U(1)' models at the LHC

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Based on E. Accomando, C. Corianò, LDR, J. Fiaschi, C. Marzo, S. Moretti
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Outline

1. The minimal *Z'* model

2. LHC constraints

3. RG and high energy behaviour

4. LHC phenomenology

The minimal *Z'* model

- Z' naturally arises from many GUT scenarios such as SO(10), E_6, L-R, string-theory constructions, KK theories, etc.
- Interesting phenomenology potentially accessible at colliders:
  Z' usually accompanied by extra degrees of freedom (seesaw can be implemented)
- Possibility to explain baryogenesis through resonant leptogenesis

➢ Gauge sector

$$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)'$$

➢ Fermion sector

SM-singlet right-handed neutrinos ν_R

required by anomaly cancellation

➢ Scalar sector

SM-singlet scalar χ

required by SSB of U(1)'

provides Majorana masses for ν_R

➢ New states: *Z' gauge boson, 3 heavy neutrinos, 1 real scalar*

➢ New parameters:

$g'_1, \tilde{g}, M_{Z'}, \alpha, m_{H2}, m_{\nu_h}$

The minimal *Z'* model: *a comment on the kinetic mixing*

- The most general Lagrangian allowed by gauge invariance admits a *kinetic mixing* between the two abelian field strengths

$$\mathcal{L} = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} - \frac{1}{4} F'^{\mu\nu} F'_{\mu\nu} - \frac{\kappa}{2} F^{\mu\nu} F'_{\mu\nu}$$

even if absent at tree-level it can be reintroduced by radiative corrections

- The kinetic Lagrangian can be recast into a diagonal form thus introducing a non-diagonal covariant derivative

$$\mathcal{D}_\mu = \partial_\mu + i g_1 Y B_\mu + i(\tilde{g} Y + g'_1 Y_{B-L}) B'_\mu + \dots$$

an additional abelian gauge factor can always be described by a linear combination of the hypercharge and of the B-L quantum number

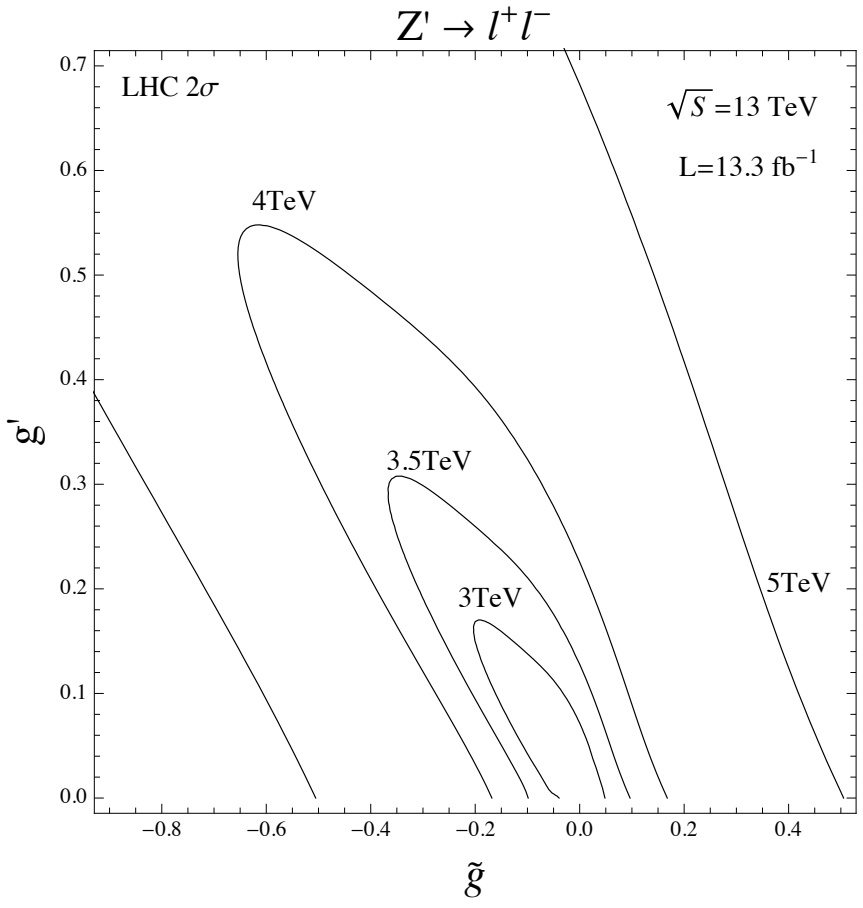
- We can explore an entire class of minimal Abelian models through the ratio of the gauge couplings $\tilde{g}/g'_1$

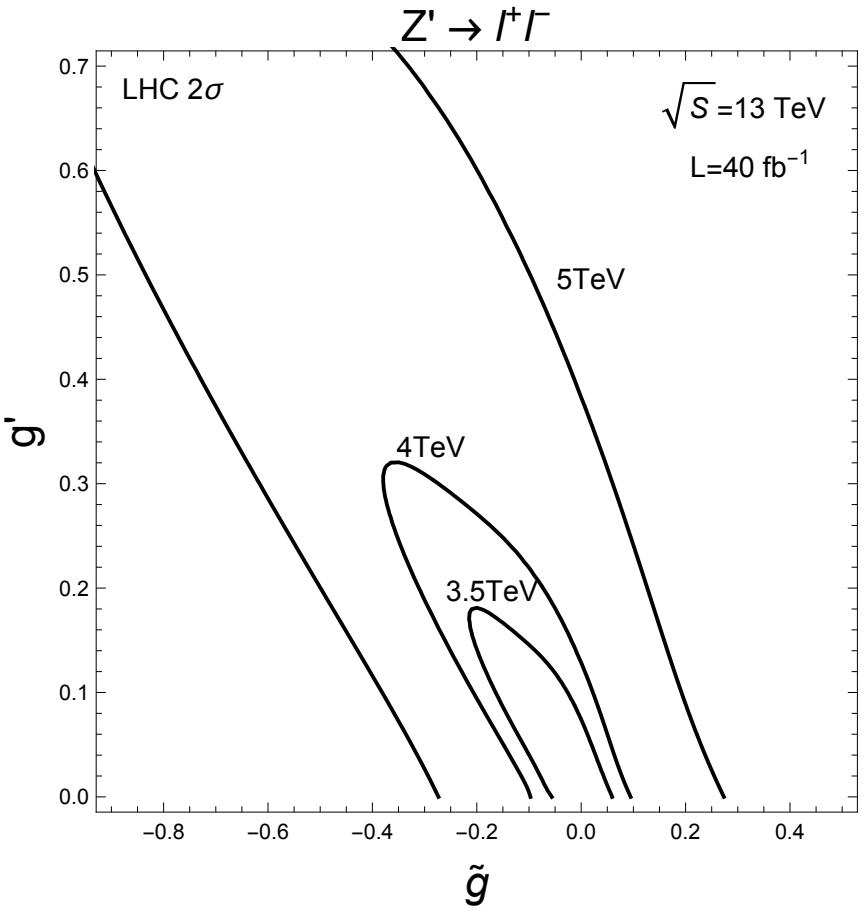
- Typical benchmark models:

  $g'_1 = 0$: sequential SM
  $\tilde{g} = 0$: pure B-L
  $\tilde{g} = -2g'_1$: $U(1)_R$
  $\tilde{g} = -4/5\, g'_1$: $U(1)_X$ from SO(10)

