Higgs to Photons Beyond the Standard Model

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ULB, 27 feb. 2009

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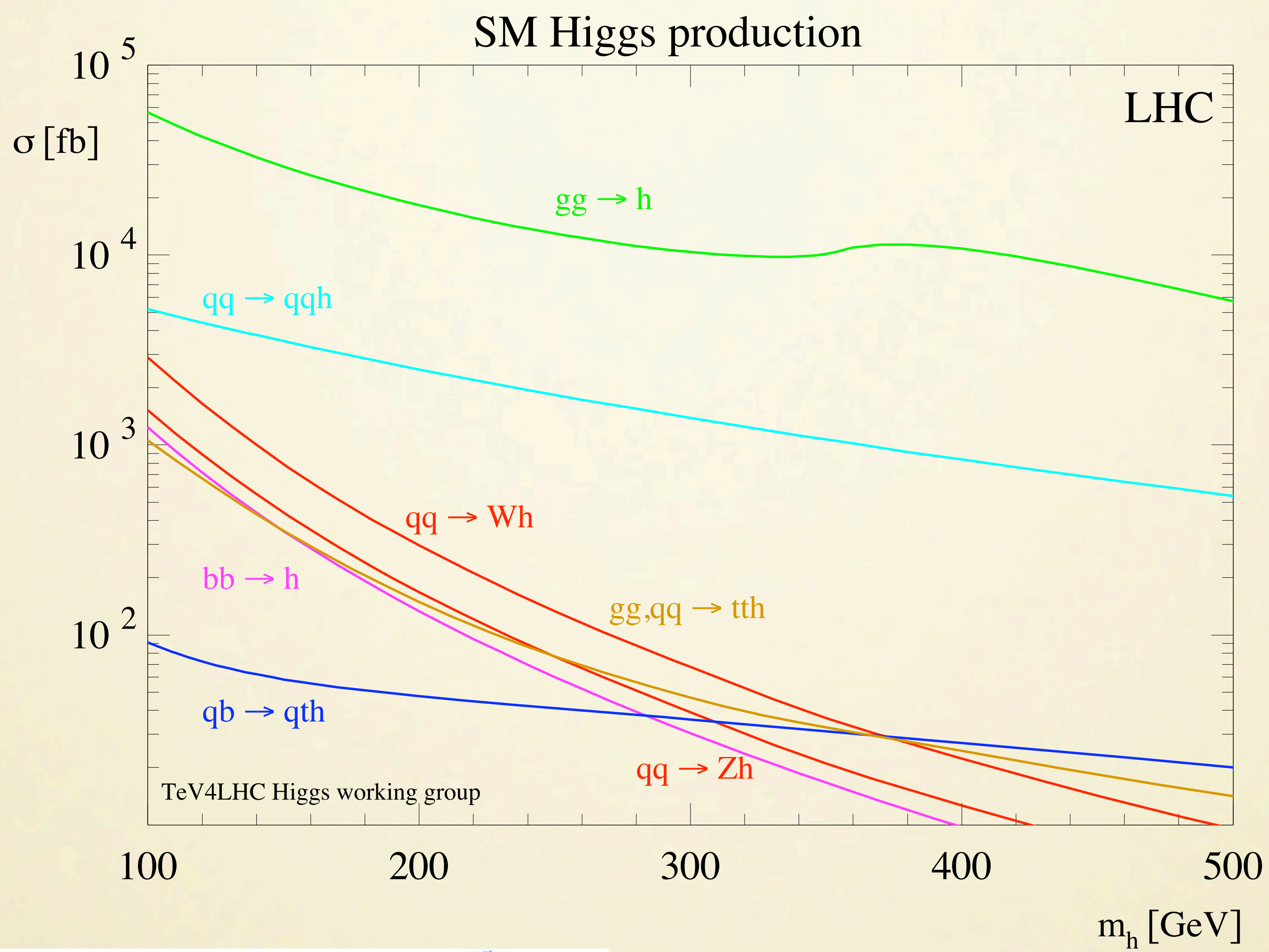
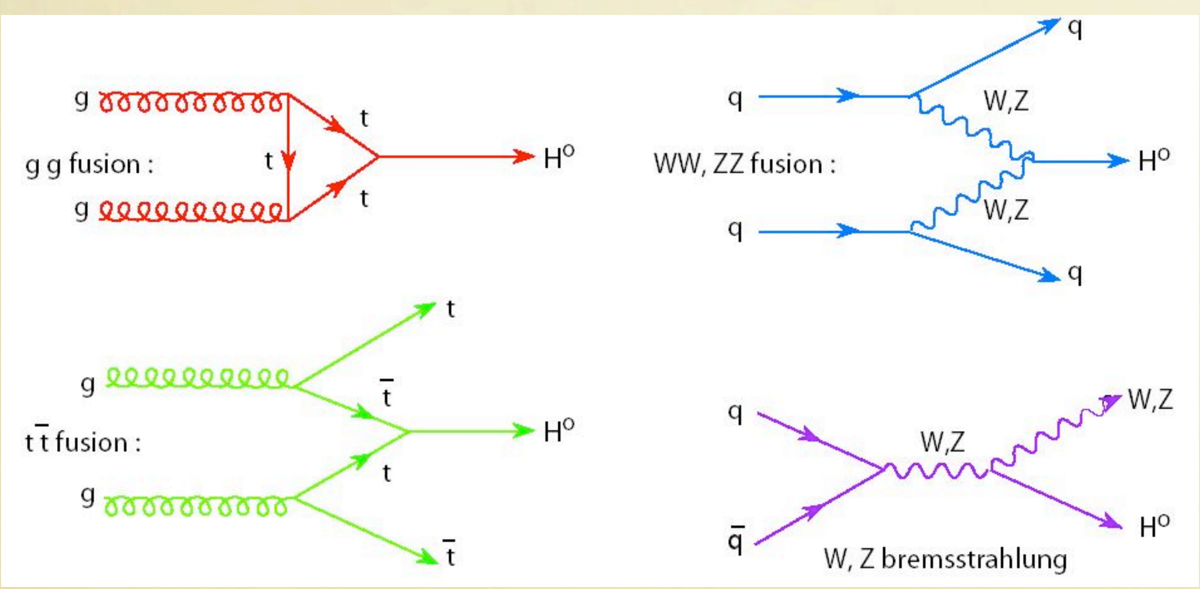
An old friend: the Higgs Boson

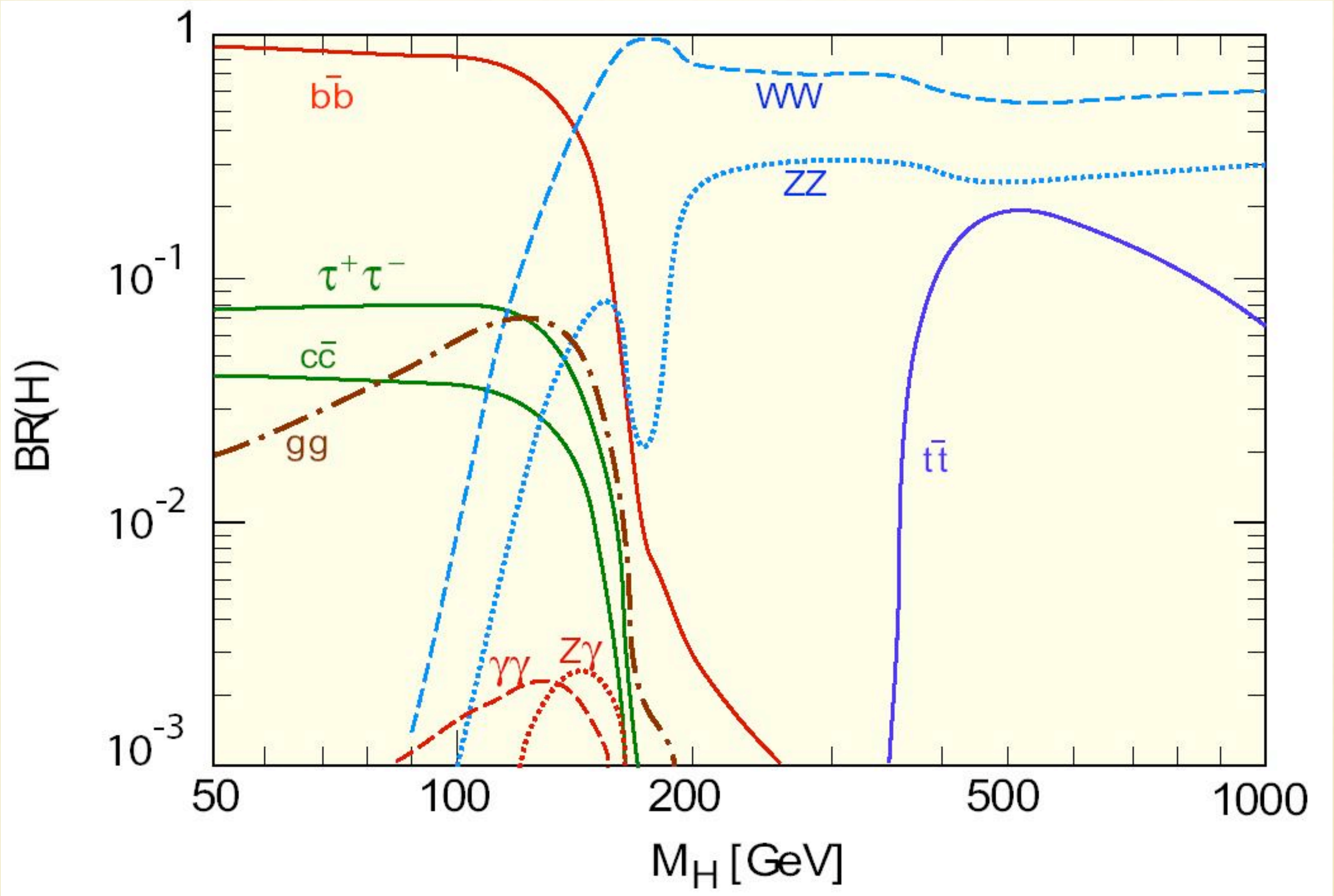
- The Higgs Boson is the most valuable game at the LHC
- New Physics motivated by the radiative instability of the Brout-Englert-Higgs mechanism
- If we detect New Physics, how can we test if it has anything to do with the Higgs?
- Higgs properties



