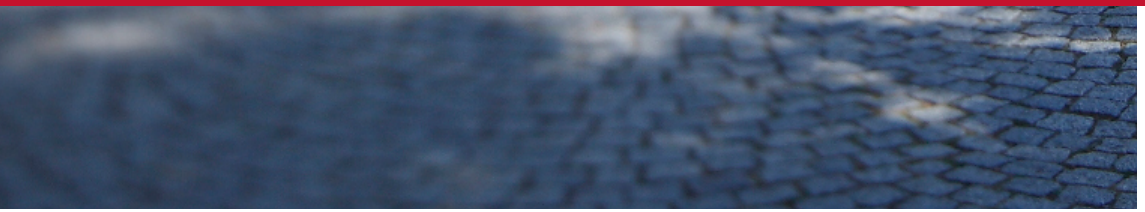
Very rare, exclusive, hadronic decays in QCD factorization

Matthias König
THEP, Johannes Gutenberg-University (Mainz)

QCD@Work
International Workshop on QCD Theory and Experiment
Martina Franca, 27 June, 2016



PRISMA
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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!

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Price to pay: Very **small branching ratios** and difficult reconstruction!

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

Derivation of 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]

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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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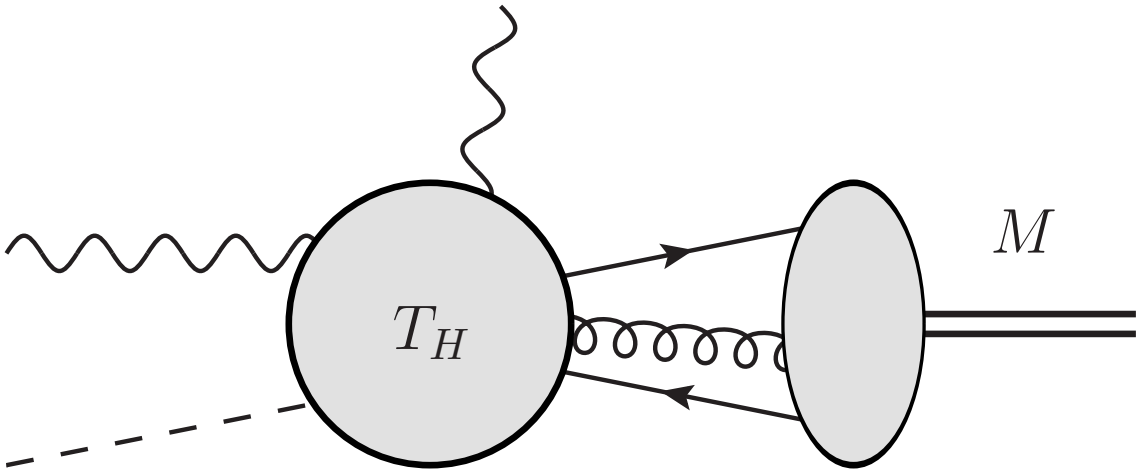

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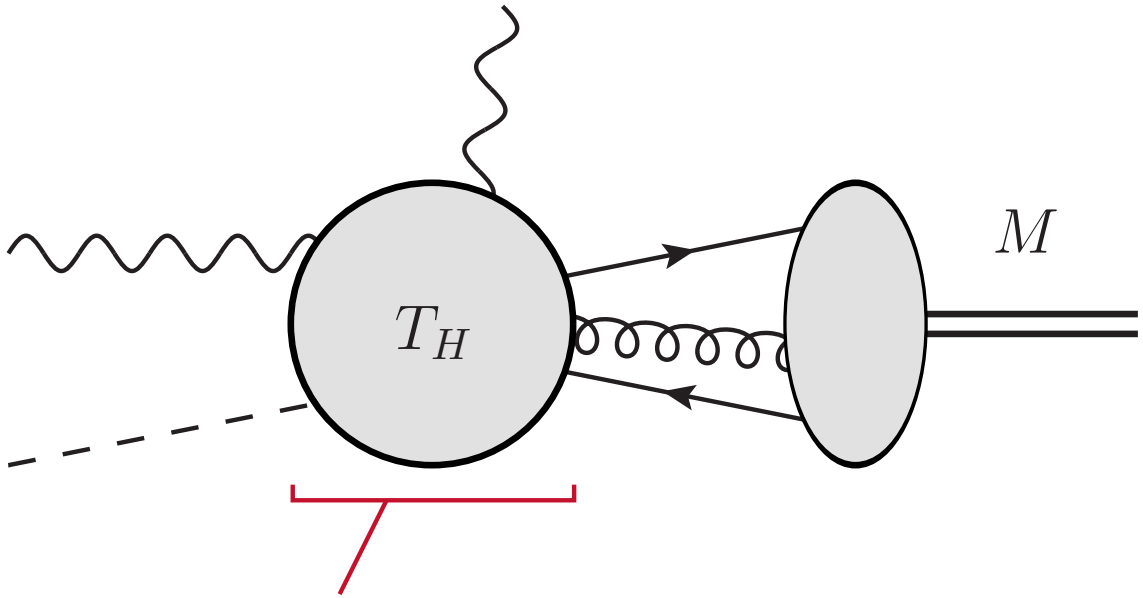

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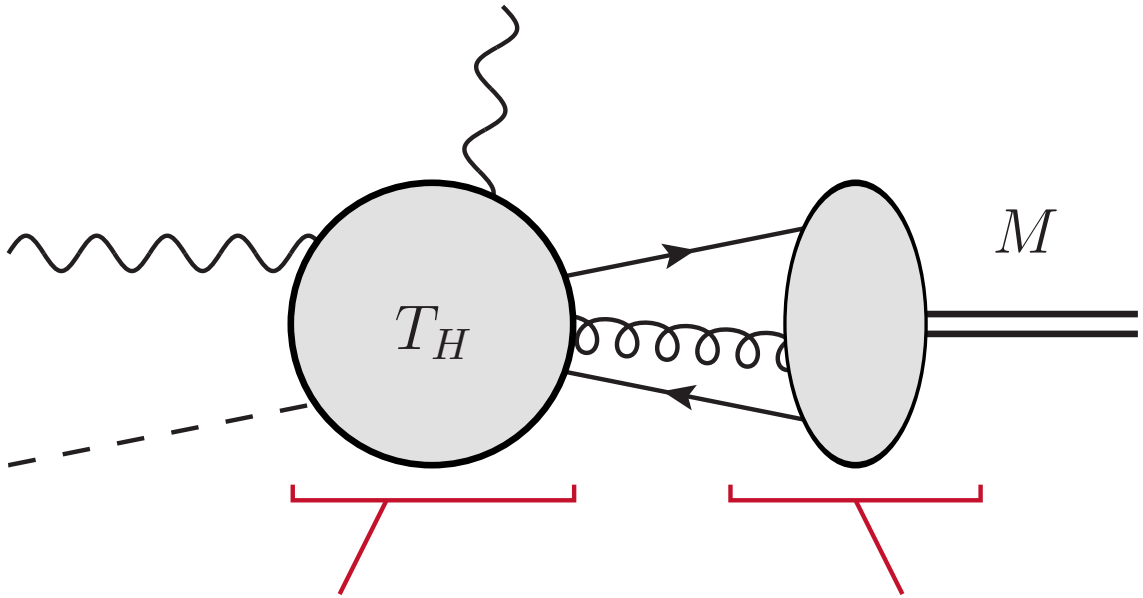

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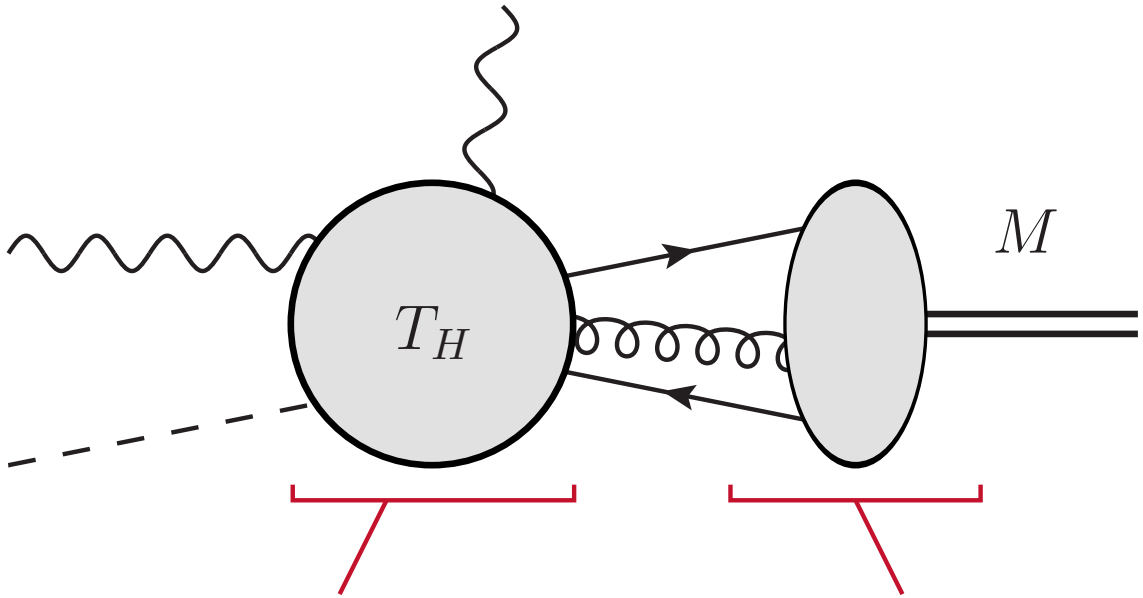

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The **scale separation** in the case at hand **calls for an effective theory** description!

