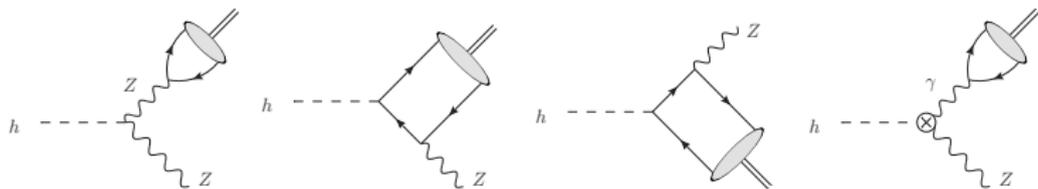# Exclusive Radiative Higgs Decays in the Standard Model and Beyond

Stefan Alte, Johannes Gutenberg-Universität Mainz

Matthias König and Matthias Neubert

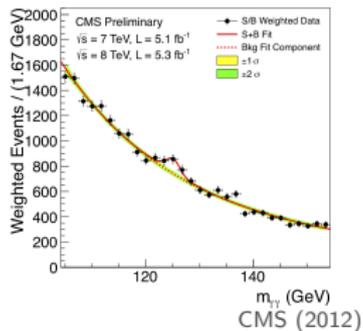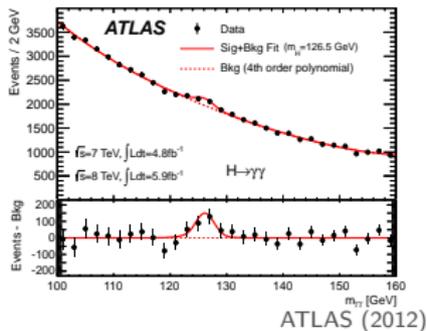HEFT2016, Copenhagen   26 October 2016

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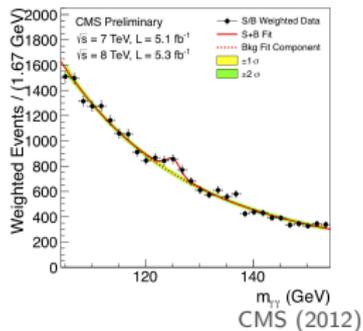
Introduction

Back in the year 2012 ...

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CMS (2012)
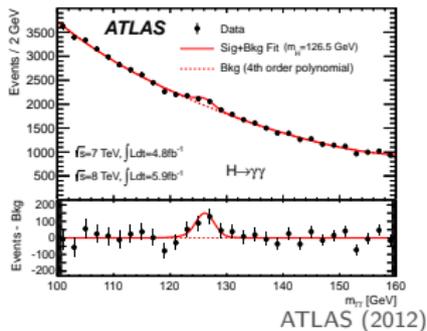
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... the **final piece in the SM puzzle** - the **Higgs boson** - was discovered

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

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

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

$$+ \frac{\alpha}{4\pi v} \left(\kappa_{\gamma\gamma} \, h \, F_{\mu\nu} F^{\mu\nu} - \tilde{\kappa}_{\gamma\gamma} \, h \, F_{\mu\nu} \tilde{F}^{\mu\nu} \right.$$

$$\left. + \frac{2\kappa_{\gamma Z}}{\sin\theta_W \cos\theta_W} \, h \, F_{\mu\nu} Z^{\mu\nu} - \frac{2\tilde{\kappa}_{\gamma Z}}{\sin\theta_W \cos\theta_W} \, h \, F_{\mu\nu} \tilde{Z}^{\mu\nu} \right)$$

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

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$$
\begin{aligned}
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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 ($q \neq t$)** in the decays $h \to M\gamma$ Bodwin et al. (2013); Kagan et al. (2015)
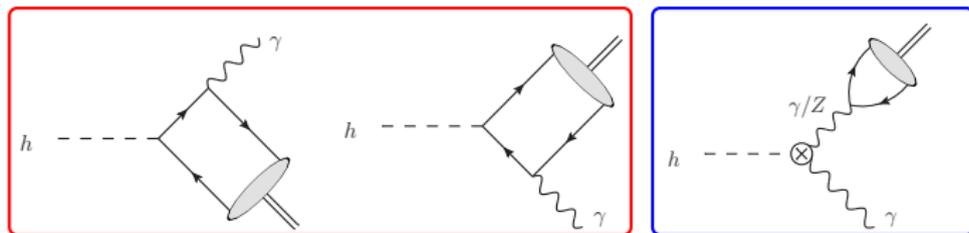
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Current LHC measurements: no strong constraints on the parameters κ_q Kagan et al. (2015); Perez et al. (2015)

