Rare hadronic decays of the Higgs boson

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Outline

- Introduction and motivation
- Higgs decays to heavy quarkonia and the Hcc, Hbb couplings
- Measuring the Higgs Yukawa matrix with decays to light mesons

Based on the following work:

- Bodwin, FP, Stoynev, Velasco 1306.5770
- Kagan, Perez, FP, Soteq, Stoynev, Zupan 1406.1722
- Bodwin, Chung, Ee, Lee, FP 1407.6695

The flavor puzzle

- Why mixing is maximal in the lepton sector and small in the quark sector?
- We have no understanding of the pattern of lepton masses in the SM
- These parameters come from the couplings of the Higgs to fermions

$$V_q = \begin{pmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.00065 & (3.51 \pm 0.15) \times 10^{-3} \\ 0.22520 \pm 0.00065 & 0.97344 \pm 0.00016 & (4.12^{+0.11}_{-0.05}) \times 10^{-2} \\ (8.67 \pm 0.30) \times 10^{-3} & (4.04^{+0.11}_{-0.05}) \times 10^{-2} & 0.999146^{+0.000021}_{-0.000046} \end{pmatrix}$$

$$|U|_{3\sigma} = \begin{pmatrix} 0.79 - 0.85 & 0.51 - 0.59 & 0.13 - 0.18 \\ 0.20 - 0.54 & 0.42 - 0.73 & 0.58 - 0.81 \\ 0.21 - 0.55 & 0.41 - 0.73 & 0.57 - 0.80 \end{pmatrix}$$

from Y. Nir, LHC top-charm workshop 2014

Higgs-fermion couplings

- What are we learning about Yukawa couplings from LHC measurements?
- WW, ZZ, γγ, bb, ττ: mainly couplings of the Higgs to gauge bosons, and to 3rd-generation fermions
- What about 2nd-generation fermions? μμ possible in Run II, what about quarks?

???

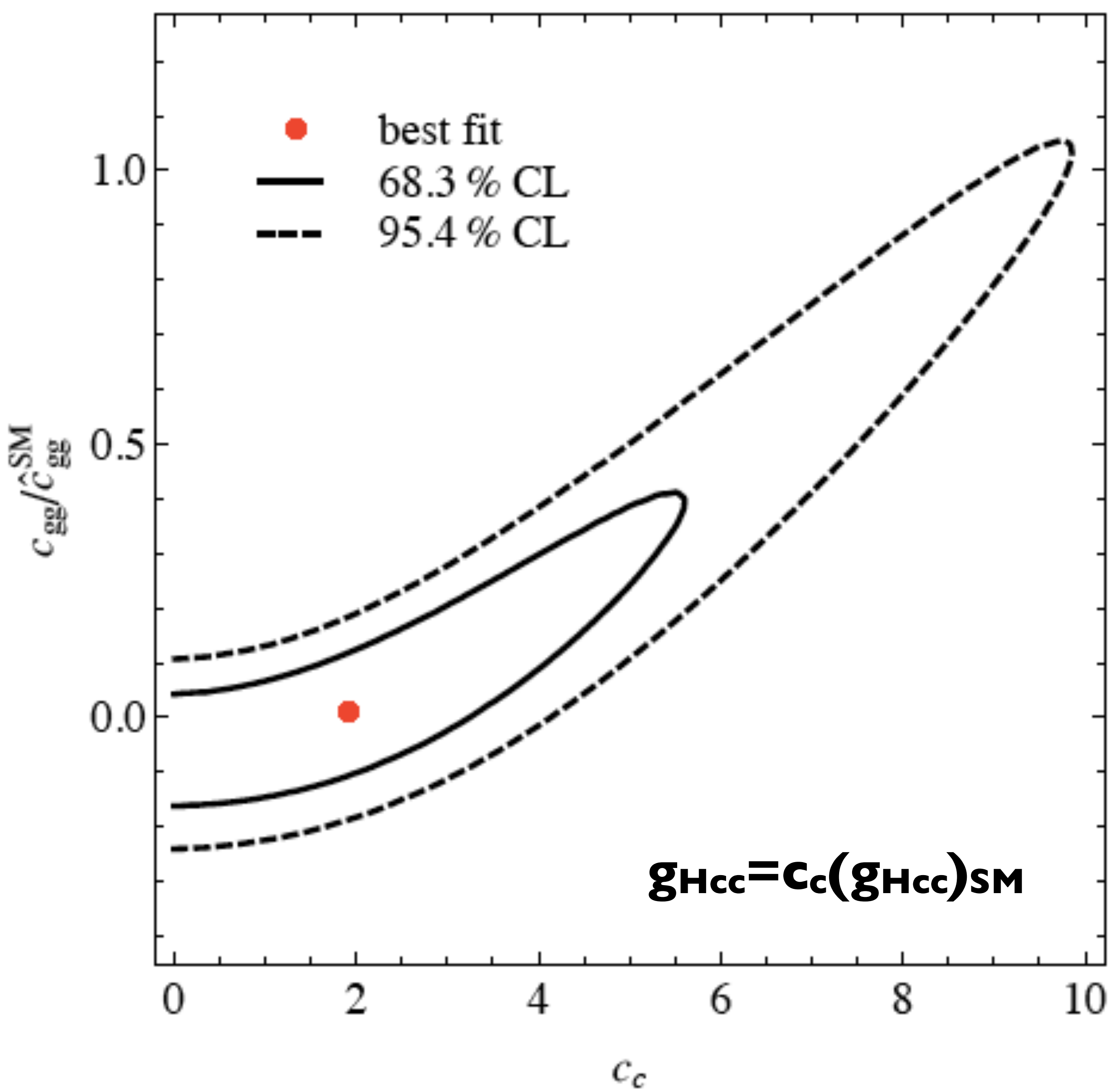
Model	$\frac{Y_{tt}}{Y_{tt}^{\mathrm{SM}}}$	$\frac{Y_{cc}/Y_{tt}}{m_c/m_t}$	Y_{ct}/Y_{tt}
SM	1	1	0
2HDM-NFC	c_α/s_β	1	0
2HDM-MFV	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(Y_b^2 V_{cb})$
1HDM-FN	$1+\mathcal{O}(v^2/\Lambda^2)$	$1+\mathcal{O}(v^2/\Lambda^2)$	$\mathcal{O}(V_{cb} v m_t/\Lambda^2)$

