# Exclusive radiative Higgs decays as probes of light-quark Yukawa couplings

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erc
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An Effective Field Theory Assault on the
Zeptometer Scale: Exploring the Origins of
Flavor and Electroweak Symmetry Breaking

# Introduction

Precise measurements of the **couplings of the Higgs boson** to SM particles provide a rich laboratory to search for new physics

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

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

**Yukawa couplings** to light fermions ($f \neq t$) are of particular relevance, since they can be modified significantly in many BSM models

Giudice, Lebedev (2008)
Harnik, Kopp, Zupan (2012)
Bauer, Carena, Gemmler: 1506.01719
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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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$h \to q\bar{q}$ rate measurements can determine the combination $\left(\kappa_q^2 + \tilde{\kappa}_q^2\right)$ for *q*=*b* (and bound it for *q*=*c*), but how can we access the couplings of other quarks, and how can we distinguish between $\kappa_q$ and $\tilde{\kappa}_q$ ?

EDMs only give weak constraints on $\tilde{\kappa}_{f\neq t}$, namely $|\tilde{\kappa}_b| < 1.9$ and $|\tilde{\kappa}_\tau| < 2.4$ at 90% CL and for SM-like *hee* coupling (cf. $|\tilde{\kappa}_t| < 0.01$ and $|\tilde{\kappa}_{\gamma\gamma}| < 0.006$)

Brod, Haisch, Zupan (2013)

# Introduction

**How, even if the Higgs boson couples to light quarks is so far largely unexplored !**

Our work is motivated by recent investigations of exclusive Higgs decays h→V$\gamma$, which were proposed as a way to probe for non-standard Yukawa couplings of the Higgs boson to light quarks

Bodwin, Petriello, Stoynev, Velasco (2013)
Kagan *et al.* (2014); Bodwin *et al.* (2014)

Such measurements are extremely challenging at LHC and future colliders

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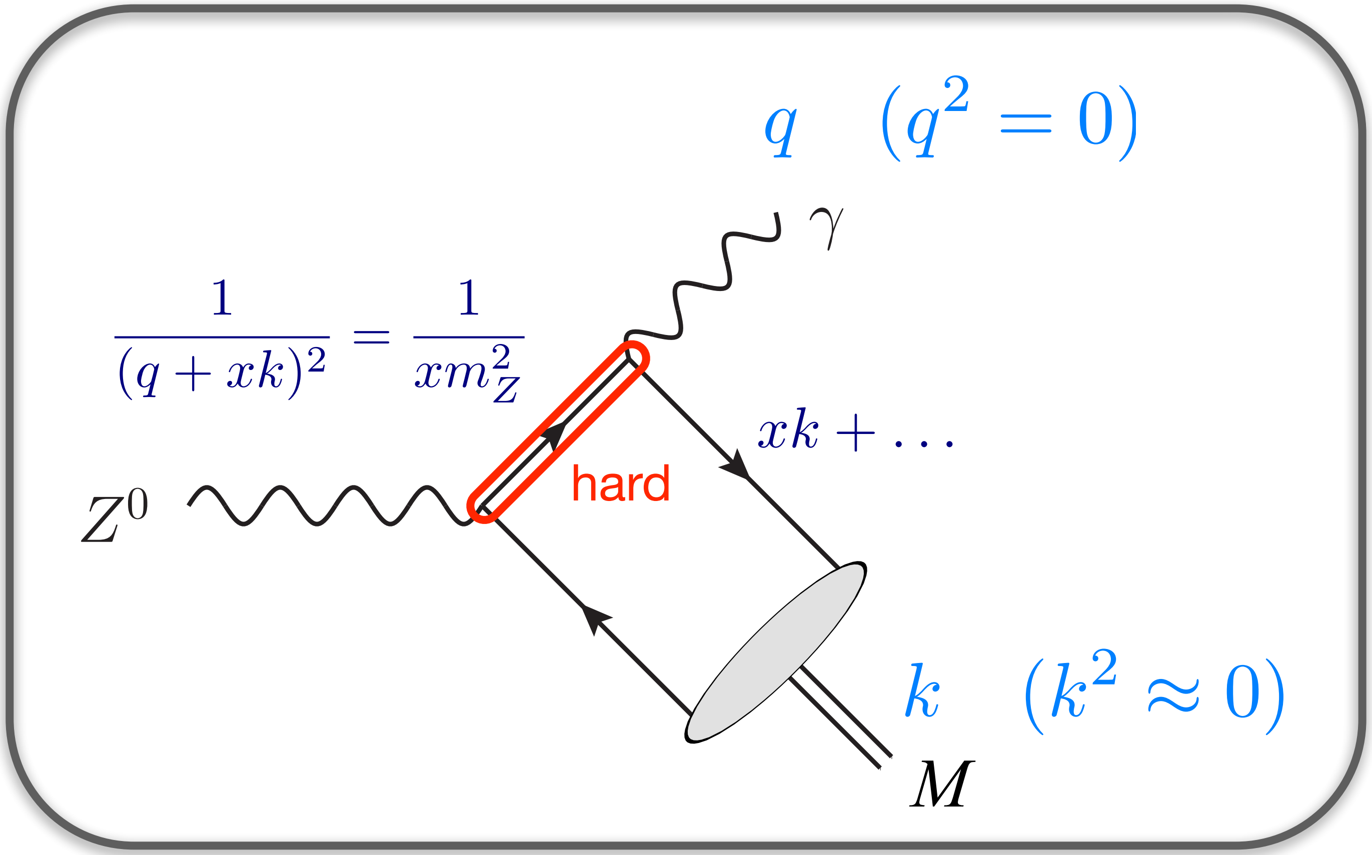
Based on:
"Exclusive radiative decays of W and Z bosons in QCD factorization"
Yuval Grossman, Matthias König, MN (arXiv:1501.06569, JHEP)

"Exclusive radiative Higgs decays as probes of light-quark Yukawa couplings" Matthias König, MN (arXiv:1505.03870, JHEP)

# Theoretical framework: QCD factorization

# Physical picture: Exclusive Z→Mγ decays

- intermediate propagator is highly virtual ($q^2 \sim m_Z^2$) and can be “integrated out”, giving rise to a **hard function** H(x)
- field operators for the external quark (and gluon) fields can be separated by **light-like distances**, since $k^2 \approx 0$
- simple application of SCET tools



At leading power in an expansion in $\Lambda_{\rm QCD}/m_Z$, one obtains the **QCD factorization theorem**:

Brodsky, Lepage (1979); Efremov, Radyushkin (1980)

$$\mathcal{A} = -i f_M E \int_0^1 dx\, H_M(x,\mu)\, \phi_M(x,\mu) + \text{power corrections}$$

decay constant:
extractable from data

hard function:
calculable in PT

LCDA:
non-perturbative hadronic physics

# Light-cone distribution amplitudes (LCDAs)

Momentum distribution of partons in a given Fock state of a meson (quark-antiquark, quark-antiquark-gluon, …):

$$\langle M(k)|\,\bar{q}(t\bar{n})\,\frac{\not{\bar{n}}}{2}\,(\gamma_5)\,[t\bar{n},0]\,q(0)|0\rangle = -if_M E \int_0^1 dx\, e^{ixt\bar{n}\cdot k}\,\phi_M(x,\mu)$$

Expansion in **Gegenbauer polynomials** (diagonalizes evolution at LO):

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

- Gegenbauer moments fall off faster than 1/n for large n
- for light mesons, the odd moments are SU(3)-violating effects
- all moments $a_n^M(\mu) \to 0$ (except $a_0^M \equiv 1$) in the limit $\mu \to \infty$
- model predictions obtained using lattice QCD, QCD sum rules and effective field theories (NRQCD, HQET)

Ball, Braun (1996); Ball *et al.* (2006, 2007)
Arthur *et al.* (2010)
Braguta, Likhoded, Luchinsky (2006)
Grozin, MN (1996); …

