# Light Higgs bosons in Two-Higgs-Doublet Models

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Based on **[arXiv:1412.3385]**

In collaboration with
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GDR Terascale
Saclay, 30 March 2015

# Motivations

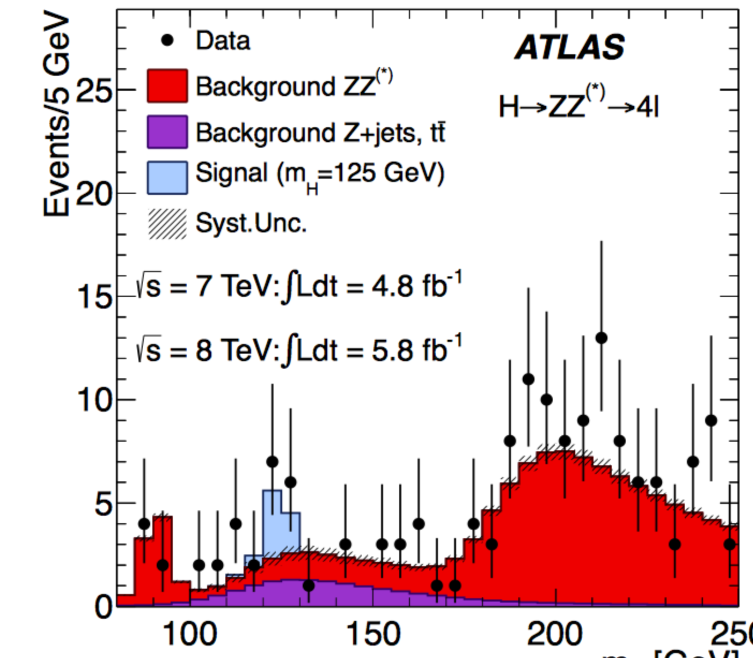
The 2012 discovery of a **Standard Model (SM)-like Higgs boson** is the **major achievement** of the LHC Run I

It is important to asses all possibilities regarding the **existence** of **other Higgs states**

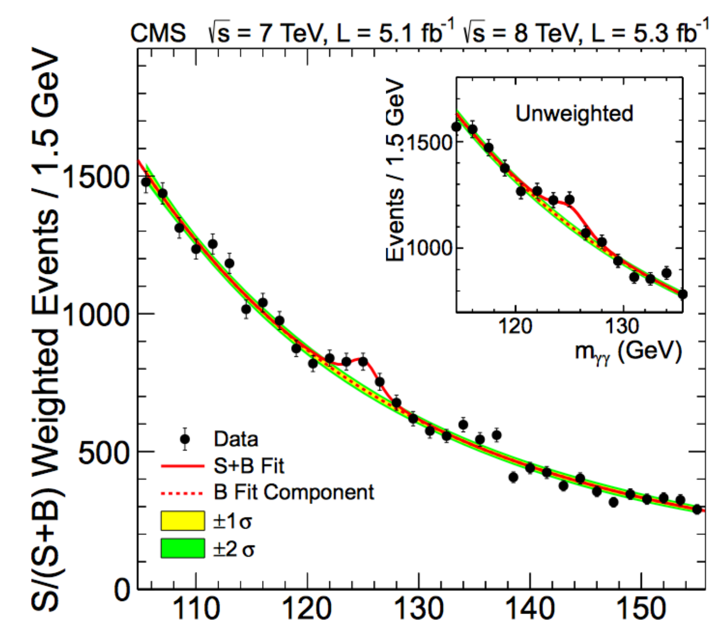
**Two-Higgs-doublet models** (THDM) are a simple and appealing framework to study such considerations

The **decoupling limit** is often considered to obtain a Higgs state with SM properties

Here, we consider scenarios in which some of the Higgs states can be **very light**: with **mass <125/2**




[ATLAS-HIGG-2012-27]




[CMS-HIG-2012-28]

# Two-Higgs-doublet models

General presentation

Constraints imposed

Presence of light states

# Two-Higgs-doublet models

- **Two-Higgs-doublet model** (2HDM): minimal extension of the SM, include a second Y=+1 Higgs doublet

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

$$\Phi_1 \to \Phi_1, \Phi_2 \to -\Phi_2$$

- Hypotheses: Softly broken Z2 symmetry, no CP-violation, no tree-level flavor changing neutral current (FCNC)
- Five physical degrees of freedom: 2 CP-even (h, H) ($m_h \leq m_H$), 1 CP-odd (A), 2 charged ($H^+$ ,$H^-$) states
- Both h and H can be identified with the SM-like state, we will consider both **h125** and **H125 scenarios**
- Free parameters: $m_h, m_H, m_A, m_{H^\pm}, m_{12}^2, \tan\beta\ [0.5, 60], \alpha\ [-\pi/2, \pi/2]$
$\tan\beta$: ratio of the 2 Higgs vevs, $\alpha$: mixing angle of the CP-even mass matrix

# Flavor structure & couplings

Most general renormalizable Yukawa sector:

$$-\mathcal{L}_{\rm Yuk} = \mathcal{Y}_1^U \bar{U}\Phi_1 Q + \mathcal{Y}_2^U \bar{U}\Phi_2 Q + \mathcal{Y}_1^D \bar{D}\Phi_1^* Q + \mathcal{Y}_2^D \bar{D}\Phi_2^* Q$$
$$+ \mathcal{Y}_1^E \bar{E}\Phi_1^* L + \mathcal{Y}_2^E \bar{E}\Phi_2^* L + \text{h.c.}$$

$\Rightarrow$ Generic tree-level FCNC

**Four discrete choices**, to **insure absence of tree-level FCNC** [Paschos 77', Glashow & Weinberg 77']

We consider two of them, the so-called **Type I** and **Type II models**

**Type I:** $\Phi_1 \leftrightarrow$ up, down-type fermions

**Type II:** $\Phi_1 \leftrightarrow$ down-type fermions

$\Phi_2 \leftrightarrow$ up-type fermions

| | Type I and II | Type I | | Type II | |
|---|---|---|---|---|---|
| Higgs | $C_V$ | $C_U$ | $C_D$ | $C_U$ | $C_D$ |
| $h$ | $\sin(\beta-\alpha)$ | $c_\alpha/s_\beta$ | $c_\alpha/s_\beta$ | $c_\alpha/s_\beta$ | $-s_\alpha/c_\beta$ |
| $H$ | $\cos(\beta-\alpha)$ | $s_\alpha/s_\beta$ | $s_\alpha/s_\beta$ | $s_\alpha/s_\beta$ | $c_\alpha/c_\beta$ |
| $A$ | 0 | $\cot\beta$ | $-\cot\beta$ | $\cot\beta$ | $\tan\beta$ |

$$C_i = C_i^{\rm 2HDM}/C_i^{\rm SM}$$

# Numerical setup & Constraints

**Numerical setup:**

- Branching ratio and theoretical constraints from **2HDMC** [Eriksson, Rathsman, Stål] [arXiv:0902.0851]
- Cross sections from **SusHi** [Herlander, Liebler, Mantler] [arXiv:1212.3942]

**Theoretical:**

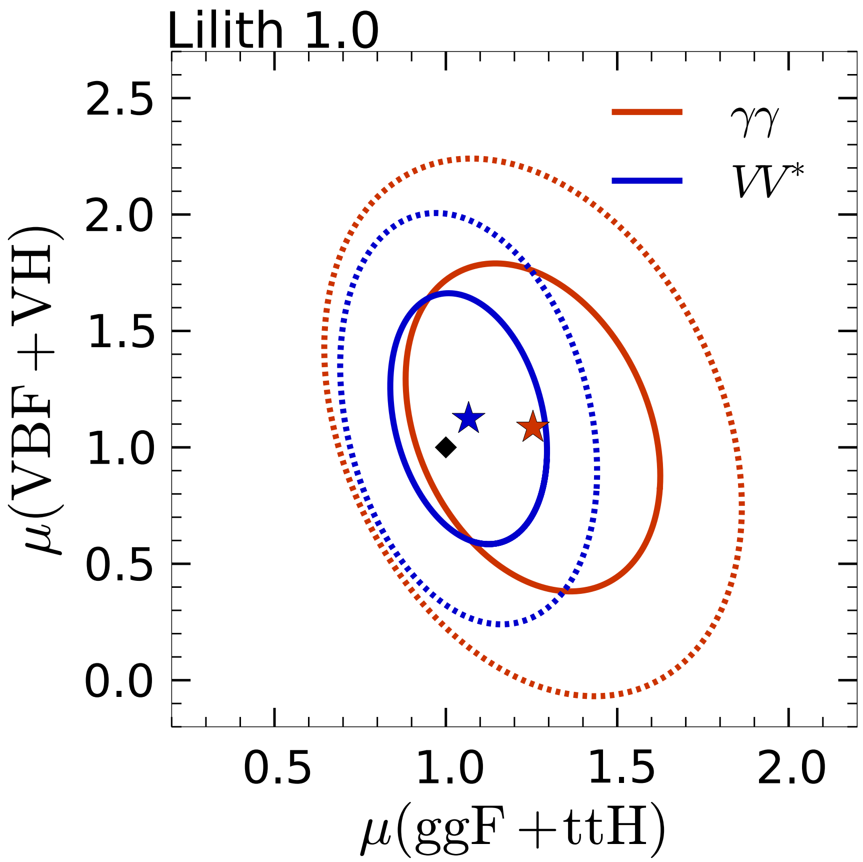
- **Stability** of the scalar potential
- **Perturbativity** of the self-couplings
- Tree-level **unitarity** of the Higgs-Higgs scattering matrices

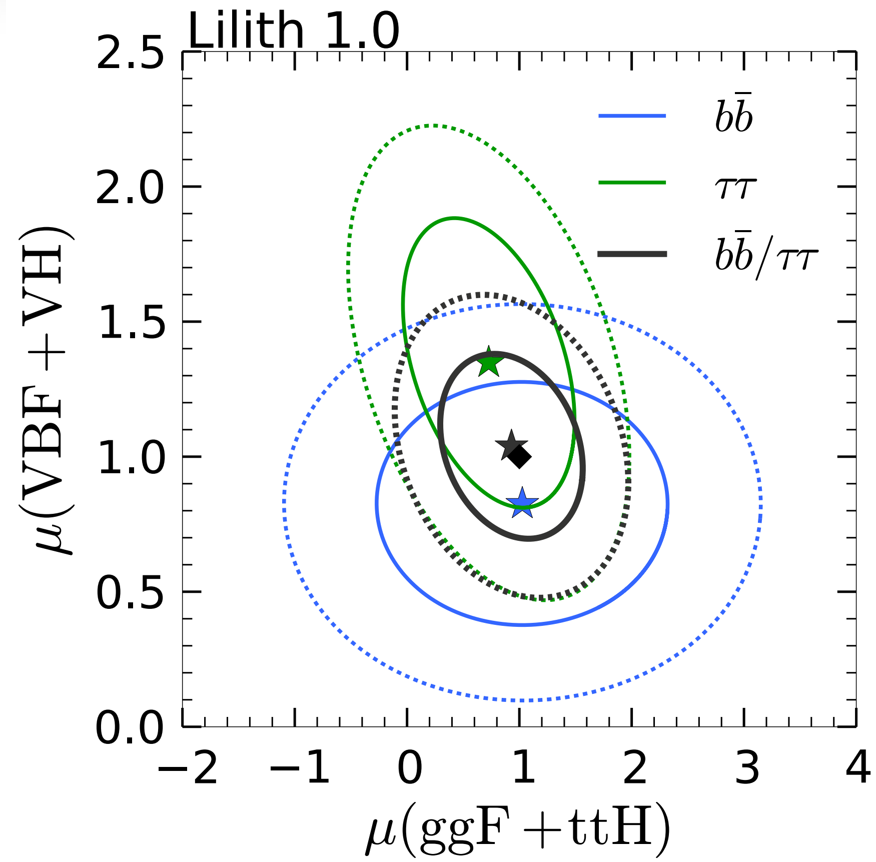
**Experimental:**

- **S, T, U** Peskin-Takeuchi parameters (→Higgs mass splitting)
- **B-physics** constraints (→lower bound on charged Higgs mass)
- **LHC** heavy Higgs searches ($H\to ZZ$, $A\to\tau\tau$, $gg\to bbA\to bb\tau\tau$ ...)
- **LEP** Higgs searches ($e^+e^-\to Zh$, $e^+e^-\to Z^*\to Ah$, $e^+e^-\to H^+H^-$)
- 125 GeV Higgs **signal strengths**

# Combined signal strengths

**Status as of October 2014**




[JB, B. Dumont, S. Kraml] [arXiv:1409.1588]

**Combining** signal strength measurements from LHC and Tevatron, one obtains an approximation to the **Higgs likelihood**

We **require** 95% C.L. agreement with the combined signal strengths for **all individual decay modes** ( $\gamma\gamma, WW^*, ZZ^*, b\bar{b}, \tau\tau$ )

*Lilith*

LIght LIkelihood fiT for the Higgs

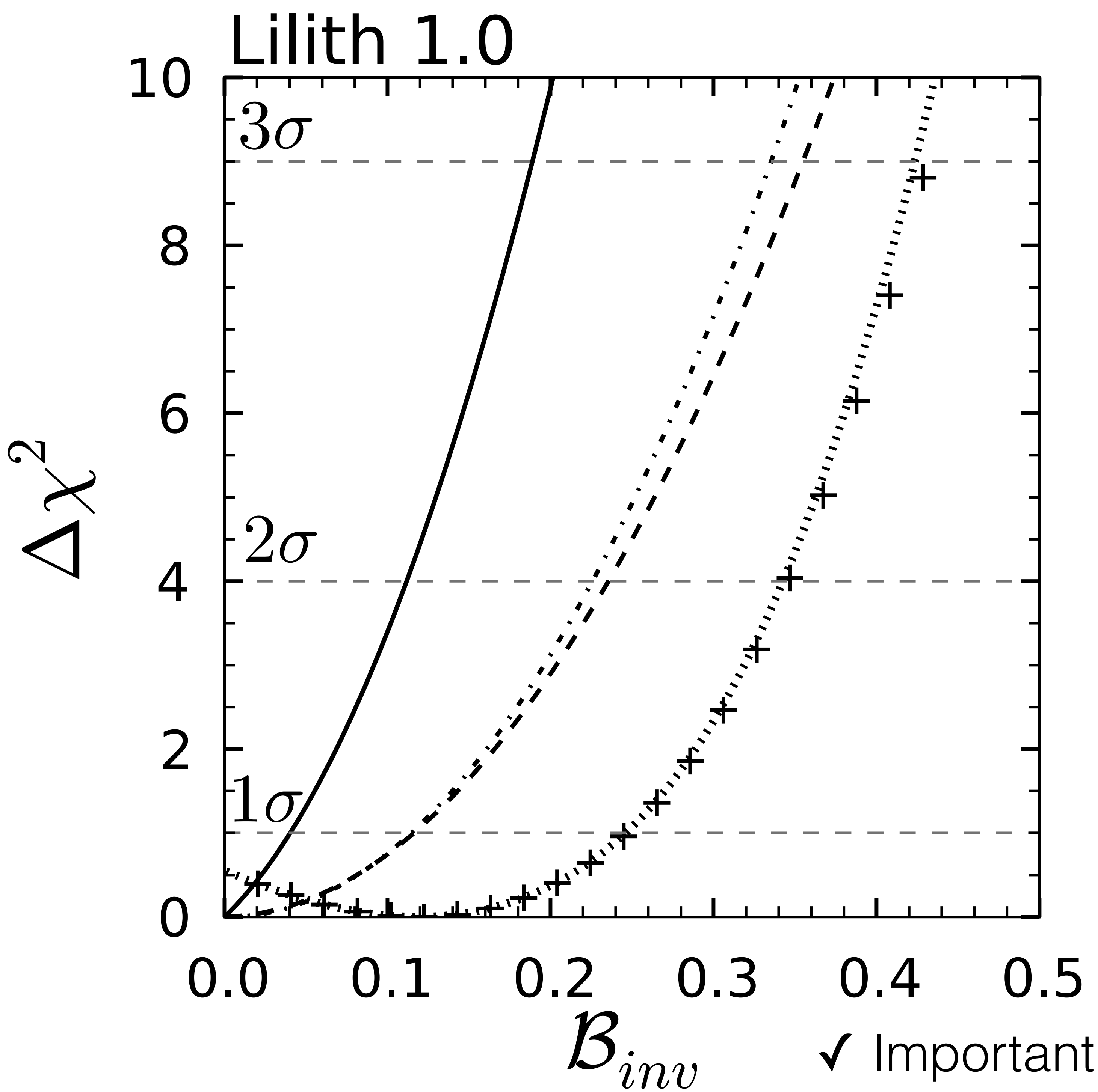
[JB, B. Dumont] [arXiv:1502.04138]

