Very Rare, Exclusive Higgs Decays in QCD Factorization

Matthias König
THEP, Johannes Gutenberg-University (Mainz)

Higgs Hunting
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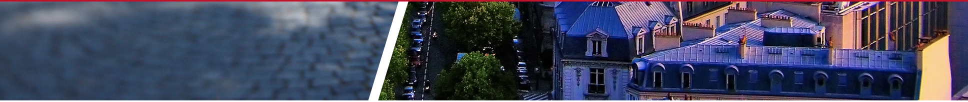

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Hunting the Higgs

We did hunt the Higgs successfully and we **consider the SM to be completed**.

While it does describe observation nicely, the Higgs sector has an **unsatisfactory amount of free parameters**.

Many open questions are linked to the question whether these parameters are just what they are or **can be predicted from a more fundamental principle**.

The premise for new physics searches nowadays: **Leave no stone unturned!**

Exclusive hadronic decays can serve as probes for new physics, revealing more information when combined with "more conventional" searches!

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

Exclusive Radiative Z-Boson Decays to Mesons with Flavor-Singlet Components
Stefan Alte, MK, Matthias Neubert

JHEP 1602 (2016) 162, arXiv:1512.09135

Exclusive Radiative Higgs Decays as Probes of Light-Quark Yukawa Couplings
MK, Matthias Neubert

JHEP 1508 (2015) 012, arXiv:1505.03870

Exclusive Weak Radiative Higgs Decays and Flavor-Changing Higgs-Top Couplings
Stefan Alte, MK, Matthias Neubert

arXiv:160x.soon

Outline

QCD-factorization
The factorization formula

History

The framework of QCD factorization was originally developed by Brodsky, Efremov, Lepage and Radyushkin in the beginning of the 1980's.

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

[Brodsky, Lepage (*1980*), Phys. Rev. D 22, 2157]

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

[Efremov, Radyushkin (*1980*), Phys. Lett. B 94, 245]

The factorization formula was **derived using light-cone perturbation theory**.

The derivation **can also be phrased in** the language of **soft-collinear effective theory**.

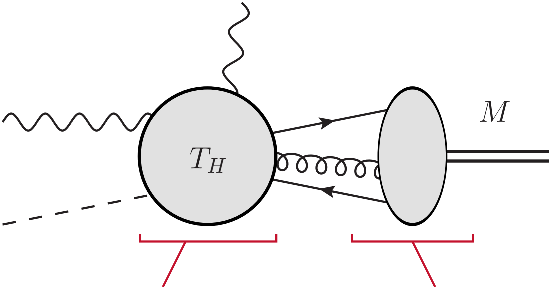
[Bauer et al. (*2001*), Phys. Rev. D 63, 114020]

[Bauer Pirjol, Stewart (*2002*), Phys. Rev. D 65, 054022]

[Beneke, Chapovsky, Diehl, Feldmann (*2002*), Nucl. Phys. B 643, 431]

An effective theory approach

QCD factorization: The **hadronization** happens well **after the hard scattering has taken place** → separation of scales.



Hard interactions, calculable in perturbation theory

Non-perturbative physics, hadronic input

The **scale separation** in the case at hand **calls for an effective theory** description!

The factorization formula

The amplitude can now be written as:

$$i\mathcal{A} = \int \mathcal{C}(t,\dots)\langle M(k)|\, J_q(t,\dots)\,|0\rangle dt$$
$$= \int T_H(x,\mu)\,\phi_M(x,\mu)\,dx$$

The **hadronic matrix element** defines the light-cone distribution amplitude **(LCDA)**, which encodes the non-perturbative physics.

The **Wilson coefficients** $\mathcal{C}$ contain the hard scattering processes that are integrated out at the factorization scale.

The **LCDAs** are expanded in **Gegenbauer polynomials**:

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

$a_n^M(\mu)$: scale-dependent expansion coefficients

Large logarithms $\alpha_s \log \mu_H/\Lambda_{\mathrm{QCD}}$ are **resummed** through renormalization group evolution.

Hadronic Higgs decays
Radiative hadronic Higgs decays

Idea: Use hadronic Higgs decays to probe non-standard Higgs couplings.

[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]

Light quark Yukawa couplings could **differ significantly from the SM** prediction, this is still **compatible with observation**!

