

Phenomenology of minimal Z' models: *from the LHC to the GUT scale*

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Based on E. Accomando, C. Corianò, LDR, J. Fiaschi, C. Marzo, S. Moretti
arXiv:1605.02910

Outline

1. The minimal Z' model
2. EWPTs and 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

$$\mathcal{D}_\mu = \partial_\mu + ig_1 Y B_\mu + i(\tilde{g} Y + g'_1 Y_{B-L}) B'_\mu + \dots$$

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:

$$g'_1 = 0 : \text{sequential SM}$$

$$\tilde{g} = 0 : \text{pure B-L}$$

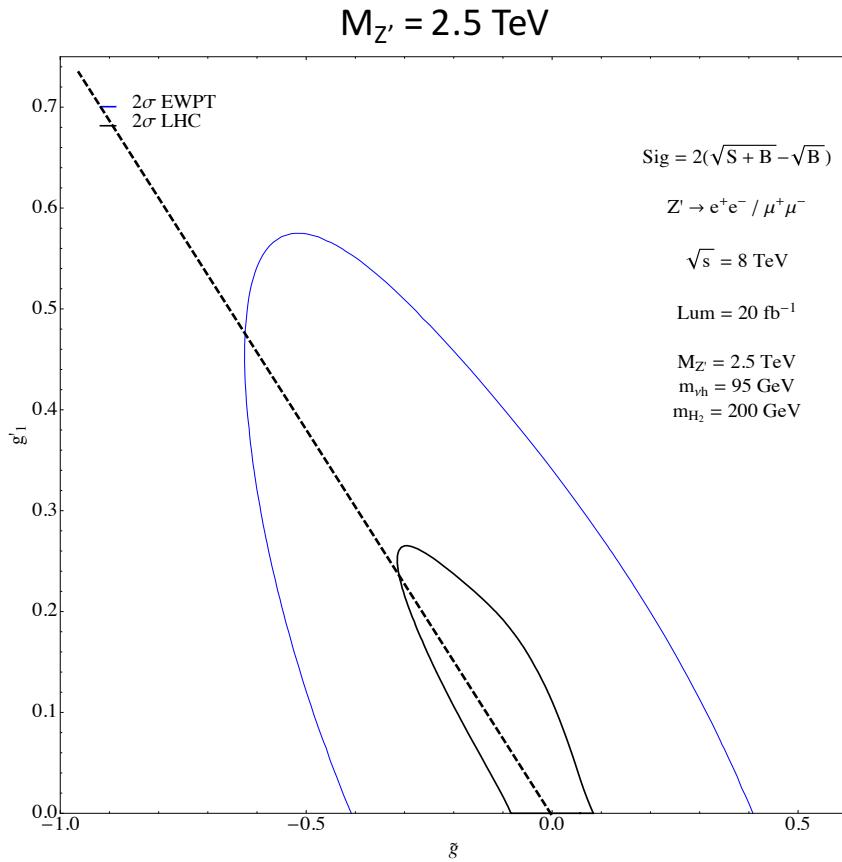
$$\tilde{g} = -2g'_1 : \text{U(1)}_R$$

$$\tilde{g} = -4/5g'_1 : \text{U(1)}_X \text{ from SO(10)}$$

Constraints from EWPTs and LHC searches

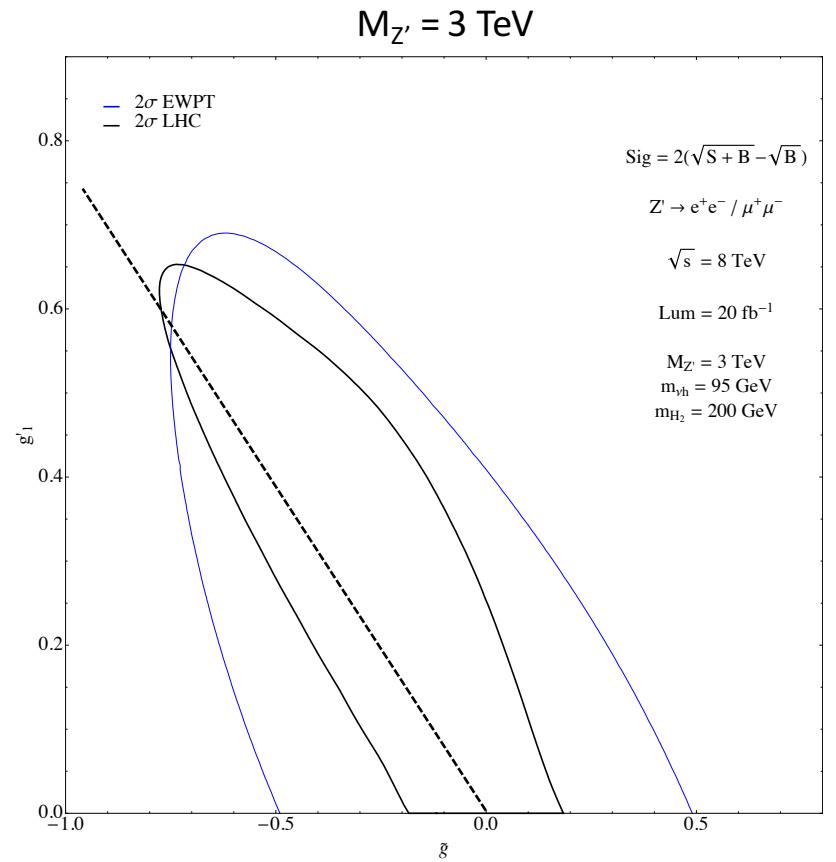
2σ significance contour levels in the $\tilde{g} - g'_1$ space