Constraints from LHC searches

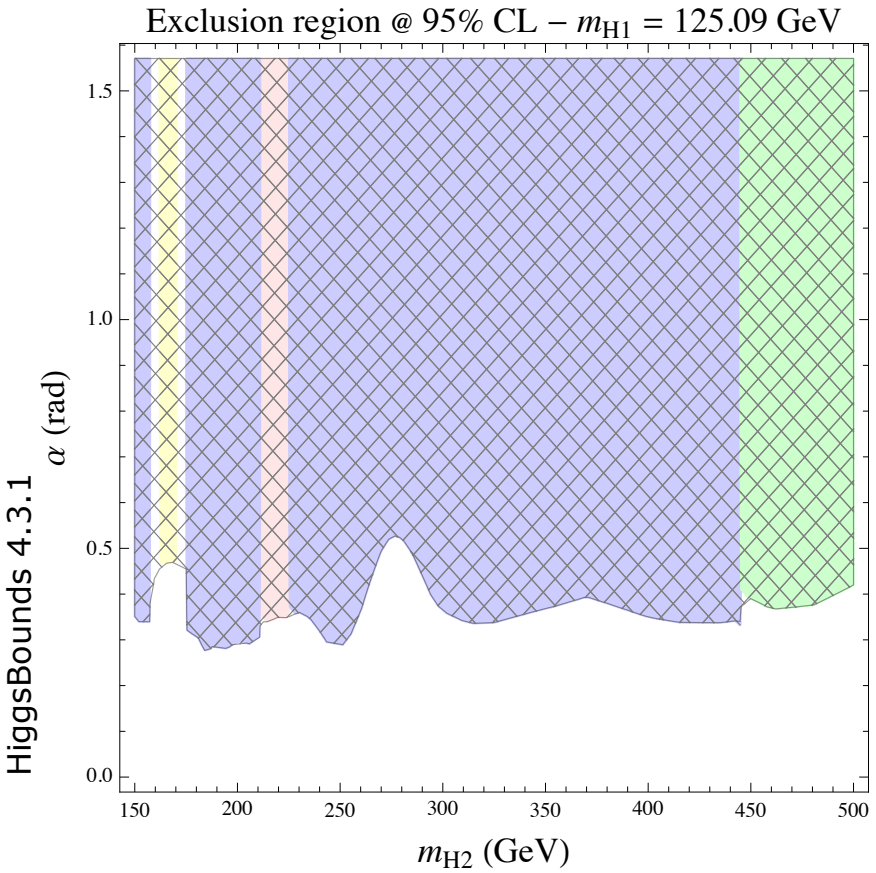
2σ significance contour levels in the $\tilde{g} - g'_1$ space

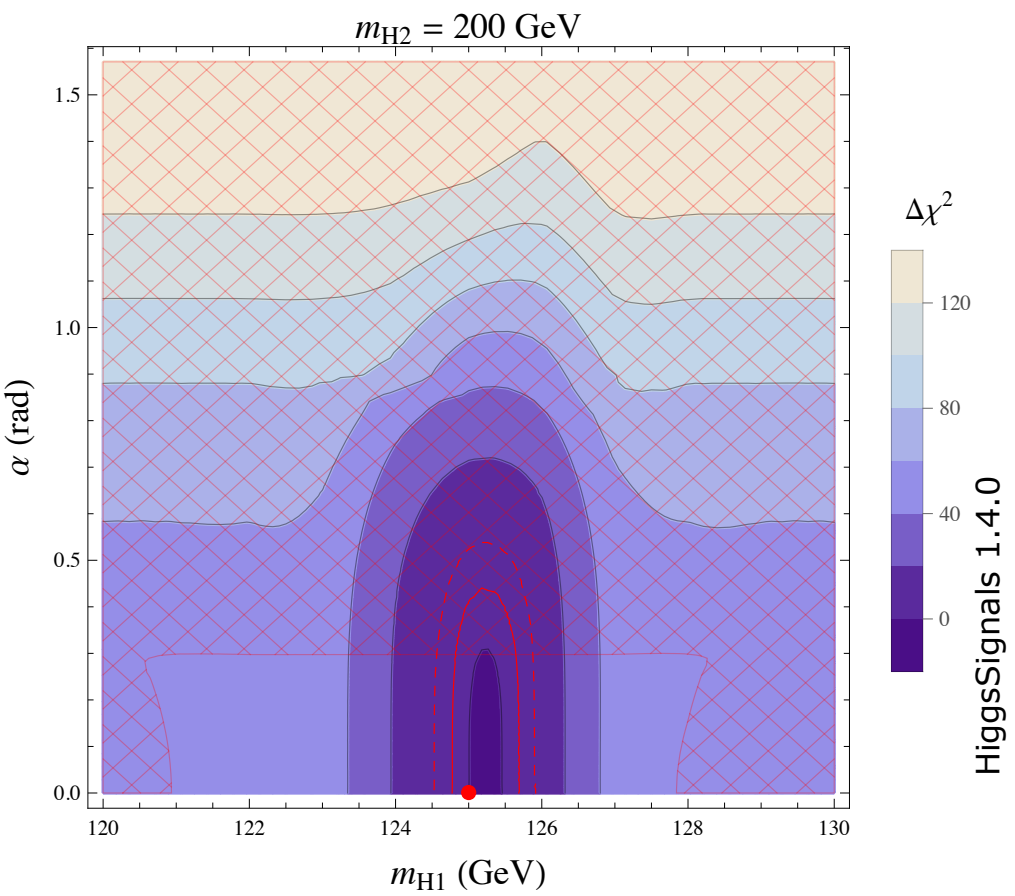




Constraints from LHC searches

The extended scalar sector is strongly constrained by Higgs searches at the LHC





- *full leptonic decay of two Z*
- *full leptonic decay of two W*
- *full and semi leptonic decay of ZZ and WW*
- *combined search in γγ, ZZ, WW, ττ, bb*

χ^2 compatibility fit with the Higgs signal measurements

Renormalisation group evolution

establish a direct connection between accessible EW scale spectra and a potential underlying GUT structure

low energy parameters ⟷ RGE ⟷ *high energy structure*

along the RG evolution we require:

perturbativity of the couplings

stability of the vacuum

unification (work in progress)

- delineate the viable parameter space from both a *phenomenological perspective* and its *theoretical consistency*
- ultimately direct experimental investigations towards key analyses enabling one to make an assessment of the high energy structure of the model

Renormalisation group evolution

Some technical details:

	β functions	matching conditions
LO	one loop	tree level
NLO	two loop	one loop
NNLO	three loop	two loop

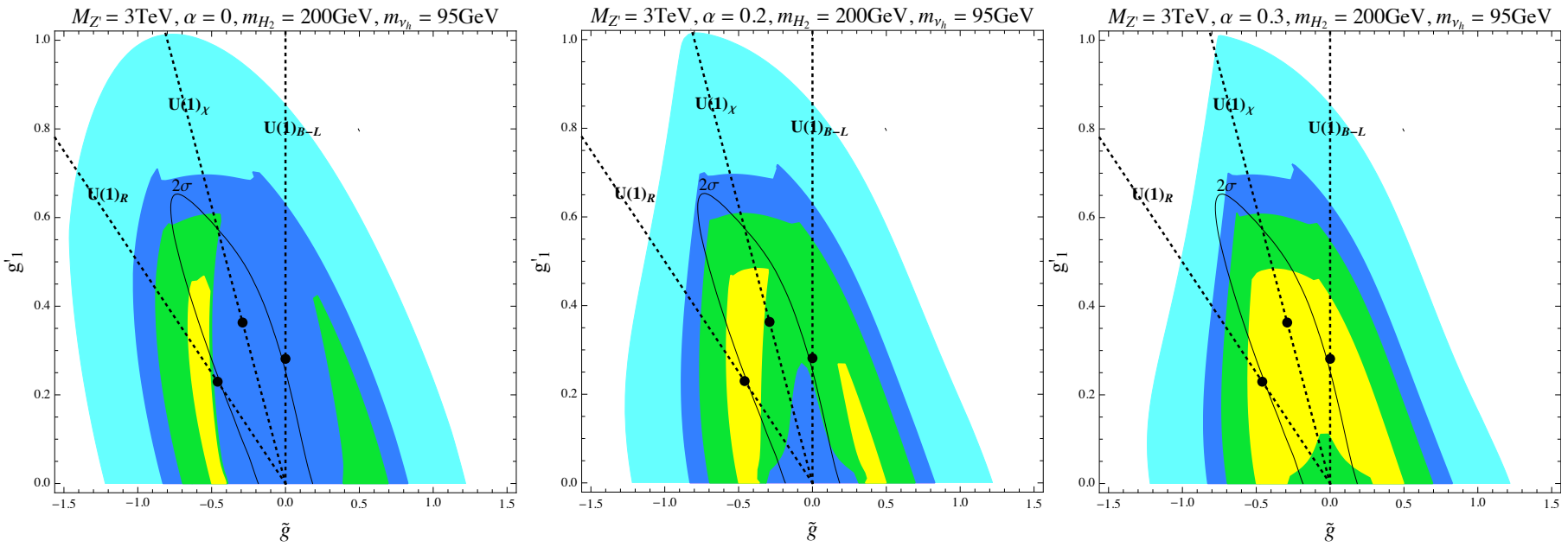
- A complete NNLO analysis is only available for the SM
- NLO analysis can be implemented for a general QFT
  - 2L β functions are known
  - 1L matching conditions must be computed for each model

