Dark sector search with hadrons

—Wish list beyond Belle II Physics Book—

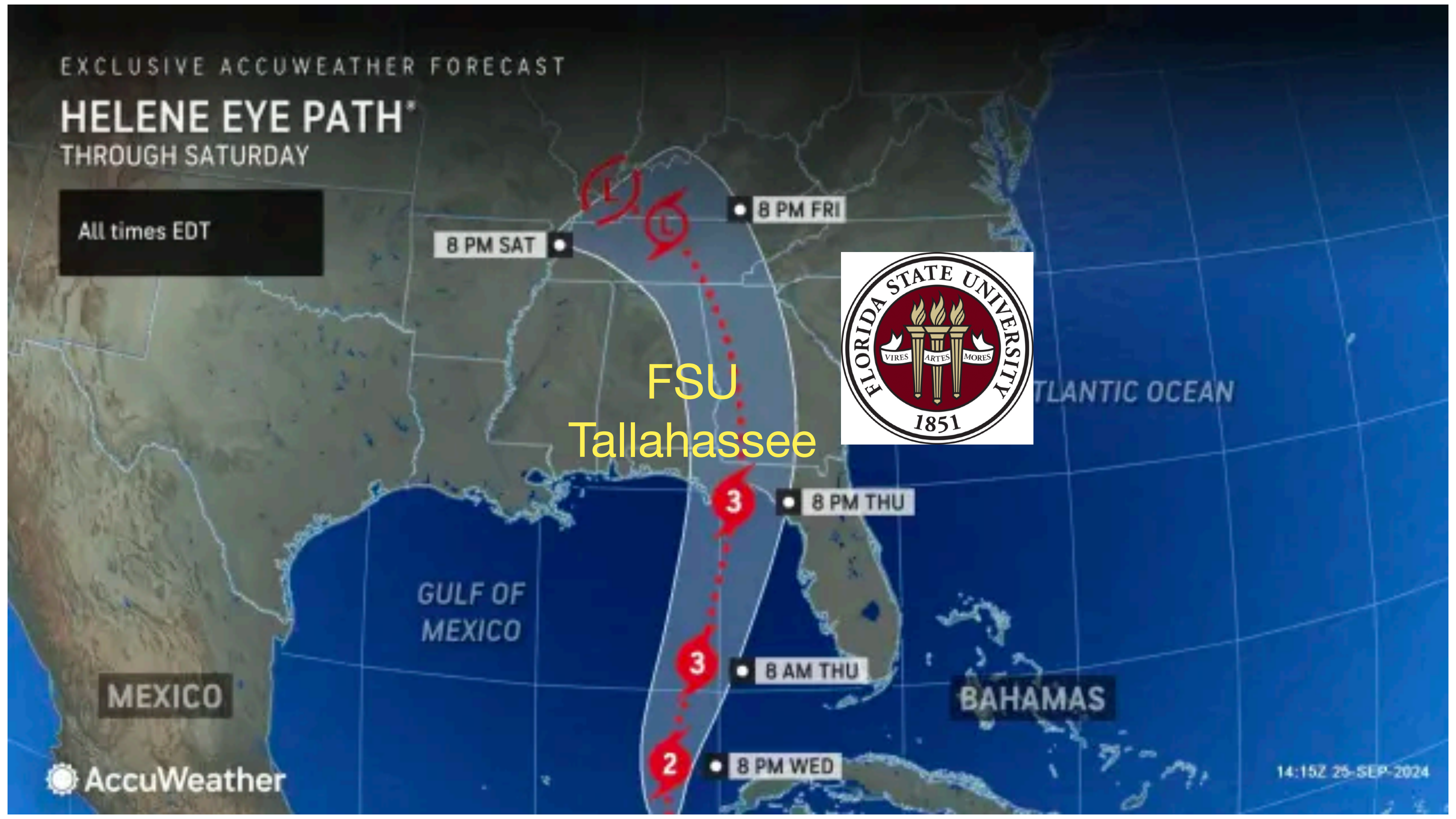
Oct 14, 2024 [Belle II Physics Week, KEK]

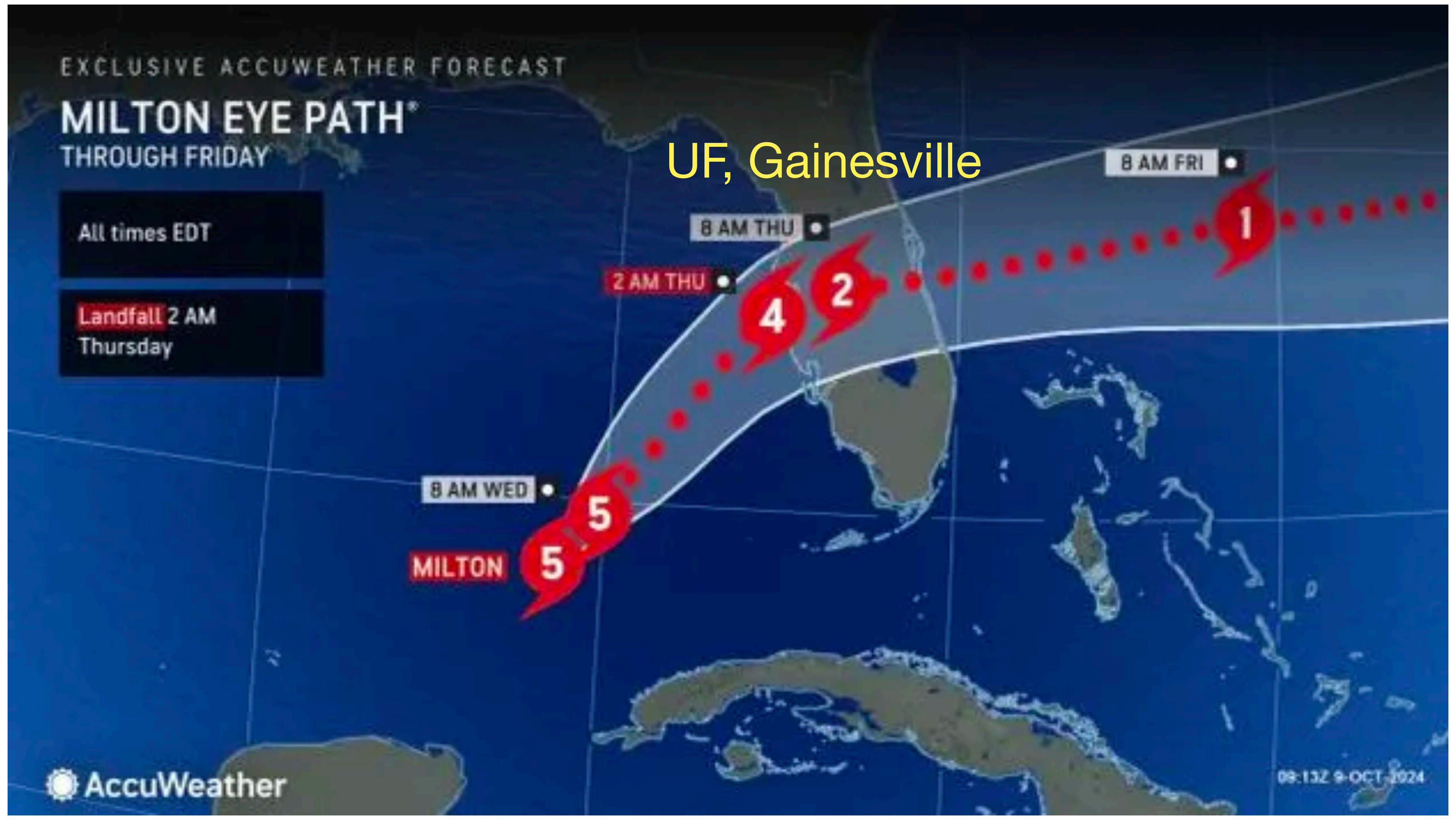
Kohsaku Tobioka [Tobi]

Florida State University, KEK Theory center

Before start…

Degeneracy in Florida





Before start…

- Originally I wanted to overview many proposals for Belle II, but I realize I already have many for given time. [Apologies!]

->My wish list for young exp colleagues. [**5 modes**]

B-factory is quite unique

https://www.irasutoya.com/

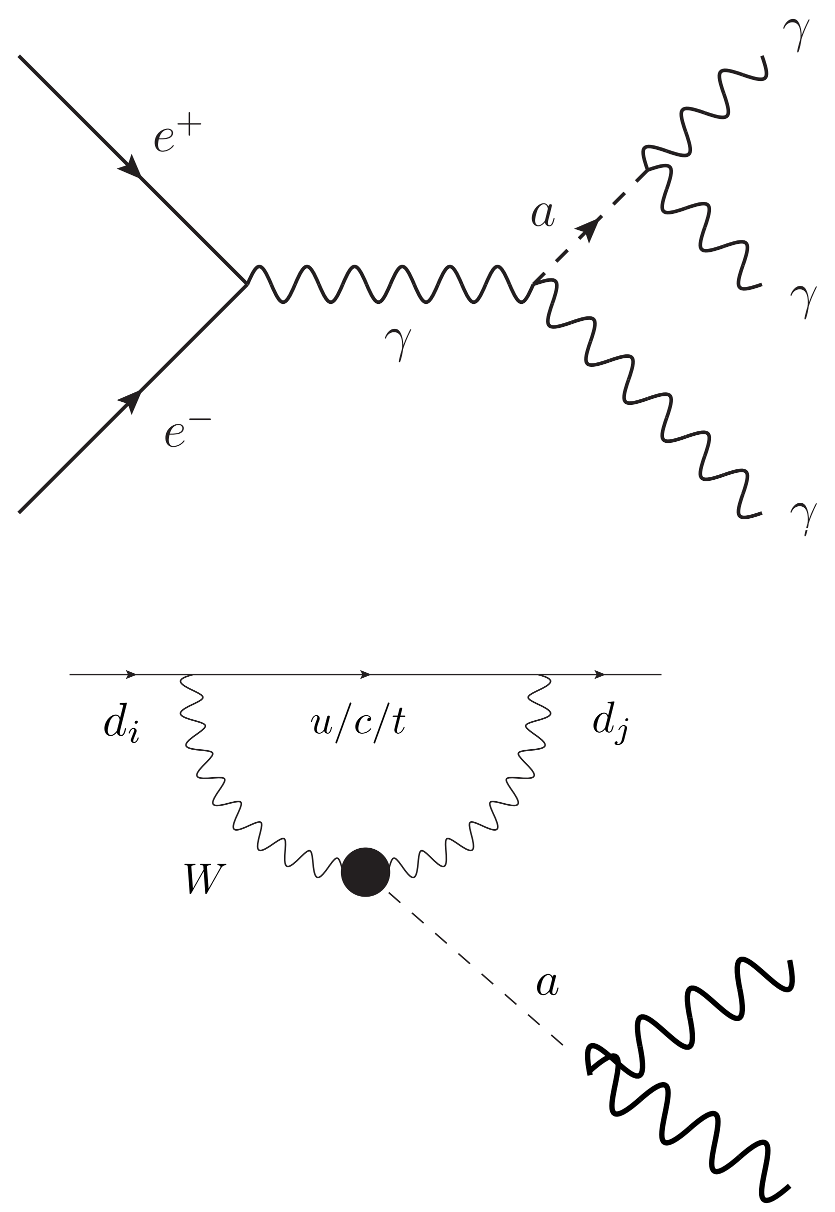
- I'm attending only Mon/Tue/(Wed?), but feel free to interact/email or ZOOM. Many collaborations with experimentalists started over corridor chats (for me).

ktobioka@fsu.edu not @ufl.edu…

BSM wishlist beyond Belle II Physics Book

This list will be expanded [all the afternoon talks!]

Only electroweak boson couplings!!



- Many interesting channels with **hadronic/gluon couplings**
  Heavy QCD axion

[S. Gori's talk for lepton couplings.]

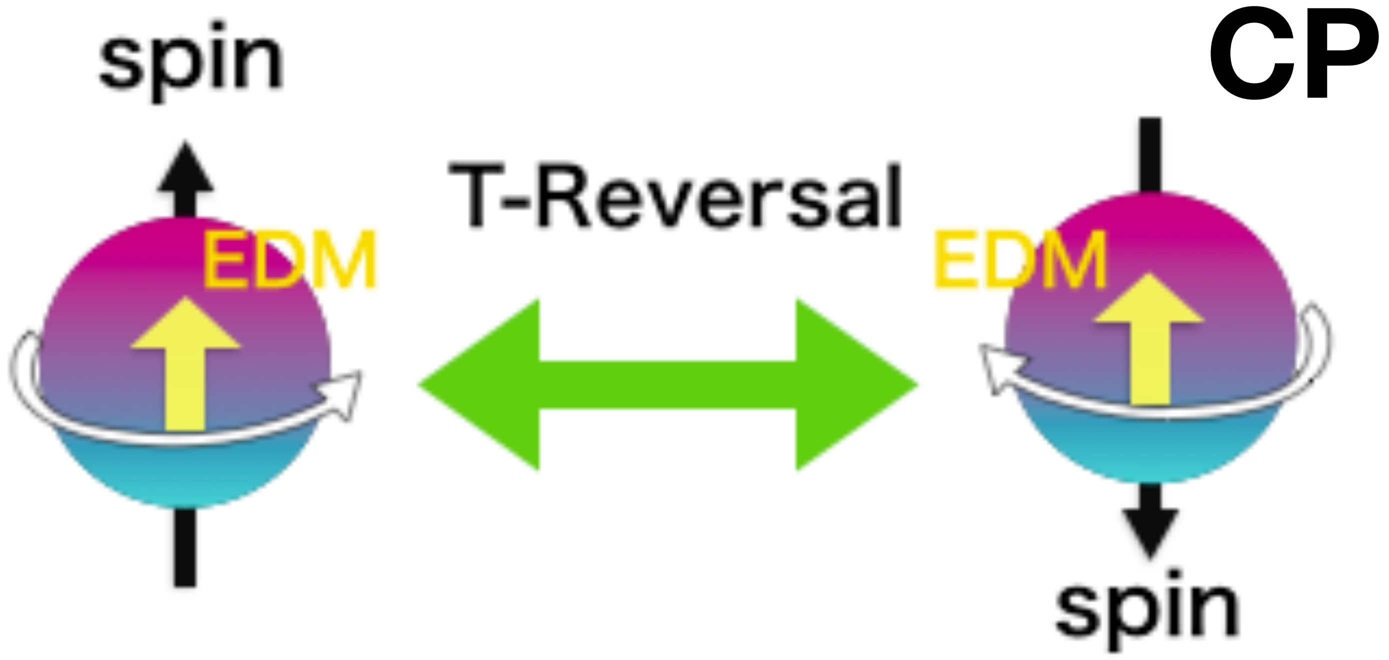
Strong CP problem and QCD Axion

The strong CP problem

$$\frac{\alpha_s \bar{\theta}}{8\pi} G^{a\mu\nu} \tilde{G}^{a\mu\nu}$$

- The unknown of the SM: CP phase in the strong sector
- Neutron EDM sets a very stringent upper bound: $\bar{\theta} \lesssim 10^{-10}$
- We expect the order 1 number because CP is violated in the CKM matrix (thanks to Belle and Babar).
  If we start from CP conserving theory for θ, we need to break it to explain CKM.

CP odd



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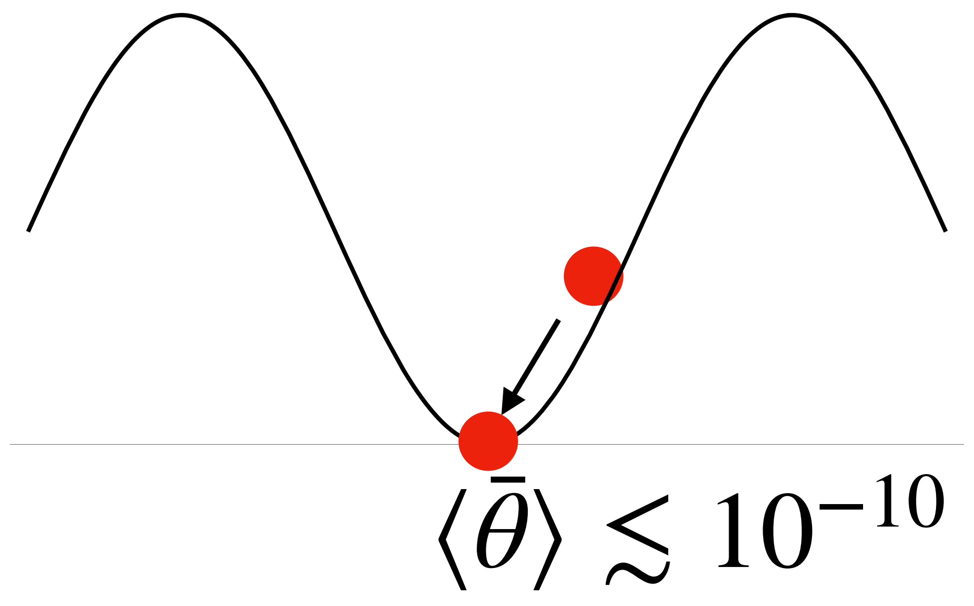
QCD Axion solution

$$\frac{\alpha_s}{8\pi} \frac{a}{f_a} G^{a\mu\nu} \tilde{G}^{a\mu\nu}$$

after QCD phase transition



- Promote $\bar{\theta}$ to a *field* a/f_a *dynamically settles the CP phase to the minimum.*
- *Peccei-Quinn symmetry:* Global U(1) that generates the axion *as* a Nambu-Goldstone boson. **f_a is the breaking scale**.
- Attractive **dark matter** candidate, typically m_a<meV.

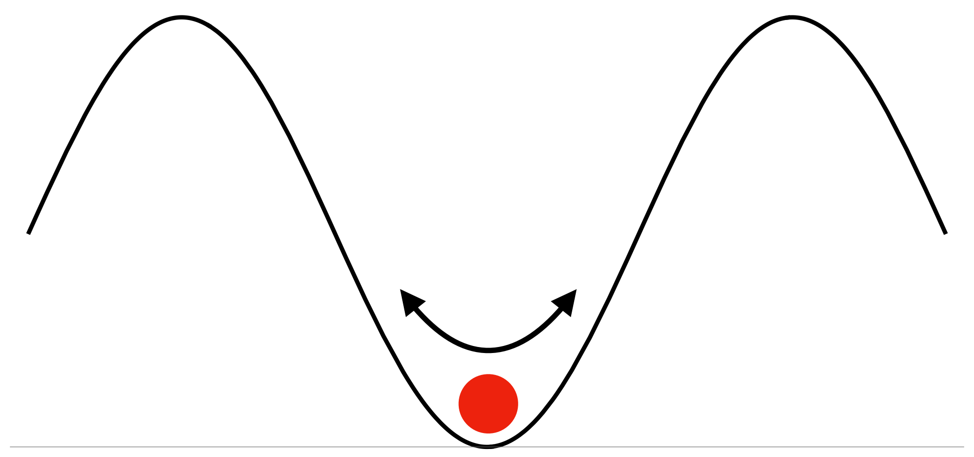
From QCD Axion to Heavy QCD Axion

- Standard QCD axion has mass prediction

$$m_a \sim \frac{m_\pi f_\pi}{f_a} \sim 0.1\mathrm{MeV}\left(\frac{100\mathrm{GeV}}{f_a}\right)$$

- Heavy QCD axion, axion heavier than "standard mass"

$$m_a \sim \left(m_0^2 + \frac{m_\pi f_\pi}{f_a}\right)^{1/2} \gg \frac{m_\pi f_\pi}{f_a}$$



Models: additional QCD SU(3)' to raise m_a
Berezhiani et al('01); Hook('04); Fukuda et al('04).
Dimopoulos et al('16); Hook et al('19); Valenti ('22)…
Another class: Agrawal and Howe ('17)…

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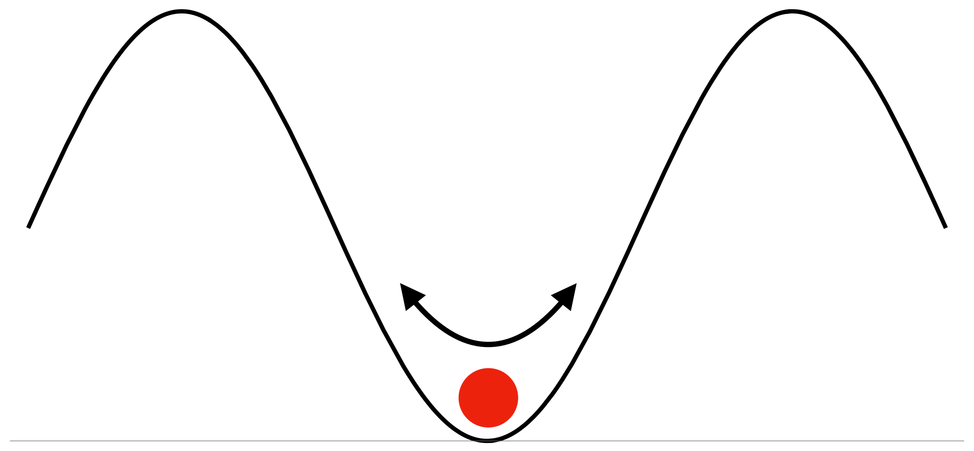

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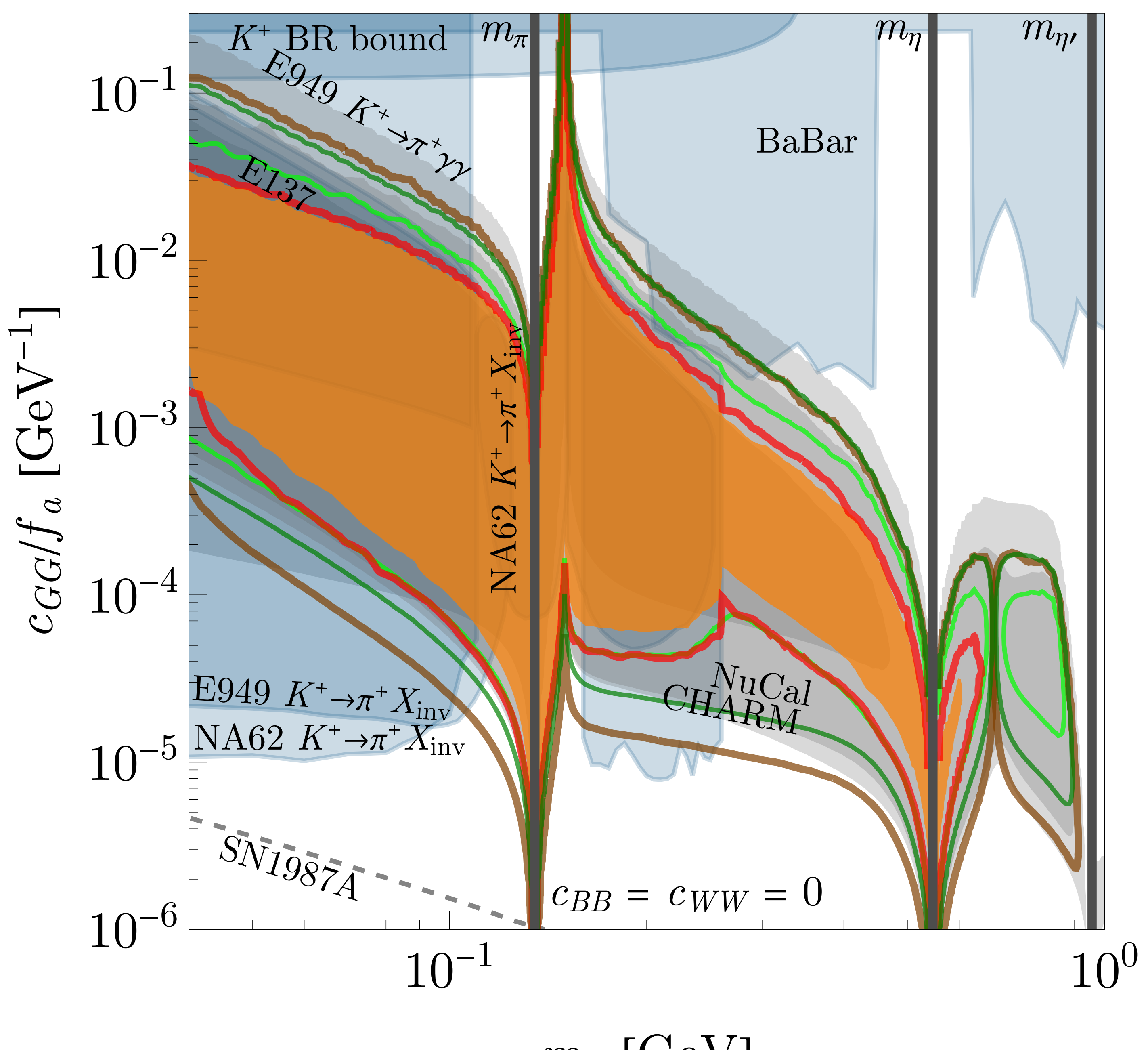
Why interesting?

1. Viable with lower f_a . Should cover m_a>100MeV.
2. Better quality of PQ symmetry

✴It it not dark matter
because it decays in cosmological time scale



ALPs: Axion-like Particles **vs Heavy QCD Axion**

	▸ **Typical ALPs**	▸ **Heavy QCD Axion**
• couplings	$\frac{\alpha_W c_2}{8\pi} aW\tilde{W}$ $\quad \frac{\alpha_1 c_1}{8\pi} aB\tilde{B}$	Must: $\frac{c_g \alpha_s}{8\pi}\frac{a}{f_a} G^{a\mu\nu}\tilde{G}^{a\mu\nu}$
	$\frac{\alpha_{EM} c_\gamma}{8\pi} aF\tilde{F} = \frac{g_{a\gamma\gamma}}{4} aF\tilde{F}$	Optional: $aB\tilde{B},\ aW\tilde{W},\ aF\tilde{F}$
• mass	Completely free	Heavier than standard one $m_a \gg \frac{m_\pi f_\pi}{f_a}$

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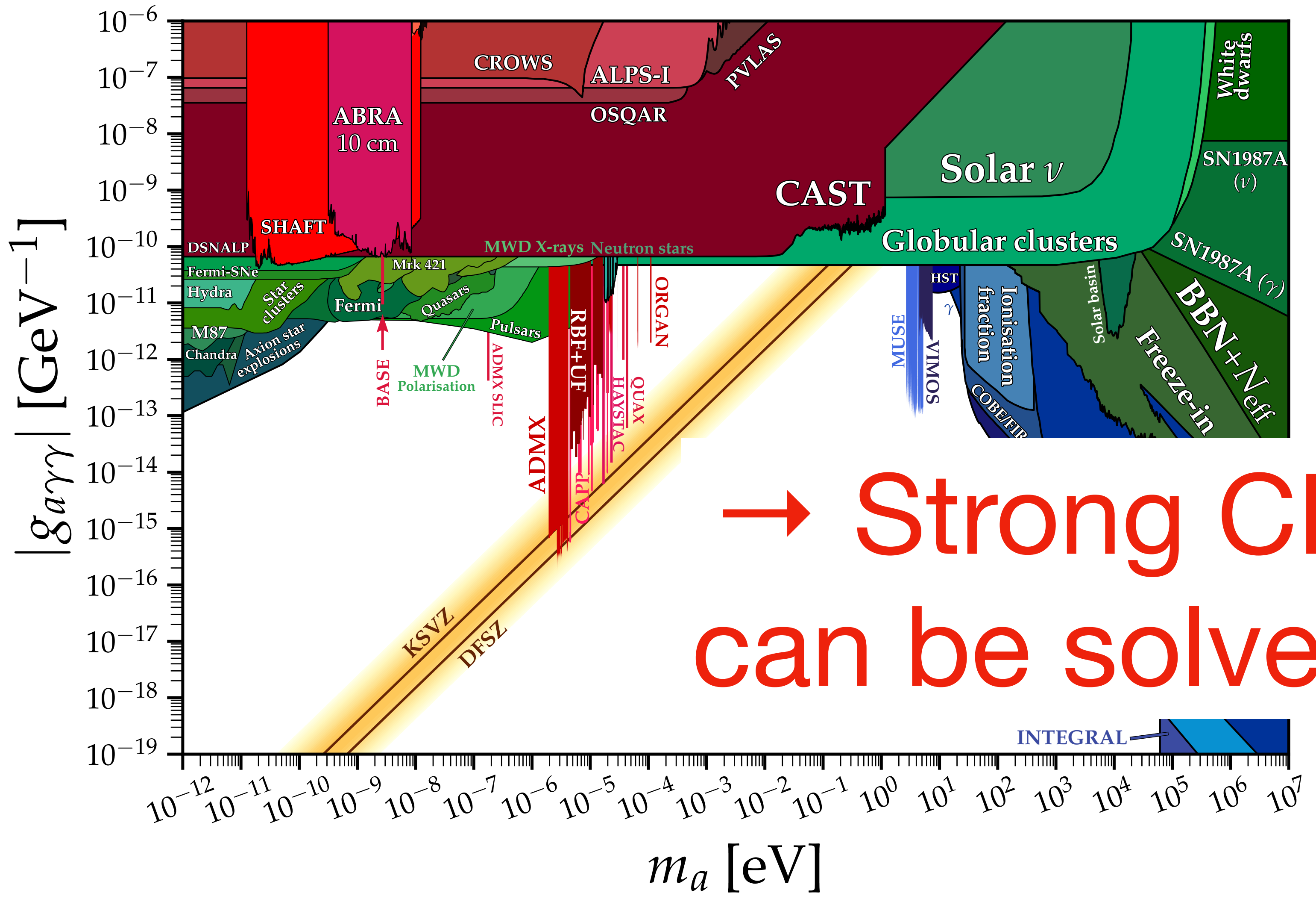


→ Strong CP can be solved

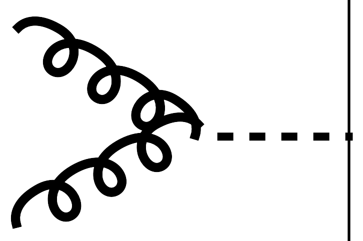
Why Belle II is unique? Resonance search

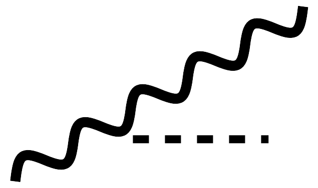
- To get ideas, consider resonance search, from LHC to lower mass

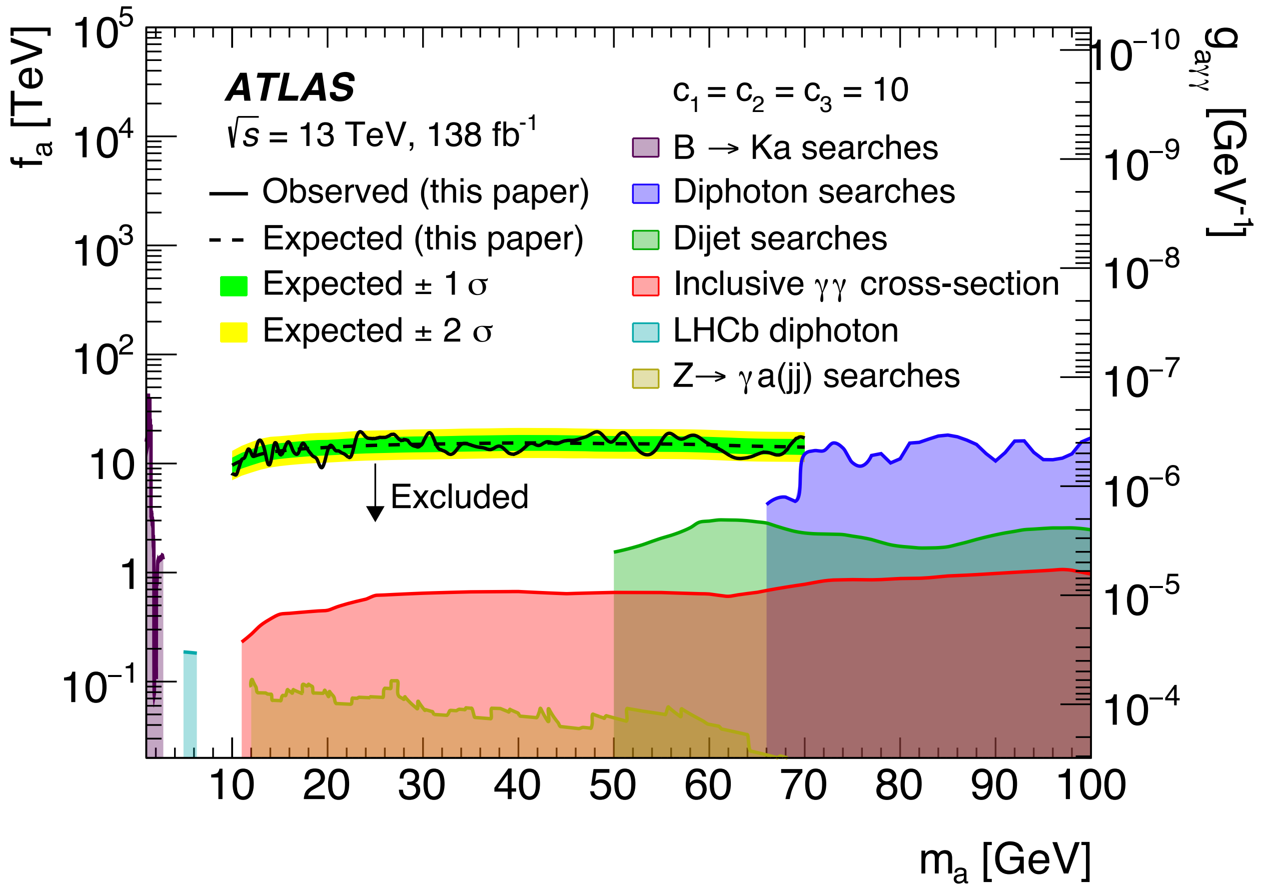
  Using narrow width approximation with $c_\gamma \sim c_g$:

$$\sigma \cdot \mathrm{BR} \sim \frac{\Gamma_{\mathrm{prod}}}{m_a E_{CM}^2} \frac{\Gamma_{\mathrm{decay}}}{\Gamma_{\mathrm{tot}}} \qquad \alpha_s^2 \gg \alpha_{EM}^2 \to \Gamma_{tot} \sim \Gamma_g \gg \Gamma_\gamma$$

