Constraints on BSM theories at LHC with Higgs decays into two photons

Abdelhak DJOUADI

(LPT CNRS & U. Paris-Sud)

1. What next after the Higgs discovery?

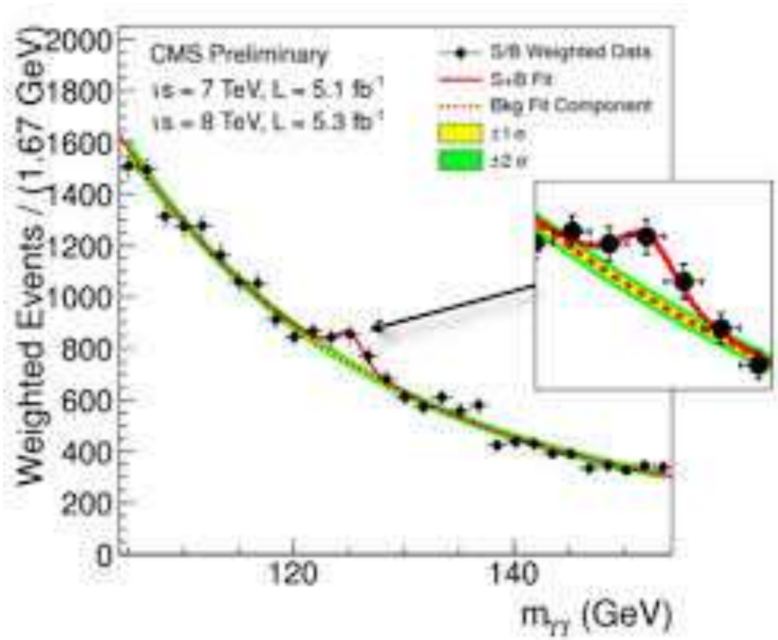
2. Theoretical uncertainties on the Higgs rates

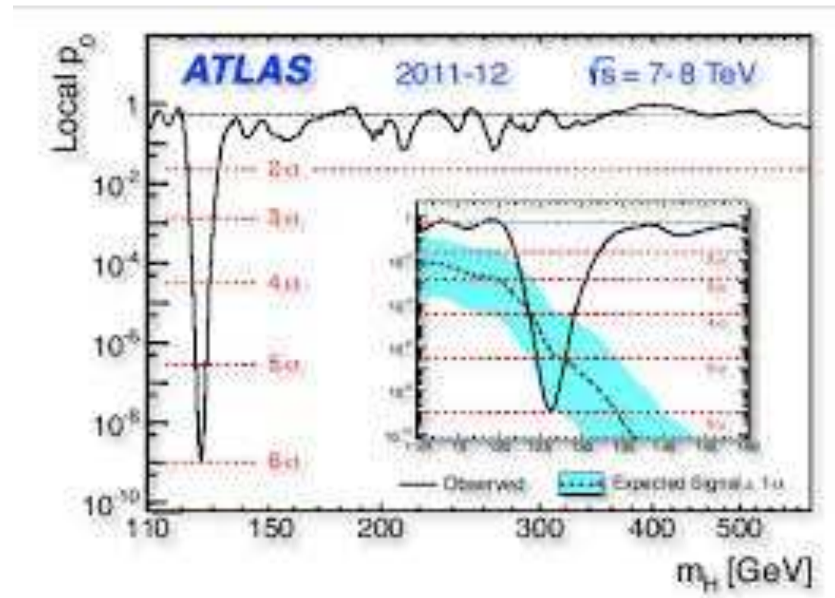
3. Search for BSM with $\mathrm{R}_{\gamma\gamma}$

4. Conclusion

1. What next after the Higgs discovery?

Now that the Higgs is discovered and proved to be approximately SM–like.





Is particle physics closed and we should all go home?

1. What next after the Higgs discovery?

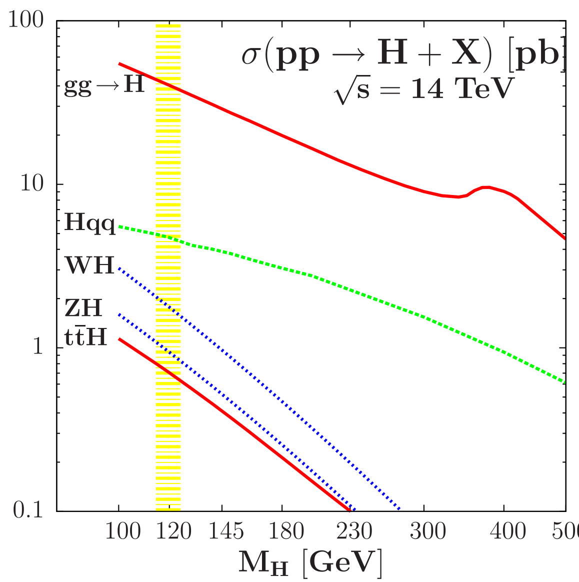
What should we be doing the next 10–30 years in Particle Physics?

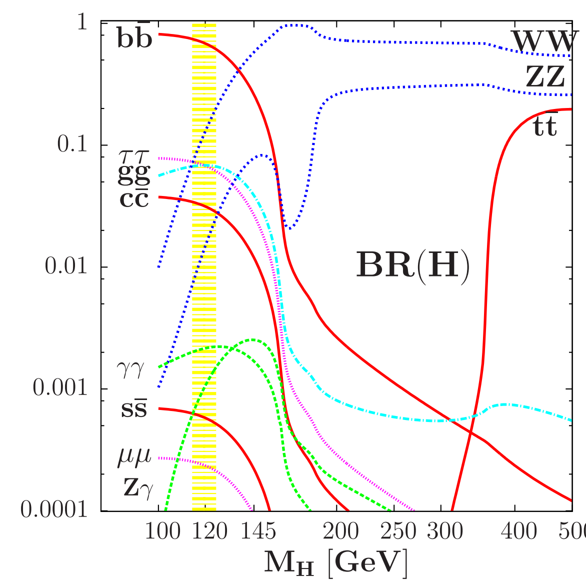
Need to check that H is indeed responsible of sEWSB (and SM-like?)

$\Rightarrow$ measure its fundamental properties in the most precise way:

- its mass and total decay width (invisible width due to dark matter?),
- its spin–parity quantum numbers (CP violation for baryogenesis?),
- its couplings to fermions and gauge bosons and check if they are only proportional to particle masses (no new physics contributions?),
- its self-couplings to reconstruct the potential V_S that makes EWSB.

Possible for $M_H \approx$ 125 GeV as all production/decay channels useful!

