Rare exclusive decays of the Higgs and electroweak gauge bosons

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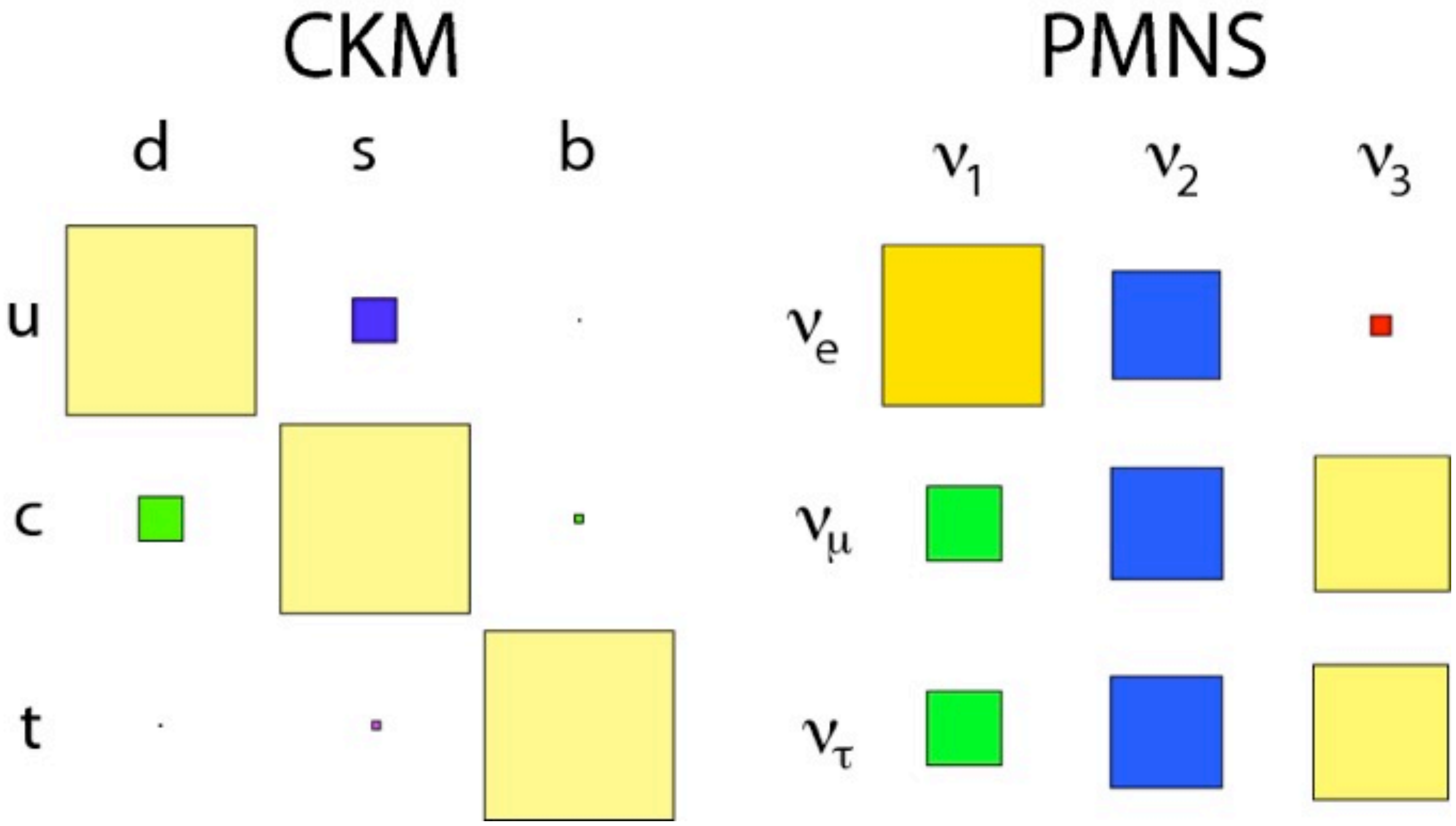
Outline

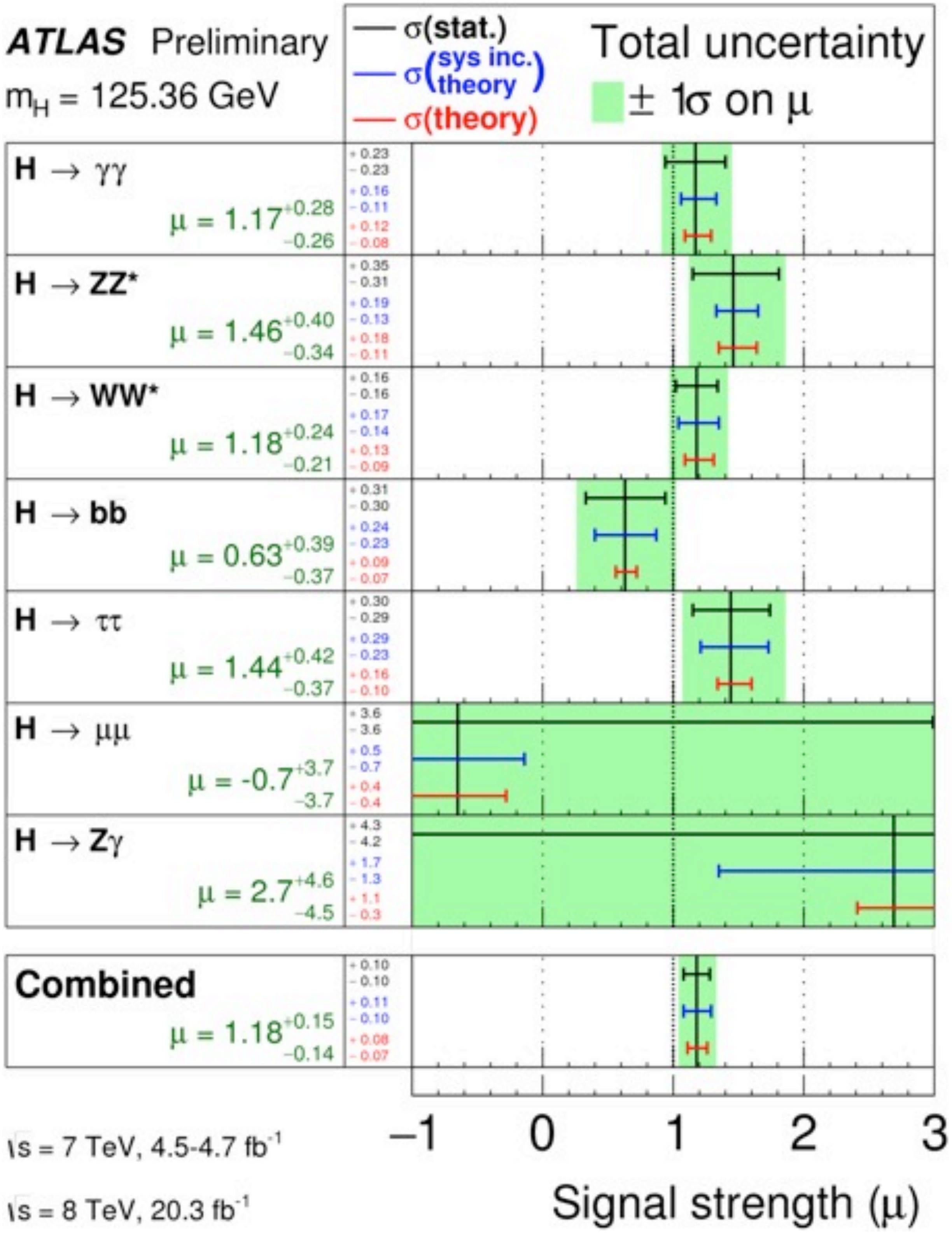
- Introduction and motivation
- The Higgs-charm coupling: charm tagging at the LHC
- The Higgs-charm coupling: rare decays to J/ψ
- Measuring the Higgs Yukawa matrix with decays to light mesons
- Exclusive radiative decays of the W and Z bosons
- Conclusions