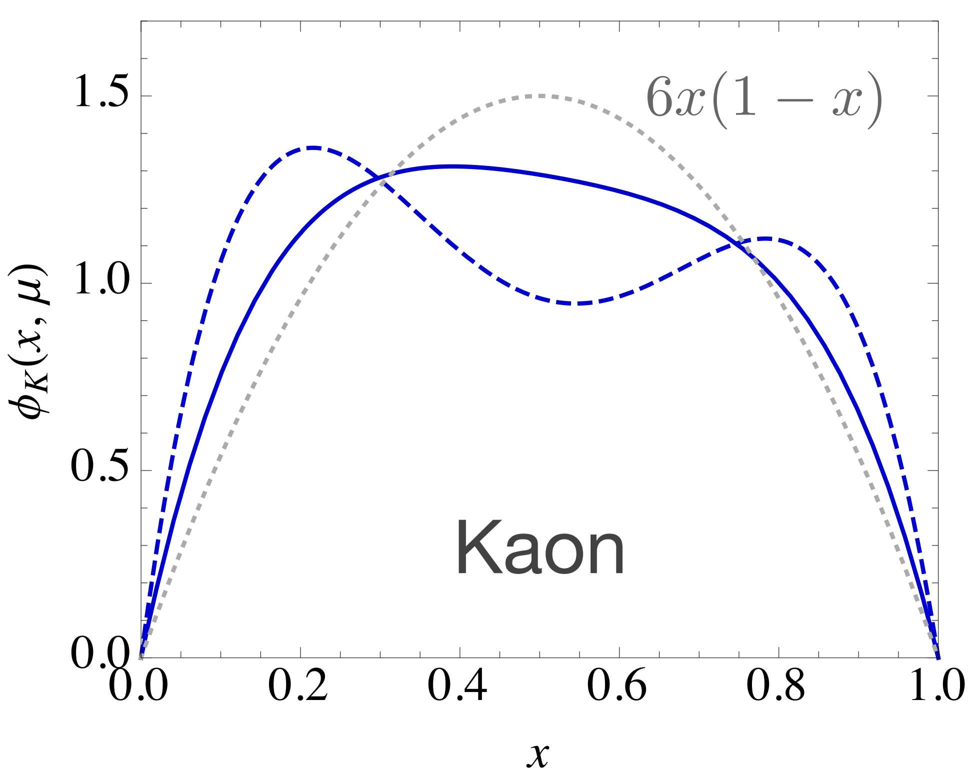
# RG evolution effects

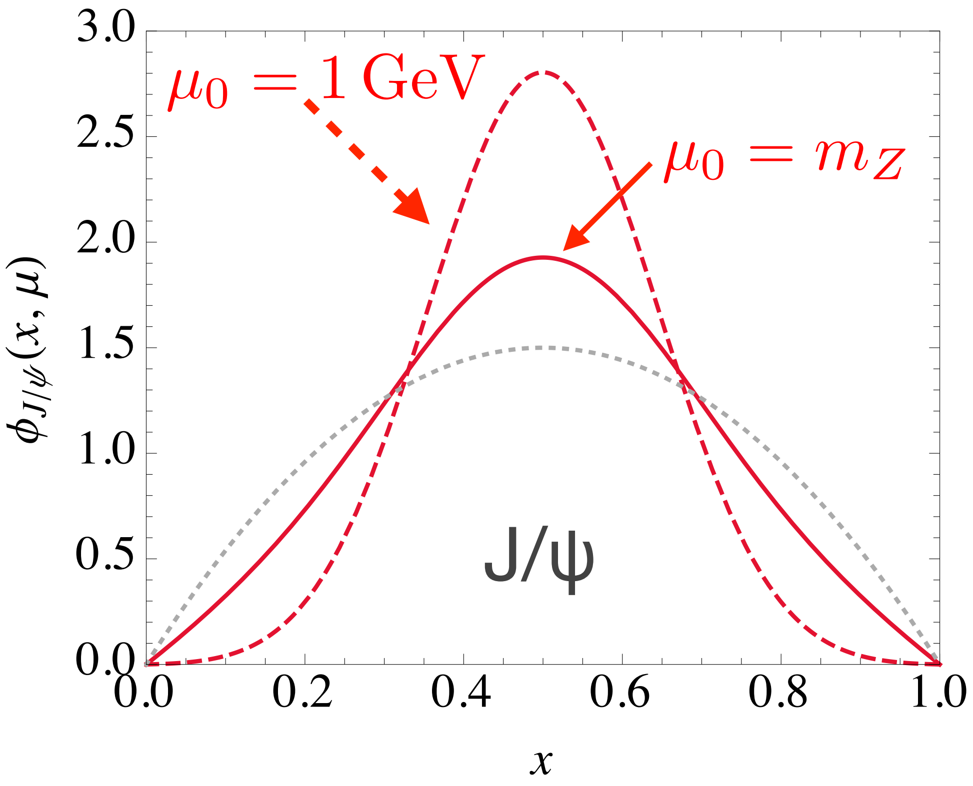
**RG evolution** from $\mu_0$ up to the **electroweak scale** changes the shapes of the LCDAs significantly, as they approach closer to the asymptotic form $\phi_M(x,\mu\to\infty)=6x(1-x)$

positive and increasing with n

Evolution of moments:

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





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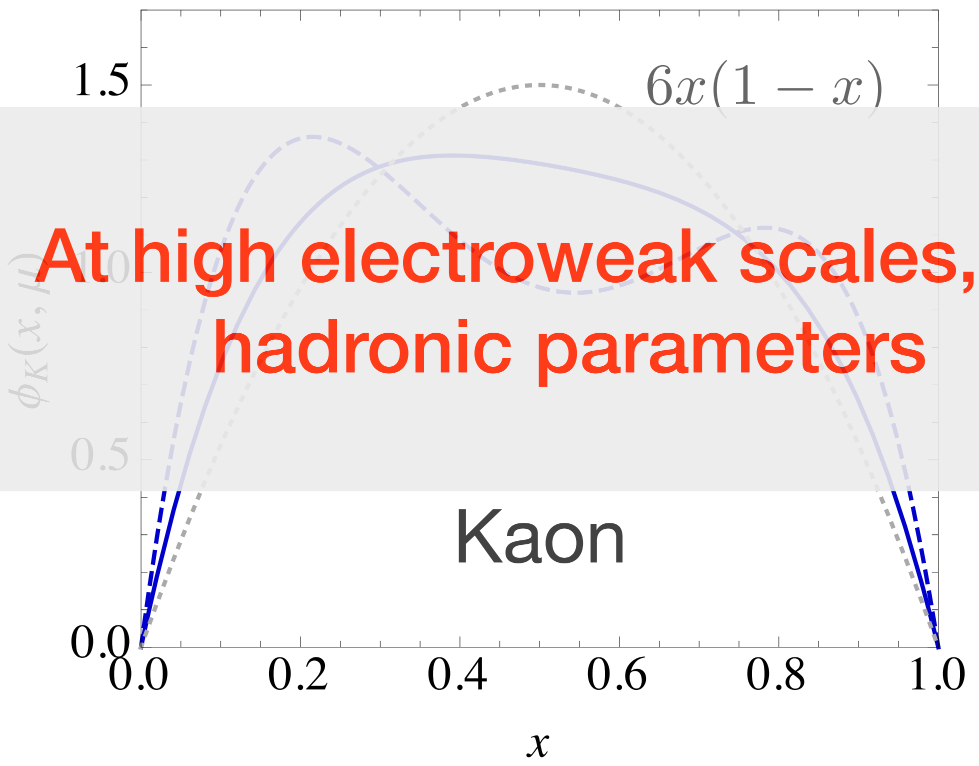
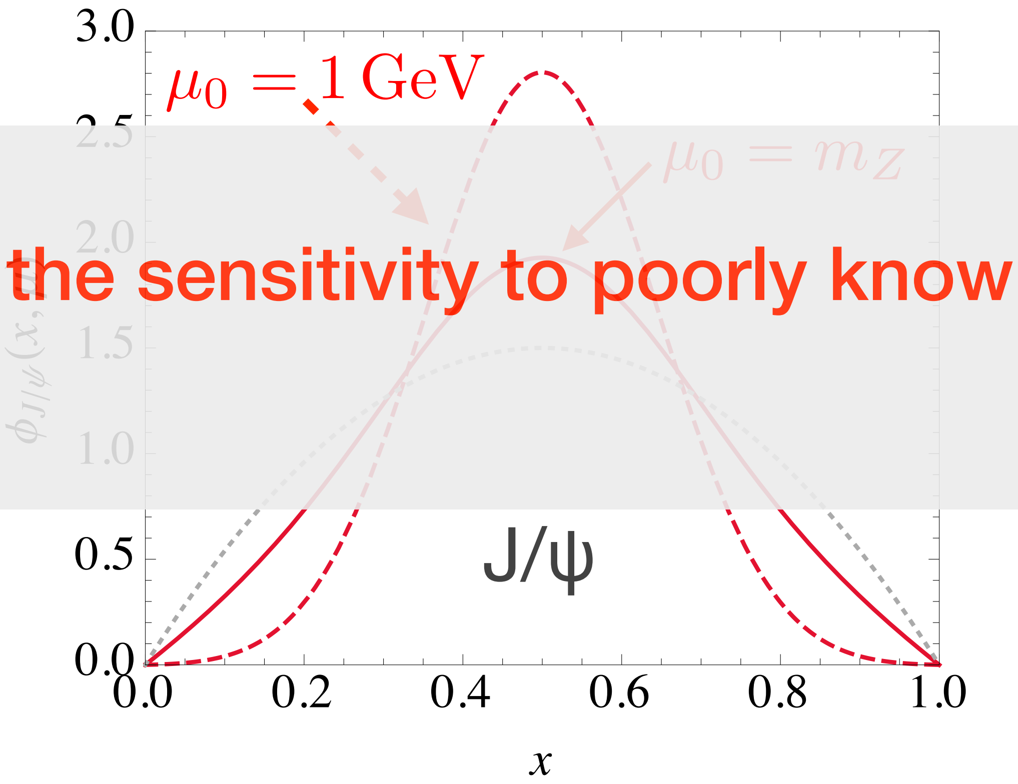


