# 2HDM interpretation of A$\to$Zh$\to \ell\ell$bb results

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# Intro


## Intro

- We already presented the status of the $A \to Zh \to \ell\ell bb$ analysis;
- We have expected limit (and sensitivity) in term of $\sigma * BR$
- we want to present the results in term of some model:
- the obvious choice are:
  - 2HDM: in a suitable parameter space
  - MSSM: in some benchmark declination, such as $m_h^{max}$ (discussion later)
- discussion and results here.

# 2HDM models

- Considering only 2HDM Type I and II:

Type I all quarks couple to just one of the higgs doublet

Type II up- and down-type quarks couple to different higgs doublet (MSSM)

  - TypeIII and IV differs only for the leptons coupling to Higgs doublets;

- Many free parameters: $m_h$, $m_H$, $m_A$, $m_{H^\pm}$, $m_{12}$, $\beta$, $\alpha$, $\lambda_{6,7}$
  - assume $m_h = 125.7\ GeV$
  - no CP-violation at tree-level: $\lambda_{6,7} = 0$
  - $A$ searches are not strongly dependent on $m_H$ and $m_{H^\pm}$, and a large mass splitting would give contribution to $\rho$: $m_H = m_{H^\pm} = m_A$;
  - $m_{12}^2 = m_A^2 \frac{\tan\beta}{1+\tan^2\beta}$ ($Z_2$ broken as in MSSM) as suggested by Higgs WG[1]
  - What remains is a mass: $m_A$ and two mixing angles $\beta$ and $\alpha$
  - standard values for SM parameters.

[1] M.Pelliccioni, High mass BSM Higgs phenomenology, CMS Higgs Workshop, 6/12/13

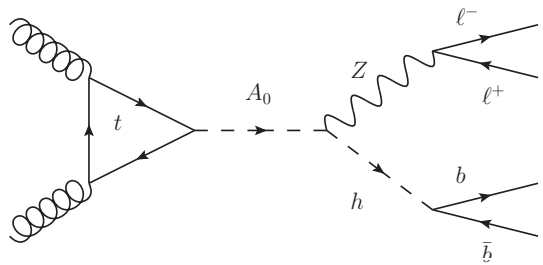
# Tools

- As suggested by HWG we have used:
- SuShi 1.2.0 for cross-section calculation;
- 2HDMC 2.6.4 for BR calculations;
- in both cases: NNLO
- *pdf*: MSTW2008LO90CL, NLO, NNLO
- Show results in $\tan\beta$ vs $\cos(\beta-\alpha)$ plane for different $m_A$.
  - $m_A = 225, 250, 275, 300, 325, 350, 400, 500, 600$ *GeV*;
  - $0.1 \leq \tan\beta \leq 100$ in variable step (finer at low $\tan\beta$);
  - $0 \leq \cos(\beta-\alpha) \leq 1.$ with step 0.02;
    - ⋆ *alignement limit* $\cos(\beta-\alpha) \to 0$, $h \to h_{SM}$
- AZh should not have asymmetry for $\cos(\beta-\alpha) >< 0$
- I'm not able to generate SuShi and 2HDMC with $\cos(\beta-\alpha) < 0$ anyhow!
  - input are $\tan\beta$ and $\sin(\beta-\alpha)$, so I don't know how to have $\cos(\beta-\alpha) = \sqrt{1-\sin^2(\beta-\alpha)}$ negative
  - help asked to expert

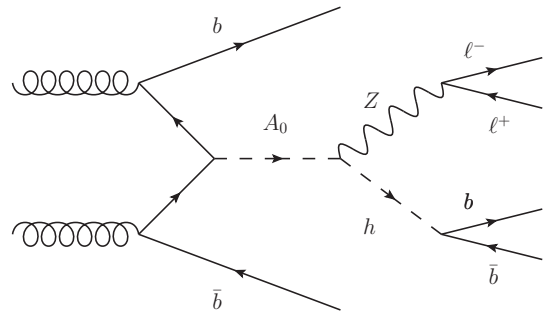
# Cross-sections

Two production mechanism available:

- gluon-fusion $gg \to A$ (dominant)



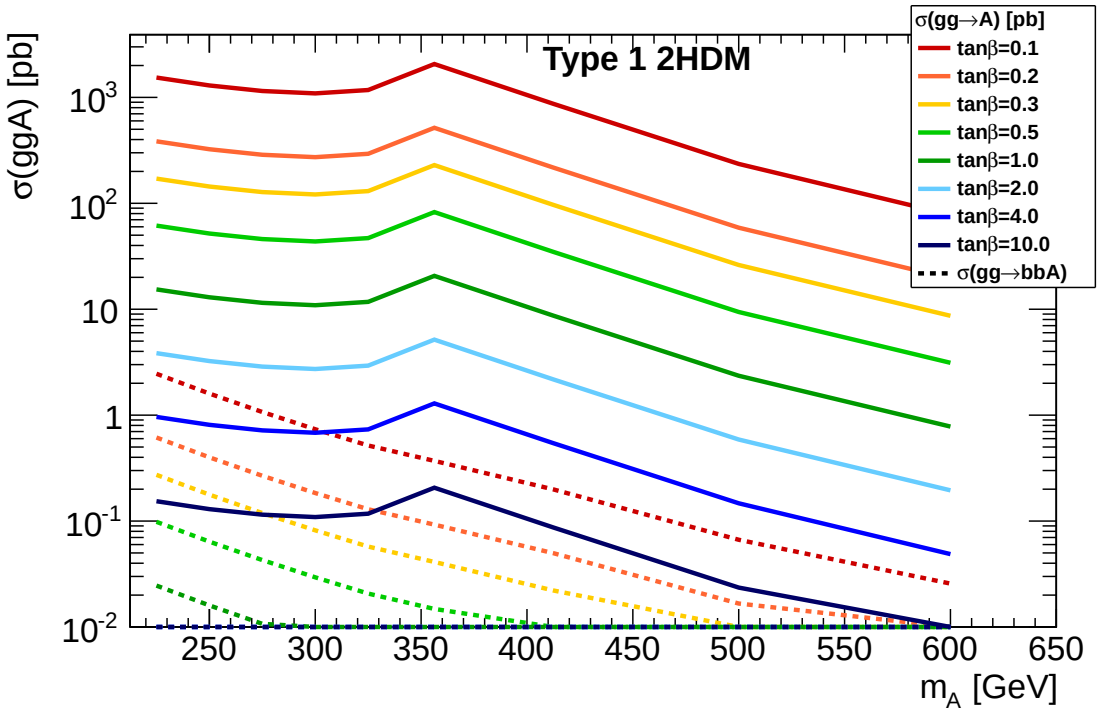

- b-associated production $gg \to Abb$




No dependence on $\alpha$ for either TypeI and TypeII 2HDM, so we can plot $\sigma$ vs $m_A$ vs $\tan\beta$

# Type I $\sigma$

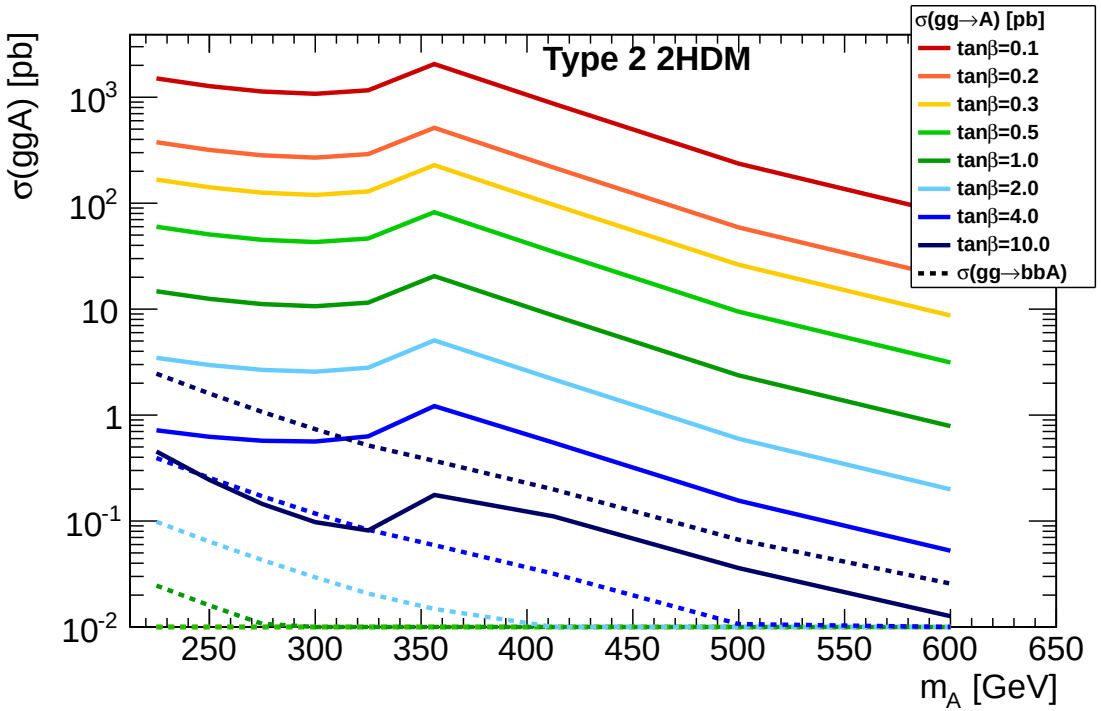
$\sigma(ggA)$ (full line)
$\sigma(bbA)$ (dashed line)
vs $m_A$ for different tan $\beta$;




- $\sigma(ggA)$ higher for lower tan $\beta$;
- $\sigma(ggA) \gg \sigma(bbA)$
- $\sigma(bbA)$ has the same dependence on tan $\beta$ as $\sigma(ggA)$: higher for lower tan $\beta$. No crossing!
- NB. TypeI 2HDM: all quarks couple to the same doublet.

# Type II $\sigma$

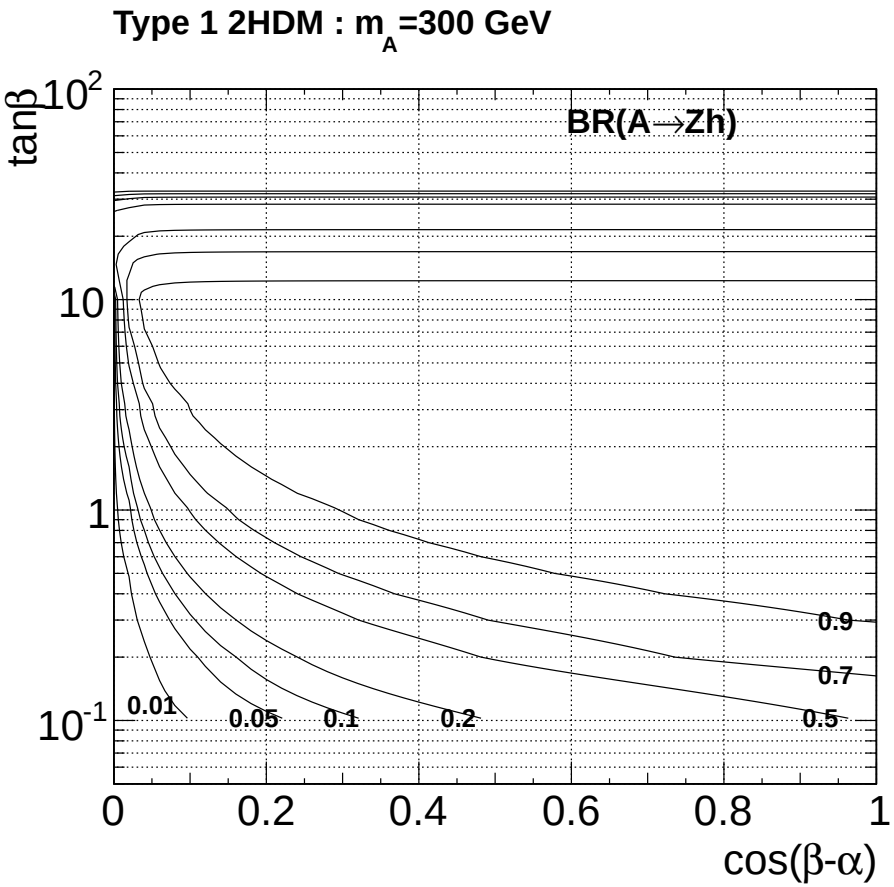
$\sigma(ggA)$ (full line)
$\sigma(bbA)$ (dashed line)
vs $m_A$ for different tan $\beta$;

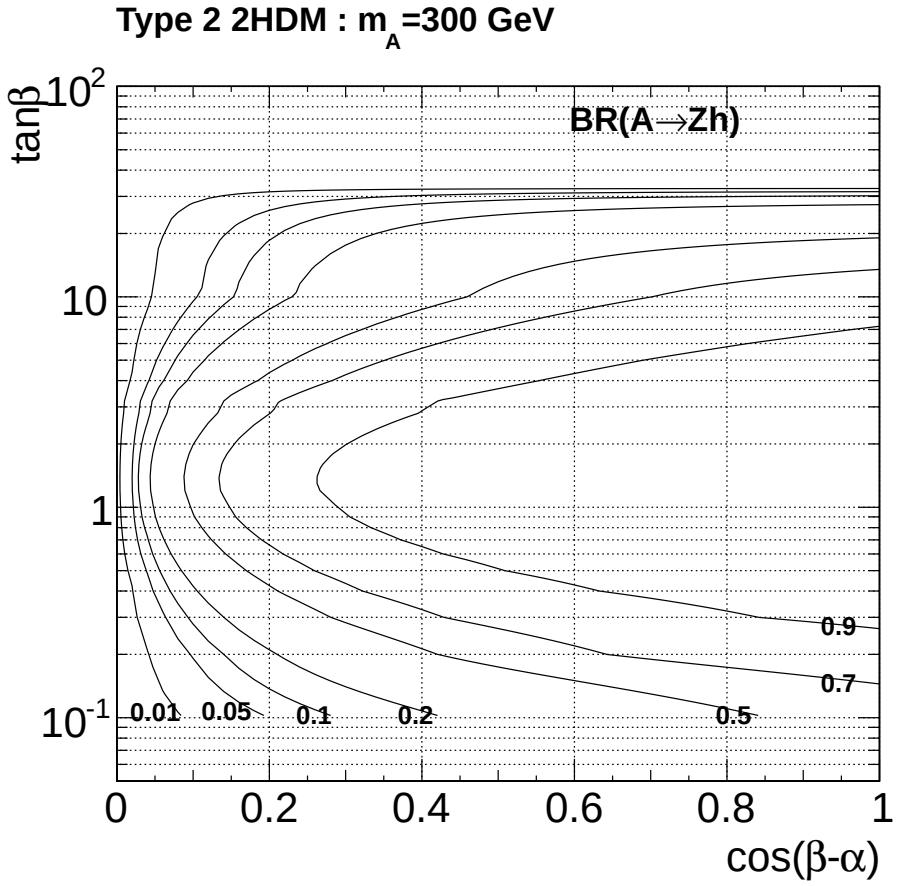



- $\sigma(ggA)$ higher for lower tan $\beta$;
- $\sigma(bbA)$ increase with tan $\beta$, so it becomes more and more important wrt $\sigma(ggA)$ for high tan $\beta$;
- NB. TypeII 2HDM: up and down quarks couple to the different doublet, as in MSSM.

# BR($A \to Zh$): $m_A = 300$ GeV

BR depends on both $\tan\beta$ and $\cos(\beta - \alpha)$: shown for $m_A = 300$ GeV

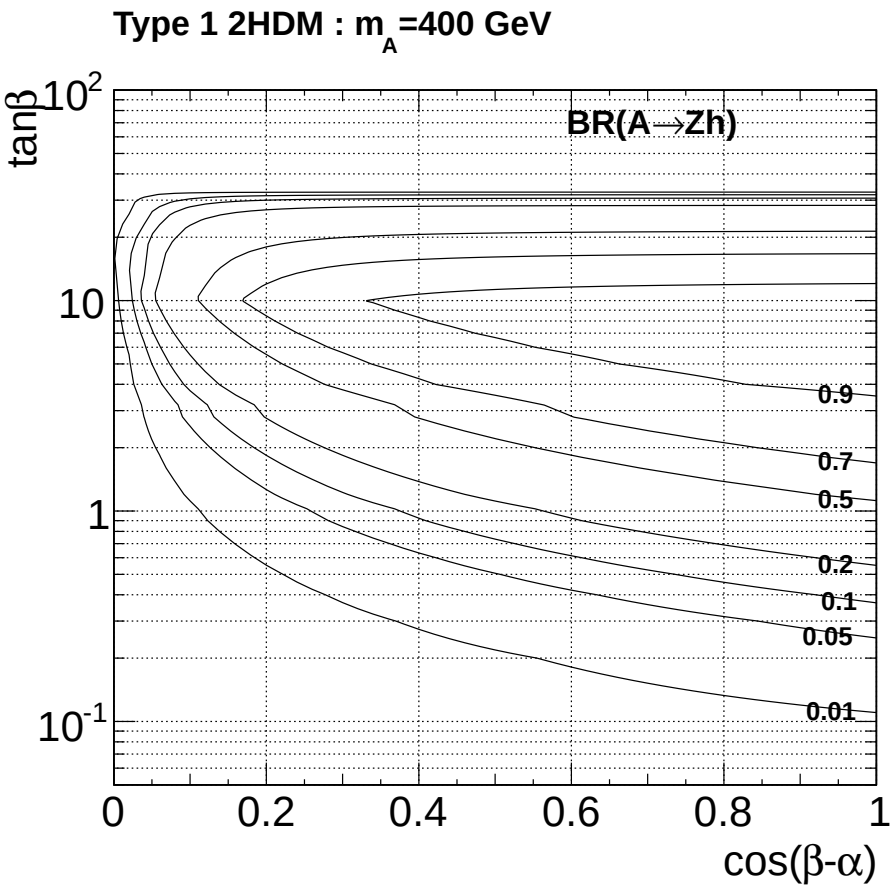


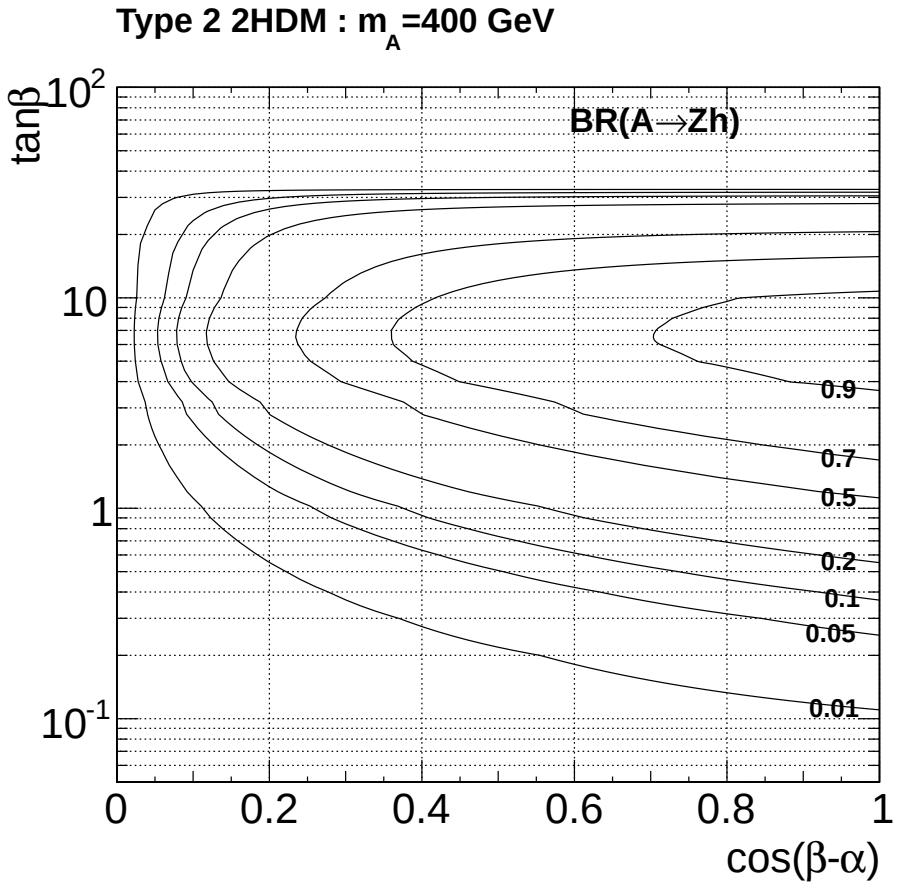




other mass points on backup

# BR($A \to Zh$): $m_A = 400\ GeV$

## $m_A = 400\ GeV$: $A \to tt$ is open

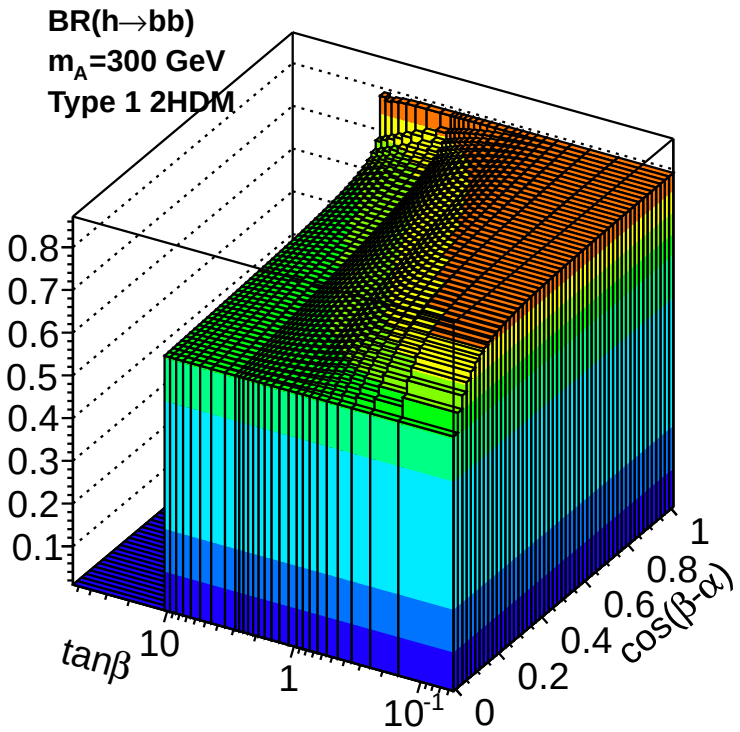


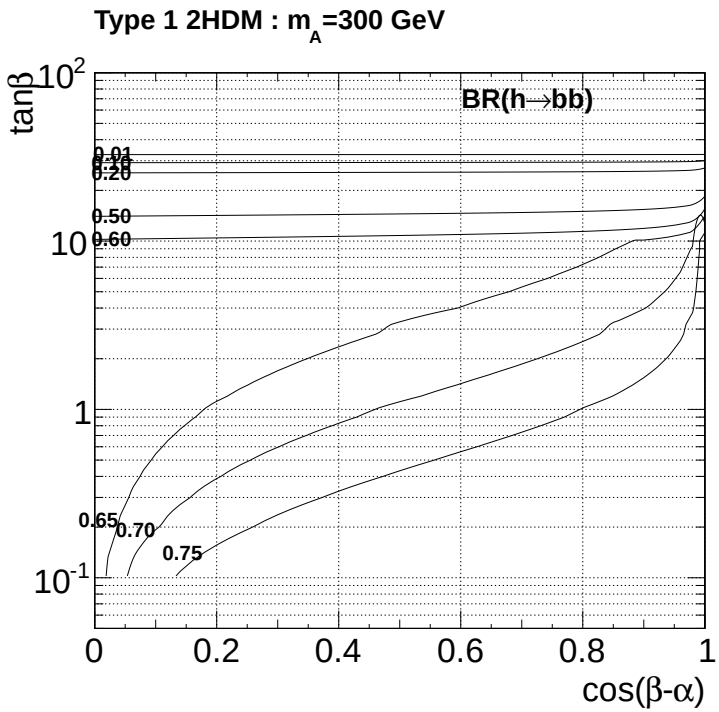




other mass points on backup

# BR($h \to bb$) Type I

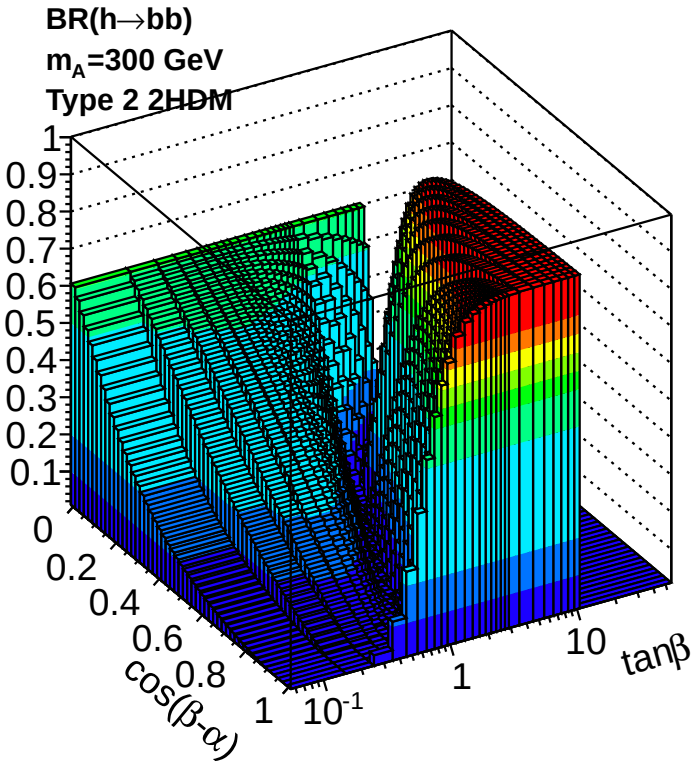
- BR($h \to bb$) in 2HDM is in general different from SM ($BR_{SM} \approx 0.6$);
- SM achieved in the *alignement* limit ($cos(\beta - \alpha) = 0$);
- BR varies in very different way for TypeI and TypeII;
- No dependence on $m_A$.