Matching conditions provide the initial value of the running couplings computed in the $\overline{\text{MS}}$ renormalisation scheme as a function of the physical on-shell parameters

$$\alpha_{\overline{MS}} = \alpha_{OS} + \delta\,\alpha_{OS}\Big|_{fin}$$

High energy behaviour

Perturbativity of the couplings and stability of the vacuum and in the $\tilde{g} - g'_1$ space



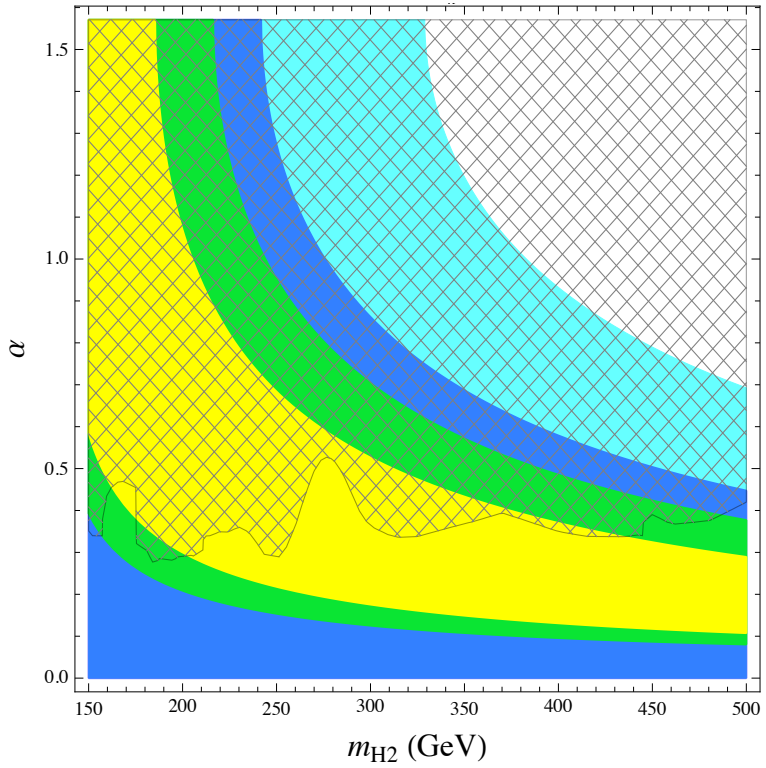
- 10^5 GeV $< Q_{max} < 10^8$ GeV
- 10^8 GeV $< Q_{max} < 10^{10}$ GeV
- 10^{10} GeV $< Q_{max} < 10^{15}$ GeV
- $Q_{max} > 10^{15}$ GeV

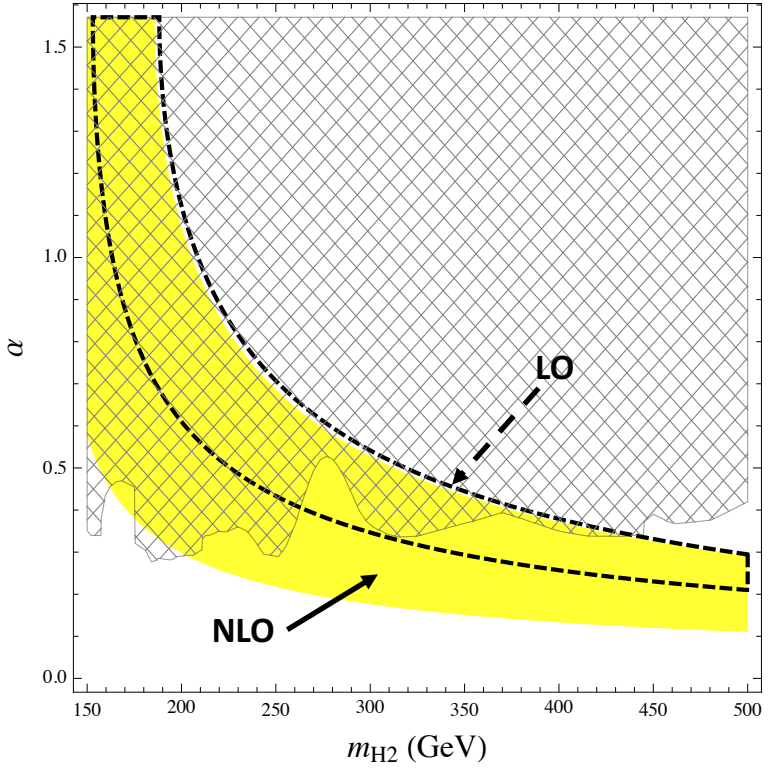
Black dots represent some benchmark models
($U(1)_R$, $U(1)_X$, $U(1)_{B-L}$)
usually addressed in the literature

- The destabilising effect of heavy neutrinos is suppressed
- Stability improves as α moves away from zero

High energy behaviour

Perturbativity of the couplings and stability of the vacuum and in the $m_{H2} - \alpha$ space





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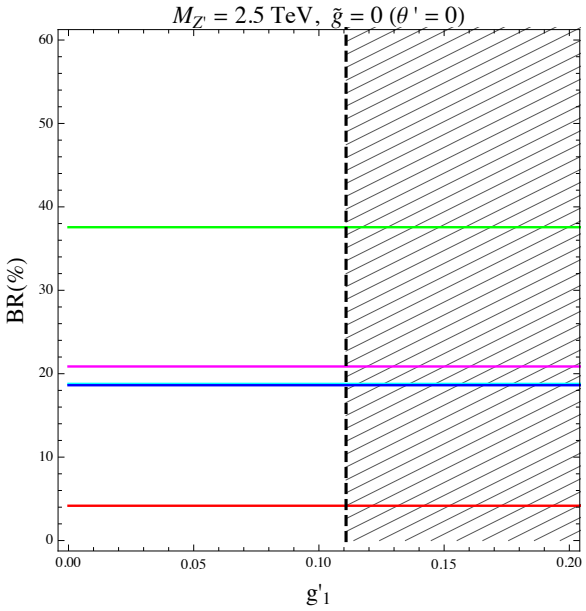
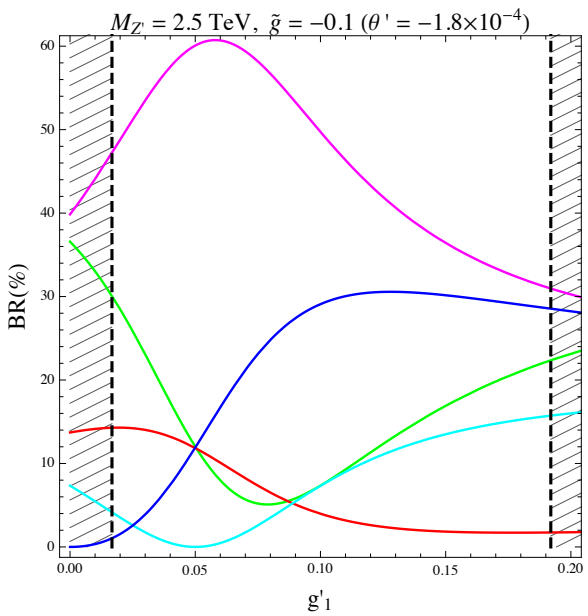
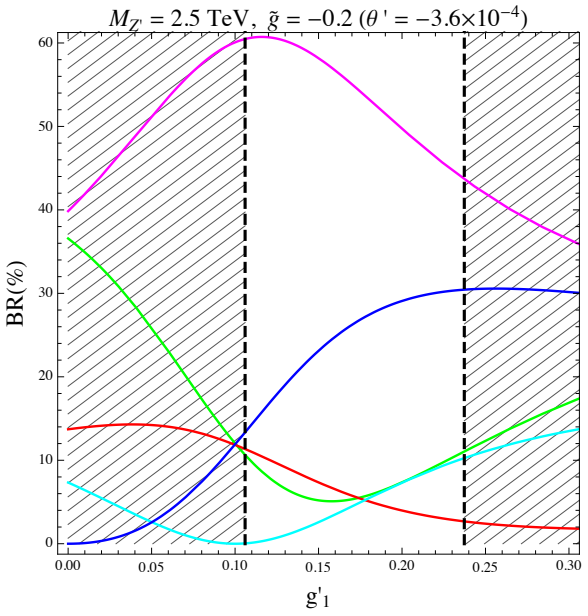
Comparison between NLO (yellow region) and LO (region in dashed line) results

