Exclusive Radiative Higgs Decays in the Standard Model and Beyond

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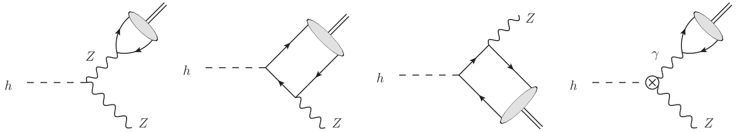
Matthias König and Matthias Neubert



Exotic Higgs Decays Meeting, SLAC 8 November 2016

Introduction

Back in the year 2012 ...

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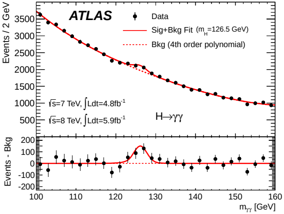

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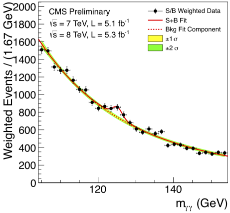

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... the **final piece in the SM puzzle** - the **Higgs boson** - was discovered

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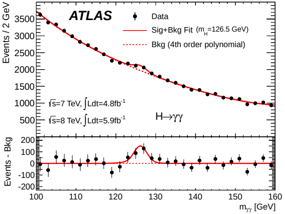

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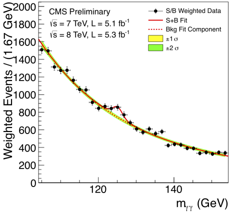

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The path to new physics may open up in the **properties of the Higgs boson** due to its **key role in the SM!**

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"*Exclusive Radiative Higgs Decays as Probes of Light-Quark Yukawa Couplings*", König and Neubert (2015), JHEP **1508** (2015) 012, arXiv: **1505.03870**

"*Exclusive Weak Radiative Higgs Decays in the Standard Model and Beyond*", Alte, König and Neubert (2016), arXiv: **1609.06310**

Effective Higgs Couplings

$$\mathcal{L}_{\text{eff}}^{\text{Higgs}} = \kappa_W \, \frac{2m_W^2}{v} \, h \, W_\mu^+ W^{-\mu} + \kappa_Z \, \frac{m_Z^2}{v} \, h \, Z_\mu Z^\mu - \frac{h}{\sqrt{2}} \sum_{f=u,d,e} \left(\bar{f}_L \, Y_f \, f_R + \text{h.c.} \right)$$

$$(Y_f)_{ii} = (\kappa_{f_i} + i\tilde{\kappa}_{f_i}) \frac{\sqrt{2} m_{f_i}}{v}$$

$$+ \frac{\alpha}{4\pi v} \Bigg(\kappa_{\gamma\gamma} \, h \, F_{\mu\nu} F^{\mu\nu} - \tilde{\kappa}_{\gamma\gamma} \, h \, F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{2\kappa_{\gamma Z}}{\sin\theta_W \cos\theta_W} \, h \, F_{\mu\nu} Z^{\mu\nu} - \frac{2\tilde{\kappa}_{\gamma Z}}{\sin\theta_W \cos\theta_W} \, h \, F_{\mu\nu} \tilde{Z}^{\mu\nu} \Bigg)$$

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SM: blue parameters $\to 1$, red parameters $\to 0$, $Y_f \to$ diagonal, $\kappa_{f_i} \to 1$, $\tilde{\kappa}_{f_i} \to 0$

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The Lagrangian $\mathcal{L}_{\text{eff}}^{\text{Higgs}}$ allows for a **model-independent analysis** of the Higgs couplings

Exclusive Radiative Decays $h \to M\gamma$

König and Neubert (2015)

Light-Quark Yukawa Couplings

Idea: access the **light-quark Yukawa couplings** $(\boldsymbol{q \neq t})$ in the decays $h \to M\gamma$ Bodwin et al. (2013); Kagan et al. (2015)

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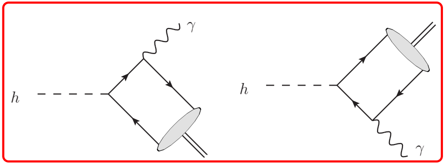
Current LHC measurements: no strong constraints on the parameters κ_q Kagan et al. (2015); Perez et al. (2015)