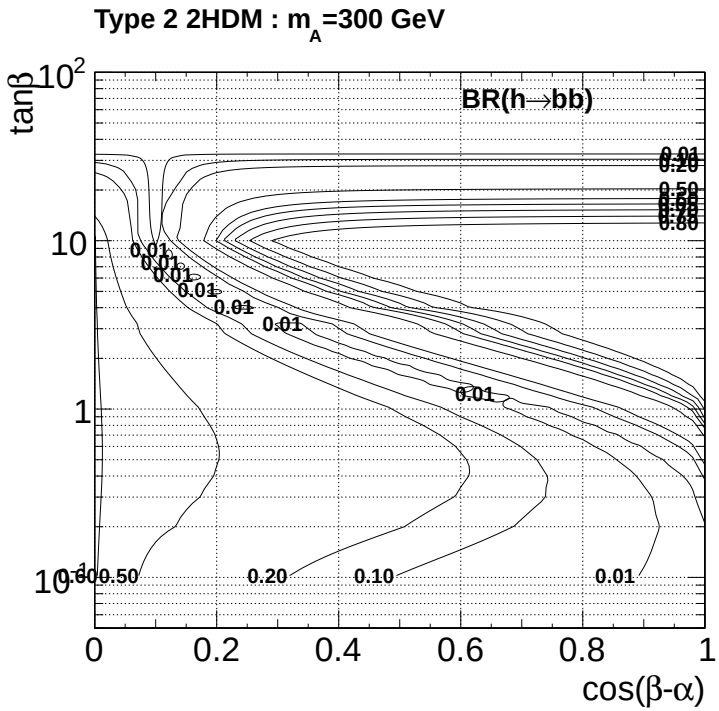


# BR($h \to bb$) Type II

- For Type II a deep valley, with BR$\sim$ 0, is present;
- coupling `hQd`: Type I $\cos\alpha/\sin\beta$ Type II $-\sin\alpha/\cos\beta$
- So BR($h \to bb$)=0 for $\sin\alpha = 0$

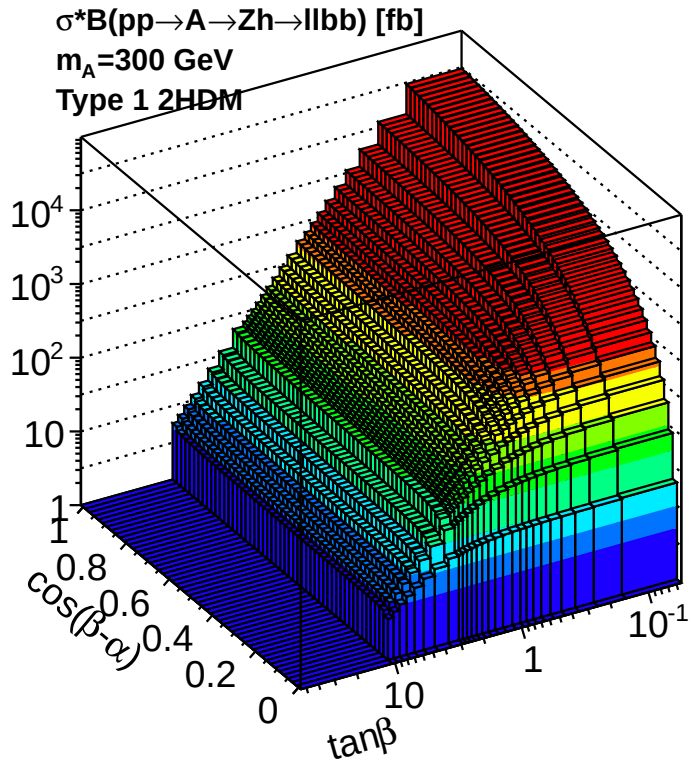


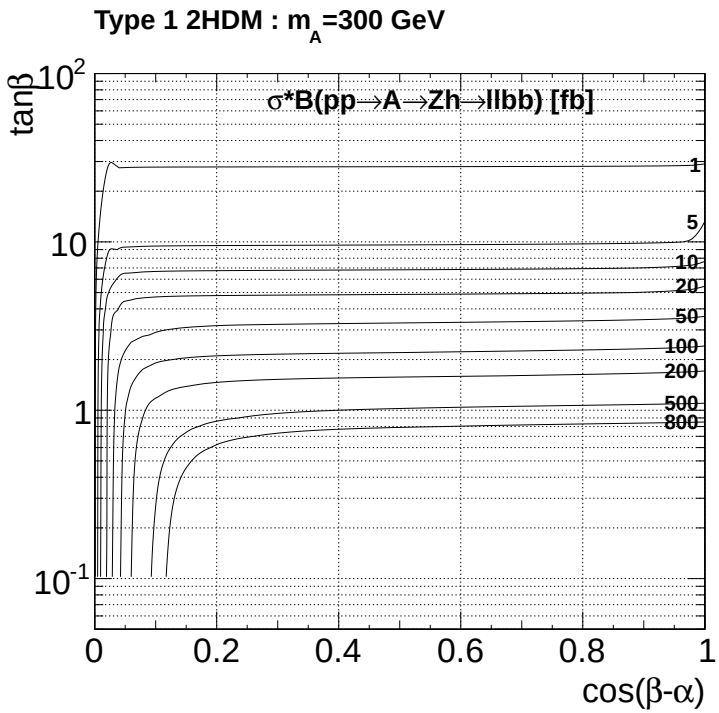




NB: plot rotated

# $\sigma \times BR(A \to Zh \to \ell\ell bb)$ Type I, $m_A = 300\ GeV$

## $\sigma(ggA + bbA)$, BR($Z \to \ell\ell$) included

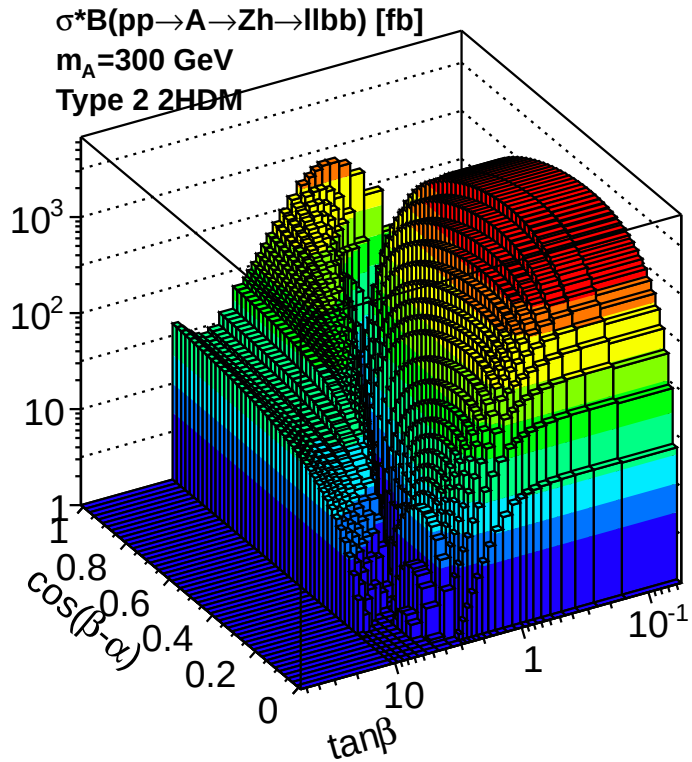


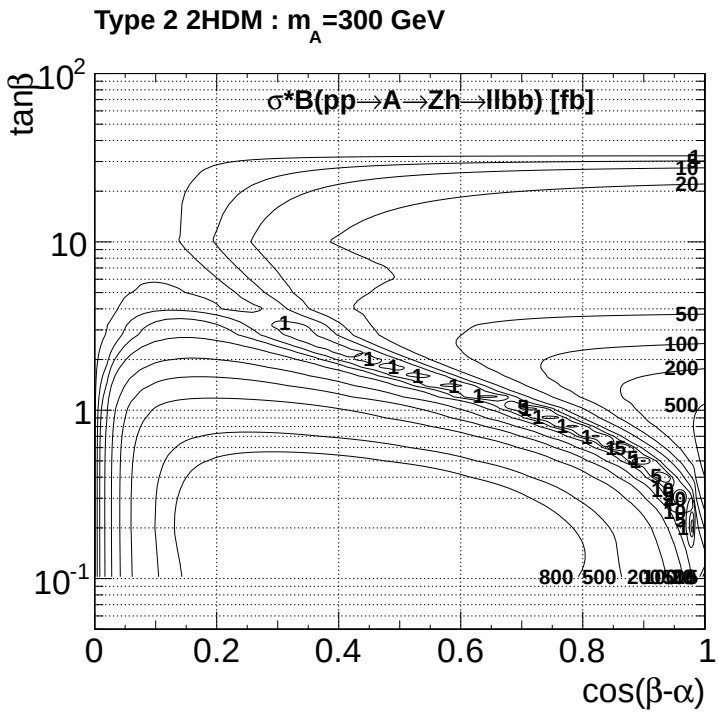




NB: plot rotated
other mass points on backup

# $\sigma \times BR(A \to Zh \to \ell\ell bb)$ Type II, $m_A = 300\ GeV$

## $\sigma(ggA + bbA)$, BR($Z \to \ell\ell$) included

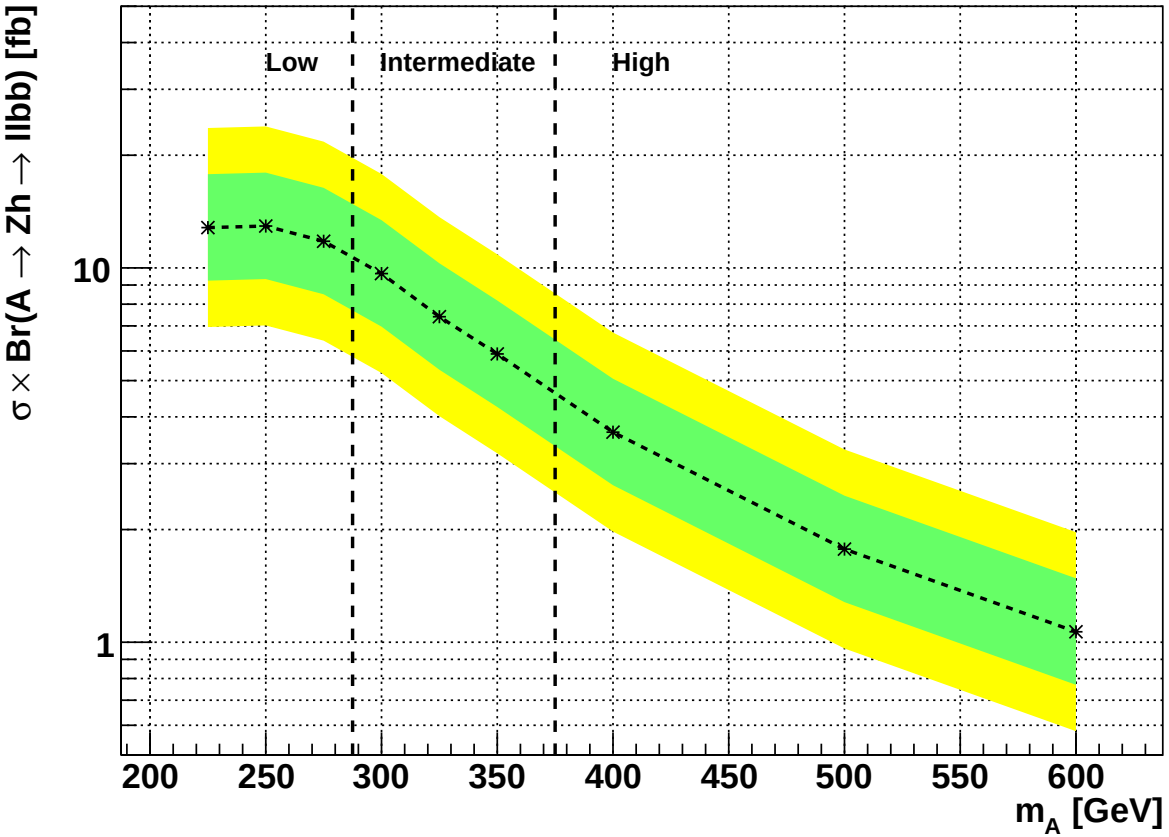



NB: plot rotated
other mass points on backup

# Expected Limits on $\sigma \times BR(A \to Zh \to \ell\ell bb)$

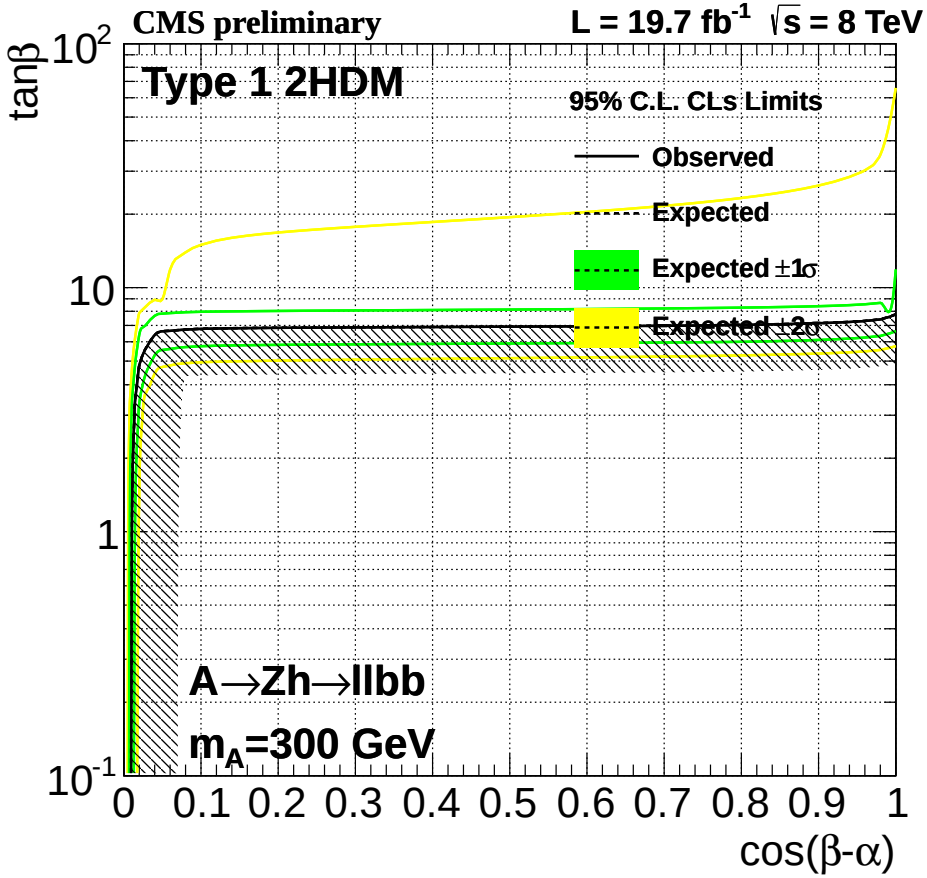
| $m_A$ [GeV] | 225 | 250 | 275 | 300 | 325 | 350 | 400 | 500 | 600 |
|---|---|---|---|---|---|---|---|---|---|
| expected [fb] | 12.8 | 12.9 | 11.8 | 9.66 | 7.41 | 5.89 | 3.64 | 1.77 | 1.07 |

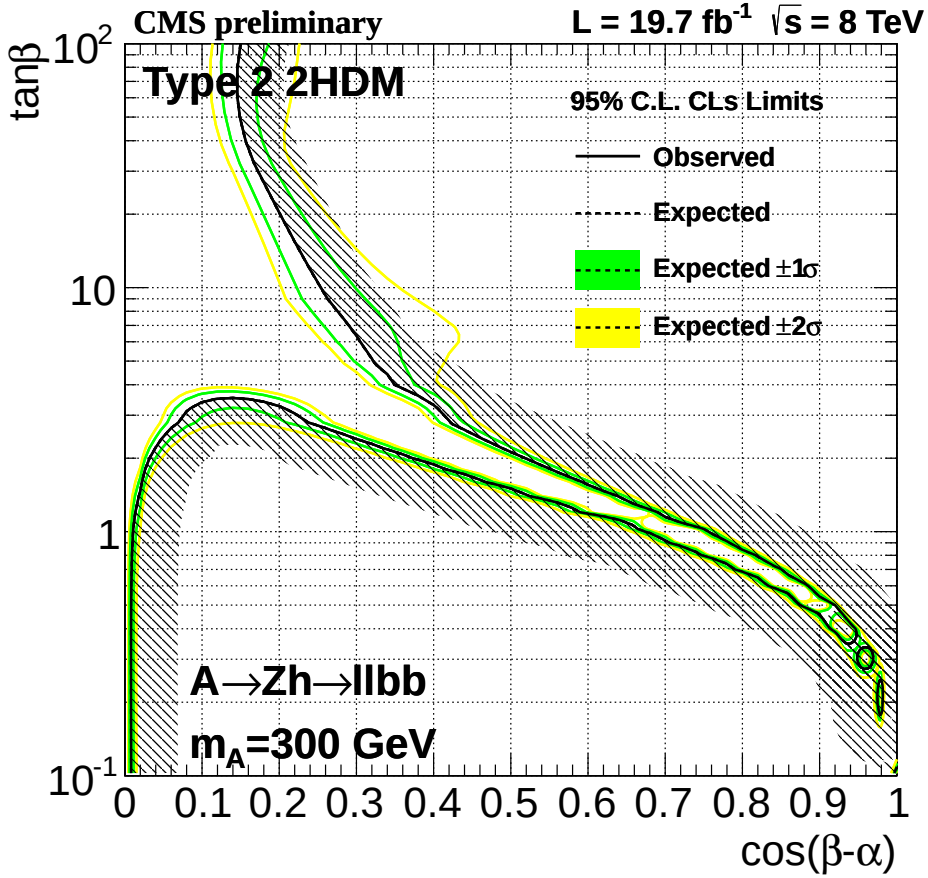



as shown by Alberto last week

# Expected exclusion regions

Expected limits **(Observed≡Expected, we are still blind!)** in $\tan\beta$ vs $\cos(\beta-\alpha)$ plane, $m_A = 300$ *GeV*



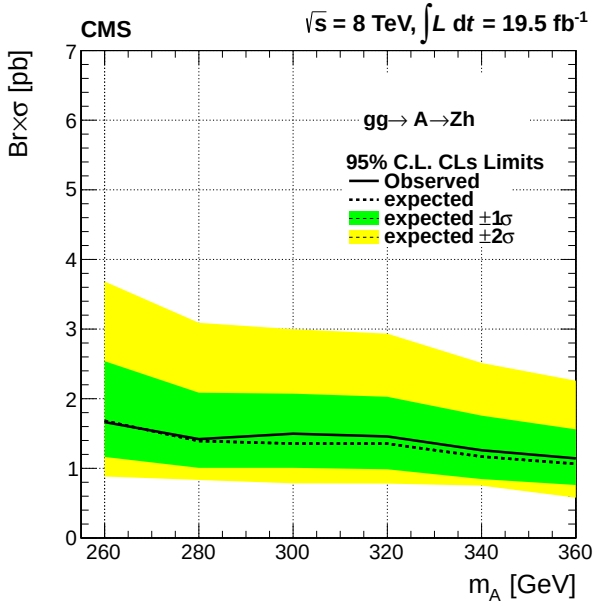

other mass points on backup

# Comparison with HIG-13-025

## HIG-13-025

Search for extended Higgs sectors in the $H \to hh$ and $A \to Zh$ channels in $\sqrt{s} = 8$ TeV $pp$ collisions with multileptons and photons final states

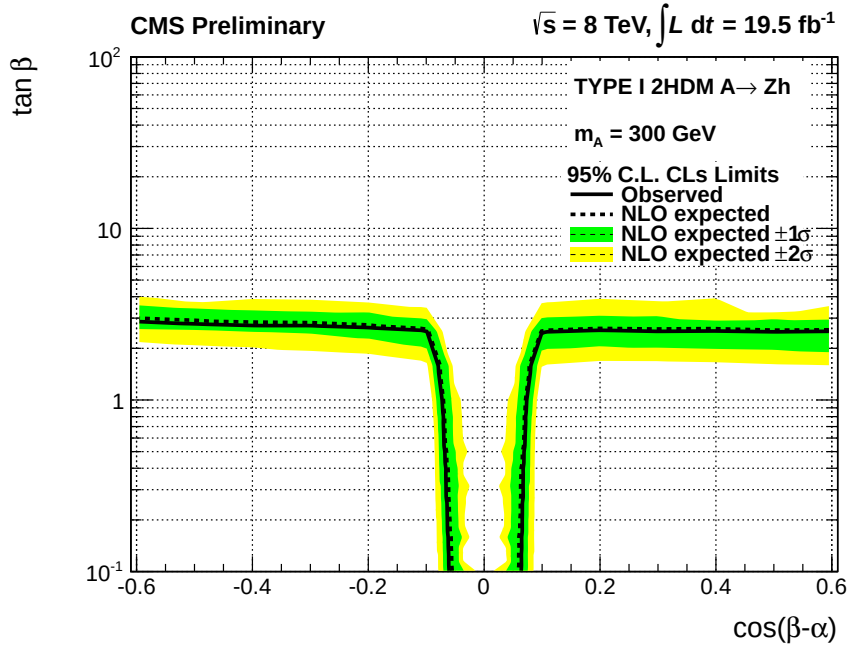
### Limits on $\sigma * BR$ for $A \to Zh$ only




we expect to exclude $\sigma * BR \lesssim 12$ *fb*

and up to $m_A \in [225 - 600]$ *GeV*

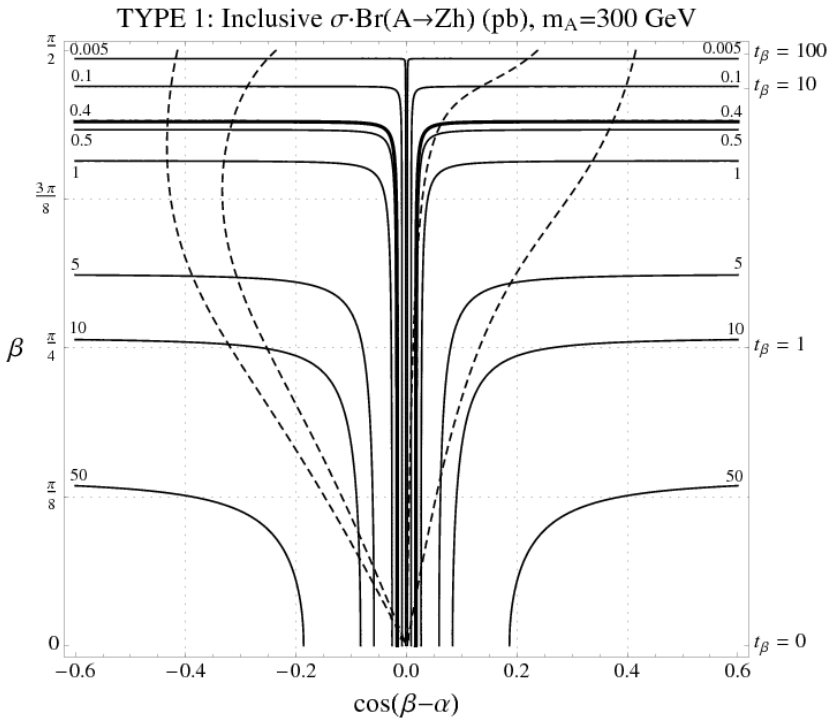
### Limits on Type I 2HDM plane

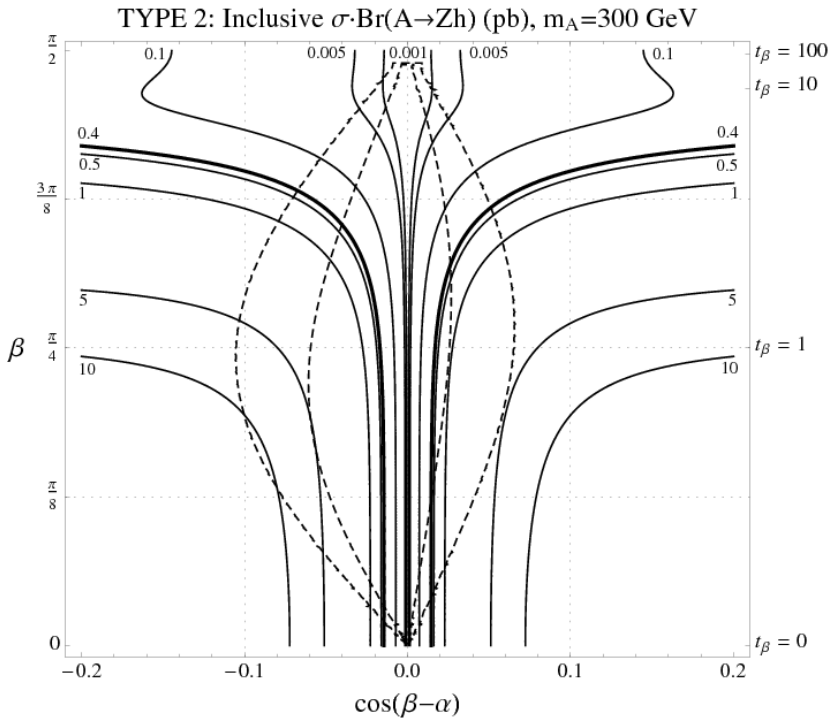



we expect to reach $\tan\beta \lesssim 7$

# Exclusion from SM-like Higgs fit

Dashed contour(s) are the allowed region at 68%(90%) CL after best fit to the signal of the SM-like Higgs[2]



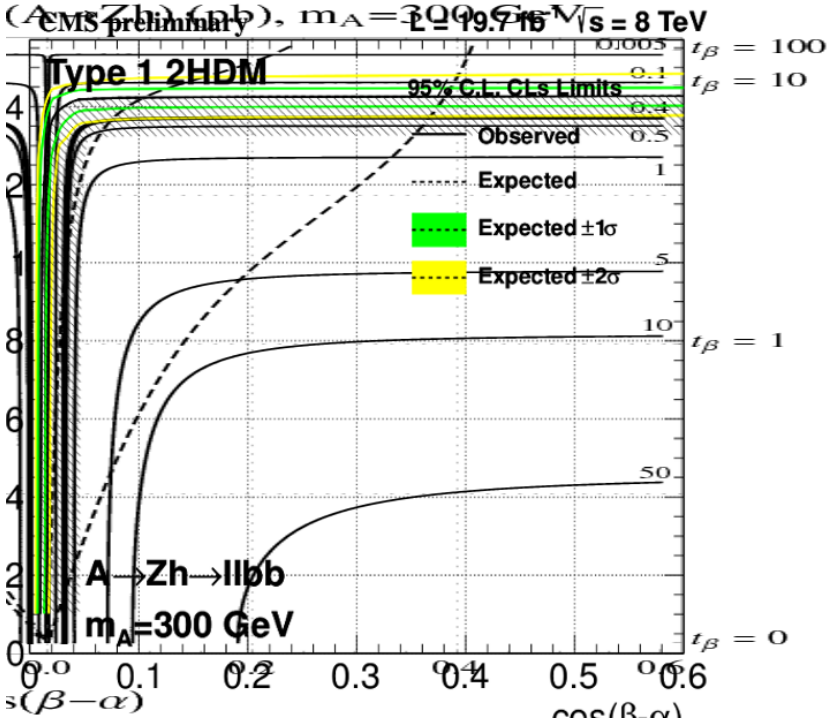

Warning: $\beta$ (not $\tan\beta$) vs $|\cos\beta - \alpha| < 0.6(\textit{left})/0.2(\textit{right})$ (not 1.0)

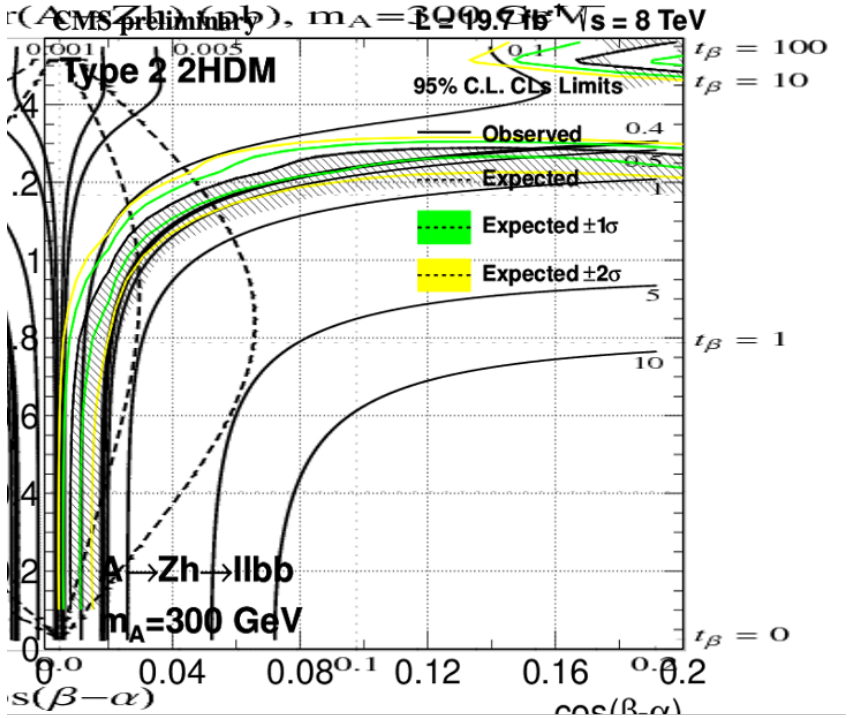
[2] N. Craig, J. Galloway, S. Thomas, "Searching for Signs of the Second Higgs Doublet", 1305.2424

# Exclusion from SM-like Higgs fit

Dashed contour(s) are the allowed region at 68%(90%) CL after best fit to the signal of the SM-like Higgs[2]

We can exclude an interesting region!