Z' decays

Z' branching ratios







in the pure B-L
charged lep. decay is preferred

- *Z' -> charged leptons*
- *Z' -> light neutrinos*
- *Z' -> light quarks*
- *Z' -> top quarks*
- *Z' -> heavy neutrinos*

The decay mode hierarchy is drastically changed when $\tilde{g} \neq 0$

$g'_1 = 0$ recovers the SSM limit

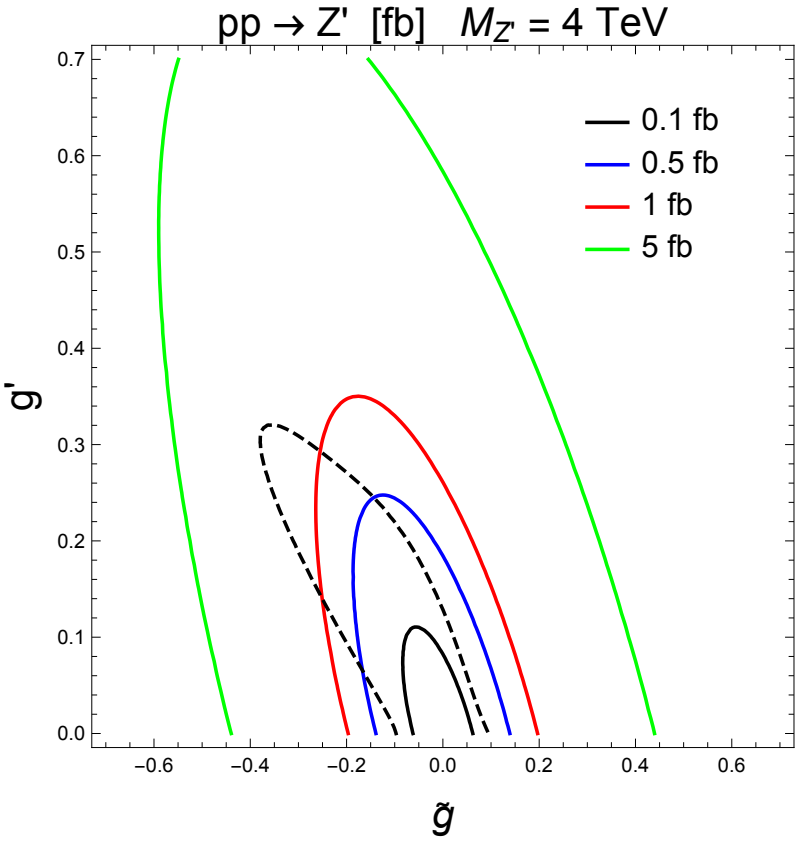
$\tilde{g} \neq 0$ opens new Z' decay channels

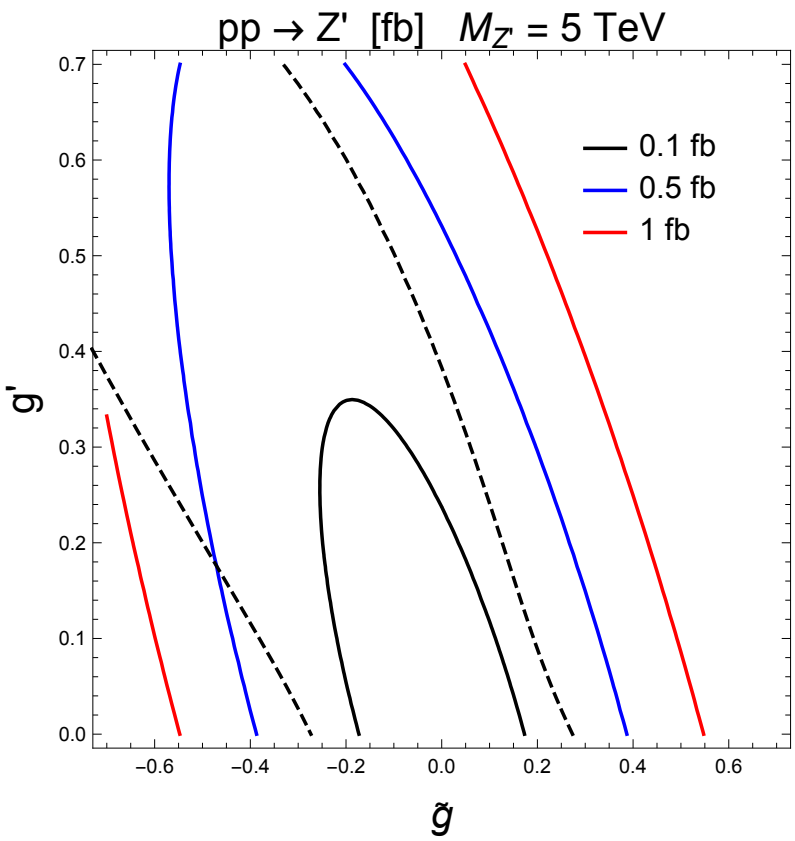
BR ~ 2 % each

$$\begin{cases} Z' \to WW \\ Z' \to Z\ H_1 \\ Z' \to Z\ H_2 \end{cases}$$

Z' production

Z' on-shell production cross section at the LHC (13TeV)

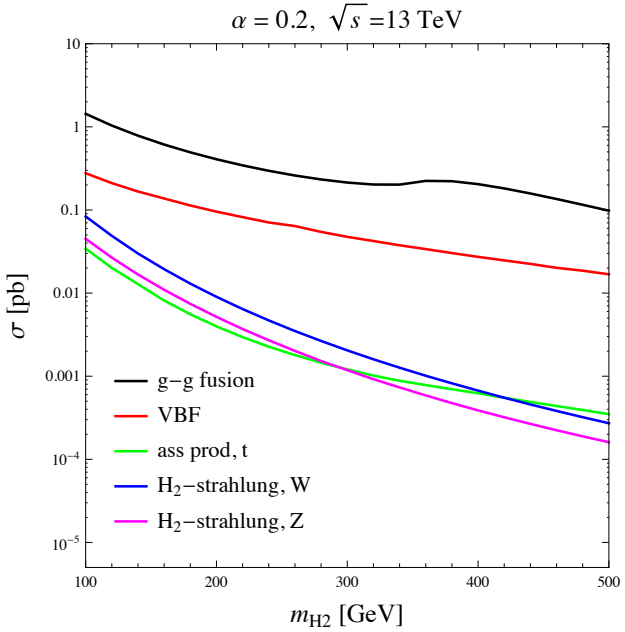


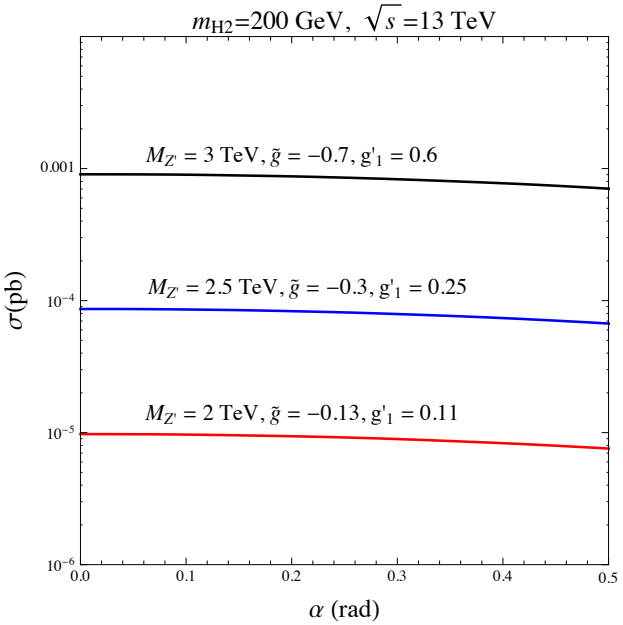


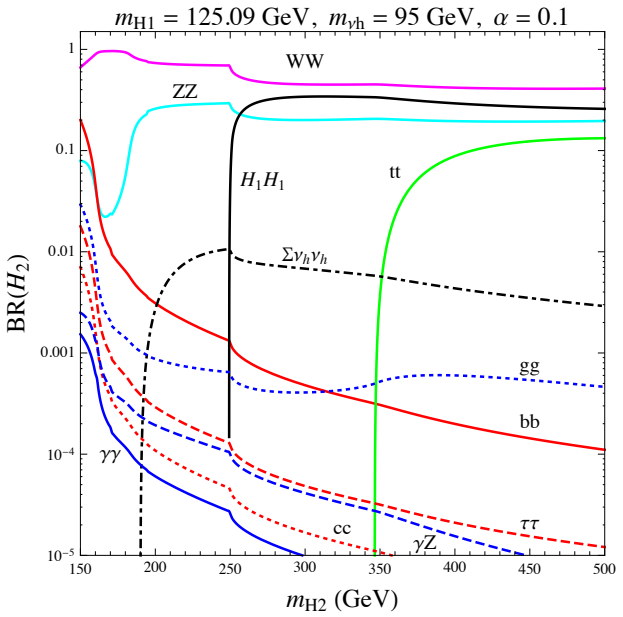
Dashed lines: 2σ significance contour levels from DY at 13 TeV and L = 40/fb

