

Testing the possibility of a light CP-odd Higgs

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ijcLab
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The 2 Higgs doublet model

- Natural extension of the Standard Model involving a second $SU(2)$ scalar doublet. It is present in many **flavor** , **dark matter** and **neutrino mass generation** models. It can provide additional **CP violation**, a **first order phase transition** allowing for baryogenesis, ...

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- Extended scalar sector

CP-even

h and H

h is the 125 GeV Higgs boson
while H is heavier

Charged

$H^\pm$

charged Higgs boson that is
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CP-odd

A

CP-odd scalar that can be
light $m_A < m_h/2$!

How can we look for it ?

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Flavor paths to pseudoscalar discovery

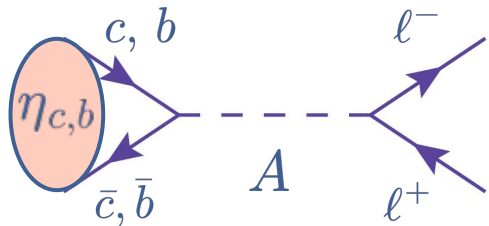
$$\mathcal{L}_A \supset i \frac{m_f}{v} \xi_A^f A(\bar{f} \gamma_5 f) - \frac{m_A^2}{2} A^2$$

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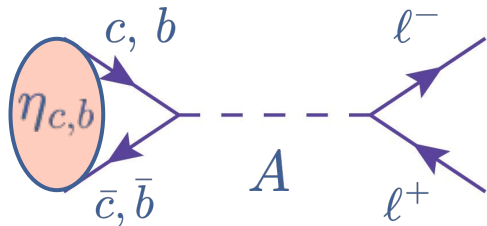
A can be a mediator



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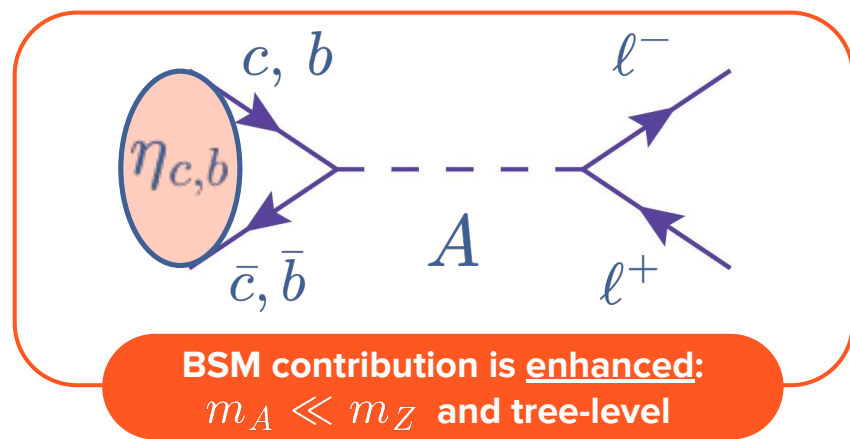
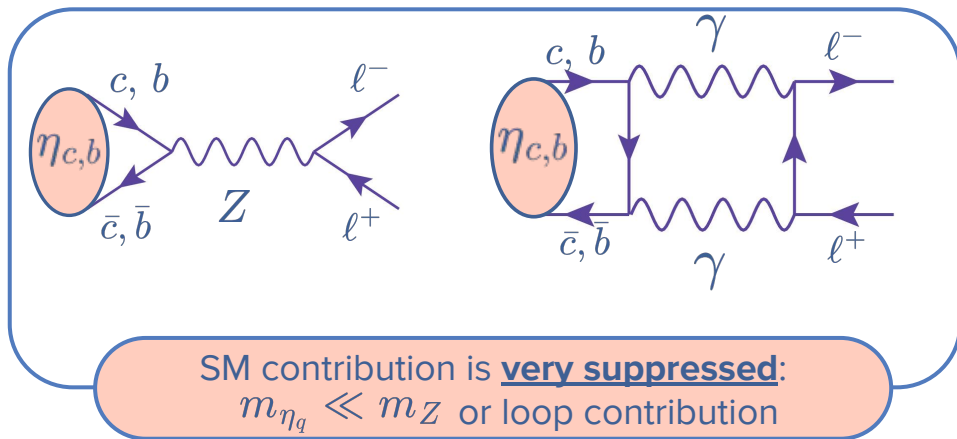
**A can mix with
pseudoscalar mesons**