----- Leptophobic direction
 $g'_1/\tilde{g} \sim -3/4$



EWPTs from LEP2 data

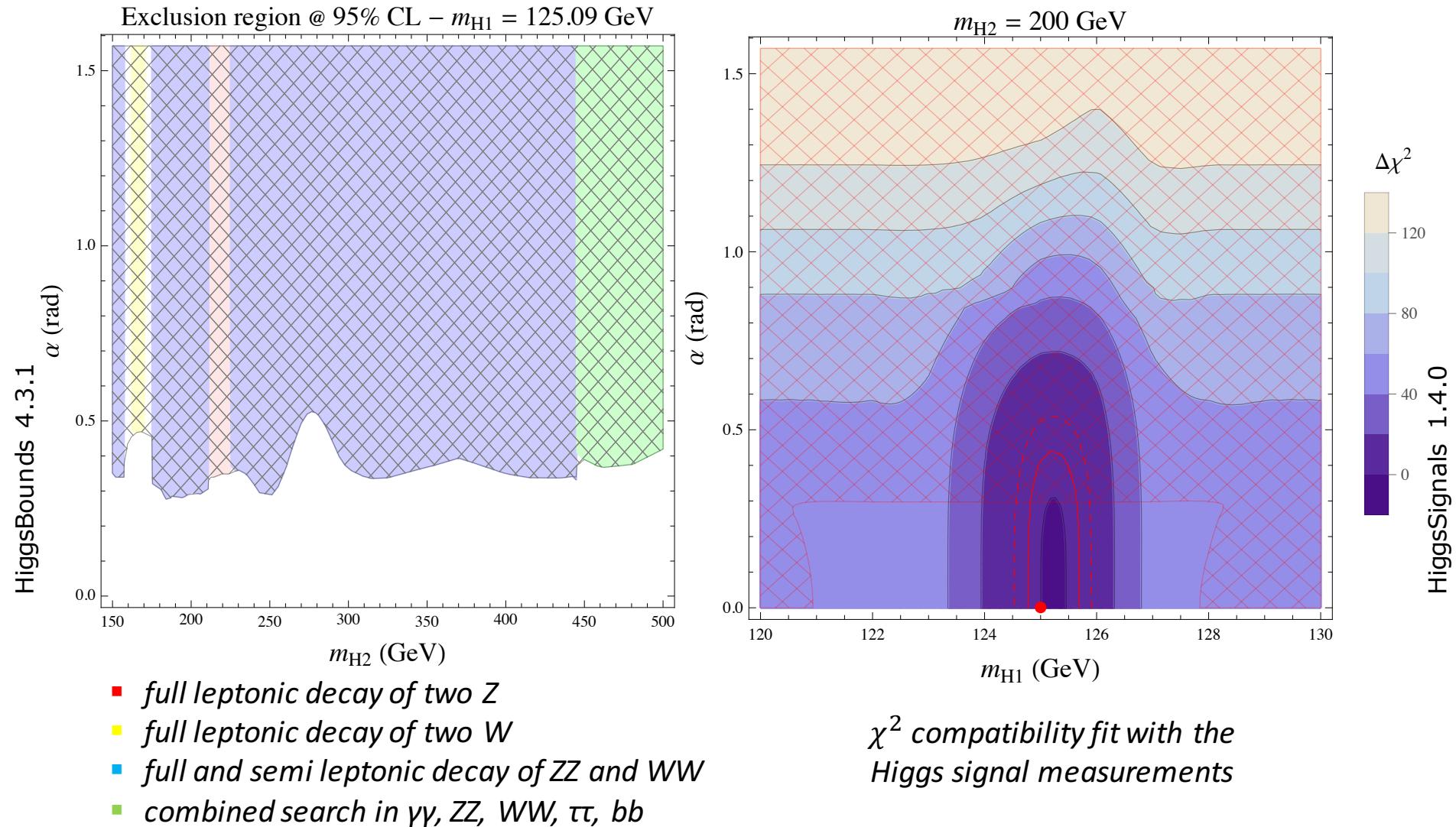
Di-lepton channel at LHC 8 TeV $L = 20 \text{ fb}^{-1}$



LHC studies represent a strong improvement with respect to the EW ones

Constraints from EWPTs and LHC searches

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



Renormalisation group evolution

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

see C. Marzo's talk for more details

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



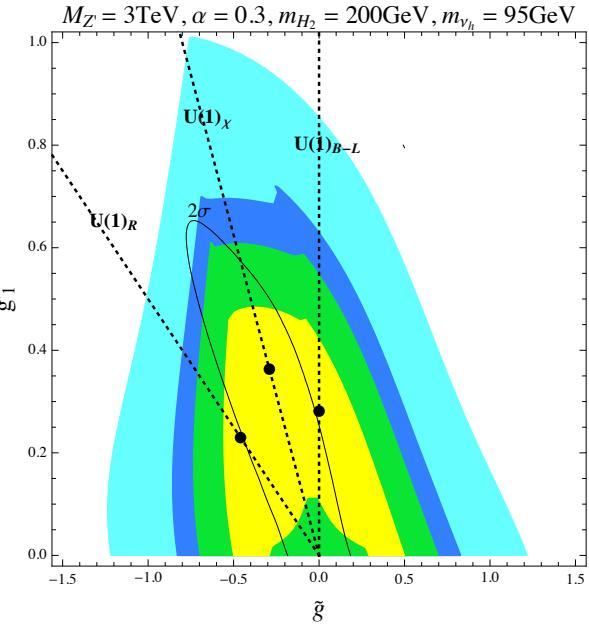
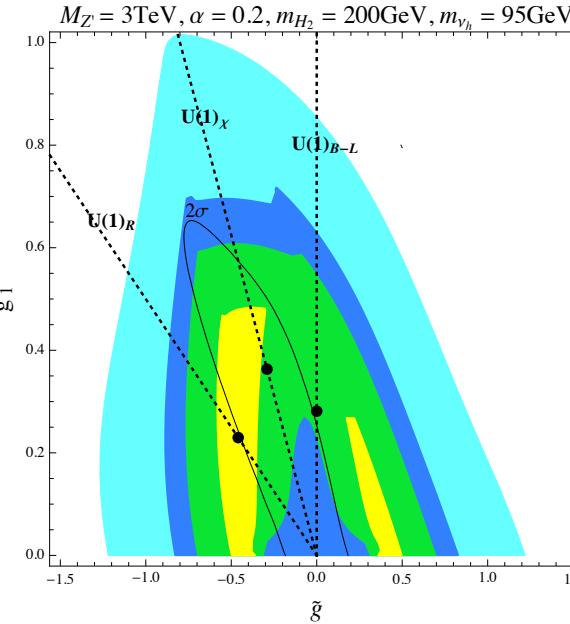
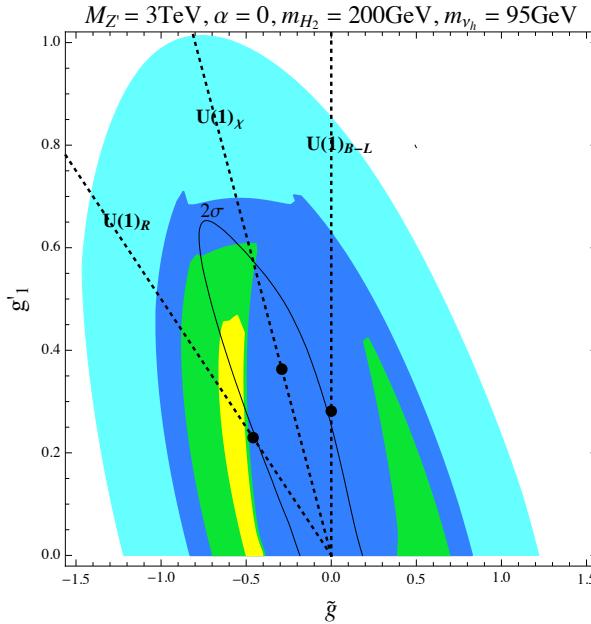
- A complete NNLO analysis is only available for the SM
- NLO analysis can be implemented for a general QFT
 - 2L β functions are known
 - 1L matching conditions must be computed for each model