Work with the effective Lagrangian:

$$\mathcal{L}_{\text{eff}}^{\text{Higgs}} = \kappa_W \frac{2m_W^2}{v} h W_\mu^+ W^{-\mu} + \kappa_Z \frac{m_Z^2}{v} h Z_\mu Z^\mu - \sum_f \frac{m_f}{v} h \bar{f} \left(\kappa_f + i\tilde{\kappa}_f \gamma_5\right) f$$

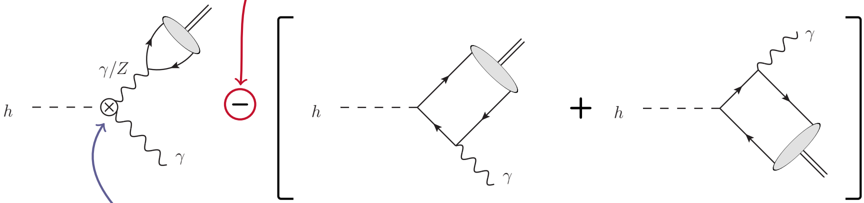
$$+ \frac{\alpha}{4\pi v} \left(\kappa_{\gamma\gamma} h F_{\mu\nu} F^{\mu\nu} - \tilde{\kappa}_{\gamma\gamma} h F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{2\kappa_{\gamma Z}}{s_W c_W} h F_{\mu\nu} Z^{\mu\nu} - \frac{2\tilde{\kappa}_{\gamma Z}}{s_W c_W} h F_{\mu\nu} \tilde{Z}^{\mu\nu} \right)$$

blue terms: $\to 1$ in SM, **red terms**: $\to 0$ in SM!

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

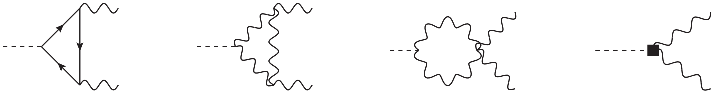
Several different diagram topologies:

destructive interference!

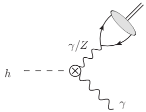


directly proportional to κ_q and $\tilde{\kappa}_q$

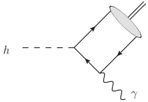
Contains contributions to $h \to (Z/\gamma)^*\gamma$, both SM and NP



We want to probe the **Higgs couplings to light fermions**. The indirect contributions however are **sensitive to many other couplings**, like $\kappa_{\gamma\gamma}$, $\kappa_{Z\gamma}$, κ_W, $\kappa_f \ldots$



In most cases, **these contributions dominate** over the direct contributions due to the small Yukawa couplings.



We **normalize the branching ratio to the $h \to \gamma\gamma$ branching ratio**, which also makes our prediction insensitive to the total Higgs width:

$$\frac{\mathrm{BR}(h \to V\gamma)}{\mathrm{BR}(h \to \gamma\gamma)} = \frac{\Gamma(h \to V\gamma)}{\Gamma(h \to \gamma\gamma)} = \frac{8\pi\alpha^2(m_V)}{\alpha} \frac{Q_V^2 f_V^2}{m_V^2} \left(1 - \frac{m_V^2}{m_h^2}\right)^2 |1 - \kappa_q \Delta_V$$

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

this contains the direct amplitude!

corrections from the indirect contributions due to off-shellness

Assuming SM couplings of all particles, we find:

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

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

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

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

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

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

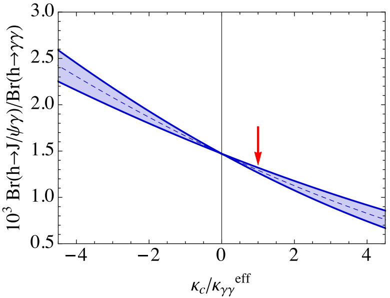
$$\mathrm{BR}(h \to \Upsilon(3S)\gamma) = \left(2.13 \pm 0.04_f\,{}^{+0.75}_{-1.12}{}_{\mathrm{direct}} \pm 0.10_{h\to\gamma\gamma}\right) \boxed{\cdot 10^{-9}}$$

A **general feature**: $h \to V\gamma$ decays are **rare**.

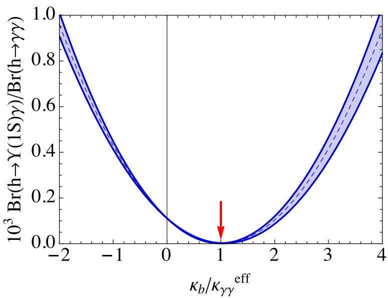
But: What is wrong with the Υ-channels?

