Quarkonium Decays in Invisibles ALPs

57th Rencontres de Moriond on EW Interactions, La Thuile 18-25/03

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Based on: L. Merlo, F. Pobbe, O. Sumensari and S.R: JHEP, 06:091, 2019
A.W.M. Guerrera and S.R.: Fortsch.Phys. 2023 2200192 (arXiv:2211.08343),
A.W.M. Guerrera et al.: In preparation arXiv:2303.xxxx

HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

Why Axion Like Particles ?

- Axion SOLUTION to the strong CP–problem:
  - ☆ Extend the SM with (at least) an extra scalar field endowed with a $U(1)_{PQ}$ global symmetry;
  - ☆ Spontaneous symmetry breaking (non linearly realised) at a scale $f_a \gg v_{EW}$ (invisible axions KSVZ, DFSZ). The only physical d.o.f. at low energy is the (p)NGB;
  - ☆ Through the axial anomaly an effective coupling with (at least) gluons are generated: $(a/f_a)\, Tr[G^{\mu\nu}\tilde{G}_{\mu\nu}]$
  - ☆ QCD non perturbative effects force the p(NGB) to take a vev (solving the strong CP problem) and a mass:

$$\boxed{\overline{\theta} = \theta + \frac{\langle a \rangle}{f_a} = 0}$$

$$\boxed{m_a f_a \approx m_\pi f_\pi}$$

Why Axion Like Particles ?

- Spontaneously broken global $U(1)$ symmetries are a common feature of many BSM frameworks;
- Many different HIERARCHY problems may be solved introducing "AXION-LIKE PARTICLES" (ALPs):
  - ☆ Cosmology (Axion Inflation), EW Hierarchy (Relaxion), Flavour Symmetry (Flaxion or Axiflavon);
- Main (pheno) difference between AXION vs ALPs:
  - ☆ AXION = fixed by QCD relation $m_a f_a \approx m_\pi f_\pi$

    $(10^{-7} \lesssim m_a \lesssim 1)$ eV and $(10^{7} \lesssim f_a \lesssim 10^{12})$ TeV;
  - ☆ ALPs = free relation (strong CP problem not solved)

    $m_a \sim$ GeV and $f_a \sim$ TeV can be considered;

The ALP Effective Lagrangian

- The Dimension 5 Effective Lagrangian describing the interaction between ALP and SM particles (EW scale):

$$\delta\mathcal{L}_{\text{eff}} = -\frac{c_G}{4}\frac{a}{f_a}G_a^{\mu\nu}\widetilde{G}^a_{\mu\nu} - \frac{c_B}{4}\frac{a}{f_a}B^{\mu\nu}\widetilde{B}_{\mu\nu} - \frac{c_W}{4}\frac{a}{f_a}W^{\mu\nu}\widetilde{W}_{\mu\nu}$$

$$-\frac{\partial_\mu a}{2f_a}\left(\overline{Q}_L X_L \gamma^\mu Q_L + \overline{u}_R X_R^u \gamma^\mu u_R + \overline{d}_R X_R^d \gamma^\mu d_R\right) + c_{a\Phi}\xcancel{\frac{\partial_\mu a}{2f_a}\Phi^\dagger}\overleftrightarrow{D}_\mu\Phi$$

- For the following discussion it will be sufficient to consider the following Low Energy Effective Lagrangian describing ALP-photon ($c_{a\gamma\gamma}$) and ALP-fermion (c_{aff}) flavour conserving (but non universal) couplings:

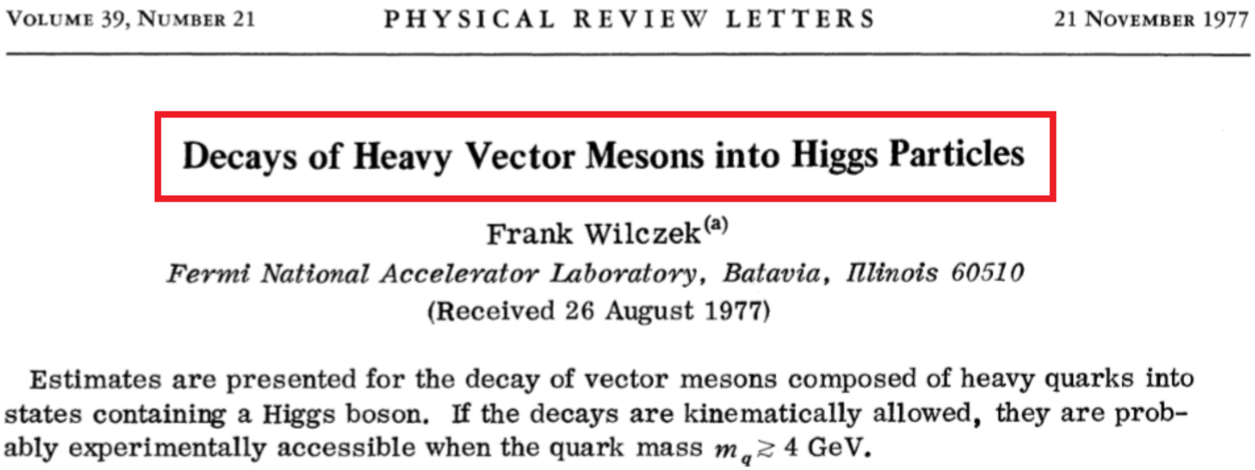
$$\delta\mathcal{L}_{\text{eff}}^{LE} \supset -\frac{c_{a\gamma\gamma}}{4}\frac{a}{f_a}F^{\mu\nu}\widetilde{F}_{\mu\nu} + i\, c_{aff}\, m_i \frac{a}{f_a}\overline{f}_i\gamma_5\gamma^\mu f_i$$