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

$$\alpha_{\overline{\text{MS}}} = \alpha_{os} + \delta \alpha_{os} \Big|_{fin}$$

High energy behaviour

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



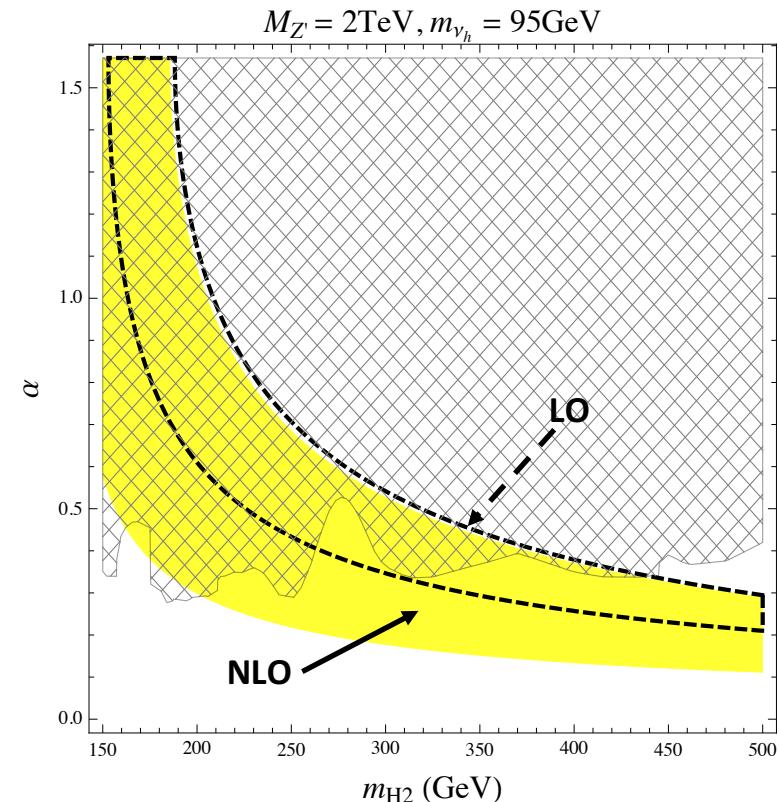
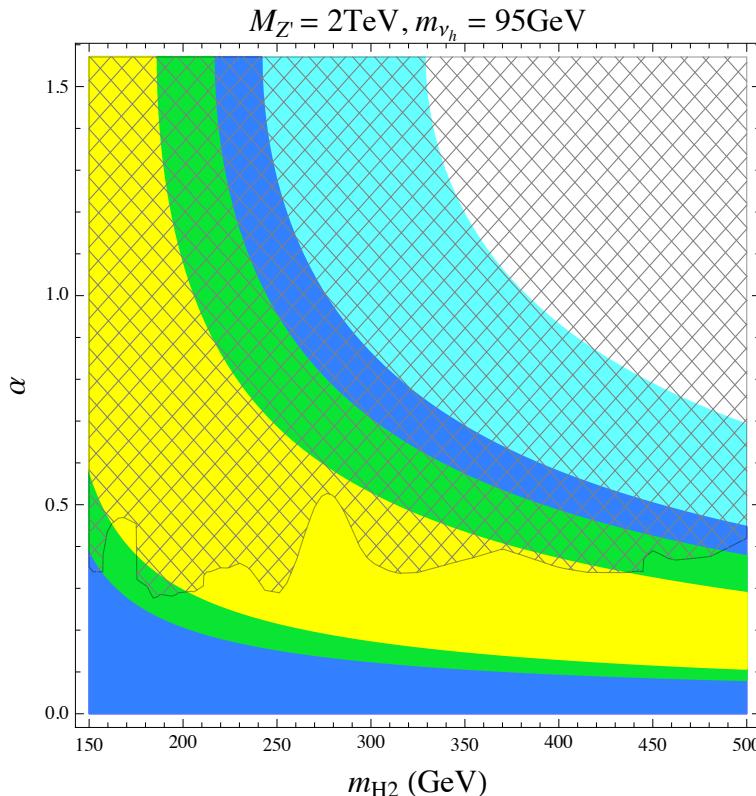
- $10^5 \text{ GeV} < Q_{\max} < 10^8 \text{ GeV}$
- $10^8 \text{ GeV} < Q_{\max} < 10^{10} \text{ GeV}$
- $10^{10} \text{ GeV} < Q_{\max} < 10^{15} \text{ GeV}$
- $Q_{\max} > 10^{15} \text{ GeV}$

*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

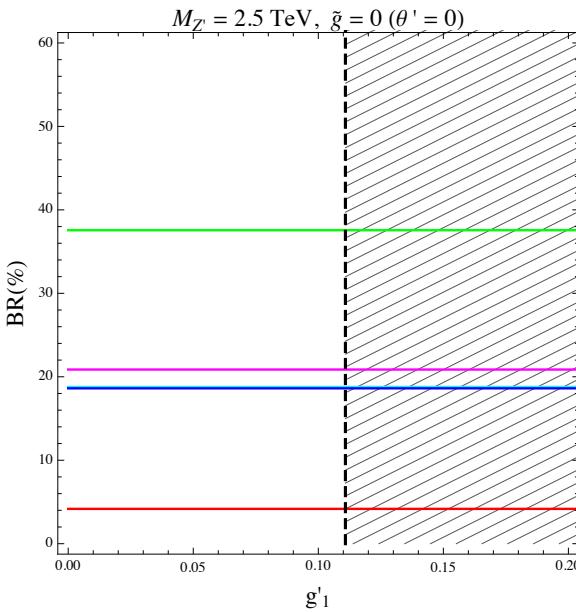


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Comparison between NLO (yellow region) and LO (region in dashed line) results

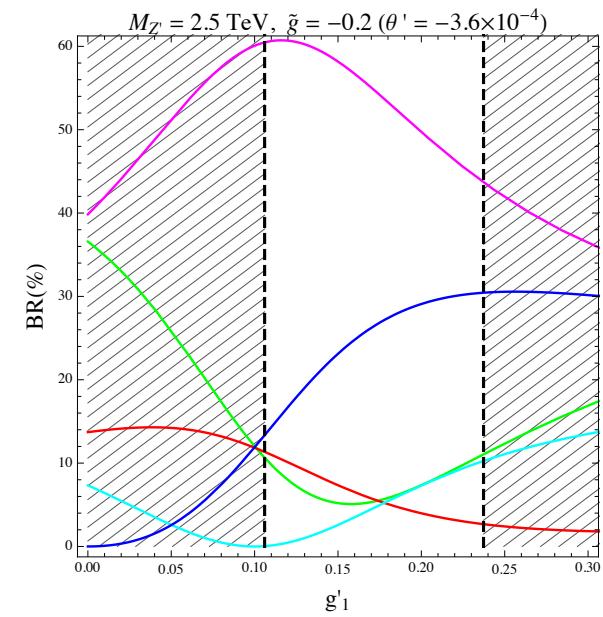
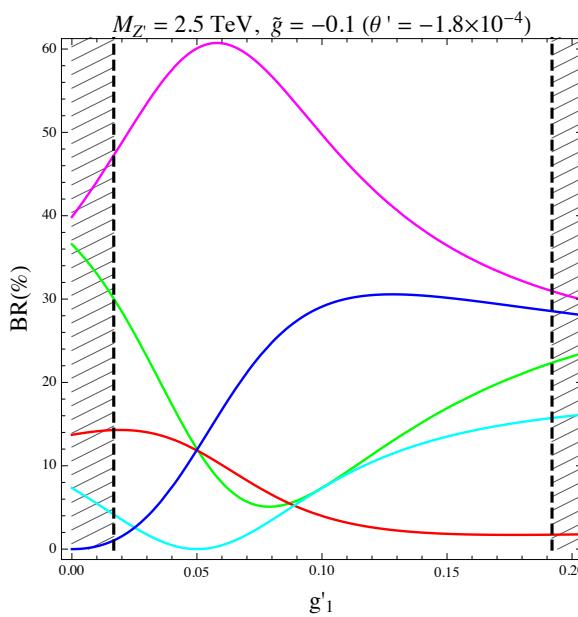
Z' decays

