Light quark Yukawa couplings

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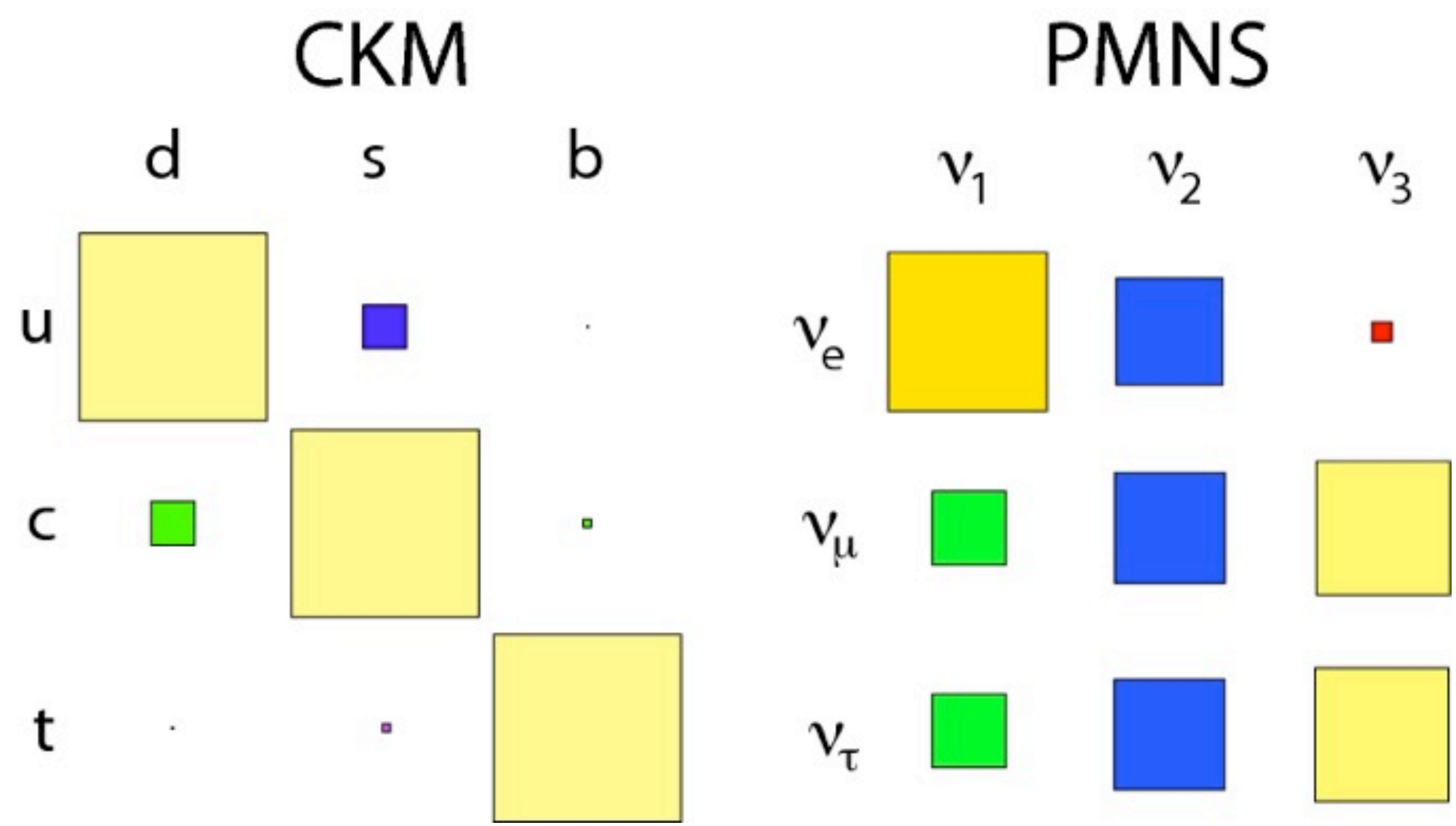
Outline

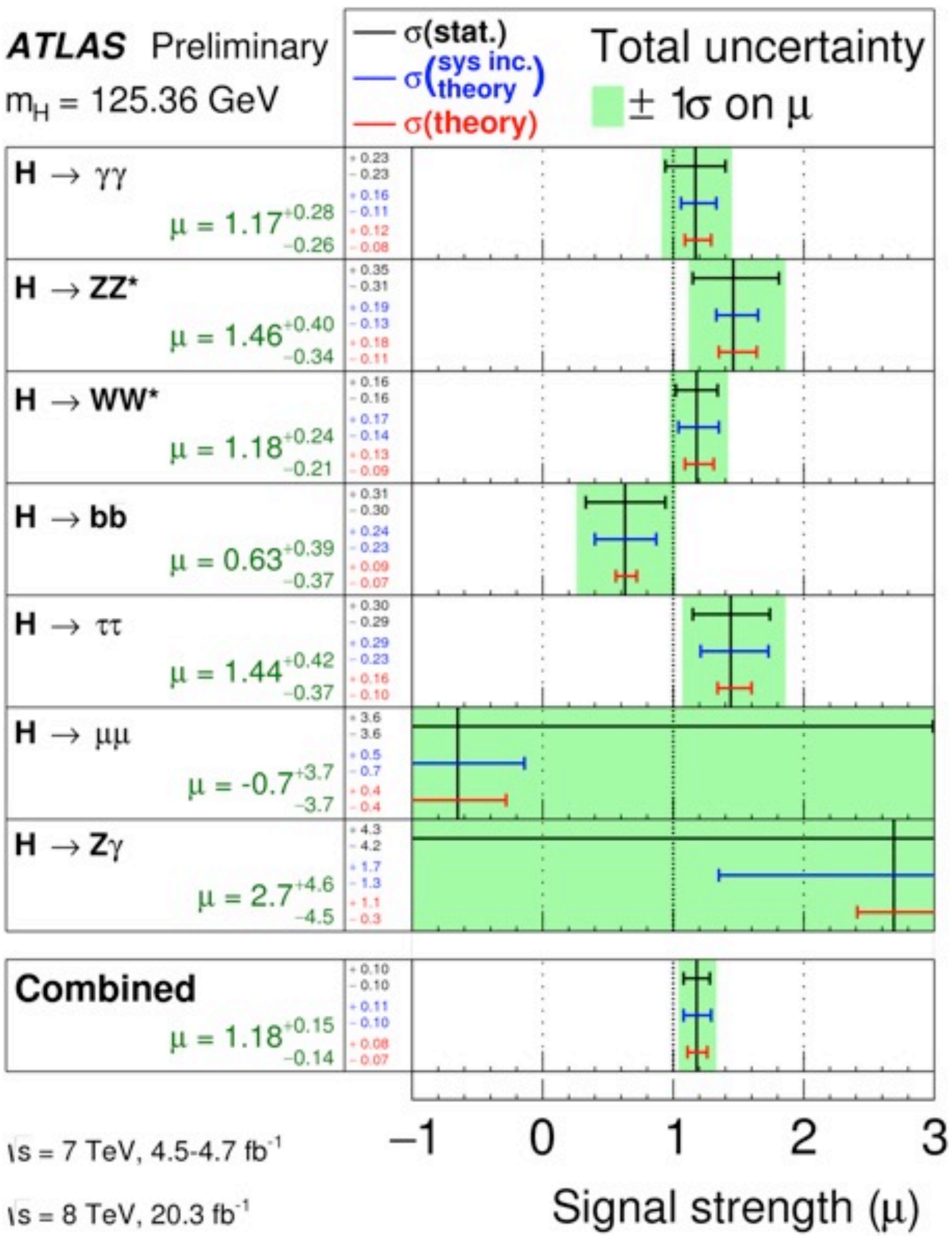
- Introduction and motivation
- The Higgs-charm coupling: charm tagging at the LHC
- The Higgs-charm coupling: rare decays to J/ψ
- Measuring the Higgs Yukawa matrix with decays to light mesons
- Exclusive radiative decays of the W and Z bosons
- Conclusions

