Higgs boson visible and invisible constraints on hidden sectors

in collaboration with Mathias Pierre [2208.05505]

IRN Terascale in Nantes

18th of October 2022

Thomas Biekötter

Introduction

Hidden sectors as dark matter

Field(s) χ without charge under SM gauge groups (singlets)

Higgs-portal dark matter

$\mathbf{SM}:\quad |H|^2$ has mass dimension two $\rightarrow$ (most) relevant operator

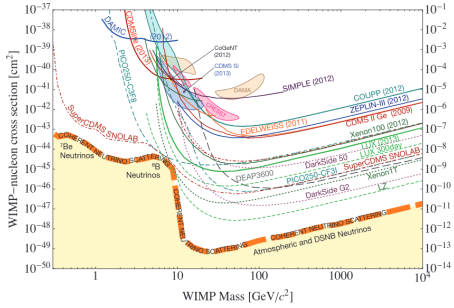
Introduction

Light hidden sectors

Theory

- Light WIMPs
- Extended Higgs sectors
- Pseudo Nambu-Goldstone bosons
- Axions
- Dark photons

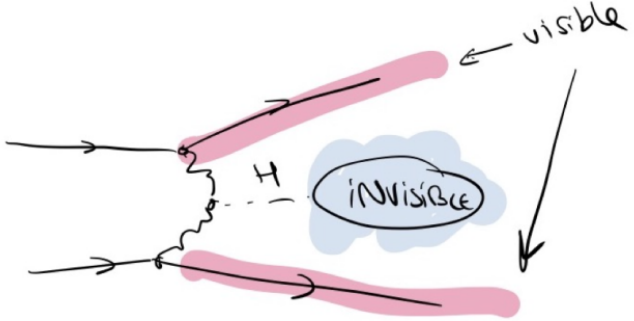
Experiment



[1410.4960]

Introduction

Can be probed at the LHC: Invisible decay of h_{125}



[ATLAS-PHOTO-2022-005-1]

Direct searches: Most sensitive in VBF production mode

$\rightarrow$ **"Direct limits"** on $\mathrm{BR}_{\mathrm{inv}}$

Introduction

Direct searches: Experimental status

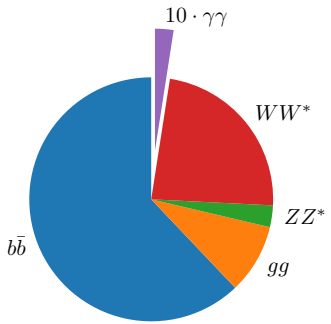
Collaboration	$\sqrt{s}$ [TeV]	Data [fb^{-1}]	h_{125} production	Exp. [%]	**Obs. [%]**
CMS [28]	$8 + 13$	$19.7 + 140$	VBF	10	**18***
CMS [29]	$7 + 8 + 13$	$4.9 + 19.7 + 38.2$	VBF + VH + ggHj	15	**19**
CMS [30]	13	35.9	VH + ggHj	40	**53**
CMS [31]	13	35.9	ZH	44	**45**
ATLAS [32]	$7 + 8 + 13$	$4.7 + 20.3 + 139$	VBF + ttH	11	**11***
ATLAS [33]	$7 + 8 + 13$	$4.7 + 20.3 + 36.1$	VBF + VH	17	**26**
ATLAS [34]	13	139	VBF	10.3	**14.5**
ATLAS [35]	13	36.1	ZH	39	**67**
ATLAS [36]	13	36.1	VH	58	**83**

[See our paper for the ATLAS/CMS references]

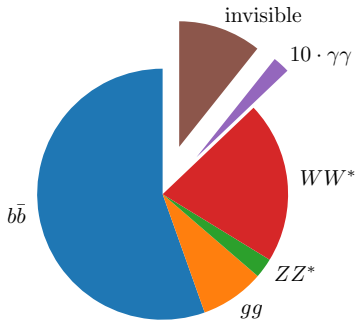
Introduction

But we know so much more: Cross-section measurements of h_{125}

Standard Model BRs (just a sketch)



