
4. **B** $\to KK_L\left(\to \pi^0\pi^+\pi^-\right)$ $c\tau_{K_L} \approx 15$ **m is too long** $\Rightarrow$ $N_B \approx 5$ **events around** $m_a = m_{K_L}$

$a \rightarrow 2\gamma$

- Signal: **B**$\rightarrow K a(\rightarrow \gamma\gamma)$
- **Vertex can't be resolved!**

$a \to 2\gamma$

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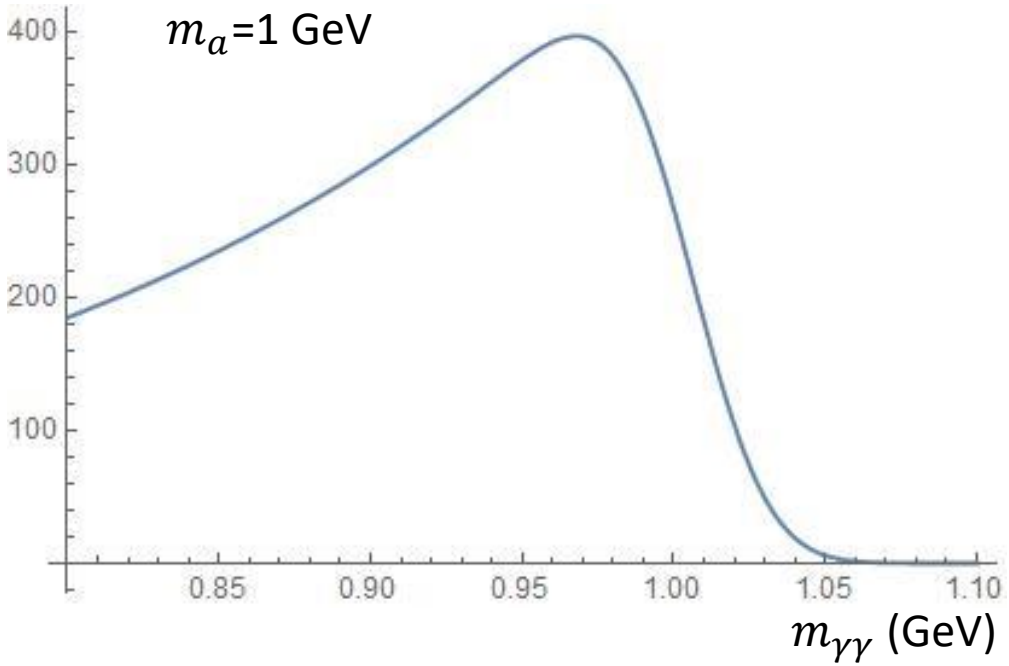
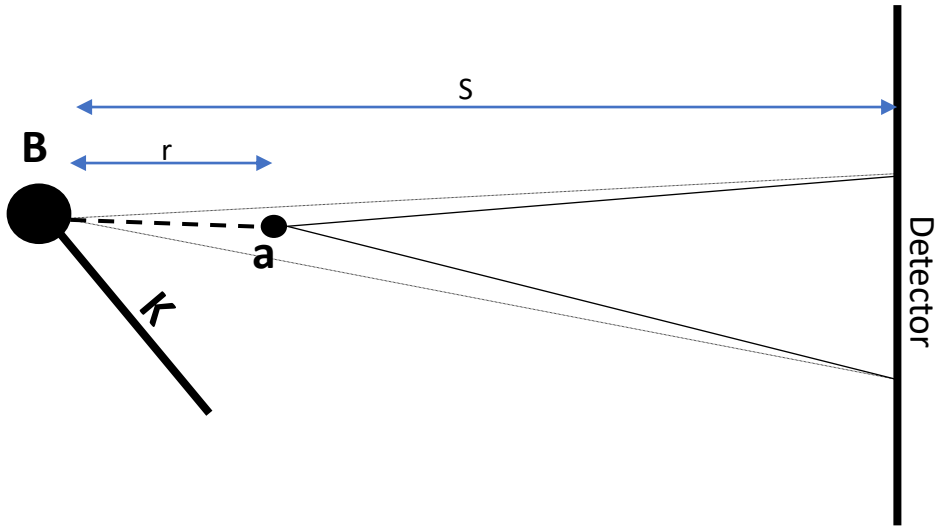
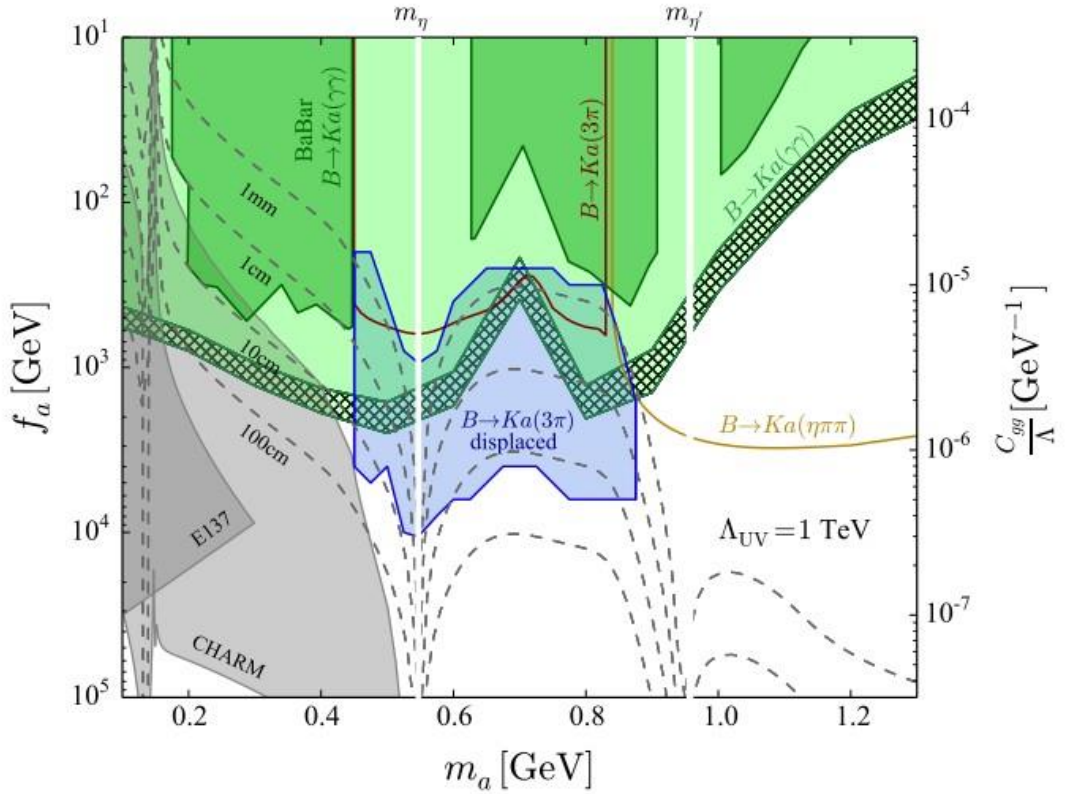
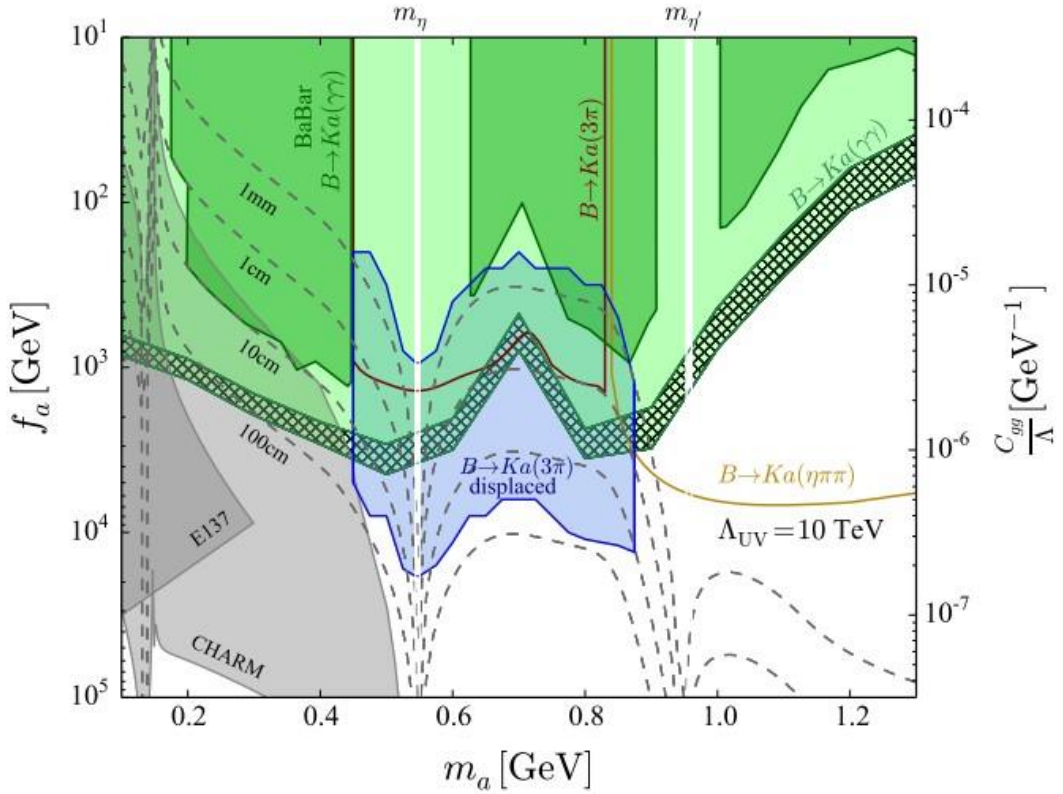
- $m_{\gamma\gamma} = m_a(1 - r/S)$