Prod \ BR	$\frac{\Gamma_g}{\Gamma_{tot}} : a \to \text{hadrons}$	$\frac{\Gamma_\gamma}{\Gamma_{tot}} : a \to \gamma\gamma$
Gluon fusion Γ_g	$\sim \Gamma_g$	$\sim \Gamma_\gamma$
Photon fusion, brem Γ_γ	$\sim \Gamma_\gamma$	$\sim \frac{\Gamma_\gamma^2}{\Gamma_g} \sim 10^{-2}\Gamma_\gamma$







[A. Mariotti, F. Sala, D. Redigolo, KT, 1710.01743; ATLAS 2211.04172]

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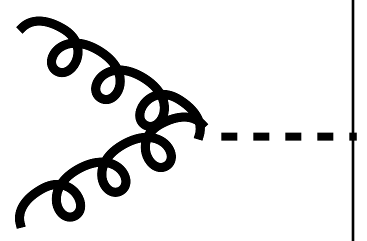

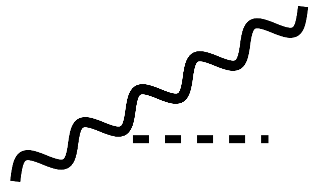

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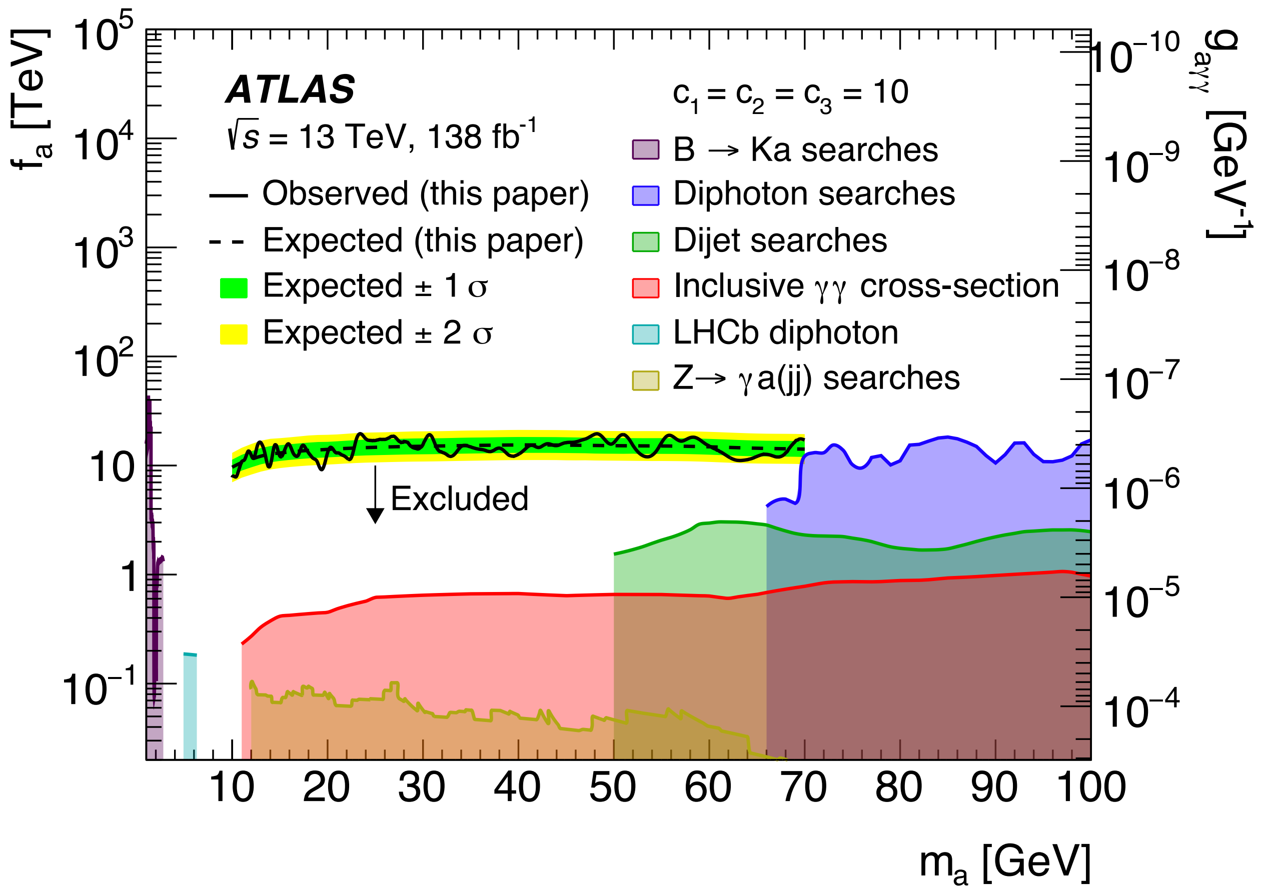

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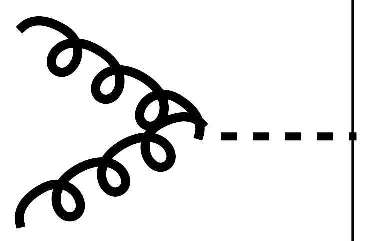

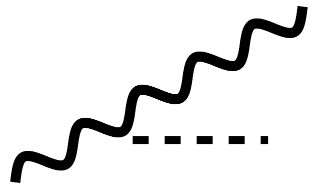

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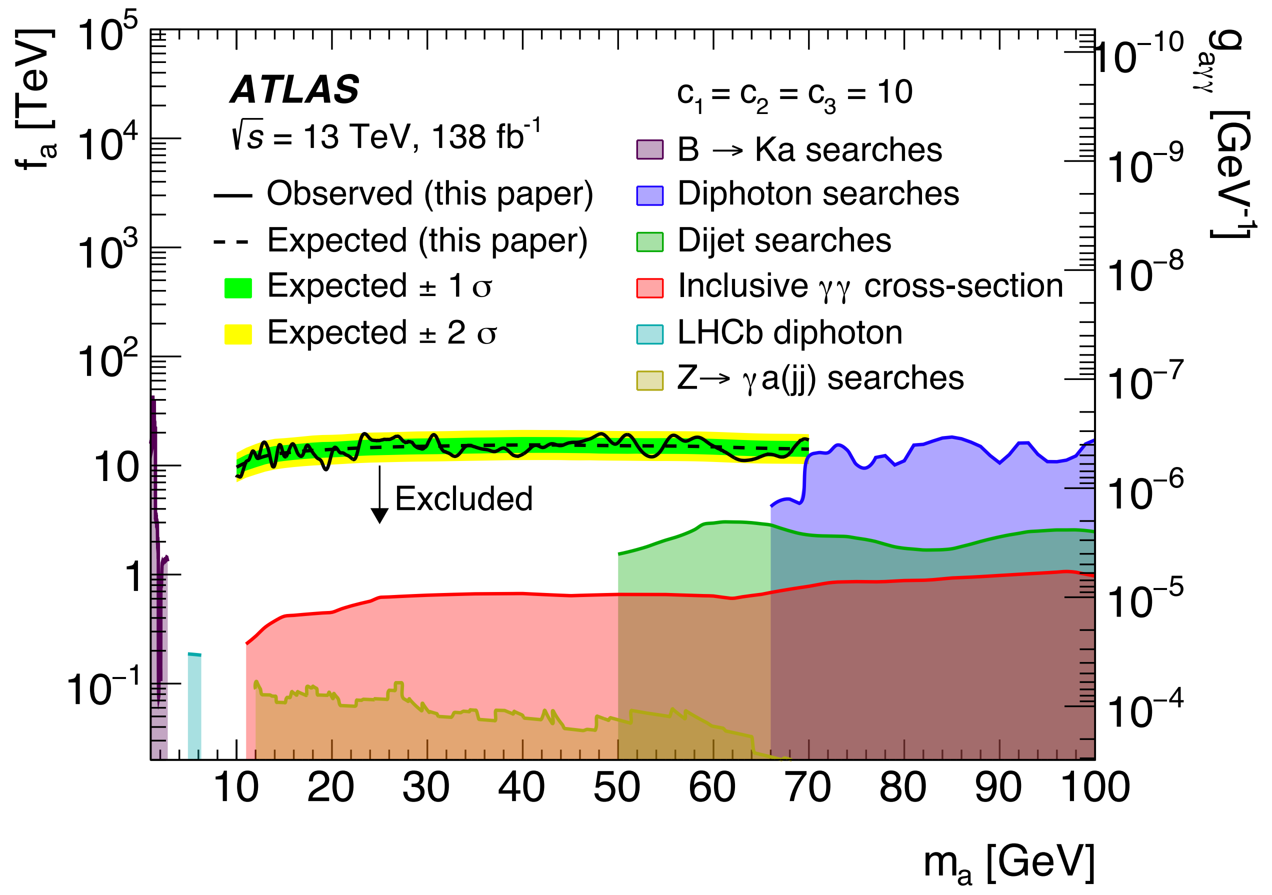

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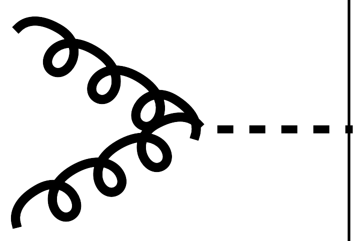

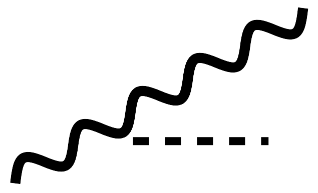

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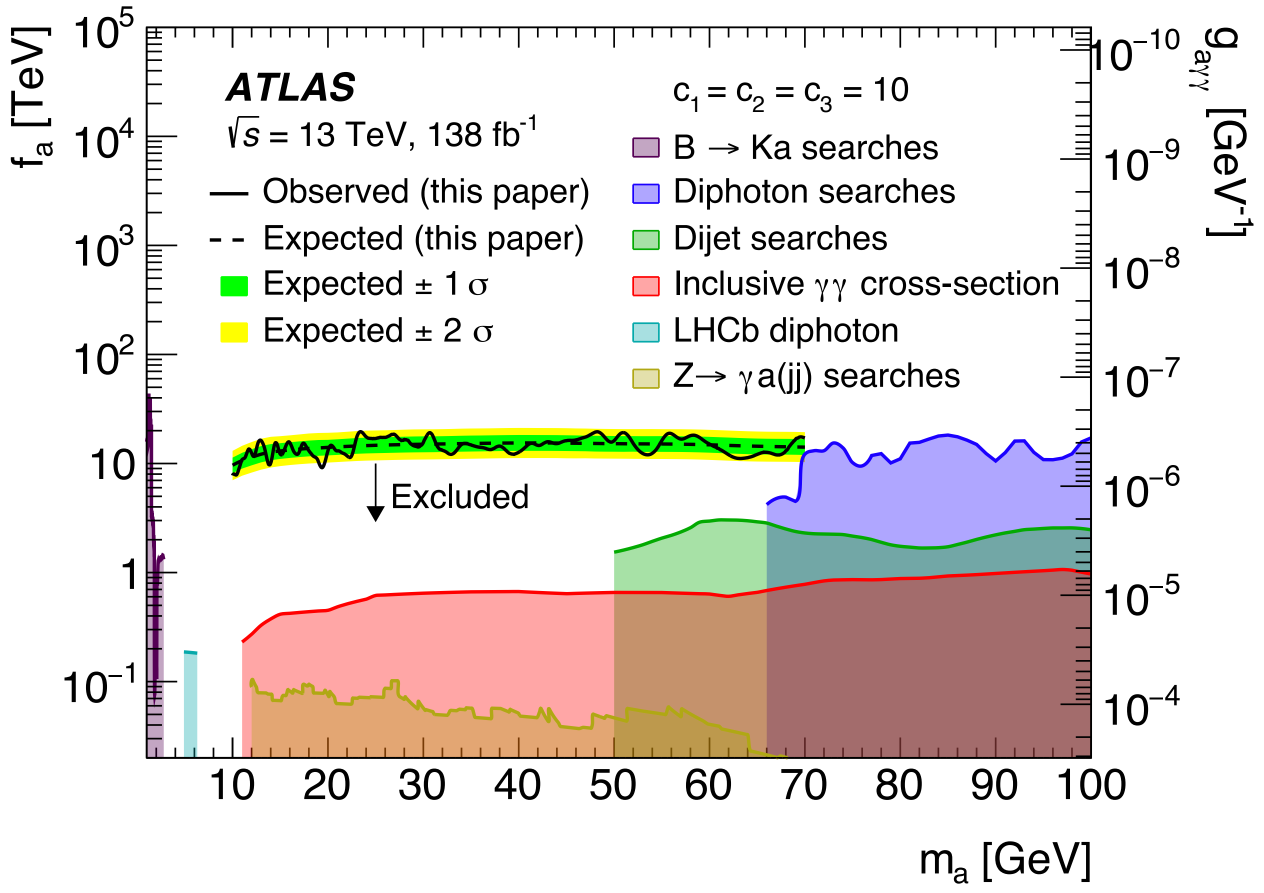
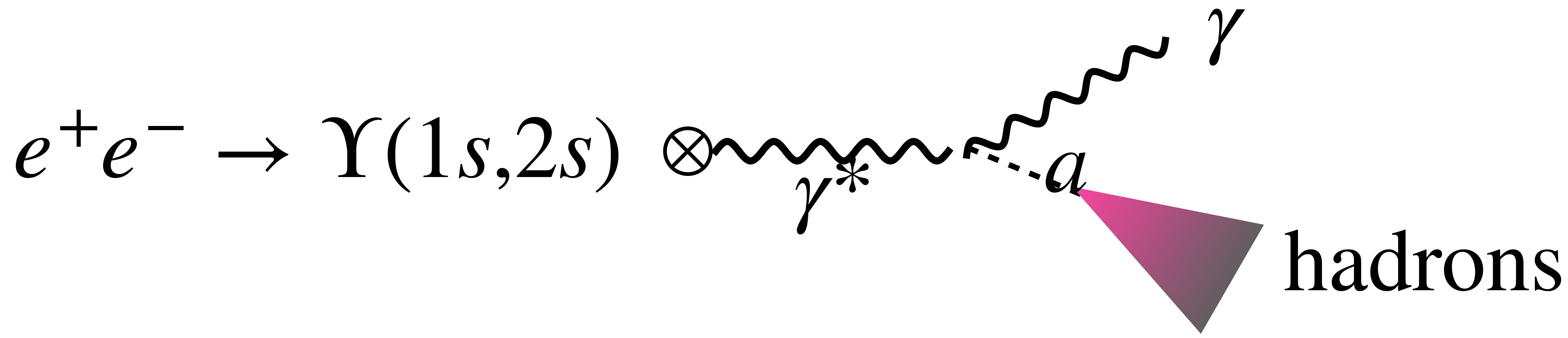
Photon fusion, brem Γ_γ	$\sim \Gamma_\gamma$ Using B-factory triggers Probe **m_a=0.5-7GeV** **ee→Υ→γa, a→had. Babar. Belle II?**	$\sim \frac{\Gamma_\gamma^2}{\Gamma_g} \sim 10^{-2}\Gamma_\gamma$

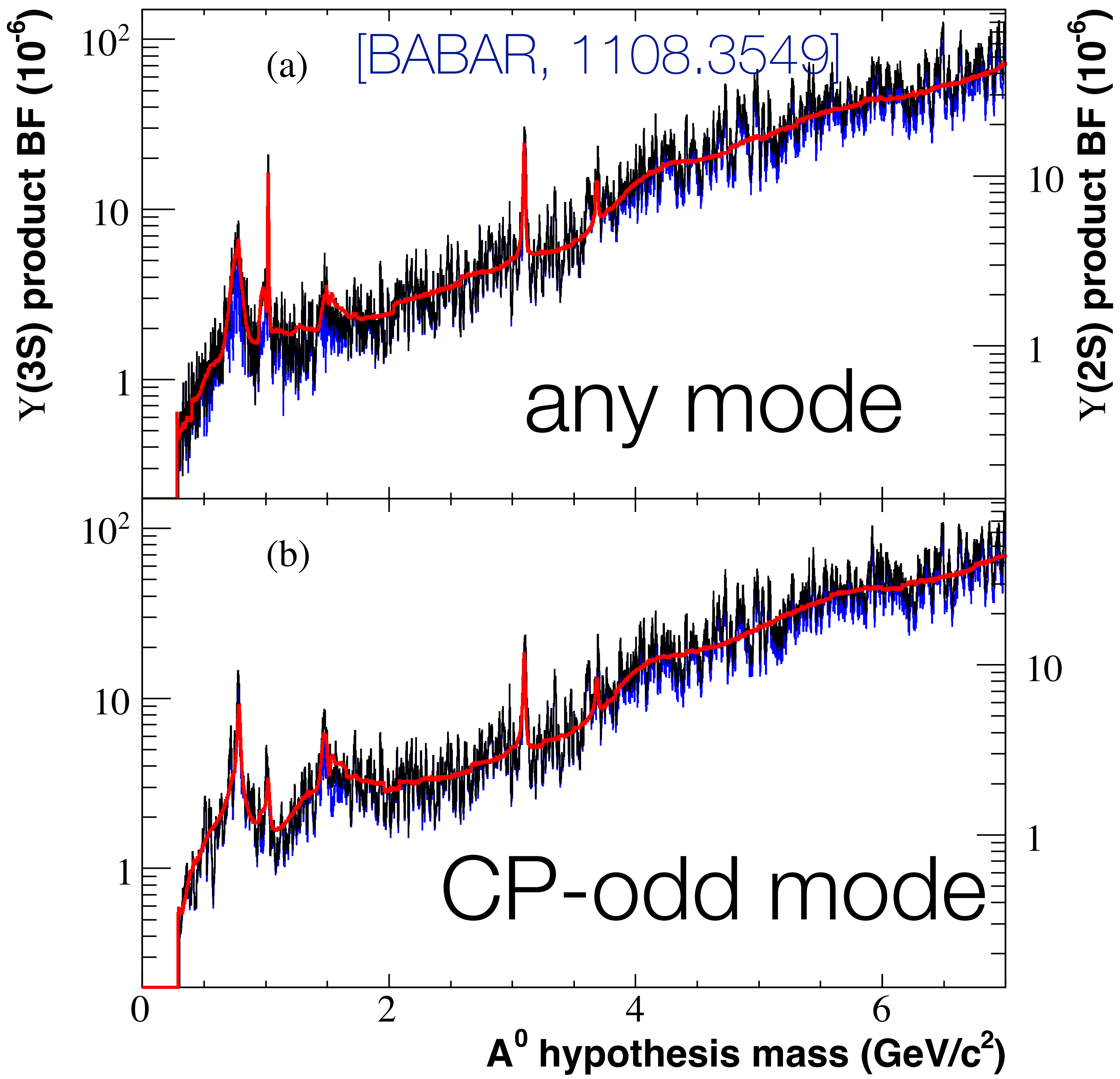


[A. Mariotti, F. Sala, D. Redigolo, KT, 1710.01743; ATLAS 2211.04172]

Wish 1: $e^+e^- \to \Upsilon(1s,2s) \to \gamma a, a \to$ hadrons

- Upsilon(1S,2S) can decay to $\gamma a(\Gamma_\gamma)$ and use $a \to$ hadrons with BR~100%





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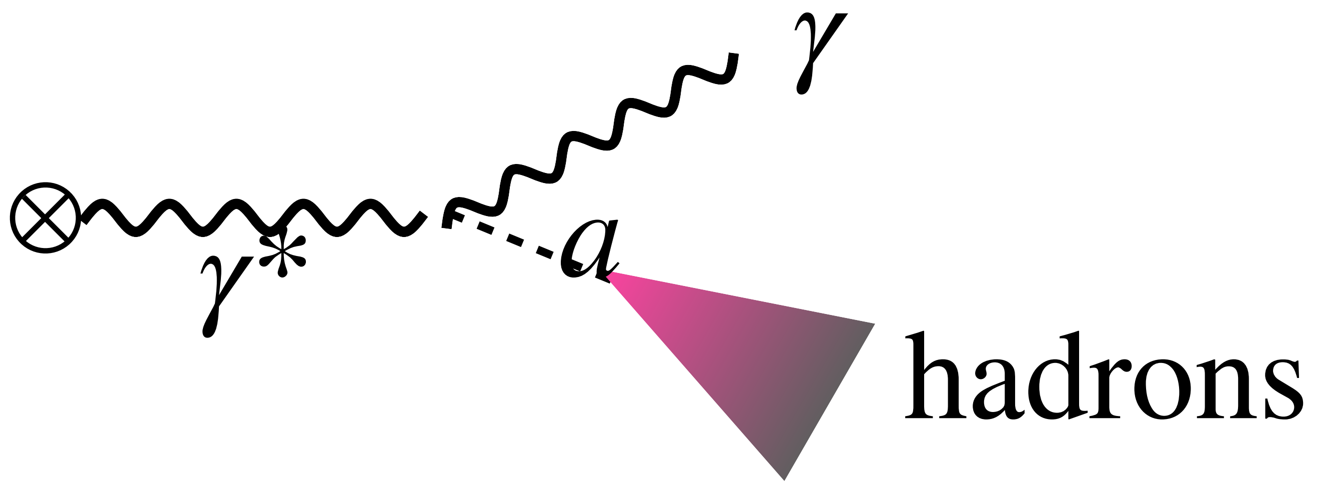
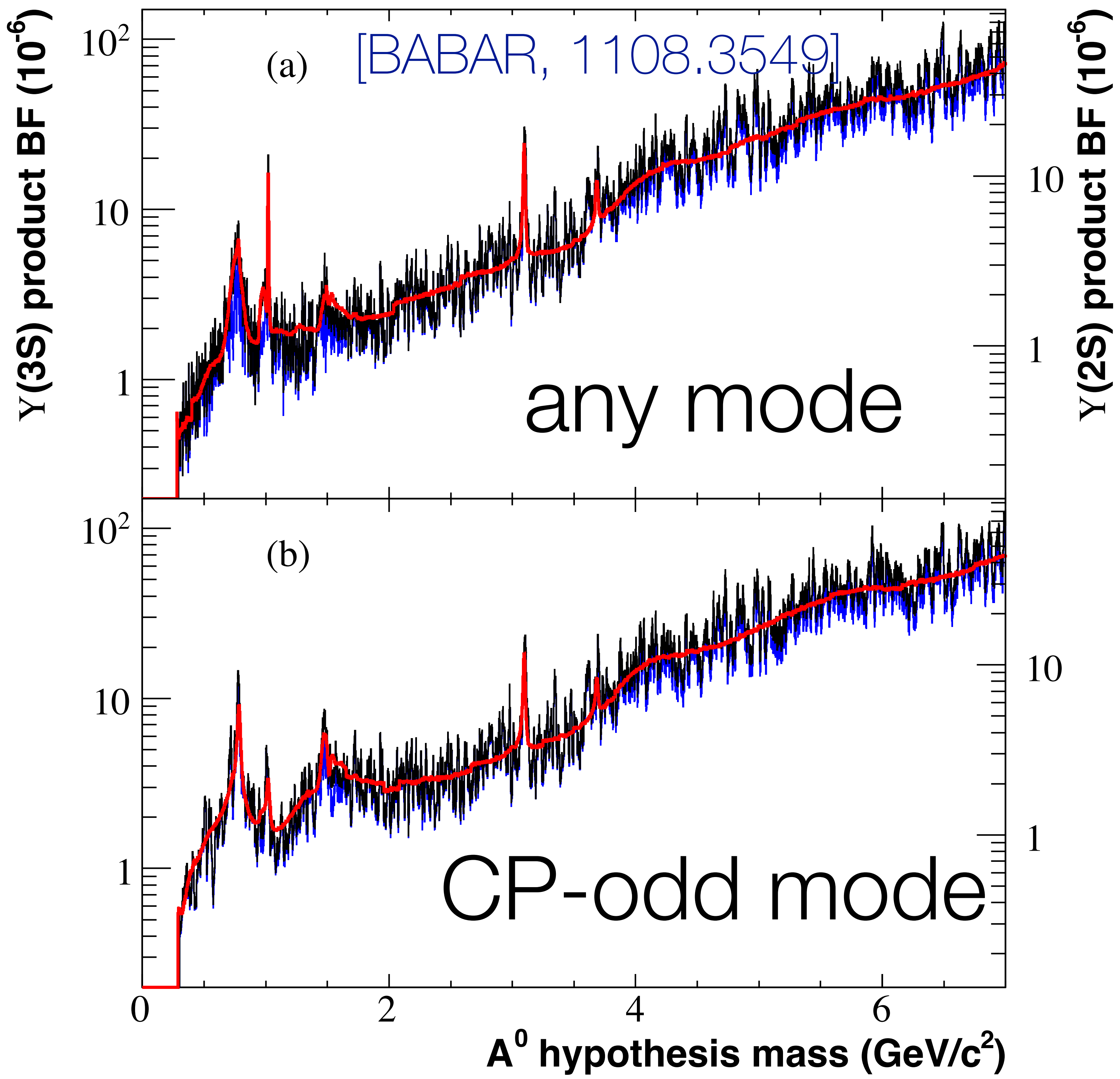
$e^+e^- \to \Upsilon(1s,2s) \otimes$

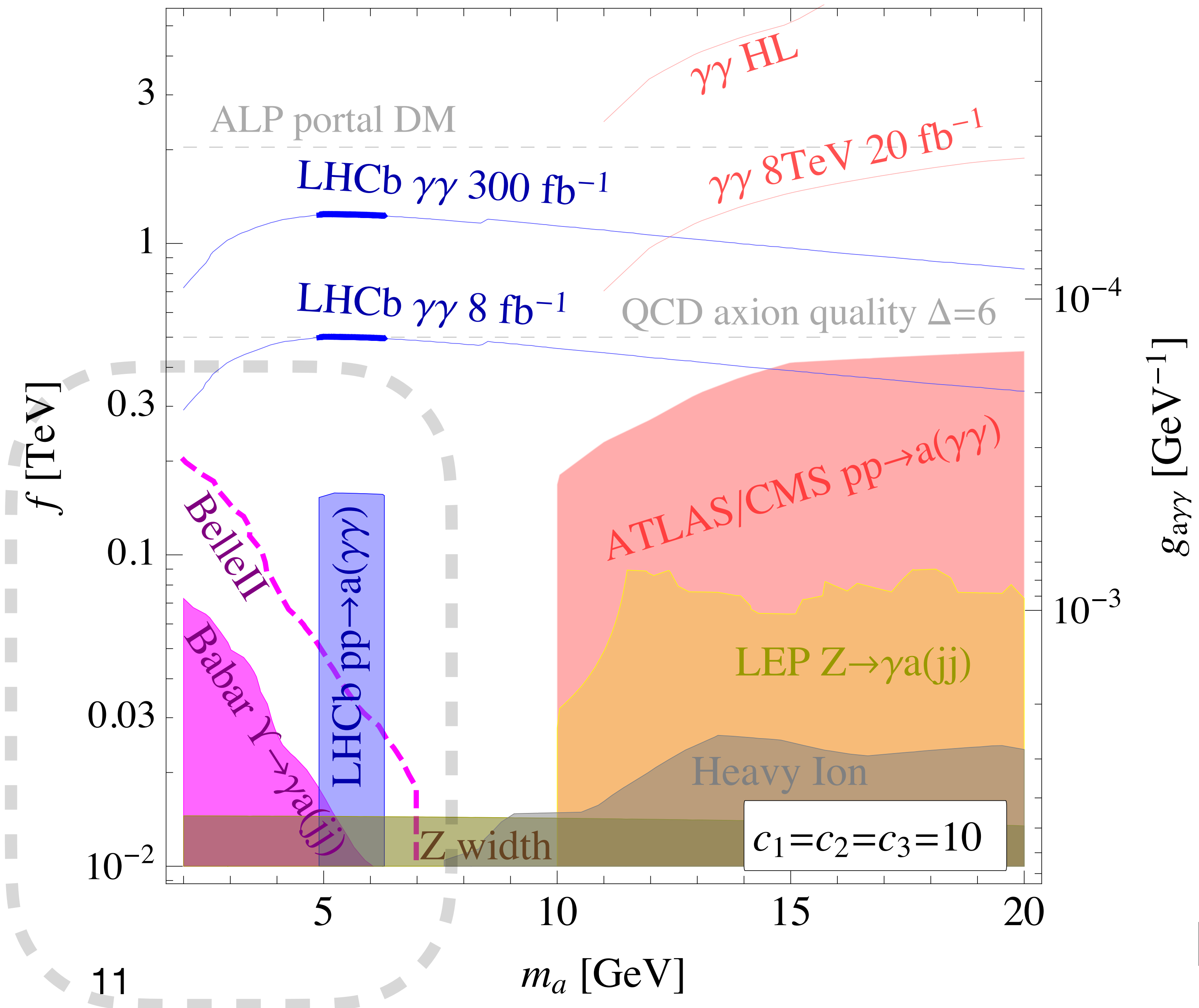




B-factory is unique

- Calculate rate and rescale to Belle II (x100)

$$\frac{\mathrm{BR}(\Upsilon \to \gamma a)}{\mathrm{BR}(\Upsilon \to \mu\bar{\mu})} \simeq 2E^2 \frac{\alpha_{\rm em}}{4\pi} \left(\frac{m_\Upsilon}{4\pi f}\right)^2 \left(1 - \frac{m_a^2}{m_\Upsilon^2}\right)^3$$



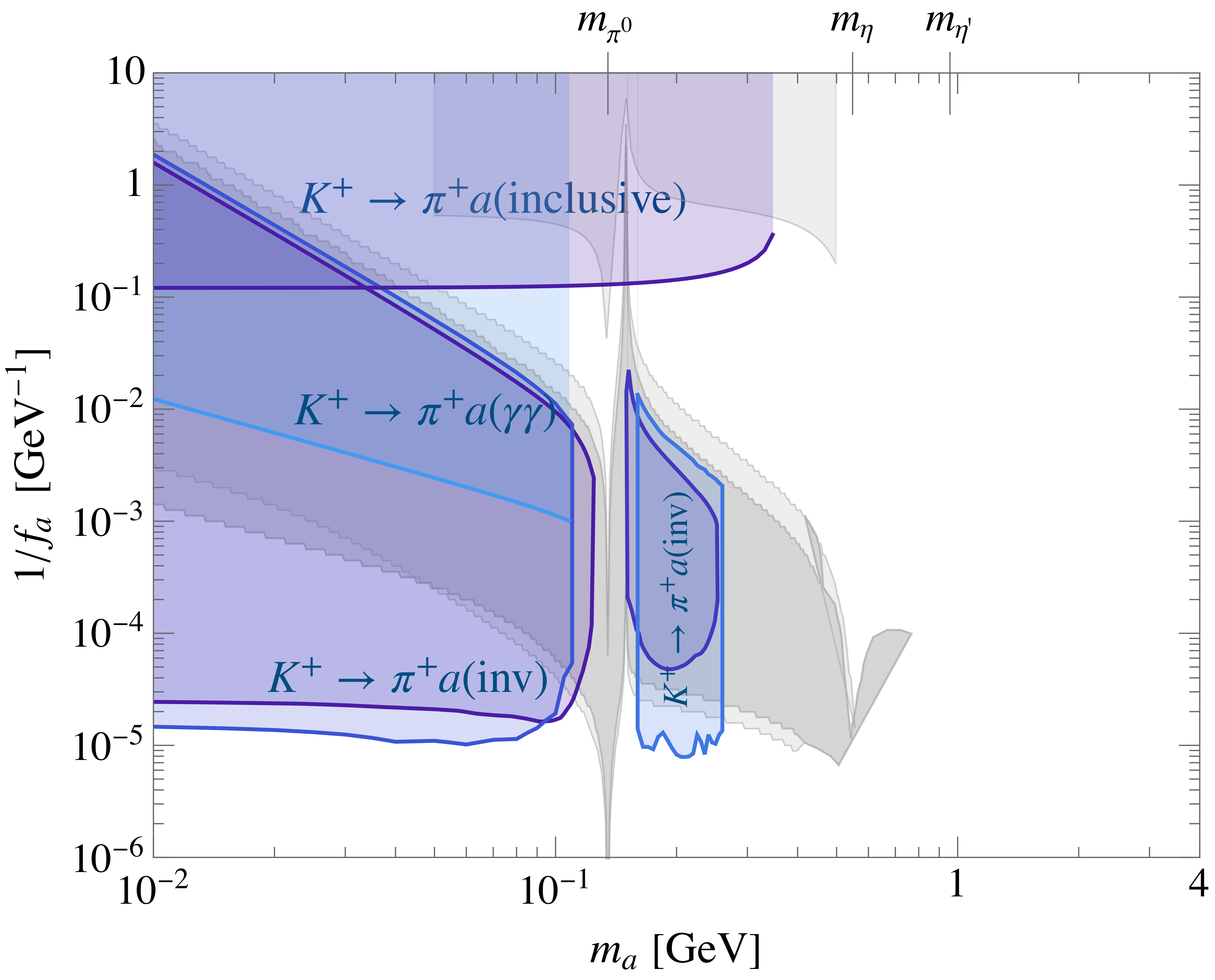
Mass coverage: 0.5GeV-7GeV

- LHCb analysis is on-going.