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

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

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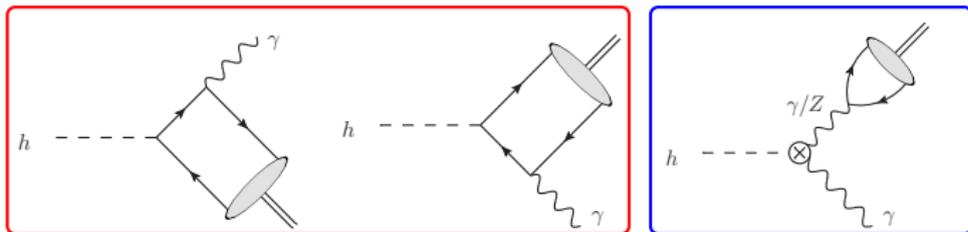
Decay Topologies

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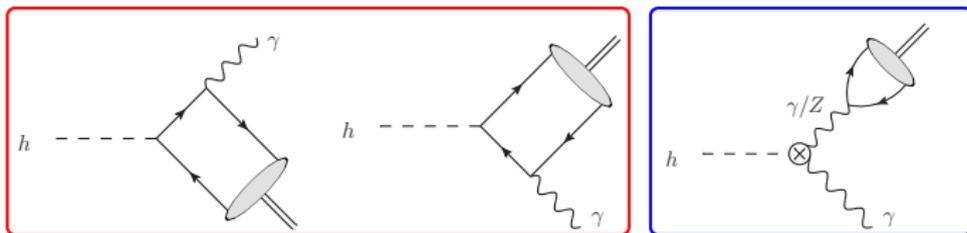
The direct contribution involves κ_q and $\tilde{\kappa}_q$ and is calculated within the
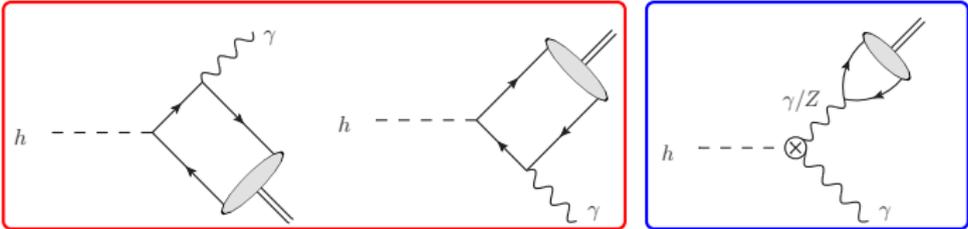**QCD factorisation approach** Brodsky, Lepage (1979); Efremov, Radyushkin (1980); Chernyak, Zhitnitsky (1984)

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The effective vertex includes the **SM contributions** Bergström and Hulth (1985)
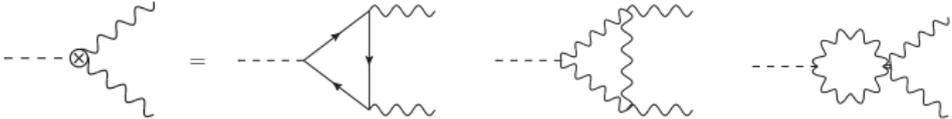
as well as the **NP contributions** $\kappa_{\gamma\gamma}$ and $\kappa_{\gamma Z}$

Decay Amplitude

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

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

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Neglecting numerically small terms, one finds for a J/ψ meson

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

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It is challenging to access $\boldsymbol{\kappa_c}$ since the dominant terms arise from the indirect contribution

Reduction of Theoretical Uncertainties

Need to **know** the indirect contribution **very precisely**

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**Subtract** the indirect contribution **without assuming that SM is correct**