Meson Decays into invisible ALP

Flavour Factories are the main playground for studying ALP fermion/photon couplings for m_a in KeV-GeV range

- Invisible ALP decays are a very clean channel:
  - Invisible ALP = long living ALP ($\tau_a \gtrsim 100$ ps) or mainly decaying in an invisible sector (DM portal);
  - Very simple signature: missing energy/momentum;
- Different promising channels:
  - Hadronic Decays: $M \to M' a$ (i.e. $K \to \pi a, B \to K a$);
  - Leptonic Decays: $M \to \ell \nu_\ell a$ (i.e. $K, B \to \mu \nu_\mu a$);
  - Quarkonium radiative Decays: $M \to \gamma a$ $\left(\text{i.e. } \Upsilon(ns) \to \gamma a\right)$;

Quarkonium Decays in ALP

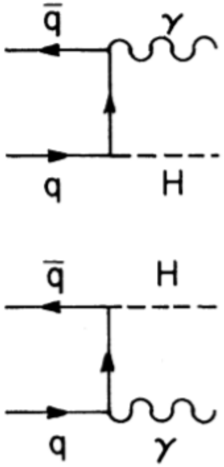


VOLUME 39, NUMBER 21 PHYSICAL REVIEW LETTERS 21 NOVEMBER 1977

Decays of Heavy Vector Mesons into Higgs Particles

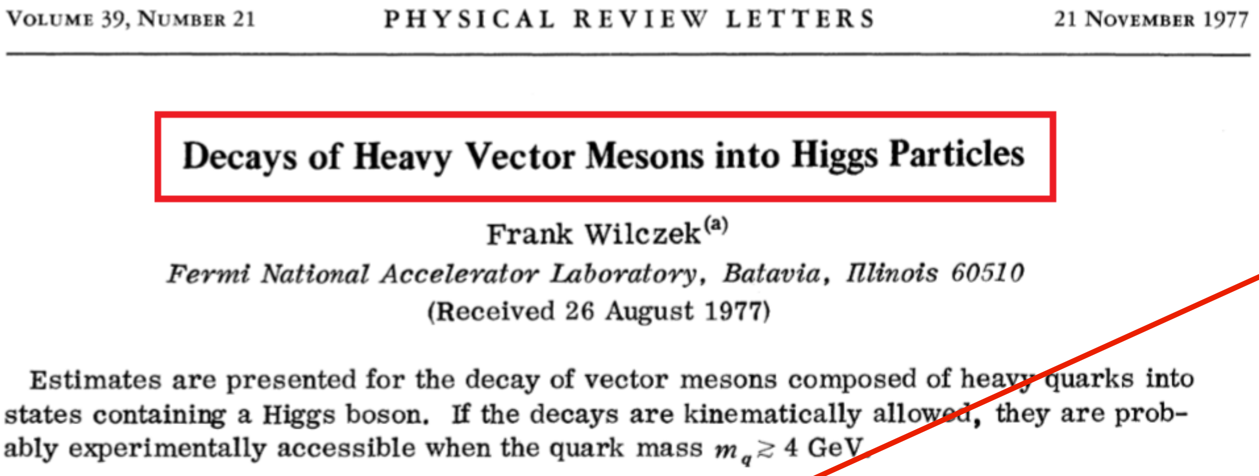
Frank Wilczek[(a)]
Fermi National Accelerator Laboratory, Batavia, Illinois 60510
(Received 26 August 1977)

Estimates are presented for the decay of vector mesons composed of heavy quarks into states containing a Higgs boson. If the decays are kinematically allowed, they are probably experimentally accessible when the quark mass $m_q \gtrsim 4$ GeV.



Quarkonium decays are very clean signatures.

