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

Abdelhak DJOUADI

(LPT CNRS & U. Paris-Sud)

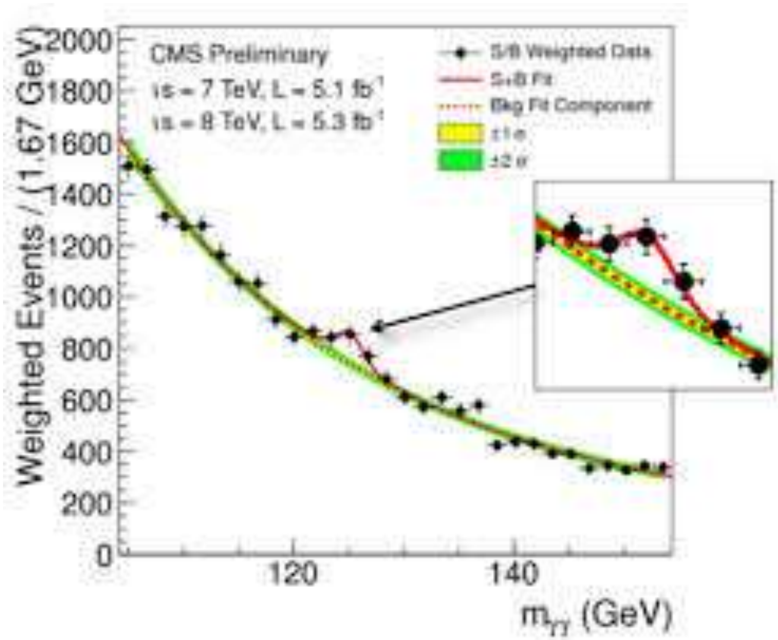
What next after the Higgs discovery?

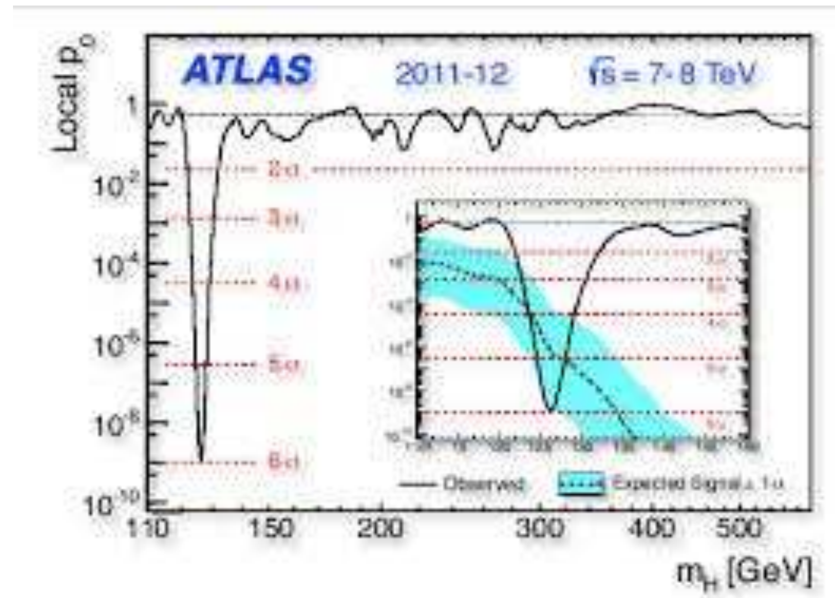
$\mathrm{D}_{\gamma\gamma}$

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

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?

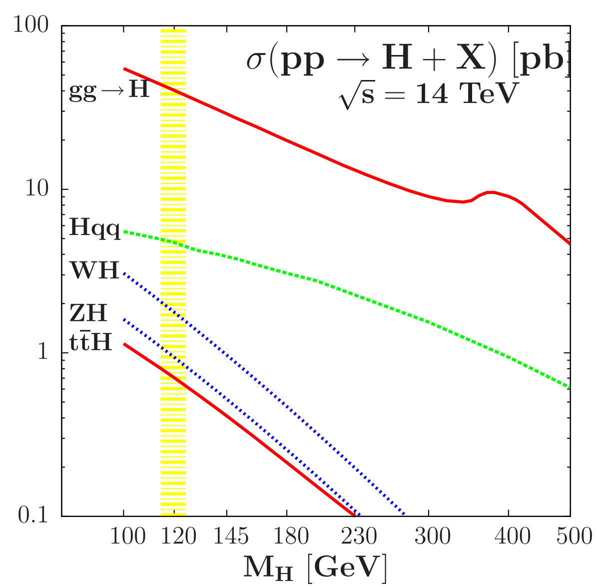
What should we be doing the next 10–30 years in Particle Physics?

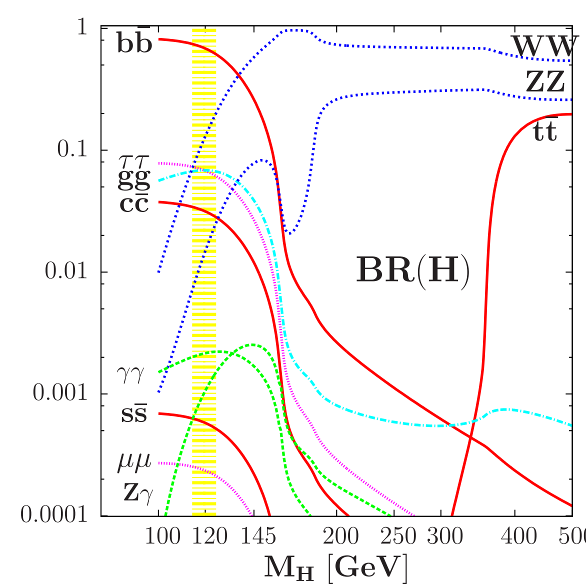
Need to check that H is indeed responsible of sEWSB (and SM-like?)