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

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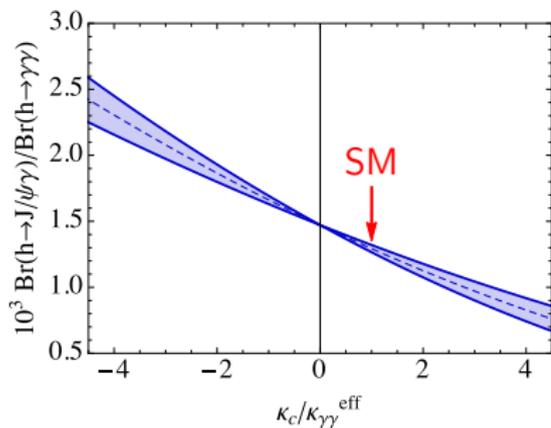
Additional benefit: no dependence on Γ_h

Branching Ratios as Functions of κ_q
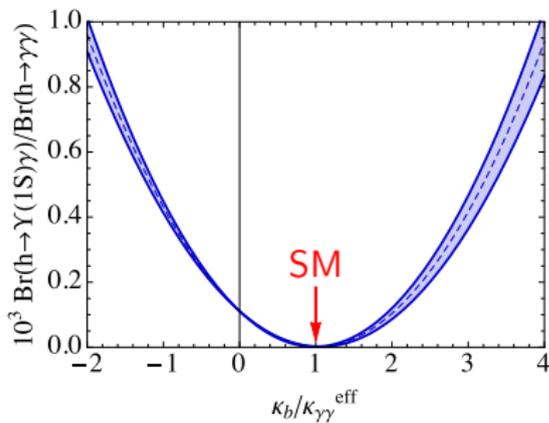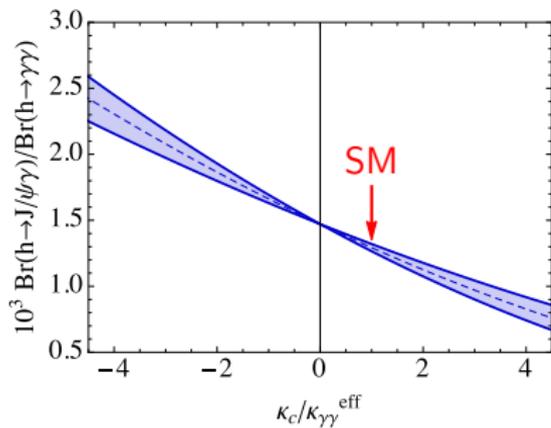
Assumption: **no CP-odd coupling ($\tilde{\kappa}_q \to 0$)**
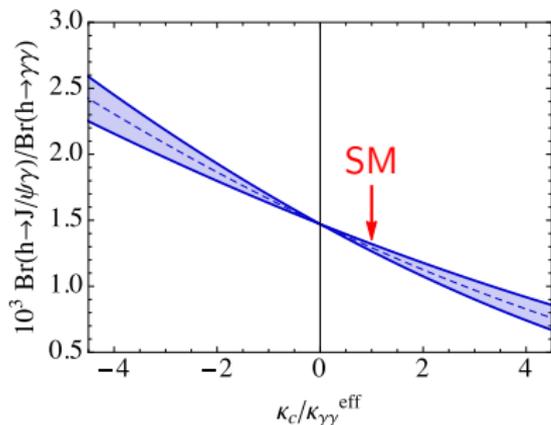
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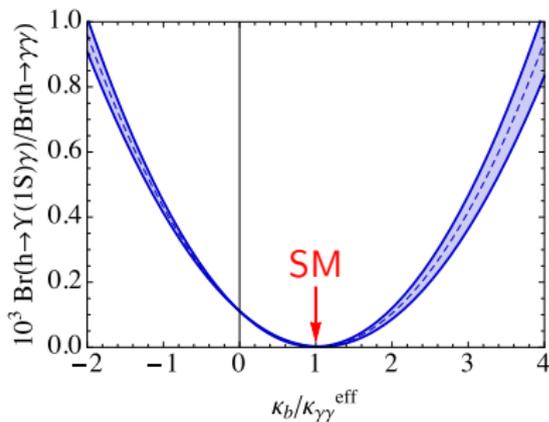
Br($h \to J/\psi\gamma$) exhibits a **mild dependence on κ_c**

