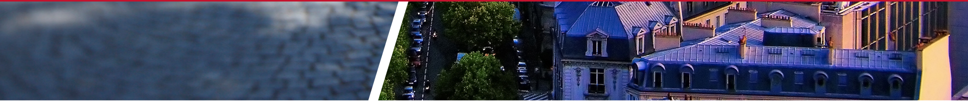
Very Rare, Exclusive Higgs Decays in QCD Factorization

Matthias König
THEP, Johannes Gutenberg-University (Mainz)

Higgs Hunting
Paris, 31 August, 2016



PRiSMA
Cluster of Excellence
Precision Physics, Fundamental Interactions and Structure of Matter

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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]

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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** $\rightarrow$ separation of scales.

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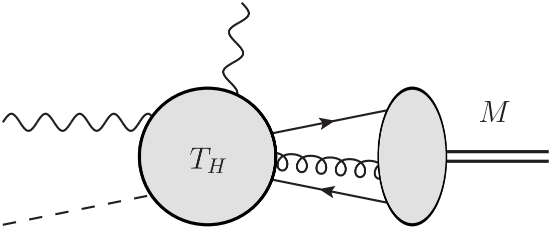

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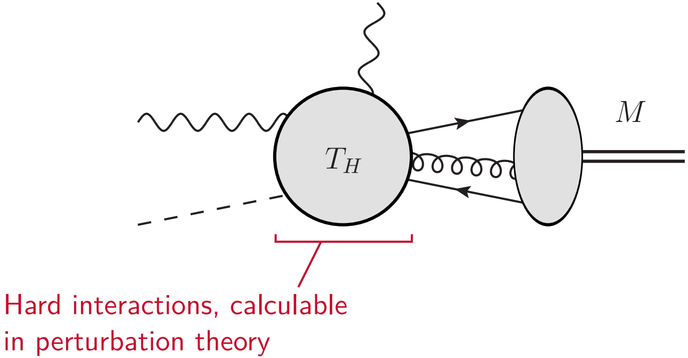

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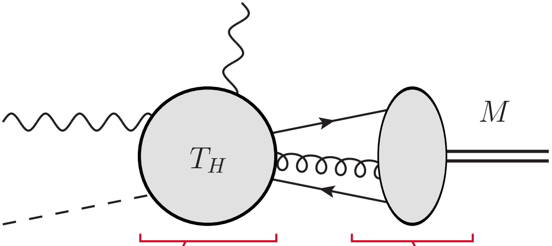

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Non-perturbative physics, hadronic input

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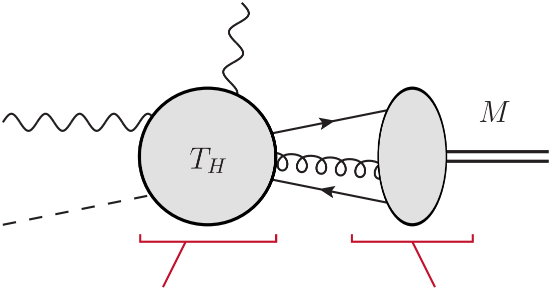

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The **scale separation** in the case at hand **calls for an effective theory** description!

The factorization formula

The amplitude can now be written as:

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

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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

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Large logarithms $\alpha_s \log \mu_H/\Lambda_{\text{QCD}}$ 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]
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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!

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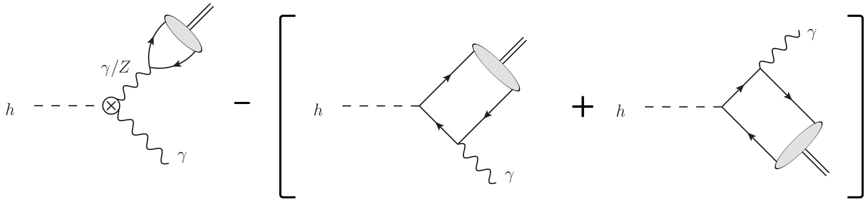
$\to$ Provides a model independent analysis of NP effects in $h \to V\gamma$ decays!