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Strategy: Using SCET, write down **all effective operators** from **collinear partons** that can excite the meson from the QCD vacuum.

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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** $\langle M \,|\, J \,|\, 0 \rangle$.

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With our effective operator $J_q(t) = \bar{q}_c(t\bar{n})\,\Gamma\,[t\bar{n}, 0]\,q_c(0)$ the amplitude for $X \to M + V$ is then given by:

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

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The **hadronic matrix element** defines a function analogous to the decay constants. In fact, these are just the local case ($t = 0$) above. The generalization to our **bi-local current operator**

$$\langle M(k)|\, J_q(t, \dots)\,|0\rangle \sim f_M \int e^{i(t\bar{n})\cdot(xk)}\phi_M^q(x)dx$$

defines the light-cone distribution amplitude (**LCDA**), which encodes the non-perturbative physics in the exclusive hadronic final state.

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For mesons with a **flavor-singlet** component, there is an analogous **contribution from two gluons**.

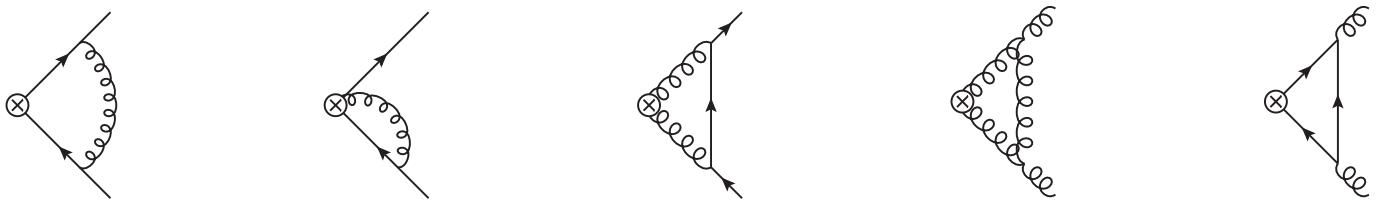
QCD-factorization
Light-cone distribution amplitudes

Renormalization of the LCDAs

Remember, we are dealing with a **huge scale hierarchy**: m_Z vs. Λ_{QCD}

$\Rightarrow$ Large logarithms $\alpha_s \log(m_Z/\Lambda_{\mathrm{QCD}})$ need to be resummed.

Examples of corrections to the LCDAs at $\mathcal{O}(\alpha_s)$:



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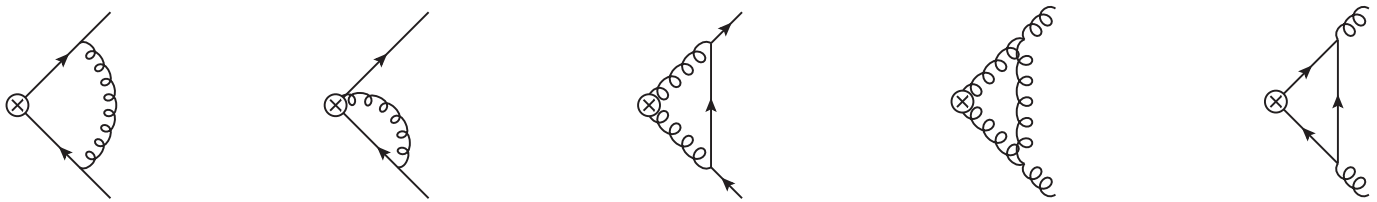

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$$\begin{pmatrix} \phi_q^{\mathrm{ren}} \\ \phi_g^{\mathrm{ren}} \end{pmatrix} = \begin{pmatrix} \text{\raisebox{-0.5ex}{\image{}}} & \text{\raisebox{-0.5ex}{\image{}}} \\ \text{\raisebox{-0.5ex}{\image{}}} & \text{\raisebox{-0.5ex}{\image{}}} \end{pmatrix} \otimes \begin{pmatrix} \phi_q^{\mathrm{bare}} \\ \phi_g^{\mathrm{bare}} \end{pmatrix}$$

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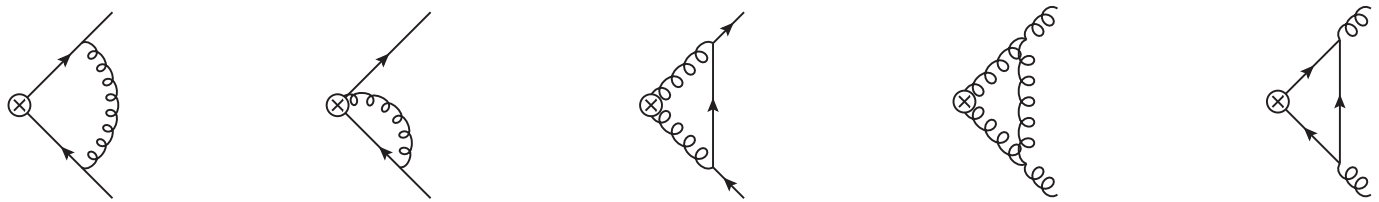

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$$\begin{pmatrix} \phi_q^{\mathrm{ren}}(x,\mu) \\ \phi_g^{\mathrm{ren}}(x,\mu) \end{pmatrix} = \int_0^1 \left[\mathbf{1} \cdot \delta(x-y) \; + \; \frac{\alpha_s(\mu)}{4\pi\epsilon} \begin{pmatrix} V_{qq}(x,y) & V_{qg}(x,y) \\ V_{gq}(x,y) & V_{gg}(x,y) \end{pmatrix} \right] \begin{pmatrix} \phi_q^{\mathrm{bare}}(y) \\ \phi_g^{\mathrm{bare}}(y) \end{pmatrix} dy$$

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

[Terentev (*1981*), Sov. J. Nucl. Phys. 33, 911]

[Ohrndorf (*1981*), Nucl. Phys. B 186, 153]

[Shifman, Vysotsky (*1981*), Nucl. Phys. B 186, 475]

[Baier, Grozin (*1981*), Nucl.Phys. B192 476-488]

Renormalization

The LCDAs are expanded in the eigenfunctions of the evolution Kernels:

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

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At higher orders, moments of order n mix with moments of order $k < n$.

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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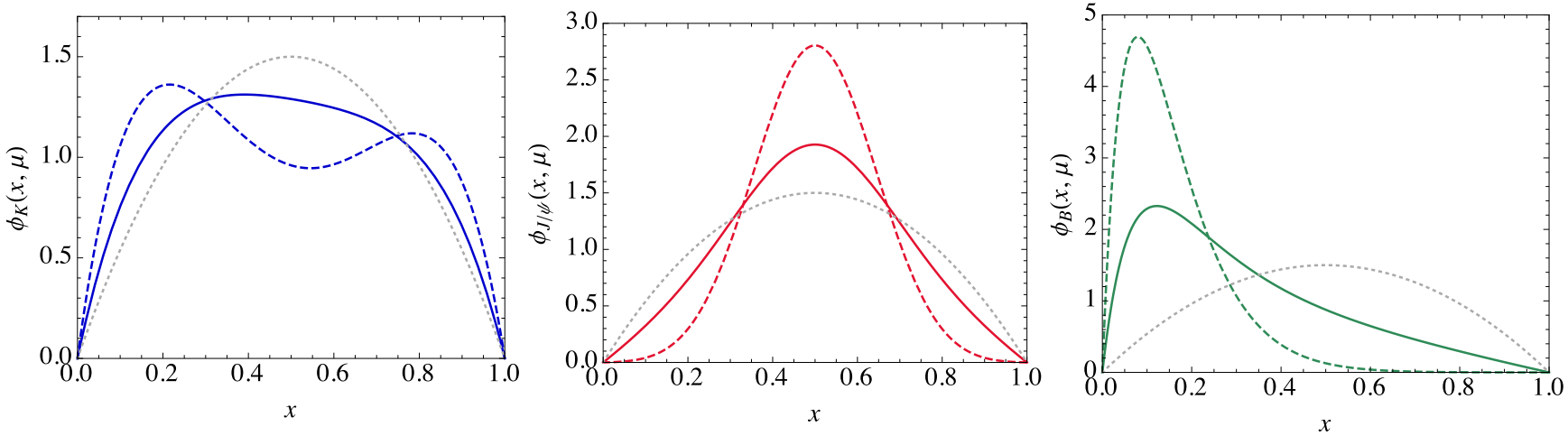

a) K LCDA b) J/ψ LCDA c) B LCDA

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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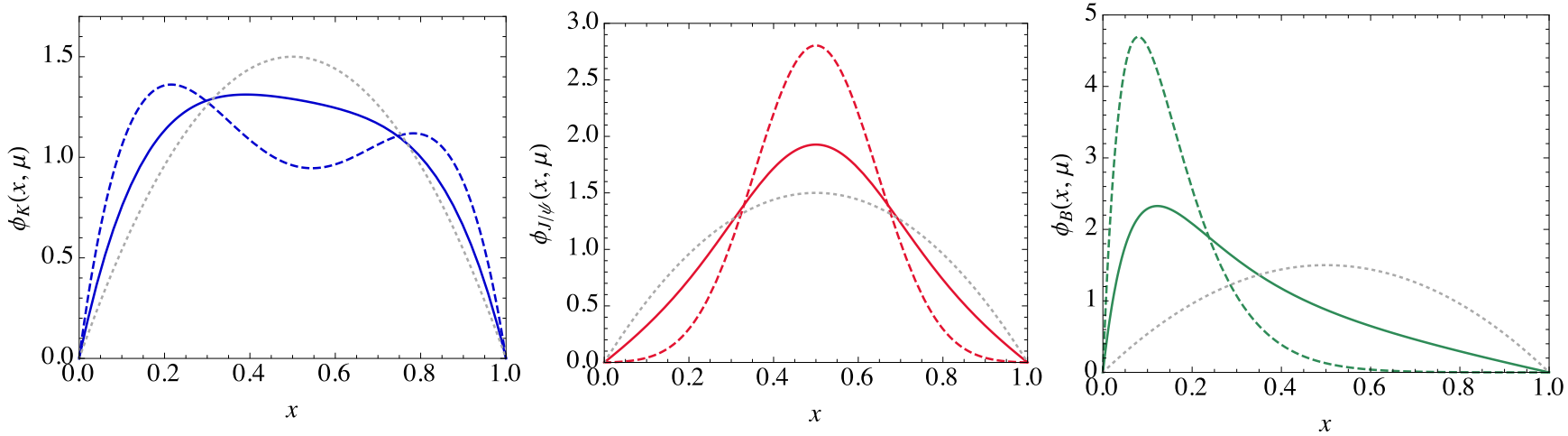

