# Phenomenology of minimal *Z'* models: *from the LHC to high energy scales*

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Based on E. Accomando, C. Corianò, LDR, J. Fiaschi, C. Marzo, S. Moretti, arXiv:1605.02910
and in collaboration with E. Olaiya, C. Shepherd-Themistocleous

# 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 $\nu_R$

required by anomaly cancellation

➢ Scalar sector

SM-singlet scalar $\chi$

required by SSB of U(1)'

provides Majorana masses for $\nu_R$

➢ 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

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

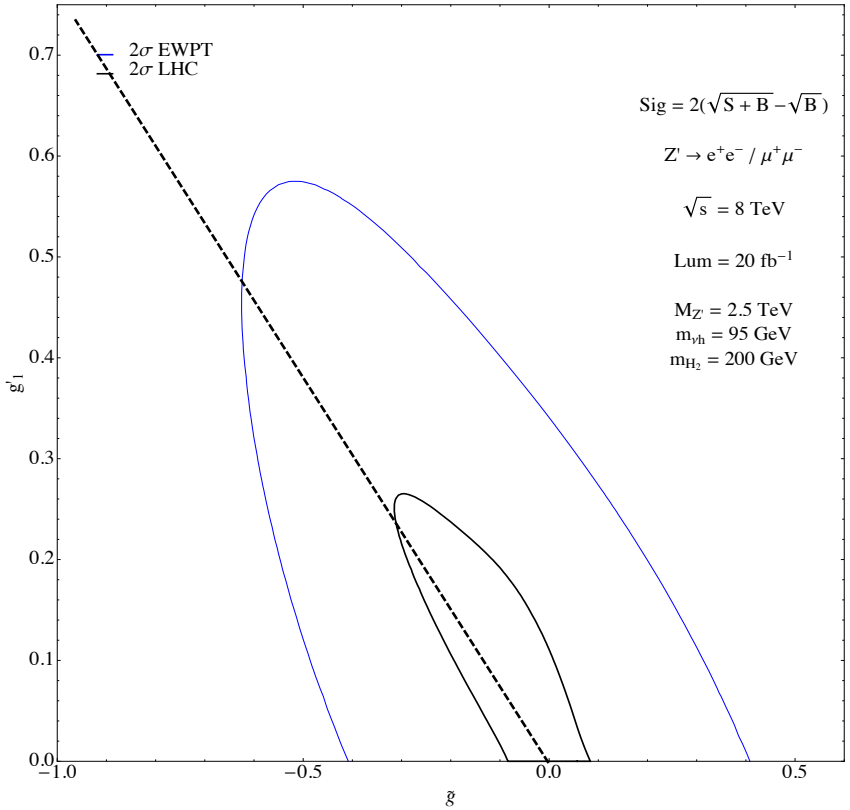
$\tilde{g} = -4/5g'_1$: $U(1)_X$ from SO(10)

# Constraints from EWPTs and LHC searches

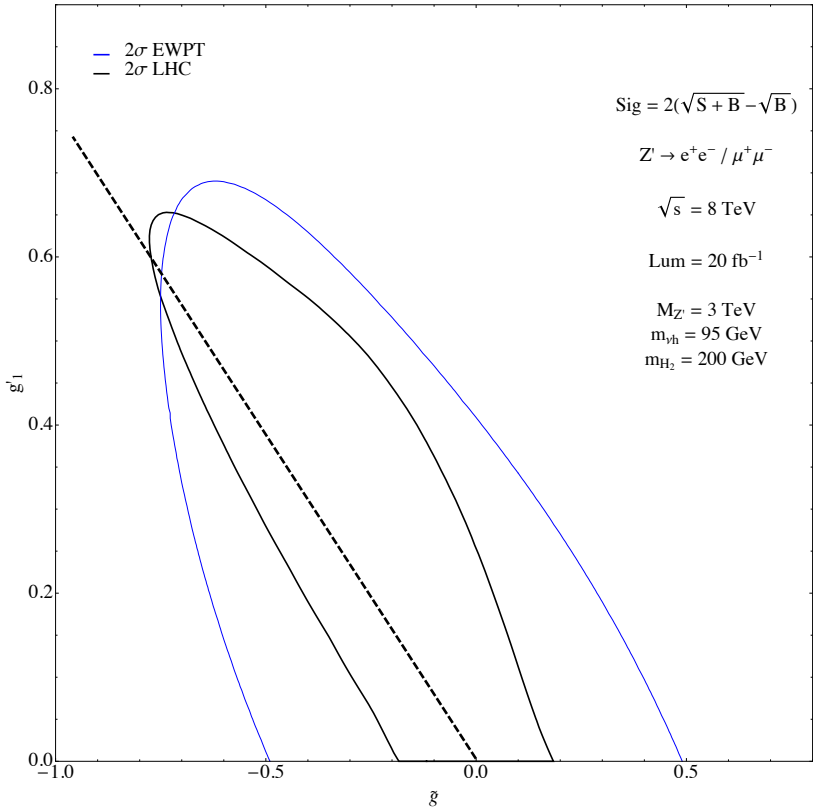
2σ significance contour levels in the $\tilde{g} - g'_1$ space