$$\langle A | \mathcal{L}_A | \eta_q \rangle = \frac{\xi_A^q}{2v} f_{\eta_q} m_{\eta_q}^2 = \delta m^2$$



$$\begin{pmatrix} \eta_{c,b}^{\text{phys}} \\ A^{\text{phys}} \end{pmatrix} = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} \eta_{c,b}^0 \\ A^0 \end{pmatrix}$$

$$\eta_{c,b} \rightarrow \ell^+ \ell^-$$



M^4	e^-	μ^-	τ^-
η_c	~ 0.002	~ 0.08	~ 4.6 (2S)
η_b	~ 170	~ 1800	~ 6700

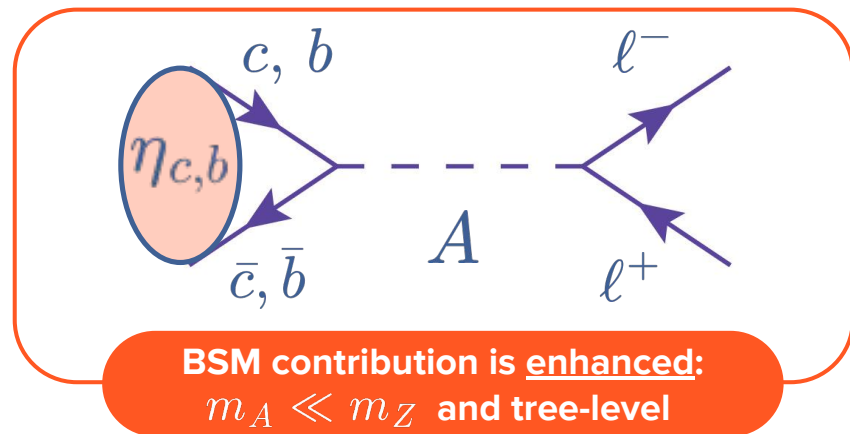
$$R_q^\ell = \frac{\mathcal{B}^A(\eta_q \rightarrow \ell^+ \ell^-)}{\mathcal{B}^{SM}(\eta_q \rightarrow \ell^+ \ell^-)} = \boxed{M^4} \frac{(\xi_A^q \xi_A^\ell)^2}{(m_A^2 - m_{\eta_q}^2)^2}$$

$$\eta_{c,b} \rightarrow \ell^+ \ell^-$$

Most sensitive channel: $\eta_b \rightarrow \tau^+ \tau^-$

$$\mathcal{B}^{SM} \approx 5 \times 10^{-9}$$

measurable!



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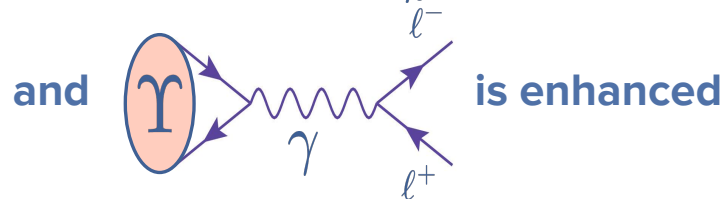
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BUT $m_\Upsilon - m_{\eta_b} \sim 62 \text{ MeV}$



so it's difficult to disentangle

$$\Upsilon \rightarrow \ell\ell \quad \text{and} \quad \eta_b \rightarrow \ell\ell$$

