Double Higgs production in a singlet-extended Higgs model

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based on work done in collaboration with
V. Martin Lozano and C. B. Park
arXiv:1306:xxxx

Planck 2013, Bonn May 2013

Outline

- Introduction
- The singlet extension. Constraints
  - LHC bounds
  - Indirect bounds
- The $H \to hh$ decay
  - Channel and signatures
  - Kinematic variables & cuts
- A short coment on Dark Matter
- Conclusion

Introduction

Higgs era

- The discovery by ATLAS and CMS of a new scalar boson at the LHC opens a new era in particle physics
- Since there are several Higgs production modes (gF, VBF, associated WH and ZH, and associated ttH) and five of its decay modes have been measured it is already possible to extract its couplings and compare with SM predictions.

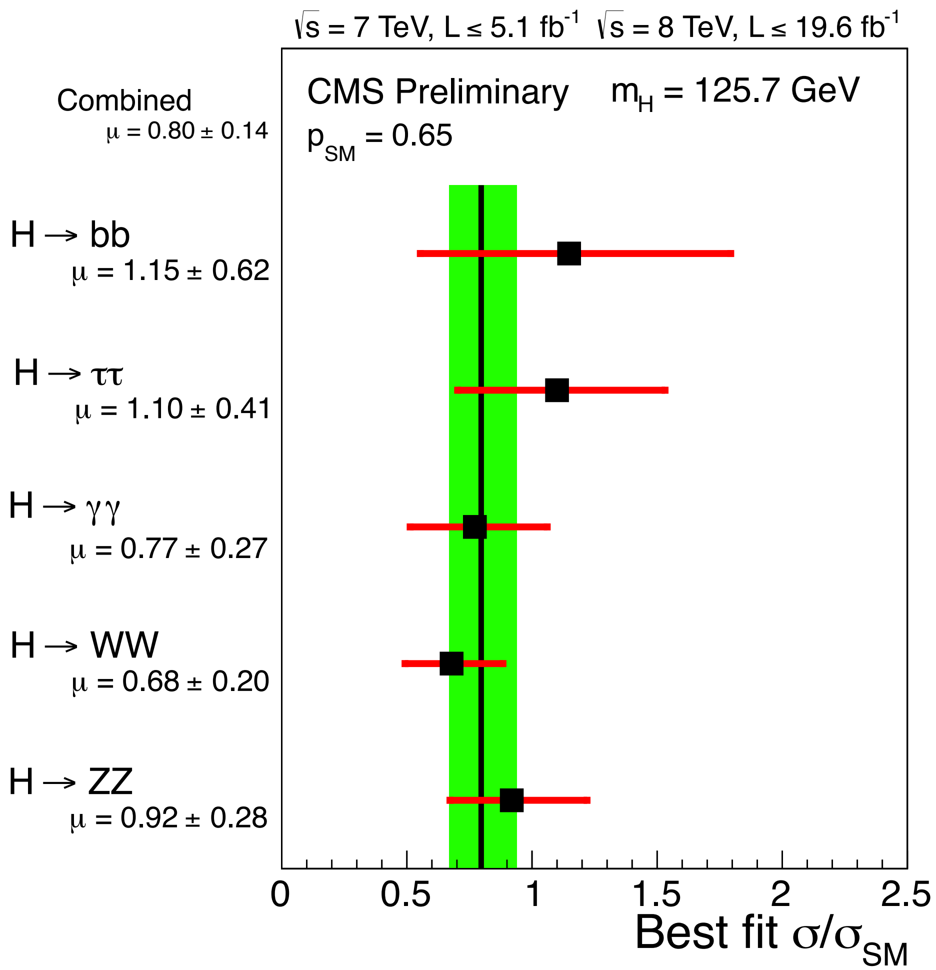
Decay Mode	ATLAS (M_H = 125.5 GeV)	CMS (M_H = 125.7 GeV)
$H \to bb$	-0.4 ± 1.0	1.15 ± 0.62
$H \to \tau\tau$	0.8 ± 0.7	1.10 ± 0.41
$H \to \gamma\gamma$	1.6 ± 0.3	0.77 ± 0.27
$H \to WW^*$	1.0 ± 0.3	0.68 ± 0.20
$H \to ZZ^*$	1.5 ± 0.3	0.92 ± 0.28
Combined	**1.30 ± 0.20**	**0.80 ± 0.14**

(also Tevatron)