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

$M_{Z'}$ = 2.5 TeV




$M_{Z'}$ = 3 TeV



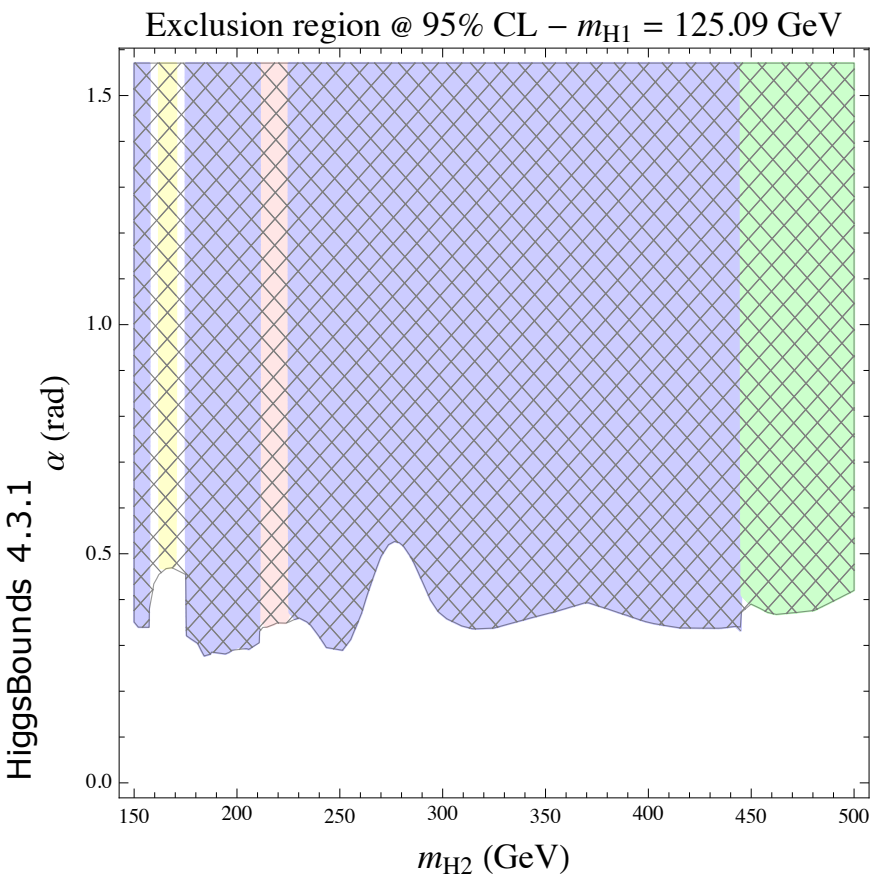

EWPTs from LEP2 data

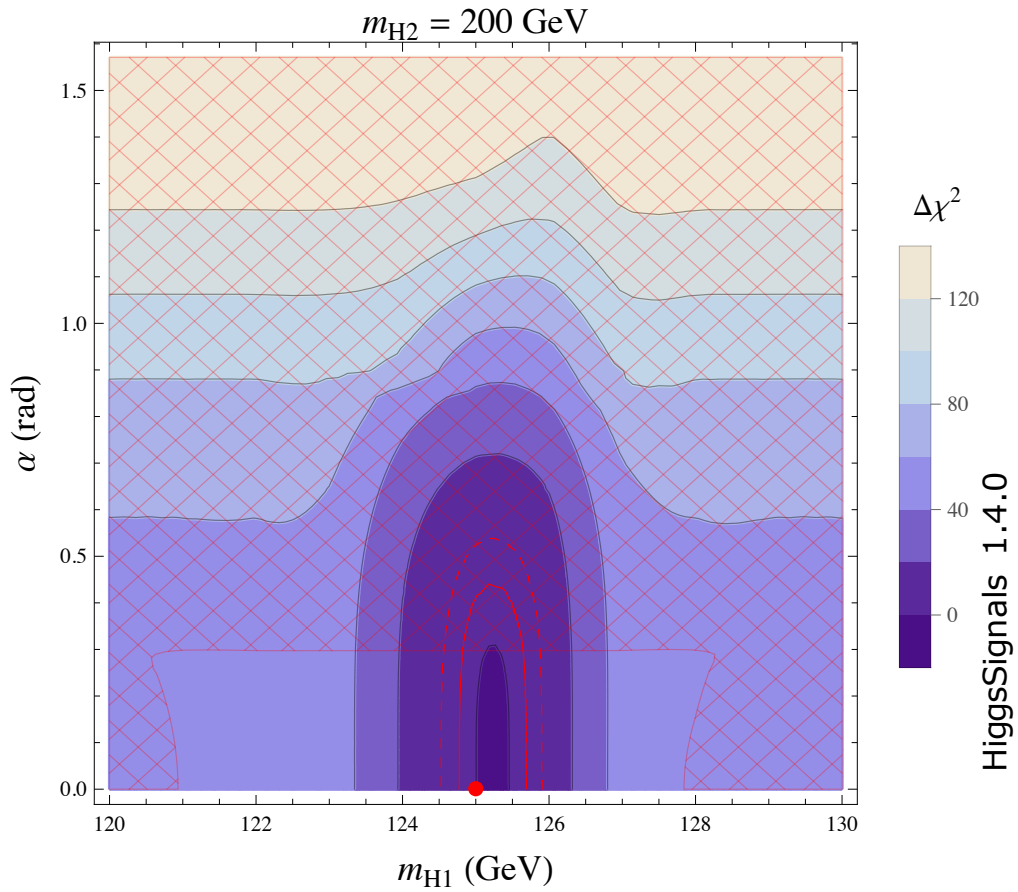
Di-lepton channel at LHC 8 TeV L = 20 $fb^{-1}$

*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




- *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*

*$\chi^2$ 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*

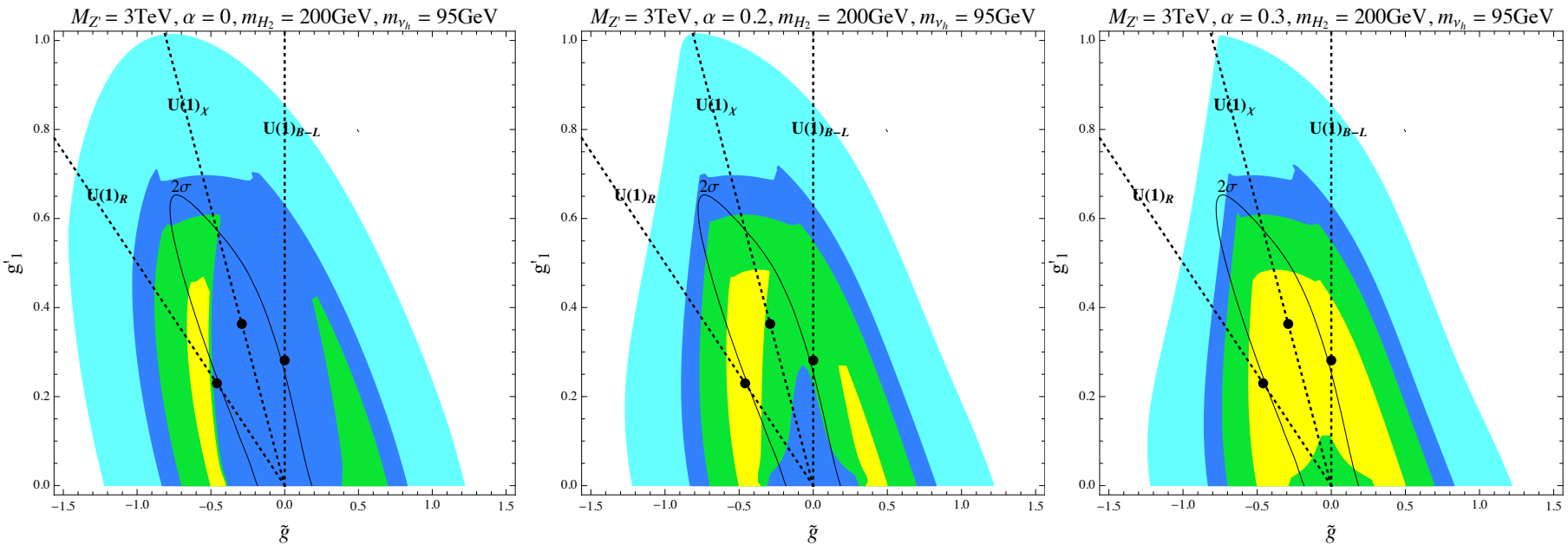
*stability of the vacuum*

*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

# High energy behaviour

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



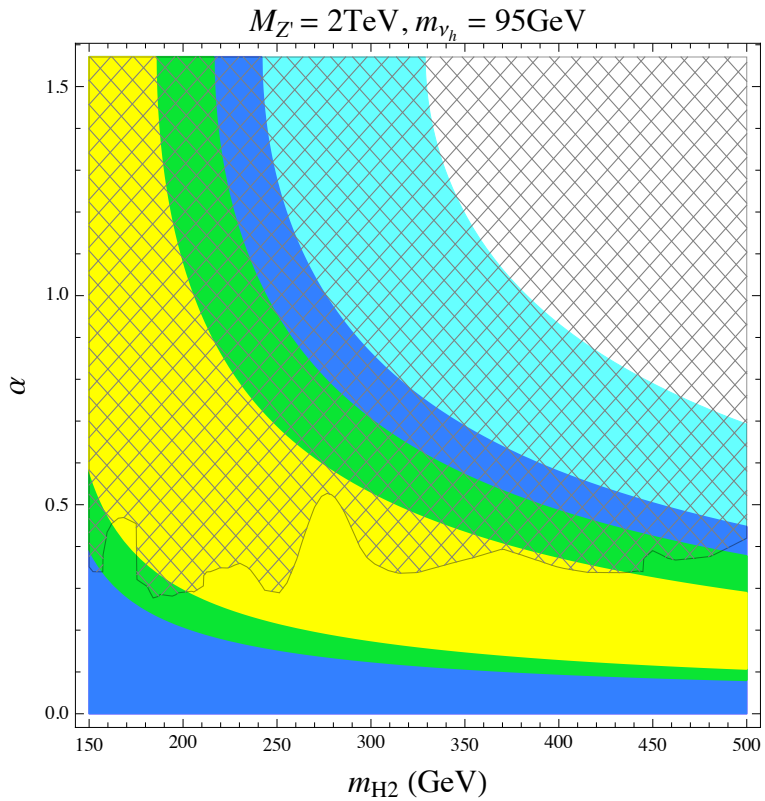

- $10^5$ GeV $< Q_{max} < 10^8$ GeV
- $10^8$ GeV $< Q_{max} < 10^{10}$ GeV
- $10^{10}$ GeV $< Q_{max} < 10^{15}$ GeV
- $Q_{max} > 10^{15}$ GeV

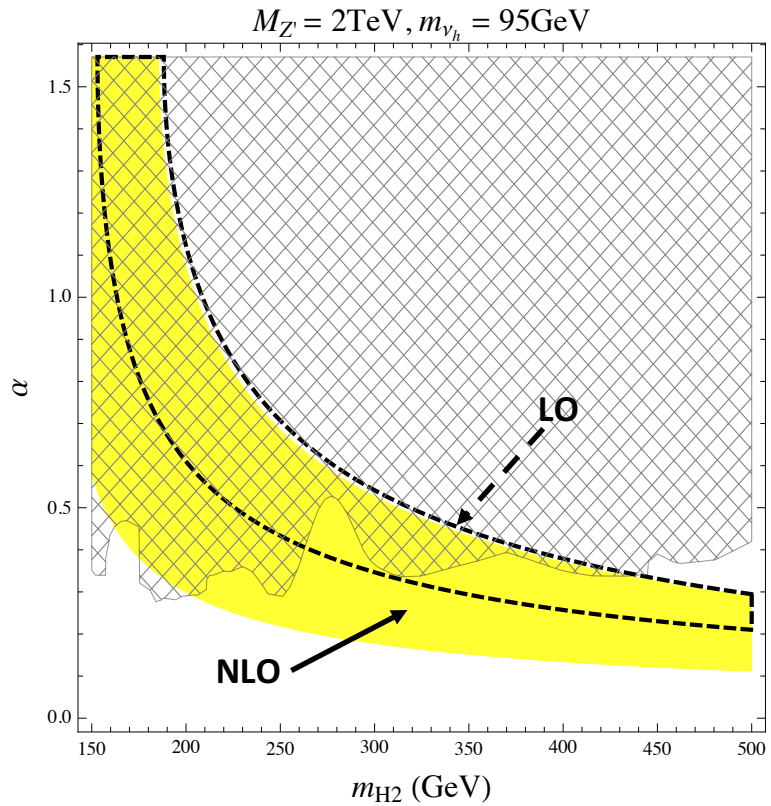
*Black dots represent some benchmark models ($U(1)_R$, $U(1)_X$, $U(1)_{B-L}$) usually addressed in the literature*