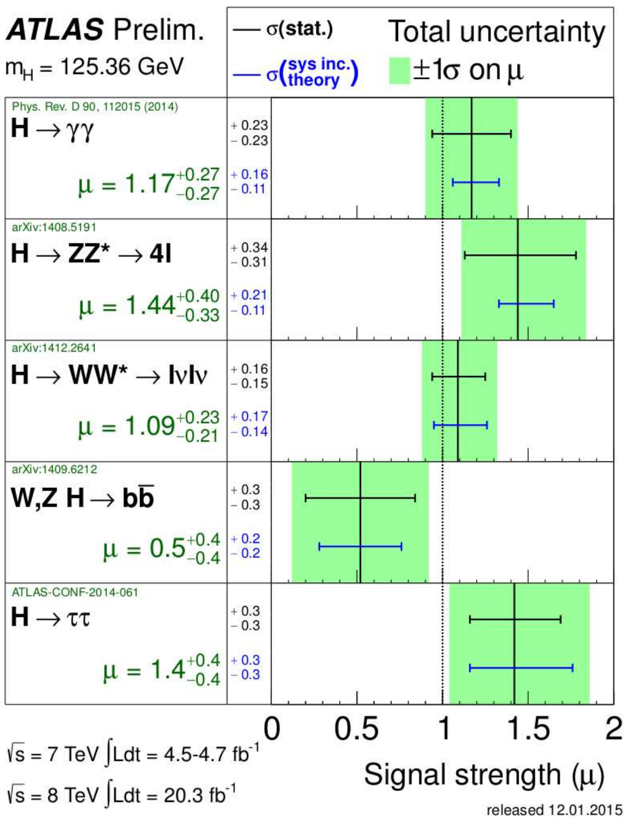


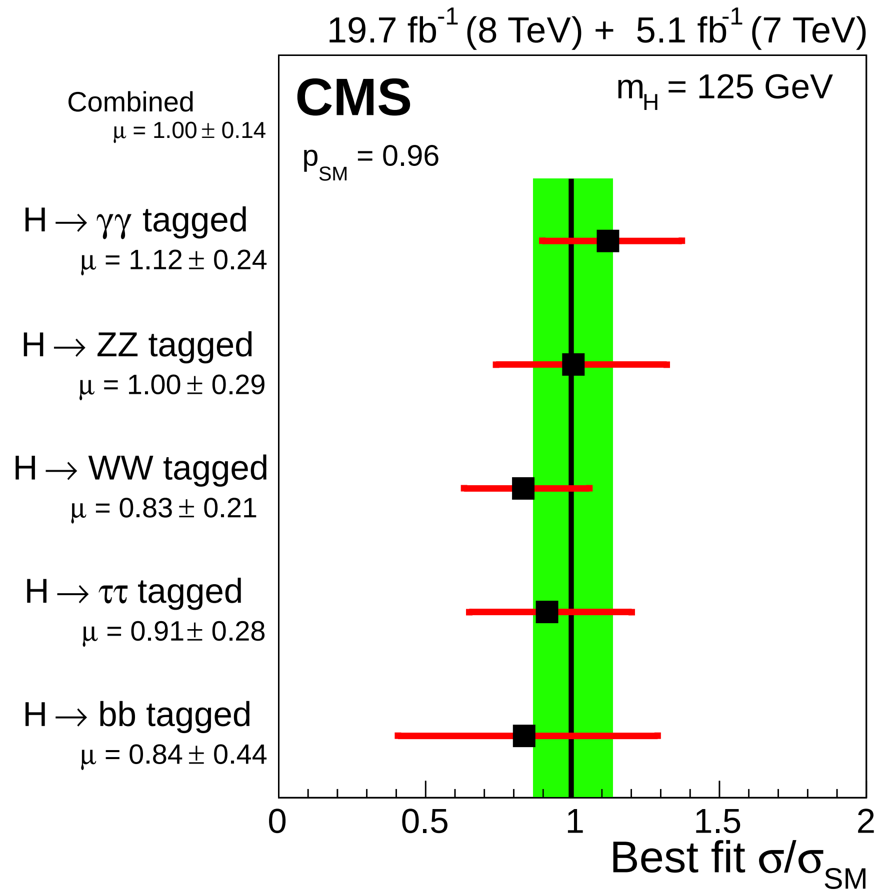


1. What next after the Higgs discovery?

In fact part of this second chapter has alreday started. Latest results on

$$\mu_{\mathbf{XX}} = \sigma^{\mathbf{p}}(\mathbf{pp} \to \mathbf{H}) \times \mathbf{BR}(\mathbf{H} \to \mathbf{XX})|_{\mathbf{exp/SM}}$$





Measurement for couplings already precise at the 10–15% level!

This is particularly the case in the $\mathbf{H} \to \gamma\gamma,\ \mathbf{H} \to \mathbf{VV}\ (\mathbf{V} = \mathbf{W}, \mathbf{Z})$ **cases..**

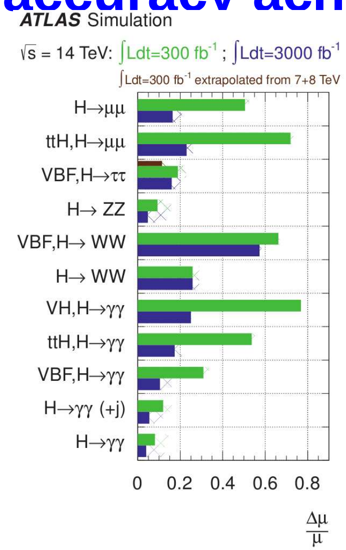
1. What next after the Higgs discovery?

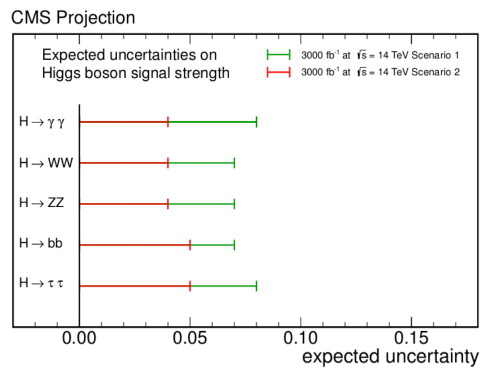
Is this enough to probe effects of new physics or BSM?

No! Not in the case of weakly interacting theories like 2HDM, SUSY, etc...

effects expected to be at level of $\Delta\mu_{\rm XX} \approx \frac{\rm C_{NEW}\alpha_W}{\pi} \approx \frac{\rm M_h^2}{\rm M_{NEW}^2} \approx$ **a few %**

Is a 1% accuracy achievable at upgraded LHC with high luminosities?