$\Rightarrow$ 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 alreday 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

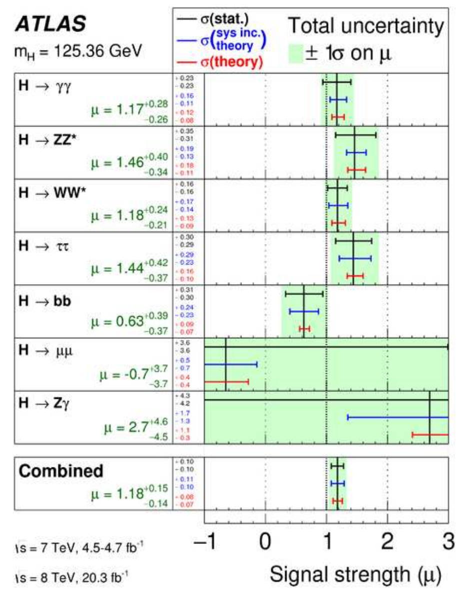
Fit of all LHC Higgs data $\Rightarrow$ agreement at 15–30% level

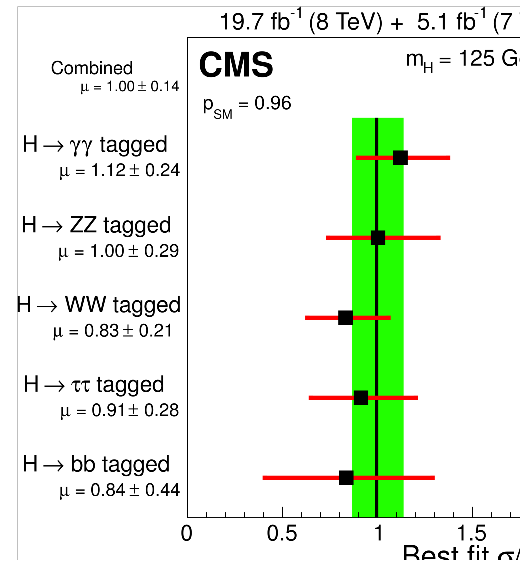
$$\mu_{\rm tot}^{\rm ATLAS} = 1.18 \pm 0.15$$

$\Rightarrow$ **Pierre**

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

$\Rightarrow$ **Guillelmo**





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

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

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...

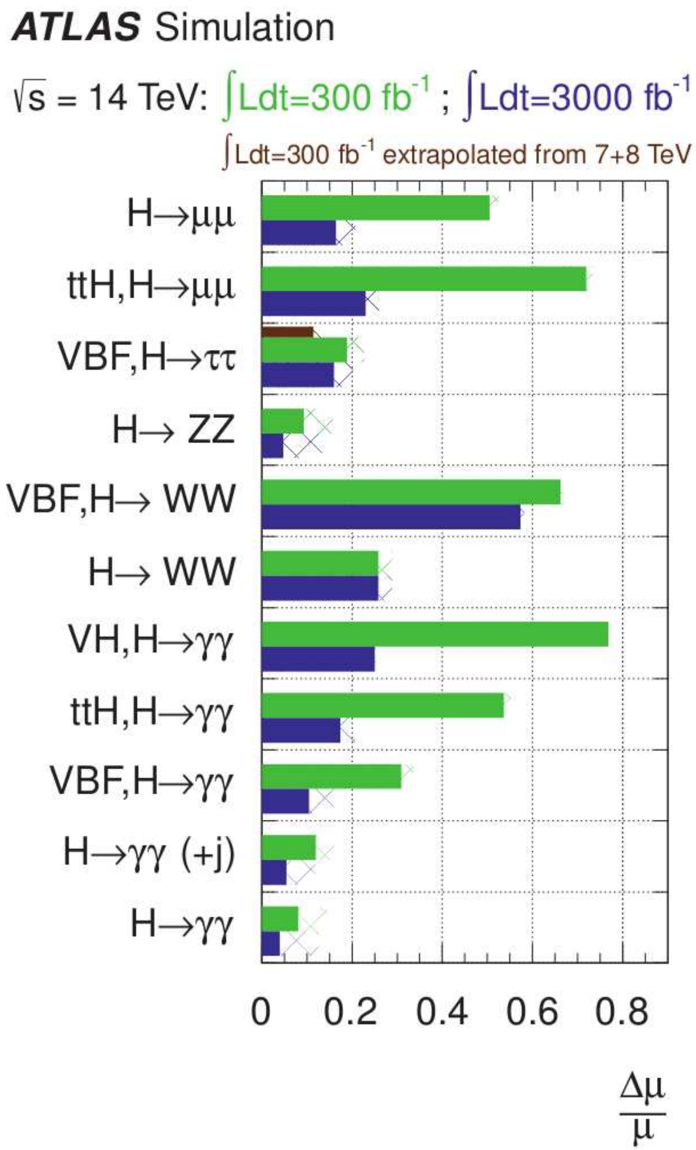
effects expected to be at level of $\Delta\mu_{\rm XX} \approx \frac{\rm C_{NEW}\alpha_W}{\pi} \approx \frac{\rm M_h^2}{\rm M_{NEW}^2} \approx$ **a few %**