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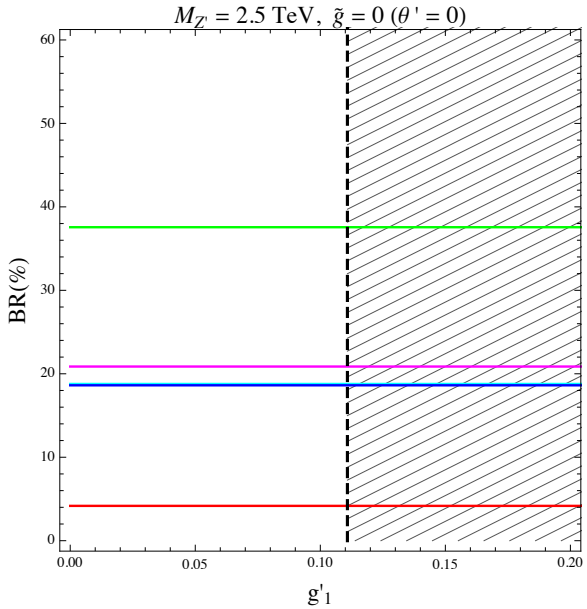
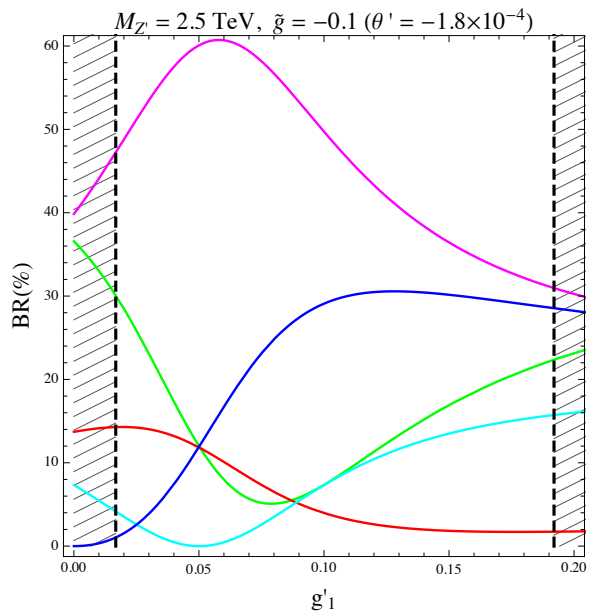
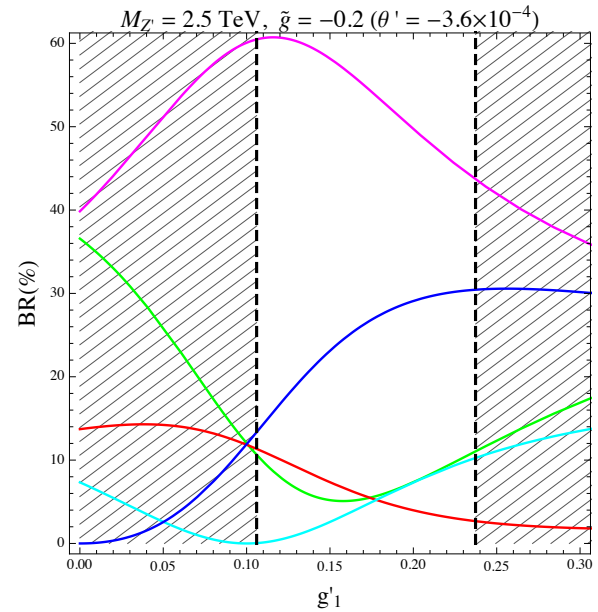
*Comparison between NLO (yellow region) and LO (region in dashed line) results*