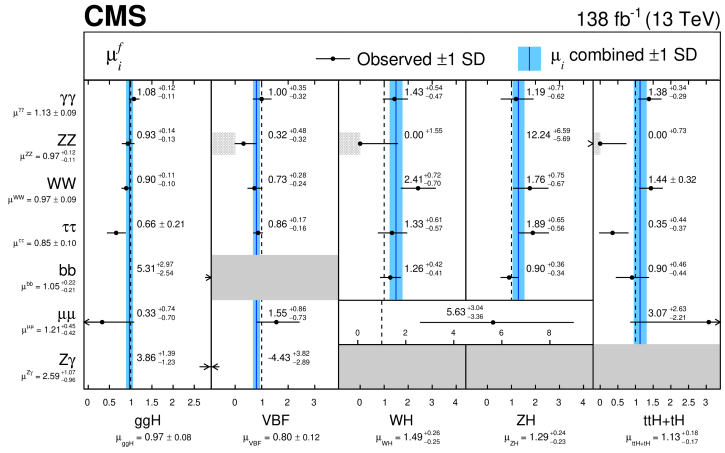
Impact of BSM channel: $\mathrm{BR}_{\mathrm{inv}}$



$\rightarrow$ **“Inirect limits”** on $\mathrm{BR}_{\mathrm{inv}}$

Introduction

Indirect constraints on $\mathrm{BR}_{\mathrm{inv}}$ from cross-section measurements

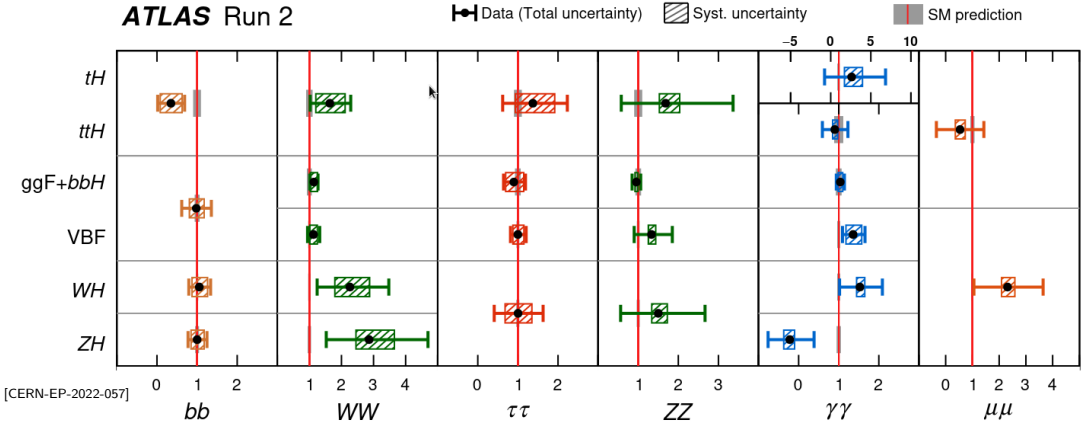


[CMS-HIG-22-001]

Previous talk by Gautier Hamel de Monchenault!

Introduction

Indirect constraints on $\mathrm{BR}_{\mathrm{inv}}$ from cross-section measurements



[CERN-EP-2022-057]

Previous talk by Giovanni Marchiori!