Kaon



J/ψ

At high electroweak scales, the sensitivity to poorly known hadronic parameters

# Power-suppressed corrections

Power-suppressed contributions to the decay amplitudes **with given helicities** are organized in an expansion in powers of $(\Lambda_{\text{QCD}}/m_Z)^2$ for light mesons and $(m_M/m_Z)^2$ for mesons containing heavy quarks

These corrections are **tiny**, of order $10^{-4}$ for light mesons and at most 1% for the heaviest meson we will consider — the $\Upsilon$(1S)

The QCD factorization approach thus allows for precise predictions, which are limited only by our incomplete knowledge of the LCDAs

# Radiative decays $h \to V\gamma$ as probes of light-quark Yukawa couplings

# Factorization of the decay amplitude

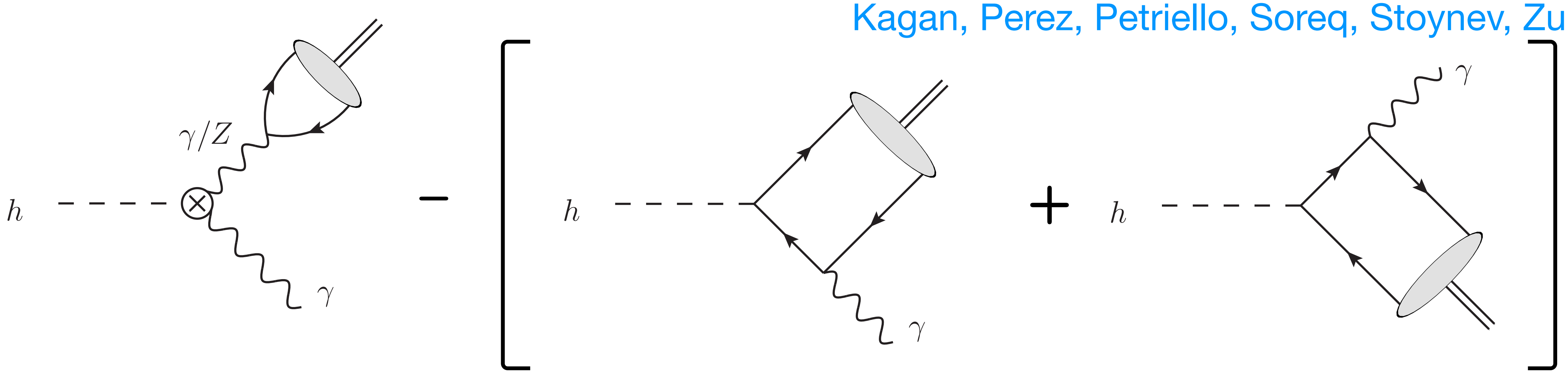
Form-factor decomposition of the decay amplitude:

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

**Destructive interference** of two competing decay topologies:

Bodwin, Petriello, Stoynev, Velasco (2013)

Kagan, Perez, Petriello, Soreq, Stoynev, Zupan (2014)



**direct** contribution, proportional to $\kappa_q$ and $\tilde{\kappa}_q$

$$\frac{y_q}{\sqrt{2}} = (\kappa_q + i\tilde{\kappa}_q)\,\frac{m_q}{v}$$

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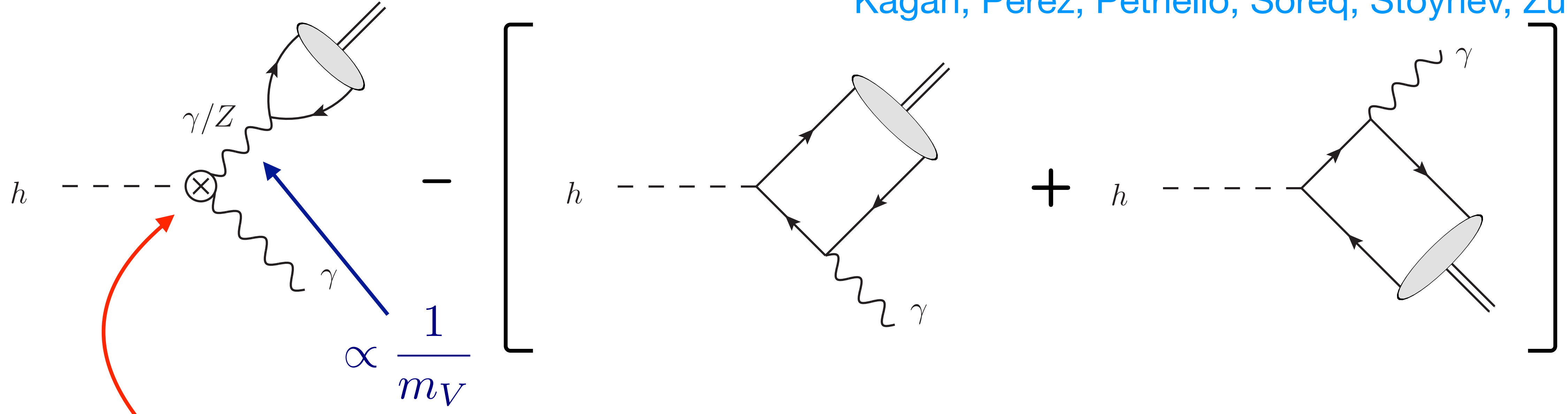
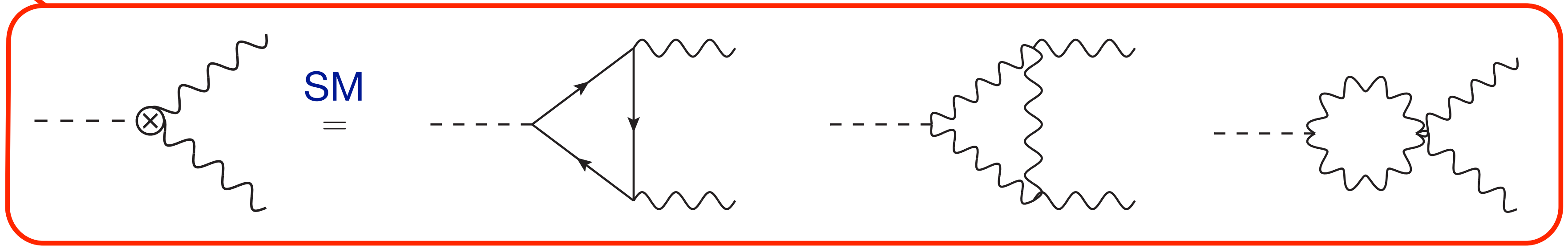


**indirect** contribution, induced via $h\to\gamma+(\gamma/Z)^*$ transition (SM and NP )



# Factorization of the decay amplitude

Previous analyses basically allowed for new physics only in the Higgs couplings to light quarks (in fact only $\kappa_q$) and worked at tree level in $\alpha_s$