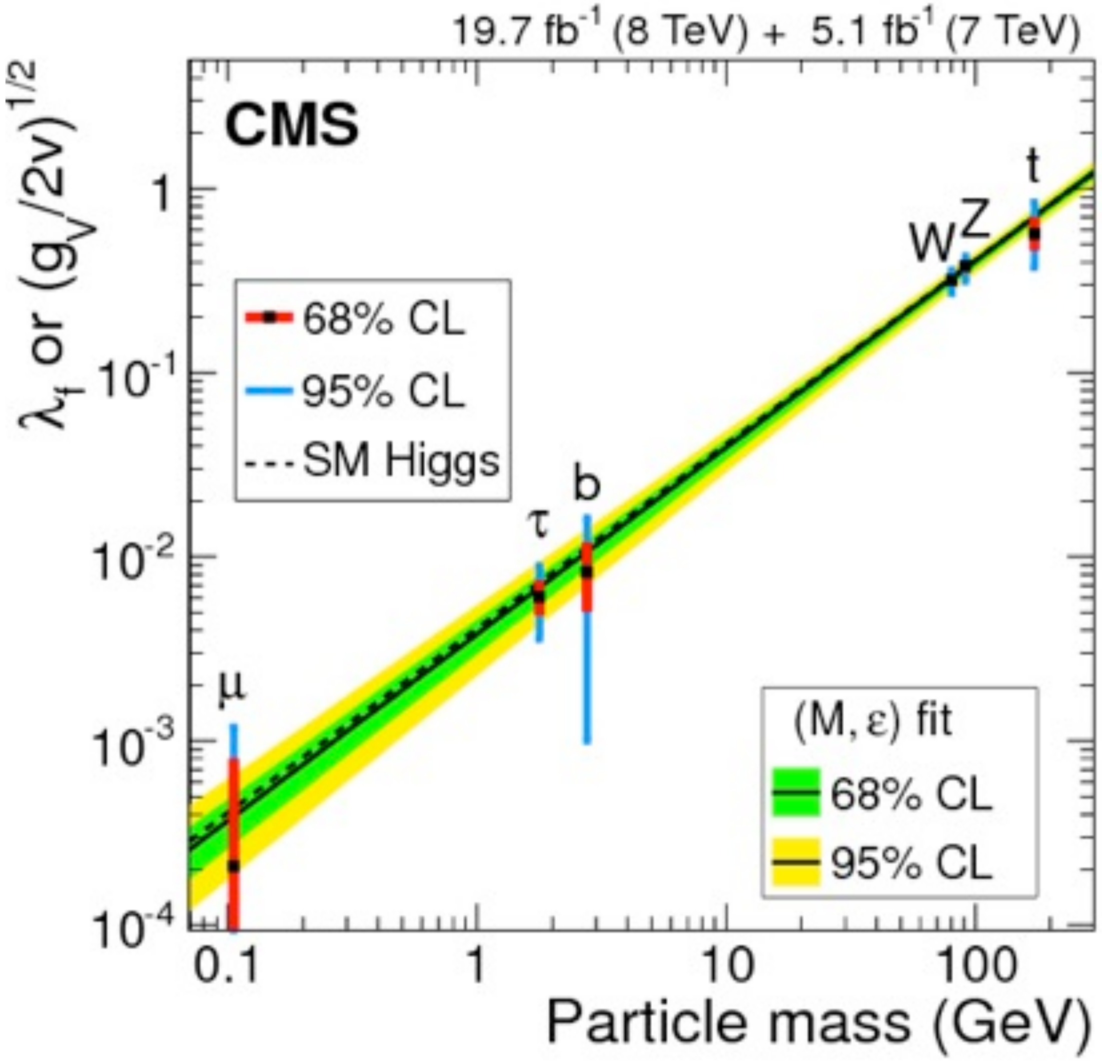
The Standard Model flavor puzzle

- 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!

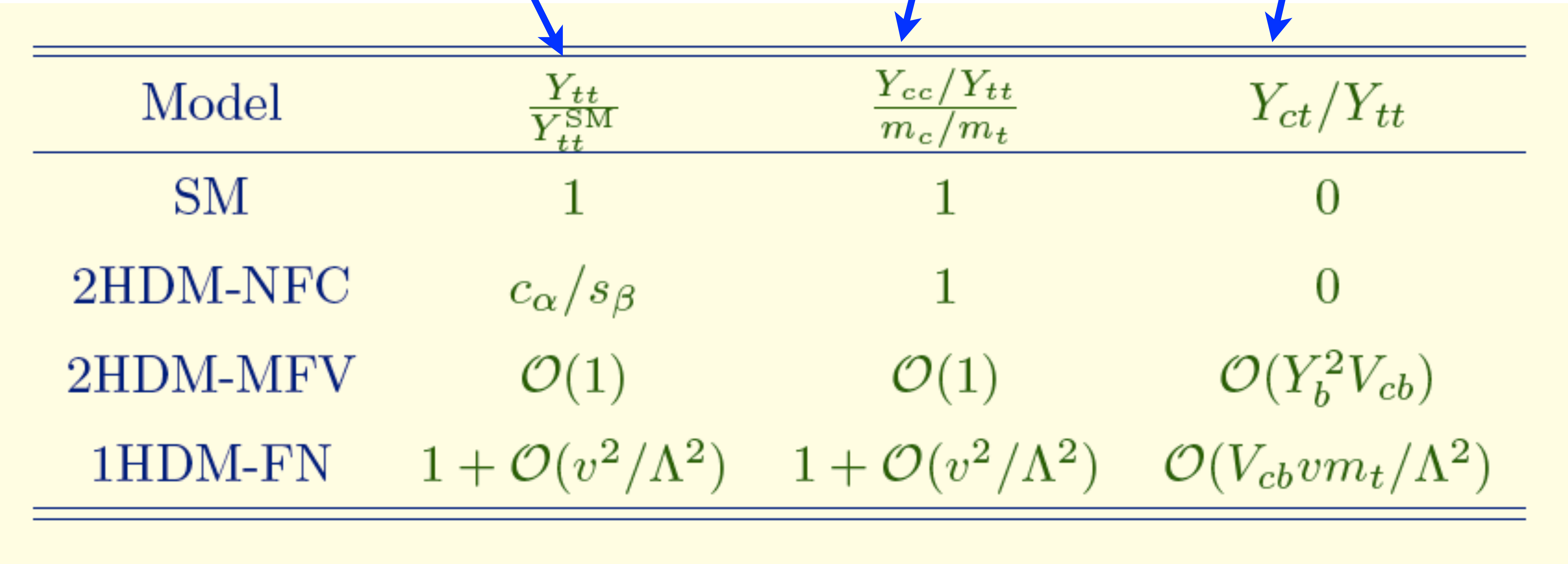
Higgs-fermion couplings

- 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



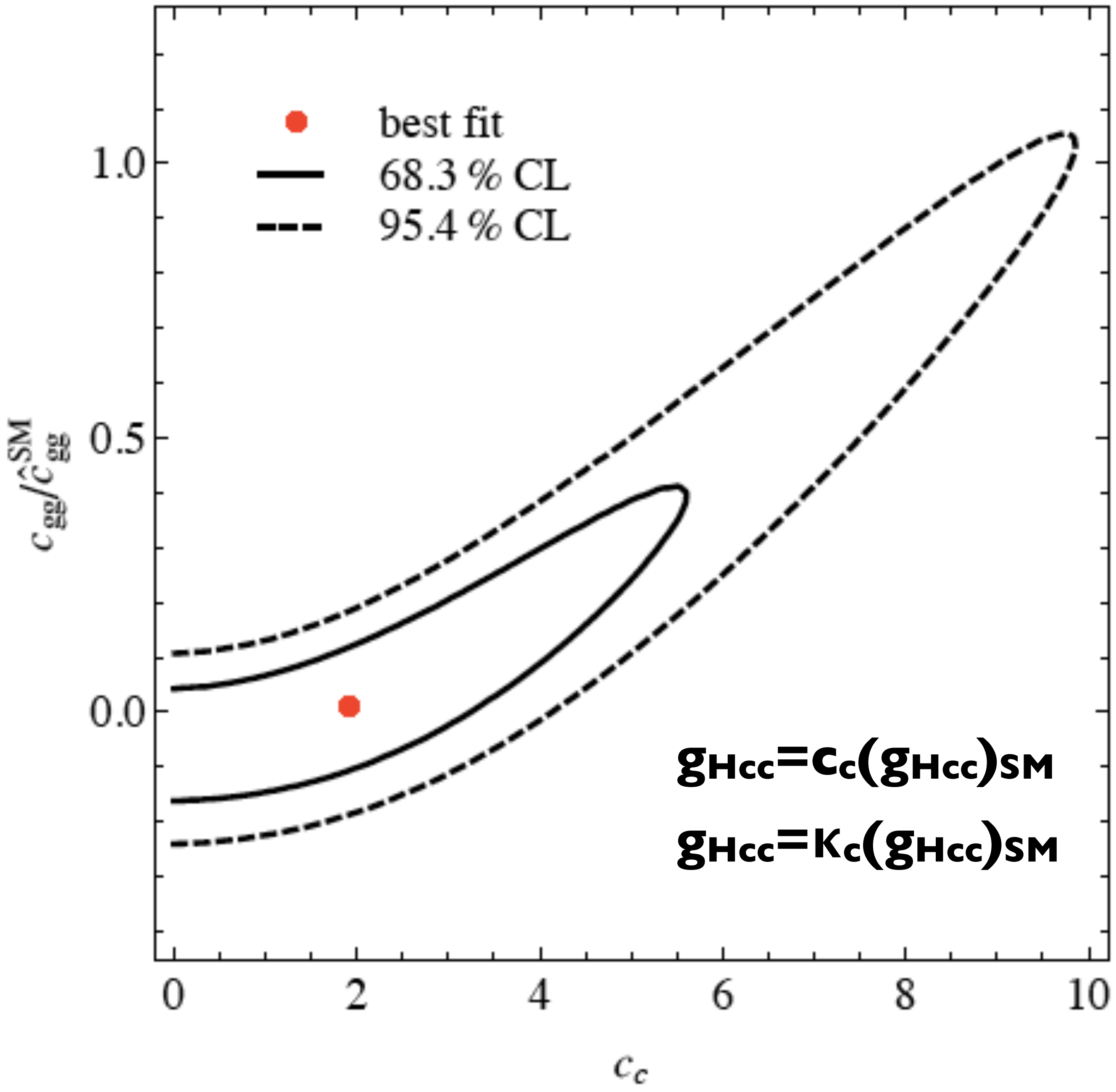
Model	$\frac{Y_{tt}}{Y_{tt}^{\text{SM}}}$	$\frac{Y_{cc}/Y_{tt}}{m_c/m_t}$	Y_{ct}/Y_{tt}
SM	1	1	0
2HDM-NFC	c_α/s_β	1	0
2HDM-MFV	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(Y_b^2 V_{cb})$
1HDM-FN	$1+\mathcal{O}(v^2/\Lambda^2)$	$1+\mathcal{O}(v^2/\Lambda^2)$	$\mathcal{O}(V_{cb} v m_t/\Lambda^2)$

- 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)



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

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

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

$$\kappa_c \lesssim 6.2$$

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)