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Mixing quarkonium - A

A and $q\bar{q}$ have the same quantum numbers $\begin{pmatrix} \eta_{c,b}^{\text{phys}} \\ A^{\text{phys}} \end{pmatrix} = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} \eta_{c,b}^0 \\ A^0 \end{pmatrix}$
 $\Rightarrow$ **they mix**

$$\mathcal{L}_{\text{mix}} = -\frac{1}{2} (\eta_{c,b}^0 A^0) \begin{pmatrix} m_{\eta_{c,b}^0}^2 - im_{\eta_{c,b}^0} \Gamma_{\eta_{c,b}^0} & \delta m^2 \\ \delta m^2 & m_{A^0}^2 - im_{A^0} \Gamma_{A^0} \end{pmatrix} \begin{pmatrix} \eta_{c,b}^0 \\ A^0 \end{pmatrix}$$

$$\tan 2\theta = \frac{2\delta m^2}{m_{\eta_{c,b}^0}^2 - m_{A^0}^2 - i \left(m_{\eta_{c,b}^0} \Gamma_{\eta_{c,b}^0} - m_{A^0} \Gamma_{A^0} \right)}$$

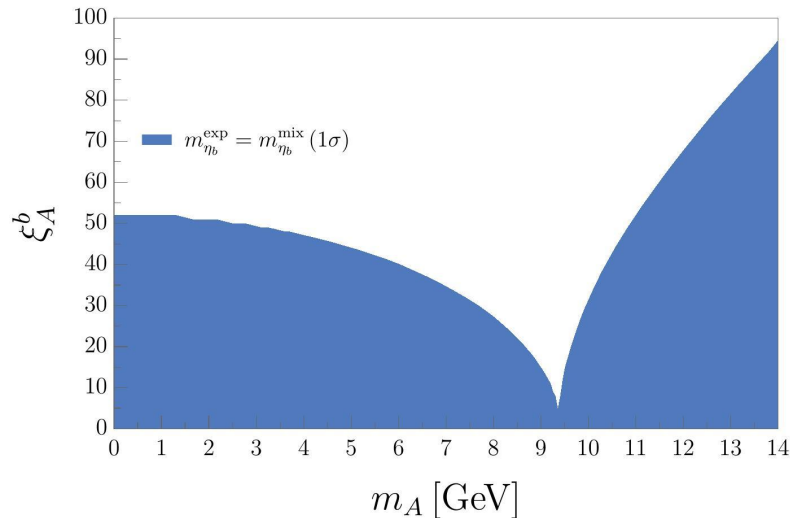
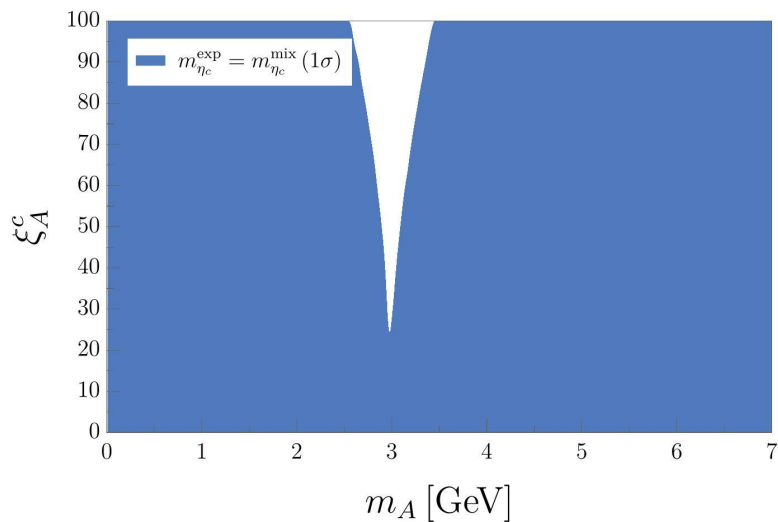
$$\delta m^2 = \frac{\xi_{A^0}^q}{2v} f_{\eta_q^0} m_{\eta_q^0}^2$$

Theoretical mass vs experimental mass

$$m_{\eta^{\text{phys}}}^2 \approx \frac{1}{2} \left(m_{\eta^0}^2 + m_{A^0}^2 \pm \sqrt{4\delta m^4 + (m_{\eta^0}^2 - m_{A^0}^2)^2} \right)$$

