Into the multi-TeV scale with $\mathbf{H \to \gamma\gamma / H \to ZZ^*}$

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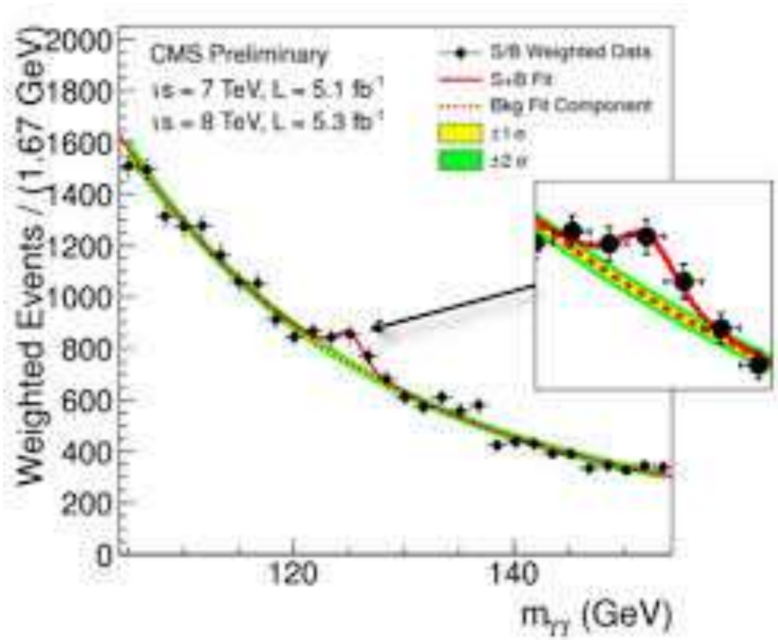
What next after the Higgs discovery?

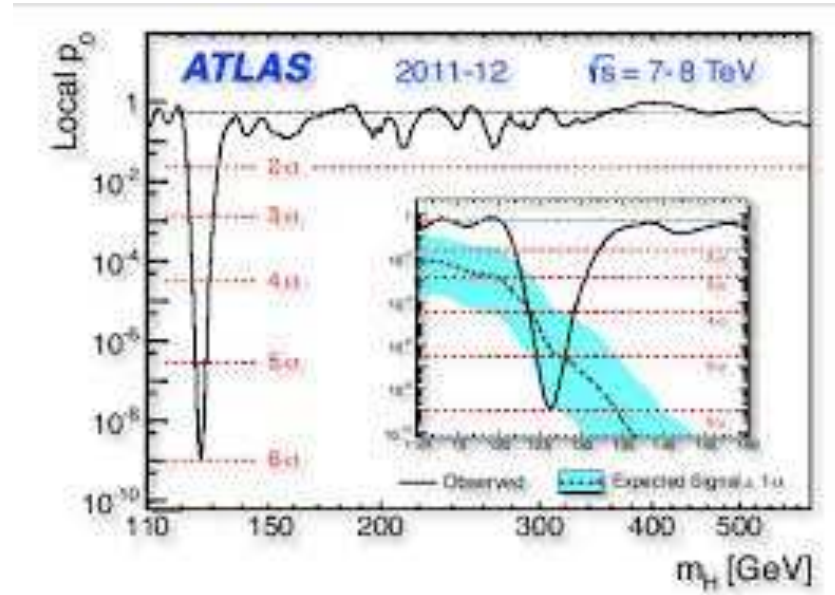
$$\mathbf{D_{\gamma\gamma} = \Gamma(H \to \gamma\gamma)/\Gamma(H \to ZZ^*)}$$

Search for beyond the SM with $\mathbf{D_{\gamma\gamma}}$

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/multiverse?

What next after the Higgs discovery?

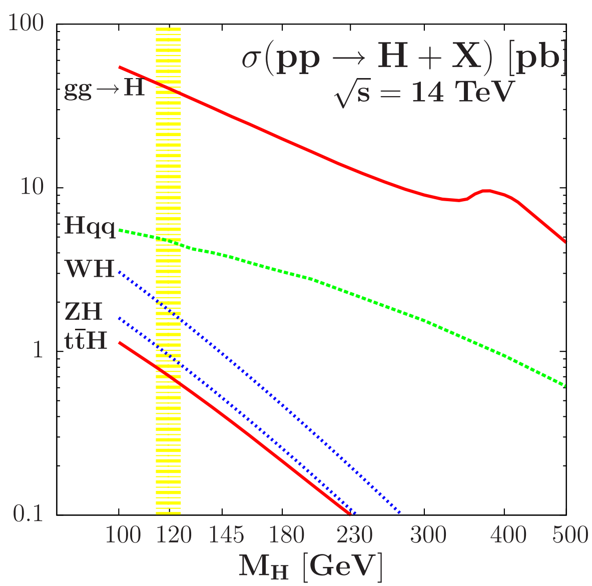
What should we be doing the next 10–30 years in Particle Physics?

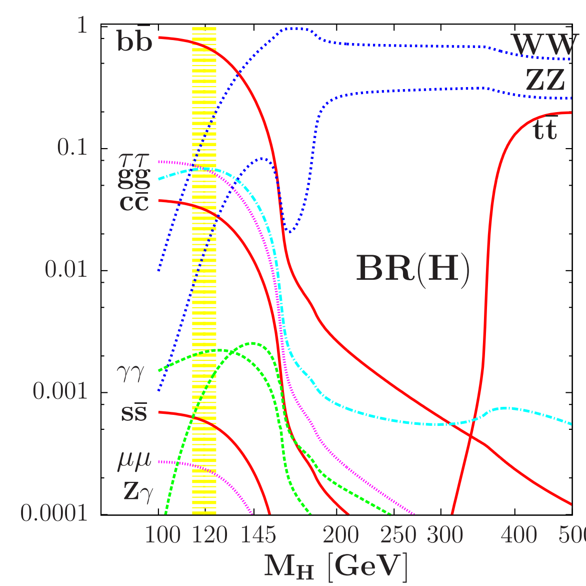
Besides continuing to search directly for the signs of new physics, we need to check that H is indeed responsible of sEWSB (and SM-like?)

$\Rightarrow$ 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!





What next after the Higgs discovery?

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

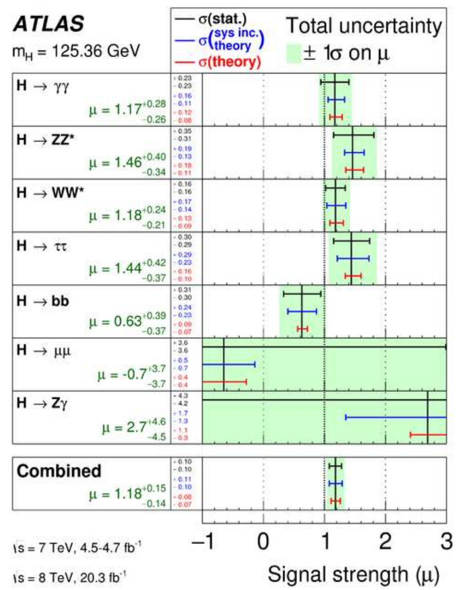
$$\mu_{\rm XX} = \sigma^{\rm p}({\rm pp} \to {\rm H}) \times {\rm BR}({\rm H} \to {\rm XX})|_{\rm exp/SM}$$

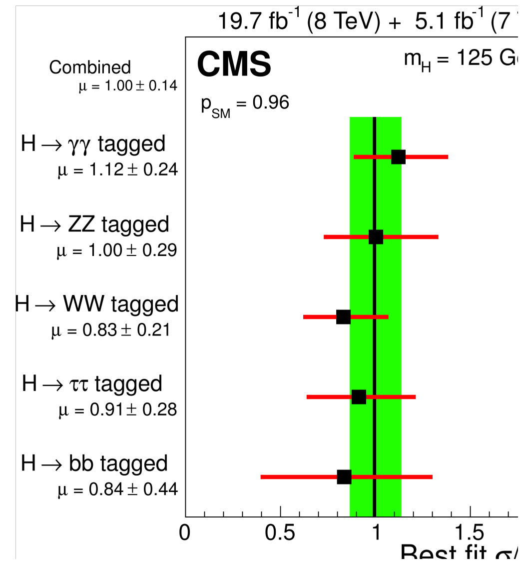
$\sigma\times$BRs compatible with those expected in the SM

Fit of all LHC Higgs data $\Rightarrow$ agreement at 15–30% level

$$\mu_{\rm tot}^{\rm ATLAS} = 1.18 \pm 0.15$$

$$\mu_{\rm tot}^{\rm CMS} = 1.00 \pm 0.14$$





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

Brand new: $\mu_{\rm tot}^{\rm ATLAS+CMS} = 1.09^{+0.07+0.04+0.07}_{-0.07-0.04-0.06} \approx 1.1 \pm 0.1$

This is particularly the case in the two very clean detection channels

$$\rm H \to \gamma\gamma,\ H \to ZZ^* \to 4\ell^\pm$$

What next after the Higgs discovery?