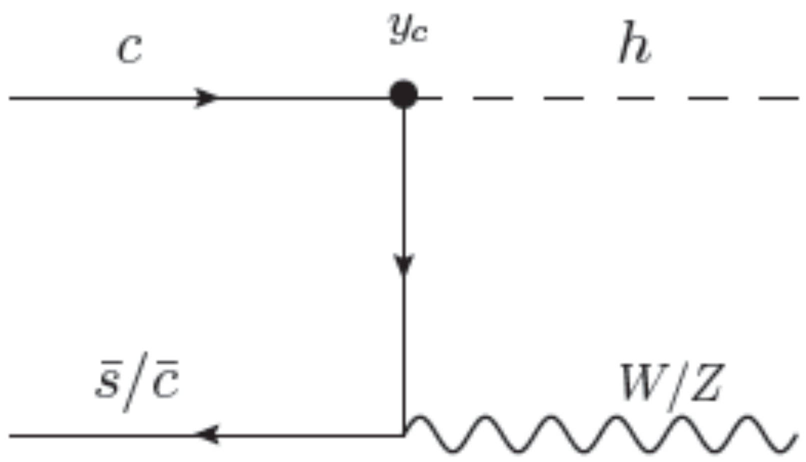
$$\mu_b = \frac{\sigma\,\mathrm{BR}_{b\bar{b}}}{\sigma_{\mathrm{SM}}\mathrm{BR}^{\mathrm{SM}}_{b\bar{b}}} \to \frac{\sigma\,\mathrm{BR}_{b\bar{b}}\,\epsilon_{b_1}\epsilon_{b_2} + \sigma\,\mathrm{BR}_{c\bar{c}}\,\epsilon_{c_1}\epsilon_{c_2}}{\sigma_{\mathrm{SM}}\mathrm{BR}^{\mathrm{SM}}_{b\bar{b}}\,\epsilon_{b_1}\epsilon_{b_2}}$$

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

- 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:

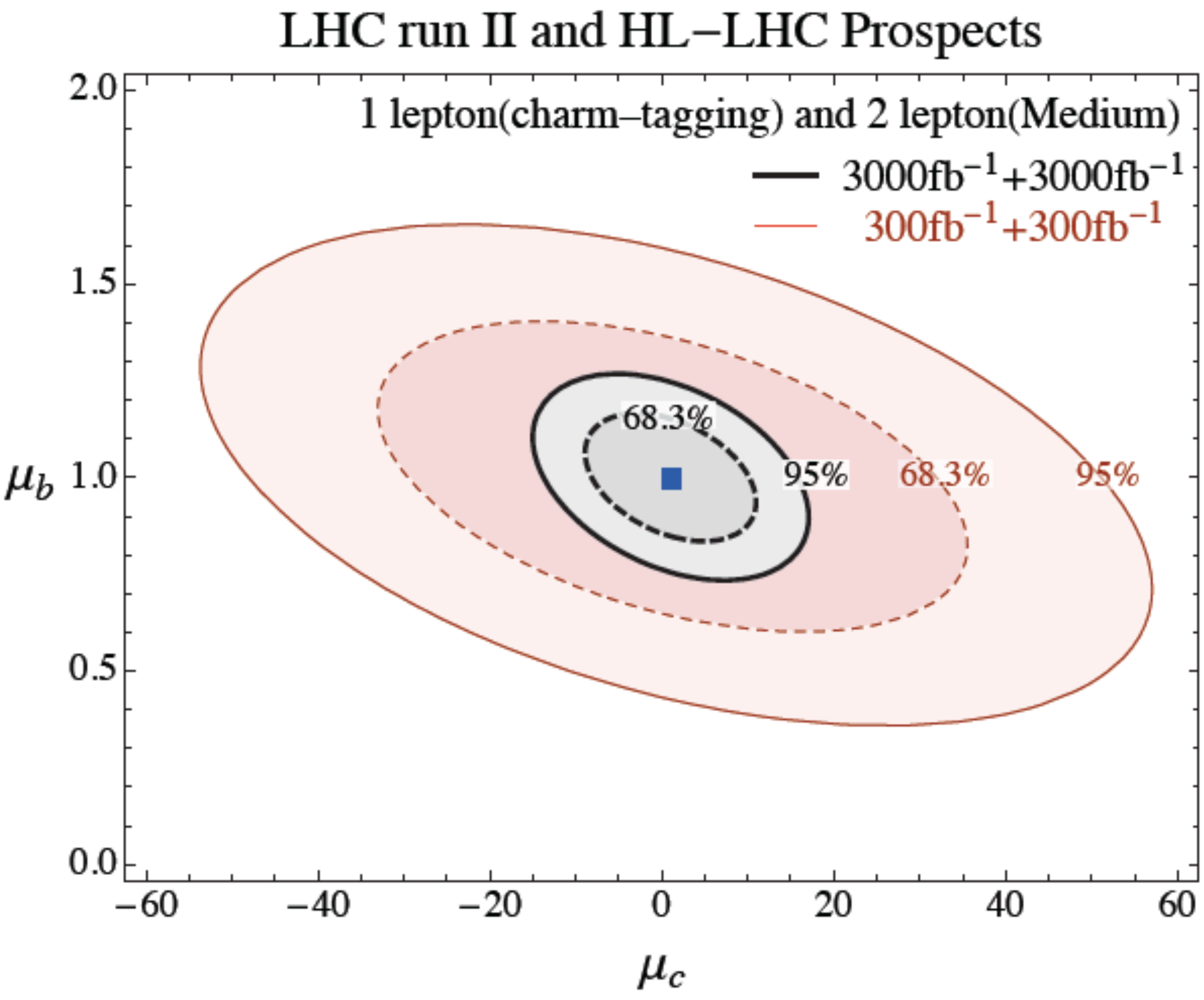


these together allow a bound on the Hcc coupling to be established:

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

(assumes k_V=1)

Future prospects for charm-tagging



Perez, Soreq, Stamou, Tobioka 1503.00290

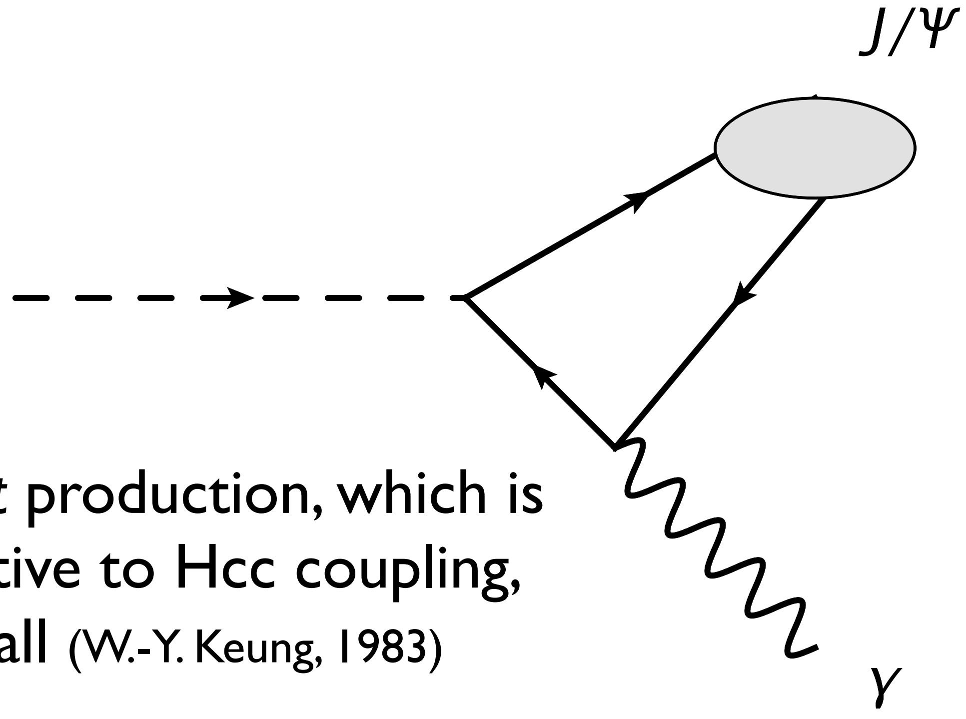
$$\Delta\mu_c = \begin{cases} 23\,(45) & \text{with } 300\ \text{fb}^{-1} \\ 6.5\,(13) & \text{with } 3000\ \text{fb}^{-1} \end{cases}$$

$$68.3\,(95)\%\ \text{CL}$$

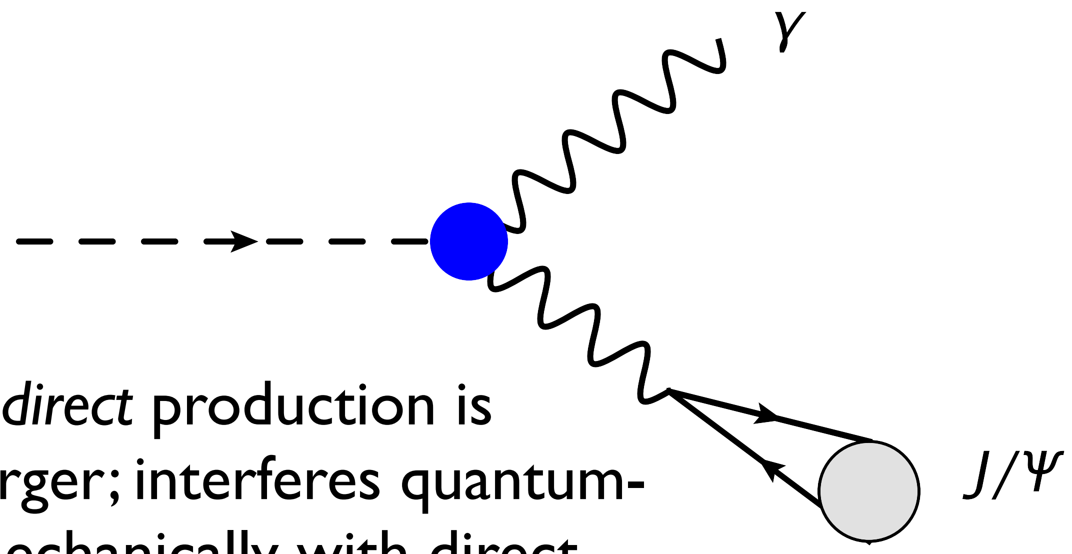
- Will be able to probe a signal strength of O(10)xSM