Several different diagram topologies:



The $h \to V\gamma$ decays

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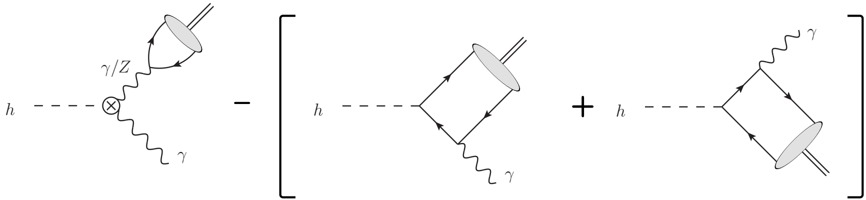

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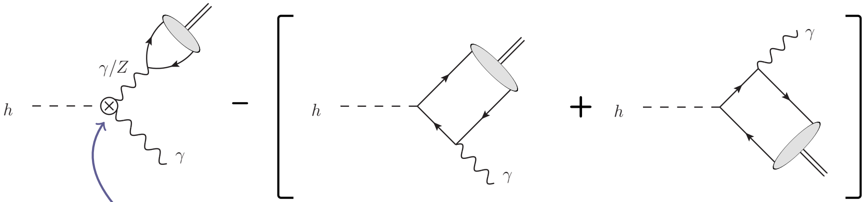

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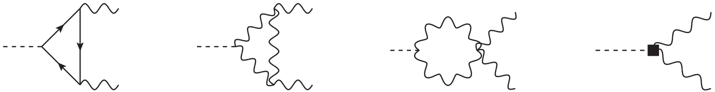
Contains contributions to $h \to (Z/\gamma)^*\gamma$, both SM and NP



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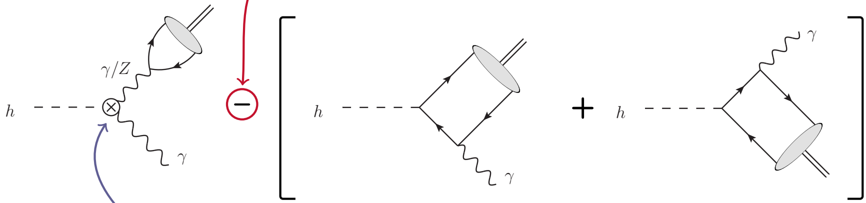
destructive interference!



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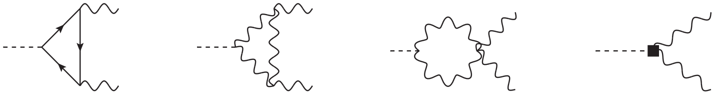
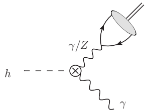


We want to probe the **Higgs couplings to light fermions**. The indirect contributions however are **sensitive to many other couplings**, like $\kappa_{\gamma\gamma}$, $\kappa_{Z\gamma}$, κ_W, κ_f...



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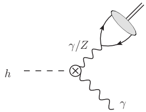

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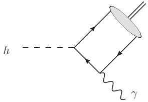

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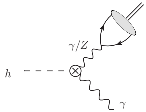

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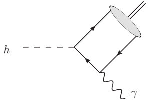

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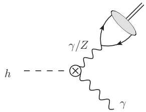

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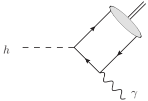

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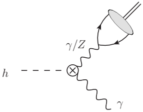

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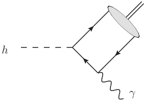

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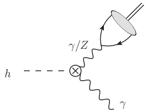

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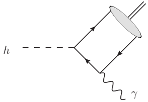

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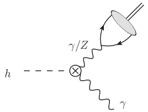

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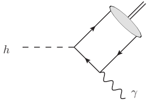

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this contains the direct amplitude! ($\kappa_q \Delta_V$)

corrections from the indirect contributions due to off-shellness (δ_V)

The $h \to V\gamma$ decays

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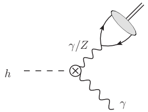

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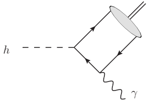

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$\to$ only very weak sensitivity to the indirect contributions!

Nummerical results

Assuming SM couplings of all particles, we find:

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

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

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$$\mathrm{BR}(h \to \Upsilon(1S)\gamma) = \left(4.61 \pm 0.06_f {}^{+1.75}_{-1.21}{}_{\mathrm{direct}} \pm 0.22_{h\to\gamma\gamma}\right) \cdot 10^{-9}$$
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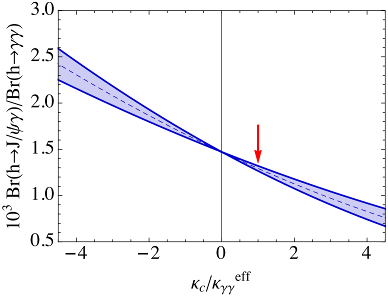
A **general feature**: $h \to V\gamma$ decays are **rare**.