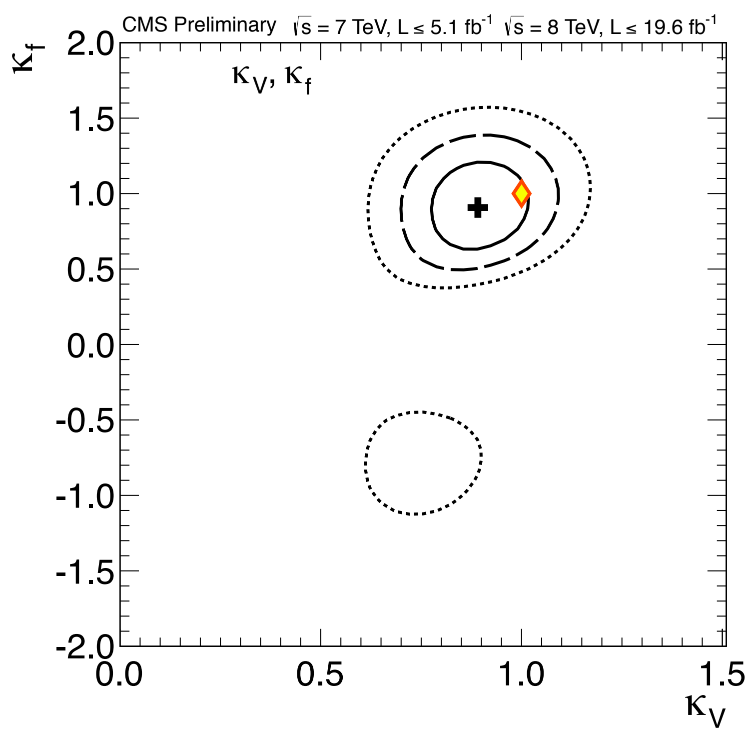
Signal strength

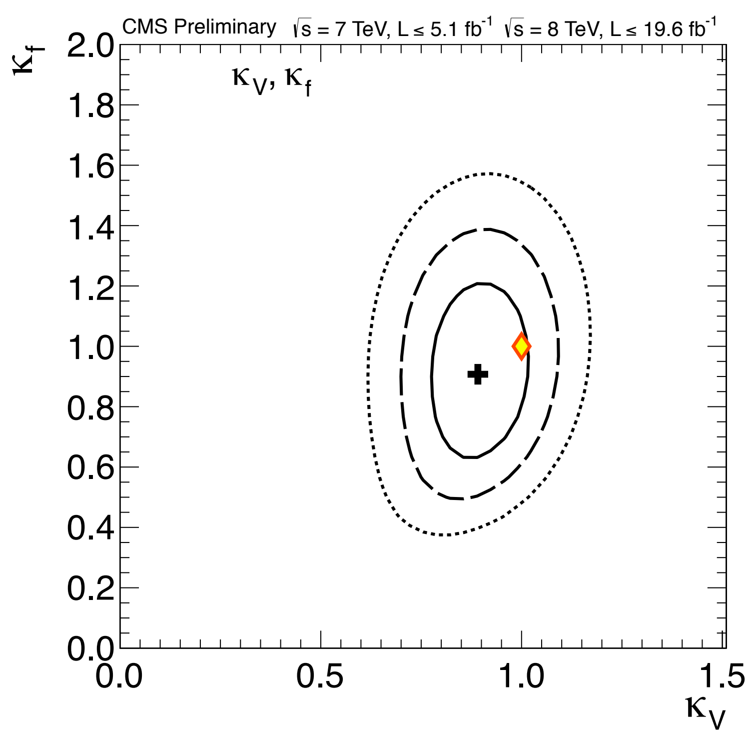
Introduction

Example: CMS analysis



CMS PAS HIG-13-005





- SM predictions inside 1-1.5σ region of the measured values ⇒ limits on
  - Invisible width
  - Extended Higgs sectors
  - Partially composite Higgs models
  - ... new particles (hϒϒ)

Introduction

In this talk:

- We will consider the **SM + 1 real Singlet model**
- h-H mixing ⇒ decreasing of SM Higgs couplings
- Same (indirect) effect than an invisible Higgs width
- Direct production at the LH?