Introduction

Obtaining the **indirect constraints** on $\mathrm{BR}_{\mathrm{inv}}$ in a model:

Theory input

Predictions for cross sections, BRs (, mass) of h_{125}

Compare

$\leftrightarrow$

Experimental data

Large amount of data in terms of total cross sections, signal rates and STXS

Public code: `HiggsSignals`*

χ^2 fit to the cross sectio measurements of h_{125}

$\Rightarrow$ Set limits on the parameter space of the model (e.g. $\mathrm{BR}_{\mathrm{inv}}$)

*Now incorporated in `HiggsTools` package: https://gitlab.com/higgsbounds/higgstools

[Paper should be on the arXiv tomorrow]

Introduction

1. Constrains in terms of effective Lagrangian

$$\mathcal{L} = \sum_{f=u,d,\ell} c_f \left(\frac{m_f}{v}\right) h_{125}\, \bar{f} f + c_V \left(\frac{2m_W^2}{v}\right) h_{125}\, W^{+\mu} W^-_\mu + c_V \left(\frac{m_Z^2}{v}\right) h_{125}\, Z^\mu Z_\mu + \mathcal{L}_{\text{inv}}$$

$$\Rightarrow \Delta\chi^2\left(c_u, c_d, c_\ell, c_V, \mathrm{BR}_{\text{inv}}\right) \ , \qquad \Delta\chi^2 \text{ defined with respect to SM}$$

Earlier analyses of this kind: [J.R. Espinosa, M. Mühlleitner, C. Grojean, M. Trott], [G. Belanger, B. Dumont, U. Ellwanger, J.F. Gunion, S. Kraml], [J. Bernon, B. Dumont, S. Kraml], [P. Bechtle, S. Heinemyer, T. Klingl, T. Stefaniak, G. Weiglein, J. Wittbrodt], ...

2. Application to UV-complete models

c_i are determined by underlying model parameters and $\mathcal{L}_{\text{inv}}$ is specified

Higgs-portal dark matter models

Scalar singlet-portal dark matter

(Pseudo-)Nambu-Goldstone bosons

Two-Higgs-doublet extensions

h_{125} with SM-like couplings

SM-like couplings:

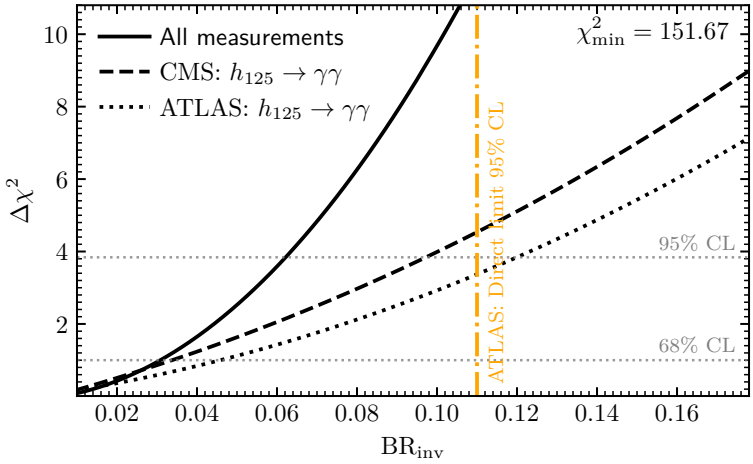
$$c_f = c_V = 1$$

Only BSM contribution:
$\mathrm{BR}(h_{125} \to \mathrm{inv})$

Indirect limit:

$$\mathrm{BR}_{\mathrm{inv}} < \mathbf{6.2}\% \text{ at } \mathbf{95}\%$$

Meas. of $h_{125} \to \gamma\gamma$ alone give rise to an indirect limit stronger than the direct limit on $\mathrm{BR}_{\mathrm{inv}}$ [CMS-HIG-19-015]



Direct limit: [ATLAS-CONF-2020-052]