- **Statistical uncertainty:** $20\%/\sqrt{3\times100} \lesssim 1\%$

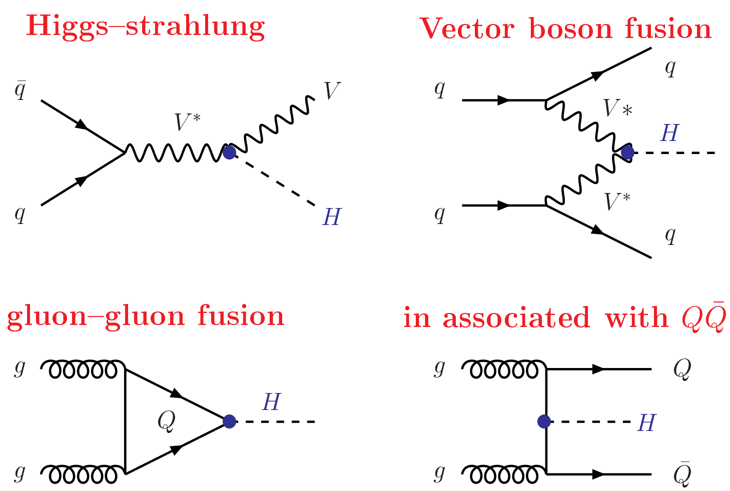
  at least in the clean $\rm H\to\gamma\gamma, VV$ **channels**
- **Systematical uncertainties: can be reduced at the level of a few %**

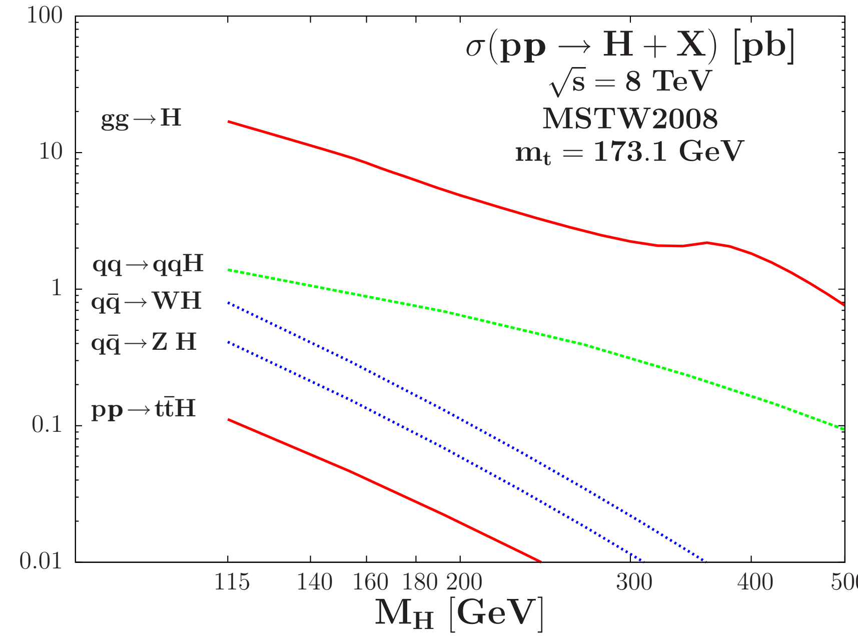
  some common to many channels (lumi...).
- **Theoretical uncertainty: will be by far the limiting issue!**

$\Rightarrow$ **How big is it? How much can it be reduced? Can it be removed?**

2. Theoretical uncertainties on the Higgs rates

Main Higgs production channels





Large production cross sections

with gg→ H by far dominant process

$$\sigma \approx 20 \text{ fb}^{-1} @ 8 \text{ TeV}$$

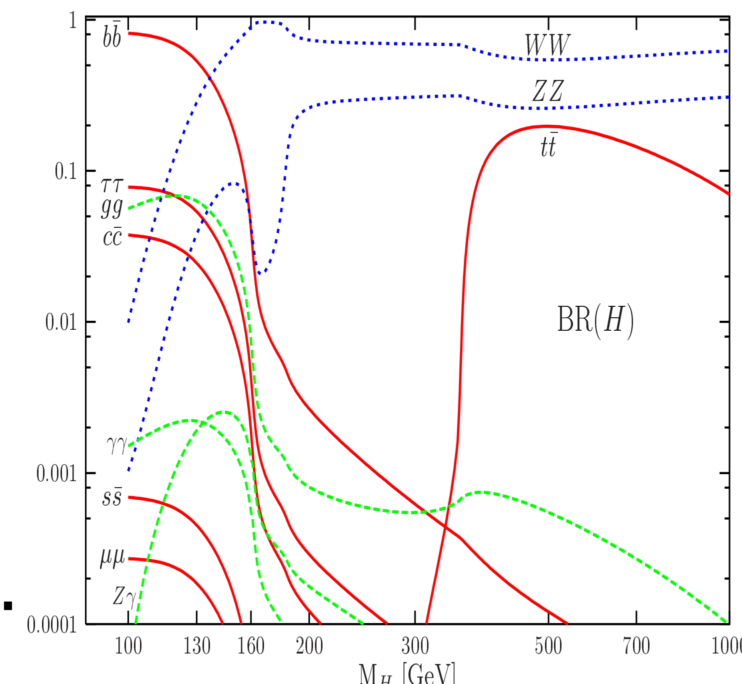
$$\sigma \approx 50 \text{ fb}^{-1} @ 14 \text{ TeV}$$

Takes ≈ 85% of total Higgs rate.

VBF 2d largest: $\sigma_{\mathbf{VBF}}/\sigma_{\mathbf{ggH}} \lesssim \frac{1}{10}$

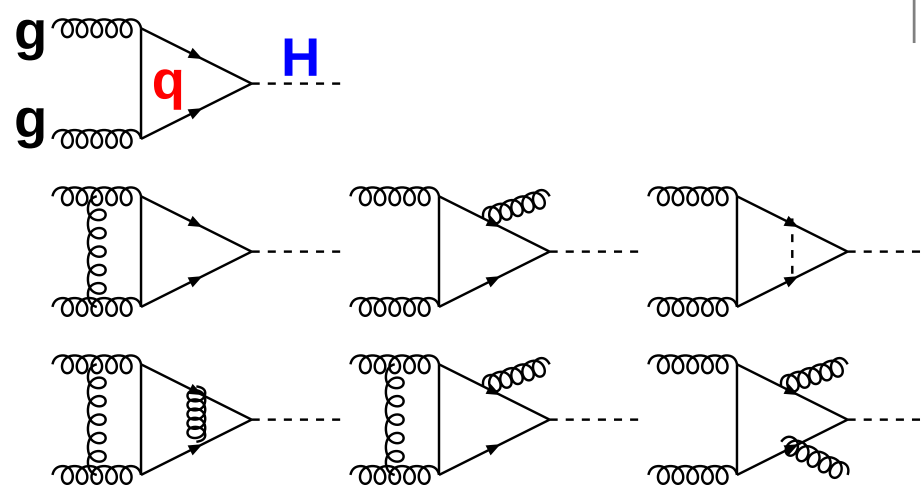
Note BR(H$\to \gamma\gamma, \mathbf{ZZ} \to 4\ell) \approx 10^{-3}$

... not so small # of events at the end...



2. Theoretical uncertainties on the Higgs rates

The $\sigma^{\rm theory}_{gg\to H}$ long story (70s–now) ...



LO[a]: already at one loop

QCD: exact NLO[b] : $\mathrm{K} \approx$2

EFT NLO[c]: good approx.

EFT NNLO[d]: $\mathrm{K} \approx$3

EFT NNLL[e]: $\approx +$10%

EFT other HO[f]: a few %.