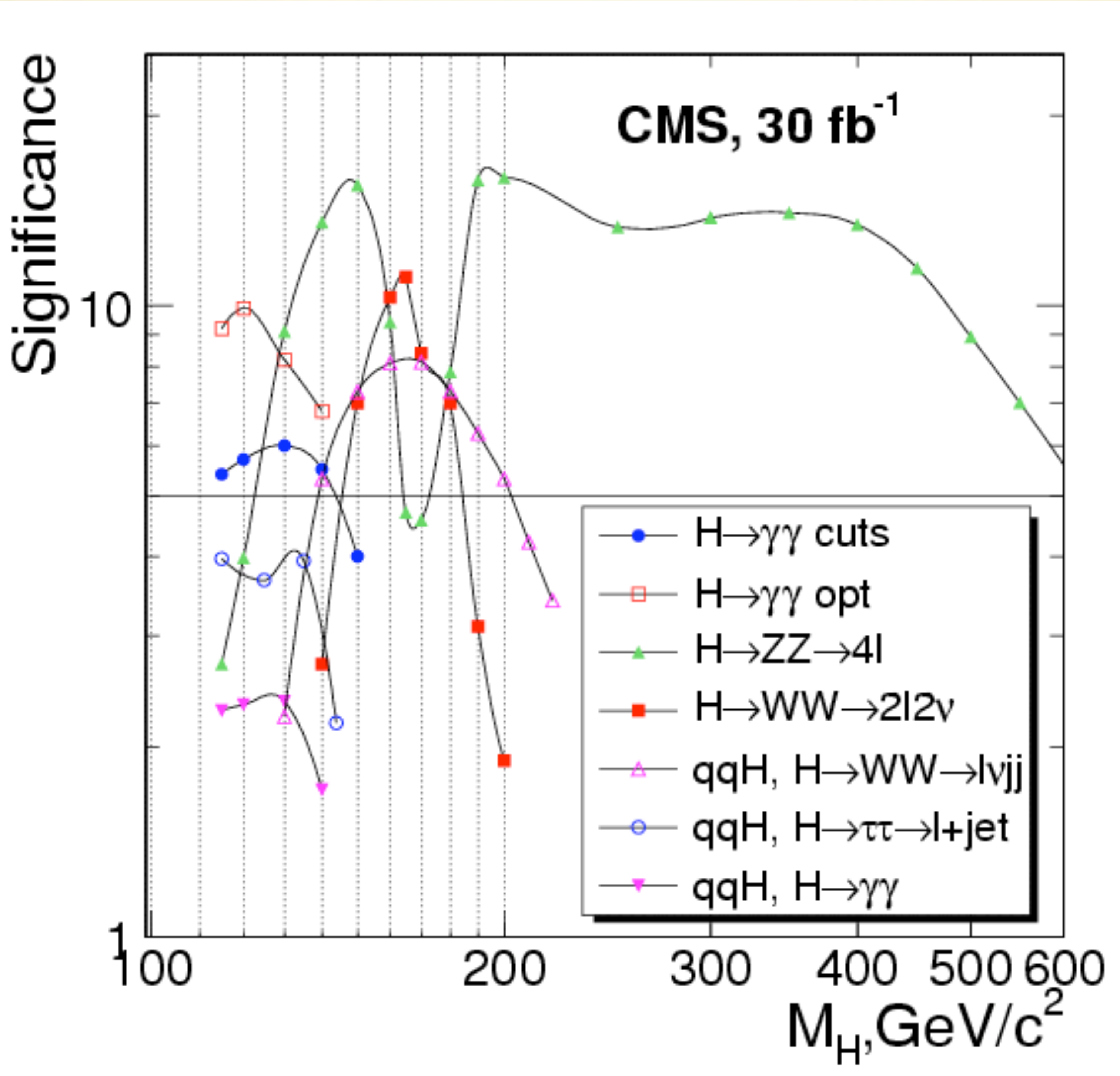


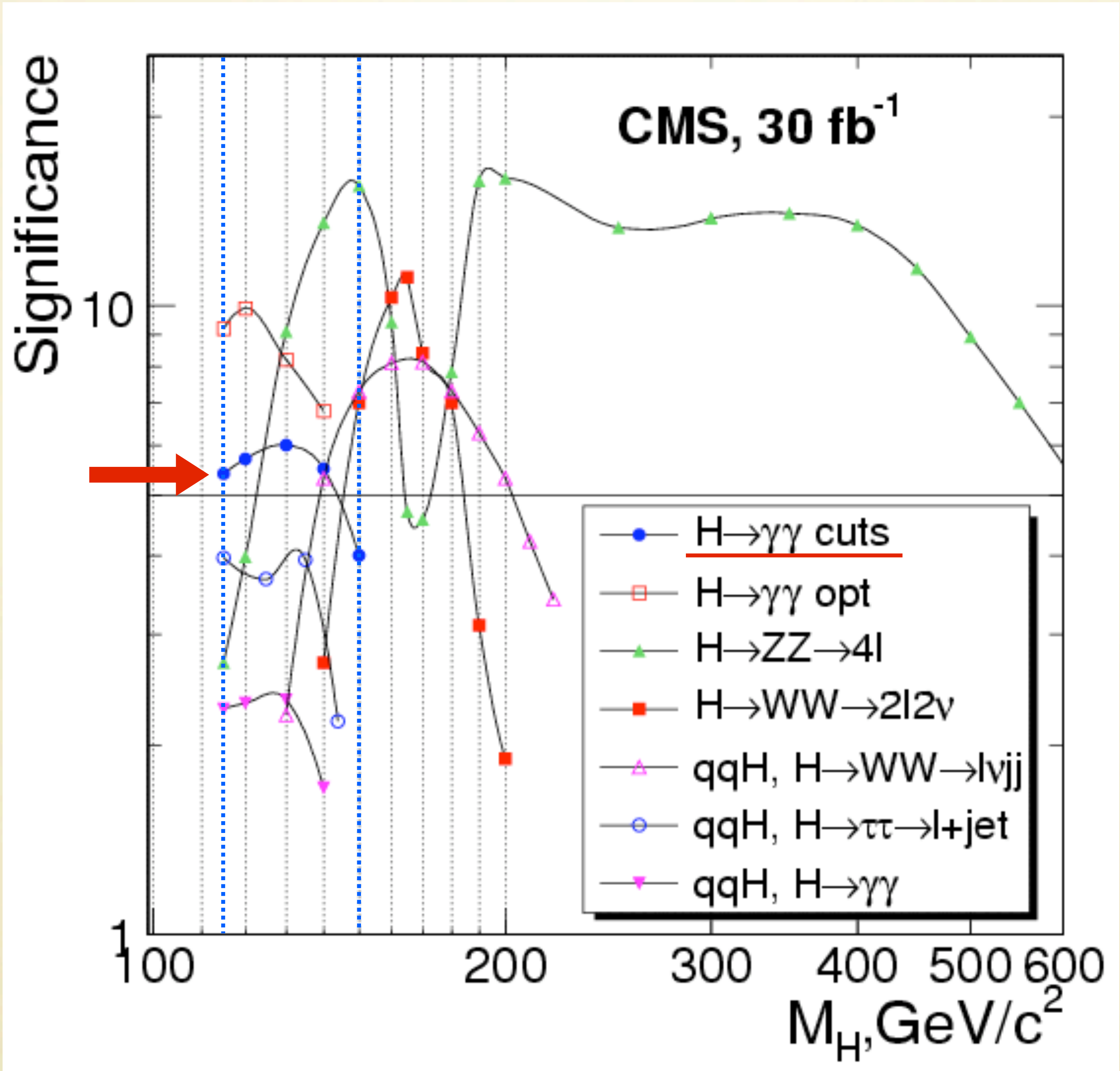
The main production channel
is via gluon fusion (loop induced!)