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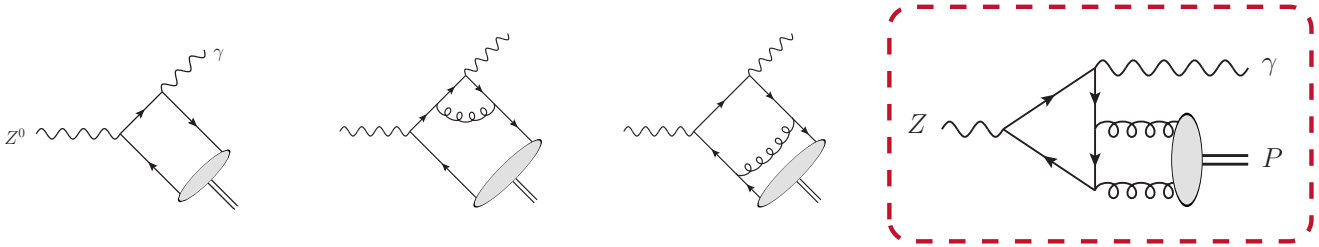
At high scales compared to $\Lambda_{\rm QCD}$ (e.g. $\mu \sim m_Z$) the sensitivity to poorly-known a_n^M, b_n^M is greatly reduced!

Hadronic decays of electroweak gauge bosons

The $Z \to M\gamma$ amplitude

The decay amplitude is governed by diagrams:



singlets only!

Form factor decomposition:

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

The $Z \to M\gamma$ amplitude

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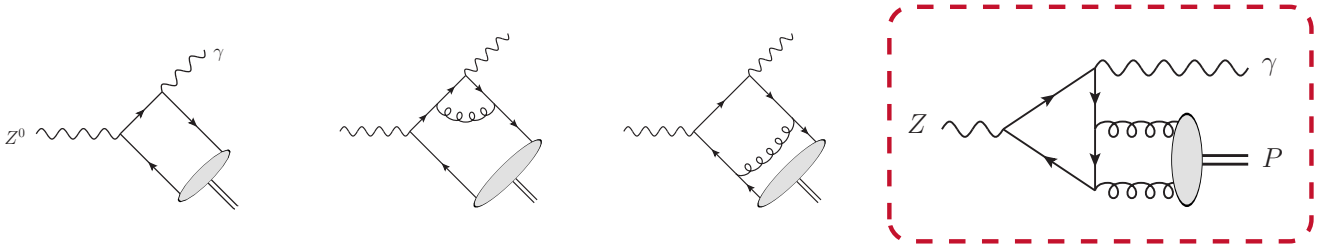

singlets only!

Form factor decomposition:

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

The form factors contain the contain the convolution integrals:

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

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

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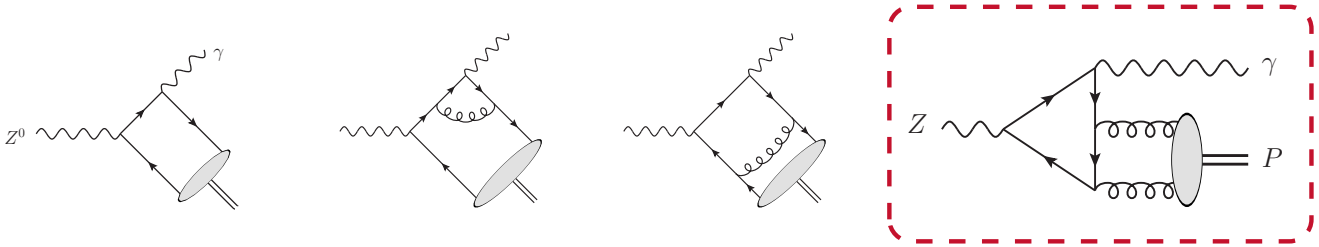

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Evaluating the hard function at $\mu = m_Z$ and evolving it down to $\mu_{\rm hadr}$ resums large logarithms $\left[\alpha_s \log(m_Z^2/\mu^2)\right]^n$.

Results for $Z \to M\gamma$

JG|U

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
$\Upsilon(4S)\,\gamma$	$(1.22\,^{+0.02}_{-0.02}{}_{\mu}\ \pm 0.13_f\ {}^{+0.02}_{-0.02}{}_{\sigma})\ \cdot 10^{-8}$	1.71	0.93
$\Upsilon(nS)\,\gamma$	$(9.96\,^{+0.18}_{-0.19}{}_{\mu}\ \pm 0.09_f\ {}^{+0.20}_{-0.15}{}_{\sigma})\ \cdot 10^{-8}$	13.96	7.59

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scale dependence

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scale dependence

decay constant

Results for $Z \to M\gamma$

JG|U

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scale dependence

decay constant

LCDA shape

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obtained when using only asymptotic form of LCDA

$$\phi_{\mathrm{M}}(\mathrm{x}) = 6\mathrm{x}(1-\mathrm{x})$$

Results for $Z \to M\gamma$

JG|U

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Results for $Z \to M\gamma$

JG|U

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The form factors become:

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

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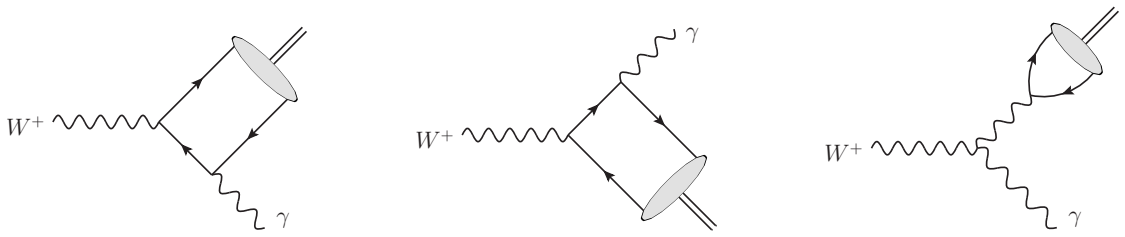
$\to$ RGE from high to low scale reduces sensitivity to a_n^M!

Results for $W \to M\gamma$

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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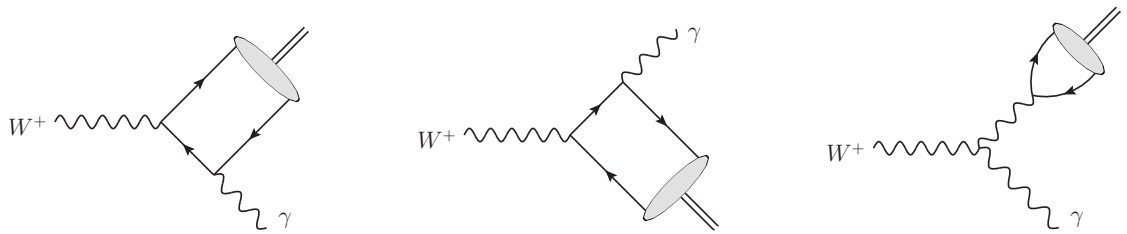

mode	Branching ratio	asym.	LO
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$\rho^\pm\gamma$	$(8.74\,^{+0.17}_{-0.26}{}_{\mu} \pm 0.33_f \pm 1.02_{a_2} \pm 1.57_{a_4}) \cdot 10^{-9}$	6.48	15.12
$K^\pm\gamma$	$(3.25\,^{+0.05}_{-0.09}{}_{\mu} \pm 0.03_f \pm 0.24_{a_1} \pm 0.38_{a_2} \pm 0.51_{a_4}) \cdot 10^{-10}$	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
$D_s\gamma$	$(3.66\,^{+0.02}_{-0.07}{}_{\mu} \pm 0.12_{\mathrm{CKM}} \pm 0.13_f\,^{+1.47}_{-0.82}{}_{\sigma}) \cdot 10^{-8}$	0.98	8.59
$D^\pm\gamma$	$(1.38\,^{+0.01}_{-0.02}{}_{\mu} \pm 0.10_{\mathrm{CKM}} \pm 0.07_f\,^{+0.50}_{-0.30}{}_{\sigma}) \cdot 10^{-9}$	0.32	3.42
$B^\pm\gamma$	$(1.55\,^{+0.00}_{-0.03}{}_{\mu} \pm 0.37_{\mathrm{CKM}} \pm 0.15_f\,^{+0.68}_{-0.45}{}_{\sigma}) \cdot 10^{-12}$	0.09	6.44