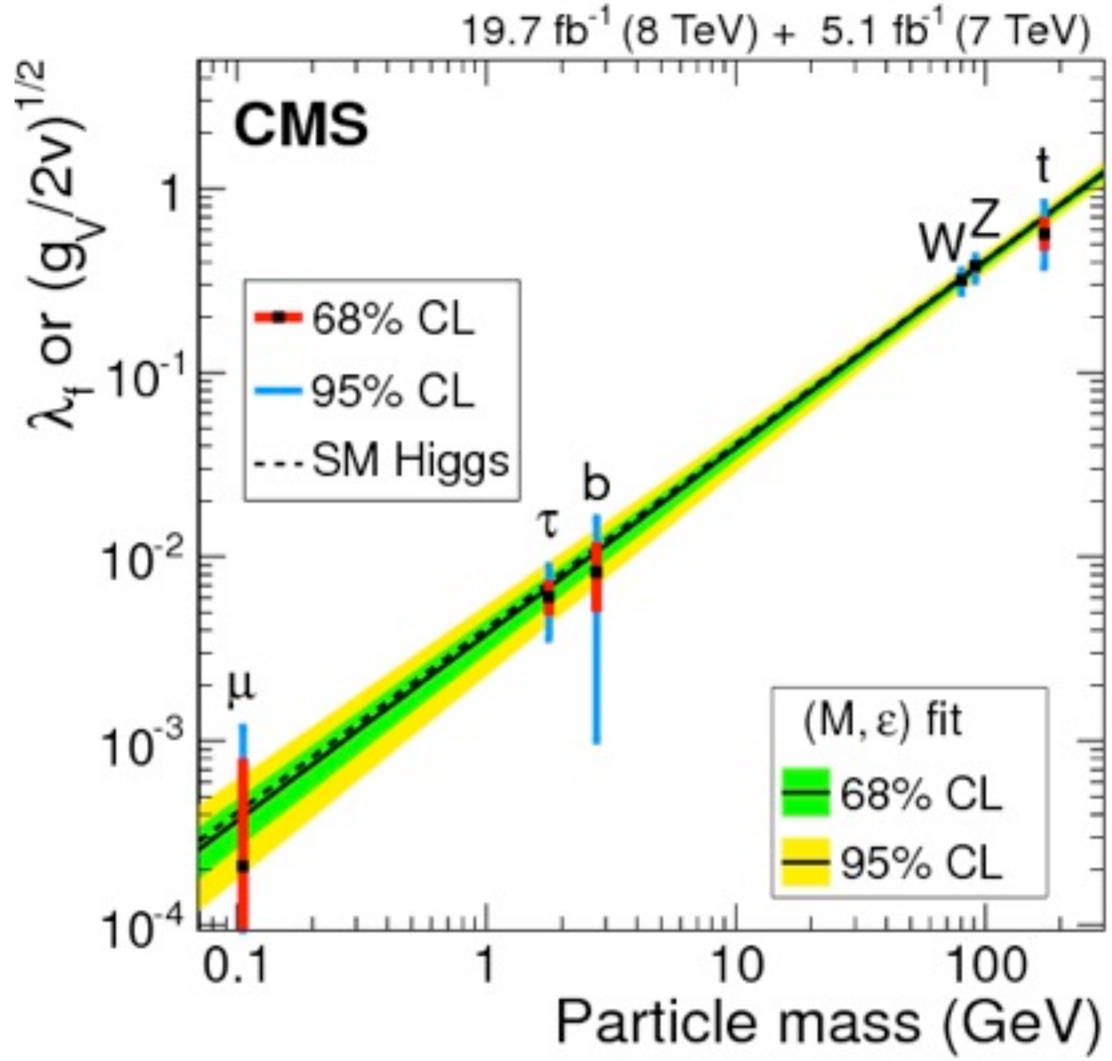
The Standard Model flavor puzzle

- 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



Higgs measurements at the LHC





- LHC primarily provides information on Higgs couplings to 3rd-generation and electroweak gauge bosons
- Need ideas on how to probe of 1st and 2nd-generation couplings!

Higgs-fermion couplings

- The pattern of Higgs couplings to different fermions can provide insight into the flavor structure underlying the Standard Model

get from gg production indirectly, or ttH directly

???

get from t→cH decays

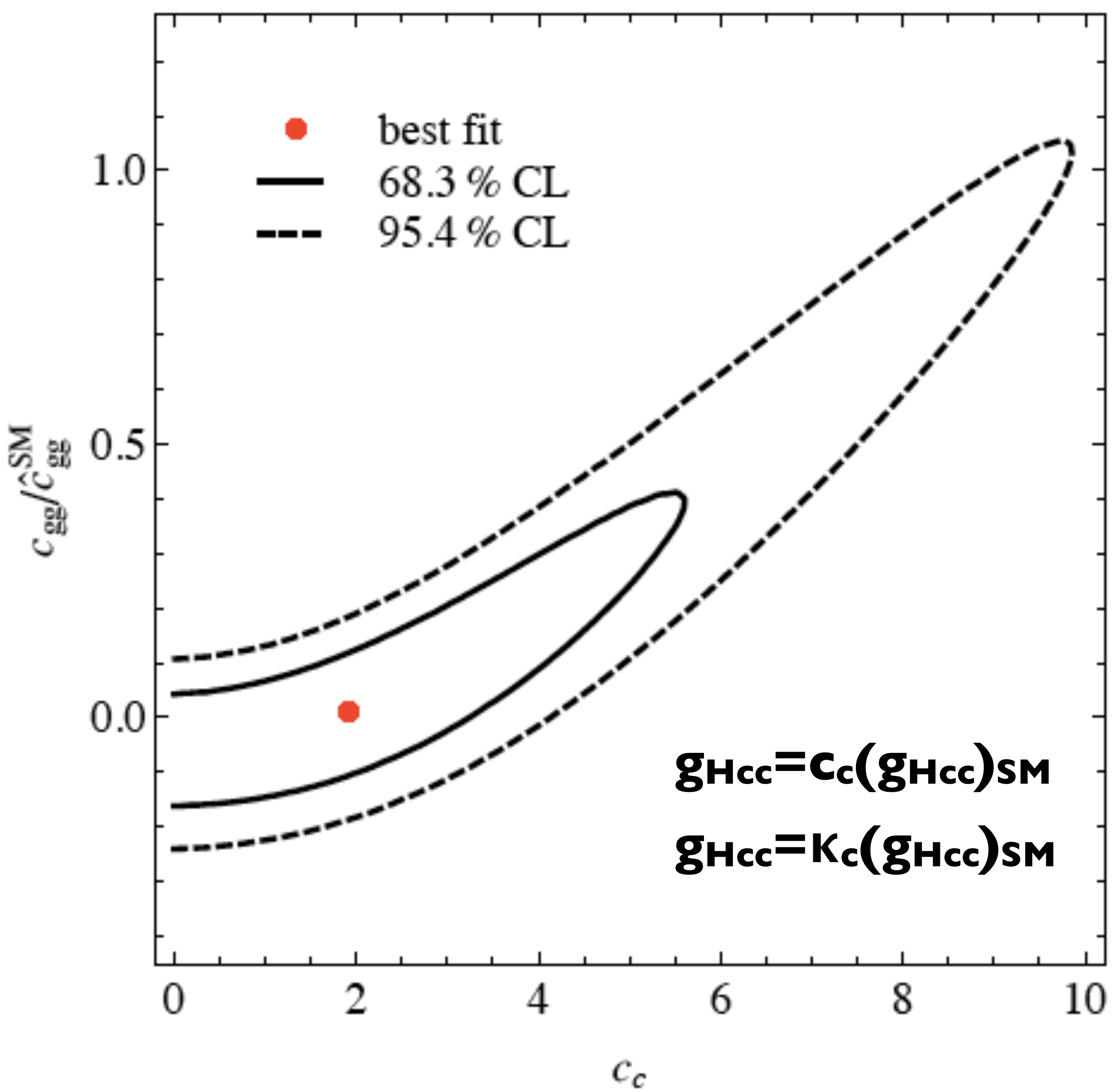
Model	$\frac{Y_{tt}}{Y_{tt}^{\rm SM}}$	$\frac{Y_{cc}/Y_{tt}}{m_c/m_t}$	Y_{ct}/Y_{tt}
SM	1	1	0
2HDM-NFC	c_α/s_β	1	0
2HDM-MFV	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(Y_b^2 V_{cb})$
1HDM-FN	$1+\mathcal{O}(v^2/\Lambda^2)$	$1+\mathcal{O}(v^2/\Lambda^2)$	$\mathcal{O}(V_{cb} v m_t/\Lambda^2)$

- For example: 2HDM with MFV can have Y_{cc}/Y_{cc}^{SM}~5 or more

Delaunay, Golling, Perez, Soreq 1310.7029

Measuring the Higgs-charm coupling

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



$g_{Hcc}=c_c(g_{Hcc})_{SM}$

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

- Current data provide some constraint on this from the inclusive Higgs production rate, through the contribution of cc→H

$$\kappa_c \lesssim 6.2$$

Perez, Soreq, Stamou, Tobioka 1503.00290

- Limit strongly correlated with Hgg and other couplings; is there a way to access it directly?