# $Z'$ 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

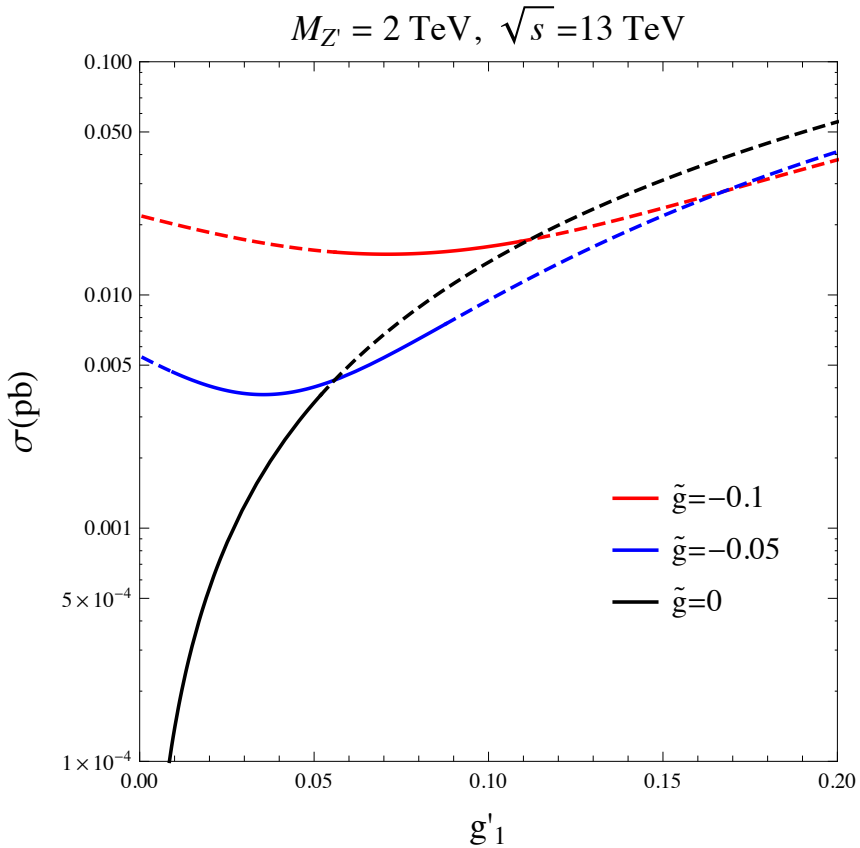
BR ~ 2 % each

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

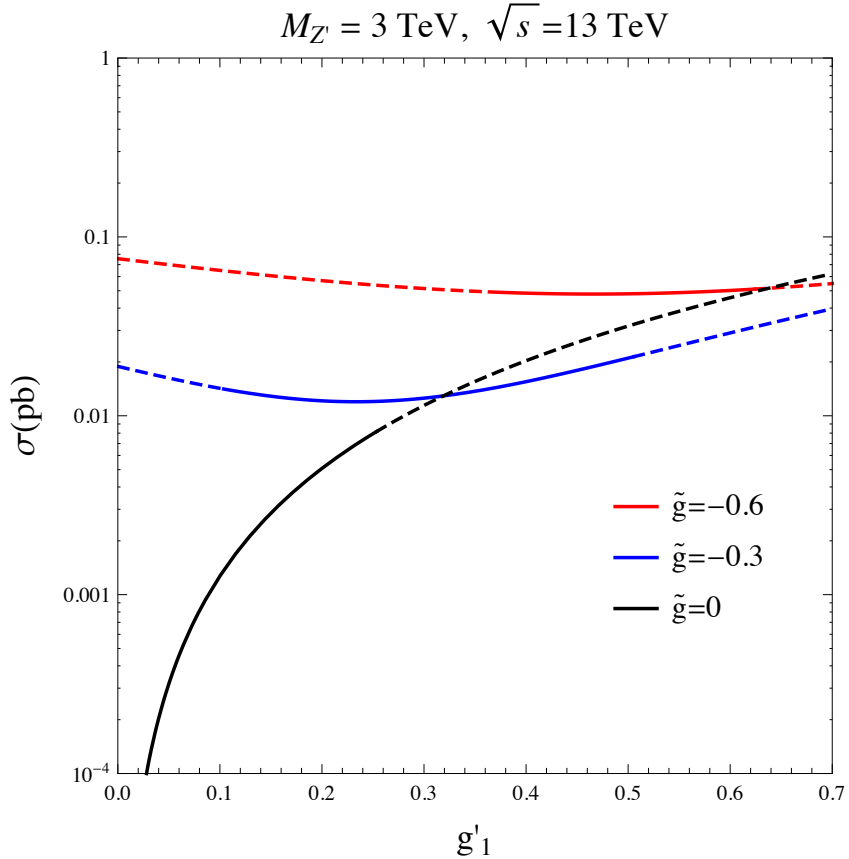
# *Z'* production

*Z'* on-shell production cross section at the LHC

*dashed lines are excluded by LHC Run 1*




σ up to ~ 10 fb

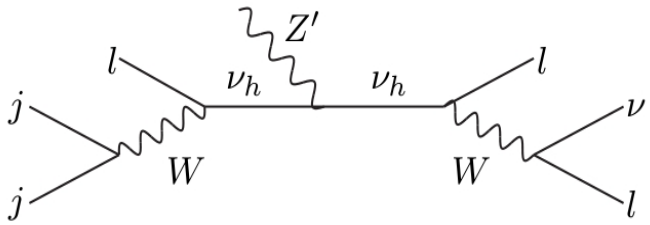


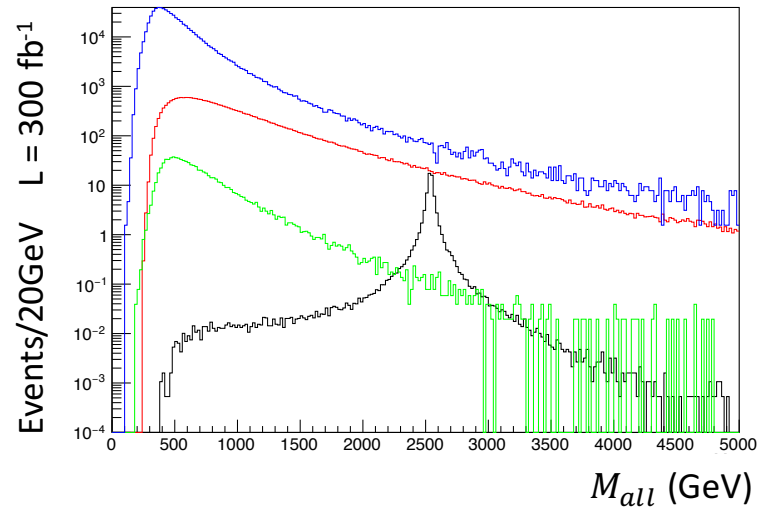

σ up to ~ 100 fb

# $Z'$ signatures

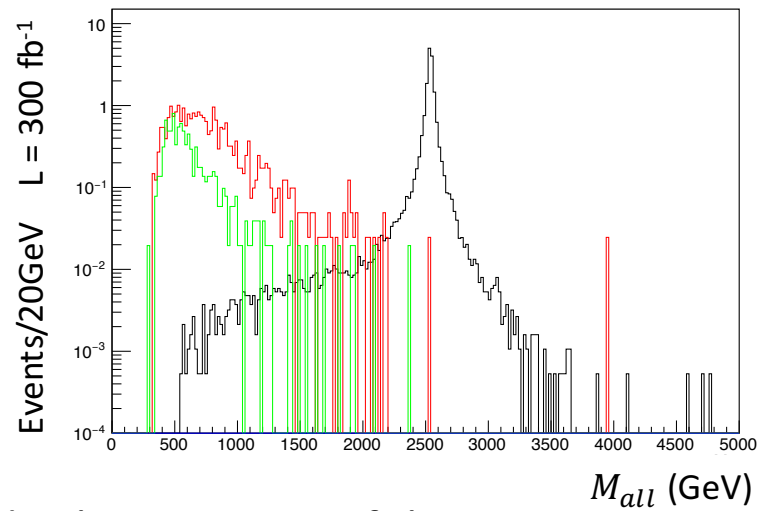
$M_{Z'} = 2.5\ TeV, m_{\nu_h} = 200\ GeV$

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




No cuts




Cuts applied except on $M_{all}$

## Backgrounds

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

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

# Z' signatures

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

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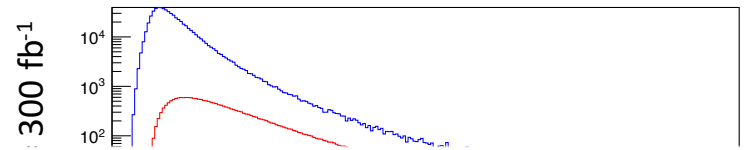
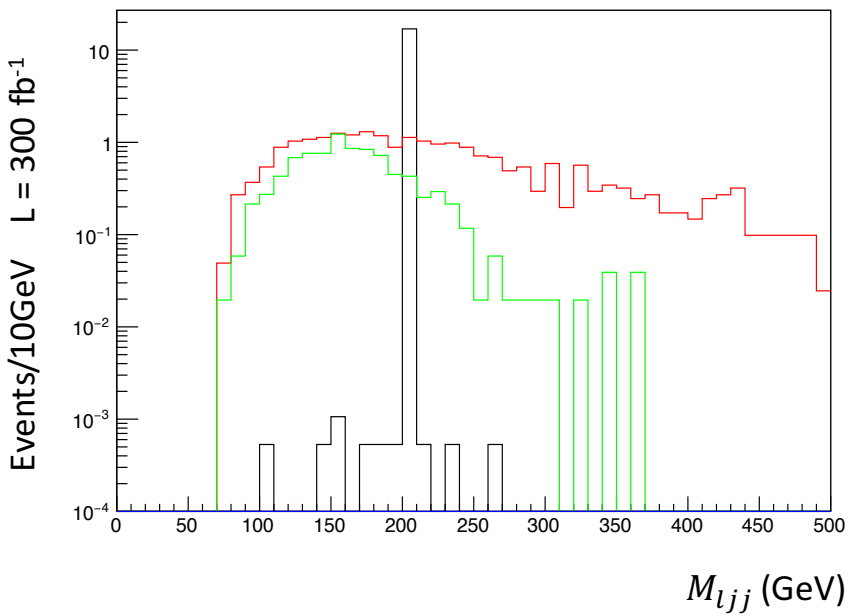
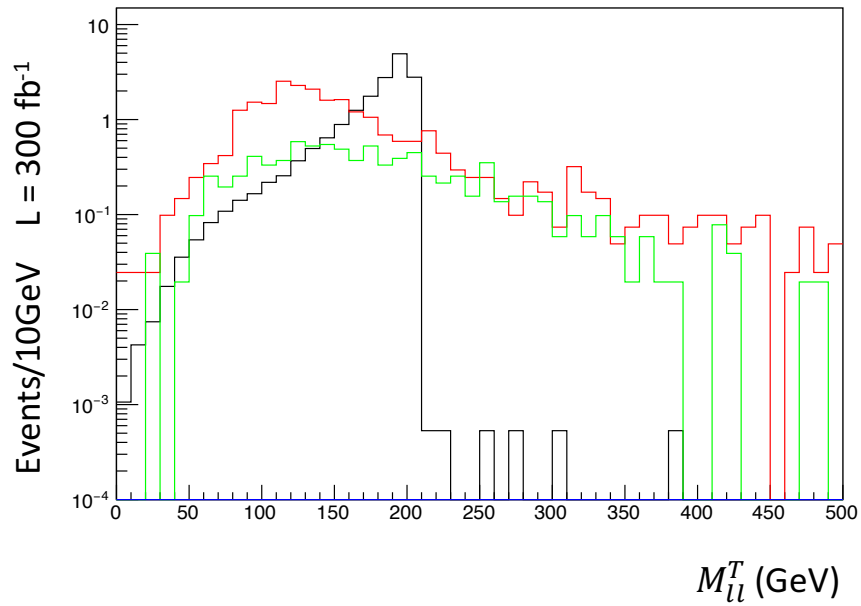



