Exclusive Radiative Higgs Decays as Probes of Light-Quark Yukawa Couplings

Matthias König
Johannes Gutenberg-University Mainz

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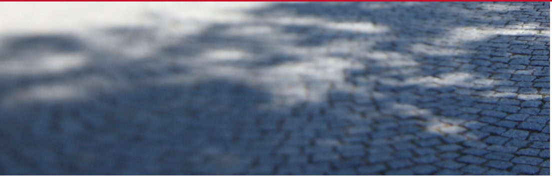

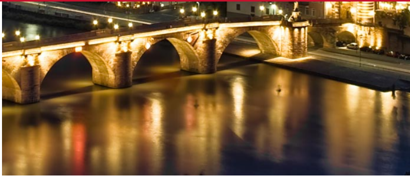

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Precision Physics, Fundamental Interactions and Structure of Matter

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Motivation

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We have a **Higgs**! What now?

On one side, we believe to understand that EWSB is responsible for the particle masses in the SM.

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- RG instability of the Higgs mass if coupled to heavy NP (hierarchy problem)
- Why is the EW symmetry broken in the first place? The Higgs mechanism only gives us the "how", but not the "why".
- Is there a deeper pattern in particle masses and mixings?
- many more! (neutrinos, dark matter, gravity, ...)

Extensions of the SM often involve changes to the Higgs sector: SUSY, nHDM, compositeness, warped extra-dimensions, ...

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Extensions of the SM often involve changes to the Higgs sector:
SUSY, nHDM, compositeness, warped extra-dimensions, ...
$\Rightarrow$ determining the properties of the Higgs is extremely important!

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Especially for flavor physics, the **quark Yukawa couplings** are important:

Higgs couplings seem to be **non-universal** and exhibit a large hierarchy from $y_e = \mathcal{O}(10^{-6})$ to $y_t = \mathcal{O}(1)$ (in the SM).

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Exclusive, radiative hadronic decays of the Higgs can provide new, complementary information on the quark Yukawa couplings. Combined with direct measurements, one might be able to extract more information.

[Isidori, Manohar, Trott (*2013*), Phys. Lett. B 728, 131]

[Bodwin, Petriello, Stoynev, Velasco (*2013*), Phys. Rev. D 88, no. 5, 053003]

[Kagan et al. (*2014*), arXiv:1406.1722]

[Bodwin et al. (*2014*), arXiv:1407.6695]

Motivation

Based on:

Exclusive Radiative Decays of W and Z Bosons in QCD Factorization

Yuval Grossman, MK, Matthias Neubert

JHEP 1504 (2015) 101, arXiv:1501.06569

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Exclusive Radiative Higgs Decays as Probes of Light-Quark Yukawa Couplings

MK, Matthias Neubert

arXiv:1505.03870

Outline

1. QCD factorization
   - A sketch
   - Light cone distributions for mesons

2. Exclusive hadronic decays of the Higgs
   - Two competing topologies
   - Phenomenology

QCD factorization
A sketch

QCD factorization

To calculate the $h \to V\gamma$ decay amplitudes, we deploy a framework called **QCD-factorization**.

[Brodsky, Lepage (*1979*), Phys. Lett. B 87, 359]

[Efremov, Radyushkin (*1980*), Theor. Math. Phys. 42, 97]

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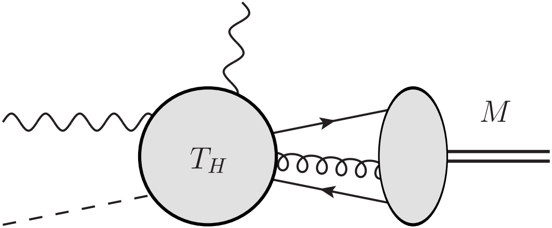

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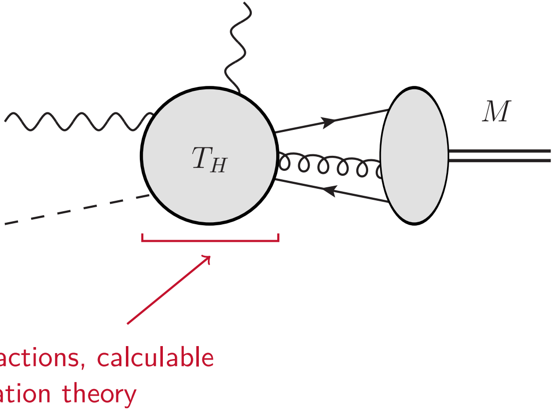