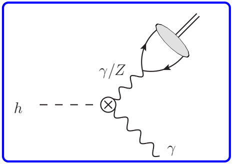
$$\sqrt{|\kappa_u|^2 + |\tilde{\kappa}_u|^2} < 3000$$

$$\sqrt{|\kappa_d|^2 + |\tilde{\kappa}_d|^2} < 1500$$

$$\sqrt{|\kappa_s|^2 + |\tilde{\kappa}_s|^2} < 75$$

Decay Topologies





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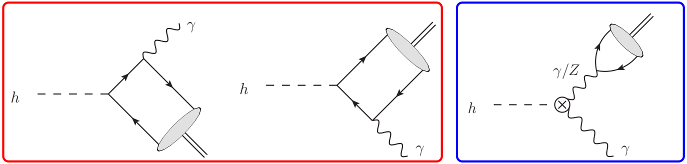

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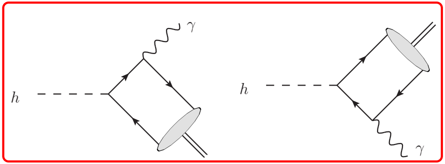

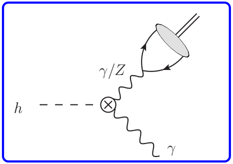

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The indirect contribution involves an **off-shell gauge boson** which **converts into the meson**

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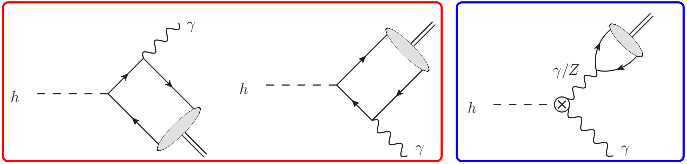

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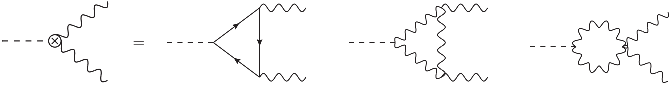
The effective vertex includes the **SM contributions** Bergström and Hulth (1985)



as well as the **NP contributions** $\kappa_{\gamma\gamma}$ and $\kappa_{\gamma Z}$

Decay Amplitude

$$i\mathcal{A}(h \to M\gamma) = -\frac{e\, f_M}{2}\left[\left(\varepsilon_M^* \cdot \varepsilon_\gamma^* - \frac{q\cdot\varepsilon_M^*\, k\cdot\varepsilon_\gamma^*}{k\cdot q}\right) F_1^M - i\epsilon_{\mu\nu\alpha\beta}\frac{k^\mu q^\nu \varepsilon_M^{*\alpha}\varepsilon_\gamma^{*\beta}}{k\cdot q} F_2^M\right]$$

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The form factors receive **direct and indirect** contributions

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Neglecting numerically small terms, one finds for a $\boldsymbol{J/\psi}$ meson

$$F_1^{J/\psi} = -0.137\kappa_W + 0.030\kappa_t + 0.033\kappa_{\gamma\gamma} + 0.007\boldsymbol{\kappa_c} + \dots$$

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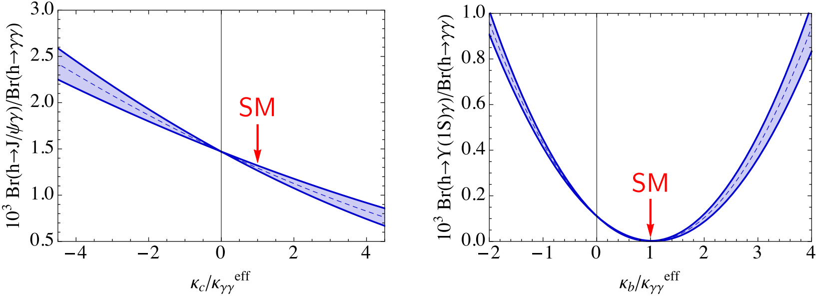
It is challenging to access κ_c since the dominant terms arise from the indirect contribution