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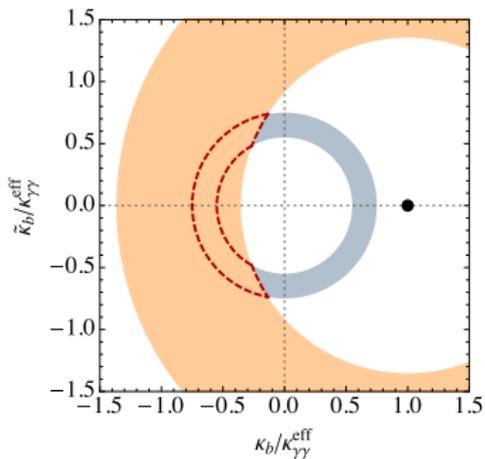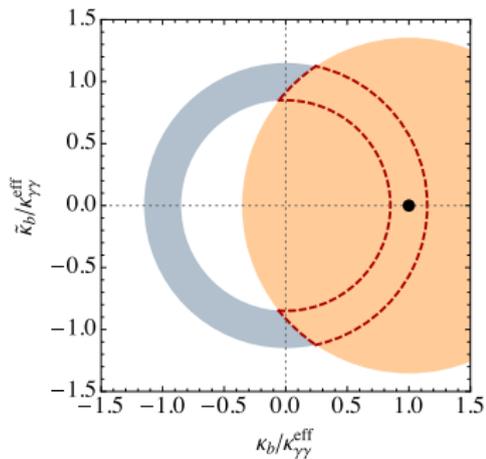Assumption: **no CP-odd coupling ($\tilde{\kappa}_q \to 0$)**
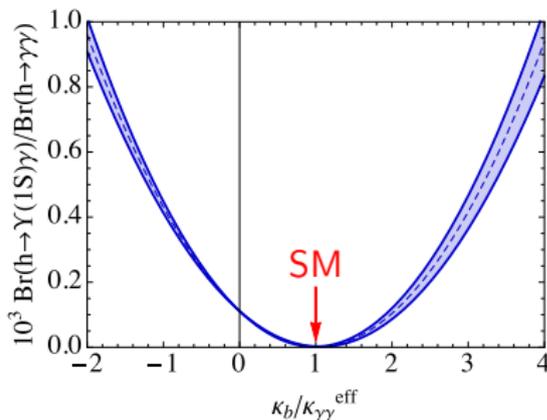
Br($h \to J/\psi\gamma$) exhibits a **mild dependence on κ_c**

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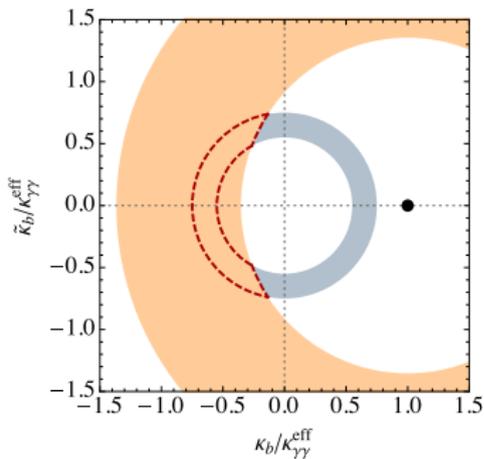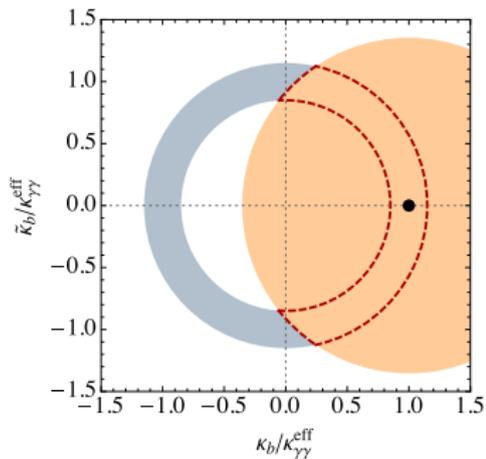
Possible future scenarios