Charm tagging

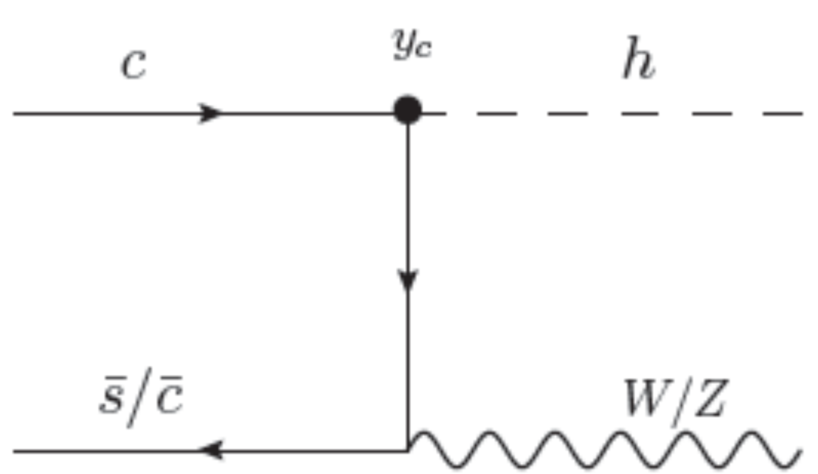
- Charm jets feature displaced vertices; searches for VH→Vbb will also admit H→cc decays (Perez, Soreq, Stamou, Tobioka 1503.00290)

$$\mu_b = \frac{\sigma\,\mathrm{BR}_{b\bar{b}}}{\sigma_{\mathrm{SM}}\mathrm{BR}^{\mathrm{SM}}_{b\bar{b}}} \to \frac{\sigma\,\mathrm{BR}_{b\bar{b}}\,\epsilon_{b_1}\epsilon_{b_2} + \sigma\,\mathrm{BR}_{c\bar{c}}\,\epsilon_{c_1}\epsilon_{c_2}}{\sigma_{\mathrm{SM}}\mathrm{BR}^{\mathrm{SM}}_{b\bar{b}}\,\epsilon_{b_1}\epsilon_{b_2}} = \mu_b + \frac{\mathrm{BR}^{\mathrm{SM}}_{c\bar{c}}}{\mathrm{BR}^{\mathrm{SM}}_{b\bar{b}}}\frac{\epsilon_{c_1}\epsilon_{c_2}}{\epsilon_{b_1}\epsilon_{b_2}}\,\mu_c\,,$$

- Disentangle Hbb and Hcc couplings with two different tagging criteria:

ATLAS	Med	Tight	CMS	Loose	Med1	Med2	Med3
ϵ_b	70%	50%	ϵ_b	88%	82%	78%	71%
ϵ_c	20%	3.8%	ϵ_c	47%	34%	27%	21%

- Also have an additional relevant production mode for large Hcc coupling:

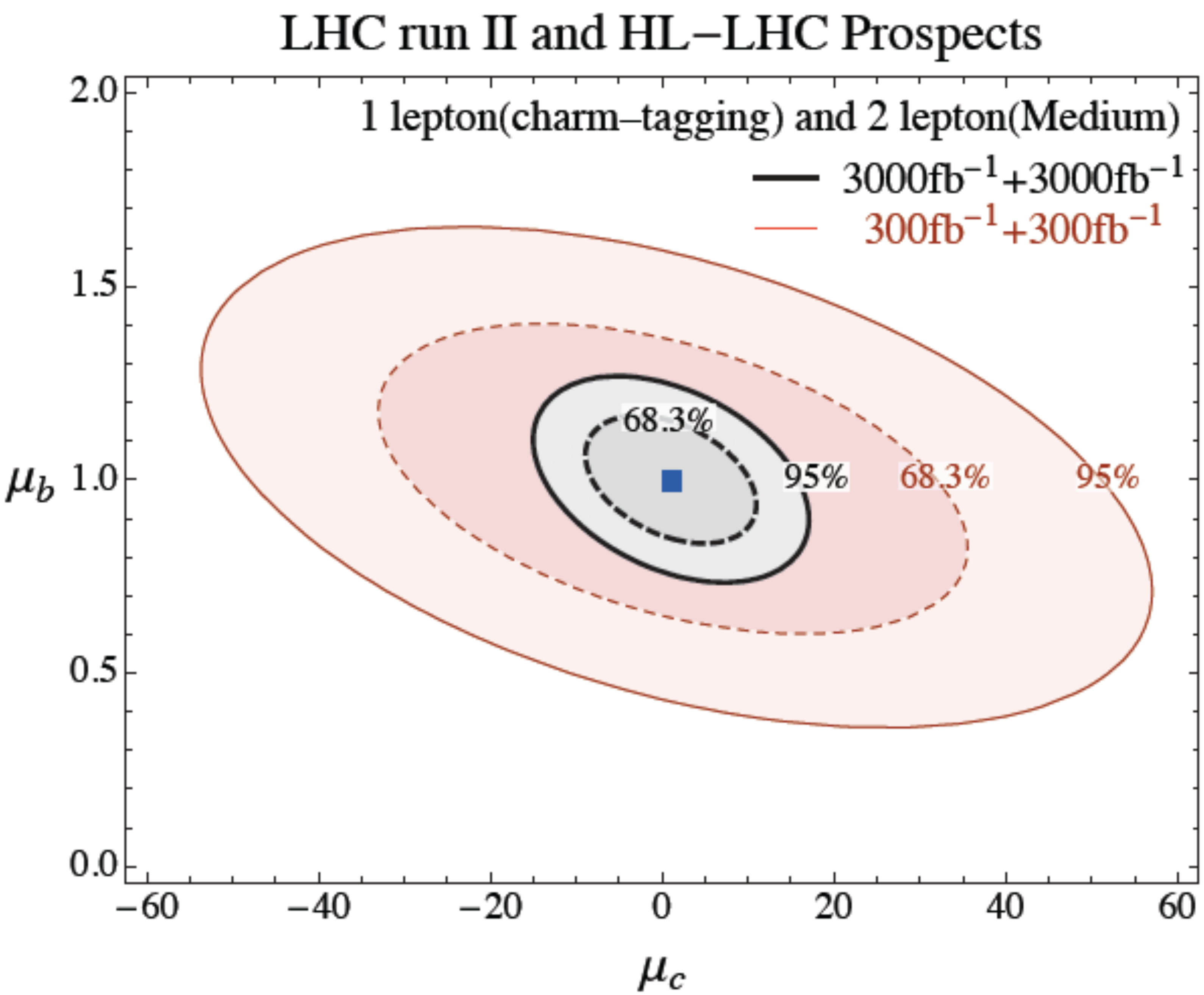


these together allow a bound on the Hcc coupling to be established:

$$\kappa_c \lesssim 234 \text{ at } 95\% \text{ CL}$$

(assumes k_V=1)

Future prospects for charm-tagging



Perez, Soreq, Stamou, Tobioka 1503.00290

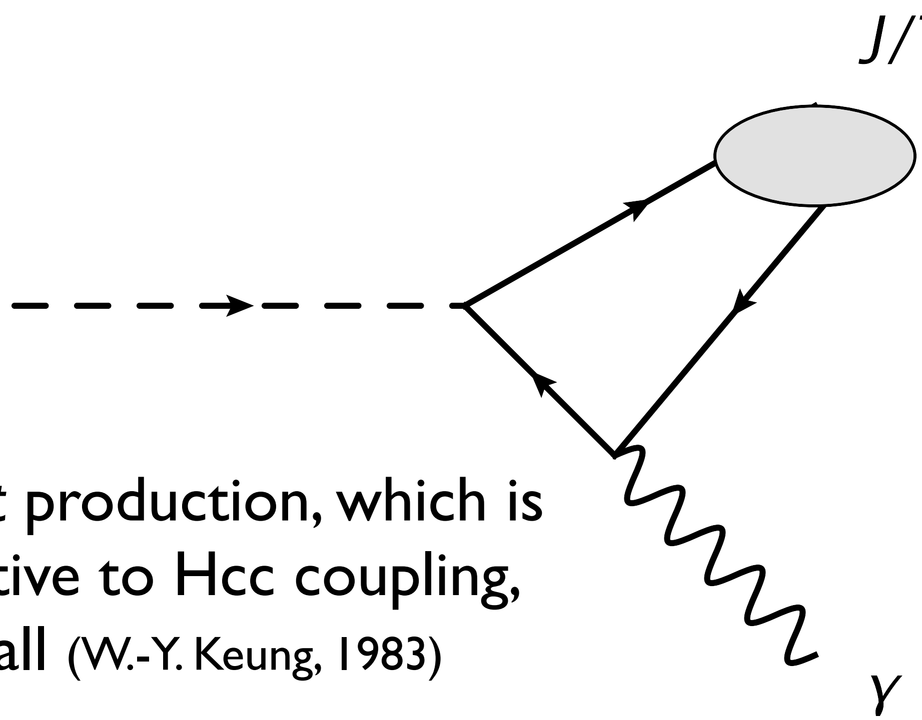
$$\Delta\mu_c = \begin{cases} 23\,(45) & \text{with } 300\ \text{fb}^{-1} \\ 6.5\,(13) & \text{with } 3000\ \text{fb}^{-1} \end{cases}$$

68.3 (95)% CL

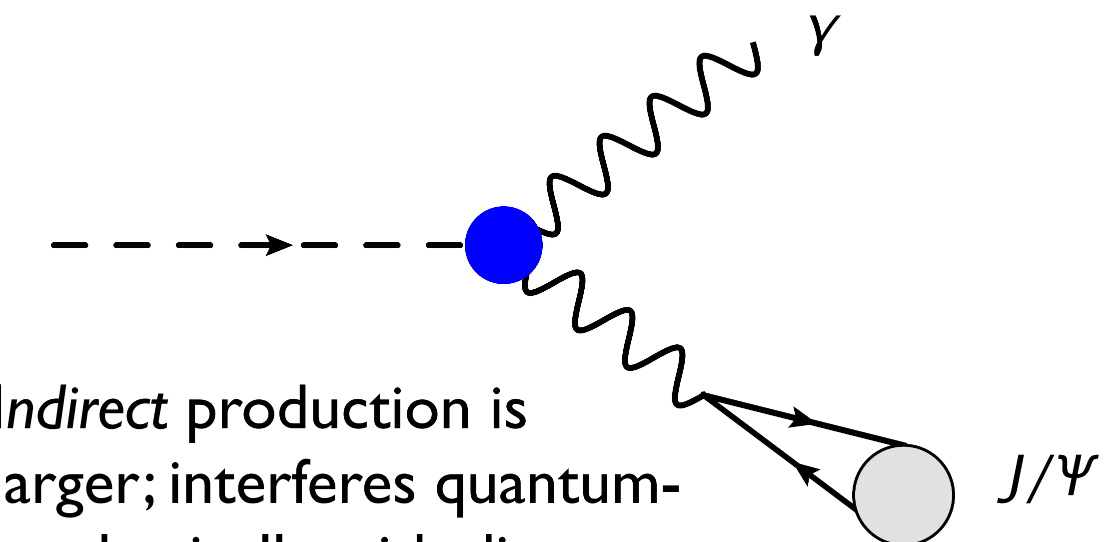
- Will be able to probe a signal strength of O(10)xSM
- Also possible to search for a single charm-tagged jet in the pp→hc channel Brivio, Goertz, Isidori 1507.02916