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

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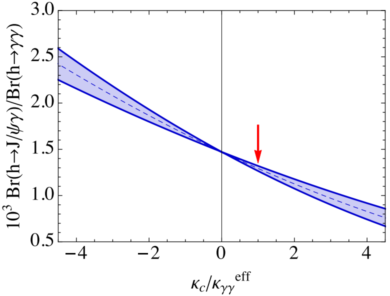

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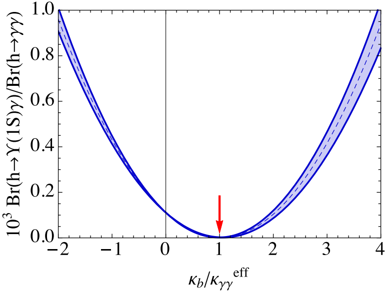
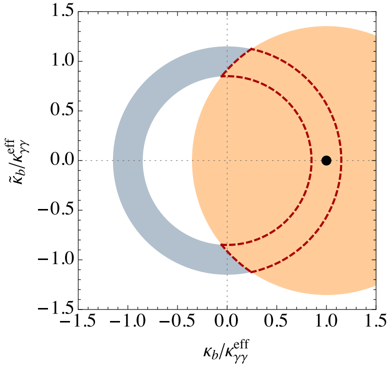


Ratio of BR for $\Upsilon(1S)$

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

⇒ This leads to a **strong sensitivity to NP effects**!

Possible future scenarios:



Blue circles: direct measurements of $h \to q\bar{q}$ constrain $\kappa_q^2 + \tilde{\kappa}_q^2$

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Phenomenology

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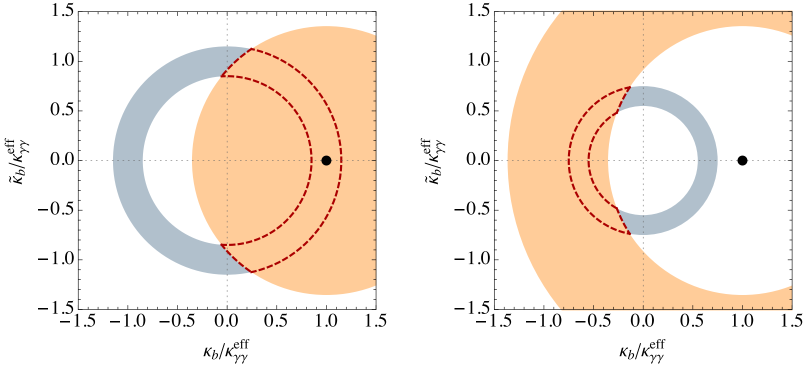

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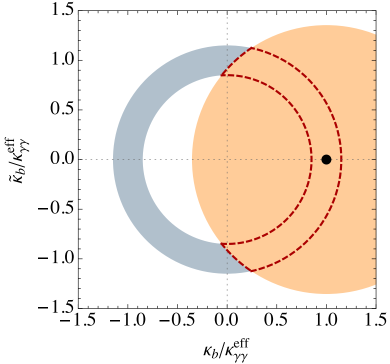

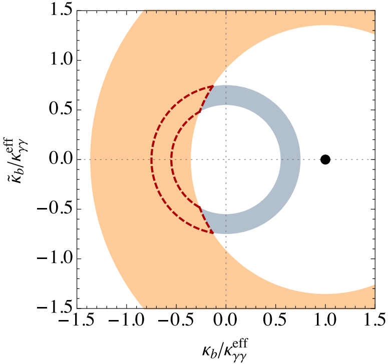

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$\Rightarrow$ From the **overlap** one can find information on the CP-odd coupling, **even the sign** of the CP-even coupling!

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]

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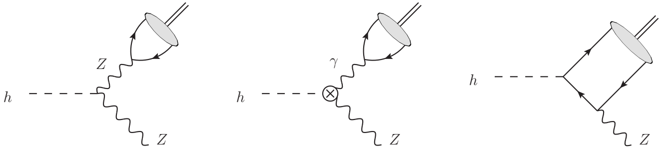

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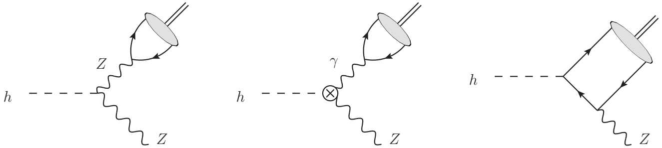

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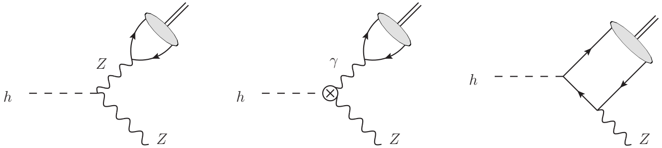

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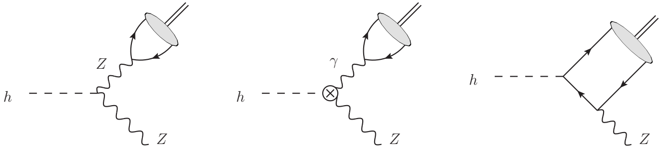

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The bound on $\kappa_{\gamma Z}$ from CMS is:

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

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

Conclusions

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JG|U

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Thank you for your attention!