Bodwin, Petriello, Stoynev, Velasco (2013)
Kagan, Perez, Petriello, Soreq, Stoynev, Zupan (2014)

In the present work, we:

- allow for **generic new-physics effects** in the Higgs sector (incl. CPV)
- include **NLO QCD corrections** and resummation of large logarithms in the direct contribution
- include QCD and EW corrections in the indirect (pole) contributions and account for the **off-shellness** of the $\gamma^*$ and Z*
- include the effects of ρ-ω-ϕ mixing
- update extraction of hadronic input parameters

Most importantly, we exploit the dependence on both $\kappa_q$ and $\tilde{\kappa}_q$ to obtain **independent information** on both parameters

# Direct contribution to the form factors

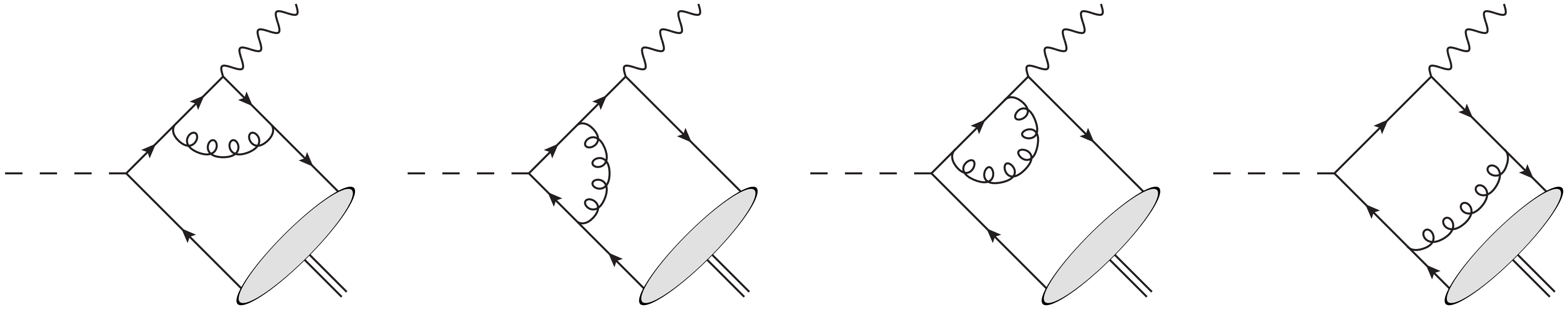
Results obtained at NLO in QCD factorization:

$$F^V_{1,\mathrm{direct}} = \frac{m_q}{m_b}\boxed{\kappa_q}Q_q\,F_V\,, \qquad F^V_{2,\mathrm{direct}} = \frac{m_q}{m_b}\boxed{\tilde{\kappa}_q}Q_q\,F_V$$

Reduced form factors:

$$F_V = \frac{m_b(\mu)}{v}\,\frac{f_V^\perp(\mu)}{f_V}\int_0^1 dx\,\frac{\phi_V^\perp(x,\mu)}{x(1-x)}\left[1+\frac{C_F\alpha_s(\mu)}{4\pi}\,h(x,m_h,\mu)+\mathcal{O}(\alpha_s^2)\right]$$

$$h(x,m_h,\mu) = 2\ln\left[x(1-x)\right]\left(\ln\frac{m_h^2}{\mu^2}-i\pi\right)+\ln^2 x+\ln^2(1-x)-3$$



# Direct contribution to the form factors

Resumming large logarithms using RG evolution up to the electroweak scale $\mu \sim m_h$, and accounting for various sources of theoretical uncertainties, we obtain:

| Meson | Form factor with errors [%] | Combined value [%] |
|---|---|---|
| $F_{\rho^0}$ | $4.30\,^{+0.04}_{-0.05}{}_{\mu} \pm 0.03_{m_b} \pm 0.24_f \pm 0.12_{a_2} \pm 0.22_{a_4}$<br>$+i\big(0.67\,^{+0.14}_{-0.10}{}_{\mu} \pm 0.00_{m_b} \pm 0.04_f \pm 0.03_{a_2} \pm 0.06_{a_4}\big)$ | $(4.30 \pm 0.35) + i(0.67 \pm 0.14)$ |
| $F_{\omega}$ | $4.26\,^{+0.04}_{-0.05}{}_{\mu} \pm 0.03_{m_b} \pm 0.30_f \pm 0.14_{a_2} \pm 0.21_{a_4}$<br>$+i\big(0.66\,^{+0.14}_{-0.10}{}_{\mu} \pm 0.00_{m_b} \pm 0.05_f \pm 0.03_{a_2} \pm 0.06_{a_4}\big)$ | $(4.26 \pm 0.40) + i(0.66 \pm 0.14)$ |
| $F_{\phi}$ | $4.53\,^{+0.04}_{-0.05}{}_{\mu} \pm 0.03_{m_b} \pm 0.24_f \pm 0.15_{a_2} \pm 0.23_{a_4}$<br>$+i\big(0.70\,^{+0.14}_{-0.10}{}_{\mu} \pm 0.01_{m_b} \pm 0.04_f \pm 0.04_{a_2} \pm 0.06_{a_4}\big)$ | $(4.53 \pm 0.37) + i(0.70 \pm 0.15)$ |
| $F_{J/\psi}$ | $4.54\,^{+0.02}_{-0.04}{}_{\mu} \pm 0.03_{m_b} \pm 0.70_f\,^{+0.13}_{-0.17}{}_{\sigma_V}$<br>$+i\big(0.63\,^{+0.11}_{-0.08}{}_{\mu} \pm 0.00_{m_b} \pm 0.10_f\,^{+0.03}_{-0.04}{}_{\sigma_V}\big)$ | $(4.54 \pm 0.72) + i(0.63 \pm 0.14)$ |
| $F_{\Upsilon(1S)}$ | $5.04\,^{+0.02}_{-0.03}{}_{\mu} \pm 0.04_{m_b} \pm 0.18_f\,^{+0.09}_{-0.07}{}_{\sigma_V}$<br>$+i\big(0.66\,^{+0.12}_{-0.08}{}_{\mu} \pm 0.00_{m_b} \pm 0.02_f\,^{+0.02}_{-0.01}{}_{\sigma_V}\big)$ | $(5.04 \pm 0.21) + i(0.66 \pm 0.10)$ |
| $F_{\Upsilon(2S)}$ | $5.09\,^{+0.02}_{-0.04}{}_{\mu} \pm 0.04_{m_b} \pm 0.24_f\,^{+0.13}_{-0.12}{}_{\sigma_V}$<br>$+i\big(0.68\,^{+0.12}_{-0.09}{}_{\mu} \pm 0.00_{m_b} \pm 0.03_f\,^{+0.03}_{-0.02}{}_{\sigma_V}\big)$ | $(5.09 \pm 0.27) + i(0.68 \pm 0.11)$ |
| $F_{\Upsilon(3S)}$ | $5.11\,^{+0.02}_{-0.04}{}_{\mu} \pm 0.04_{m_b} \pm 0.24_f\,^{+0.15}_{-0.14}{}_{\sigma_V}$<br>$+i\big(0.69\,^{+0.12}_{-0.09}{}_{\mu} \pm 0.00_{m_b} \pm 0.03_f\,^{+0.04}_{-0.03}{}_{\sigma_V}\big)$ | $(5.11 \pm 0.29) + i(0.69 \pm 0.12)$ |

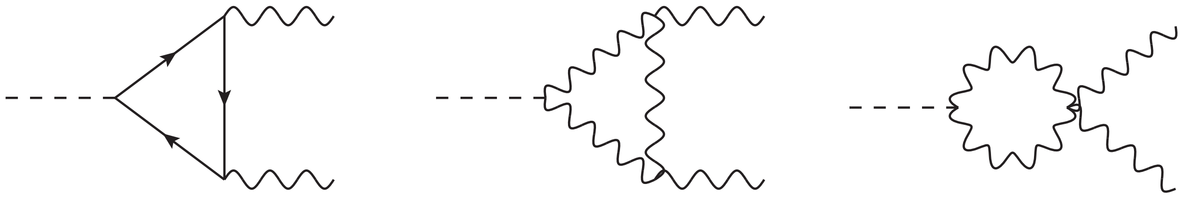
# Indirect contribution to the form factors