**Information, Download:**

**http://lpsc.in2p3.fr/projects-th/lilith/**

**(Google: lilith higgs)**

# Invisible/undetected branching ratio constraints




✓ Important constraints in the light Higgs scenarios

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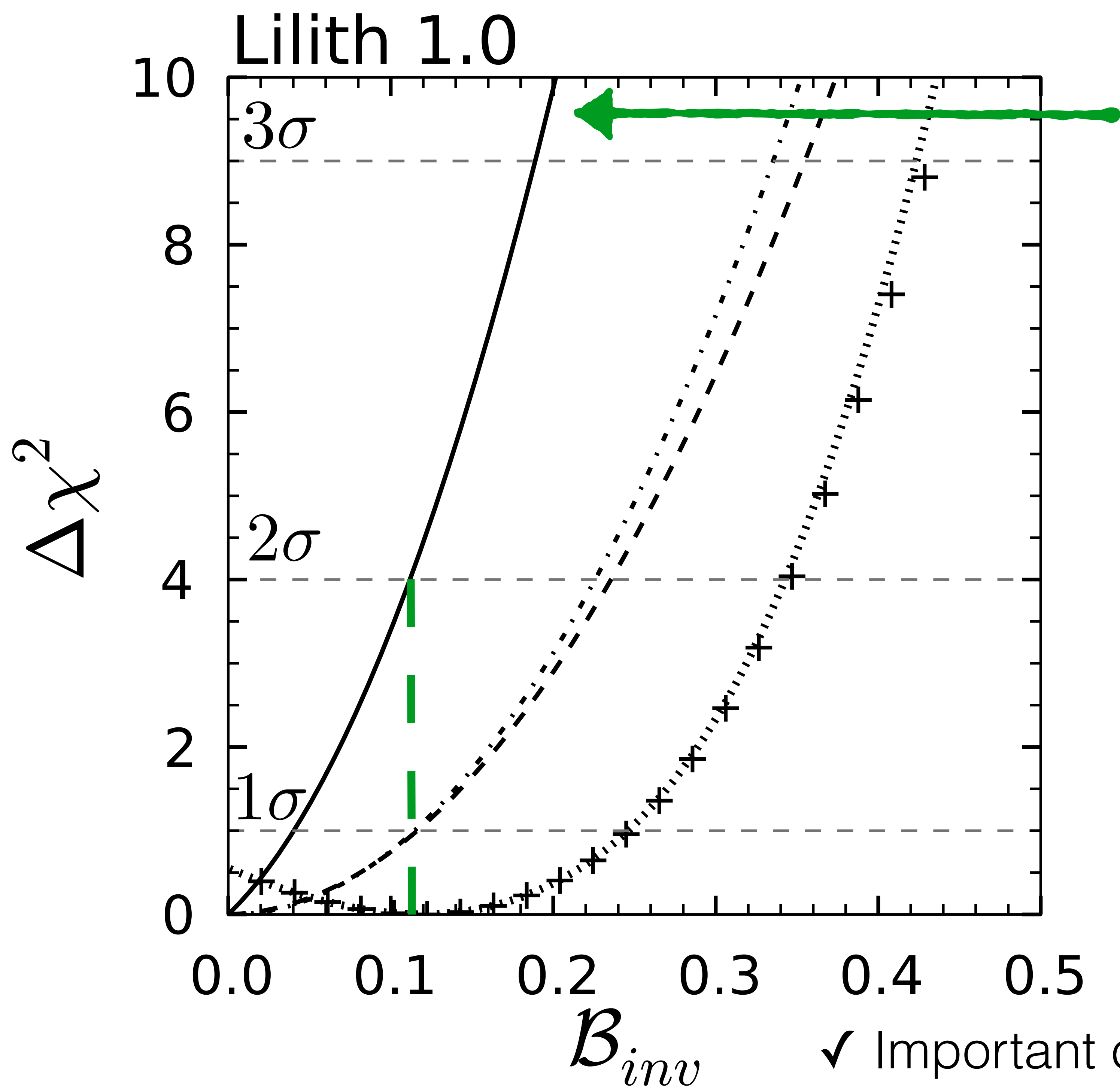


SM+invisible

$\mathcal{B}_{inv} < 0.11$ at 95.4% C.L.

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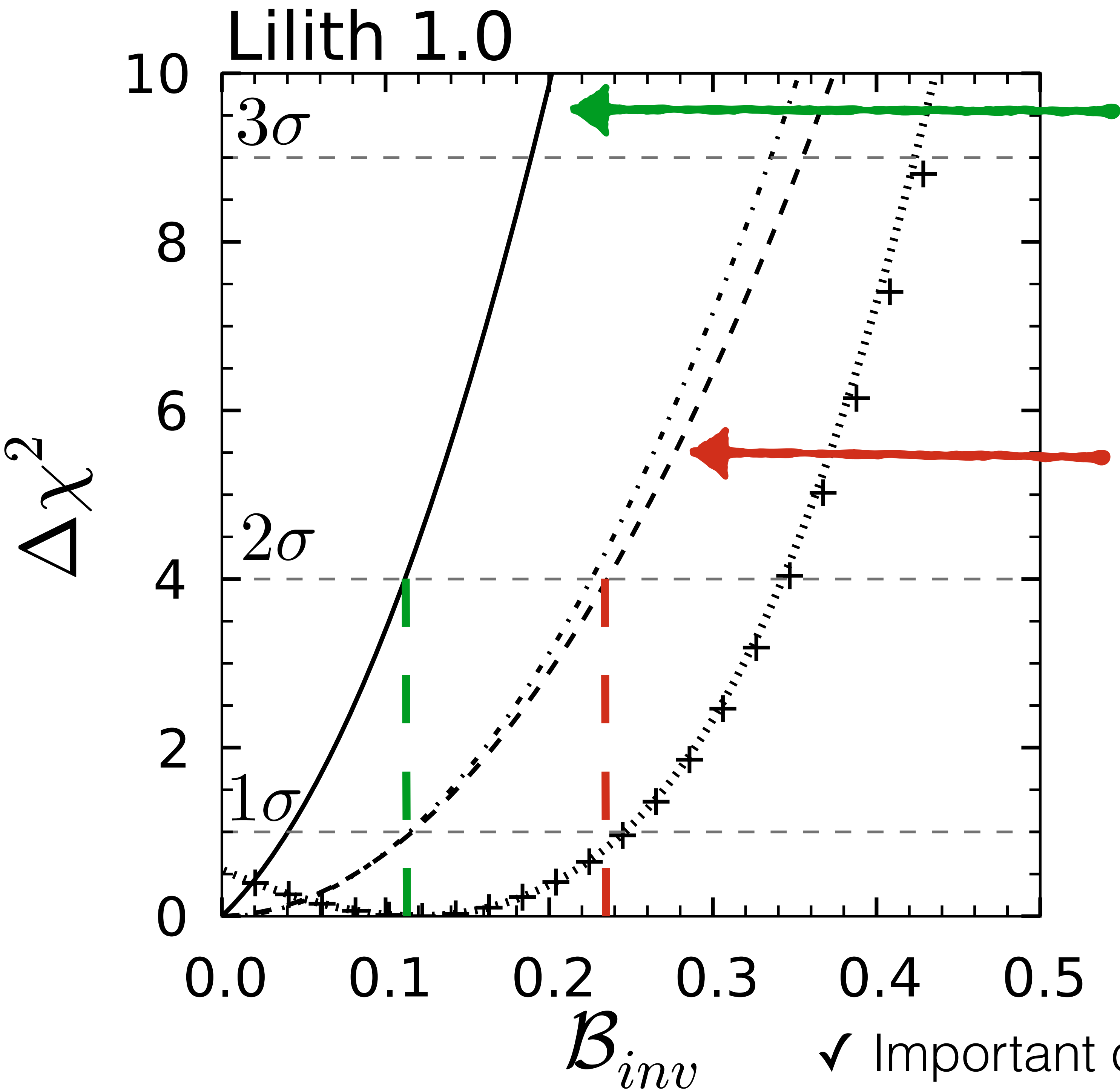


SM+invisible

$\mathcal{B}_{inv} < 0.11$ at 95.4% C.L.

$C_U$, $C_D$, $C_V$ <1 +invisible

$\mathcal{B}_{inv} \lesssim 0.24$ at 95.4% C.L.

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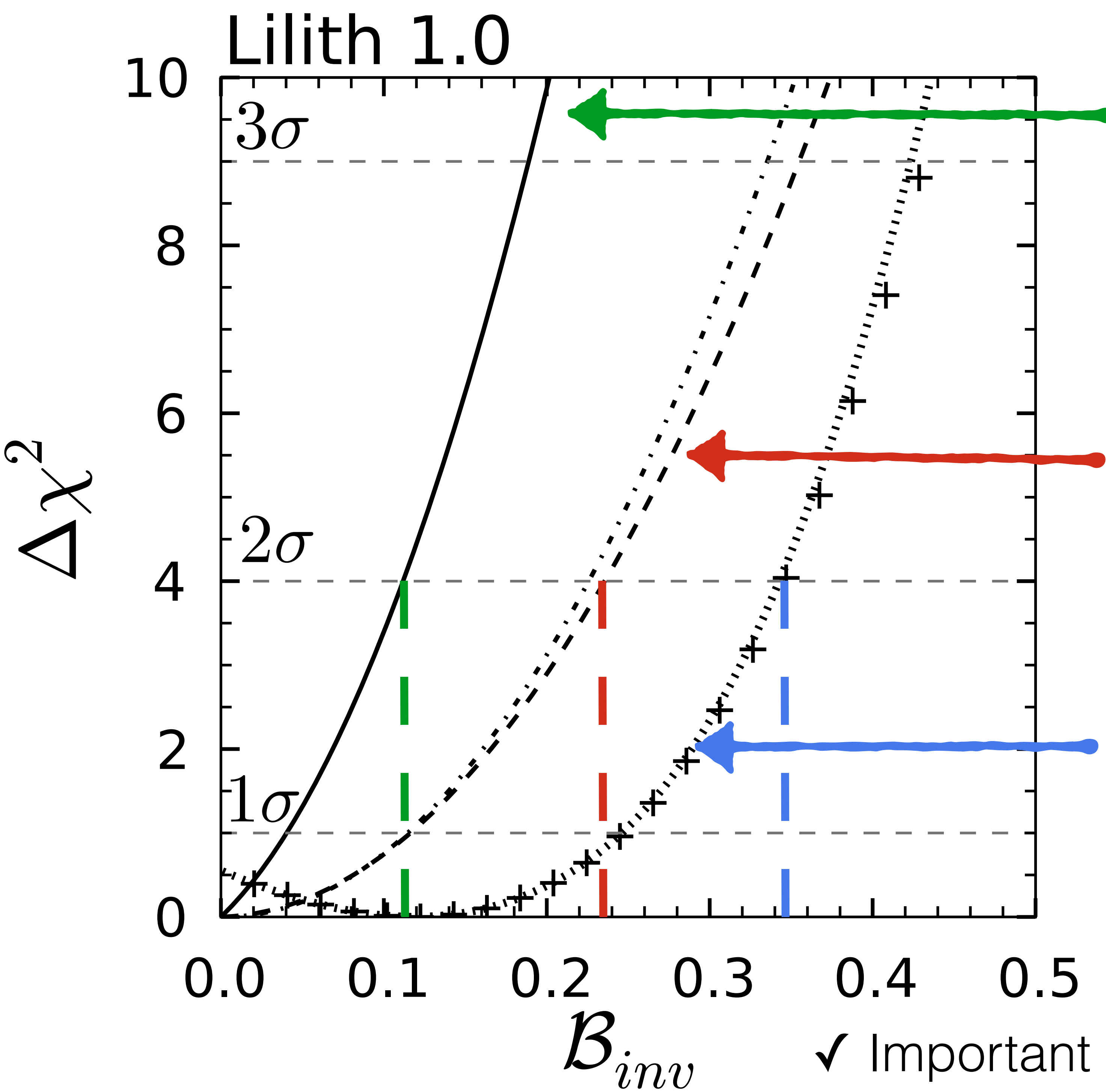


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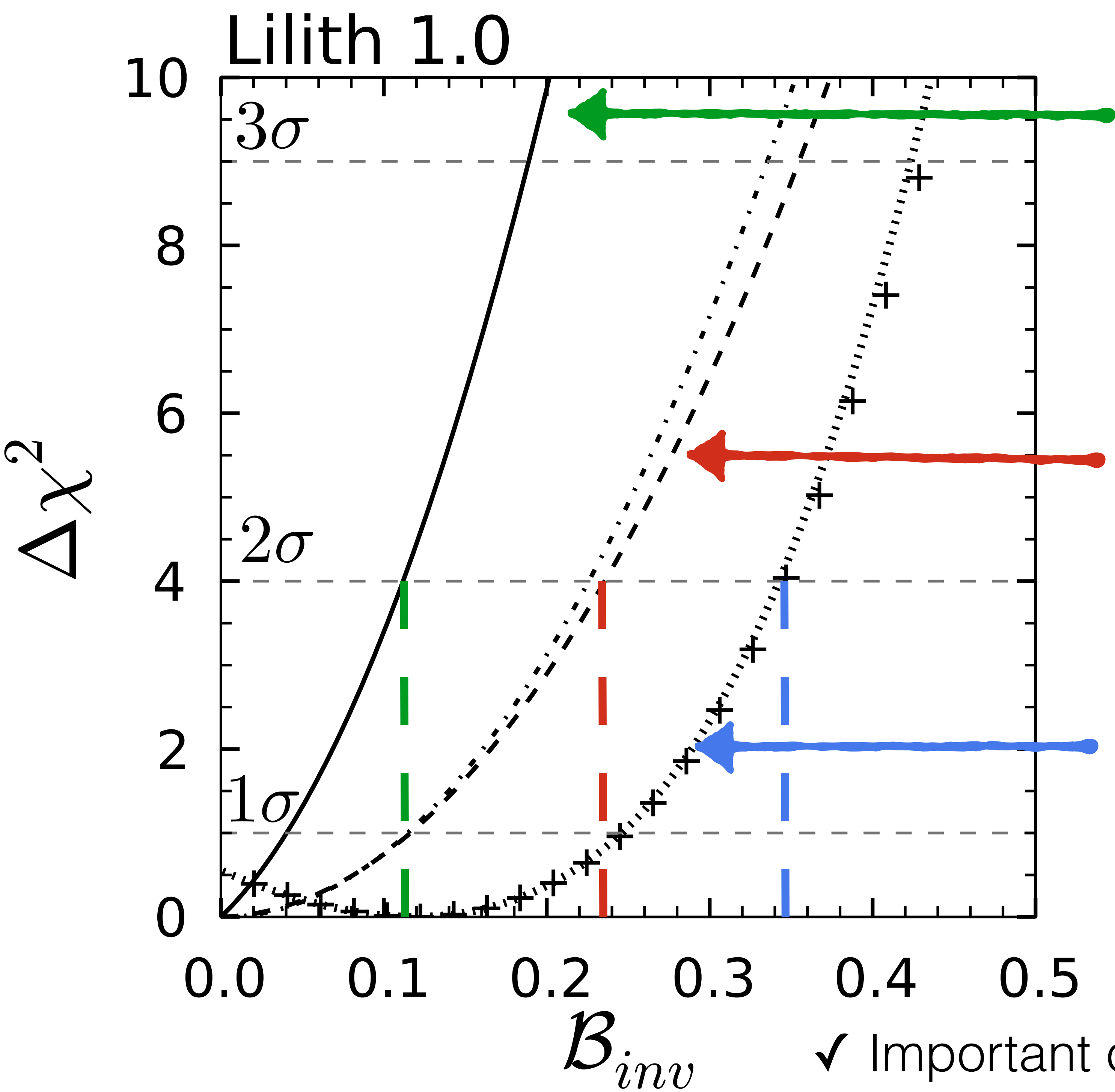



SM+invisible

$\mathcal{B}_{inv} < 0.11$ at 95.4% C.L.

$C_U$, $C_D$, $C_V$ <1 +invisible

$\mathcal{B}_{inv} \lesssim 0.24$ at 95.4% C.L.

**Roughly the same limits for undetected BR**

$C_U$, $C_D$, $C_V$ +invisible

$\mathcal{B}_{inv} \lesssim 0.34$ at 95.4% C.L.