[X. Cid Vidal, A. Mariotti, F. Sala, D. Redigolo, KT, 1710.01743]]

MeV-GeV range, kaon and proton beam-dump

- LHC down to 10GeV(2GeV). $K^+ \to \pi^+ a$ constraints $m_a < m_K - m_\pi \sim$ **0.35GeV**



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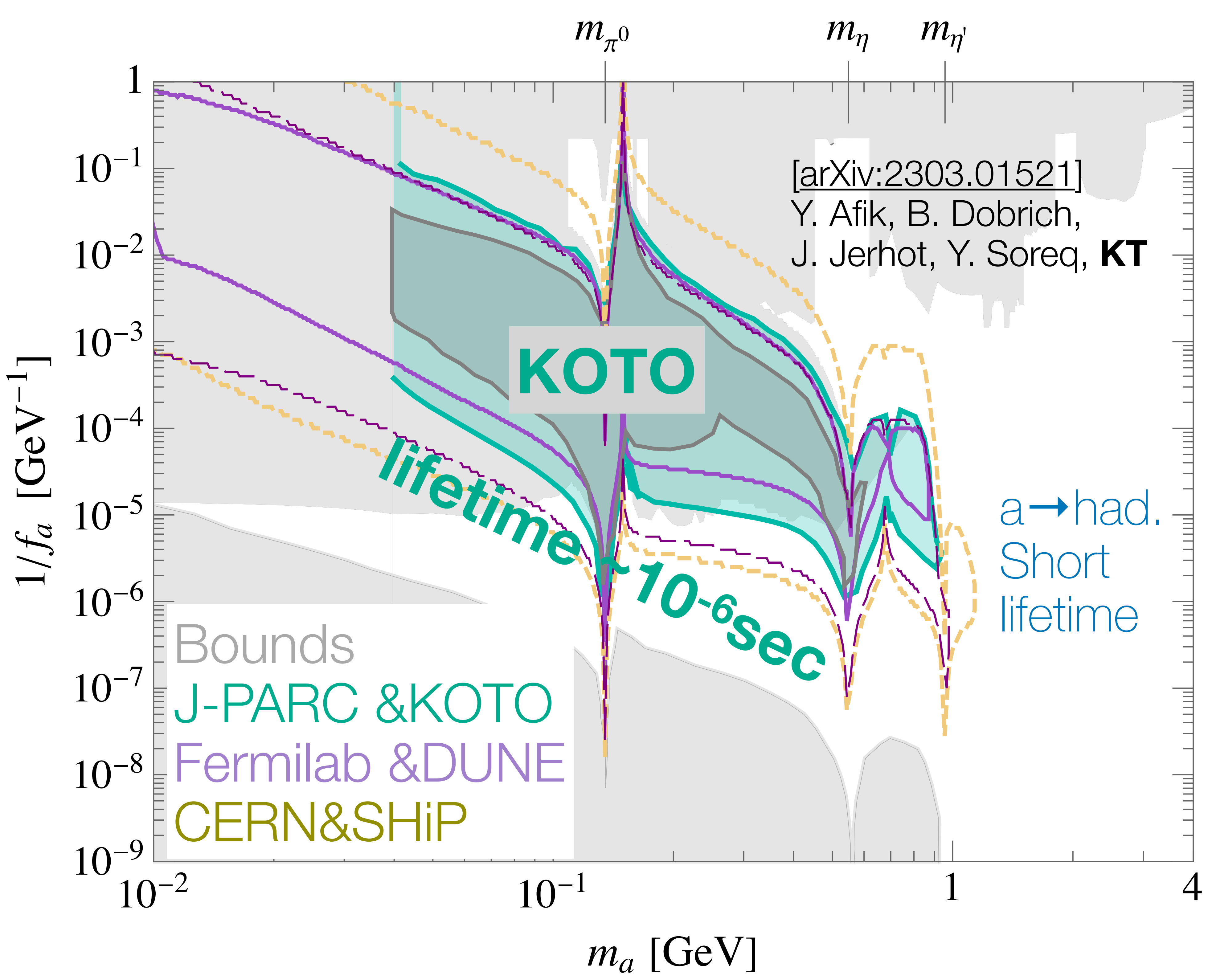

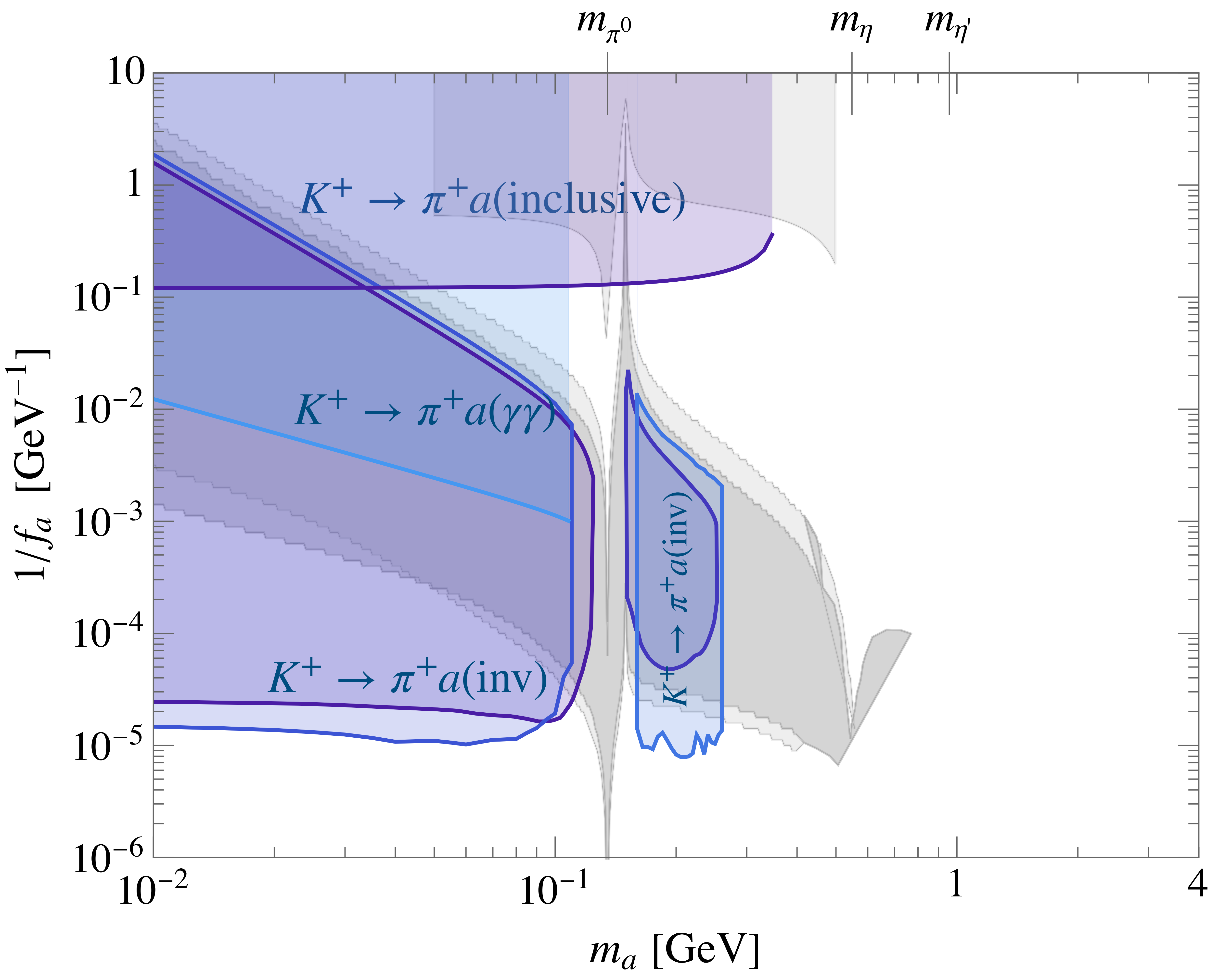

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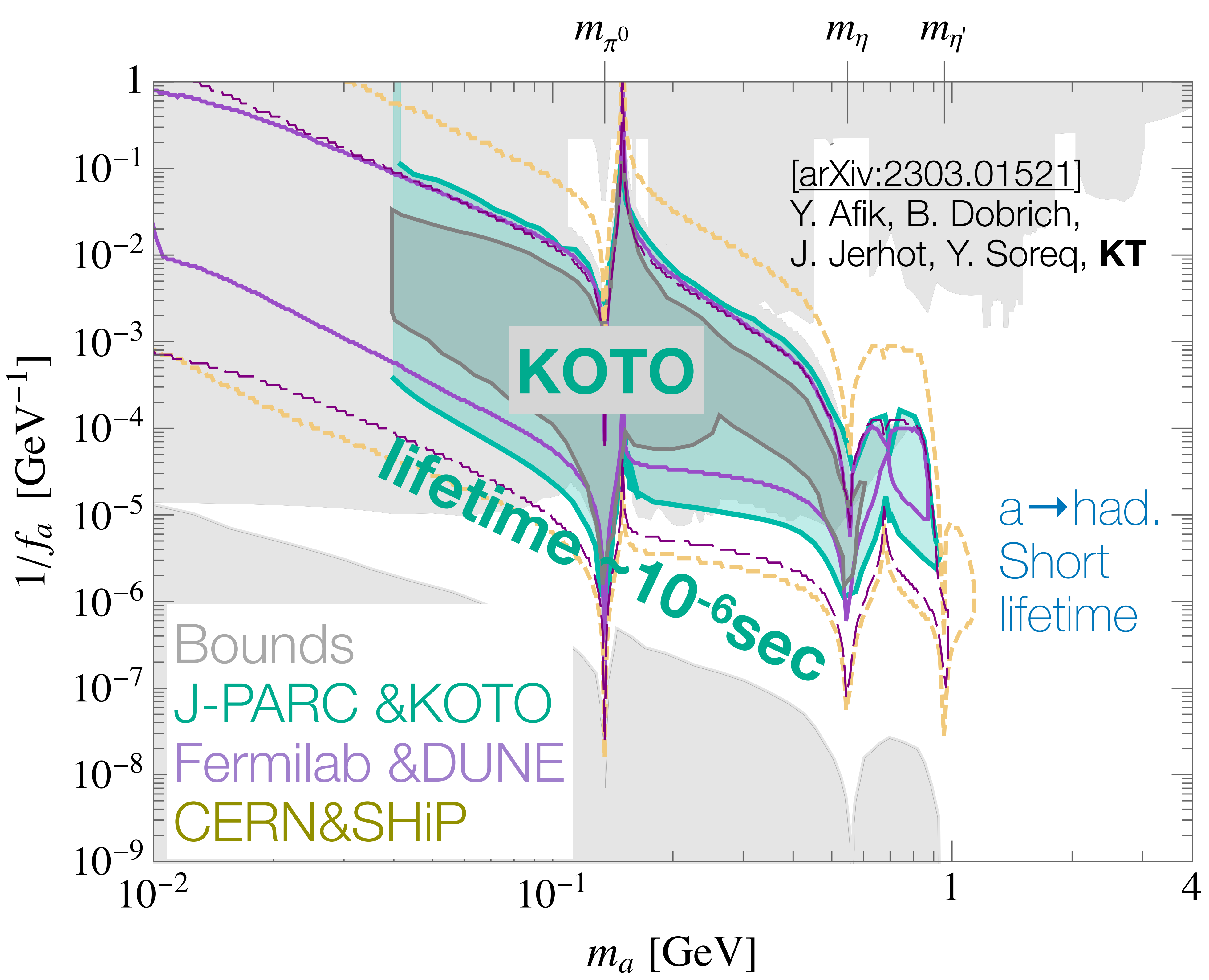
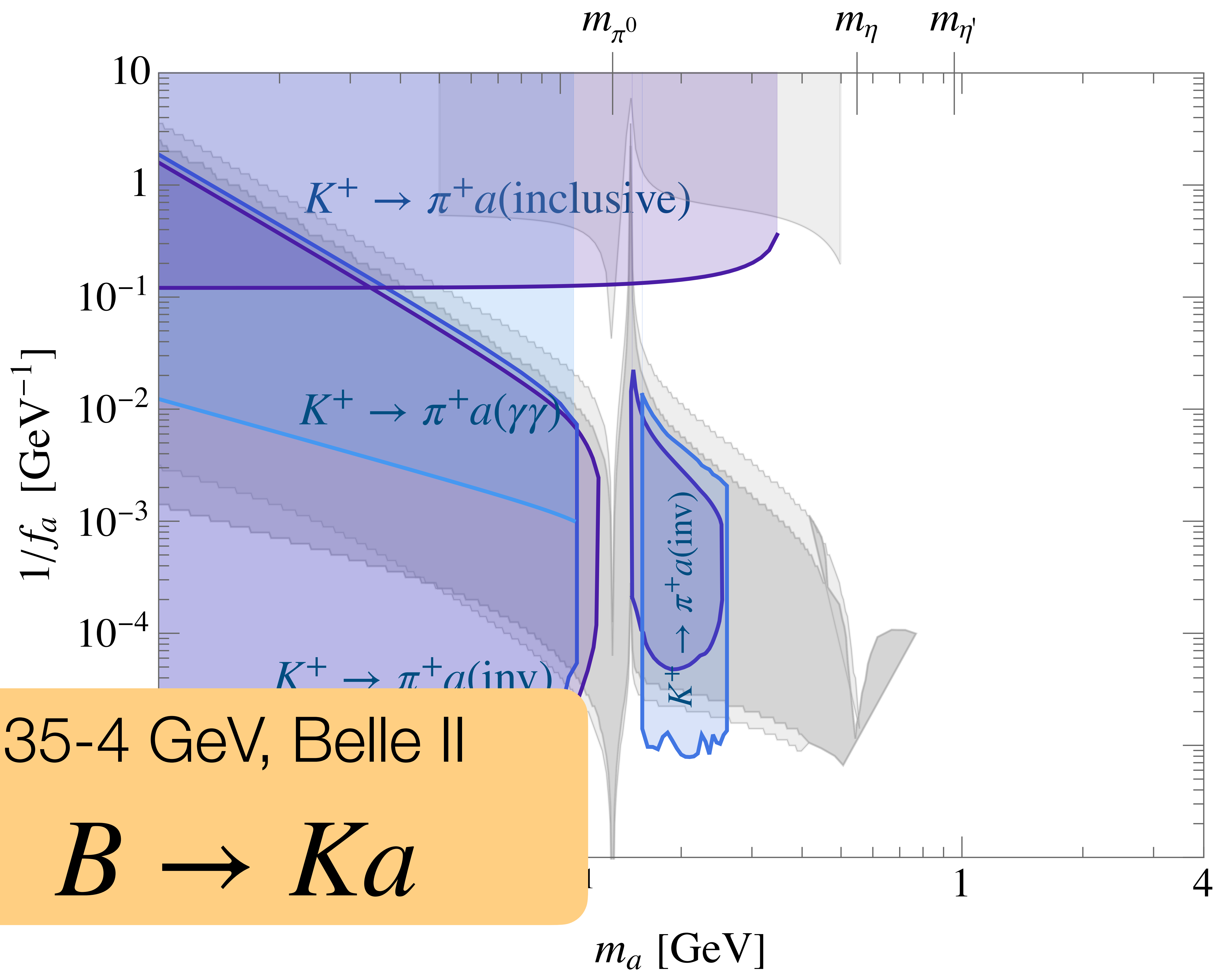
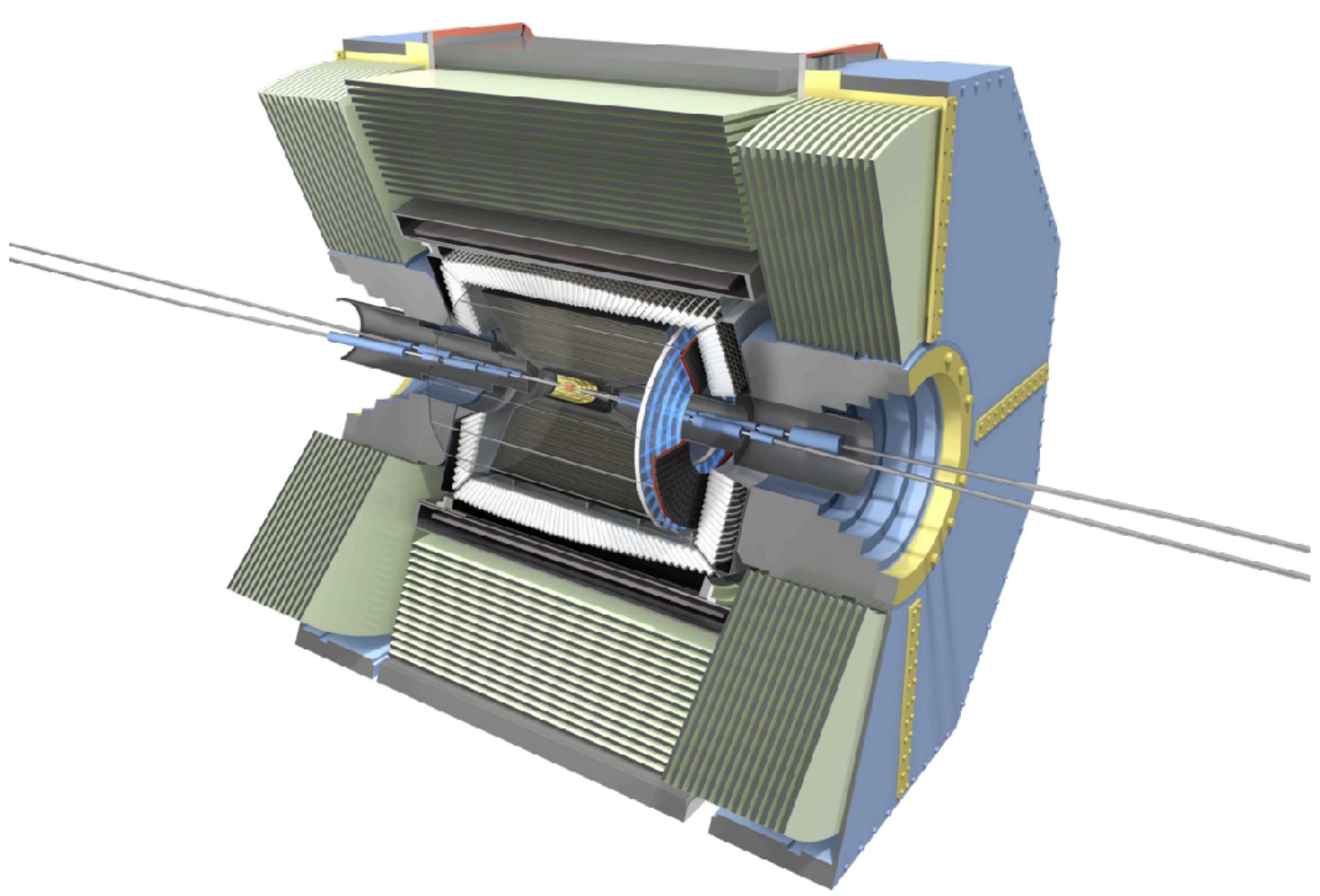




- 0.35-4 GeV, Belle II

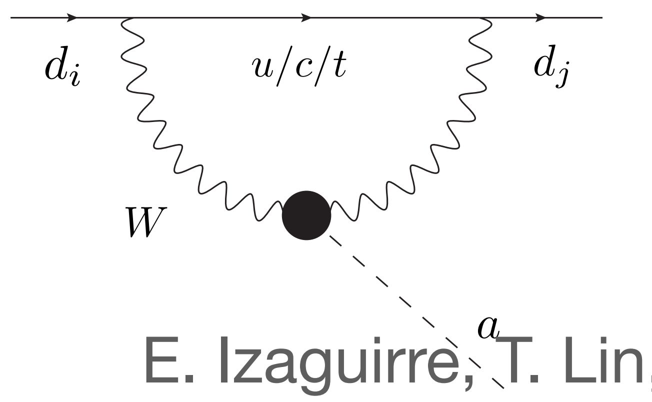
$$B \to Ka$$

$B \to Ka$ for m_a~GeV



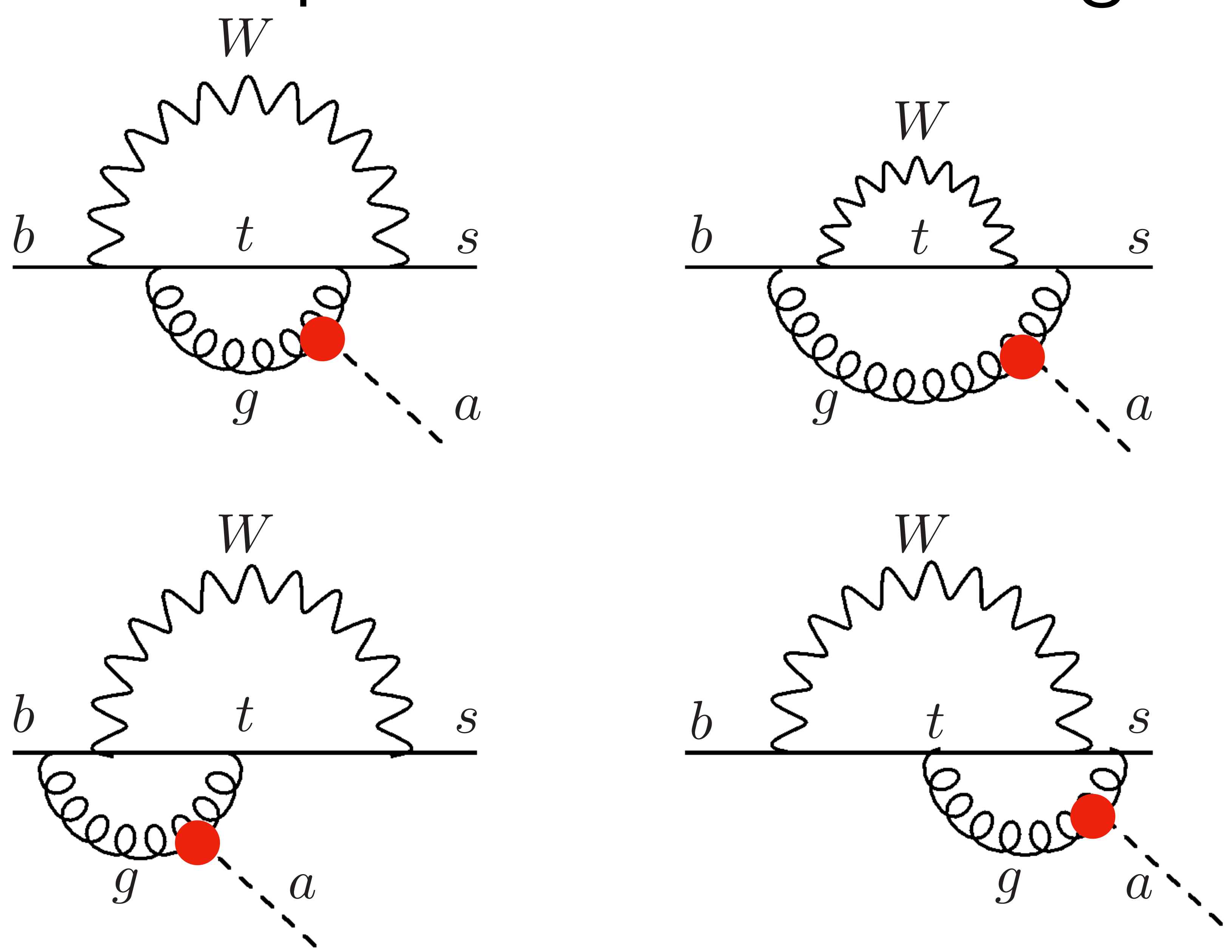
Production rate of $B \to Ka$

- If the optional aWW coupling exists,
  there is 1-loop contribution [finite due to GIM, diverge at 2-loop].



E. Izaguirre, T. Lin, B. Shuve

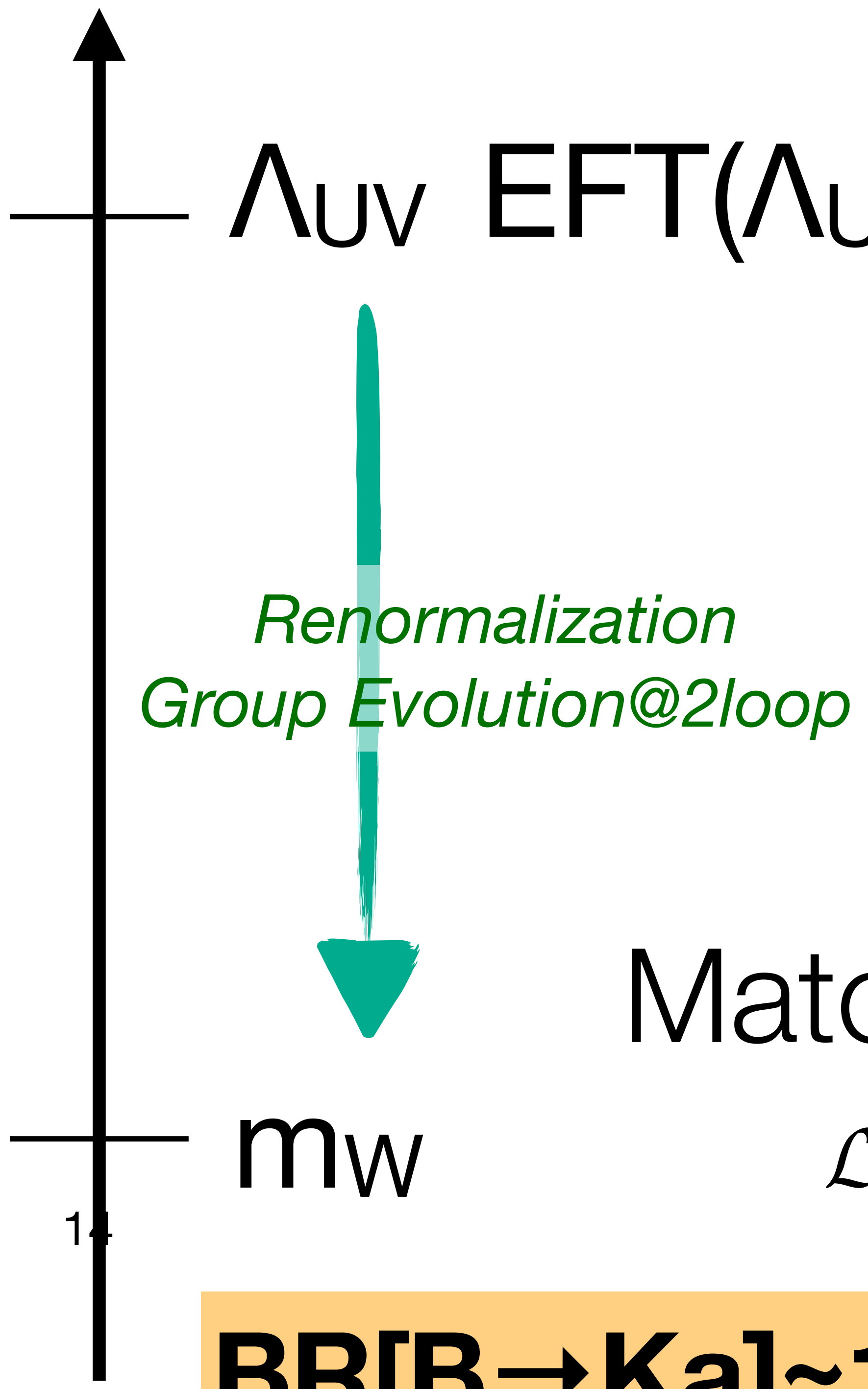
- Robust production is from gluon coupling: leading is at 2-loop!



Need 2-loop to generate $b \to sa$ from aGG

- 1-loop QCD for aqq
- 1-loop with W-boson for flavor changing

PRD 104 (**2021**) 055036
S. Chakraborty, M. Kraus, V. Loladze, T. Okui, **KT**



EFT(Λ_{UV})

$$\mathcal{O}_{gg} = \frac{1}{8\pi}\frac{a}{f_a} G^a_{\mu\nu}\tilde{G}^{a\mu\nu} ,$$

$$\mathcal{O}_{qq} = \sum_q \frac{\partial_\mu a}{f_a} \bar{q}\gamma^\mu\gamma_5 q ,$$

$$\mathcal{O}_{bs} = \frac{\partial_\mu a}{f_a} \bar{s}_L\gamma^\mu\gamma_5 b_L + \text{h.c.} .$$

Matching to weak-scale EFT @2loop

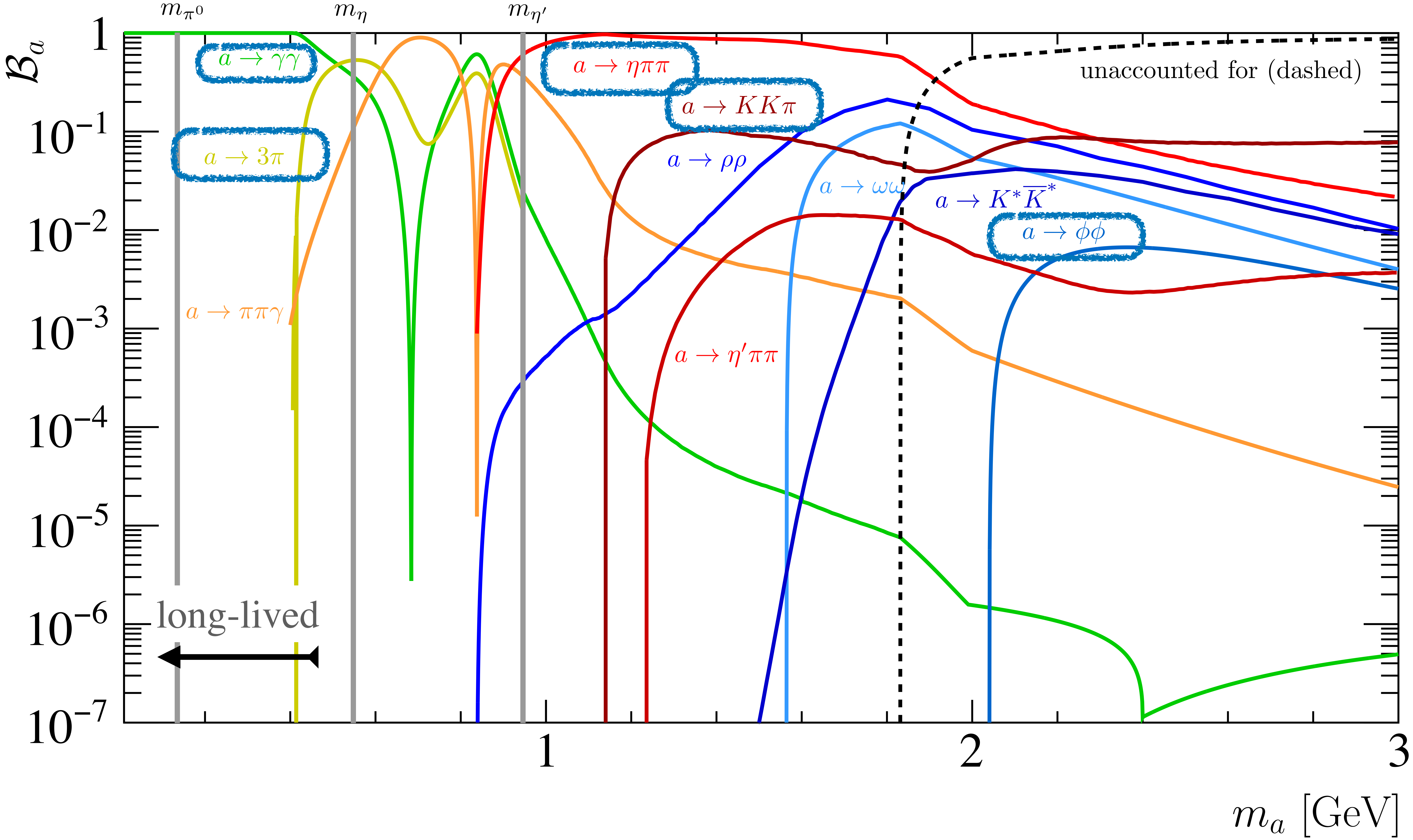
$$\mathcal{L}_{bsa} = C_W \frac{\partial_\mu a}{f_a} \bar{s}_L\gamma^\mu\gamma_5 b_L$$

BR[B→Ka]~10^{-5} (f_a/100GeV)$^{-2}$

Heavy QCD axion decay patterns

[1811.03474, D. Aloni, Y. Soreq, M. Williams]

- Chiral perturbation theory, m_a<1GeV
- Data-driven method, m_a~1-2GeV [essential for $B \to Ka$]
  Axion-vector meson-vector meson



Heavy QCD axion decay patterns

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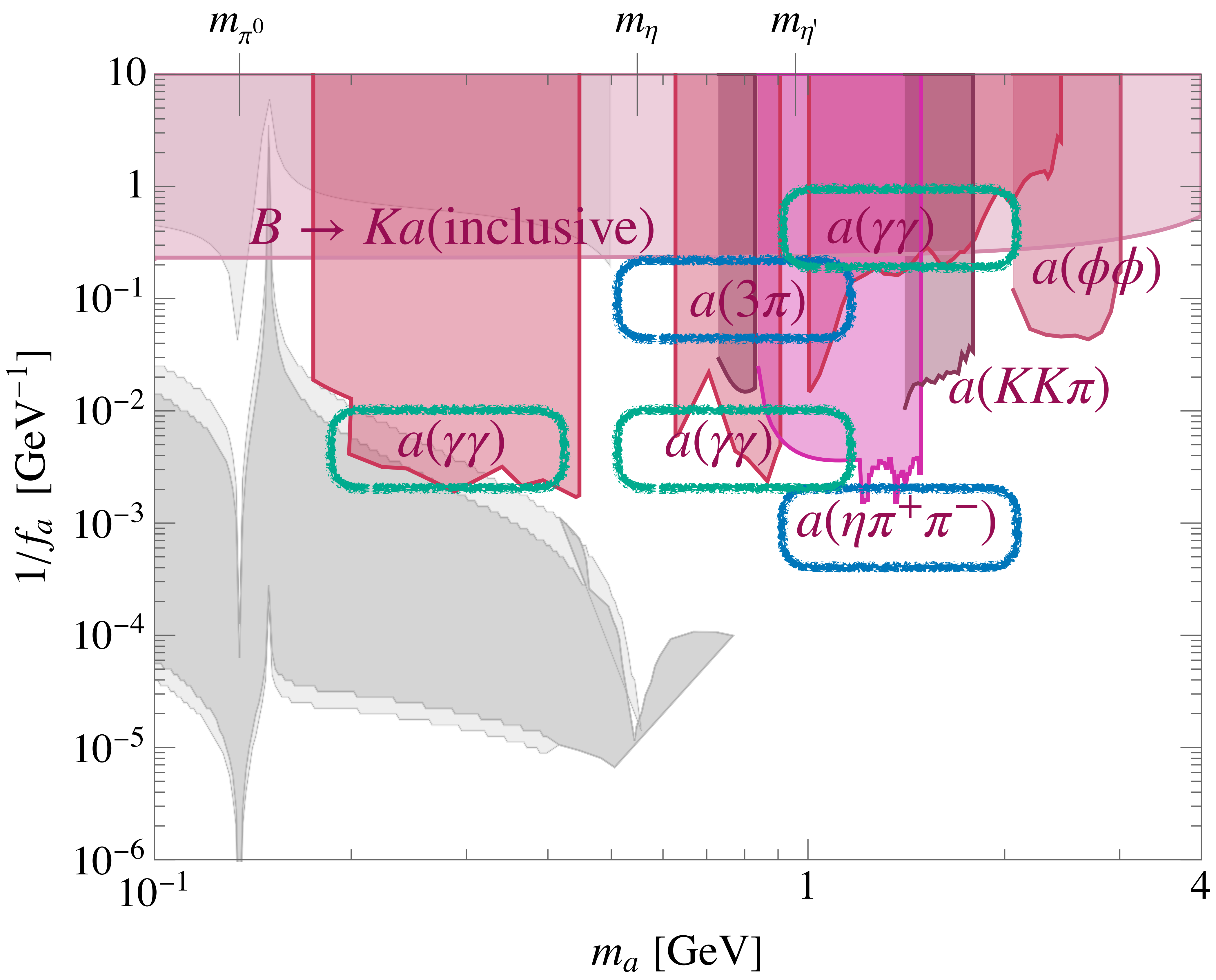
- Recast
  Old (Babar) and new (Belle II) analyses

  $B \to KX(\pi^0\pi^+\pi^-, \eta\pi^+\pi^-, KK\pi, \phi\phi, \gamma\gamma),$

- Need similar/dedicated analyses at Belle II
  Also new searches.