Phenomenology

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



Ratio of BR for J/ψ

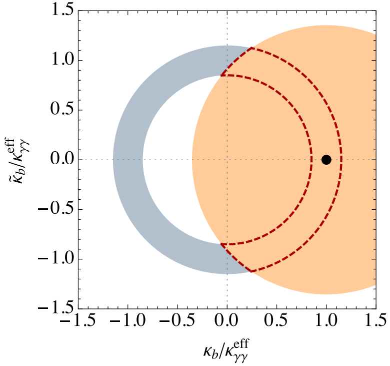


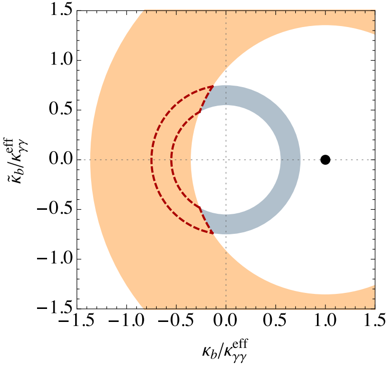
Ratio of BR for $\Upsilon(1S)$

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**!

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 can find information on the CP-odd coupling, **even the sign** of the CP-even coupling!

Hadronic Higgs decays
Weak radiative hadronic Higgs decays

Higgs decay to a meson and a Z-boson

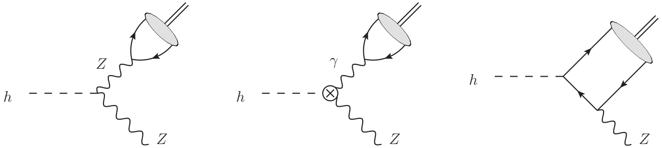
For select mesons, literature exists on these modes.

[Isidori, Manohar, Trott (*2014*), Phys.Lett. B728 131-135]

[Gao (*2014*), Phys.Lett. B737 366-368]

[Modak, Srivastava (*2014*), 1411.2210]

There are three contributions:



While the diagrams $h \to Z(\gamma^* \to V)$ are **loop-suppressed**, the photon is off-shell only by m_V^2, **lifting** the **suppression**.

The indirect diagrams **interfere destructively**, enhancing the **sensitivity to the effective coupling** $\kappa_{\gamma Z}$. $(\mathcal{O} \sim hF_{\mu\nu}Z^{\mu\nu})$

The direct contributions are only important for **heavy quarkonia**.

The bound on $\kappa_{\gamma Z}$ from CMS is:

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

From this we get (for SM and for saturated bounds):

Mode	SM Branching ratio $[10^{-6}]$	NP range
$h \to \pi^0 Z$	$(2.30 \pm 0.01_f \pm 0.09_\Gamma)$	
$h \to \eta Z$	$(0.83 \pm 0.08_f \pm 0.03_\Gamma)$	
$h \to \eta' Z$	$(1.24 \pm 0.12_f \pm 0.05_\Gamma)$	
$h \to \rho^0 Z$	$(7.19 \pm 0.09_f \pm 0.28_\Gamma)$	1.83 – 53.3
$h \to \omega Z$	$(0.56 \pm 0.01_f \pm 0.02_\Gamma)$	0.06 – 4.56
$h \to \phi Z$	$(2.42 \pm 0.05_f \pm 0.09_\Gamma)$	1.77 – 9.12
$h \to J/\psi Z$	$(2.30 \pm 0.06_f \pm 0.09_\Gamma)$	1.59 – 13.10
$h \to \Upsilon(1S) Z$	$(15.38 \pm 0.21_f \pm 0.60_\Gamma)$	13.7 – 20.8
$h \to \Upsilon(2S) Z$	$(7.50 \pm 0.14_f \pm 0.29_\Gamma)$	
$h \to \Upsilon(3S) Z$	$(5.63 \pm 0.10_f \pm 0.22_\Gamma)$	

Conclusions

Conclusions

- Exclusive **hadronic decays of heavy electroweak bosons** are an interesting application of the QCD factorization approach in a **theoretically clean** environment due to the **high factorization scale** (power corrections tiny, RGE suppresses hadronic parameters).
- Hadronic decays of the Higgs exhibit **interesting dependences on Higgs couplings**, due to the **interplay of different diagrams**.
- Radiative decays $h \to M\gamma$ can **probe Yukawa couplings along with CP phases** and not just the absolute value.
- Weak radiative decays $h \to MZ$ are **sensitive to the coupling of the effective operator** $hF_{\mu\nu}Z^{\mu\nu}$.
- The **downside** are the **small branching ratios** which make these modes **challenging**. But **HL-LHC** should be able to see some of them and we don't know what kind of **machine** the **future** brings...