Rare Higgs decays as probes for Higgs couplings to first- and second-generation quarks

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Higgs boson decays to quarkonia and the $H\bar{c}c$ coupling

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Relativistic corrections to Higgs-boson decays to quarkonia

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An Exclusive Window onto Higgs Yukawa Couplings

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BSM Higgs couplings to first two generations

- Various models exist where Hccbar coupling alone could be enhanced (up to few times)
  - in an Effective Field Theory (EFT) the Hqqbar coupling is not related to m_q
  - two Higgs doublet model (2HDM)
  - General Minimal Flavor Violation (MFV) Scenario with one Higgs Doublet
  - pseudo-Nambu-Goldstone Boson model

More generally in EFT

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

Yukawa matrix $Y_{ij} = \lambda_{ij} + 3\frac{v^2}{2\Lambda^2}\lambda'_{ij}$

Norm. to SM: $Y_{qq} = \kappa_q \frac{m_q}{v}$

Norm. to b-quark Yukawa: $Y_{qq} = \bar{\kappa}_q \frac{m_b}{v}$

if no flavor violation and only $\lambda_{22} \neq 0$

$$Y_{ss} = \bar{\kappa}_s \frac{\sqrt{2} m_b}{v} = \lambda_{ss} + 3\frac{v^2}{2\Lambda^2}\lambda'_{ss}$$

or $\bar{\kappa}_s = \frac{m_s}{m_b} + 2\frac{v^2}{2\Lambda^2}\frac{v}{\sqrt{2} m_b}\lambda'_{ss}$

in MFV

$$\lambda_{ij} = a_0 Y_d,$$

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

$$\bar{\kappa}_b = 1 + \frac{v^2}{\Lambda^2}(c_0 + c_2 y_t^2)\frac{y_b v}{\sqrt{2} m_b},$$

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

if $\mathcal{L} \supset -\frac{y_f}{\Lambda^{2n}}\bar{f}_L f_R H (H^\dagger H)^n + h.c.$ then

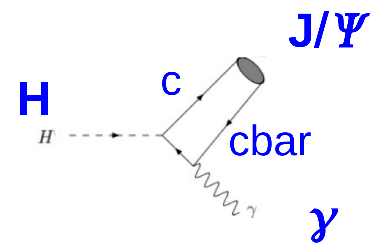
$$\bar{\kappa}_s = (2(n_s - n_b) + 1)\frac{m_s}{m_b} = (2(n_s - n_b) + 1) \cdot 0.020$$

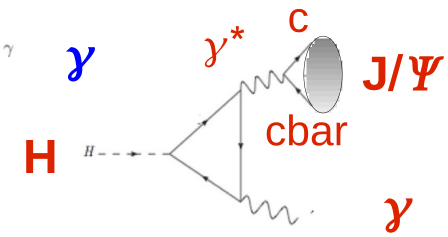
Depending on models Higgs to light quark couplings can be enhanced (and still allowed)

See also Phys.Rev. D89 (2014) 033014

Hqqbar coupling measurement by interference

The charm of the rare decay H → J/Ψ + γ





Direct production : proceeds through the Hccbar coupling

Indirect production : proceeds through a virtual photon exchange with subsequent transition to a bound ccbar state (J/Ψ)

Why do we care about the two? It turns out that according to the SM Br(direct) ~ 5×10^{-8} and Br(indirect) ~ 2.5×10^{-6}. More importantly, the former has **destructive interference** with the latter leading to 20% reduction (in SM) of the branching fraction.

Other Higgs to meson decays

Similarly **H → ϒ + γ** and **H → ϕ(1020) + γ** give handle on **H to bbbar and H to ssbar** couplings. More generally **H → M + V** (meson + vector boson) decays are relevant though experimentally **V = γ** provides best signatures.

A program based on rare Higgs decays can potentially map the entire Yukawa structure of Higgs (including off-diagonal elements).

Underlying theory to H → J/Ψ + γ

The partial decay width is:

$$\Gamma(H \to V\gamma) = \frac{1}{8\pi}\frac{m_H^2 - m_V^2}{m_H^2}\left|\mathcal{A}_{\text{direct}} + \mathcal{A}_{\text{indirect}}\right|^2$$

The direct amplitude is known for a long time (Phys. Rev. D 27, 2762 (1983)):

$$\mathcal{A}_{\text{direct}} = 2\sqrt{3}e_Q e\kappa_c\left(\sqrt{2}G_F m_V\right)^{1/2}\frac{m_H^2 - m_V^2}{\sqrt{m_H}(m_H^2 - m_V^2/2 - 2m_Q^2)}\phi_0(V)$$

ϕ_0 is the wave function of the quarkonium state at the origin and is known (it is real to a good approximation)

e – charges, m – masses; Q denotes the c-quark, V denotes the vector meson (J/Ψ), H is Higgs