*The heavy neutrino mass can be identified*

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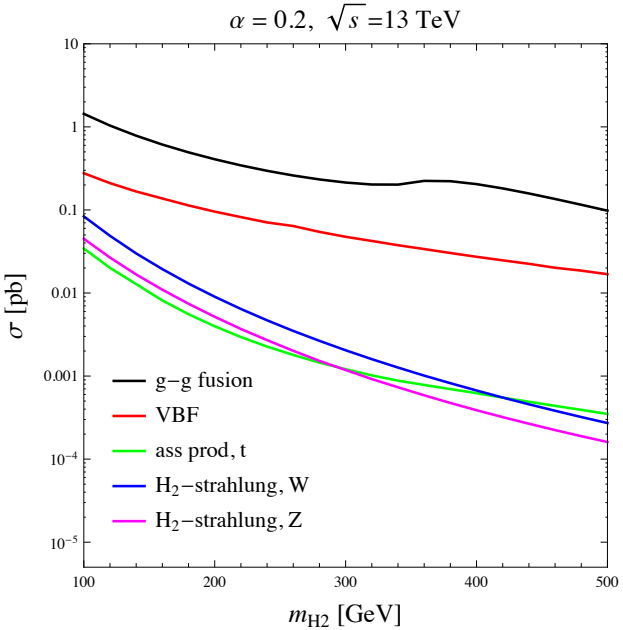
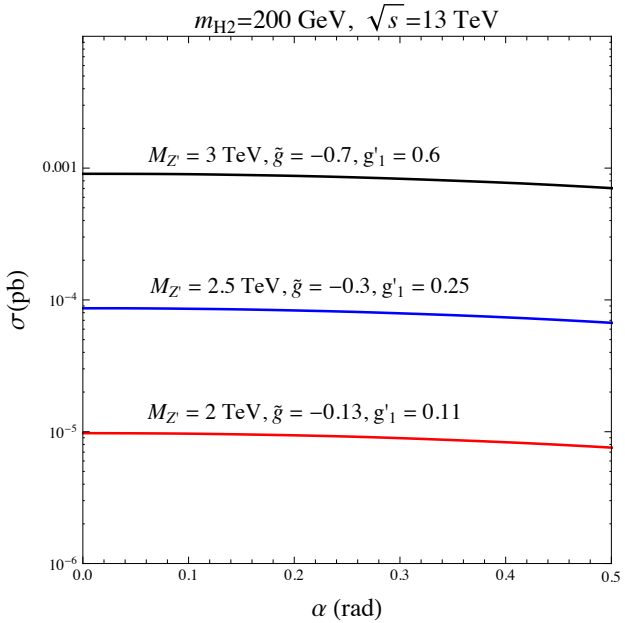
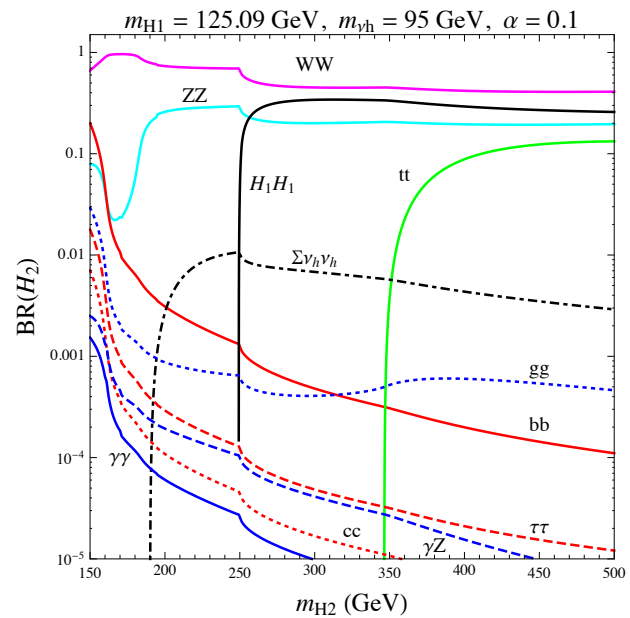
# Heavy Higgs production and decay

(LHC 13 TeV)




*Standard production mechanisms*

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

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

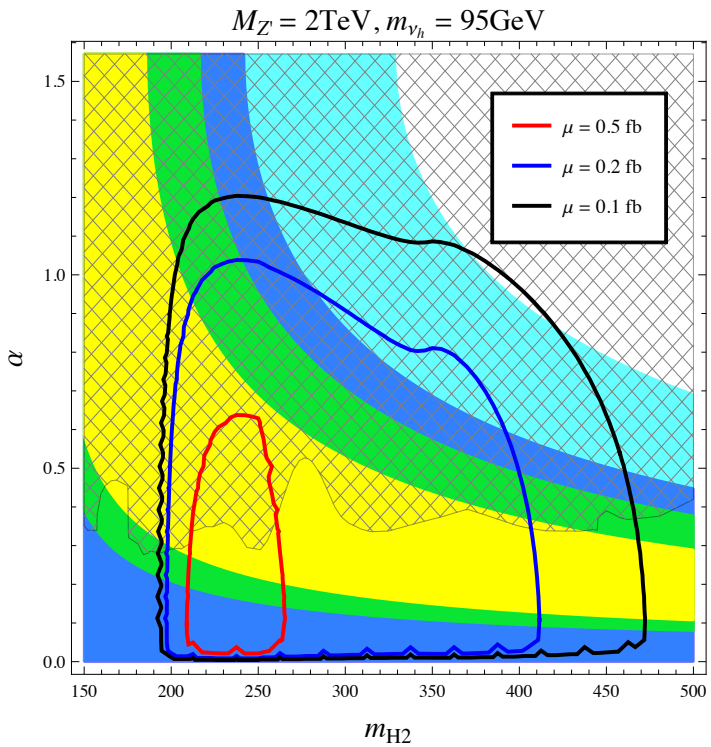
- $H_2$ couplings to SM particles are rescaled by sin α with respect to the SM Higgs
- Gluon fusion is the main production mode: $\sigma\left(M_{H_2}, \alpha\right) \sim (\sin\alpha)^2\, \sigma_{SM}\left(M_{H_2}\right)$
- New decay channels: $H_2 \to \nu_h \nu_h$, $H_2 \to H_1 H_1$

# Heavy Higgs production and decay

- Favoured discovery channels $\begin{cases} pp \to H_2 \to WW & \sigma \text{ up to} \sim 200 \text{ fb} - 1 \text{ pb} \\ pp \to H_2 \to ZZ & \sigma \text{ up to} \sim 200 \text{ fb} \\ pp \to H_2 \to t\bar{t} & \sigma \text{ up to} \sim 50 \text{ fb} \end{cases}$ (LHC 13 TeV)

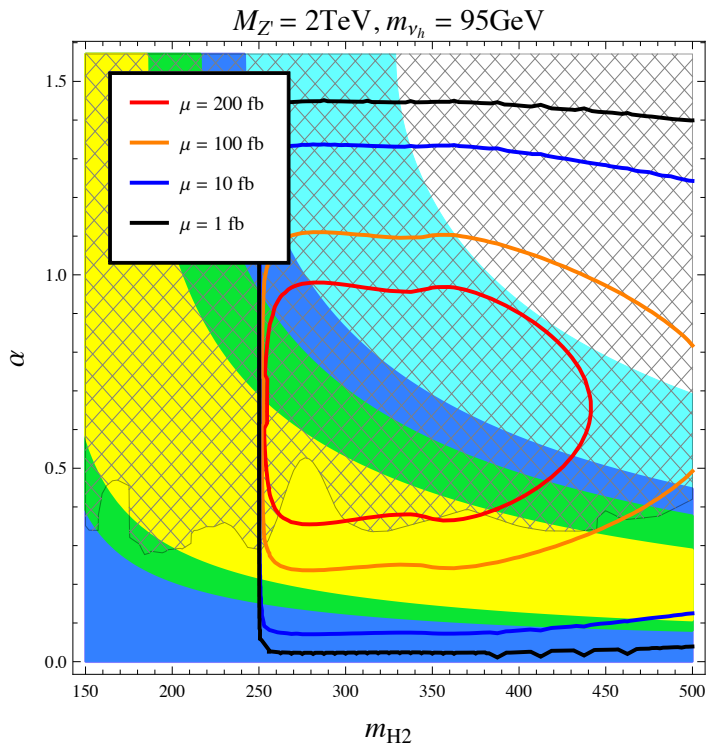
- σ x BR contour level in the $m_{H2} - \alpha$ space

