LHC physics beyond the Standard Model

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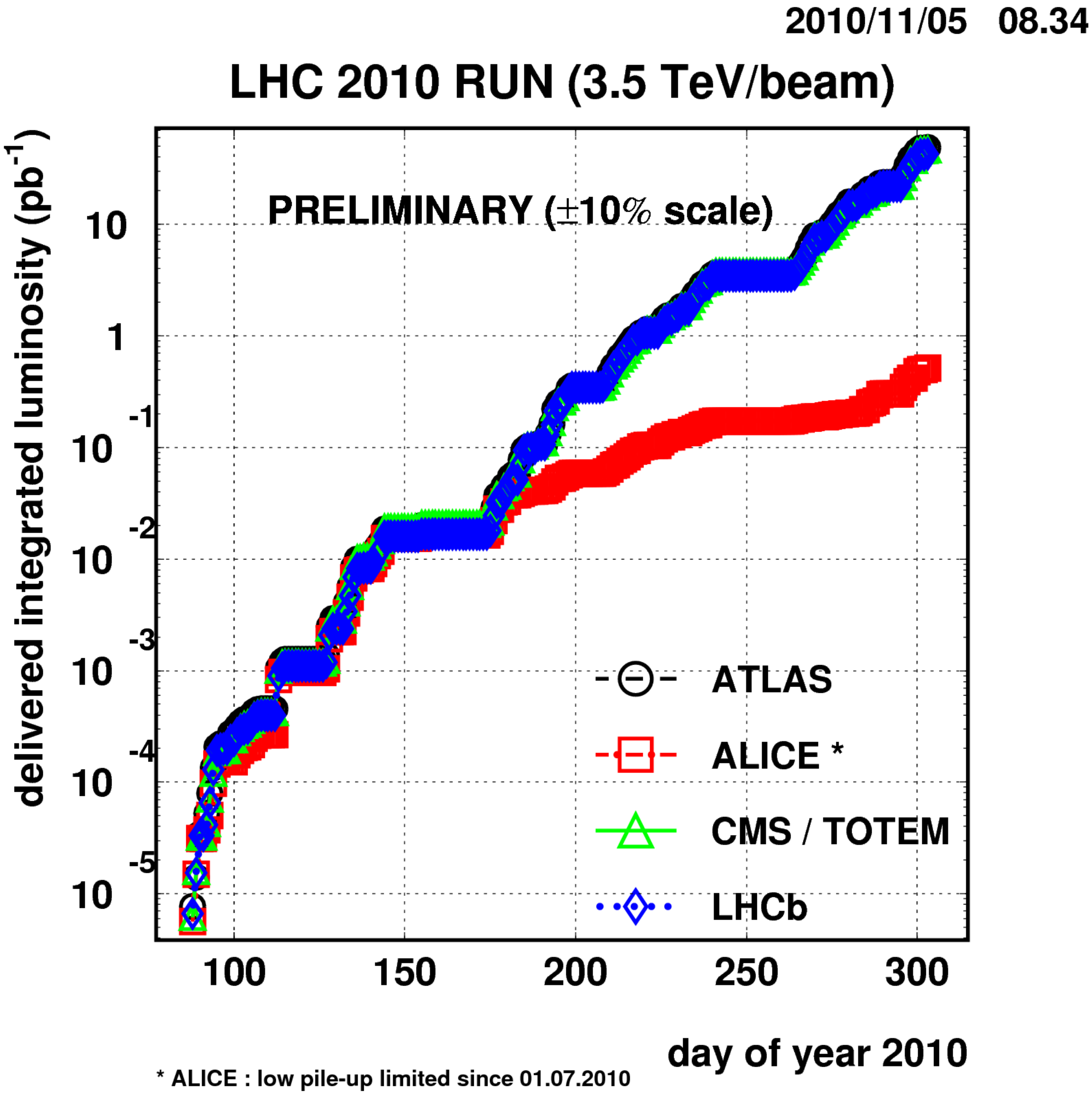
Outline

- LHC data in pp collisions (a short reminder)
- Beyond the SM : where and how general?

- A couple of interesting possibilities (and 2 different strategies)
- heavy vector-like fermions
- Higgs -> γγ

- Conclusions

2010 LHC pp luminosity



2010/11/05 08.34

* ALICE : low pile-up limited since 01.07.2010

2011 LHC pp luminosity*

Reasonable numbers

Peak luminosity	6.4 x 10^32
Integrated per day	11 pb-1
200 days	2.2 fb-1
Stored energy	72 MJ

Ultimate

Peak luminosity	2.2 x 10^33
Integrated per day	38 pb-1
200 days	7.6 fb-1
Stored energy	134 MJ

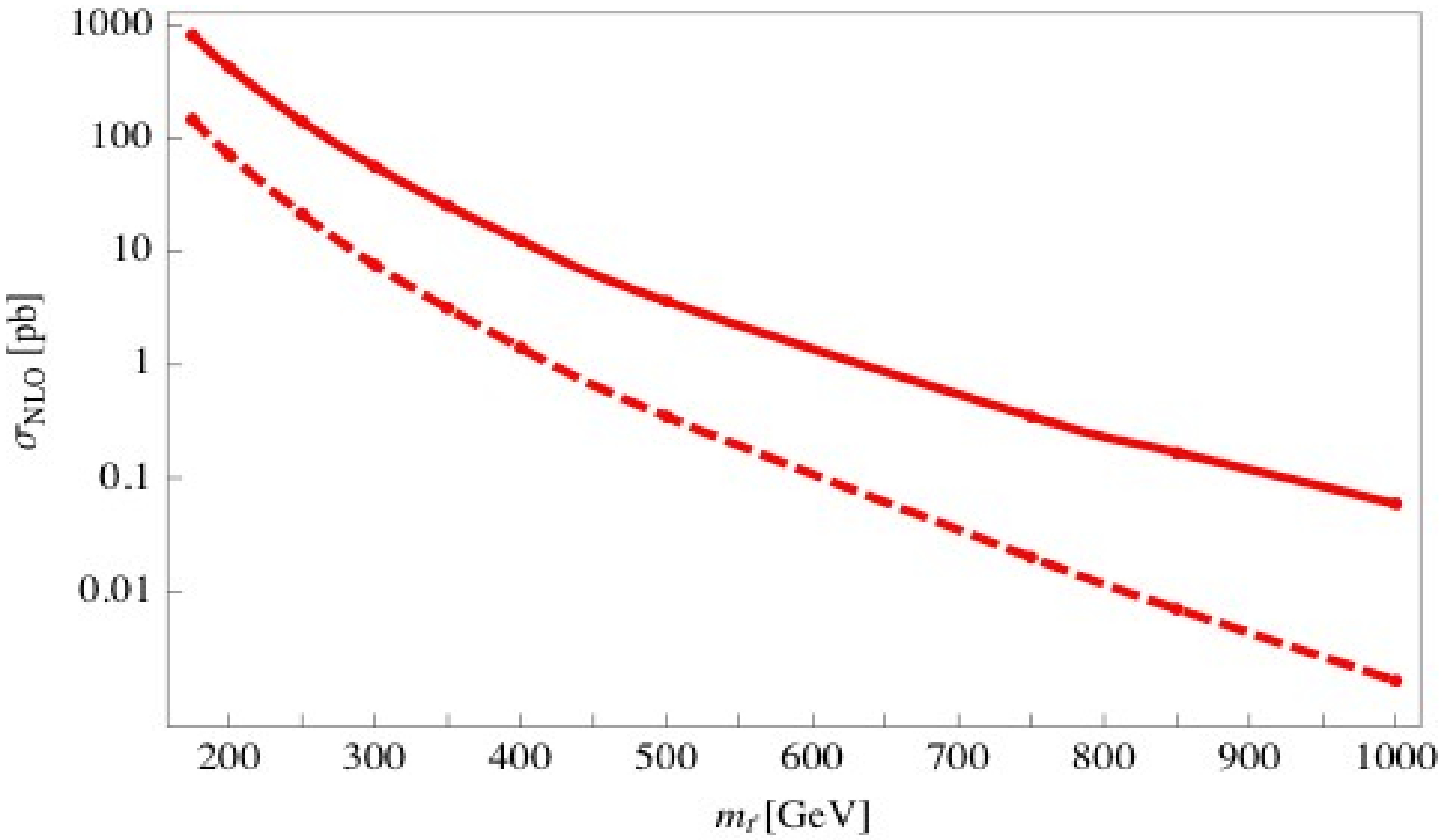
* from R.Bailey, LHC status report Nov.2010

Heavy vector-like fermions

- Usual “wisdom” on heavy fermion is based on a sample 4th generation, or vector-like singlet case
- But :
  - Vector-like fermions may have different behavior
  - Many models have this kind of fermions (Xdim, Little Higgs, dynamical models...)
- Typical constraints (mt'>335 GeV, mb'>385 GeV from CDF) do not necessarily apply (as they assume 100% BR to W q)
- Cross-sections at LHC are within (short term) reach

ArXiv:1007.2933 (JHEP)

Sample cross sections



Heavy quarks pair production at the LHC in pb as a function of the quark mass. Dashed (lower) line corresponds to the 7 TeV cm energy solid (upper) line to 14 TeV.