$k_c = g_{Hc\bar{c}} / g_{Hc\bar{c}}^{SM}$ is a factor allowing the c-quark Yukawa coupling to H to deviate from SM

The indirect amplitude can be written in terms of the H→$\gamma\gamma$ amplitude:

which is also known

$$\mathcal{A}_{\text{indirect}} = \frac{e g_{V\gamma}}{m_V^2}\left[16\pi\Gamma(H \to \gamma\gamma)\right]^{1/2}\frac{m_H^2 - m_V^2}{m_H^2}\left[1 - \left(\frac{m_V}{183.43\text{ GeV}}\right)^2\right]$$

It can be shown that the V-to-γ coupling is $g_{V\gamma} = -e_Q\sqrt{2N_c}\sqrt{2m_V}\,\phi_0$

From it follows that the interference between the two terms is destructive.

Uncertainties in the calculations

Indirect Amplitude

The leading correction (triple-gluon quarkonium production) is suppressed by ~10^{-6} (see the paper)

Missing higher order corrections: ~ 1%

From m_t and m_W uncertainties : few x 10^{-4}

$$\mathcal{A}_{\rm indirect} = \frac{e g_{V\gamma}}{m_V^2}\left[16\pi\Gamma(H\to\gamma\gamma)\right]^{1/2}\frac{m_H^2-m_V^2}{m_H^2}\left[1-\left(\frac{m_V}{183.43\ {\rm GeV}}\right)^2\right]$$

$$\left(g_{V\gamma} = -\frac{e_Q}{|e_Q|}\left[\frac{3m_V^3\Gamma(V\to l^+l^-)}{4\pi\alpha^2(m_V)}\right]^{\frac{1}{2}} \right)$$

Uncertainties in the quarkonium leptonic widths: 2.5%

1% error on m_H results in 3.5% on the width.

We already know the Higgs mass at sub-percent level and by the time we need it it will be a negligible contribution.

The total uncertainty on the indirect width is 2.7% .

From there it follows that
contributions from the direct production (or rather the interference with the indirect production) can be determined (measured) well if effects with no better than this precision are investigated.

Uncertainties in the calculations (2)

Direct Amplitude

$$E^2 \equiv m_Q^2 - q^2 \equiv m_Q^2(1 + v^2)$$

in ccbar rest frame → $p = (E, \mathbf{0}) \quad q = (0, \boldsymbol{q})$

υ is the velocity of the quark inside the quarkonium state

$$\langle v^{2n} \rangle = \frac{1}{m_Q^{2n}} \frac{\langle V(\boldsymbol{\epsilon})|\psi^\dagger(-\frac{i}{2}\overleftrightarrow{\boldsymbol{\nabla}})^{2n}\boldsymbol{\sigma}\cdot\boldsymbol{\epsilon}\chi|0\rangle}{\langle V(\boldsymbol{\epsilon})|\psi^\dagger\boldsymbol{\sigma}\cdot\boldsymbol{\epsilon}\chi|0\rangle}$$

relativistic corrections

$$i\mathcal{M}_{\rm dir}[H \to V + \gamma] = \sqrt{2m_V}\phi_0\, i\mathcal{M}_{\rm dir}^{(0)}[H \to V + \gamma] \sum_{n=0}^{\infty} \frac{1}{n!}\left(\frac{\partial}{\partial v^2}\right)^n R(v^2)\Big|_{v=0} \langle v^{2n} \rangle$$

$$\left[\left(1 - \frac{5}{6}\langle v^2 \rangle\right) g_{SV} + \frac{1}{3}\langle v^2 \rangle c_2(\mu) F_{HQ\bar{Q}}(\mu)\right]$$

Newly calculated uncertainties on the direct amplitude from:
order α_s^2.: 2%
Order $\alpha_s \upsilon^2$: 5%
Order υ^4: 9%
m_c : 0.6% (negligible)

expansion evolution change (now from m_Q to m_H)

leading logarithms:
$$F_{HQ\bar{Q}}(\mu) = [\alpha_s(\mu_0)/\alpha_s(\mu)]^{-3C_F/\beta_0}$$

$c_2(\mu) = c_2(\alpha_s(\mu),\mu)$

<u>The total uncertainty on the direct width is 10%</u>

Numerical results (H → J/Ψ + γ)

According to the (SM) calculations:

$$\Gamma_{\rm SM}(H \to J/\psi + \gamma) = 1.17^{+0.05}_{-0.05} \times 10^{-8}\ {\rm GeV}$$