h_{125} with modified couplings

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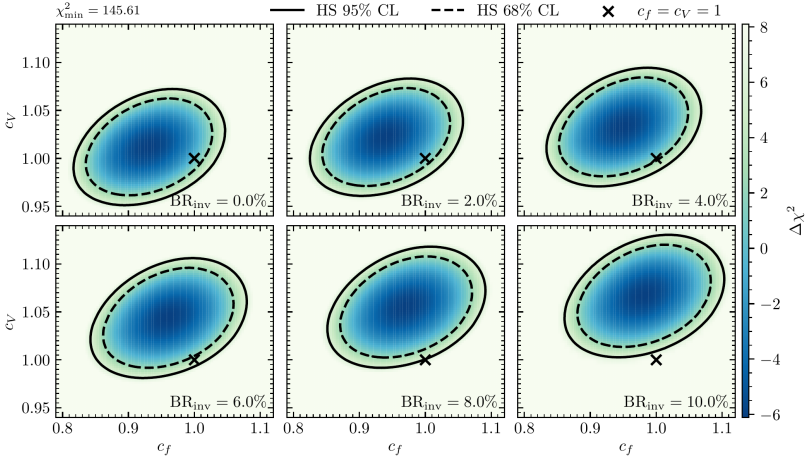
Common LHC benchmark scenario:

$\{c_f, c_V\}$, where $c_f \equiv c_u = c_d = c_\ell$

Allowed regions in $\{c_f, c_V\}$ plane for all $\mathrm{BR}_{\mathrm{inv}}$ values

Complementarity of direct and indirect constrains on $\mathrm{BR}_{\mathrm{inv}}$ if $h_{125} \neq h_{\mathrm{SM}}$



UV-completion: e.g. 2HDM type I ($c_V \leq 1$)

$\Delta\chi^2 < 0 \Rightarrow \chi^2 < \chi^2_{\mathrm{SM}}$

Higgs-portal dark matter

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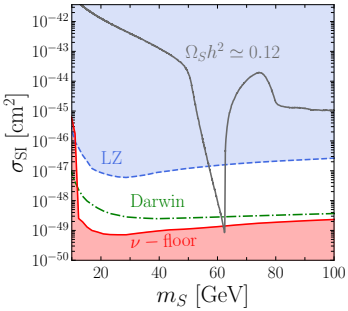
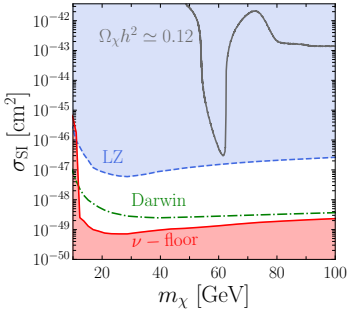
Real scalar DM

$$\mathcal{L}_S = -\frac{1}{4}\lambda_S |H|^2 S^2$$



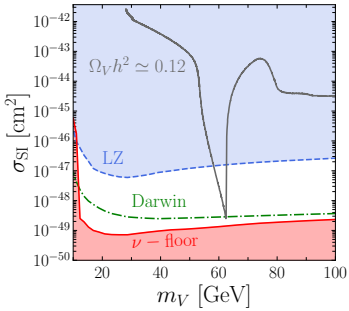
Dirac fermion DM

$$\mathcal{L}_\chi = -\frac{1}{4}\frac{\lambda_\chi}{\Lambda}|H|^2 \bar{\chi}\chi$$



Vector boson DM

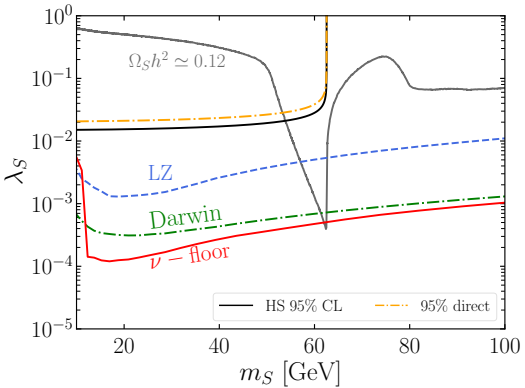
$$\mathcal{L}_V = -\frac{1}{4}\lambda_V |H|^2 V^\mu V_\mu$$