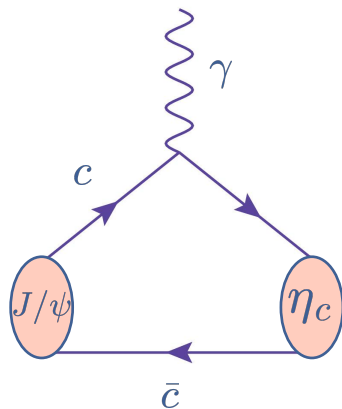
[MeV]

$m_{\eta_c^{\text{phys}}}$	$m_{\eta_c^0}$	$m_{\eta_b^{\text{phys}}}$	$m_{\eta_b^0}$
2984.1 ± 0.4	2976.6 ± 1.1	9398.7 ± 2.0	9402.9 ± 2.5

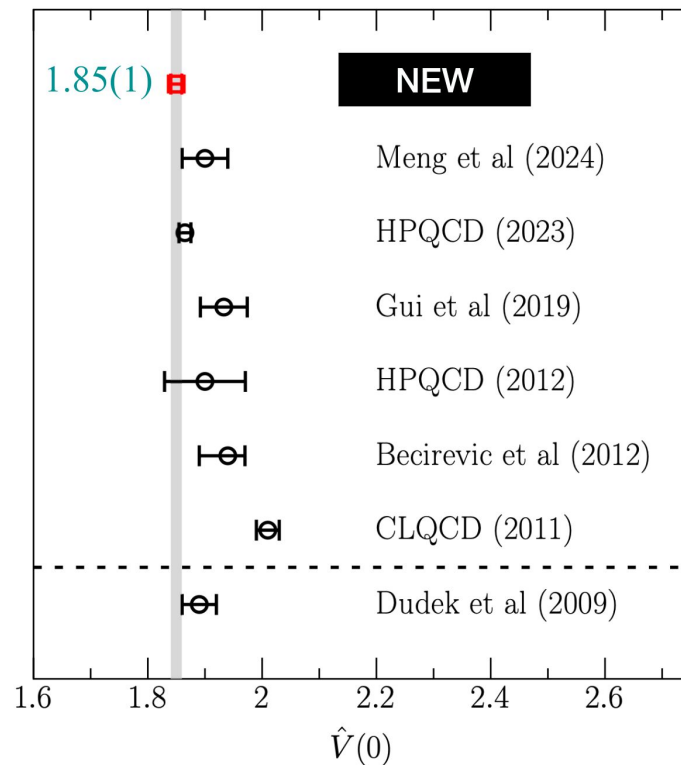


Radiative decays $V \rightarrow P\gamma$

- $J\psi \rightarrow \eta_c \gamma$, $\Upsilon \rightarrow \eta_b \gamma$



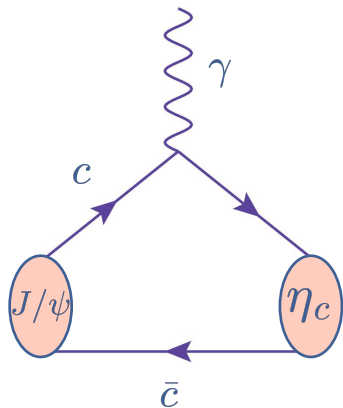
$$\langle \eta_c^0(k) | \bar{c} \gamma_\mu c | J/\psi(p, \lambda) \rangle = \varepsilon_{\mu\nu\alpha\beta} \varepsilon_\lambda^{*\nu} p^\alpha k^\beta \frac{2V(q^2)}{m_{J/\psi} + m_{\eta_c^0}}$$