Br($h \rightarrow \Upsilon\gamma$) as Functions of κ_b and $\tilde{\kappa}_b$
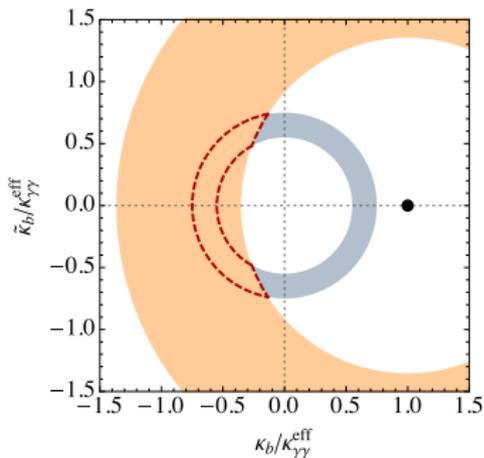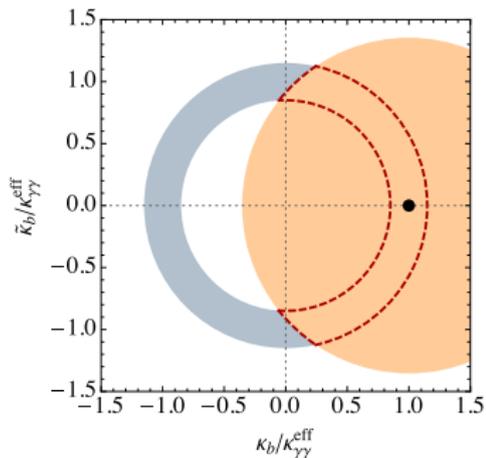
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Blue: measurements of $h \rightarrow b\bar{b}$
Orange: measurements of $h \rightarrow \Upsilon\gamma$

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Blue: measurements of $h \to b\bar{b}$
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The **overlap** can provide **information about the CP nature**

Branching Ratios in the SM

$$\mathrm{BR}(h \to \rho^0 \gamma) = (1.68 \pm 0.02_f \pm 0.08_{h\to\gamma\gamma}) \cdot 10^{-5}$$

$$\mathrm{BR}(h \to \omega\gamma) = (1.48 \pm 0.03_f \pm 0.07_{h\to\gamma\gamma}) \cdot 10^{-6}$$

$$\mathrm{BR}(h \to \phi\gamma) = (2.31 \pm 0.03_f \pm 0.11_{h\to\gamma\gamma}) \cdot 10^{-6}$$

$$\mathrm{BR}(h \to J/\psi\gamma) = (2.95 \pm 0.07_f \pm 0.06_{\mathrm{direct}} \pm 0.14_{h\to\gamma\gamma}) \cdot 10^{-6}$$

$$\mathrm{BR}(h \to \Upsilon(1S)\gamma) = \left(4.61 \pm 0.06_{f}{}^{+1.75}_{-1.21}{}_{\mathrm{direct}} \pm 0.22_{h\to\gamma\gamma}\right) \cdot 10^{-9}$$

$$\mathrm{BR}(h \to \Upsilon(2S)\gamma) = \left(2.34 \pm 0.04_{f}{}^{+0.75}_{-0.99}{}_{\mathrm{direct}} \pm 0.11_{h\to\gamma\gamma}\right) \cdot 10^{-9}$$

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The decays $h \to M\gamma$ are rare in the SM

Exclusive Radiative Decays $h \to MZ$

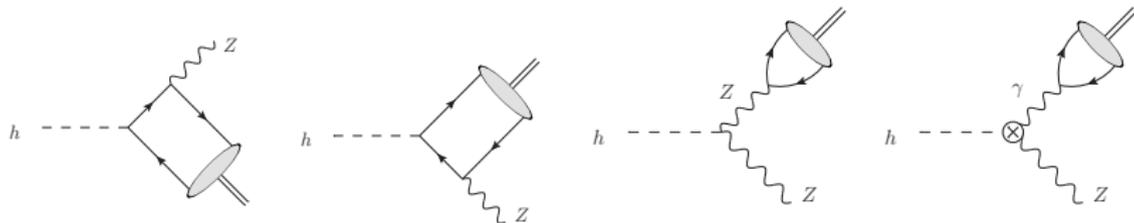Alte, König and Neubert (2016)