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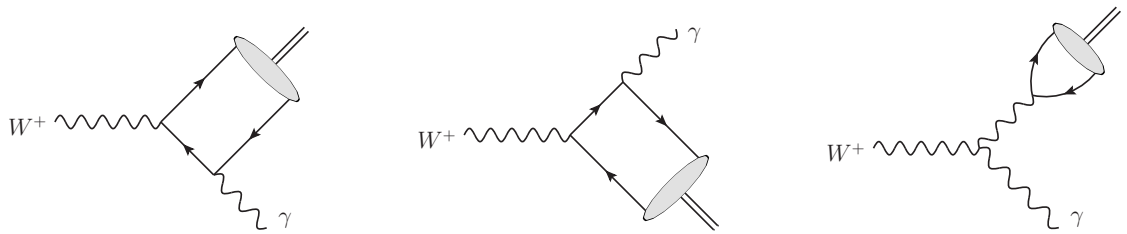

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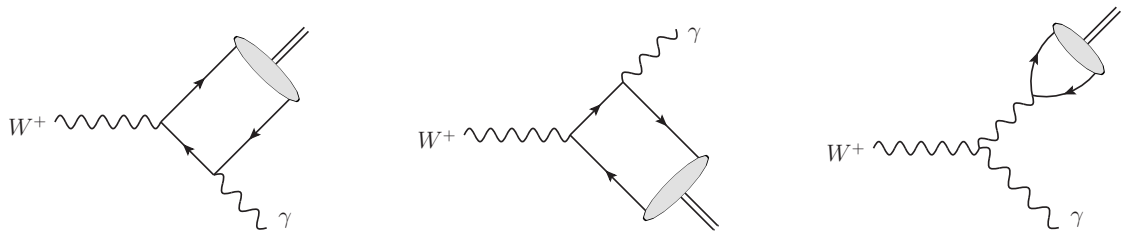
$K^{*\pm}\gamma$	$(4.78\,^{+0.09}_{-0.14}{}_{\mu} \pm 0.28_f \pm 0.39_{a_1} \pm 0.66_{a_2} \pm 0.80_{a_4}) \cdot 10^{-10}$	3.18	8.47
$D_s\gamma$	$(3.66\,^{+0.02}_{-0.07}{}_{\mu} \pm 0.12_{\mathrm{CKM}} \pm 0.13_f\,^{+1.47}_{-0.82}{}_{\sigma}) \cdot 10^{-8}$	0.98	8.59
$D^\pm\gamma$	$(1.38\,^{+0.01}_{-0.02}{}_{\mu} \pm 0.10_{\mathrm{CKM}} \pm 0.07_f\,^{+0.50}_{-0.30}{}_{\sigma}) \cdot 10^{-9}$	0.32	3.42
$B^\pm\gamma$	$(1.55\,^{+0.00}_{-0.03}{}_{\mu} \pm 0.37_{\mathrm{CKM}} \pm 0.15_f\,^{+0.68}_{-0.45}{}_{\sigma}) \cdot 10^{-12}$	0.09	6.44

flavour off-diagonal mesons allowed

Results for $W \to M\gamma$

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:



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
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introduces uncertainties from CKM elements

Hadronic Higgs decays
Radiative hadronic Higgs decays

The $h \to V\gamma$ 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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[Bodwin et al. (*2014*), arXiv:1407.6695]

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JG|U

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Work with the effective Lagrangian:

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

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

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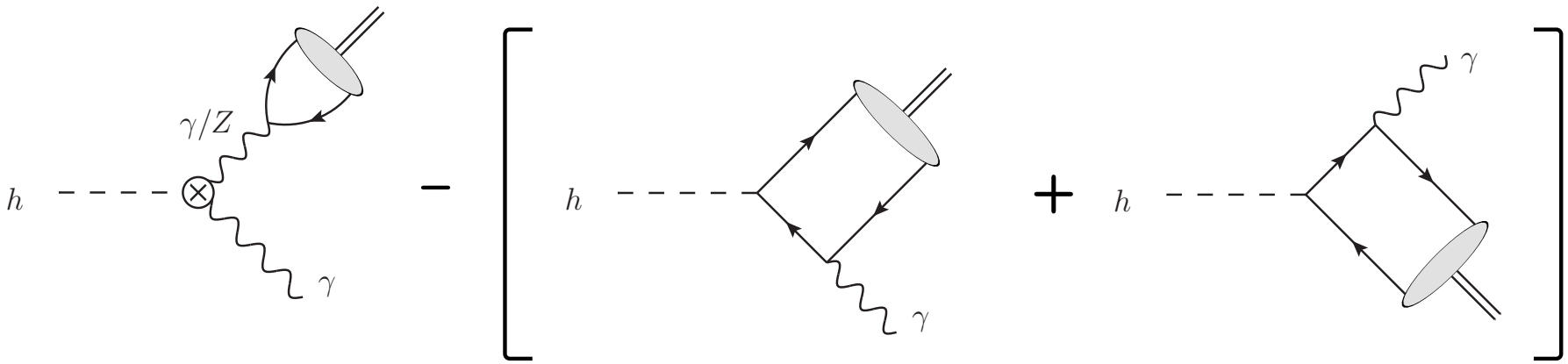
$\to$ Provides a model independent analysis of NP effects in $h \to V\gamma$ decays!

The $h \to V\gamma$ decays

Several different diagram topologies:



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JG|U

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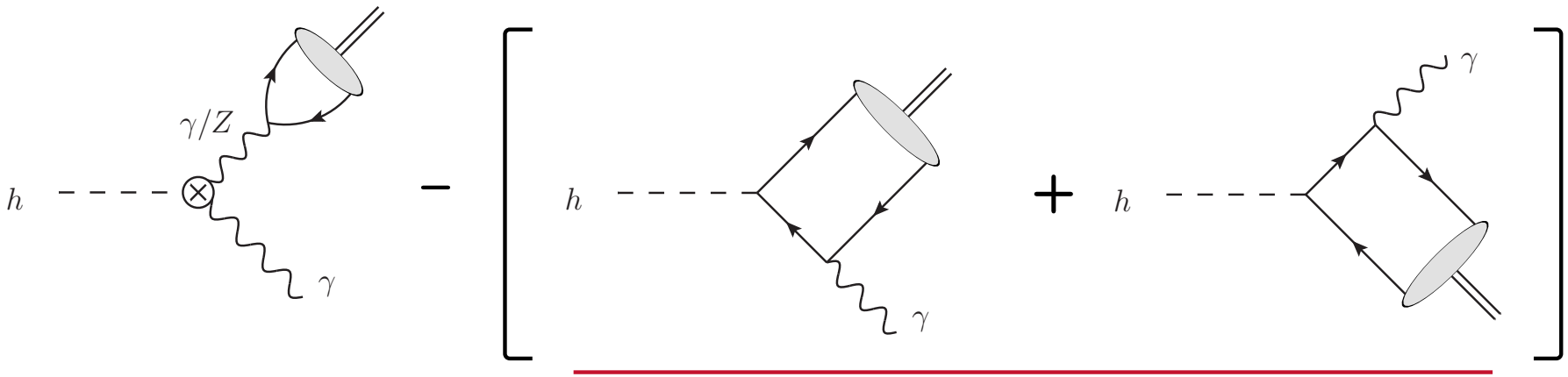

directly proportional to κ_q and $\tilde{\kappa}_q$

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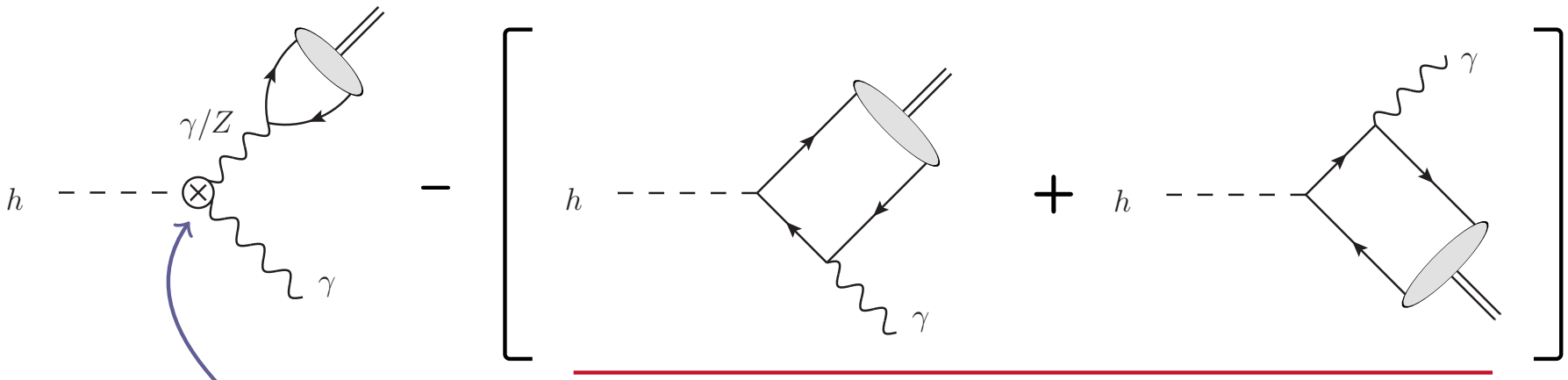

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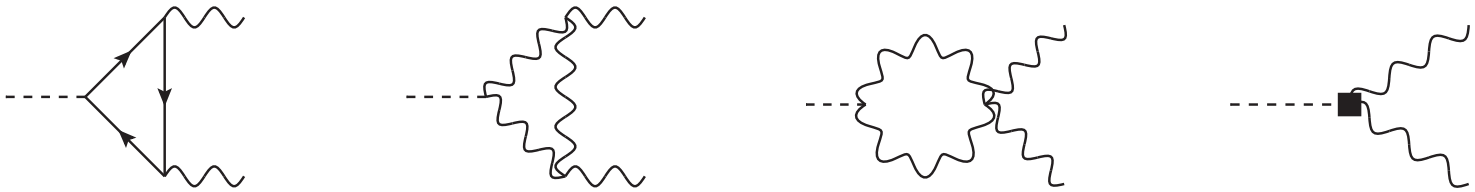
Contains contributions to $h \to (Z/\gamma)^*\gamma$, both SM and NP