Quarkonium Decays in ALP



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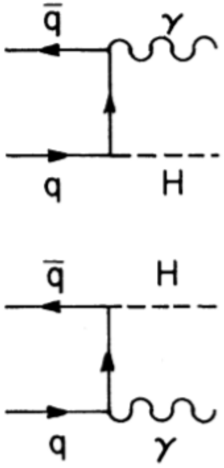
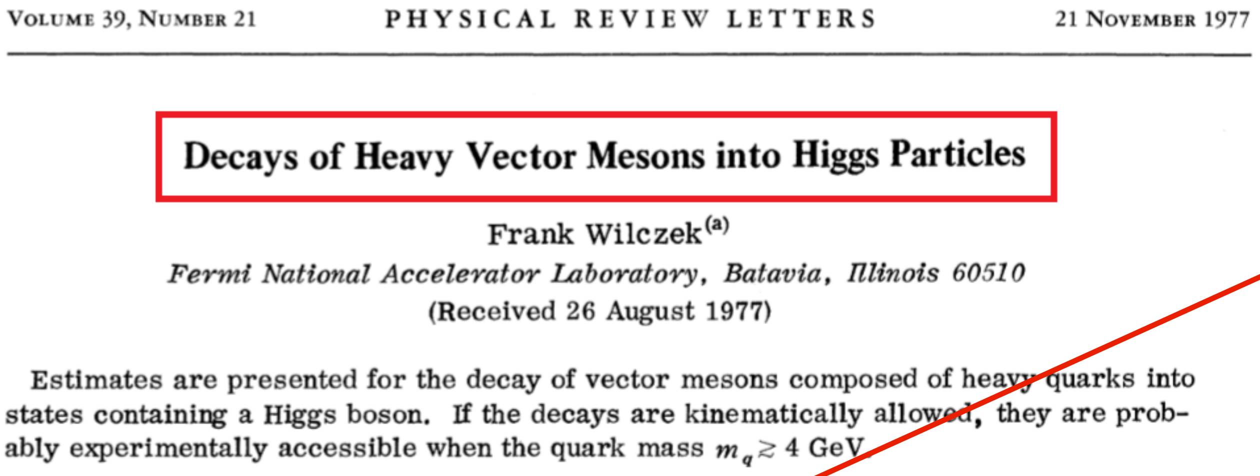


Resonant contribution = On-shell meson decay

Quarkonium Decays in ALP



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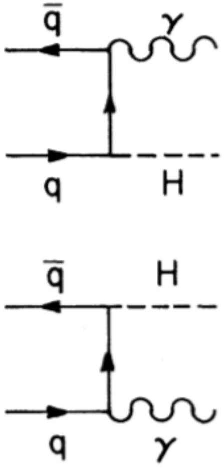


Resonant contribution = On-shell meson decay

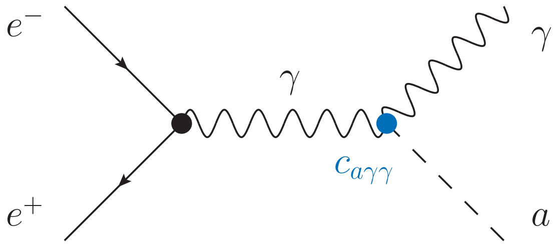
- Resonant contributions provide a clear and direct access to (flavour conserving) ALP-quark couplings c_{aqq} ;
- Underlying assumption: negligible ALP-photon coupling $c_{a\gamma\gamma}$ (i.e. loop suppressed). Fine for independent limits on c_{aqq} (but not true for a general ALP model).

Quarkonium Decays in ALP

At e^+e^- machines (BABAR/BELLE) both Non-Resonant (NR) and Resonant (R) contributions to ALP production can in general be present:

  - Introduces several TH/EXP "interpretation" issues;

- Non-Resonant contribution to ALP production at e^+e^- collider depend ONLY on $c_{a\gamma\gamma}$ (neglecting c_{aee} contributions):

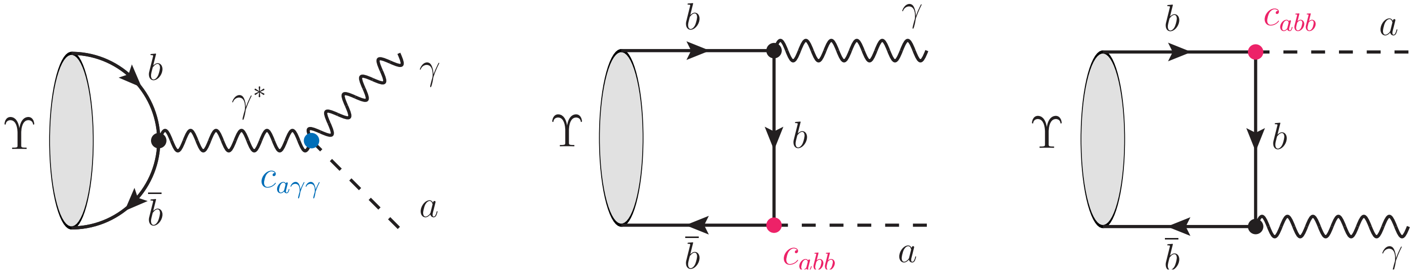


$$\sigma_{NR}(s) = \frac{\alpha_{em}}{24}\frac{c_{a\gamma\gamma}^2}{f_a^2}\left(1-\frac{m_a^2}{s}\right)^3$$

One may (naively) assume it's negligible w.r.t. resonant ones, if experiments are running at some $q\bar{q}$ resonance;

Quarkonium Decays in ALP

- **Resonant** contributions to ALP production depend simultaneously on $c_{a\gamma\gamma}$ and c_{aqq}