Decay Topologies

Previous studies on some decay modes exist Isidori et al. (2014); Gao (2014); Gonzalez-Alonso and Isidori (2014); Modak and Srivastava (2014)
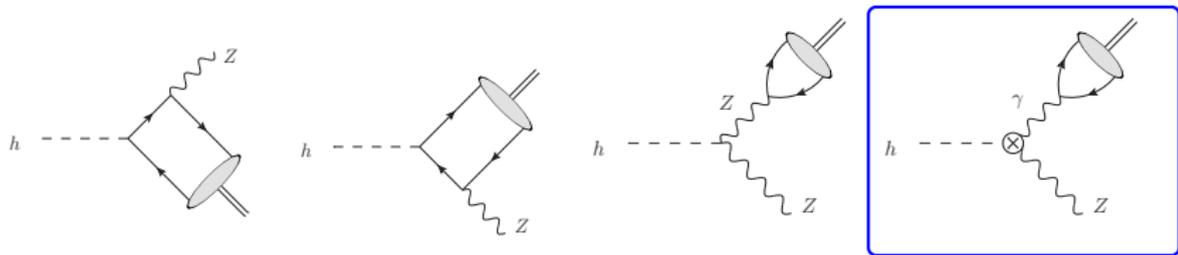
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The **diagram $h \rightarrow Z(\gamma^* \rightarrow M)$** is **loop suppressed** but the off-shellness of the photon yields an **enhancement factor** $\left(\frac{m_h}{m_M}\right)^2$

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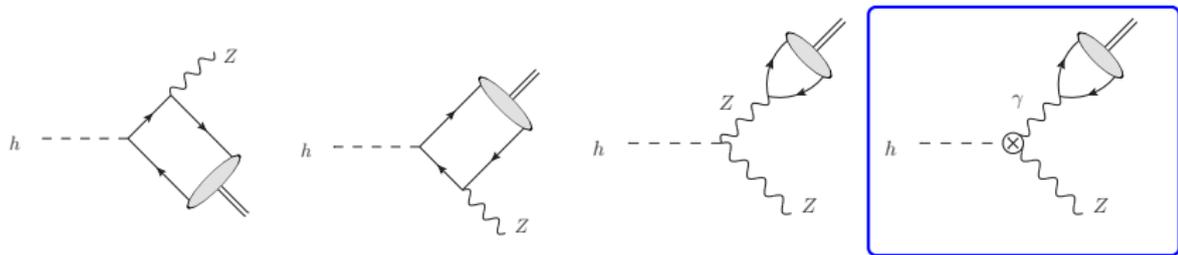Gonzalez-Alonso and Isidori (2014); Modak and Srivastava (2014)

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Decay into **pseudoscalar (P)** or **vector mesons (V)**

Sensitivity to New-Physics Parameters

Pseudoscalar mesons (all units are MeV)

$$F^{\pi^0 Z} \approx 46.1 \, \kappa_Z \qquad F^{\eta Z} \approx 27.7 \, \kappa_Z \qquad F^{\eta' Z} \approx -33.8 \, \kappa_Z$$

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Vector mesons

$$F_\parallel^{J/\psi\, Z} \approx 38.69\,\kappa_Z - 1.75 + 0.73\,\kappa_{\gamma Z}^{\text{eff}}$$