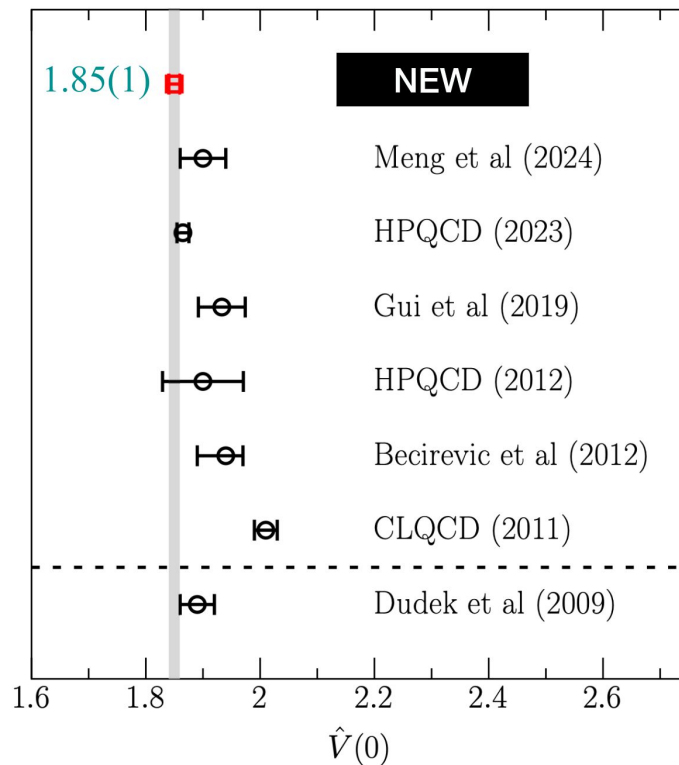
soon on arXiv.. by ETMC

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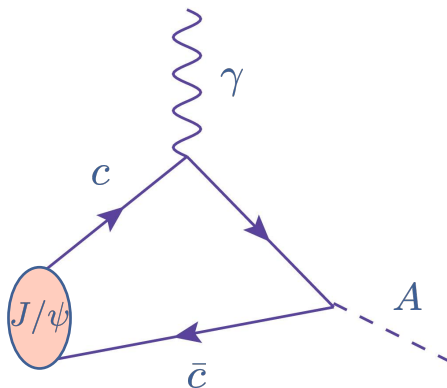
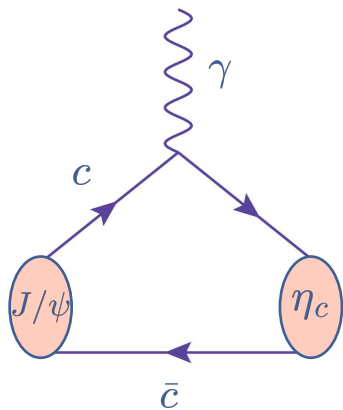
$$\Gamma_{SM}(J/\psi \rightarrow \eta_c \gamma) = \frac{2}{3} Q_c^2 \alpha_{em} (m_{J/\psi} + m_{\eta_c^0}) \left(\frac{m_{J/\psi} - m_{\eta_c^0}}{m_{J/\psi}} \right) [V(0)]^2$$



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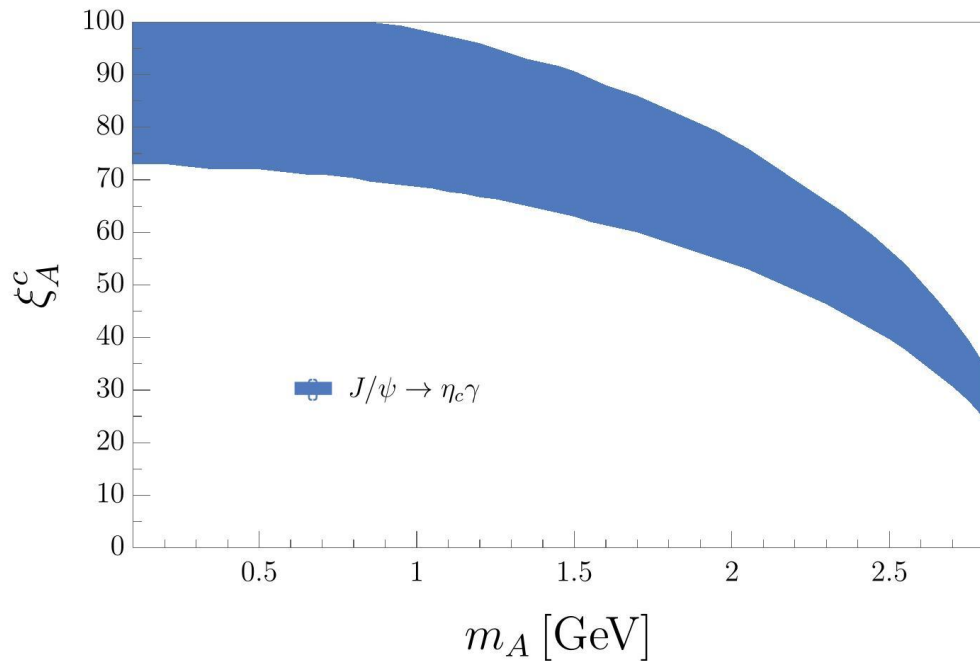