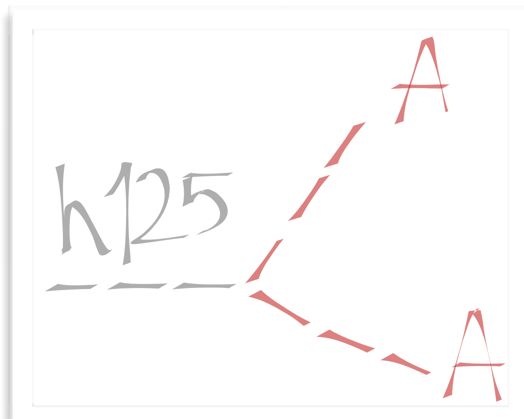
✓ Important constraints in the light Higgs scenarios

[JB, B. Dumont, S. Kraml] [arXiv:1409.1588]

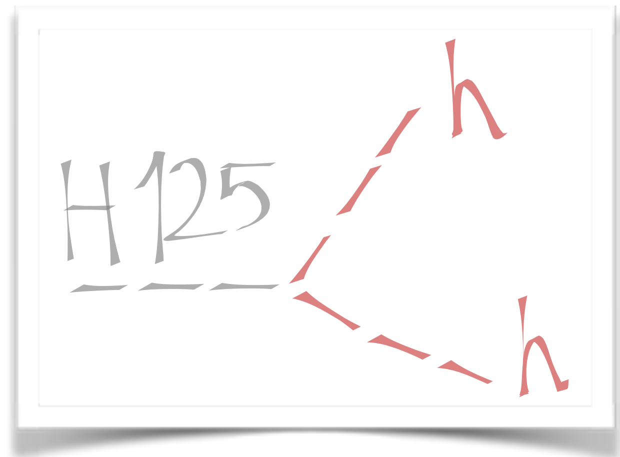
# Light states

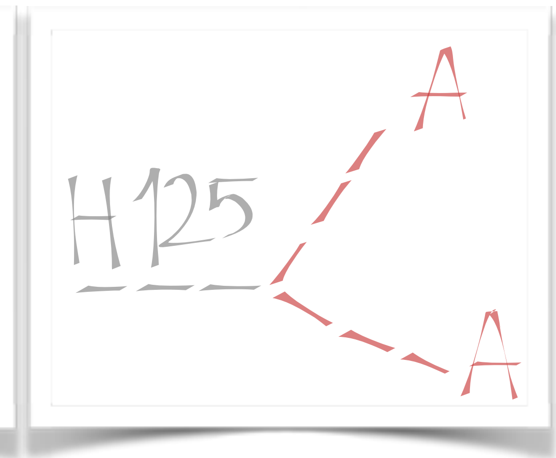
We consider the presence of light states m<125/2 in both the h125 and H125 scenarios:

**Open modes**




$Y = h125 \quad X = A$




$Y = H125 \quad X = A, h$

**Severe constraints** on the **tri-Higgs couplings** from the observed signal strengths: **(rough estimation assuming fermionic SM-like couplings for Y and mY=125)**

$$R(XX) \equiv \frac{\Gamma(Y \to XX)}{\Gamma(Y \to bb)_{\text{tree}}} = \frac{1}{12}\left(\frac{g_{YXX}v}{m_Y m_b}\right)^2 \frac{\beta(m_X)}{\beta^3(m_b)}$$

$$\text{BR}(Y \to XX) \lesssim 0.3 \Leftrightarrow R(XX) \lesssim \frac{5}{6} \Leftrightarrow |g_{YXX}| \lesssim \mathcal{O}(10\ \text{GeV})$$

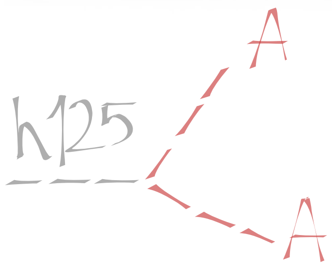
while $|g_{YXX}| \sim \mathcal{O}(\text{TeV})$ naturally

# h125 scenarios

Setup

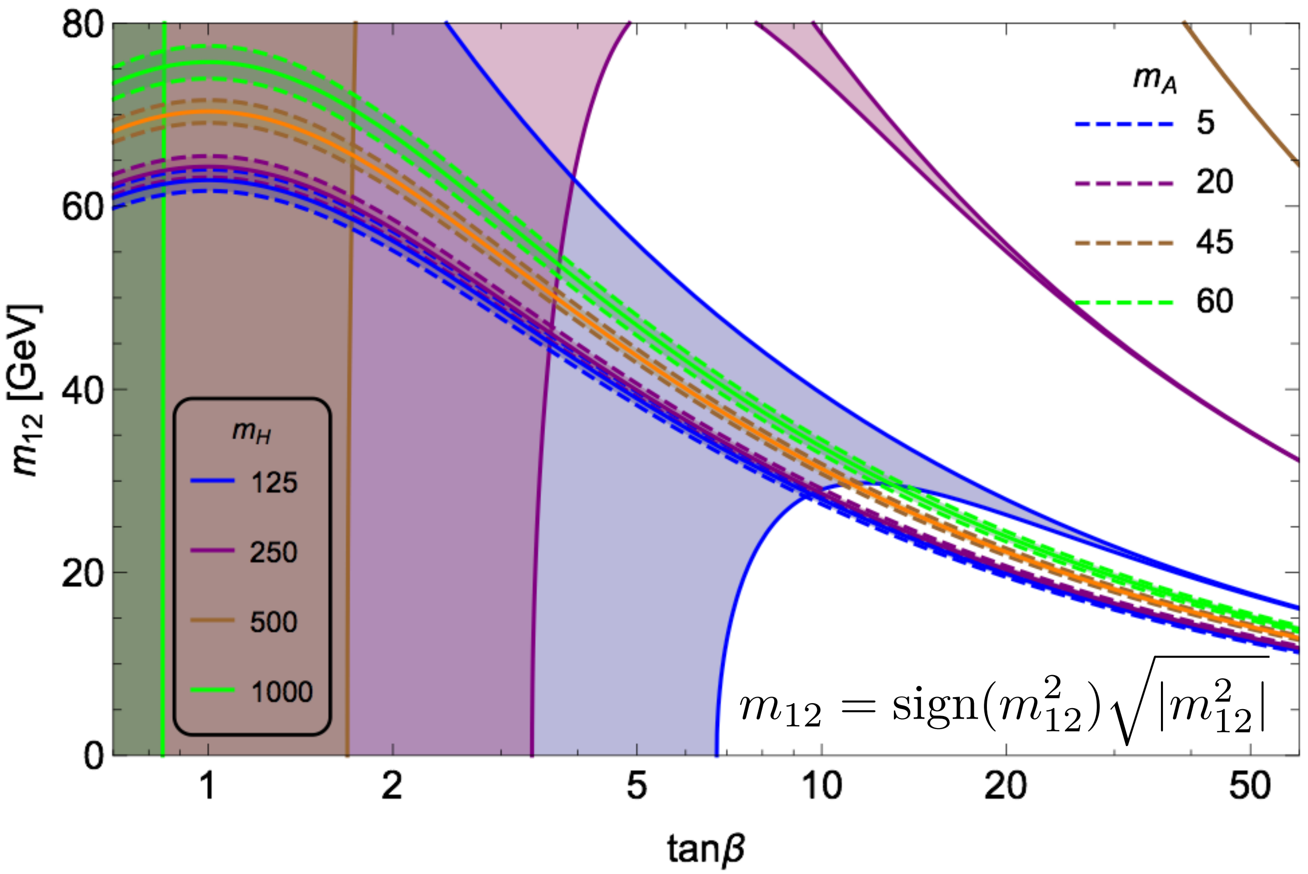
Results

# hAA tri-Higgs coupling




$$g_{hAA} = \frac{1}{2v}\left[\left(2m_A^2 - m_h^2\right)\frac{\cos(\alpha-3\beta)}{\sin 2\beta} + \left(8m_{12}^2 - \sin 2\beta\left(2m_A^2+3m_h^2\right)\right)\frac{\cos(\beta+\alpha)}{\sin^2 2\beta}\right]$$

- In the SM-limit $\sin(\beta-\alpha)=1$ : $g_{hAA} = -\frac{2m_A^2 + m_h^2 - 2m_{12}^2 \sec\beta \csc\beta}{v}$




Solid+dashed lines:
BR(h→AA)≤0.3 as a function of $m_A$

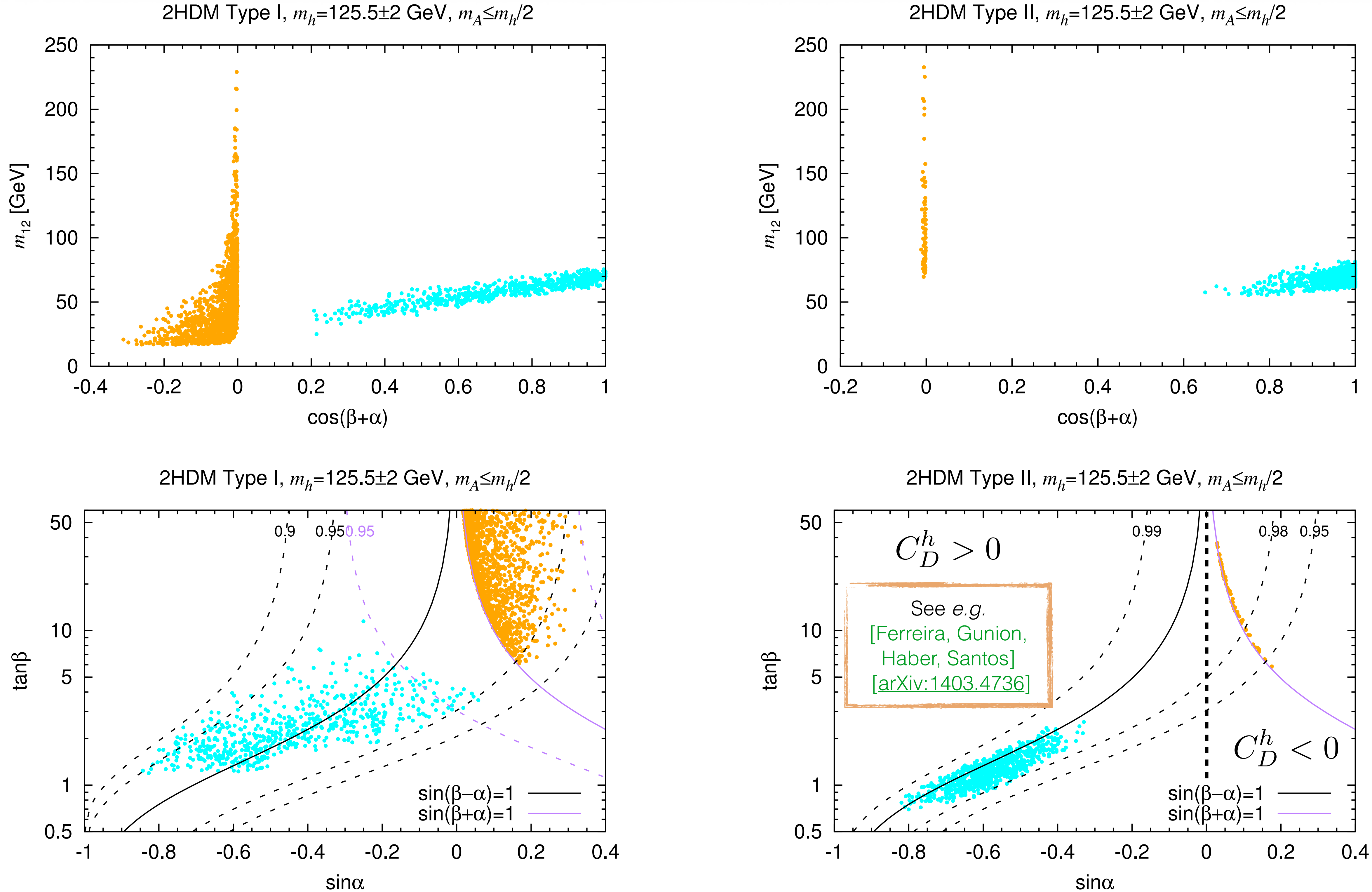
Filled regions :
allowed by perturbativity
as a function of $m_H$

Simultaneous requirement of small
h→AA branching ratio and perturbativity
⟹ Moderate $t_\beta$ & small $m_{12}$

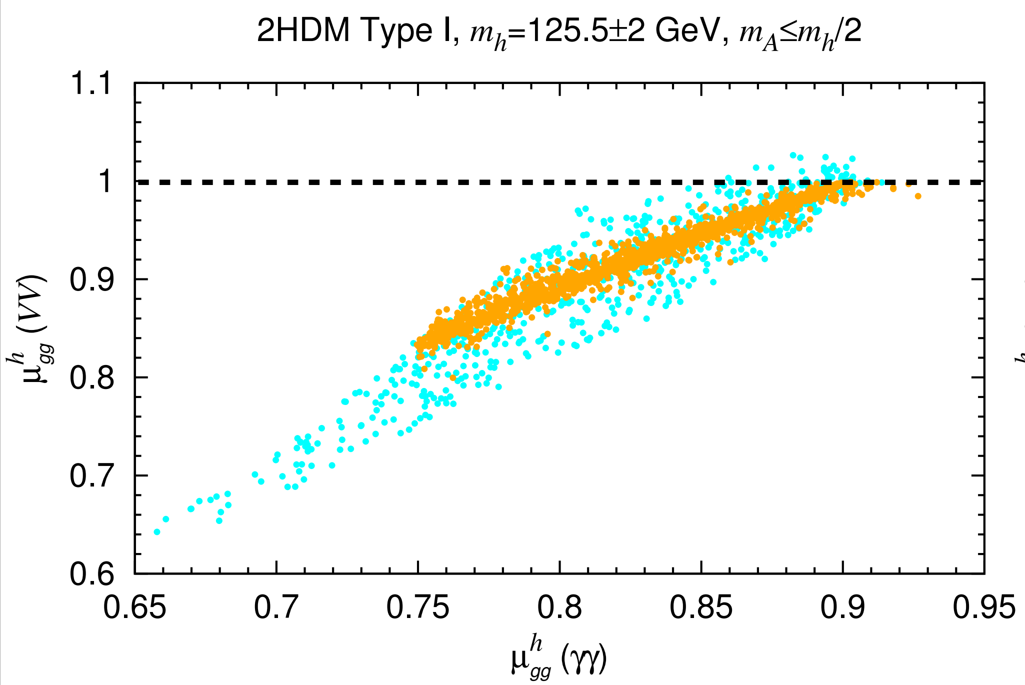
→ **Blue points**

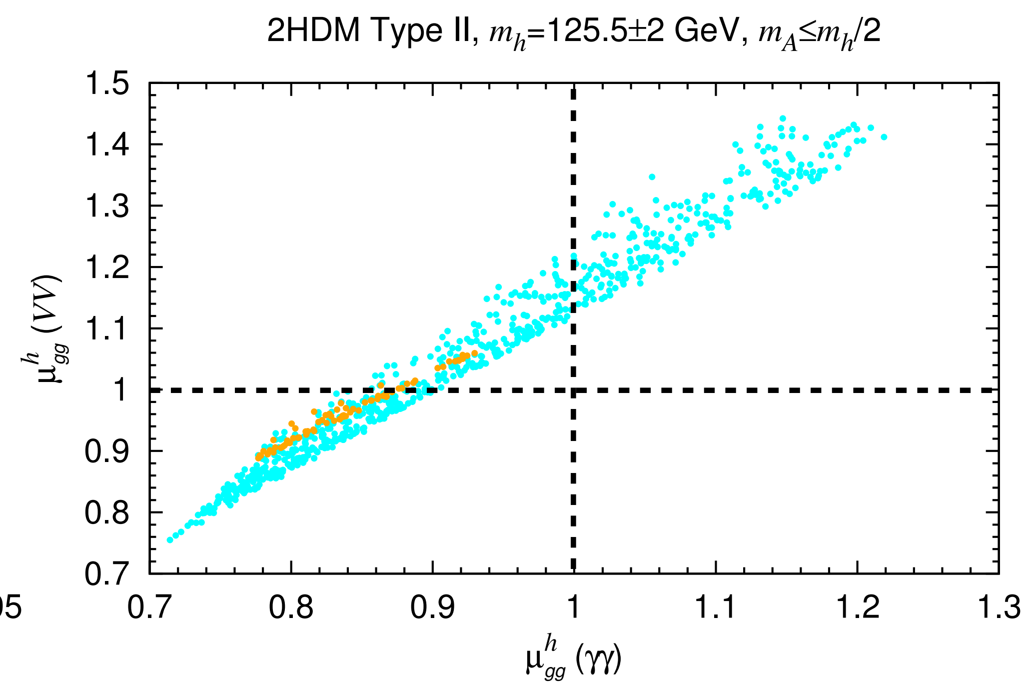
- Away from the SM-limit, a region with $\sin(\beta+\alpha)\sim 1$, larger $m_{12}$ and $\tan\beta$ also leads to small hAA coupling → **Orange points**