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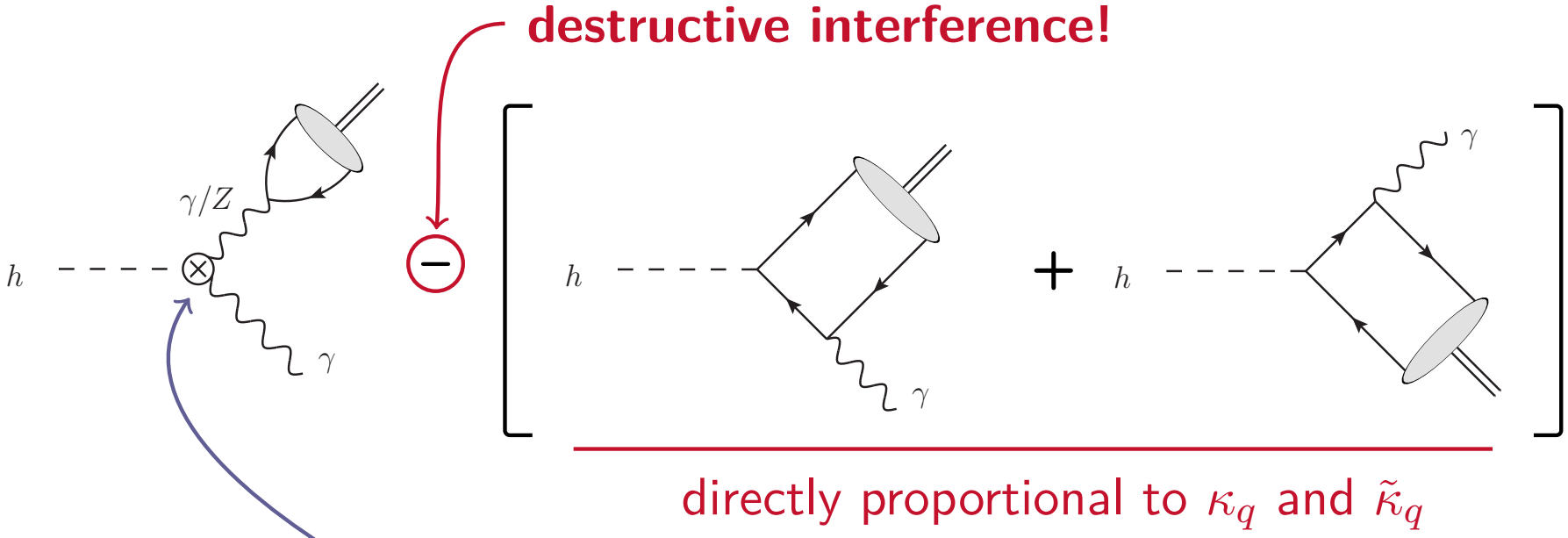

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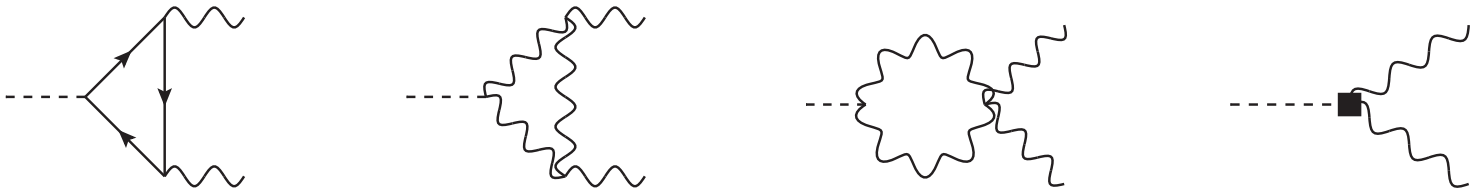

The $h \to V\gamma$ decays

JG|U

Form factor decomposition:

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

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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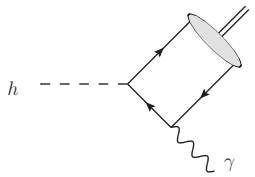

$$F^1_{V,\text{direct}} \propto \kappa_q \frac{f_V^\perp(\mu)}{f_V}\left[1 + \frac{C_F \alpha_s(\mu)}{\pi}\log\frac{m_h^2}{\mu^2}\right]\left(\sum_{n=0}^{\infty} C_{2n}(m_h,\mu) a_{2n}^{V_\perp}(\mu)\right)$$

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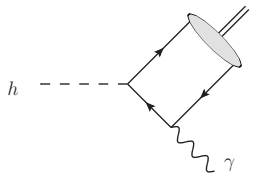

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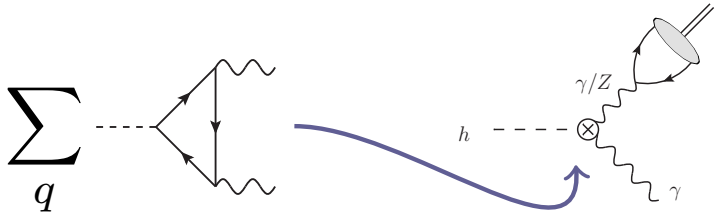
The **indirect** form factors however, are proportional to all κ_X in the Lagrangian!



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

Originally, we wanted 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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JG|U

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To reduce the theoretical uncertainty, we **normalize the branching ratio to the $h \to \gamma\gamma$ branching ratio**, which also makes our prediction insensitive to the total Higgs width:

$$\frac{\mathrm{BR}(h \to V\gamma)}{\mathrm{BR}(h \to \gamma\gamma)} =$$

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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!

Nummerical results

JG|U

Assuming SM couplings of all particles, we find:

$$\begin{aligned}
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A **general feature**: $h \to V\gamma$ decays are **rare**.

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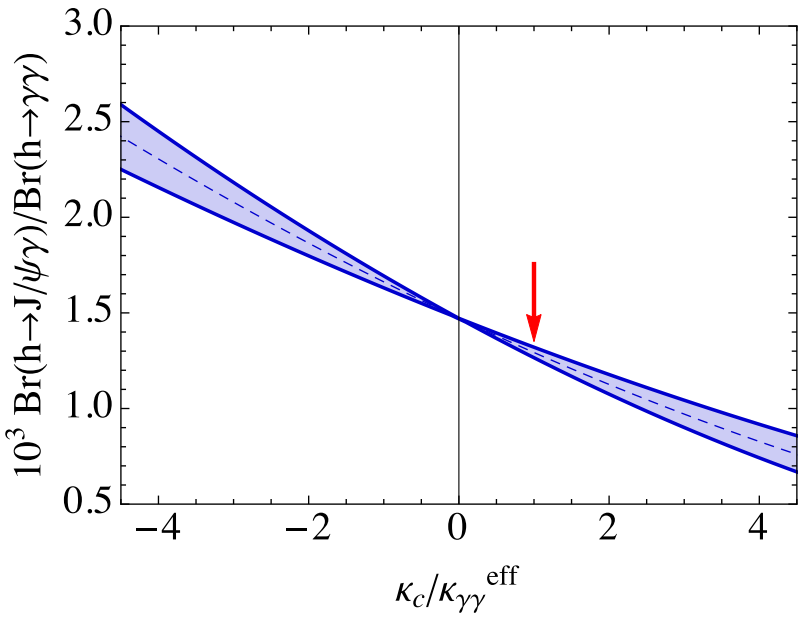
But: What is wrong with the Υ-channels?

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



Ratio of BR for J/ψ

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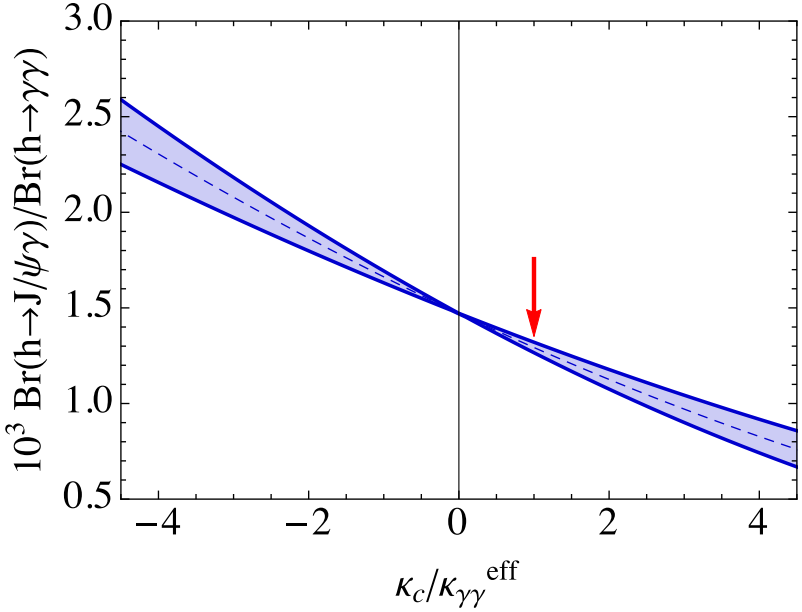