Quarkonium interferometry

- Access this coupling using H→J/Ψ+γ! Bodwin, FP, Stoynev, Velasco 1306.5770



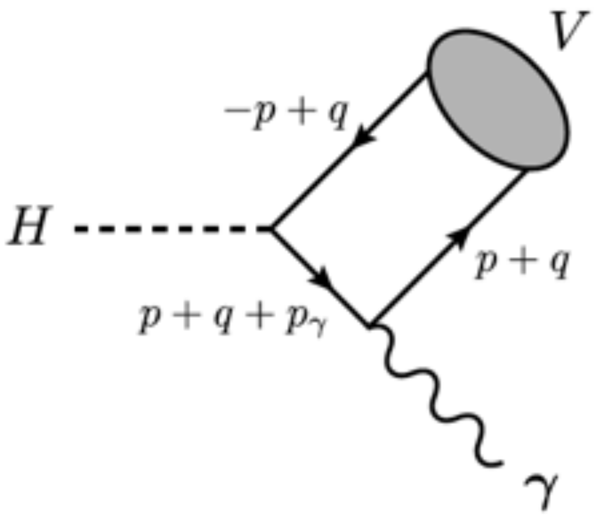
Direct production, which is sensitive to Hcc coupling, is small (W.-Y. Keung, 1983)

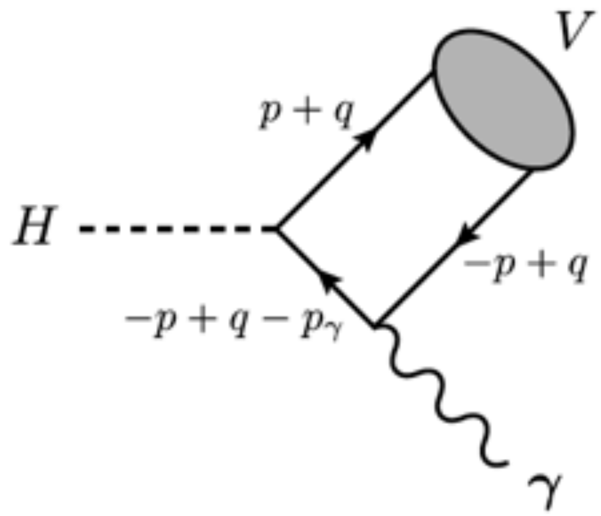


Indirect production is larger; interferes quantum-mechanically with direct production

- 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





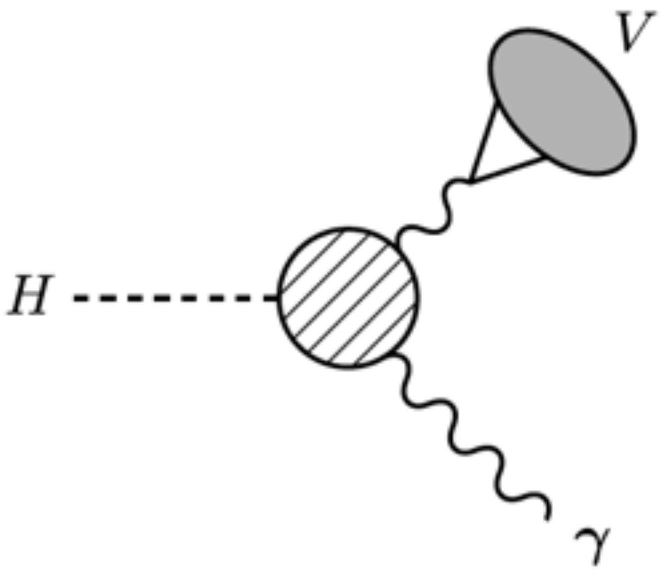
- Calculational framework: NRQCD to O(v^2) cross-checked using light-cone distribution amplitudes

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

quarkonium wave-function at origin

amplitude for $^3S_1$ cc production

leading relativistic correction, -10%



- Effective H$\gamma\gamma^*$ 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 H$\gamma\gamma^*$ coupling

Theory prediction for J/ψ

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

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

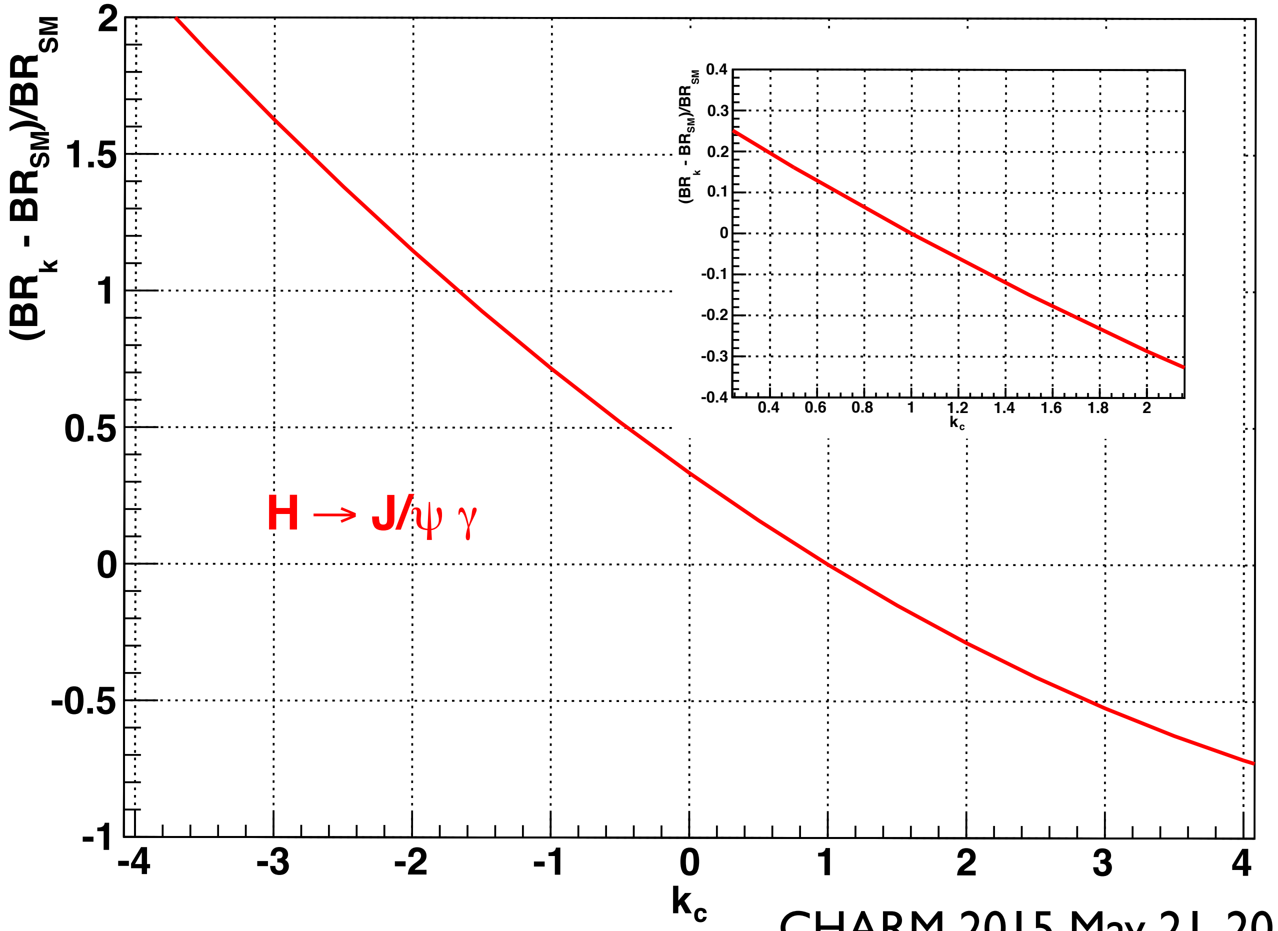
$$\Gamma(H \to J/\psi + \gamma) = \left|(11.9 \pm 0.2) - (1.04 \pm 0.14)\kappa_c\right|^2 \times 10^{-10}\ \mathrm{GeV}$$

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:

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



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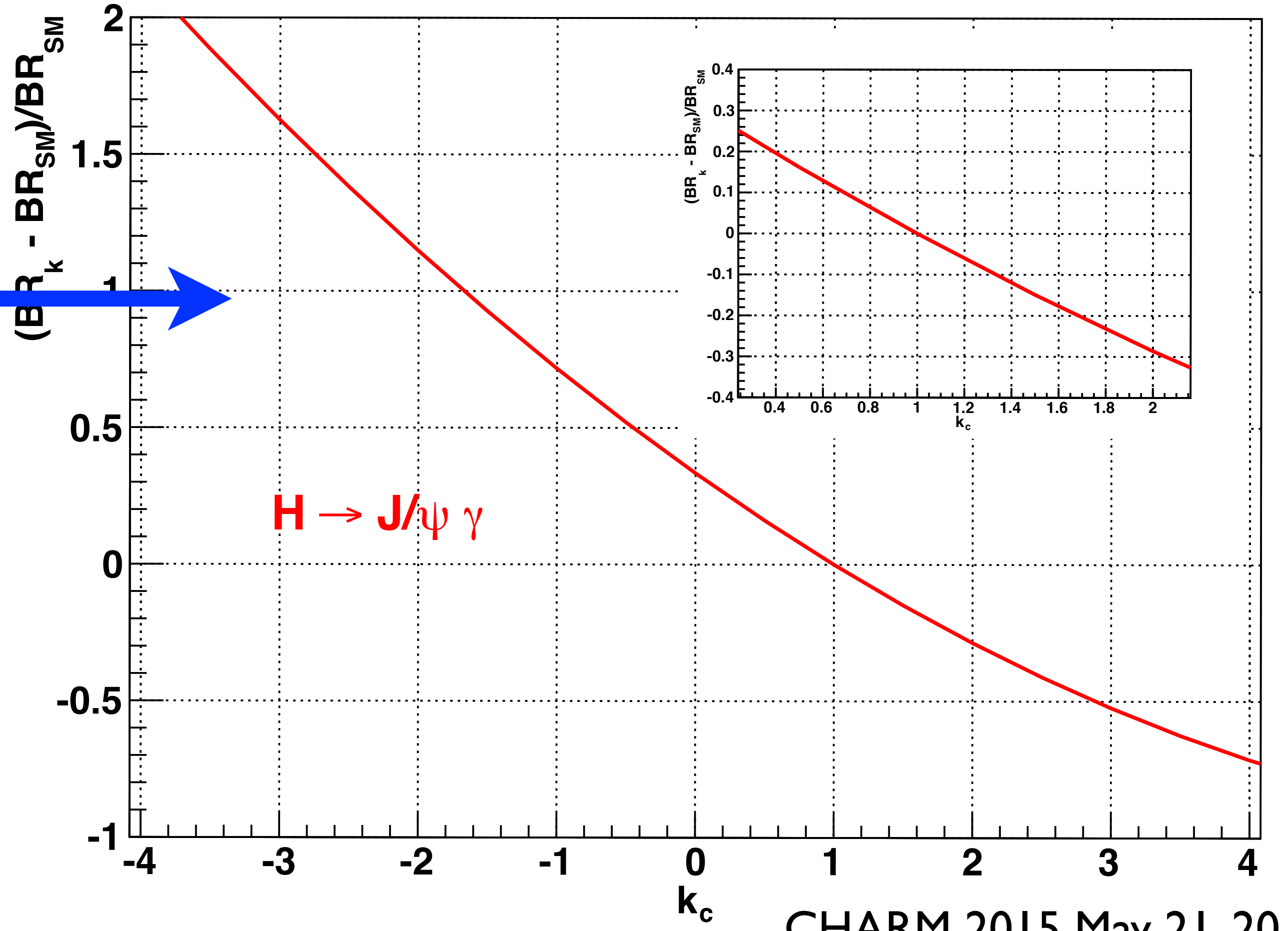
Dominant uncertainty on indirect amplitude: leptonic width of J/ψ

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

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



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

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

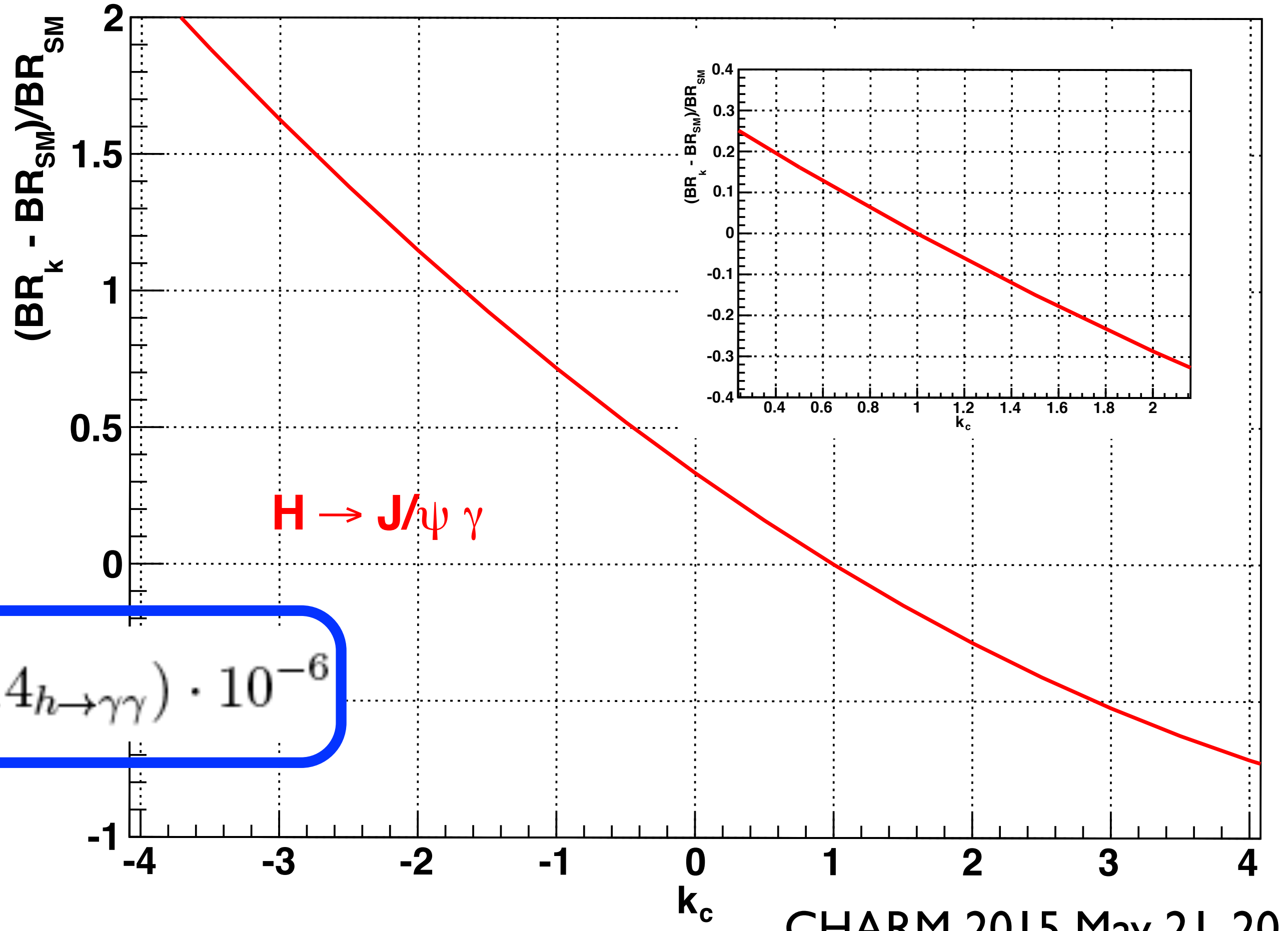
- Branching ratio in the SM:

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

- New calculation using QCD-factorization approach in agreement:

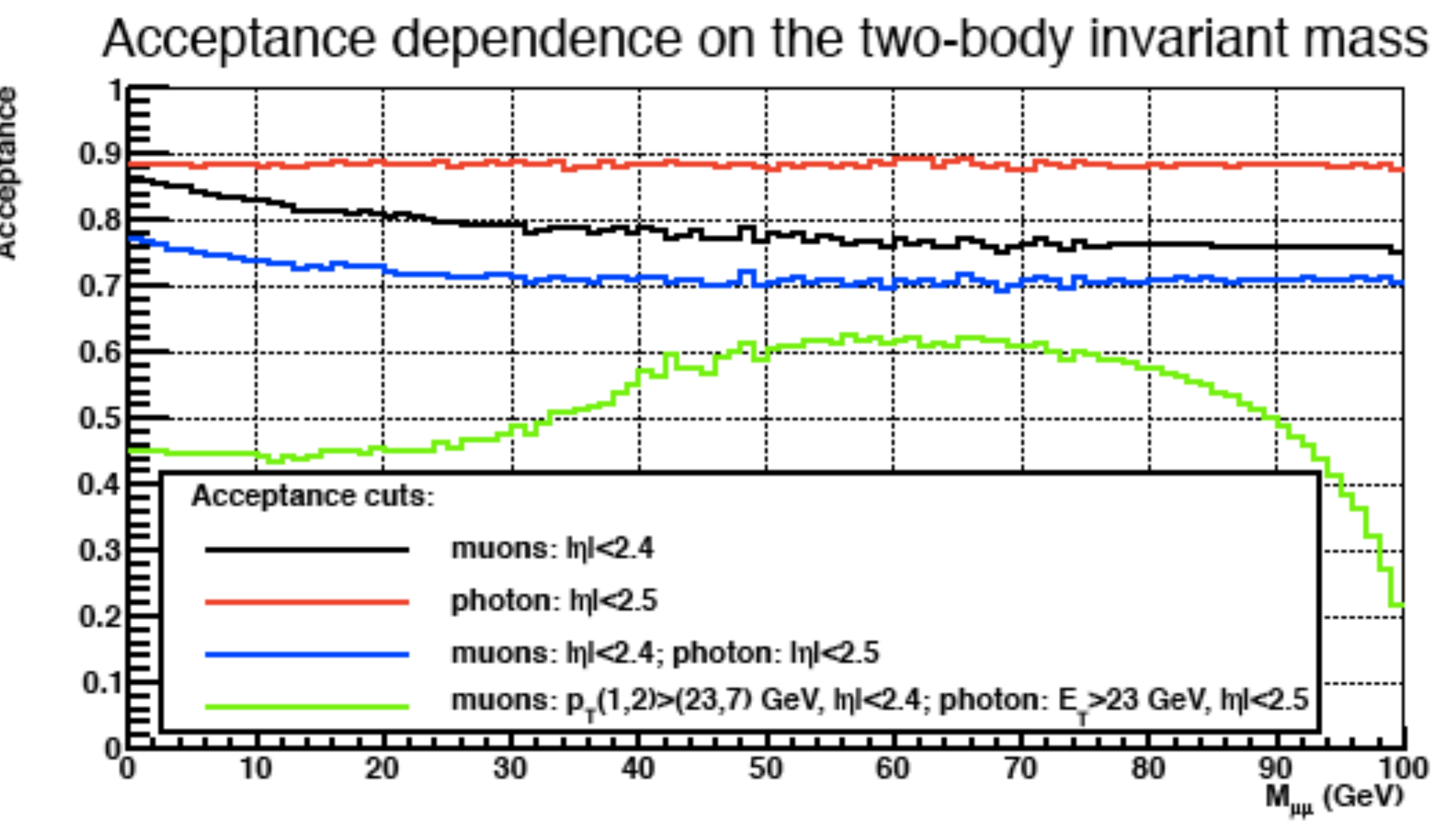
$$\mathrm{Br}(h \to J/\psi\,\gamma) = (2.95 \pm 0.07_{f_{J/\psi}} \pm 0.06_{\rm direct} \pm 0.14_{h\to\gamma\gamma}) \cdot 10^{-6}$$