A general description of heavy vector-like fermions

- Completely general description is not possible, however generic 'broad' assumption can be :
- new fermions interact with the SM fermions via Yukawa interactions.
- The Q-numbers of the new fermions under the weak SU(2)L × U(1)Y gauge group are limited by interaction with the Higgs doublet and one of the SM fermions.
- Possible Q-numbers give :
  - 1 SM-like singlet
  - 3 doublets : 1 with SM Y, the others Y+/-1
  - 2 triplets with Y+/-1

Mixing effects

- Yukawa coupling generates a mixing between the new state(s) and the SM ones
- Type 1 : singlet and triplets couple to SM L-doublet
  - Singlet ψ = (1, 2/3) = U : only a top partner is present
  - triplet ψ = (3, 2/3) = $\{X, U, D\}^T$, the new fermion contains a partner for both top and bottom, plus X with charge 5/3
  - triplet ψ = (3, −1/3) = $\{U, D, X\}^T$, the new fermions are a partner for both top and bottom, plus X with charge −4/3

$$\mathcal{L}_{\text{mass}} = -\frac{y_u v}{\sqrt{2}} \bar{u}_L u_R - x\, \bar{u}_L U_R - M\, \bar{U}_L U_R + h.c.$$

$$\begin{pmatrix} \cos\theta_u^L & -\sin\theta_u^L \\ \sin\theta_u^L & \cos\theta_u^L \end{pmatrix} \begin{pmatrix} \frac{y_u v}{\sqrt{2}} & x \\ 0 & M \end{pmatrix} \begin{pmatrix} \cos\theta_u^R & \sin\theta_u^R \\ -\sin\theta_u^R & \cos\theta_u^R \end{pmatrix}$$

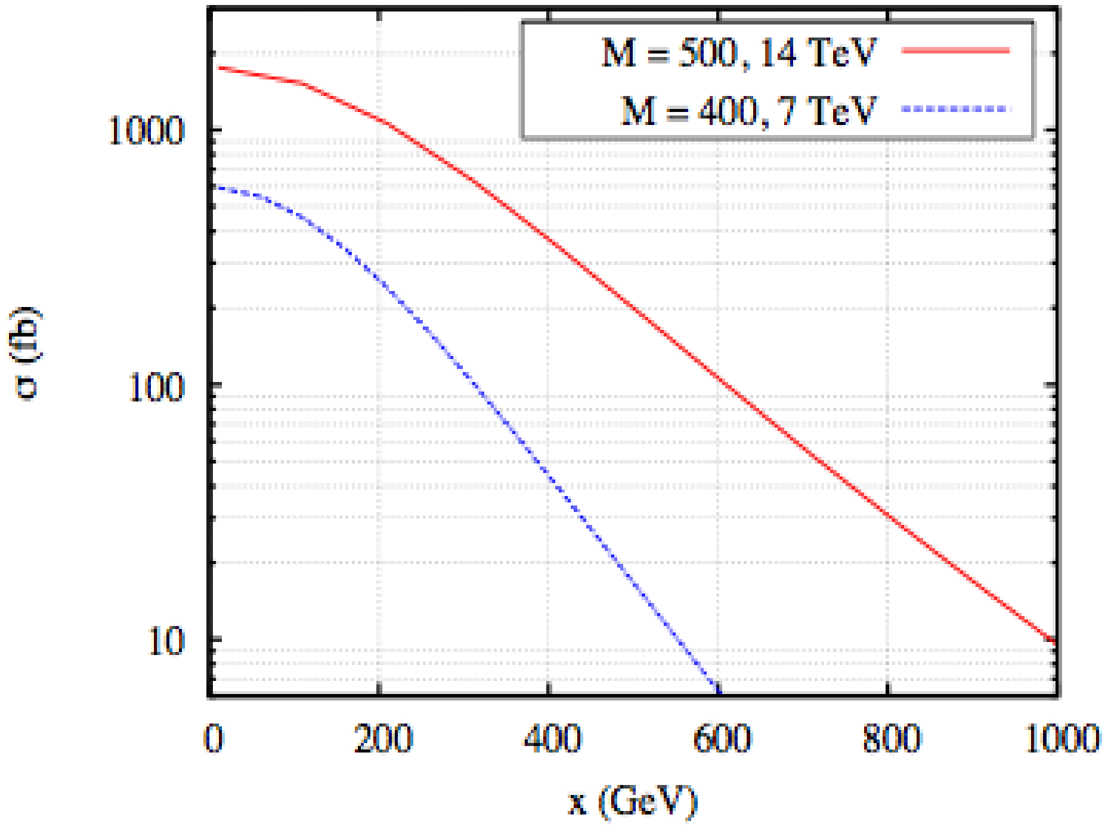
Mixing effects

- Type 2 : new doublets couple to SM R-singlet
  - SM doublet case ψ = (2, 1/6) = $\{U, D\}^T$, the vector-like fermions are a top and bottom partners
  - non-SM doublets ψ = (2, 7/ 6) = $\{X, U\}^T$, the vector-like fermions are a top partner and a fermion X with charge 5/3
  - non-SM doublets ψ = (2, -5/ 6) = $\{D,X\}^T$, the vector-like fermions are a bottom partner and a fermion X with charge -4/3

$$\mathcal{L}_{\text{mass}} = -\frac{y_u v}{\sqrt{2}}\,\bar{u}_L u_R - x\,\bar{U}_L u_R - M\,\bar{U}_L U_R + h.c.$$

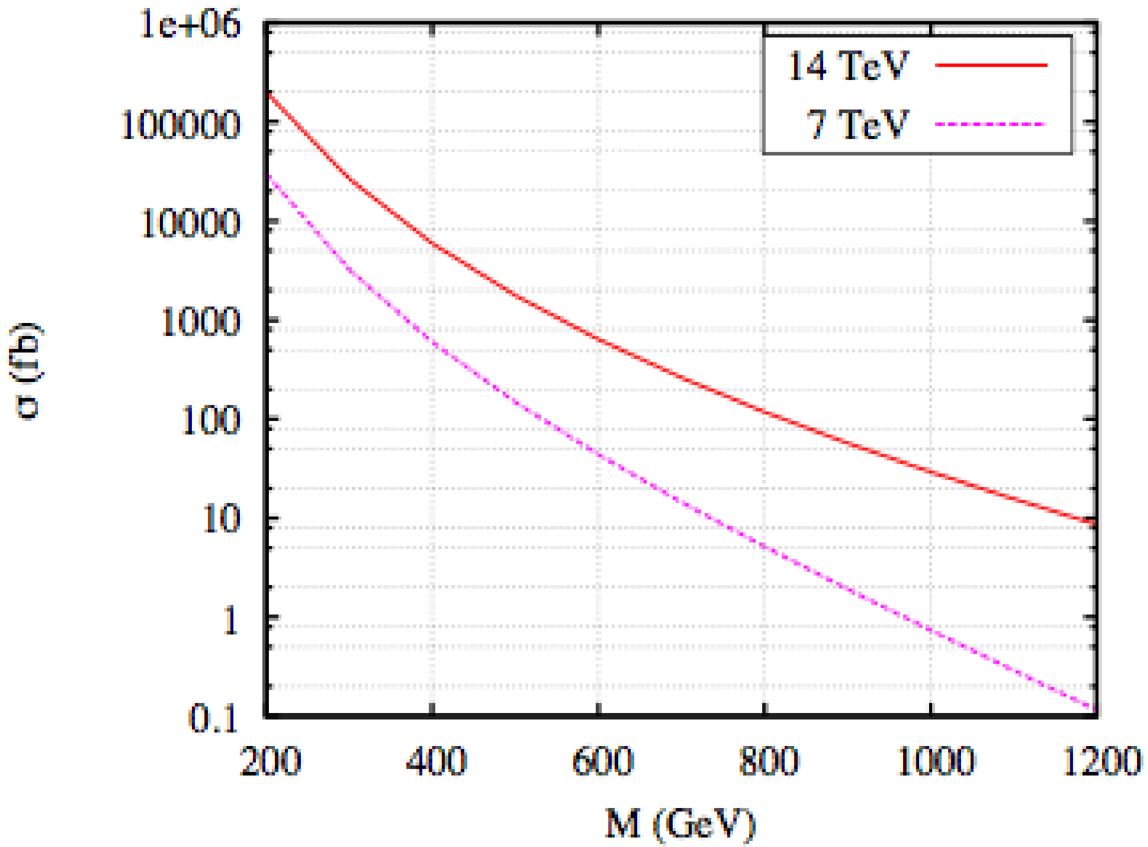
$$\begin{pmatrix} \cos\theta_u^L & -\sin\theta_u^L \\ \sin\theta_u^L & \cos\theta_u^L \end{pmatrix} \begin{pmatrix} \frac{y_u v}{\sqrt{2}} & 0 \\ x & M \end{pmatrix} \begin{pmatrix} \cos\theta_u^R & \sin\theta_u^R \\ -\sin\theta_u^R & \cos\theta_u^R \end{pmatrix}$$