$$pp \to H_2 \to \nu_h \nu_h$$




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

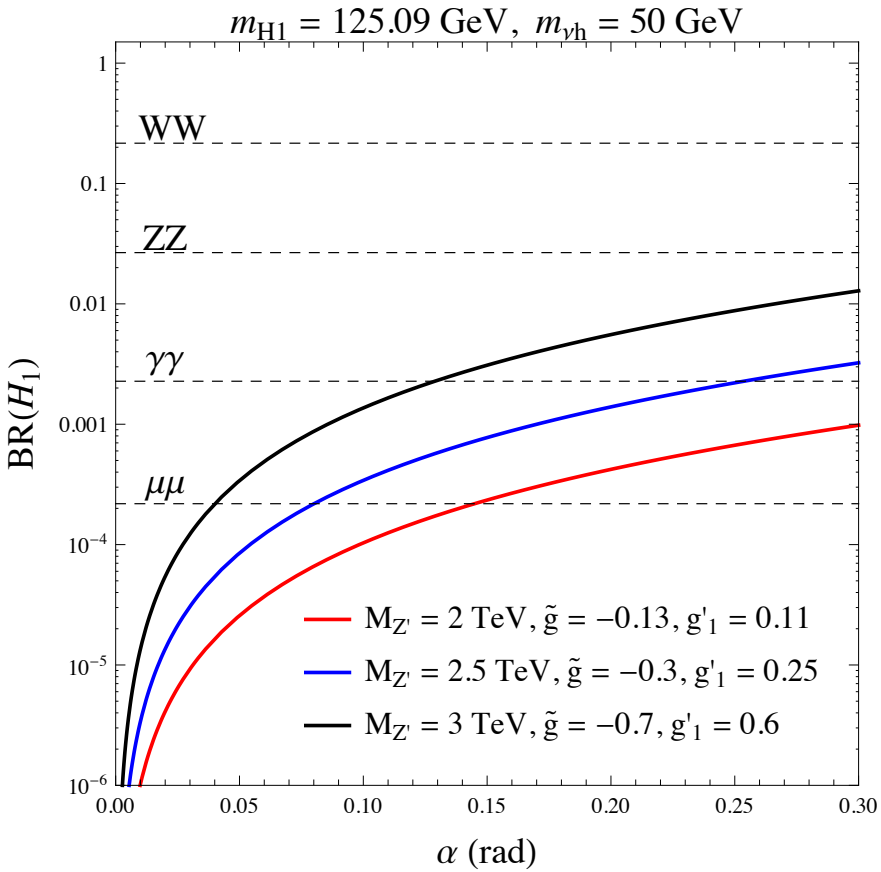
$$pp \to H_2 \to H_1 H_1$$

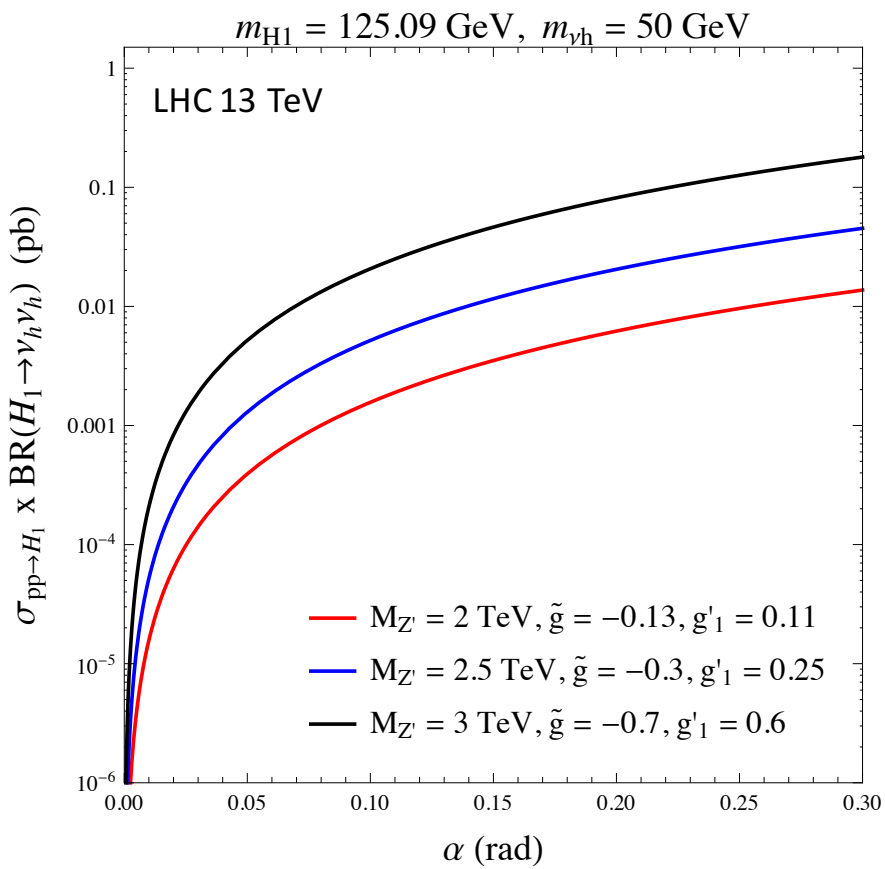



*interesting cross section*

# 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%

σ spans from 10 fb to 100 fb

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

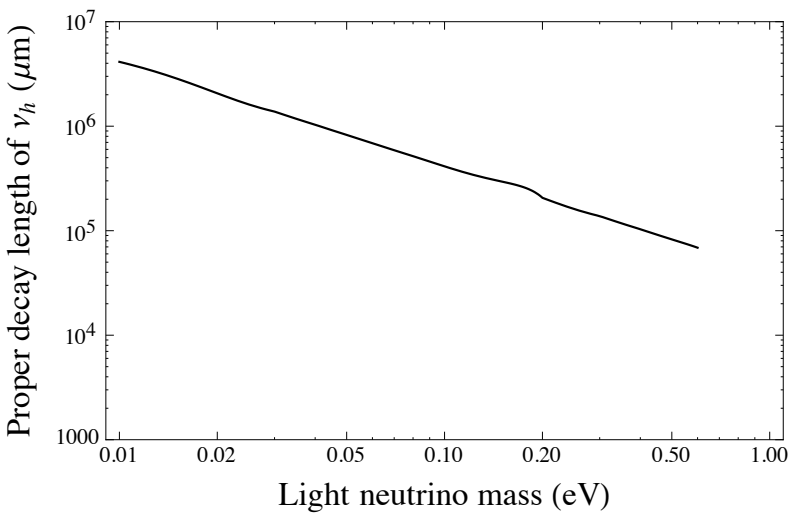
# SM-like Higgs new decay channel

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

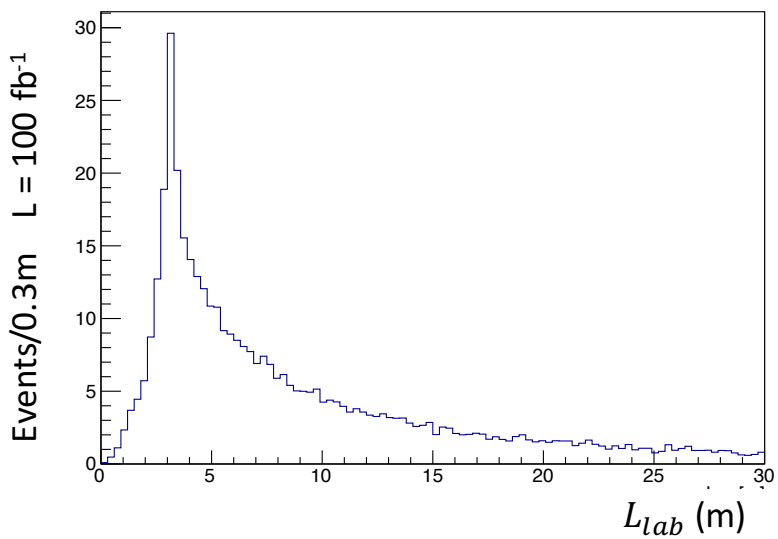
| | *signals* | *main backgrounds* |
|---|---|---|
| (1) | $H \to \nu_h \nu_h \to 3l + 2j + E_{Tmiss}\ (1\ \nu_l)$ | $WZjj, t\bar{t}, t\bar{t}l\nu$ |
| (2) | $H \to \nu_h \nu_h \to 4l + E_{Tmiss}\ (2\ \nu_l)$ | $WWZ$ |

Heavy neutrinos are very long-lived particles: *displaced vertices*

*example:* $m_{\nu_h}$ *= 50 GeV*




*$\nu_h$ decay length (lab frame) distribution extracted from process (2)*



# Conclusions

- Minimal Z' extensions of the SM
  *neutral gauge boson, scalar and RH neutrinos*