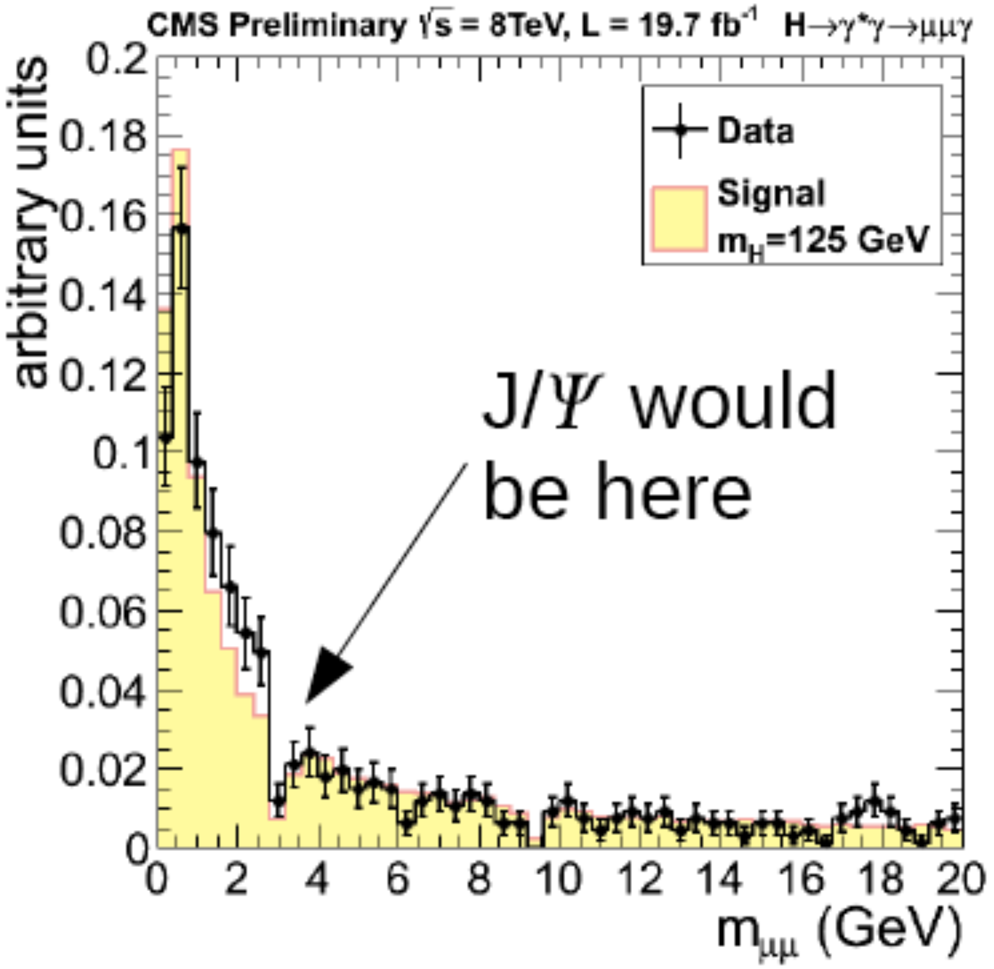
Koenig, Neubert 1505.03870



Experimental prospects

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



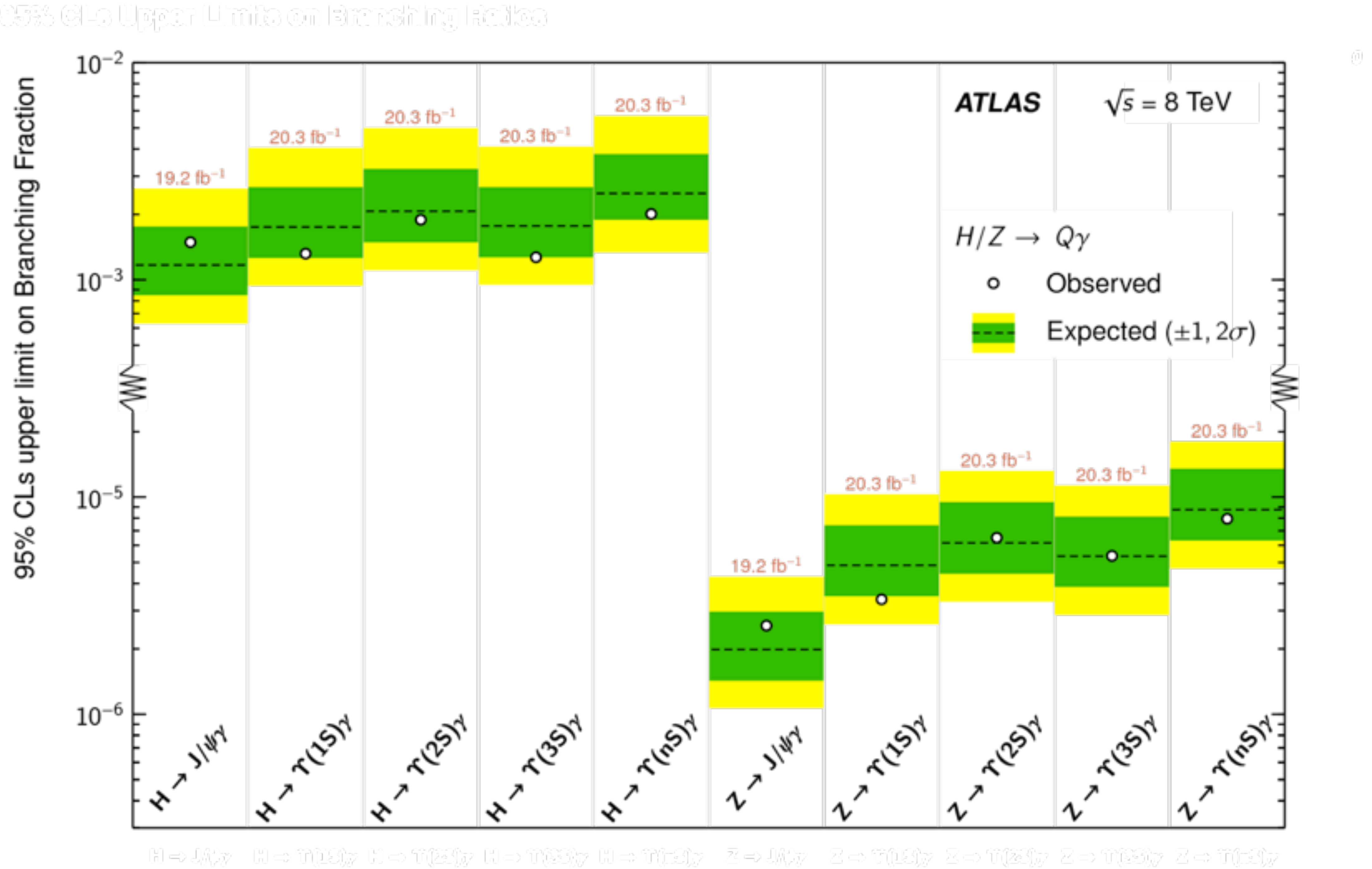


J/Ψ would be here

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!