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

The coefficient $\kappa_{\gamma Z}^{\text{eff}}$ parameterises **NP effects in the effective $h\gamma Z$ 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)
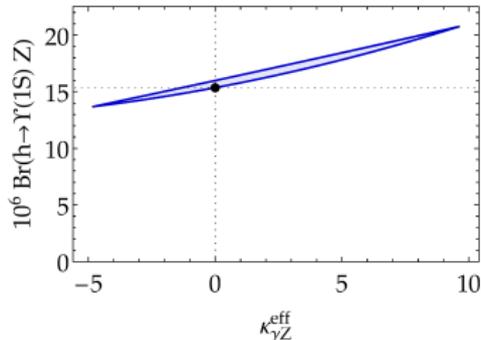
$$\sqrt{\left|\kappa_{\gamma Z}^{\text{eff}} - 2.395\right|^2 + \left|\tilde{\kappa}_{\gamma Z}^{\text{eff}}\right|^2} < 7.2$$
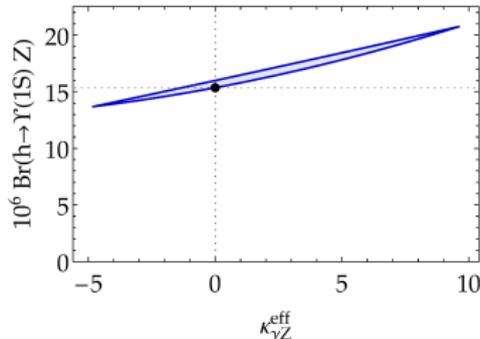
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$\text{Br}(h \to \Upsilon(1S)Z)$ as a function of $\kappa_{\gamma Z}^{\text{eff}}$

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

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

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

Branching Ratios in the Standard Model

Normalised to the **theory prediction for the Higgs width Γ_H:**

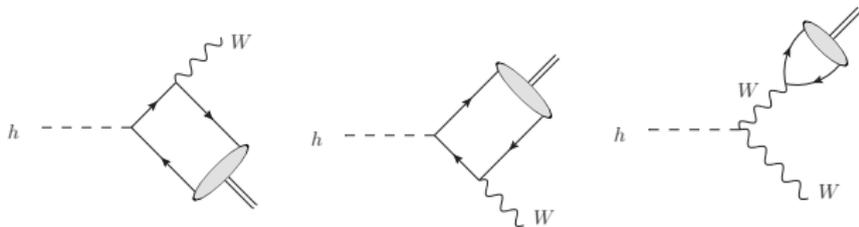| Decay mode	Branching ratio $[10^{-6}]$
$h \to \pi^0 Z$	$2.30 \pm 0.01_f \pm 0.09_{\Gamma_h}$
$h \to \eta Z$	$0.83 \pm 0.08_f \pm 0.03_{\Gamma_h}$
$h \to \eta' Z$	$1.24 \pm 0.12_f \pm 0.05_{\Gamma_h}$
$h \to \rho^0 Z$	$7.19 \pm 0.09_f \pm 0.28_{\Gamma_h}$
$h \to \omega Z$	$0.56 \pm 0.01_f \pm 0.02_{\Gamma_h}$
$h \to \phi Z$	$2.42 \pm 0.05_f \pm 0.09_{\Gamma_h}$
$h \to J/\psi\, Z$	$2.30 \pm 0.06_f \pm 0.09_{\Gamma_h}$
$h \to \Upsilon(1S)\, Z$	$15.38 \pm 0.21_f \pm 0.60_{\Gamma_h}$
$h \to \Upsilon(2S)\, Z$	$7.50 \pm 0.14_f \pm 0.29_{\Gamma_h}$
$h \to \Upsilon(3S)\, Z$	$5.63 \pm 0.10_f \pm 0.22_{\Gamma_h}$

Exclusive Radiative Decays $h \to MW$

Alte, König and Neubert (2016)

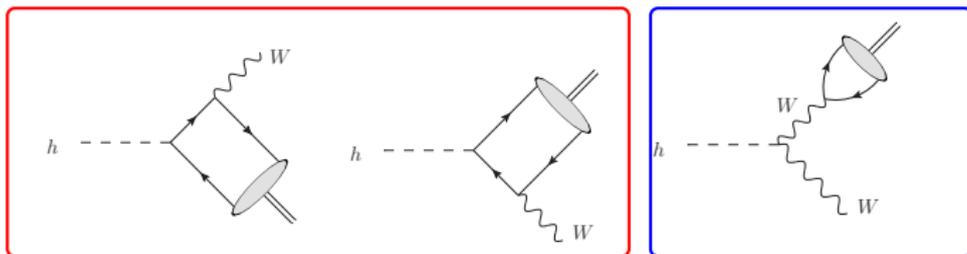**Idea:** access **flavour-changing quark Yukawa** couplings in the decays $h \rightarrow MW$ Kagan et al. (2015)