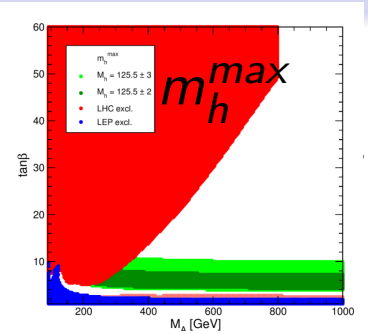



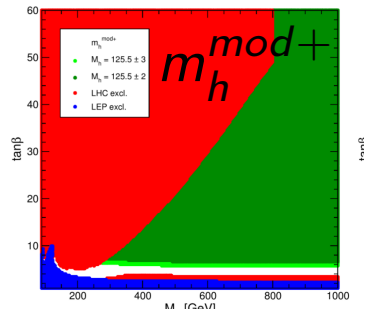

Warning: $\beta$ (not $\tan\beta$) vs $|\cos\beta - \alpha| < 0.6(\textit{left})/0.2(\textit{right})$ (not 1.0)

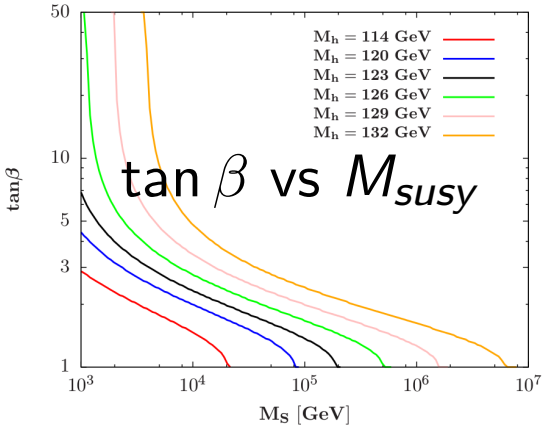
[2] N. Craig, J. Galloway, S. Thomas, "Searching for Signs of the Second Higgs Doublet", 1305.2424

# MSSM

- Which MSSM declination should be used?
- In widely used $m_h^{max}$ benchmark [a] correct $m_h$ only for a rather narrow band in the $\tan\beta, m_A$ plane around $\tan\beta \gtrsim 5$.
- likewise for $m_h^{mod\pm}$ (higher $\tan\beta$ allowed);
- in both cases $M_{susy}$ is rather low, so $A \to sparticles$ allowed, low sensitivity for $A \to Zh$, so very hard to reach $\tan\beta \gtrsim 5$
- very large $M_{susy} \gtrsim 10 - 100$ $TeV$ scenarios [b], allow for correct $m_h$ at low $\tan\beta$.
  But no actual benchmark scenario available.



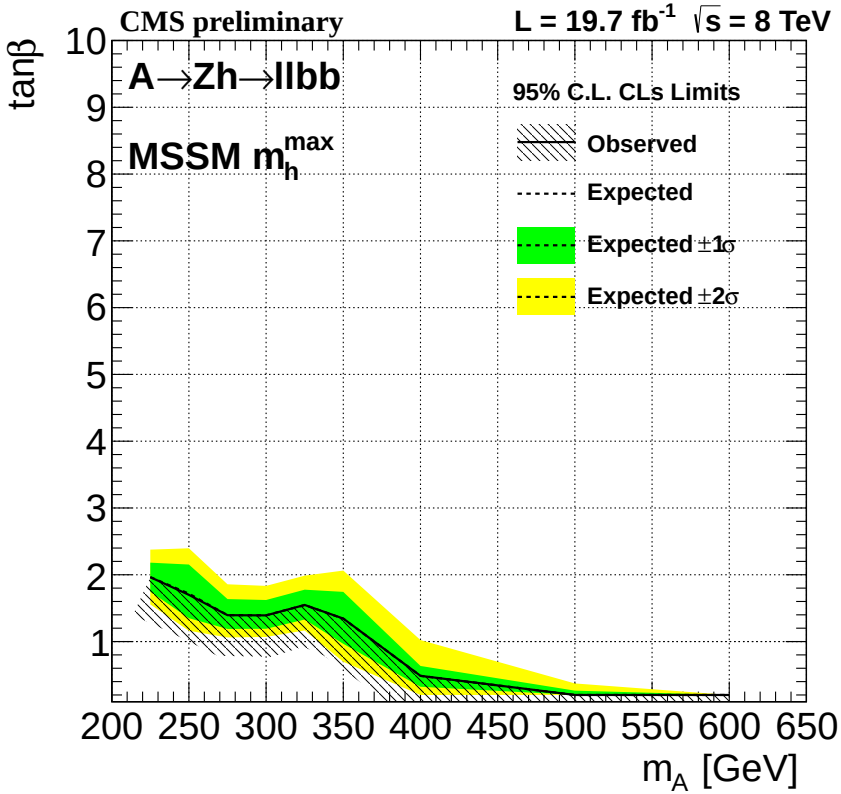



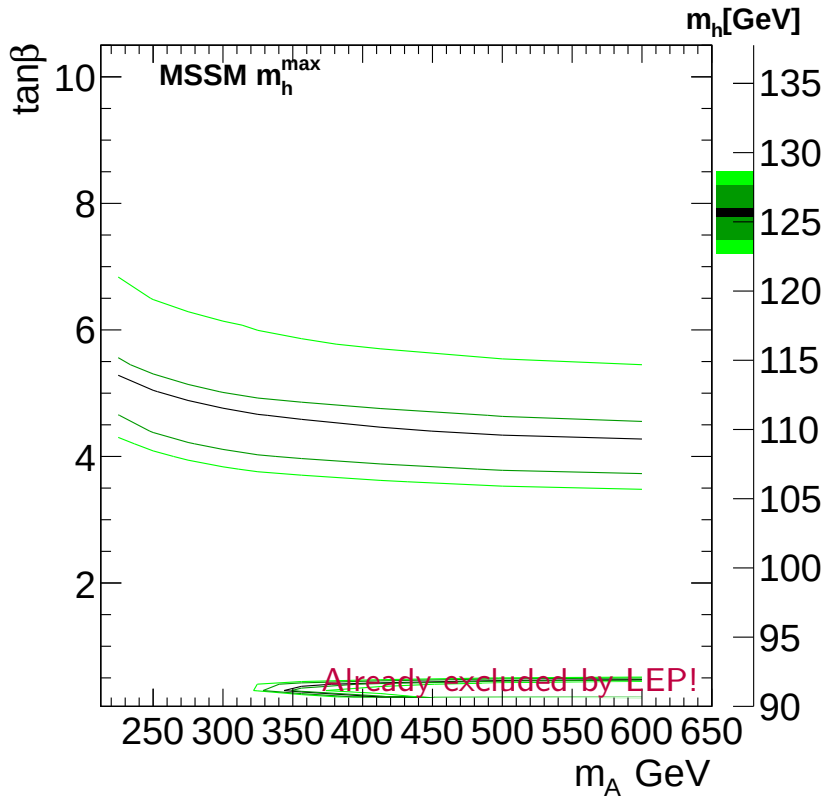

[a] arXiv:1404.0327, arXiv:1302.7033
[b] arXiv:1304.1787

# Expected limit for MSSM $m_h^{max}$

Expected limits **(Observed≡Expected, we are still blind!)** in $\tan\beta$ vs $m_A$ plane, for MSSM $m_h^{max}$




Using SuShi+FeynHiggs 2.10.0




$m_h = 125.7 \pm 2(3)$ *GeV* in MSSM $m_h^{max}$

# Conclusion

- Expected limits on $\sigma \times BR(A \to Zh \to \ell\ell bb)$ interpreted in 2HDM Type I and Type II scenarios
- Shown also some comparison with similar analisys and existings esclusions
- Shown results also for MSSM $m_h^{max}$, although not a viable benchmark for this analysis
  - To be noted that HIG-13-025 ($H \to hh$ and $A \to Zh$ in multileptons and photons final states) shows exclusion only for 2HDM
- Feeding the AN with all this material...
- Feedback is welcome!


# Backup


## Backup slides

# 2HDM Generalities

- A simple extension of the SM is the addition of a 2nd Higgs doublet
- It gives rise to 5 Higgs Bosons: h, H, A, $H^{\pm}$
- Is the 125 GeV the lightest among the 5?
- 2HDM models are classified depending on the fermion coupling:
  - **Type I**: all quarks couple to just one of the Higgs doublets
    → fermio-phobic limit
  - **Type II**: the Q=2/3 right handed quarks couple to one Higgs doublet and the Q=-1/3 right handed quarks couple to the other
    →MSSM is a type II at tree level

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} -\sin\alpha & \cos\alpha \\ \cos\alpha & \sin\alpha \end{pmatrix} \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix}$$

$$\begin{pmatrix} A \\ G \end{pmatrix} = \begin{pmatrix} -\sin\beta & \cos\beta \\ \cos\beta & \sin\beta \end{pmatrix} \begin{pmatrix} \chi_1 \\ \chi_2 \end{pmatrix}$$

| $y_{2HDM}/y_{SM}$ | Type I | Type II |
|---|---|---|
| $\xi_h^V$ | $\sin(\beta-\alpha)$ | $\sin(\beta-\alpha)$ |
| $\xi_h^u$ | $\cos\alpha/\sin\beta$ | $\cos\alpha/\sin\beta$ |
| $\xi_h^d$ | $\cos\alpha/\sin\beta$ | $-\sin\alpha/\sin\beta$ |
| $\xi_H^V$ | $\cos(\beta-\alpha)$ | $\cos(\beta-\alpha)$ |
| $\xi_H^u$ | $\sin\alpha/\sin\beta$ | $\sin\alpha/\sin\beta$ |
| $\xi_H^d$ | $\sin\alpha/\sin\beta$ | $\cos\alpha/\cos\beta$ |

Mixing angles:
α and β

$\phi_1, \phi_2$ : CP-even fields
$\chi_1, \chi_2$ : CP-odd fields

$$\tan\beta = \frac{v_2}{v_1}$$

# 2HDM Lagrangian

## 2HDM Couplings

Couplings that include Three h, H, A, $H^{+-}$ require Additional Parameters

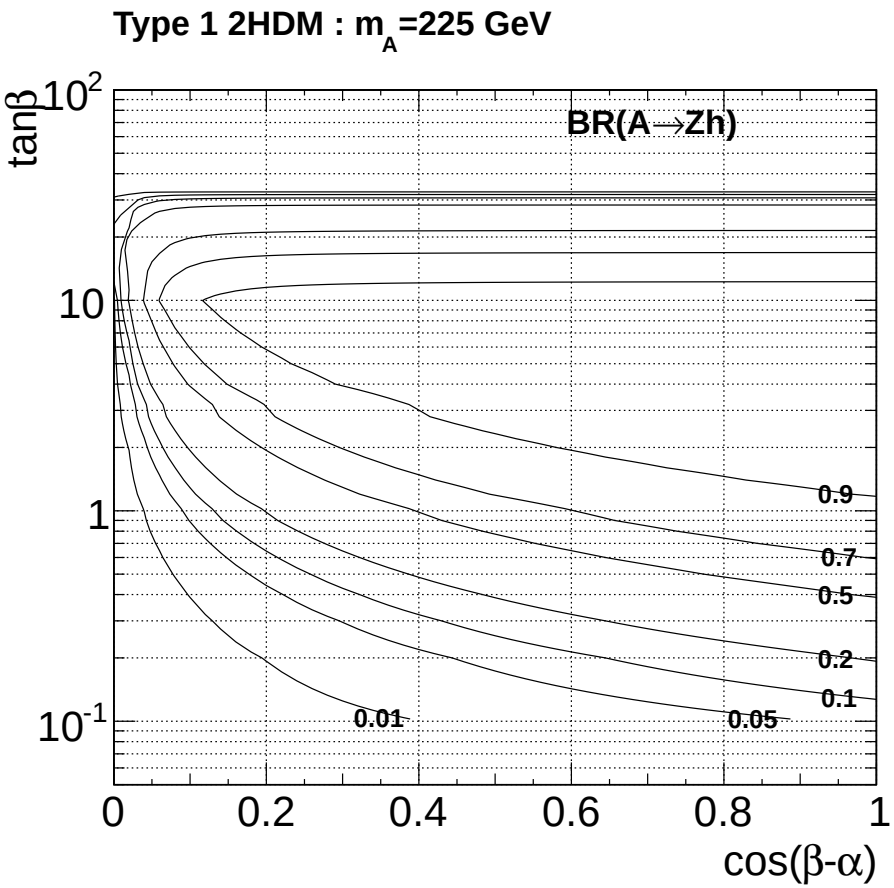
(Renormalizable) Tree-Level Potential

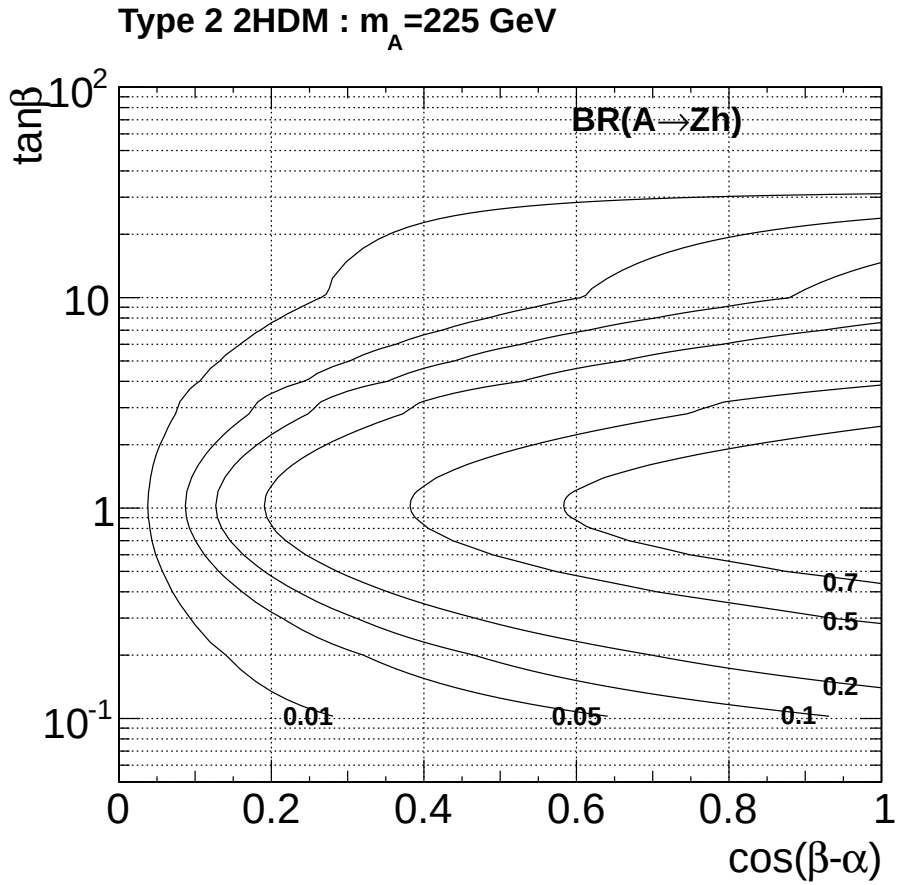
$$
\begin{aligned}
V = & \, m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left[ m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.} \right] \\
& + \frac{1}{2} \lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2} \lambda_2 (\Phi_2^\dagger \Phi_2) + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\
& + \left[ \frac{1}{2} \lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \lambda_6 (\Phi_1^\dagger \Phi_1)(\Phi_1^\dagger \Phi_2) + \lambda_7 (\Phi_2^\dagger \Phi_2) \Phi_1^\dagger \Phi_2 + \text{h.c.} \right]
\end{aligned}
$$

Can Trade: $\alpha$, $\beta$, $m_h$, $m_H$, $m_A$, $m_{H^{+-}}$, vev for $m_{11}$, $m_{22}$, $m_{12}$, $\lambda_1$, $\lambda_2$, $\lambda_3$, $\lambda_4$

# BR($A \to Zh$): $m_A = 225$ GeV

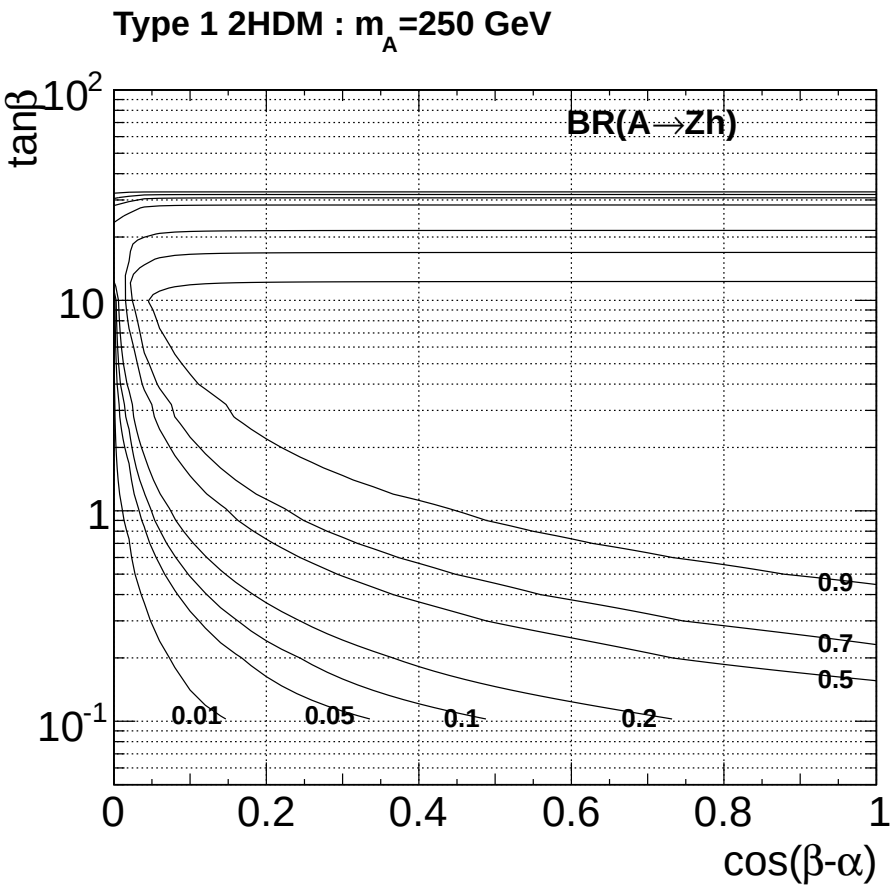
Depends on both $\tan\beta$ and $\cos(\beta - \alpha)$: shown for $m_A = 225$ GeV

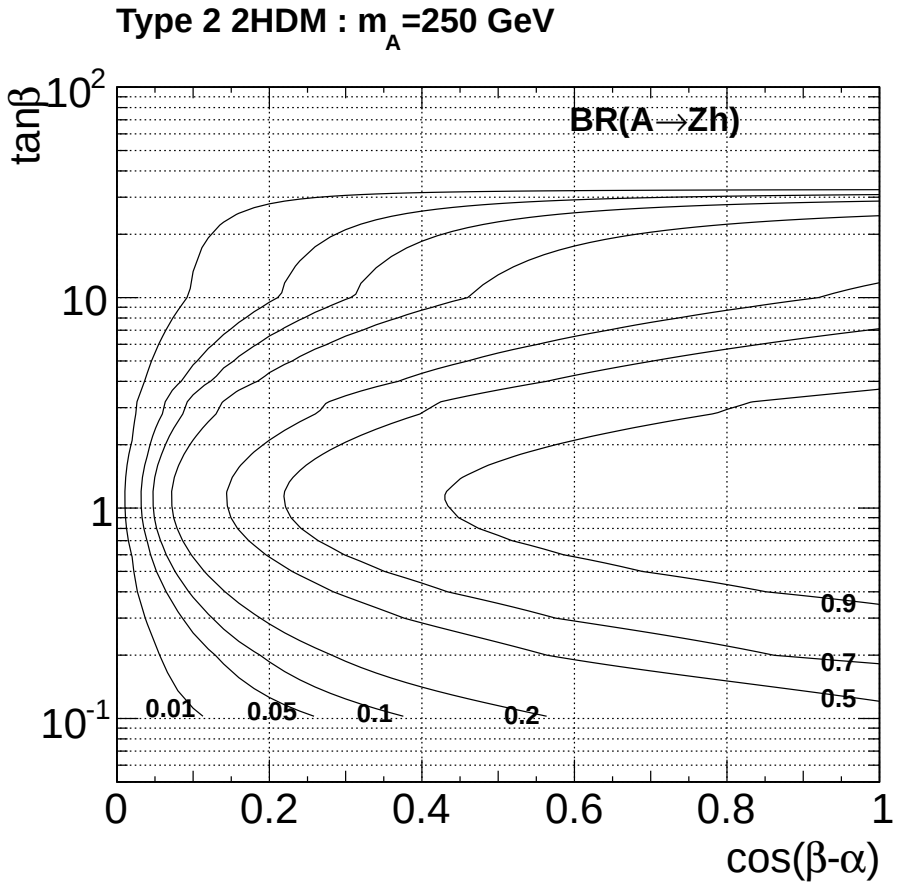


# BR($A \to Zh$): $m_A = 250$ GeV

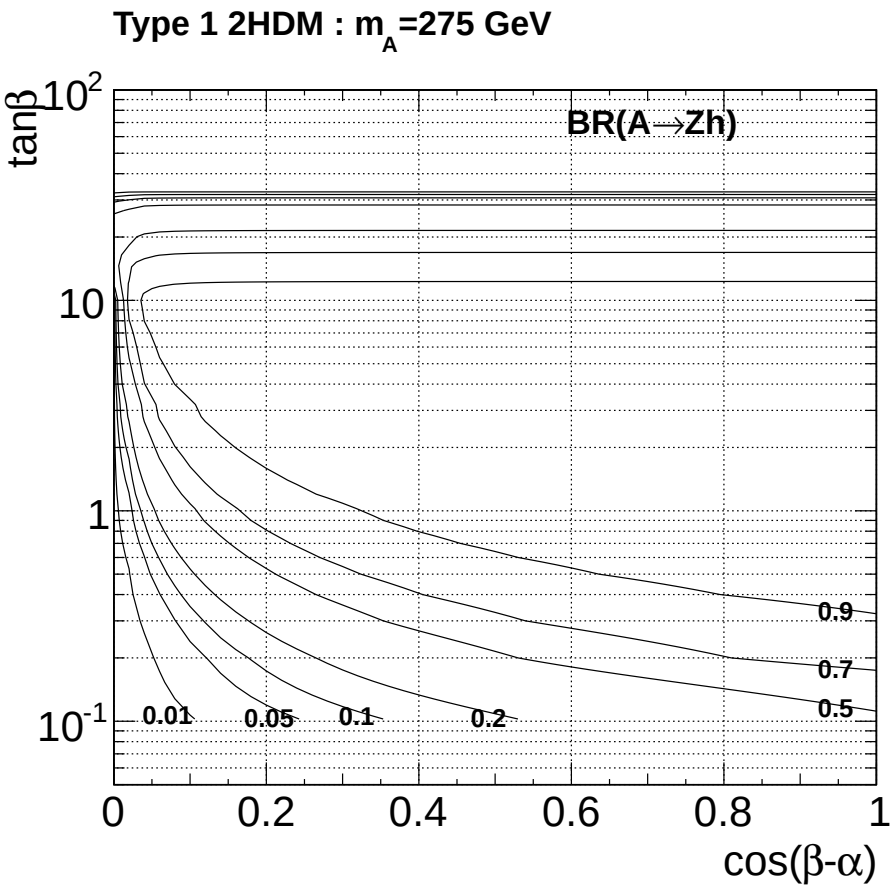
Depends on both $\tan\beta$ and $\cos(\beta - \alpha)$: shown for $m_A = 250$ GeV

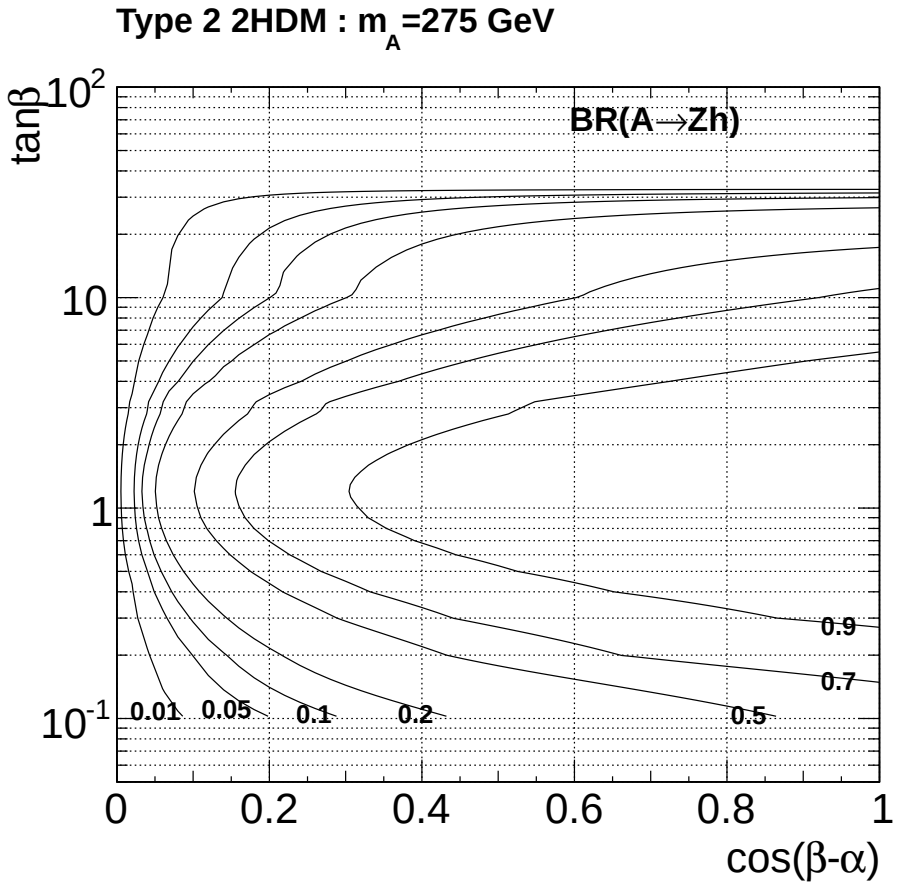


# BR($A \to Zh$): $m_A = 275$ GeV

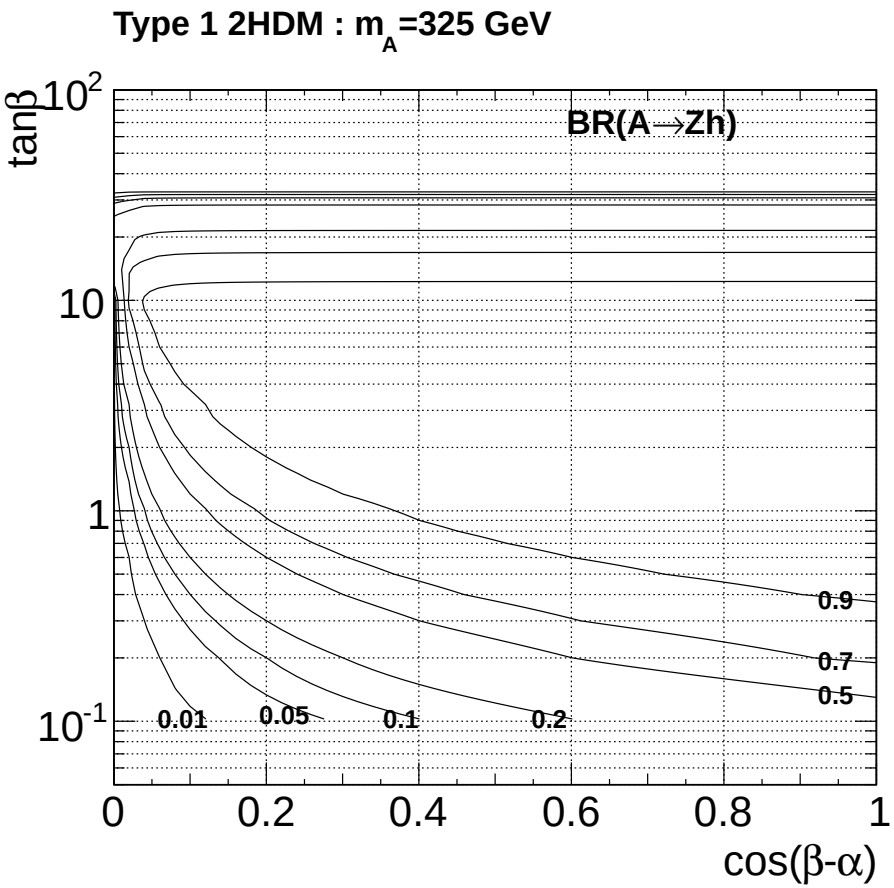
Depends on both $\tan\beta$ and $\cos(\beta - \alpha)$: shown for $m_A = 275$ GeV