# Parameters overview: hl25



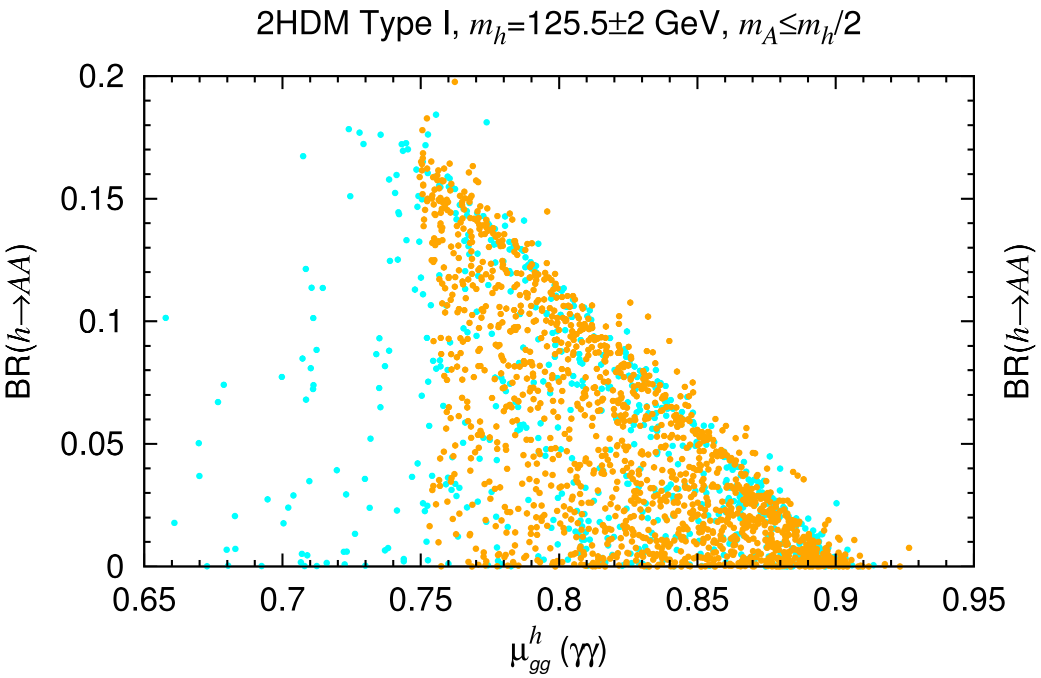
# Signal strengths: h125

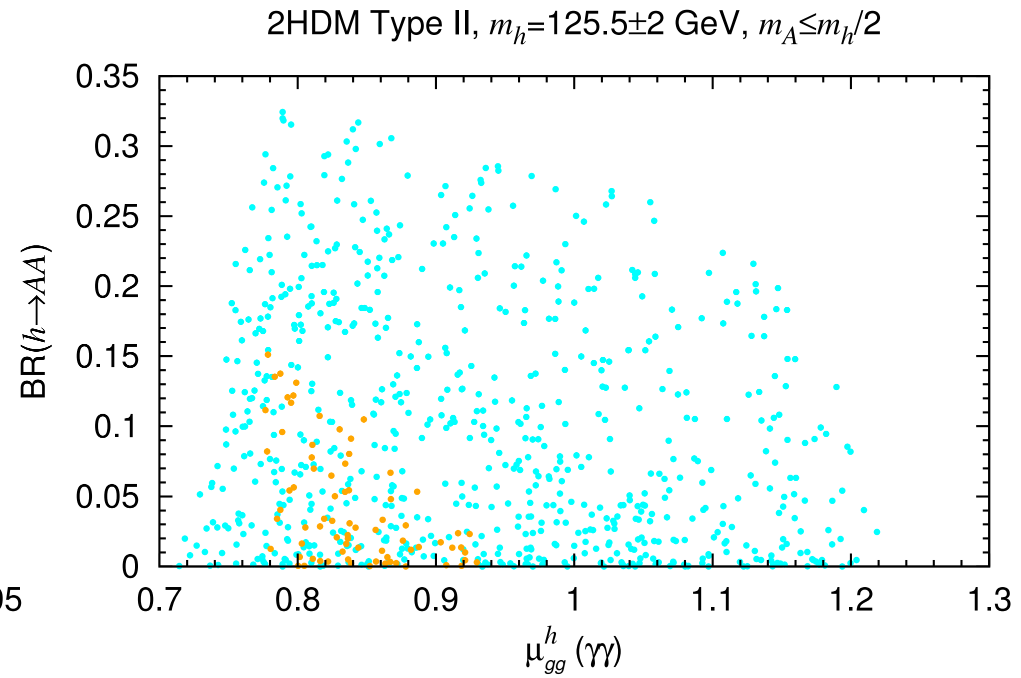



Except for blue points in Type II scenario: μ(gg,$\gamma\gamma$) <1

Impossible to achieve SM μ(gg,VV) and μ(gg,$\gamma\gamma$) simultaneously

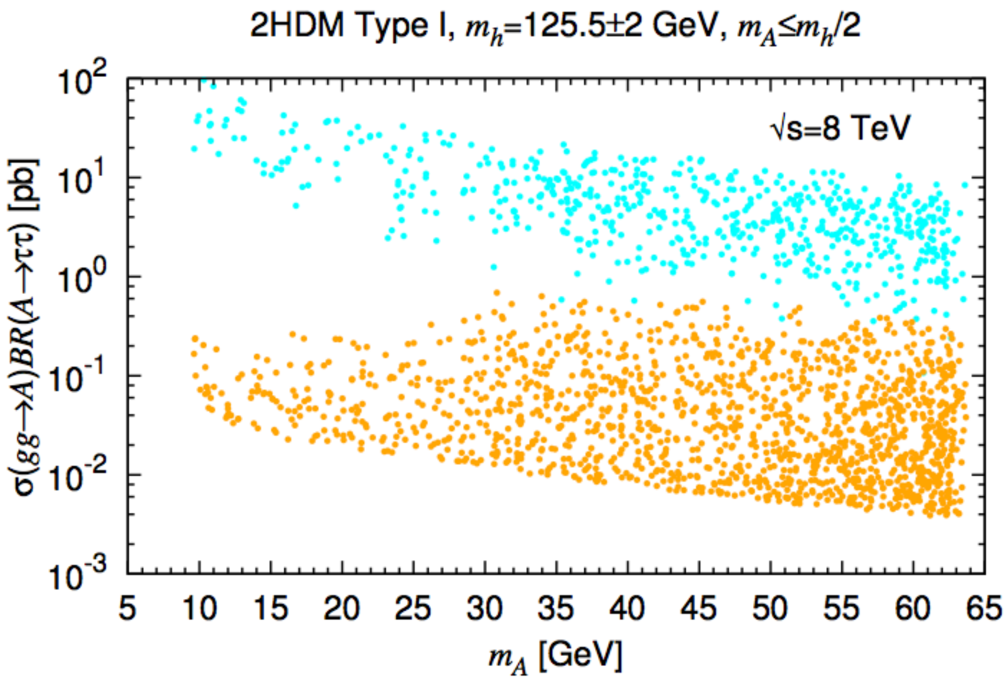


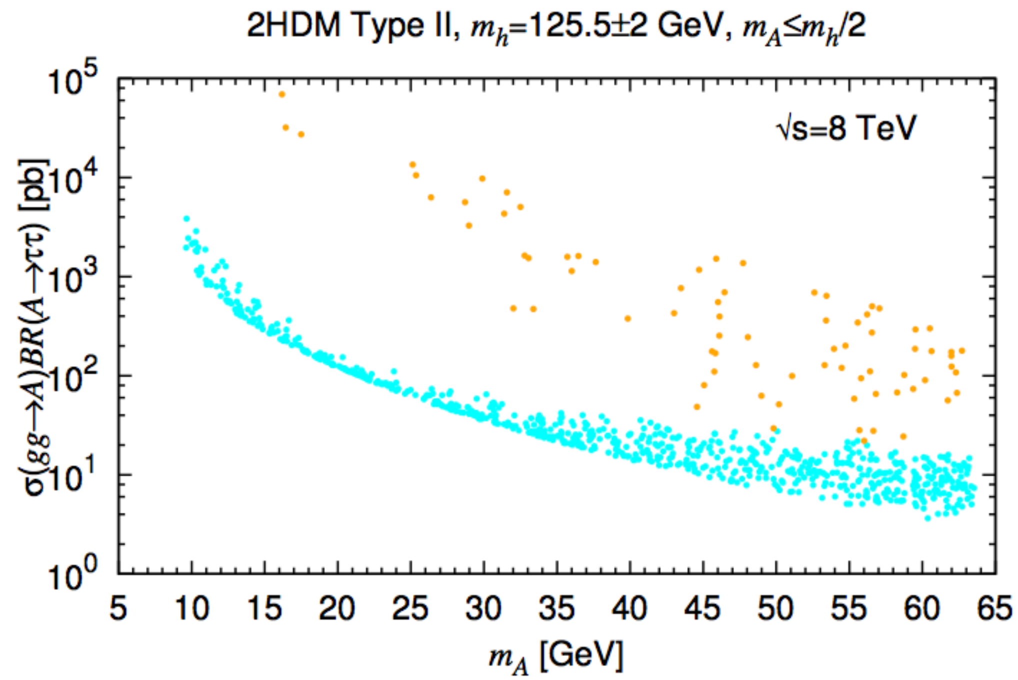




μ(gg,$\gamma\gamma$)~1 and sizable h→AA observed: strong preference for Type II and $C_D$<0 excluded

# Cross sections: h125

$gg \to A \to \tau\tau$

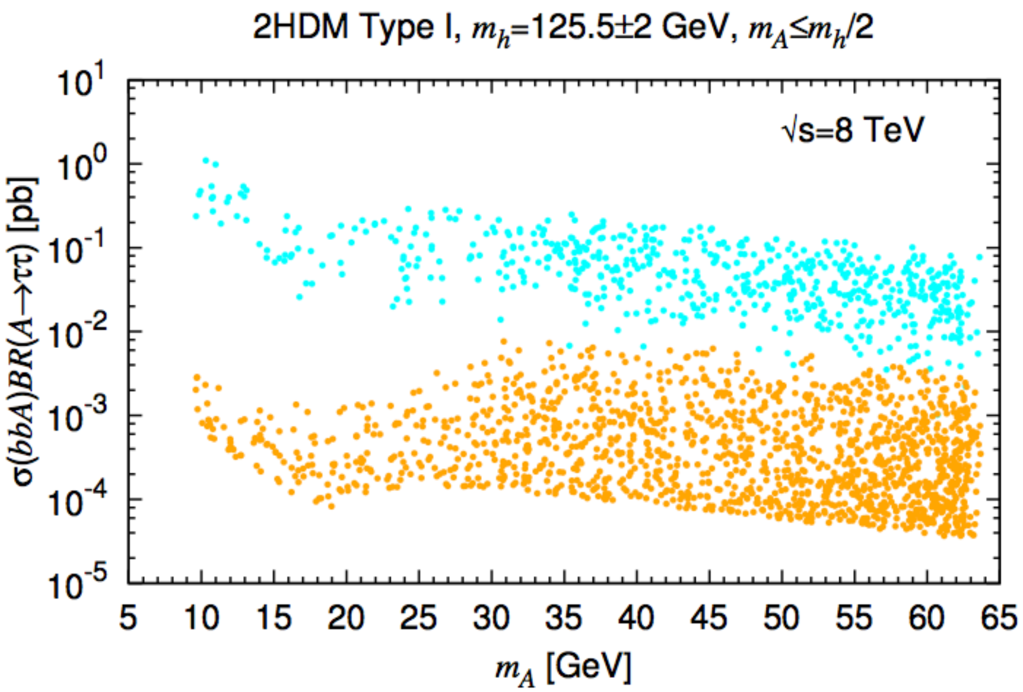


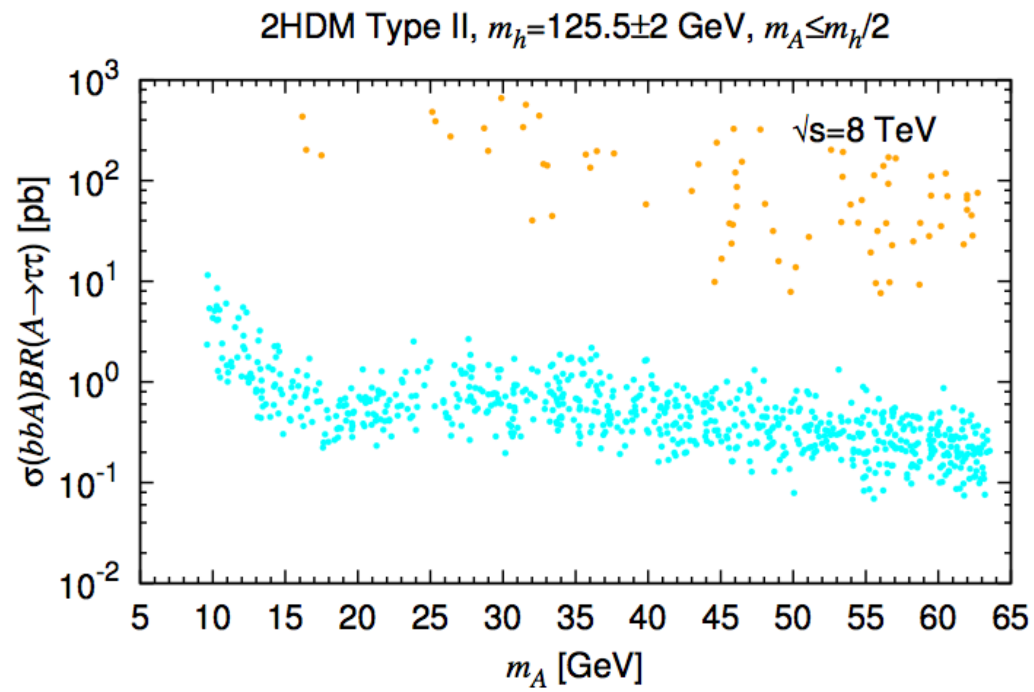




Generally very large cross sections over the full mass range

O(10 pb) should be observable in the current dataset

$b\bar{b}A,\, A \to \tau\tau$




A→μμ: same shape, factor 100 smaller

At 14 TeV: gain of factor~2 in σ

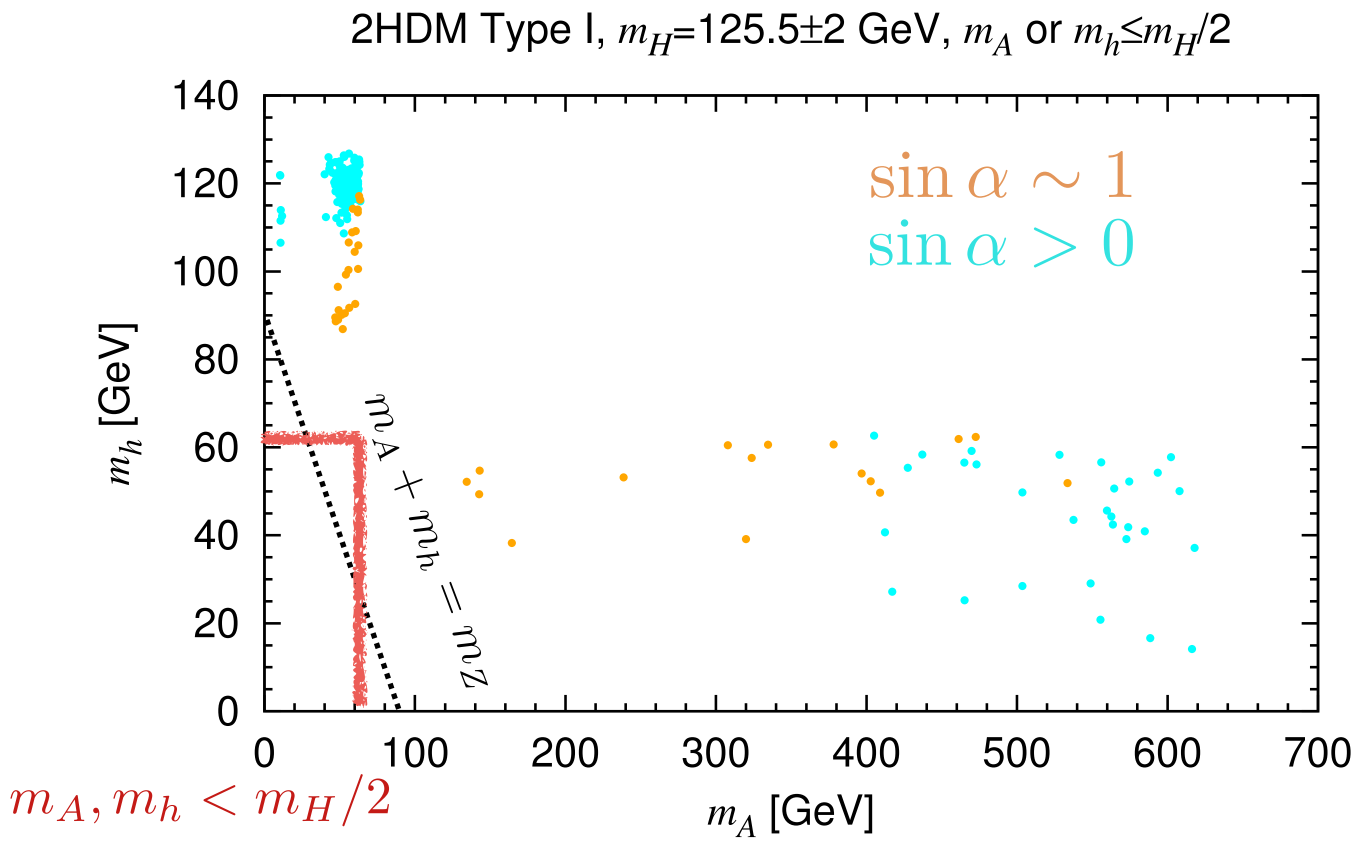
# H125 scenarios

Setup

Results

# Light states in H125 scenarios

- **Type I**: **Both** A and h can be lighter than $m_H/2$ but **not simultaneously**




Both the HVV and ZhA vertices are proportional to $\cos(\beta - \alpha)$ which is close to maximal by virtue of H being SM-like

LEP limits on $e^+e^- \to Z^* \to Ah$ are evaded via kinematic suppression of the cross section

**$m_A<m_H/2$: red points**

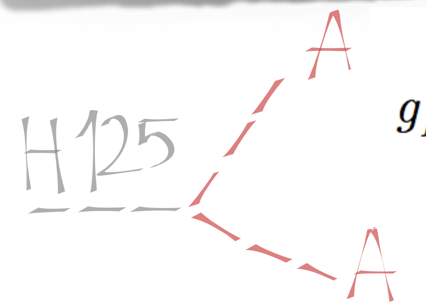
**$m_h<m_H/2$: blue points**

- **Type II**: B-physics + STU constraints: $m_{H^\pm} \gtrsim 300\ \mathrm{GeV} \Rightarrow m_A \gtrsim 200\ \mathrm{GeV}$