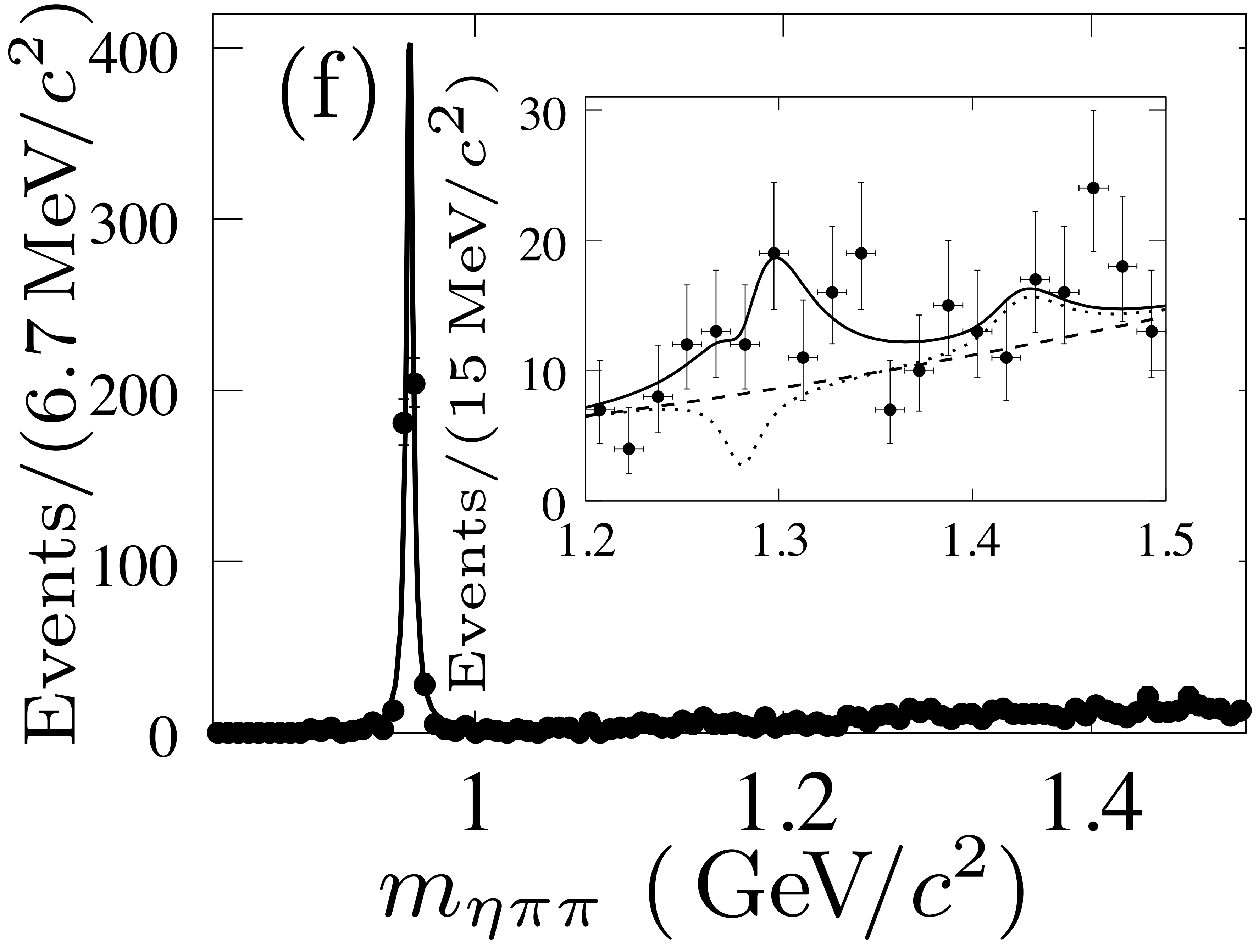
Wish 2: $B \to Ka$ and $a \to \eta\pi\pi$

- **Babar** [0804.0411] $B^+ \to K^+\eta_X(\to \eta\pi\pi)$ *search*

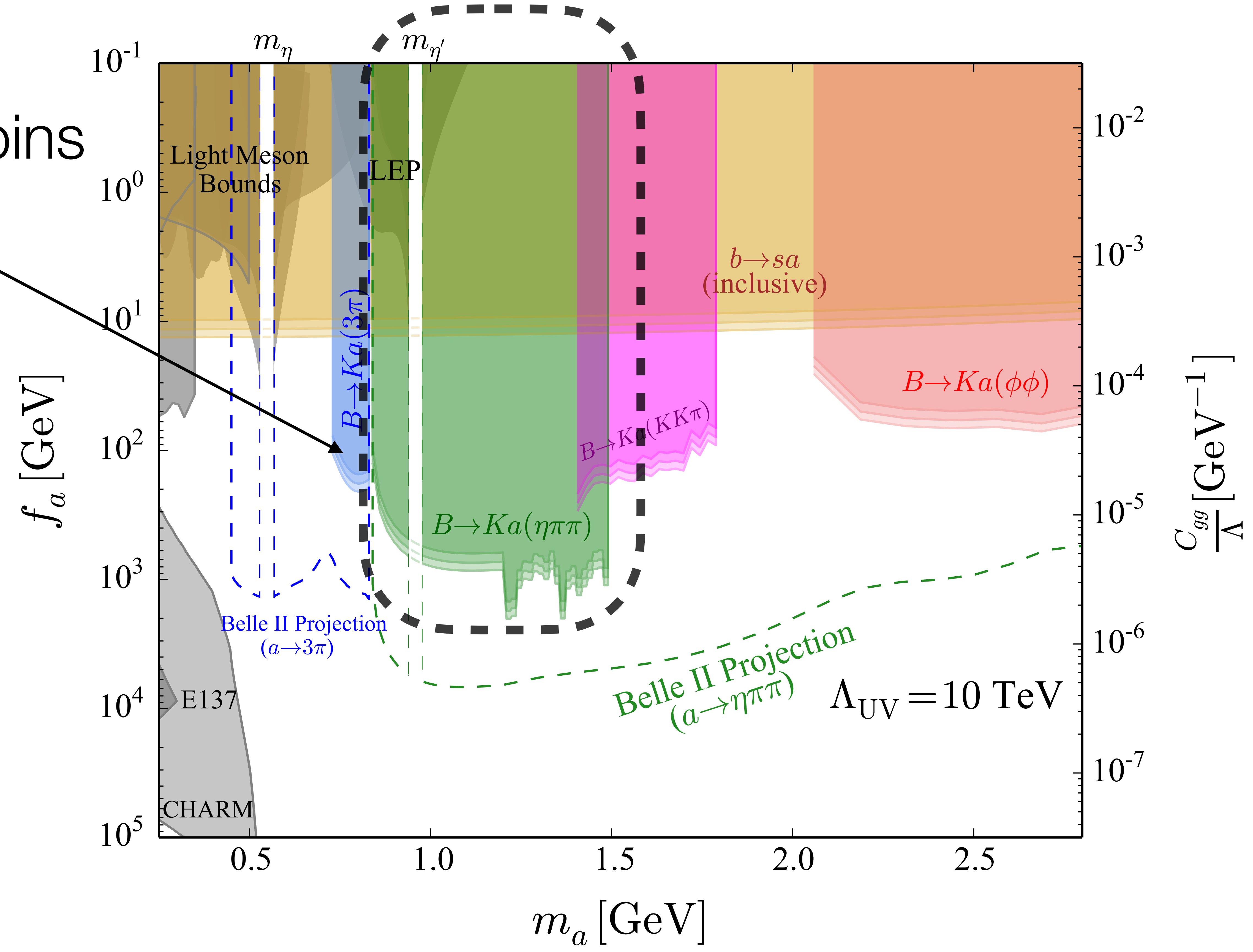
  3.9x10[8]$B\bar{B}$, 0.85 GeV <m_a<1.5 GeV

- Take axion peak smearing same as η' peak

  require $S < (D - B) + 2\sqrt{D}$ inside relevant 2 bins



PRD 104 (**2021**) 055036
S. Chakraborty, M. Kraus, V. Loladze, T. Okui, **KT**



Wish 2: $B \to Ka$ and $a \to \eta\pi\pi$

- **Babar** [0804.0411] $B^+ \to K^+\eta_X(\to \eta\pi\pi)$ *search*
  3.9x10[8]$B\bar{B}$, 0.85 GeV <m_a<1.5 GeV

- Take axion peak smearing same as η' peak
  require $S < (D - B) + 2\sqrt{D}$ inside relevant 2 bins

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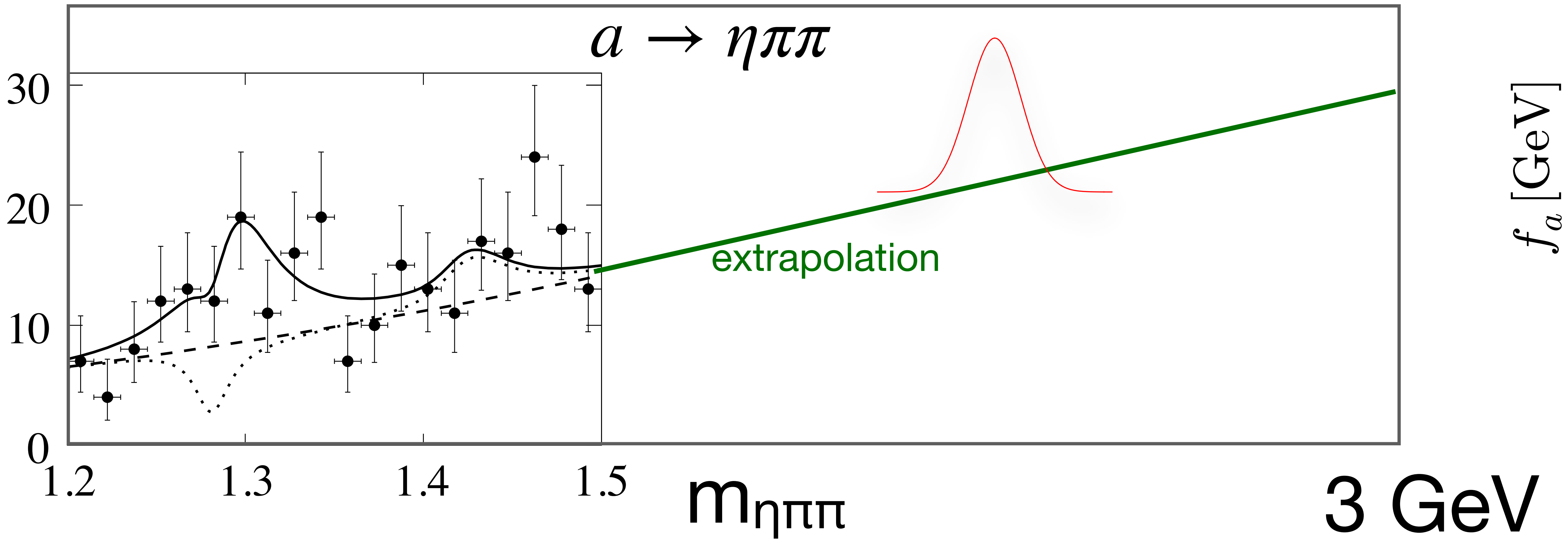
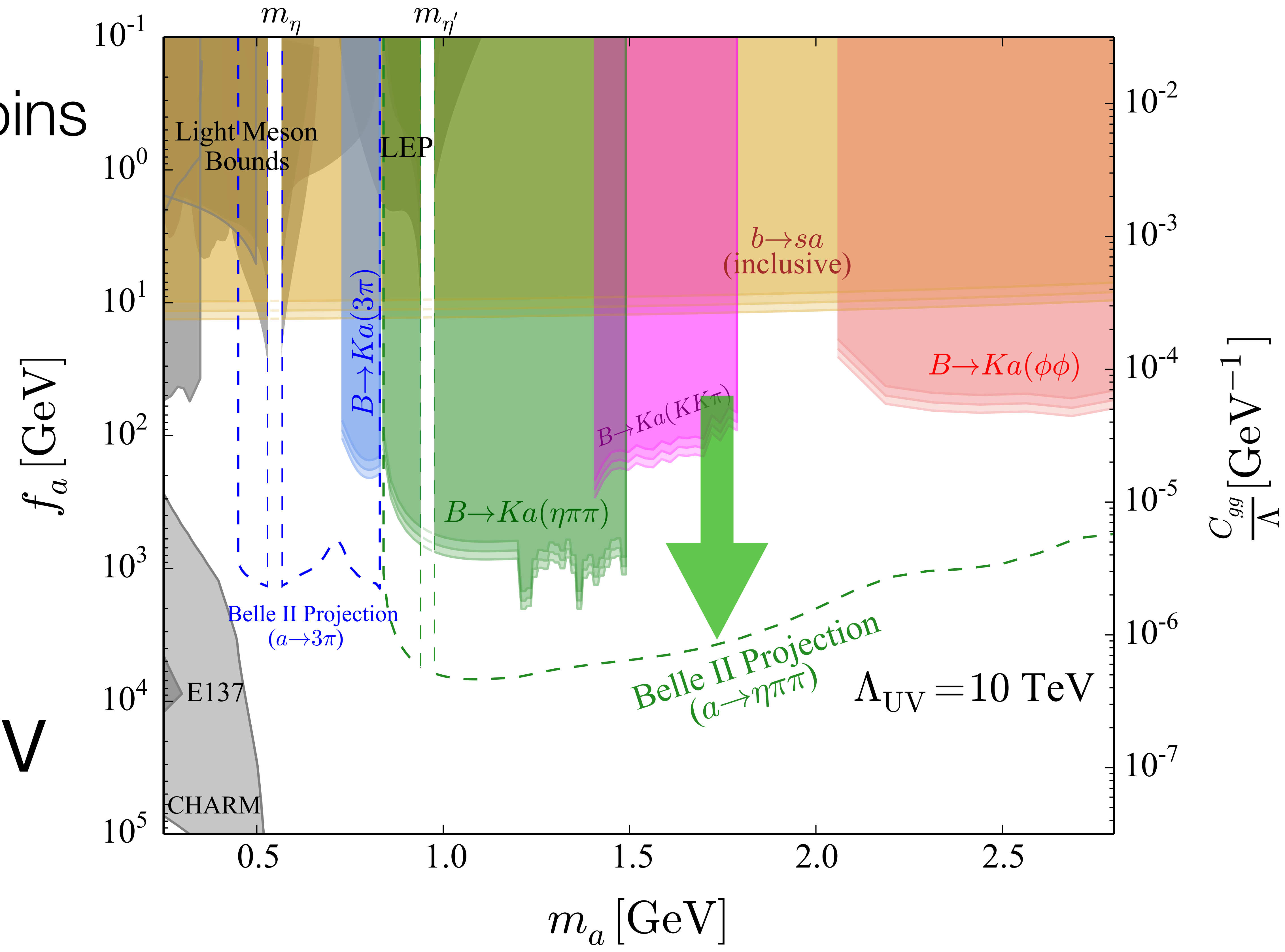
S. Chakraborty, M. Kraus, V. Loladze, T. Okui, **KT**





Wish 3: $B \to Ka$, prompt/displaced $a \to 3\pi$

- Belle [1311.6666] $B^{+,0} \to K^{+,0}\omega(\to \pi^+\pi^-\pi^0)$ search
- 7.7x10^8 $B\bar{B}$ pairs, 0.73 GeV <m$_a$< 0.83 GeV
  ⇒Recast $\mathrm{BR}(B^0 \to K^0 a, a \to \pi^+\pi^-\pi^0) < 4.9 \times 10^{-6}$

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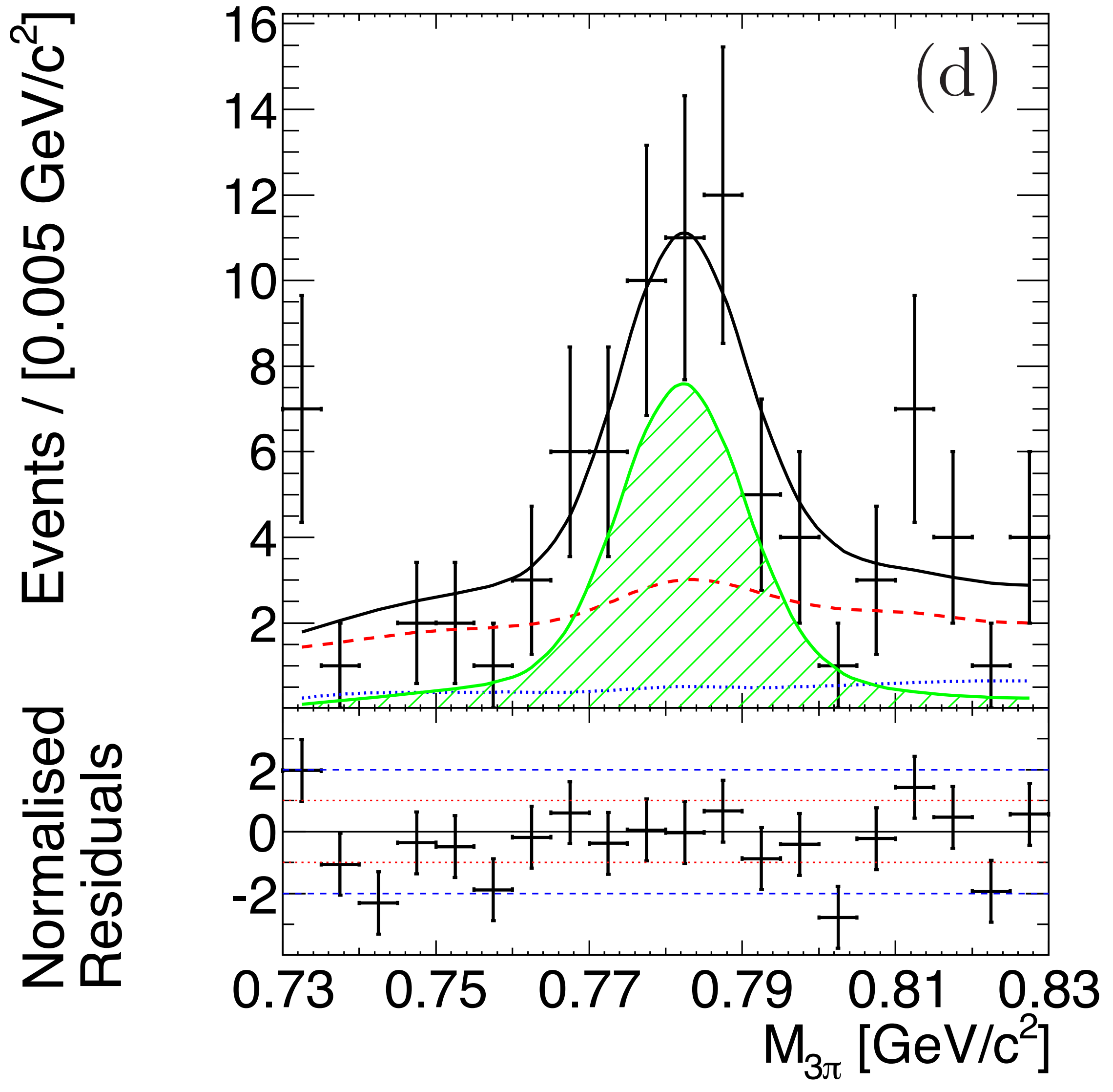

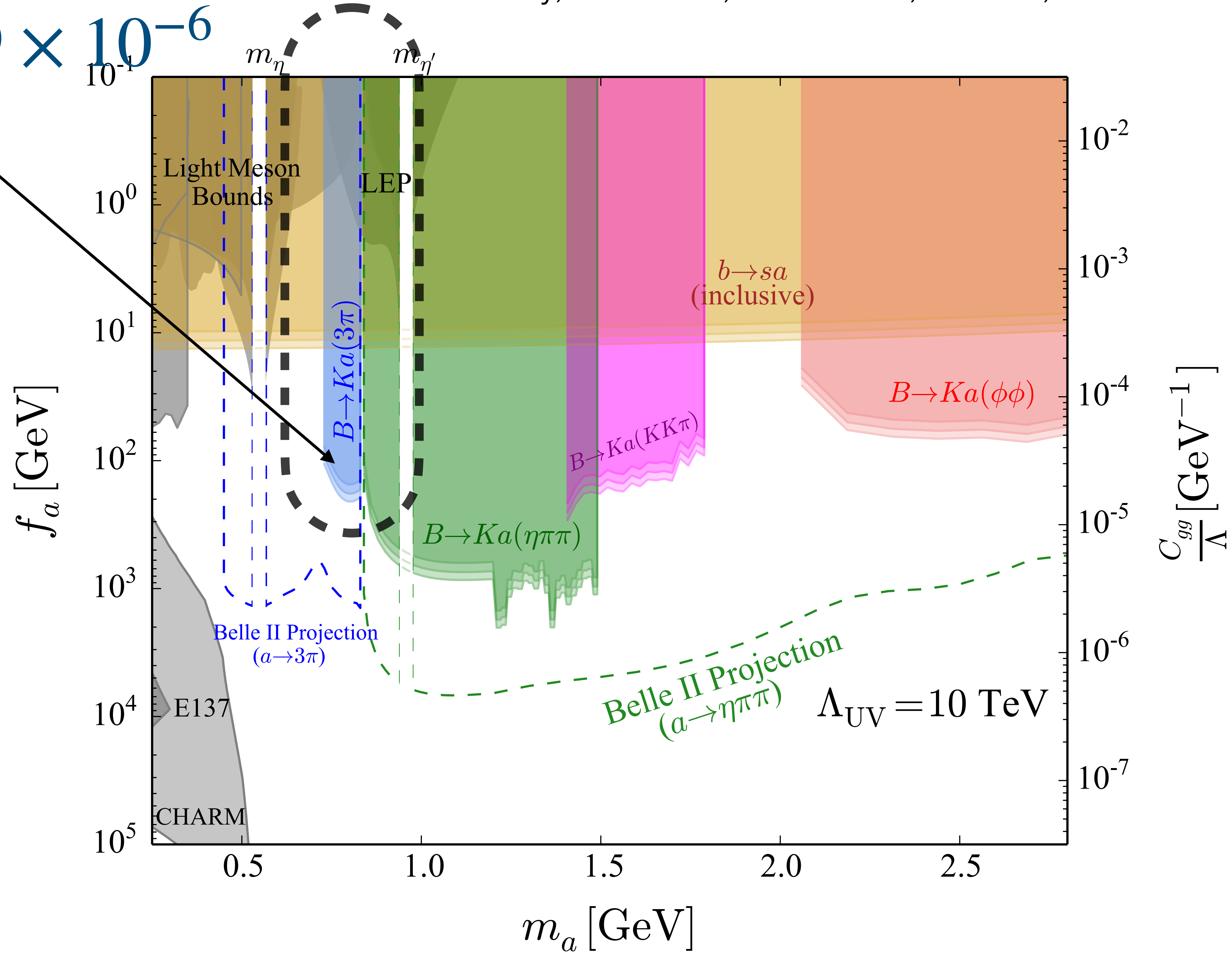

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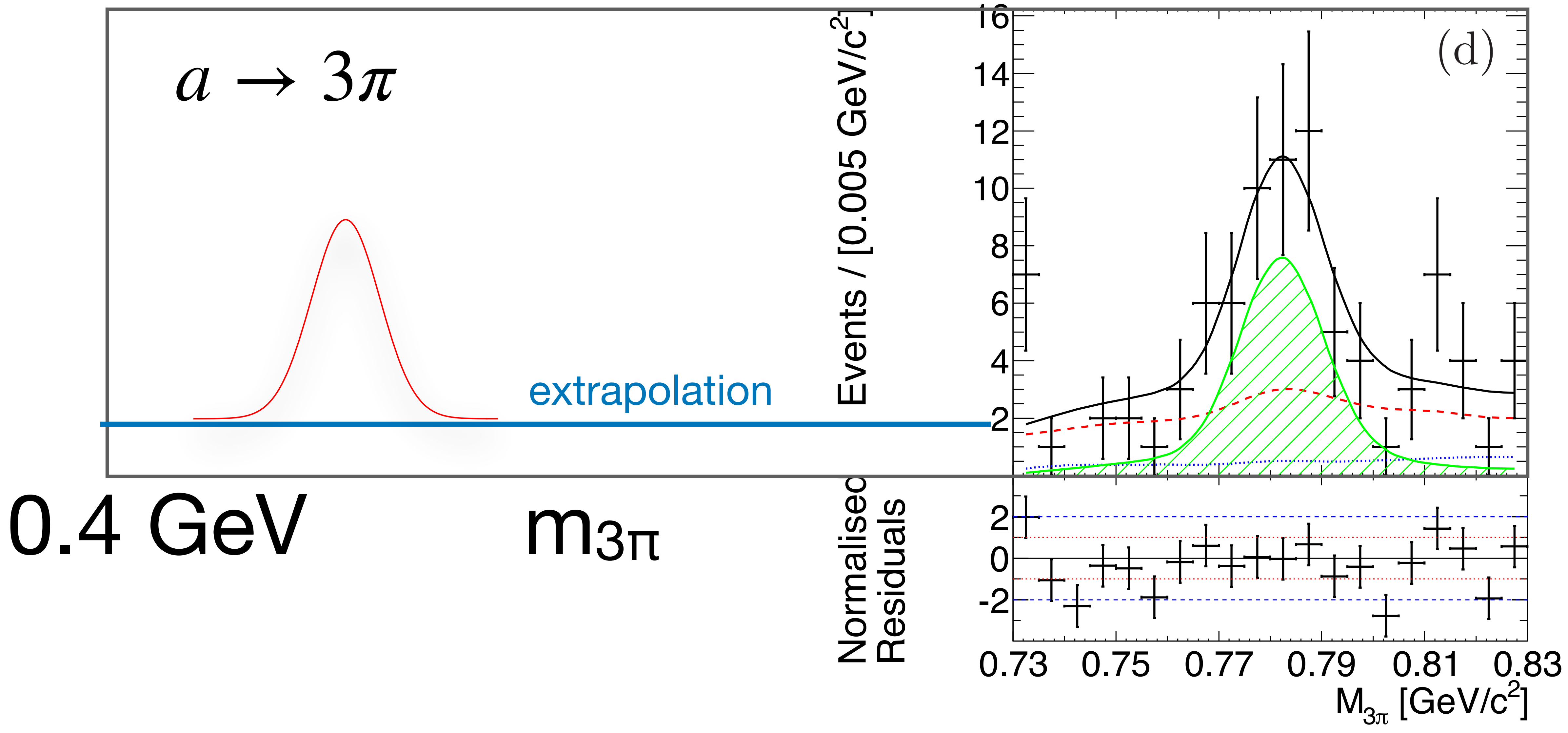
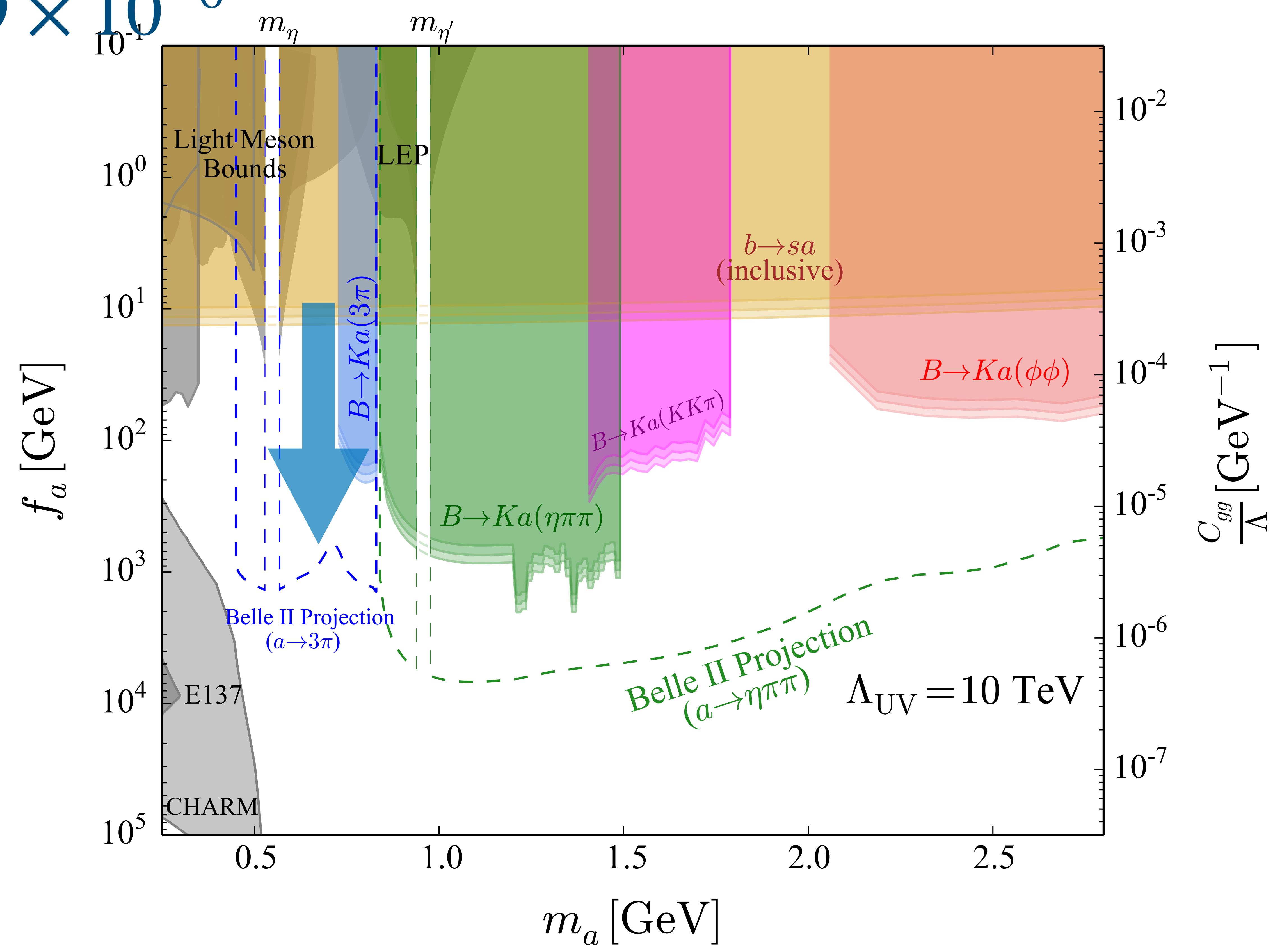
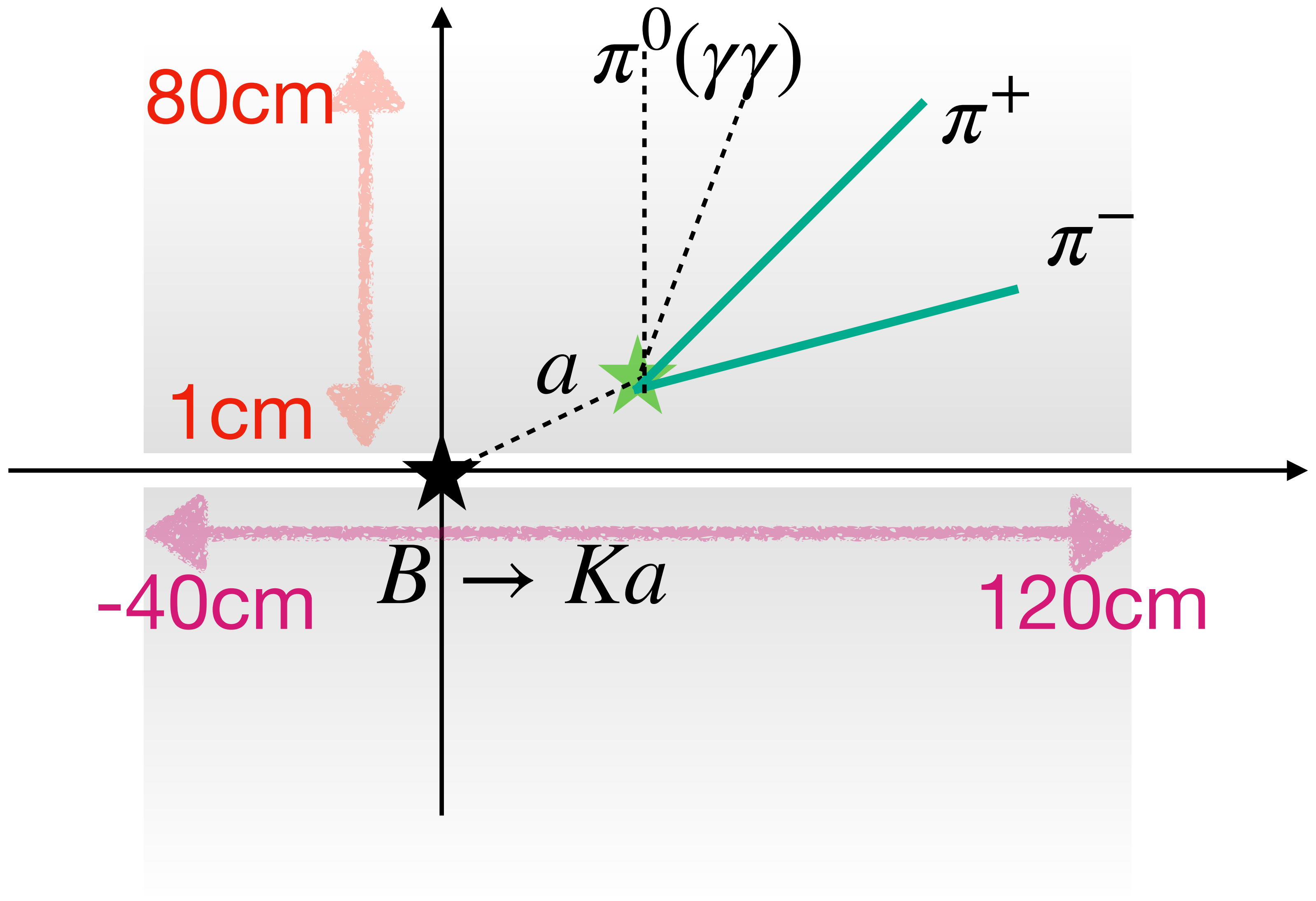