Followed by Vector Boson Fusion.



Sizable photon decay for 100<mH<150.


CMS, 30 fb^{-1}
Significance
10
1
100
200
300
400
500
600
M_H,GeV/c^2
H→γγ cuts
H→γγ opt
H→ZZ→4l
H→WW→2l2ν
qqH, H→WW→lνjj
qqH, H→ττ→l+jet
qqH, H→γγ



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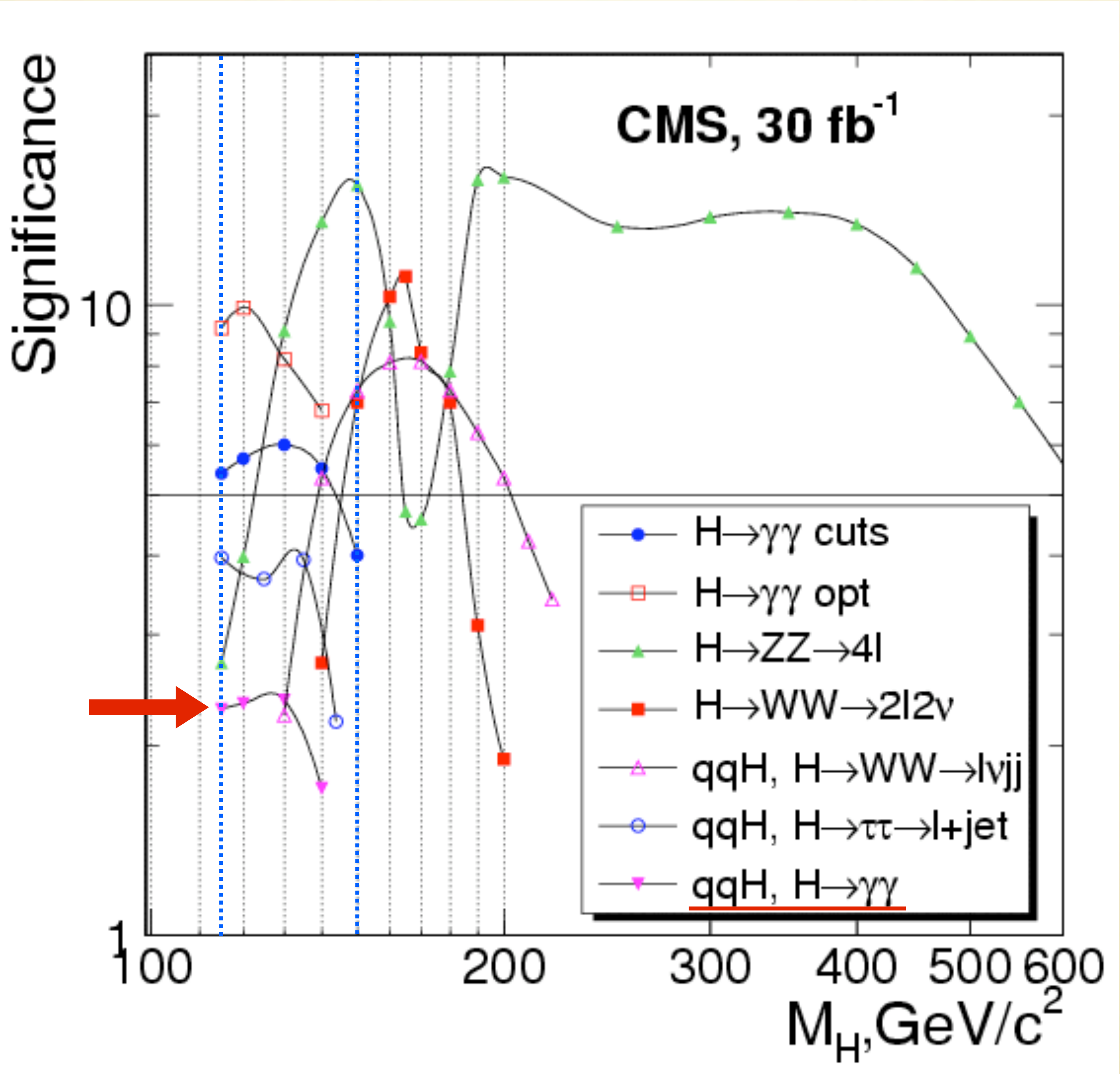

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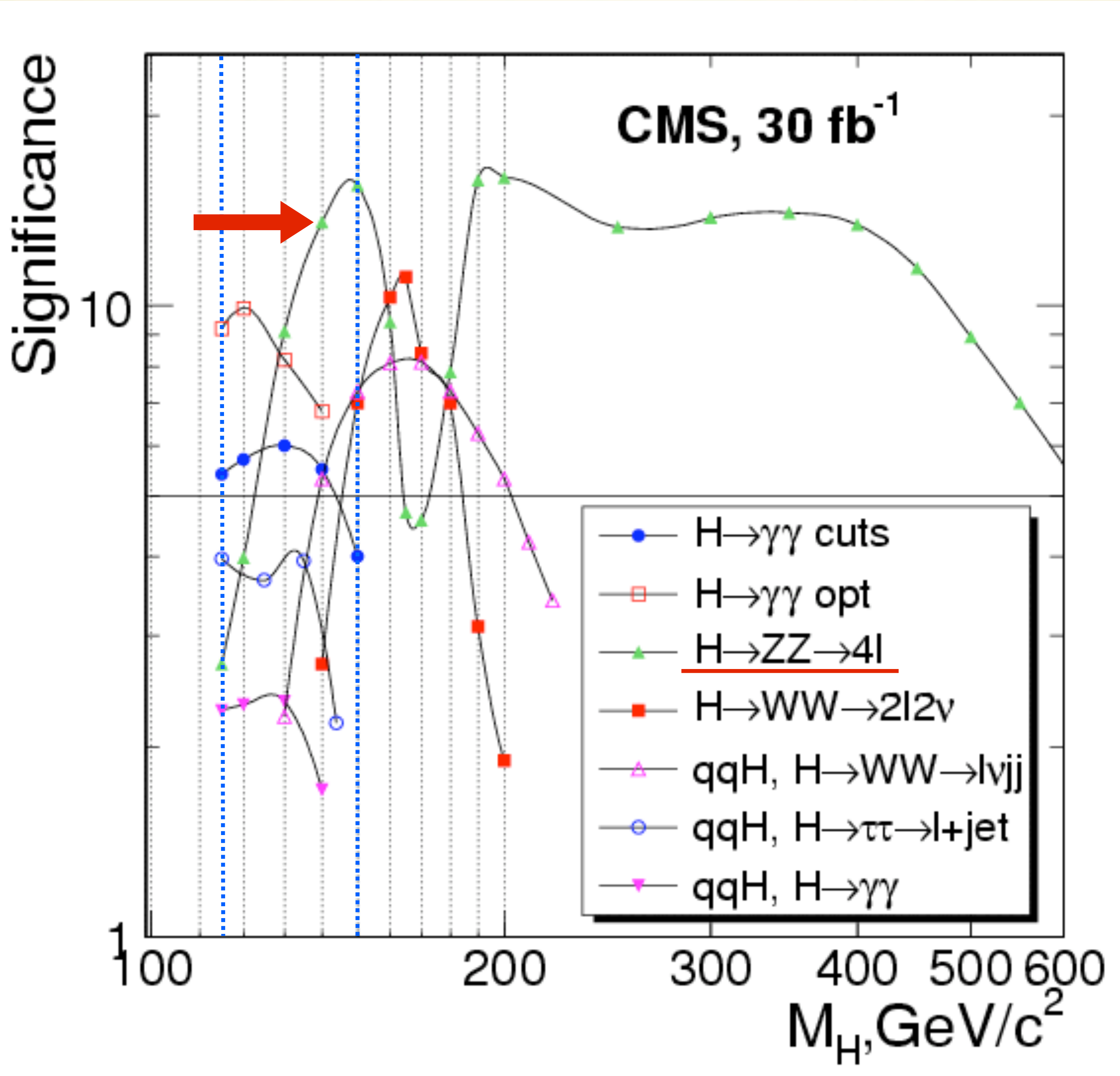
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- H to photons and gluons couplings are loop induced
- sensitive to massive particles that play a role in the EWSB (top and W)
- most sensitive to New Physics (in the EWSB sector)!
- what can we learn from measuring them?