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Related work: incomplete list of refs:

S. Baek, P. Ko, W. Park 2013
S. Baek, P. Ko, W. Park 2012
C. Englert, T. Plehn, M. Raugh, D. Zerwas, P.M. Zerwas 2012
C. Englert, T. Plehn, D. Zerwas, P.M. Zerwas 2011
M. Pruna, T. Robens 2013
M. Dolan, C. Englert, Spannowsky 2013

Introduction

Motivation

- Adding a singlet is the MINIMAL extension of the Higgs sector

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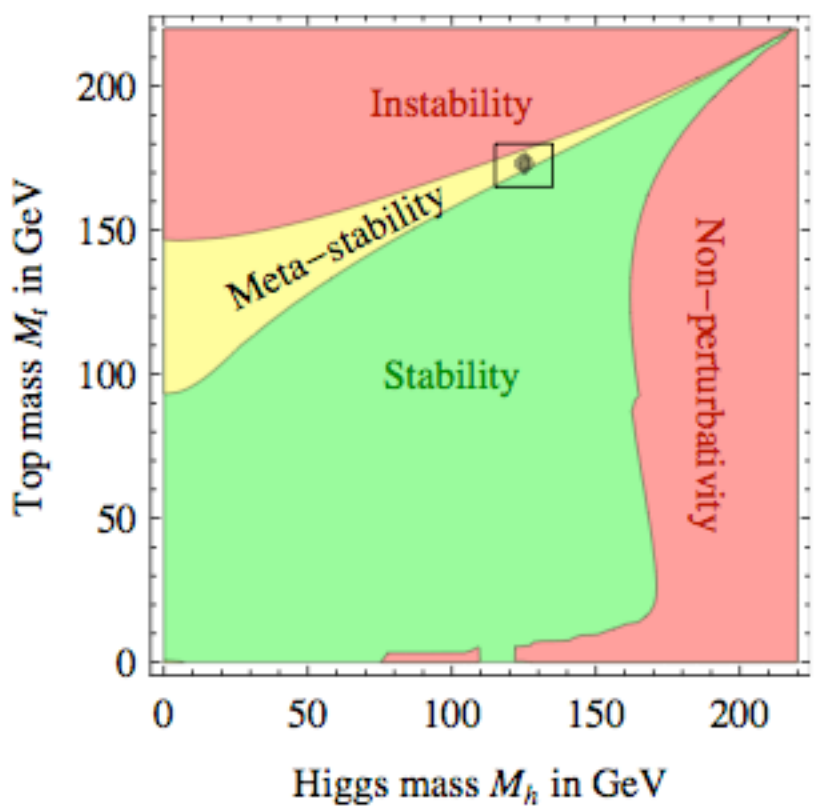
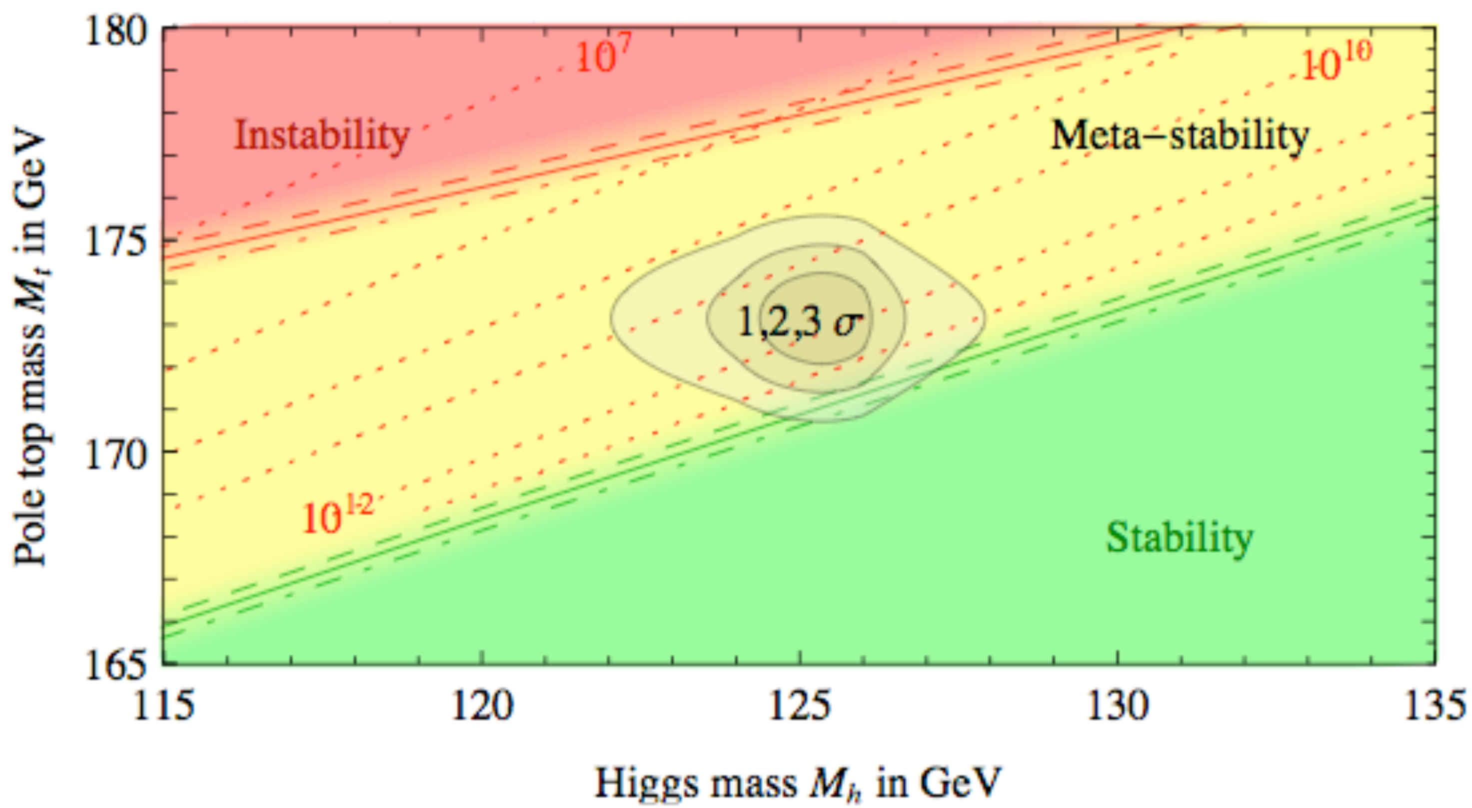
- Could help to stabilize the Higgs potential at high energy (~ M_{Planck})