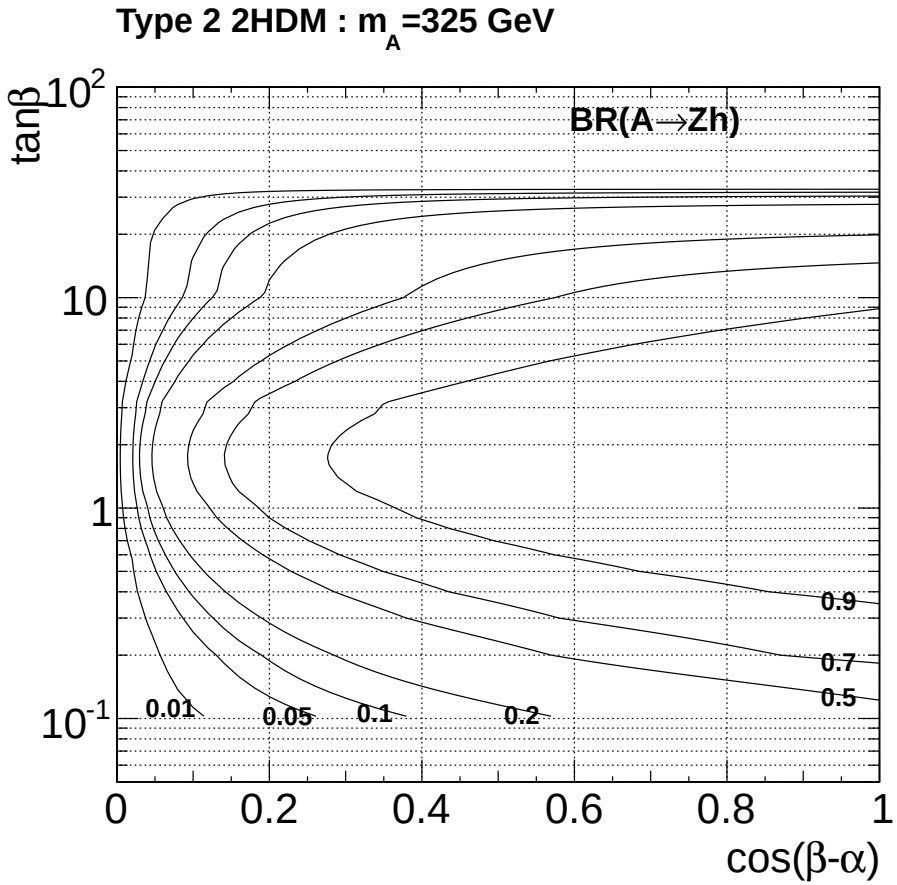


# BR($A \to Zh$): $m_A = 325$ GeV

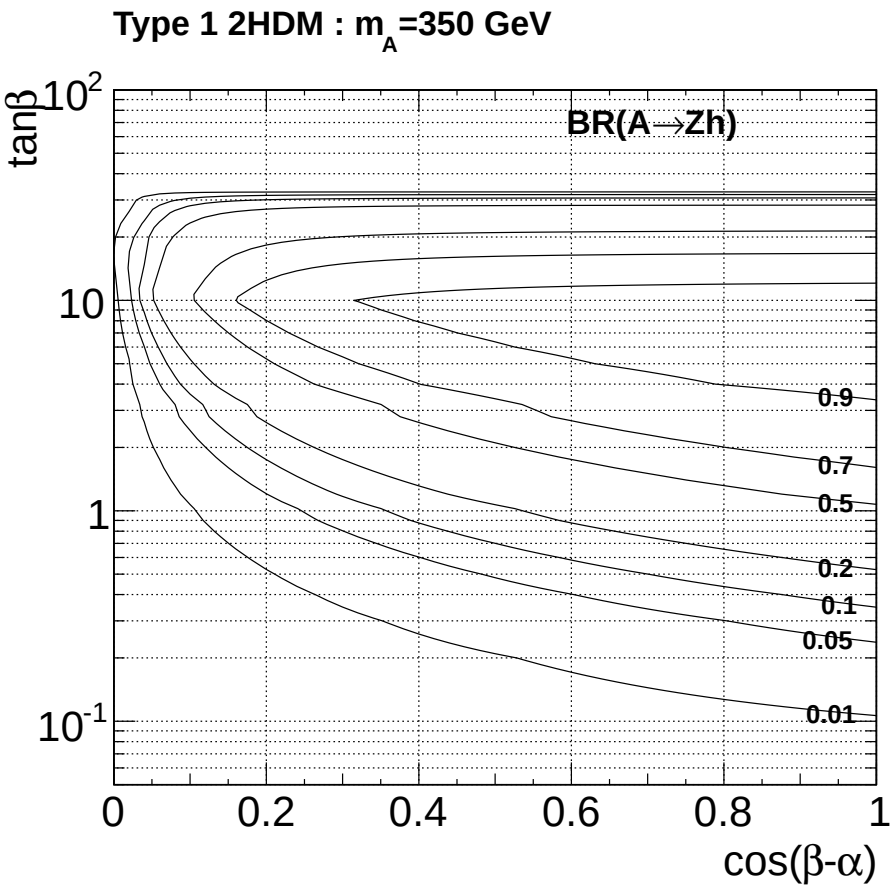
Depends on both $\tan\beta$ and $\cos(\beta - \alpha)$: shown for $m_A = 325$ GeV

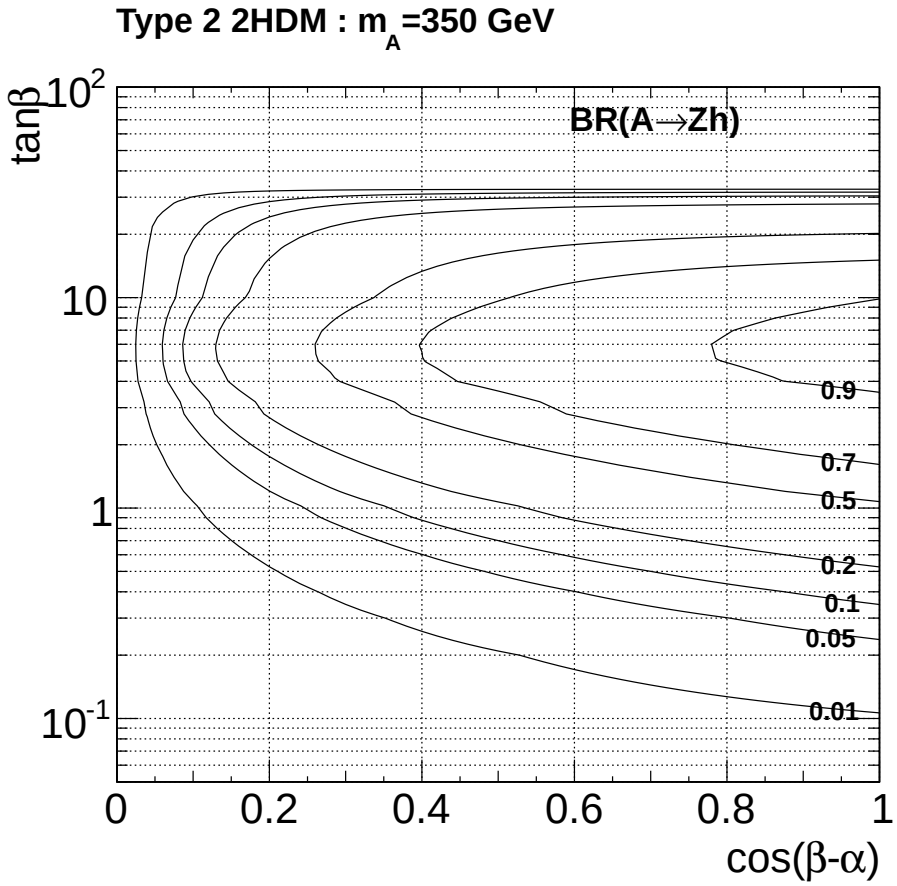


# BR($A \to Zh$): $m_A = 350$ *GeV*

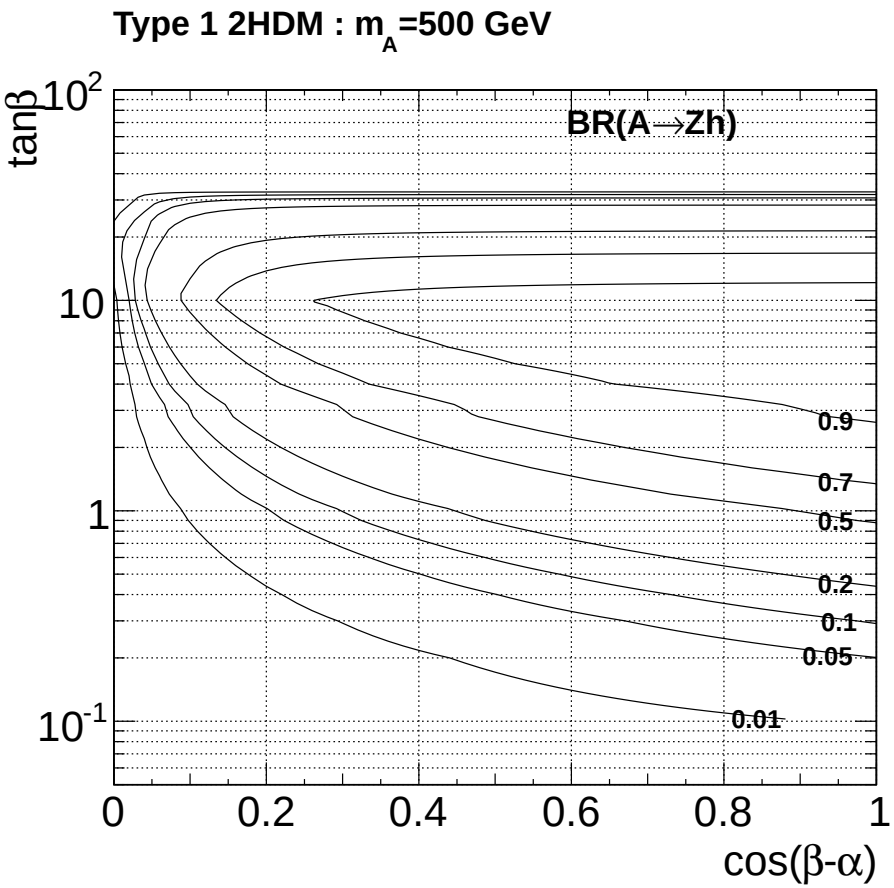
Depends on both $\tan\beta$ and $\cos(\beta - \alpha)$: shown for $m_A = 350$ *GeV*

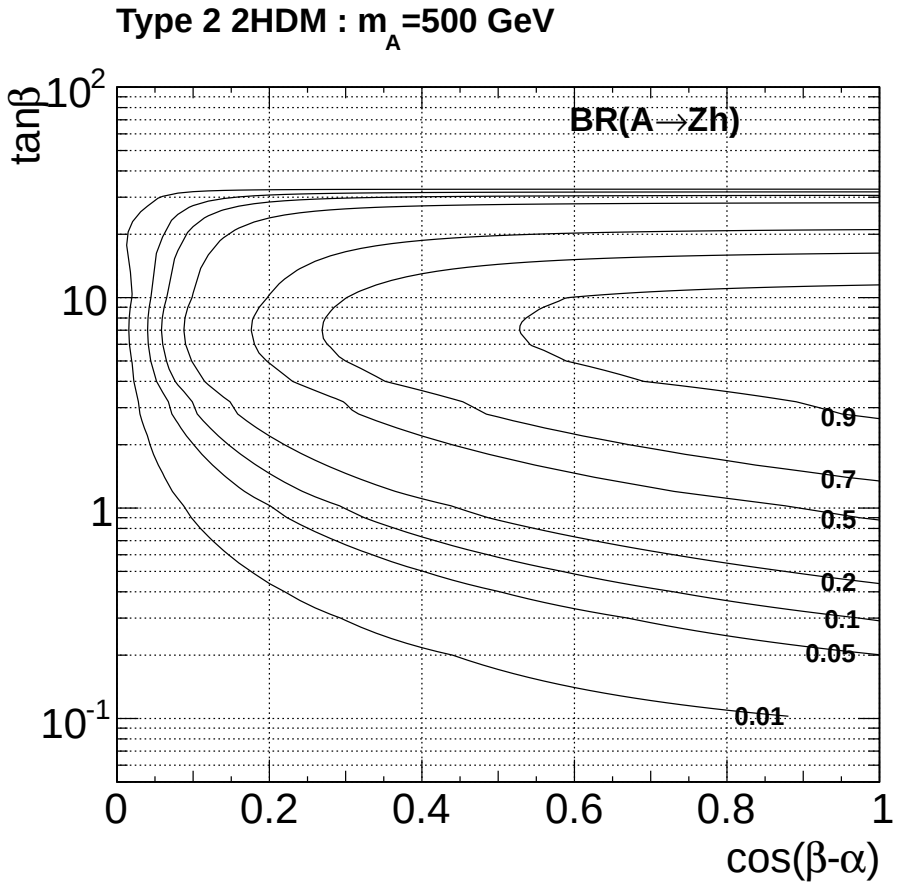


# BR($A \to Zh$): $m_A = 500$ *GeV*

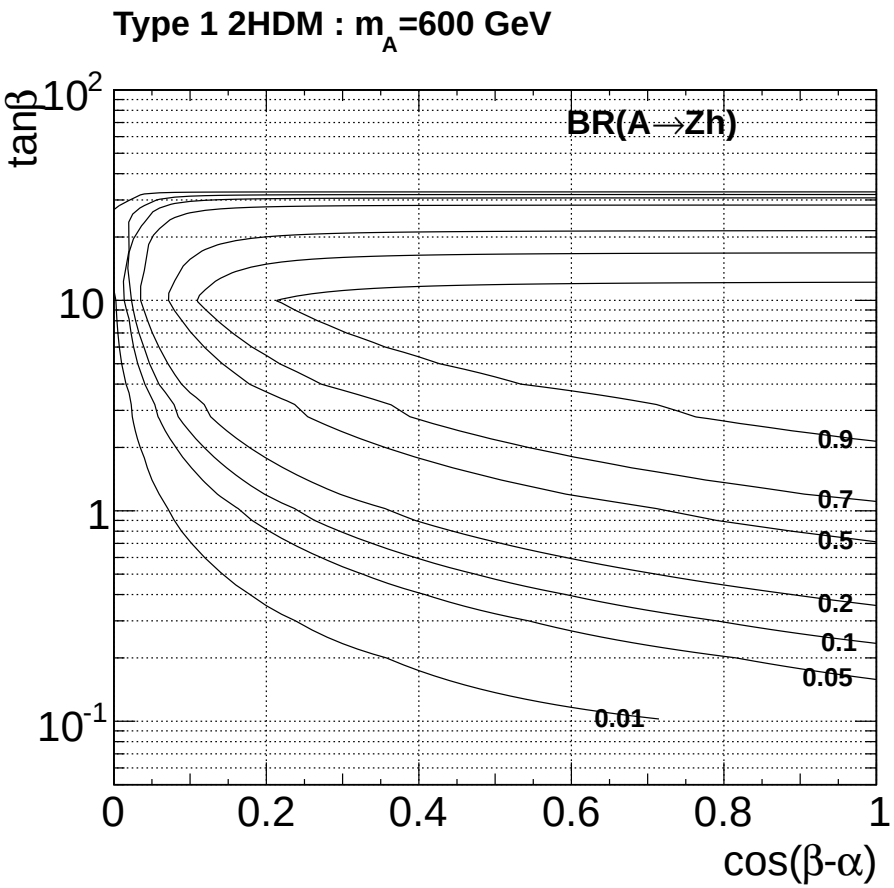
Depends on both $\tan\beta$ and $\cos(\beta - \alpha)$: shown for $m_A = 500$ *GeV*

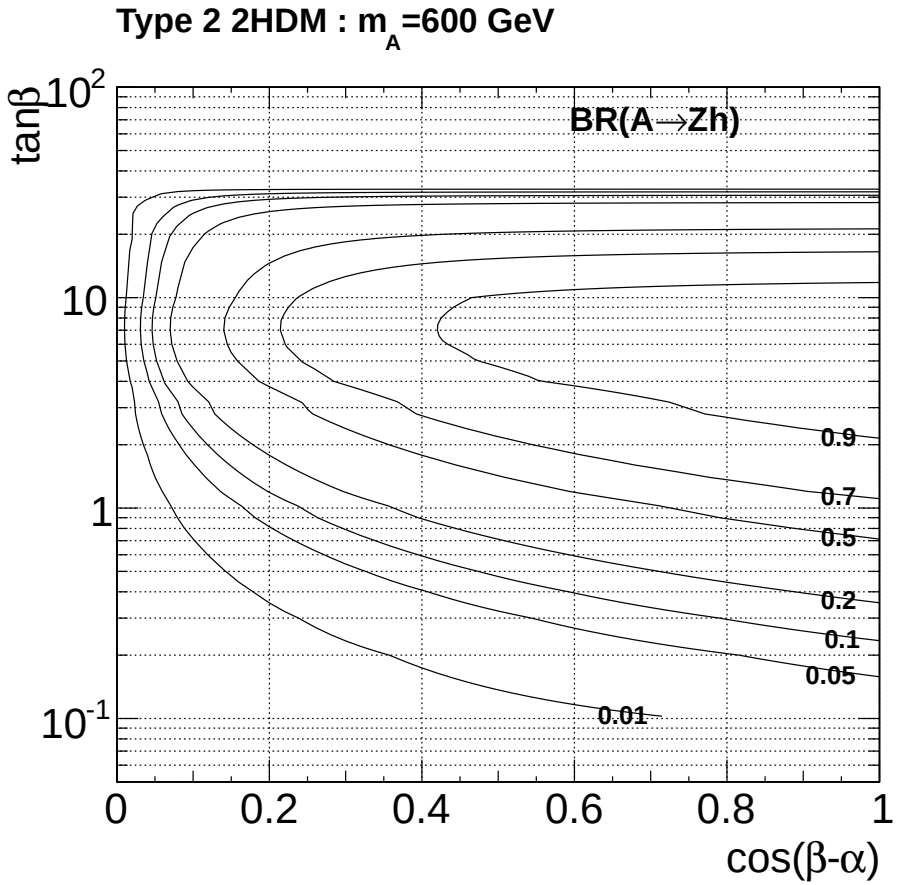


# BR($A \to Zh$): $m_A = 600$ GeV

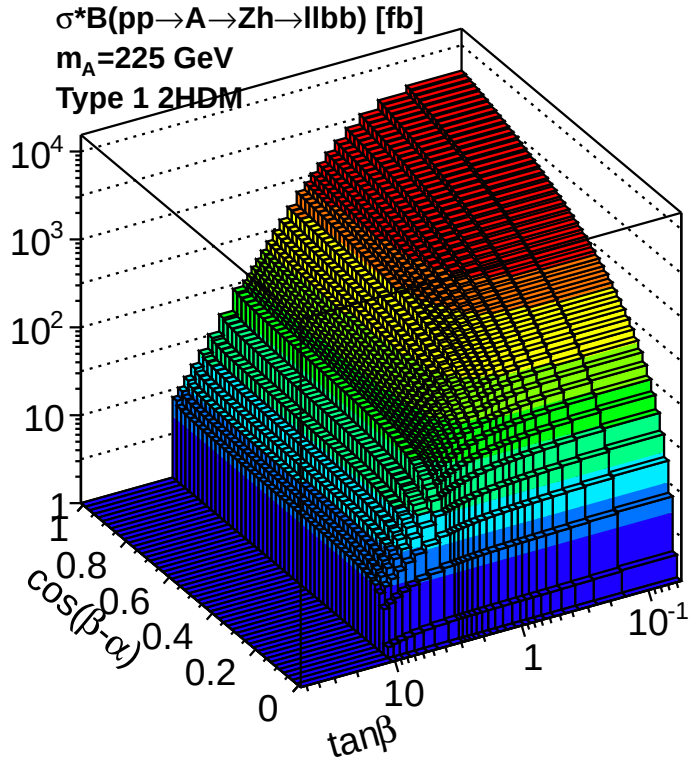
Depends on both $\tan\beta$ and $\cos(\beta - \alpha)$: shown for $m_A = 600$ GeV