Definitions:

$$\Gamma_{\gamma\gamma} = \frac{G_F \alpha^2 m_H^3}{128\sqrt{2}\pi^3} \left| A_W(\tau_W) + \sum_{\text{fermions}} N_{c,f} Q_f^2 A_F(\tau_f) + \sum_{NP} N_{c,NP} Q_{NP}^2 A_{NP}(\tau_{NP}) \right|^2$$

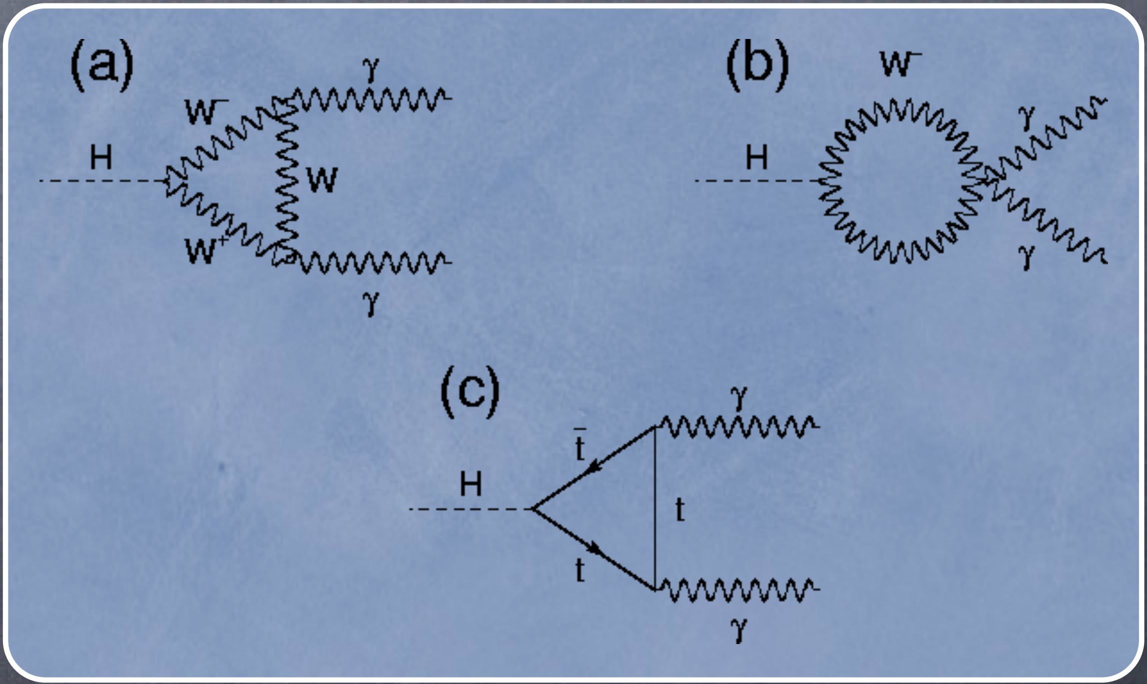
$$\Gamma_{gg} = \frac{G_F \alpha_s^2 m_H^3}{16\sqrt{2}\pi^3} \left| \frac{1}{2} \sum_{\text{quarks}} A_F(\tau_f) + \sum_{NP} C(r_{NP}) A_{NP}(\tau_{NP}) \right|^2$$

$$\tau_x = \frac{m_H^2}{4m_x^2}$$

$$A_F(0) = \frac{4}{3}\,, \quad A_W(0) = -7\,, \quad A_S(0) = \frac{1}{3}\,.$$

Non decoupling because the Higgs couplings are proportional to the mass!

$$A(\infty) \to 0$$



For New Physics loops: $A_{NP} = \frac{v}{m_{NP}} \frac{\partial m_{NP}}{\partial v} A_{F,W,S}$

Simple parameterization:

$$\Gamma_{\gamma\gamma} = \frac{G_F \alpha^2 m_H^3}{128\sqrt{2}\pi^3} \left| A_W(\tau_W) + 3\left(\frac{2}{3}\right)^2 A_t(\tau_t)\,[1+\kappa_{\gamma\gamma}] + \dots \right|^2$$

$$\Gamma_{gg} = \frac{G_F \alpha_s^2 m_H^3}{16\sqrt{2}\pi^3} \left| \frac{1}{2} A_t(\tau_t)\,[1+\kappa_{gg}] + \dots \right|^2$$

where

$$\kappa_{\gamma\gamma} = \sum_{NP} \frac{3}{4} N_{c,NP} Q_{NP}^2 \, \frac{v}{m_{NP}} \frac{\partial m_{NP}}{\partial v} \, \frac{A_{F,W,S}(m_{NP})}{A_t}$$

$$\kappa_{gg} = \sum_{NP} 2C(r_{NP}) \, \frac{v}{m_{NP}} \frac{\partial m_{NP}}{\partial v} \, \frac{A_{F,W,S}(m_{NP})}{A_t}$$

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$$\kappa_{gg} = \sum_{NP} 2C(r_{NP}) \frac{v}{m_{NP}} \frac{\partial m_{NP}}{\partial v} \frac{A_{F,W,S}(m_{NP})}{A_t}$$

For heavy new physics:

$$\frac{A_{NP}}{A_t} = \begin{cases} 1 & \text{for fermions} \\ -\frac{21}{4} & \text{for vectors} \\ \frac{1}{4} & \text{for scalars} \end{cases}$$

Simple parameterization:

$$\Gamma_{\gamma\gamma} = \frac{G_F \alpha^2 m_H^3}{128\sqrt{2}\pi^3} \left| A_W(\tau_W) + 3\left(\frac{2}{3}\right)^2 A_t(\tau_t)\,[1+\kappa_{\gamma\gamma}] + \ldots \right|^2$$

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$$\kappa_{gg} = \sum_{NP} 2C(r_{NP}) \frac{v}{m_{NP}} \frac{\partial m_{NP}}{\partial v} \frac{A_{F,W,S}(m_{NP})}{A_t}$$

Decoupling: $$\frac{v}{m_{NP}} \frac{\partial m_{NP}}{\partial v} \sim \frac{v^2}{m_{NP}^2}$$

Simple parameterization:

$$\Gamma_{\gamma\gamma} = \frac{G_F \alpha^2 m_H^3}{128\sqrt{2}\pi^3} \left| A_W(\tau_W) + 3\left(\frac{2}{3}\right)^2 A_t(\tau_t)\,[1+\kappa_{\gamma\gamma}] + \ldots \right|^2$$

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Given the spectrum as a function of he Higgs VEV,
the contribution can be easily calculated!

Simple parameterization:

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$$\Gamma_{gg} = \frac{G_F \alpha_s^2 m_H^3}{16\sqrt{2}\pi^3} \left| \frac{1}{2} A_t(\tau_t)\,[1+\kappa_{gg}] + \ldots \right|^2$$

Anomalous W and top to Higgs couplings can also be cast in the kappa parameters:

Top: $$\kappa_{\gamma\gamma}(top) = \kappa_{gg}(top) = \frac{v}{m_t}\frac{\partial m_t}{\partial v} - 1$$

W: $$\kappa_{\gamma\gamma}(W) = \frac{3}{4}\left(\frac{v}{m_W}\frac{\partial m_W}{\partial v} - 1\right)\frac{A_W(\tau_W)}{A_F(\tau_{top})}$$

$$\kappa_{gg}(W) = 0$$

Formalism easily extendable to non-minimal Higgs sectors!

