Higgs Boson Decays to ccbar

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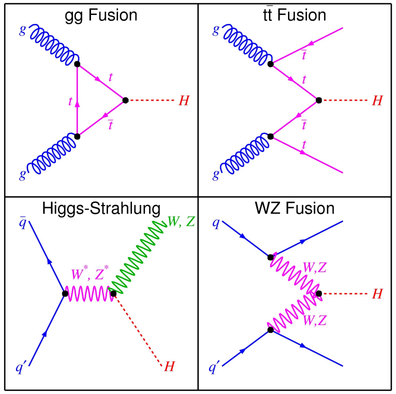
Production mechanisms of Higgs (@LHC)

In SM:

Four main Higgs production mechanisms

Each allowing to test the Higgs properties from different perspective

ggF

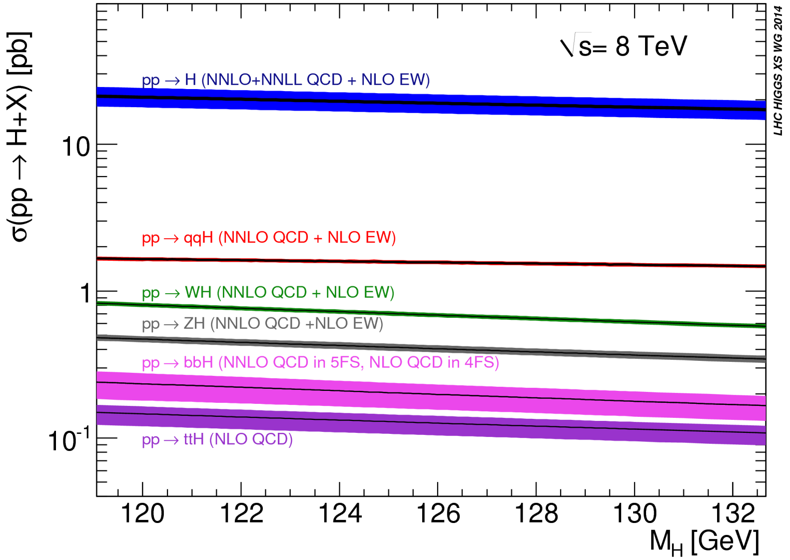


ttH (and bbH)

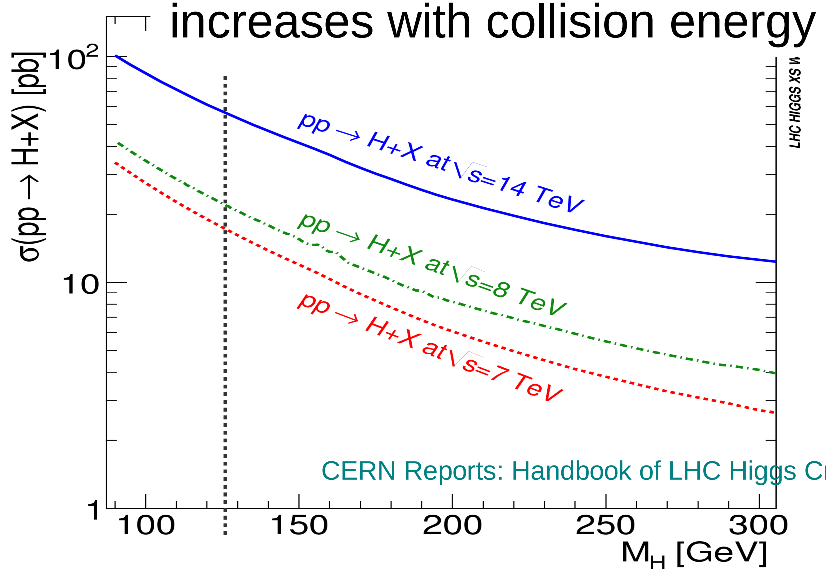
VH

VBF

The dominant Higgs production mode is ggF



Higgs production cross-section increases with collision energy



CERN Reports: Handbook of LHC Higgs Cross Sections

~ 1 M Higgs bosons expected to have been born at LHC to date

	m_H (GeV)	Cross Section (pb)	+error %	- error %	+scale %	-scale %	+(PDF+α_s) %	-(PDF+α_s) %
14 TeV	125	49.85	19.6	-14.6	12.2	-8.4	7.4	-6.2
8 TeV	125	19.27			7.2	-7.8	7.5	-6.9