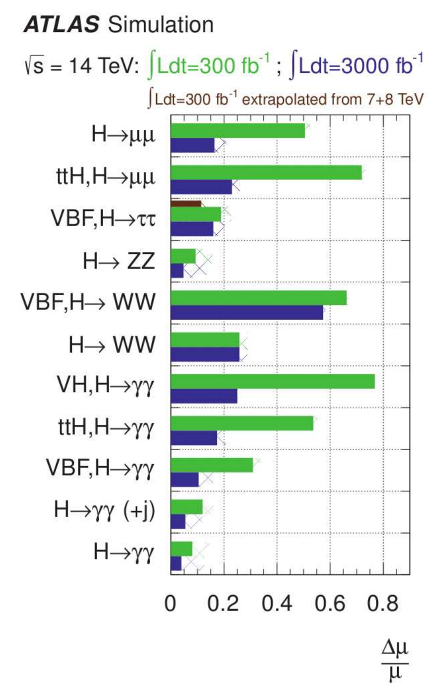
channel	ATLAS	CMS
$\mu_{\gamma\gamma}$	$1.17\,{}^{+0.23}_{-0.23}\,{}^{+0.16}_{-0.11}\,\left({}^{+0.12}_{-0.08}\right)$	$1.14\,{}^{+0.21}_{-0.21}\,{}^{+0.16}_{-0.10}\,\left({}^{+0.09}_{-0.05}\right)$
μ_{ZZ}	$1.46\,{}^{+0.35}_{-0.31}\,{}^{+0.19}_{-0.13}\,\left({}^{+0.18}_{-0.11}\right)$	$0.93\,{}^{+0.26}_{-0.23}\,{}^{+0.13}_{-0.09}$

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 $\Delta\mu_{XX} \approx \frac{c_{NEW}\alpha_W}{\pi} \approx \frac{M_h^2}{M_{NEW}^2} \approx 1\%$

Is a 1% accuracy achievable at upgraded LHC with very high luminosities ($\approx 3000\ \mathrm{fb}^{-1}$)?

- **The statistical error:** $\frac{20\%}{\sqrt{3\times100}} \lesssim 1\%$ **in the clean** $H \to \gamma\gamma, VV$ **channels (latest ATLAS+CMS combo:** $\lesssim$ **1–2%!)**
- **Systematical error: reduced below 1%? some are common (luminosity, etc.).**
- **Theoretical uncertainty (if** $\gg$**1%): will be then by far the limiting issue!**



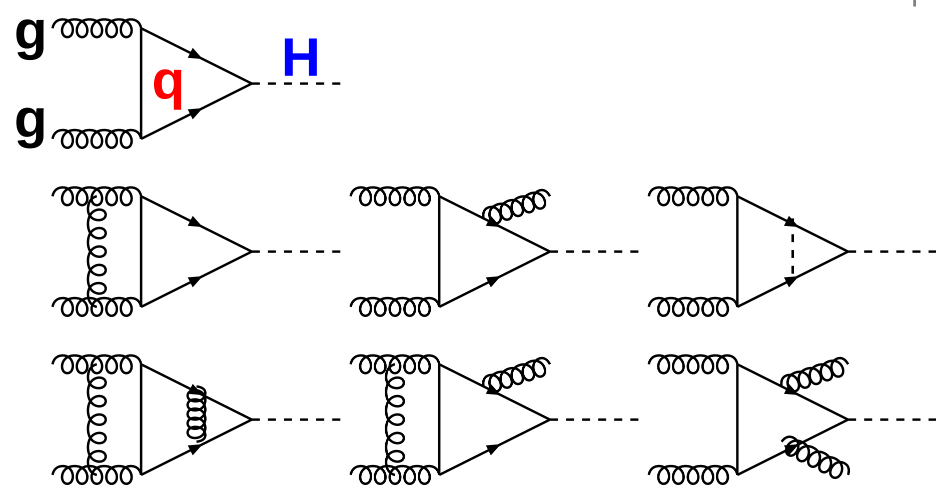
⇒ How big is it? How much can it be reduced? Can it be removed?

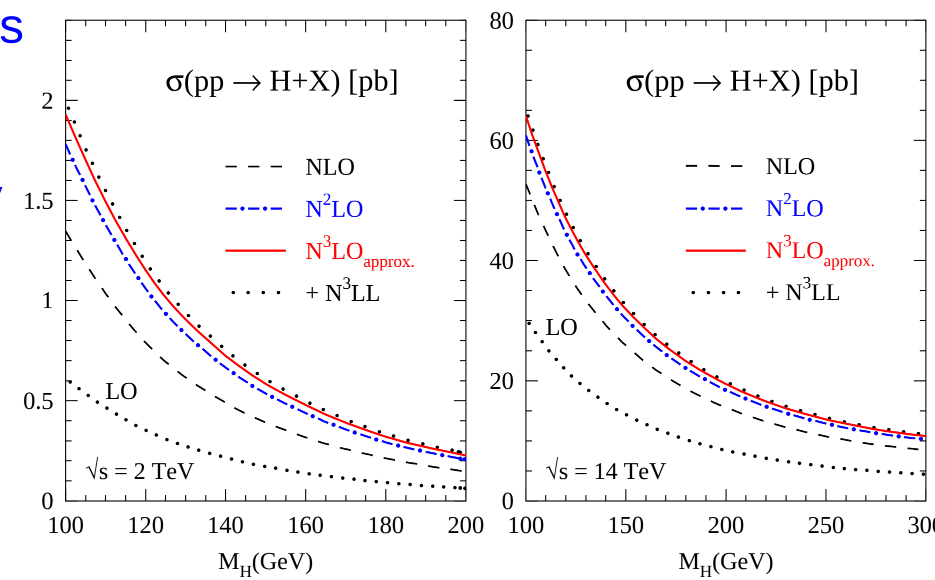
$\mathbf{D}_{\gamma\gamma}$

LO[a]: already at one loop
QCD: exact NLO[b] : $\mathrm{K} \approx$ 1.7
EFT NLO[c]: good approx.
EFT NNLO[d]: $\mathrm{K} \approx$ 2
EFT NNLL[e]: $\approx +$ (5%)
EFT N3LO[f]: $\approx$ 3 %.
EW: EFT NLO: [g]: $\approx \pm$ very small
exact NLO[h]: $\approx \pm$ a few %
QCD+EW[i]: a few %
Distributions: a few programs[j]

[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] Anastasiou et al. (2015)!
[g] Gambino+AD; Degrassi et al.
[h] Actis+Passarino+Sturm+Uccirati
[i] Anastasiou+Boughezal+Pietriello
[j] Anastasiou et al.; Grazzini, Nason,...