get from gg production indirectly, or ttH directly

get from $t \to cH$ decays

Measuring the Higgs-charm coupling

- Begin with the charm quark Hcc coupling can have O(1) differences from the SM result (benchmarks given later)

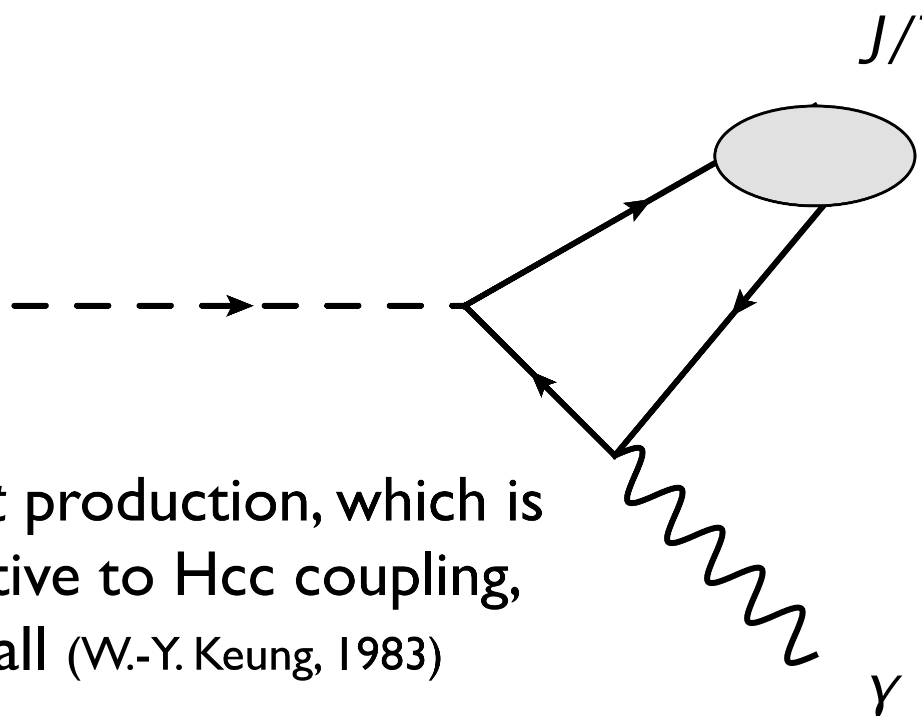


Delaunay, Golling, Perez, Soreq 1310.7029

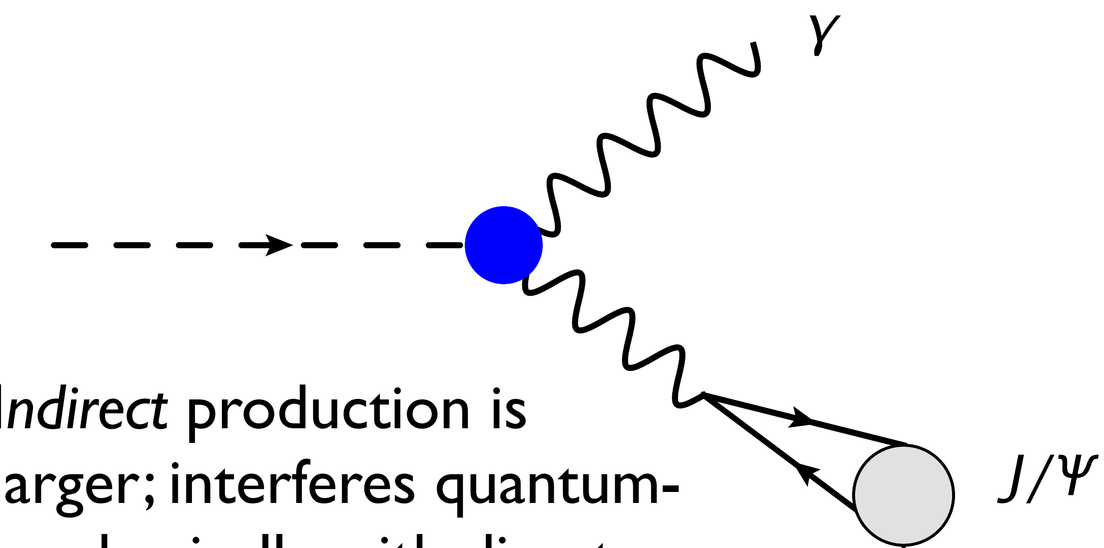
- Current data provide some constraint on this from the inclusive Higgs production rate, through the contribution of cc→H
- Limit strongly correlated with Hgg and other couplings
- Is there a way to directly access Hcc?
- One possibility: charm tagging for direct H→cc decays Delaunay et al. 1310.7029