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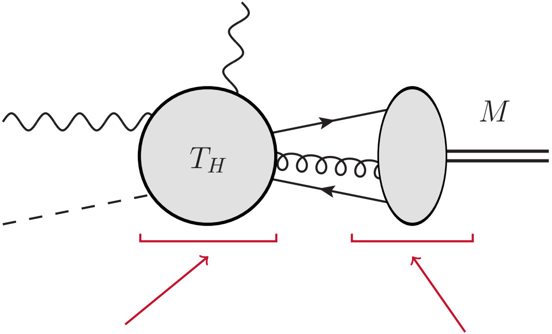

Hard interactions, calculable in perturbation theory

Non-perturbative physics, hadronic input parameters from lattice/sum-rules/HQET/NRQCD(/experiment)

The **amplitude** will be **organized into** a **series expansion** in the small parameter

$$\lambda = \frac{\Lambda_{\mathrm{QCD}}}{\mu_H}$$

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In the case of $h \to V\gamma$, the hard scale is set by m_h and **power-corrections are definitely under control**.

QCD factorization

Light cone distributions for mesons

Gegenbauer expansion of the LCDAs

- The leading-twist LCDA $\phi_M(x,\mu)$ can be interpreted as the amplitude for finding a quark with longitudinal momentum fraction x and the anti-quark with momentum $\bar{x} = 1 - x$

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$$\langle P(k)|\, \bar{q}(t\bar{n}) \frac{\bar{\not{n}}}{2} \gamma^5 \, [t\bar{n}, 0] \, q(0) \, |0\rangle = -i f_M E \int_0^1 dx \, e^{ixt\bar{n}\cdot k} \phi_M(x,\mu)$$

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- For light mesons information about the LCDAs has to be extracted from lattice QCD or sum rules. For mesons containing a heavy quark (or for heavy quarkonia), this can be addressed with HQET (or NRQCD).

Gegenbauer expansion of the LCDAs

We expand the LCDAs in the basis of Gegenbauer polynomials:

$$\phi_M(x,\mu) = 6x(1-x)\left[1 + \sum_{n=1}^{\infty} a_n^M(\mu)\, C_n^{(3/2)}(2x-1)\right]$$

where $C_n^{(\alpha)}(x)$ are the Gegenbauer polynomials. The scale-dependence of the LCDA is in the Gegenbauer moments $a_n^M(\mu)$

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$\rightarrow$ RG evolution important AND works in our favor

RG evolution of the LCDAs

- The Gegenbauer expansion yields a diagonal scale-evolution of the coefficients:

$$a_n^M(\mu) = \left(\frac{\alpha_s(\mu)}{\alpha_s(\mu_0)}\right)^{\gamma_n/2\beta_0} a_n^M(\mu_0)$$

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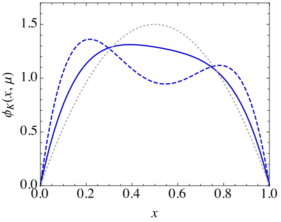
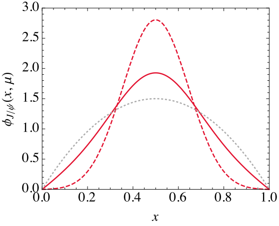
- Every anomalous dimension γ_n is strictly positive

$$\Rightarrow a_n^M(\mu \to \infty) \to 0$$
$$\Rightarrow \phi_M(x, \mu \to \infty) \to 6x(1-x)$$

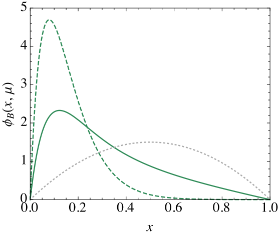
RG evolution of the LCDAs



a) K LCDA

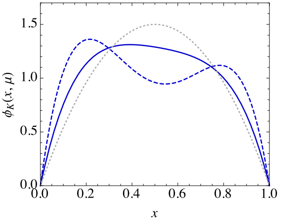


b) J/ψ LCDA



c) B LCDA

LCDAs for mesons at different scales, dashed lines: $\phi_M(x, \mu = \mu_0)$, solid lines: $\phi_M(x, \mu = m_Z)$, grey dotted lines: $\phi_M(x, \mu \to \infty)$



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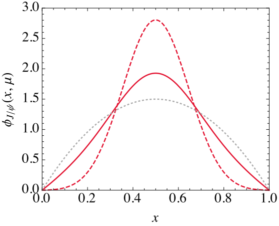

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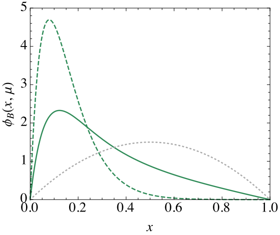

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At high scales compared to Λ_{QCD} (e.g. $\mu \sim m_Z$) the sensitivity to poorly-known a_n^M is greatly reduced!