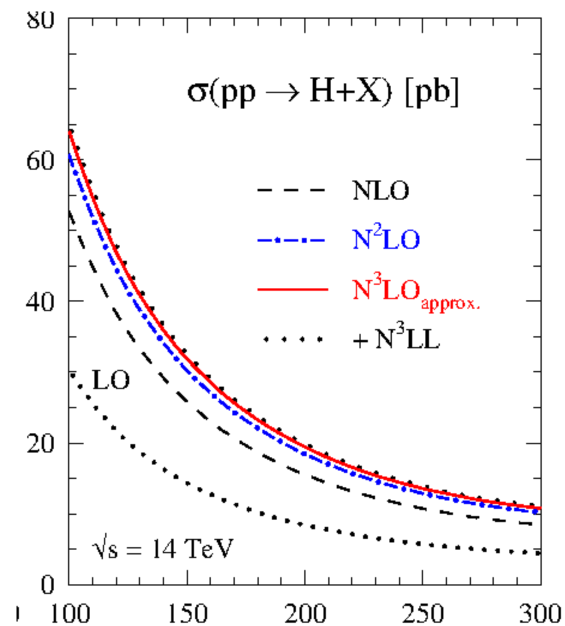
EW: EFT NLO: [g]: $\approx \pm$ very small

exact NLO[h]: $\approx \pm$ a few %

QCD+EW[i]: a few %

Very recent: N^{3}LO calculation[j] $\approx +$3%

[a] Georgi+Glashow+Machacek+Nanopoulos
[b] Spira+Graudenz+Zerwas+AD (exact)
[c] Spira+Zerwas+AD; Dawson (EFT)
[d] Harlander+Kilgore, Anastasiou+Melnikov
Ravindran+Smith+van Neerven
[e] Catani+de Florian+Grazzini+Nason
[f] Moch+Vogt; Ahrens et al., Bonvini et al.
[g] Gambino+AD; Degrassi et al.
[h] Actis+Passarino+Sturm+Uccirati
[i] Anastasiou+Boughezal+Pietriello
[j] Anastasiou et al.



Moch+Vogt

2. Theoretical uncertainties on the Higgs rates

Despite of that, the $gg \to H$ cross section still affected by uncertainties

- **Higher-order or scale uncertainties:**

K-factors large $\Rightarrow$ HO could be important
HO estimated by varying scales of process

$$\mu_0/\kappa \le \mu_R, \mu_F \le \kappa\mu_0$$

at LHC: $\mu_0 = \frac{1}{2}M_H$, $\kappa = 2 \Rightarrow \Delta^{\rm NNLO}_{\rm scale} \approx 10\%$
$\Rightarrow$ now 4–5% with N^{3}LO result

- **gluon PDF+associated α_s uncertainties:**

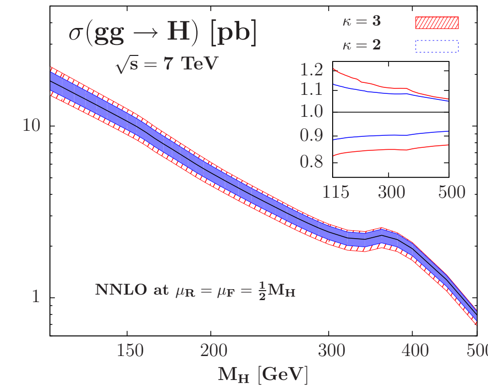
gluon PDF at high–x less constrained by data
α_s uncertainty (WA, DIS?) affects $\sigma \propto \alpha_s^2$
PDF4LHC recommend: $\Delta_{\rm pdf} \approx 10\%$@LHC
$\Rightarrow$ to be improved to 3–4% in future?

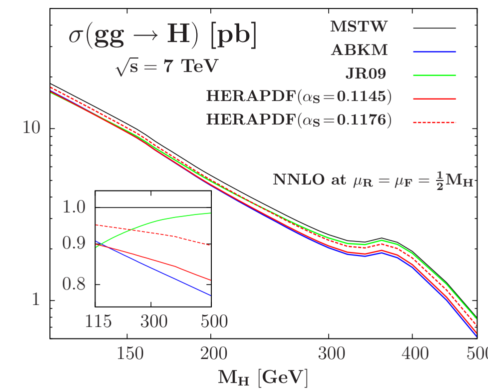
- **Uncertainty from EFT approach at NNLO**

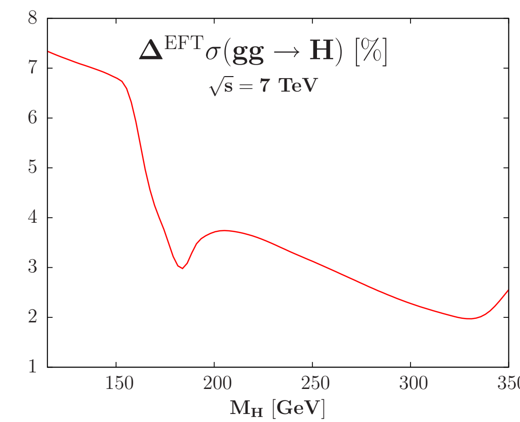
$m_{\rm loop} \gg M_H$ good for top if $M_H \lesssim 2m_t$
but not above and not b ($\approx 10\%$), W/Z loops
Estimate from (exact) NLO: $\Delta_{\rm EFT} \approx 5\%$

total $\Delta\sigma^{\rm TH}_{gg\to H} \approx$ 15–20%@LHC

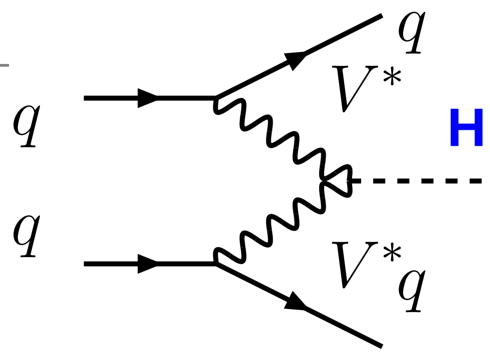
$\Rightarrow$ could be improved to $\approx$ 10% ??







2. Theoretical uncertainties on the Higgs rates



Large σ for small $\mathrm{M_H}$ and high $\sqrt{\mathrm{s}}$
$\Rightarrow$ most important after $\mathrm{gg \to H}$.
Radiative corrections well under control:

– NLO QCD corrections order 10% (also with cuts and for distributions).

– Dominant NNLO corrections also calculated: very small.

– EW corrections are also rather small, of order of a few %.

for inclusive $\Delta\sigma^{\mathrm{TH}}_{\mathrm{VBF}} \approx 5\% \Rightarrow$ very clean!

But need to perform specific kinematics cuts to select the VBF topology:

- **forward jet tagging: the two final jets are very forward peaked.**
- **– jets with large energies of $\mathcal{O}$(1 TeV) and sizeable $\mathrm{P_T}$ of $\mathcal{O}(\mathrm{M_V})$.**
- **central jet vetoing: Higgs decay products are central and isotropic.**
- **small hadronic activity in the central region no QCD (trigger uppon).**

$\Rightarrow$ allows to suppress backgrounds to the level of H signal: $\mathrm{S/B} \sim 1$.