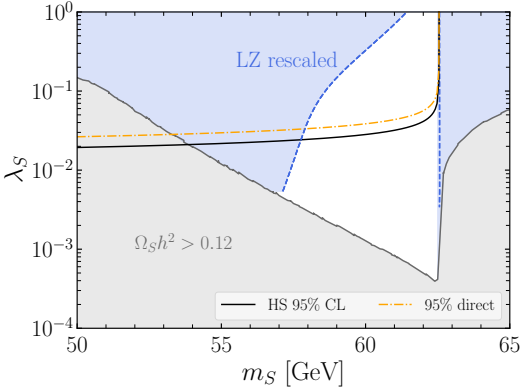


Remaining parameter space where $h_{125} \to \text{inv}$ becomes kinematically allowed

Higgs-portal dark matter

Real scalar DM $\sigma_{\rm SI}^{\rm LZ} = \sigma_{\rm SI}^{\rm LZ}|_{\Omega_{\rm DM}h^2=0.12} \left(\frac{\Omega_{\rm DM}h^2}{0.12}\right)$

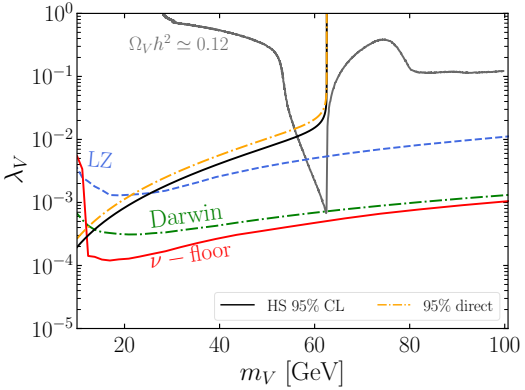


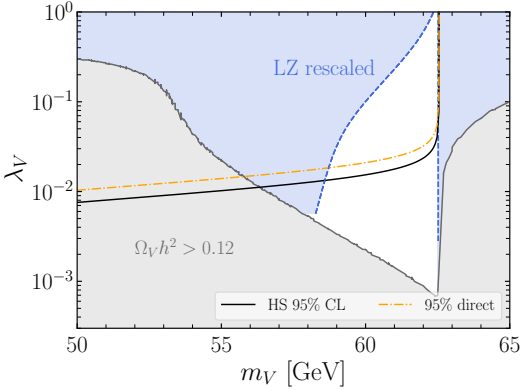


Indirect limits on $\mathrm{BR}_{\rm inv}$ are the **strongest constraint** in large parts of remaining parameter space

Higgs-portal dark matter

Vector boson DM $\sigma_{\rm SI}^{\rm LZ} = \sigma_{\rm SI}^{\rm LZ}|_{\Omega_{\rm DM}h^2=0.12} \left(\frac{\Omega_{\rm DM}h^2}{0.12}\right)$





Indirect limits on $\mathrm{BR}_{\rm inv}$ are the **strongest constraint** in large parts of remaining parameter space

(p)NG bosons

Complex scalar field charged under global U(1) symmetry:

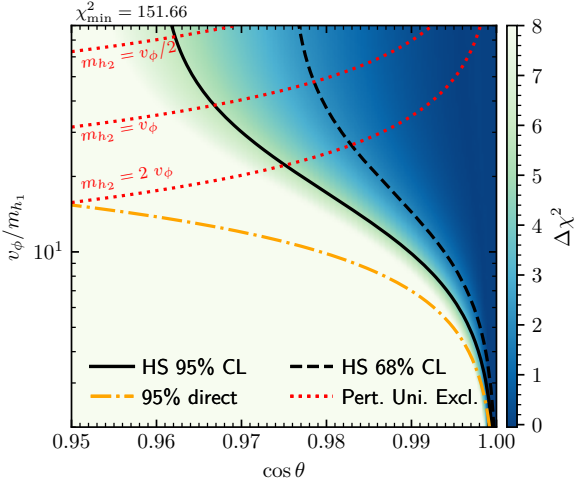
$$\Phi = (v_\phi + \phi)e^{ia/v_\phi}/\sqrt{2}$$

(p)NG boson arises if U(1) is spontaneously broken: $\langle\phi\rangle = v_\phi$