Heavy Higgs production and decay

(LHC 13 TeV)







Standard production mechanisms

$q\bar{q} \rightarrow Z'^{*} \rightarrow Z'H_2$

low σ but it is the only accessible channel for α = 0

- H_2 couplings to SM particles are rescaled by sin α with respect to the SM Higgs
- Gluon fusion is the main production mode: $\sigma\left(M_{H_2}, \alpha\right) \sim (\sin\alpha)^2\, \sigma_{SM}\left(M_{H_2}\right)$
- New decay channels: $H_2 \rightarrow \nu_h \nu_h,\ H_2 \rightarrow H_1 H_1$

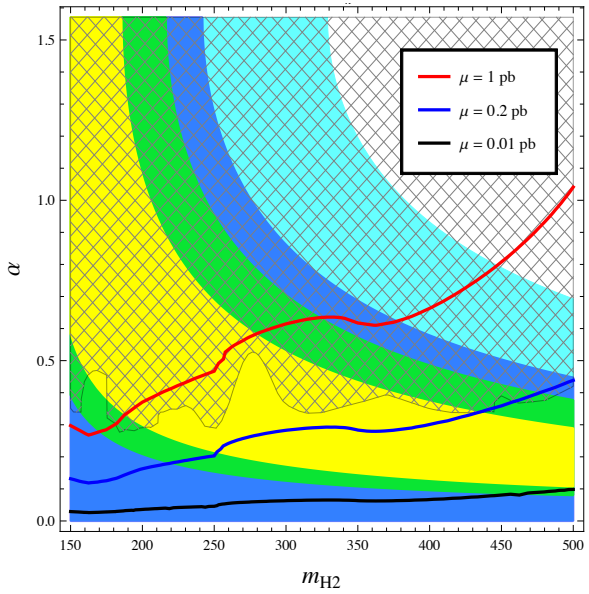
Heavy Higgs production and decay

- Favoured discovery channels

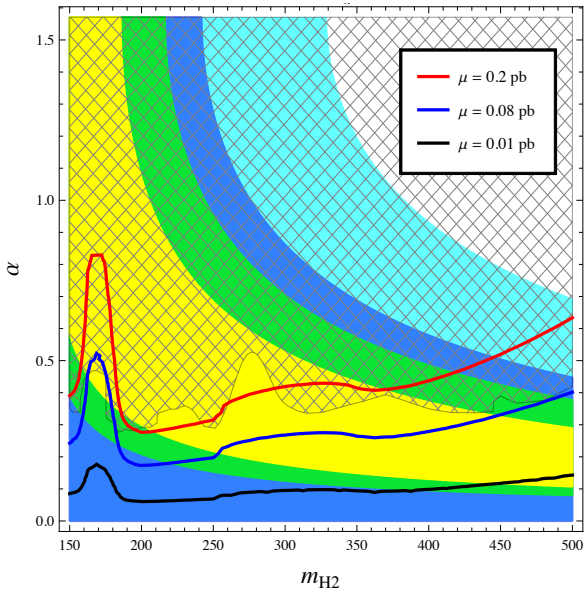
$$\begin{cases} pp \to H_2 \to WW & \text{σ up to } \sim 200 \text{ fb} - 1 \text{ pb} \\ pp \to H_2 \to ZZ & \text{σ up to } \sim 200 \text{ fb} \\ pp \to H_2 \to t\bar{t} & \text{σ up to } \sim 50 \text{ fb} \end{cases}$$

σ x BR contour level in the $m_{H2} - \alpha$ space (LHC 13 TeV)

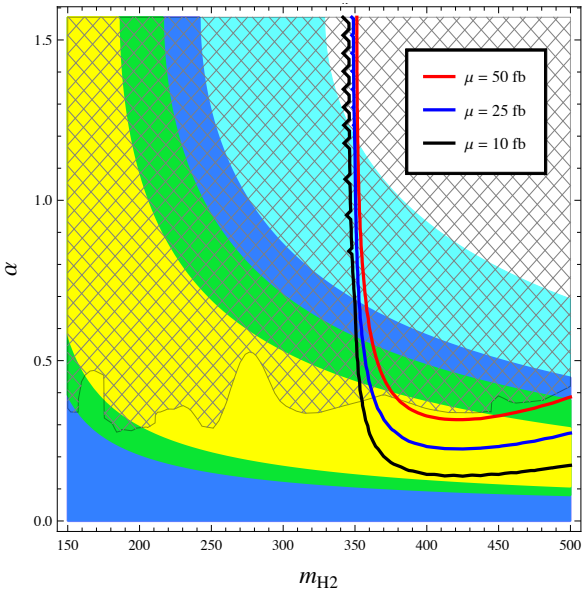
$pp \to H_2 \to WW$



$pp \to H_2 \to ZZ$



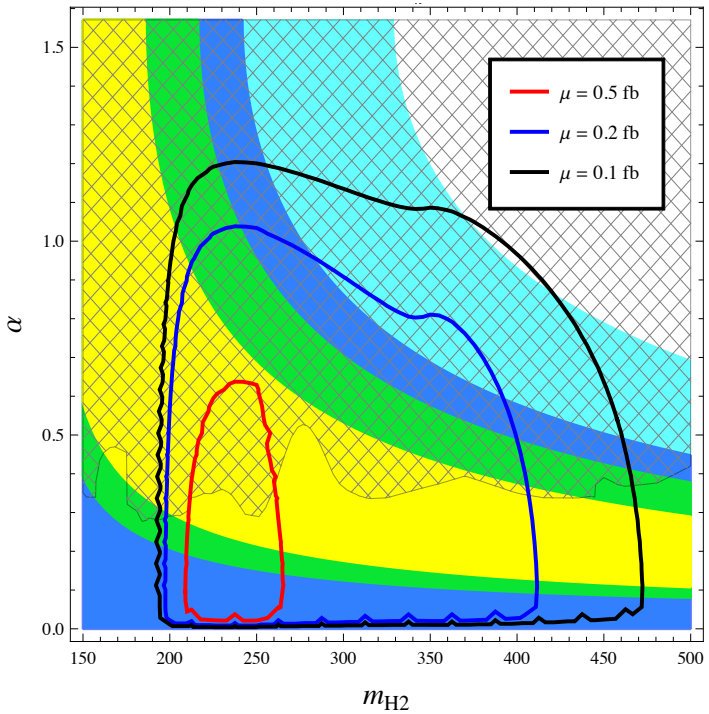
$pp \to H_2 \to t\bar{t}$



Heavy Higgs production and decay

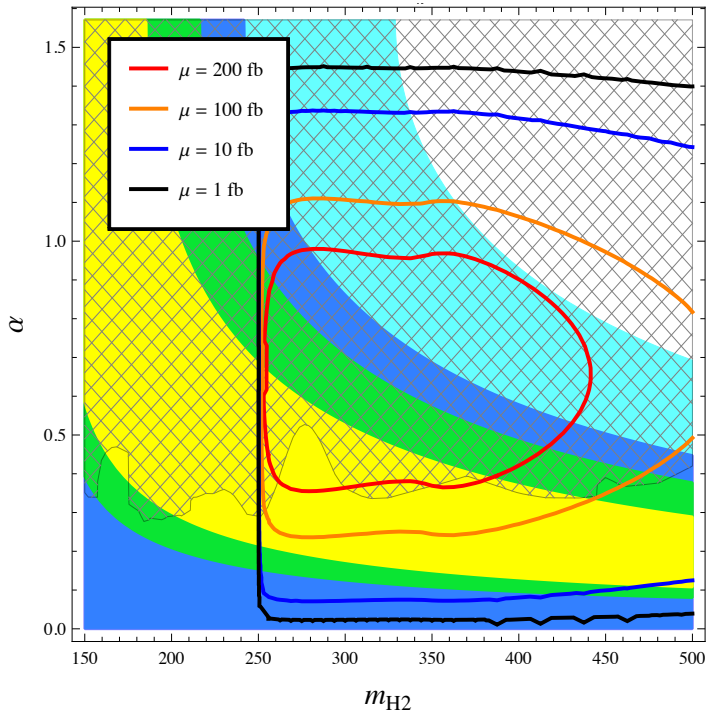
σ x BR contour level in the $m_{H2} - \alpha$ space (LHC 13 TeV)