- 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

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

# Backup slides

# 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

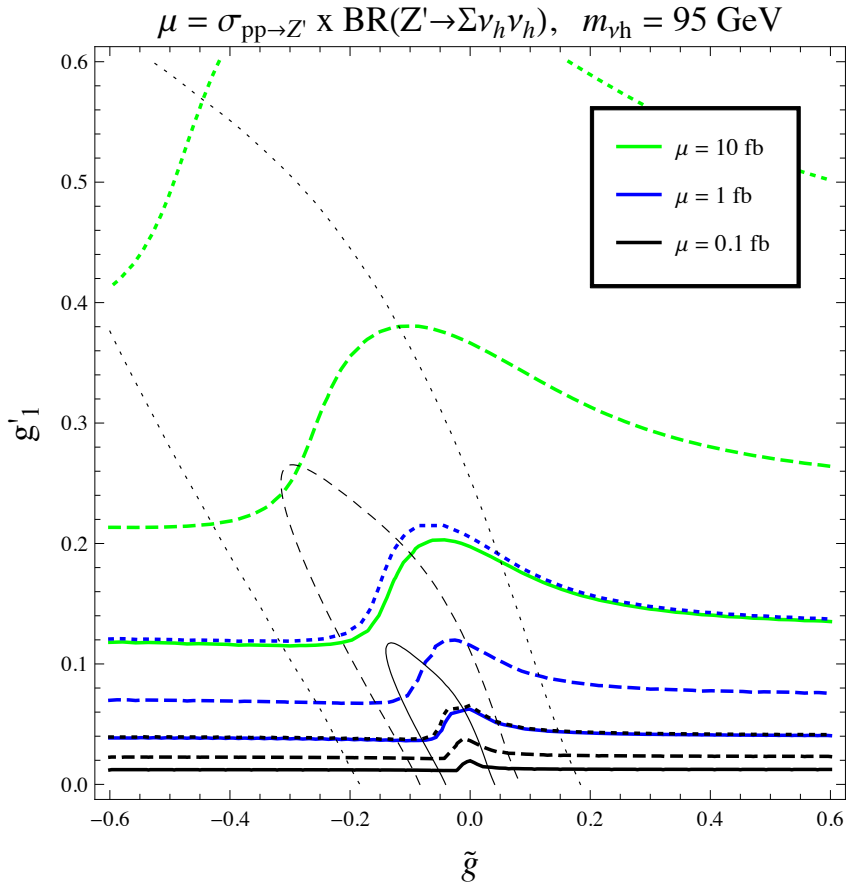
*Matching conditions* provide the initial value of the running couplings computed in the $\overline{\mathrm{MS}}$ renormalisation scheme as a function of the physical on-shell parameters

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

# Heavy neutrinos production from Z'

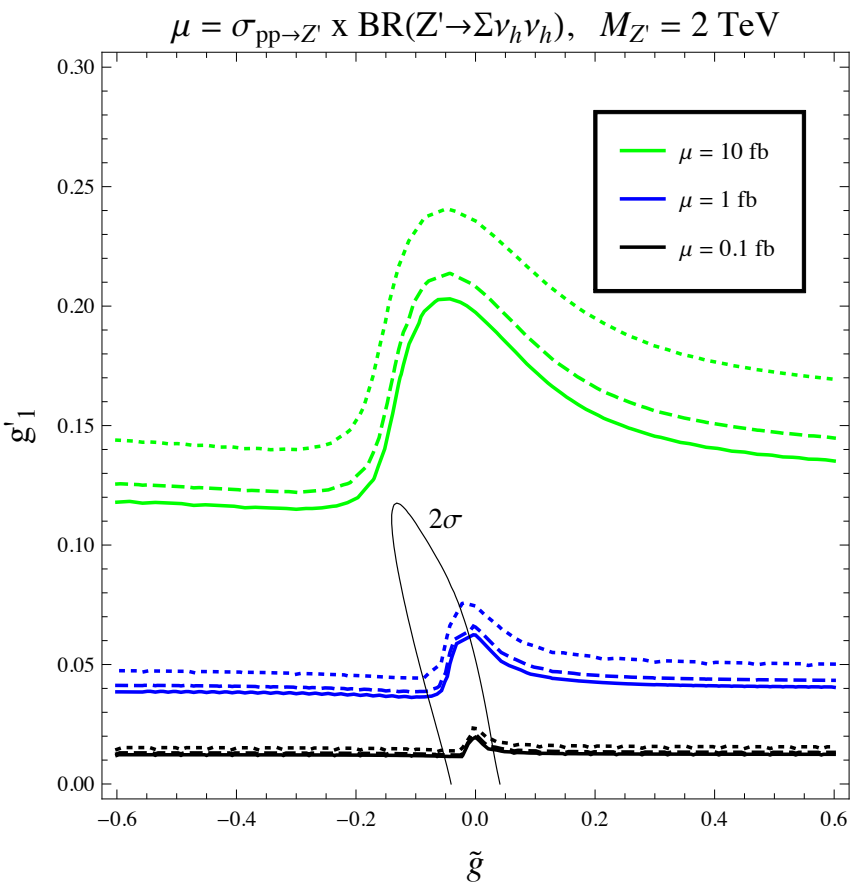
σ x BR contour level in the $\tilde{g} - g'_1$ space (LHC 13 TeV)

$m_{\nu h}$ fixed



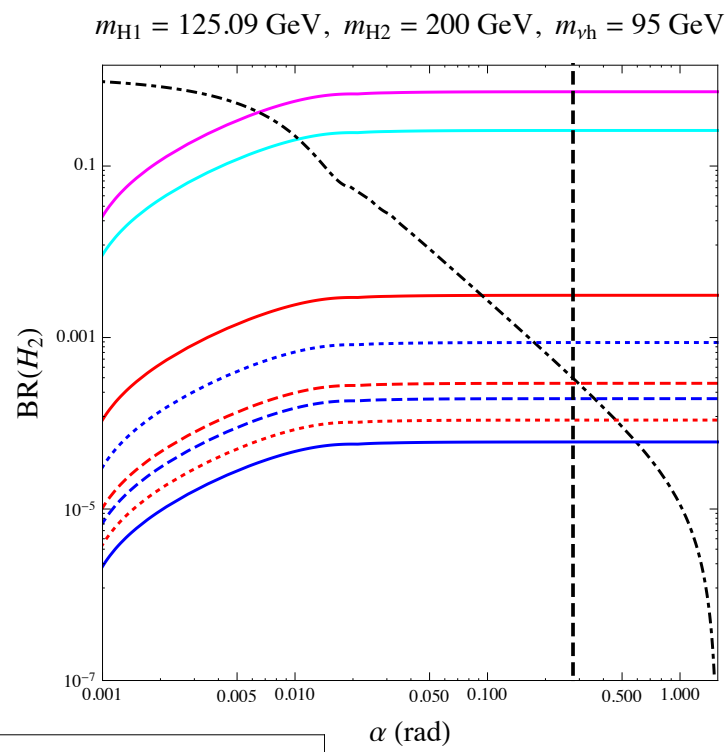

Solid, dashed and dotted lines refer to $M_{Z'}$ = 2, 2.5, 3 TeV, respectively

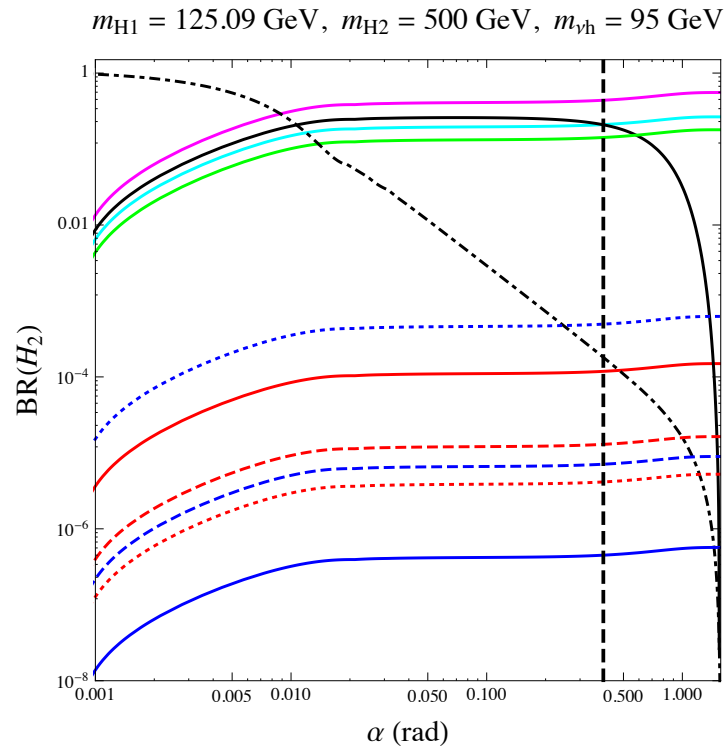
$M_{Z'}$ fixed

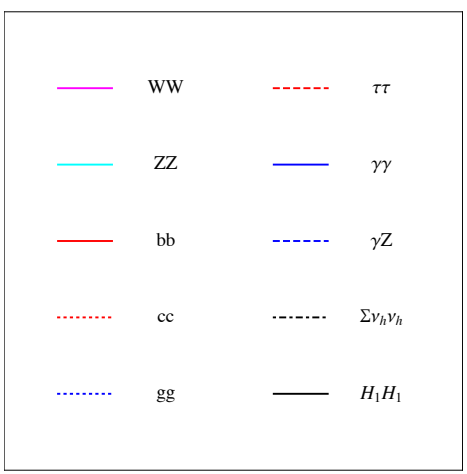



Solid, dashed and dotted lines refer to $m_{\nu h}$ = 95, 300, 500 GeV, respectively