Resonance pole dominance

$$\mathcal{M}_A = -\frac{\mathcal{M}_{\eta_c^0} \delta m^2}{p_A^2 - m_{\eta_c^0}^2 + im_{\eta_c^0} \Gamma_{\eta_c^0}}$$

$$\mathcal{M}(J/\psi \rightarrow \eta_c^{\text{phys}} \gamma) = \cos \theta \mathcal{M}_{\eta_c^0} + \sin \theta \mathcal{M}_A$$

Radiative decay $J/\psi \rightarrow \eta_c \gamma$



$$\mathcal{B}_{exp}(J/\psi \rightarrow \eta_c \gamma) = (1.82 \pm 0.15)\%$$

$$\Gamma_{J/\psi} = 92.6 \pm 1.7 \text{ keV}$$

In blue, allowed region to be compatible at 2σ with $\mathcal{B}_{exp}$

Radiative

These limits are disputable!



As the photon is very soft ($E_\gamma \approx 115 \text{ MeV}$), it is a difficult measurement whose value is still debated!

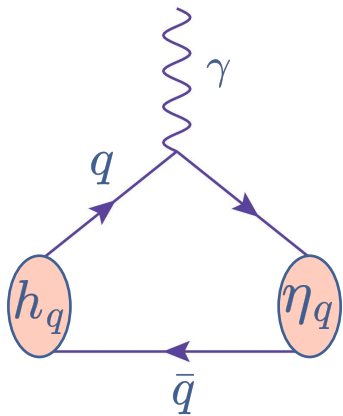
Way out : investigate a radiative decay with a harder photon

$$\Rightarrow h_{b,c} \rightarrow \eta_{b,c} \gamma$$

Radiative decays

$$\Gamma_{SM}(h_q \rightarrow \eta_q \gamma) = \frac{2Q_q^2}{3} \alpha \frac{m_{h_q}^2 - m_{\eta_q}^2}{m_{h_q}} |F_1^q(0)|^2$$

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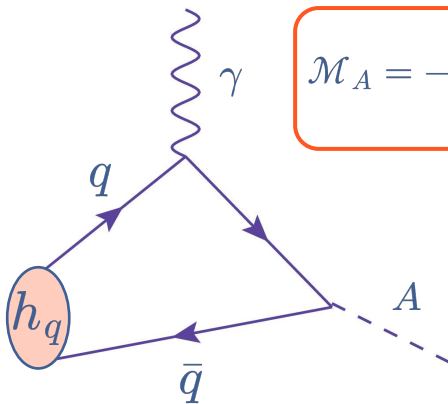
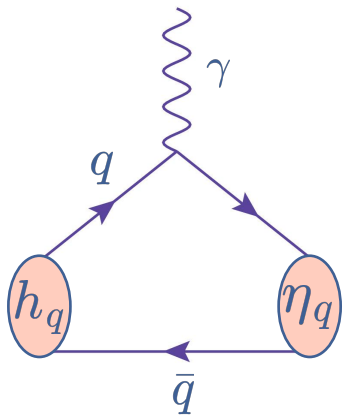
$$\langle \eta_q(k) | J_{\text{em}}^\mu | h_q(p, \varepsilon_\lambda) \rangle = 2iQ_q \left[m_{h_q} F_1^q(q^2) \left(\varepsilon_\lambda^{\star\mu} - \frac{\varepsilon_\lambda^\star \cdot q}{q^2} q^\mu \right) + F_2^q(q^2) \left(\frac{m_{h_q}^2 - m_{\eta_q}^2}{q^2} q^\mu - (p+k)^\mu \right) \right]$$