Z' branching ratios



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

- $Z' \rightarrow \text{charged leptons}$
- $Z' \rightarrow \text{light neutrinos}$
- $Z' \rightarrow \text{light quarks}$
- $Z' \rightarrow \text{top quarks}$
- $Z' \rightarrow \text{heavy neutrinos}$



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

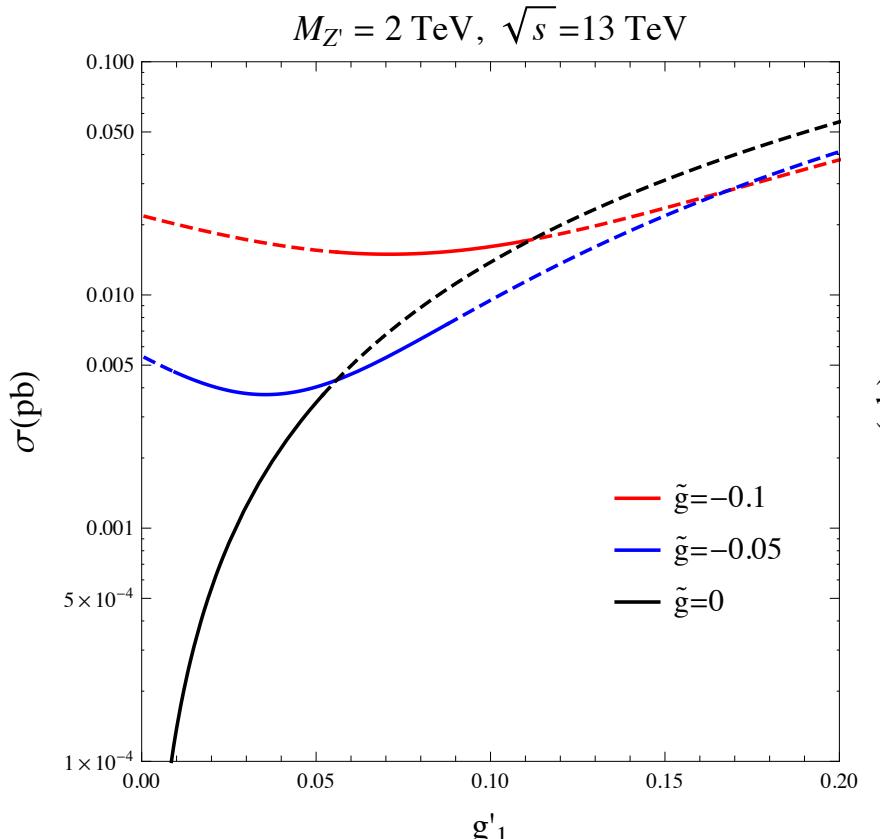
$\text{BR} \sim 2\% \text{ each}$

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

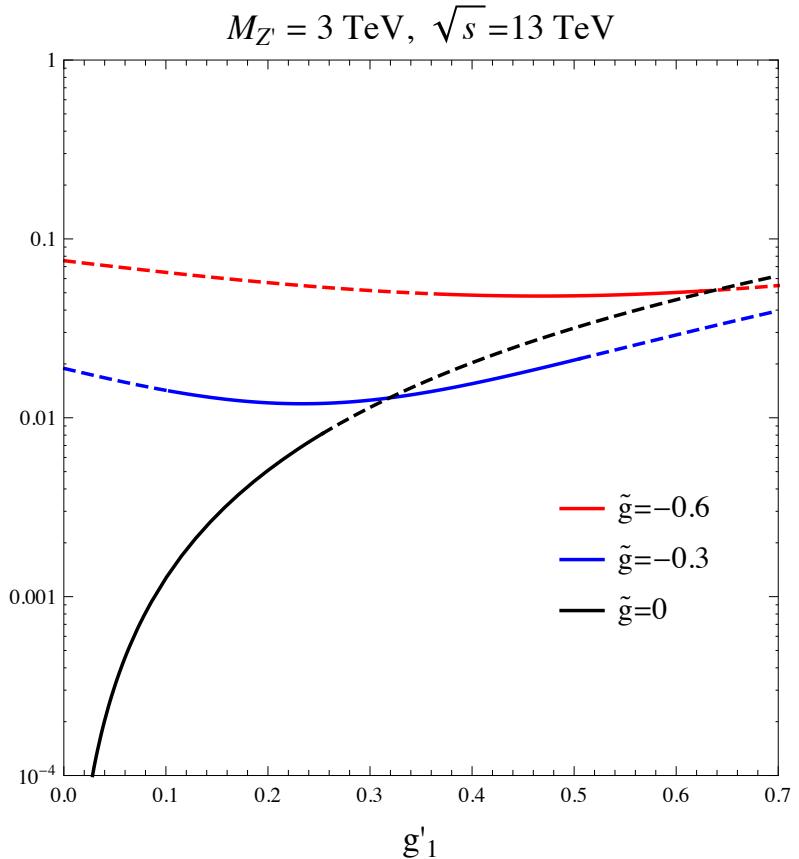
Z' production

Z' on-shell production cross section at the LHC

dashed lines are excluded by LHC Run 1



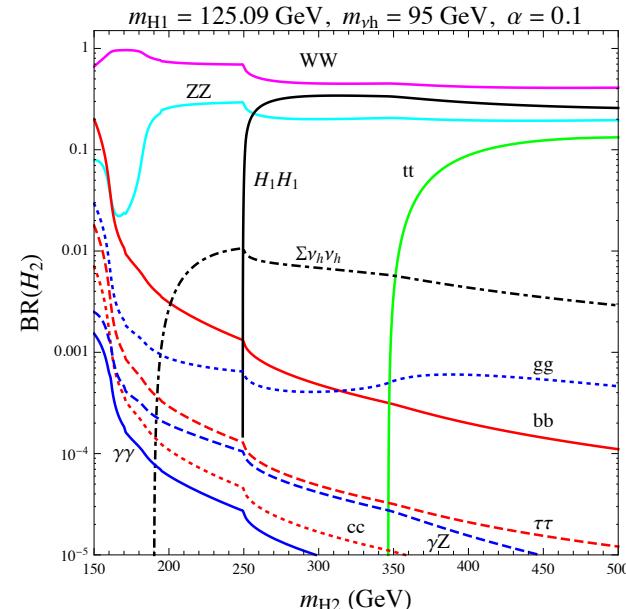
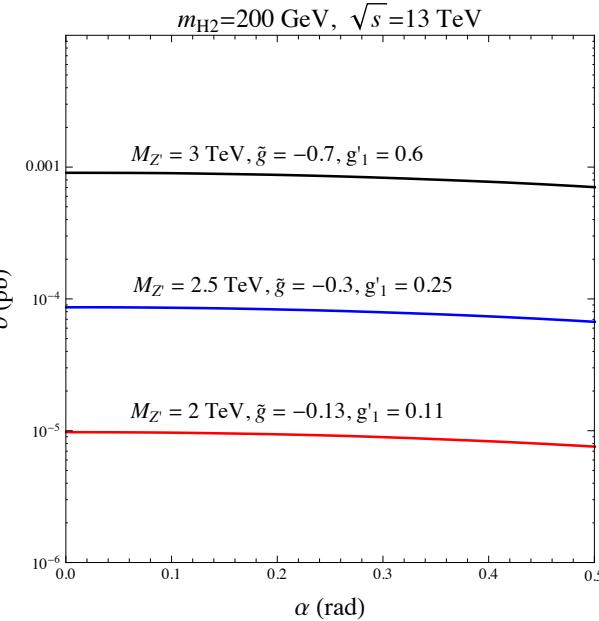
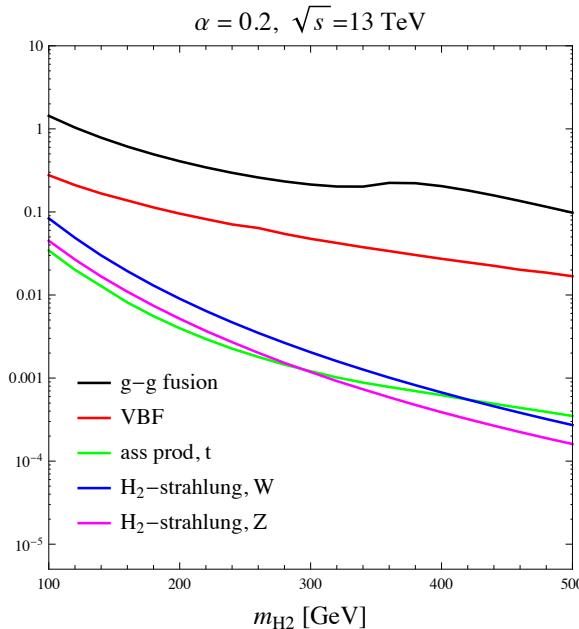
σ up to $\sim 10 \text{ fb}$