However, the various VBF cuts make the signal theoretically less clean:

- **dependence on many cuts and variables, impact of HO less clear,**
- **contamination from the $\mathrm{gg \to H+jj}$ process not that small...**

2. Theoretical uncertainties on the Higgs rates

There are also theoretical uncertainties on the Higgs BRs

- **Input quark masses in $\mathbf{H \to b\bar{b}, c\bar{c}}$**

$$\mathbf{m_Q^{pole} \to \overline{m}_Q(\mu = M_H)}$$

– $\mathbf{\overline{m}_b(M_b) = 4.19 \pm 0.03}$ **GeV**

– $\mathbf{\overline{m}_c(M_c) = 1.27 \pm 0.08}$ **GeV**

- **Theory+experimental error on α_s :**

$\mathbf{\alpha_s(M_Z^2) = 0.118 \pm 0.0014}$ **@NNLO**

- **Scale error for higher orders**

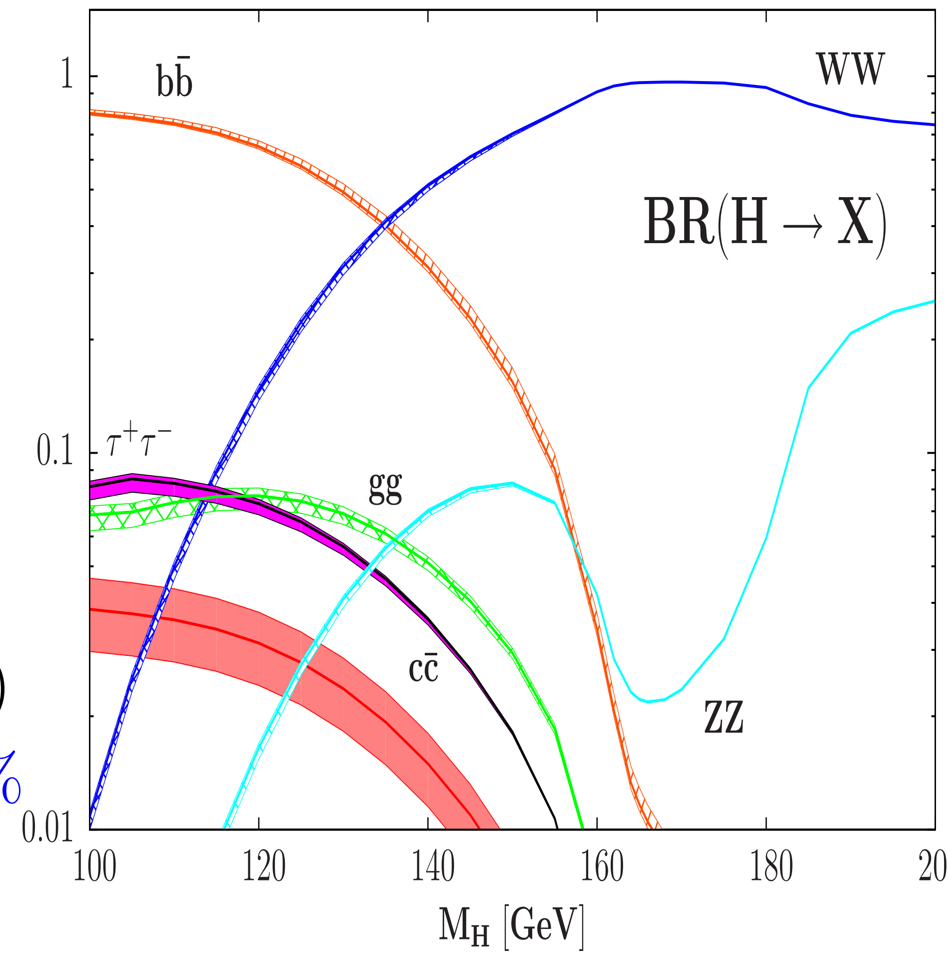
$\Rightarrow$ **non-negligible uncertainties on BRs**

$\mathbf{\Gamma(H \to b\bar{b}) \approx 60\% \Gamma_H^{tot} \Rightarrow \mathcal{O}(5-8\%)}$

$\Rightarrow \mathbf{\Delta BR(H \to \gamma\gamma, VV, \tau\tau, bb) \approx 5\%}$

To be added to $\mathbf{\Delta^{TH}\sigma(pp \to H)}$

Note : total width not known and subject to theoretical ambiguities (invisible, etc..)



3. Ratios of rates and $D_{\gamma\gamma}$

Best way to eliminate the theory uncertainty is to use ratios of signal rates

Take for instance $\mathbf{H \to VV}$ with $\mathbf{V = W \to \ell\nu}$ or $\mathbf{Z \to \ell\ell}$ as reference,

and for detection channel $\mathbf{H \to XX}$ with Higgs produced in process p:

$$\mathbf{D_{XX} = \sigma^{p}(pp \to H \to XX)/\sigma^{p}(pp \to H \to VV)}$$
$$\mathbf{= \sigma^{p}(pp \to H) \times BR(H \to XX)/\sigma^{p}(pp \to H) \times BR(H \to VV)}$$
$$\mathbf{= BR(H \to XX)/BR(H \to VV)}$$
$$\mathbf{= \Gamma(H \to XX)/\Gamma(H \to VV)}$$

$$\mathbf{D_{XX} = c_X^2/c_V^2}$$

Works only if one selects exactly the same kinematical configuration

(same selection cuts and hence "efficiencies") for the channels X and V!

$$\mathbf{D_{XX} = \frac{\epsilon_{gg}^{X}\sigma(gg \to H \to XX) + \epsilon_{VBF}^{X}\sigma(qq \to Hqq \to qqXX) + \epsilon_{HV}^{X}\sigma(q\bar{q} \to VH \to VXX)}{\epsilon_{gg}^{V}\sigma(gg \to H \to VV) + \epsilon_{VBF}^{V}\sigma(qq \to Hqq \to qqVV) + \epsilon_{HV}^{V}\sigma(q\bar{q} \to VH \to VVV)}}$$
$$\mathbf{= \frac{\epsilon_{gg}^{X}\sigma(gg \to H) + \epsilon_{VBF}^{X}\sigma(qq \to Hqq) + \epsilon_{HV}^{X}\sigma(q\bar{q} \to VH)}{\epsilon_{gg}^{V}\sigma(gg \to H) + \epsilon_{VBF}^{V}\sigma(qq \to Hqq) + \epsilon_{HV}^{V}\sigma(q\bar{q} \to VH)} \times \frac{\Gamma(H \to XX)}{\Gamma(H \to VV)}}$$
$$\mathbf{= \frac{\Gamma(H \to XX)}{\Gamma(H \to VV)} = c_X^2/c_V^2}$$

3. Ratios of rates and $D_{\gamma\gamma}$

- The theoretical uncertainties from the cross sections drop out
- The parametric uncertainties from the branching ratios drop out
- The theoretical ambiguities in the Higgs total width also drop out

$\Rightarrow D_{XX}$ **measures only the ratio of squared couplings!**

Extremely clean theoretically. And maybe also experimentally useful:

- **Some common experimental systematical errors also drop out:**

– common uncertainty from the luminosity measurement

– other common systematics such as errors on efficiencies etc...?