Recent values 2504.16807 : $F_1^c(0) = -0.552(10)$ $F_1^b(0) = -0.290(15)$

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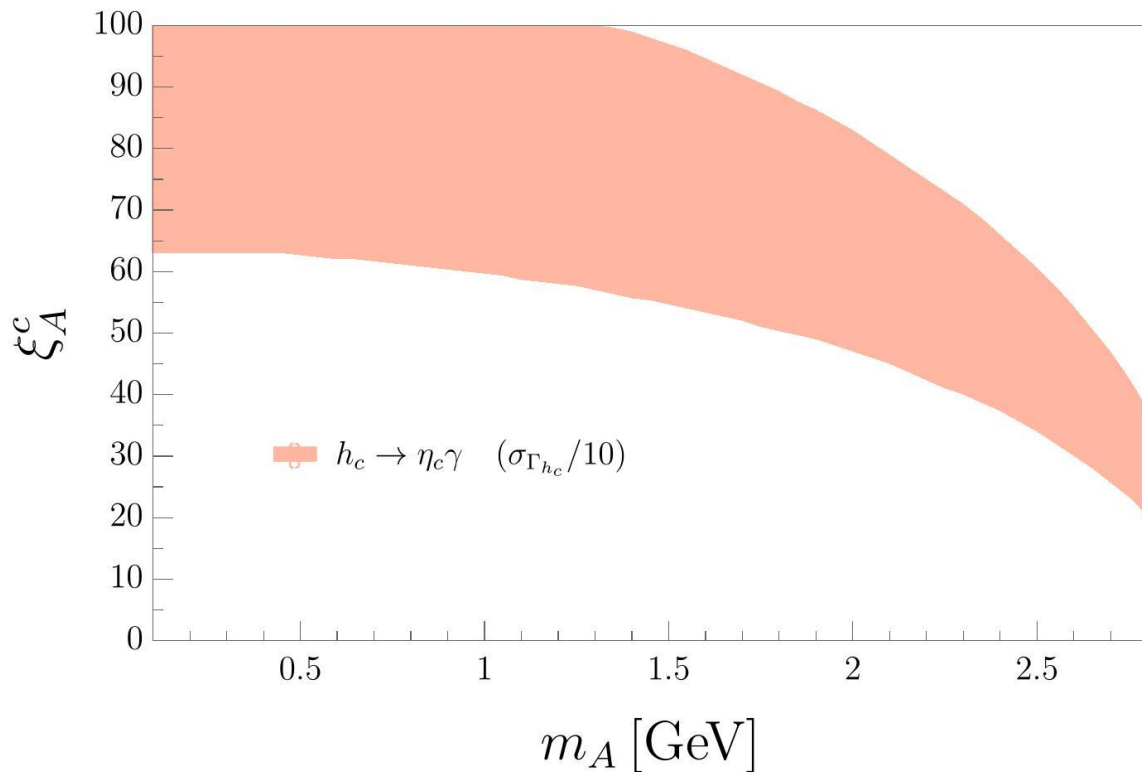
Radiative decay $h_c \rightarrow \eta_c \gamma$

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$$\Gamma_{h_c} = 0.78 \pm 0.28 \text{ MeV}$$