σ up to $\sim 100 \text{ fb}$

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 $\sin \alpha$ with respect to the SM Higgs
- Gluon fusion is the main production mode: $\sigma(M_{H_2}, \alpha) \sim (\sin \alpha)^2 \sigma_{SM}(M_{H_2})$
- 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

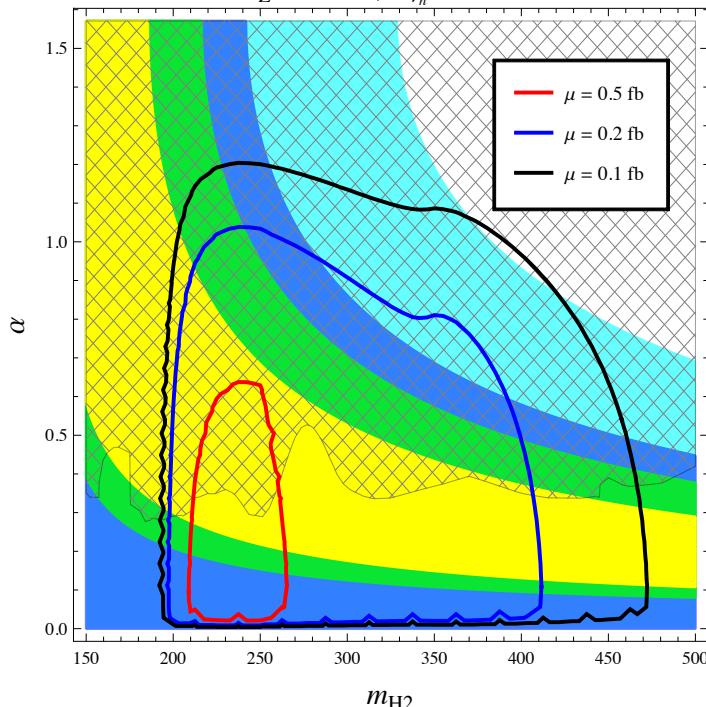
$$\begin{cases} pp \rightarrow H_2 \rightarrow WW \\ pp \rightarrow H_2 \rightarrow ZZ \\ pp \rightarrow H_2 \rightarrow t\bar{t} \end{cases}$$

σ up to ~ 200 fb – 1 pb
 σ up to ~ 200 fb
 σ up to ~ 50 fb

(LHC 13 TeV)
- $\sigma \times \text{BR}$ contour level in the $m_{H_2} - \alpha$ space

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

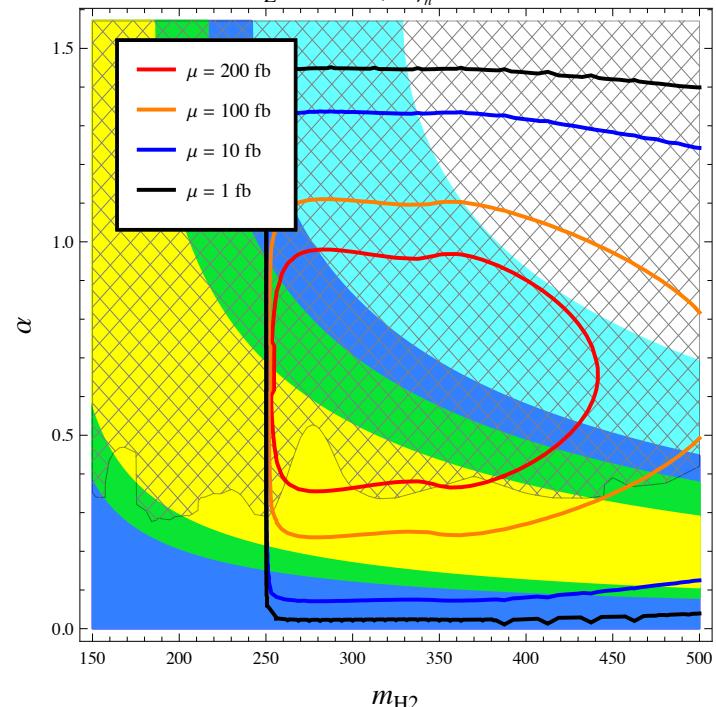
$M_{Z'} = 2\text{TeV}, m_{\nu_h} = 95\text{GeV}$