The $\sigma^{\rm theory}_{gg\to H}$ long story (1978–2015)





Moch+Vogt

$D_{\gamma\gamma}$

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: $\mu_0 = \frac{1}{2}M_H, \kappa = 2 \Rightarrow \Delta^{NNLO}_{scale} \approx 10\%$

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

gluon PDF at high–x less constrained by data

α_s uncertainty (WA, DIS?) affects $\sigma \propto \alpha_s^2$

$\Rightarrow$ large discrepancy between NNLO PDFs

PDF4LHC recommend: $\Delta_{pdf} \approx 10\%$@lHC

- **Uncertainty from EFT approach at NNLO**

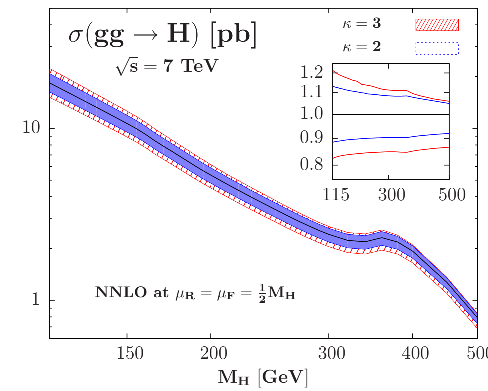
$m_{loop} \gg M_H$ good for top if $M_H \lesssim 2m_t$

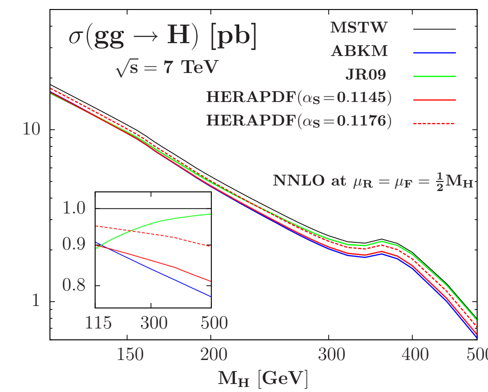
but not above and not b ($\approx 10\%$), W/Z loops

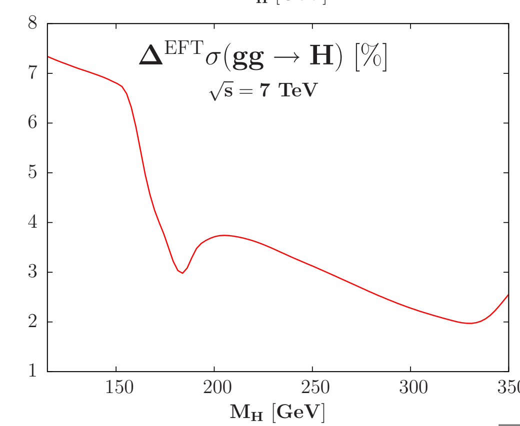
Estimate from (exact) NLO: $\Delta_{EFT} \approx 5\%$

total $\Delta\sigma^{NNLO}_{gg\to H\to X}$ ≈10–20%@lHC

LHC-HxsWG; Baglio+AD $\Rightarrow$ $H \to \gamma\gamma / H \to ZZ^*$



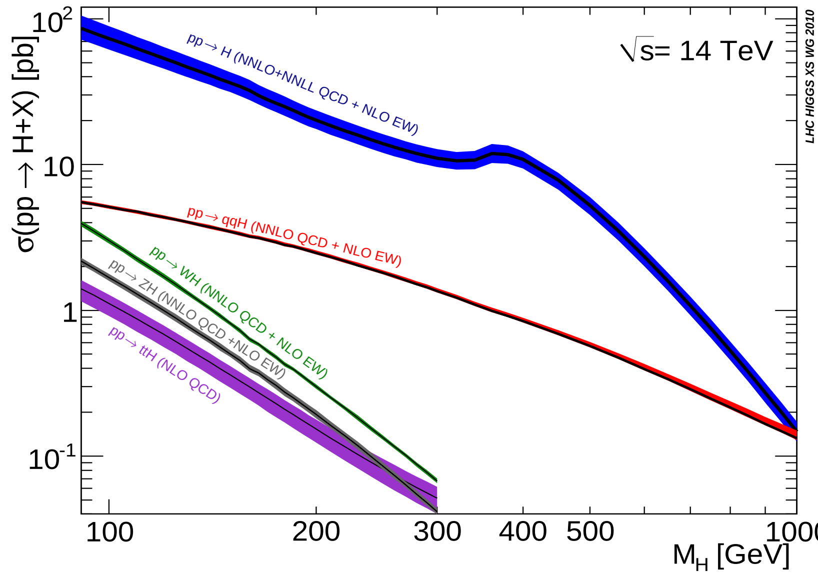




$\mathbf{D}_{\gamma\gamma}$

Production cross sections

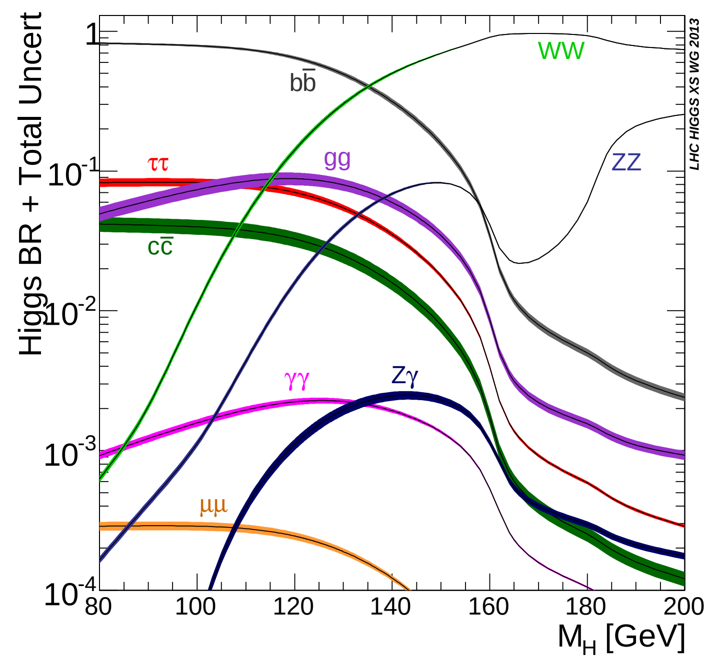
gg$\longrightarrow$ H by far dominant process
($\approx$ 85% of the events before cuts)
$\Rightarrow$ O(10%) total TH uncertainty .....
followed by cleaner VBF+VH modes:
only $\lesssim$ 15% of rate before cuts...
smaller TH error only for inclusive...
$\Rightarrow$ O(10%) for total uncertainty?



LHC HxsWG

Decay branching ratios

Dominant decay $\mathrm{H} \to \mathrm{b\bar{b}} \approx 60\%$
Affected by QCD+parametric errors:
from $\mathrm{m_b}$ and α_s only, a few % $\Rightarrow$
migrate to O(5%) error in other modes
such as $\mathrm{H} \to \gamma\gamma, \mathrm{ZZ}, \mathrm{WW}, \tau\tau$
(partial widths very precise $\lesssim$ 1%).



$\Rightarrow$ too large theory uncertainties!
(even if reduced by a factor of 2)...

$\mathbf{D}_{\gamma\gamma}$

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:

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

To first approximation: $\mathbf{D_{XX} = c_X^2/c_V^2}$

Works only if one selects exactly the same kinematical configuration
(i.e. same ”fiducial cross sections”) for the two channels X and V!

- 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

$\Rightarrow \mathbf{D_{XX}}$ measures only the ratio of partial decay widths!