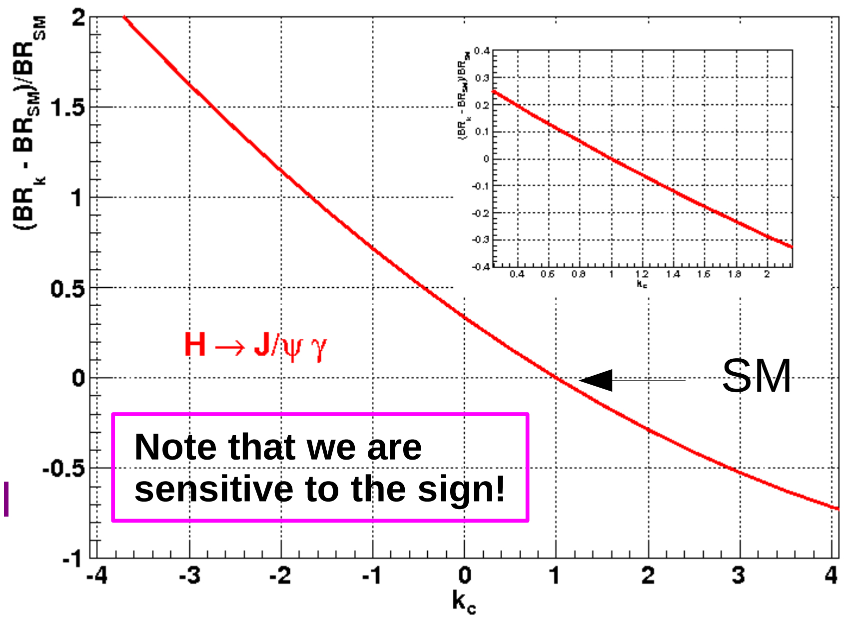
Taking as input the full Higgs /H(125)/ width:

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

If direct production only → ~5 x 10^{-8}

The theoretical uncertainty is under very good control

Br deviation from SM as a function of the Yukawa coupling deviation from SM



Realistically, only lepton decays of J/Ψ can be explored experimentally – this brings the visible cross-section (or Br) further down.

We estimate the Br of the H→$\mu\mu\gamma$ continuum (Higgs Dalitz decays) in the region of the J/Ψ peak defined approximately by the experimental resolution to be

$$\mathrm{BR_{cont}}(H \to \mu^+\mu^-\gamma) = 2.3 \times 10^{-7} \qquad @m_{\mu^+\mu^-} \in [m_{J\psi} - 0.05\,\mathrm{GeV}, m_{J\psi} + 0.05\,\mathrm{GeV}]$$

This is comparable in size to the visible Br in the muon channel from H→J/Ψ+γ .
Thus the process should be visible over the background.

Numerical results (H → ϒ + γ)

According to the (SM) calculations:

$$\Gamma_{\rm SM}(H \to \Upsilon + \gamma) = 3.52^{+8.07}_{-3.42} \times 10^{-12}\ {\rm GeV}$$

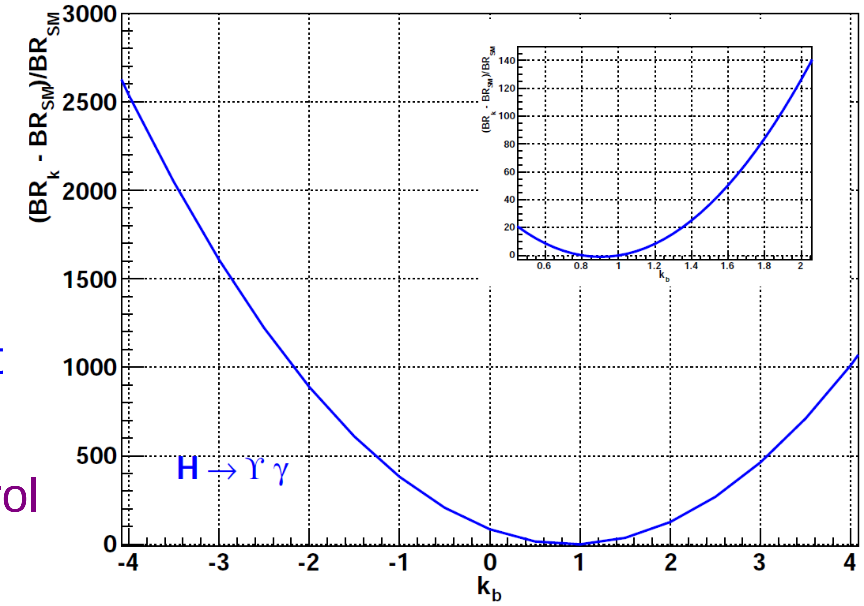
Taking as input the full Higgs /H(125)/ width:

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

The branching is small because direct and indirect productions nearly cancel each other (in SM).