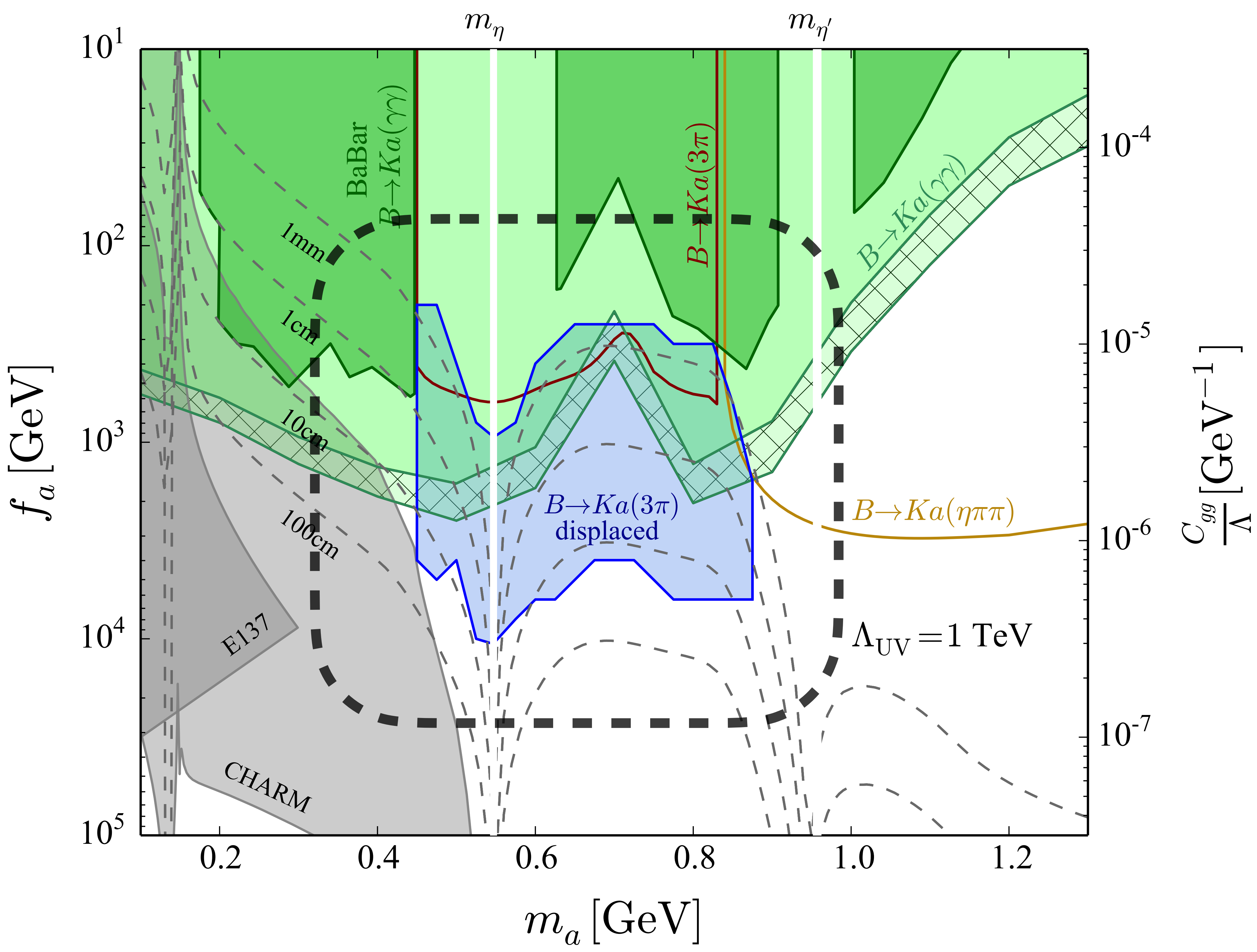


Wish 3: $B \to Ka$, prompt/displaced $a \to 3\pi$

- **Displaced decay** is also possible because 2 charged pions reconstruct vertex.
- **Very low background due to >1cm DV**.
  $B \to KK^*(\to \pi^0 K_L, K_L \to \pi^+\pi^-)$

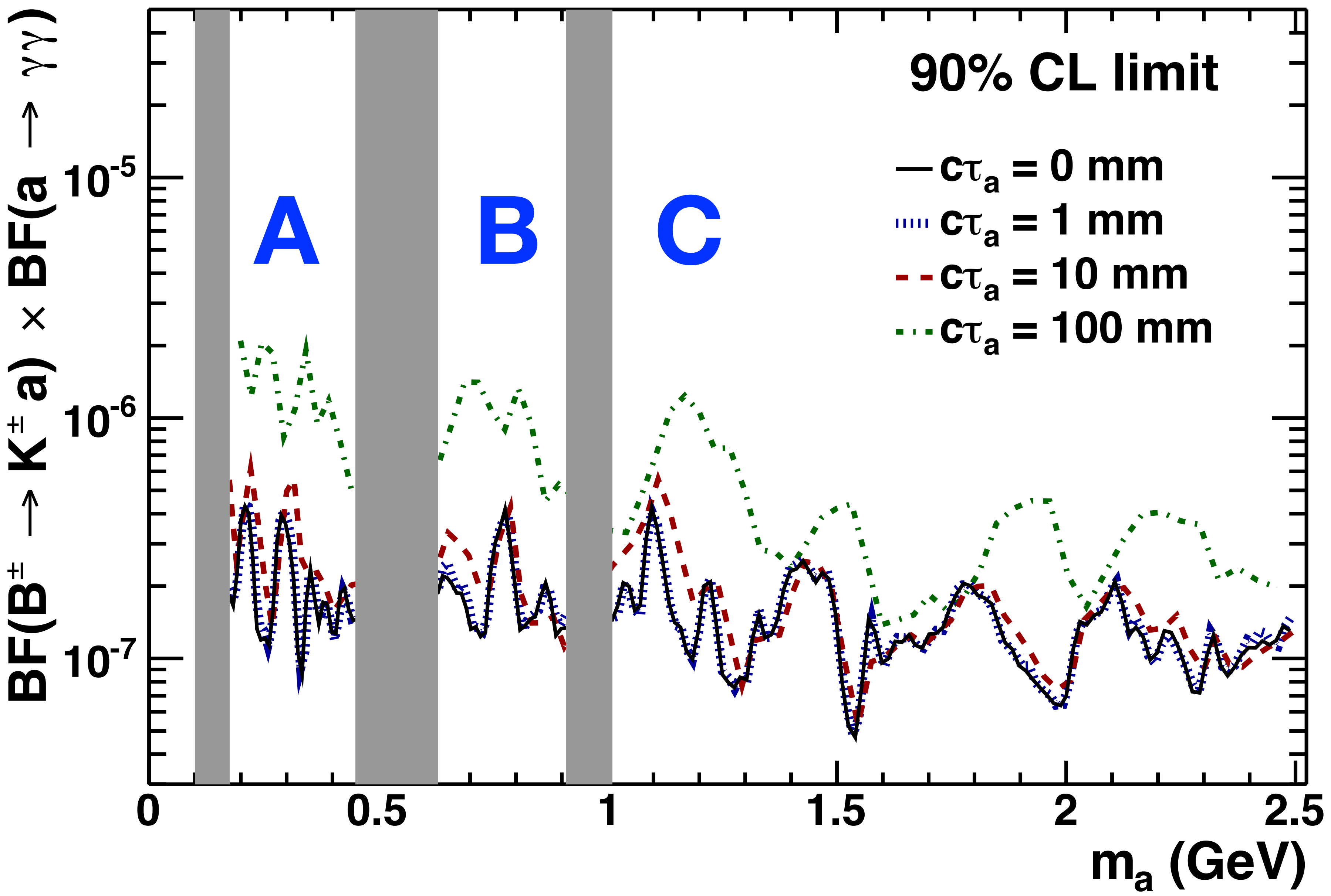
Phys.Rev.D 105 (2022) L071701
E. Bertholet, S. Chakraborty, V. Loladze, T. Okui, A. Soffer, **KT**





Wish 4: $B \to Ka$ and $a \to \gamma\gamma$

- Babar [2111.01800] (B. Shuve) dedicated ALP search. Reinterpret.
- Same/better analysis can be done at Belle II.



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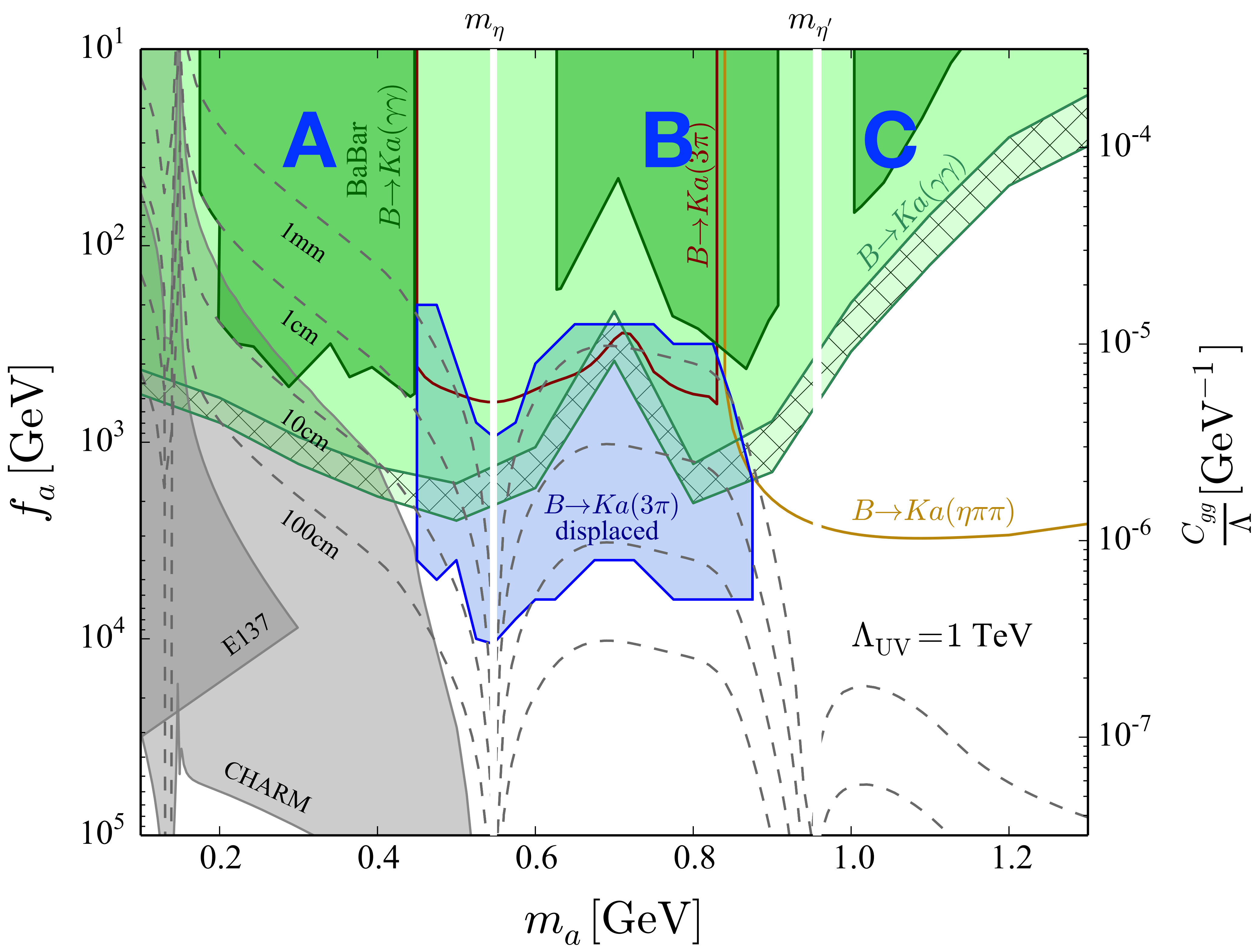
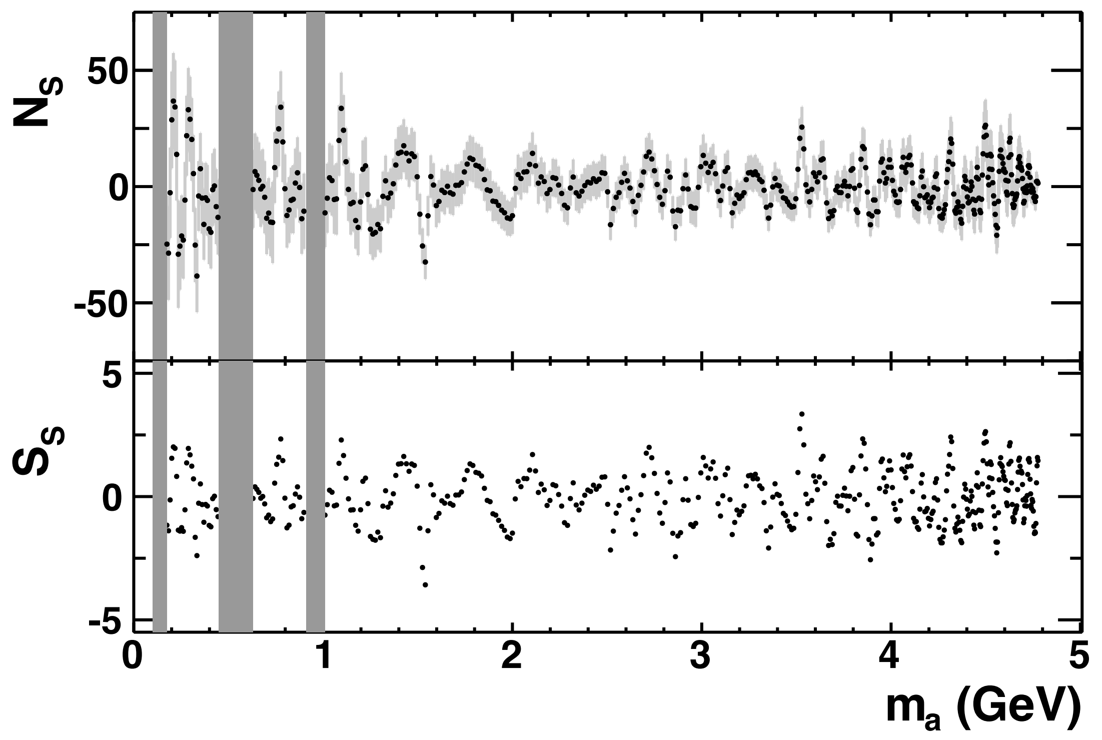
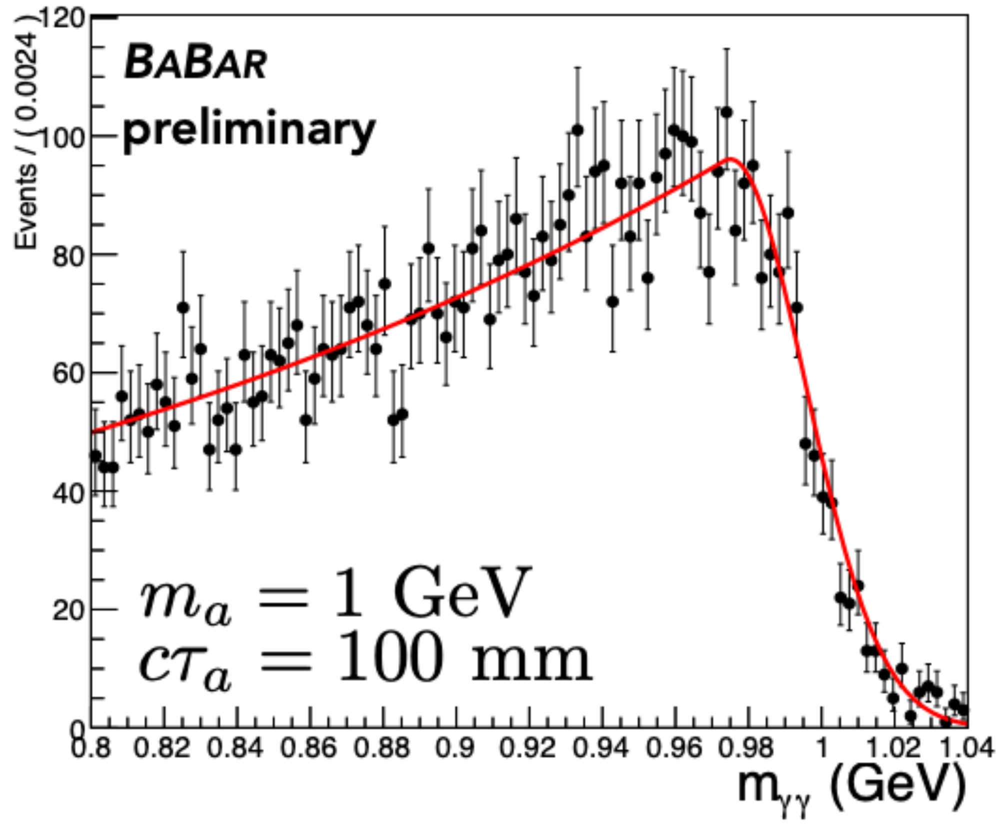


Wish 4: $B \to Ka$ and $a \to \gamma\gamma$

- For long-lived axion distribution smeared, mesons and axion don't overlap. Gap regions can be covered.

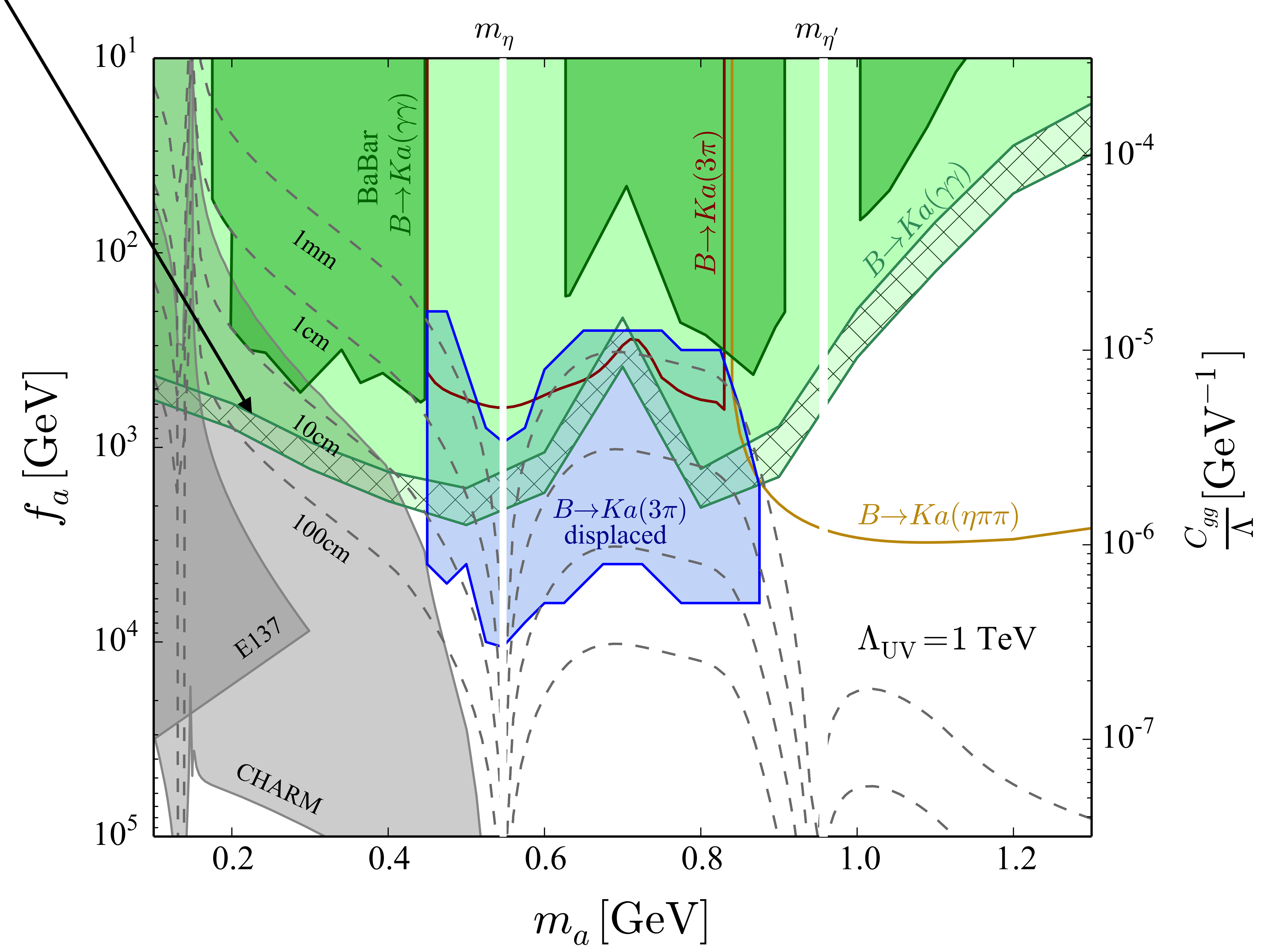




https://indico.cern.ch/event/868940/contributions/3814877/

Phys.Rev.D 105 (2022) L071701

E. Bertholet, S. Chakraborty, V. Loladze, T. Okui, A. Soffer, **KT**

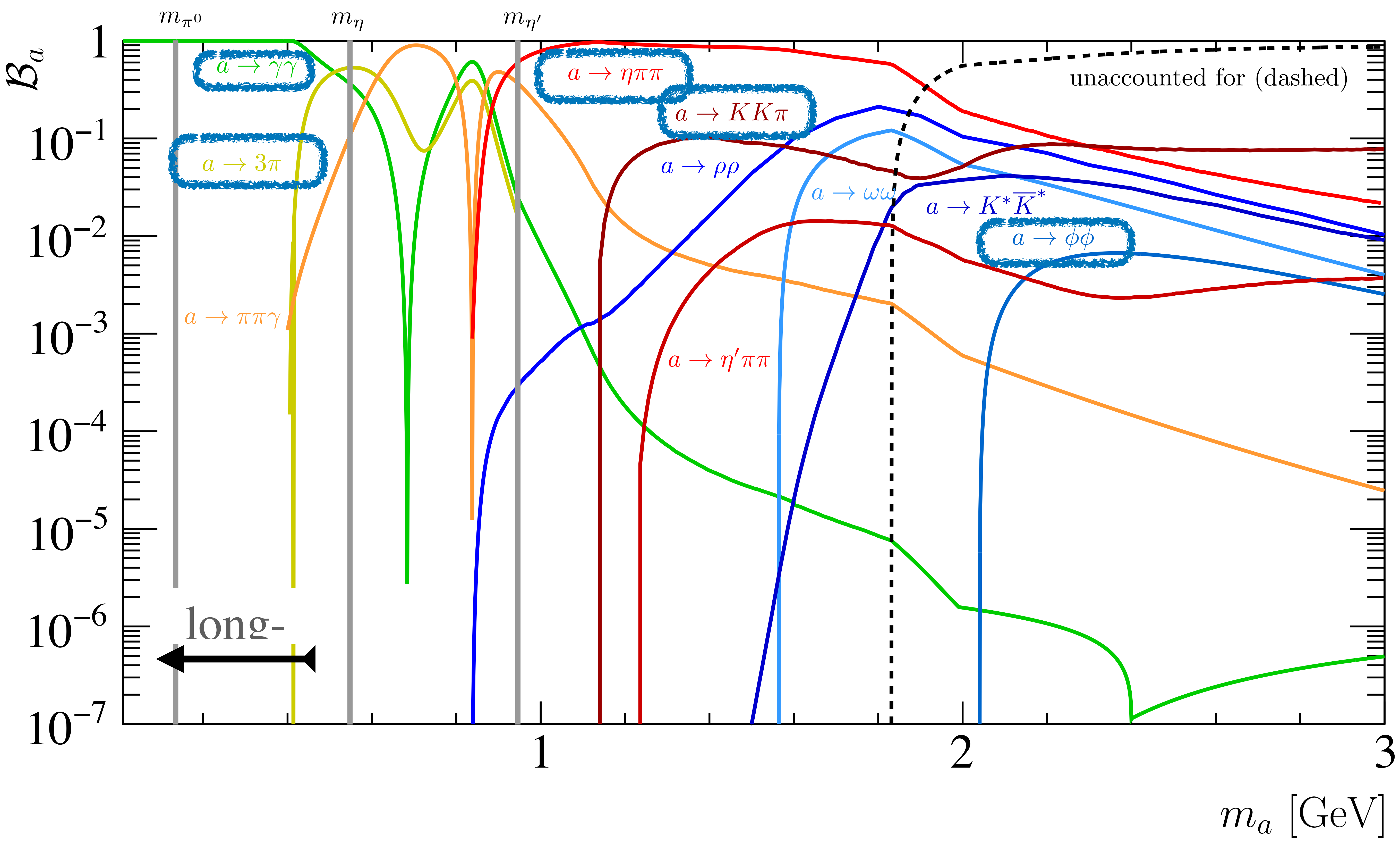


- Further improvement [2311.01837] NA62 K→πa with long-lived a→γγ. Basically look at $(p_{K^+} - p_{\pi^+})^2$ *not* $m_{\gamma\gamma}^2$ Report signal efficiency as f(τa).

Wish 5: $B \to Ka$, $a \to$ hadrons

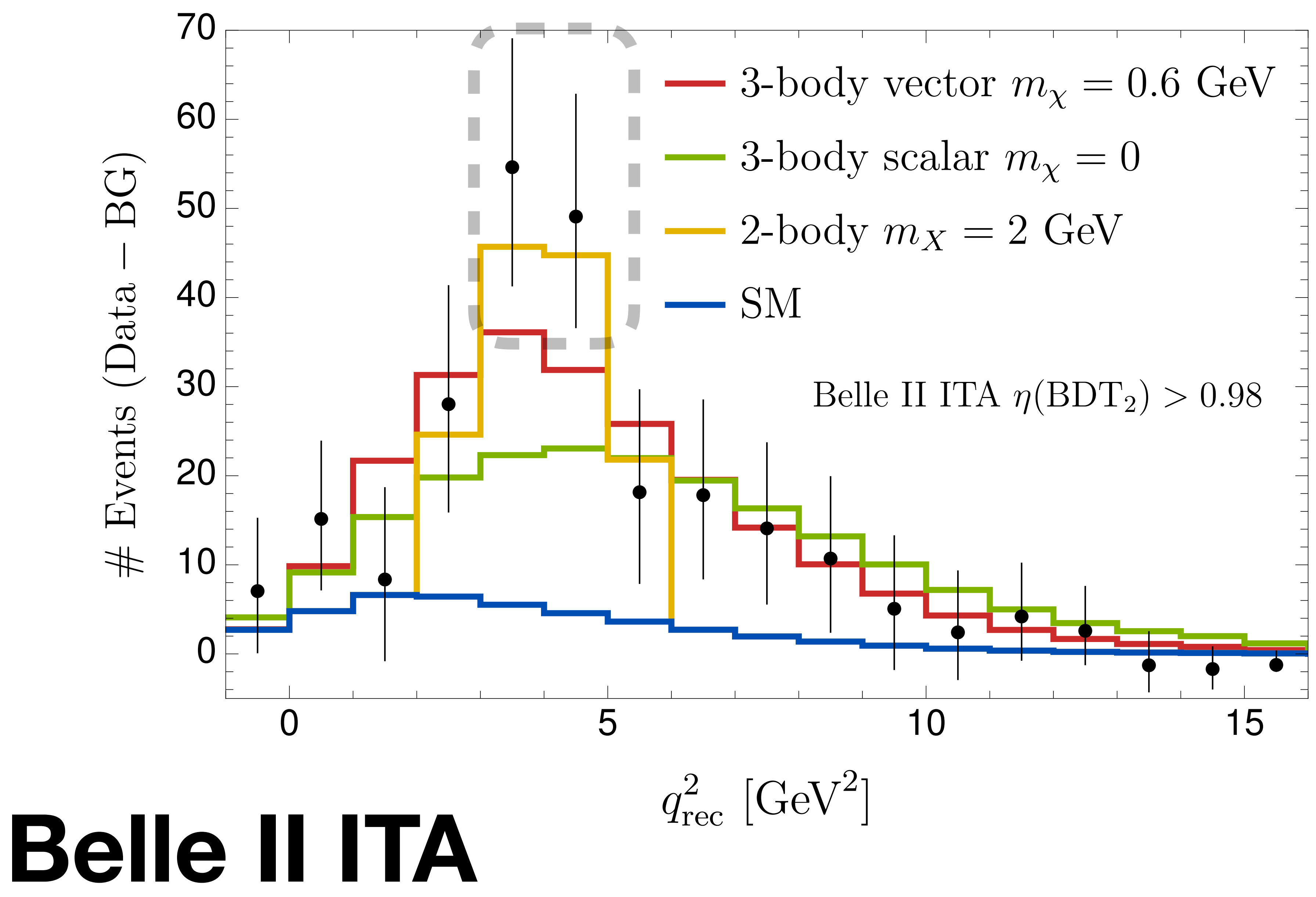
- **Exclusive BR** calculation is unstable for **ma>2GeV** but **inclusive mode** can be used. Similar to $e^+e^- \to \Upsilon \to \gamma a(\to \text{hadrons})$

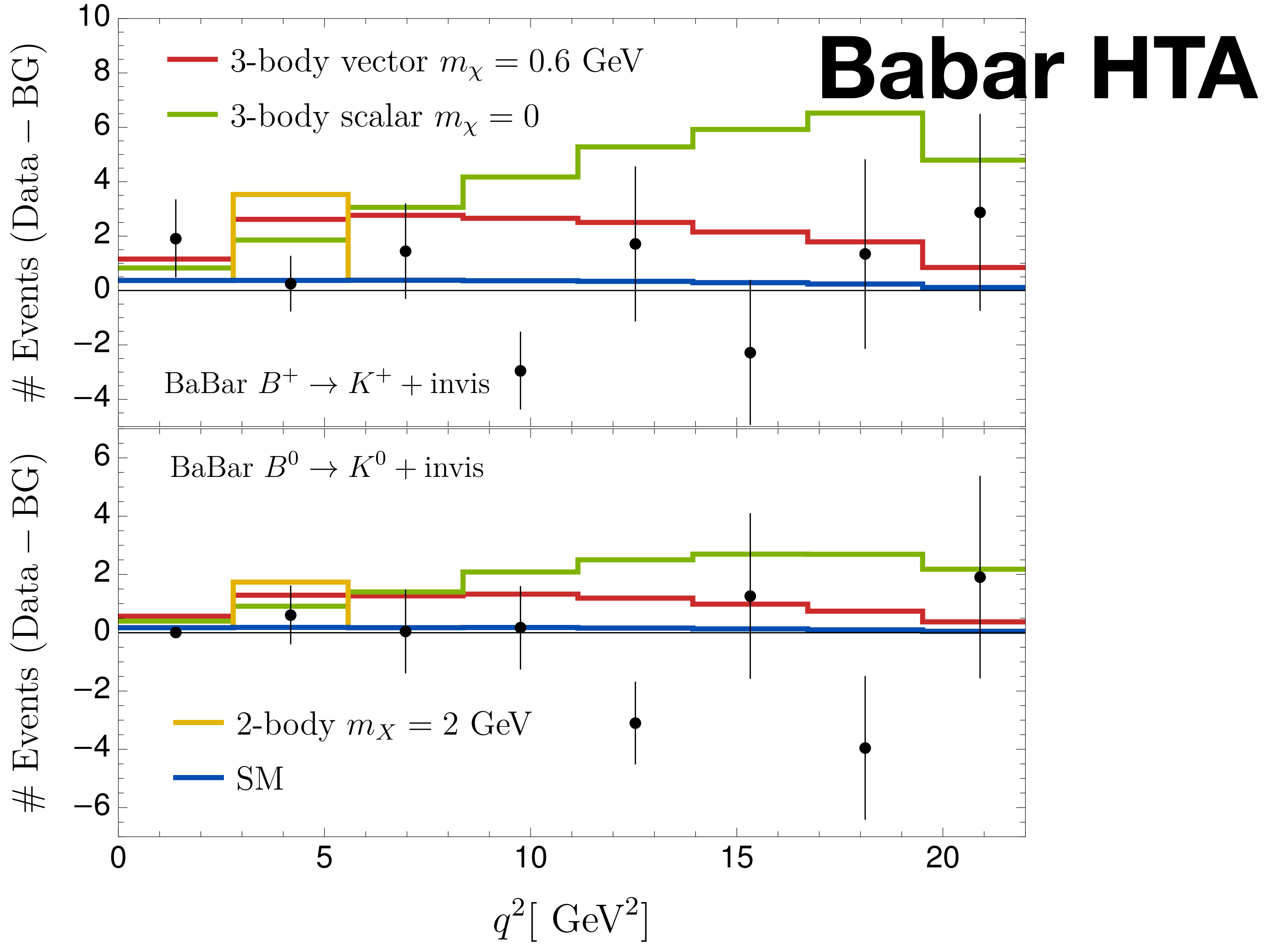
- Mass reach ~4 GeV
- Sensitivity ??