this channel represents a peculiar feature of this minimal class of Z' models

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

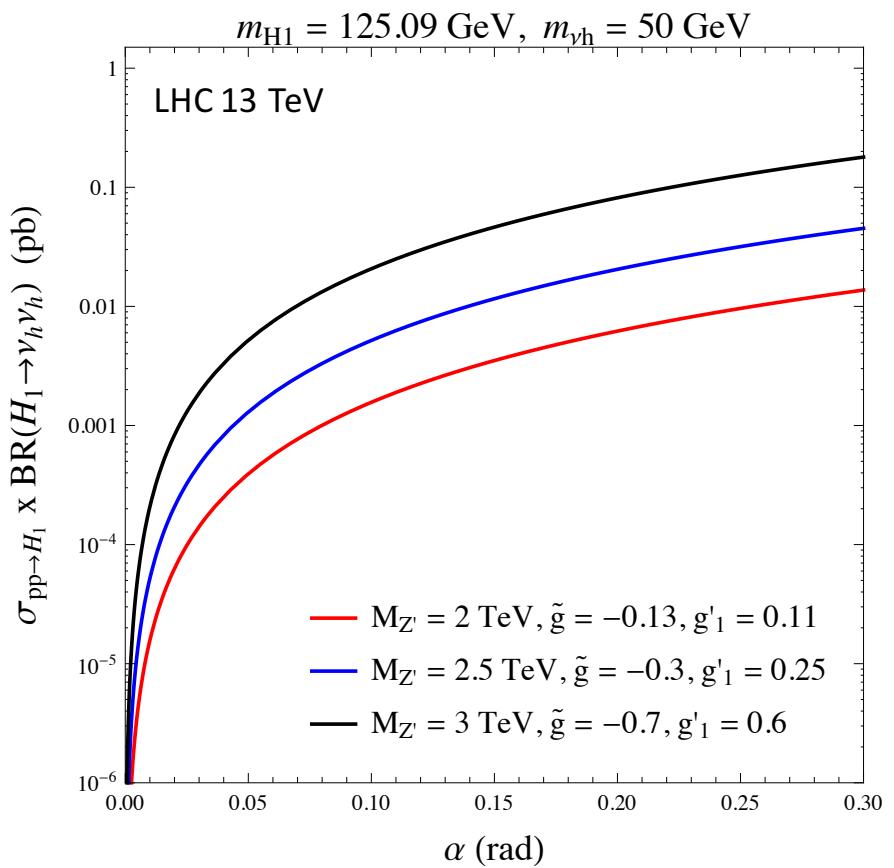
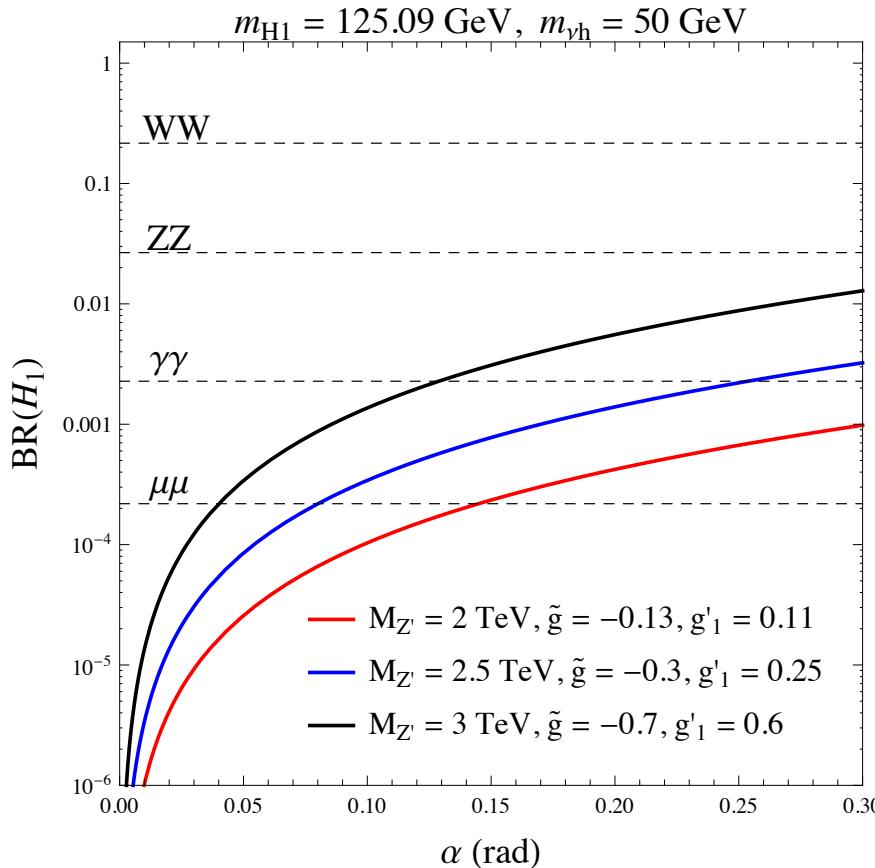
$M_{Z'} = 2\text{TeV}, m_{\nu_h} = 95\text{GeV}$



interesting cross section

SM-like Higgs new decay channel

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



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

Conclusions

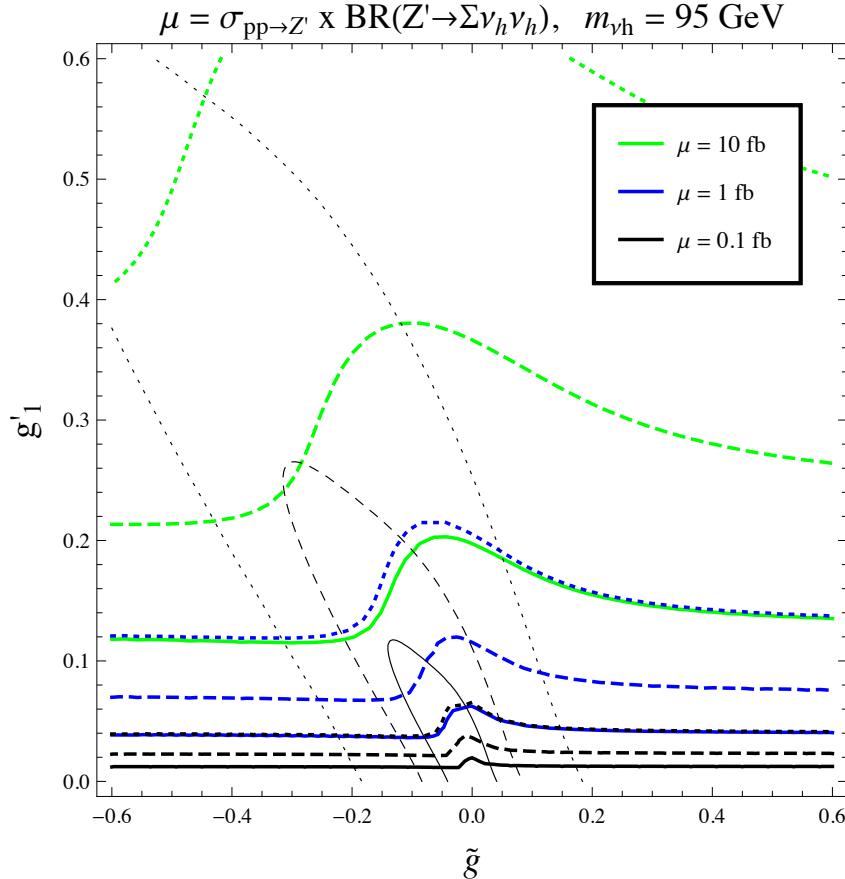
- Minimal Z' extensions of the SM
neutral gauge boson, scalar and RH neutrinos
- Peculiar signatures:
 $pp \rightarrow Z' \rightarrow \nu_h \nu_h$ (heavy neutrinos are long-live particles: *displaced vertices*)
 $pp \rightarrow Z'^* \rightarrow Z' H_2$
 $pp \rightarrow H_2 \rightarrow \nu_h \nu_h$, $pp \rightarrow H_2 \rightarrow H_1 H_1$
 $pp \rightarrow H_1 \rightarrow \nu_h \nu_h$
- LHC Run-I significantly constrains the parameter space
- RG methods can be effectively used to establish a connection between EW scale parameters and the underlying GUT structure

Backup slides

Heavy neutrinos production from Z'