Inv. decay of $h_1 = h_{125}$ to pNG bosons pairs

$$\Gamma_{h_1 \to aa} = \frac{s_\theta^2}{32\pi}\frac{m_{h_1}^3}{v_\phi^2}, \quad m_a \ll 125 \text{ GeV}$$

Independent limits on θ and $\mathrm{BR}_{\mathrm{inv}}$ insufficient → combined analysis (black line) needed



θ: Mixing angle between $h_1, h_2 \Rightarrow c_{f,V} = \cos\theta$

A second Higgs doublet

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Motivations

Supersymmetry	CP violation (axion)	Dark matter
1st-order EW phase transition	Gravitational waves	EW baryogenesis

Dark matter origin

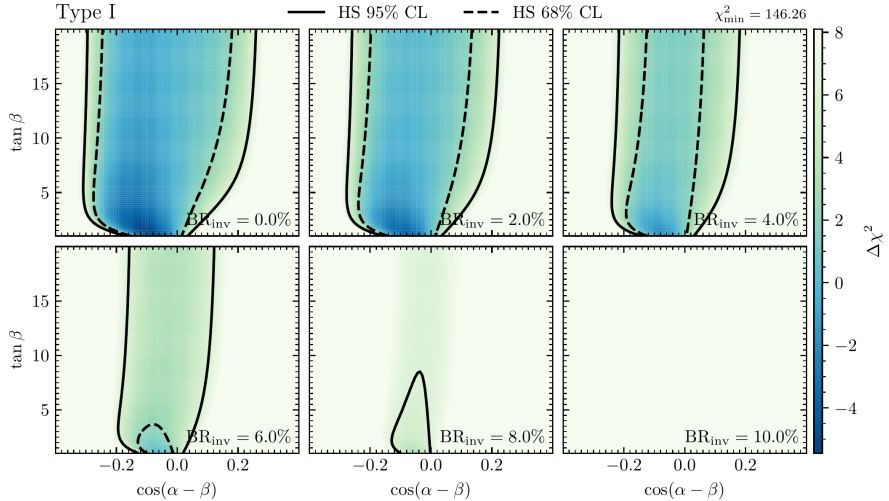
– DM candidate from within the second doublet $\rightarrow$ inert 2HDM

– Higgs doublets as portal to hidden sector $\rightarrow$ e.g. S2HDM, 2HDM+a

2HDM with softly broken Z_2 symmetry avoids FCNF

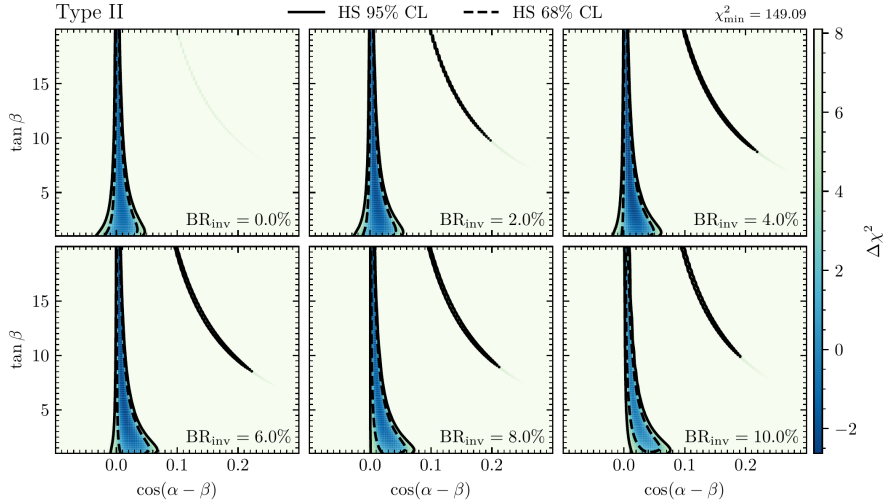
$\rightarrow$ Four different Yukawa types: I, II (Susy-like), III (lepton-specific) and IV (flipped)
Couplings of h_{125} in decoupling limit given by mixing angle α and $\tan\beta = v_2/v_1$