$\mathbf{D}_{\gamma\gamma}$

- **Extremely clean theoretically, although some information will be lost.**
- **And maybe it has also some advantages from the experimental side?**

e.g. some common experimental systematical errors also drop out:

– common uncertainty from the luminosity measurement

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

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

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

$$\mathbf{D}_{\tau\tau} = \frac{\sigma(\mathbf{pp \to H \to}\tau\tau)}{\sigma(\mathbf{pp \to H \to VV})} = \frac{\Gamma(\mathbf{H \to}\tau\tau)}{\Gamma(\mathbf{H \to VV})} = \mathbf{d}_{\tau\tau} \frac{\mathbf{c}_\tau^2}{\mathbf{c_V^2}}$$

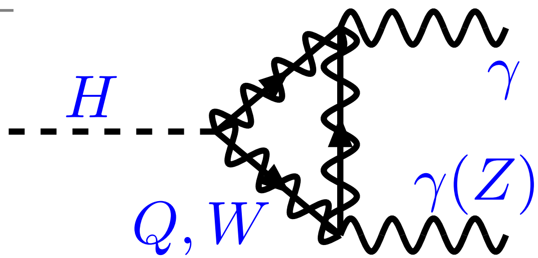
$$\mathbf{D_{bb}} = \frac{\sigma(\mathbf{q\bar{q} \to HV \to bbV})}{\sigma(\mathbf{q\bar{q} \to HV \to VVV})} = \frac{\Gamma(\mathbf{H \to bb})}{\Gamma(\mathbf{H \to VV})} = \mathbf{d_{bb}} \frac{\mathbf{c}_\tau^2}{\mathbf{c_V^2}}$$

$$\mathbf{D}_{\gamma\gamma} = \frac{\sigma(\mathbf{pp \to H \to}\gamma\gamma)}{\sigma(\mathbf{pp \to H \to VV})} = \frac{\Gamma(\mathbf{H \to}\gamma\gamma)}{\Gamma(\mathbf{H \to VV})} = \mathbf{d}_{\gamma\gamma} \frac{\mathbf{c}_\gamma^2}{\mathbf{c_V^2}}$$

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

AD, Eur.Phys.J. C73 (2013) 2498, arXiv:1208.3436

$D_{\gamma\gamma}$



$$\Gamma = \frac{G_\mu \, \alpha^2 \, M_H^3}{128\,\sqrt{2}\,\pi^3} \left| \sum_f N_c e_f^2 A_{\frac{1}{2}}^H(\tau_f) + A_1^H(\tau_W) \right|^2$$

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

$$A_1^H(\tau) = -[2\tau^2 + 3\tau + 3(2\tau - 1) f(\tau)]\,\tau^{-2}$$

- **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!

Contribution A_s^p of particle p of spin s with Higgs coupling g_{Hpp}:

$$A_0^p = -\tfrac{1}{3} g_{Hpp}^2 / m_P^2,\; A_{1/2}^p = +\tfrac{4}{3} g_{Hpp}^2 / m_P^2,\; A_1^p = -7 g_{Hpp}^2 / m_P^2,$$

If $g_{Hpp} \propto m_p \Rightarrow A_0^p \to +\frac{1}{3}, A_{1/2}^p \to -\frac{4}{3}, A_1^p \to +7$.

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

AD+Spira+Zerwas, Vicini et al., Passarino et al., AD+Gambino, Denner et al.,..

$\mathbf{D}_{\gamma\gamma}$

In the SM, the top and W loop contributions to the $\mathrm{H} \to \gamma\gamma$ amplitude is

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

Assuming the custodial symmetry relation $\mathrm{g_{HZZ}} = \mathrm{g_{HWW}} = \mathrm{c_V}$

(which is well checked experimentally and hard to violate in theory)

The SM value of the ratio $\mathrm{D}_{\gamma\gamma} = \mathrm{c}_{\gamma}^{2}/\mathrm{c}_{\mathbf{V}}^{2}$ is then simply given by

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

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

Big question: how well this observable can be experimentally measured?

If it is $\mathcal{O}(1\%)$, then best possible probe of new physics at the LHC:

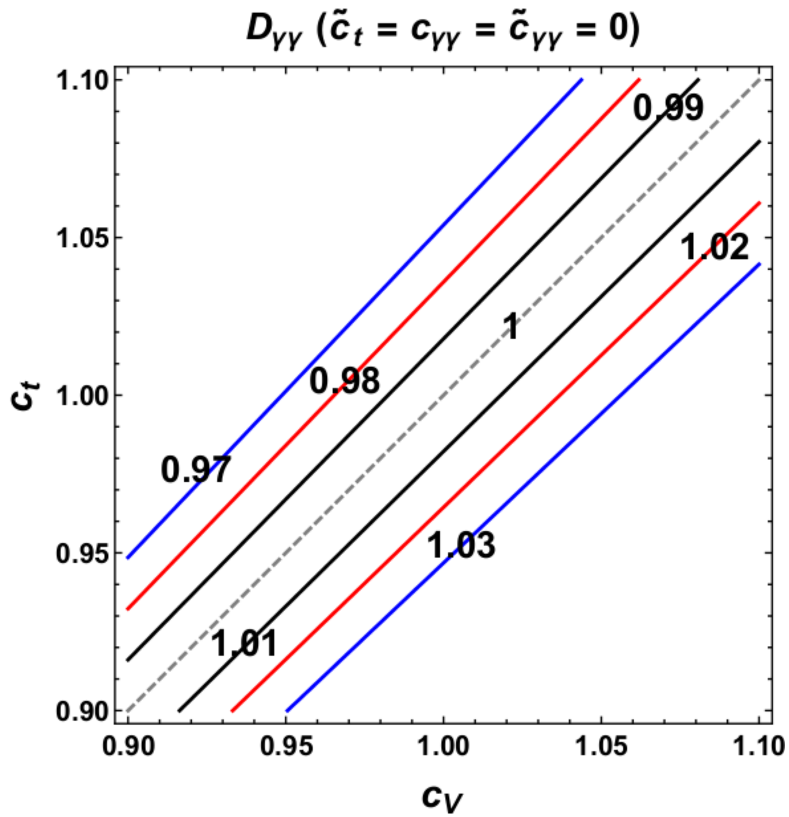
- such accuracy was envisaged only at the "clean" $\mathrm{e^+e^-}$ machines..
- impact comparable to $\sin^2\theta_{\mathrm{W}}$ at LEP and $\mathrm{M_W}$ at Tevatron/LHC..
- the g-2 of the LHC?

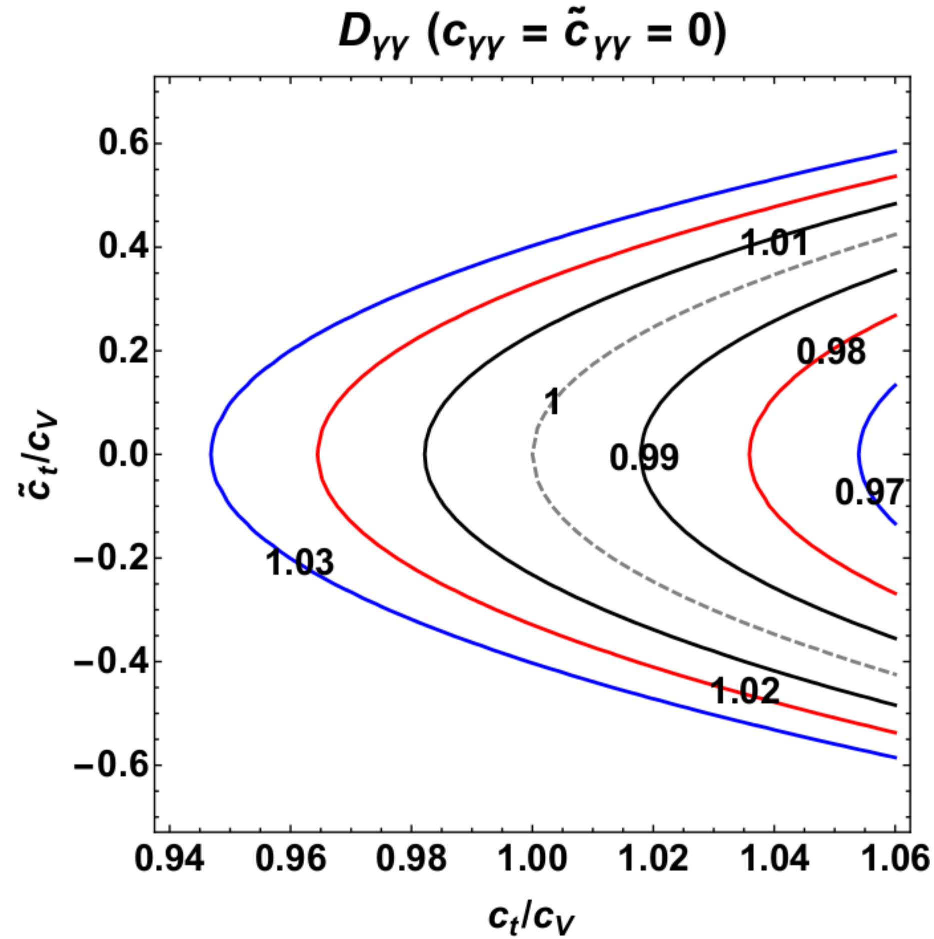
Examples of BSM searches that can be done with the observable follow.