Simple parameterization:

$$\Gamma_{\gamma\gamma} = \frac{G_F \alpha^2 m_H^3}{128\sqrt{2}\pi^3} \left| A_W(\tau_W) + 3\left(\frac{2}{3}\right)^2 A_t(\tau_t)\,[1+\kappa_{\gamma\gamma}] + \ldots \right|^2$$

$$\Gamma_{gg} = \frac{G_F \alpha_s^2 m_H^3}{16\sqrt{2}\pi^3} \left| \frac{1}{2} A_t(\tau_t)\,[1+\kappa_{gg}] + \ldots \right|^2$$

Normalizing with the top contribution has many advantages:

- New physics likely to be linked to top physics;
- for a top partner $\kappa_{\gamma\gamma} = \kappa_{gg}$;
- same sign for a single new particle;
- positive kappas reduce photon and enhance gluon widths.

Now, we can write observables in terms of those parameters:

The total Higgs production cross section
(normalized with the SM one) is

$$\bar{\sigma}(H) = \left(\frac{\sigma_{gg}^{NP} + \sigma_{VBF}^{SM} + \sigma_{VH,\bar{t}tH}^{SM}}{\sigma_{gg}^{SM} + \sigma_{VBF}^{SM} + \sigma_{VH,\bar{t}tH}^{SM}} \right) \simeq \left(\frac{(1+\kappa_{gg})^2 \sigma_{gg}^{SM} + \sigma_{VBF}^{SM} + \sigma_{VH,\bar{t}tH}^{SM}}{\sigma_{gg}^{SM} + \sigma_{VBF}^{SM} + \sigma_{VH,\bar{t}tH}^{SM}} \right)$$

Note that we neglected corrections to the couplings of the Higgs:
especially to the bottom and W!

- Corrections to the bottom Yukawa will invalidate our analysis (see SUSY)
- Marginal effects from the W couplings: VBF or total width
- Possible to extend the analysis with more parameters!

Now, we can write observables in terms of those parameters:

The photon Branching Ratio
(normalized with the SM one) is

$$\overline{BR}(H \to \gamma\gamma) = \frac{\Gamma_{\gamma\gamma}^{NP}}{\Gamma_{\gamma\gamma}^{SM}} \, \frac{\Gamma_{\rm tot}^{SM}}{\Gamma_{gg}^{NP} + \Gamma_{\gamma\gamma}^{NP} + \Gamma_{\rm others}^{SM}}$$

$$\simeq \left(1 + \frac{\kappa_{\gamma\gamma}}{\frac{9}{16} A_W(\tau_W) + 1}\right)^2 \, \frac{\Gamma_{\rm tot}^{SM}}{(1+\kappa_{gg})^2 \Gamma_{gg}^{SM} + (\Gamma_{\rm tot}^{SM} - \Gamma_{gg}^{SM})}$$

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Example 1:
4th generation.

Add a full chiral 4th generation:
190 GeV < mQ < 2 TeV
100 GeV < mL < 2 TeV

- The gluon loop counts number of color triplets:

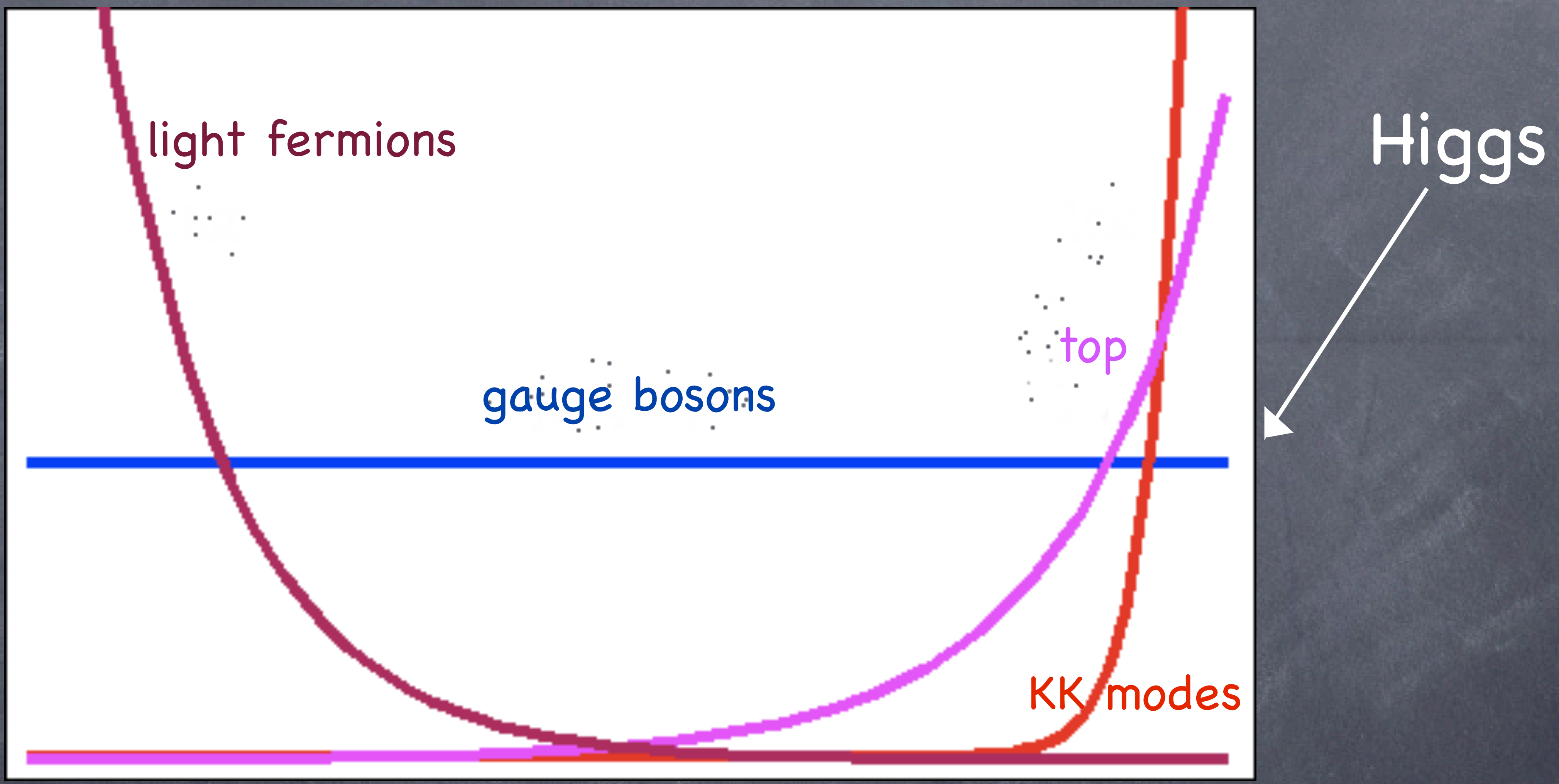
$$\kappa_{gg} = 2$$

- The photon loop depends on charges:

$$\kappa_{\gamma\gamma} = \frac{3}{4}\left[3\left(\frac{2}{3}\right)^2 + 3\left(-\frac{1}{3}\right)^2 + 1\right] = 2$$

- All in all, like two tops!

Example 2:
models of flavour in extra dimension



Fermion mass hierarchy generated by exponential localization:
Order(1) masses in the bulk, Order(1) Yukawas on the brane!

Do the light fermion KK modes contribute?

Gauge boson (W): negligible!

Spectrum fixed by the Boundary Conditions:

$$\begin{cases} \partial_5 W_\mu^+(y_1) = 0 \\ \partial_5 W_\mu^+(y_2) + \frac{g_5^2 V^2}{4} W_\mu^+(y_2) = 0 \end{cases}$$

$$W^+(y,x) = \sum_n f_n(m_n y)\ W_n(x)^+ \quad \Rightarrow \quad m_n \frac{f'(m_n y_2)}{f(m_n y_2)} + \frac{g_5^2 V^2}{4} = 0$$

The function f is determined by the geometry.

Gauge boson (W): negligible!

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Total derivate in V;
solve in V as a function of m_n:

$$\frac{v}{m_n}\frac{\partial m_n}{\partial v} = \frac{2\frac{f'}{f}}{\frac{f'}{f} + m_n y_2 \left(\frac{f''}{f} - \left(\frac{f'}{f}\right)^2 \right)}$$

Gauge boson (W): negligible!