A second Higgs doublet



$\cos(\alpha-\beta) = 0$: Alignment limt $h_{125} = h_{\rm SM}$

A second Higgs doublet



$\cos(\alpha-\beta) = 0$: Alignment limt $h_{125} = h_{\rm SM}$

Conclusions

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Direct searches for $h_{125} \to$ invisible: Direct limits on $\mathrm{BR}_{\mathrm{inv}}$

- Straight forward to apply
- Limits more model-independent

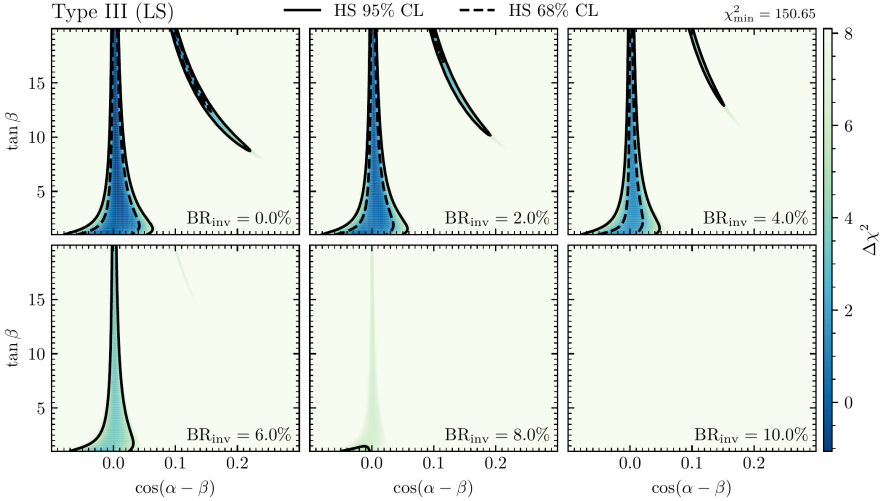
Cross-section measurements of h_{125}: Indirect limits on $\mathrm{BR}_{\mathrm{inv}}$

- Extraction of limits requires some effort (huge amount of data)
- Limits model-dependent

Complementarity: Depending on the properties of h_{125} direct or indirect limits on $\mathrm{BR}_{\mathrm{inv}}$ can be stronger

Both should be taken into account

A second Higgs doublet



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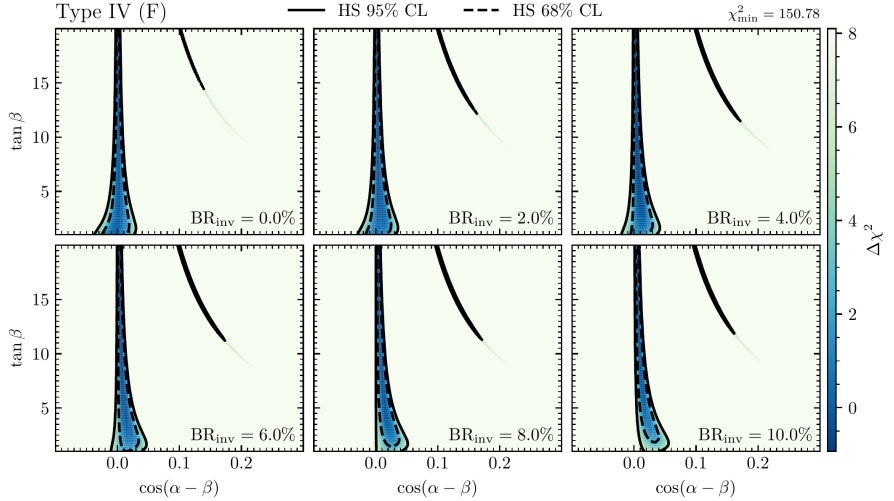

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