Quarkonium interferometry

- Access this coupling using $H \to J/\Psi + \gamma$! Bodwin, FP, Stoynev, Velasco 1306.5770



Direct production, which is sensitive to Hcc coupling, is small (W.-Y. Keung, 1983)



Indirect production is larger; interferes quantum-mechanically with direct production

- Larger indirect mechanism drags up the direct one; provides sensitivity to the Hcc coupling
- Theoretically very clean; few-percent uncertainties: Bodwin, Chung, Ee, Lee, FP 1407.6695
- Interference gives unique information on the phase of the Hcc coupling

Theory prediction for J/ψ

- Partial width for general Hcc coupling:

$g_{Hcc}=\kappa_c\ (g_{Hcc})_{SM}$

$$\Gamma(H \to J/\psi + \gamma) = \left|(11.9 \pm 0.2) - (1.04 \pm 0.14)\kappa_c\right|^2 \times 10^{-10}\ \mathrm{GeV}$$

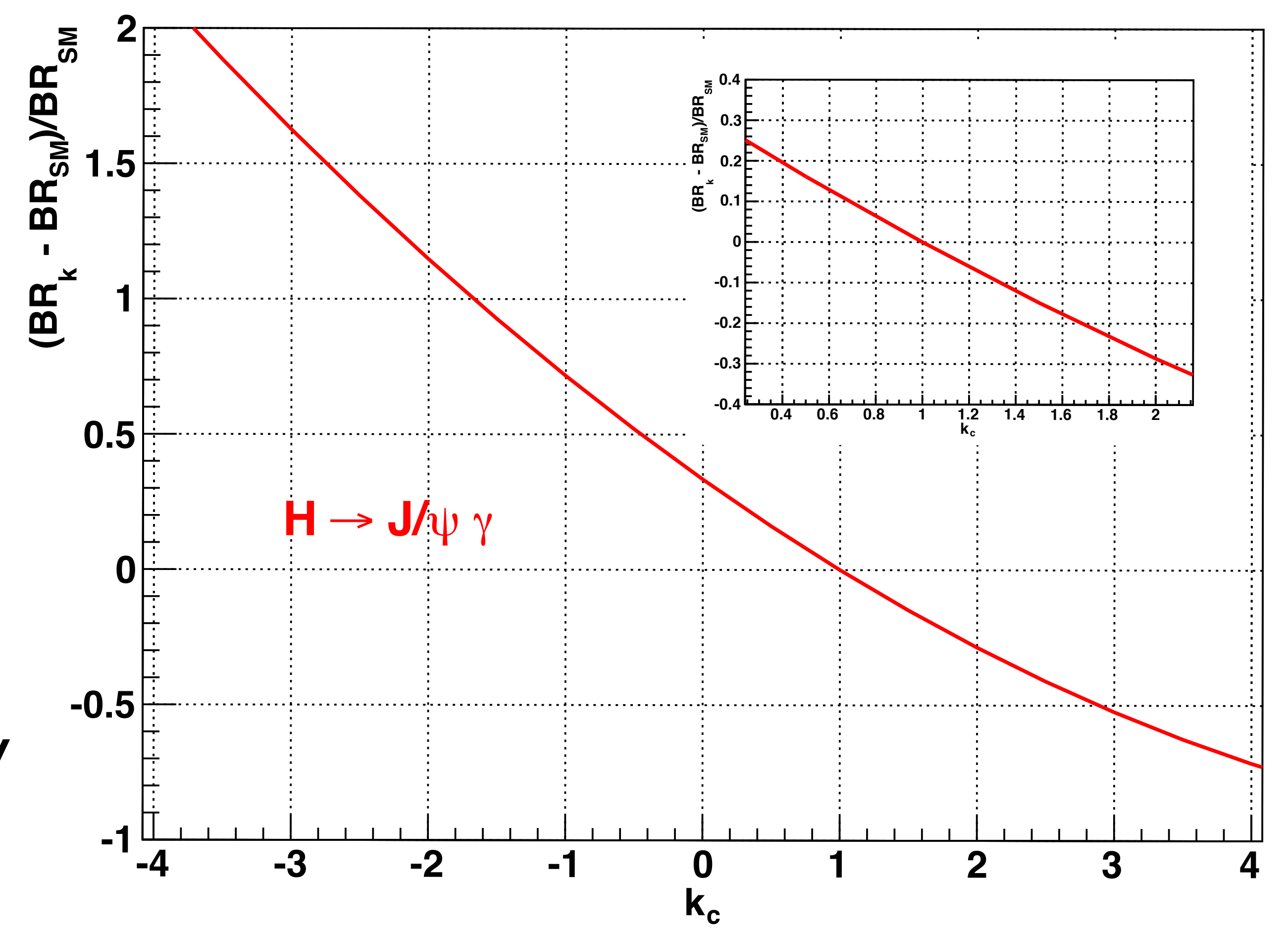
Dominant uncertainty on indirect amplitude: leptonic width of J/ψ

Dominant uncertainty on direct amplitude: uncalculated v^4 corrections in NRQCD

- Branching ratio in the SM:

$$\mathcal{B}_{\mathrm{SM}}(H \to J/\psi + \gamma) = 2.79^{+0.16}_{-0.15} \times 10^{-6}$$

This is a 3 ab^{-1} measurement! Only possible with a high luminosity LHC; O(100) $l^+l^-\gamma$ events in the SM after acceptance×efficiency