Higgs Decay Modes

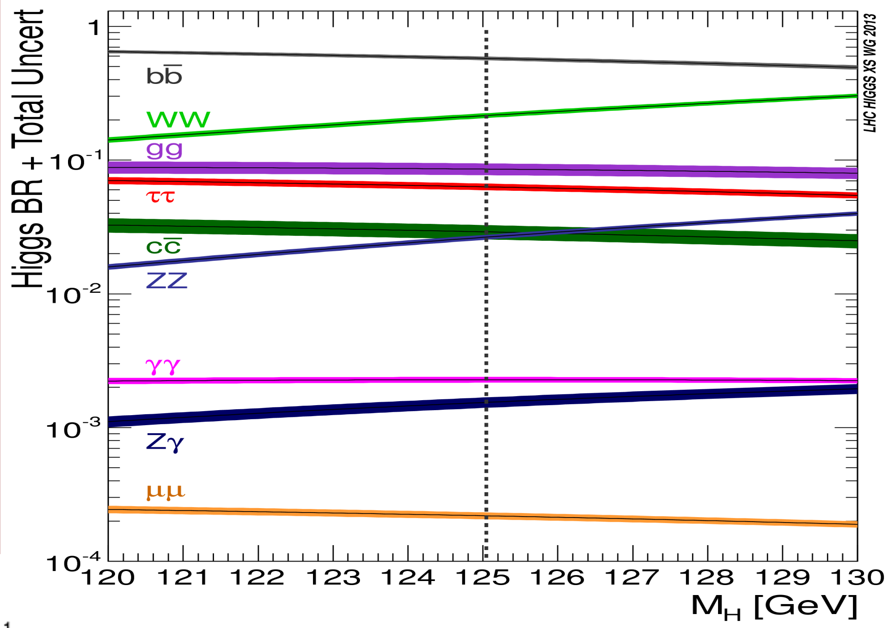
The best measured decays (signatures) are the ones to gauge bosons

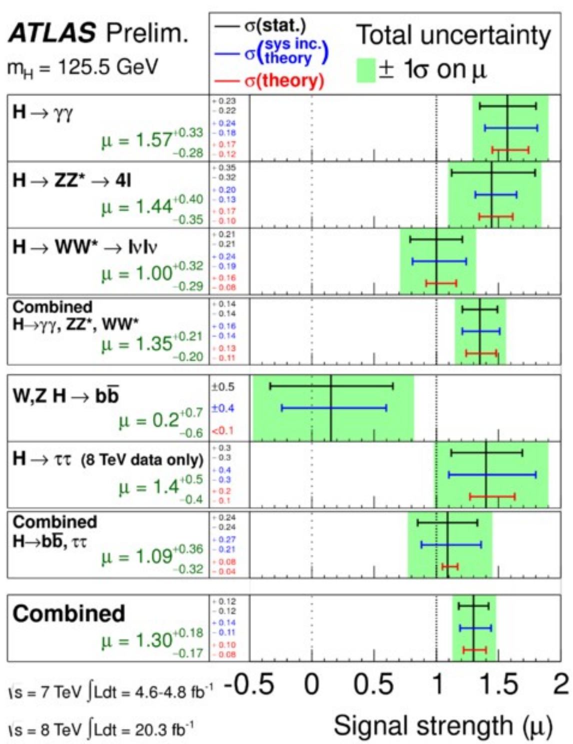
Only third generation fermion couplings to Higgs are a priori considered to be accessible (except muons in farther LHC future)