In the Breit-Wigner approximation one has:

$$\sigma_R(s) = \sigma_{\text{peak}} \frac{m_\Upsilon^2 \Gamma_\Upsilon^2}{(s - m_\Upsilon^2) - m_\Upsilon^2 \Gamma_\Upsilon^2} \mathcal{B}(\Upsilon \to \gamma\, a) \qquad \left(\sigma_{\text{peak}} = \frac{12\pi}{m_\Upsilon^2} \mathcal{B}(\Upsilon \to ee) \right)$$

$$\mathcal{B}(\Upsilon \to \gamma a) = \frac{\alpha_{\text{em}}}{216\, \Gamma_\Upsilon} m_\Upsilon f_\Upsilon^2 \left(1 - \frac{m_a^2}{m_\Upsilon^2} \right) \left[\frac{c_{a\gamma\gamma}}{f_a} \left(1 - \frac{m_a^2}{m_\Upsilon^2} \right) - 2 \frac{c_{abb}}{f_a} \right]^2$$

with the matrix element $\langle 0 | \bar{b} \gamma^\mu b | \Upsilon(p) \rangle = m_\Upsilon\, f_\Upsilon\, \varepsilon^\mu(p)$;

Quarkonium Decays in ALP

Phenomenological analysis of $\Upsilon(ns) \to \gamma\, a$ is quite puzzling:

- $\Upsilon(1s,2s,3s)$ resonances are very narrow compared to BABAR/BELLE beam energy uncertainty ($\sigma_{\rm w} \approx 5$ MeV). They are NOT experimentally resolved;
- $\Upsilon(4s)$ is a very spread resonance (Belle II analysis);

$\Upsilon(nS)$	Γ_Υ [keV]	$\sigma_{\rm peak}$ [nb]	ρ	$\langle\sigma_{\rm res}\rangle_{\rm vis}/\sigma_{\text{non res.}}$
$\Upsilon(1S)$	54.02			
$\Upsilon(2S)$	31.98			
$\Upsilon(3S)$	20.32			
$\Upsilon(4S)$	20.5×10^3			

Quarkonium Decays in ALP

- The "visible" $\Upsilon(1s,2s,3s)$ resonant contributions (obtained by smearing) get highly suppressed (by a factor $\rho \approx 10^{-3}$)

$$\langle \sigma_{\rm R}(m_\Upsilon^2)\rangle_{\rm vis} = \int {\rm d}\,q\, \frac{\sigma_{\rm R}(q^2)}{\sqrt{2\pi}\sigma_W} \exp\left[-\frac{(q-m_\Upsilon)^2}{2\sigma_W^2}\right]$$

[Eidelman et al. 1601.07987]

$$\overset{\Gamma \ll \sigma_W}{=} \rho\, \sigma_{\rm peak} \mathcal{B}\left(\Upsilon(nS) \to \gamma\, a\right)$$

$$\rho = \sqrt{\frac{\pi}{8}\frac{\Gamma_\Upsilon}{\sigma_W}} \sim 10^{-2} \div 10^{-3}$$

$\Upsilon(nS)$	Γ_Υ [keV]	$\sigma_{\rm peak}$ [nb]	ρ	$\langle\sigma_{\rm res}\rangle_{\rm vis}/\sigma_{\text{non res.}}$
$\Upsilon(1S)$	54.02	$3.9(18)\times 10^3$	6.1×10^{-3}	$\mathbf{0.53(5)}$
$\Upsilon(2S)$	31.98	$2.8(2)\times 10^3$	3.7×10^{-3}	$\mathbf{0.21(3)}$
$\Upsilon(3S)$	20.32	$3.0(3)\times 10^3$	2.3×10^{-3}	$\mathbf{0.16(3)}$
$\Upsilon(4S)$	20.5×10^3	$2.10(10)$	0.83	$3.0(3)\times 10^{-5}$

Quarkonium Decays in ALP

Which is the cross-section to use when comparing with (Babar/Belle) experiments? Non-Resonant or Resonant?

It DEPENDS analysis by analysis

Three complementary searches can be done at B-Factories

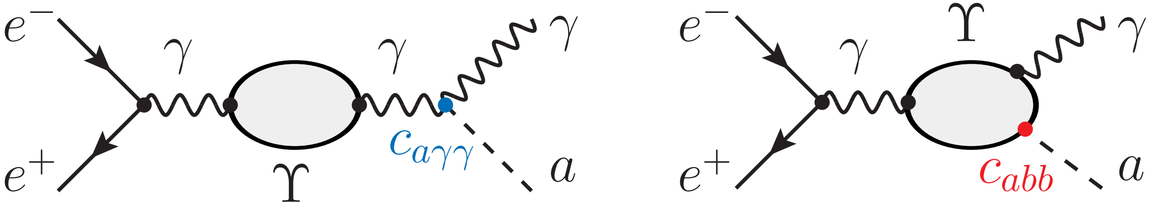
1. Purely **RESONANT** searches: the $\Upsilon(nS)$ resonance is reconstructed kinematically (see Belle 1809.05222);
2. Mixed **(NON)-RESONANT** searches: the $\Upsilon(nS)$ resonance is NOT reconstructed (see Babar 0808.0017);
3. **NON-RESONANT** searches: the $\Upsilon(4S)$ case (see BelleII arXiv:2007.13071);

Quarkonium Decays in ALP

1. Purely **RESONANT** searches: $\Upsilon(1S)$ is reconstructed;

$\Upsilon(2S) \to \Upsilon(1S)\,\pi^+\pi^-\,(\Upsilon(1S) \to \gamma\,a)$ [Babar: 1007.4646]

$\Upsilon(3S) \to \Upsilon(1S)\,\pi^+\pi^-\,(\Upsilon(1S) \to \gamma\,a)$ [Belle: 1809.05222]