$$pp \rightarrow H_2 \rightarrow \nu_h \nu_h$$



this channel represents a perculiar feature of this minimal class of *Z'* models

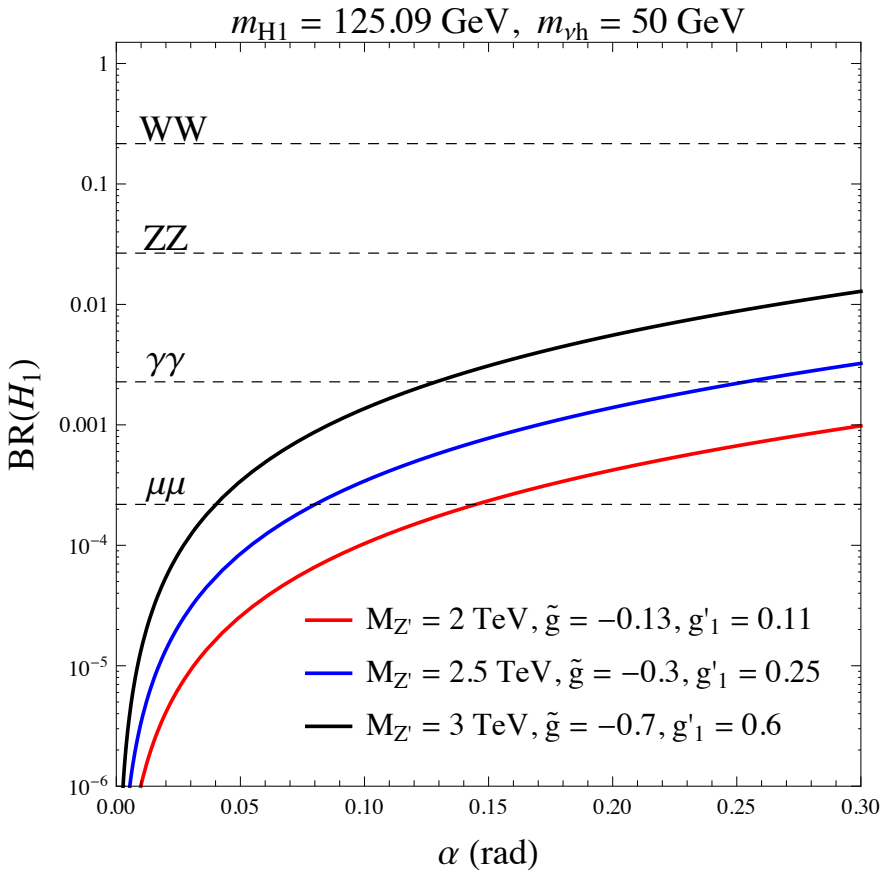
$$pp \rightarrow H_2 \rightarrow H_1 H_1$$



interesting cross section

SM-like Higgs new decay channel

When $m_{H_1} > 2m_{\nu_h}$ a new decay channel becomes accessible $H_1 \to \nu_h \nu_h$

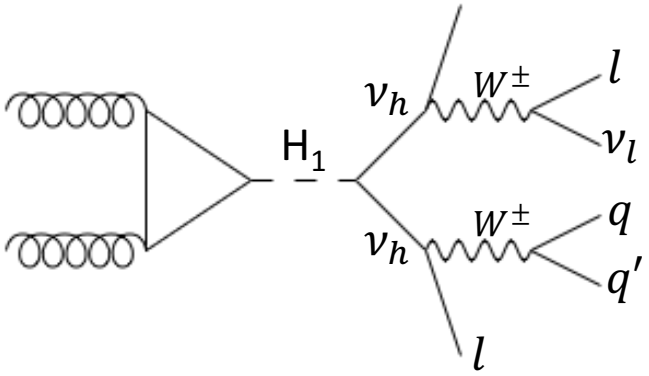


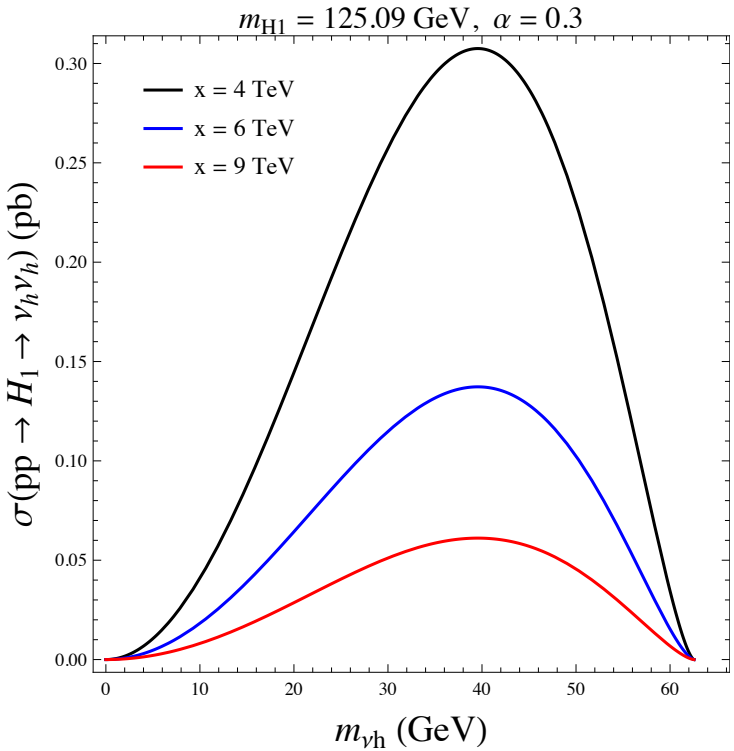
BR spans from 0.1% to 1%

$$H_1 \nu_h \nu_h \sim (\sin\alpha)\frac{m_{\nu_h}}{x} \sim (\sin\alpha)\frac{m_{\nu_h}}{M_{Z'}} g'_1$$

Heavy neutrino production processes

1. *Heavy neutrino production from the* **SM-like Higgs**
2. *Heavy neutrino production from the* **Heavy Higgs**
3. *Heavy neutrino production from the* **Z'**





Heavy neutrinos with $m_{\nu_h} < m_{H_1}/2$ are long-lived and may appear as displaced vertices in the detectors

LHC @ 13 TeV

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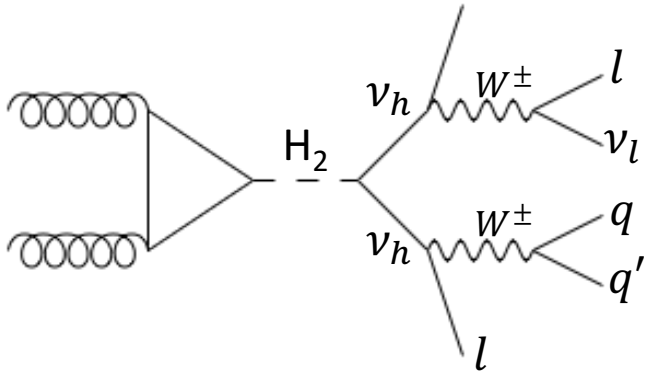