Result involves loop contributions from all charged SM particles, e.g.:

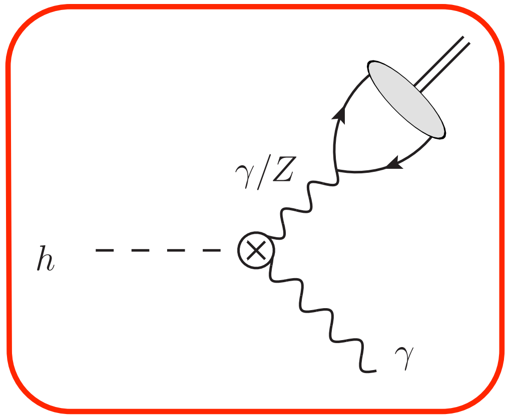
$$F^V_{1,\text{indirect}} = \frac{\alpha(m_V)}{\pi} \frac{m_h^2 - m_V^2}{m_V\, v} \left[ Q_V\, C_{\gamma\gamma}(x_V) - \frac{v_V}{(s_W c_W)^2} \frac{m_V^2}{m_Z^2 - m_V^2} C_{\gamma Z}(x_V) \right]$$

with:

$$C_{\gamma\gamma,\gamma Z}(x_V) =$$



$+$ new physics



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with:

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

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

Contribution of the **on-shell h→γγ amplitude** (including all its radiative corrections), which is sensitive to many new-physics parameters, can be eliminated by considering a **ratio of decay rates**

# Master formula

Ratio of branching fractions:

$$\frac{\mathrm{Br}(h\to V\gamma)}{\mathrm{Br}(h\to\gamma\gamma)}=\frac{\Gamma(h\to V\gamma)}{\Gamma(h\to\gamma\gamma)}=\frac{8\pi\alpha^2(m_V)}{\alpha}\,\frac{Q_V^2 f_V^2}{m_V^2}\left(1-\frac{m_V^2}{m_h^2}\right)^2\frac{\left|1-\Delta_V\right|^2+\left|r_{\mathrm{CP}}-\tilde{\Delta}_V\right|^2}{1+|r_{\mathrm{CP}}|^2}$$

Advantages:

- leading term predicted without theoretical uncertainties
- off-shellness effects and h→γZ$^*$→γV contribution (included in $\Delta_V$) are power suppressed $\sim m_V^2/m_{h,Z}^2$ and very small even for ϒ(1S)
- ratio of branching ratios is insensitive to the unknown total Higgs width
- parameter $r_{\mathrm{CP}}$ accounts for CP violation in h→γγ decay and is bounded to be <1% in magnitude (EDMs), hence it is safe to set $r_{\mathrm{CP}}$=0

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Theoretical predictions for the hadronic quantities:

power corrections

$$\Delta_\phi=\Big[(0.0021\pm0.0002)+i(0.0003\pm0.0001)\Big]\,\frac{\kappa_s}{\kappa_{\gamma\gamma}^{\mathrm{eff}}}+0.00014$$

$$\Delta_{J/\psi}=\Big[(0.086\pm0.014)+i(0.012\pm0.003)\Big]\,\frac{\kappa_c}{\kappa_{\gamma\gamma}^{\mathrm{eff}}}+0.00005$$

$$\Delta_{\Upsilon(1S)}=\Big[(0.948\pm0.040)+i(0.130\pm0.019)\Big]\,\frac{\kappa_b}{\kappa_{\gamma\gamma}^{\mathrm{eff}}}+0.0184-0.0015i$$

Almost identical expressions (with $\kappa_q$ replaced by $\tilde{\kappa}_q$ ) hold for $\tilde{\Delta}_V$

# Key observations

Theoretical predictions for the hadronic quantities:

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- interference with the direct amplitude is a small effect for ϕ, J/ψ and lighter mesons, which are therefore primarily sensitive to $\kappa_q \propto \text{Re}(y_q)$
- on the other hand, one finds an almost perfect destructive interference for $\Upsilon$(1S), where (apart form tiny imaginary part) the decay amplitude has a **magic zero** at $\kappa_b/\kappa_{\gamma\gamma}^{\text{eff}} = 1.055 \pm 0.045$

[also: Bodwin, Chung, Ee, Lee, Petriello (2014)]

# Key observations

This fortuitous cancellation is **accidental** in the SM — a gift of Nature, which offers us a wonderful **opportunity** to search for new physics!

Predictions for SM branching ratios:

$$\begin{aligned}
\mathrm{Br}(h \to \rho^0 \gamma) &= (1.68 \pm 0.02_{f_\rho} \pm 0.08_{h\to\gamma\gamma}) \cdot 10^{-5} \\
\mathrm{Br}(h \to \omega \gamma) &= (1.48 \pm 0.03_{f_\omega} \pm 0.07_{h\to\gamma\gamma}) \cdot 10^{-6} \\
\mathrm{Br}(h \to \phi \gamma) &= (2.31 \pm 0.03_{f_\phi} \pm 0.11_{h\to\gamma\gamma}) \cdot 10^{-6} \\
\mathrm{Br}(h \to J/\psi\, \gamma) &= (2.95 \pm 0.07_{f_{J/\psi}} \pm 0.06_{\text{direct}} \pm 0.14_{h\to\gamma\gamma}) \cdot 10^{-6} \\
\mathrm{Br}(h \to \Upsilon(1S)\, \gamma) &= (4.61 \pm 0.06_{f_{\Upsilon(1S)}} \,{}^{+\,1.75}_{-\,1.21}{}_{\text{direct}} \pm 0.22_{h\to\gamma\gamma}) \cdot \boxed{10^{-9}} \\
\mathrm{Br}(h \to \Upsilon(2S)\, \gamma) &= (2.34 \pm 0.04_{f_{\Upsilon(2S)}} \,{}^{+\,0.75}_{-\,0.99}{}_{\text{direct}} \pm 0.11_{h\to\gamma\gamma}) \cdot \boxed{10^{-9}} \\
\mathrm{Br}(h \to \Upsilon(3S)\, \gamma) &= (2.13 \pm 0.04_{f_{\Upsilon(3S)}} \,{}^{+\,0.75}_{-\,1.12}{}_{\text{direct}} \pm 0.10_{h\to\gamma\gamma}) \cdot \boxed{10^{-9}}
\end{aligned}$$

Branching fractions of $10^{-6}$ may be accessible in the high-luminosity run at the LHC (with 3 $\mathrm{ab}^{-1}$ of integrated luminosity)