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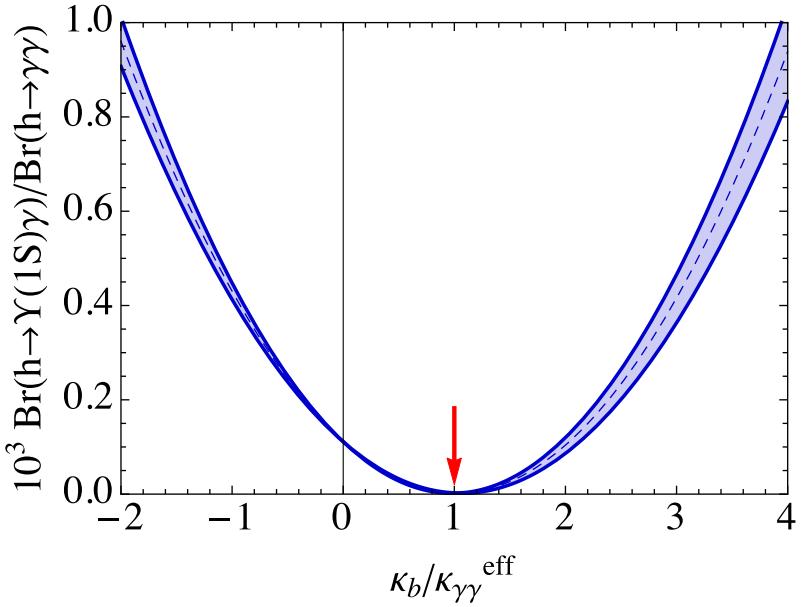


Ratio of BR for $\Upsilon(1S)$

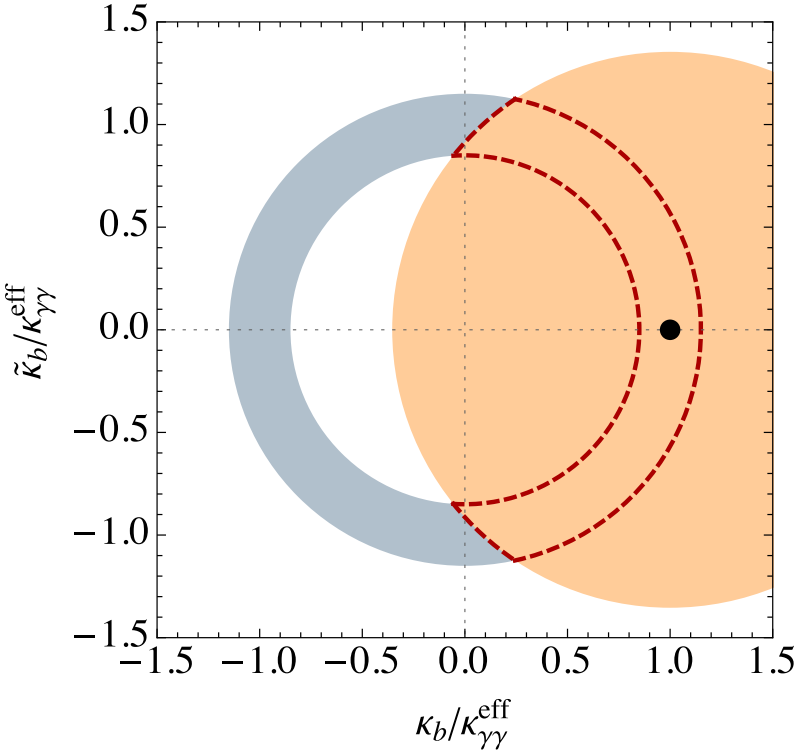
Usually, the **indirect contributions** are the **dominant** ones, however **for the Υ**, the **direct contribution** is **comparable**, leading to a **cancellation** between the two.

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

Phenomenology

JG|U

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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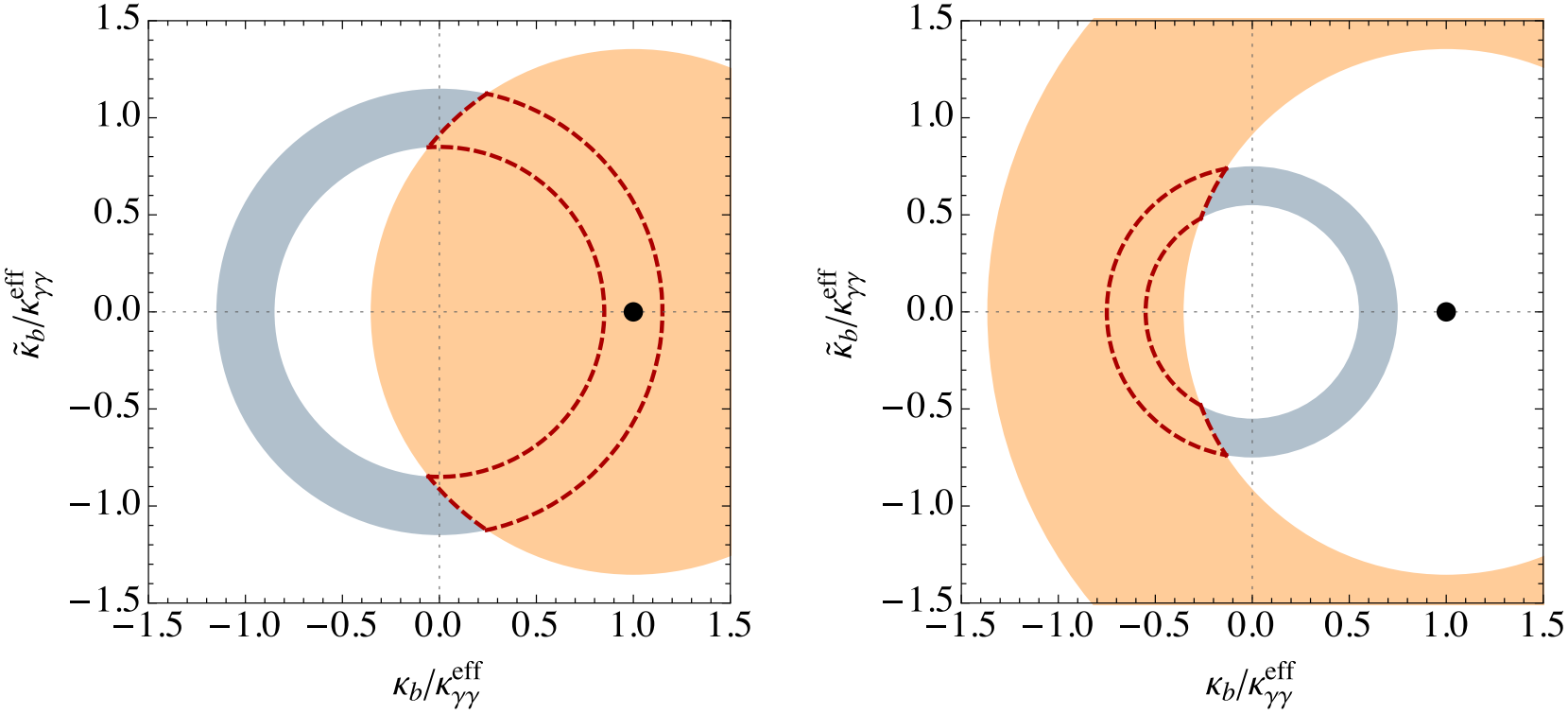

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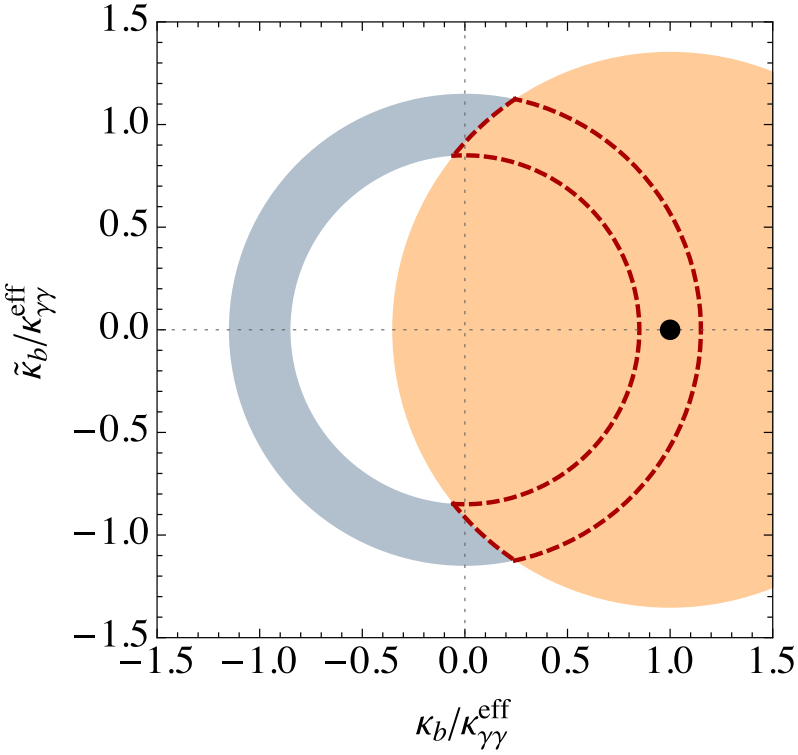