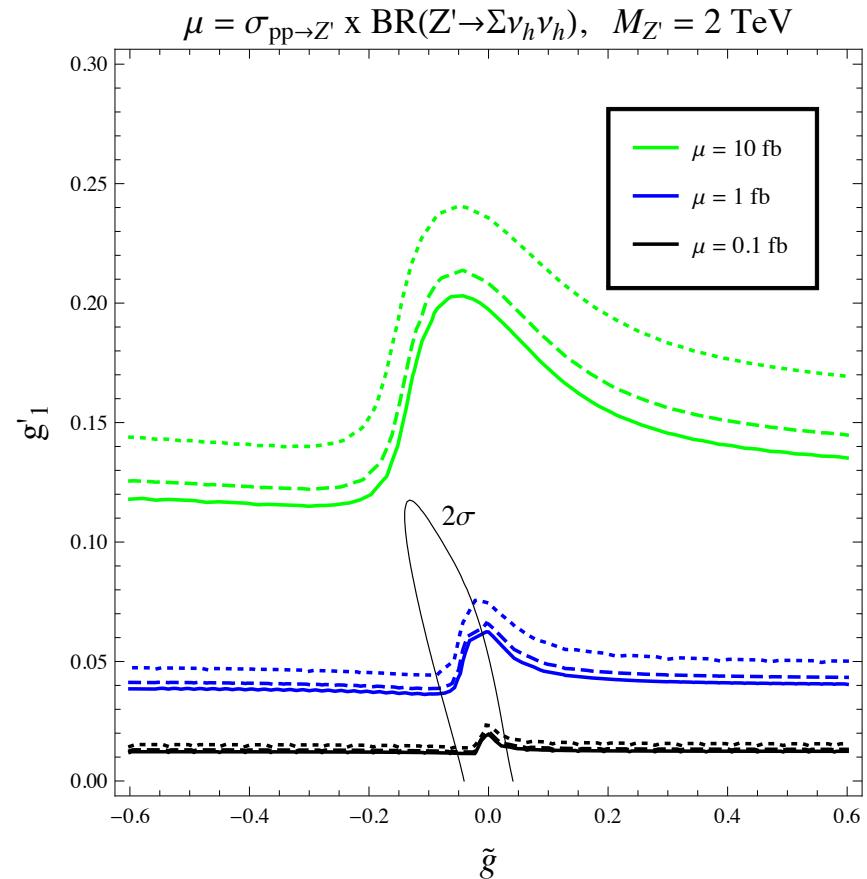
$\sigma \times \text{BR}$ contour level in the $\tilde{g} - g'_1$ space (LHC 13 TeV)

m_{vh} fixed



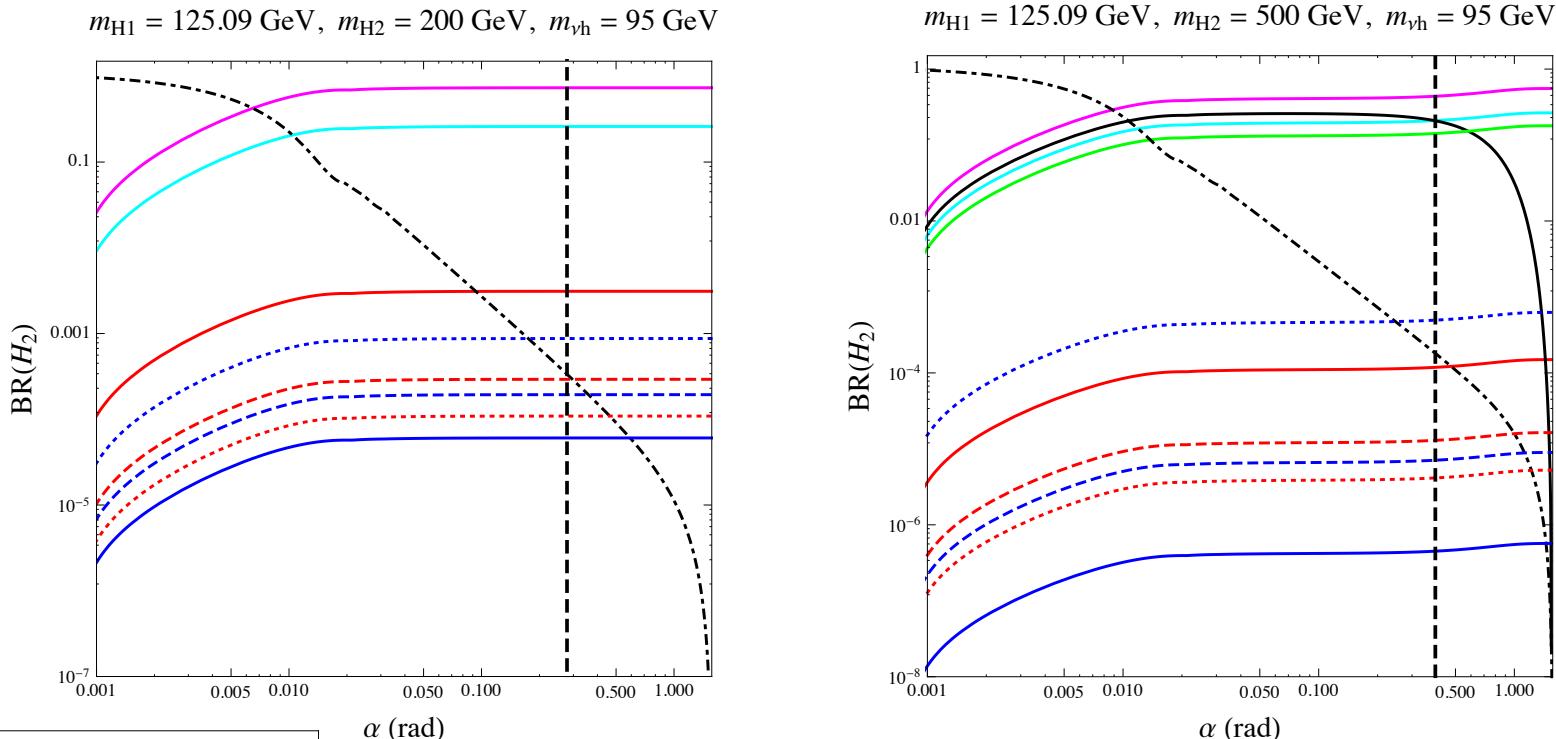
Solid, dashed and dotted lines refer to $M_{Z'} = 2, 2.5, 3 \text{ TeV}$, respectively

$M_{Z'}$ fixed



Solid, dashed and dotted lines refer to $m_{vh} = 95, 300, 500 \text{ GeV}$, respectively

Heavy Higgs branching ratios

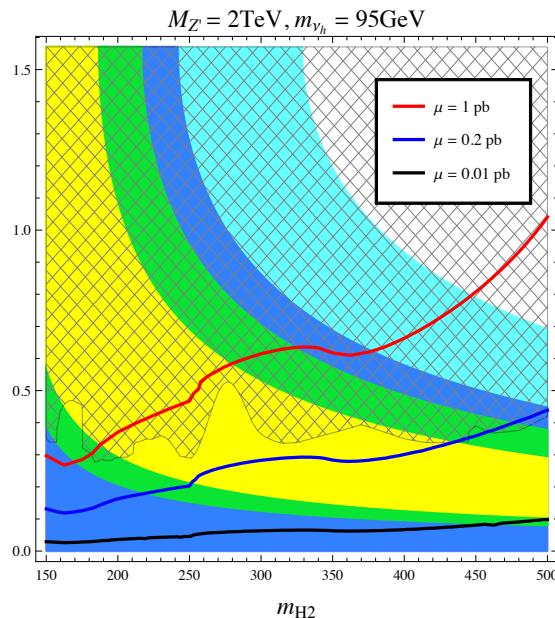


- The BR into heavy neutrinos drops as α increases $H_2\nu_h\nu_h \sim \cos\alpha$
- The BR into light higgses shows a non-trivial α dependence
- The regions on the right of the vertical dashed lines are excluded by Higgs searches