The ratios that can already be built are the following ones:

$$D_{ww} = \frac{\sigma(pp \to H \to WW)}{\sigma(pp \to H \to VV)} = \frac{\Gamma(H \to WW)}{\Gamma(H \to VV)} = d_{ww} \frac{c_W^2}{c_V^2}$$

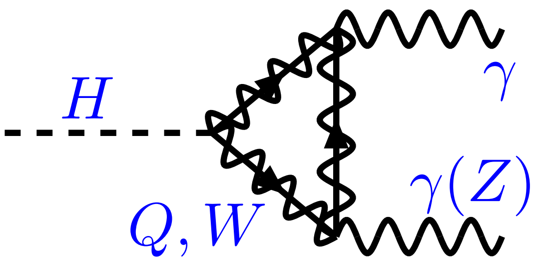
$$D_{\tau\tau} = \frac{\sigma(pp \to H \to \tau\tau)}{\sigma(pp \to H \to VV)} = \frac{\Gamma(H \to \tau\tau)}{\Gamma(H \to VV)} = d_{\tau\tau} \frac{c_\tau^2}{c_V^2}$$

$$D_{bb} = \frac{\sigma(q\bar{q} \to HV \to bbV)}{\sigma(q\bar{q} \to HV \to VVV)} = \frac{\Gamma(H \to bb)}{\Gamma(H \to VV)} = d_{bb} \frac{c_\tau^2}{c_V^2}$$

$$D_{\gamma\gamma} = \frac{\sigma(pp \to H \to \gamma\gamma)}{\sigma(pp \to H \to VV)} = \frac{\Gamma(H \to \gamma\gamma)}{\Gamma(H \to VV)} = d_{\gamma\gamma} \frac{c_\gamma^2}{c_V^2}$$

Best probe by far is $D_{\gamma\gamma}$ which measures the deviation of the $\gamma\gamma$ loop!

3. Ratios of rates and $D_{\gamma\gamma}$



$$\Gamma = \frac{G_\mu \alpha^2 M_H^3}{128\sqrt{2}\pi^3} \left| \sum_f N_c e_f^2 A^H_{\frac{1}{2}}(\tau_f) + A^H_1(\tau_W) \right|^2$$

$$A^H_{1/2}(\tau) = 2[\tau + (\tau-1)f(\tau)]\,\tau^{-2}$$

$$A^H_1(\tau) = -[2\tau^2 + 3\tau + 3(2\tau-1)f(\tau)]\,\tau^{-2}$$

- **Photon massless and Higgs has no charge: must be a loop decay.**
- **In SM: only W–loop and top-loop are relevant (b–loop too small).**
- **For $m_i \to \infty \Rightarrow A_{1/2} = \frac{4}{3}$ and $A_1 = -7$: W loop dominating!**

(approximation $\tau_W \to 0$ valid only for $M_H \lesssim 2M_W$: relevant here!).

$\gamma\gamma$ width counts the number of charged particles coupling to Higgs!

Contrubution A^p_s of particle p of spin s with Higgs coupling g_{Hpp}:

$$A^p_0 = -\tfrac{1}{3} g^2_{Hpp}/m^2_P,\; A^p_{1/2} = +\tfrac{4}{3} g^2_{Hpp}/m^2_P,\; A^p_1 = -7 g^2_{Hpp}/m^2_P,$$

If $g_{Hpp} \propto m_p \Rightarrow A^p_0 \to -\frac{4}{3}, A^p_{1/2} \to +\frac{1}{3}, A^p_1 \to +7$.

Small/calculated QCD and EW corrections: only of order few percent.

3. Ratios of rates and $D_{\gamma\gamma}$

In the SM, the top and W loop contributions to the ratio $\gamma\gamma$ amplitude is

$$\mathbf{c_\gamma \approx 1.26 \times |c_W - 0.21\, c_t|}$$

Assuming the custodial symmetry relation $g_{HZZ} = g_{HWW} = c_V$
(which is well checked experimentally and hard to violate in theory)
The SM value of the ratio $D_{\gamma\gamma} = c_\gamma^2/c_V^2$ is simply given by

$$\mathbf{c_\gamma^2/c_V^2 \approx 6.5 \times |1 - \tfrac{1}{5} c_t/c_V|^2}$$

with $c_V = c_t = 1$ in SM. Any new physics effects will alter this value.

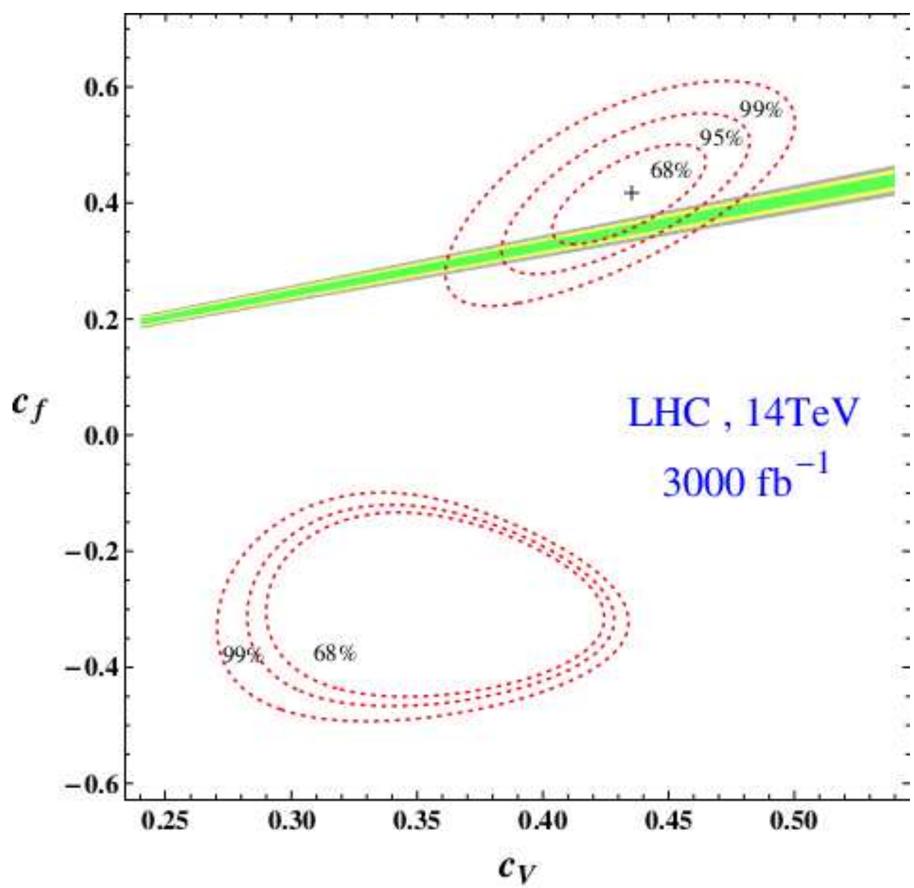
How well this observable can be experimentally measured? If it is $\mathcal{O}(1\%)$ best probe of new physics atht you can imagine at the LHC (equivalent to $\sin^2\theta_W$ at LEP and M_W at the Tevatron/LHC).