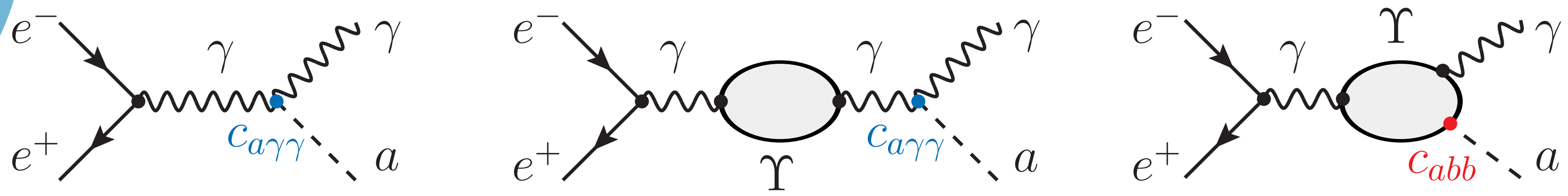
In this case one probes effectively

$$\mathcal{B}(\Upsilon(1S) \to \gamma a) \times \mathcal{B}(a \to \dots) \propto \left[\frac{c_{a\gamma\gamma}}{f_a}\left(1 - \frac{m_a^2}{m_\Upsilon^2}\right) - 2\frac{c_{abb}}{f_a}\right]^2$$

WARNING: Possibility of destructive interference

Quarkonium Decays in ALP

2. Mixed **(NON)-RESONANT** searches: $\Upsilon(nS)$ is not reconstructed: $\Upsilon(3S) \to \gamma\, a$ [Babar: 1007.4646]



In this case one probes effectively

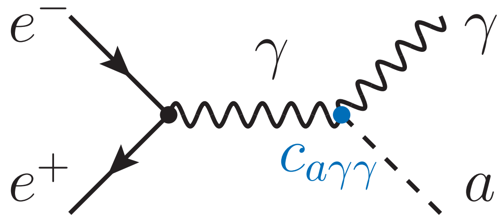
$$\langle \sigma_R + \sigma_{NR} \rangle_{\text{vis}} \approx \langle \sigma_R[c_{a\gamma\gamma}, c_{abb}] \rangle_{\text{vis}} \left(1 + \frac{\sigma_{NR}[c_{a\gamma\gamma}]}{\langle \sigma_R[c_{a\gamma\gamma}, c_{abb}] \rangle_{\text{vis}}} \right)$$

WARNING: Experimental papers only provide $\mathcal{B}(\Upsilon(nS) \to \gamma\, a)$ and the experimental limits need to be RECASTED.

WARNING: If $c_{a\gamma\gamma} \approx c_{abb}$ the NR term dominates (factor 2-5)

Quarkonium Decays in ALP

3. **NON-RESONANT** searches: $\Upsilon(4S)$ resonance is so spread that resonant contributions can be neglected (factor 10^{-5})



In this case one probes effectively

$$\sigma_{NR}(s) = \frac{\alpha_{em}}{24}\frac{c_{a\gamma\gamma}^2}{f_a^2}\left(1-\frac{m_a^2}{s}\right)^3$$

No experimental searches yet on $e^+e^- \to \gamma\, a$ using $\Upsilon(4S)$ data

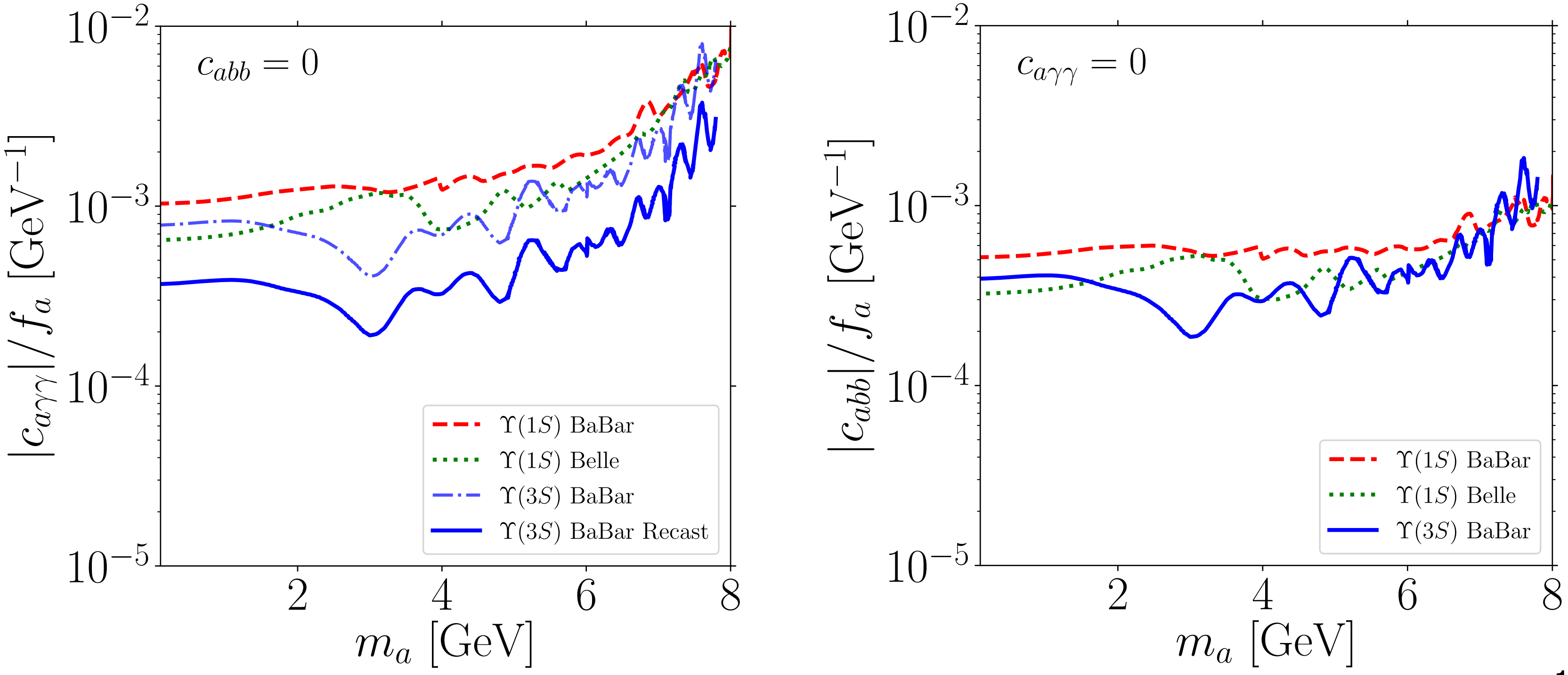
One can use available BelleII analysis $e^+e^- \to \gamma\, a\ (a \to \gamma\gamma)$ where $\mathcal{B}(a \to \gamma\gamma) = 1$ has been assumed [BelleII: 2007.13071]