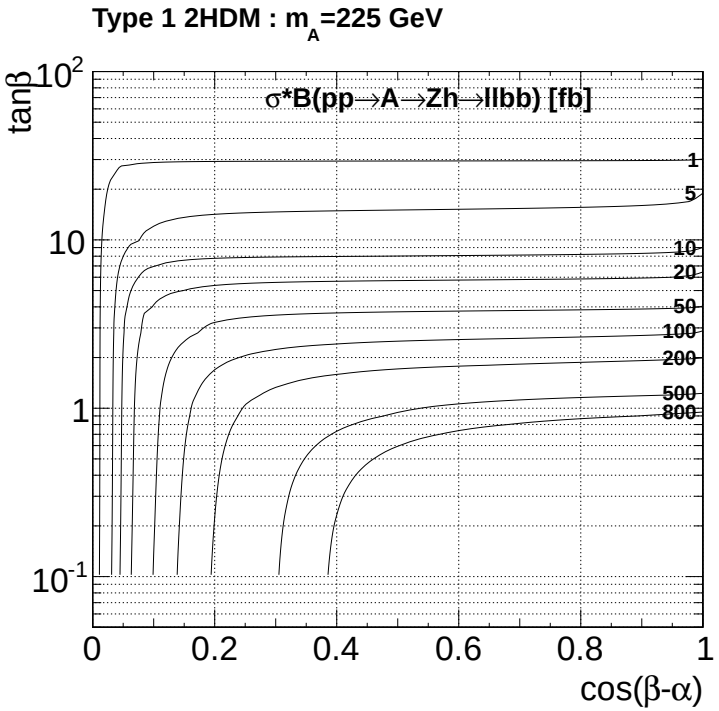


# $\sigma \times BR(A \to Zh \to \ell\ell bb)$ Type I, $m_A = 225\ GeV$

## Including BR($Z \to \ell\ell$)

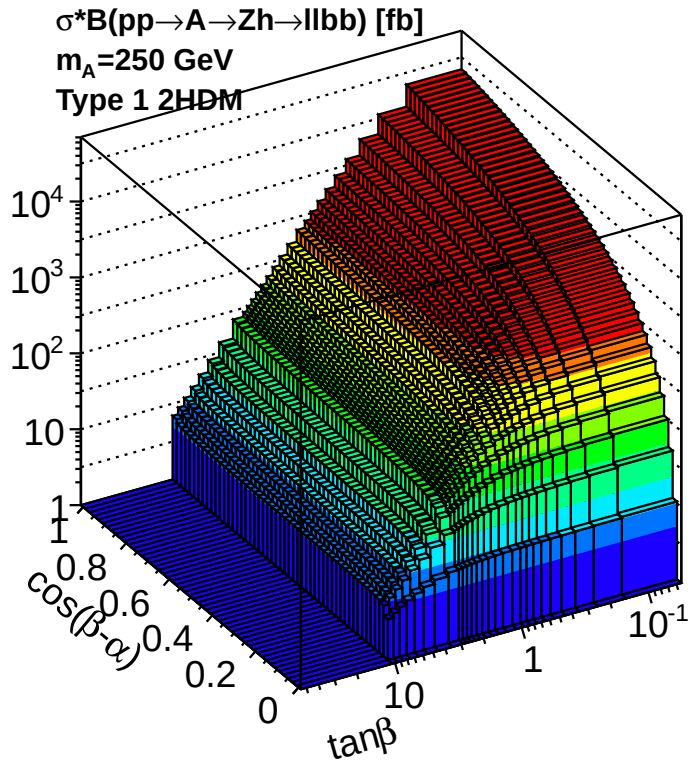


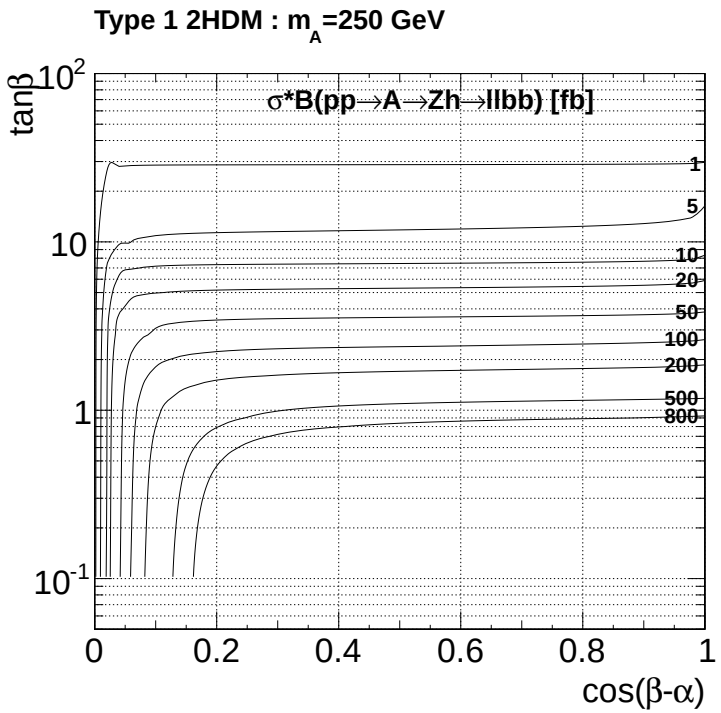




NB: plot rotated
other mass points on backup

# $\sigma \times BR(A \to Zh \to \ell\ell bb)$ Type I, $m_A = 250\ GeV$

## Including BR($Z \to \ell\ell$)

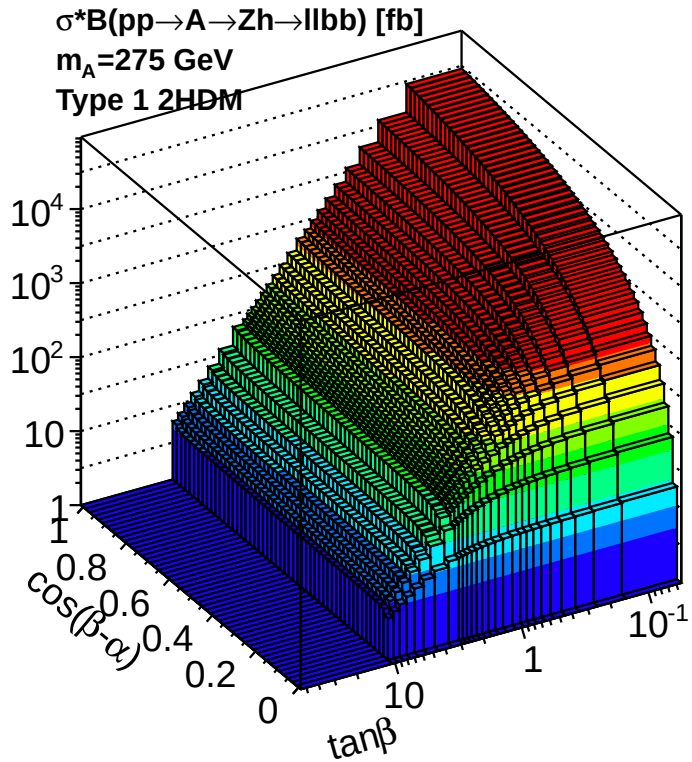


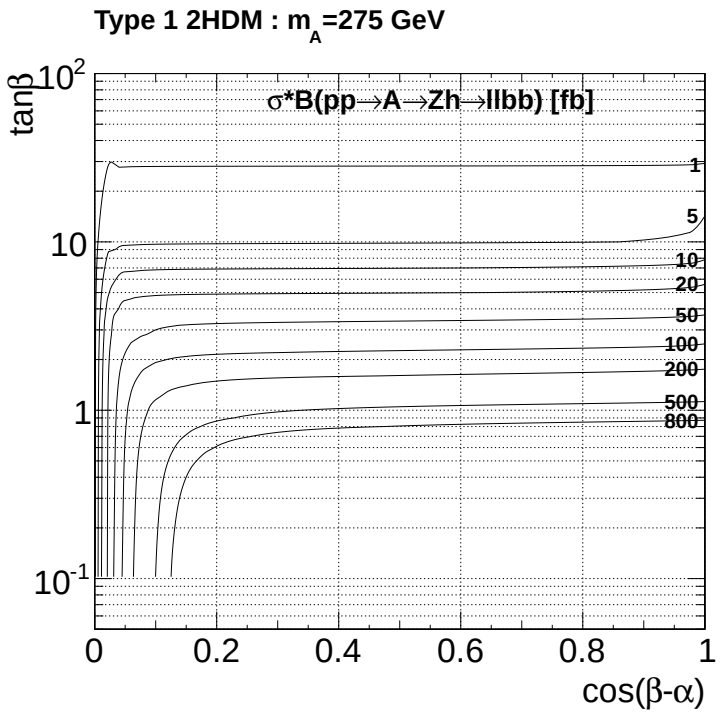




NB: plot rotated
other mass points on backup

# $\sigma \times BR(A \to Zh \to \ell\ell bb)$ Type I, $m_A = 275\ GeV$

## Including BR($Z \to \ell\ell$)

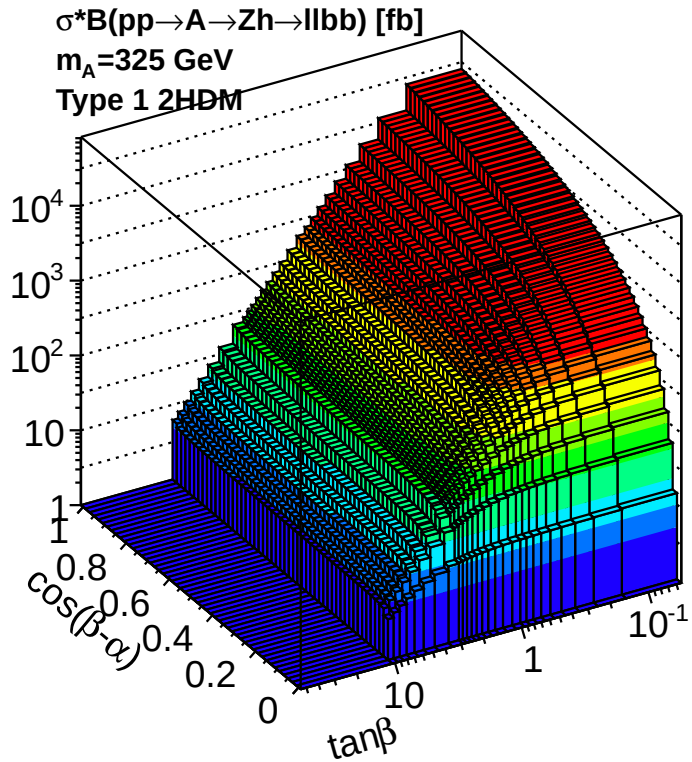


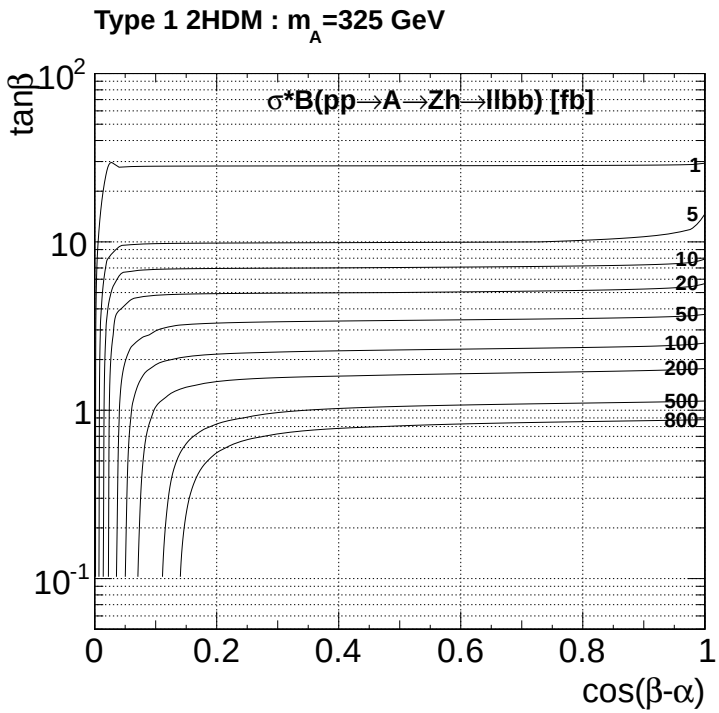




NB: plot rotated
other mass points on backup

# $\sigma \times BR(A \to Zh \to \ell\ell bb)$ Type I, $m_A = 325\ GeV$

## Including BR($Z \to \ell\ell$)

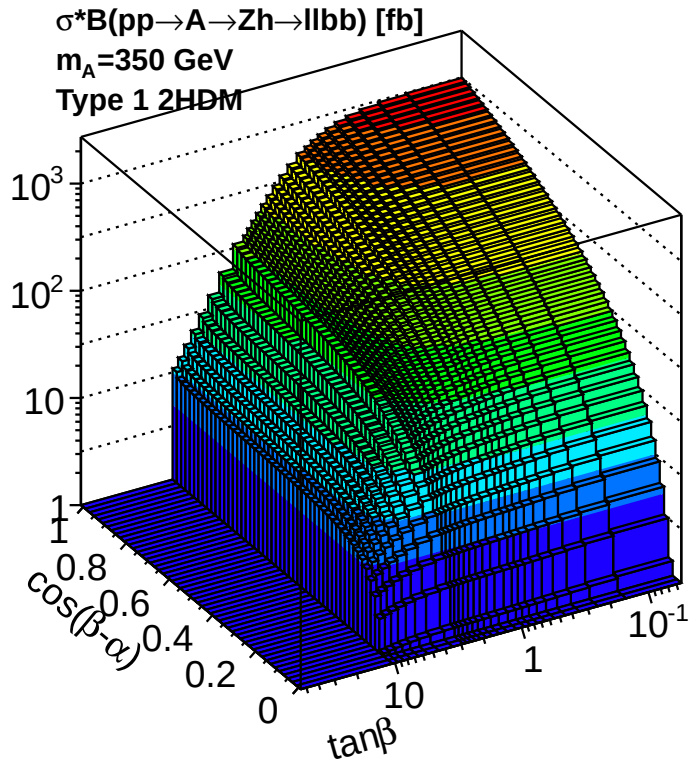


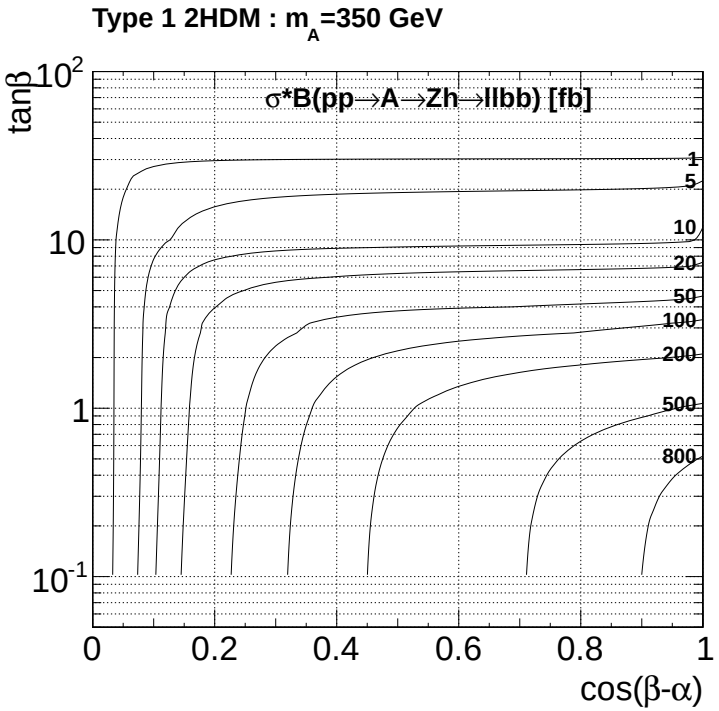




NB: plot rotated
other mass points on backup

# $\sigma \times BR(A \to Zh \to \ell\ell bb)$ Type I, $m_A = 350\ GeV$

## Including BR($Z \to \ell\ell$)

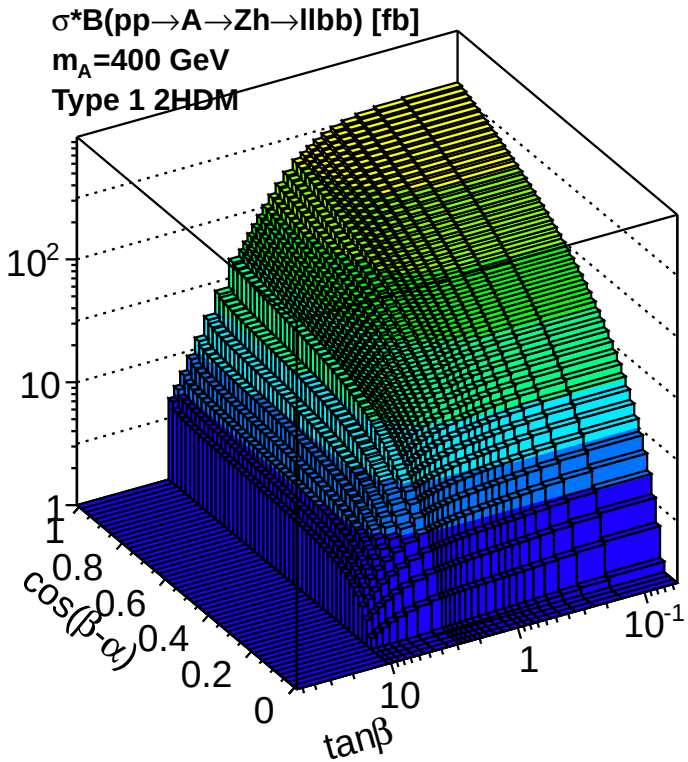


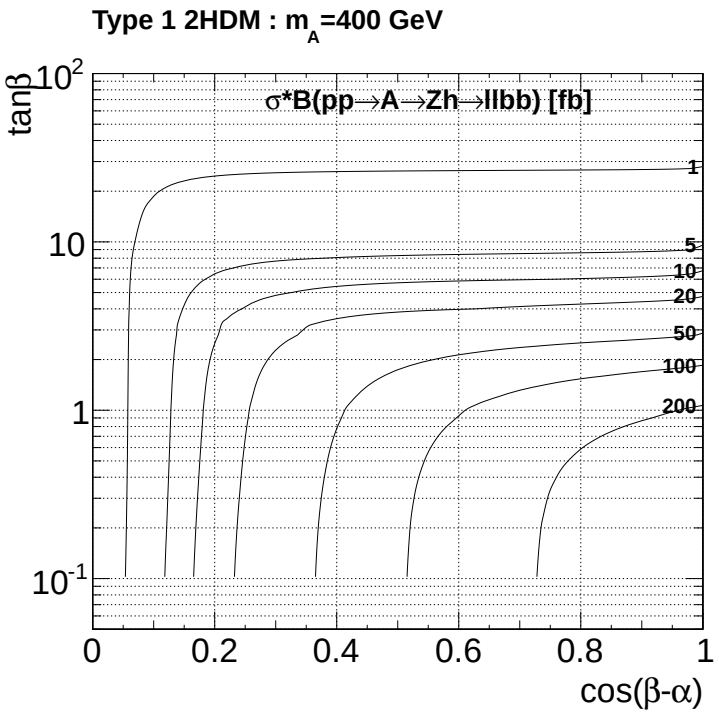




NB: plot rotated
other mass points on backup

# $\sigma \times BR(A \to Zh \to \ell\ell bb)$ Type I, $m_A = 400\ GeV$

## Including BR($Z \to \ell\ell$)

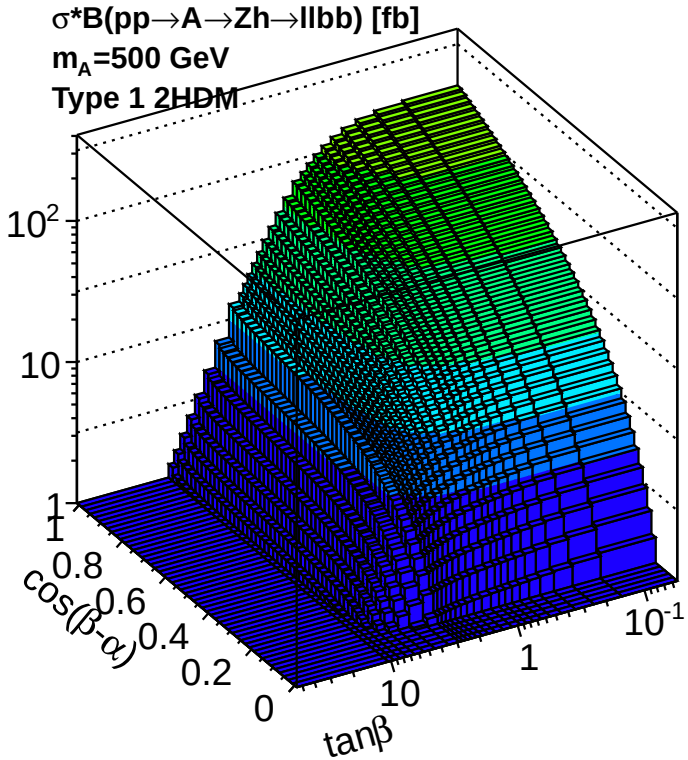


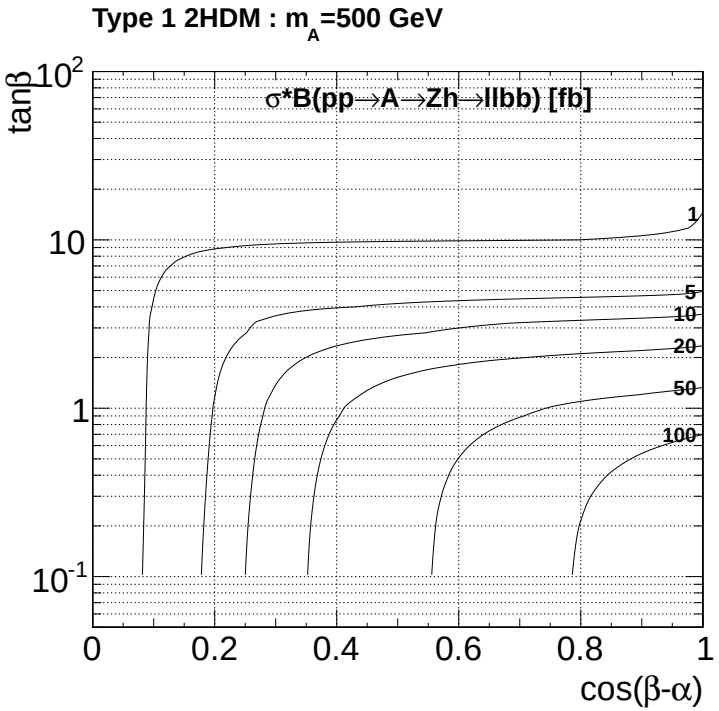




NB: plot rotated
other mass points on backup

# $\sigma \times BR(A \to Zh \to \ell\ell bb)$ Type I, $m_A = 500\ GeV$

## Including BR($Z \to \ell\ell$)

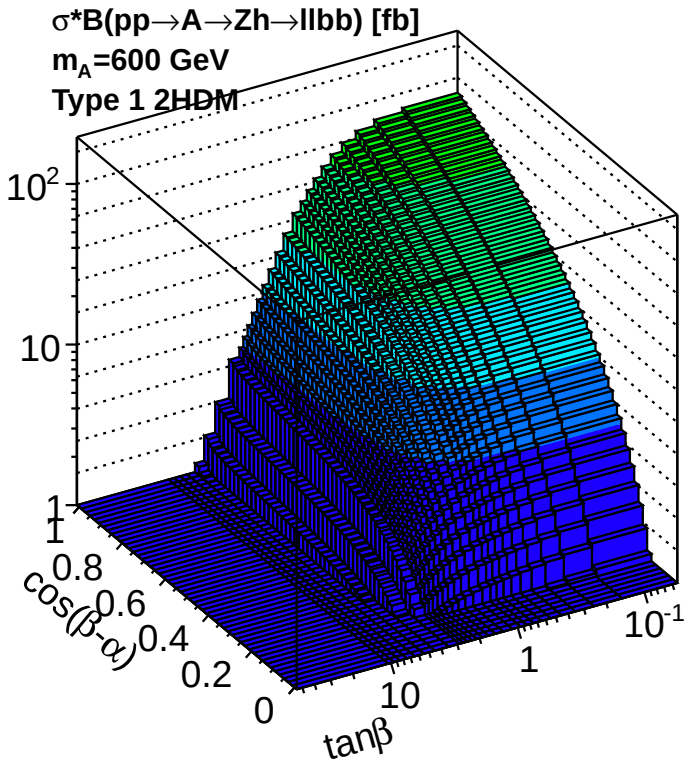


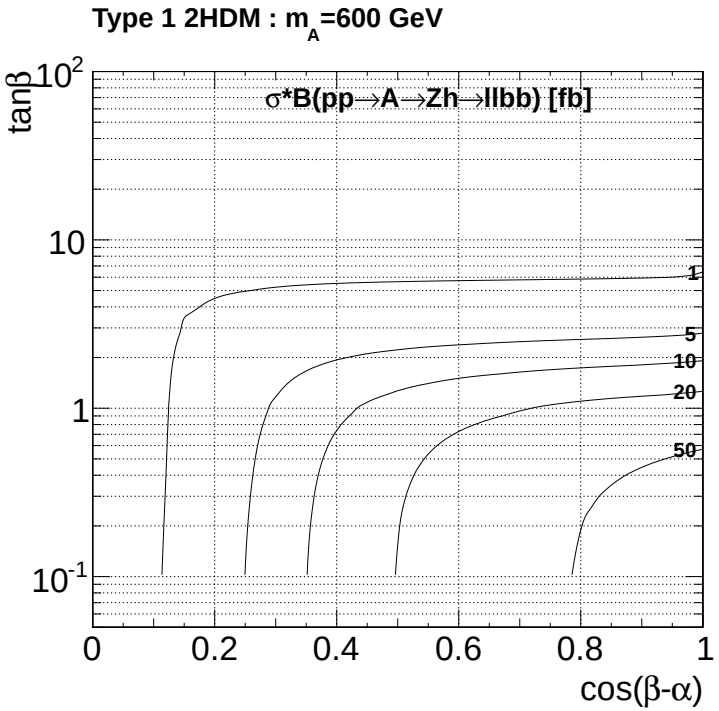




NB: plot rotated