Numerically, we found that, both in flat and warped XD:

$$\sum_{n=0}^{\infty} \frac{v}{m_n} \frac{\partial m_n}{\partial v} = 1$$

Probably because Higgs couples to boundary field with standard couplings: neglecting masses, we expect no correction.

$$\kappa_{\gamma\gamma} \propto \left(1 - \frac{v}{m_W} \frac{\partial m_W}{\partial v}\right) A_W(\tau_W) + \sum_{n=1}^{\infty} \frac{v}{m_n} \frac{\partial m_n}{\partial v} A_W(0) =$$

$$= \left(1 - \frac{v}{m_W} \frac{\partial m_W}{\partial v}\right) \left(A_W(\tau_W) - A_W(0)\right) \sim 0$$

Fermions: it depends...

Gauge-Higgs unification in flat space:

same bulk mass for left and right-handed fields ML = MR = M

$m_l \simeq 2\tilde{M}\pi\beta\, e^{-2\pi\tilde{M}L}$ β contains VEV and Yukawa

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β contains VEV and Yukawa

KK masses (n>1):

$$m_n^2 L^2 = \tilde{M}^2 L^2 + n^2 \pm \frac{2n^2}{\sqrt{n^2 + \tilde{M}^2 L^2}}\beta + \frac{n^4 + 3\tilde{M}^2 L^2 n^2}{(n^2 + \tilde{M}^2 L^2)^2}\beta^2 + \mathcal{O}(\beta^3)$$

Contribution proportional to the sum:

$$\sum_n \frac{\beta}{m_n}\frac{\partial m_n}{\partial \beta} = -2\beta^2 \sum_{n=1}^{\infty} \frac{n^4 - 3\tilde{M}^2 L^2 n^2}{(n^2 + \tilde{M}^2 L^2)^2} =$$

$$-\frac{\pi^2\beta^2}{\sinh^2 \pi\tilde{M}L}\left(\frac{\pi\tilde{M}L}{\tanh\pi\tilde{M}L} - 1\right) \simeq -\frac{m_l^2}{2\tilde{M}^2}\left(\frac{\pi\tilde{M}L}{\tanh\pi\tilde{M}L} - 1\right).$$

Fermions: it depends...

Different bulk masses:

case ML = - MR = M

$$m_l \simeq 2\tilde{M}\pi\beta\, e^{-2\pi\tilde{M}L}$$

β contains VEV and Yukawa

KK masses (n>1):

$$m_n^2 L^2 = \tilde{M}^2 L^2 + n^2 \pm \frac{2n^2}{\sqrt{n^2+\tilde{M}^2L^2}}\beta + \frac{(1-2\pi\tilde{M}L)n^4 + (3-2\pi\tilde{M}L)\tilde{M}^2L^2n^2}{(n^2+\tilde{M}^2L^2)^2}\beta^2 + \mathcal{O}(\beta^3)$$

Contribution proportional to the sum:

$$\sum_n \frac{\beta}{m_n}\frac{\partial m_n}{\partial\beta} = -2\beta^2 \sum_{n=1}^{\infty} \frac{(1+2\pi\tilde{M}L)n^4 - (3-2\pi\tilde{M}L)\tilde{M}^2L^2n^2}{(n^2+\tilde{M}^2L^2)^2} =$$

$$-\frac{\pi^2\beta^2}{4\sinh^3\pi\tilde{M}L}\Big(\cosh(3\pi\tilde{M}L) + (4\pi\tilde{M}L-1)\cosh(\pi\tilde{M}L) - 4(\pi\tilde{M}L+1)\sinh(\pi\tilde{M}L)\Big)$$

$$\simeq -\pi^2\beta^2 \sim -0.075\left(\frac{2\mathrm{TeV}}{m_{KK}}\right)^2\left(\frac{m_f}{m_{top}}\right)^2 .$$

Fermions: it depends...

For ML ≠ MR, all fermions contribute

$$\sum_n \frac{\beta}{m_n}\frac{\partial m_n}{\partial \beta} \simeq -\pi^2\beta^2$$

(we numerically checked it for generic masses)

$$\kappa_{\gamma\gamma} = \kappa_{gg} \simeq 6(-\pi^2\beta^2) \sim -0.45\left(\frac{2\mathrm{TeV}}{m_{KK}}\right)^2$$

Fermions: it depends...

The same happens in warped case, however:

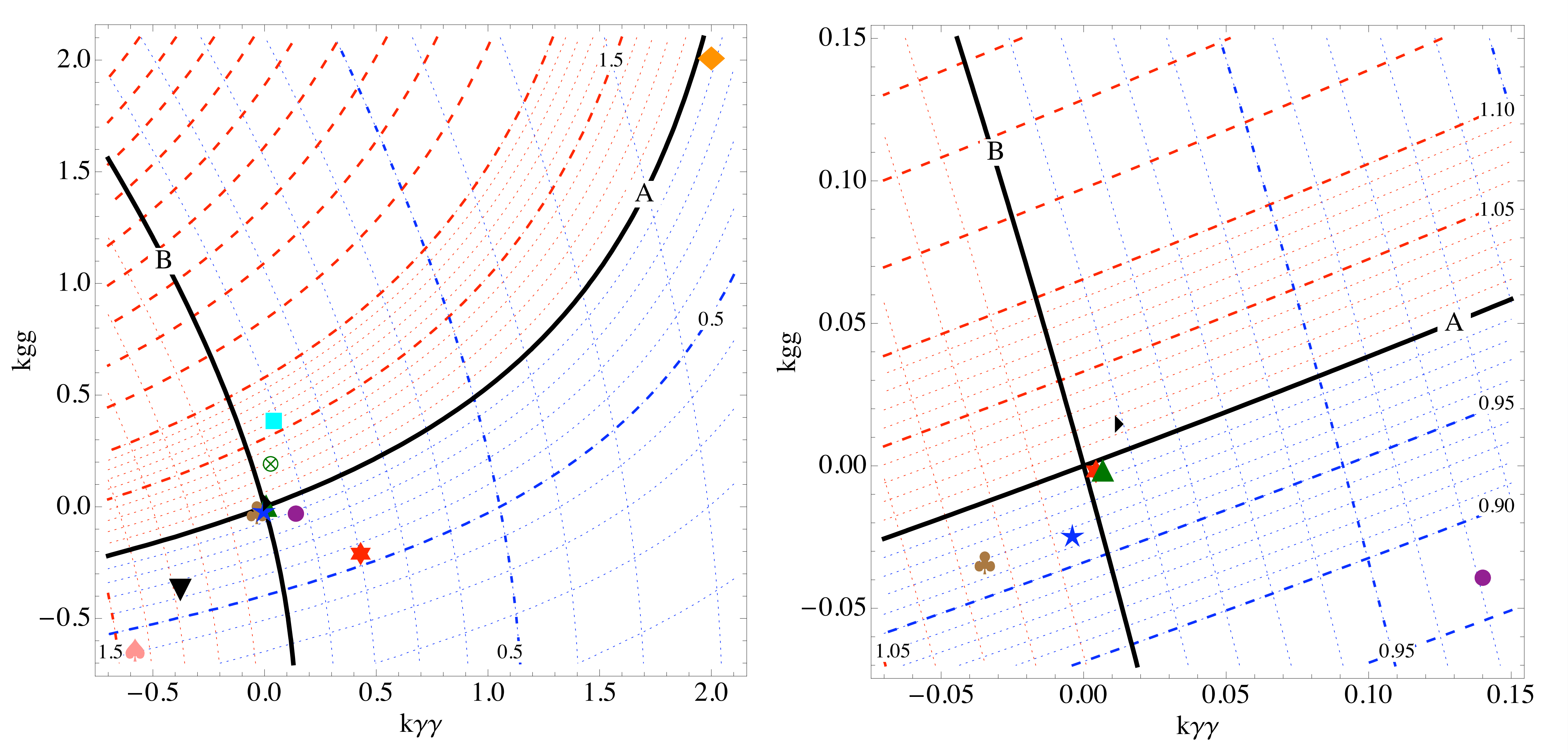
- each KK mode decouples from the Higgs for ML = MR: it depends on the wave functions being approx. proportional.

The result does not depend on the specific localization pattern e/o flavour structure!
It only depends on the overall KK mass...