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

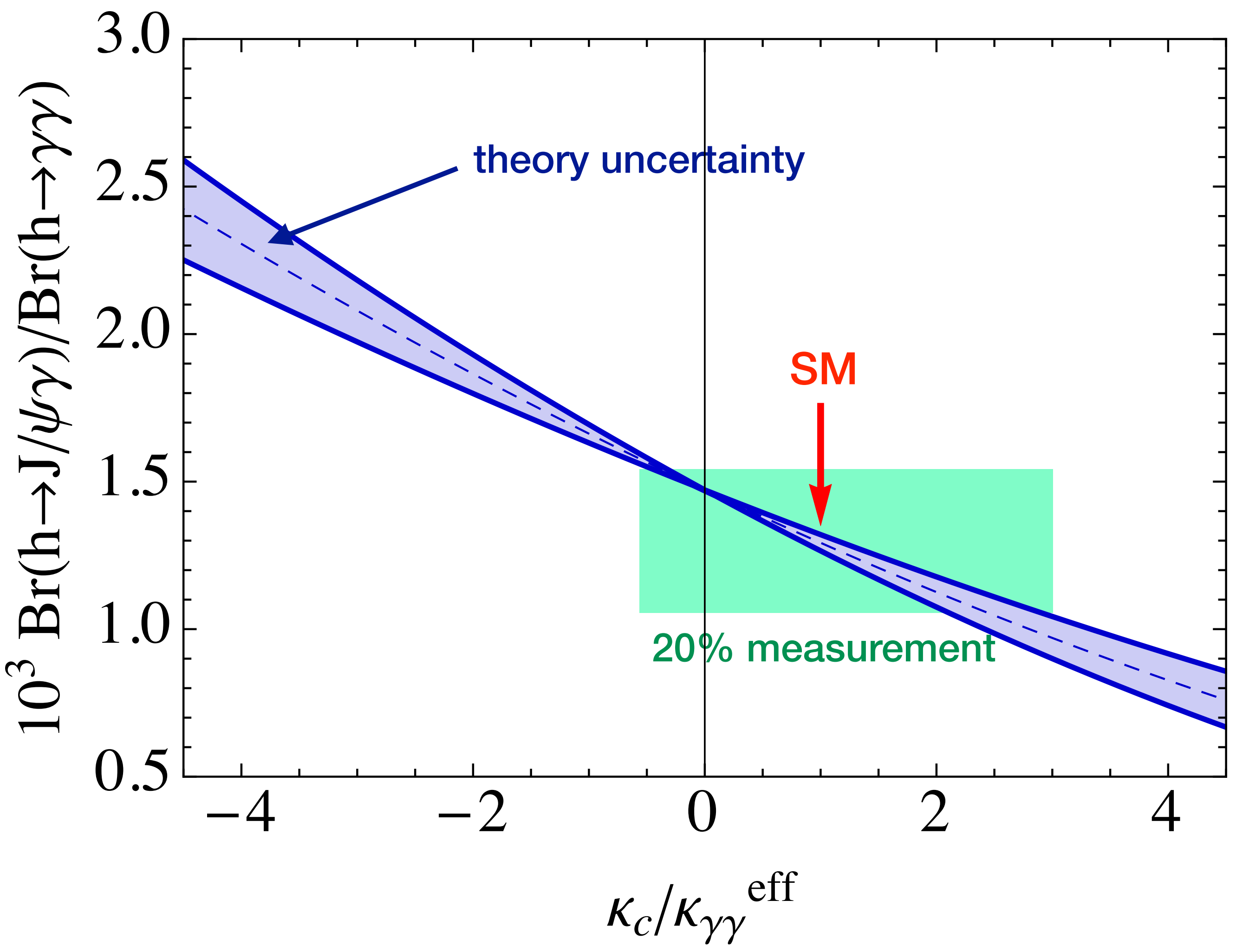
$$\mathrm{Br}(h \to \Upsilon(1S)\, \gamma) = (4.61 \pm 0.06 \quad {}^{+1.75} \quad \pm 0.22 \quad ) \cdot 10^{-9}$$

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

**Seeing even a single $h \to \Upsilon(nS)\,\gamma$ event at the LHC would be a clear sign of new physics !**

Branching fractions of $10^{-6}$ may be accessible in the high-luminosity run at the LHC (with 3 $\mathrm{ab}^{-1}$ of integrated luminosity)

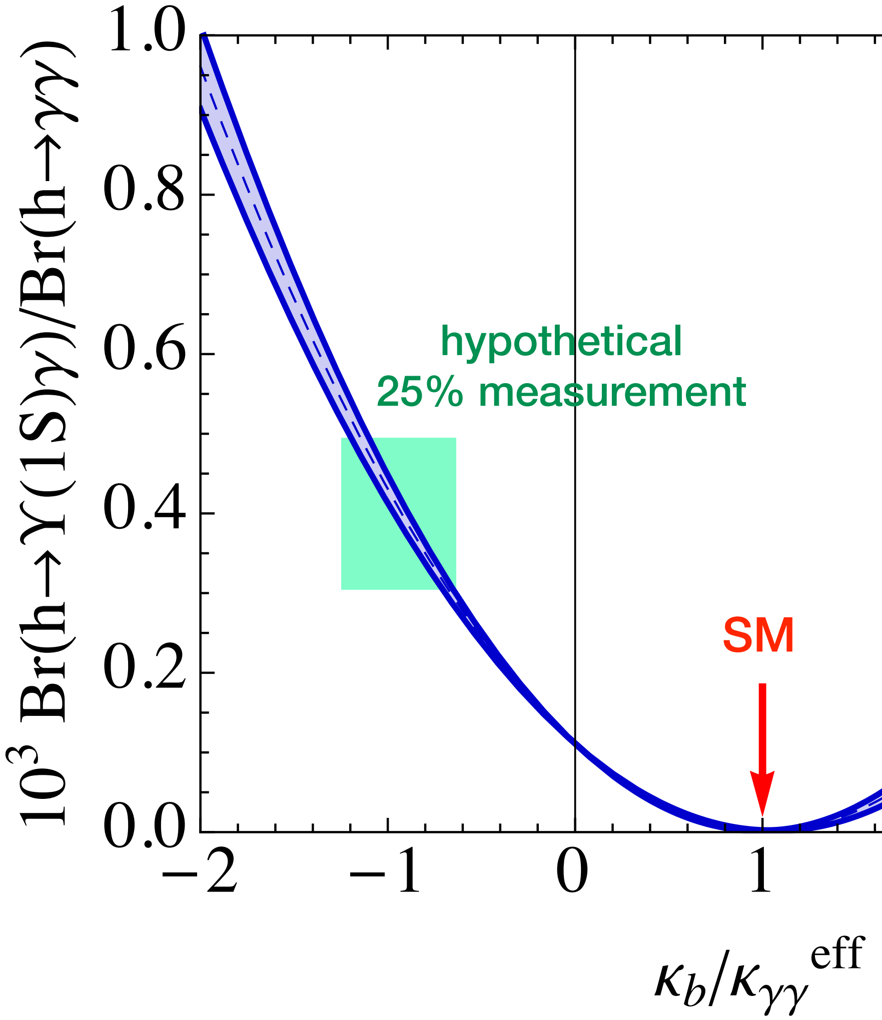
# Predictions for h→J/ψ γ (no CP violation)



Features:

- SM branching ratio ~ $3{\cdot}10^{-6}$ challenging [also: Bodwin, Chung, Ee, Lee, Petriello (2014)]
- with $1.7{\cdot}10^{8}$ Higgs boson (per exp.) produced in 3 $ab^{-1}$ in high-luminosity run at LHC, one can hope for **~100 events** (using leptonic J/ψ decays)
- a 20% measurement would constrain $-0.50 < \kappa_c/\kappa_{\gamma\gamma}^{\text{eff}} < 3.1$

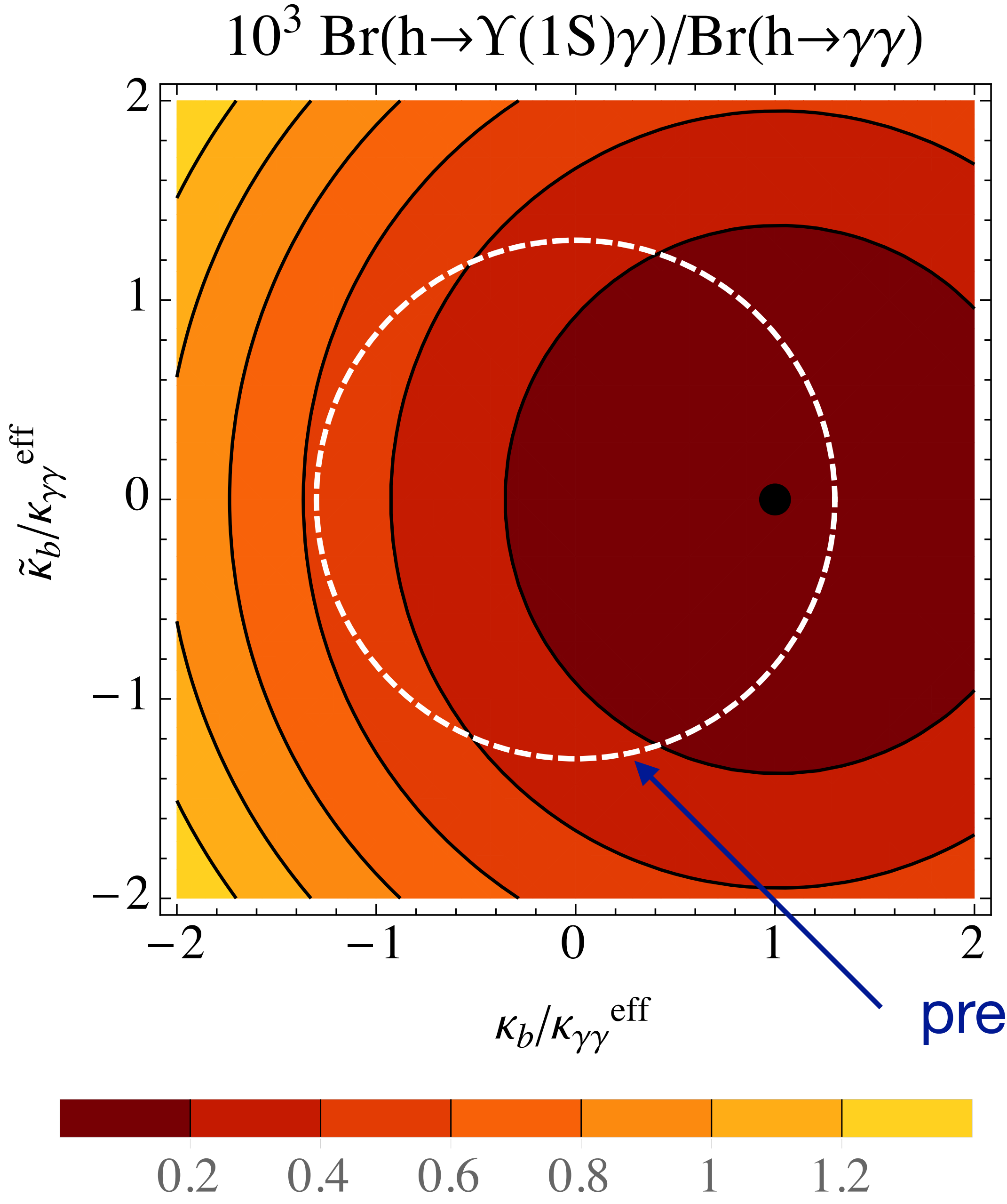
# Predictions for h→Υ(1S) γ (no CP violation)