AD, J. Quevillon and R. Vega-Morales, arXiv:1509.03913

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

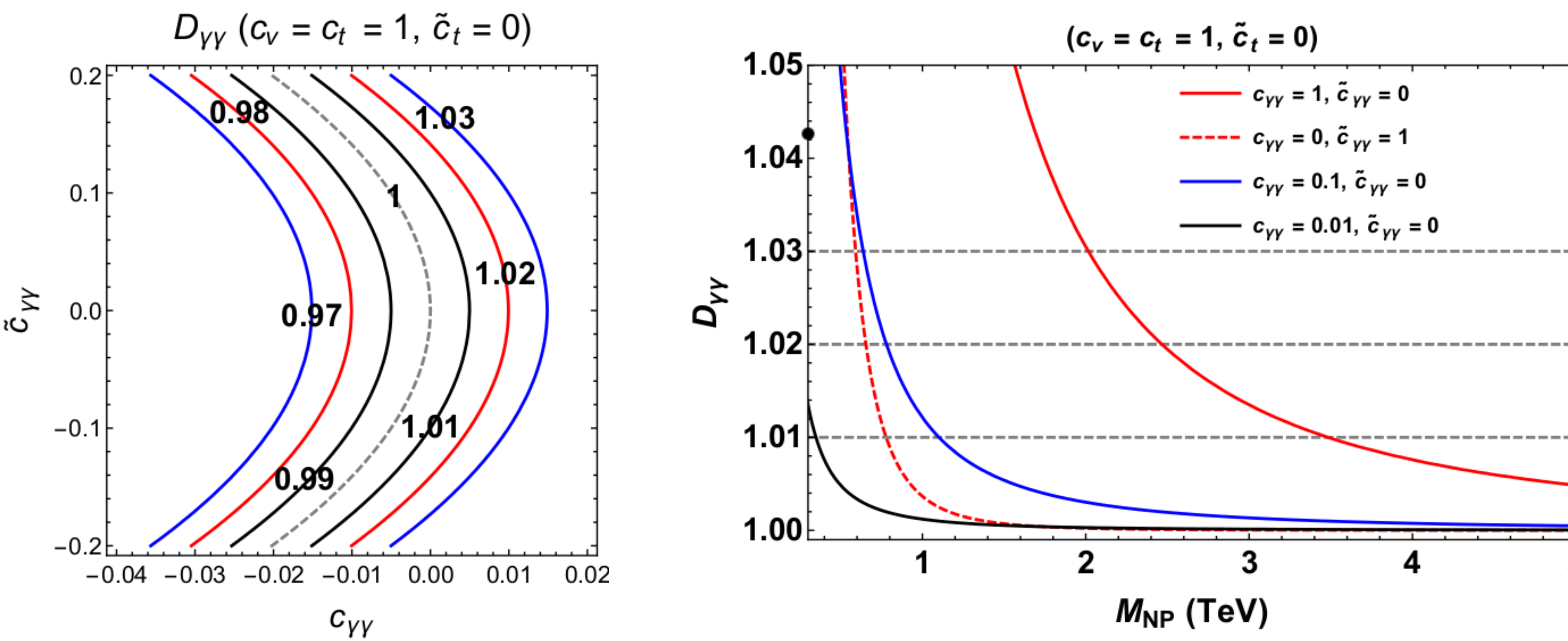
$$\mathcal{L} = \frac{H}{v}\Big(c_V(2M_W^2 W_\mu^+ W^{-\mu} + M_Z^2 Z_\mu Z^\mu) - m_t \bar{t}(c_t + i\tilde{c}_t\gamma^5)t + \frac{c_{\gamma\gamma}}{4}F^{\mu\nu}F_{\mu\nu} + \frac{\tilde{c}_{\gamma\gamma}}{4}\tilde{F}^{\mu\nu}F_{\mu\nu}\Big)$$





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

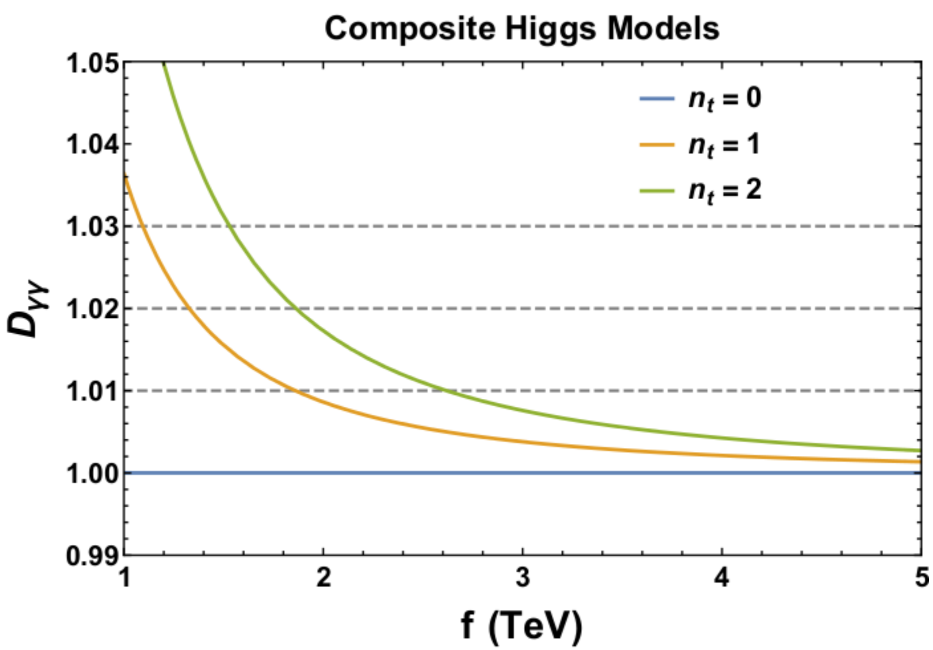
$$\mathcal{L} = \frac{H}{v}\Big(c_V(2M_W^2 W_\mu^+ W^{-\mu} + M_Z^2 Z_\mu Z^\mu) - m_t \bar{t}(c_t + i\tilde{c}_t\gamma^5)t + \frac{c_{\gamma\gamma}}{4}F^{\mu\nu}F_{\mu\nu} + \frac{\tilde{c}_{\gamma\gamma}}{4}\tilde{F}^{\mu\nu}F_{\mu\nu}\Big)$$