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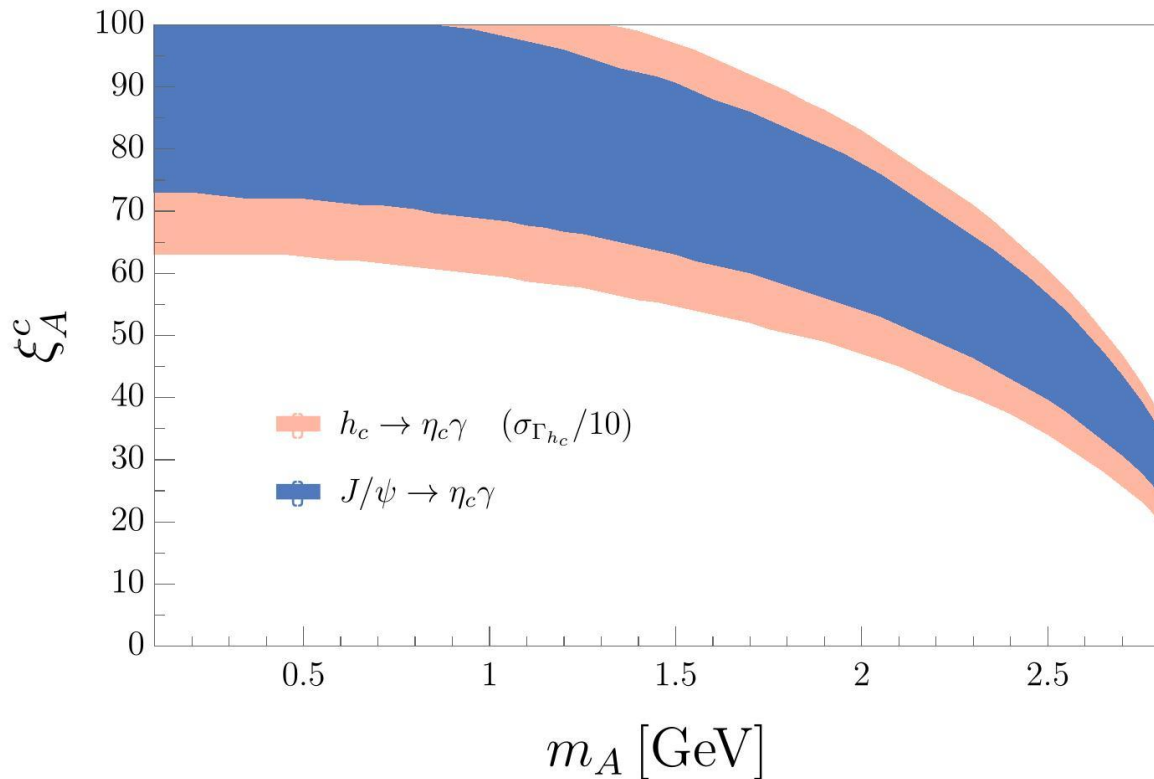
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Let's see what constraints (2σ) we can obtain by dividing the uncertainty by 10

$$\Gamma_{h_c}^{\text{fut}} = 0.78 \pm 0.03 \text{ MeV}$$

Radiative decays



Improving the precision on the width can provide insight on both radiative decays!

Similarly, measuring the width of h_b would allow us to constrain ξ_A^b . **All theoretical inputs (Form Factors) are already known!**

Outlook

We can test the possibility of a light CP-odd higgs through :

- their **mixing with pseudoscalar quarkonia** thanks to **radiative decays**,
- **leptonic decays** of **pseudoscalar quarkonia**, especially $\eta_b \rightarrow \tau^+ \tau^-$

Radiative decays are theoretically well known in the SM thanks to **LQCD**, and a better experimental handle of the **particle widths** (Γ_{h_q}) would help solve the question of the light CP odd higgs existence.

NB: this is valid for any pseudoscalar boson (ALP, majoron, ...)

Paths to New Physics

Heavy new physics ?

⇒ the SM is an EFT : exploration of NP through SMEFT higher dimensional operators, for example

$$\mathcal{L}_{EFT} \supset \frac{C}{\Lambda^2} (\bar{c} \gamma^\nu c_L) (\bar{\mu} \gamma^\nu \mu_L)$$

Light new physics ?

⇒ Strong CP problem, Dark Matter, neutrino physics can push us towards light BSM too