Exclusive hadronic decays of the Higgs

Two competing topologies

The $h \to V\gamma$ decays

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$$+ \frac{\alpha}{4\pi v} \left(\kappa_{\gamma\gamma} h F_{\mu\nu} F^{\mu\nu} - \tilde{\kappa}_{\gamma\gamma} h F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{2\kappa_{\gamma Z}}{s_W c_W} h F_{\mu\nu} Z^{\mu\nu} - \frac{2\tilde{\kappa}_{\gamma Z}}{s_W c_W} h F_{\mu\nu} \tilde{Z}^{\mu\nu} \right)$$

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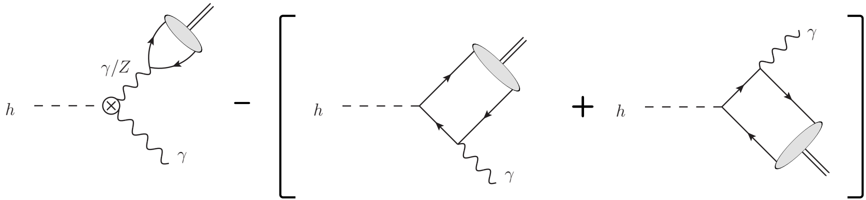
$\rightarrow$ Provides a model independent analysis of NP effects in $h \to V\gamma$ decays!

Several different diagram topologies:



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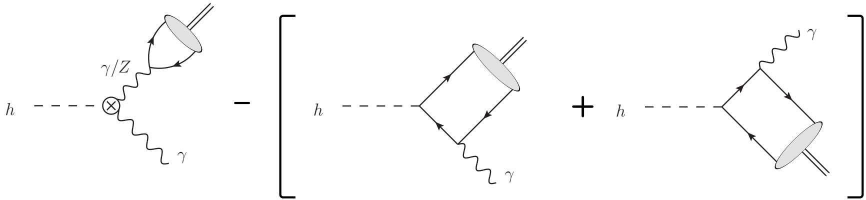

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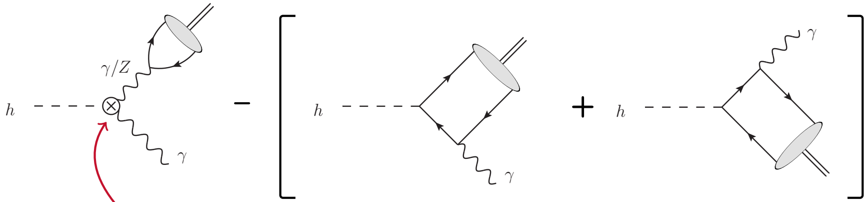

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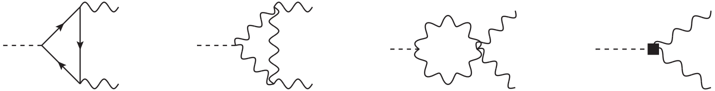

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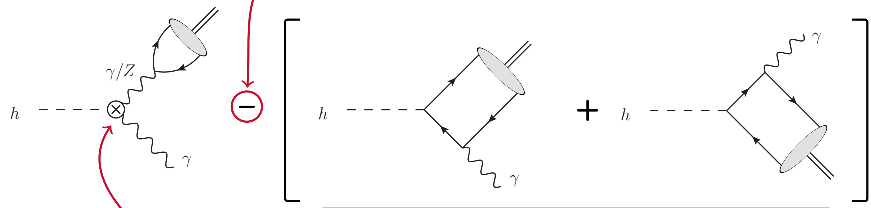
destructive interference!



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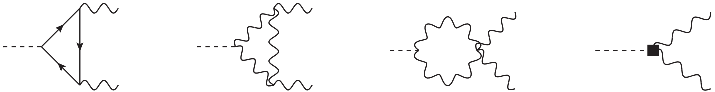

The $h \to V\gamma$ decays

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

Contributions from both diagram topologies, the **direct** contributions $(h \to (q\bar{q} \to V)\gamma)$ and the **indirect** contributions $(h \to (Z/\gamma \to M)\gamma)$.

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$$\mathrm{Re}\, I_V(m_h) = 1.01 + 1.13a_2^{V\perp}(m_h) + 1.21a_4^{V\perp}(m_h) + 1.29a_6^{V\perp}(m_h) + \ldots$$

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Reduces uncertainty from hadronic input parameters!