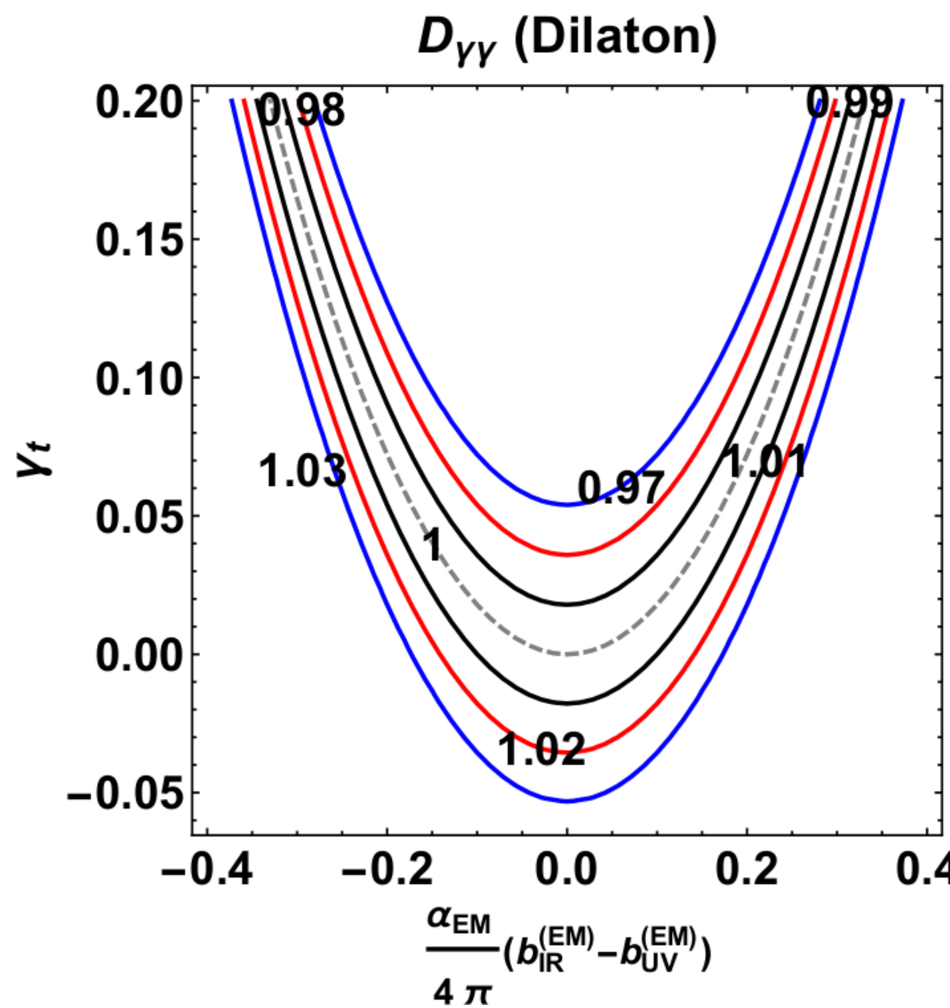


Search for BSM with $D_{\gamma\gamma}$

$$c_t/c_V = [1-(1+n)\xi]/((1-\xi)), \;\; \tilde{c}_t = c_{\gamma\gamma} = \tilde{c}_{\gamma\gamma} = 0$$

$$c_t/c_V = (1+\gamma_t), \;\; c_{\gamma\gamma}/c_V = \alpha/(4\pi)(b_{IR}^{EM} - b_{UV}^{EM}), \; \tilde{c}_t = \tilde{c}_{\gamma\gamma} = 0,$$





Search for BSM with $\mathbf{D}_{\gamma\gamma}$

In the MSSM we need two Higgs doublets $\mathbf{H_1} = \begin{pmatrix} \mathbf{H_1^0} \\ \mathbf{H_1^-} \end{pmatrix}$ and $\mathbf{H_2} = \begin{pmatrix} \mathbf{H_2^+} \\ \mathbf{H_2^0} \end{pmatrix}$,

after EWSB, three dof for $\mathbf{W_L^\pm, Z_L} \Rightarrow$ 5 physical states: $\mathbf{h, H, A, H^\pm}$.

Only two free parameters at tree-level to describe the system $\tan\beta, \mathbf{M_A}$:

$$\mathbf{M^2_{h,H} = \frac{1}{2}\left\{M_A^2 + M_Z^2 \mp [(M_A^2 + M_Z^2)^2 - 4M_A^2 M_Z^2 \cos^2 2\beta]^{1/2}\right\}}$$

$$\mathbf{M^2_{H^\pm} = M_A^2 + M_W^2}$$

$$\mathbf{\tan 2\alpha = \frac{-(M_A^2+M_Z^2)\sin 2\beta}{(M_Z^2-M_A^2)\cos 2\beta} = \tan 2\beta\, \frac{M_A^2+M_Z^2}{M_A^2-M_Z^2}}\ \ \left(-\frac{\pi}{2} \le \alpha \le \mathbf{0}\right)$$

$$\mathbf{M_h \lesssim M_Z |\cos 2\beta| + RC \lesssim 130\ GeV}\ ,\ \mathbf{M_H \approx M_A \approx M_{H^\pm} \lesssim M_{EWSB}}.$$

- **Couplings of $\mathbf{h, H}$ to VV are suppressed; no AVV couplings (CP).**
- **For $\tan\beta \gg 1$: couplings to b (t) quarks enhanced (suppressed).**

Φ	$g_{\Phi\bar{u}u}$	$g_{\Phi\bar{d}d}$	$g_{\Phi VV}$
h	$\frac{\cos\alpha}{\sin\beta} \to 1$	$\frac{\sin\alpha}{\cos\beta} \to 1$	$\sin(\beta-\alpha) \to 1$
H	$\frac{\sin\alpha}{\sin\beta} \to 1/\tan\beta$	$\frac{\cos\alpha}{\cos\beta} \to \tan\beta$	$\cos(\beta-\alpha) \to 0$
A	$1/\tan\beta$	$\tan\beta$	0

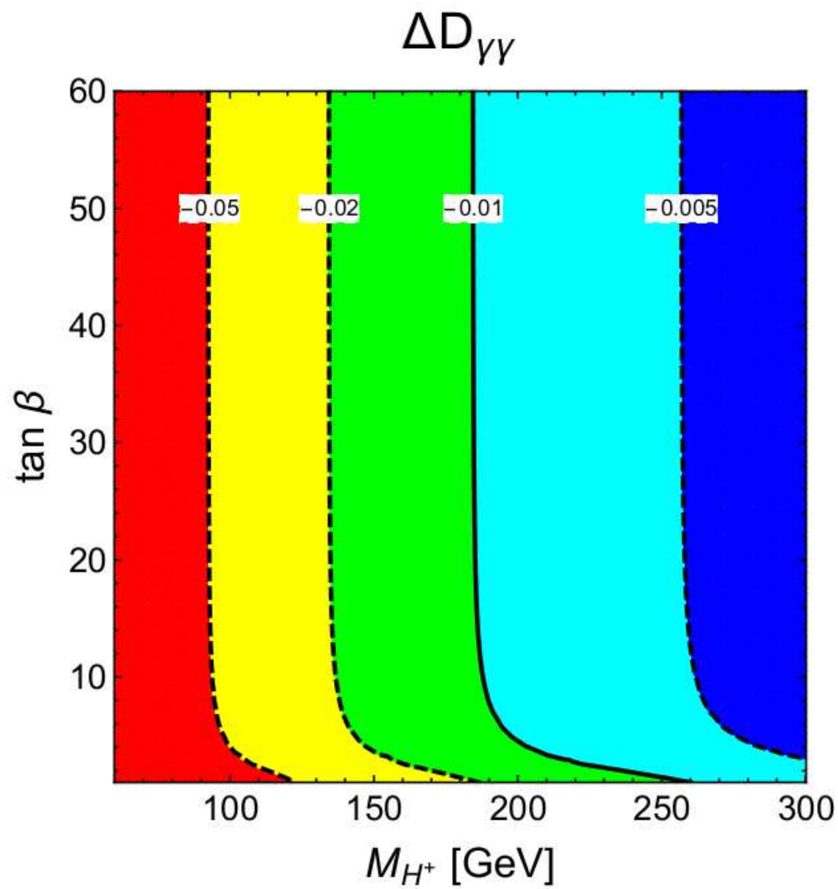
In decoupling limit: MSSM Higgs sector reduces to SM with a light h.