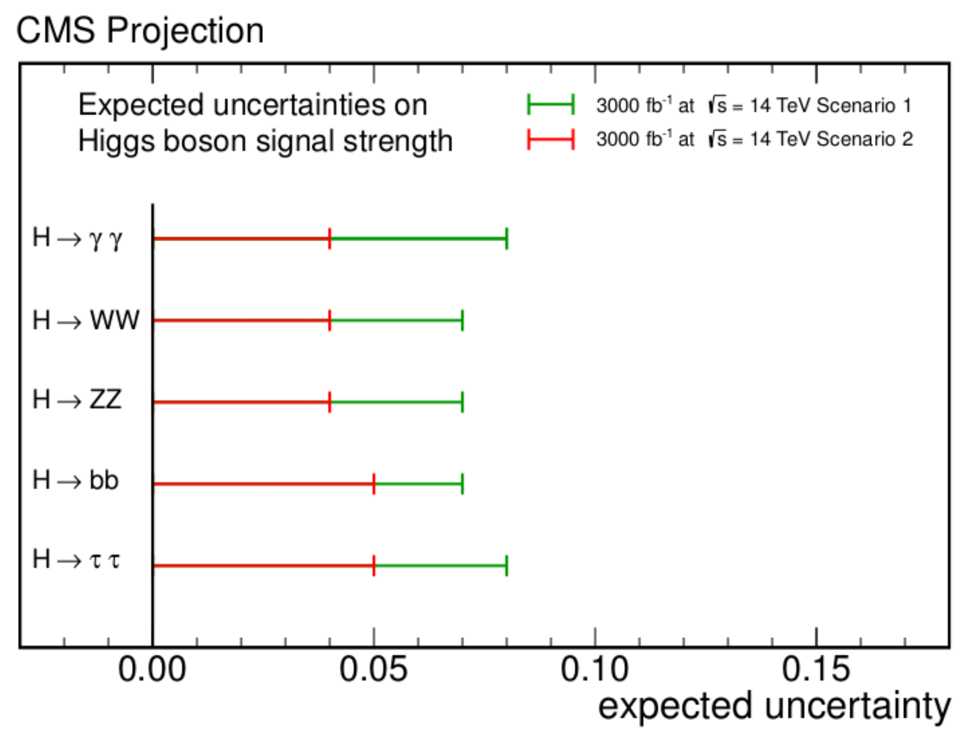
Is a 1% accuracy achievable at upgraded LHC with high luminosities?

- **Statistical uncertainty:** $20\%/\sqrt{3\times 100} \lesssim 1\%$
  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?**

What next after the Higgs discovery?





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

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:

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

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

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 squared couplings!**

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

- 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:

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

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

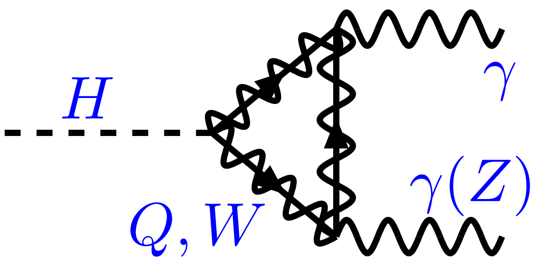
$$\mathbf{D_{bb}} = \frac{\sigma(\mathbf{q\bar{q}}\to\mathbf{HV}\to\mathbf{bbV})}{\sigma(\mathbf{q\bar{q}}\to\mathbf{HV}\to\mathbf{VVV})} = \frac{\boldsymbol{\Gamma}(\mathbf{H}\to\mathbf{bb})}{\boldsymbol{\Gamma}(\mathbf{H}\to\mathbf{VV})} = \mathbf{d_{bb}}\frac{\mathbf{c}_\tau^2}{\mathbf{c_V^2}}$$

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

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

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



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

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

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

- **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!

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

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

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

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

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

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 $\mathrm{D}_{\gamma\gamma} = \mathrm{c}_\gamma^2/\mathrm{c}_\mathrm{V}^2$ is then simply given by

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

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:

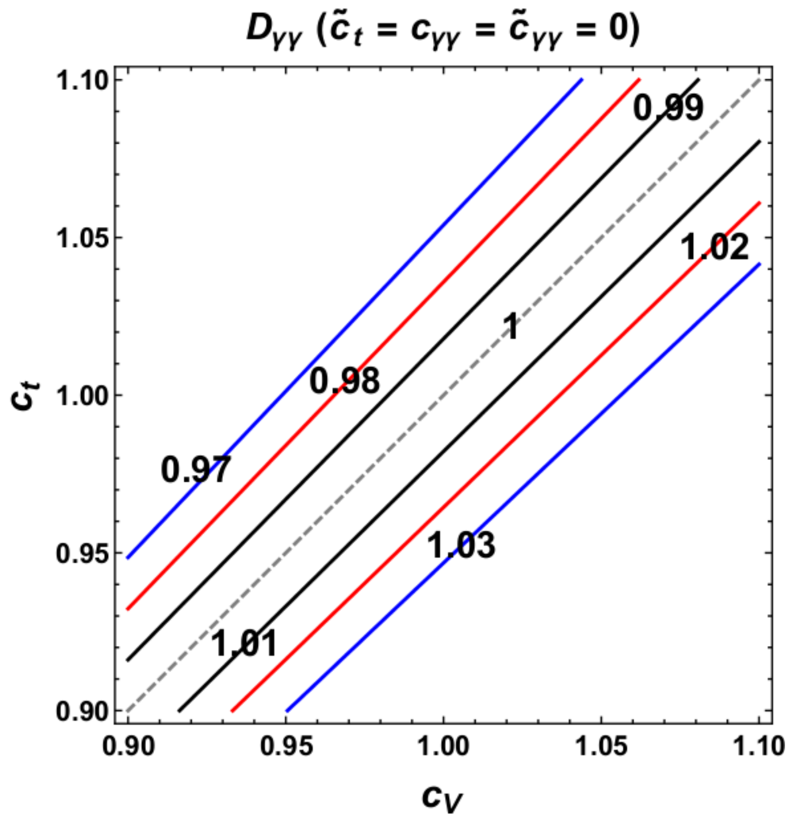
- **such accuracy was envisaged only at the "clean" $\mathrm{e^+e^-}$ machhines..**
- **impact comparable to $\sin^2\theta_\mathrm{W}$ at LEP and $\mathrm{M_W}$ at Tevatron/LHC..**
- **the g-2 of the LHC?**