other mass points on backup

# $\sigma \times BR(A \to Zh \to \ell\ell bb)$ Type I, $m_A = 600\ GeV$

## Including BR($Z \to \ell\ell$)

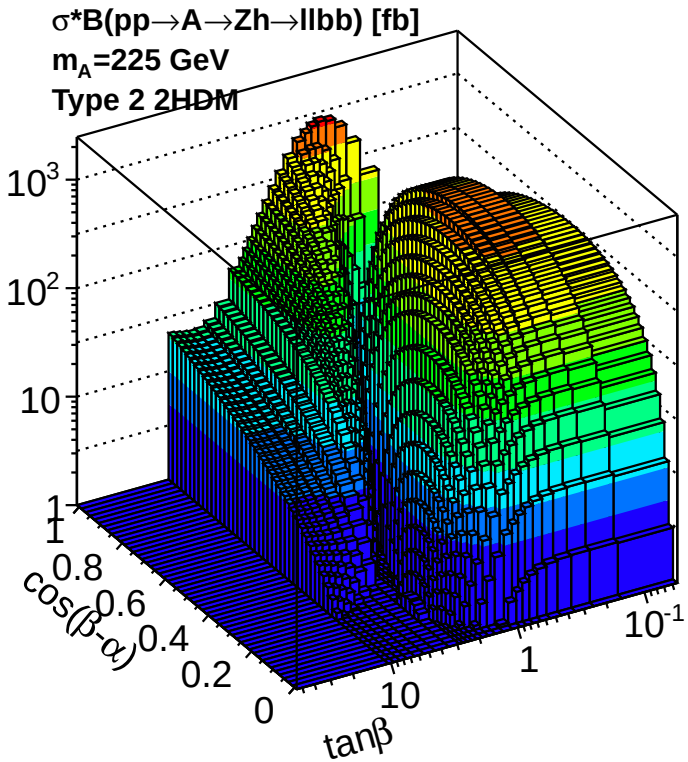


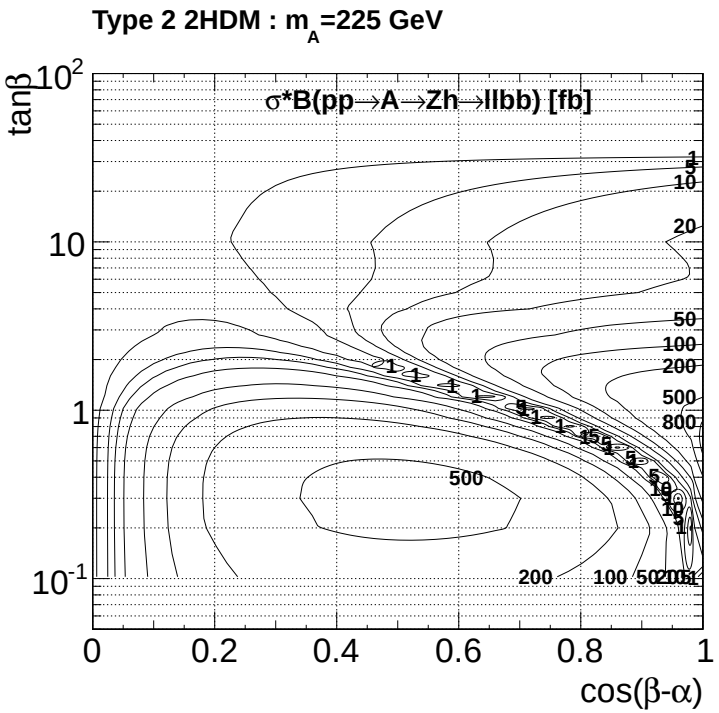




NB: plot rotated
other mass points on backup

# $\sigma \times BR(A \to Zh \to \ell\ell bb)$ Type II, $m_A = 225$ GeV

## Including BR($Z \to \ell\ell$)

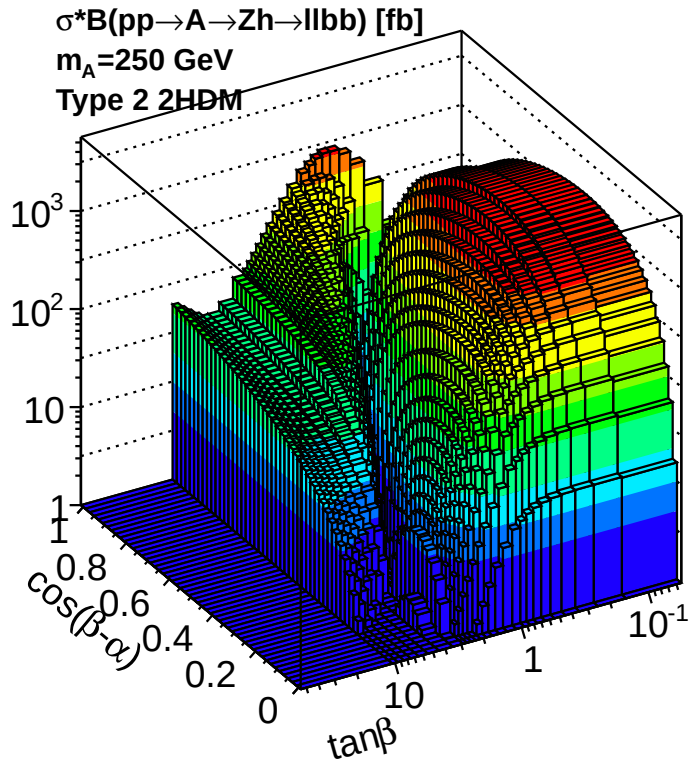


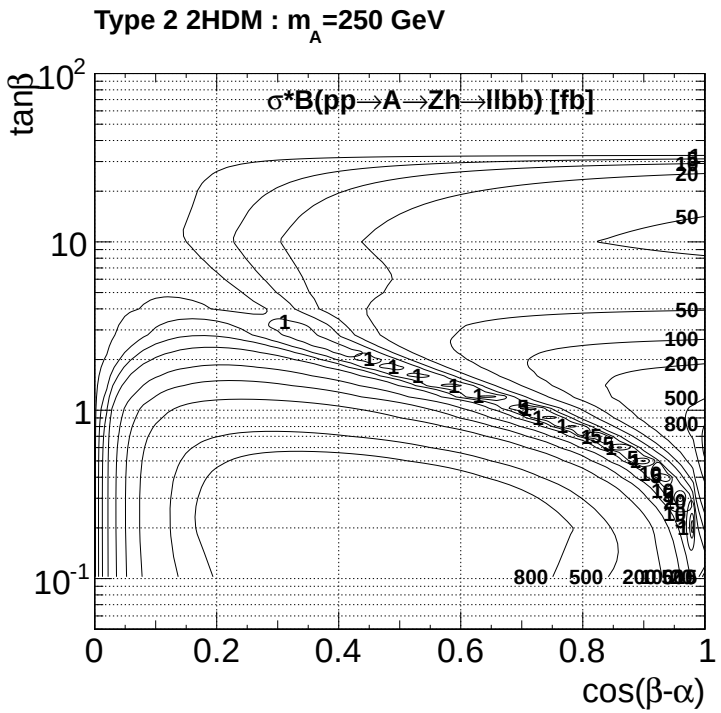




NB: plot rotated
other mass points on backup

# $\sigma \times BR(A \to Zh \to \ell\ell bb)$ Type II, $m_A = 250\ GeV$

## Including BR($Z \to \ell\ell$)

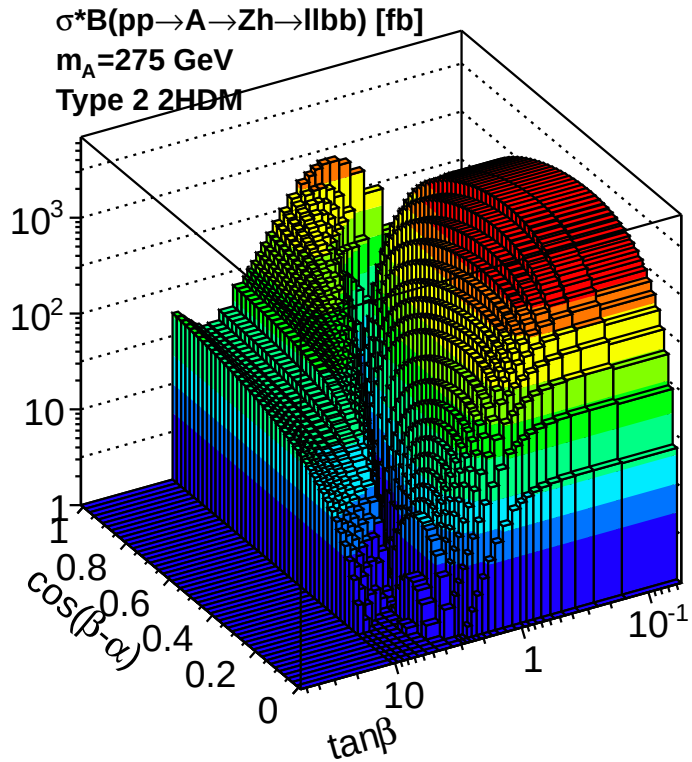


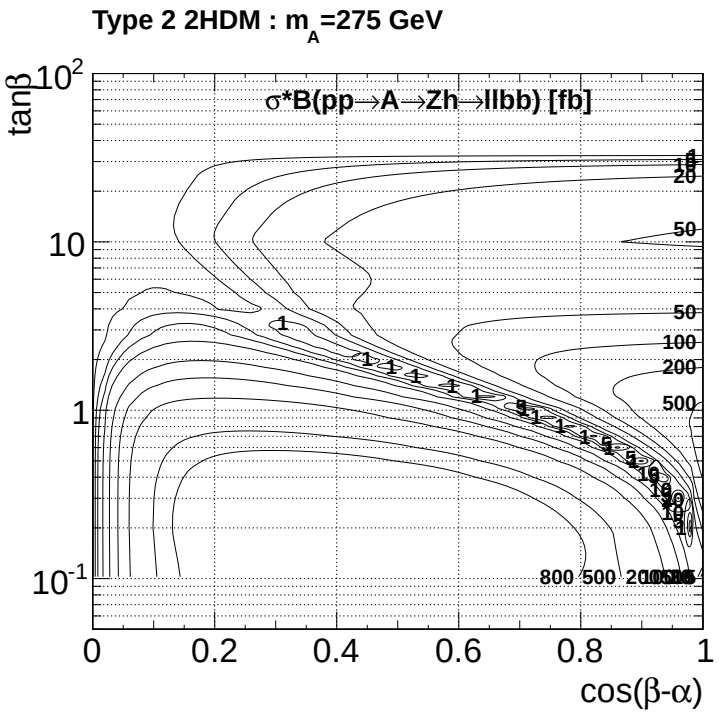




NB: plot rotated
other mass points on backup

# $\sigma \times BR(A \to Zh \to \ell\ell bb)$ Type II, $m_A = 275\ GeV$

## Including BR($Z \to \ell\ell$)

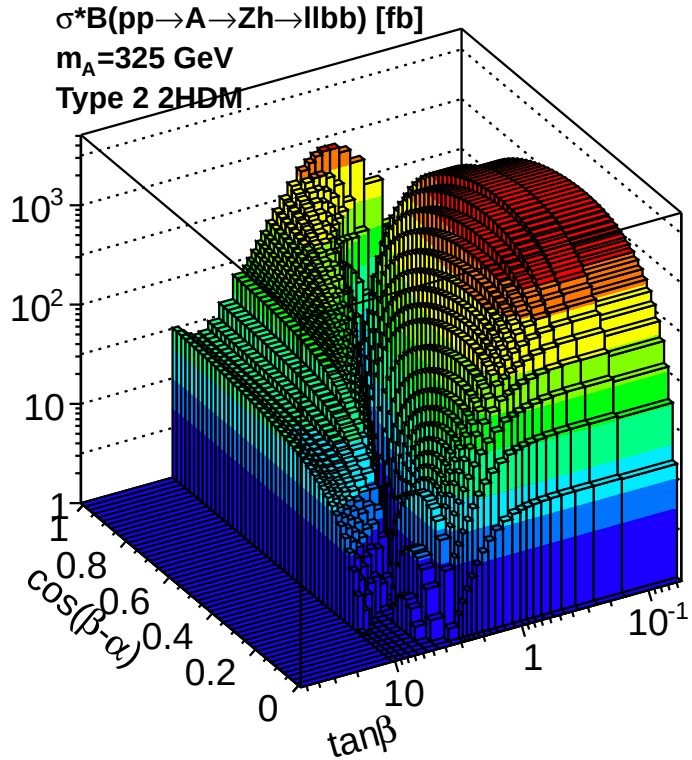


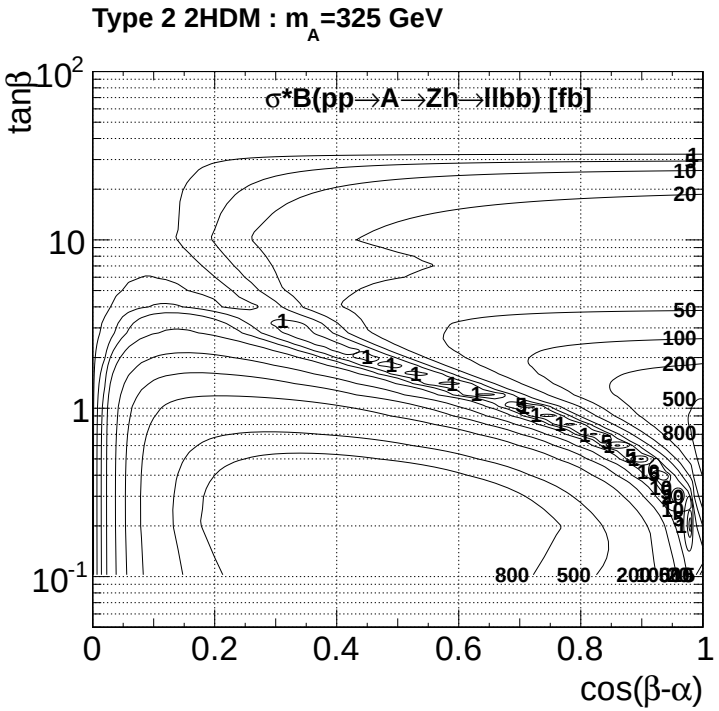




NB: plot rotated
other mass points on backup

# $\sigma \times BR(A \to Zh \to \ell\ell bb)$ Type II, $m_A = 325$ GeV

## Including BR($Z \to \ell\ell$)

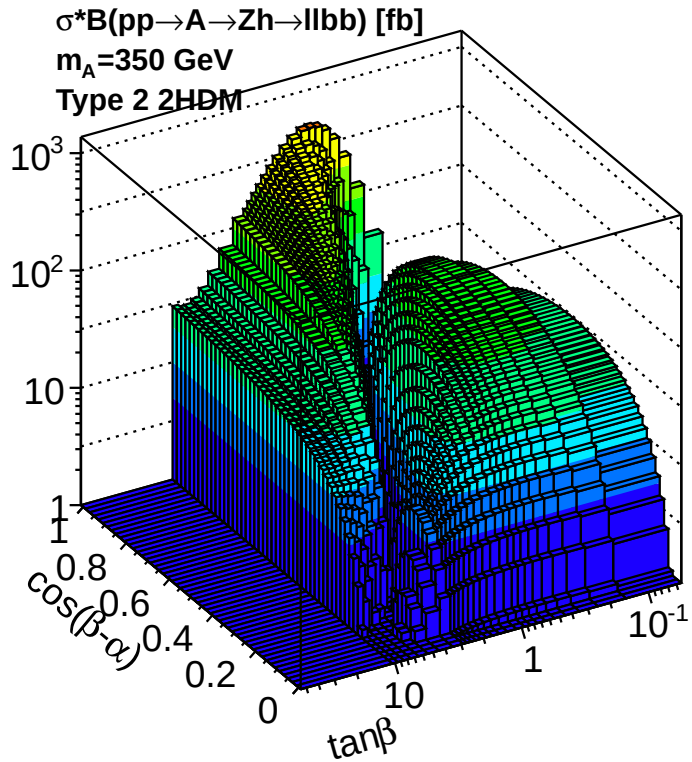


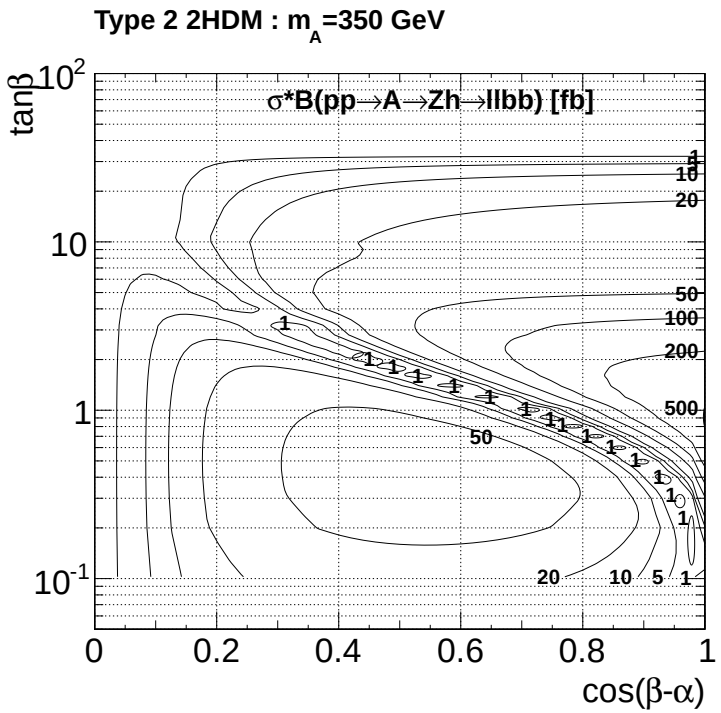




NB: plot rotated
other mass points on backup

# $\sigma \times BR(A \to Zh \to \ell\ell bb)$ Type II, $m_A = 350$ GeV

## Including BR($Z \to \ell\ell$)

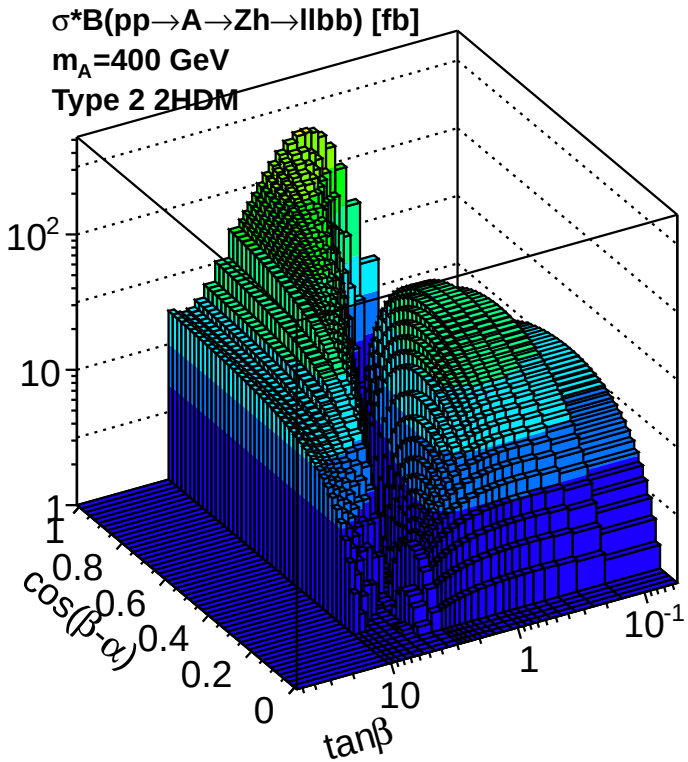


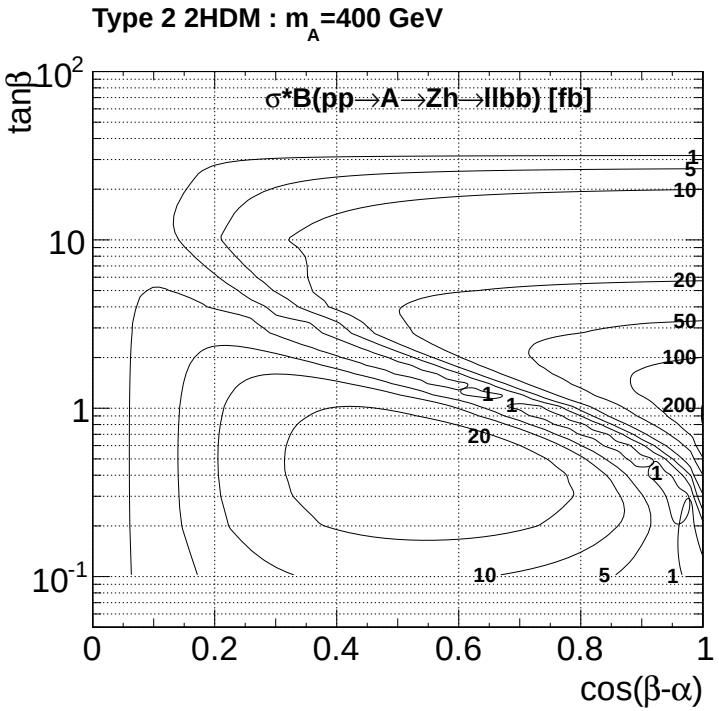




NB: plot rotated
other mass points on backup

# $\sigma \times BR(A \to Zh \to \ell\ell bb)$ Type II, $m_A = 400\ GeV$

## Including BR($Z \to \ell\ell$)

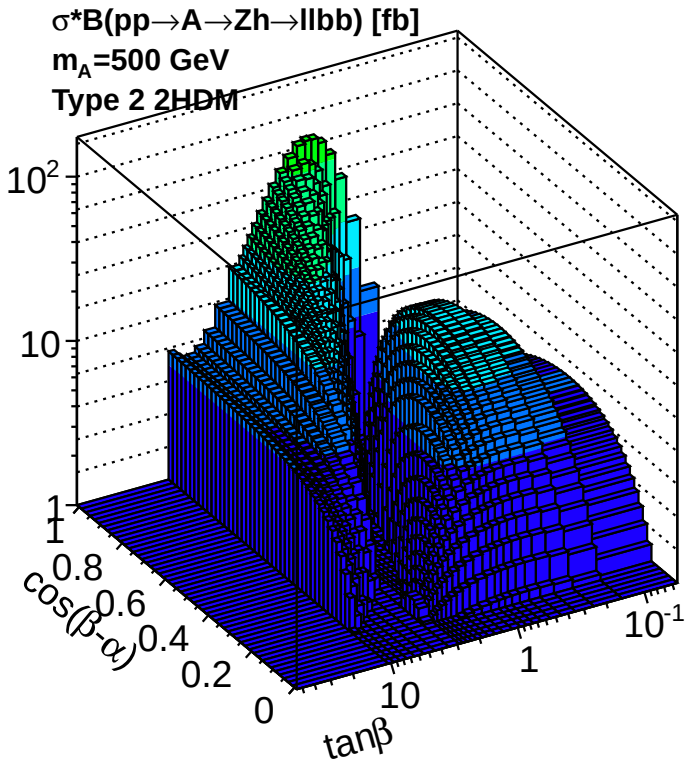


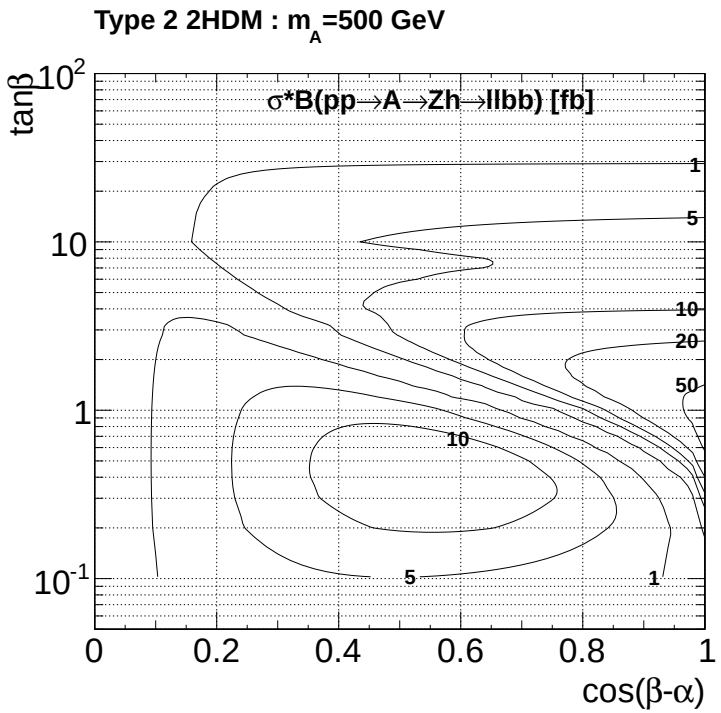




NB: plot rotated
other mass points on backup