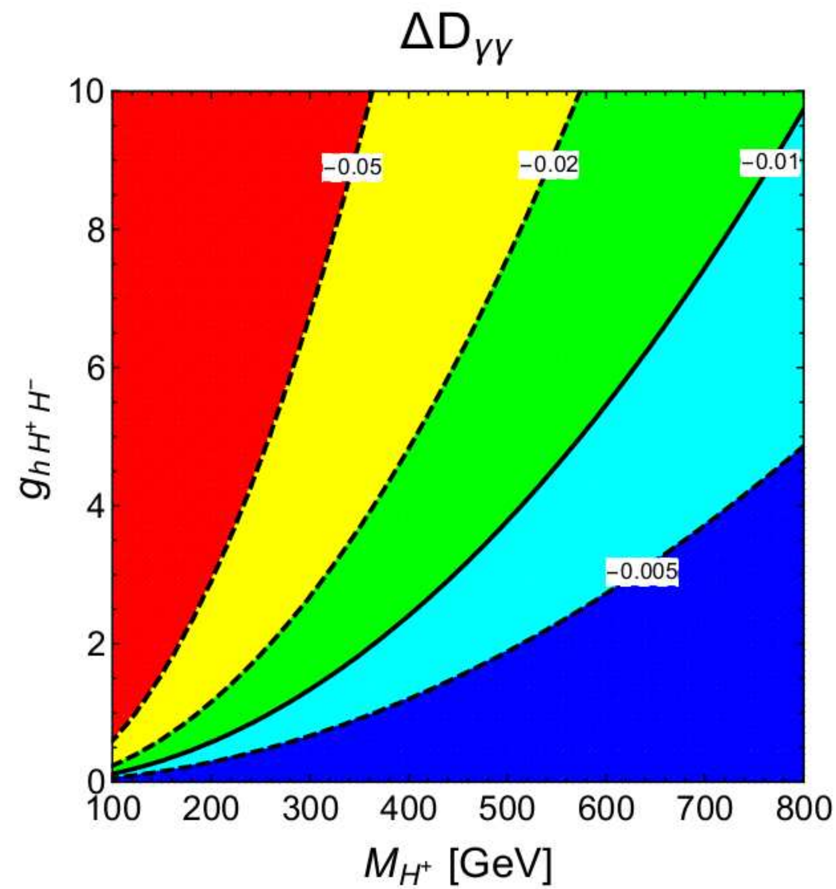
Search for BSM with $D_{\gamma\gamma}$

(h)MSSM and 2HDM: charged Higgs contributions

$$g_{hH^+H^+} = \sin(\beta-\alpha) + \cos 2\beta \sin(\beta+\alpha)/(2c_W^2) \stackrel{M_A \gg M_Z}{\rightarrow} 1 - \frac{\cos^2 2\beta}{2c_W^2}$$

coupling too small in MSSM but not in a general 2HDM



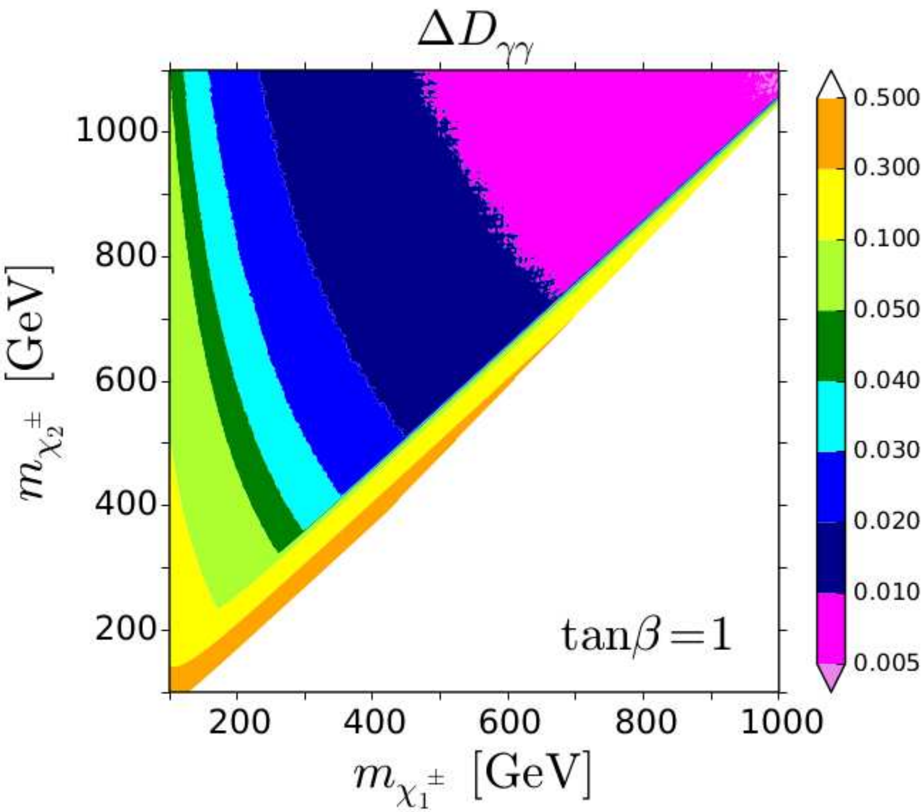


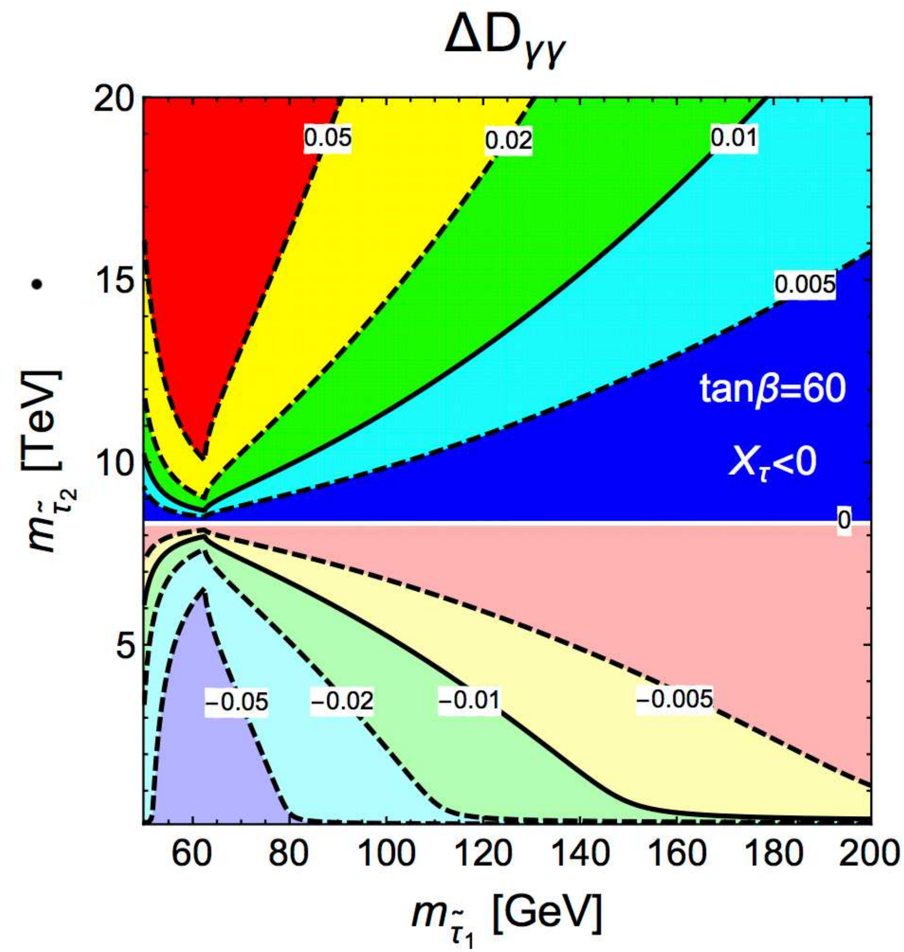
NB: charged Higgses are difficult to find for $M_{H^\pm} \gtrsim$ 200 GeV at low tanβ!