[see Sascha Dreyer talk]

Quarkonium Decays in ALP

- Individual limits on $c_{a\gamma\gamma}$ (left) and c_{abb} (right) as function of m_a using Babar/Belle invisible $\Upsilon(nS)$ decay data.

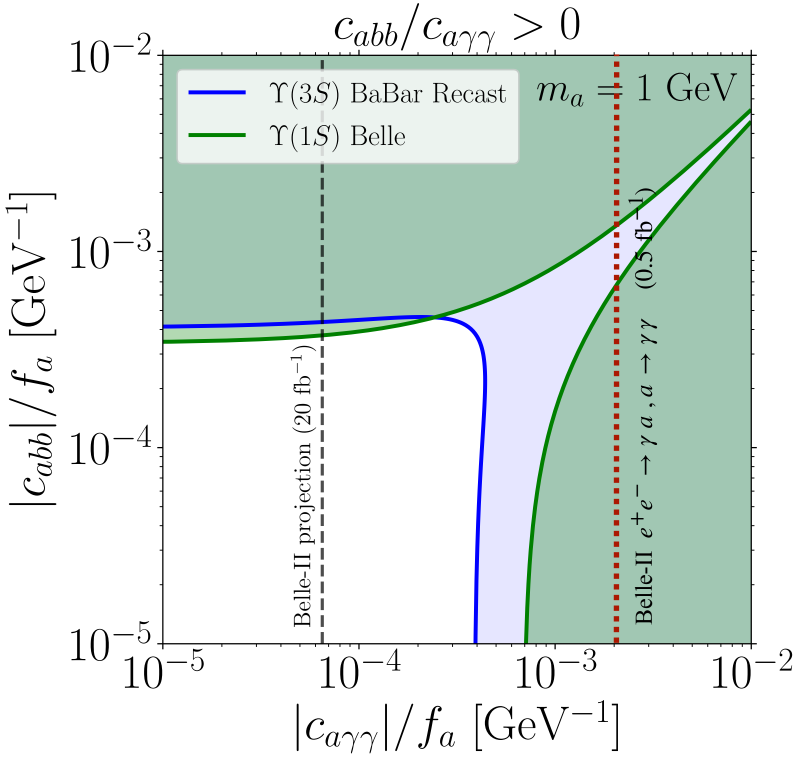
The ALP/NP SCALE $f_a > 5$ TeV (assuming $c_{a\gamma\gamma} = c_{abb} \simeq 1$)