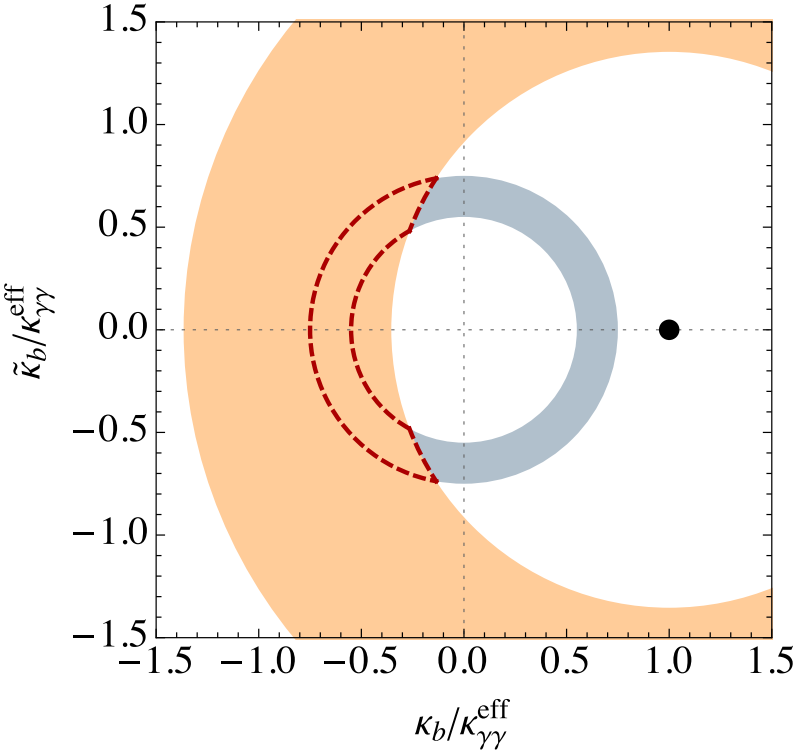

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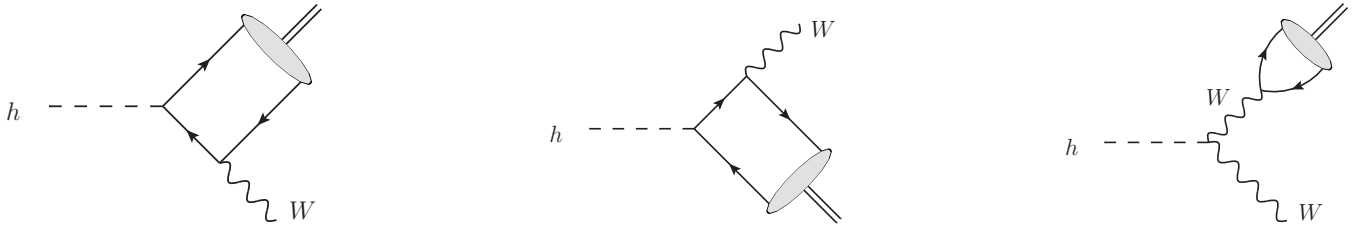
$\Rightarrow$ From the **overlap** one can find information on the CP-odd coupling, **even the sign** of the CP-even coupling!

Hadronic Higgs decays
Weak radiative hadronic Higgs decays

Flavor-changing Higgs couplings from $h \to M^+W^-$

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



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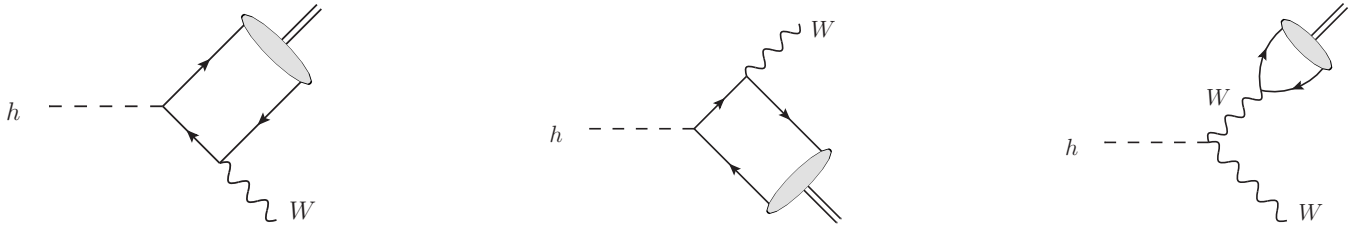

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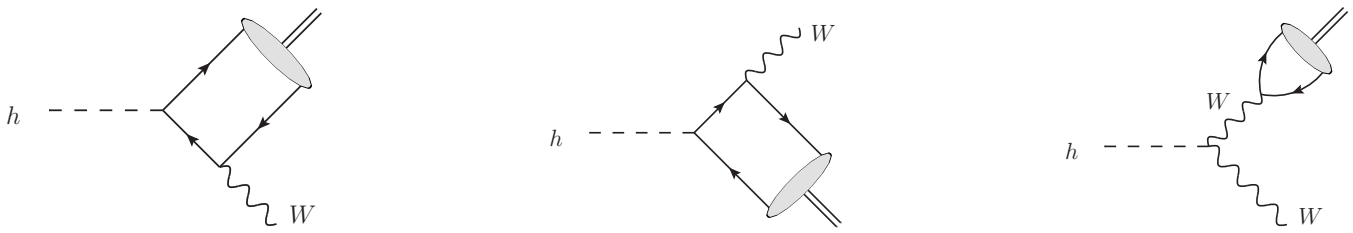

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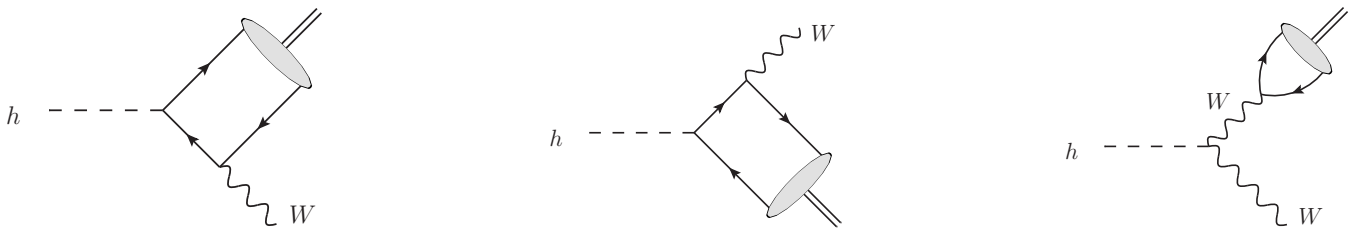

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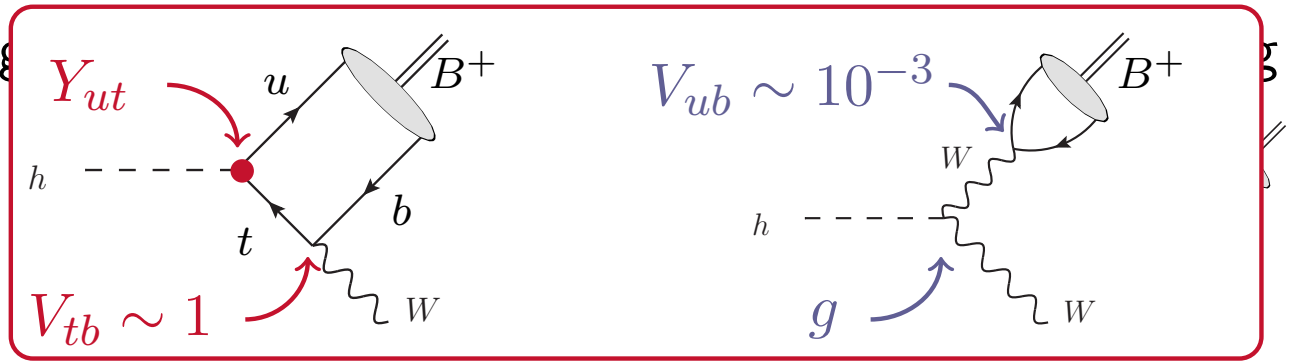

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JG|U

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

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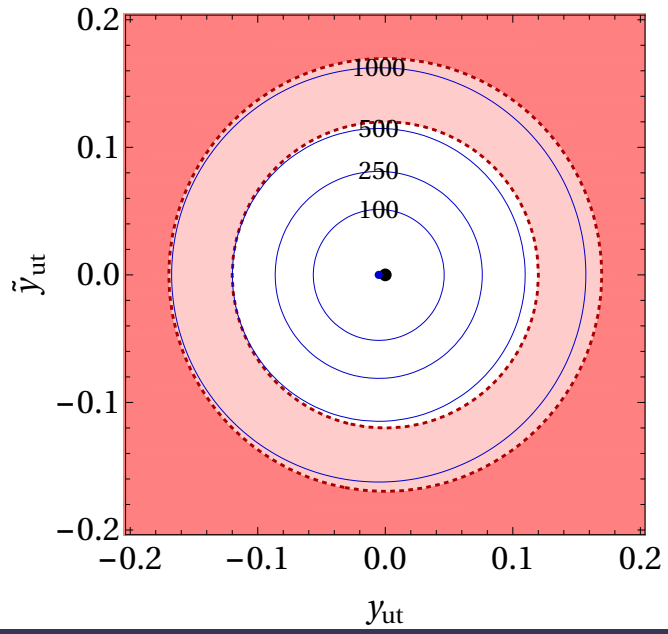

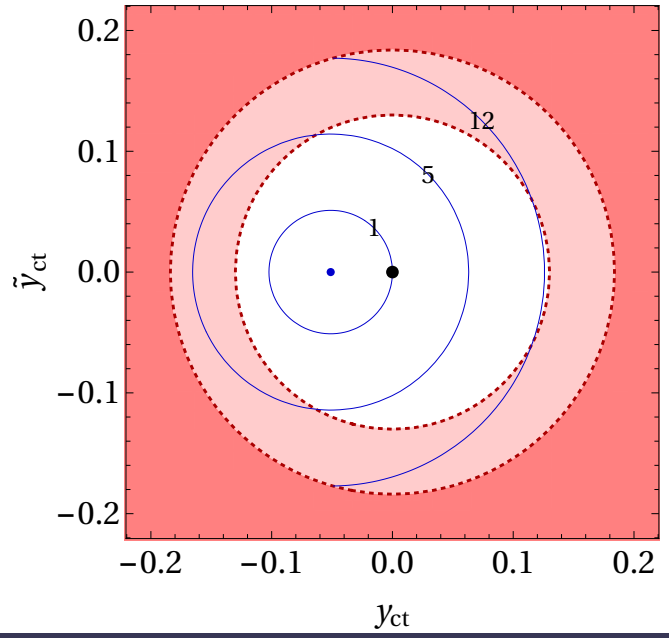

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Thank you for your attention!