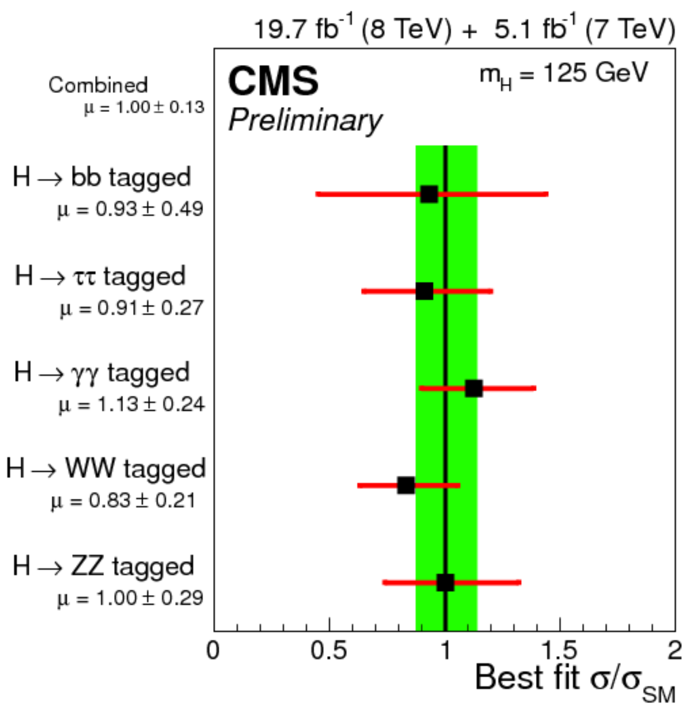
The highest Br process bbbar is not easy to measure

Although signal strengths ($\sigma Br/(\sigma Br)^{SM}$) are consistent with SM for fermions this is within ~20-30 %

SM predictions vs M_H







CMS	Significance (m_H = 125.0 GeV)		
Combination	Expected (pre-fit)	Expected (post-fit)	Observed
$H\to ZZ$ tagged	6.3 σ	6.3 σ	6.5 σ
$H\to\gamma\gamma$ tagged	5.1 σ	5.3 σ	5.6 σ
$H\to WW$ tagged	5.7 σ	5.4 σ	4.7 σ
$H\to bb$ tagged	2.2 σ	2.3 σ	2.0 σ
$H\to\tau\tau$ tagged	4.1 σ	3.9 σ	3.8 σ

ATLAS-CONF-2014-009

CMS-PAS-HIG-14-009

Hccbar coupling

- Hccbar coupling can be extracted from the invisible (undetectable) Higgs Br(Inv)
  albeit with <u>very strong</u> 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

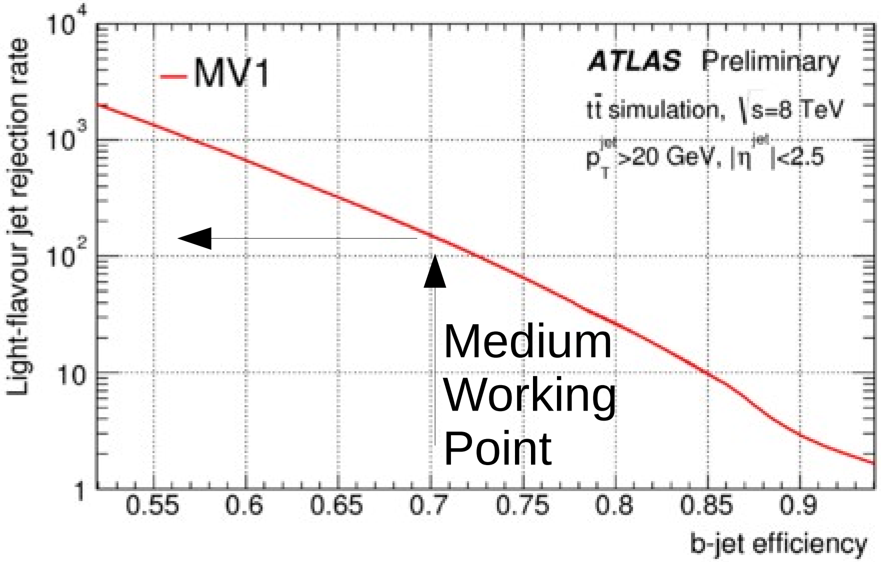
  - significant anti-correlation between Hccbar and Hbbbar in associated Higgs production
  - Hbbar and Hccbar signal strengths are experimentally correlated
  - the combined Hbbar and Hccbar signal strength depends on the (exp.) tagging efficiencies