Quarkonium interferometry

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



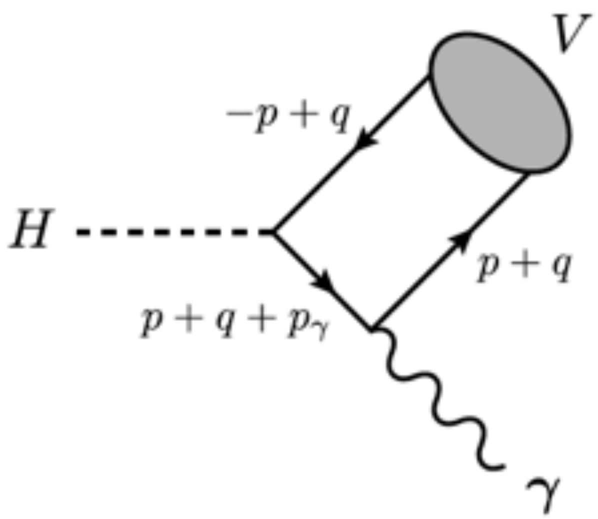
Direct production, which is sensitive to Hcc coupling, is small (W.-Y. Keung, 1983)

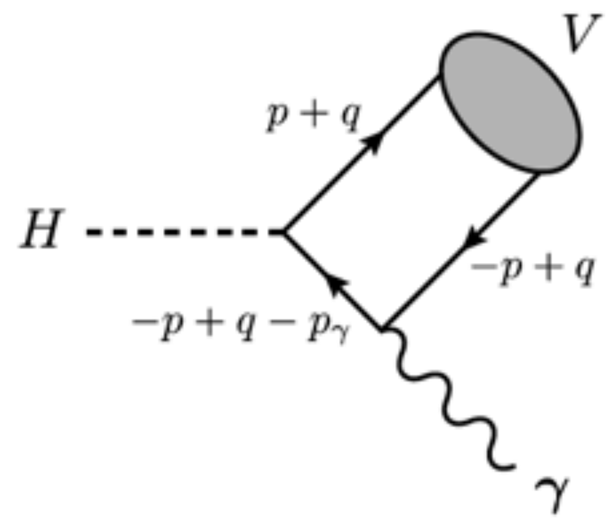


Indirect production is larger; interferes quantum-mechanically with direct production

- 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

Structure of the amplitudes





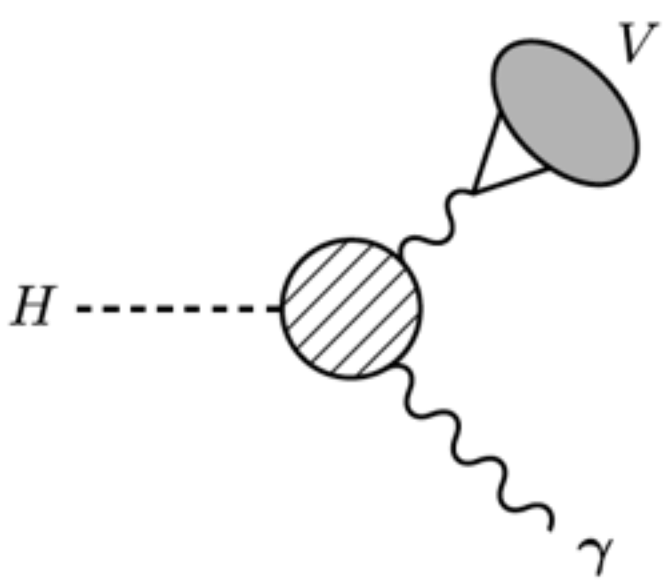
- Calculational framework: NRQCD to O(v^2) cross-checked using light-cone distribution amplitudes

$$i\mathcal{M}_{\rm dir}[H\to V+\gamma] \;\approx \sqrt{2m_V}\,\phi_0\, i\mathcal{M}^{(0)}_{\rm dir}[H\to V+\gamma]\left[1-\frac{1}{2}\langle v^2\rangle + O(\langle v^4\rangle)\right]$$

quarkonium wave-function at origin

amplitude for $^3S_1$ cc production

leading relativistic correction, -10%



- Effective Hγγ* coupling mediated by W, top loops

$$\mathcal{M}_{indirect} = -e\frac{\alpha}{\pi}\frac{g_{V\gamma}}{m_V^2}\left(\sqrt{2}G_F\right)^{1/2}\mathcal{I}\left[2p_\gamma\cdot\epsilon_V^* p_V\cdot\epsilon_\gamma^* - (m_H^2-m_V^2)\epsilon_\gamma^*\cdot\epsilon_V^*\right]$$

effective coupling derived from quarkonium decay constant

loop-induced Hγγ* coupling

Theory prediction for J/ψ

- Partial width for general Hcc coupling (Bodwin, FP, Stoynev, Velasco 1306.5770):

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

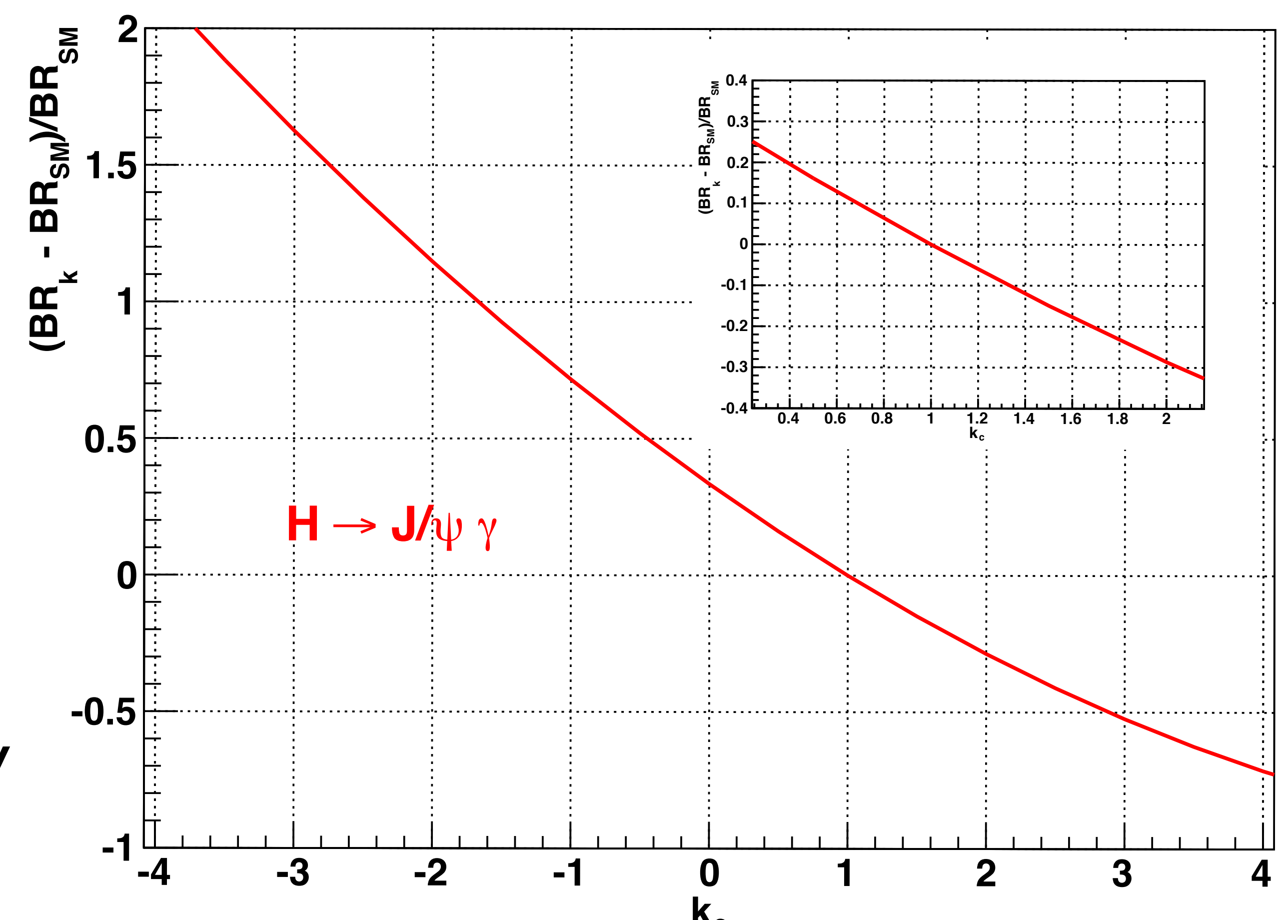
$$\Gamma(H \to J/\psi + \gamma) = \left|(11.9 \pm 0.2) - (1.04 \pm 0.14)\kappa_c\right|^2 \times 10^{-10}\ \mathrm{GeV}$$