Production cross sections



Non-SM doublet pp → t' $\bar{t}'$ production as a function of x for fixed mass

Production cross sections

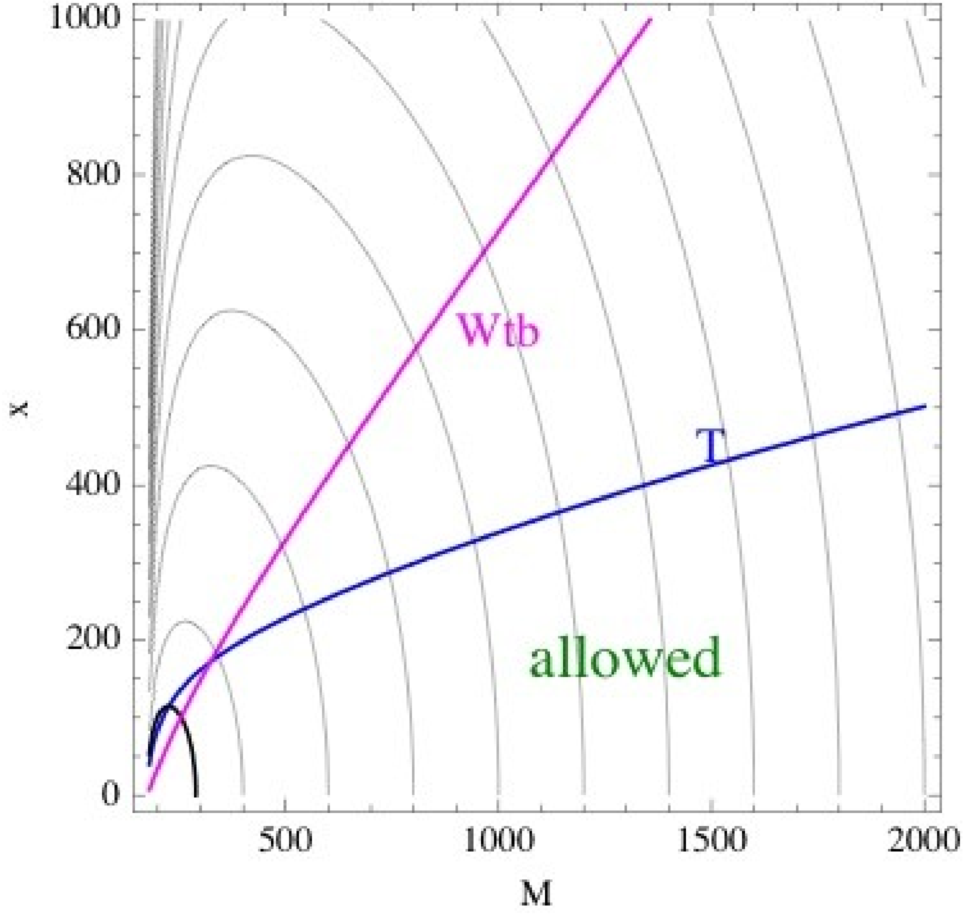


Non-SM doublet pp → $X\bar{X}$ cross section as function of the M mass

Relevant bounds

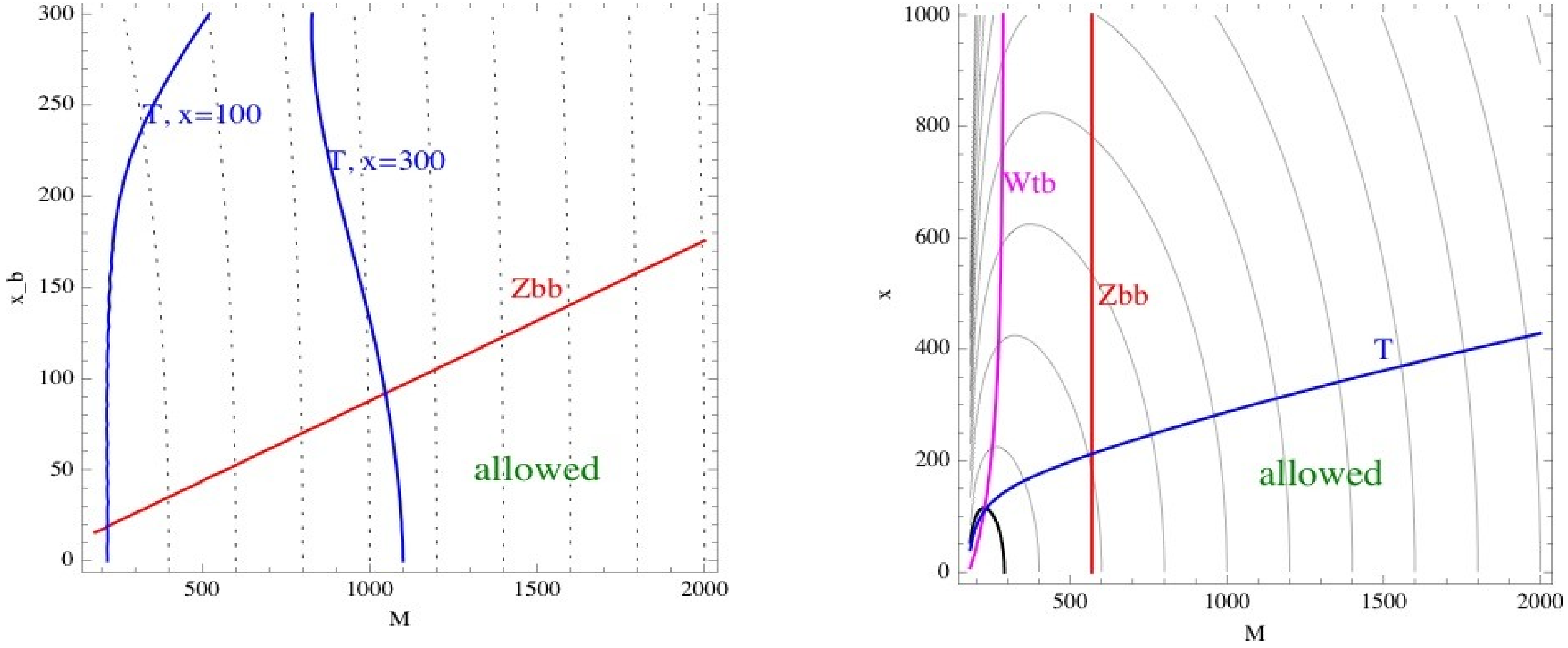
- Tree-level bounds
  - W → t b, ~ +/-20% variation still allowed (TeVatron data)
  - Z → b $\bar{b}$ +1% → -0.2% in the left coupling and +20% → -5% in the right coupling (L and R are correlated)
  - CKM bounds very tight if 1st and 2nd generation mixing allowed
- Loop level bounds are model dependent as
  - new particles are expected in the loops (not only the new heavy fermions)
  - The Higgs mass affects the bounds
  - Sample test with the T-parameter