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Backup slides

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The non-perturbative **hadronization** is **encoded in the matrix element** of the current operators between the **QCD vacuum** and the **hadronic final state** $\langle M \,|\, J \,|\, 0 \rangle$.

Renormalization

When scale-evolved to high scales, all Gegenbauer moments decrease:

$$\mu \;\to\; \infty \quad \Rightarrow \quad a_n, b_n \;\to\; 0 \quad \Leftrightarrow \quad \phi_q \to 6x(1-x)$$

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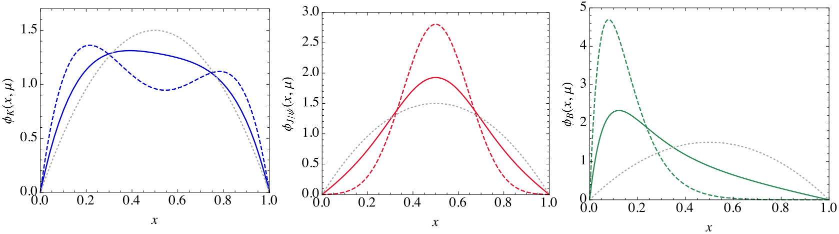

a) K LCDA b) J/ψ LCDA c) B LCDA

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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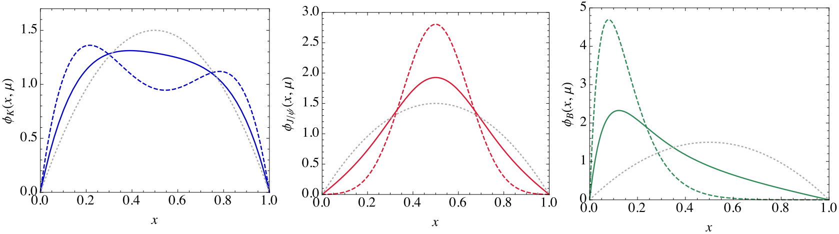

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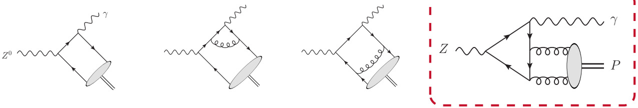
At high scales compared to $\Lambda_{\rm QCD}$ (e.g. $\mu \sim m_Z$) the sensitivity to poorly-known a_n^M, b_n^M is greatly reduced!

The $Z \to M\gamma$ amplitude

The decay amplitude is governed by diagrams:



singlets only!

Form factor decomposition:

$$i\mathcal{A} = \pm \frac{egf_M}{2\cos\theta_W} \left[i\epsilon_{\mu\nu\alpha\beta} \frac{k^\mu q^\nu \varepsilon_Z^\alpha \varepsilon_\gamma^{*\beta}}{k \cdot q} F_1^M - \left(\varepsilon_Z \cdot \varepsilon_\gamma^* - \frac{q \cdot \varepsilon_Z \, k \cdot \varepsilon_\gamma^*}{k \cdot q} \right) F_2^M \right]$$

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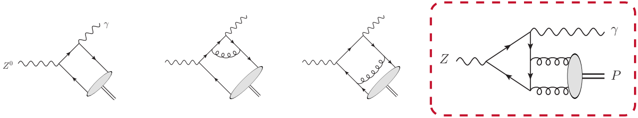

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The form factors contain the contain the convolution integrals:

$$F^M \sim \int_0^1 dx\, H(x,\mu)\phi_M(x,\mu) = \sum_n C_{2n}(\mu)a_{2n}^M(\mu)$$

$$C_n(\mu) = 1 + \frac{C_F\alpha_s(\mu)}{4\pi}\left\{3\log\frac{m_Z^2}{\mu^2} + \dots\right\}$$

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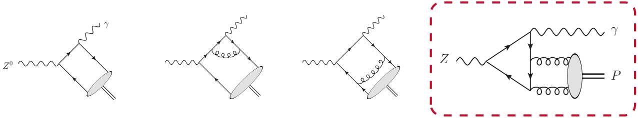

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Evaluating the hard function at $\mu = m_Z$ and evolving it down to μ_{hadr} resums large logarithms $\left[\alpha_s \log(m_Z^2/\mu^2)\right]^n$.