Branching Ratios as Functions of κ_q

Assumption: **no CP-odd coupling ($\tilde{\kappa}_q \to 0$)**



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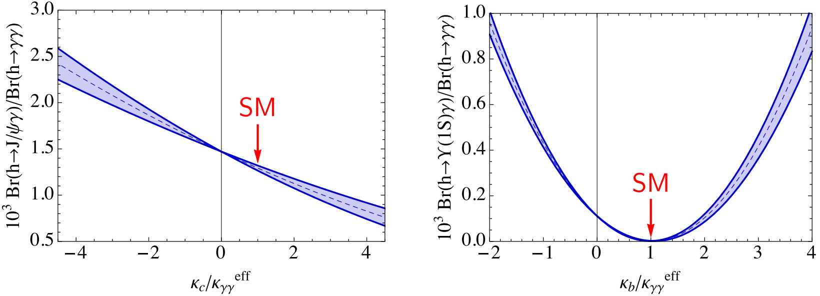

Br($h \to J/\psi\gamma$) exhibits a **mild dependence on κ_c**

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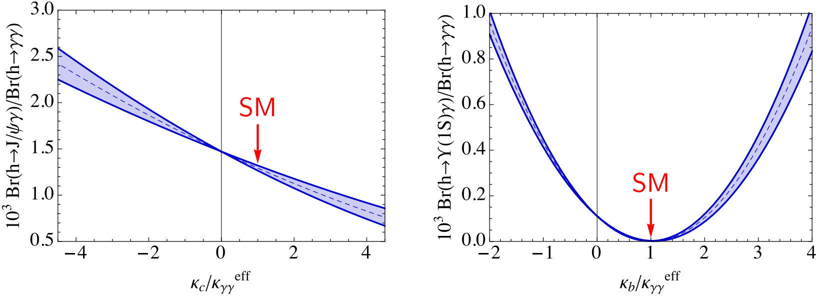

Br($h \to J/\psi\gamma$) exhibits a **mild dependence on κ_c**

Br($h \to \Upsilon(1S)\gamma$) depends **strongly on κ_b** due to a **fortituous cancellation of the direct and the indirect contribution**

Exclusive Radiative Decays $h \to MZ$

Alte, König and Neubert (2016)

Decay Topologies

Previous studies on some decay modes exist Isidori et al. (2014); Gao (2014); Gonzalez-Alonso and Isidori (2014); Modak and Srivastava (2014)

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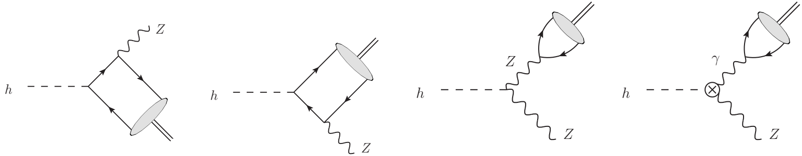

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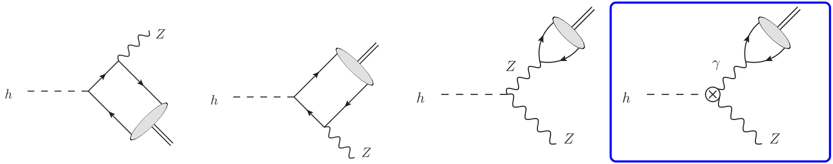

The **diagram $h \to Z(\gamma^* \to M)$** is **loop suppressed** but the off-shellness of the photon yields a factor $\mathbf{1/m_M^2}$

Sensitivity to New-Physics Parameters

For a $\boldsymbol{J/\psi}$ **meson**, we find (all units are MeV)

$$F_{\parallel}^{J/\psi\, Z} \approx 38.69\,\kappa_Z - 1.75 + 0.73\,\boldsymbol{\kappa_{\gamma Z}^{\text{eff}}}$$
$$F_{\perp}^{J/\psi\, Z} \approx -294.8 + 123.1\,\boldsymbol{\kappa_{\gamma Z}^{\text{eff}}} + 38.69\,\kappa_Z + 1.95\,\kappa_c$$

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The coefficient $\boldsymbol{\kappa_{\gamma Z}^{\mathrm{eff}}}$ parameterises **NP effects in the effective $\boldsymbol{h\gamma Z}$ vertex** and **vanishes in the SM**