The theoretical uncertainty is under very good control

Br deviation from SM as a function of the Yukawa coupling deviation from SM



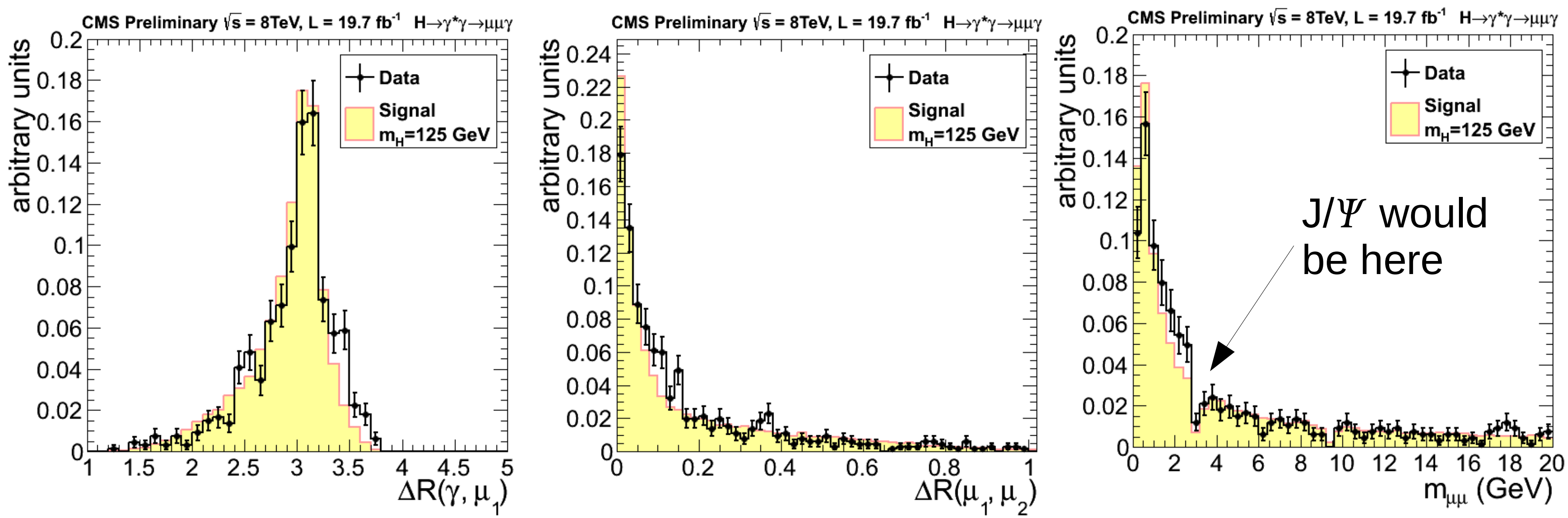
Realistically, only lepton decays of ϒ can be explored experimentally – this brings the visible cross-section (or Br) further down.

This SM process can never be observed experimentally.
However the very same reasons suppressing the Br in SM makes it very sensitive to BSM.

Feasibility of the H → J/Ψ + γ measurement

Can we really measure this process?

CMS has public results on the mentioned Higgs Dalitz decay (muon channel).
They do remove the main resonance contributions (J/Ψ and Υ). There is no difference between this analysis and a H→J/Ψ + γ analysis <u>except</u> the di-lepton mass range.