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:

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



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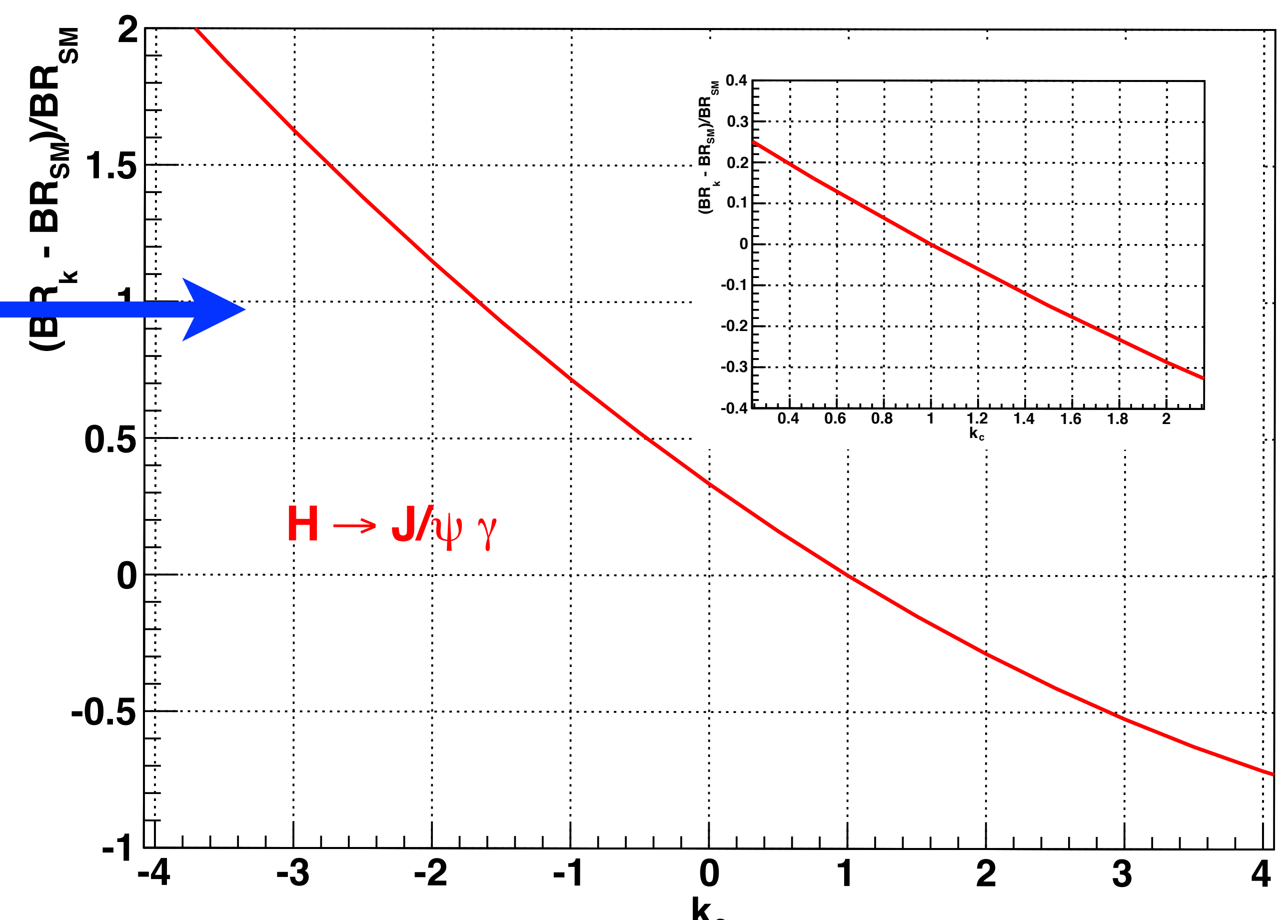
- Note the sensitivity to the sign of κ_c.
- Unique to this channel, won't get this information with an inclusive H→cc search



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- Branching ratio in the SM:

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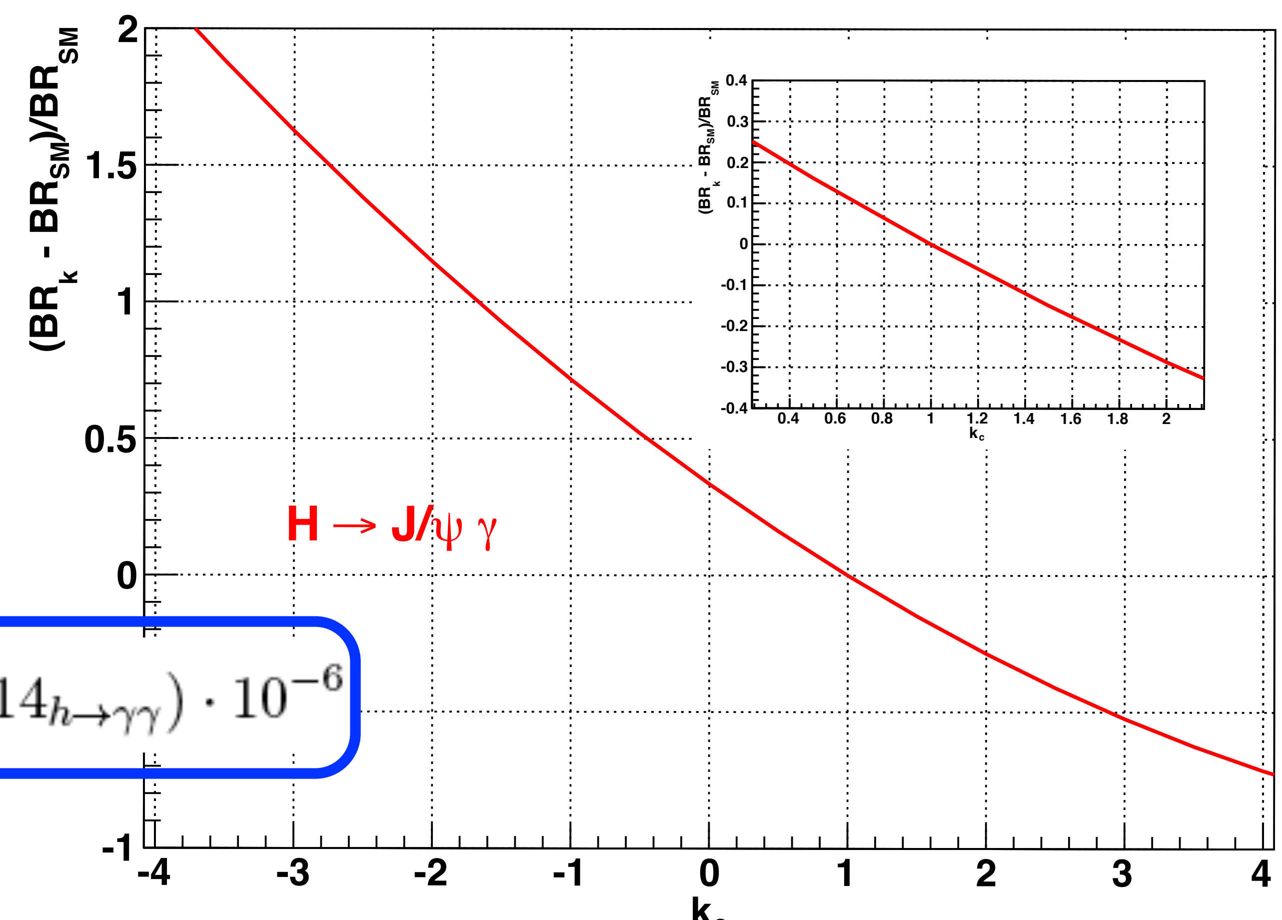
- New calculation using QCD-factorization approach in agreement:

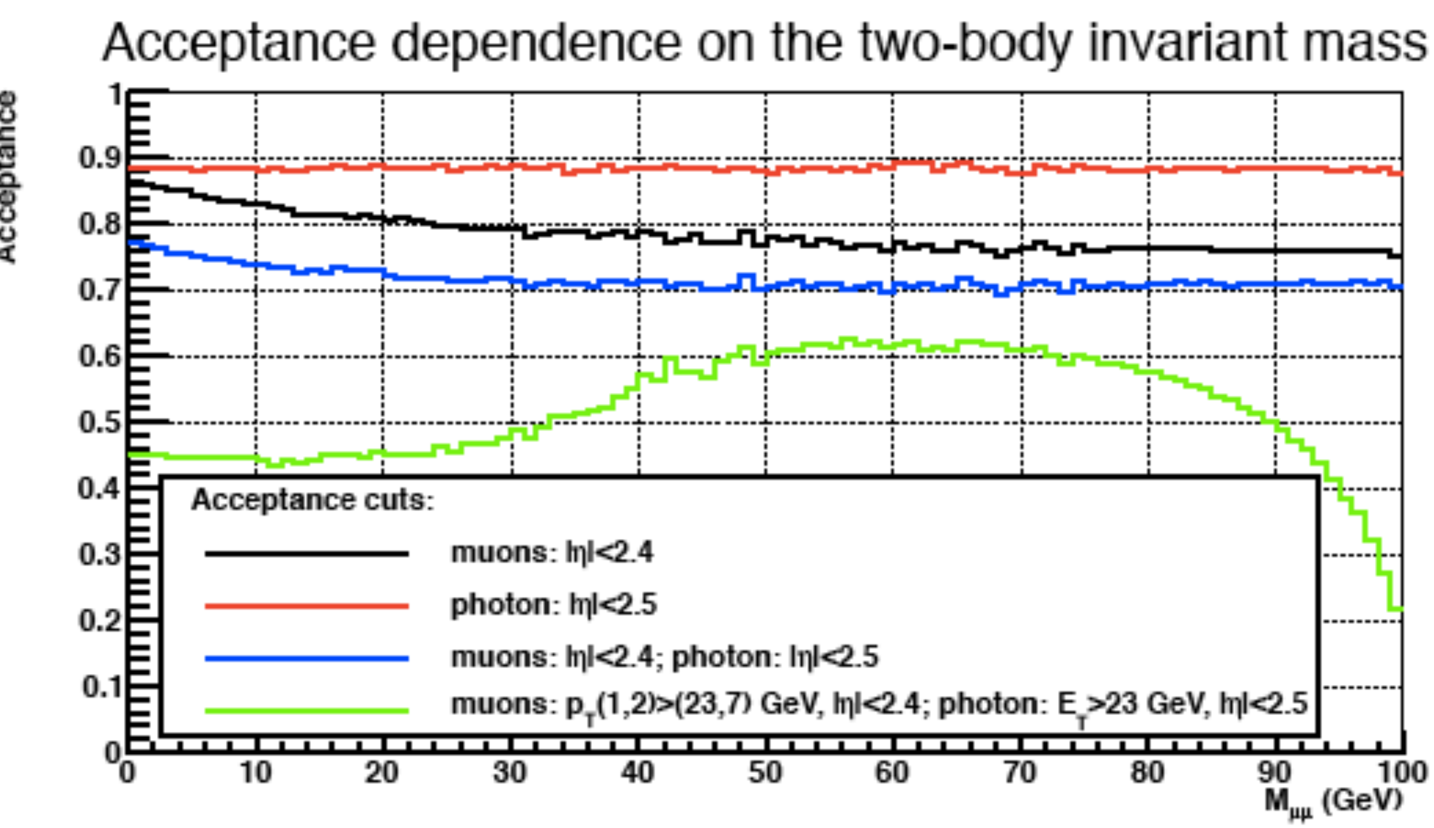
$$\mathrm{Br}(h \to J/\psi\, \gamma) = (2.95 \pm 0.07_{f_{J/\psi}} \pm 0.06_{\rm direct} \pm 0.14_{h\to\gamma\gamma}) \cdot 10^{-6}$$