Results for $Z \to M\gamma$

For the branching ratios $\mathrm{BR}(Z \to M\gamma)$ we find:

$Z \to \dots$	Branching ratio	asym.	LO
$\pi^0\gamma$	$(9.80\,{}^{+0.09}_{-0.14}{}_{\mu} \pm 0.03_f \pm 0.61_{a_2} \pm 0.82_{a_4}) \cdot 10^{-12}$	7.71	14.67
$\eta\gamma$	$(2.36\,{}^{+0.02}_{-0.04}{}_{\mu} \pm 1.19_f \pm 0.04_{\phi}) \cdot 10^{-10}$		
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$\rho^0\gamma$	$(4.19\,{}^{+0.04}_{-0.06}{}_{\mu} \pm 0.16_f \pm 0.24_{a_2} \pm 0.37_{a_4}) \cdot 10^{-9}$	3.63	5.68
$\phi\gamma$	$(8.63\,{}^{+0.08}_{-0.13}{}_{\mu} \pm 0.41_f \pm 0.55_{a_2} \pm 0.74_{a_4}) \cdot 10^{-9}$	7.12	12.31
$\omega\gamma$	$(2.89\,{}^{+0.03}_{-0.05}{}_{\mu} \pm 0.15_f \pm 0.29_{a_2} \pm 0.25_{a_4}) \cdot 10^{-8}$	2.54	3.84
$J/\psi\,\gamma$	$(8.02\,{}^{+0.14}_{-0.15}{}_{\mu} \pm 0.20_f\,{}^{+0.39}_{-0.36}{}_{\sigma}) \cdot 10^{-8}$	10.48	6.55
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$\Upsilon(nS)\,\gamma$	$(9.96\,{}^{+0.18}_{-0.19}{}_\mu \pm 0.09_f\ {}^{+0.20}_{-0.15}{}_\sigma) \cdot 10^{-8}$	13.96	7.59

scale dependence ↑ (the μ uncertainties)

decay constant ↑ (the f uncertainties)

Results for $Z \to M\gamma$

For the branching ratios $\mathrm{BR}(Z \to M\gamma)$ we find:

$Z \to \ldots$	Branching ratio	asym.	LO
$\pi^0\gamma$	$(9.80\,{}^{+0.09}_{-0.14}{}_{\mu} \pm 0.03_f \pm 0.61_{a_2} \pm 0.82_{a_4}) \cdot 10^{-12}$	7.71	14.67
$\eta\gamma$	$(2.36\,{}^{+0.02}_{-0.04}{}_{\mu} \pm 1.19_f \pm 0.04_{\phi}) \cdot 10^{-10}$		
$\eta'\gamma$	$(6.68\,{}^{+0.08}_{-0.11}{}_{\mu} \pm 0.49_f \pm 0.12_{\phi}) \cdot 10^{-9}$		
$\rho^0\gamma$	$(4.19\,{}^{+0.04}_{-0.06}{}_{\mu} \pm 0.16_f \pm 0.24_{a_2} \pm 0.37_{a_4}) \cdot 10^{-9}$	3.63	5.68
$\phi\gamma$	$(8.63\,{}^{+0.08}_{-0.13}{}_{\mu} \pm 0.41_f \pm 0.55_{a_2} \pm 0.74_{a_4}) \cdot 10^{-9}$	7.12	12.31
$\omega\gamma$	$(2.89\,{}^{+0.03}_{-0.05}{}_{\mu} \pm 0.15_f \pm 0.29_{a_2} \pm 0.25_{a_4}) \cdot 10^{-8}$	2.54	3.84
$J/\psi\,\gamma$	$(8.02\,{}^{+0.14}_{-0.15}{}_{\mu} \pm 0.20_f\,{}^{+0.39}_{-0.36}{}_{\sigma}) \cdot 10^{-8}$	10.48	6.55
$\Upsilon(1S)\,\gamma$	$(5.39\,{}^{+0.10}_{-0.10}{}_{\mu} \pm 0.08_f\,{}^{+0.11}_{-0.08}{}_{\sigma}) \cdot 10^{-8}$	7.55	4.11
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scale dependence — **decay constant** — **LCDA shape**

For the branching ratios $\mathrm{BR}(Z \to M\gamma)$ we find:

$Z \to \ldots$	Branching ratio		asym.	LO
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obtained when using only asymptotic form of LCDA

$$\phi_M(x) = 6x(1-x)$$

Results for $Z \to M\gamma$

For the branching ratios $\mathrm{BR}(Z \to M\gamma)$ we find:

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obtained when using only LO hard functions