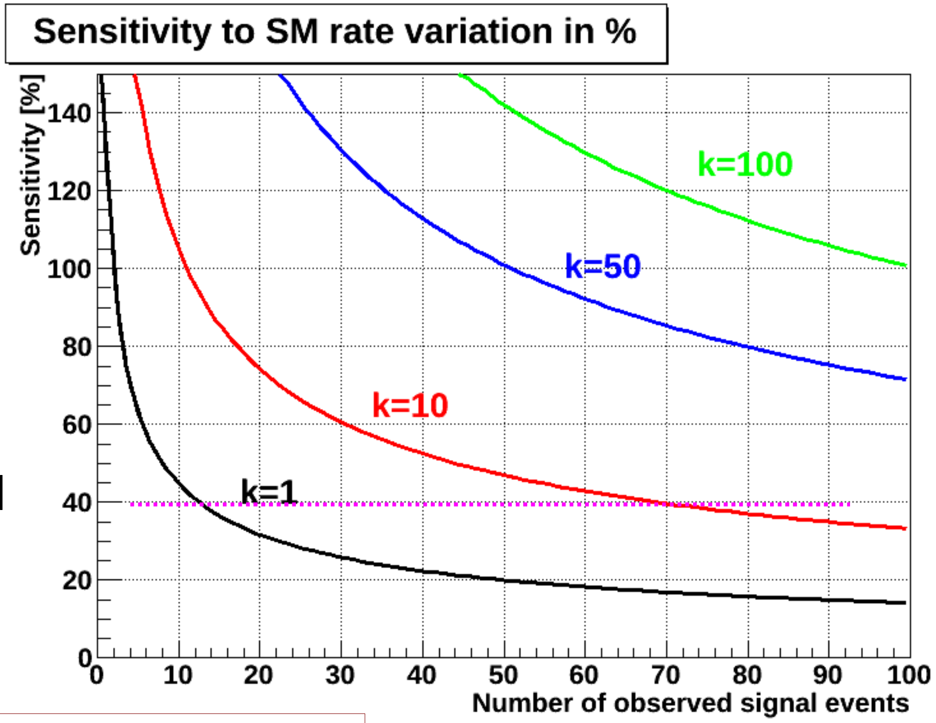
CMS-PAS-HIG-14-003

The acceptance times efficiency of their signal is about 30% with a background to signal ratio k = B/S < 40 (in the Higgs mass region).
No categorization of events or multivariate techniques were used.

It is clear that H→J/$\Psi(\mu\mu)$ + γ is/will be reconstructable with relatively high efficiency (there are no expectations of significant degradation of the performance with time).
It is expected that B/S will be lower (two resonances explored instead of one).

Experimental sensitivity (H → J/Ψ + γ)

We estimate that if both lepton and muon channels are reconstructed with 50% acceptance x efficiency we'll see ~50 signal events from combined ATLAS and CMS data from 3000 fb^{-1} LHC.



Defining Sensitivity as S/sqrt(B+S) and using the k=B/S we can try to judge about the experimental perspectives. The observation in the H→$\gamma\gamma$ channel was announced at Sensitivity ~ 40%

- The main uncertainty will be statistical (from background)
- We can *probably* assume k=40 as a _current_ working estimate
- Categorization of events and kinematic handles against background typically (in past) increase sensitivity by 10-20%
- On the other hand it may be more difficult to get high efficiency for the electron channel (both trigger and off-line)

It is an assumption that experiments will plan accordingly to record the relevant data.

We are at the limit to observe the (SM) decay with full LHC data.
In any case strong limits on the Hccbar Yukawa coupling can be set.

H → ϕ(1020) + γ

O(20%) error (mostly from meson decay const.; needs to be reduced: lattice QCD, leptonic decays of mesons)

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

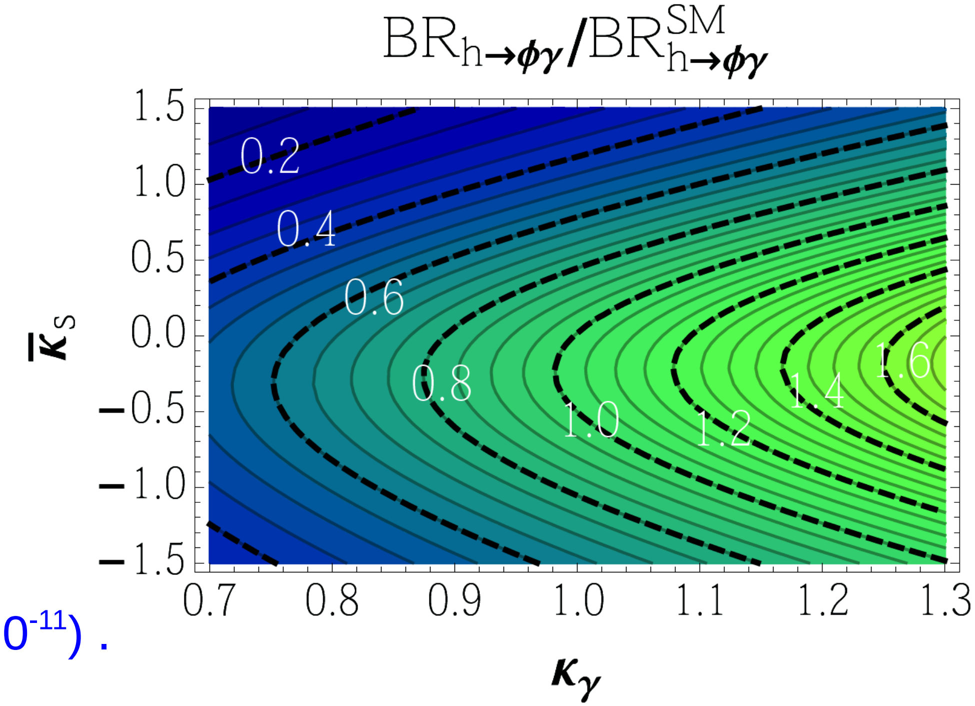
==0.57 in SM

$\bar{\kappa}$'s are Yukawa couplings to Higgs normalized to the b-quark Yukawa coupling

<u>SM:</u>

$$\kappa_\gamma = \kappa_V = 1$$
$$\bar{\kappa}_s = m_s/m_b \simeq 0.020$$

In SM the direct amplitude itself contributes at $O(10^{-11})$.