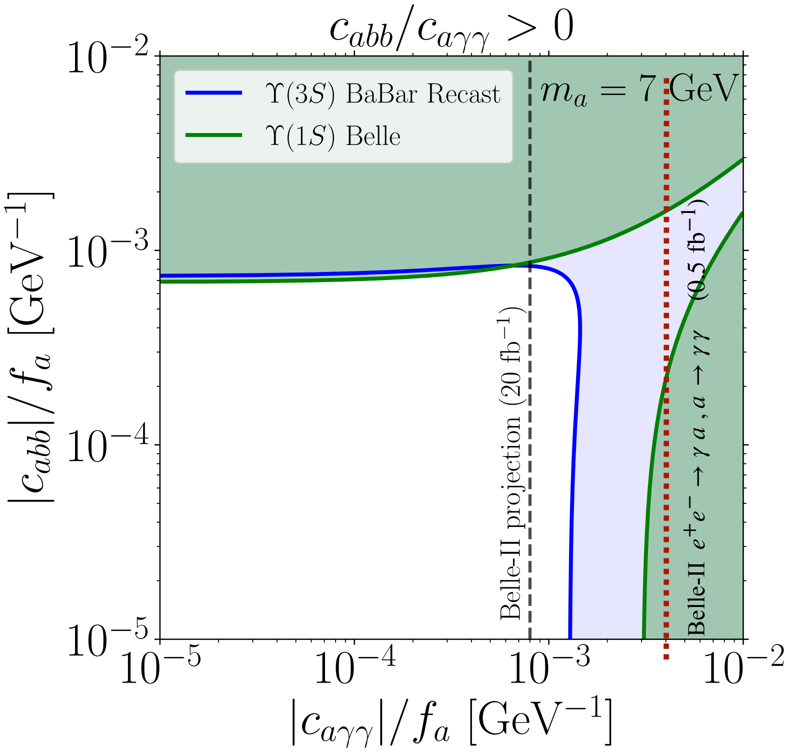


Quarkonium Decays in ALP

- Combined bounds on $c_{a\gamma\gamma}$ and c_{abb} for $m_a = 1\,(7)$ GeV left (right) from Babar/Belle invisible $\Upsilon(nS)$ decay data.

Different (Non) Resonant searches remove flat directions





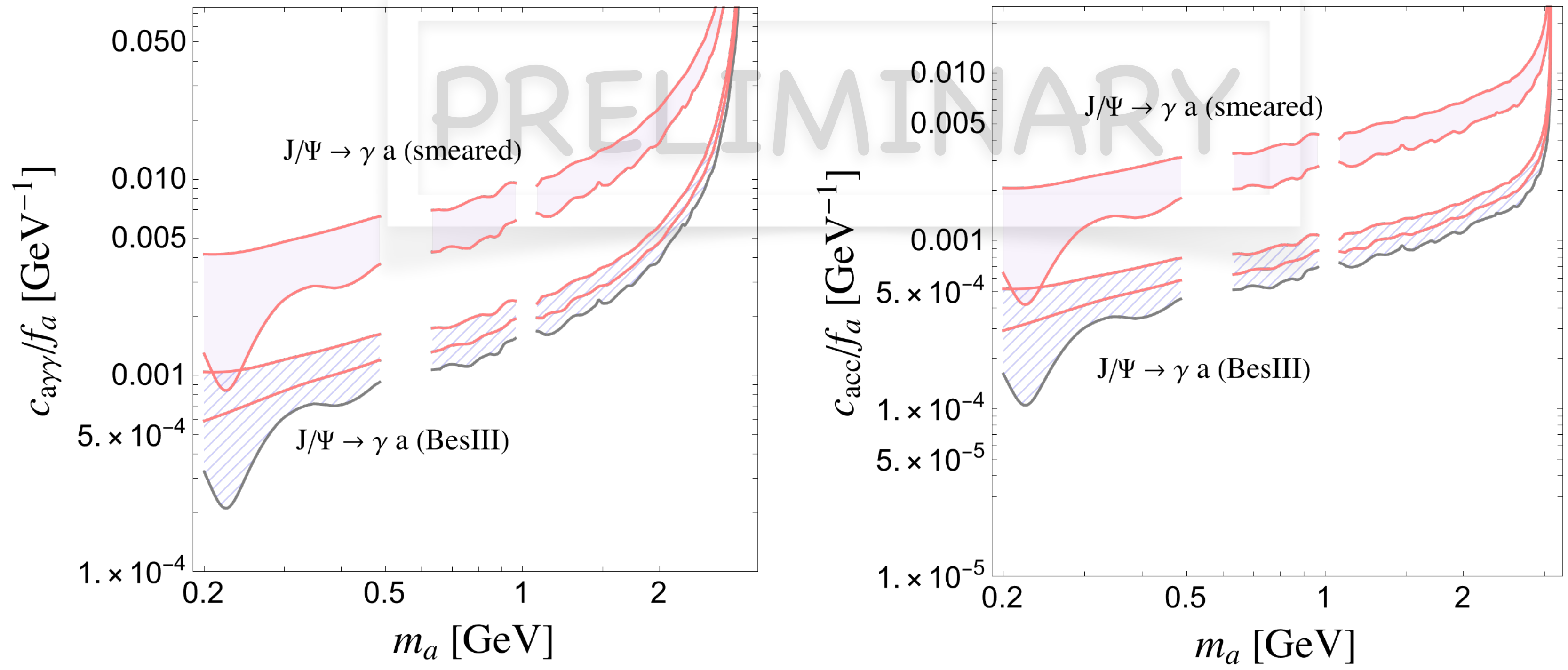
Quarkonium Decays in ALP

- The J/ψ case. **Resonant** channel (J/ψ fully reconstructed)