Results for $Z \to M\gamma$

JG|U

For the branching ratios $\mathrm{BR}(Z \to M\gamma)$ we find:

$Z \to \dots$	Branching ratio	asym.	LO
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The form factors become:

$$\begin{aligned}\mathrm{Re}\,F_1^M &= \mathcal{Q}_M \left[0.94 + 1.05\,a_2^M(m_Z) + 1.15\,a_4^M(m_Z) + 1.22\,a_6^M(m_Z) + \dots\right] \\ &= \mathcal{Q}_M \left[0.94 + 0.41\,a_2^M(\mu_h) + 0.29\,a_4^M(\mu_h) + 0.23\,a_6^M(\mu_h) + \dots\right]\end{aligned}$$

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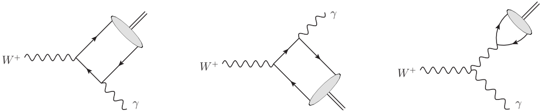
$\to$ RGE from high to low scale reduces sensitivity to a_n^M!

The analysis in the case for $W \to M\gamma$ is almost the same, only this time, an indirect diagram exists involving the local matrix element:



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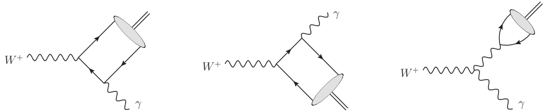

mode	Branching ratio	asym.	LO
$\pi^{\pm}\gamma$	$(4.00\,^{+\,0.06}_{-\,0.11}\,{}_{\mu} \pm 0.01_f \pm 0.49_{a_2} \pm 0.66_{a_4}) \cdot 10^{-9}$	2.45	8.09
$\rho^{\pm}\gamma$	$(8.74\,^{+\,0.17}_{-\,0.26}\,{}_{\mu} \pm 0.33_f \pm 1.02_{a_2} \pm 1.57_{a_4}) \cdot 10^{-9}$	6.48	15.12
$K^{\pm}\gamma$	$(3.25\,^{+\,0.05}_{-\,0.09}\,{}_{\mu} \pm 0.03_f \pm 0.24_{a_1} \pm 0.38_{a_2} \pm 0.51_{a_4}) \cdot 10^{-10}$	1.88	6.38
$K^{*\pm}\gamma$	$(4.78\,^{+\,0.09}_{-\,0.14}\,{}_{\mu} \pm 0.28_f \pm 0.39_{a_1} \pm 0.66_{a_2} \pm 0.80_{a_4}) \cdot 10^{-10}$	3.18	8.47
$D_s\gamma$	$(3.66\,^{+\,0.02}_{-\,0.07}\,{}_{\mu} \pm 0.12_{\text{CKM}} \pm 0.13_f\,^{+\,1.47}_{-\,0.82}\,{}_{\sigma}) \cdot 10^{-8}$	0.98	8.59
$D^{\pm}\gamma$	$(1.38\,^{+\,0.01}_{-\,0.02}\,{}_{\mu} \pm 0.10_{\text{CKM}} \pm 0.07_f\,^{+\,0.50}_{-\,0.30}\,{}_{\sigma}) \cdot 10^{-9}$	0.32	3.42
$B^{\pm}\gamma$	$(1.55\,^{+\,0.00}_{-\,0.03}\,{}_{\mu} \pm 0.37_{\text{CKM}} \pm 0.15_f\,^{+\,0.68}_{-\,0.45}\,{}_{\sigma}) \cdot 10^{-12}$	0.09	6.44

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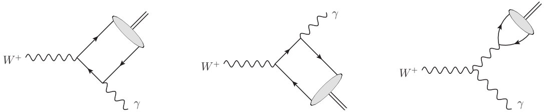

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$K^\pm\gamma$	$(3.25\,^{+\,0.05}_{-\,0.09}\,{}_\mu \pm 0.03_f \pm 0.24_{a_1} \pm 0.38_{a_2} \pm 0.51_{a_4}) \cdot 10^{-10}$	1.88	6.38
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flavour off-diagonal mesons allowed

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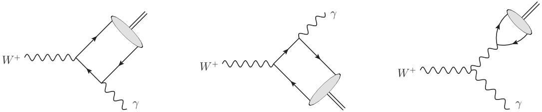

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introduces uncertainties from CKM elements

$Z \to M + \gamma$ decays as BSM probes

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Our analysis can straight-forwardly be generalized to the case of non-SM Z boson couplings to quarks!