Branching Ratios as Functions of $\kappa_{\gamma Z}^{\text{eff}}$

The decay $h \to \gamma Z$ **has not been observed** and the **direct bounds on $\kappa_{\gamma Z}^{\text{eff}}$ and $\tilde{\kappa}_{\gamma Z}^{\text{eff}}$ are modest** CMS (2013)

$$\sqrt{\left|\kappa_{\gamma Z}^{\text{eff}} - 2.395\right|^2 + \left|\tilde{\kappa}_{\gamma Z}^{\text{eff}}\right|^2} < 7.2$$

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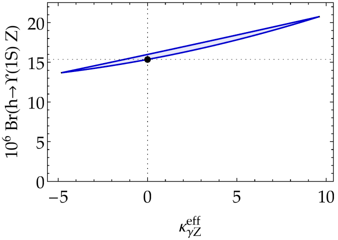
Br($h \to \Upsilon(1S) Z$) as a **function of $\kappa_{\gamma Z}^{\text{eff}}$**



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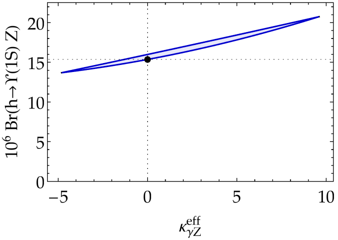

$h \to \Upsilon(1S) Z$ can serve as complementary probes of $\kappa_{\gamma Z}^{\text{eff}}$

Exclusive Radiative Decays $h \to MW$

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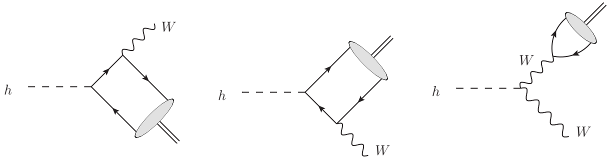

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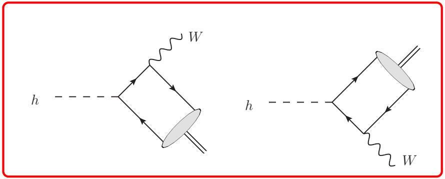

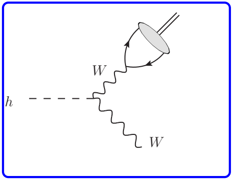

For suitable decay modes, the **indirect contribution** can be **CKM suppressed**, while the **direct contribution** includes terms **enhanced by the top-quark mass**

Flavour-Changing Quark Yukawas in $h \to MW$

$$\mathrm{Br}(h \to B^+ W^-) = 1.54 \cdot 10^{-10} \left(\kappa_W^2 + 427\,\kappa_W\,\mathrm{Re}\,Y_{ut} + 45615\,|Y_{ut}|^2\right)$$
$$\mathrm{Br}(h \to B_c^+ W^-) = 8.21 \cdot 10^{-8} \left(\kappa_W^2 + 41\,\kappa_W\,\mathrm{Re}\,Y_{ct} + 413\,|Y_{ct}|^2\right)$$

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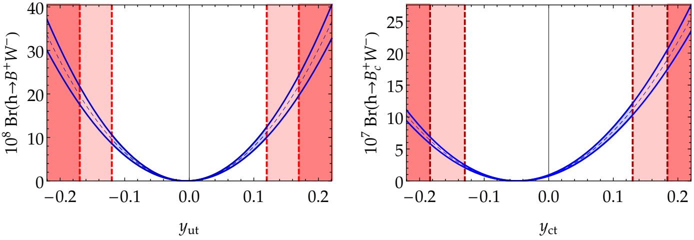
Set $\kappa_W \to 1$ and $\mathrm{Im}(Y_{qt}) \to 0$:



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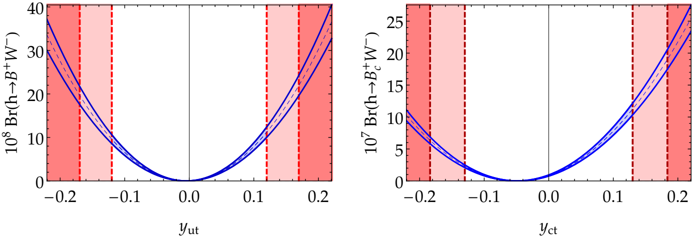