		(Acc = 0.75)	Current theory errors	Negligible theory errors
$\sqrt{s}$ [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)

K^+K^- is dominant the decay mode (~50%) of ϕ(1020), others are more difficult to identify.
The signature is experimentally observable given triggers are secured.

Other rare Higgs decays with photons

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

SM:

$$\kappa_\gamma = \kappa_V = 1$$

$$\bar{\kappa}_s = m_s/m_b \simeq 0.020$$

$$\bar{\kappa}_d = m_d/m_b \simeq 1.0\cdot 10^{-3}$$

$$\bar{\kappa}_u = m_u/m_b \simeq 4.7\cdot 10^{-4}$$

$$\frac{\mathrm{BR}_{h\to\rho\gamma}}{\mathrm{BR}_{h\to b\bar{b}}} = \frac{\kappa_\gamma\left[(1.9\pm0.15)\kappa_\gamma - 0.24\bar{\kappa}_u - 0.12\bar{\kappa}_d\right]\cdot 10^{-5}}{0.57\bar{\kappa}_b^2}$$

$$\frac{\mathrm{BR}_{h\to\omega\gamma}}{\mathrm{BR}_{h\to b\bar{b}}} = \frac{\kappa_\gamma\left[(1.6\pm0.17)\kappa_\gamma - 0.59\bar{\kappa}_u - 0.29\bar{\kappa}_d\right]\cdot 10^{-6}}{0.57\bar{\kappa}_b^2}$$

In SM they have larger or comparable Br to **H → φ(1020) + γ**.
ρ decays almost exclusively to $\pi^+\pi^-$ and is as feasible as the φ decay mode
ω decays to $\pi^+\pi^-\pi^0$ and is much more difficult to trigger on and identify.

Flavor violating decays (not present in SM)

H → M + γ with M = $B_s^{*0}, B_d^{*0}, K^{*0}, D^{*0}$

Most promising are $h \to \bar{B}^{*0}\gamma$ $h \to D^{*0}\gamma$

$$\frac{\mathrm{BR}_{h\to\bar{B}_s^{*0}\gamma}}{\mathrm{BR}_{h\to b\bar{b}}} = \frac{\mathrm{BR}^{(1)}_{\bar{B}_s^{*0}\gamma}}{0.57\bar{\kappa}_b^2}\,\frac{|\bar{\kappa}_{bs}|^2+|\bar{\kappa}_{sb}|^2}{2}$$

↔

$$\mathrm{BR}^{(1)}_{\bar{B}_s^{*0}\gamma} = (2.1\pm1.0)\cdot 10^{-7}$$

$$\mathrm{BR}^{(1)}_{\bar{B}^{*0}\gamma} = (1.4\pm0.7)\cdot 10^{-7}$$

$$\mathrm{BR}^{(1)}_{D^{*0}\gamma} = (8.6\pm8.3)\cdot 10^{-8}$$

B-modes are potentially observable at future colliders (need to develop special ID/trigger).

Rare Higgs decays of the type H $\rightarrow$ M + W/Z

With the W modes one can probe flavor violating Higgs couplings involving top quarks

For the most promising mode:

$$\frac{\mathrm{BR}_{h\to B^{*-}W^{+}}}{\mathrm{BR}_{h\to b\bar{b}}} \simeq \frac{1.2\cdot 10^{-10}\left[\kappa_V^2 + 22\bar{\kappa}_{tu}^2 + 26\bar{\kappa}_{ut}^2 + \cdots\right]}{0.57\bar{\kappa}_b^2}$$

With the current (several month old) limits from LHC: $\mathrm{BR}_{h\to B^{*-}W^{+}} \leq 1.6\cdot 10^{-7}$

Modes with Z are similar to the modes with photons discussed.
However interference terms are much smaller and thus the modes are less useful for measuring Higgs couplings to light quarks.

For both W and Z modes one needs to explore the lepton modes and for W there is no peak to explore.
These are significant experimental constraints.