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

MSSM: chargino and stau contributions

$$\propto \frac{4}{3} \times g_{h\chi_i^+\chi_i^-}/m_{\chi_i^\pm} \propto 1/m^2_{\chi_i^\pm} \qquad \propto \frac{1}{3} \times g_{h\tilde{\tau}_i\tilde{\tau}_j}/m^2_{\tilde{\tau}_i} \propto m_\tau X_\tau/m^2_{\tilde{\tau}}$$





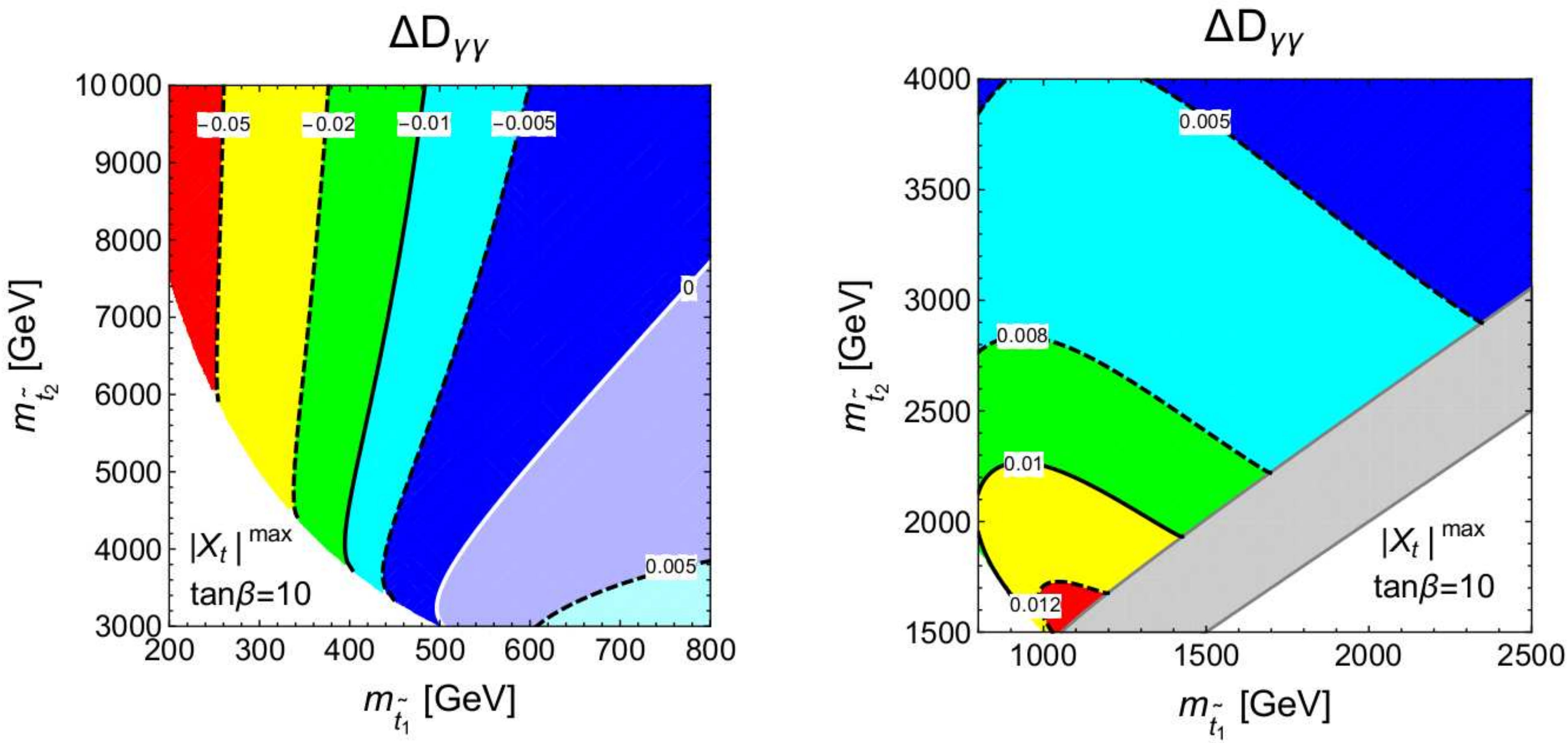
NB: no limit on charginos and stau's from LHC direct searches in some cases!

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

(h)MSSM: stop contributions

$$c_t \approx c_t^0 \times \left[1 + \frac{m_t^2}{4 m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}(m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2 - (A_t - \mu \cot\alpha)(A_t + \mu \tan\alpha)\right.$$

$$\Delta M_h^2|_{1\mathrm{loop}}^{t/\tilde{t}} \sim 3 m_t^4/(2\pi^2 v^2)[\log(M_S^2/m_t^2) + X_t^2/M_S^2 - X_t^4/(12 M_S^4)]$$

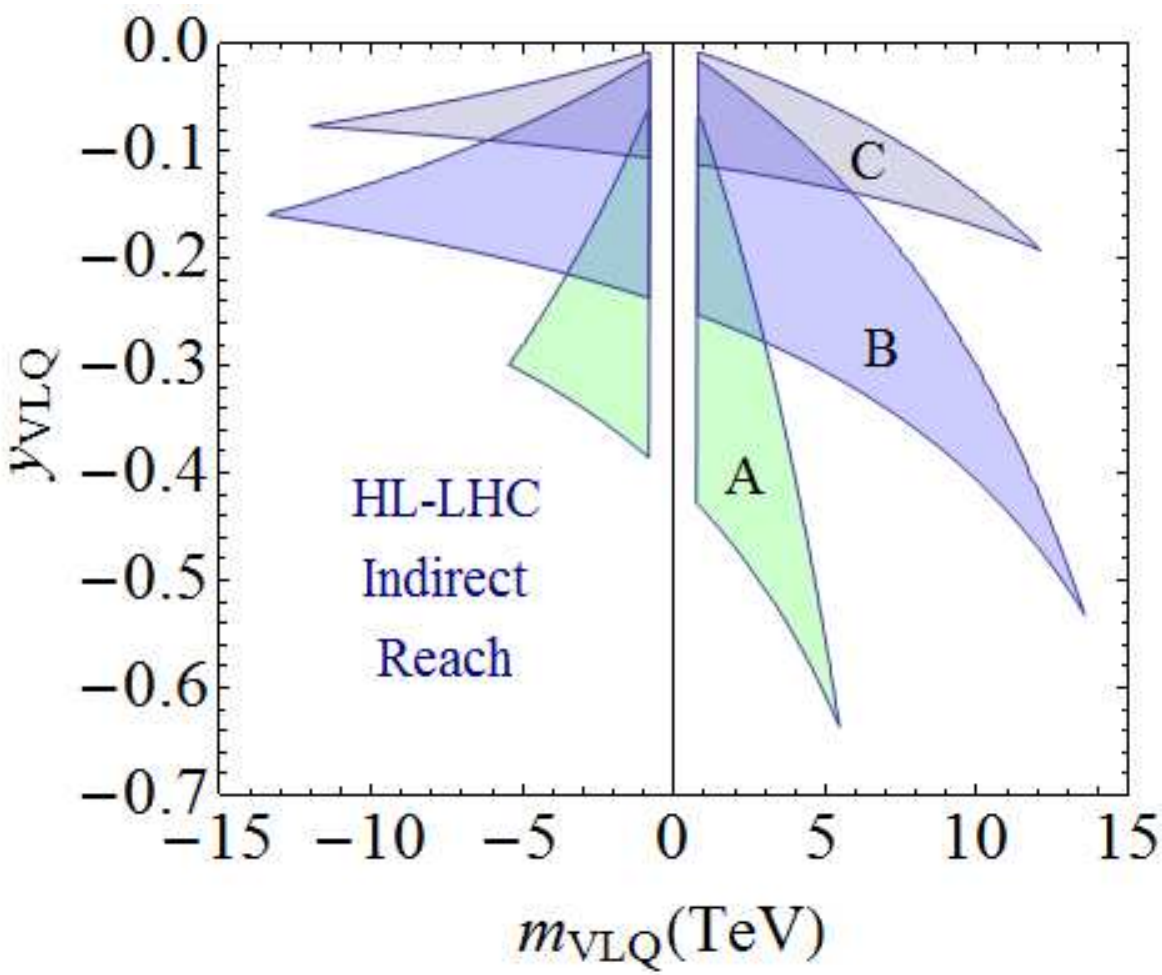


NB: loose limits on stops from LHC direct searches in general case!

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

Vector-like quarks: $Q_{VLQ} = +2/3^{(A)}, -4/3^{(B)}, +5/3^{(C)}$

Angelescu, AD, Moreau, arXiv:1510.07527.



(such VLQs can explain the observed excess in the ttH rate and not in gg→H)

NB: the present/expected limits from direct searches are 1/2 TeV only!