Our survey of models:

- ♦ fourth generation;
- ♣ supersymmetry in the MSSM golden region: stops;
- ▲ Simplest Little Higgs ($m_{W'} = 2$ TeV);
- * Littlest Higgs (T-parity: $f = 500$ GeV, without T parity $f = 5$ TeV);
- ■ colour octet model;
- ▶ Lee-Wick Standard Model (LW Higgs mass at 1 TeV);
- ⊗ Universal Extra Dimension model ($m_{KK} = 500$ GeV);
- ★ model of Gauge Higgs unification in flat space (first W resonance at 2 TeV);
- ● the Minimal Composite Higgs (Gauge Higgs unification in warped space) with the IR brane at $1/R' = 1$ TeV;
- ▼ a flat (W' at 2 TeV) and
- ♠ warped ($1/R'$ at 1 TeV) version of brane Higgs models with flavour.

mH = 120 @ LHC

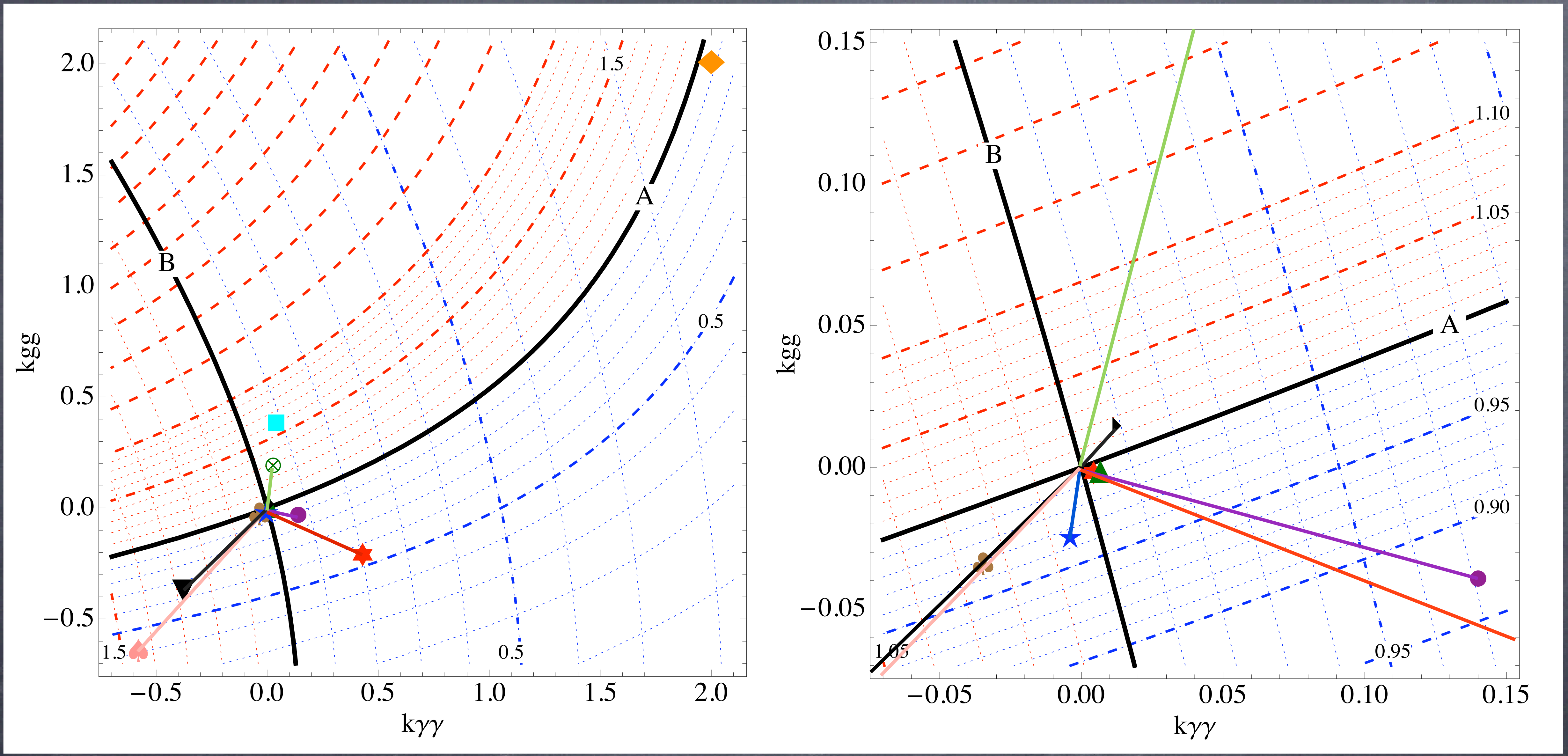


A – inclusive γγ

B – VBF γγ

4 gen, Susy, SLH, LH, LeeWick, Octet, UED, flat GH, Warped GH, flat and warped flavour

mH = 120 @ LHC



A - inclusive γγ

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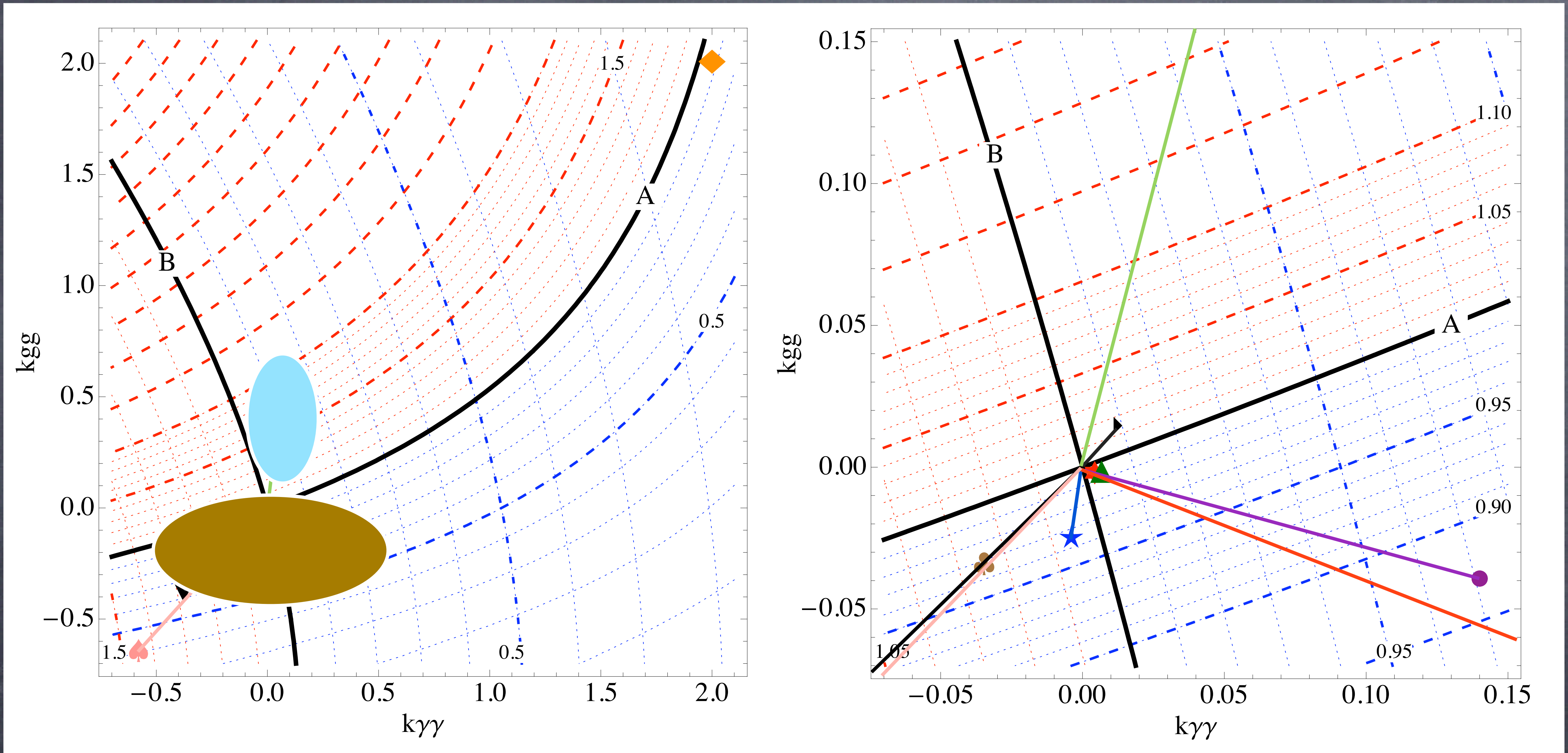