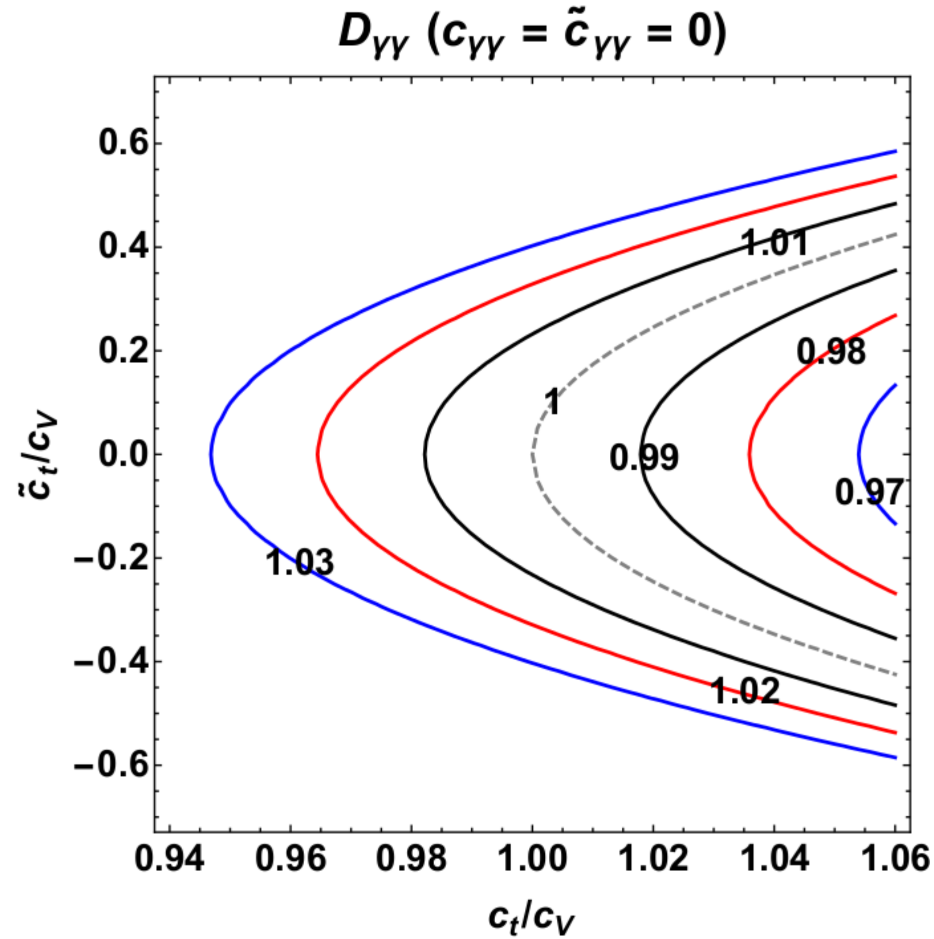
Examples of BSM searches that can be done with the observable follow.

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

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

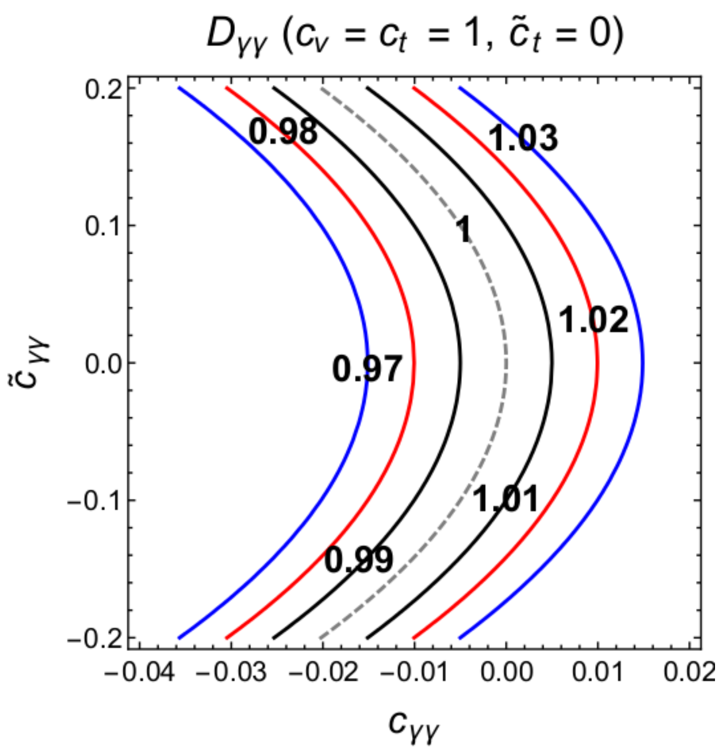
$$\mathcal{L} = \frac{H}{v}\Big(c_V (2M_W^2 W_\mu^+ W^{-\mu} + M_Z^2 Z_\mu Z^\mu) - m_t \bar{t}(c_t + i\tilde{c}_t \gamma^5) t$$
$$+ \frac{c_{\gamma\gamma}}{4} F^{\mu\nu} F_{\mu\nu} + \frac{\tilde{c}_{\gamma\gamma}}{4} \tilde{F}^{\mu\nu} F_{\mu\nu} \Big)$$