Features:

- SM branching ratio ~ $5 \cdot 10^{-9}$ hopeless [also: Bodwin, Chung, Ee, Lee, Petriello (2014)]
- may be possible to probe the **interesting region** where $\kappa_b \approx -1$
- hypothetical measurement $\text{Br}(h \to \Upsilon(1S)\,\gamma)/\text{Br}(h \to \gamma\gamma) = (0.4 \pm 0.1) \cdot 10^{-3}$ would imply a clear hint of new physics, with $-1.21 < \kappa_b/\kappa_{\gamma\gamma}^{\text{eff}} < -0.64$

# Predictions including CP-odd couplings

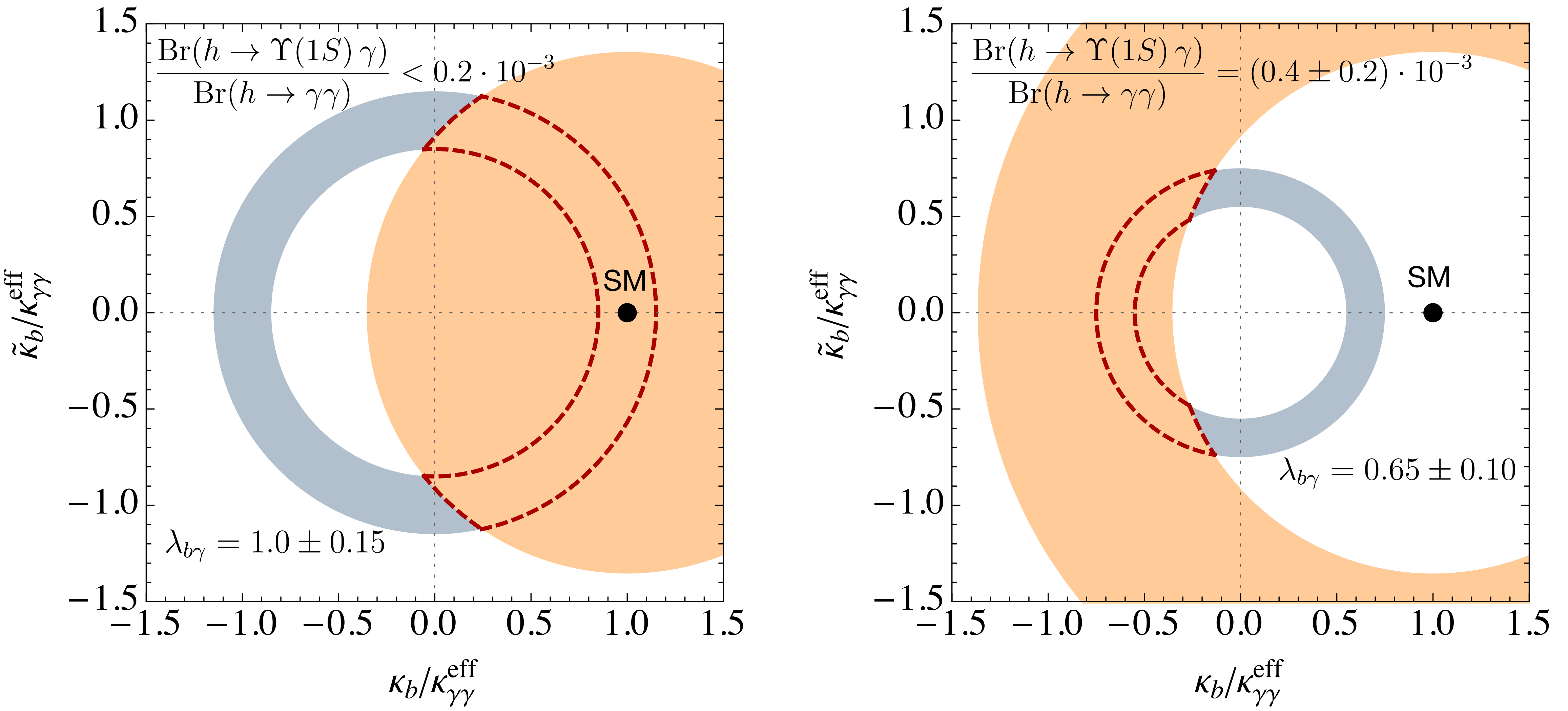


preferred region

- $h \to \Upsilon(1S)\,\gamma$ mode constrains $(1-\kappa_b)^2 + \tilde{\kappa}_b^2$, while $h \to b\bar{b}$ rate measurements constrain $\kappa_b^2 + \tilde{\kappa}_b^2$
- highly **complementary information**

# Predictions including CP-odd couplings

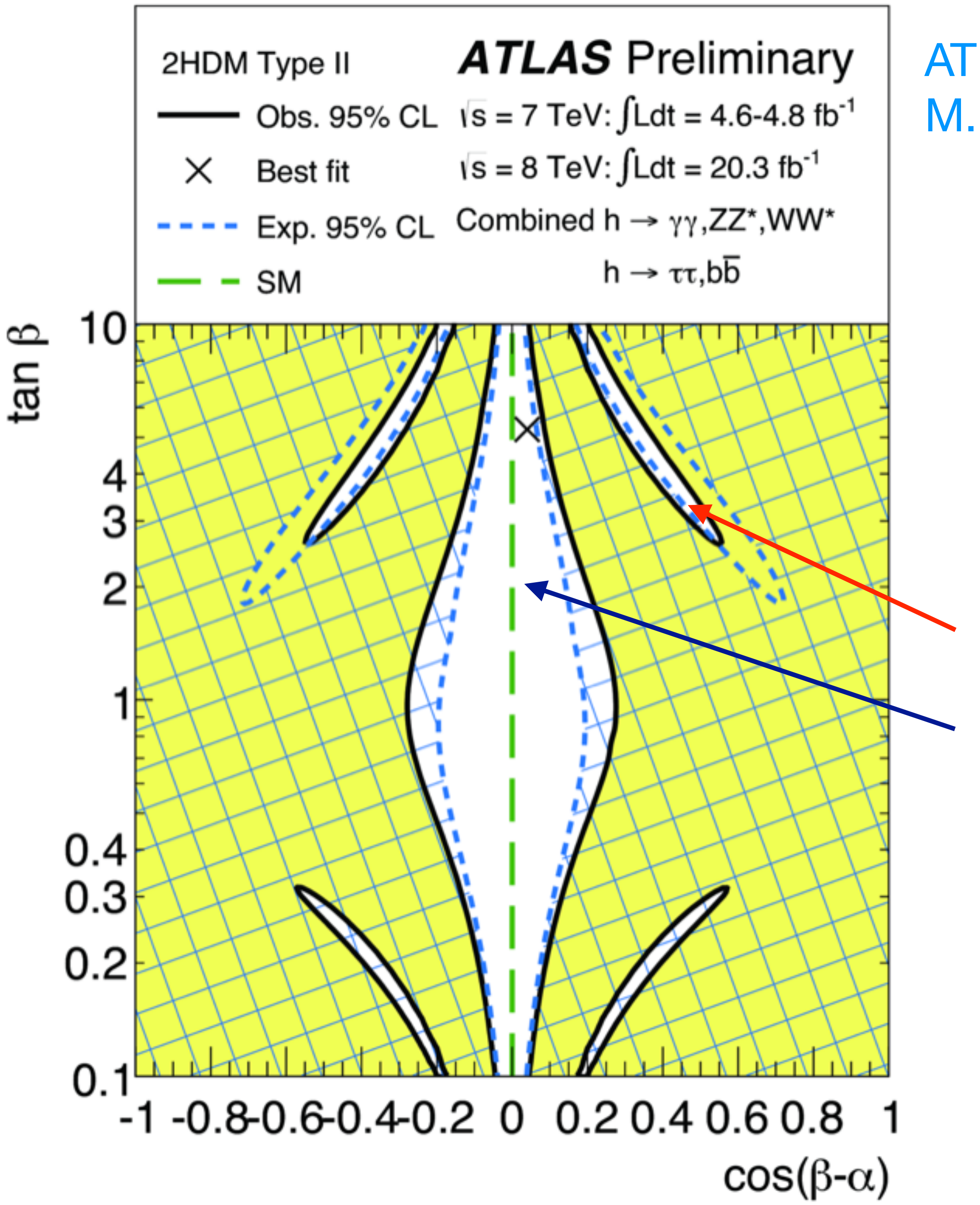
Two possible scenarios:



**This is the only method which we are aware of that can provide a path to constrain $\kappa_b$ and $\tilde{\kappa}_b$ independently !**

# Implications for BSM models

There exist well-motivated models in which $\kappa_b$ can differ significantly from its SM value, e.g. type-II 2-Higgs doublet models:



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M. Bauer: priv. discussion

branch with $\kappa_b \approx -1$

branch with $\kappa_b \approx +1$

# Conclusions

# Summary

- ★ Future Higgs factories with highest luminosities (LHC, 100 TeV collider) open up the possibility to measure very rare, exclusive radiative decays of Higgs bosons with decent precision

- ★ Exclusive radiative decays of Higgs bosons can be used to probe in a direct way the Yukawa couplings of the Higgs to light quarks, giving access to $\kappa_b,\ \tilde{\kappa}_b,\ \kappa_c$ (and perhaps even $\kappa_s$) in a way that is unrivaled by any other method known to us

**The physics case for studying these very rare decays is compelling!**

**The challenge is to make it possible to observe them!**

# BACKUP SLIDES

# Hadronic input parameters for h→Vγ

Light mesons:

| Meson $V$ | $f_V$ [MeV] | $f_V^\perp(2\,\text{GeV})/f_V$ | $a_2^{V_\perp}(\mu_0)$ | $Q_V$ | $v_V$ |
|---|---|---|---|---|---|
| $\rho^0$ | $216.3 \pm 1.3$ | $0.72 \pm 0.04$ | $0.14 \pm 0.06$ | $\frac{1}{\sqrt{2}}$ | $\frac{1}{\sqrt{2}}\left(\frac{1}{2} - s_W^2\right)$ |
| $\omega$ | $194.2 \pm 2.1$ | $0.71 \pm 0.05$ | $0.15 \pm 0.07$ | $\frac{1}{3\sqrt{2}}$ | $-\frac{s_W^2}{3\sqrt{2}}$ |
| $\phi$ | $223.0 \pm 1.4$ | $0.76 \pm 0.04$ | $0.14 \pm 0.07$ | $-\frac{1}{3}$ | $-\frac{1}{4} + \frac{s_W^2}{3}$ |

Heavy quarkonia:

| Meson $V$ | $f_V$ [MeV] | $f_V^\perp(2\,\text{GeV})/f_V$ | $\sigma_V(\mu_0)$ | $Q_V$ | $v_V$ |
|---|---|---|---|---|---|
| $J/\psi$ | $403.3 \pm 5.1$ | $0.91 \pm 0.14$ | $0.228 \pm 0.005 \pm 0.057$ | $\frac{2}{3}$ | $\frac{1}{4} - \frac{2s_W^2}{3}$ |
| $\Upsilon(1S)$ | $684.4 \pm 4.6$ | $1.09 \pm 0.04$ | $0.112 \pm 0.004 \pm 0.028$ | $-\frac{1}{3}$ | $-\frac{1}{4} + \frac{s_W^2}{3}$ |
| $\Upsilon(2S)$ | $475.8 \pm 4.3$ | $1.08 \pm 0.05$ | $0.144 \pm 0.007 \pm 0.036$ | $-\frac{1}{3}$ | $-\frac{1}{4} + \frac{s_W^2}{3}$ |
| $\Upsilon(3S)$ | $411.3 \pm 3.7$ | $1.07 \pm 0.05$ | $0.162 \pm 0.010 \pm 0.041$ | $-\frac{1}{3}$ | $-\frac{1}{4} + \frac{s_W^2}{3}$ |

- model function:

$$\phi_V^\perp(x,\mu_0) = N_\sigma \, \frac{4x(1-x)}{\sqrt{2\pi\sigma_V}} \, \exp\left[-\frac{(x-\frac{1}{2})^2}{2\sigma_V^2}\right]$$

# Comparison with existing predictions: h→Vγ

Predictions for SM branching ratios:

| | | |
|---|---|---|
| $\mathrm{Br}(h \to \rho^0\gamma) = (1.68 \pm 0.02_{f_\rho} \pm 0.08_{h\to\gamma\gamma}) \cdot 10^{-5}$ | $(1.9 \pm 0.15) \cdot 10^{-5}$ | (✓) |
| $\mathrm{Br}(h \to \omega\gamma) = (1.48 \pm 0.03_{f_\omega} \pm 0.07_{h\to\gamma\gamma}) \cdot 10^{-6}$ | $(1.6 \pm 0.17) \cdot 10^{-6}$ | (✓) |
| $\mathrm{Br}(h \to \phi\gamma) = (2.31 \pm 0.03_{f_\phi} \pm 0.11_{h\to\gamma\gamma}) \cdot 10^{-6}$ | $(3.0 \pm 0.13) \cdot 10^{-6}$ | |
| $\mathrm{Br}(h \to J/\psi\,\gamma) = (2.95 \pm 0.07_{f_{J/\psi}} \pm 0.06_{\text{direct}} \pm 0.14_{h\to\gamma\gamma}) \cdot 10^{-6}$ | $(2.79\,{}^{+0.16}_{-0.15}) \cdot 10^{-6}$ | (✓) |
| $\mathrm{Br}(h \to \Upsilon(1S)\,\gamma) = (4.61 \pm 0.06_{f_{\Upsilon(1S)}}\,{}^{+1.75}_{-1.21}{}_{\text{direct}} \pm 0.22_{h\to\gamma\gamma}) \cdot 10^{-9}$ | $(0.61\,{}^{+1.74}_{-0.61}) \cdot 10^{-9}$ | |
| $\mathrm{Br}(h \to \Upsilon(2S)\,\gamma) = (2.34 \pm 0.04_{f_{\Upsilon(2S)}}\,{}^{+0.75}_{-0.99}{}_{\text{direct}} \pm 0.11_{h\to\gamma\gamma}) \cdot 10^{-9}$ | $(2.02\,{}^{+1.86}_{-1.28}) \cdot 10^{-9}$ | (✓) |
| $\mathrm{Br}(h \to \Upsilon(3S)\,\gamma) = (2.13 \pm 0.04_{f_{\Upsilon(3S)}}\,{}^{+0.75}_{-1.12}{}_{\text{direct}} \pm 0.10_{h\to\gamma\gamma}) \cdot 10^{-9}$ | $(2.44\,{}^{+1.75}_{-1.30}) \cdot 10^{-9}$ | (✓) |

| | |
|---|---|
| 🟦 | Kagan, Perez. Petriello, Soreq, Stoynev, Zupan (2014) |
| 🟩 | Bodwin, Chung, Ee, Lee, Petriello (2014) |