Current **bounds from Br($t \to qh$)** Buschmann et al. (2016): $\sqrt{|Y_{tq}|^2 + |Y_{qt}|^2} < 0.18$

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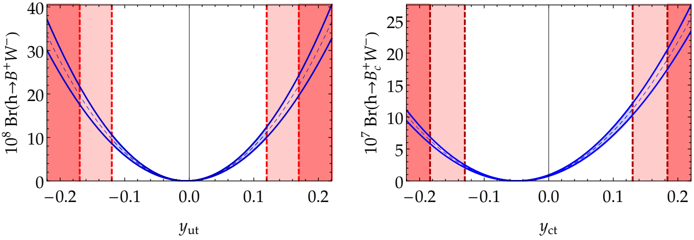

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The dependence on Y_{qt} is strong

Conclusions

General feature of the decays $h \to MV$: **rare in the SM**

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General feature of the decays $h \to MV$: **rare in the SM**

$h \to M\gamma$ can serve as **probes of light-quark Yukawa couplings**

$h \to MZ$ can provide information about $\kappa_{\gamma Z}^{\text{eff}}$

$h \to MW$ exhibit a **strong sensitivity** to the **off-diagonal Yukawa couplings involving the top quark**

Branching Ratios in the Standard Model

Branching ratios [10^{-6}]

$$\begin{aligned}
\mathrm{BR}(h \to \pi^0 Z) &= 2.30 \pm 0.01_f \pm 0.09_{\Gamma_h} \\
\mathrm{BR}(h \to \eta Z) &= 0.83 \pm 0.08_f \pm 0.03_{\Gamma_h} \\
\mathrm{BR}(h \to \eta' Z) &= 1.24 \pm 0.12_f \pm 0.05_{\Gamma_h} \\
\mathrm{BR}(h \to \rho^0 Z) &= 7.19 \pm 0.09_f \pm 0.28_{\Gamma_h} \\
\mathrm{BR}(h \to \omega Z) &= 0.56 \pm 0.01_f \pm 0.02_{\Gamma_h} \\
\mathrm{BR}(h \to \phi Z) &= 2.42 \pm 0.05_f \pm 0.09_{\Gamma_h} \\
\mathrm{BR}(h \to J/\psi\, Z) &= 2.30 \pm 0.06_f \pm 0.09_{\Gamma_h} \\
\mathrm{BR}(h \to \Upsilon(1S)\, Z) &= 15.38 \pm 0.21_f \pm 0.60_{\Gamma_h} \\
\mathrm{BR}(h \to \Upsilon(2S)\, Z) &= 7.50 \pm 0.14_f \pm 0.29_{\Gamma_h} \\
\mathrm{BR}(h \to \Upsilon(3S)\, Z) &= 5.63 \pm 0.10_f \pm 0.22_{\Gamma_h}
\end{aligned}$$

Branching Ratios in the Standard Model

$$\mathrm{BR}(h \to \rho^0\gamma) = (1.68 \pm 0.02_f \pm 0.08_{h\to\gamma\gamma}) \cdot 10^{-5}$$
$$\mathrm{BR}(h \to \omega\gamma) = (1.48 \pm 0.03_f \pm 0.07_{h\to\gamma\gamma}) \cdot 10^{-6}$$
$$\mathrm{BR}(h \to \phi\gamma) = (2.31 \pm 0.03_f \pm 0.11_{h\to\gamma\gamma}) \cdot 10^{-6}$$
$$\mathrm{BR}(h \to J/\psi\gamma) = (2.95 \pm 0.07_f \pm 0.06_{\mathrm{direct}} \pm 0.14_{h\to\gamma\gamma}) \cdot 10^{-6}$$
$$\mathrm{BR}(h \to \Upsilon(1S)\gamma) = \left(4.61 \pm 0.06_f {}^{+1.75}_{-1.21}{}_{\mathrm{direct}} \pm 0.22_{h\to\gamma\gamma}\right) \cdot 10^{-9}$$
$$\mathrm{BR}(h \to \Upsilon(2S)\gamma) = \left(2.34 \pm 0.04_f {}^{+0.75}_{-0.99}{}_{\mathrm{direct}} \pm 0.11_{h\to\gamma\gamma}\right) \cdot 10^{-9}$$
$$\mathrm{BR}(h \to \Upsilon(3S)\gamma) = \left(2.13 \pm 0.04_f {}^{+0.75}_{-1.12}{}_{\mathrm{direct}} \pm 0.10_{h\to\gamma\gamma}\right) \cdot 10^{-9}$$