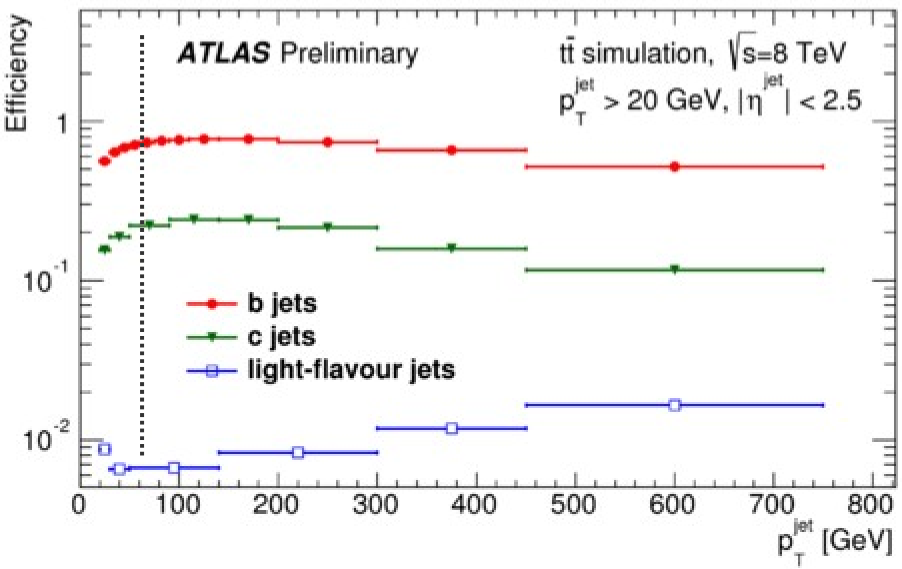
- Various models exist where Hccbar coupling alone could be enhanced (up to few times)

  - 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

Hccbar coupling measurement by jet c-tagging?

Flavor tagging in ATLAS exploits the impact parameter, secondary vertex and the topology of weak b- and c-hadron decays (jet fitter)
A neural network based algorithm is constructed assigning weight probability densities evaluated separately for b, c, and light-flavour jets ATLAS-CONF-2014-046





Recent analyses have used the c-tagging, for instance **a SUSY search** with pair of c-quarks in final state (arXiv:1407.0608 [hep-ex])

In this particular topology, it was found that:

c-tag	**b-rejection**	light- rejection	τ-rejection
20%	8	200	10
95%	2.5	(~1)	(~1)

The SM Higgs branching fraction ratio Br(bb)/Br(cc) = 20. There needs to be a significant improvement in c-tagging for direct use for Higgs. Many people consider this hard to do. Work is on-going in both ATLAS and CMS.

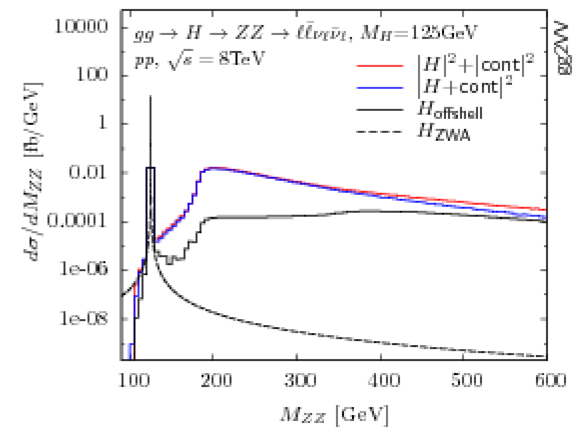
Hccbar coupling measurement by interference

Interference effects have increasing role in Higgs properties determination

A direct constraint on the Higgs width is limited by the detector resolution and a CMS constraint was put at 3.4 GeV @ 95% CL (the SM Higgs width is 4.2 MeV)

This gets dramatically improved by off-shell measurements (<u>based on good knowledge of interference with background states</u>) with the limit now at 22 MeV (24 MeV by ATLAS)!

It was also shown that similar effects shift the observed (di-photon) invariant mass distribution of on-shell Higgs.



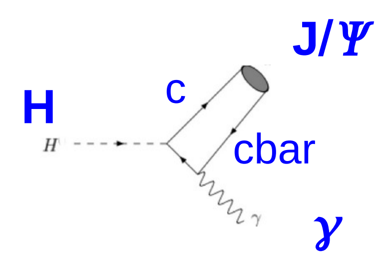
JHEP 1208 (2012) 116
Phys.Rev. D88 (2013) 054024
ATLAS-CONF-2014-042
Phys. Lett. B 736 (2014) 64

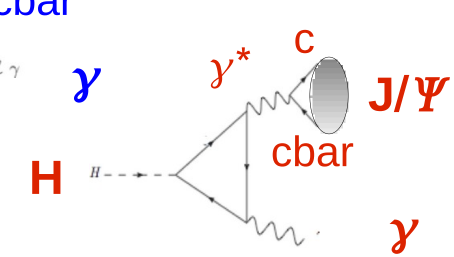
Phys. Rev. D 86, 073016(2012)

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 x 10^{-8} and Br(indirect) ~ 2.5 x 10^{-6}. <u>More importantly</u>, the former has **destructive interference** with the latter leading to 30% reduction (in SM) of the branching fraction.