Heavy vector-like singlet



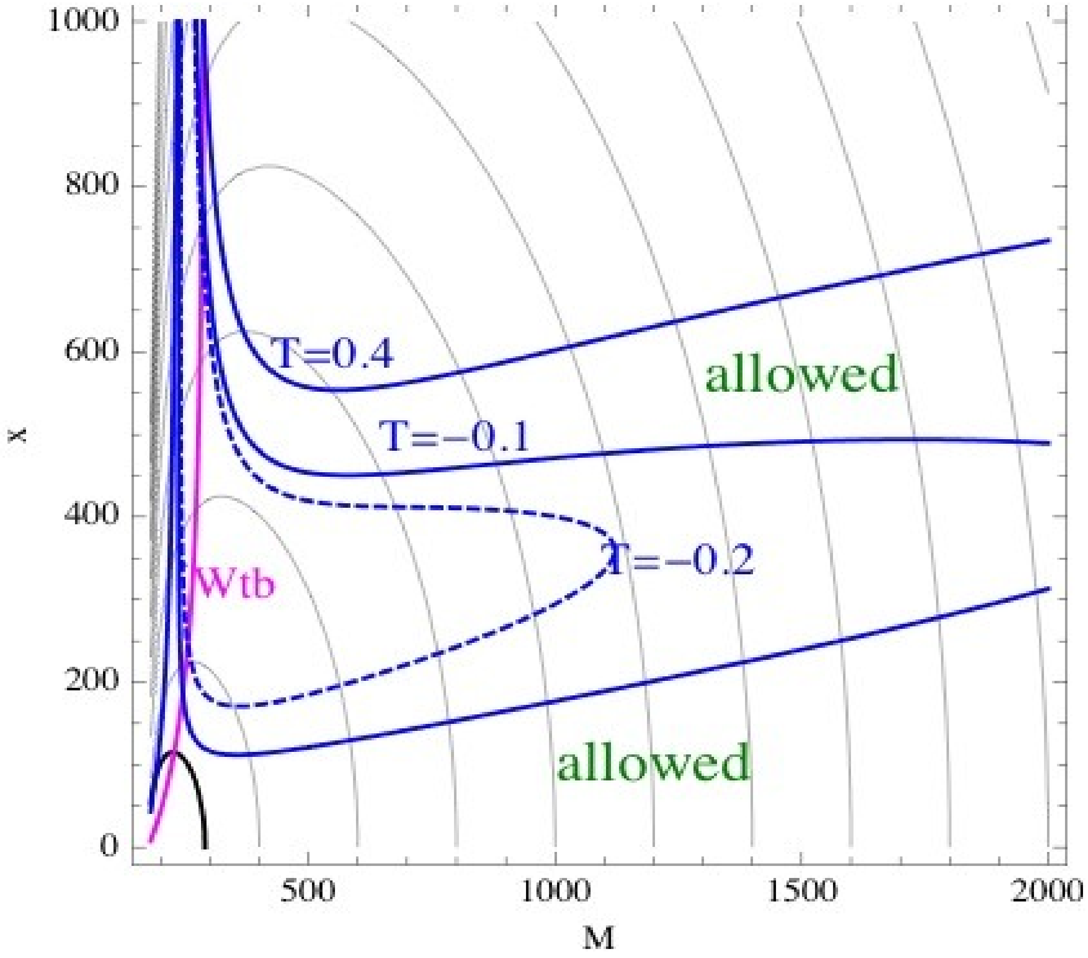
x is the mixing with top, M heavy mass before mixing,grey lines physical t' mass.

Heavy vector-like standard-like doublet



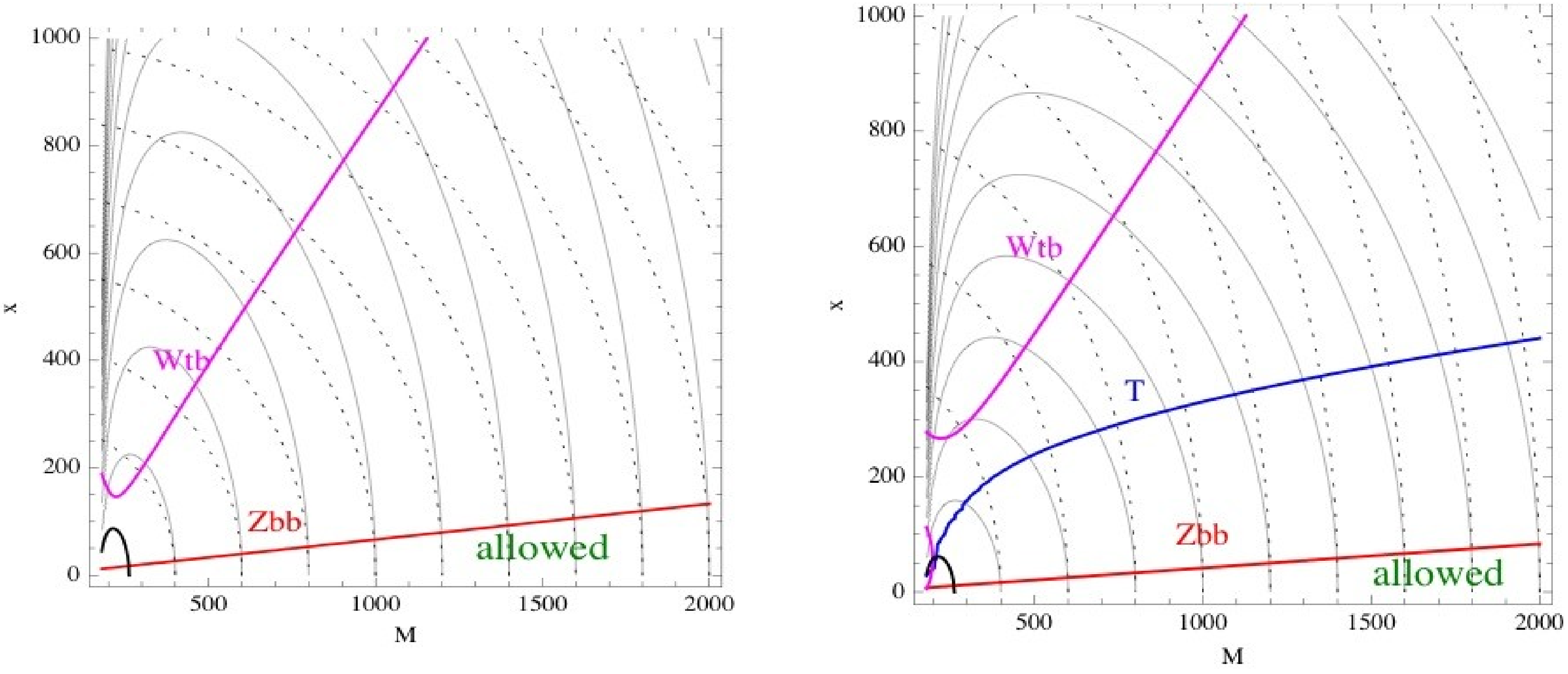
Left panel the b' limits, grey dotted lines the b' mass isocurves; right panel the t' limits (for xb=50), grey lines the t' mass isocurves

Heavy vector-like non-standard doublet



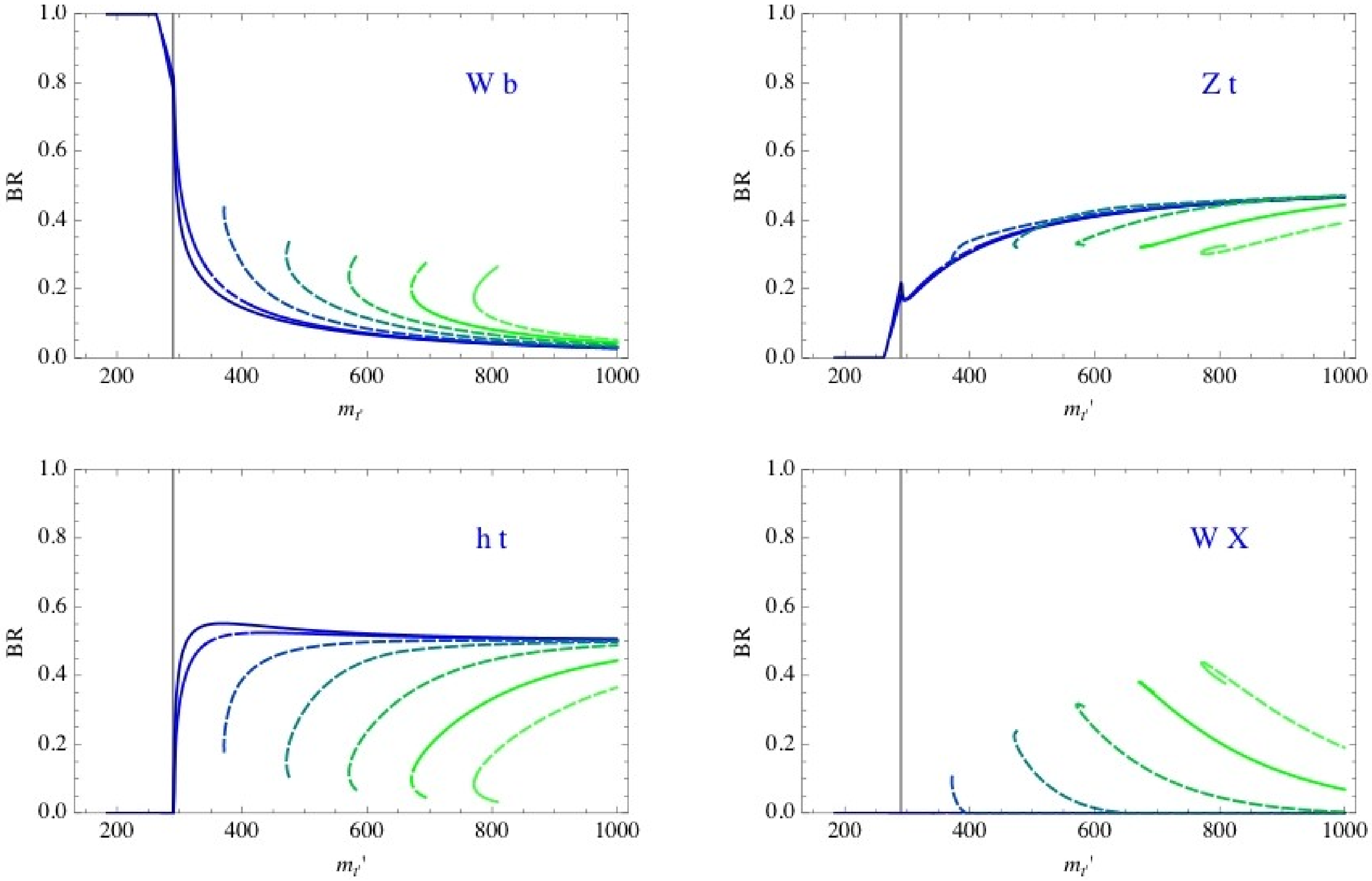
Y=7/6 non-standard doublet In black the direct bound from TeVatron. The grey lines mark isovalues of the t′ mass.