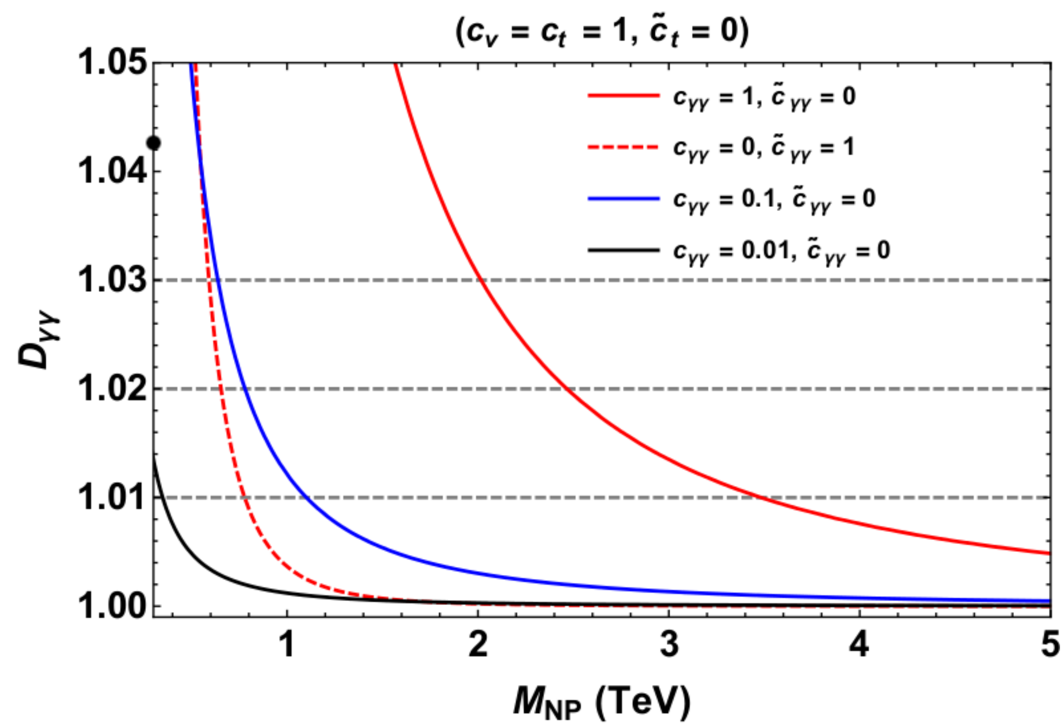




Search for BSM with $D_{\gamma\gamma}$

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

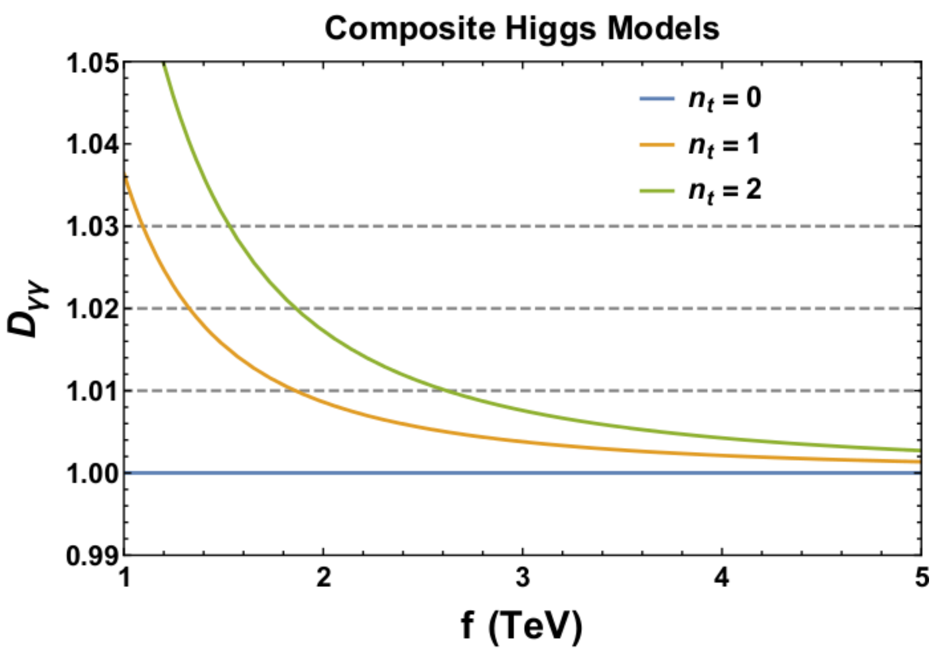


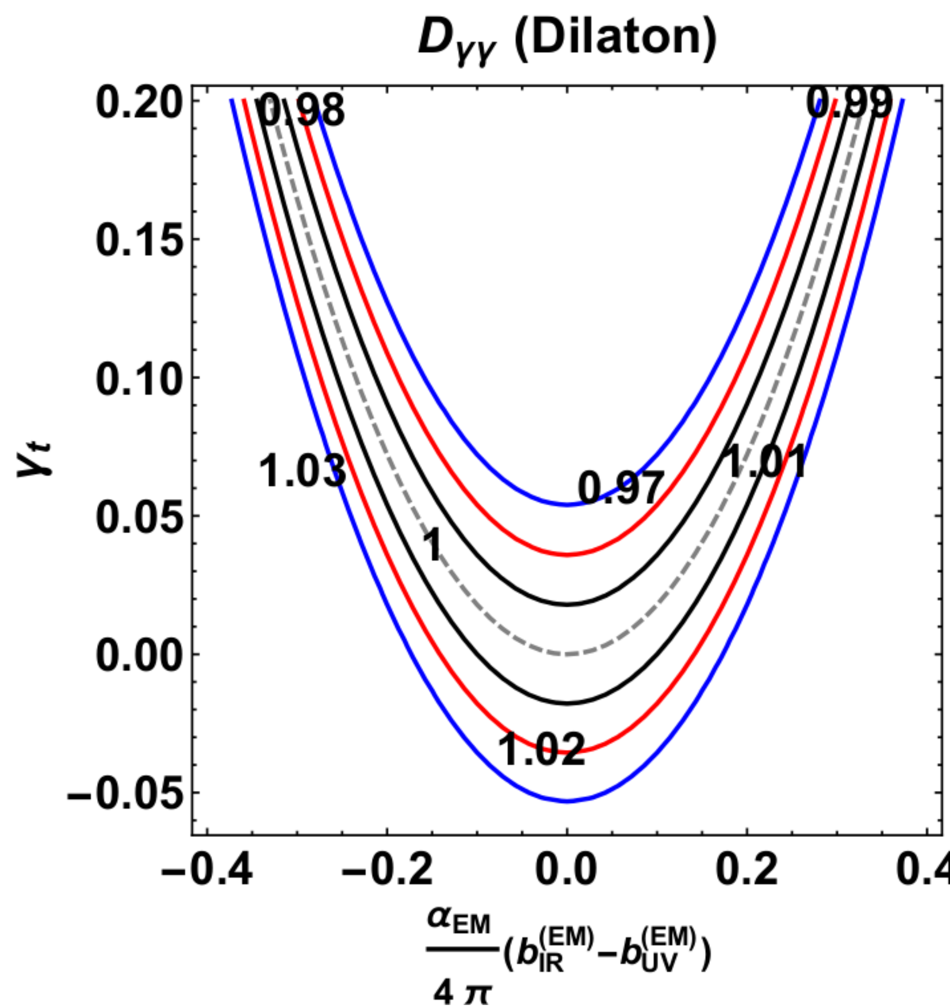


Search for BSM with $D_{\gamma\gamma}$