Excess in $B \to K + \mathrm{inv}$ and inclusive tagging

- Latest **Belle II** data shows an excess around m_{inv}~2GeV [2311.14647]
- With only this data 3-body decay (vector current) and 2-body are reasonable.
- But combining past Babar analysis disfavors 2-body kinematics.





K. Fridell, M. Ghosh, T. Okui, **KT** ('23)

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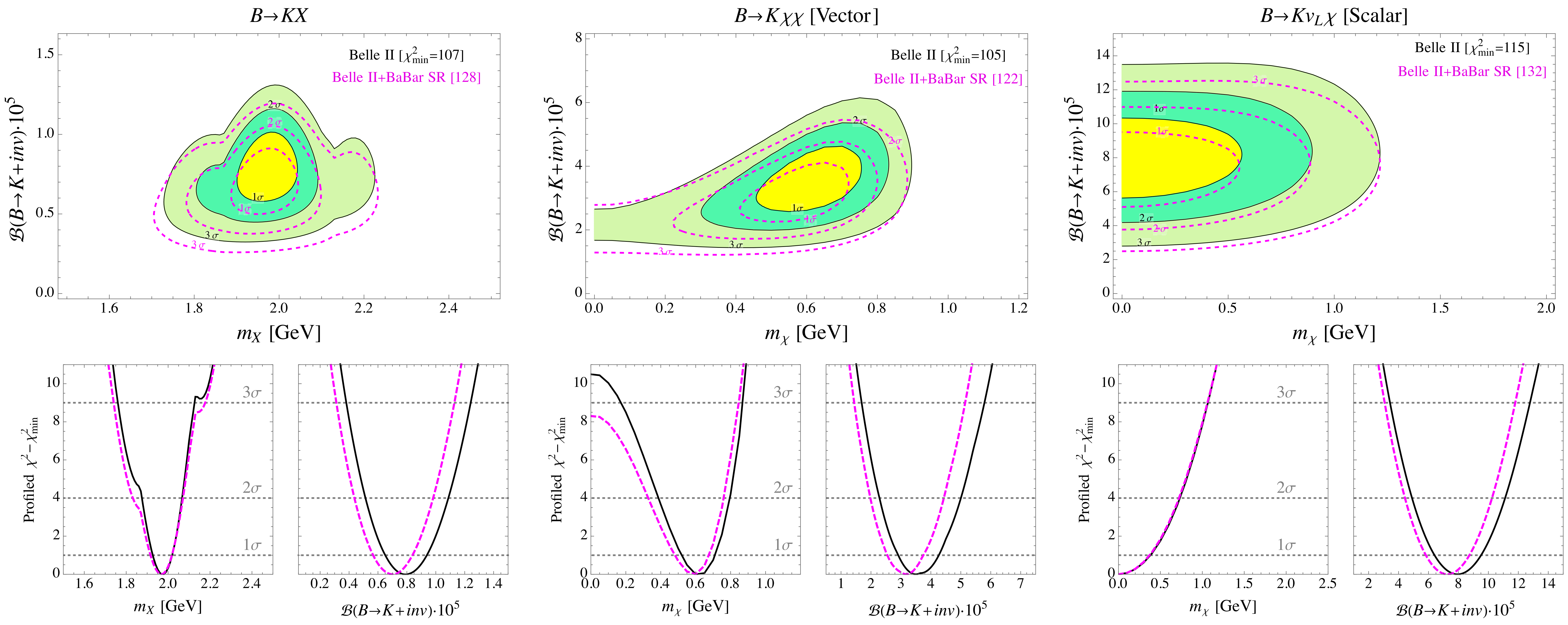


$\chi^2_{min} - 100$	2b	V	V′	S	T	SM
Belle II	**6.8**	15.2	**4.7**	15.1	11.9	44.6
+ BaBar SR	27.6	30.4	**22.1**	31.8	29.8	61.0
+ BaBar $s_B < 0.8$	**73.3**	78.8	**72.9**	90.2	86.9	106.7

K. Fridell, M. Ghosh, T. Okui, **KT** ('23)

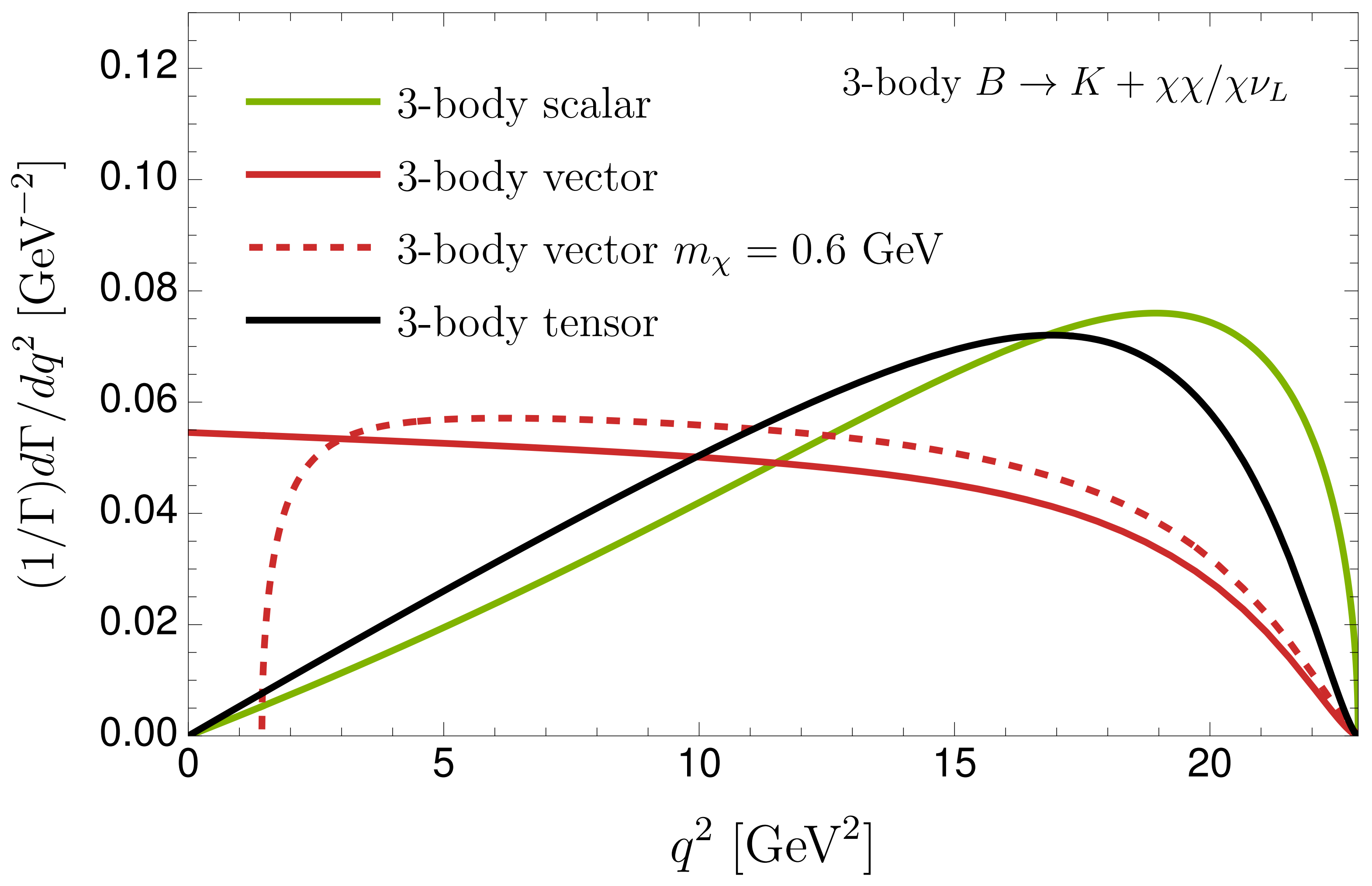
Summary

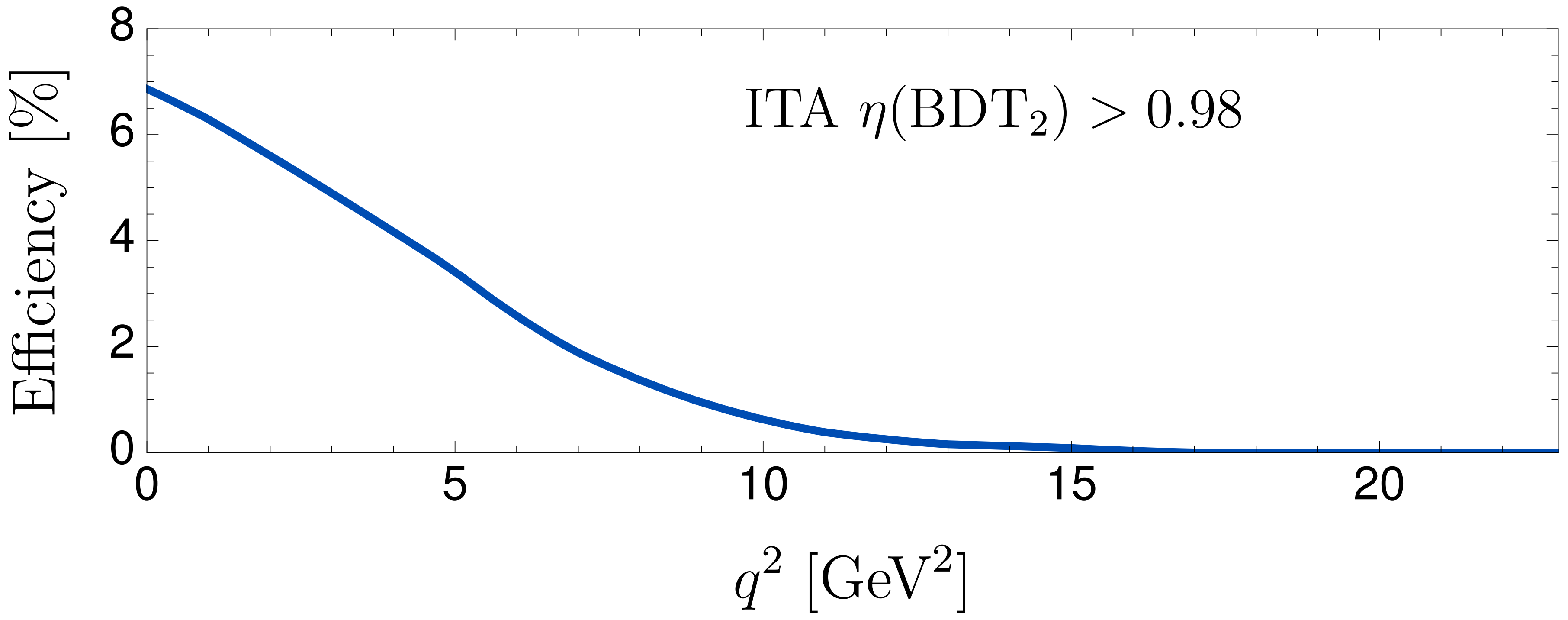
- Unique possibilities to probe Heavy QCD axion @ Belle II based on **hadrons**.
- Wishlist
  1. $e^+e^- \to \Upsilon \to \gamma a,\ a \to \text{hadrons}$ [previous work: Babar recast]
  2. $B \to Ka,\ a \to \eta\pi\pi$ [Babar recast]
  3. $B \to Ka,\ a \to \pi^+\pi^-\pi^0$ prompt [Belle recast] / displaced [new]
  4. $B \to Ka,\ a \to \gamma\gamma$ [Babar dedicated analysis, possible to improve further]
  5. $B \to Ka,\ a \to \text{hadrons}$ [new]
- CP even scalar →ππ, KK would be interesting too.

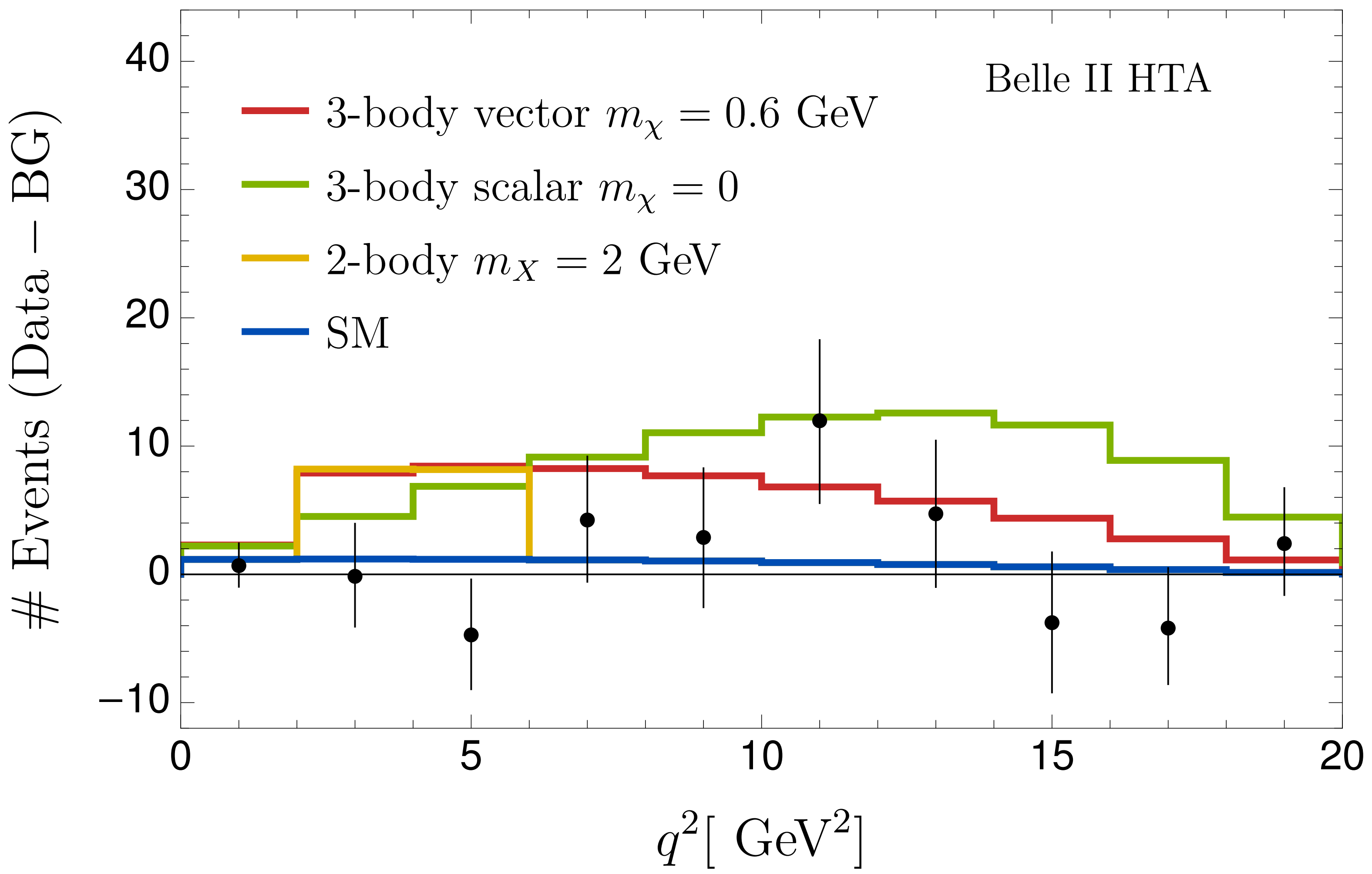
Thank you!

Backup

Excess in $B \to K + \mathrm{inv}$ and inclusive tagging

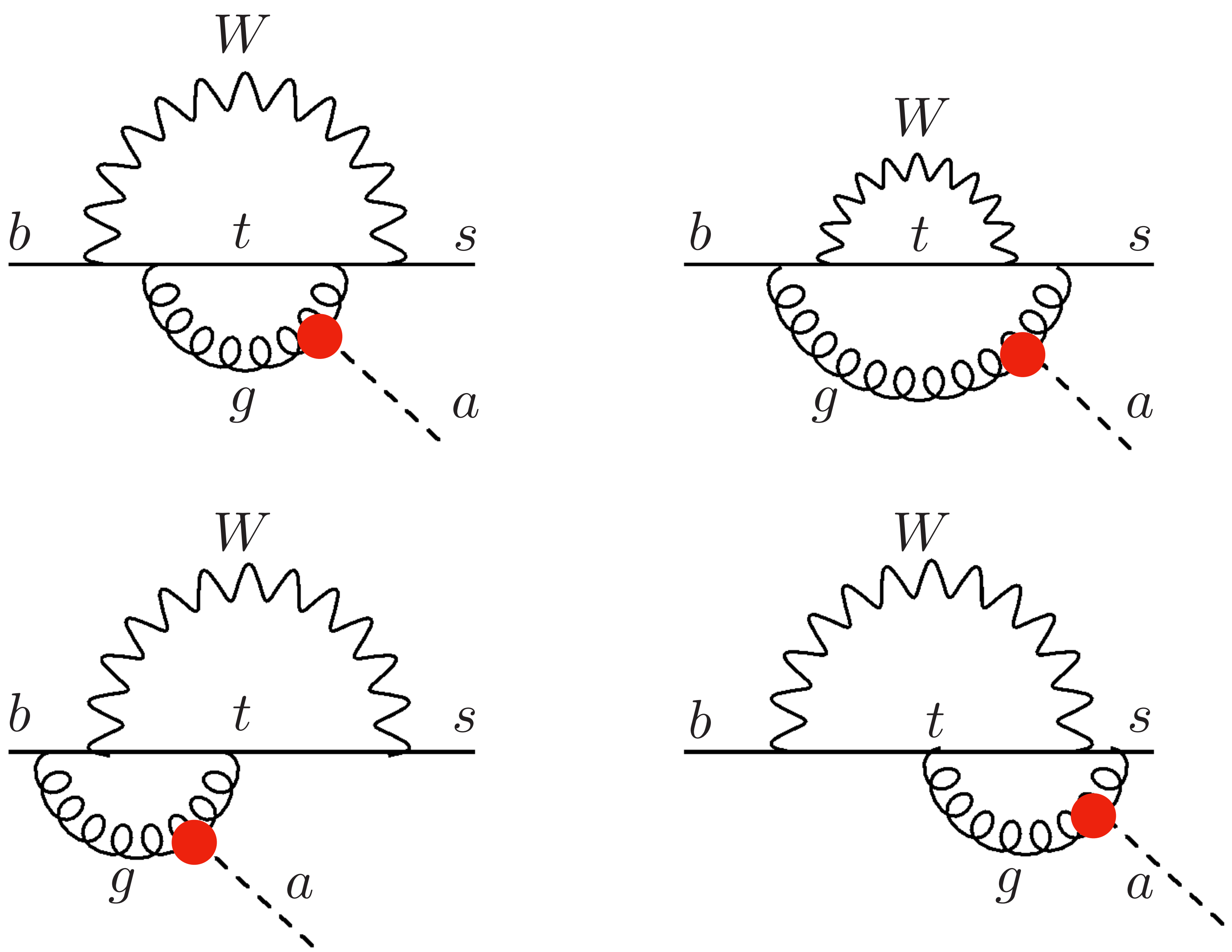


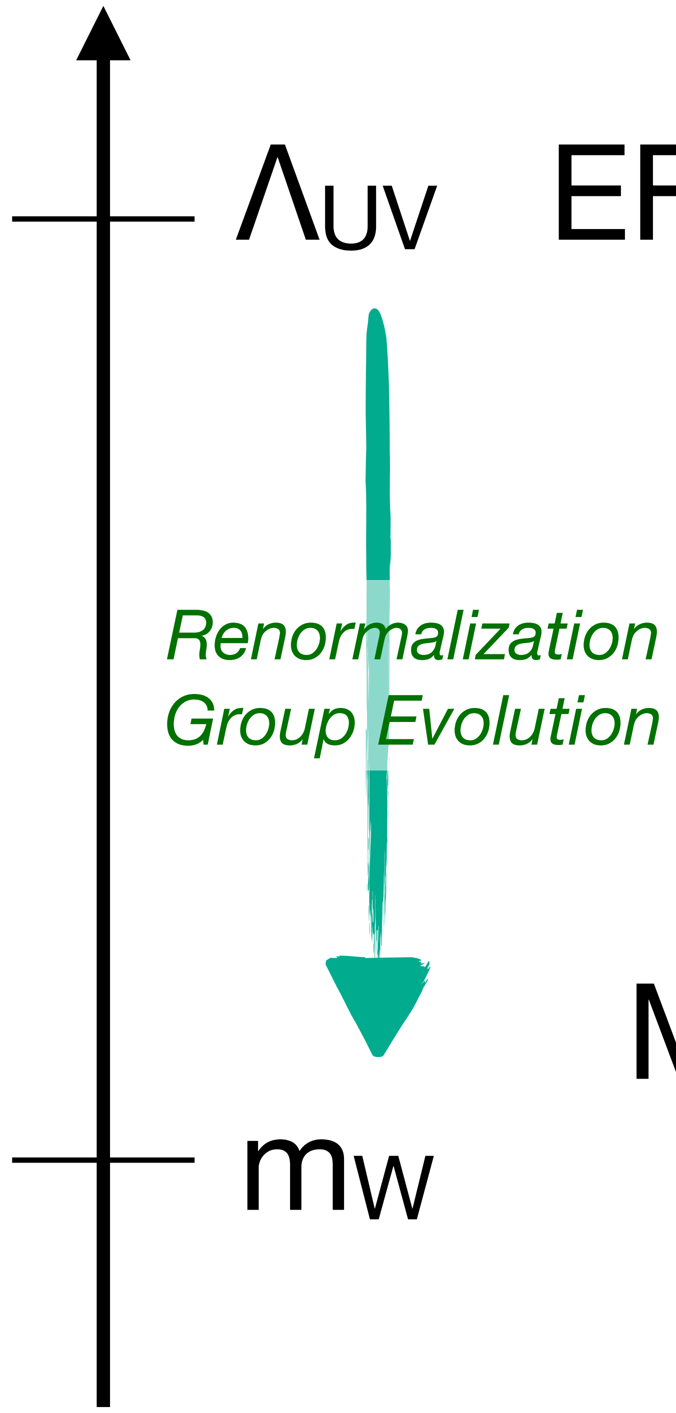




Two-loop calculation from the EFT

**two-loop is the leading order!*





$$\mathcal{O}_{gg} = \frac{1}{8\pi}\frac{a}{f_a}G^a_{\mu\nu}\tilde{G}^{a\mu\nu} \,,$$

$$\mathcal{O}_{qq} = \sum_q \frac{\partial_\mu a}{f_a}\bar{q}\gamma^\mu\gamma_5 q \,,$$

$$\mathcal{O}_{bs} = \frac{\partial_\mu a}{f_a}\bar{s}_{\rm L}\gamma^\mu\gamma_5 b_{\rm L} + \text{h.c.} \,.$$

Matching to *weak-scale EFT* *@2loop*

$$\mathcal{L}_{bsa} = C_W \frac{\partial_\mu a}{f_a}\bar{s}_{\rm L}\gamma^\mu\gamma_5 b_{\rm L}$$

Need 2-loop to generate $b \to sa$ from aGG

- 1-loop QCD for aqq
- 1-loop with W-boson for flavor changing

RGE is essential $C_W \sim \frac{\alpha_w}{4\pi}\left(\frac{\alpha_s}{4\pi}\right)^2 V_{tb}V^*_{ts}\frac{m_t^2}{m_W^2}\ln[\Lambda^2_{\rm UV}/M^2_W]$

Two boundary conditions at ΛUV

1. Size of ΛUV $(> 4\pi f_a)$→ require ΛUV >TeV
2. Size of $C_{qq}(\Lambda_{\rm UV}), C_{bs}(\Lambda_{\rm UV})$→fix as big as the counter term

Previous estimate: Ref[Yotam, etc]

Kohsaku For more detail, KEK Theory seminar by Chakraborty, Mar 15 (16) 9am EST (11 am JST)

Axion Production Rate from $B \to Ka$

$$\Gamma_{B\to Ka} = \left|C_W\right|^2 \frac{m_B^3}{64\pi f_a^2}\left(1-\frac{m_K^2}{m_B^2}\right)^2 \lambda_{Ka}\left[f_0(m_a^2)\right]^2$$

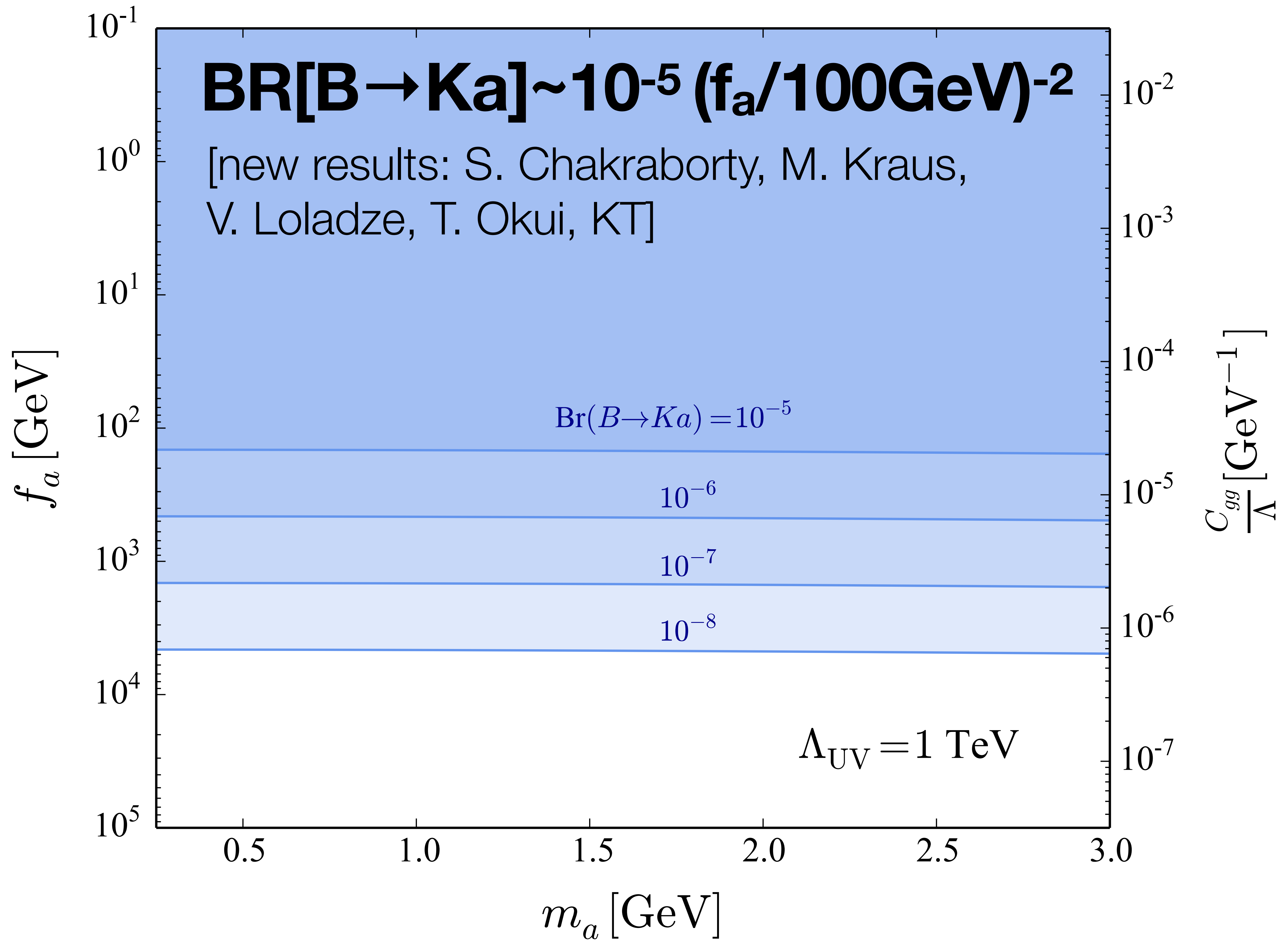
our result

- Form factor

$$f_0(m_a^2) = \frac{0.330}{1 - m_a^2/37.5\ \mathrm{GeV}^2}$$

- Phase space

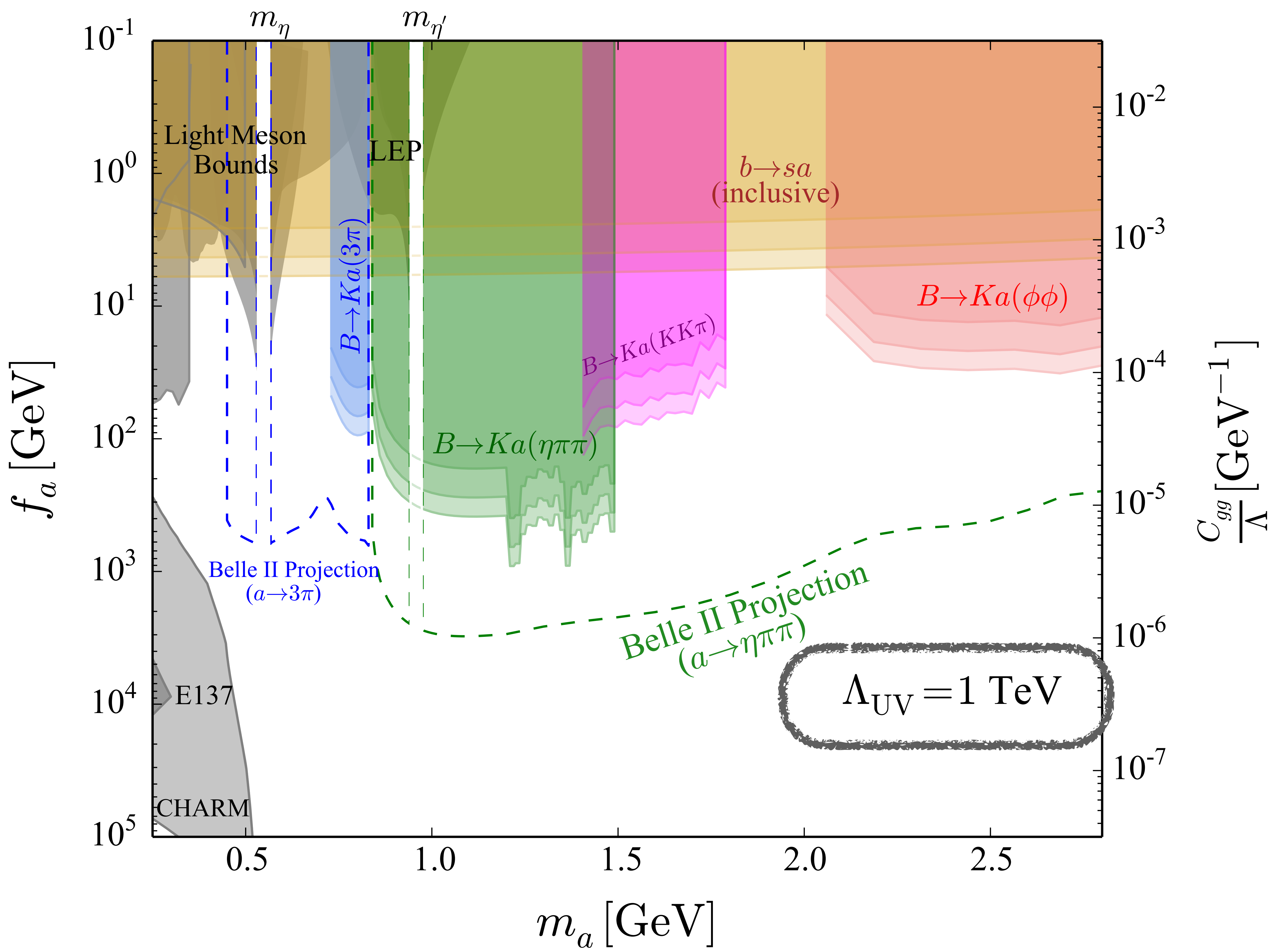
$$\lambda_{Ka} = \left[\left(1-\frac{(m_K+m_a)^2}{m_B^2}\right)\left(1-\frac{(m_K-m_a)^2}{m_B^2}\right)\right]^{\frac{1}{2}}$$