ATLAS results



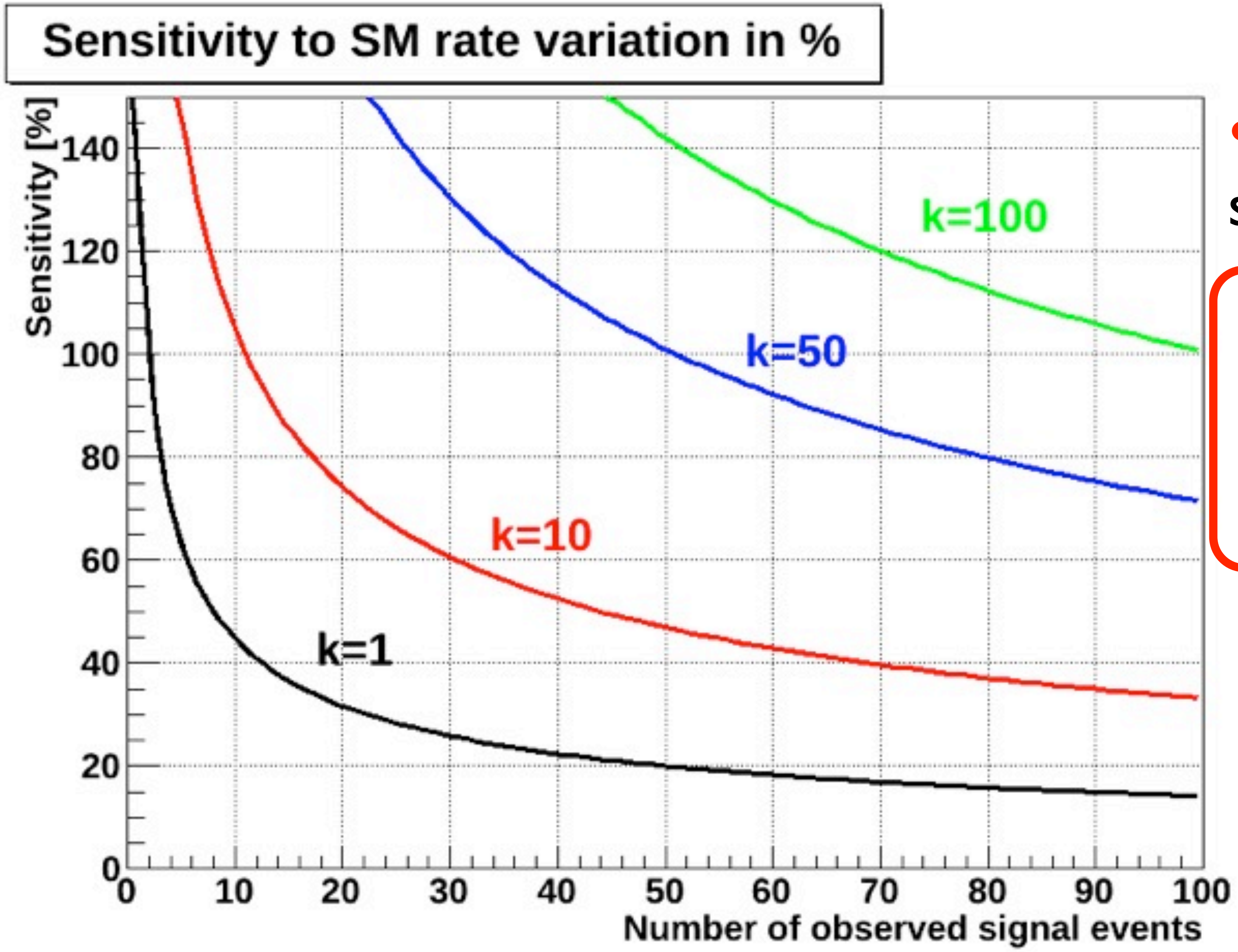
- Current limits on the Higgs branching ratios at the 10^{-3} level

$$\boxed{\kappa_c \lesssim 220}$$

from Perez et al., 1503.00290

(assumes k_γ=1)

Sensitivity



Bodwin, FP, Stoynev, Velasco 1306.5770

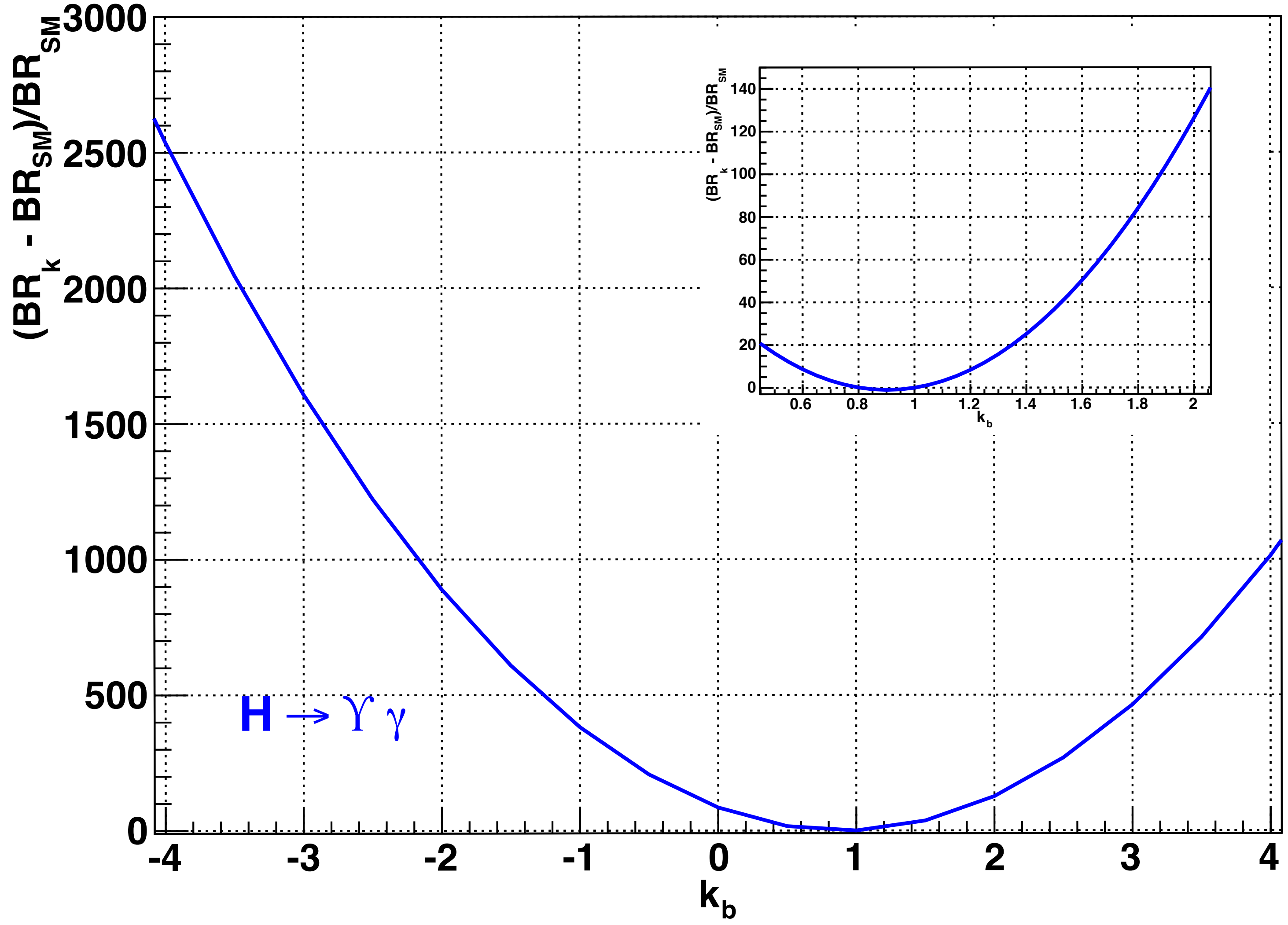
- k=B/S; for the Dalitz decay search, k=40

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

Questions for future analyses

- Can electron modes be used in addition to muons?
- Can the ±200 MeV window around the J/ψ be tightened?

Hbb at the LHC



- This is the same deviation plot for $H \to \Upsilon(1S)+\gamma$
- The y-axis is not a typo! 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

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

- Diagonal couplings: access with $h\to\rho,\omega,\Phi+\gamma$
- Contributions from both direct and indirect amplitudes

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

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

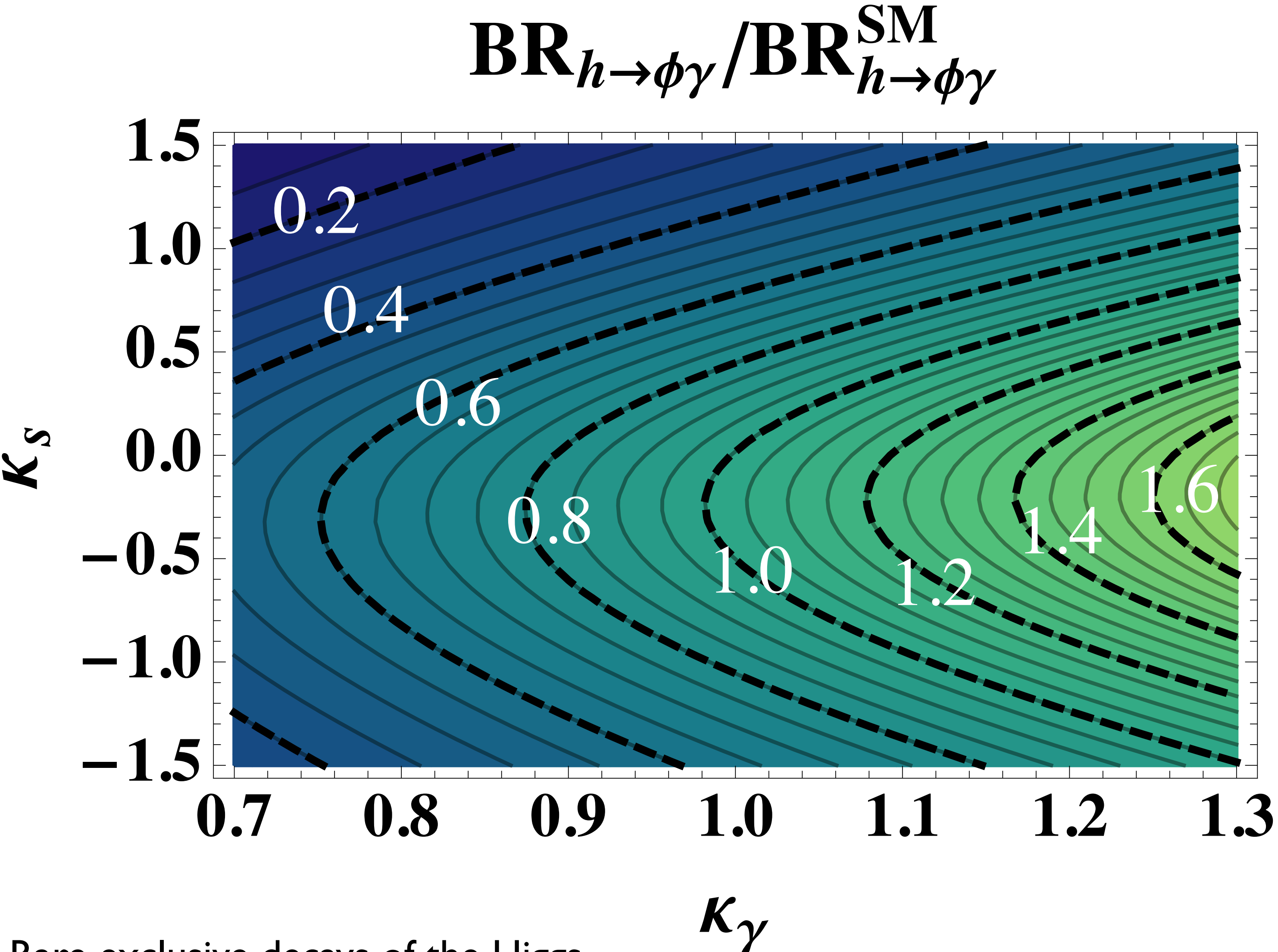
Kagan, Perez, FP, Soreq, Stoynev, Zupan 1406.1722