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Decay Topologies

Idea: access **flavour-changing quark Yukawa** couplings in the decays $h \to MW$ <small>Kagan et al. (2015)</small>

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 $h \to MW$

$$\mathrm{Br}(h \to B^+ W^-) = 1.54 \cdot 10^{-10} \left(\kappa_W^2 + 427 \, \kappa_W \, \mathrm{Re} \, Y_{ut} + 45615 \, |Y_{ut}|^2 \right)$$
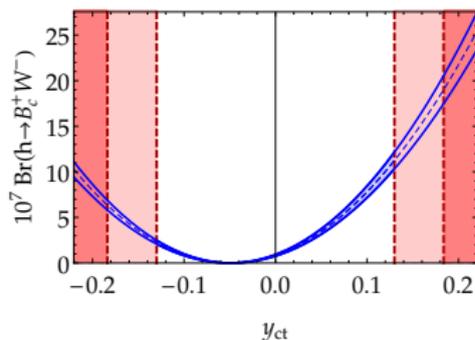
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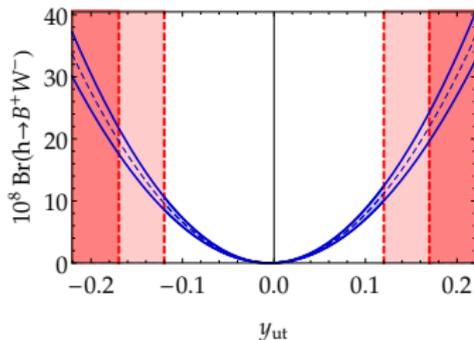
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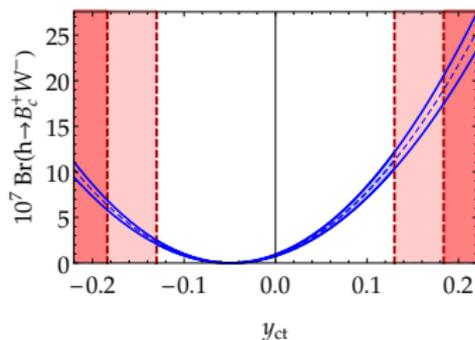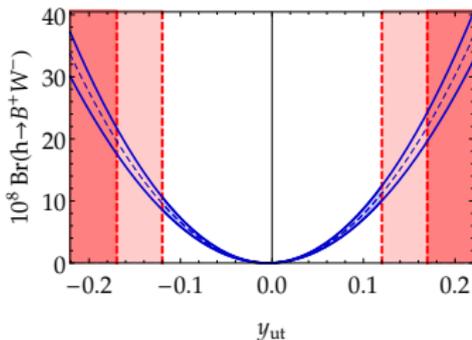
Set $\kappa_W \to 1$ and $\text{Im}(Y_{qt}) \to 0$:

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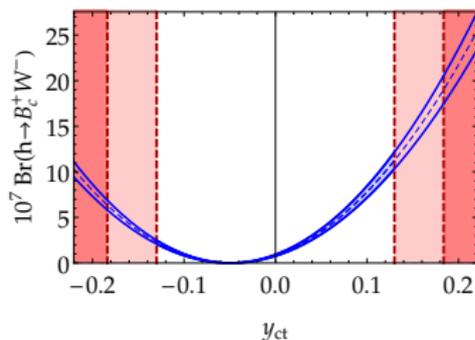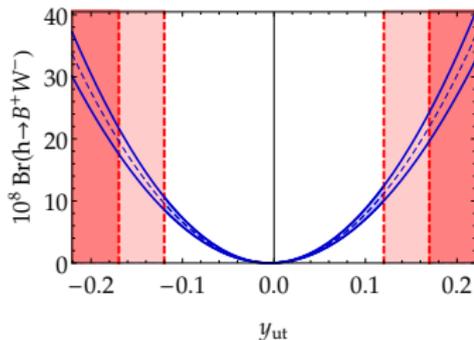

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The dependence on Y_{qt} is strong

Conclusions

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

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

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

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