Heavy vector-like triplets



Y = 2/3 left panel, Y = −1/3 right panel. In black the direct bound from TeVatron. The grey (dashed) lines mark isovalues of the mt′ (mb′) mass

Branching ratios (non SM doublet Y=7/6)



the lines correspond to x = 10, 100, 200, 300, 400, 500, 600 GeV

General mixing for non-SM doublet

$$\begin{aligned}
\mathcal{L}_{\text{mass}} &= -(d_L, s_L, b_L)\,\tilde{V}_{CKM} \begin{pmatrix} \tilde{m}_d & & \\ & \tilde{m}_s & \\ & & \tilde{m}_b \end{pmatrix} \begin{pmatrix} d_R \\ s_R \\ b_R \end{pmatrix} \\
&- (u_L, c_L, t_L, U_L) \begin{pmatrix} \tilde{m}_u & & & 0 \\ & \tilde{m}_c & & 0 \\ & & \tilde{m}_t & 0 \\ x_1 & x_2 & x_3 & M \end{pmatrix} \begin{pmatrix} u_R \\ c_R \\ t_R \\ U_R \end{pmatrix} \\
&- M X_L X_R + h.c.
\end{aligned}$$

Up quark masses can be diagonalized using two matrices V_L and V_R
The L mixing are suppressed by m/M while the R are not. This imply constraints will typically come from right-handed up-type quarks.

Bounds on 1st and 2nd generation mixing

- mixings are

  $V^{14}_R = x_1 \cos\theta_R /M \qquad V^{24}_R = x_2 \cos\theta_R /M$

- Only up-type quarks are directly affected
  - D-$\overline{D}$ mixing $x_D = \Delta m_D/\Gamma_D$: tree level $c\overline{u} \rightarrow Z^* \rightarrow u\overline{c}$ implies

    $|V^{14}_R|\,|V^{24}_R| < 3.2\ 10^{-4}$, $D \rightarrow l^+l^-$ less constraining

- Z coupling to R-handed quarks
  - Best bound from weak charge in Cesium

    $|V^{14}_R| < 0.078$

Conclusion part 1

- Heavy vector-like fermions are present in many extensions of the SM
- Present constraints not stringent in some cases
- Flavour results are helpful to establish the allowed range of mixings
- LHC can produce and discover these particles or place more stringent bounds already in 2011

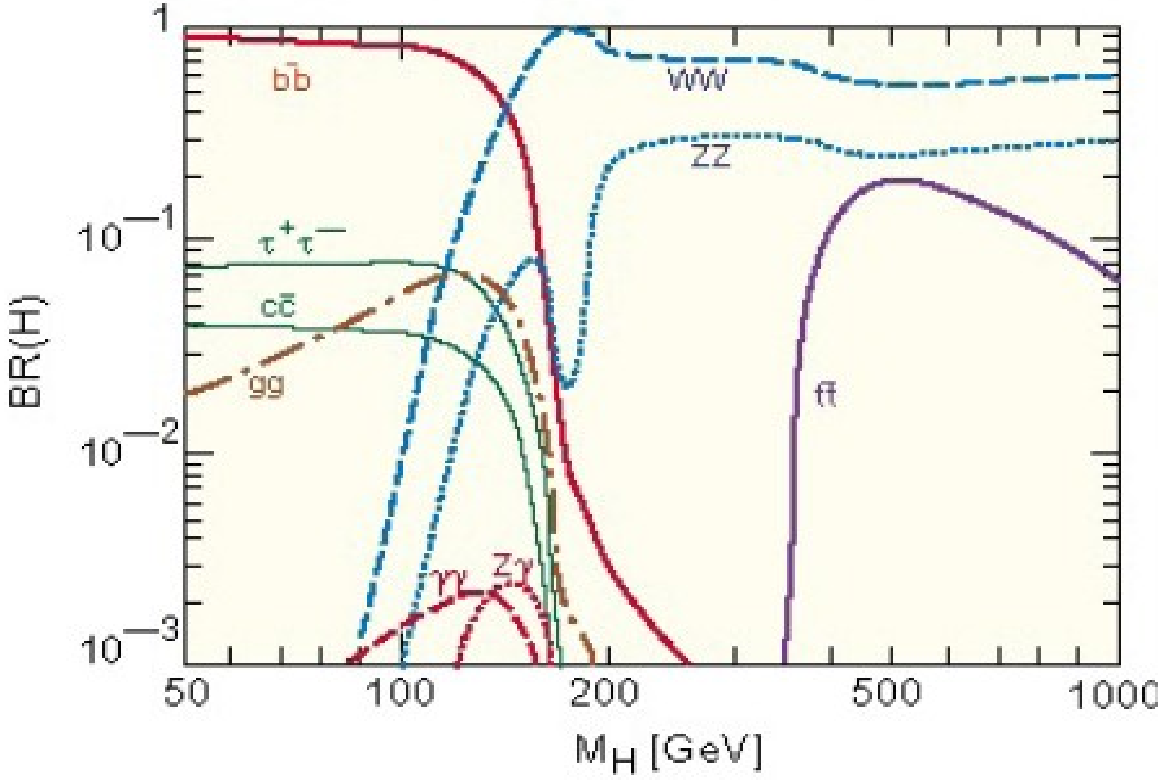
Outline part 2

- the SM Higgs
- Observables and new (largely) model independent parameterization
- Use for data analysis and model survey

ArXiv:0901.0927 (JHEP)

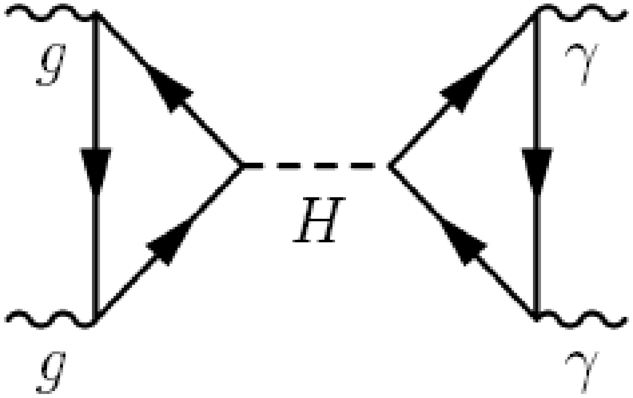
Light Higgs at LHC

- Light Higgs (115 GeV < m_H <140 GeV)
  - Production from gluon fusion
  - Decay channel through two photons
- Branching Ratio in two photons: small but “clear” signature in the EM calorimeter.



Effective Coupling between Higgs and massless vectors

- At tree level → No coupling between Higgs and massless gauge bosons.
- Decay in two gammas → Loop contributions.