$\Longrightarrow$ only h can be light

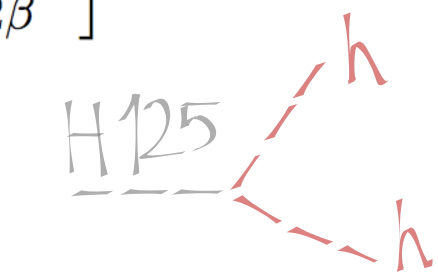
**$m_h<m_H/2$: blue points**

# HAA and Hhh tri-Higgs couplings

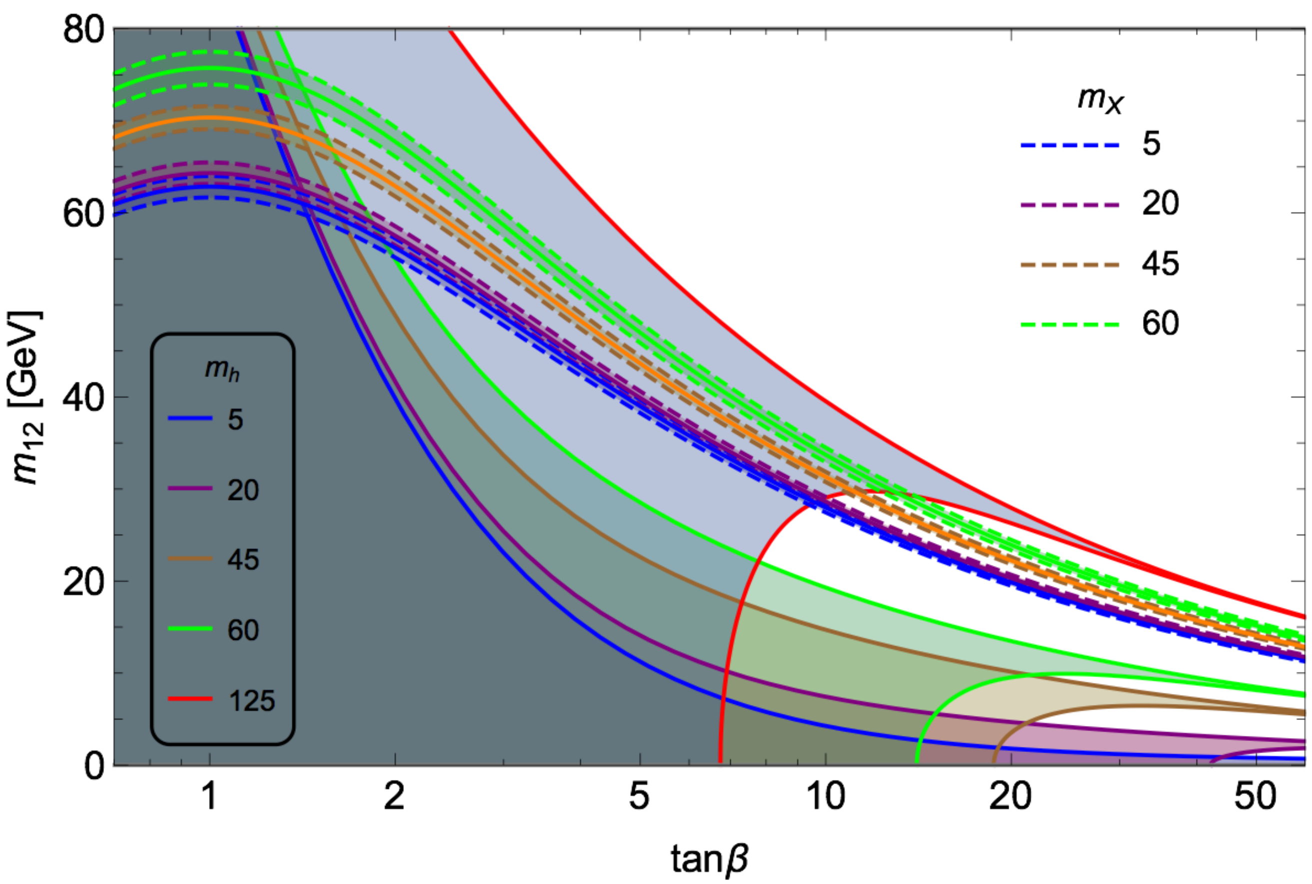



$$g_{HAA} = \frac{1}{2v}\left[(2m_A^2 - m_H^2)\frac{\sin(\alpha-3\beta)}{\sin 2\beta} + \left(8m_{12}^2 - \sin 2\beta\,(2m_A^2+3m_H^2)\right)\frac{\sin(\beta+\alpha)}{\sin^2 2\beta}\right]$$

$$g_{Hhh} = -\frac{1}{v}\cos(\beta-\alpha)\left[\frac{2m_{12}^2}{\sin 2\beta} + \left(2m_h^2+m_H^2-\frac{6m_{12}^2}{\sin 2\beta}\right)\frac{\sin 2\alpha}{\sin 2\beta}\right]$$




- In the SM-limit $\cos(\beta-\alpha)=1$ :




$$g_{HXX} = -\frac{2m_X^2 + m_H^2 - 2m_{12}^2 \sec\beta\csc\beta}{v}$$

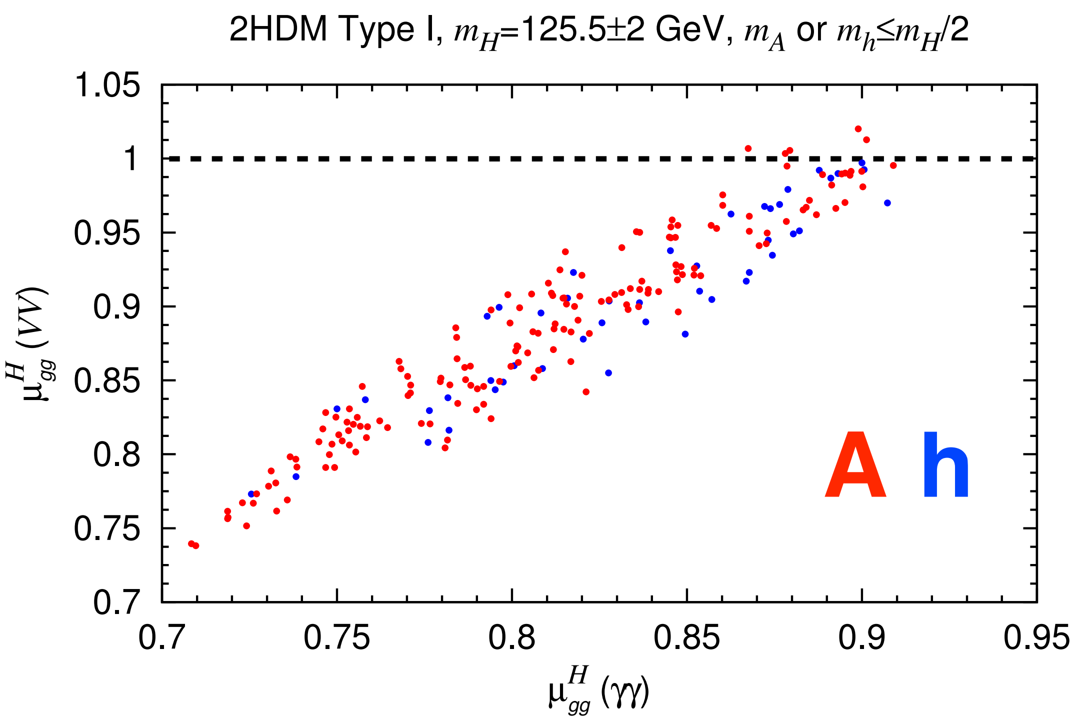
Perturbativity+small HXX coupling:

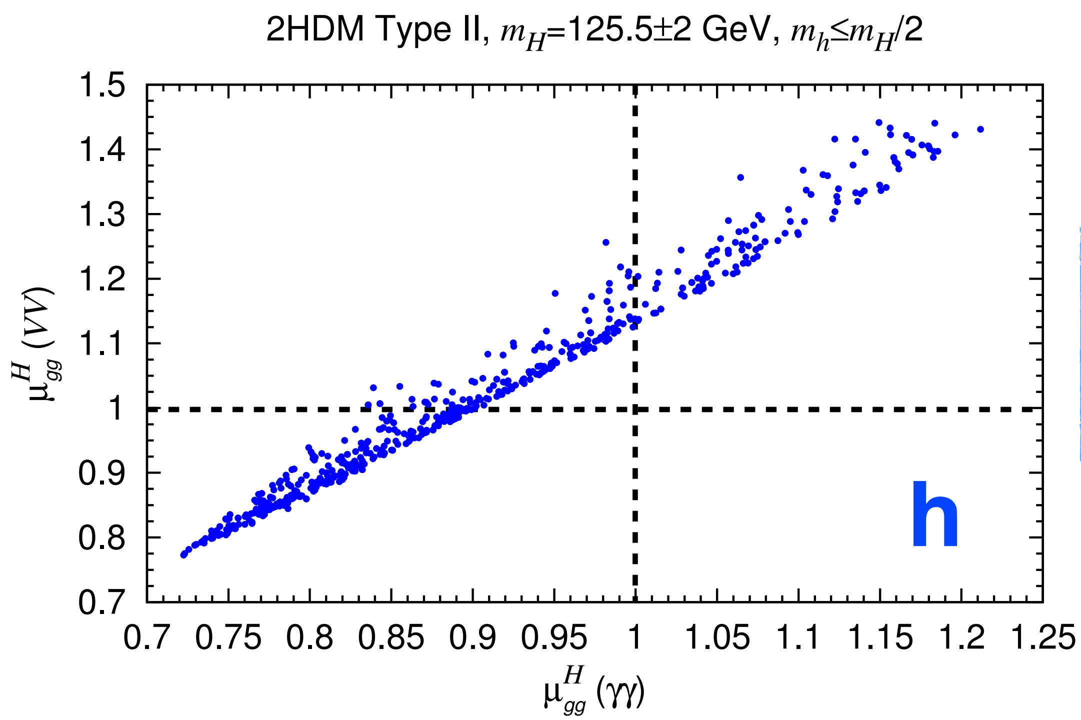
- $m_h<60$ GeV : $t_\beta \lesssim 2$
- $m_h<125$ GeV : $t_\beta \lesssim 12$

Moderate $m_{12}$

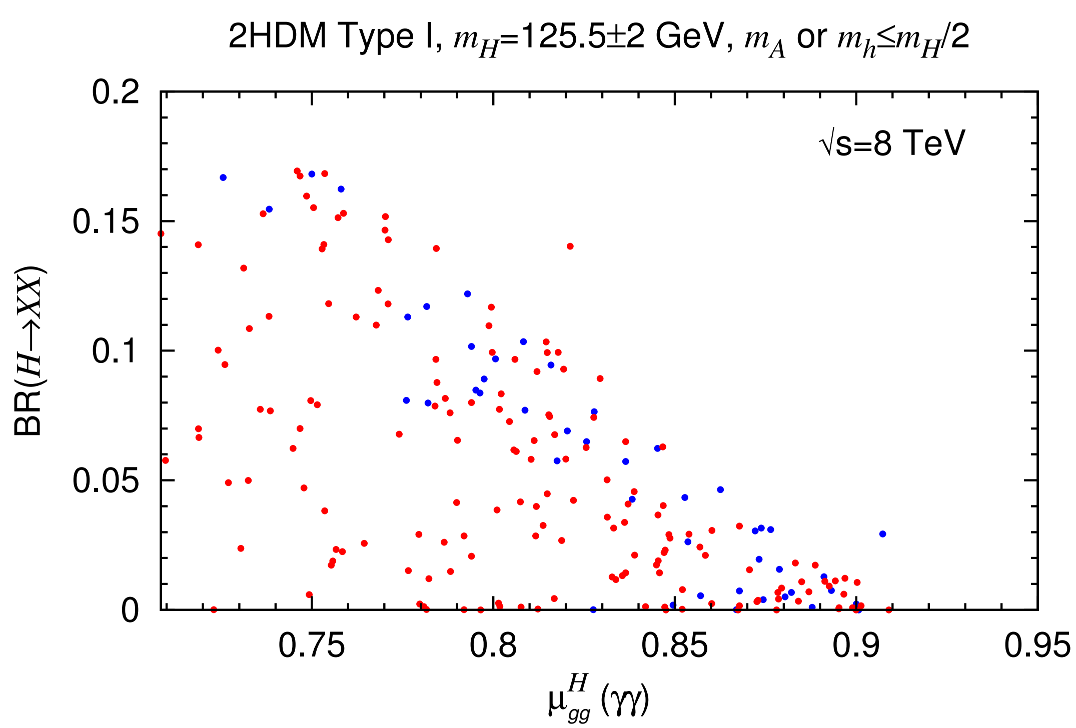
- Away from the SM-limit, in a region with $\cos(\beta+\alpha)\sim 1$ larger $t_\beta$ can be achieved, at small $m_{12}$