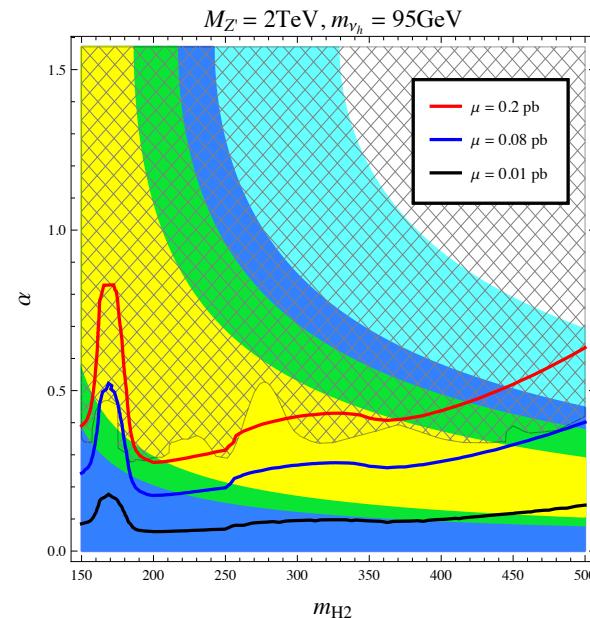
Heavy Higgs production and decay

Favoured discovery channels: $\sigma \times \text{BR}$ contour level in the $m_{H_2} - \alpha$ space (LHC 13 TeV)

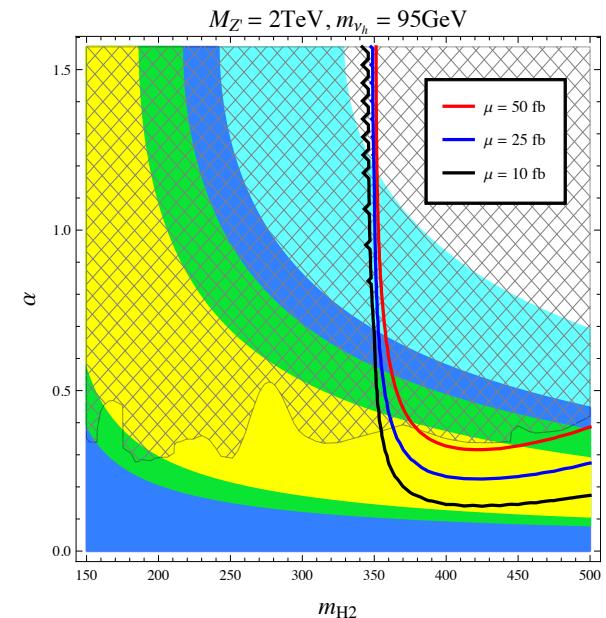
$pp \rightarrow H_2 \rightarrow WW$



$pp \rightarrow H_2 \rightarrow ZZ$



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

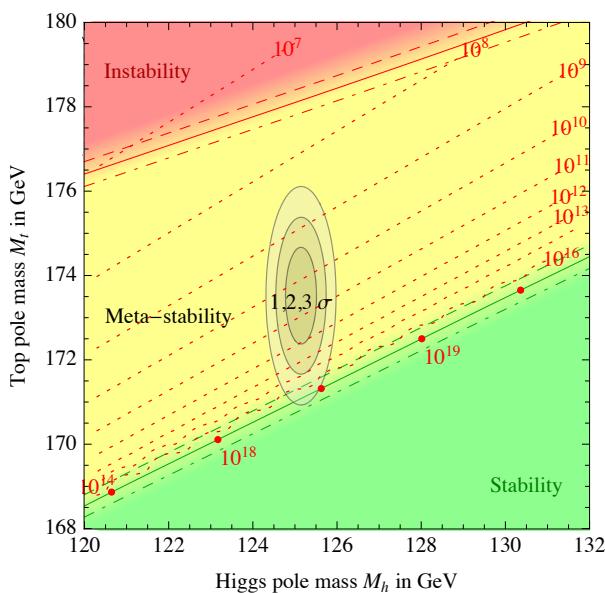


The impact of the top mass in an extended scalar sector

The dashed line corresponds to the central value of the top mass $M_t = 173.34 \pm 0.76$ GeV extracted through MC modelling of production and decay of the top quark in hadronic collisions: **MC mass**

MC mass does not represent neither the pole mass nor the \overline{MS} mass!

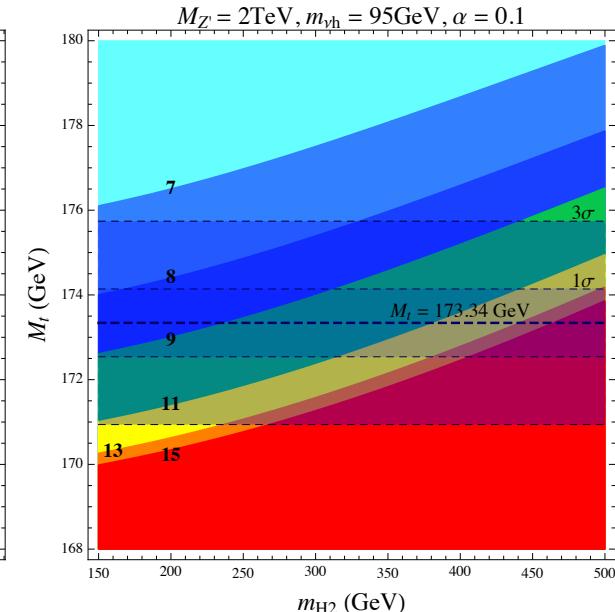
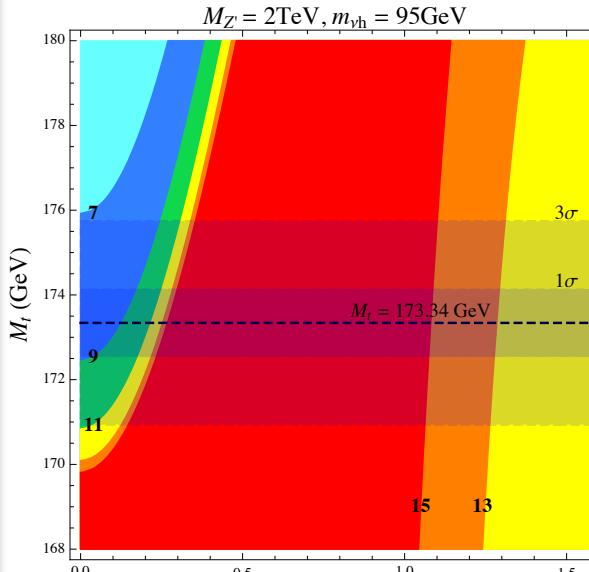
One usually assumes that the MC mass is sufficiently close to the pole mass with differences of the order of 1 GeV



it would be better to define MC generators directly in terms of the \overline{MS} Yukawa

Stability and perturbativity regions. The regions are enclosed by

$$Q_{\max} = 10^x \text{ GeV} \text{ with } x = 7, 8, 9, 11, 13, 15$$



- the mixing angle α weakens the destabilising effect of the top and eventually completely overcomes it for $\alpha > 0.4$
- the effect of m_{H2} is softened and only shifts the instability induced by the top quark to higher values of its mass