- Small couplings depending on the properties of the virtual particles running into the loop.

$$\mathcal{L}_{\gamma\gamma} = -\left(\sqrt{2}G_F\right)^{\frac{1}{2}}\frac{\alpha}{2\pi}\, I_{\gamma\gamma}\; F_{\mu\nu}F^{\mu\nu}\, H$$

$$\mathcal{L}_{gg} = -\left(\sqrt{2}G_F\right)^{\frac{1}{2}}\frac{\alpha_s(m_H^2)}{4\pi}\, I_{gg}\; G^a_{\mu\nu}G_a^{\mu\nu}\, H$$

Influence of virtual particles in the decay widths

- Effective Lagrangians → Decay widths

$$\Gamma_{\gamma\gamma} \propto |I_{\gamma\gamma}|^2 = \left| A_W(\tau_W) + \sum_{fermions} N_c Q_f^2 A_F(\tau_f) + \sum_{NP} N_c Q_{NP}^2 A_{NP}(\tau_{NP}) \right|^2$$

$$\Gamma_{gg} \propto |I_{gg}|^2 = \left| \frac{3}{4} \sum_{fermions} A_F(\tau_f) + \sum_{NP} C_c(r_{NP}) A_{NP}(\tau_{NP}) \right|^2 \quad where \quad \tau_x = \frac{m_H^2}{4m_x^2}$$

- SM: Principal contribution from top and W.

- New physics: New charged or colored particles interacting with the Higgs

  → Modification of effective vertices.

- **A** depends on the spin, the masses and the coupling of the virtual particles running into the loop.

Amplitudes and Couplings to the Higgs

- For SM, masses proportional to the Higgs VEV

$$y^{SM}_{h\bar{f}f} = \frac{m_f}{v} \quad for \quad fermions$$

$$y^{SM}_{hWW} = 2\frac{m_W^2}{v} \quad for \quad bosons$$

- Definition of A_W, A_F and A_S are well-known functions of τ

$$\begin{aligned}
A_F(\tau) &= \frac{2}{\tau^2}(\tau + (\tau - 1)f(\tau)) \\
A_W(\tau) &= -\frac{1}{\tau^2}\left(2\tau^2 + 3\tau + 3(2\tau - 1)f(\tau)\right) \\
A_S(\tau) &= -\frac{1}{\tau^2}(\tau - f(\tau))
\end{aligned}$$

$$f(\tau) = \begin{cases} \arcsin^2\sqrt{\tau} & \tau \leq 1 \\ -\frac{1}{4}\left[\log\frac{1+\sqrt{1-\tau^{-1}}}{1-\sqrt{1-\tau^{-1}}} - i\pi\right]^2 & \tau > 1 \end{cases}$$

Amplitudes and Couplings to the Higgs

- for large mass of the particle in the loop with respect to the Higgs mass :

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

- For New Physics
  - Mass of NP not necessarily proportional to Higgs VEV
  - Small correction from EW breaking

$$y_{h\bar{f}f}^{NP} = \frac{\partial m_f(v)}{\partial v} \quad and \quad y_{hWW}^{NP} = \frac{\partial m_W^2(v)}{\partial v}$$

- Definition of A_{NP} :

$$A_{NP} = \frac{v}{m_{NP}} \frac{\partial m_{NP}}{\partial v} A_{F,S,W}$$

  - Spin and mass taken into account in $A_{F,W,S}$
  - Coupling effects contained in the pre-factor

Model-independent parameterization

- Normalization of new contributions to the top's one.
  - Solutions to naturalness problem, NP closely related to top physics
- SM-like Higgs sector and tree level structure assumed
  - Only 2 parameters in this case

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

$$\Gamma_{gg}=\frac{G_F\alpha_s^2 m_H^3}{36\sqrt{2}\pi^3}\left|\frac{3}{4}A_F(\tau_{top})[1+\kappa_{gg}]+\ldots\right|^2 \quad where \quad \tau_x=\frac{m_H^2}{4\mathrm{m}_x^2}$$

$$\kappa_{\gamma\gamma}=\sum_{NP}\frac{3}{4}N_c Q_{NP}^2\frac{v}{m_{NP}}\frac{\partial m_{NP}}{\partial v}\frac{A_{F,S,W}(\tau_{NP})}{A_F(\tau_{top})}$$

$$\kappa_{gg}=\sum_{NP}\frac{4}{3}C_c(r_{NP})\frac{v}{m_{NP}}\frac{\partial m_{NP}}{\partial v}\frac{A_{F,S,W}(\tau_{NP})}{A_F(\tau_{top})}$$

Approximations and Corrections

- Light Higgs Hypothesis: $m_H{}^2 << m_{NP}{}^2$ or $\tau_{NP} << 1$
- So the **A** ratios only depend on the spin of NP

$$\frac{A_{NP}}{A_{top}} = \left\{ \begin{array}{c} 1 \quad for \quad fermions \\ -21/4 \quad for \quad vectors \\ 1/4 \quad for\, scalars \end{array} \right\}$$

- Most of time, at tree level, masses of top and W are not proportional to the Higgs VEV $\longrightarrow$ New kappas

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

$$\kappa_{\gamma\gamma}(W) = \frac{3}{4} \left(\frac{v}{m_W} \frac{\partial m_W}{\partial v} - 1 \right) \frac{A_W(\tau_W)}{A_F(\tau_{top})} \quad and \quad \kappa_{gg}(W) = 0$$

Modifications of LHC Observables

- Branching ratio for H ► γγ normalized to SM value:

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

Influence of new physics

$$\overline{BR}(H\to\gamma\gamma)\simeq\left(1+\frac{\kappa_{\gamma\gamma}}{\frac{9}{16}A_W(\tau_W)+1}\right)^2\frac{\Gamma^{SM}_{tot}}{(1+\kappa_{gg})^2\Gamma^{SM}_{gg}+(\Gamma^{SM}_{tot}-\Gamma^{SM}_{gg})}$$

- Inclusive cross section for H ► γγ normalized to SM value:

$$\overline{\sigma}(H\to\gamma\gamma)=\frac{\sigma^{NP}_{gg}+\sigma^{SM}_{VBF}+\sigma^{SM}_{VH,tH}}{\sigma^{SM}_{gg}+\sigma^{SM}_{VBF}+\sigma^{SM}_{VH,tH}}\overline{BR}(H\to\gamma\gamma)$$

Influence of new physics

$$\overline{\sigma}(H\to\gamma\gamma)\simeq\frac{(1+\kappa^2_{gg})\sigma^{SM}_{gg}+\sigma^{SM}_{VBF}+\sigma^{SM}_{VH,tH}}{\sigma^{SM}_{gg}+\sigma^{SM}_{VBF}+\sigma^{SM}_{VH,tH}}\overline{BR}(H\to\gamma\gamma)$$

Generalizations

- The previous parameterization implicitly assumes a SM-like Higgs sector and tree level structure
- Easy to take into account a more general situation
  - Multiple Higgs $\phi_i = \frac{1}{\sqrt{2}}(v_i + c_i h + \ldots)$

$$\frac{v}{m}\frac{\partial m_f(v)}{\partial v} \rightarrow \frac{v}{m}\sum_i \frac{\partial m}{\partial v_i} c_i$$

  - Mixing with scalars with no vev

$$\frac{v}{m}\frac{\partial m_f(v)}{\partial v} \rightarrow \frac{v}{m}\left(\sum_i \frac{\partial m}{\partial v_i} c_i \sum_j g_j s_j\right)$$