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

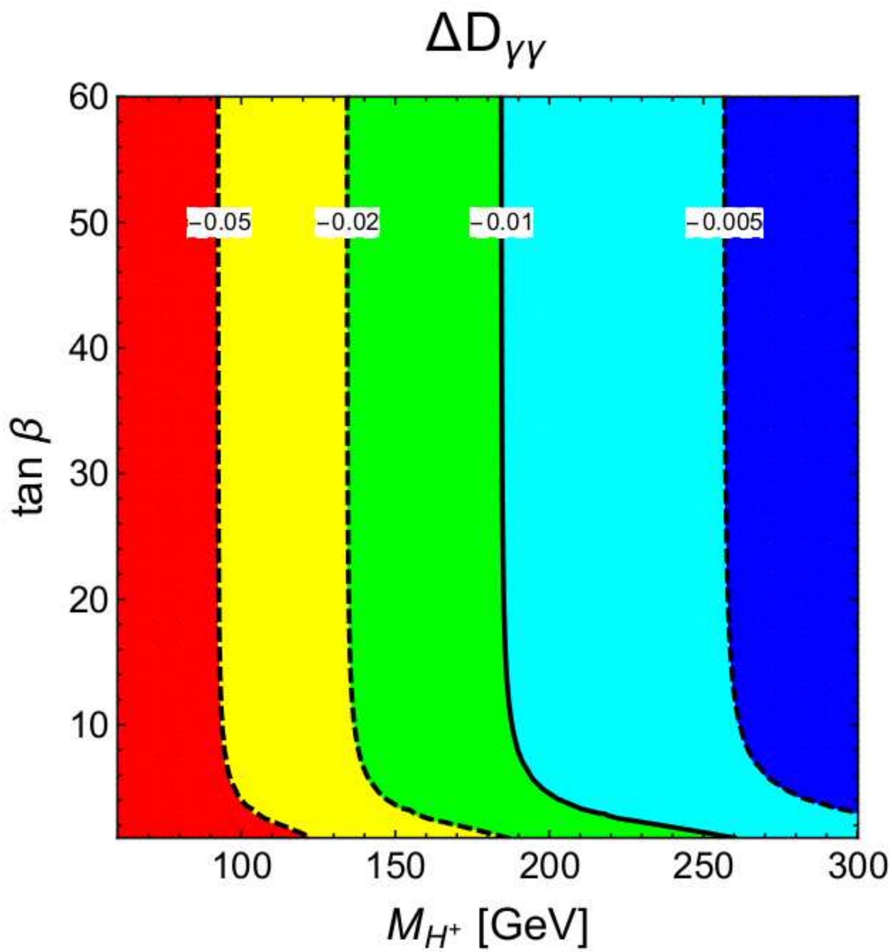
$$\mathbf{c_t/c_V = (1+\gamma_t),\ \ c_{\gamma\gamma}/c_V = \alpha/(4\pi)(b_{IR}^{EM} - b_{UV}^{EM}),\ \tilde{c}_t = \tilde{c}_{\gamma\gamma} = 0,}$$