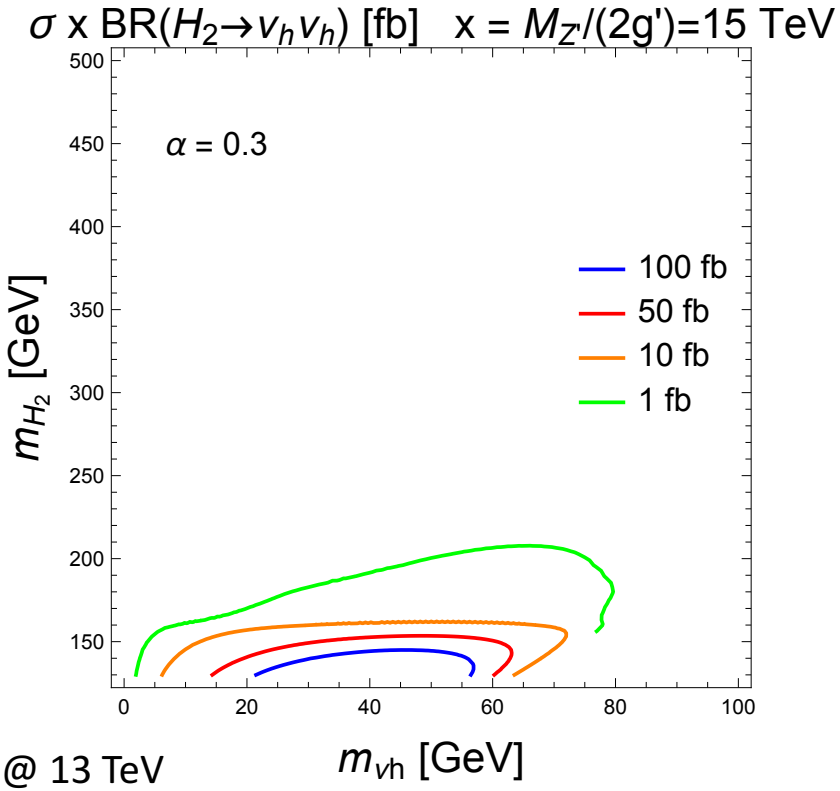

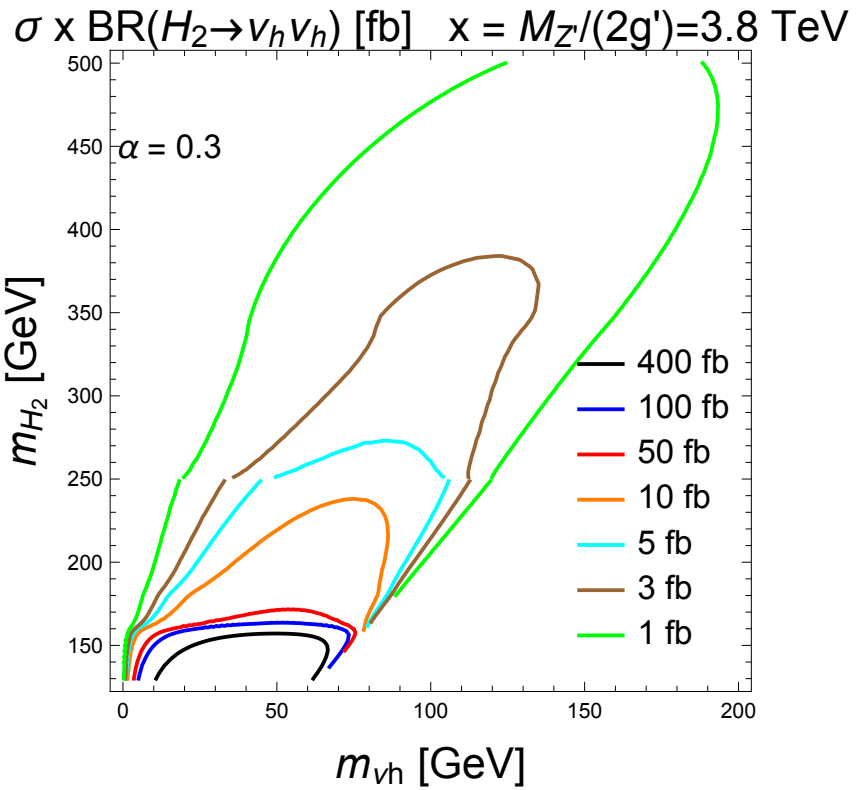

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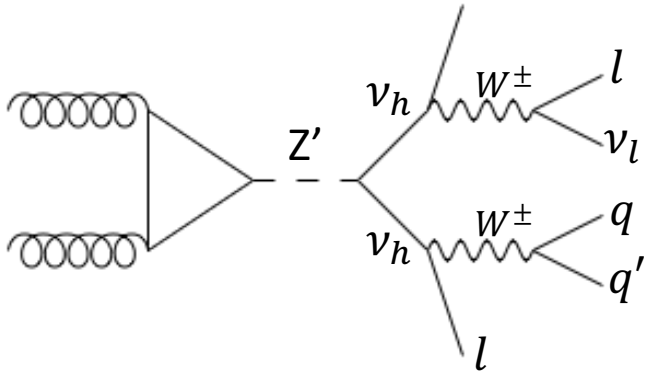
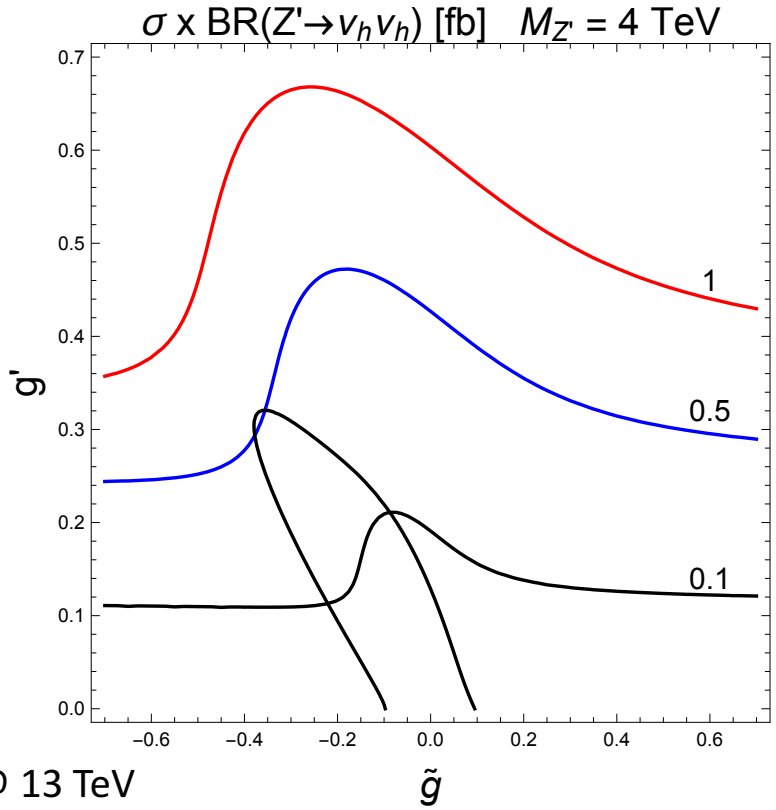
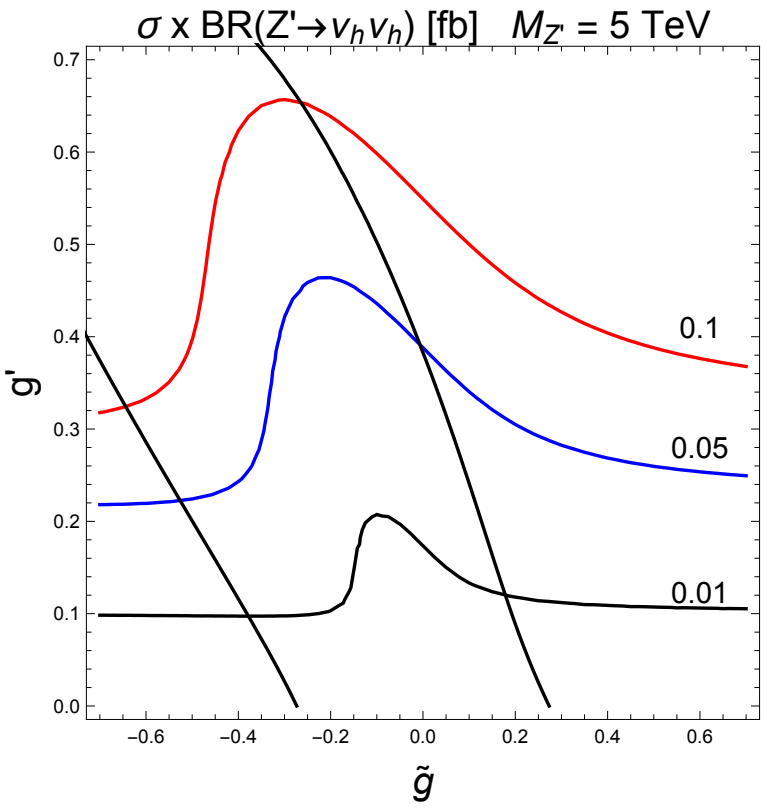