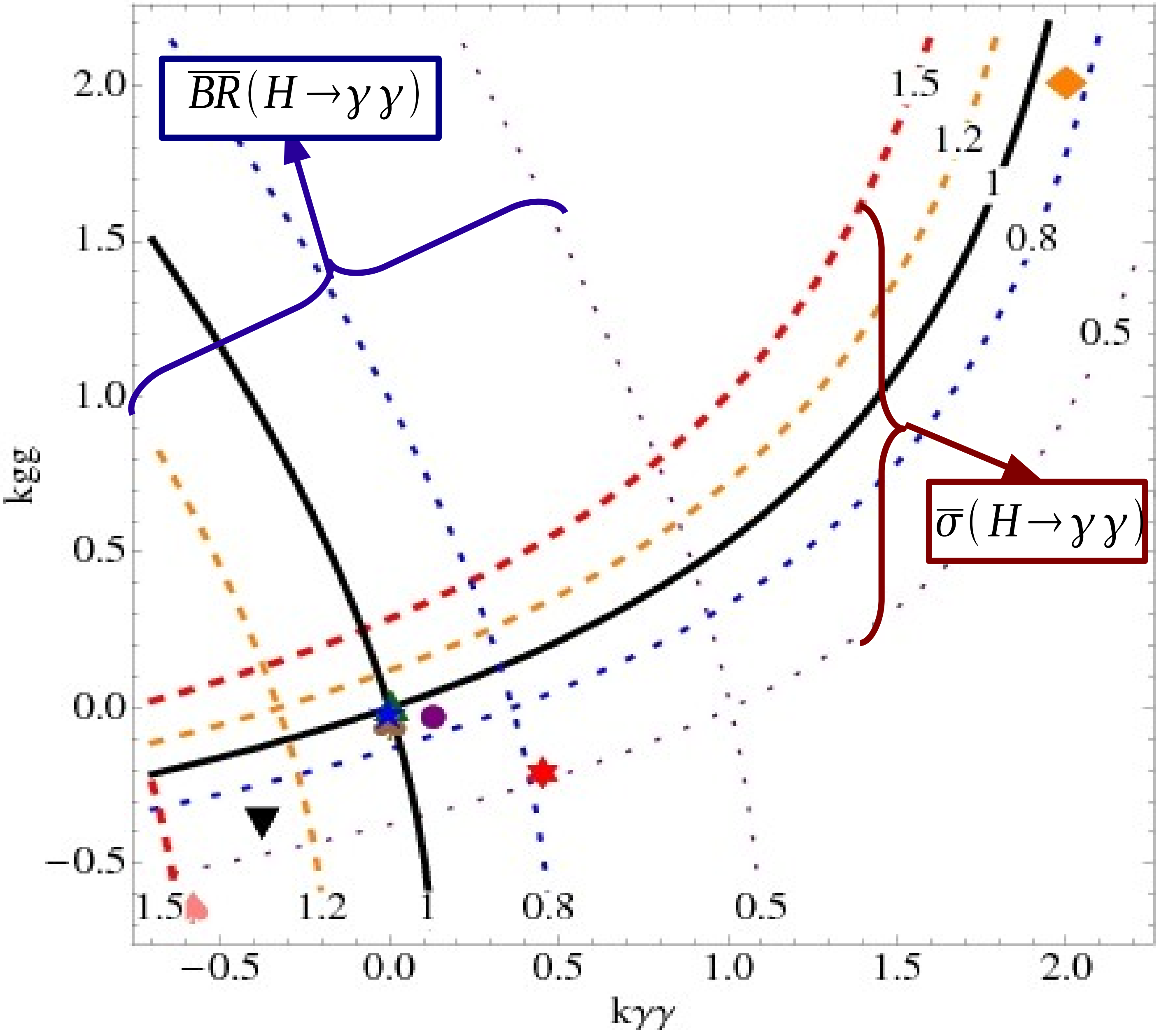
Survey of models

- 4th generation of fermion (♦)
- SUSY in the MSSM golden region (♣)
- Little Higgs models
  - Simplest Little Higgs model (▲) (W' at 2 TeV)
  - Littlest Higgs model with (f= 500 GeV) and without T-parity (f=5 TeV) (✶)
- 5D models for flat and warped space (W$^{(1)}$ at 2 TeV)
  - Universal Extra Dimension (★)
  - Minimal Composite Higgs (●)
  - Brane Higgs with flavor (▼ and ♠)

- Survey of known new physics scenarios

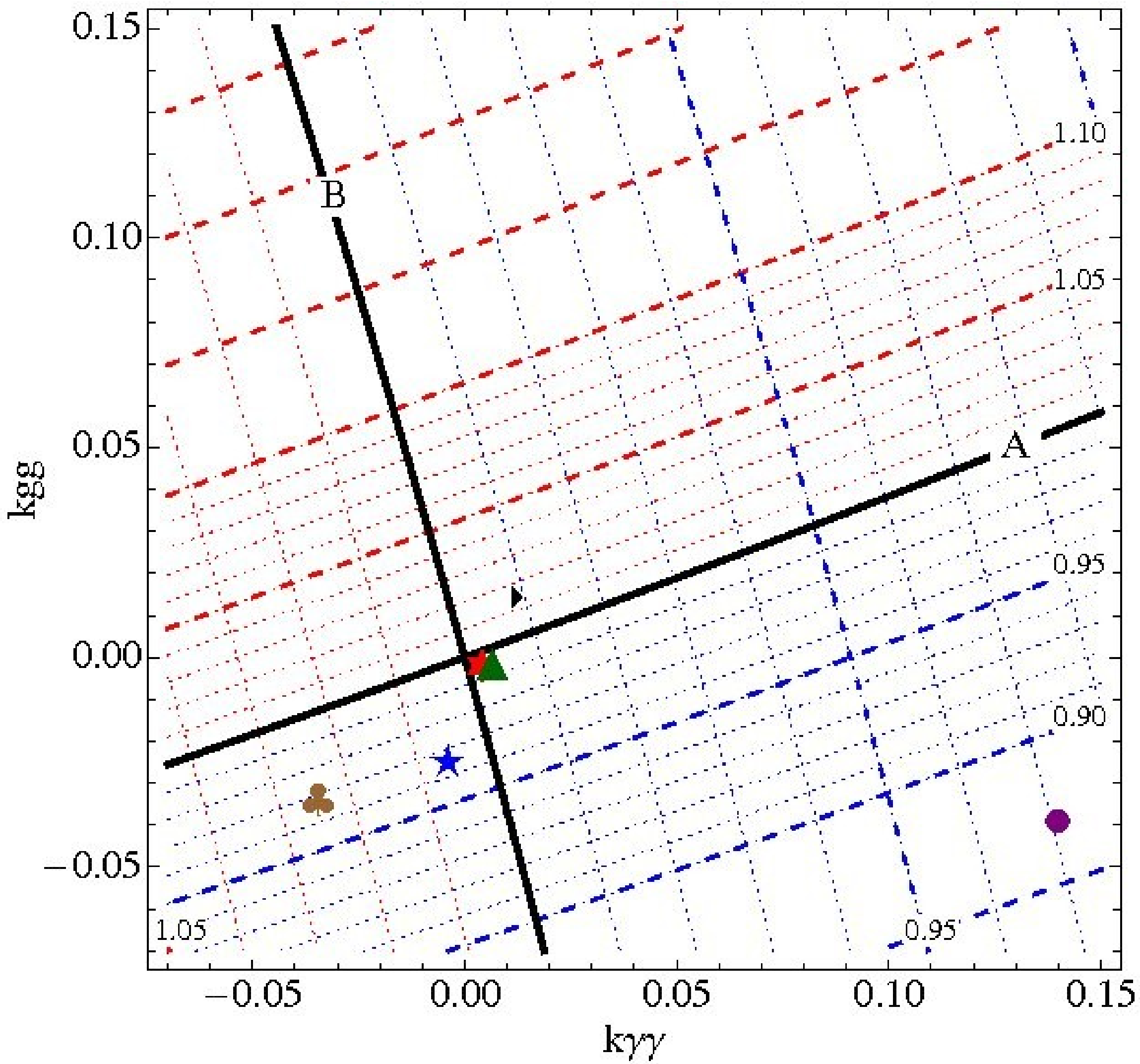
  → Impact of new physics on Higgs searches