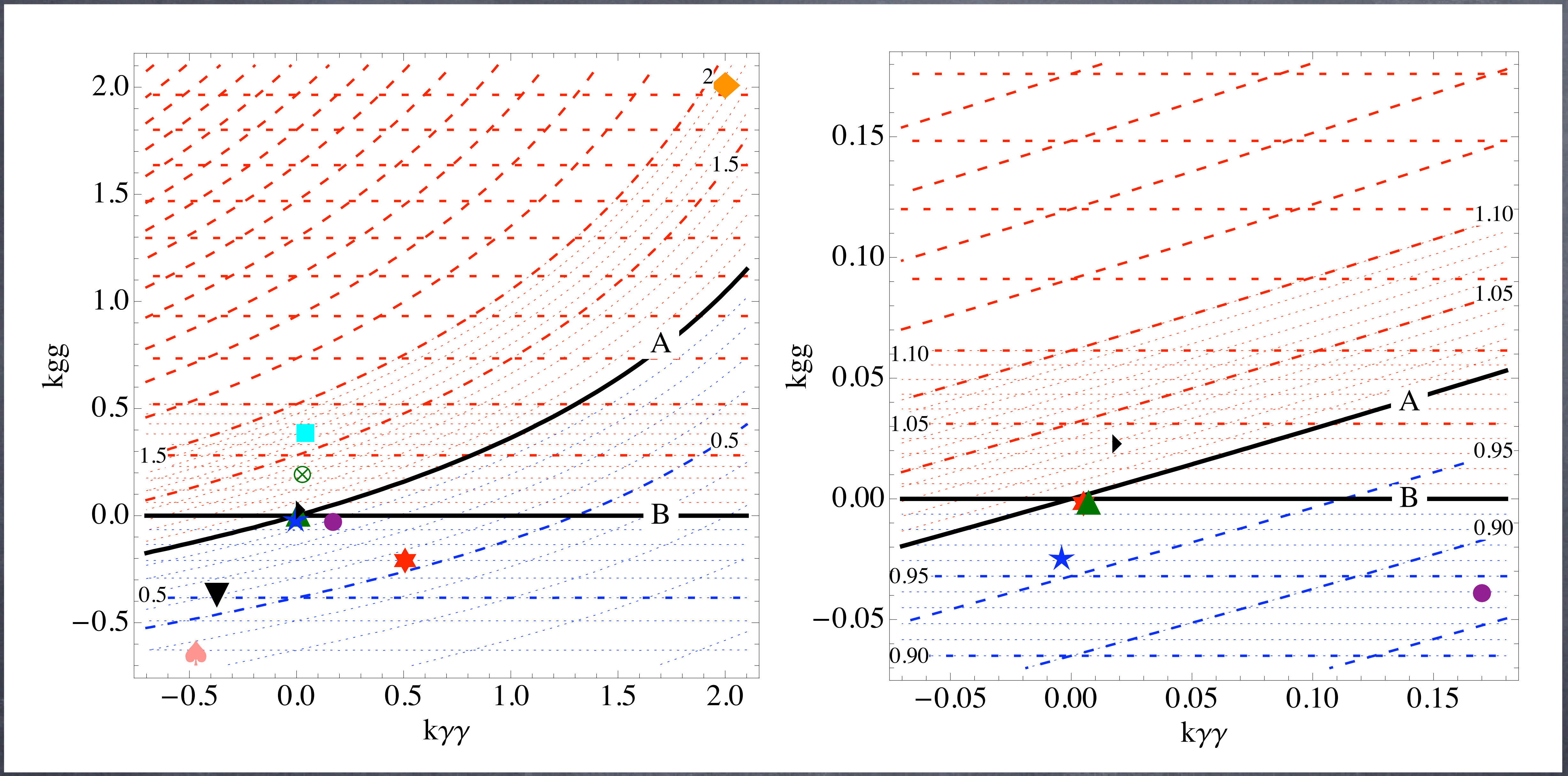
A - inclusive γγ

B - VBF γγ

4 gen | Susy | SLH | LH | LeeWick | Octet

UED | flat GH | Warped GH | flat and | warped flavour

mH = 150 @ LHC



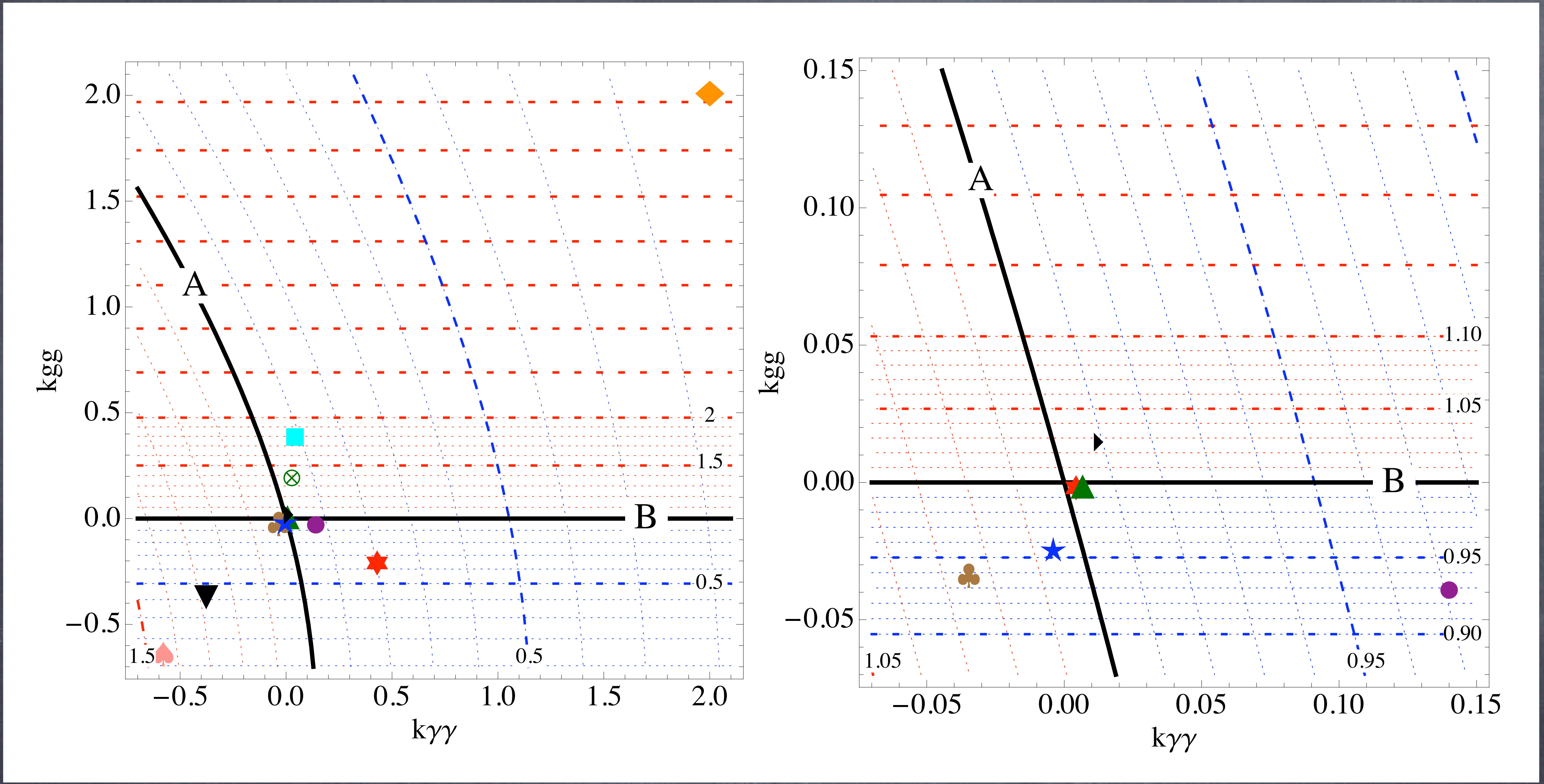
A - inclusive γγ

B - WW & ZZ

◆ 4 gen ♣ Susy ▲ SLH * LH ▶ LeeWick ■ Octet

⊗ UED ★ flat GH ● Warped GH ▼ flat and ♠ warped flavour

mH = 120 @ ILC



A - photon BR
B - gluon BR

4 gen, Susy, SLH, LH, LeeWick, Octet
UED, flat GH, Warped GH, flat and, warped flavour

Conclusions

- $H \to \gamma\gamma$ and $g\, g \to H$ are very sensitive to New Physics in the EWSB sector.
- A simple mod-ind parameterization allows easy calculation and exp. analysis.
- Many models give robust predictions, and point in a specific direction of the par. space: discrimination
- Probe new particles not directly accessible.
- Further study in collab. with experimentalists!