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with

$$C_{\gamma\gamma}(x) = \sum_q \kappa_q \frac{2 N_c Q_q^2}{3} A_f(\tau_q, x) + \sum_l \kappa_l \frac{2 Q_l^2}{3} A_f(\tau_l, x) - \frac{\kappa_W}{2} A_W^{\gamma\gamma}(\tau_W, x) + \kappa_{\gamma\gamma}$$

[Bergström, Hulth (*1985*), Nucl. Phys. B 259, 137]

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sums over **all** massive fermions

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Can be written as:

$$F_{1,\text{indirect}}^{V} \propto \left[Q_V \, C_{\gamma\gamma}(m_V^2/m_h^2) - \frac{v_V}{(s_W c_W)^2} \frac{m_V^2}{m_Z^2 - m_V^2} C_{\gamma Z}(m_V^2/m_Z^2) \right]$$

with

$$C_{\gamma\gamma}(x) = \boxed{\sum_q \kappa_q} \frac{2N_c Q_q^2}{3} A_f(\tau_q, x) + \boxed{\sum_l \kappa_l} \frac{2Q_l^2}{3} A_f(\tau_l, x) - \frac{\kappa_W}{2} A_W^{\gamma\gamma}(\tau_W, x) + \kappa_{\gamma\gamma}$$

[Bergström, Hulth (*1985*), Nucl. Phys. B 259, 137]

sums over **all** massive fermions

There could be NP in any of these contributions leading to deviations from the SM prediction for our amplitudes!

The $h \to V\gamma$ decays

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corrections from the indirect contributions due to off-shellness

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$\to$ only very weak sensitivity to the indirect contributions!

Exclusive hadronic decays of the Higgs
Phenomenology

Nummerical results

JG|U

Assuming SM couplings of all particles, we find:

$$\mathrm{BR}(h \to \rho^0\gamma) = (1.68 \pm 0.02_f \pm 0.08_{h\to\gamma\gamma}) \cdot 10^{-5}$$
$$\mathrm{BR}(h \to \omega\gamma) = (1.48 \pm 0.03_f \pm 0.07_{h\to\gamma\gamma}) \cdot 10^{-6}$$
$$\mathrm{BR}(h \to \phi\gamma) = (2.31 \pm 0.03_f \pm 0.11_{h\to\gamma\gamma}) \cdot 10^{-6}$$
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$$\mathrm{BR}(h \to \Upsilon(2S)\gamma) = \left(2.34 \pm 0.04_f{}^{+0.75}_{-0.99}{}_{\mathrm{direct}} \pm 0.11_{h\to\gamma\gamma}\right) \cdot 10^{-9}$$
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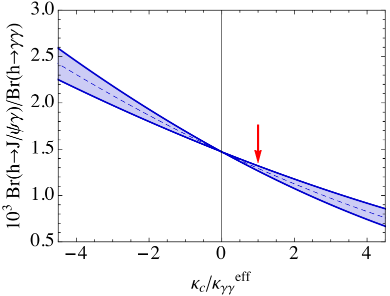
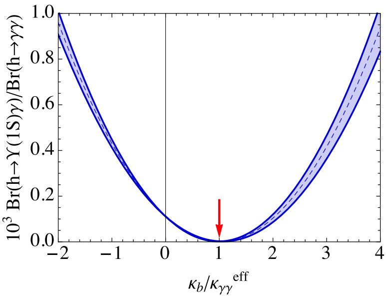
A **general feature**: $h \to V\gamma$ decays are **rare**.

But: What is wrong with the Υ-channels?

Allowing deviations of the κ_q and no CP-odd couplings:



Ratio of BR for J/ψ



Ratio of BR for $\Upsilon(1S)$

Phenomenology

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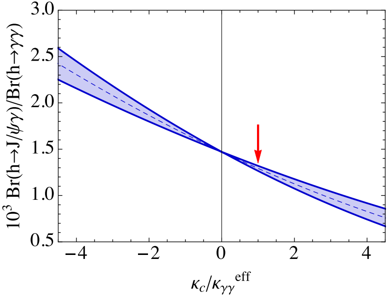