$$\psi(3686) \to \pi^+\pi^- J/\psi\,,\ J/\psi \to \gamma\, a$$

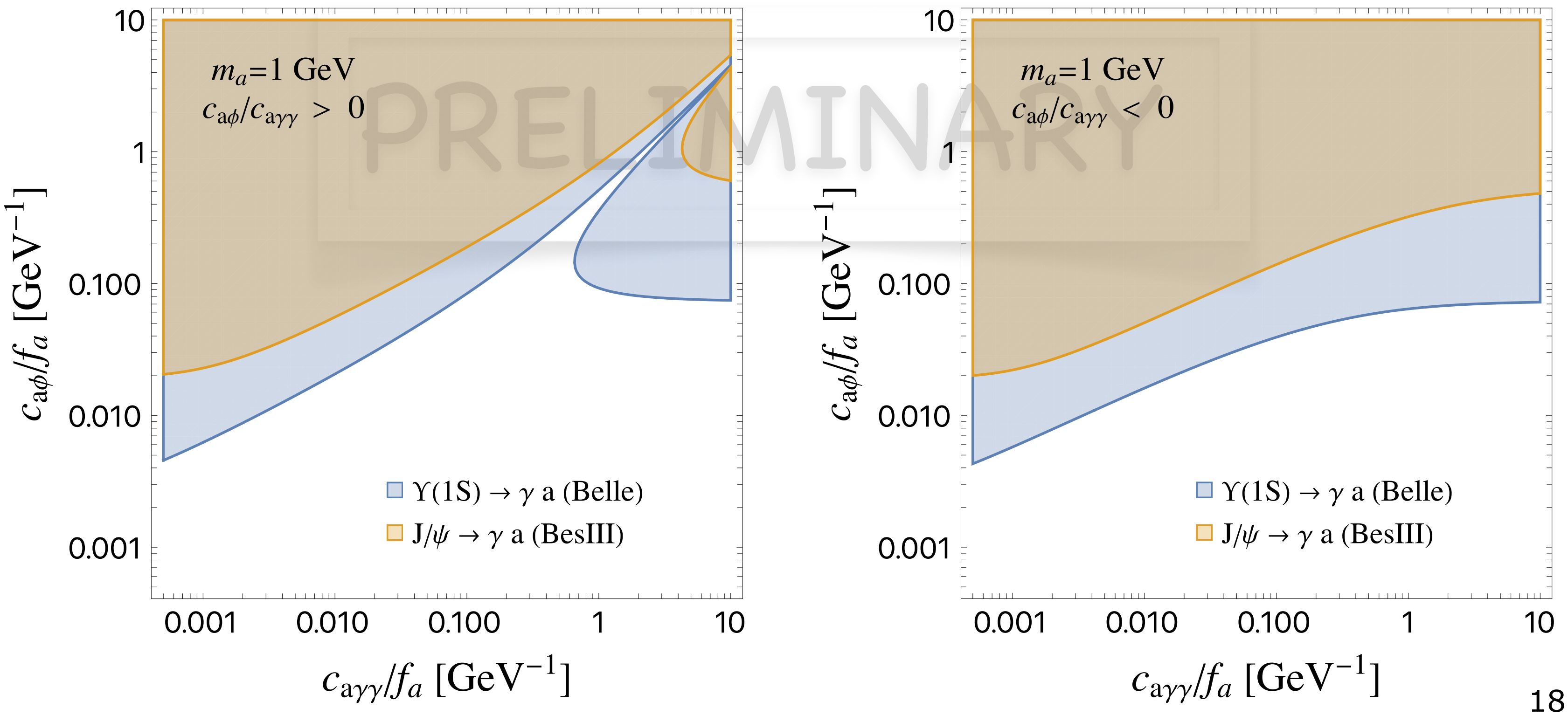
[BesIII - arXiv:2211.12699]
[see Peicheng Jiang talk]

- Smearing coefficient $\rho_{J/\psi} \approx 0.1$ (due to a larger J/ψ resonance and better energy resolution w.r.t. $\Upsilon(nS)$)



Quarkonium Decays in ALP

- Comparing $\Upsilon(1S) \to \gamma\, a$ with $J/\psi \to \gamma\, a$ resonant decays:
  - ☆ Remind that in principle they measure two different ALP-fermion couplings: c_{abb} vs c_{acc}



Summary & Outlook

- ALPs represent a wide class of models with common features (NP as new light degree of freedom);
- Flavour Factories are the optimal place for studying new light degree of freedom in the (KeV-GeV) range;
- Quarkonium decays provide clear (tree-level) bounds on ALP-quarks and ALP-photon couplings;
- Bounds on U(1) symmetry breaking scale $f_a \gtrsim \mathcal{O}(5\,\mathrm{TeV})$ assuming $c_{a\gamma\gamma} = c_{abb} \simeq 1$ or $c_{a\gamma\gamma} = c_{abb} \lesssim 0.2$ for $f_a = 1\,\mathrm{TeV}$;
- Including ALP visible decay channels (in progress);

Backup Slides

Th vs Exp problems

- Some of the experimental provided $\mathscr{B}(\Upsilon \to \gamma\, a)$ need to be recasted as obtained by without the non-resonant term;
- Be careful in extracting (theoretical) information from $\Upsilon(ns)$. One cannot simply "average" different exp. data;

But there is a even more subtle (experimental) problem

- Background: off-resonance data are subtracted from resonance one (alternative way to estimate background?)
  - Assume implicitly that signal is ONLY resonant. But "Wilzcek-like" models are exceptions in Axion or ALPs;
  - As non-resonant contribution is typically larger than resonant one, this would cancel all the signal;

Summary on ALP-fermion couplings