Conclusions

- From point of view of today
  the only way to measure or constraint Hccbar directly is by exploring the decay **H → J/Ψ + γ**

- Other modes involving light quarks have even higher Br though they are also harder to ID

- Only hadron colliders (among more under consideration to build) can bring the required statistical sensitivity to study **H → M + V**

- In a long term some theoretical uncertainties needs to be reduced

- Existing LHC analyses show signatures are experimentally observable

- It is upto LHC experiments to recognize the importance and plan accordingly for data taking

Back up

- Hccbar coupling can be extracted from the invisible (undetectable) Higgs Br(Inv)
  albeit with very strong assumptions (about other (B)SM couplings, no BSM decays)

- Br(Inv) is constrained
  - indirectly by a global fit to data :
    Br(Inv)<18% in SM or <50% in BSM (both: arXiv:1407.8236)
  - direct search:
    Br(Inv)<0.75 (0.58) from ATLAS (CMS) at 95% CL
    Phys. Rev. Lett. 112, 201802 (2014)
    arXiv:1404.1344 [hep-ex]

- Then (Phys.Rev. D89 (2014) 033014, using slightly older limit of Br(Inv)<22%) showed that Hccbar coupling is constrained at less than 3.7 (7.3 if non-SM Hgg-coupling) the SM value

  - significant anti-correlation between Hccbar and Hbbbar in associated Higgs production
  - Hbbar and Hccbar signal strengths are experimentally correlated
  - the combined Hbbar and Hccbar signal strength depends on the (exp.) tagging efficiencies

- Various models exist where Hccbar coupling alone could be enhanced (up to few times)

  - generally, in an Effective Field Theory the Hccbar coupling is not related to m_c
  - two Higgs doublet model (2HDM)
  - General Minimal Flavor Violation Scenario with one Higgs Doublet
  - pseudo-Nambu-Goldstone Boson model

Back up

There are at least three issues that need to be resolved by experiments

- Be aware of the **TRIGGER**!

  Special triggers need to be designed, separately for
  muon, electron and non-leptonic channels.
  If they are not made available promptly data is effectively lost!
  On the positive side – they are not so hard to devise (at least for muons)

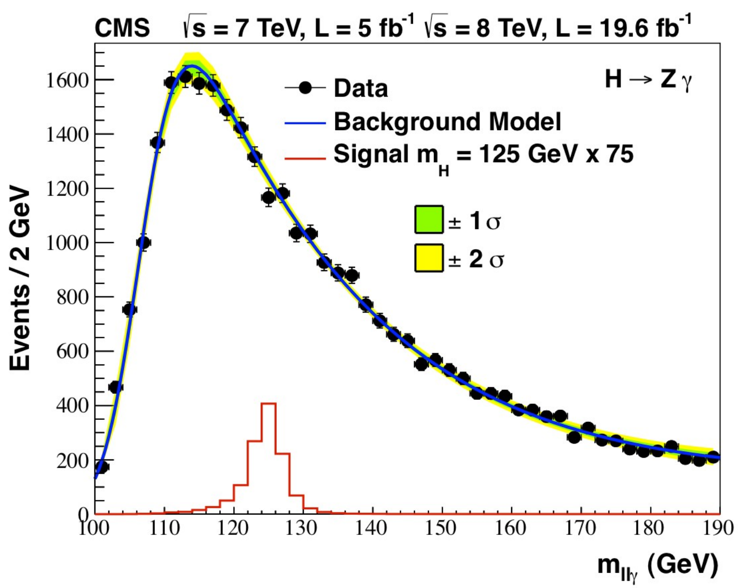
- Close-by-leptons (particles)

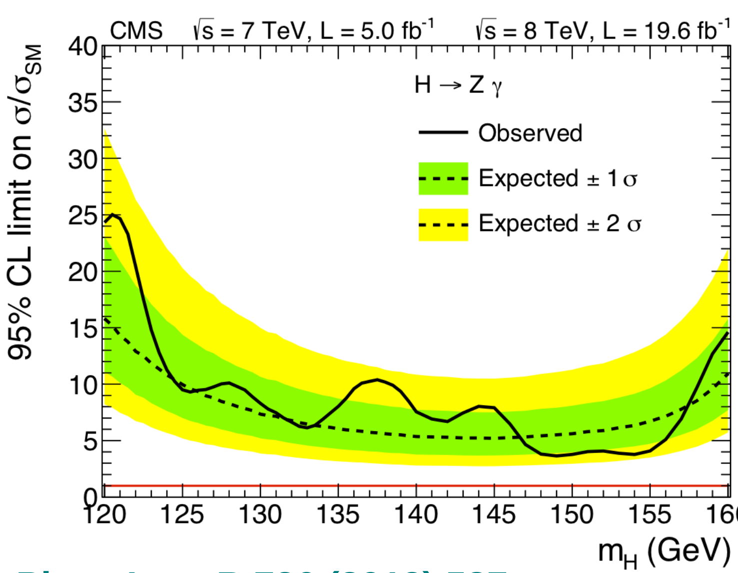
  The leptons to reconstruct are close to each other : $\Delta R \sim 0.15$
  Very likely the standard lepton reconstruction is not enough or at least not optimal.
  To gain sensitivity upgraded algorithms are needed.