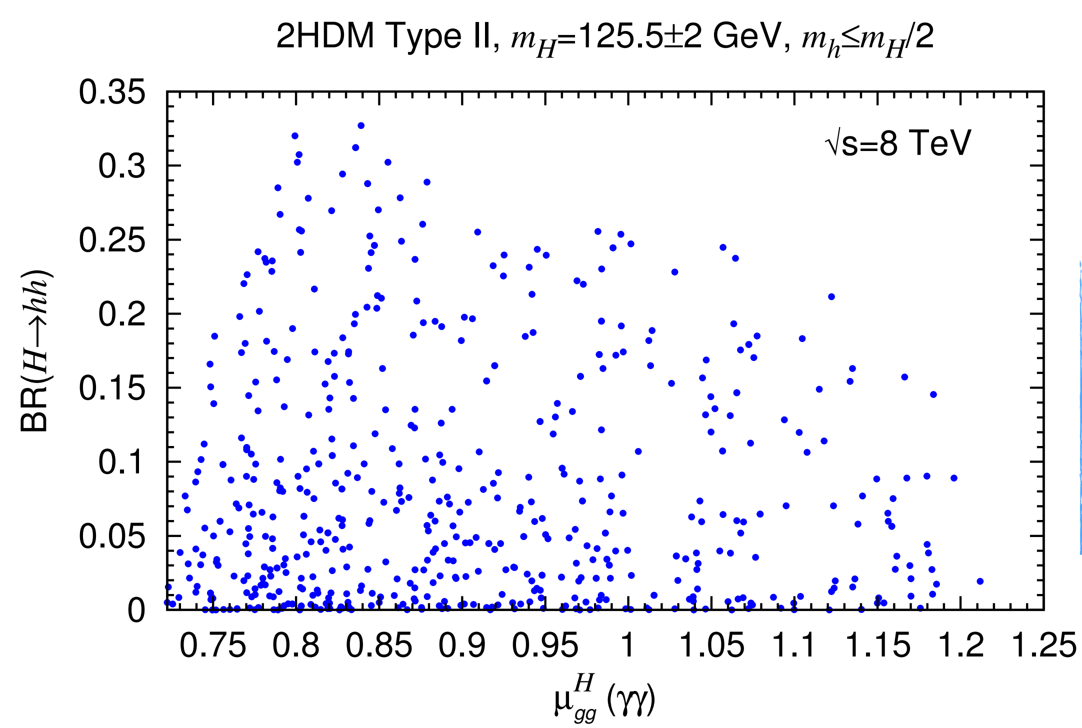
# Signal strengths: H125




Impossible to achieve SM μ(gg,VV), μ(gg,$\gamma\gamma$) simultaneously



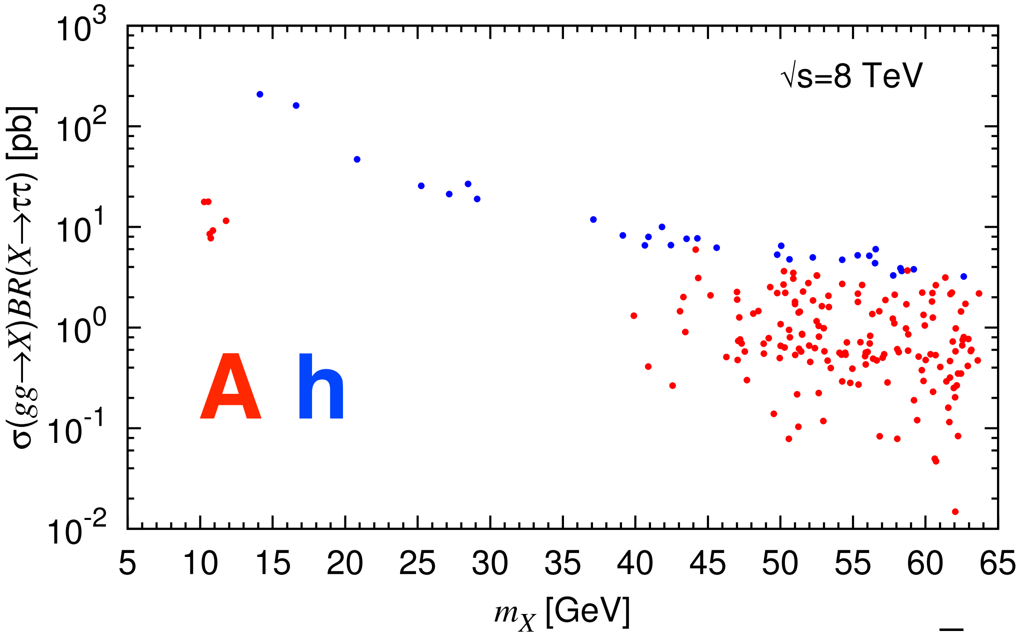




μ(gg,$\gamma\gamma$)~1 and sizable H→hh observed: strong preference for Type II

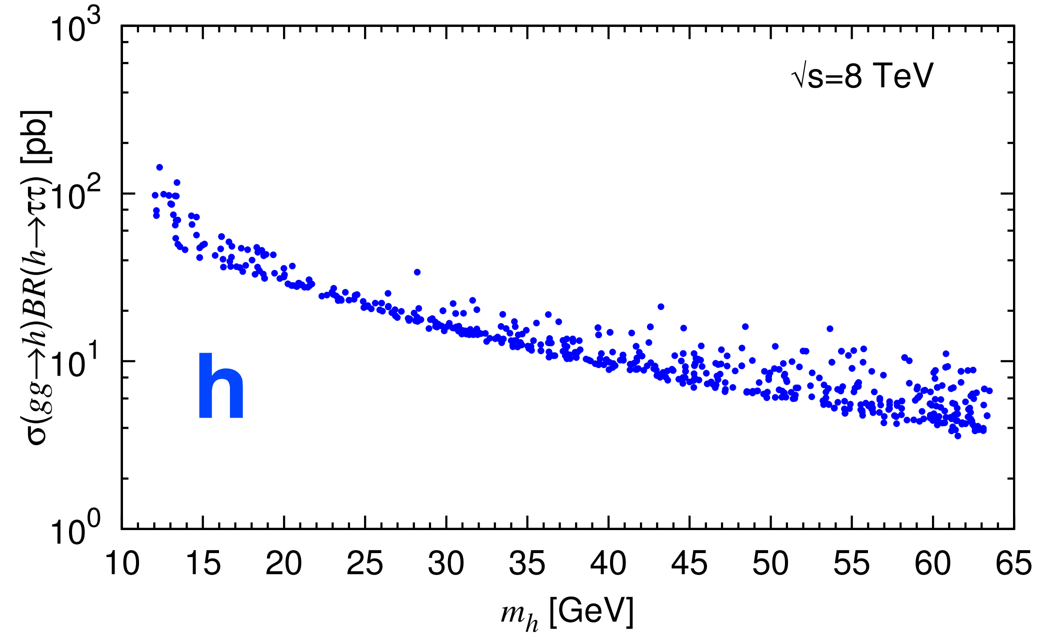
# Cross sections: H125

$gg \to A \to \tau\tau$

2HDM Type I, $m_H$=125.5±2 GeV, $m_A$ or $m_h \leq m_H/2$




2HDM Type II, $m_H$=125.5±2 GeV, $m_h \leq m_H/2$

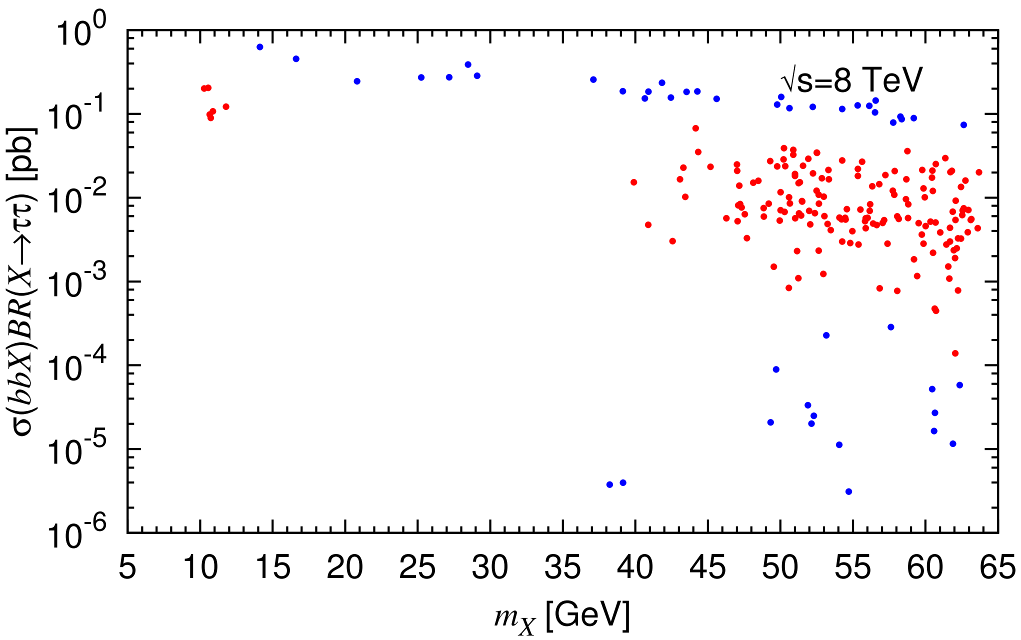



σ(ggh, h→$\tau\tau$) ≳ 10pb over the full mass range

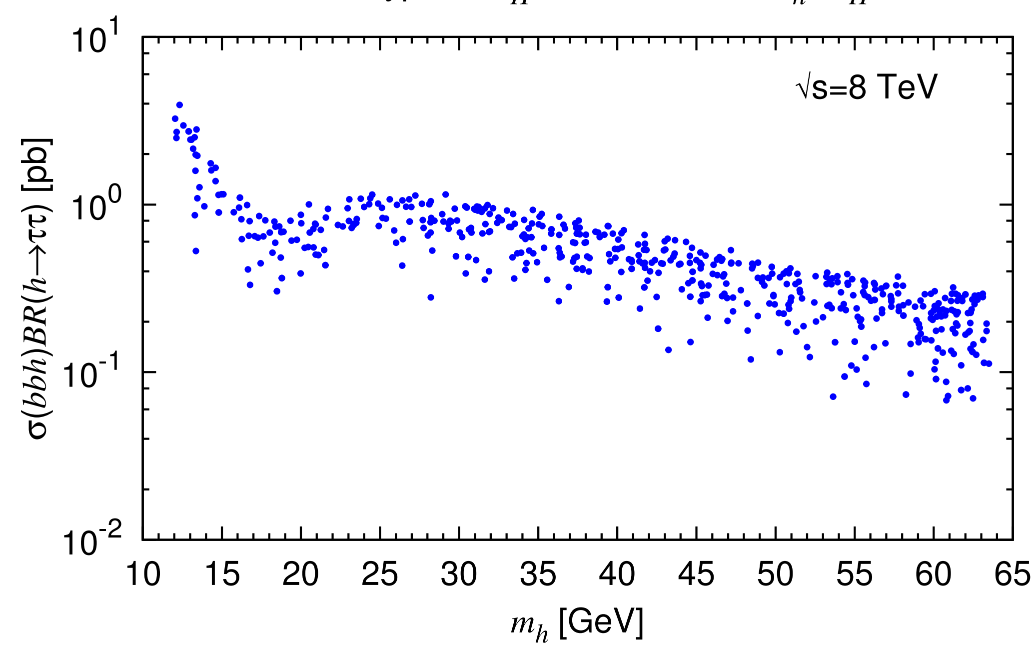
Only very light pseudo-scalars have σ(ggA, A→$\tau\tau$) ≳ 10pb

$b\bar{b}A, A \to \tau\tau$

2HDM Type I, $m_H$=125.5±2 GeV, $m_A$ or $m_h \leq m_H/2$




2HDM Type II, $m_H$=125.5±2 GeV, $m_h \leq m_H/2$




Type II: $t_\beta$≲2, no enhancement of the hbb cross-section

# Conclusions

# Conclusions

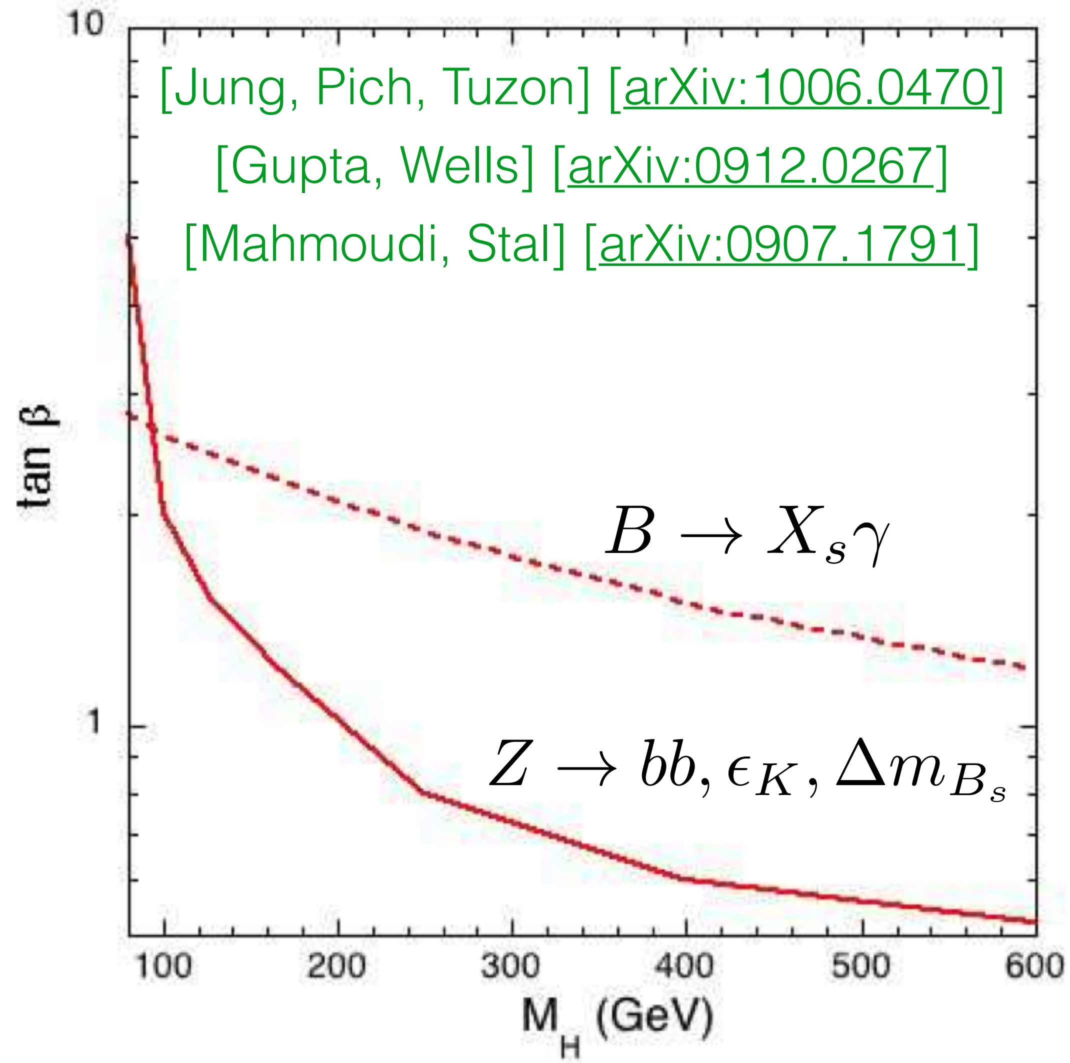
- In the context of the 2HDM of Type I and Type II, the presence of **light Higgs states** is still a possibility in both the **h125** and **H125 scenarios**
- Precise measurements of signal strengths during LHC Run II could largely test these scenarios
- Should the $\gamma\gamma$ and VV rates converge to the SM value within **~10% or better**, these scenarios would be **excluded**
- **Large cross sections** in the gluon fusion and bb associated production modes are generally possible
- Looking for these light states in the $\tau\tau$ **and μμ channels** in the existing **LHC Run I dataset** could already be a **crucial test** of these scenarios

# Backup

# Constraints

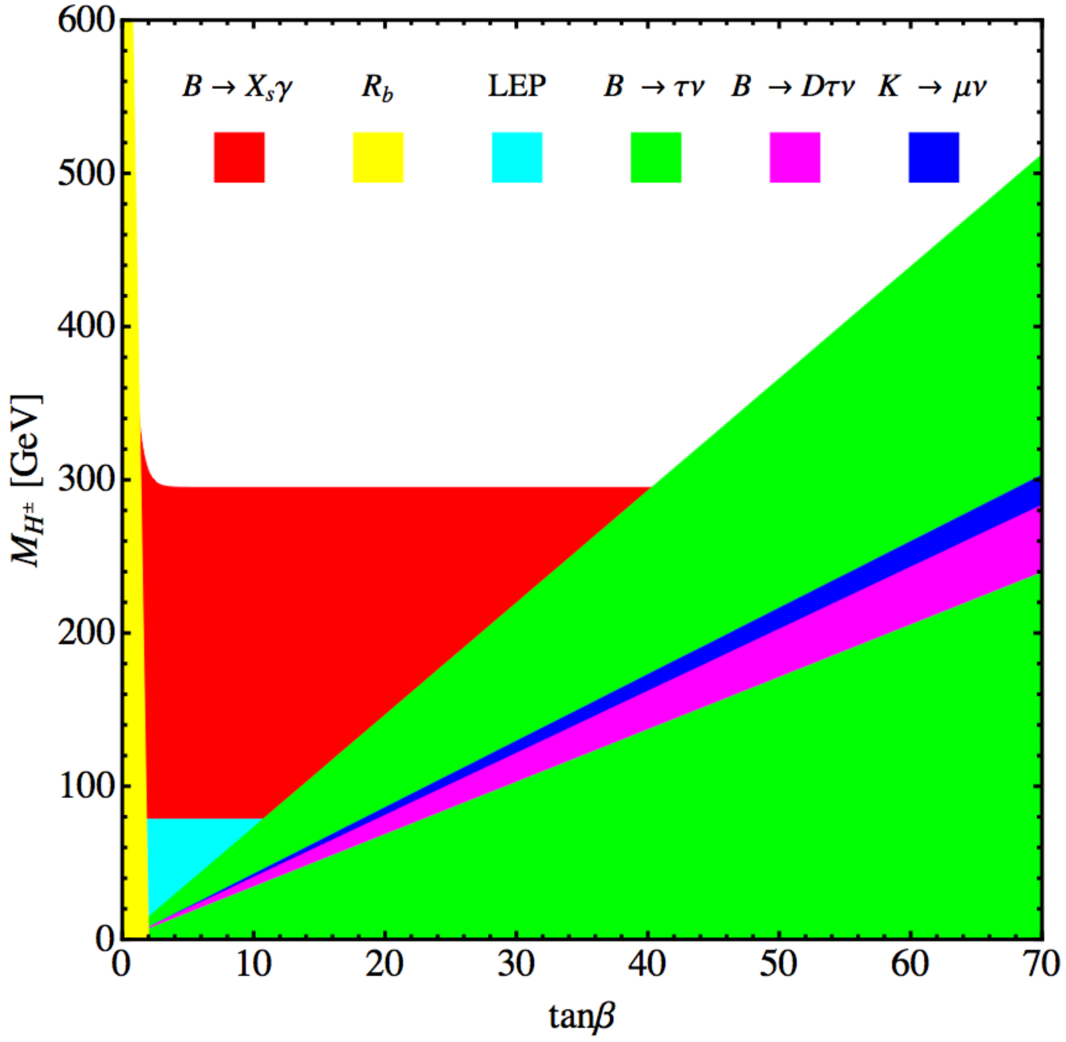
# B-physics constraints

## Type I




## Type II

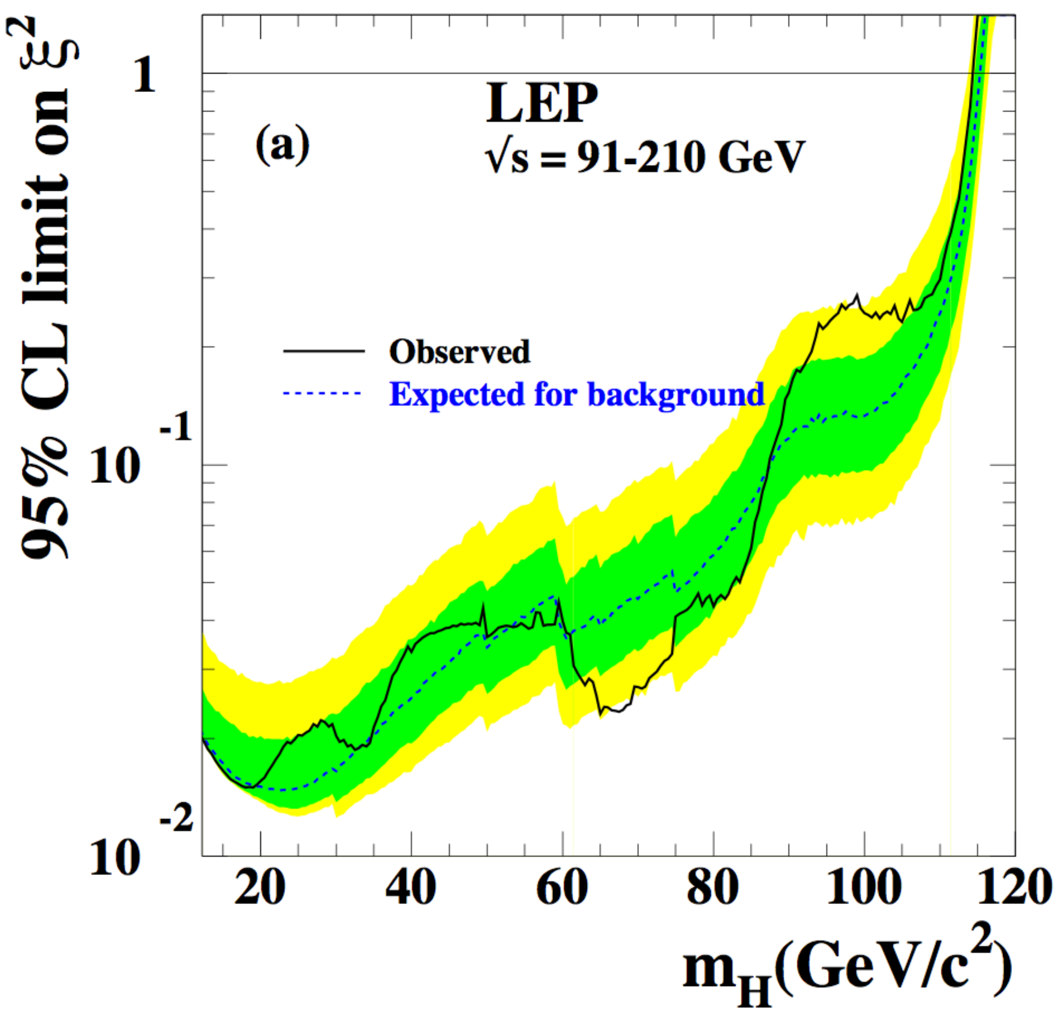
[Haish] [arXiv:0805.2141]