Examples of BSM searches that can be done with the observable follow.

4. Search for BSM with $D_{\gamma\gamma}$

$$c_\gamma^2 \approx 6.5 \times |c_W - 0.21\, c_t|^2$$

From central values of $\mu_{\gamma\gamma}, \mu_{ZZ}$ of march 2013 (ATLAS excess in $\gamma\gamma$..), extrapolation to HL–LHC with error scaling as $\Delta^{EX}/\sqrt{\mathcal{L}}$, one finds:



AD+Moreau

4. Search for BSM with $D_{\gamma\gamma}$

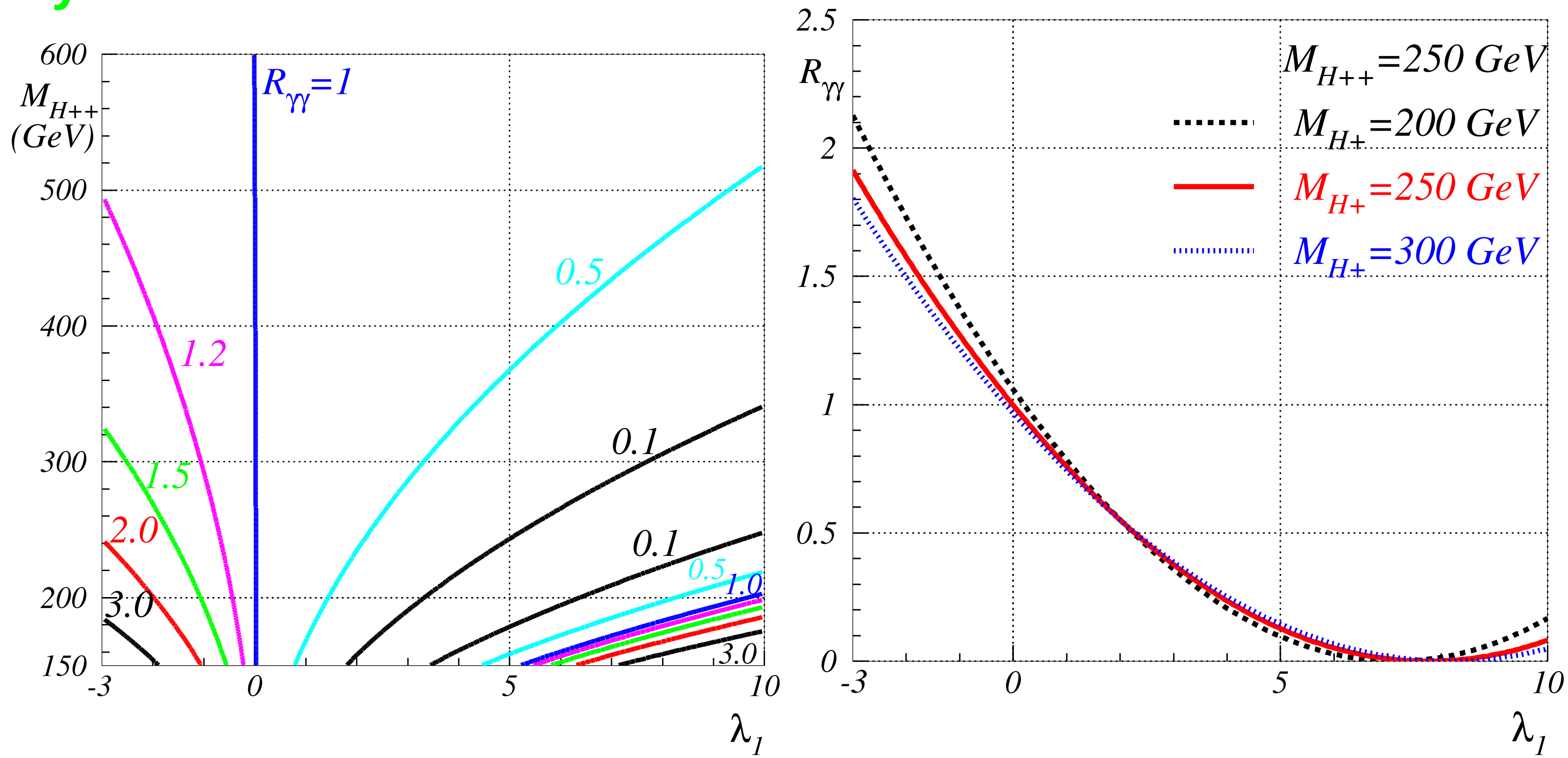
In alignment limit in extended Higgs models $\Rightarrow g_{HVV} = g_{Hff} = 1$

new physics effects appear only in the $H\gamma\gamma$ vertex: $c_\gamma \approx |1 + \hat{c}_\gamma|$

- In 2HDM: contribution of $H^\pm$ states with $\lambda_I \propto g_{HH^+H^-} = f(\tan\beta)$
- In triplet Higgs models: contribution of both $H^\pm$ and $H^{\pm\pm}$