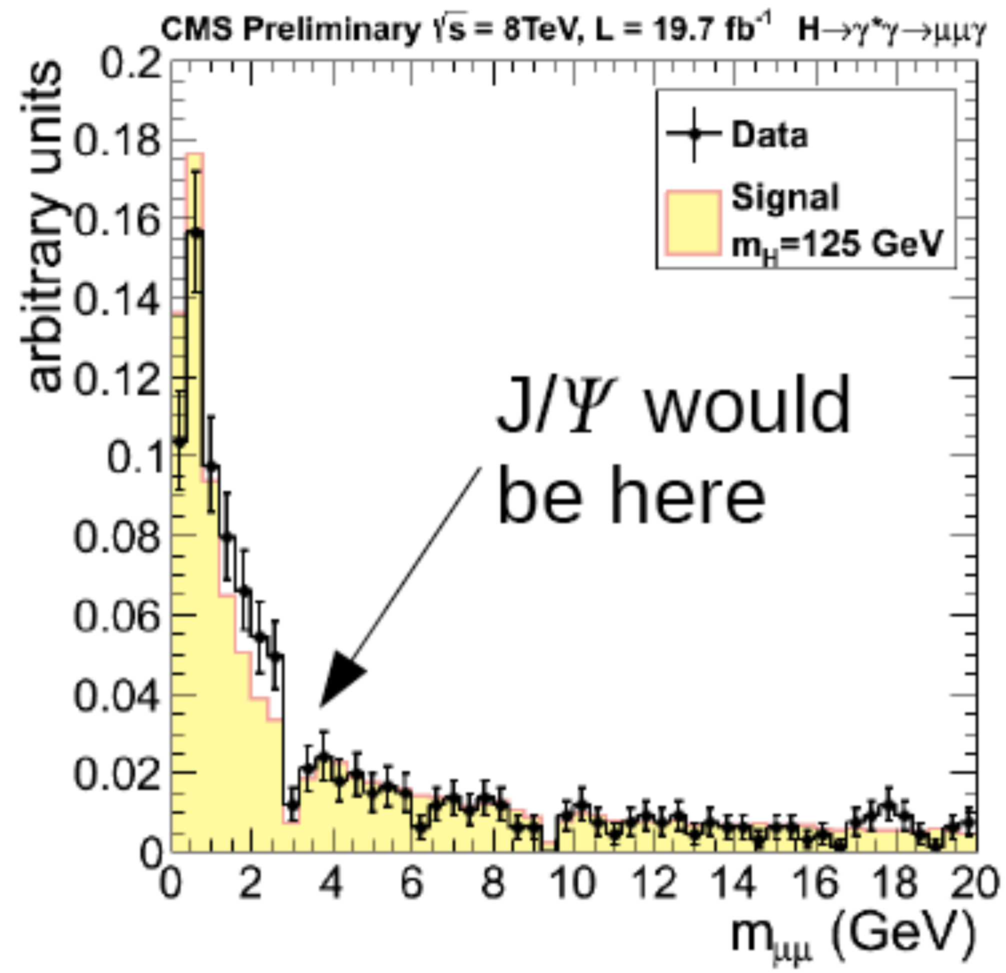
Koenig, Neubert 1505.03870



Experimental prospects

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

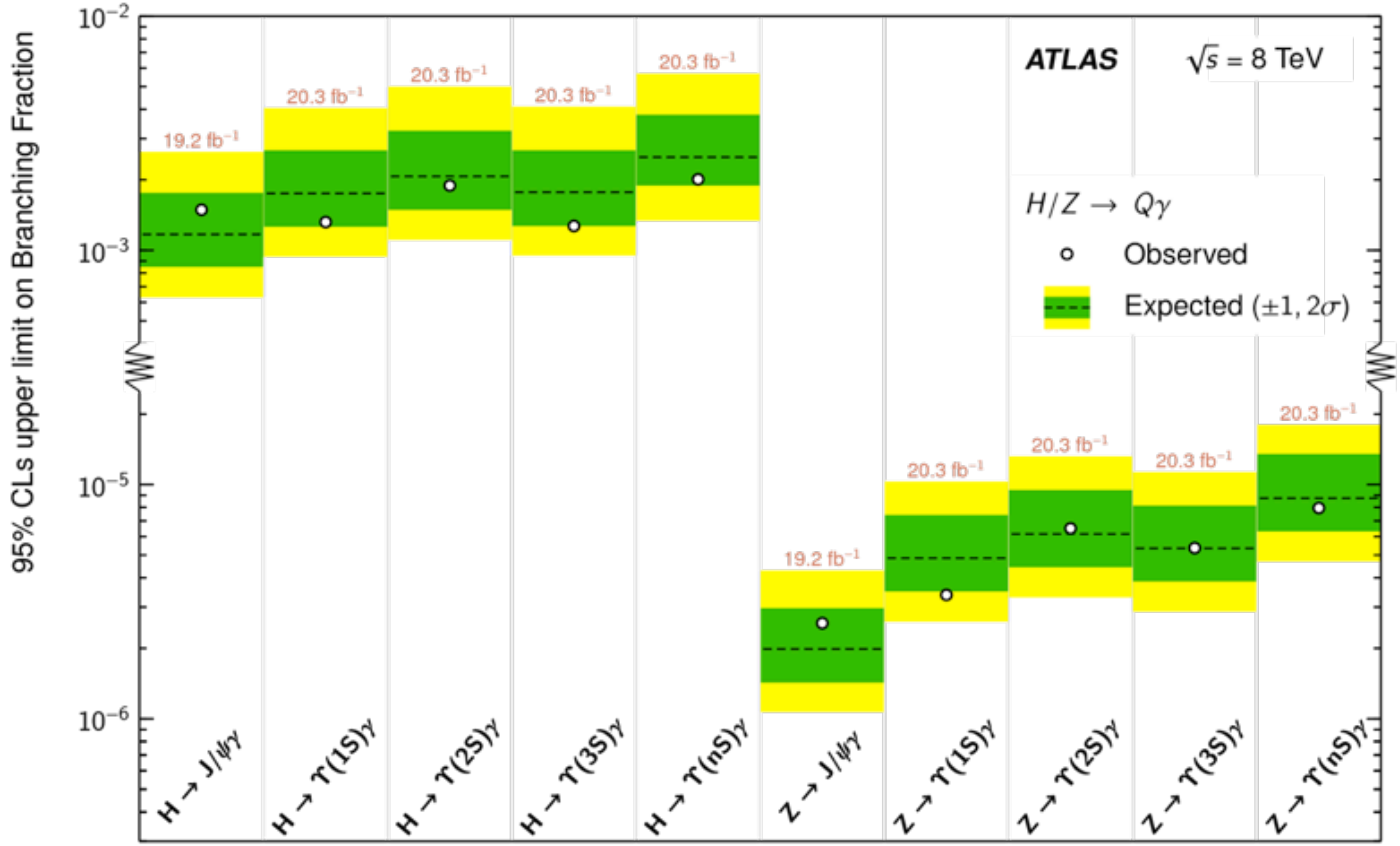




CMS-PAS-HIG-14-003

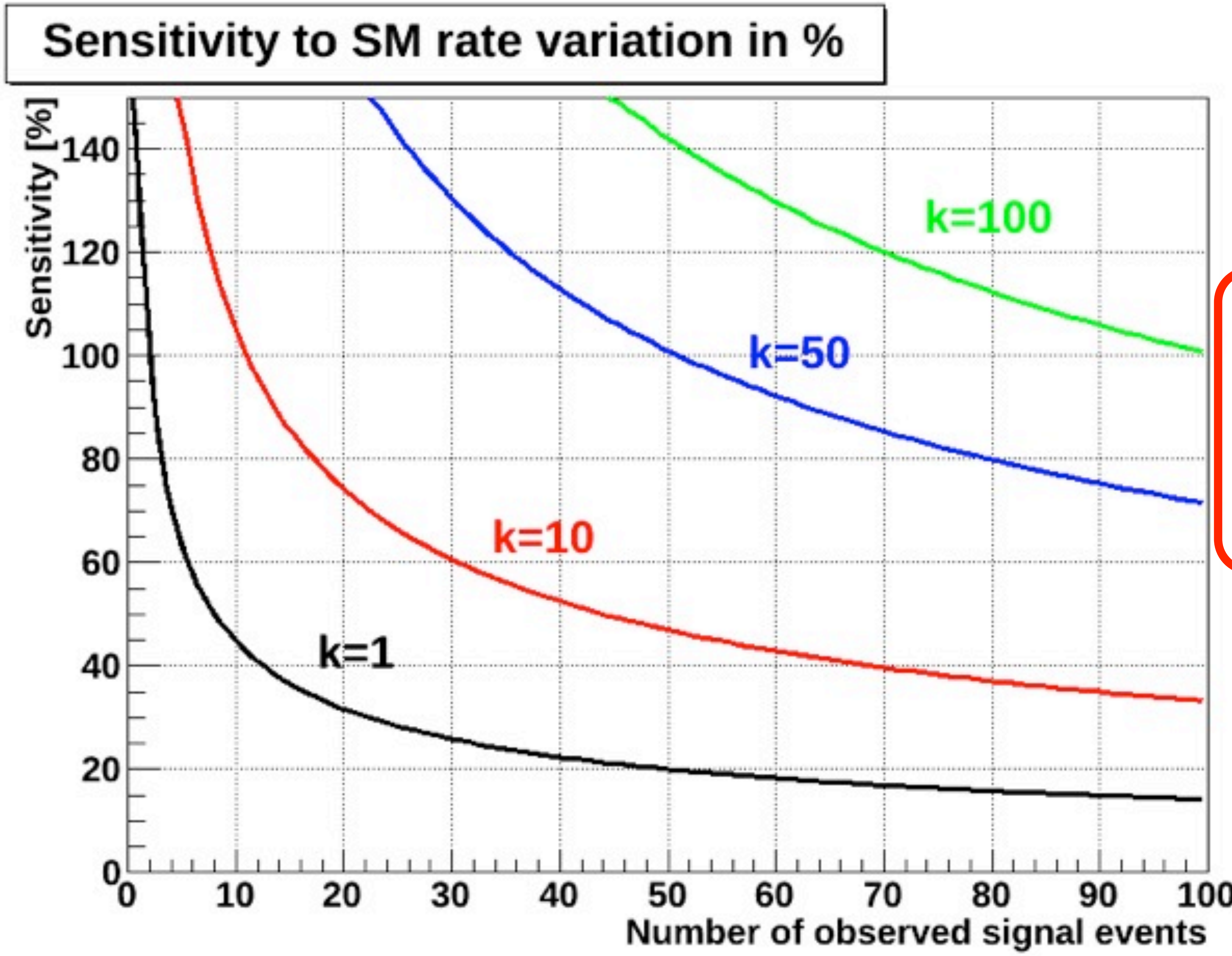
The Dalitz decay search looks for exactly this final state but removes the J/ψ and ϒ regions⇒proof-of-principle that this analysis is possible!

Experimental results



- Current limits on the Higgs branching ratios at the 10^{-3} level
- Similar limits are found by CMS

Sensitivity



Bodwin, FP, Stoynev, Velasco 1306.5770

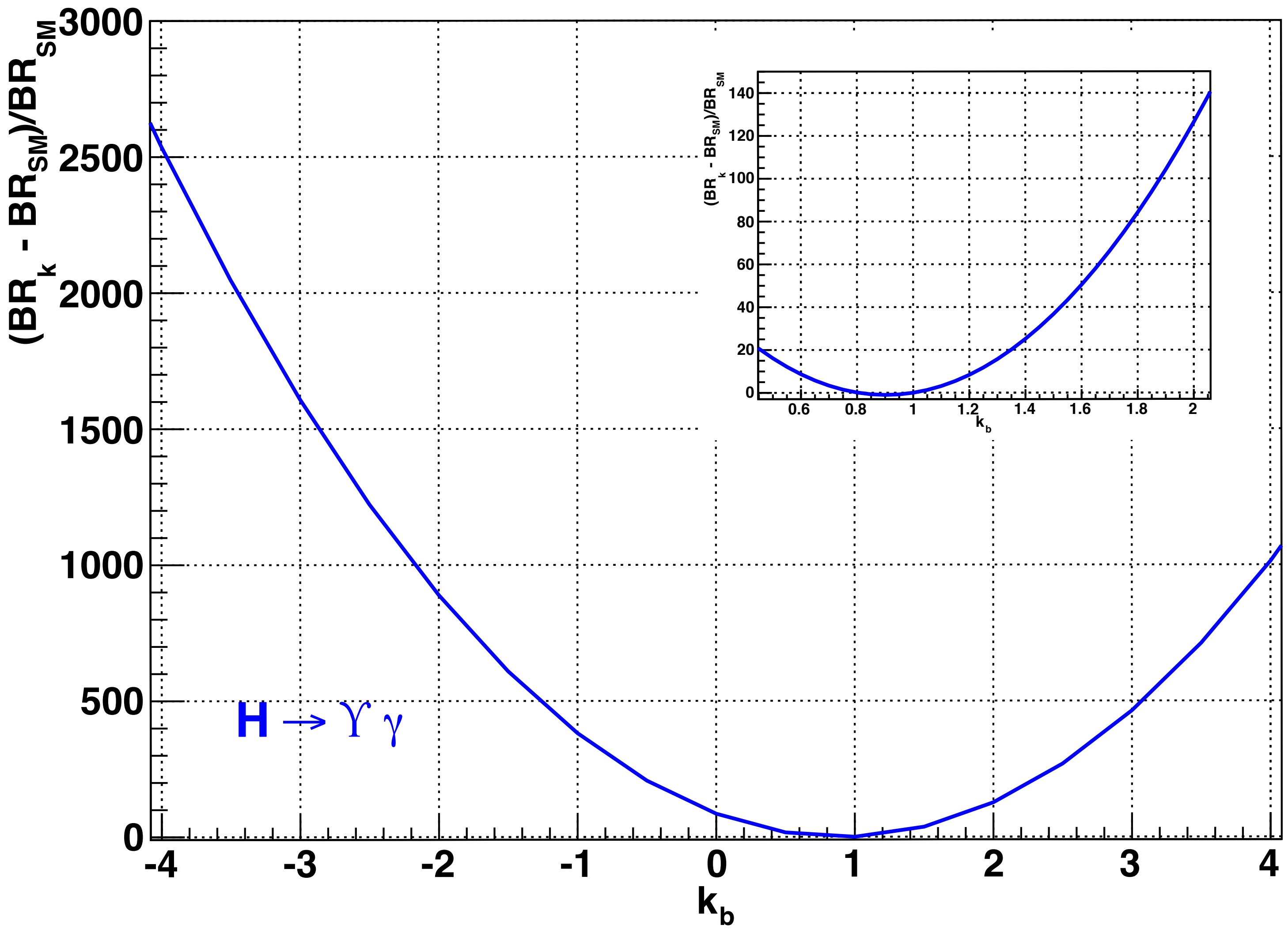
- k=B/S; for the Dalitz decay search, k=40

Observation of the SM coupling may be possible with the full HL-LHC data set; at the least stringent limits can be set

<u>Question for future analyses</u>

- Can electron modes be used in addition to muons?