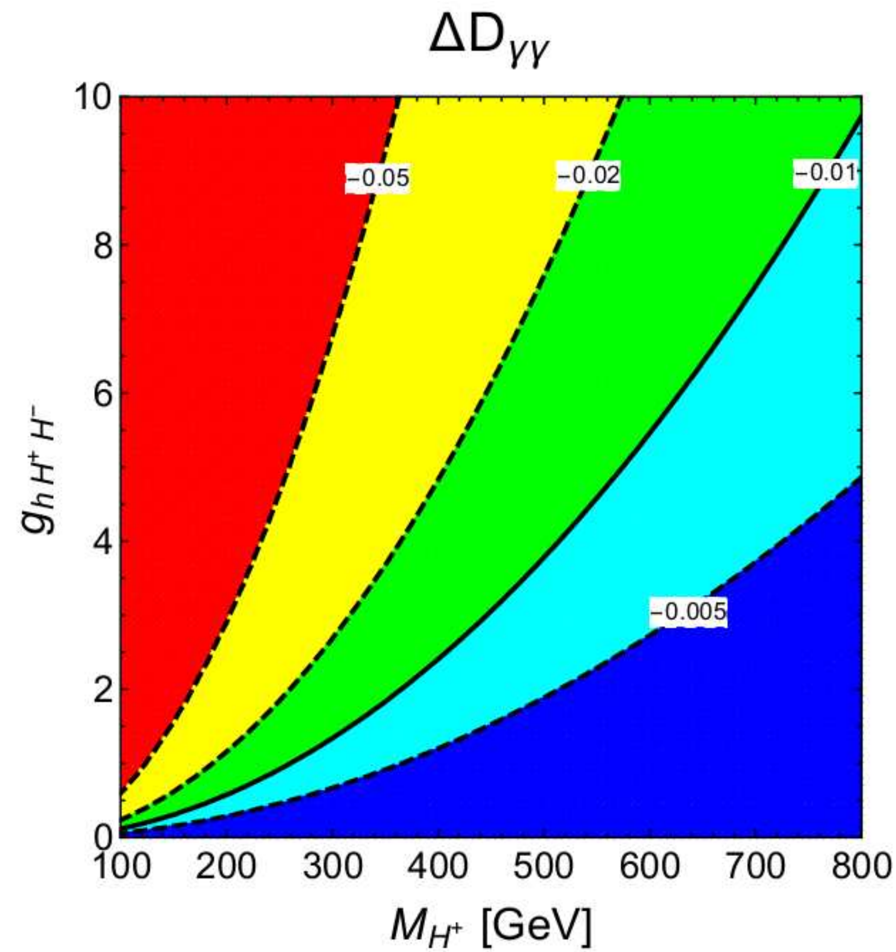




Search for BSM with $D_{\gamma\gamma}$

(h)MSSM and 2HDM: charged Higgs contributions

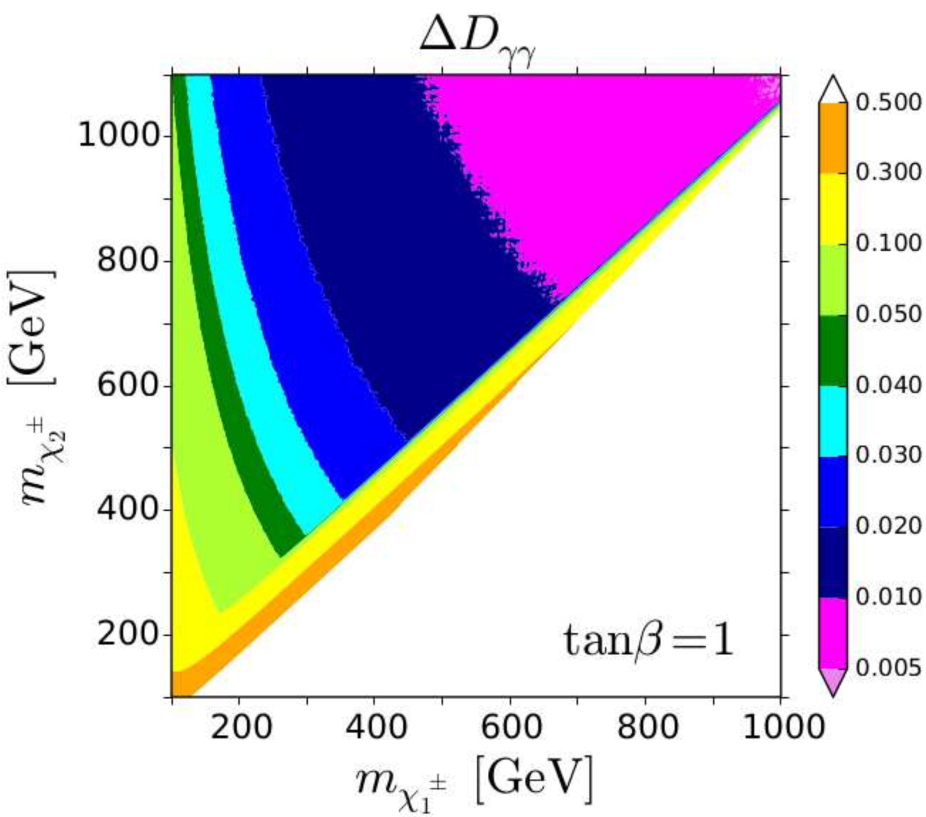




Search for BSM with $D_{\gamma\gamma}$

MSSM: chargino and stau contributions

(see also AD, Driesen, Hollik, Illana (Karlsruhe U.), hep-ph/9612362)