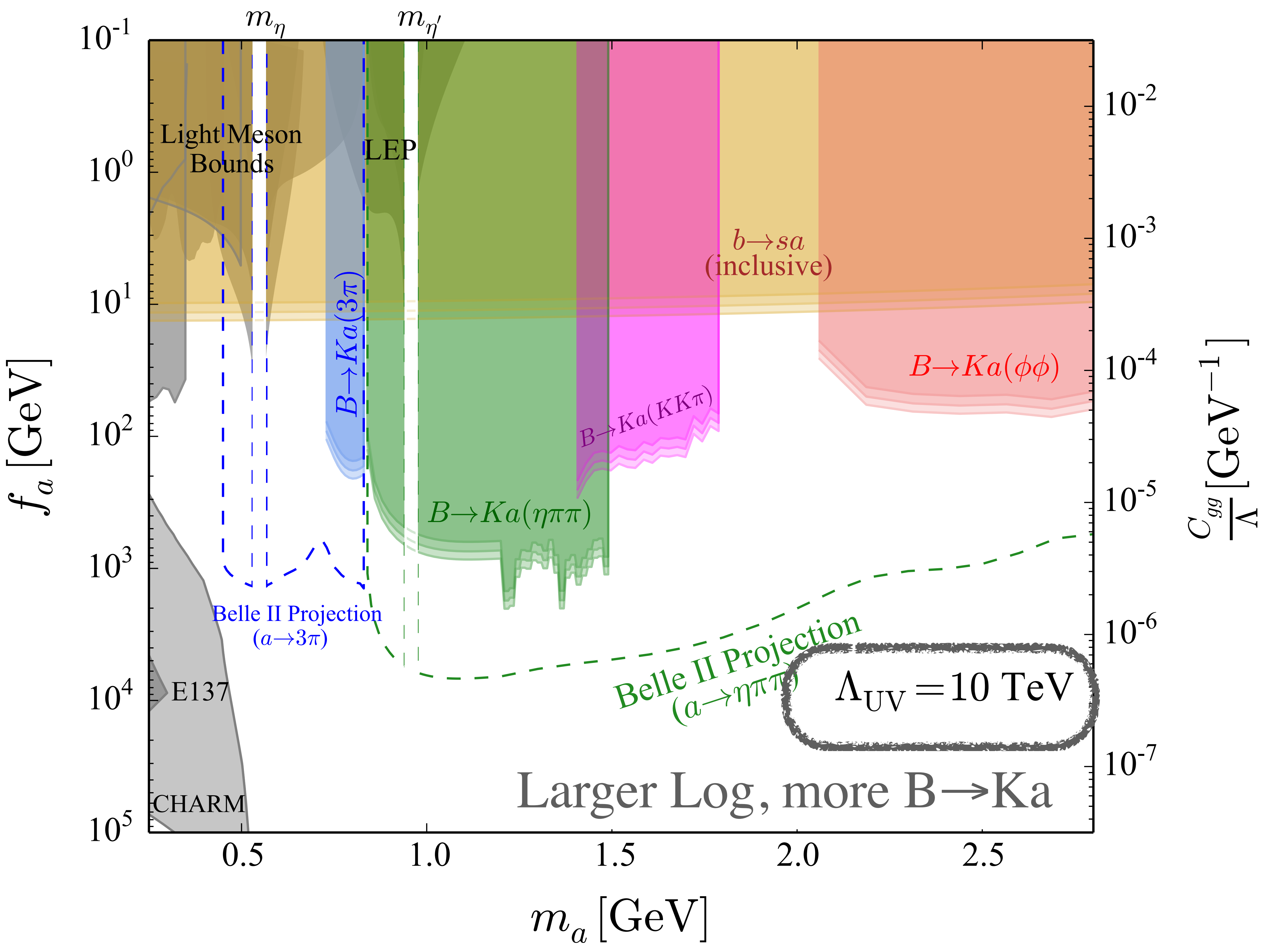


Two boundary conditions

1. Λ_{UV} 1TeV. Larger Λ_{UV} , more BR[B->Ka]
2. Size of $C_{qq}(\Lambda_{UV}), C_{bs}(\Lambda_{UV})$→here set to 0

Updated bounds from $B \to Ka$





Updated bounds from $B \to Ka$

Inclusive bound

- Test untagged BR by

$$\mathrm{BR}(B^+ \to \bar{c}X) = 97 \pm 4\%$$

- Require BR(b→sa) <11%

$$\mathrm{BR}(b \to sa) \simeq \frac{|C_W|^2}{\Gamma_B f_a^2} \frac{(m_B^2 - m_a^2)^2}{32\pi m_B}$$

- Change UV boundary conditions

-3<A,B <3 ⇒3lines[optimistic, pesmistic, A=B=0]

$$C_{qq}(\Lambda_{\rm UV}) \equiv A C_F \left(\frac{\alpha_s}{4\pi}\right)^2,$$

$$C_{bs}(\Lambda_{\rm UV}) \equiv B C_F \left(\frac{\alpha_s}{4\pi}\right)^2 \frac{\alpha_w}{4\pi} \sum_k V_{ik} V_{kj}^* \xi_k$$

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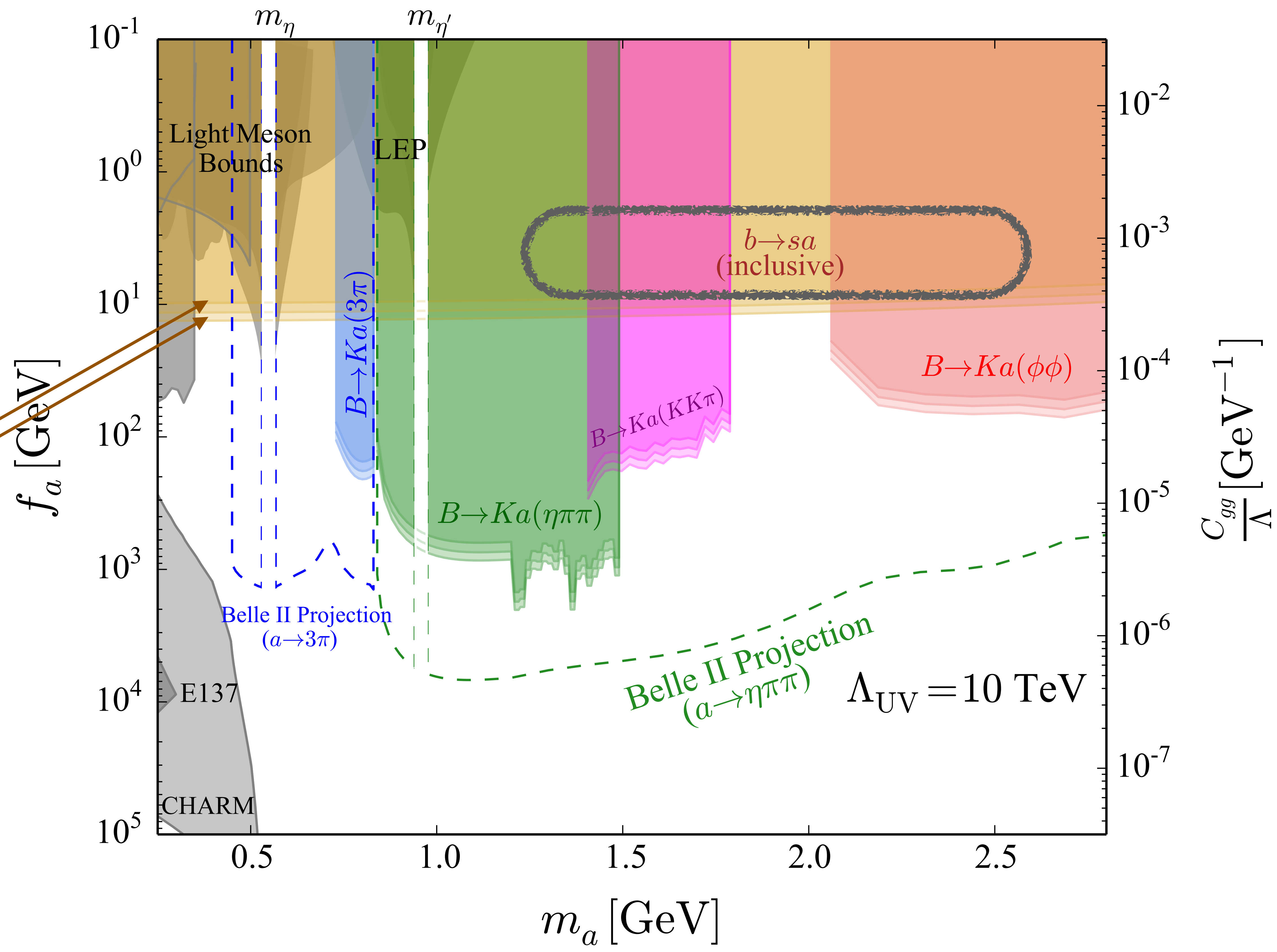
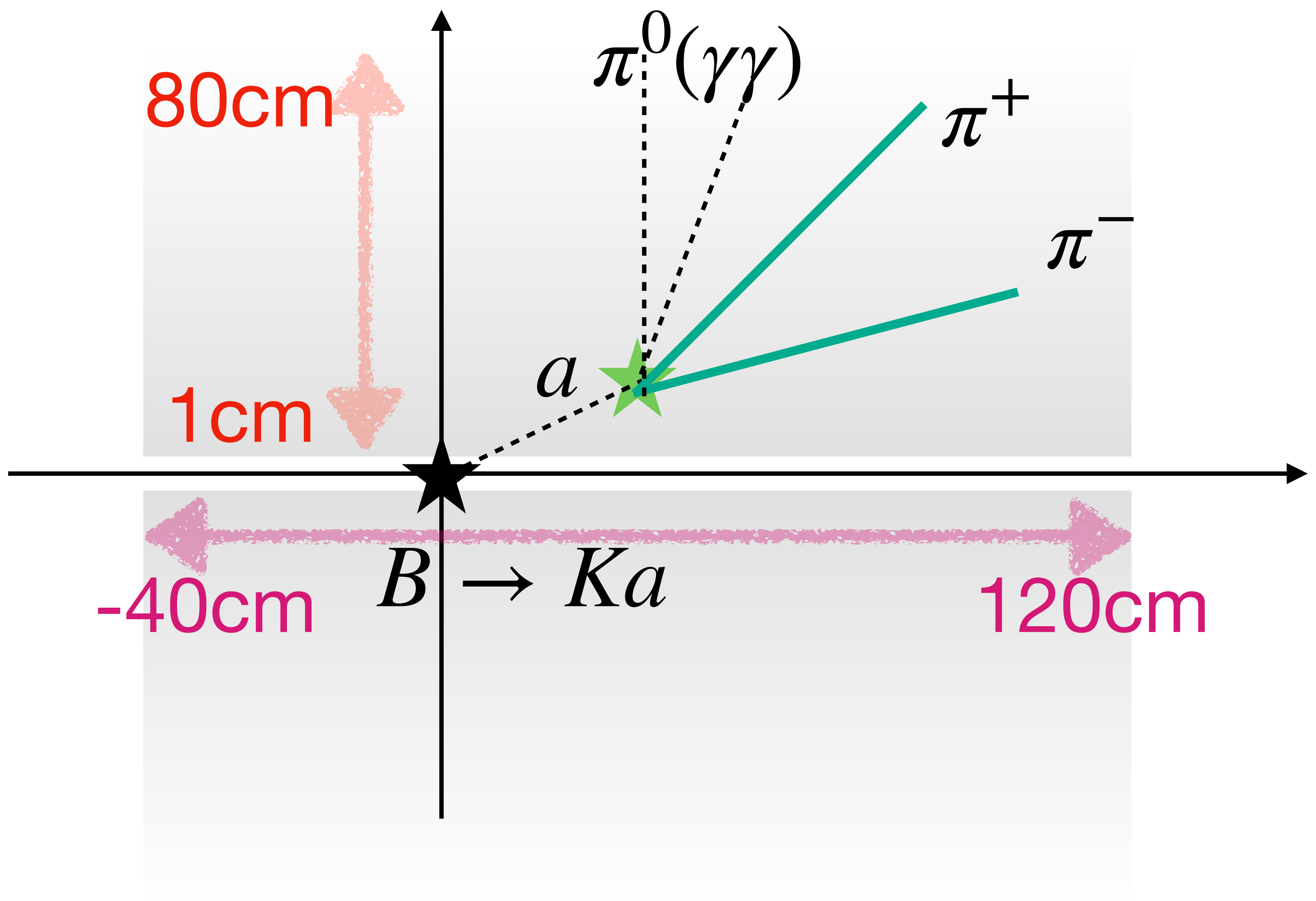
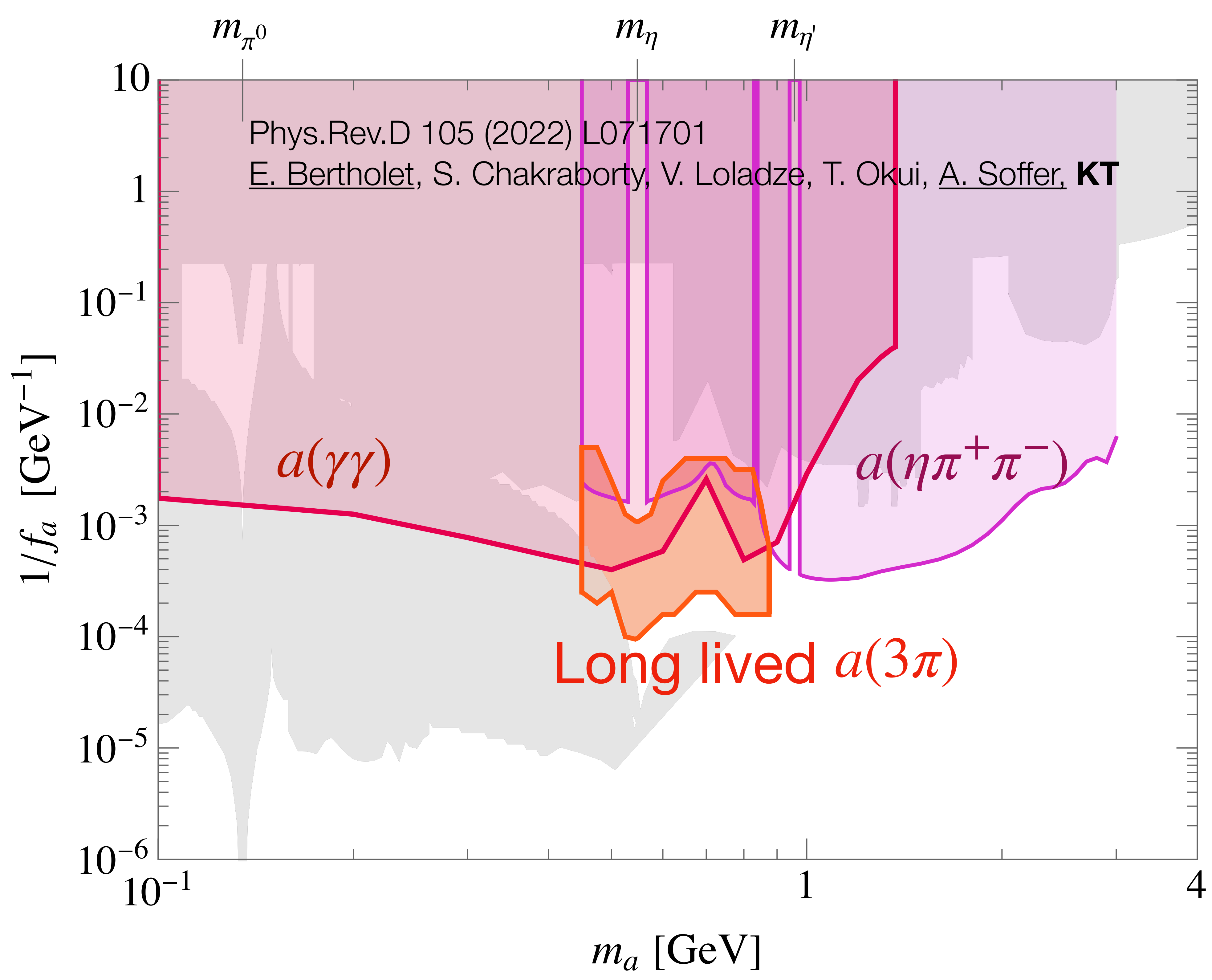


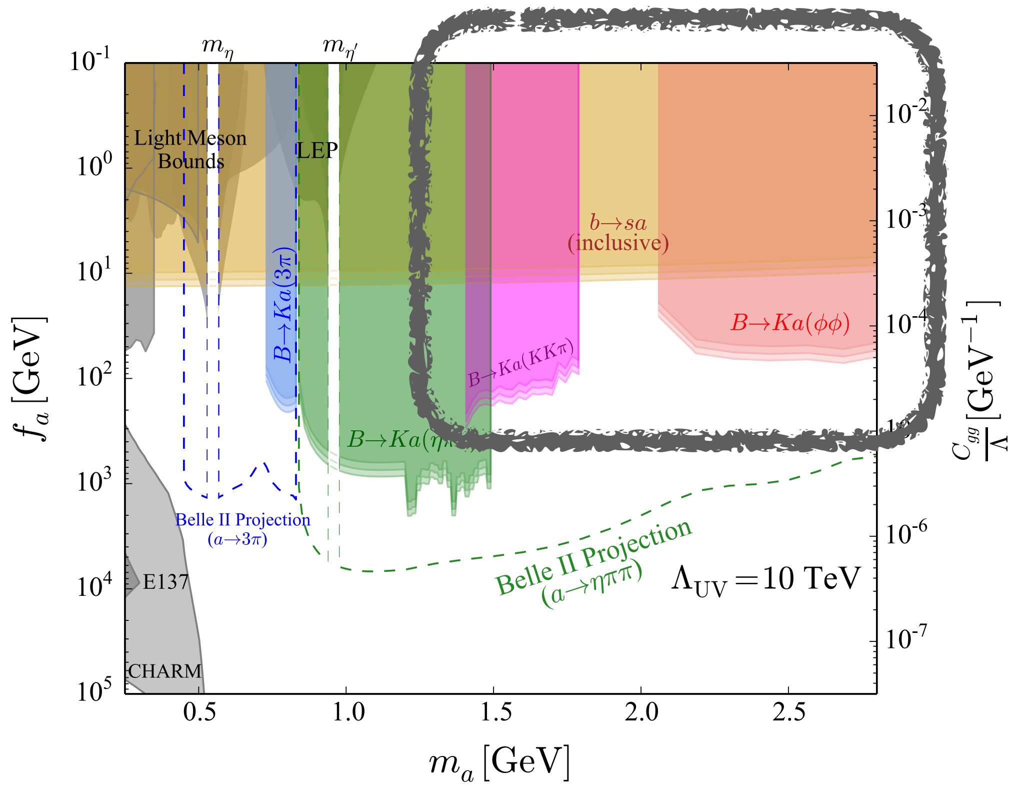
More on B decays at Belle II

for prompt decays and displaced decay (nanosecond lifetime)



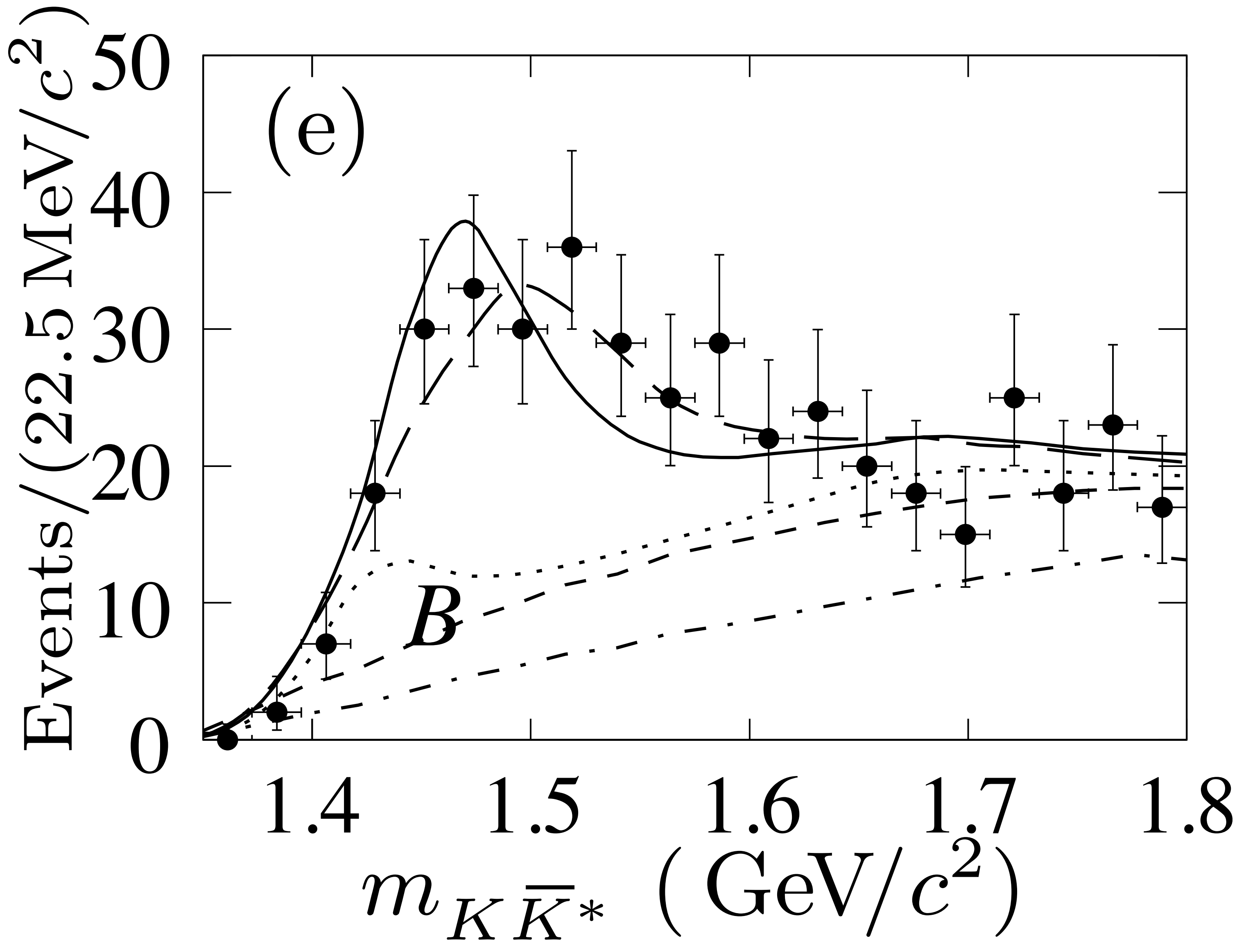


Other channels



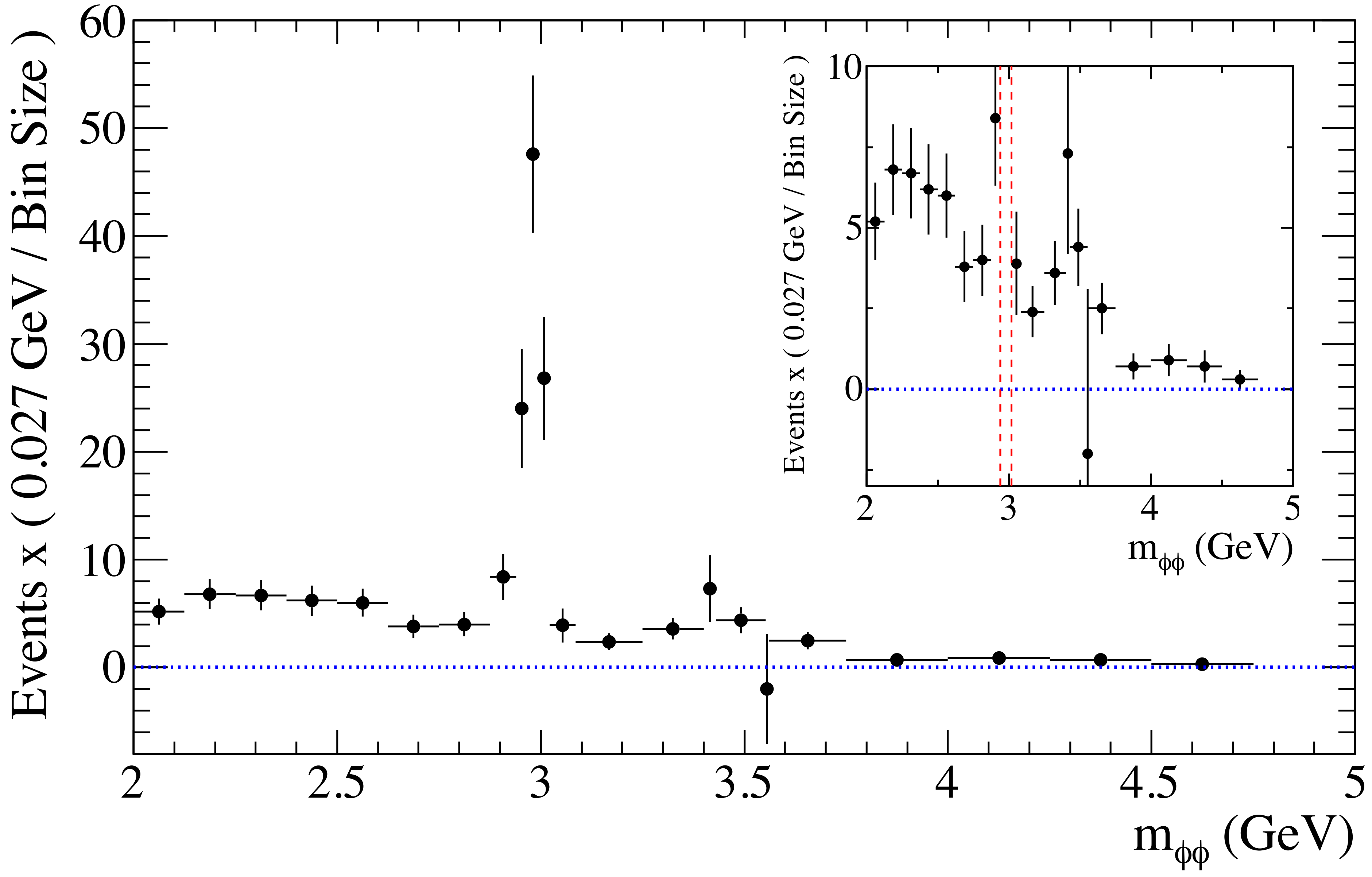
$a \to KK\pi$ **Babar** [0804.0411]
$B^+ \to K^+\eta_X(\to KK^* \to KK\pi)$ ***search***

- 3.9x10⁸$B\bar{B}$, 1.4 GeV <m_a<1.8 GeV
- take 2 bins around the axion mass (45MeV)
  $S < (D - B) + 2\sqrt{D}$



$a \to \phi\phi$ **Babar** [1105.5159]
$B \to K\phi\phi$ ***search***

- 4.6x10⁸$B\bar{B}$, 2 GeV <m_a<3 GeV
- take 1 bin around the axion mass (125MeV)
  require $2\sqrt{D}$ inside relevant bins



Typical axion search

1. **Photon coupling** is probed in most searches.

$$\frac{\alpha_s}{8\pi}\frac{a}{f_a}G\tilde{G} \xrightarrow{m_a<\Lambda_{QCD}} \frac{c_\gamma \alpha}{8\pi}\frac{a}{f_a}F\tilde{F} + (a\text{-hadron couplings})$$

Original gluon coupling — **Photon coupling**

✤ Hadronic coupling is often ignored.

2. Axion dark matter is the most popular. **Λ_{CP}~Λ_{DM}**
   Often assume it's 100% DM and extremely light.

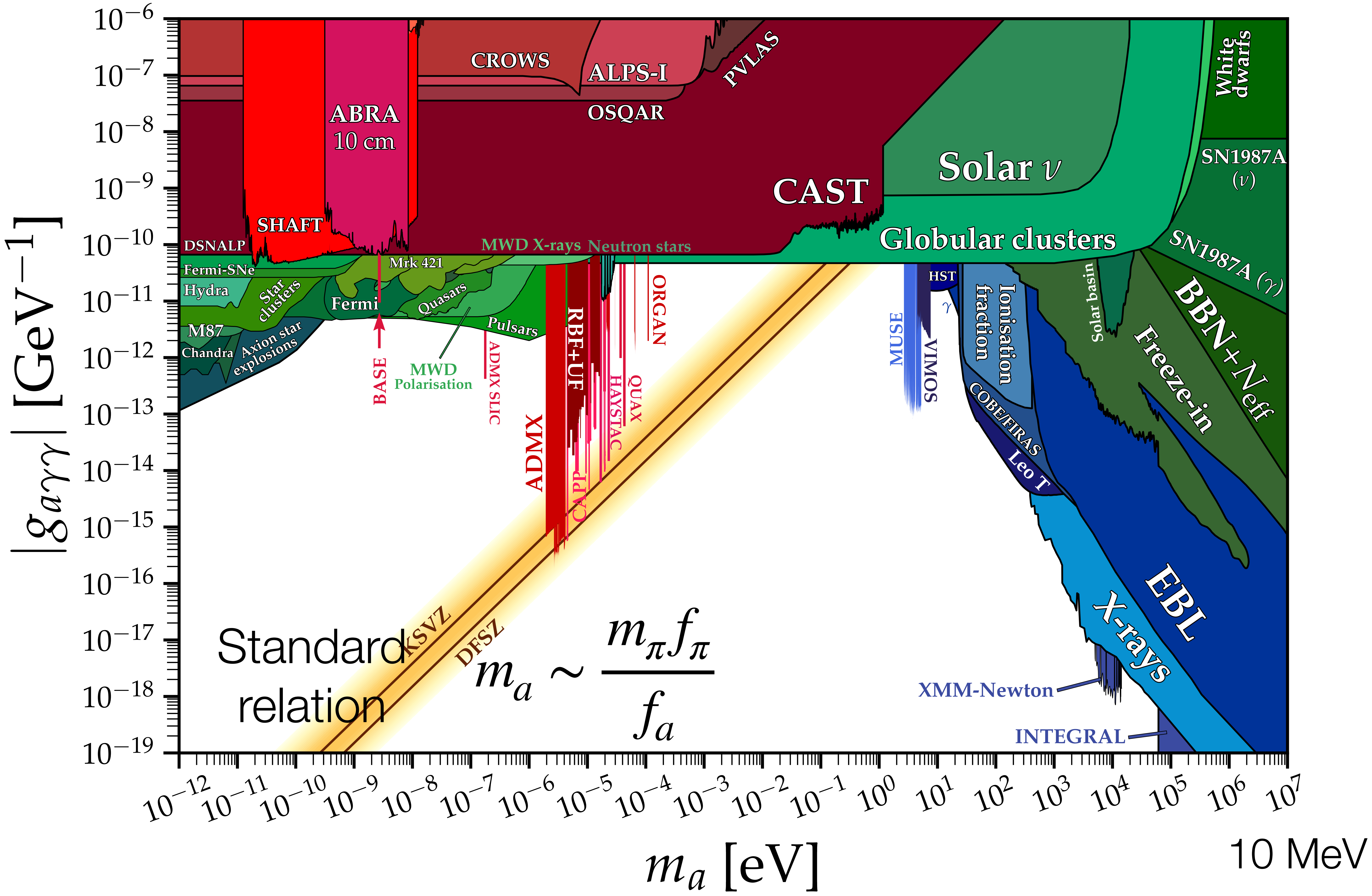
   - **Mass m_a~10^{-4}-10^{-6} eV**

Typical axion search

based on

$$\frac{c_\gamma \alpha_{EM}}{8\pi} \frac{a}{f_a} F\tilde{F} \equiv \frac{g_{a\gamma\gamma}}{4} aF\tilde{F}$$

$$\frac{1}{f_a} \propto$$



Kohsaku Tobioka, Florida State University

Typical axion search

based on

$$\frac{c_\gamma \alpha_{EM}}{8\pi}\frac{a}{f_a}F\tilde{F} \equiv \frac{g_{a\gamma\gamma}}{4}aF\tilde{F}$$

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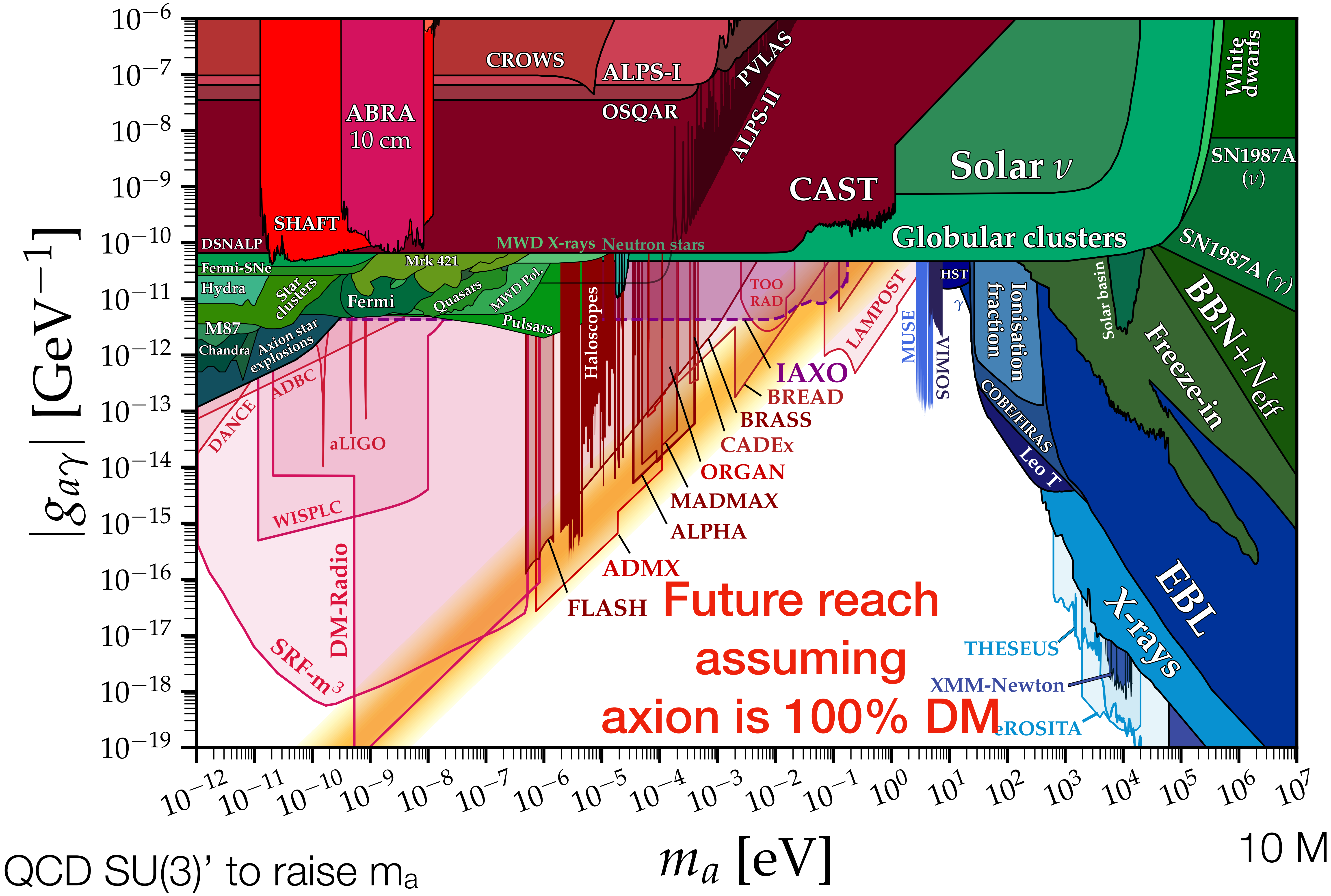

10 MeV

Models: additional QCD SU(3)' to raise m_a

Berezhiani et al('01); Hook('04); Fukuda et al('04).