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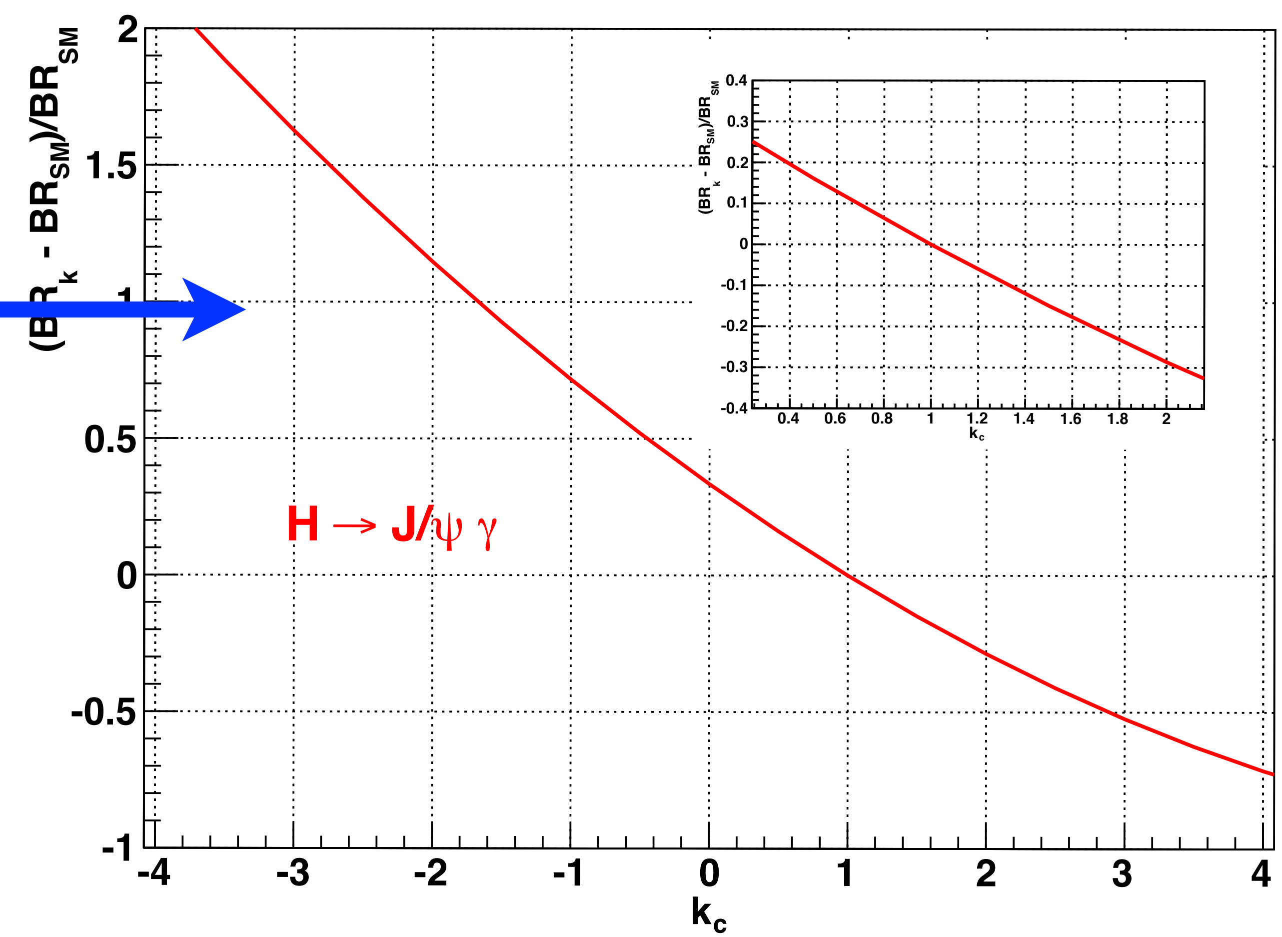
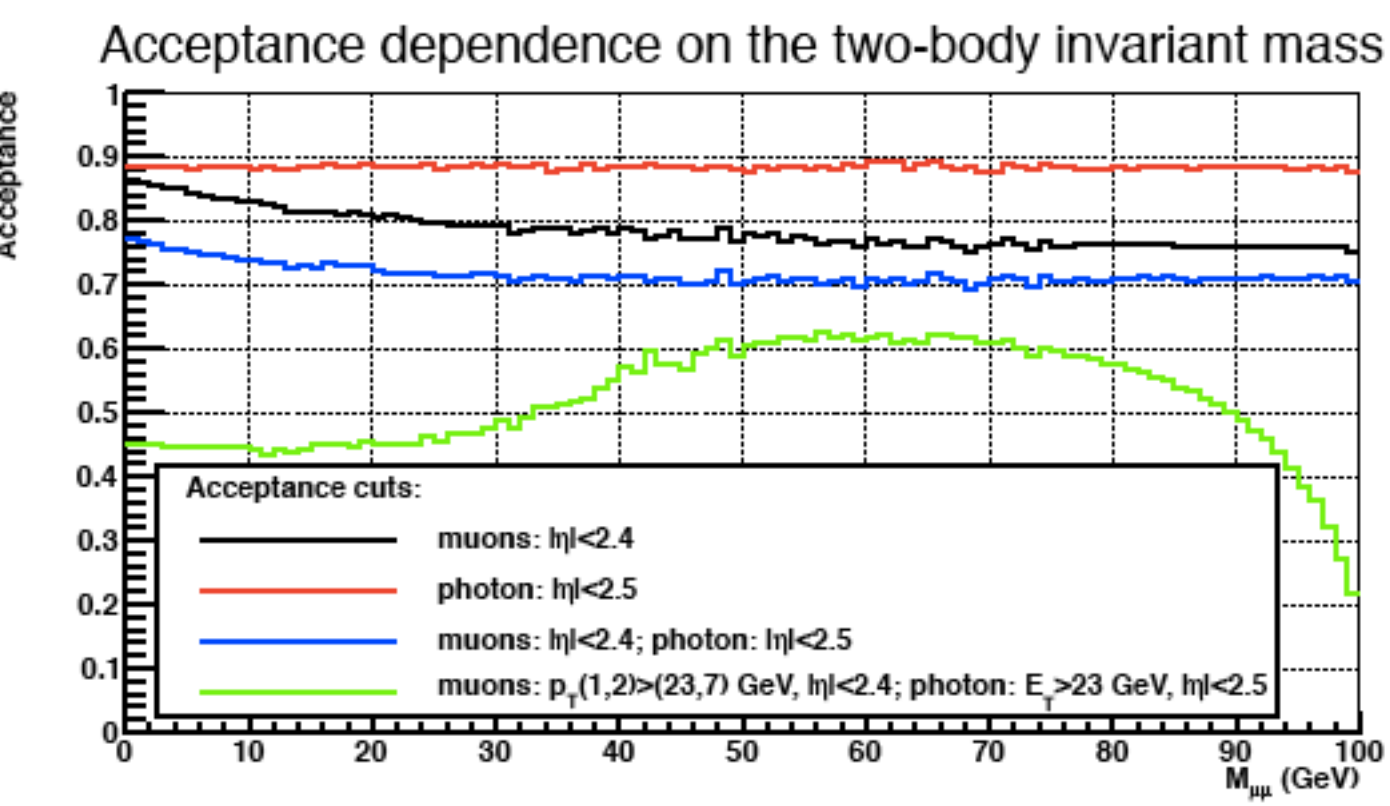