Reduction of Theoretical Uncertainties

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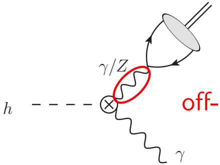

off-shellness is a small effect

Normalise $\Gamma(h \to M\gamma)$ to $\boldsymbol{\Gamma(h \to \gamma\gamma)}$: $\frac{\Gamma(h\to M\gamma)}{\Gamma(h\to\gamma\gamma)} = \frac{\mathrm{Br}(h\to M\gamma)}{\mathrm{Br}(h\to\gamma\gamma)}$

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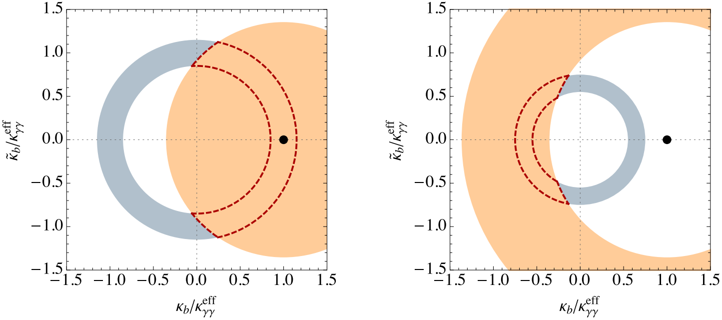
Additional benefit: no dependence on Γ_h

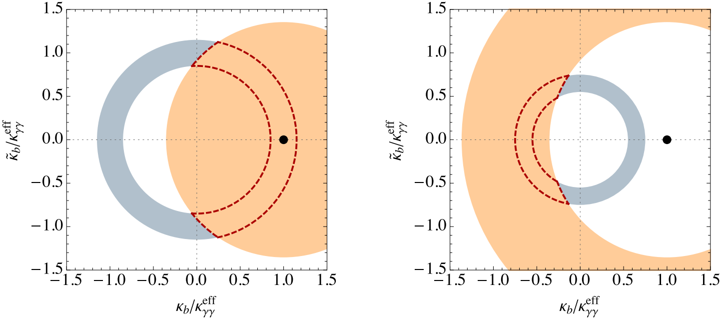
Br($h \to \Upsilon\gamma$) as Functions of κ_b and $\tilde{\kappa}_b$

Possible future scenarios



Br($h \to \Upsilon\gamma$) as Functions of κ_b and $\tilde{\kappa}_b$

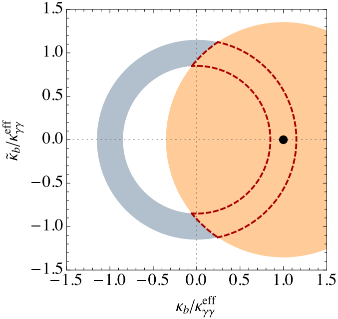
Possible future scenarios

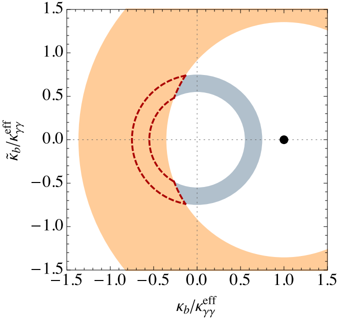


Blue: measurements of $h \to b\bar{b}$
Orange: measurements of $h \to \Upsilon\gamma$

Br($h \to \Upsilon\gamma$) as Functions of κ_b and $\tilde{\kappa}_b$

Possible future scenarios





Blue: measurements of $h \to b\bar{b}$

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The **overlap** can provide **information about the CP nature**