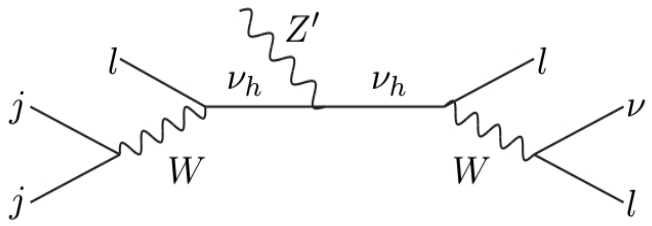


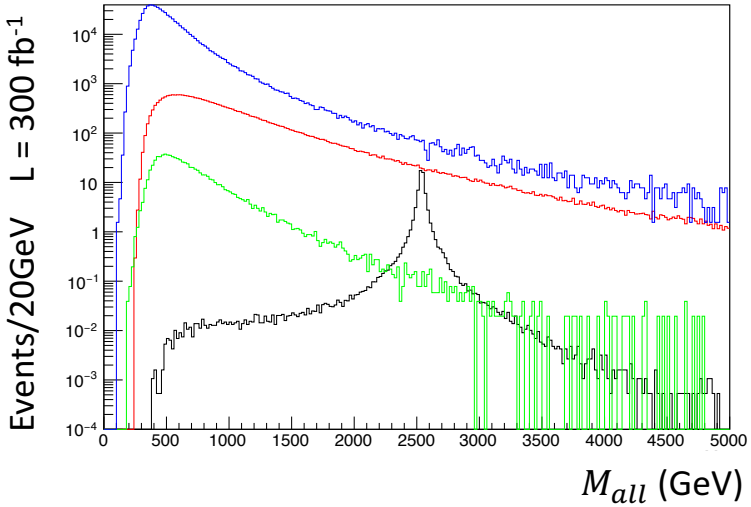
LHC @ 13 TeV

Z' signatures

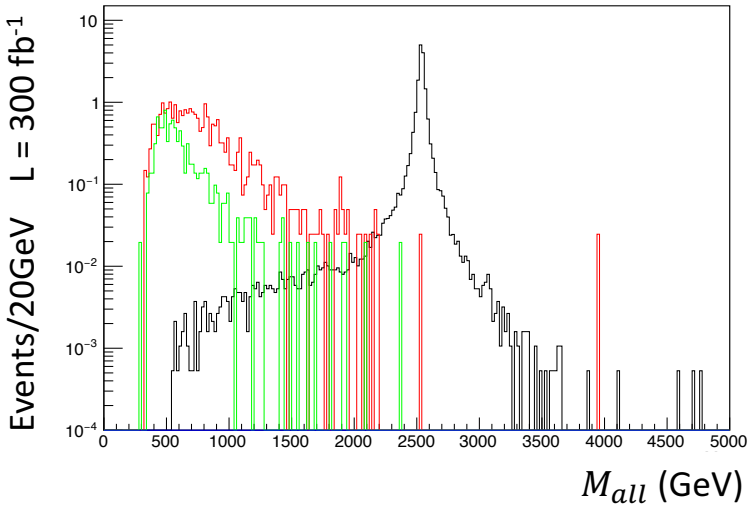
$M_{Z'} = 2.5\ TeV, m_{\nu_h} = 200\ GeV$

$$Z' \to \nu_h \nu_h \to 3l + 2j + E_{Tmiss}\ (1\ \nu_l)$$





No cuts



Cuts applied except on M_{all}

Backgrounds

- $WZjj$
- $t\bar{t}$ (with 3rd lepton from b quark)
- $t\bar{t}lv$

Cuts

- momenta, angular acceptance, isolation
- $|M_{jj} - M_W| < 20\ GeV$
- $|M_{l^+l^-} - M_Z| > 10\ GeV$
- $|M_{all} - M_{Z'}| < 250\ GeV$

The longitudinal momentum of the v_l is reconstructed from the W mass and minimising $X = |M^2_{l_1 l_2 \nu_l} - M^2_{l_3 j_1 j_2}|$

Z' signatures

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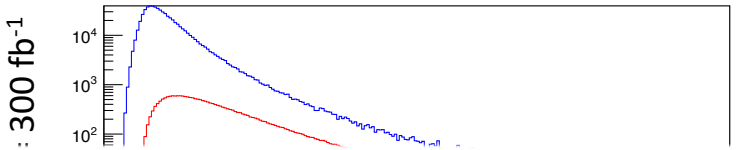
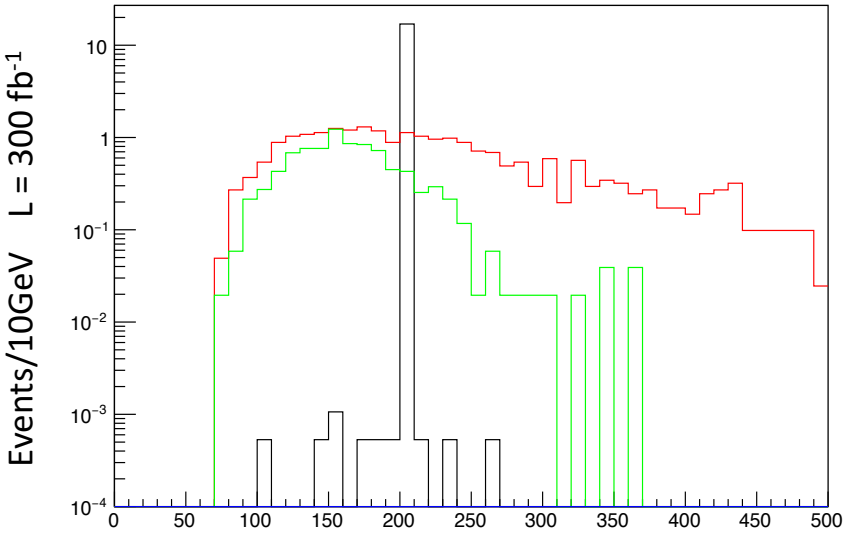
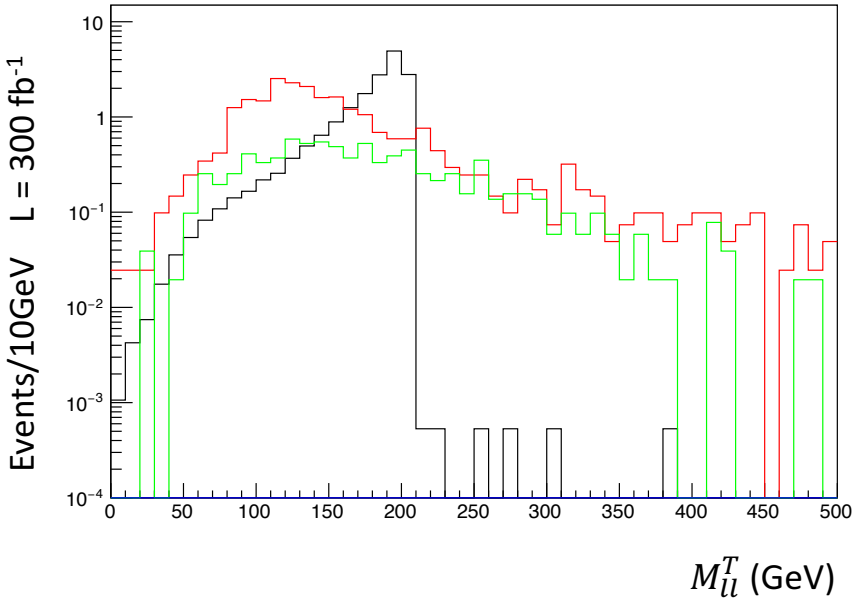


The heavy neutrino mass can be identified





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The longitudinal momentum of the ν_l is reconstructed from the W mass and minimising $X = \left|M^2_{l_1 l_2 \nu_l} - M^2_{l_3 j_1 j_2}\right|$

Conclusions

- Minimal Z' extensions of the SM
  neutral gauge boson, scalar and RH neutrinos
  and a minimal set of new parameters

- LHC (DY + HiggsBounds/HiggsSignals)significantly constrains the parameter space

- Peculiar signatures:
  $pp \to Z' \to \nu_h \nu_h$
  $pp \to Z'^{*} \to Z' H_2$
  $pp \to H_2 \to \nu_h \nu_h, pp \to H_2 \to H_1 H_1$
  $pp \to H_1 \to \nu_h \nu_h$ (heavy neutrinos are long−live particles: *displaced vertices*)

- RG methods can be effectively used to establish a connection between EW scale parameters and the underlying GUT structure