# $\sigma \times BR(A \to Zh \to \ell\ell bb)$ Type II, $m_A = 500\ GeV$

## Including BR($Z \to \ell\ell$)

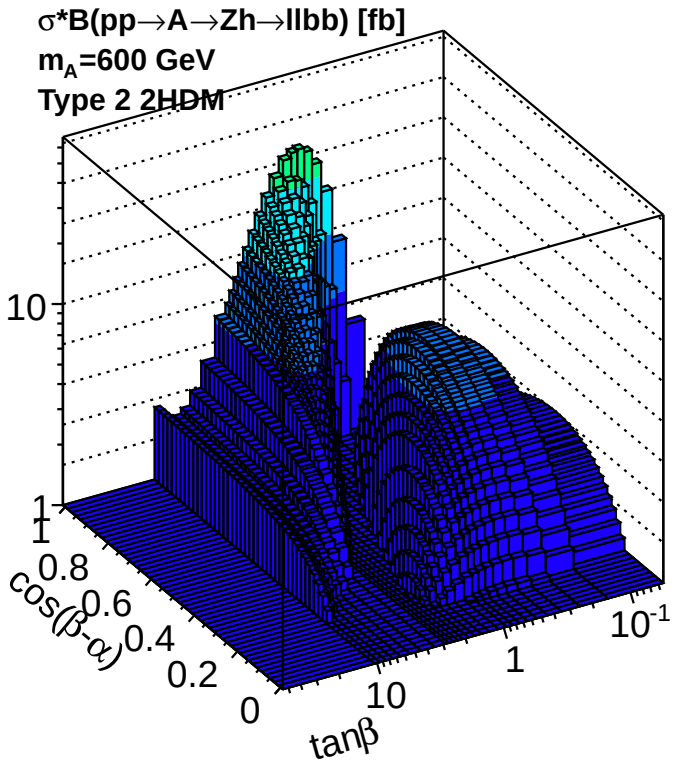


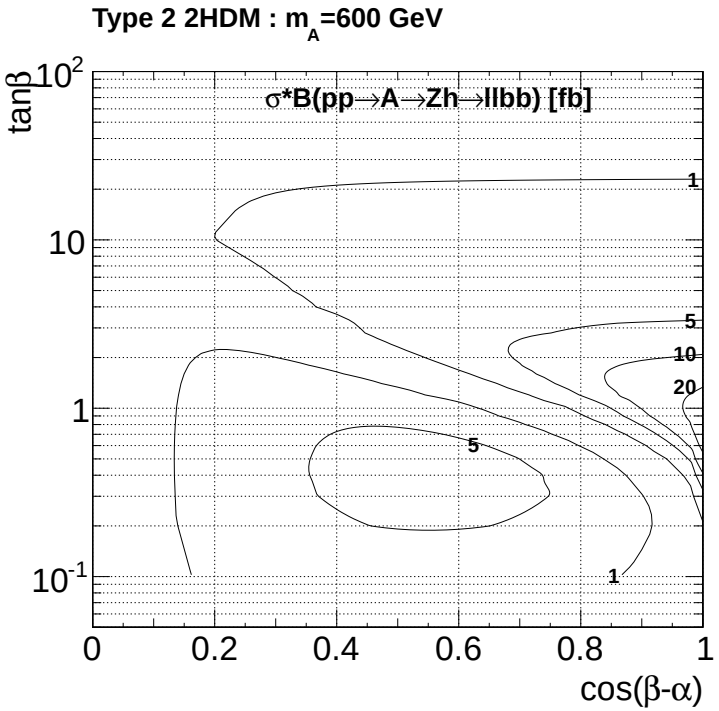




NB: plot rotated
other mass points on backup

# $\sigma \times BR(A \to Zh \to \ell\ell bb)$ Type II, $m_A = 600\ GeV$

## Including BR($Z \to \ell\ell$)

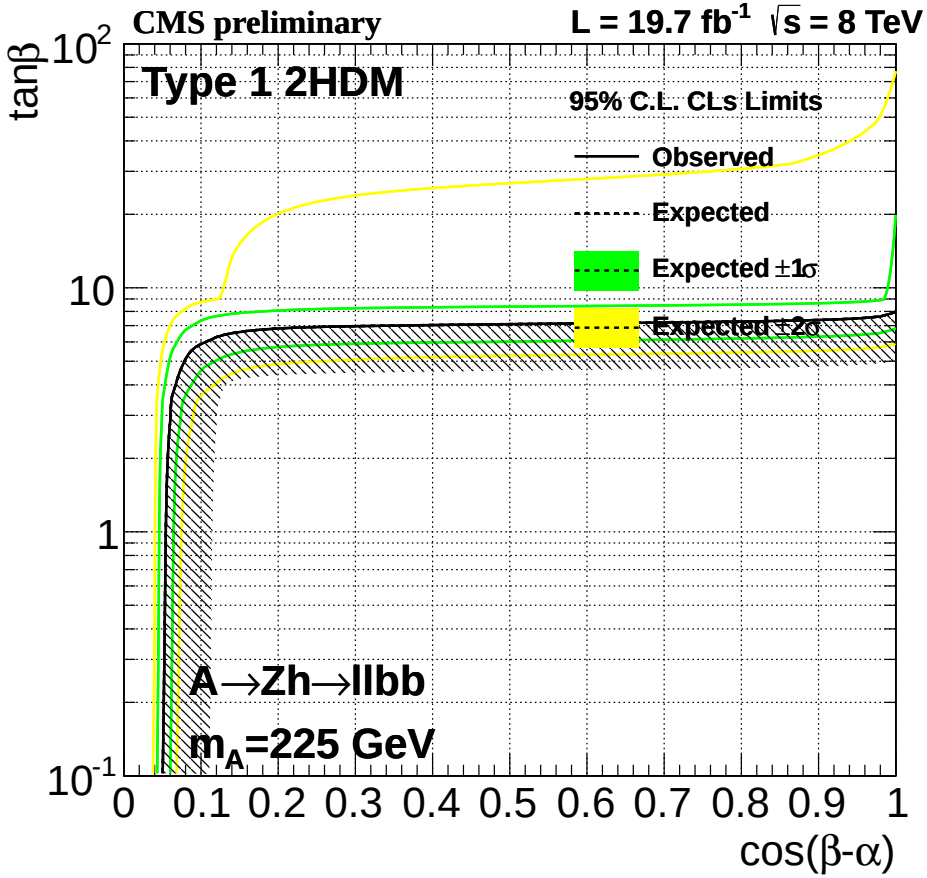


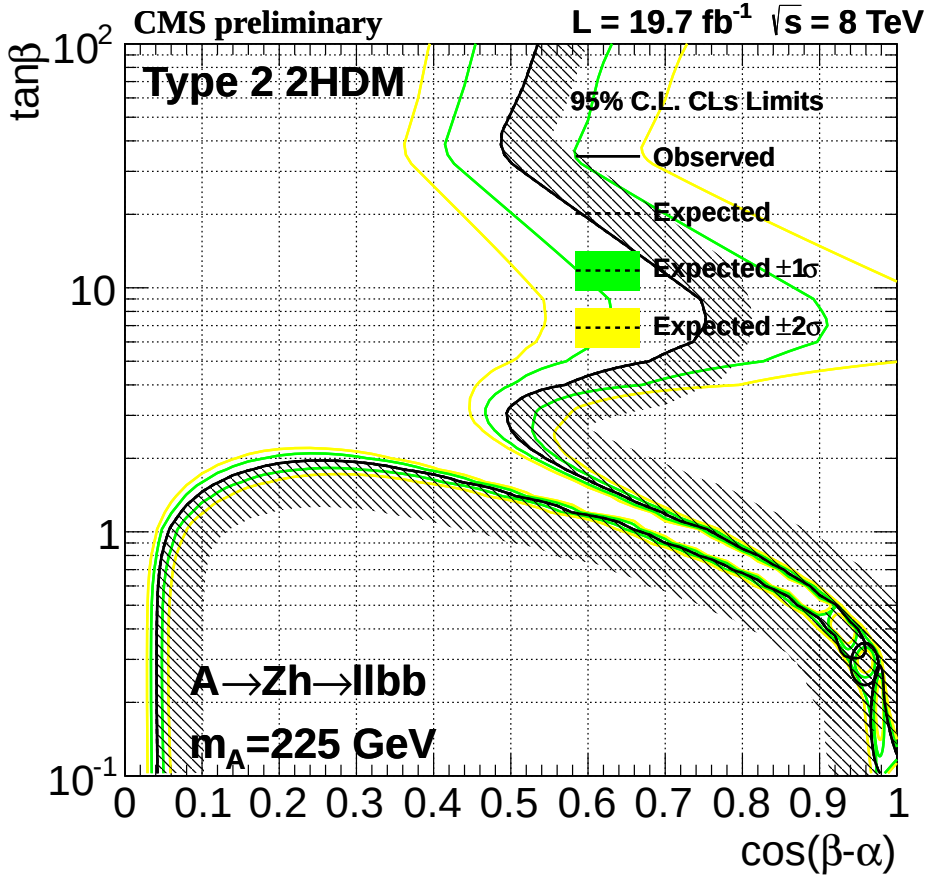




NB: plot rotated
other mass points on backup

# Expected limits

## Expected limits in $\tan\beta$ vs $\cos(\beta-\alpha)$ plane, $m_A = 225$ *GeV*

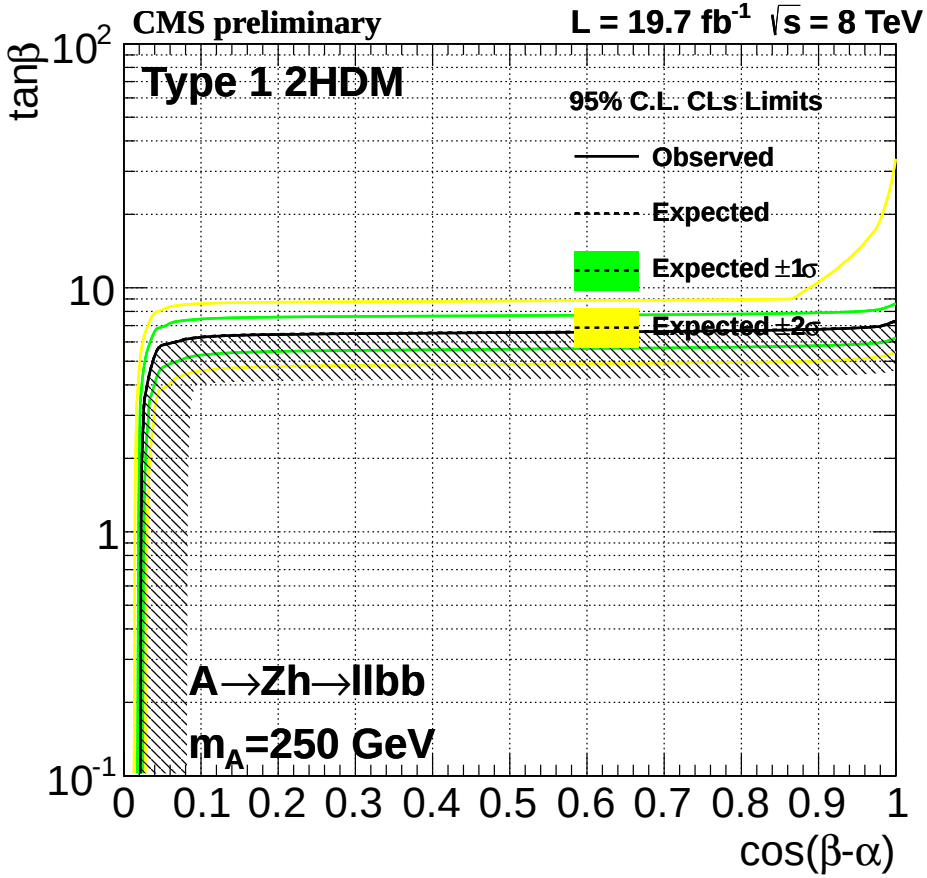


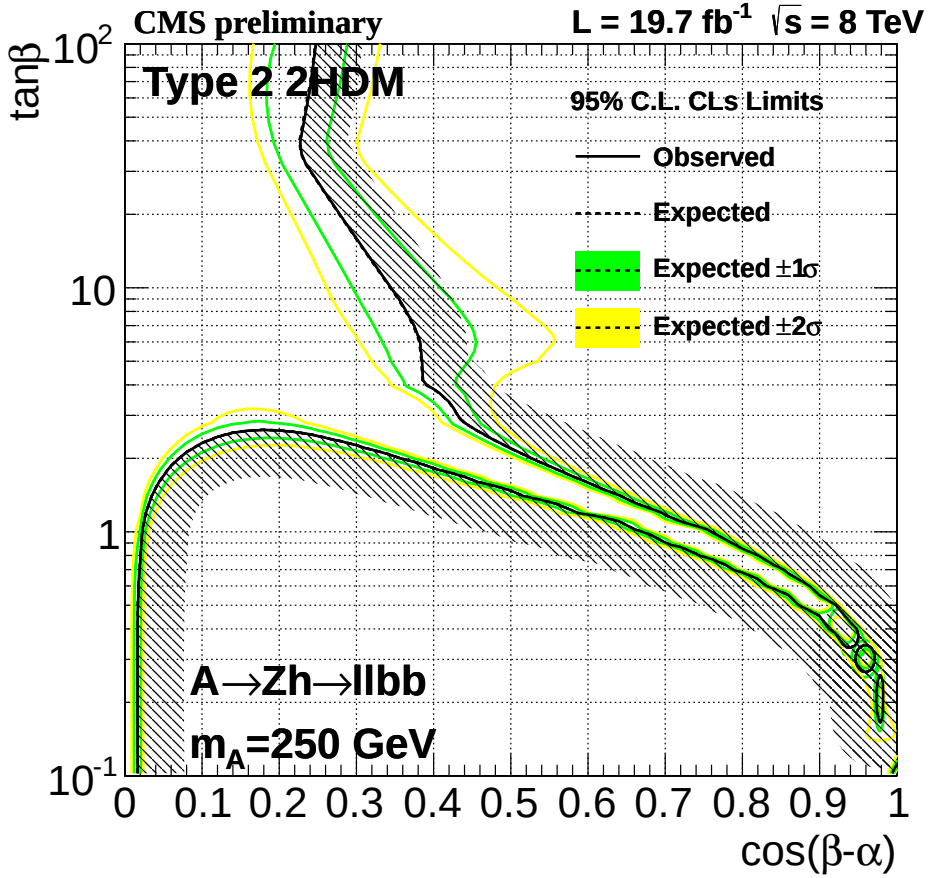




other mass points on backup

# Expected limits

## Expected limits in $\tan\beta$ vs $\cos(\beta-\alpha)$ plane, $m_A = 250$ *GeV*

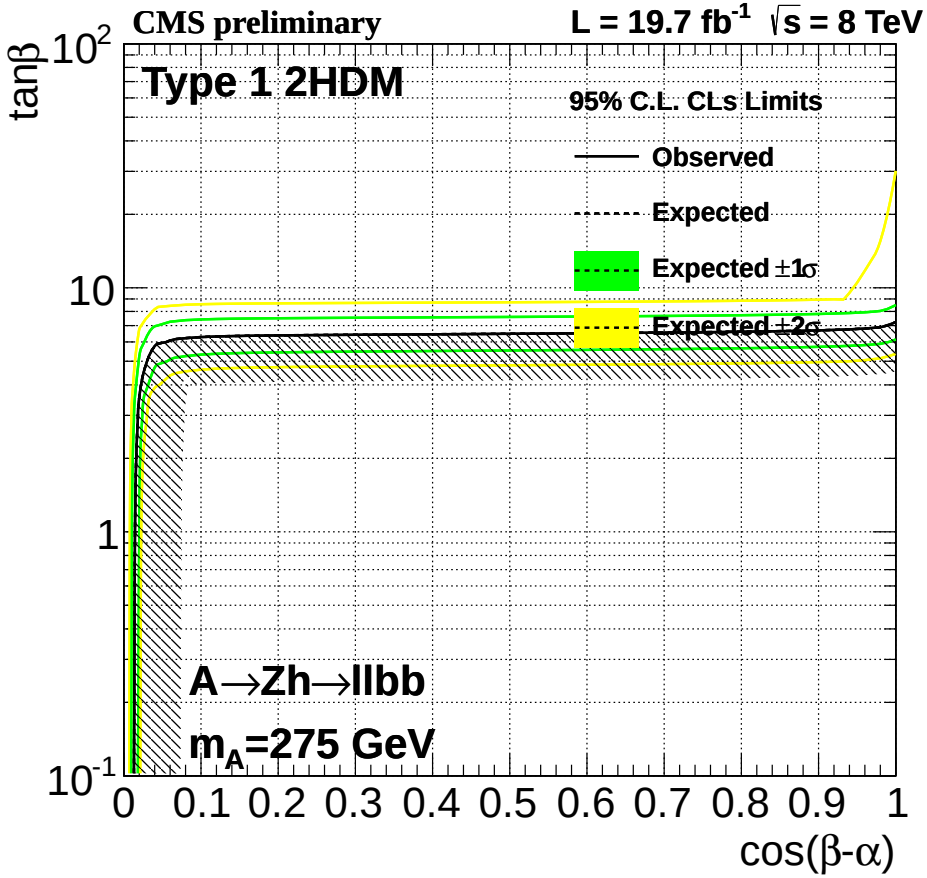


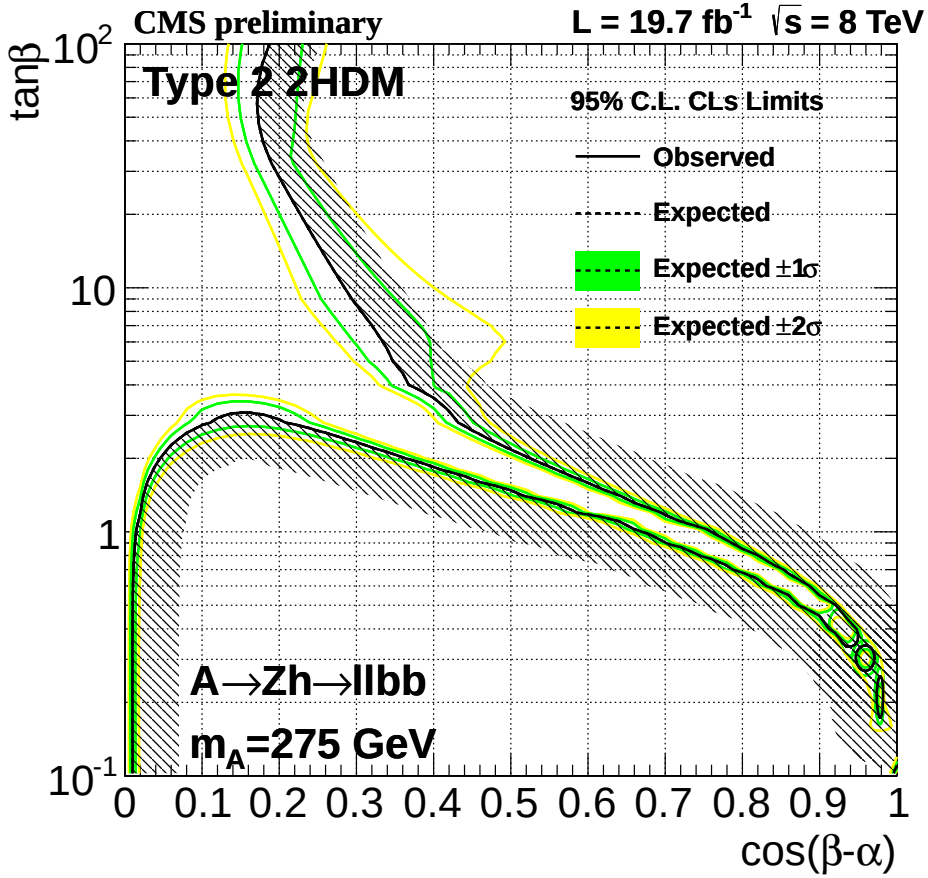




other mass points on backup

# Expected limits

## Expected limits in $\tan\beta$ vs $\cos(\beta-\alpha)$ plane, $m_A = 275$ *GeV*

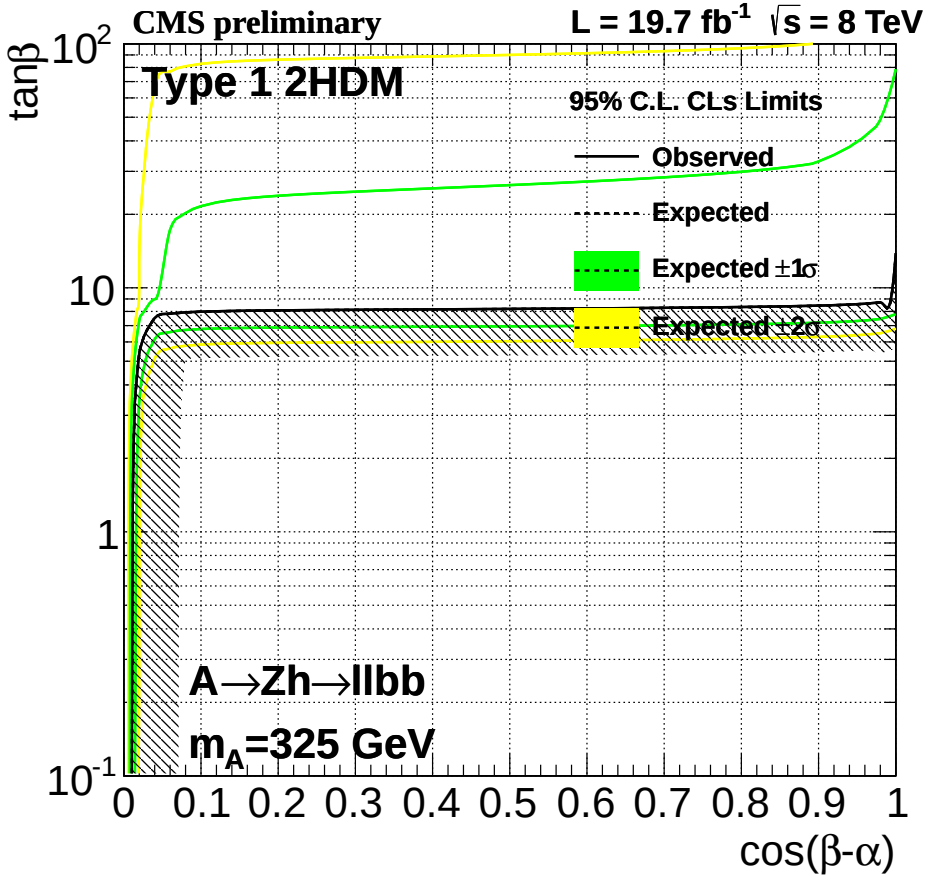


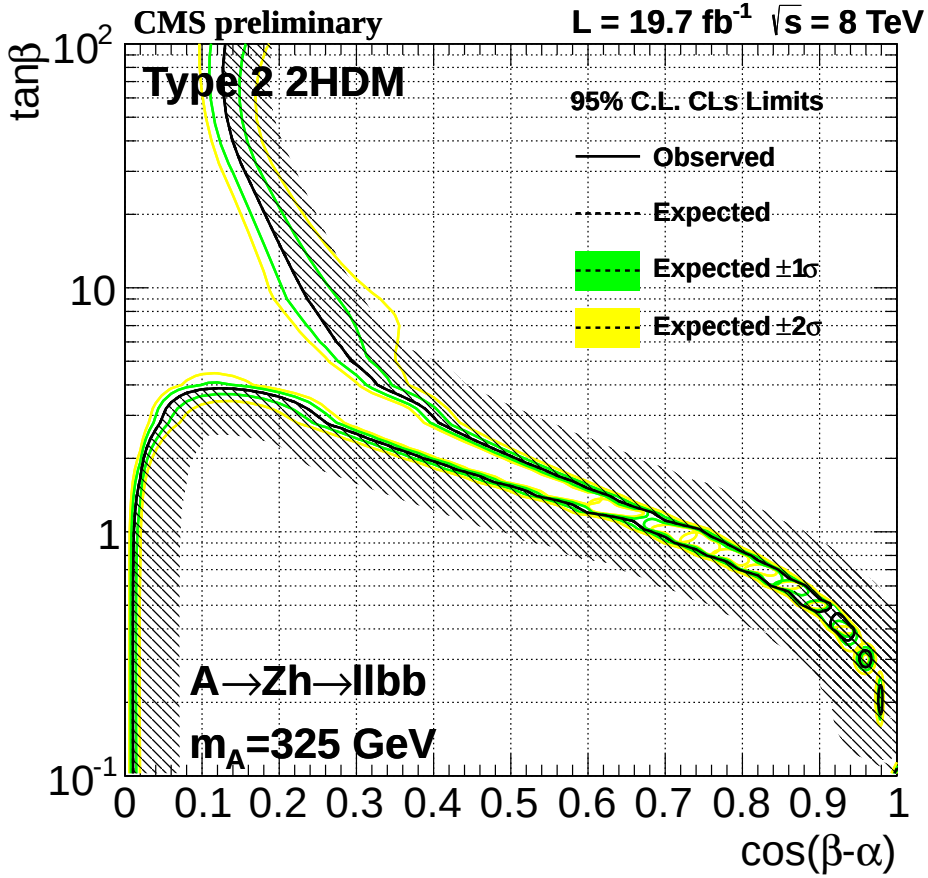




other mass points on backup

# Expected limits

## Expected limits in $\tan\beta$ vs $\cos(\beta-\alpha)$ plane, $m_A = 325$ *GeV*

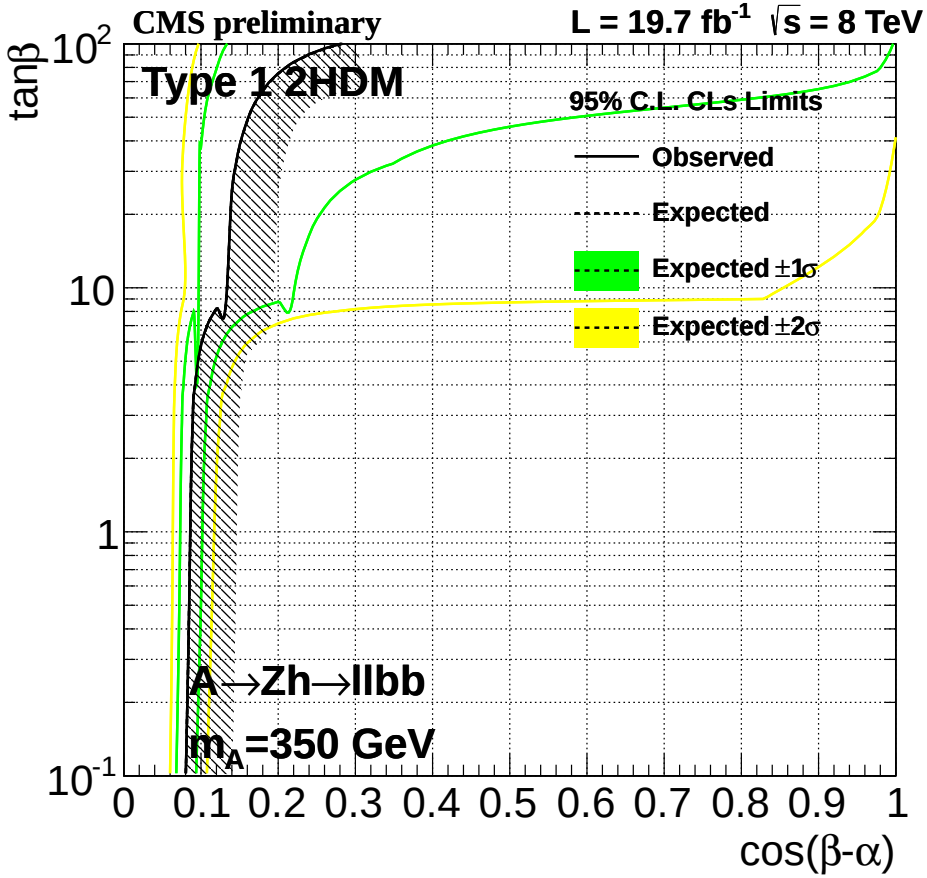


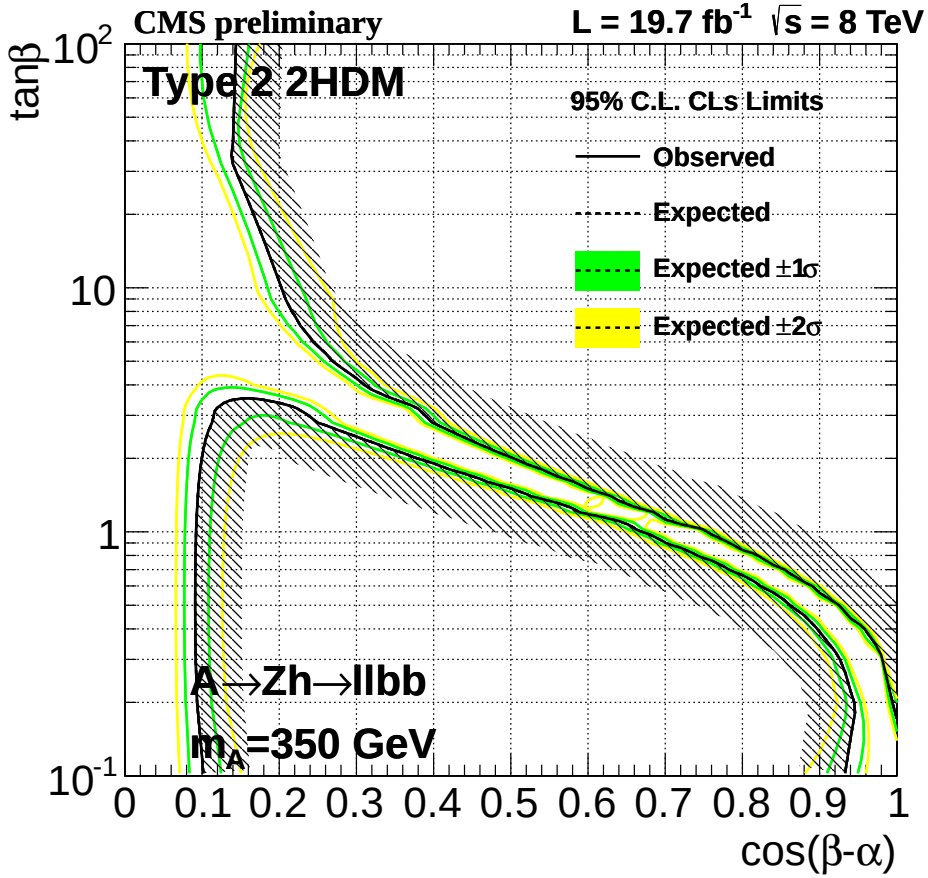




other mass points on backup

# Expected limits

## Expected limits in $\tan\beta$ vs $\cos(\beta-\alpha)$ plane, $m_A = 350$ *GeV*

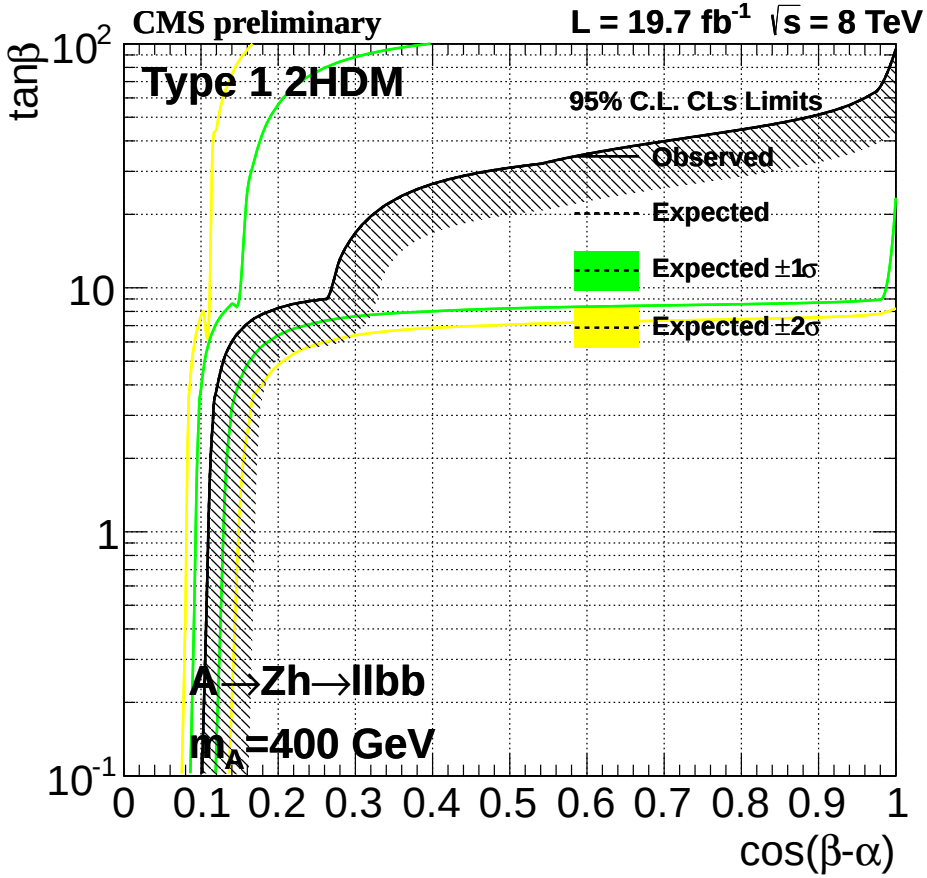


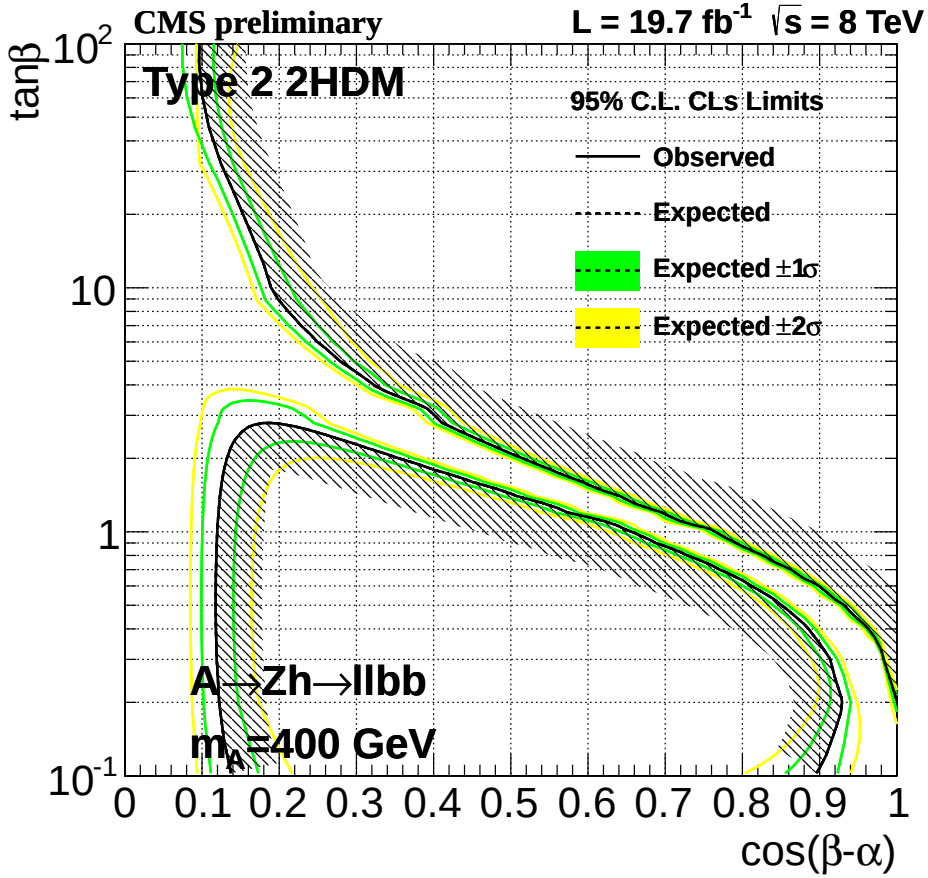




other mass points on backup

# Expected limits

## Expected limits in $\tan\beta$ vs $\cos(\beta-\alpha)$ plane, $m_A = 400$ *GeV*

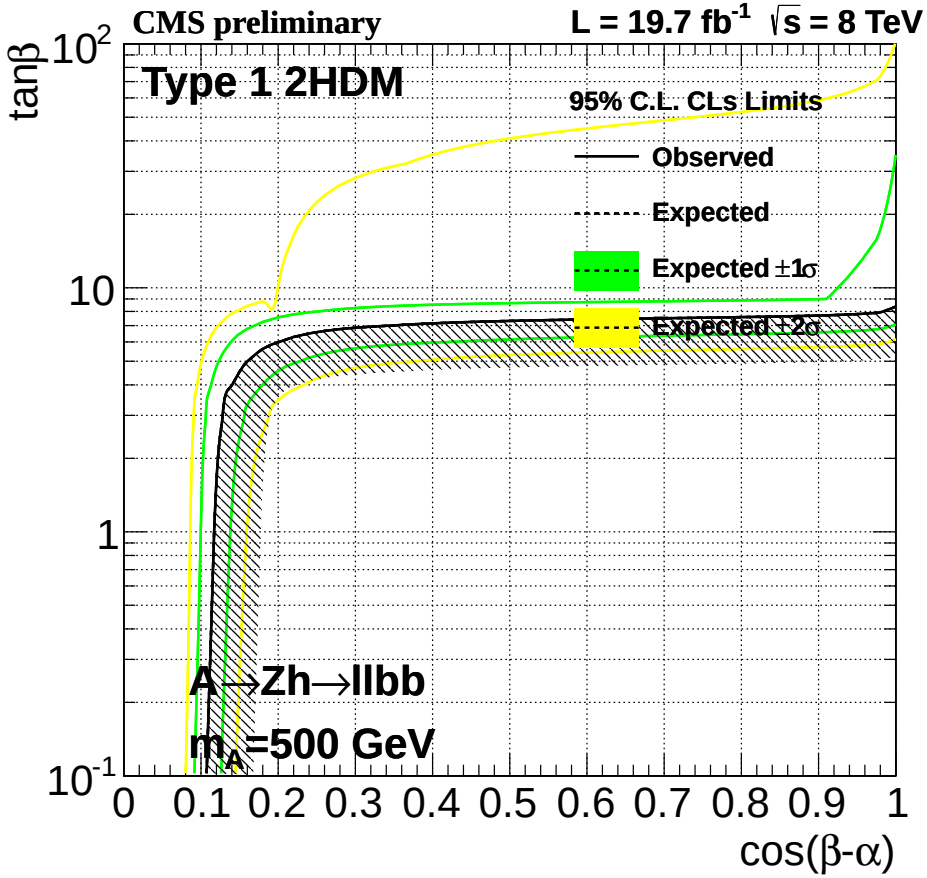