$\Rightarrow$ probe large masses of the new Higgs states witha 1% accuracy

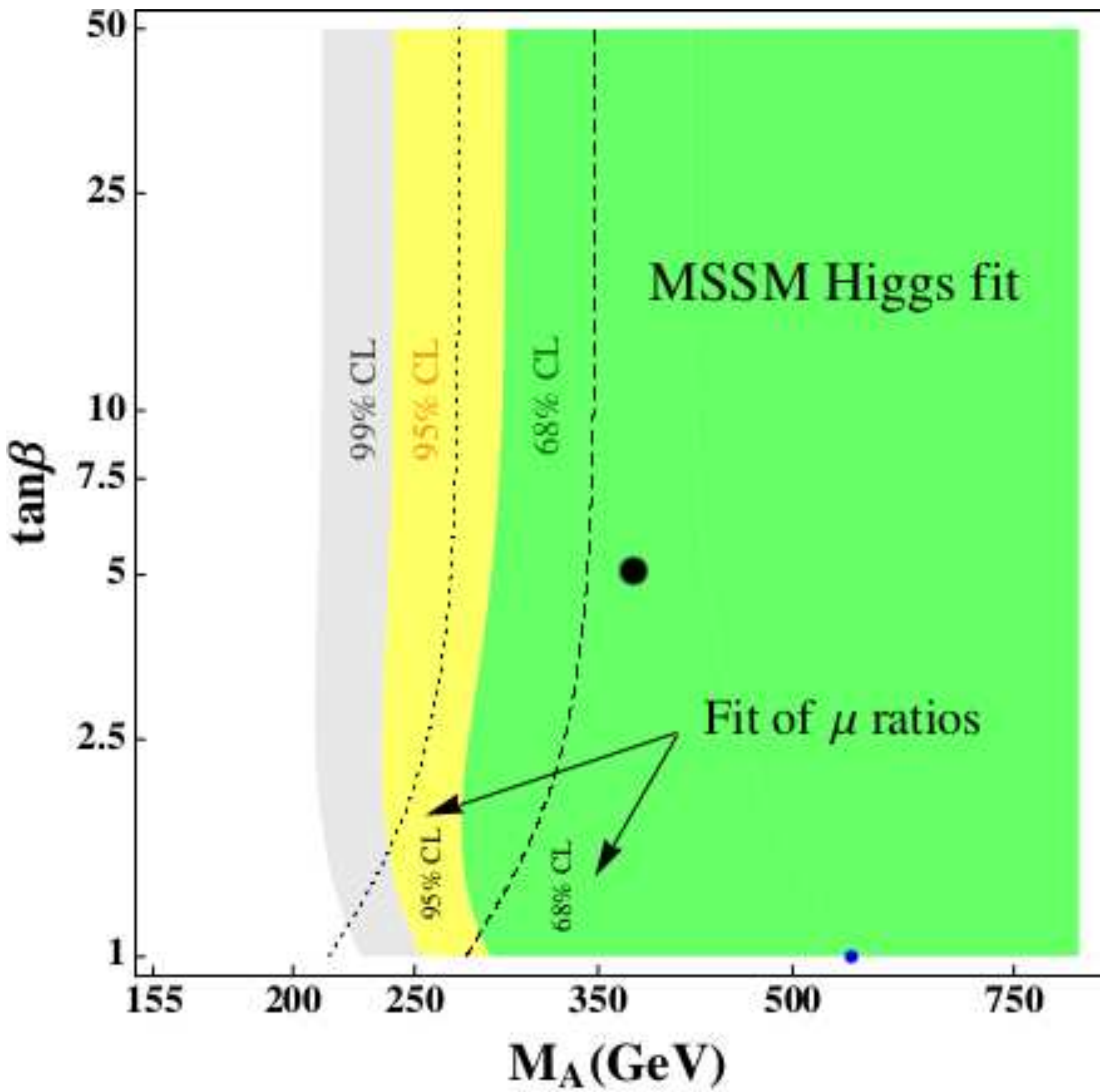
Akeroyd+Arhrib



4. Search for BSM with $D_{\gamma\gamma}$

MSSM with heavy sparticles: Higgs sector needs only two inputs (hMSSM)

fits of the h couplings ⇒ constraints on the MSSM $[M_A, \tan\beta]$ plane.



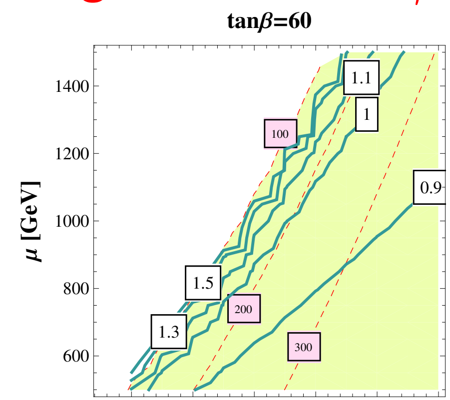
AD
Maiani
Moreau
Polosa
Quevillon
Riquer
(2013)

4. Search for BSM with $\mathrm{D}_{\gamma\gamma}$

Can SUSY loop contributions significantly change the $\mathrm{h}\to\gamma\gamma$ rate?

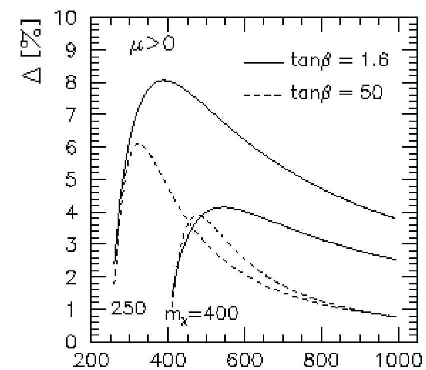
discussed in last years for $2\sigma\gamma\gamma$ excess..

$\Rightarrow$ much better job with a 1% probe!



- **light stau's and large $\mathrm{g}_{\mathrm{h}\tilde{\tau}\tilde{\tau}}\propto\mu\tan\beta$**
  (staus difficult to search at LHC..)

  Carena+Gori+Shah+Wagner

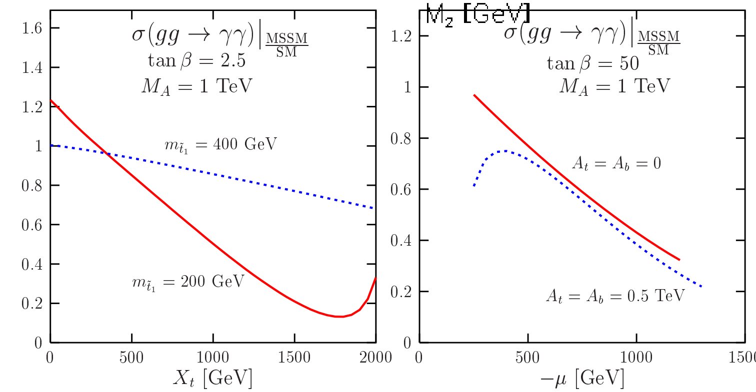


- **light $\chi_1^\pm$ in non-universal MSSM**
  $\mathcal{O}(\frac{\mathrm{gM_W}}{\mathrm{m}_{\chi_1^\pm}})$ **with** $\mathrm{g}_{\mathrm{h}\chi_1^\pm\chi_1^\pm}\propto\frac{\mu\mathrm{M_2}}{\mathrm{M_2^2}+\mu^2}$

  Driesen+Illana+Hollik+AD

- **light $\tilde{\mathrm{t}}$ with large Higgs couplings:**
  $1+\mathrm{m_t^2}/(4\mathrm{m}_{\tilde{\mathrm{t}}_1}^2\mathrm{m}_{\tilde{\mathrm{t}}_2}^2)\times(\mathrm{m}_{\tilde{\mathrm{t}}_1}^2+\mathrm{m}_{\tilde{\mathrm{t}}_2}^2-\mathrm{X_t^2})$
  $\Rightarrow$ max-mixing: $\sigma(\mathrm{gg}\to\mathrm{h})$ suppressed.
  $\Rightarrow$ no mixing: but then stops very heavy.

  Arvanitaki+Villadoro,AD



- **light $\tilde{\mathrm{b}}$ with large $\mathrm{g}_{\mathrm{h}\tilde{\mathrm{b}}\tilde{\mathrm{b}}}\propto\mu\tan\beta$**
  similar to the $\tilde{\tau}$ case at high $\tan\beta$.

Very efficient probe! complementary to direct SUSY searches...