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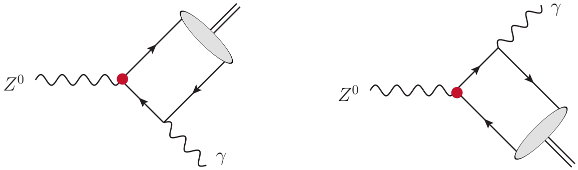

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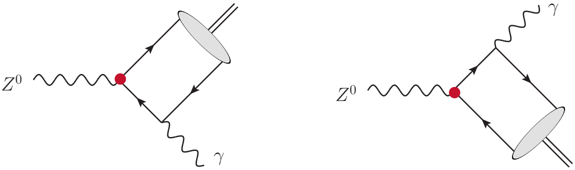

At LEP, $|a_b|$ and $|a_c|$ have been measured to 1%, using our predictions, $|a_s|$, $|a_d|$ and $|a_u|$ could be measured to $\sim 6\%$

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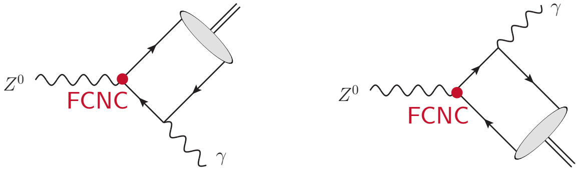

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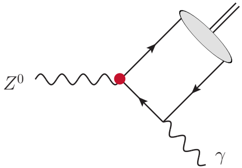
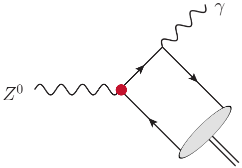
Introducing FCNC couplings allows the production of flavor off-diagonal mesons

$Z \to M + \gamma$ decays as FCNC probes

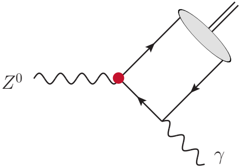


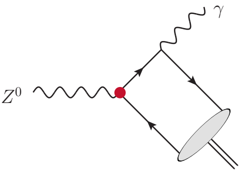


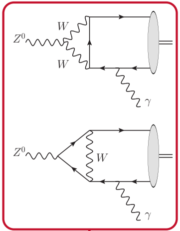
Model independent predictions for flavor off-diagonal mesons:

Decay mode	Branching ratio	SM background
$Z^0 \to K^0\gamma$	$\left[(7.70 \pm 0.83)\,\lvert v_{sd}\rvert^2 + (0.01 \pm 0.01)\,\lvert a_{sd}\rvert^2\right] \cdot 10^{-8}$	$\frac{\lambda}{\sin^2\theta_W}\,\frac{\alpha}{\pi} \sim 2 \cdot 10^{-3}$
$Z^0 \to D^0\gamma$	$\left[(5.30\,^{+\,0.67}_{-\,0.43})\,\lvert v_{cu}\rvert^2 + (0.62\,^{+\,0.36}_{-\,0.23})\,\lvert a_{cu}\rvert^2\right] \cdot 10^{-7}$	$\frac{\lambda}{\sin^2\theta_W}\,\frac{\alpha}{\pi} \sim 2 \cdot 10^{-3}$
$Z^0 \to B^0\gamma$	$\left[(2.08\,^{+\,0.59}_{-\,0.41})\,\lvert v_{bd}\rvert^2 + (0.77\,^{+\,0.38}_{-\,0.26})\,\lvert a_{bd}\rvert^2\right] \cdot 10^{-7}$	$\frac{\lambda^3}{\sin^2\theta_W}\,\frac{\alpha}{\pi} \sim 8 \cdot 10^{-5}$
$Z^0 \to B_s\gamma$	$\left[(2.64\,^{+\,0.82}_{-\,0.52})\,\lvert v_{bs}\rvert^2 + (0.87\,^{+\,0.51}_{-\,0.33})\,\lvert a_{bs}\rvert^2\right] \cdot 10^{-7}$	$\frac{\lambda^2}{\sin^2\theta_W}\,\frac{\alpha}{\pi} \sim 4 \cdot 10^{-4}$

$Z \to M + \gamma$ decays as FCNC probes







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$Z^0 \to D^0\gamma$	$\left[(5.30\,^{+\,0.67}_{-\,0.43})\,\lvert v_{cu}\rvert^2 + (0.62\,^{+\,0.36}_{-\,0.23})\,\lvert a_{cu}\rvert^2\right] \cdot 10^{-7}$	$\frac{\lambda}{\sin^2\theta_W}\,\frac{\alpha}{\pi} \sim 2 \cdot 10^{-3}$
$Z^0 \to B^0\gamma$	$\left[(2.08\,^{+\,0.59}_{-\,0.41})\,\lvert v_{bd}\rvert^2 + (0.77\,^{+\,0.38}_{-\,0.26})\,\lvert a_{bd}\rvert^2\right] \cdot 10^{-7}$	$\frac{\lambda^3}{\sin^2\theta_W}\,\frac{\alpha}{\pi} \sim 8 \cdot 10^{-5}$
$Z^0 \to B_s\gamma$	$\left[(2.64\,^{+\,0.82}_{-\,0.52})\,\lvert v_{bs}\rvert^2 + (0.87\,^{+\,0.51}_{-\,0.33})\,\lvert a_{bs}\rvert^2\right] \cdot 10^{-7}$	$\frac{\lambda^2}{\sin^2\theta_W}\,\frac{\alpha}{\pi} \sim 4 \cdot 10^{-4}$