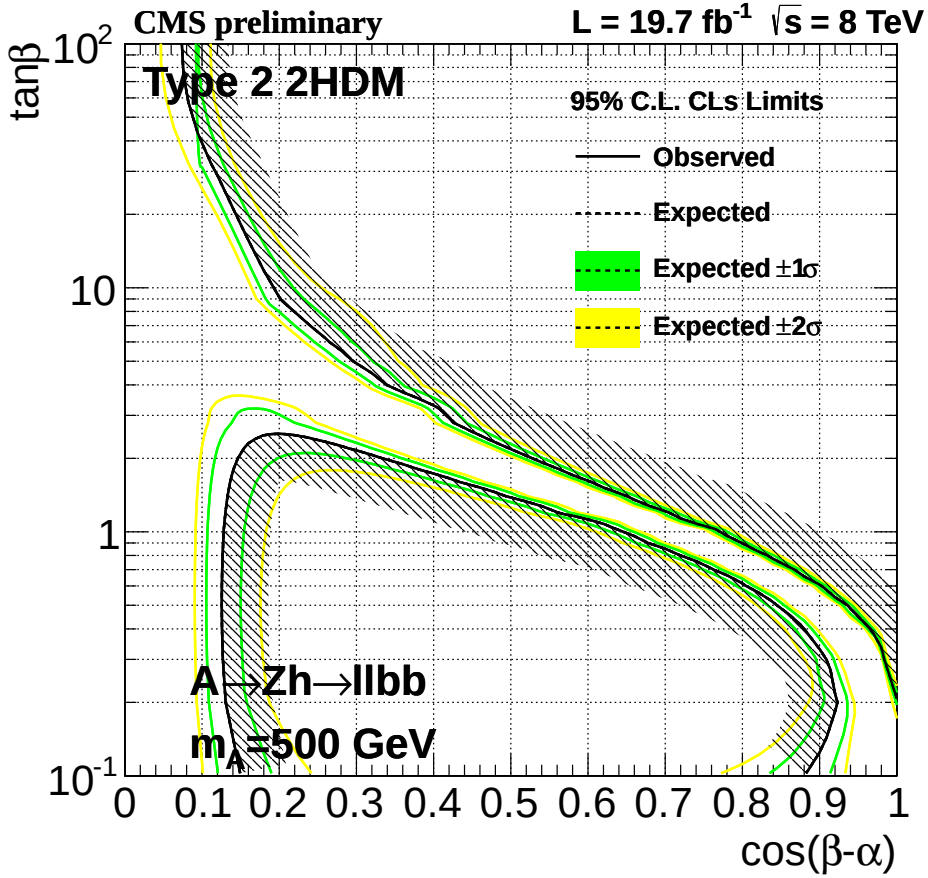




other mass points on backup

# Expected limits

## Expected limits in $\tan\beta$ vs $\cos(\beta-\alpha)$ plane, $m_A = 500$ *GeV*

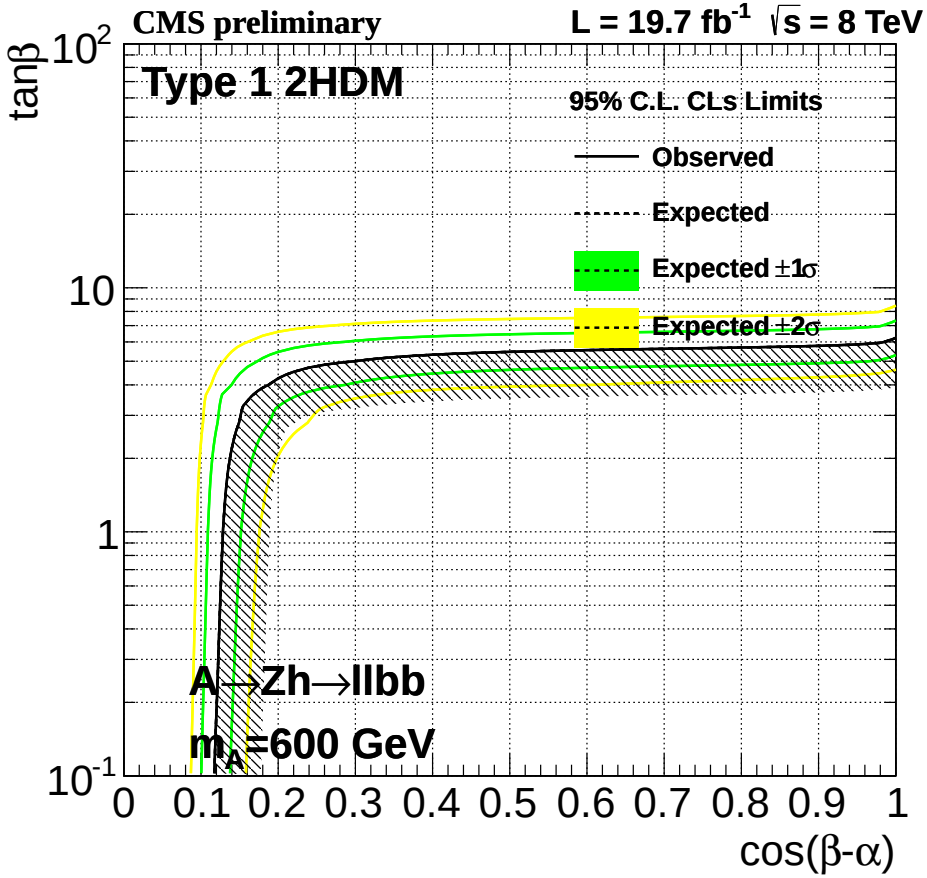


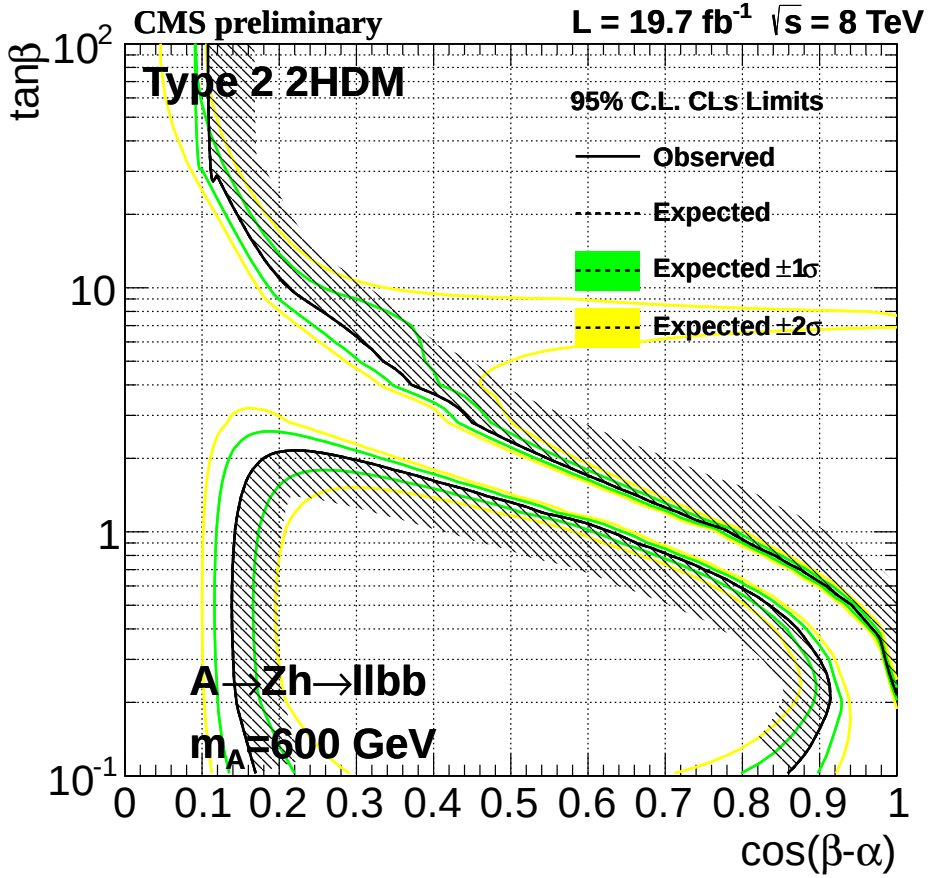




other mass points on backup

# Expected limits

## Expected limits in $\tan\beta$ vs $\cos(\beta-\alpha)$ plane, $m_A = 600$ *GeV*

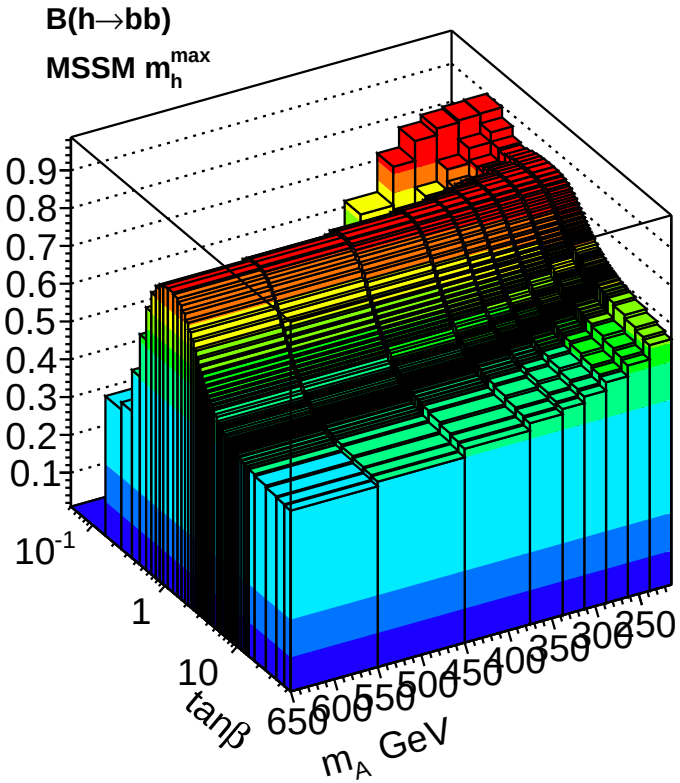


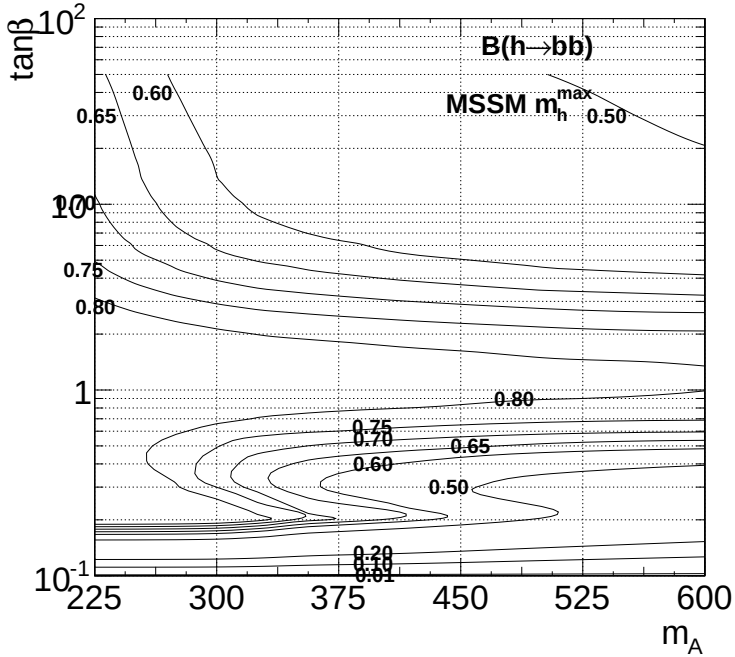




other mass points on backup

# BR($h \to bb$) MSSM $m_h^{max}$

MSSM $m_h^{max}$ Central band around $\tan\beta \sim 1$ not very SM-like

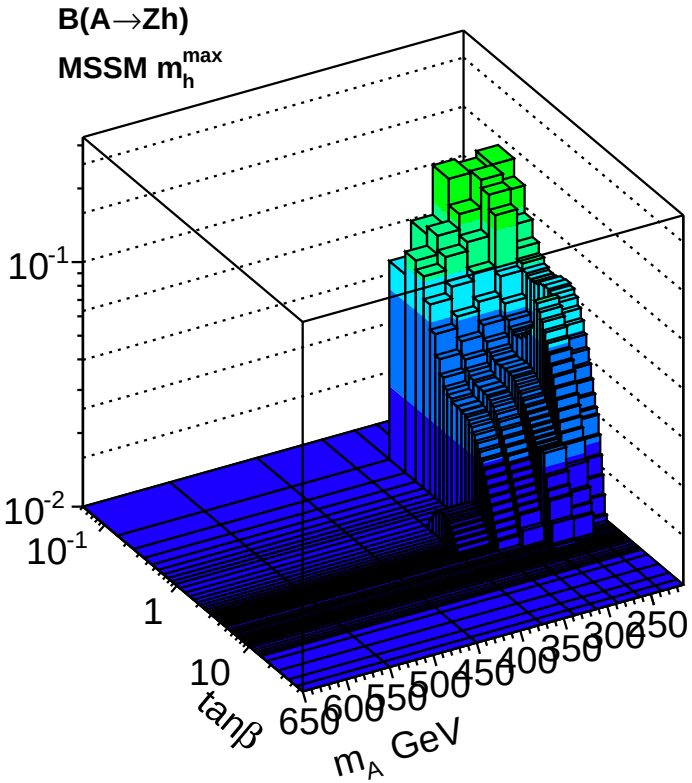


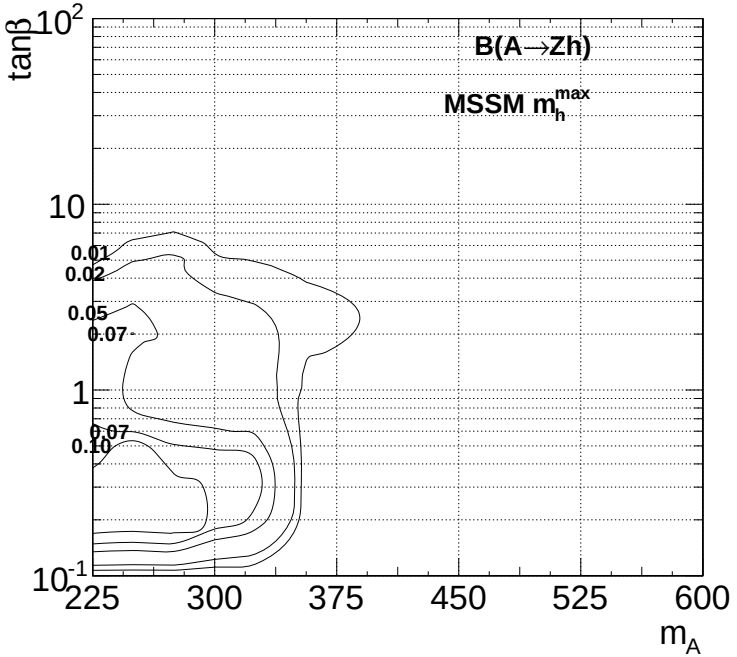




NB: plot rotated

# BR($A \to Zh$) MSSM $m_h^{max}$

MSSM $m_h^{max}$ Quite low and drop for $m_A > 2m_{top}$

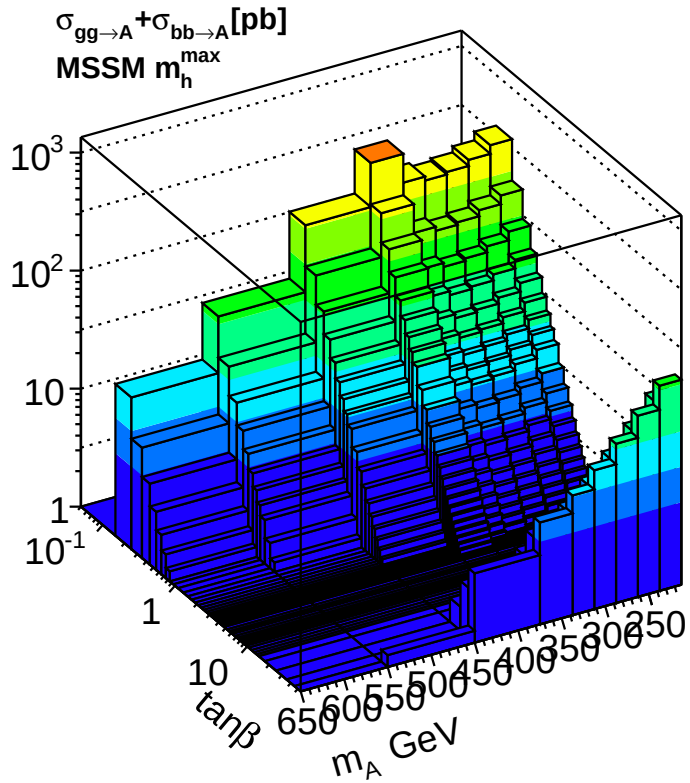


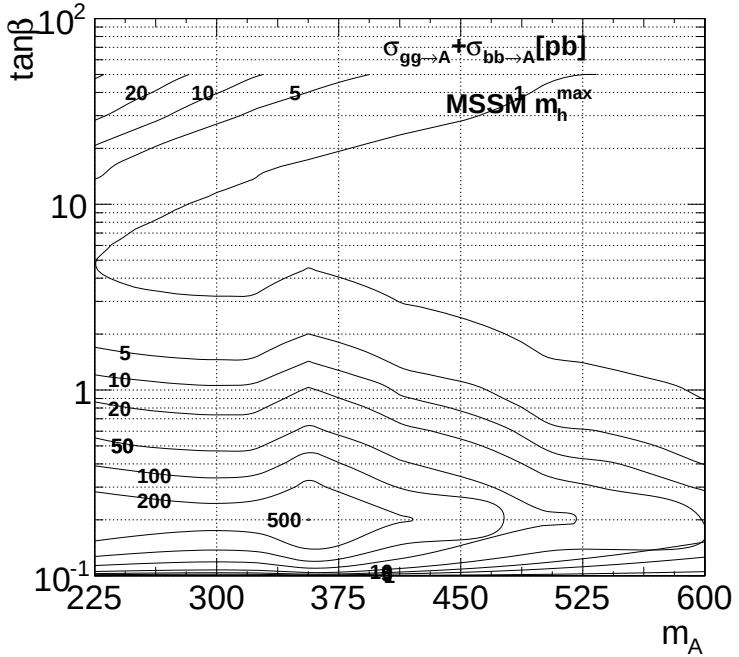




NB: plot rotated

# $\sigma(ggA + bbA))$ MSSM $m_h^{max}$

MSSM $m_h^{max}$ Contribution of $bbA$ at high tan $\beta$ visible.

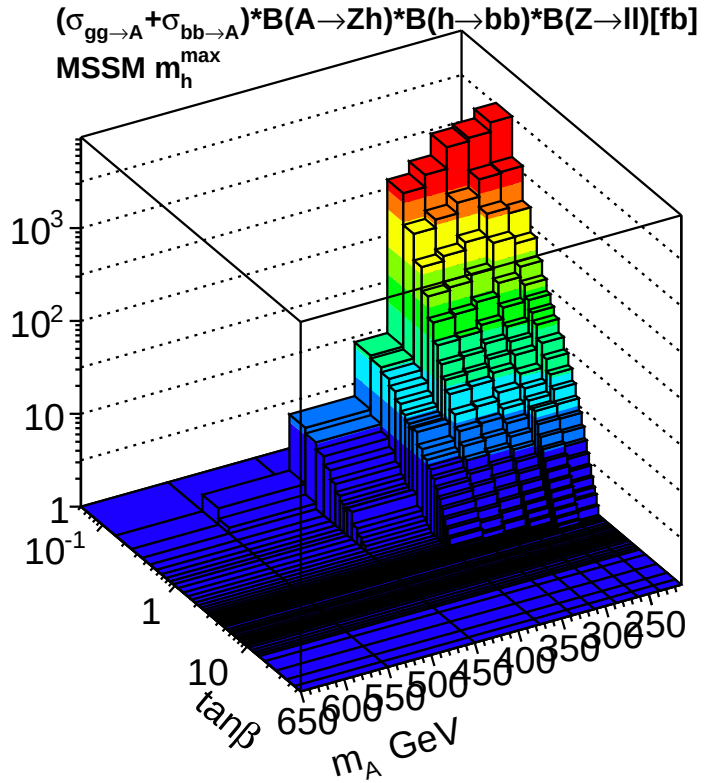


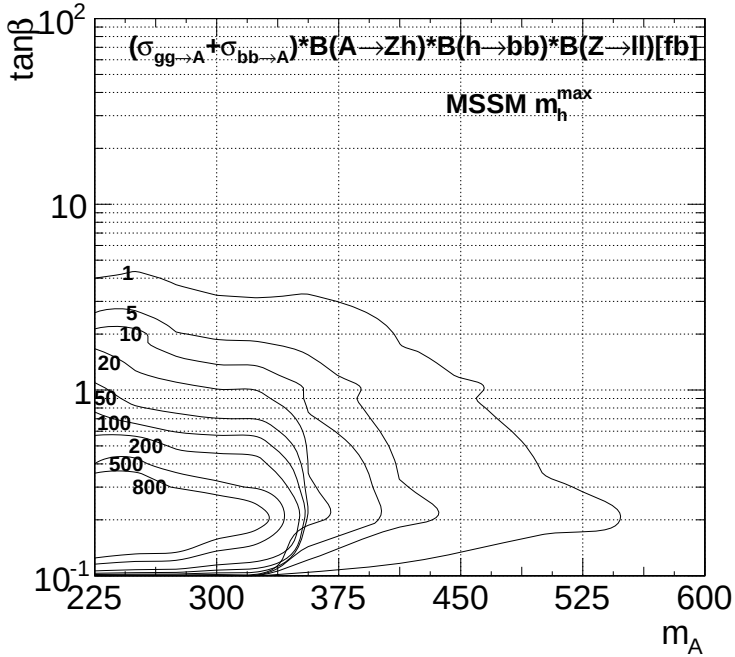




NB: plot rotated

# $\sigma \times BR(A \to Zh \to \ell\ell bb)$ MSSM $m_h^{max}$

MSSM $m_h^{max}$ sizeable for $\tan\beta \lesssim 2$ and $m_A < 350$ *GeV*

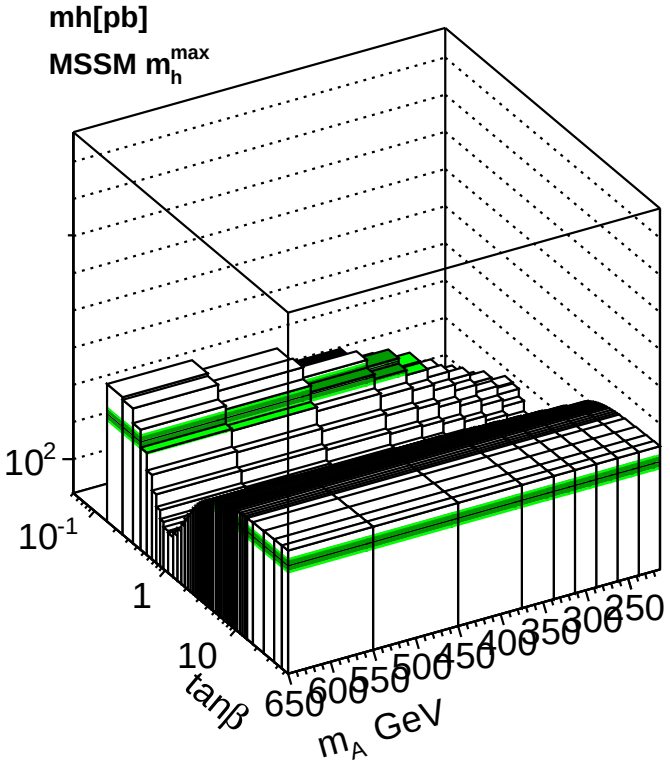


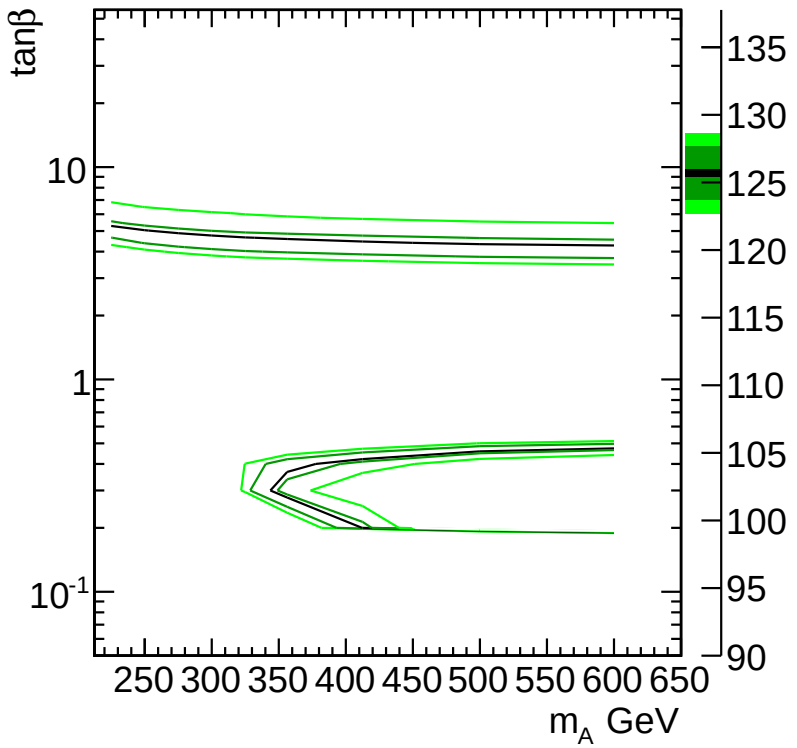




NB: plot rotated

# $m_h$ in MSSM $m_h^{max}$

MSSM $m_h^{max}$ NB: region $\tan\beta \lesssim 1$ already excluded by LEP

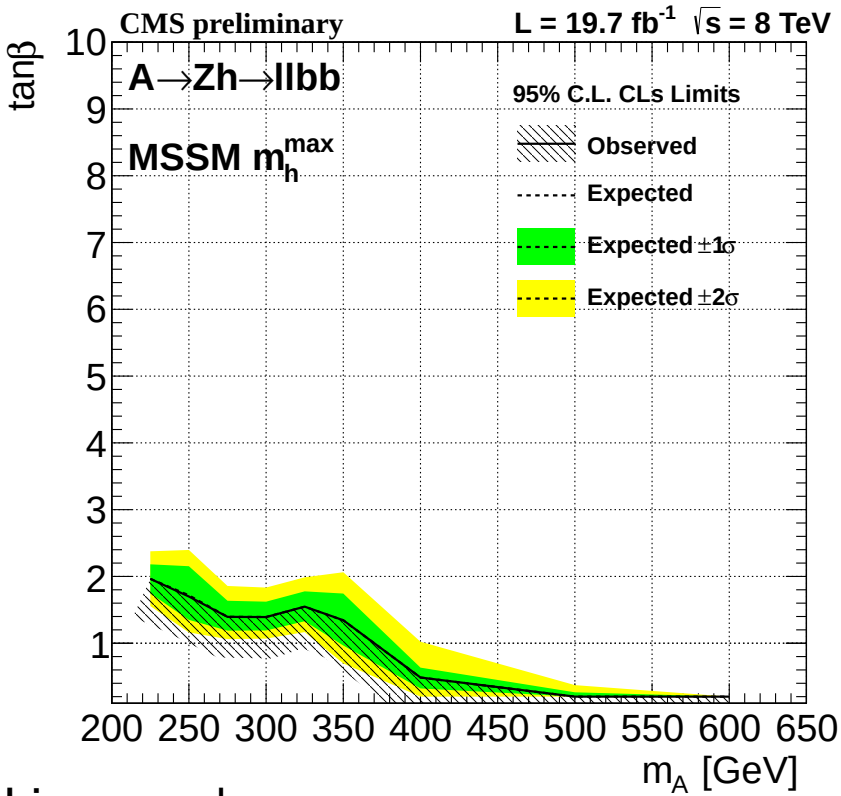


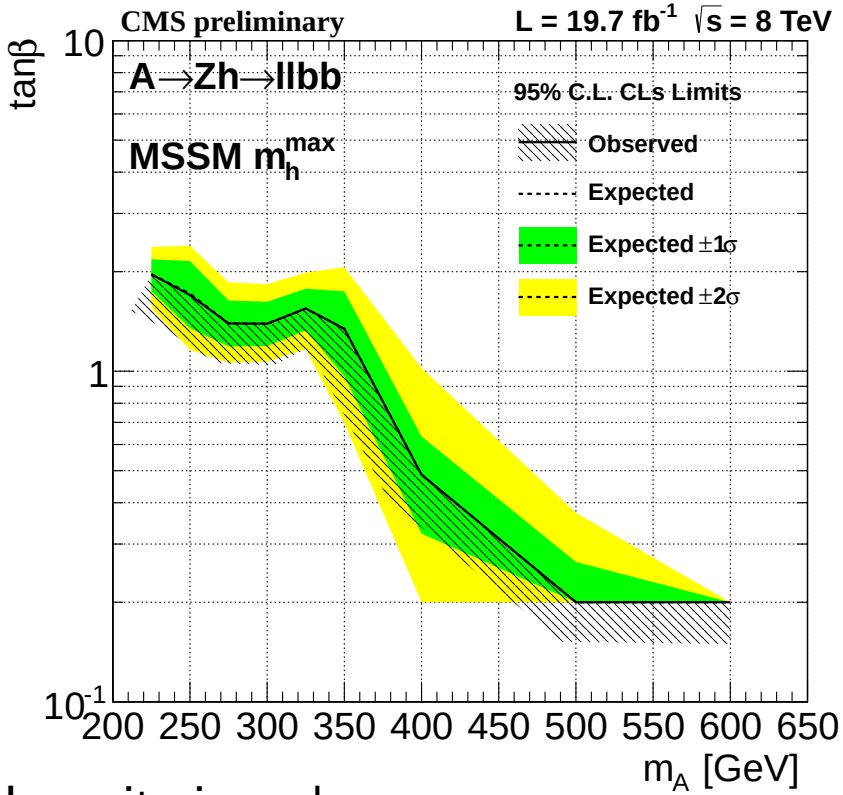

NB: plot rotated

# Expected limit for MSSM $m_h^{max}$

## MSSM $m_h^{max}$




Linear scale




Logaritmic scale