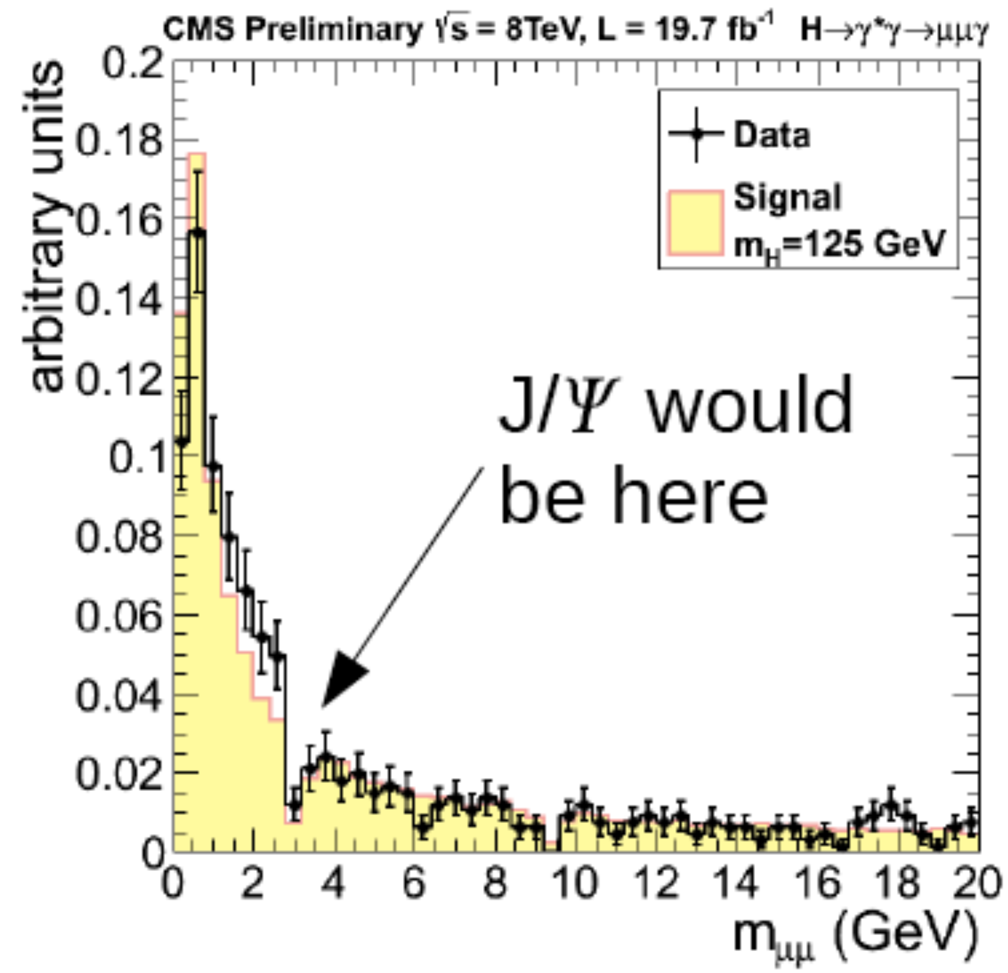
- Note the sensitivity to the sign of κ_c.
- Unique to this channel, won't get this information with an inclusive H→cc search