$Z \to M + \gamma$ decays as FCNC probes

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FCNCs would induce tree-level neutral-meson mixing, strongly constrained:

$\left\lvert \mathrm{Re}\left[(v_{sd} \pm a_{sd})^2\right]\right\rvert$	$< 2.9 \cdot 10^{-8}$	$\left\lvert \mathrm{Re}\left[(v_{sd})^2 - (a_{sd})^2\right]\right\rvert$	$< 3.0 \cdot 10^{-10}$
$\left\lvert \mathrm{Im}\left[(v_{sd} \pm a_{sd})^2\right]\right\rvert$	$< 1.0 \cdot 10^{-10}$	$\left\lvert \mathrm{Im}\left[(v_{sd})^2 - (a_{sd})^2\right]\right\rvert$	$< 4.3 \cdot 10^{-13}$
$\left\lvert (v_{cu} \pm a_{cu})^2 \right\rvert$	$< 2.2 \cdot 10^{-8}$	$\left\lvert (v_{cu})^2 - (a_{cu})^2 \right\rvert$	$< 1.5 \cdot 10^{-8}$
$\left\lvert (v_{bd} \pm a_{bd})^2 \right\rvert$	$< 4.3 \cdot 10^{-8}$	$\left\lvert (v_{bd})^2 - (a_{bd})^2 \right\rvert$	$< 8.2 \cdot 10^{-9}$
$\left\lvert (v_{bs} \pm a_{bs})^2 \right\rvert$	$< 5.5 \cdot 10^{-7}$	$\left\lvert (v_{bs})^2 - (a_{bs})^2 \right\rvert$	$< 1.4 \cdot 10^{-7}$

[Bona et al. (*2007*), JHEP 0803, 049]
[Bertone et al. (*2012*), JHEP 1303, 089]
[Carrasco et al. (*2013*), JHEP 1403, 016]

These bounds push our branching ratios down to 10^{-14}, rendering them unobservable.

Experimental considerations

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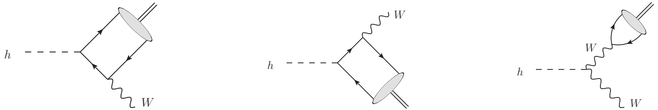
- **However**: Future lepton machines like ILC or TLEP might produce $10^{12} Z$'s and $10^{7} W$'s at the corresponding thresholds → This enables an experimental program to **test QCDF in a theoretically clean environment**!

We can imagine using $h \to MW$ as a probe of flavor-changing Yukawas.



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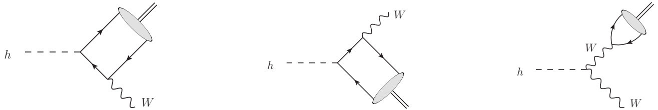

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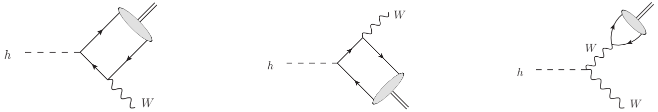

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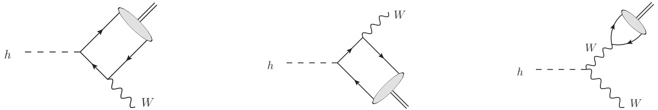

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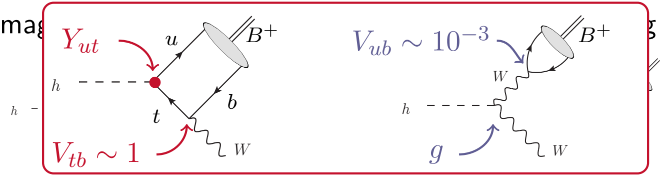

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The branching ratios expressed through flavor-changing Yukawa couplings are given by:

$$\mathrm{Br}(h \to B^+ W^-) = 1.57 \cdot 10^{-10} \left(1 + 389\,\mathrm{Re}(Y_{ut}) + 37916\,|Y_{ut}|^2\right) ,$$
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