Underlying theory* to H → J/Ψ + γ

The partial decay width is:

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

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

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

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

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

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.

* Results and most of the discussion are based on **Phys.Rev. D88 (2013) 5, 053003** /Geoffrey T. Bodwin, Frank Petriello, Stoyan Stoynev, Mayda Velasco/
Updated calculations are also taken from **arXiv:1407.6695 [hep-ph]** /Geoffrey T. Bodwin, Hee Sok Chung, June-Haak Ee, Jungil Lee, Frank Petriello/

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}

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

Uncertainties in the quarkonium leptonic widths (from were we know best ϕ_0): 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.

<u>The total uncertainty on the indirect width is 2.7% .</u>

Uncertainties in the calculations (2)

$p_{c\pm} = p \pm q$

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

v is the velocity of the quark inside the quarkonium state

Direct Amplitude

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

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

NRQCD formalism: expansion in α_s and v

relativistic corrections

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

light-cone formalism

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

expansion evolution change (now from m_Q to m_H)

leading logarithms:

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

$c_2(\mu) = c_2(\alpha_s(\mu), \log[\mu/\mu_0]^2)$

Uncertainties in the direct amplitude arise from:

ϕ_0, $\langle v^2 \rangle$ - known previously;

corrections of order α_s^2, $\alpha_s v^2$ and v^4 - recently improved - ~ 10%;

m_c - negligible;

The total uncertainty on the direct width is 10%

arXiv:1407.6695 [hep-ph]

Numerical results

According to the (SM) calculations:

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

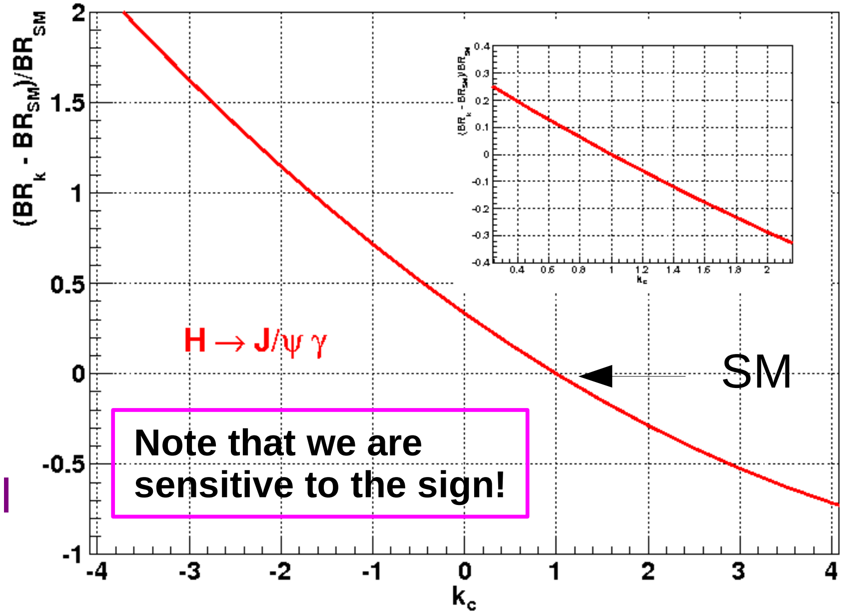
Taking as input the full Higgs /H(125)/ width:

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

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

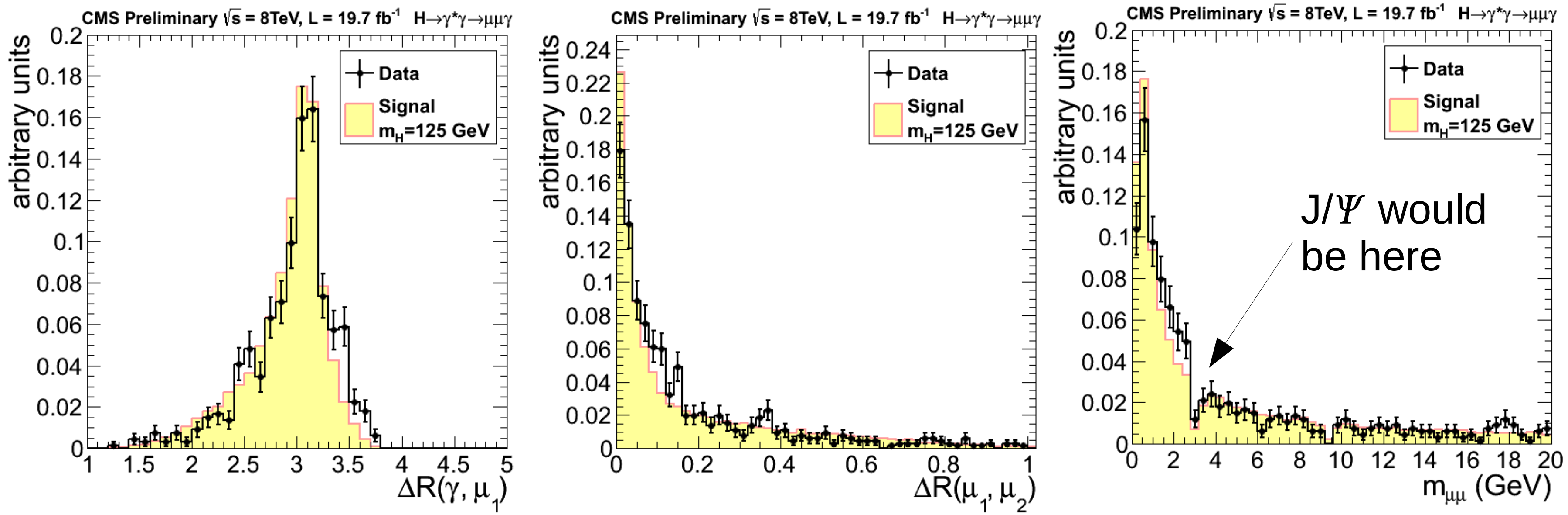
$$\mathrm{BR}_{\rm cont}(H \to \mu^+\mu^-\gamma) = 2.3 \times 10^{-7} \qquad @m_{\mu^+\mu^-} \in [m_{J\psi} - 0.05\,\mathrm{GeV}, m_{J\psi} + 0.05\,\mathrm{GeV}]$$

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.

Feasibility of the 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 except the di-lepton mass range.



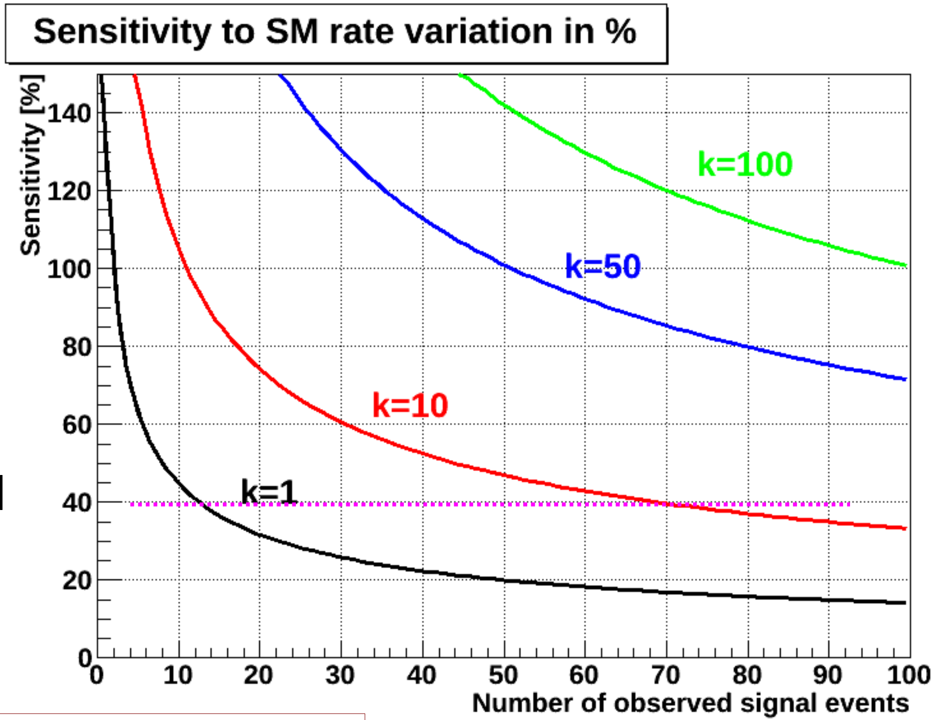
CMS-PAS-HIG-14-003

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 $\rightarrow$ 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. This is ~14% statistical error on the Br and ~40% on k_c.