The Hss coupling

- An example: h→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 for $\bar{\kappa}_s=1$



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

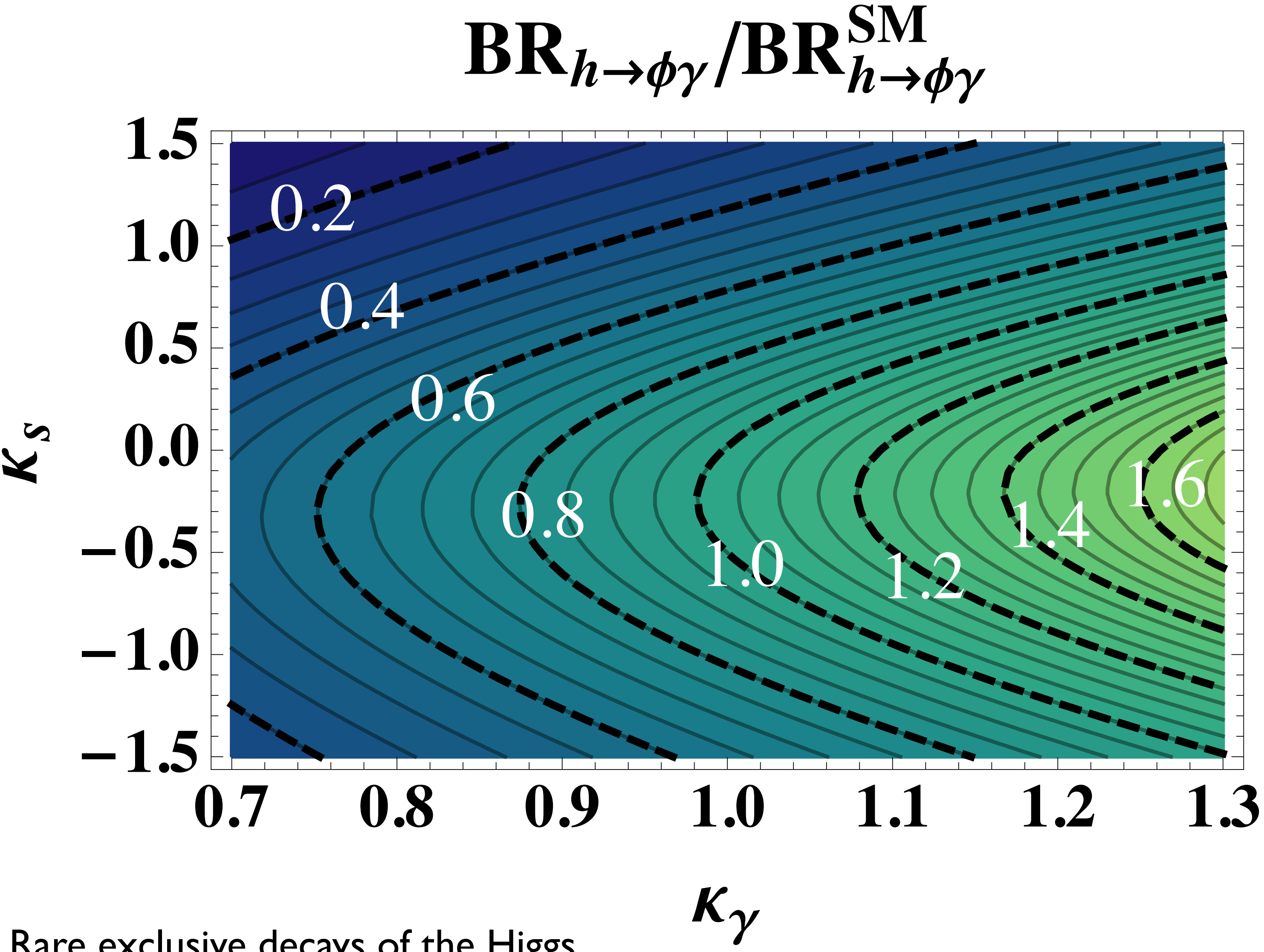
This is the only idea so far on how to directly measure these couplings!

The Hss coupling

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

$$\frac{\mathrm{BR}_{h\to\phi\gamma}}{\mathrm{BR}_{h\to b\bar{b}}}=\frac{\kappa_\gamma\left[(3.0\pm0.13)\kappa_\gamma-0.78\bar{\kappa}_s\right]\cdot10^{-6}}{0.57\bar{\kappa}_b^2}$$

Interference is a 25% effect for $\overline{\kappa}_s$=1



- 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)

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

The Hss coupling

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

$$\frac{\mathrm{BR}_{h\to\phi\gamma}}{\mathrm{BR}_{h\to b\bar{b}}} = \frac{\kappa_\gamma\left[(3.0\pm0.13)\kappa_\gamma - 0.78\bar{\kappa}_s\right]\cdot 10^{-6}}{0.57\bar{\kappa}_b^2}$$

Interference is a 25% effect

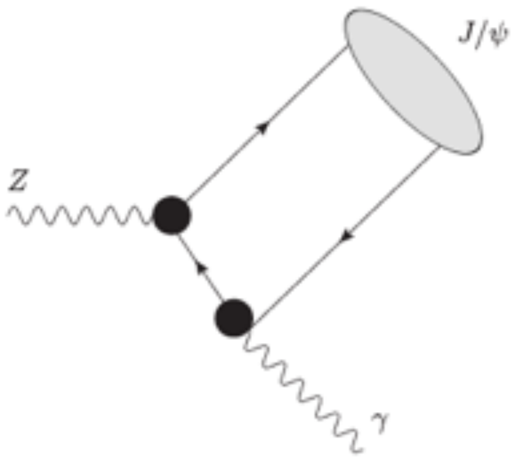
($\bar{\kappa}_s$=0.02 in the SM)

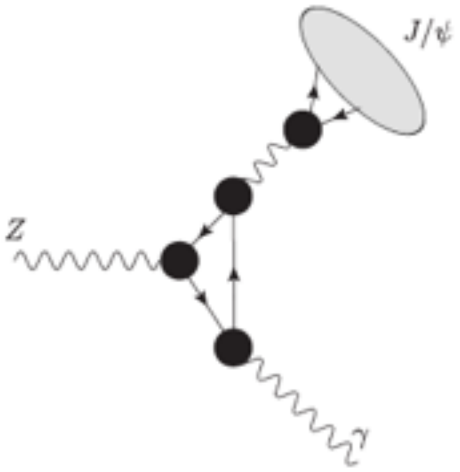
$\sqrt{s}$ [TeV]	$\int \mathcal{L}\,dt\,[\mathrm{fb}^{-1}]$	# of events (SM)	$\bar{\kappa}_s > (<)$	$\bar{\kappa}_s^{\mathrm{stat.}} > (<)$
14	3000	770	0.39 (−0.97)	0.27 (−0.81)
33	3000	1380	0.36 (−0.94)	0.22 (−0.75)
100	3000	5920	0.34 (−0.90)	0.13 (−0.63)

- 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.

Rare exclusive EW decays

- Rare Z decays to J/ψ, ϒ or Φ serve as a helpful benchmark for rare Higgs decays (Huang, FP 1411.5924); also may serve as a stringent test of the QCD factorization framework (Grossman, Koenig, Neubert 1501.06569)





$$B_{SM}(Z \to J/\psi + \gamma) = (9.96 \pm 1.86) \times 10^{-8}$$

$$B_{SM}(Z \to \Upsilon(1S) + \gamma) = (4.93 \pm 0.51) \times 10^{-8}$$

$$B_{SM}(Z \to \phi + \gamma) = (1.17 \pm 0.08) \times 10^{-8}$$

Huang, FP 1411.5924

(in agreement with 1501.06569; except Z→Φγ=0.86×10^{-8} there due to an updated f_Φ)

- Can also probe properties of the W-boson through the rare decays W→πγ, W→πππ; can also tag these in ttbar events (Mangano, Melia 1410.7475)

Conclusions

- Rare hadronic decays of the Higgs allow the couplings of the Higgs to 1st and 2nd-generation quarks to be directly probed
- $h \rightarrow J/\psi + \gamma$ 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!