Experimental prospects

- Clean signature: ~50-60 GeV photon recoiling against a J/ψ, that reconstruct to the Higgs mass; large acceptance and small backgrounds

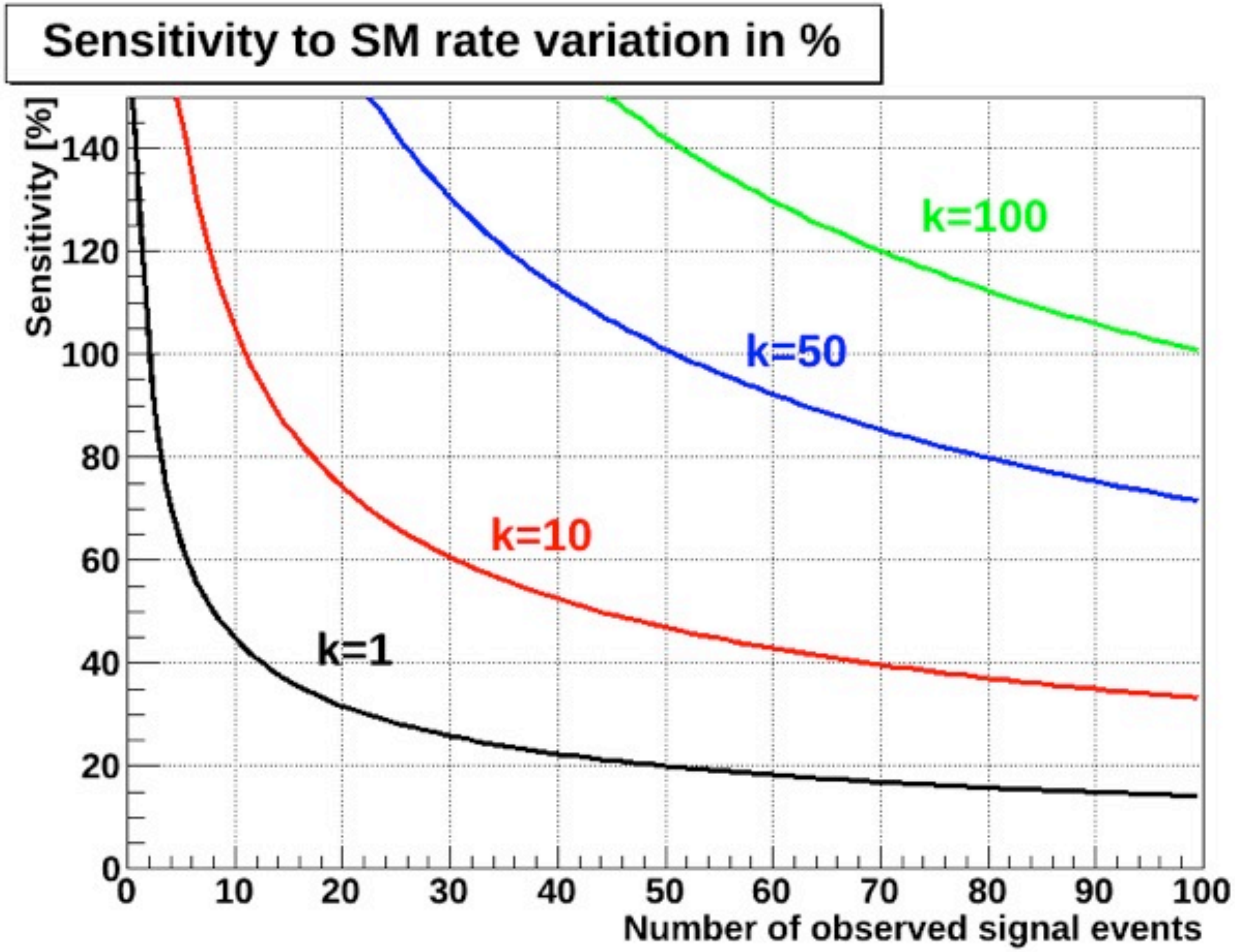




CMS-PAS-HIG-14-003

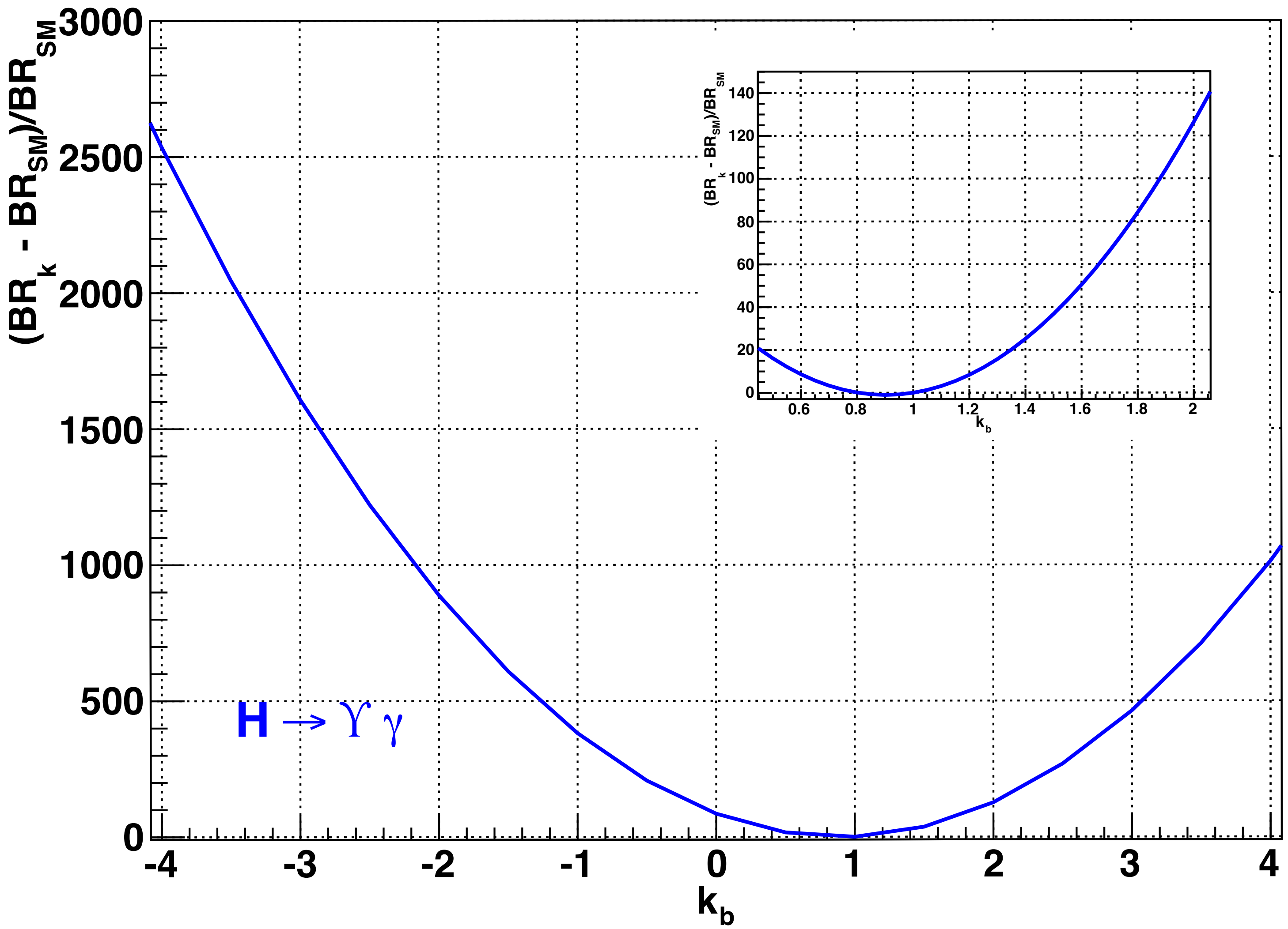
The Dalitz decay search looks for exactly this final state but removes the J/ψ and ϒ regions⇒proof-of-principle that this analysis is possible!

Sensitivity



- k=B/S; for the Dalitz decay search, k=40
- Expected to be less here, due to the presence of the additional J/ψ resonance
- Observation of the SM coupling may be possible with the full HL-LHC data set; at the least stringent limits can be set

Hbb at the LHC



- This is the same deviation plot for H→ϒ(1S)+γ
- The y-axis is not a typo! Almost a complete cancellation between direct and indirect amplitudes in the SM.

$$\mathcal{B}_{\rm SM}(H \to \Upsilon + \gamma) = 8.39^{+19.25}_{-8.16} \times 10^{-10}$$

- Any modification of Hbb leads to O(100)-O(1000) deviations in this rate

Observation of this decay mode conclusively indicates a non-SM Hbb coupling!

Mapping the Higgs Yukawa structure

- Similar decays to light mesons offer the hope of probing the entire Higgs Yukawa structure

$$\mathcal{L}_{\text{eff}} = -\sum_{q=u,d,s} \bar{\kappa}_q \frac{m_b}{v} h \bar{q}_L q_R - \sum_{q \neq q'} \bar{\kappa}_{qq'} \frac{m_b}{v} h \bar{q}_L q'_R + h.c.$$

- Diagonal couplings: access with h→ρ,ω,Φ+γ
- Contributions from both direct and indirect amplitudes

- Off-diagonal couplings: access with h→B^*γ, D^* γ, etc.
- Only a direct-amplitude contribution (photon splitting preserves flavor)