# Heavy Higgs branching ratios



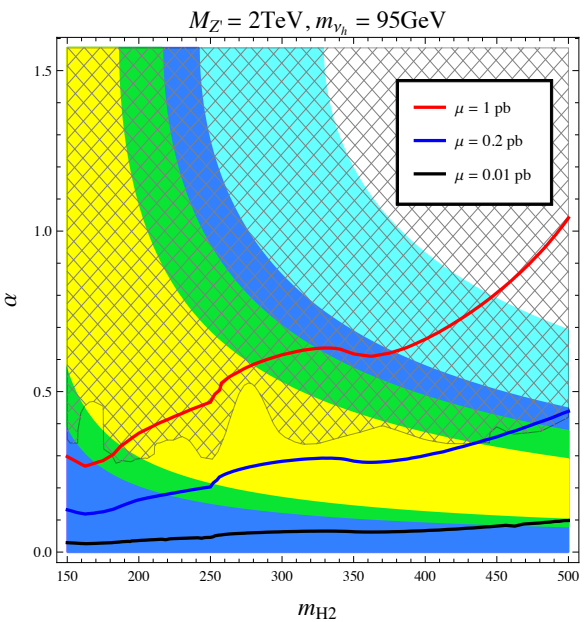




- The BR into heavy neutrinos drops as α increases $H_2\nu_h\nu_h \sim \cos\alpha$
- The BR into light higges shows a non-trivial α dependence
- The regions on the right of the vertical dashed lines are excluded by Higgs searches

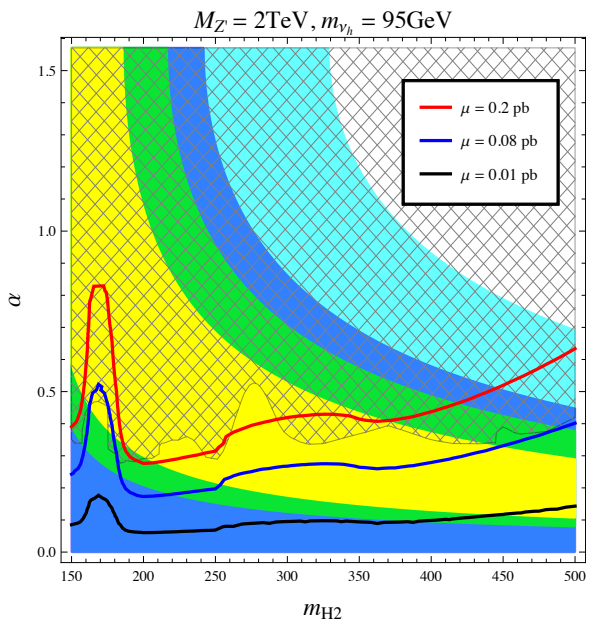
# Heavy Higgs production and decay

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

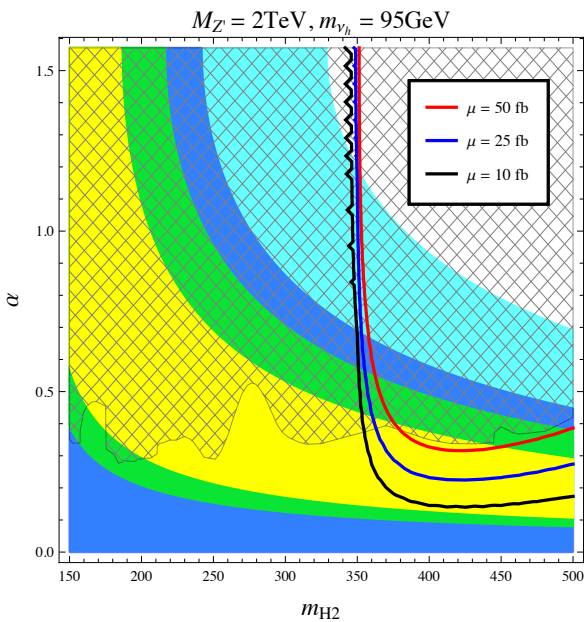
$pp \rightarrow H_2 \rightarrow WW$




$pp \rightarrow H_2 \rightarrow ZZ$




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

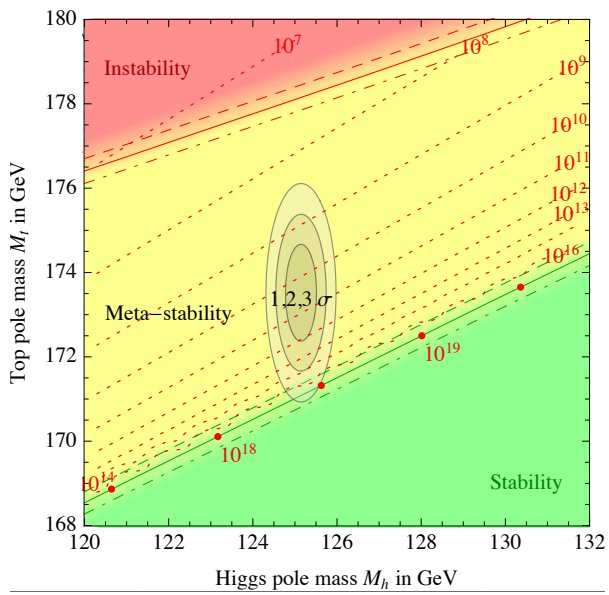


# The impact of the top mass in an extended scalar sector

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

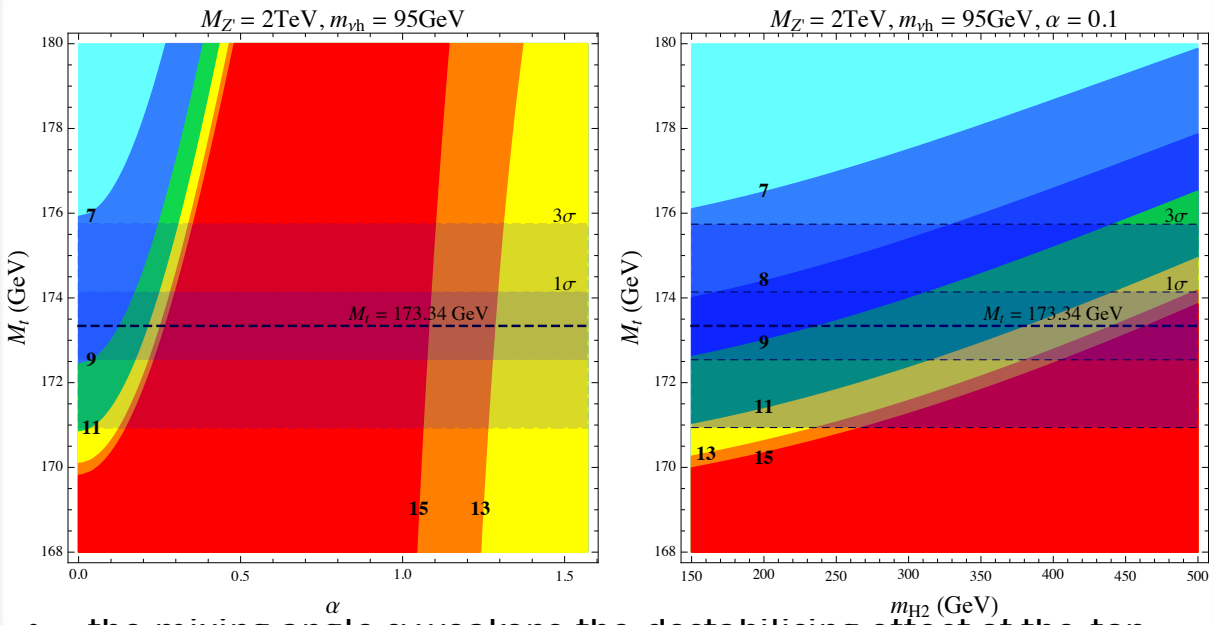
*MC mass does not represent neither the pole mass nor the $\overline{MS}$ mass!*

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 $Q_{max} = 10^x$ GeV 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 α > 0.4
- the effect of mH2 is softened and only shifts the instability induced by the top quark to higher values of its mass