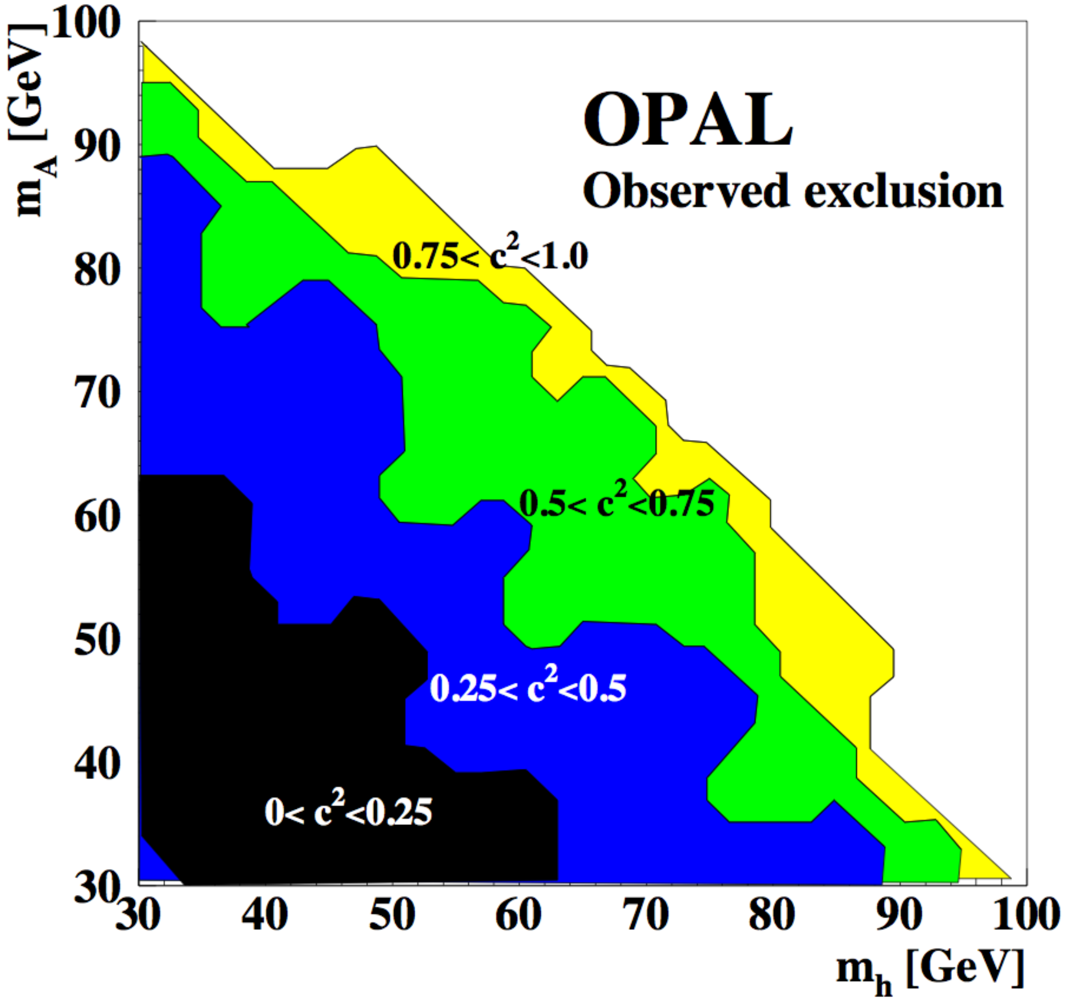

Lower bound on charged Higgs mass

# LEP constraints

$e^+e^- \to Zh$

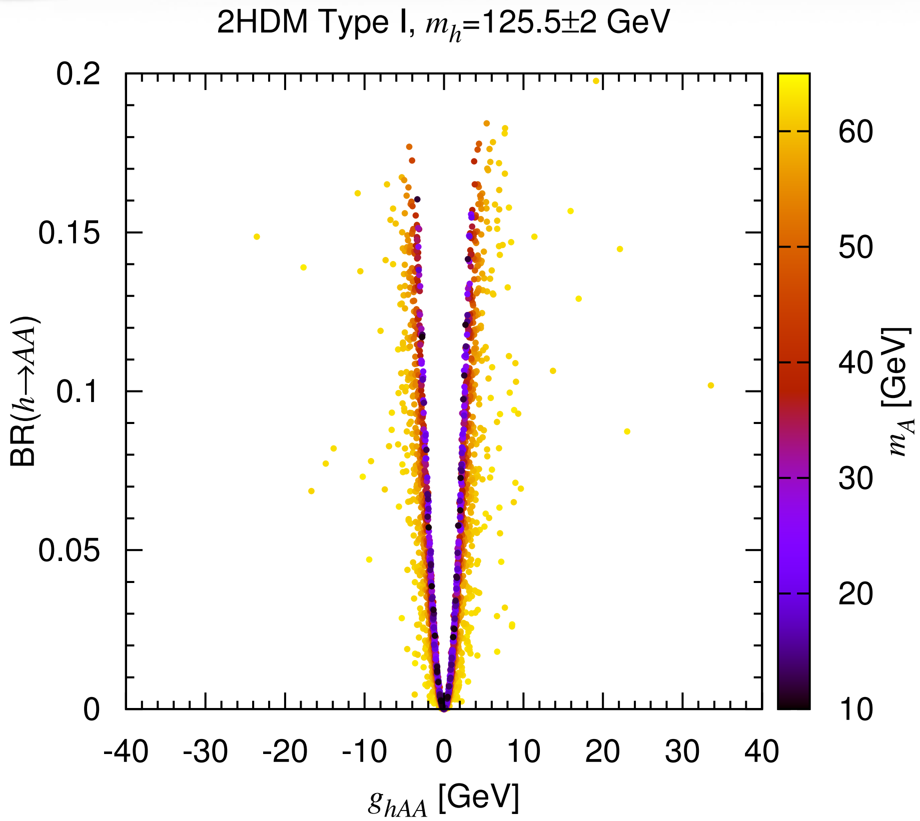


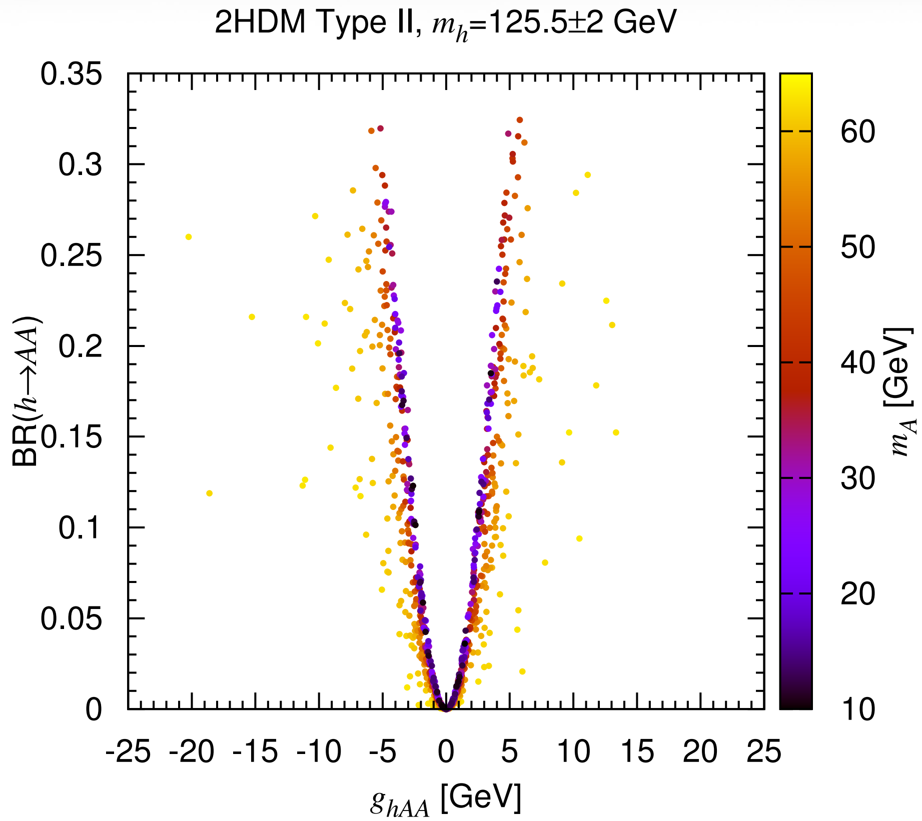

$e^+e^- \to Z^* \to Ah$



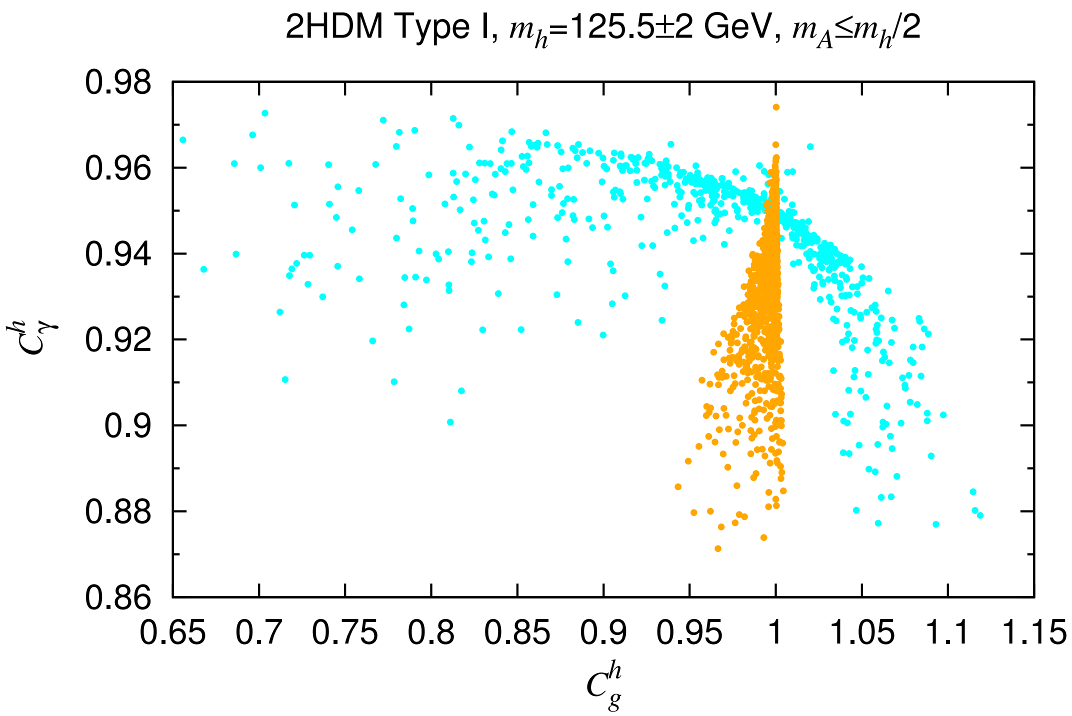
# h125 scenarios

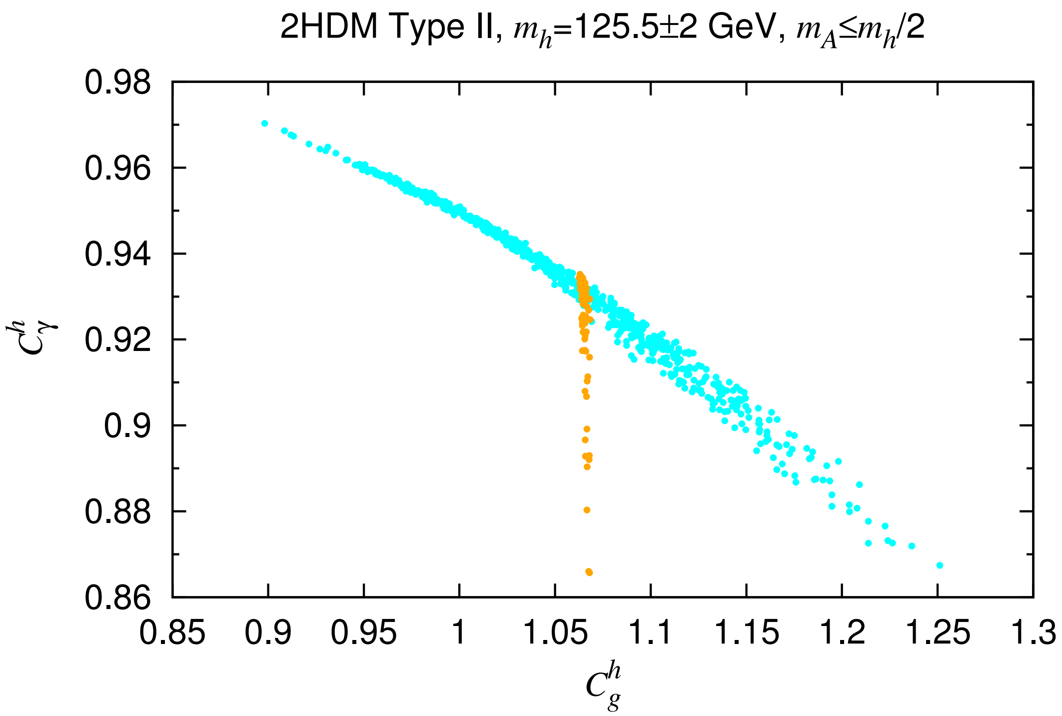
# Couplings




Strong constraint from undetected branching ratio

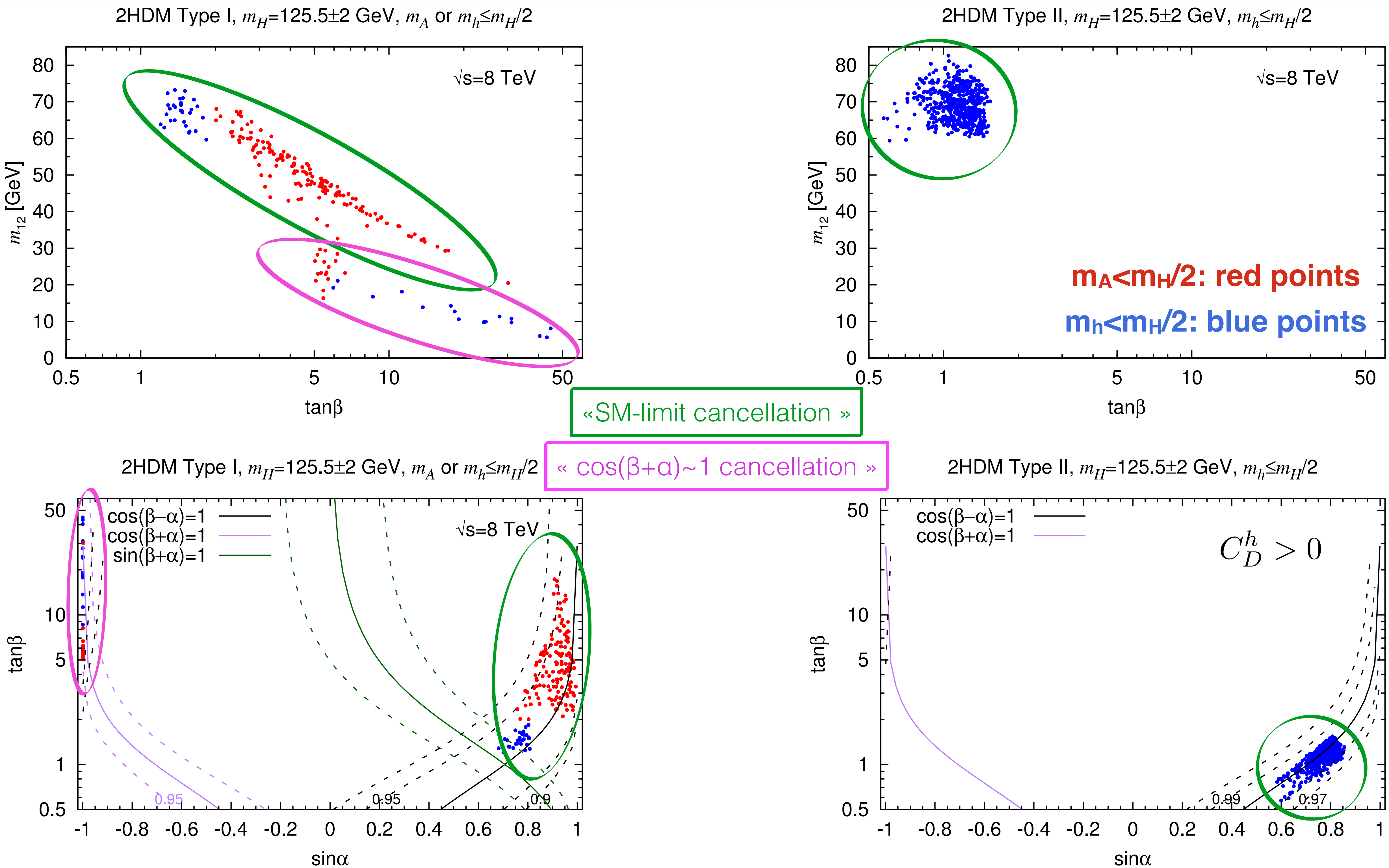



Suppressed $C_\gamma$ coupling: charged Higgs contribution

# H125 scenarios

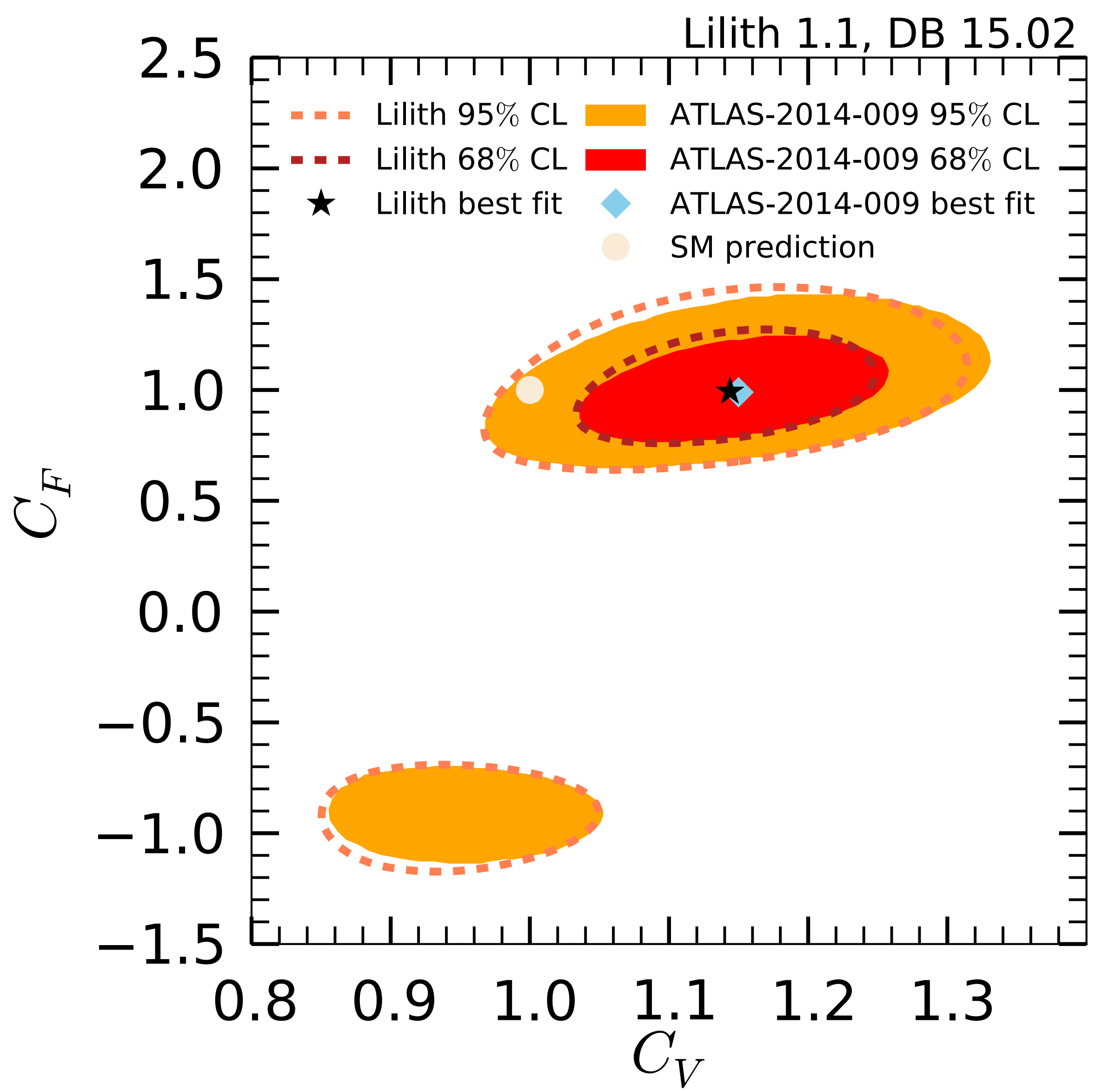
# Parameters overview: H125



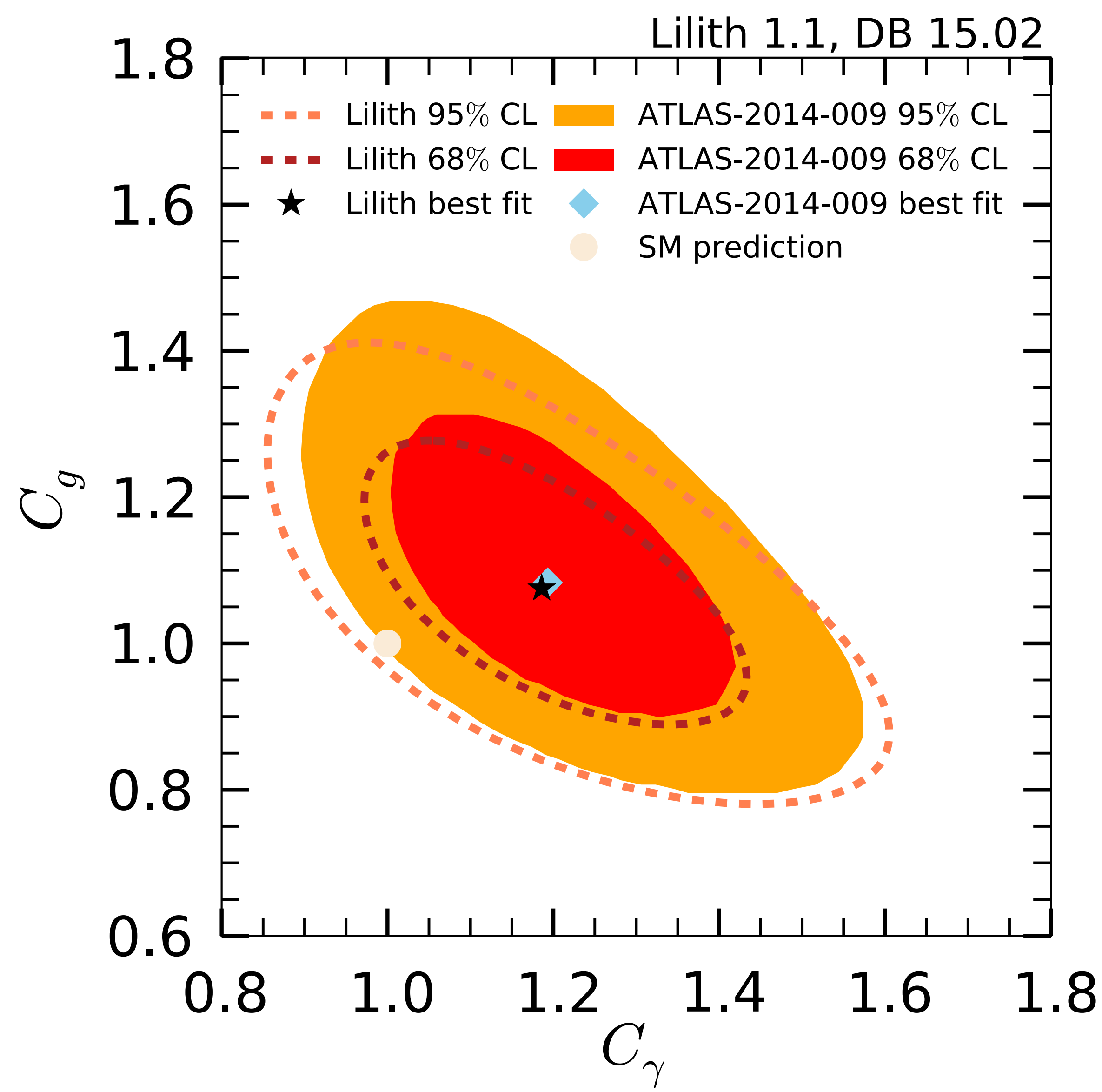