The $\kappa_{\gamma\gamma}$-κ_{gg} parameter space for LHC



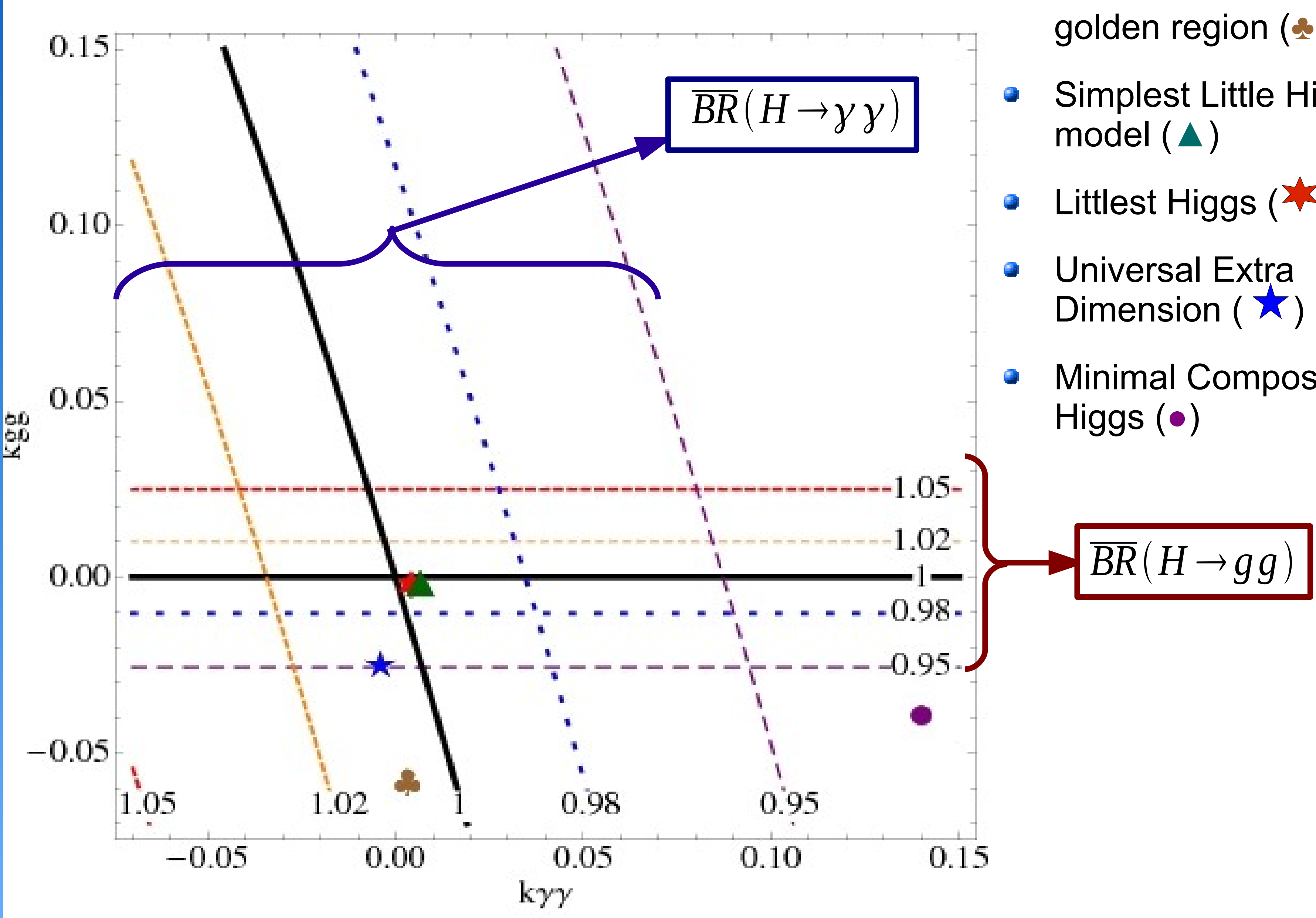
- 4^{th} generation (♦)
- SUSY in the MSSM golden region (♣)
- Simplest Little Higgs model (▲)
- Littlest Higgs (✸)
- Universal Extra Dimension (★)
- Minimal Composite Higgs (●)
- Brane Higgs with flavor
  - In flat space (▼)
  - In warped space(♠)

Zoom on the central region



- SUSY in the MSSM golden region (♣)
- Simplest Little Higgs model (▲)
- Littlest Higgs (✶)
- Universal Extra Dimension (★)
- Minimal Composite Higgs (●)

The $\kappa_{\gamma\gamma}$-κ_{gg} parameter space for ILC



- SUSY in the MSSM golden region (♣)
- Simplest Little Higgs model (▲)
- Littlest Higgs (✶)
- Universal Extra Dimension (★)
- Minimal Composite Higgs (●)

First expectations for LHC and for ILC

- Inclusive cross section is typically reduced. Enhancement will lead to unexpected new physics.
- For LHC:
  - New particles will be discovered directly first
    ➡ What is its link with EW symmetry ?
  - Pointing a quadrant in the κ's parameter space
    ➡ General behaviors of this new physics
  - Some models have signature visible at LHC.
- For ILC
  - Sizable effects for all kind of scenarios and below the direct production threshold of NP.
- $\kappa_{\gamma\gamma}$-κ_{gg} parameter space:
  - Useful tool for the study of EW symmetry breaking.
  - Complementary to the direct detection

What is obtained from theory

- Kappas are model-dependent but general features exist
- Example of a Composite Higgs Model in warped space:
  - For 1/R' ≈ 1TeV (IR-Brane Scale) ➡ $m_{W1} \approx 2{,}4$ TeV

$$\kappa_{\gamma\gamma} \propto \kappa_{gg} \propto \left(\frac{1\mathrm{TeV}}{1/R'}\right)^2$$

  - Coefficients depend on the particle properties
  - Coefficients are computed using coupling and mass spectra:

Minimal Composite		W_{light}	W_{tower}	t_{light}	t_{tower}	Total
Higgs	$\kappa_{\gamma\gamma}$	0.17	0.009	-0.029	-0.011	$+0.14$
$1/R' = 1$ TeV	κ_{gg}	0	0	-0.029	-0.011	-0.04

Implementation of the κ's parametrization

- New physics assumed to modify only Higgs loops
  - Same kinematical behaviour
- In Madgraph with HEFT model: Higgs loops described with effective vertices.
- CMS test with

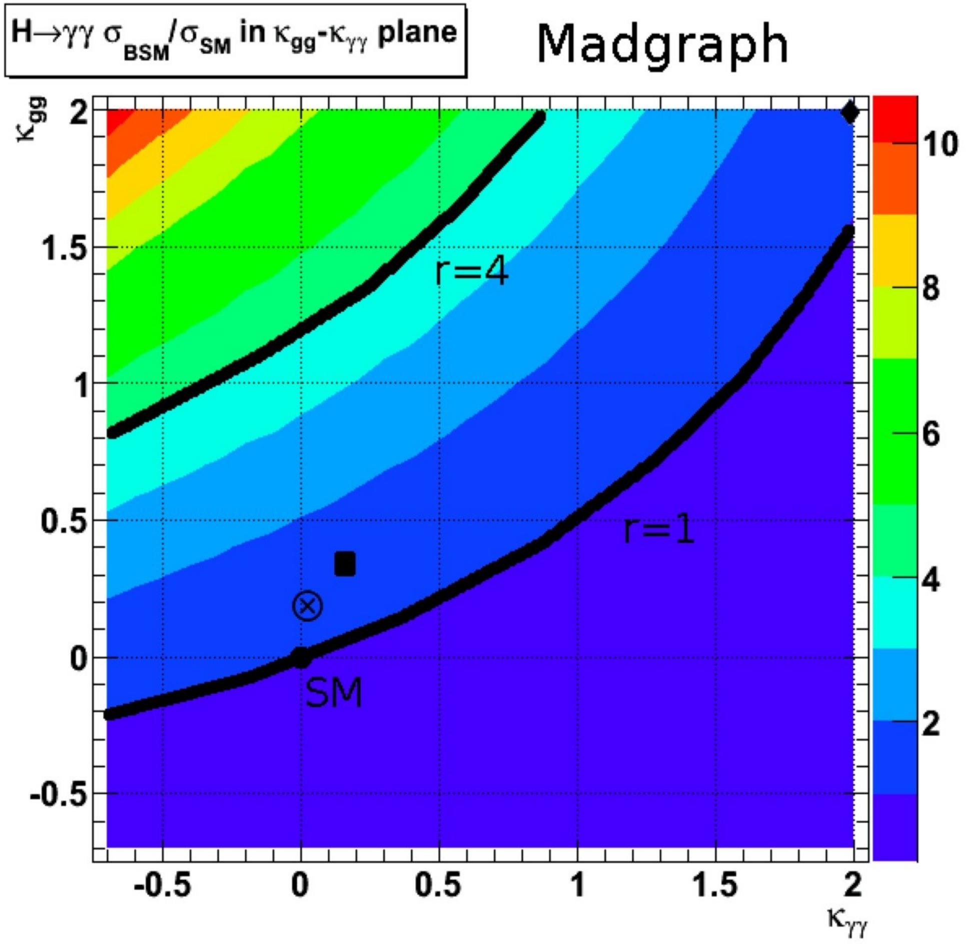
  this parameterization:

  limit on x-section

  4 times SM one

  @7 TeV 1 fb-1

  for mH=120 GeV



Conclusions

- Higgs physics will depend on new physics

- Modification of the observables could be sizable

- Parametrization proposed
  - Allows a survey of new physics with minimal assumptions
  - largely model independent
  - Generalization possible with no or few extra parameters

- Use of the parameterization
  - To give hint about the kind of expected or unexpected new physics behavior
  - To reject some models of new physics beyond SM.

Conclusions and perspectives

- Model-independent parametrization
- Applied on a large survey of various models
- Improvement and perspectives:
  - Implementation in MC simulations
  - Measurement of other channels to add new constraint