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$\rightarrow\gamma\gamma$ channel was announced at Sensitivity ~ 40%

- The main uncertainty will be statistical (from background)
- We can 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.

Experimental challenges and warnings

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 the muon and the electron channels.
  If they are not made available promptly data is effectively lost!
  On the positive side – they are not so hard to devise.

- Close-by-leptons

  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)

I talked about $H \to J/\Psi + \gamma$.
However there are interesting and complimentary (in some sense) results for $\mathbf{H \to \Upsilon + \gamma}$

Moreover, the more general topic of **H → M + V** is relevant - see arXiv:1406.1722 .
In particular $\mathbf{H \to \varphi(1020) + \gamma}$ may be the only way to **constrain the Hssbar coupling** and
the whole class of these rare decays appear to be unique for hadron colliders
(other future collides are expected to be statistically insensitive).
The challenges mentioned above are still present and bigger for non-lepton final states.

Conclusions

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

- Only hadron colliders (among more under consideration to build) can bring the required statistical sensitivity to study this channel as well as others from **H $\rightarrow$ M + V**

- Existing LHC analyses show the signature is experimentally observable

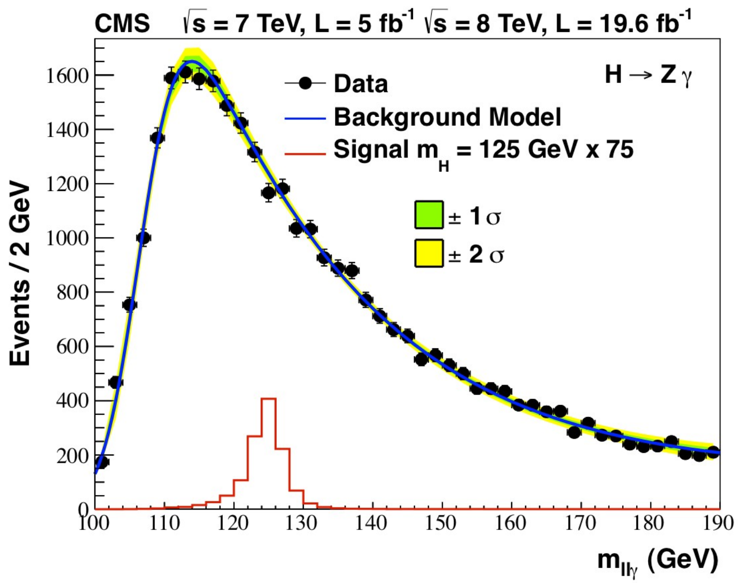
- It is realistic to expect an observation for cross-sections close or higher than SM

- BSM models exist where only the Hccbar Yukawa coupling is changed

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

Back up

CMS



H→Zγ **H Dalitz**

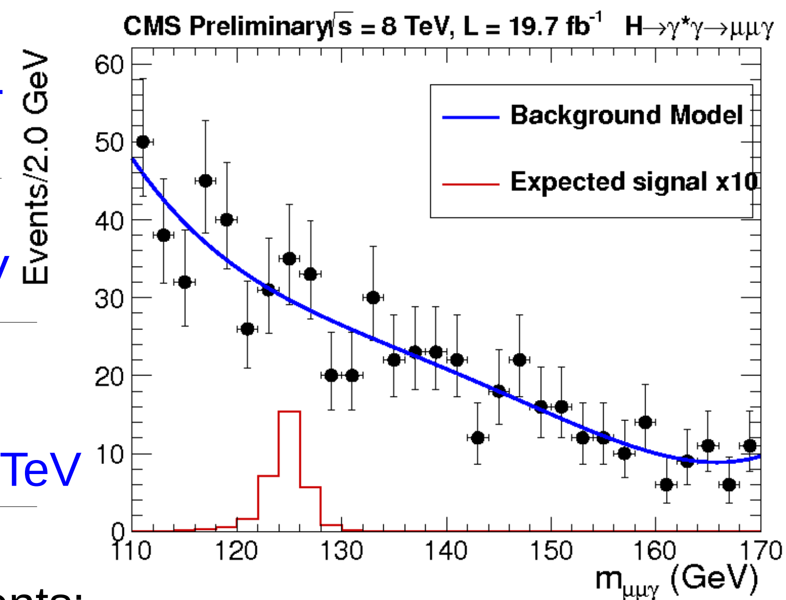
Close-by leptons back-to-back to the photon