Current limits from Higgs production: $\bar{\kappa}<1$

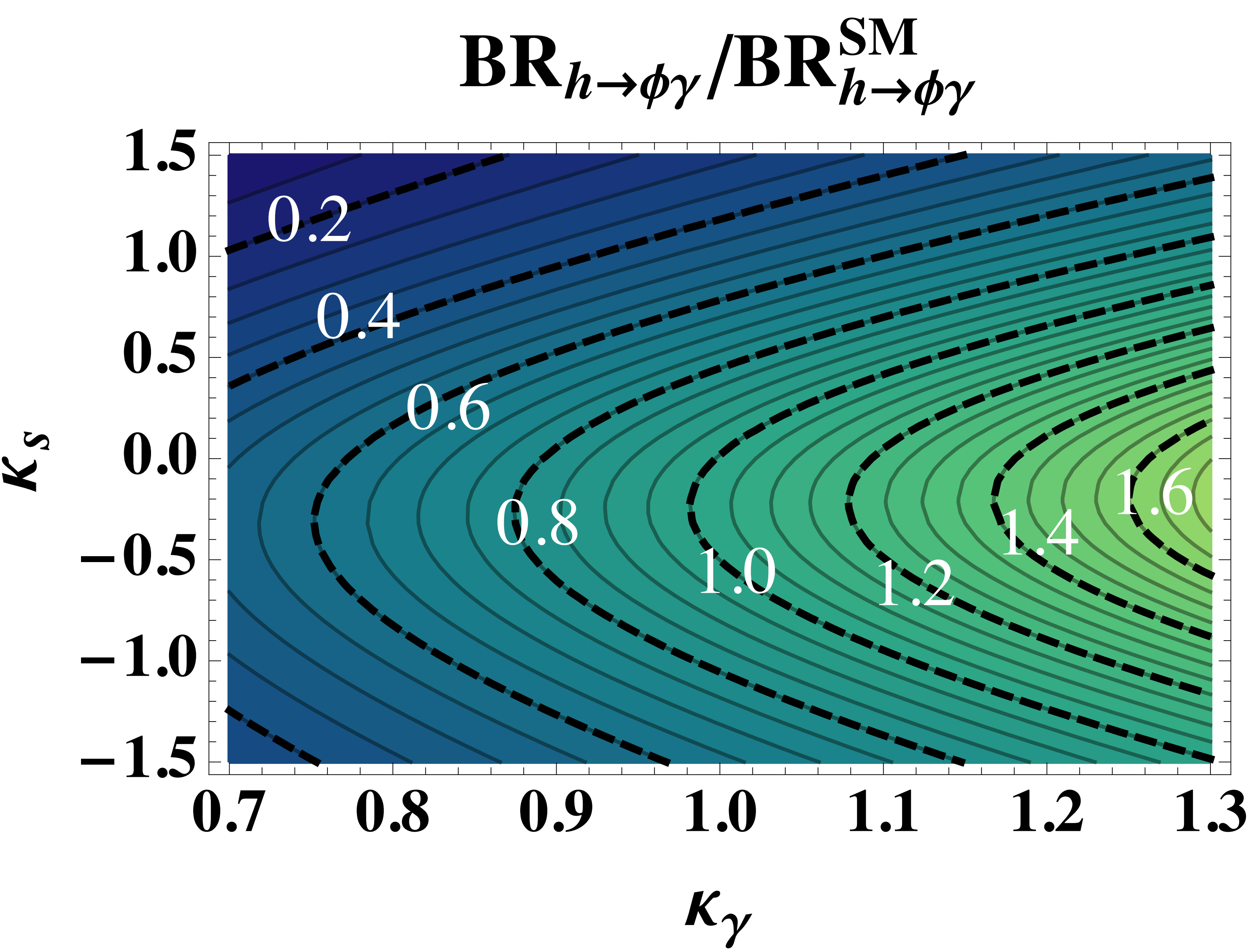
Kagan et al., 1406.1722

The Hss coupling

- An example: h→Φγ⇒access to the diagonal strange-quark coupling

$$\frac{\mathrm{BR}_{h\to\phi\gamma}}{\mathrm{BR}_{h\to b\bar{b}}} = \frac{\kappa_\gamma\left[(3.0\pm 0.13)\kappa_\gamma - 0.78\bar{\kappa}_s\right]\cdot 10^{-6}}{0.57\bar{\kappa}_b^2}$$

Interference is a 25% effect



- Error on the κ_s coefficient is ~20%; can be reduced by a combination of lattice calculations and data
- $\Phi\to K^+K^-$ which don't decay in the detector; reconstructable, the only issue is the trigger (under investigation)

This is the only idea so far on how to directly measure these couplings!

The Hss coupling

- An example: $h \to \Phi\gamma \Rightarrow$ access to the diagonal strange-quark coupling

$$\frac{\mathrm{BR}_{h\to\phi\gamma}}{\mathrm{BR}_{h\to b\bar{b}}} = \frac{\kappa_\gamma\left[(3.0\pm 0.13)\kappa_\gamma - 0.78\bar{\kappa}_s\right]\cdot 10^{-6}}{0.57\bar{\kappa}_b^2}$$

Interference is a 25% effect

$\sqrt{s}$ [TeV]	$\int \mathcal{L}\,dt$ [fb^{-1}]	# of events (SM)	$\bar{\kappa}_s > (<)$	$\bar{\kappa}_s^{\mathrm{stat.}} > (<)$
14	3000	770	0.39 (−0.97)	0.27 (−0.81)
33	3000	1380	0.36 (−0.94)	0.22 (−0.75)
100	3000	5920	0.34 (−0.90)	0.13 (−0.63)

- Sizable events rates at the HL-LHC and future hadron colliders
- Not accessible at future e^+e^- machines! Even TLEP with 4 interaction points and 10000 fb^{-1} would have only 30 predicted events.

Model benchmarks

- Not difficult to construct models with large deviations from the SM

$$\mathcal{L} = -\lambda_{ij}(\bar{f}_L^i f_R^j)H - \frac{\lambda'_{ij}}{\Lambda^2}(\bar{f}_L^i f_R^j)H(H^\dagger H) + h.c.$$

- Assume MFV and expand the dimension-6 coefficient:

$$\lambda'_{ij} = c_0 Y_d + c_1 \left(Y_d^\dagger Y_d\right) Y_d + c_2 \left(Y_u^\dagger Y_u\right) Y_d$$

$$\bar{\kappa}_s = \frac{m_s}{m_b}\left(1 + \frac{v^2}{\Lambda^2} c_0 \frac{y_s v}{\sqrt{2} m_s}\right)$$

$c_0 \approx 5$ to get $\kappa_s \approx 0.9$, consistent with all bounds and leads to a large deviation from the SM prediction for $h \to \Phi\gamma$

- Giudice-Lebedev model (0804.1753); small quark masses come from higher-dimensional operators. Easy to get $\kappa_s = 5 \times \kappa_{SM}$ or more in agreement with current data

Conclusions

- Rare hadronic decays of the Higgs allow the couplings of the Higgs to Ist and 2nd-generation quarks to be directly probed
- $h \to J/\psi + \gamma$ is theoretically and experimentally clean, and will be accessible at the HL-LHC
- Decays to light mesons allow both diagonal and off-diagonal Yukawa couplings to be probed. Event rates are large, but the trigger needs attention
- These modes are too rare to be measured at future e^+e^- machines; only possible at the HL-LHC or future hadron machines
- Can have large deviations from SM predictions; these need to be measured!