- More realistic projections
  based on simulations of planned detector upgrades will allow to tune
  the analysis and provide important feedback (better earlier than later)

Back up

CMS





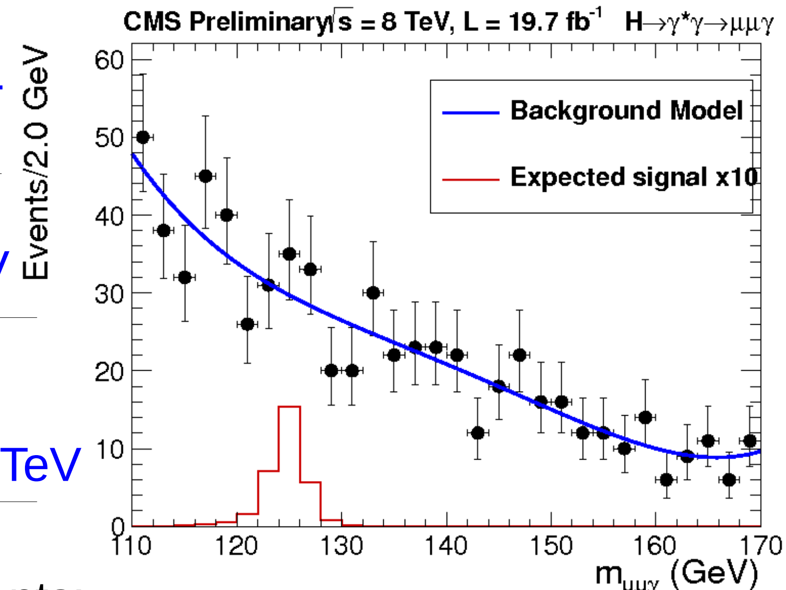
H→Zγ	H Dalitz
	Close-by leptons back-to-back to the photon
$p_T(\gamma)$~ 30 GeV	$p_T(\gamma)$ ~ 60 GeV
Electrons + muons, 7 TeV + 8 TeV	Only muons, only 8 TeV

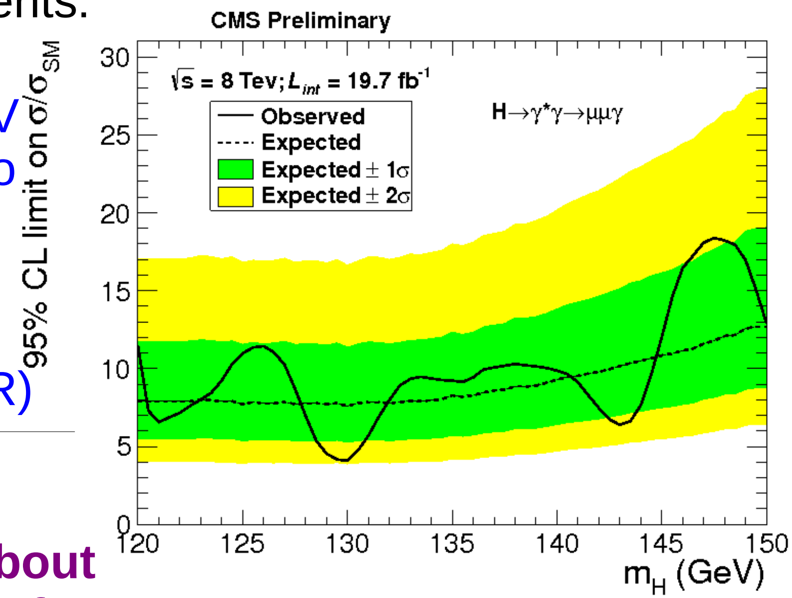
Comparative requirements:

H→Zγ	H Dalitz
M(ll)> 50 GeV	M(ll)< 20 GeV J/Ψ , Υ veto
di-lepton with mass closest to Z	di-lepton with lowest mass (ΔR)

Results /H(125)/:

Both limits are set at about one order of magnitude from SM





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CMS-PAS-HIG-14-003

Back up

CMS

$H \to \gamma^* \gamma$

Requirement	Observed event yield	Expected number of signal events for $m_H = 125$ GeV
Trigger, photon selection, $p_T^{\gamma} > 25$ GeV	0.6M	6.2
Muon selection, $p_T^{\mu 1} > 23$ GeV and $p_T^{\mu 2} > 4$ GeV	55836	4.7
110 GeV $< m_{\mu\mu\gamma} <$170 GeV	7800	4.7
$m_{\mu\mu} < 20$ GeV	1142	3.9
ΔR$(\gamma, \mu) > 1$	1138	3.9
Removal of resonances	1020	3.7
$p_T^{\gamma}/m_{\mu\mu\gamma} > 0.3$ and $p_T^{\mu\mu}/m_{\mu\mu\gamma} > 0.3$	665	3.3
122 GeV $< m_{\mu\mu\gamma} <$ 128 GeV	99	2.9