Hbb at the LHC



- This is the same deviation plot for H→ϒ(1S)+γ
- Almost a complete cancellation between direct and indirect amplitudes in the SM.
- 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

- This idea extends to the first two generations!
- Decays to light mesons offer can probe the entire Yukawa structure

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

- 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: $\bar{\kappa}<1$

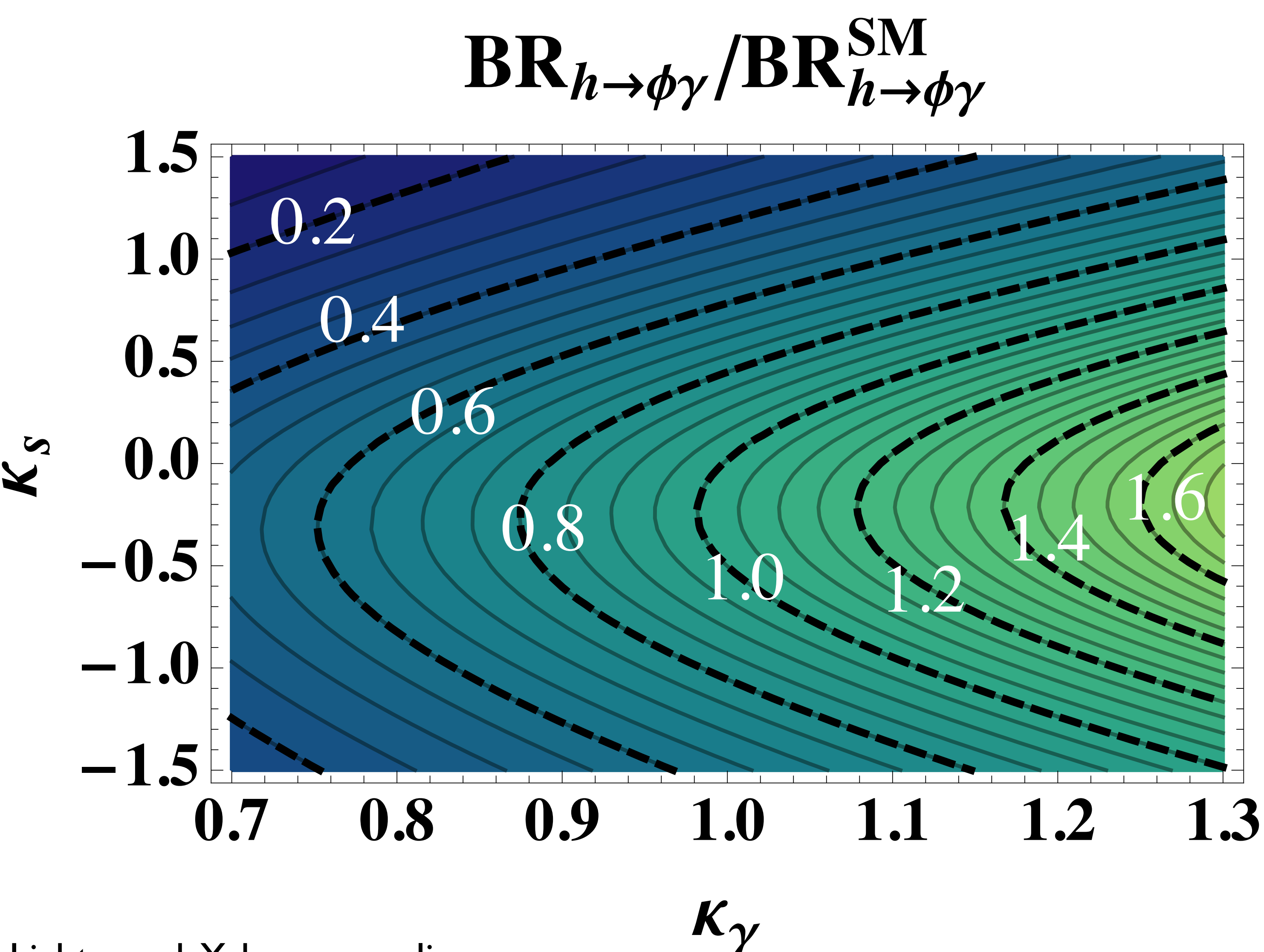
Kagan, Perez, FP, Soreq, Stoynev, Zupan 1406.1722

The Hss coupling

- An example: $h\rightarrow\Phi\gamma \Rightarrow$ 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 for $\bar{\kappa}_s = 1$



- Error on the κ_s coefficient is ~20%; can be reduced by a combination of lattice calculations and data
- $\Phi\rightarrow K^+K^-$ which don't decay in the detector; trigger on photon+FTK for the Φ?

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

The Hss coupling

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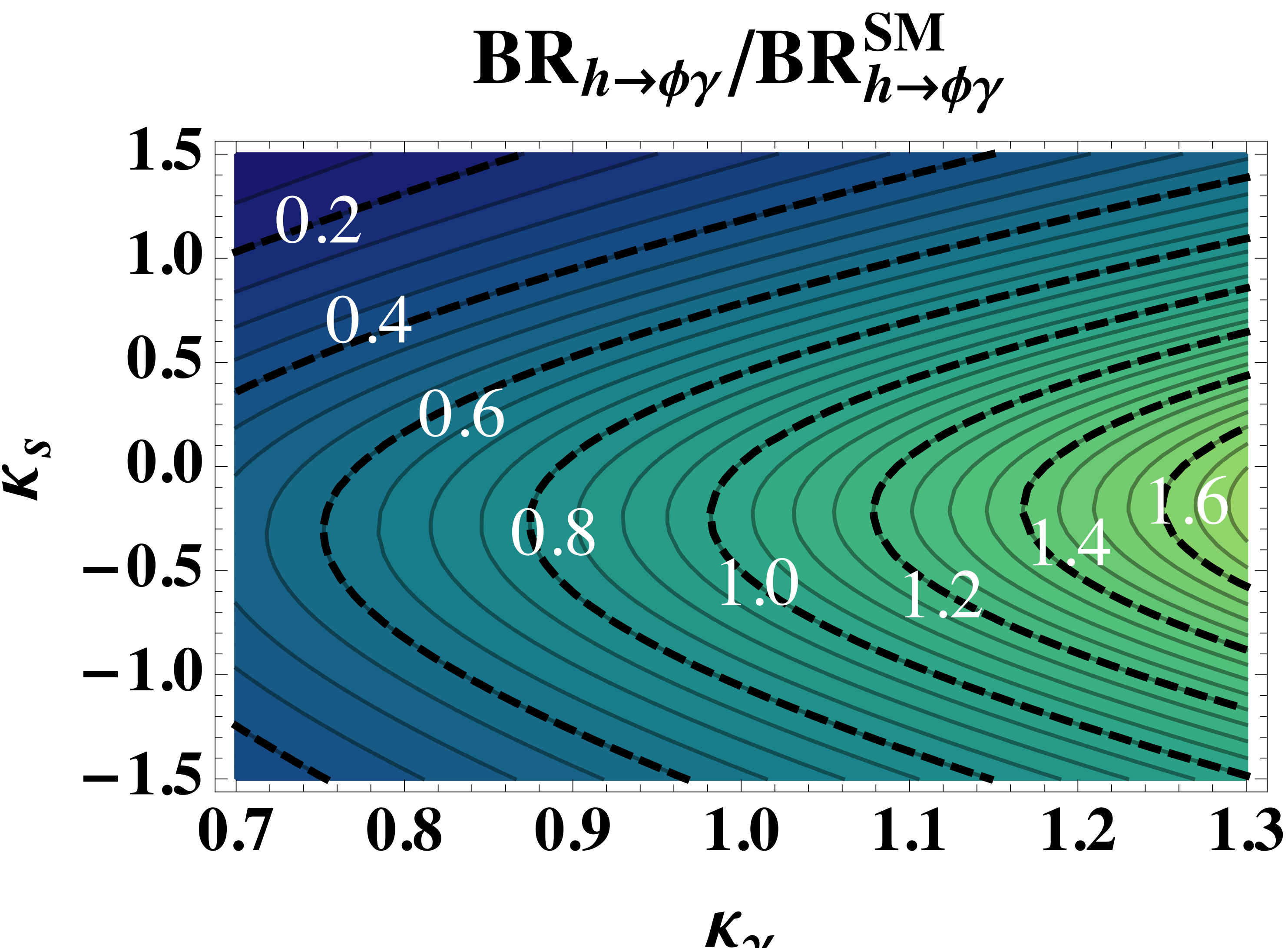

- Recent estimate: a 10% measurement of h→Φγ would permit O(30)xSM values of the strange Yukawa coupling to be probed (Koenig, Neubert 1505.03870)

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The Hss coupling

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($\bar{\kappa}_s$=0.02 in the SM)

$\sqrt{s}$ [TeV]	$\int \mathcal{L}\,dt$ [fb^{-1}]	# of events (SM)	$\bar{\kappa}_s > (<)$	$\bar{\kappa}_s^{\text{stat.}} > (<)$
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.

Conclusions

- Rare hadronic decays of the Higgs allow the couplings of the Higgs to 1st 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!