Dimopoulos et al('16); Hook et al('19); Valenti ('22)…

Another class: Agrawal and Howe ('17)…

Typical axion search

based on

$$\frac{c_\gamma \alpha_{\rm EM}}{8\pi}\frac{a}{f_a}F\tilde{F} \equiv \frac{g_{a\gamma\gamma}}{4}aF\tilde{F}$$

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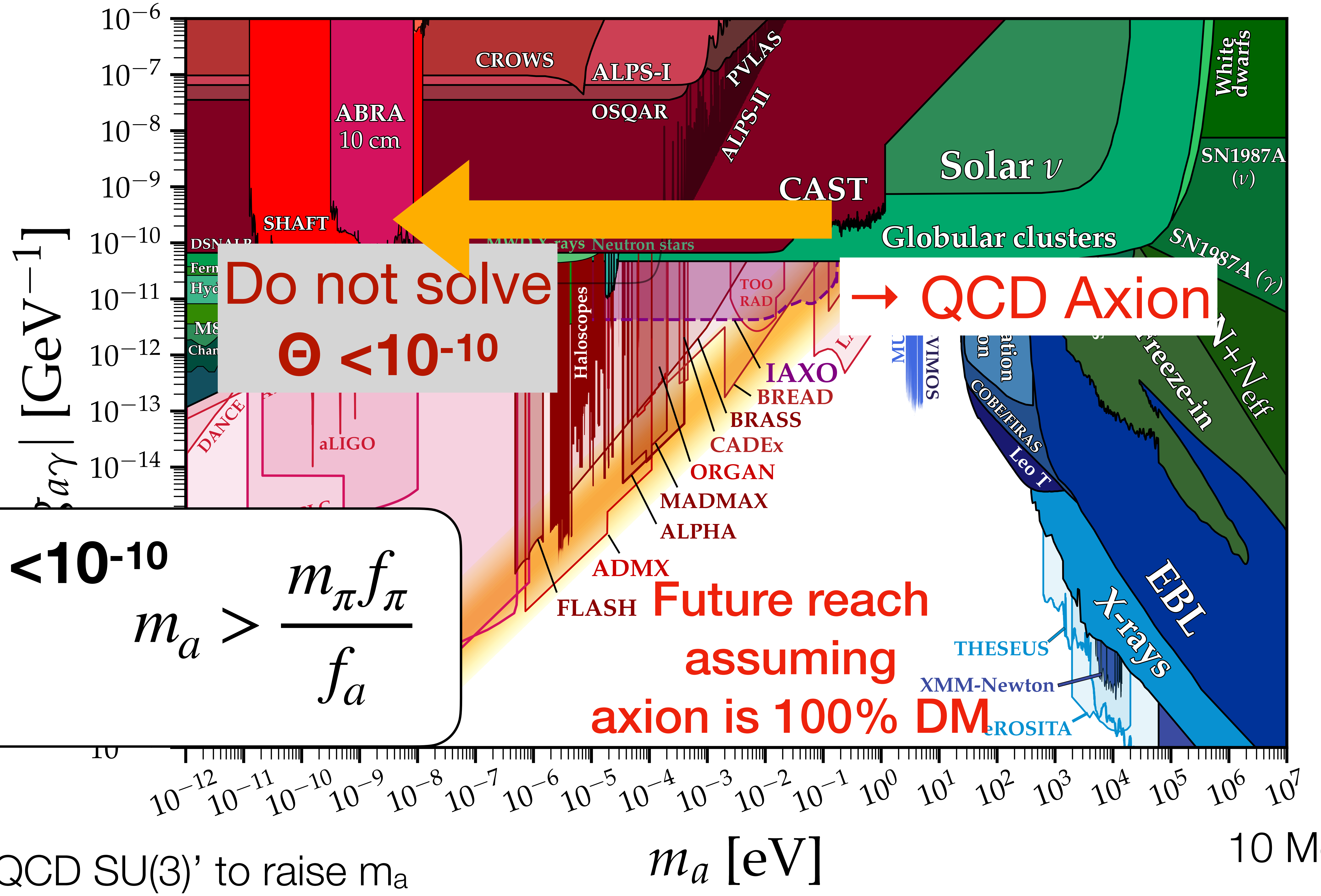

Do not solve $\Theta < 10^{-10}$

→ QCD Axion

Future reach assuming axion is 100% DM

10 MeV

Solve $\Theta < 10^{-10}$ even if $m_a > \frac{m_\pi f_\pi}{f_a}$

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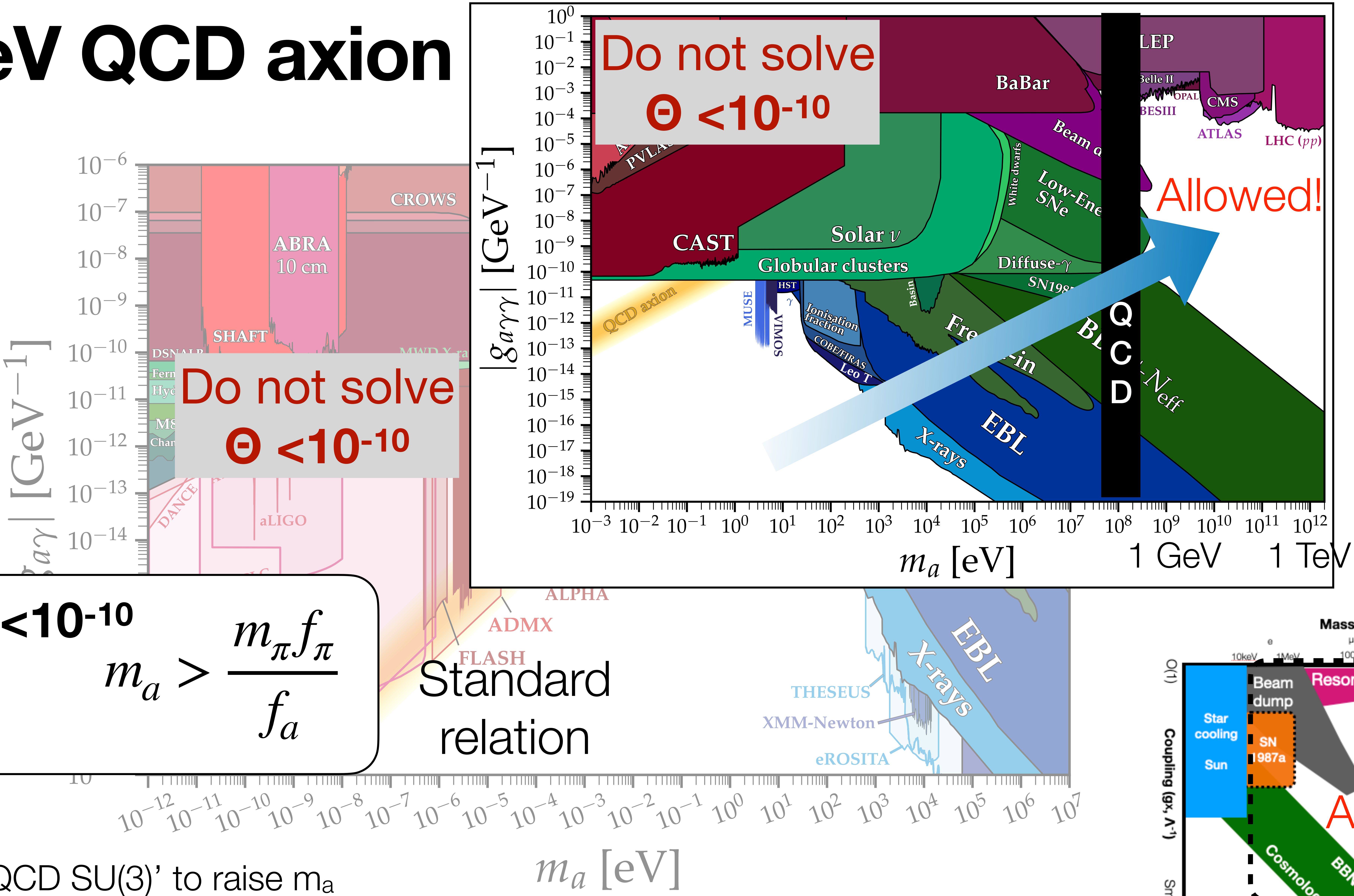
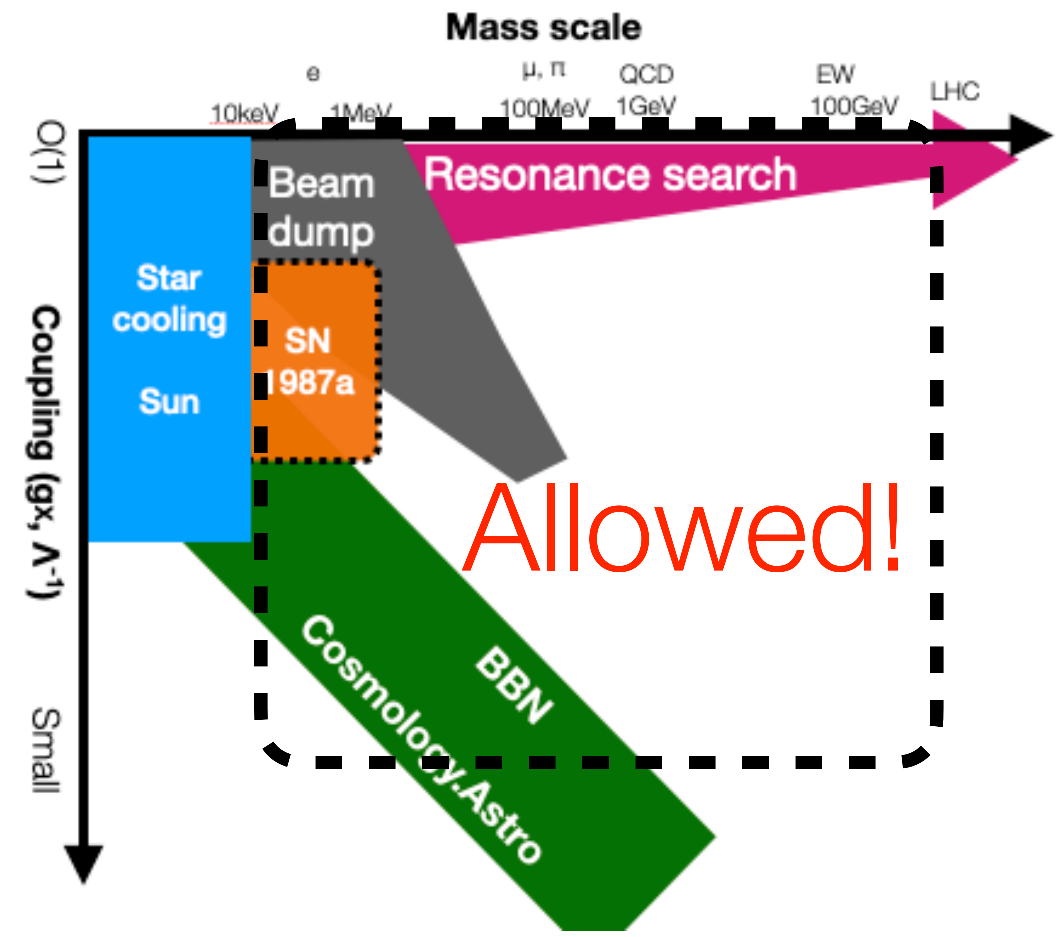
MeV-GeV QCD axion

$$\frac{1}{f_a} \propto$$



Solve **Θ <10^{-10}**
even if $m_a > \frac{m_\pi f_\pi}{f_a}$



Models: additional QCD SU(3)’ to raise m_a
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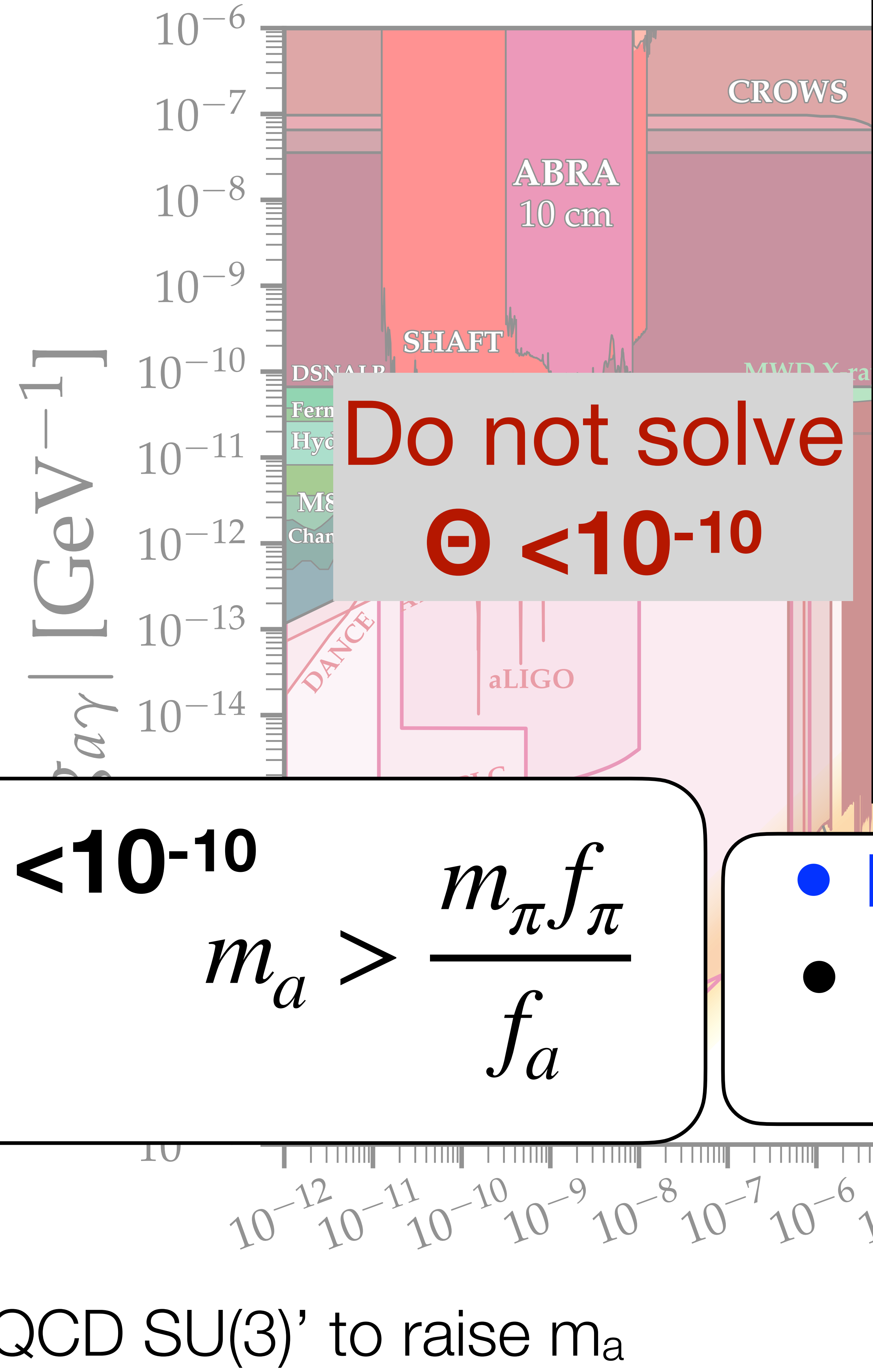
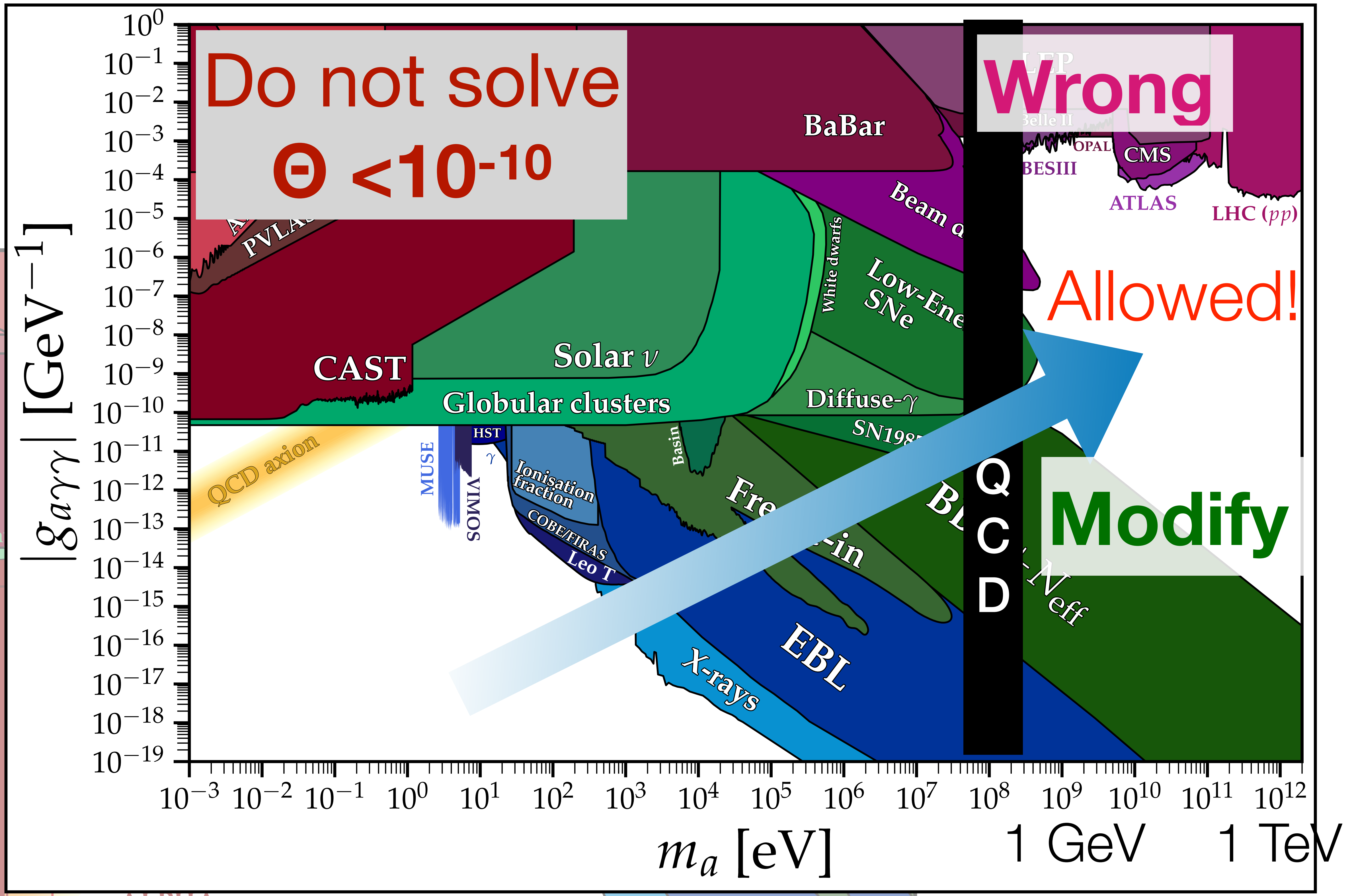
MeV-GeV QCD axion

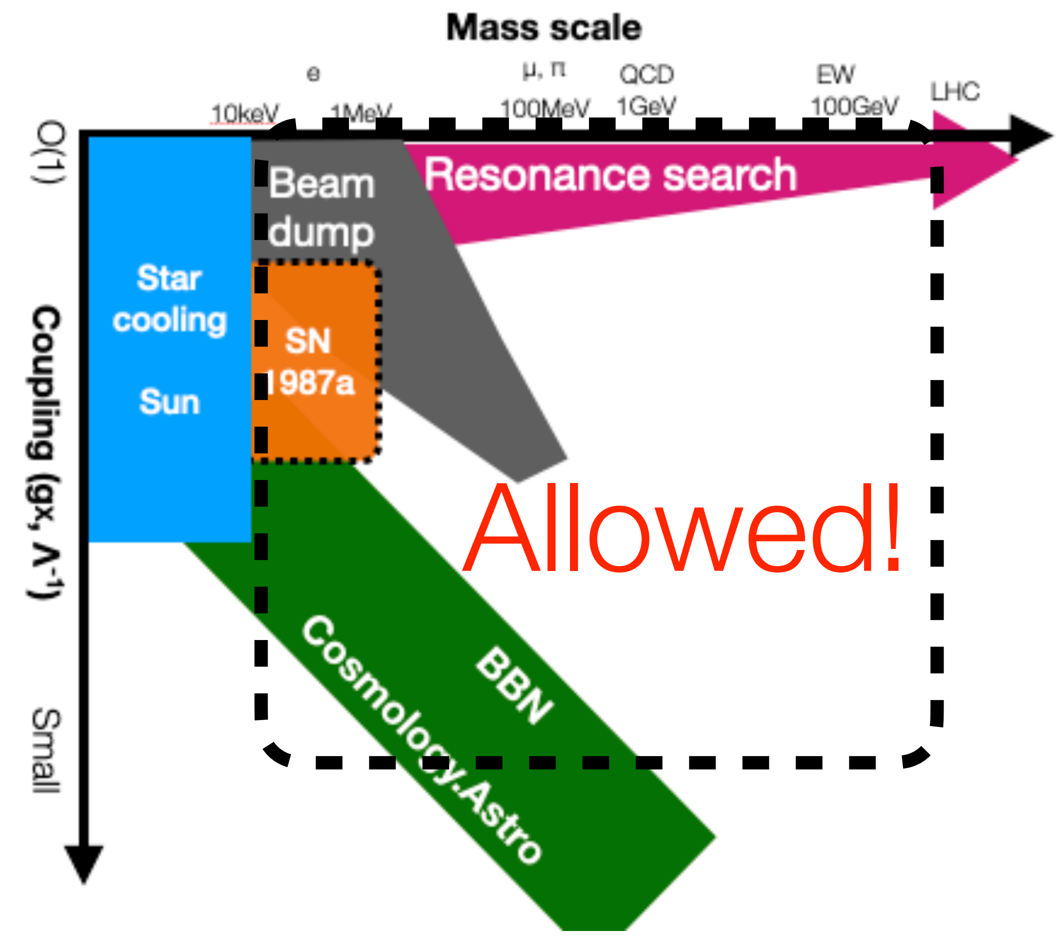
$$\frac{1}{f_a} \propto$$





Solve **Θ <10^{-10}** even if $m_a > \frac{m_\pi f_\pi}{f_a}$

- Hadronic interactions are essential.
- Lower f_a is favored, making $U(1)_{PQ}$ more robust (quality prob.)



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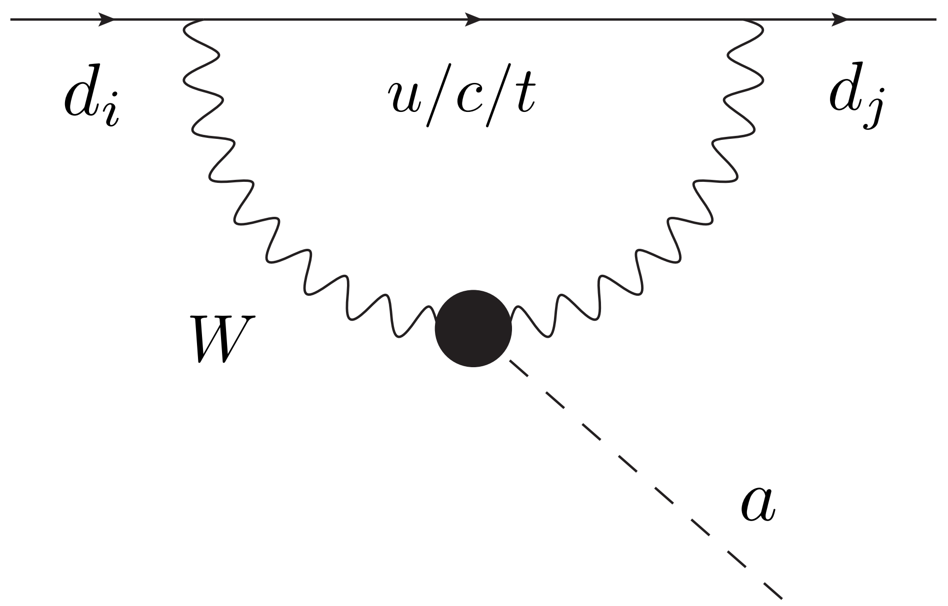
Another class: Agrawal and Howe ('17)…

Impact of other couplings

- We've considered $aG\tilde{G}$ coupling. $B \to Ka$ is from 2-loop (our work).
- Other reasonable couplings → Production from 1-loop, more signal rate.

$$\frac{\alpha_w}{8\pi}\frac{a}{f_a}W\tilde{W}$$



1611.09355 , E. Izaguirre, T. Lin, B. Shuve

For axion-quark coupling example, see 2002.04623
J. Martin Camalich, M. Pospelov, P. N. H. Vuong, R. Ziegler, J. Zupan

- As long as the strong CP problem is concerned, can't drop $aG\tilde{G}$
⇒Hadronic decay modes are still dominant ($a\to\gamma\gamma$ can be enhanced).

**Many ALPs can't solve the strong CP because $aG\tilde{G}$ is omitted.*

- Lepton-axion couplings are optional. Cleaner signal as $B \to Ka(\to \mu\mu)$
but other bounds become more stringent too (e.g. LEP, LHC)

Additional motivation: Quality problem

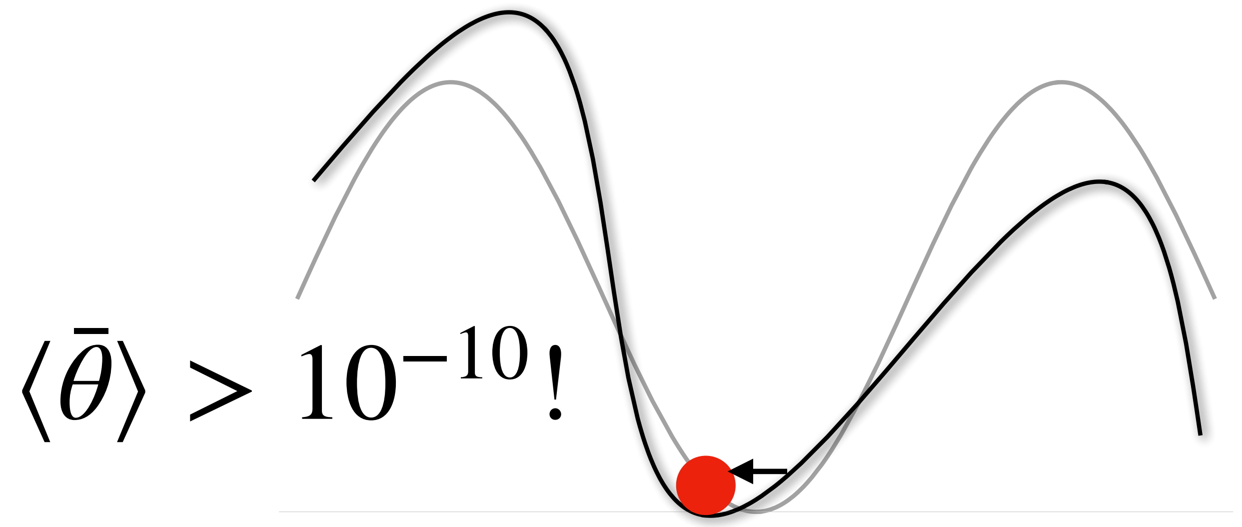
- Parameter for axion DM: $f_a=10^9$-10^{13} GeV
- With such high f_a, known theoretical issue: "*axion (PQ) quality problem*"

Refs

- Any global symmetry including $U(1)_{PQ}$ expected to be broken by the gravity

Even tiny breaking **easily ruins axion-solution for the strong CP problem**

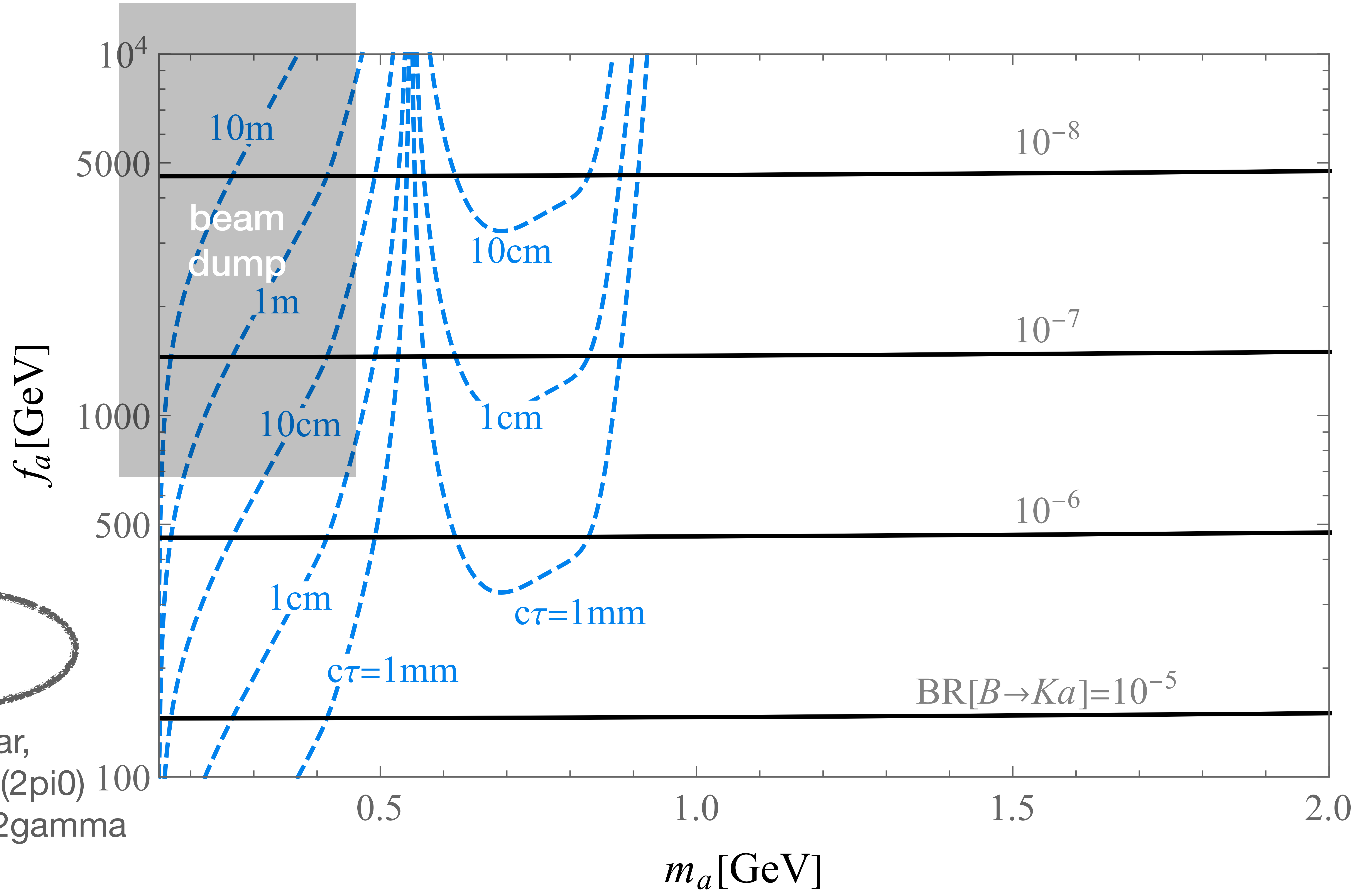
$$\frac{\Phi^2|\Phi|^4}{M_{pl}^2} \to \frac{f_a^5}{M_{pl}^2}a$$



Need model building→going to non-minimal is necessary

- The **heavy QCD axion** has no issue because f_a is much lower.
  f_a below 10TeV is generically OK.

Lifetime



7cm
in lab

BG: ee->ssbar,
->K K +hadrons(2pi0)
B->K*gamma->K+2gamma

Decay modes

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