# Lilith

# Validation of the Lilith likelihood against ATLAS results

- Trying to reproduce the official ATLAS and CMS coupling fits (profile likelihood ratio to derive the confidence intervals)



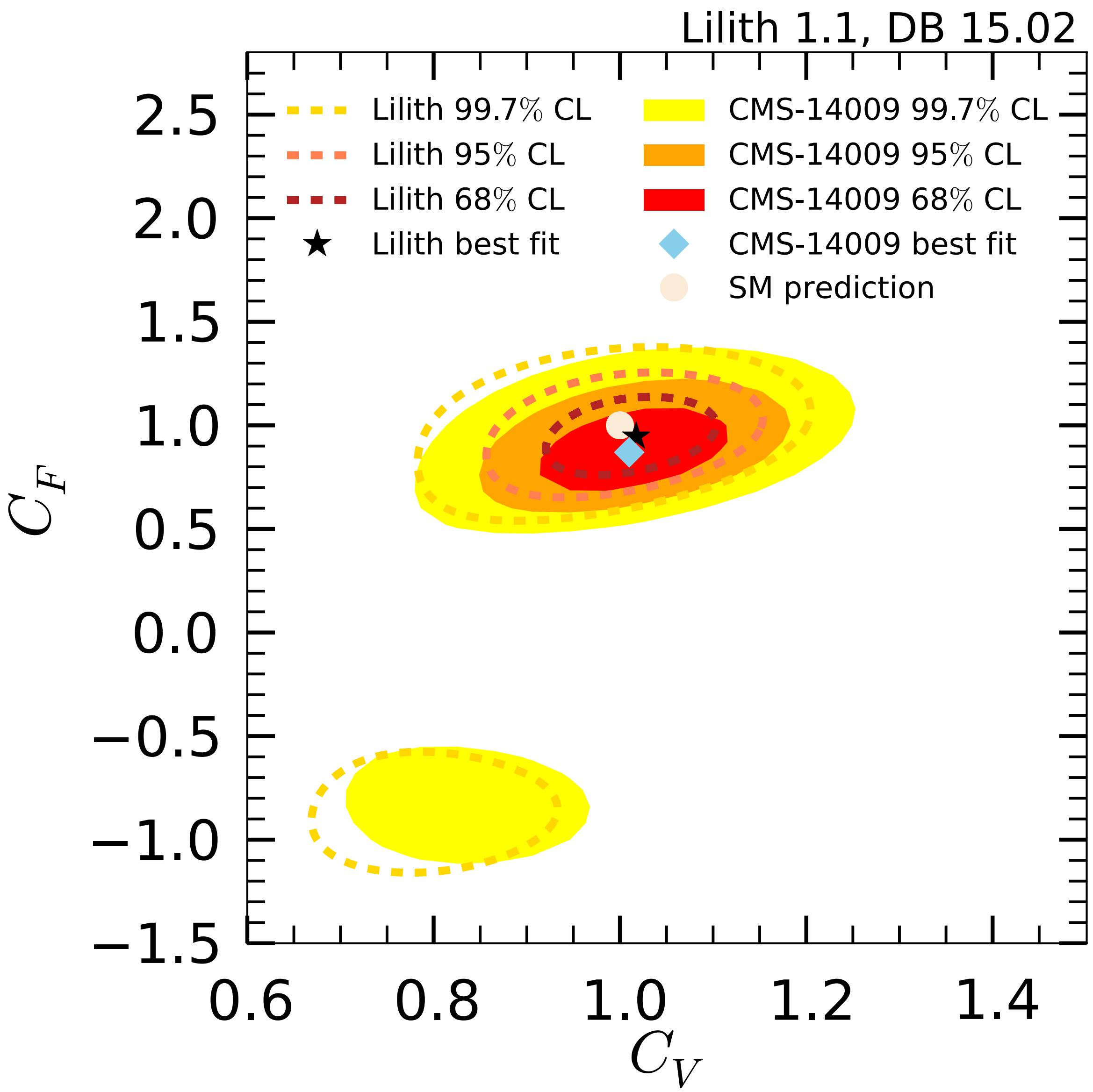

$(C_V, C_F)$ benchmark scenario



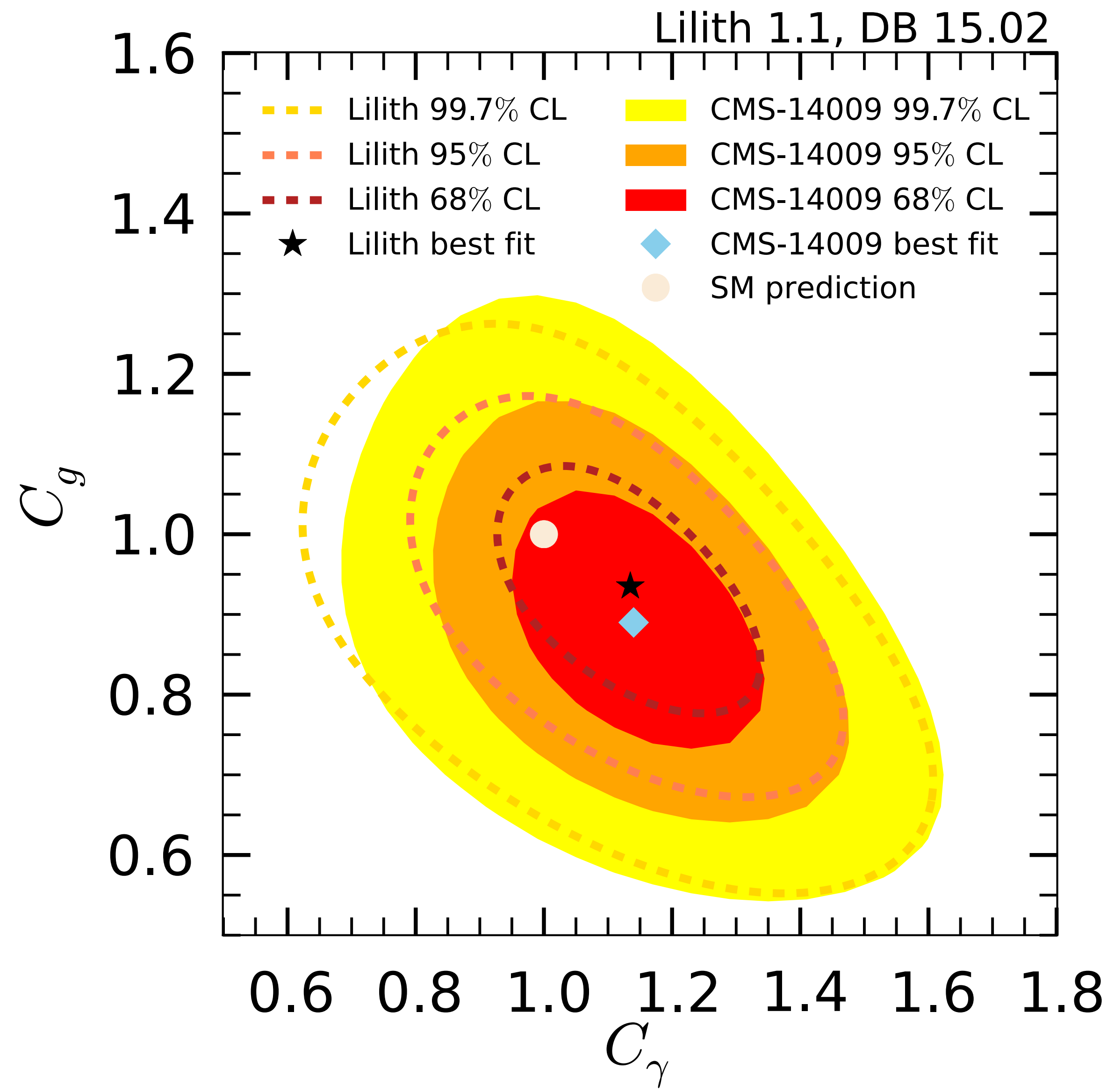

$(C_\gamma, C_g)$ benchmark scenario

# Validation of the Lilith likelihood against CMS results

- Trying to reproduce the official ATLAS and CMS coupling fits (profile likelihood ratio to derive the confidence intervals)




$(C_V, C_F)$ benchmark scenario




$(C_\gamma, C_g)$ benchmark scenario