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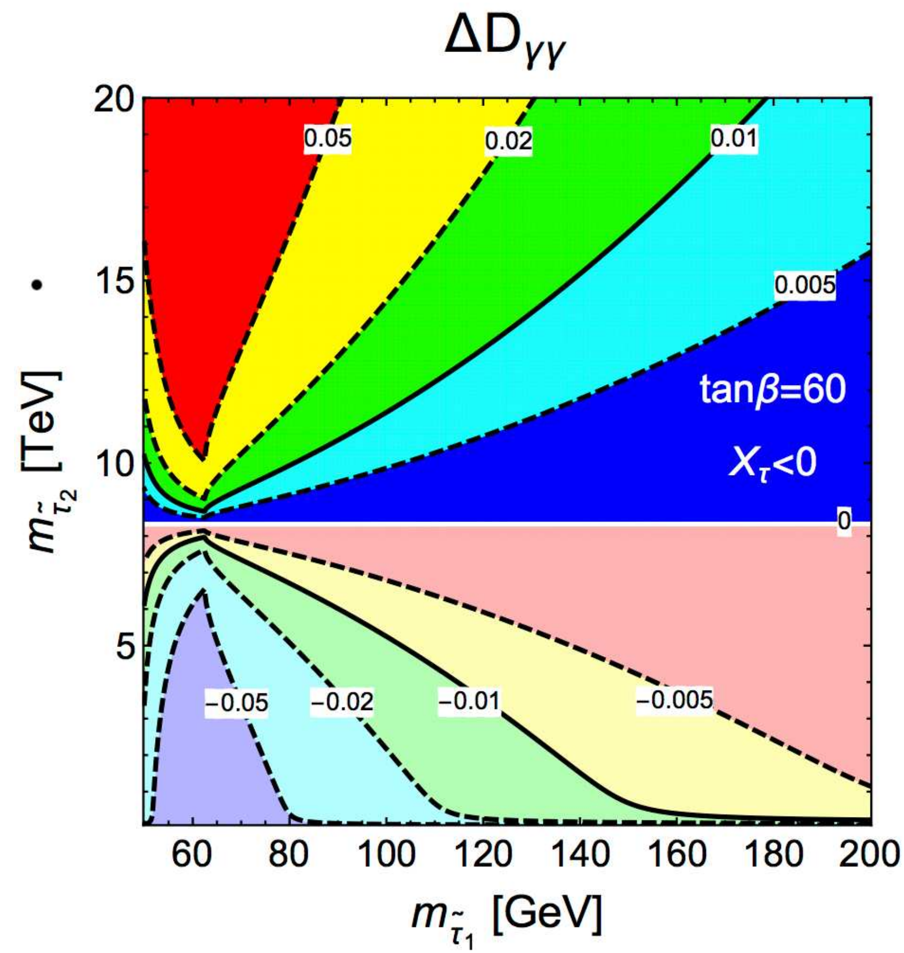
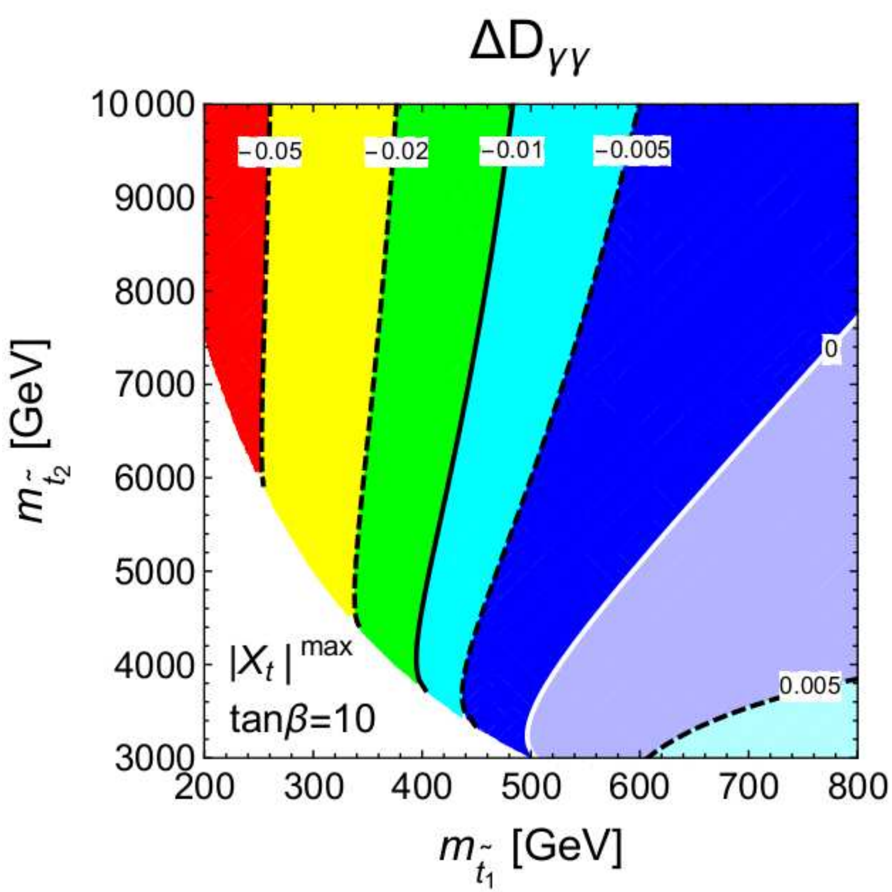
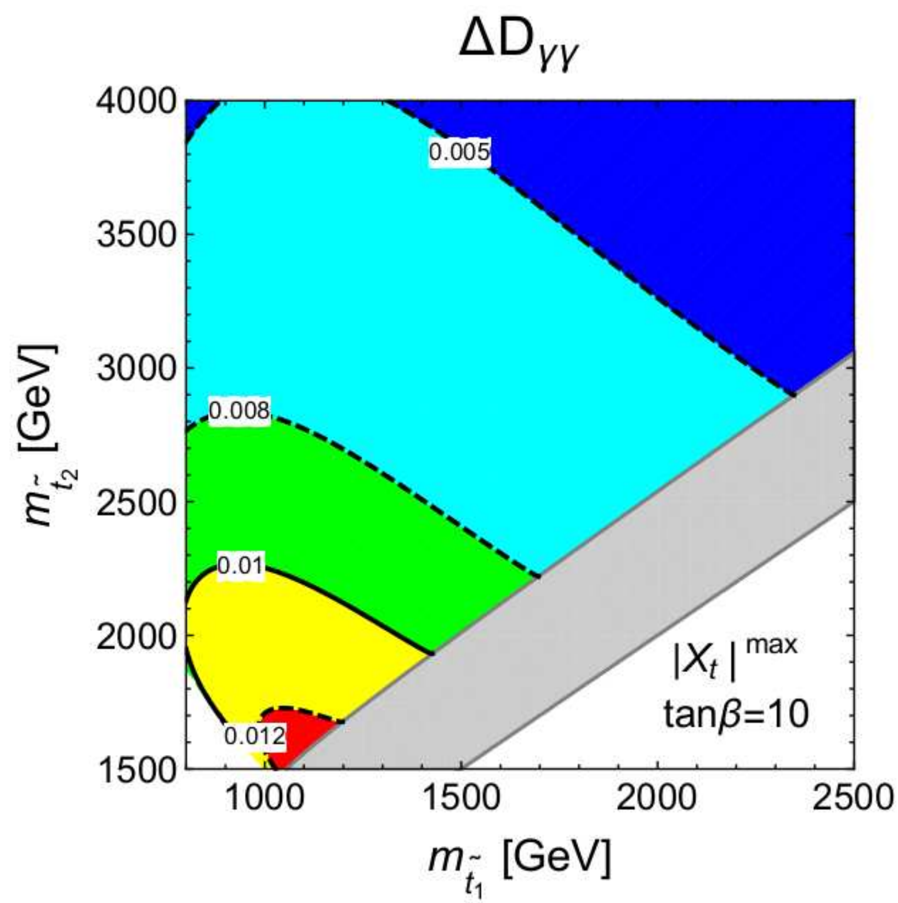


Search for BSM with $D_{\gamma\gamma}$

(h)MSSM: stop contributions

(see also AD, Driesen, Hollik, Illana (Karlsruhe U.), hep-ph/9612362)





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

Vector-like quarks: $Q_{VLQ} = +2/3, -4/3, +5/3$

Angelescu, AD, Moreau, to appear.