$a \to 3\pi$ & $a \to \gamma\gamma$ projections at Belle II

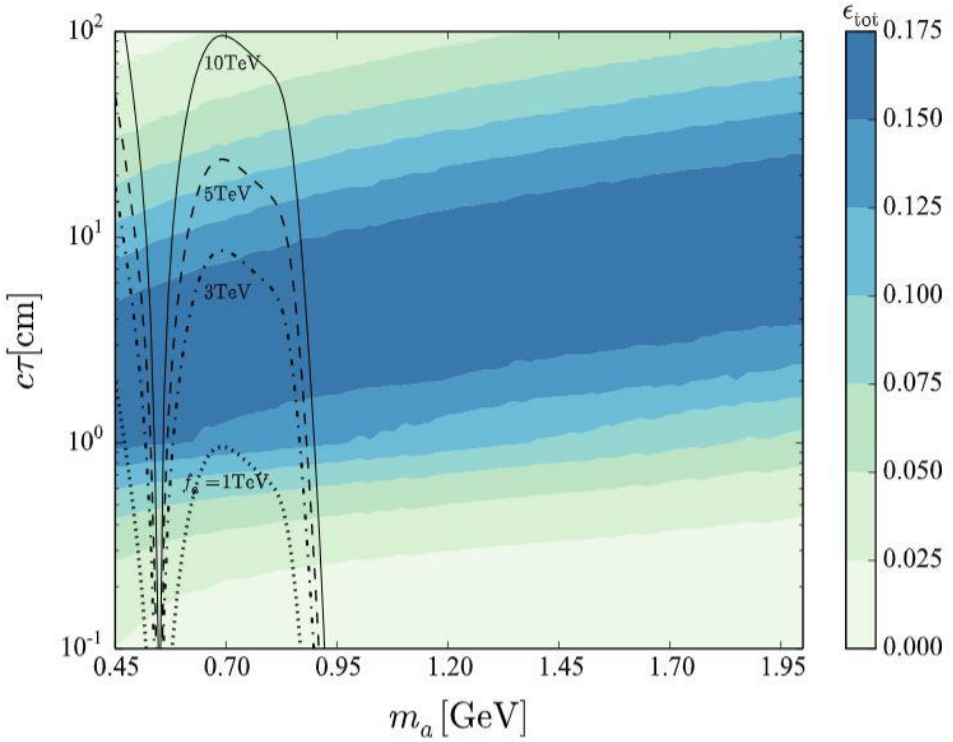




Emilie Bertholet, Sabyasachi Chakraborty, **V.L.** , Takemichi Okui, Abner Soffer, Kohsaku Tobioka **arXiv:2108.10331**

Thank you!

$a \to 3\pi$ DV efficiency



Experimental input of $a \to \gamma\gamma$ analyses

1. BaBar Collaboration, J. P. Lees et al., "Search for an Axion-Like Particle in B Meson Decays," arXiv:2111.01800
2. BaBar Collaboration, "Belle ii mγγ plots,". https://docs.belle2.org/record/1589/files/ BELLE2-NOTE-PL-2019-019.pdf.
3. BaBar Collaboration, J. P. Lees et al., arXiv:1110.6480