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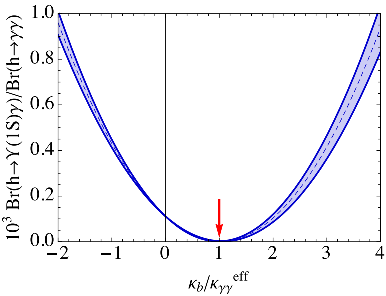
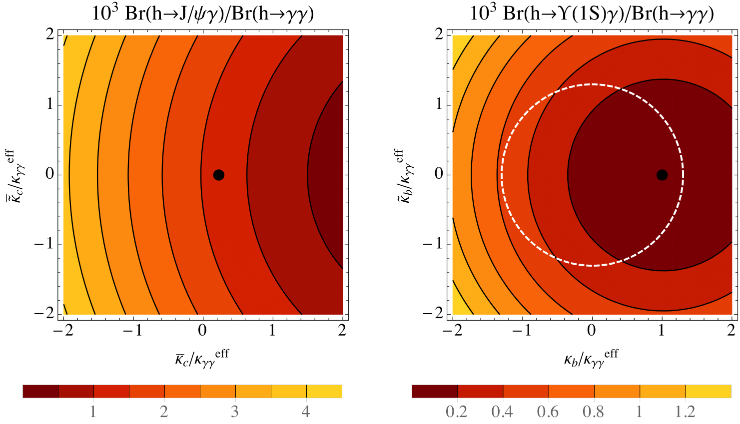


Ratio of BR for $\Upsilon(1S)$

Usually, the **indirect contributions** are the **dominant** ones, however **for the Υ**, the **direct contribution** is **comparable**, leading to a **cancellation** between the two.

$\Rightarrow$ This leads to a **strong sensitivity to NP effects**!

Allowing CP-odd couplings as well:



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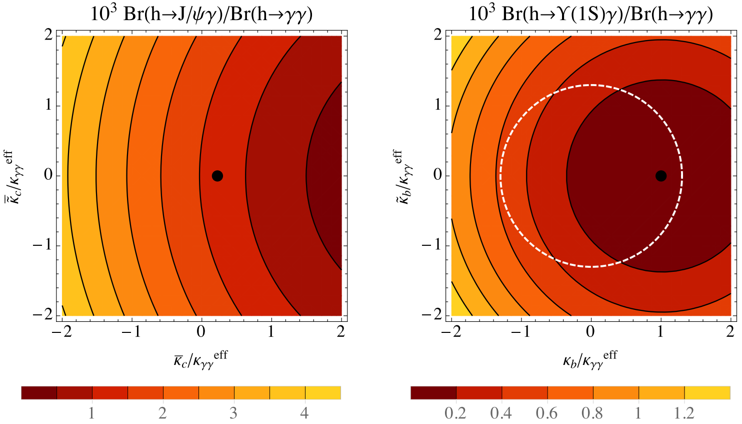
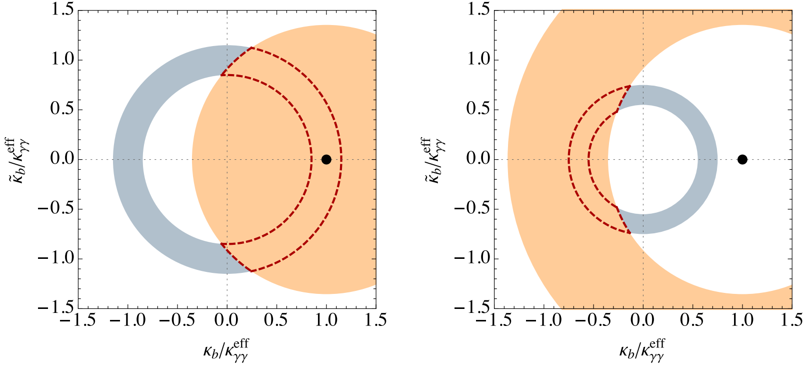


Measuring a BR gives us complementary information on $\overset{(\sim)}{\kappa}_q$!

Phenomenology

Possible future scenarios:



Blue circles: direct measurements of $h \to q\bar{q}$ constrain $\kappa_q^2 + \tilde{\kappa}_q^2$
Red circles: measurements of $h \to \Upsilon\gamma$ constrain $(1-\kappa_q)^2 + \tilde{\kappa}_q^2$

$\Rightarrow$ From the overlap one find information on the CP-odd coupling as well as the overall size of the CP-even coupling!

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- The HL-LHC run will deliver higher statistics, a possible future 100 TeV collider can serve as a Higgs factory
- Decays to lighter mesons harder to reconstruct, efficiency of $\epsilon_{\phi\gamma} = 0.75$ has been estimated

[Kagan et al. (*2014*), arXiv:1406.1722]

Conclusions

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Thank you for your attention!

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