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Backup slides

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

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

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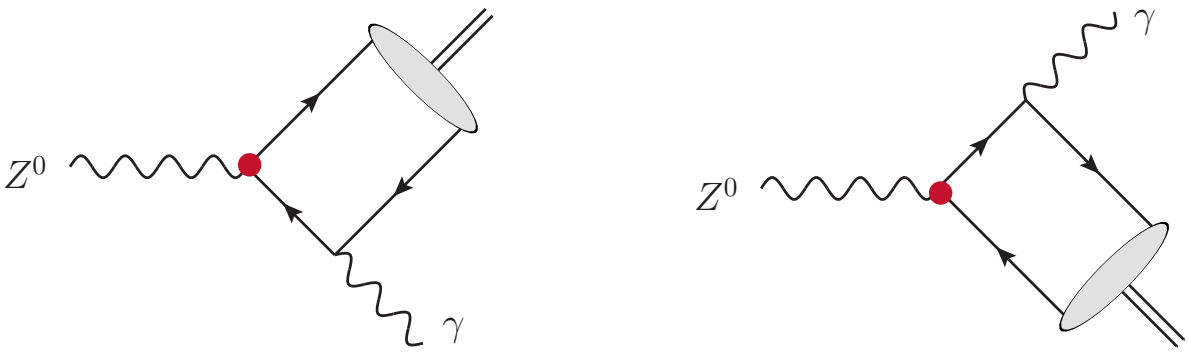

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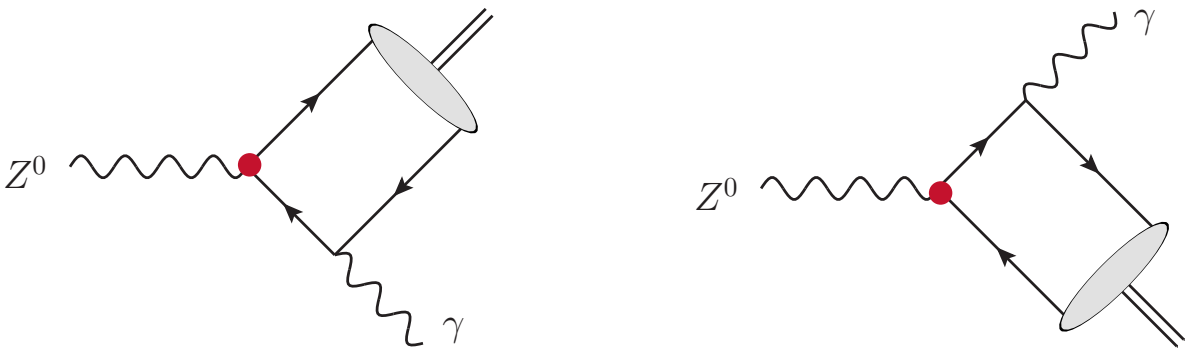

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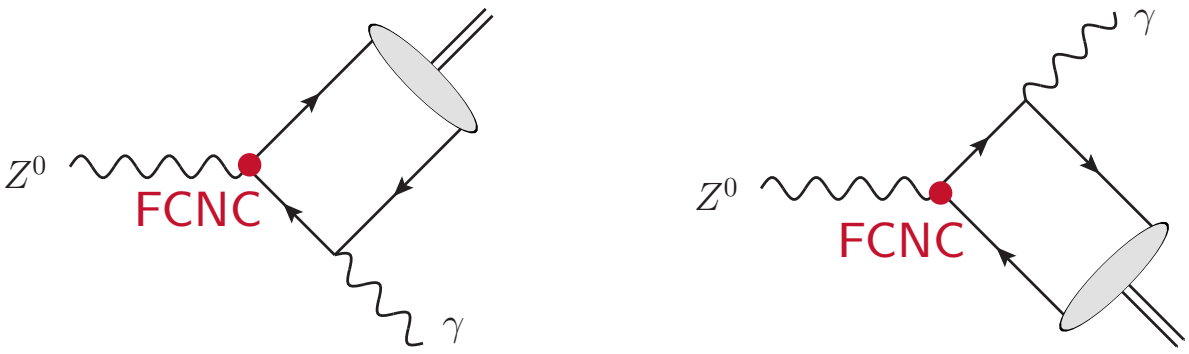

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Introducing FCNC couplings allows the production of flavor off-diagonal mesons

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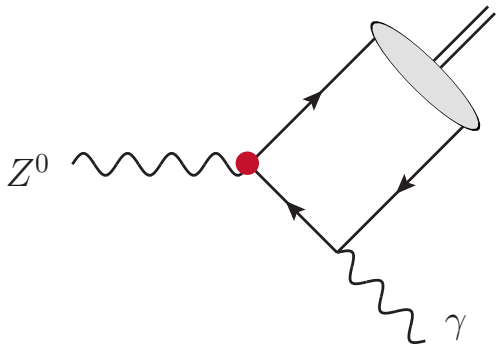

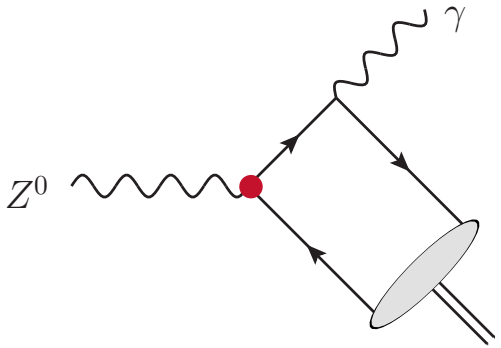

Model independent predictions for flavor off-diagonal mesons:

Decay mode	Branching ratio	SM background
$Z^0 \to K^0\gamma$	$\left[(7.70 \pm 0.83)\,\lvert v_{sd}\rvert^2 + (0.01 \pm 0.01)\,\lvert a_{sd}\rvert^2\right] \cdot 10^{-8}$	$\frac{\lambda}{\sin^2\theta_W}\,\frac{\alpha}{\pi} \sim 2 \cdot 10^{-3}$
$Z^0 \to D^0\gamma$	$\left[(5.30\,^{+0.67}_{-0.43})\,\lvert v_{cu}\rvert^2 + (0.62\,^{+0.36}_{-0.23})\,\lvert a_{cu}\rvert^2\right] \cdot 10^{-7}$	$\frac{\lambda}{\sin^2\theta_W}\,\frac{\alpha}{\pi} \sim 2 \cdot 10^{-3}$
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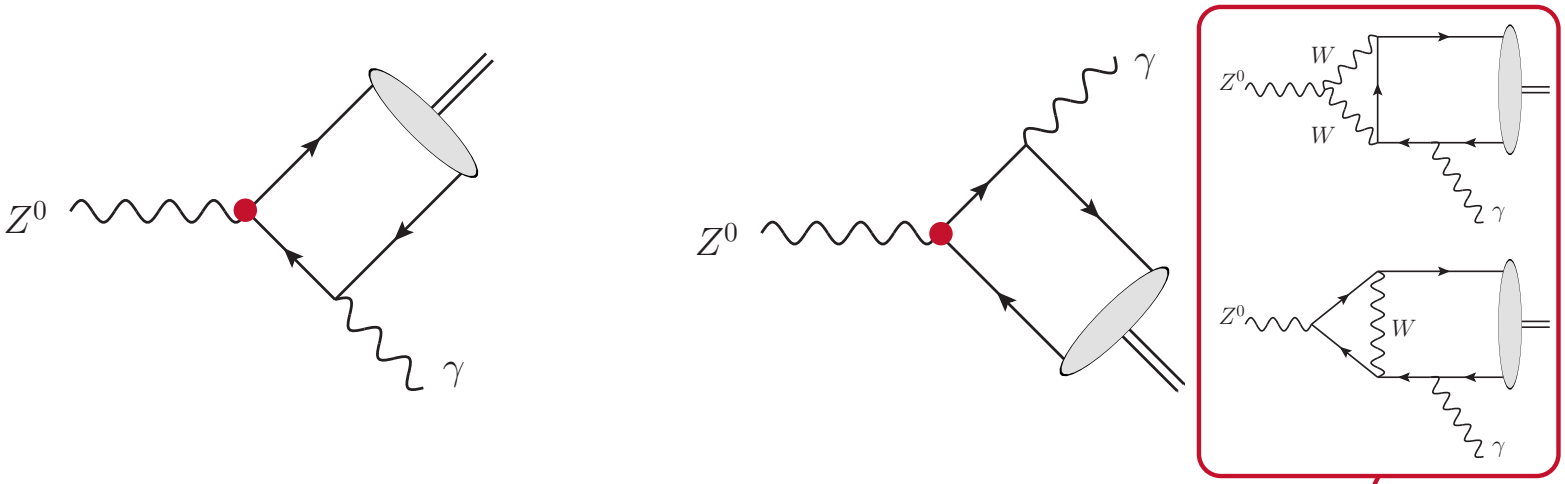

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FCNCs would induce tree-level neutral-meson mixing, strongly constrained:

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

[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 $\to$ This enables an experimental program to **test QCDF in a theoretically clean environment**!