$p_T(\gamma)$~ 30 GeV

$p_T(\gamma)$ ~ 60 GeV

Electrons + muons, 7 TeV + 8 TeV

Only muons, only 8 TeV



Comparative requirements:

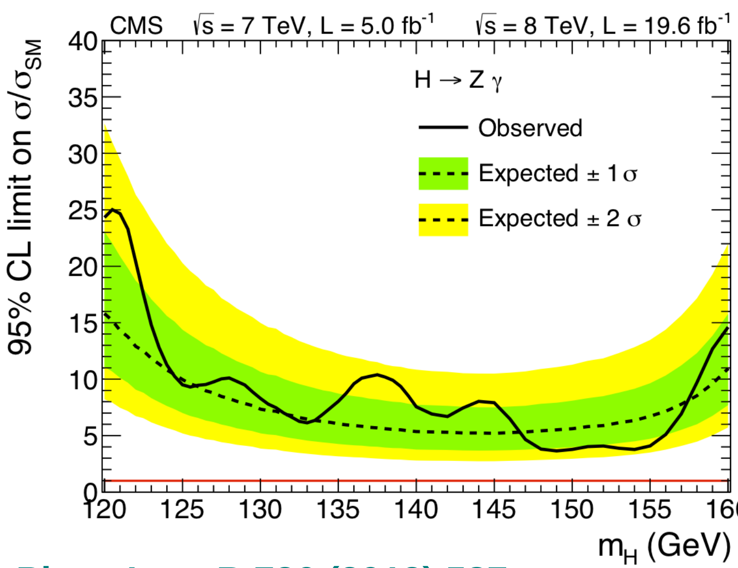
M(ll)> 50 GeV

M(ll)< 20 GeV

J/Ψ , Υ veto

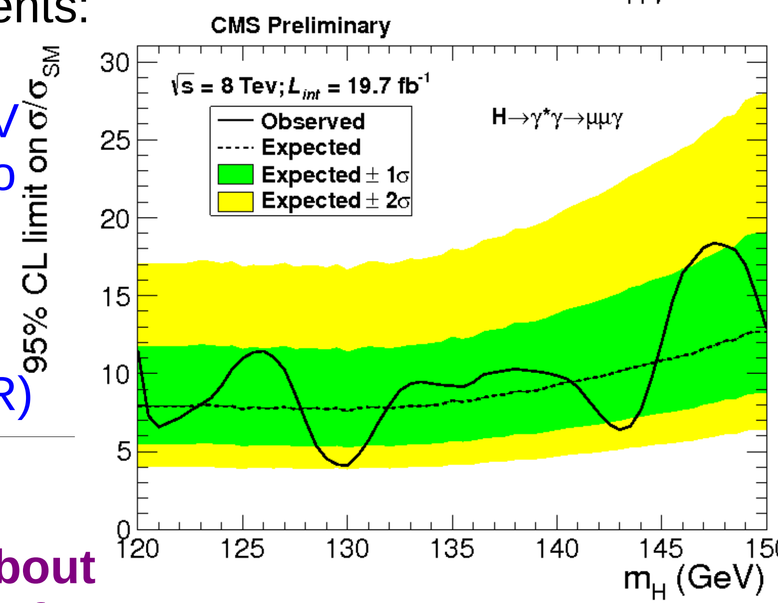
di-lepton with mass closest to Z

di-lepton with lowest mass (ΔR)



Results /H(125)/:

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



Phys. Lett. B 726 (2013) 587

CMS-PAS-HIG-14-003

Back up

CMS

H→γ*γ

Requirement	Observed event yield	Expected number of signal events for $m_{\rm H} = 125$ 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
$\Delta R(\gamma, \mu) > 1$	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