Pictures from:

Degrassi, Di Vita, Elias-Miro, Espinosa, Giudice, Isidori & Strumia 2012

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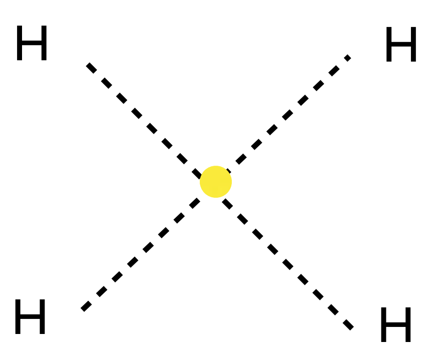
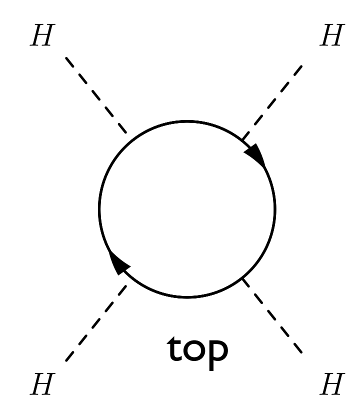
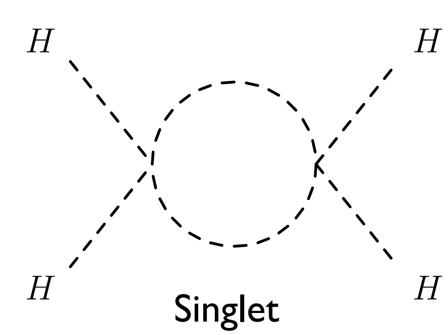


λ_H is driven to negative values by the top Yukawa



λ_H RGEs get a POSITIVE contribution from the singlet



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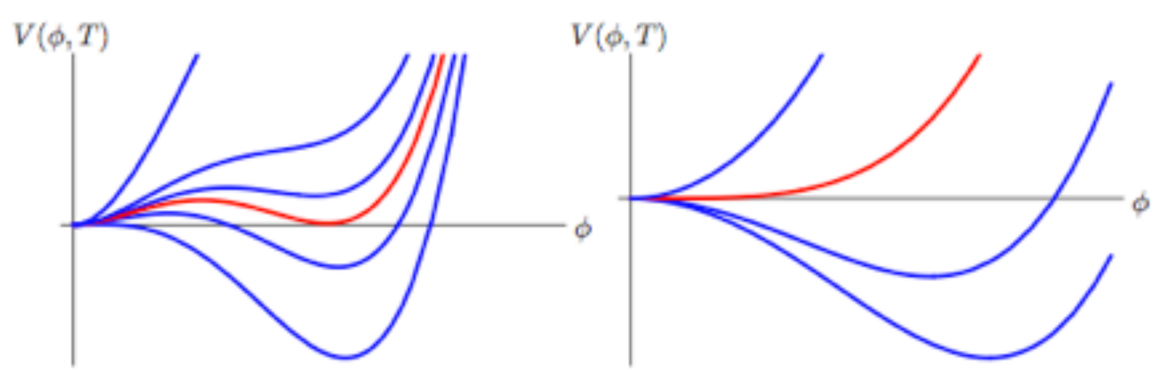
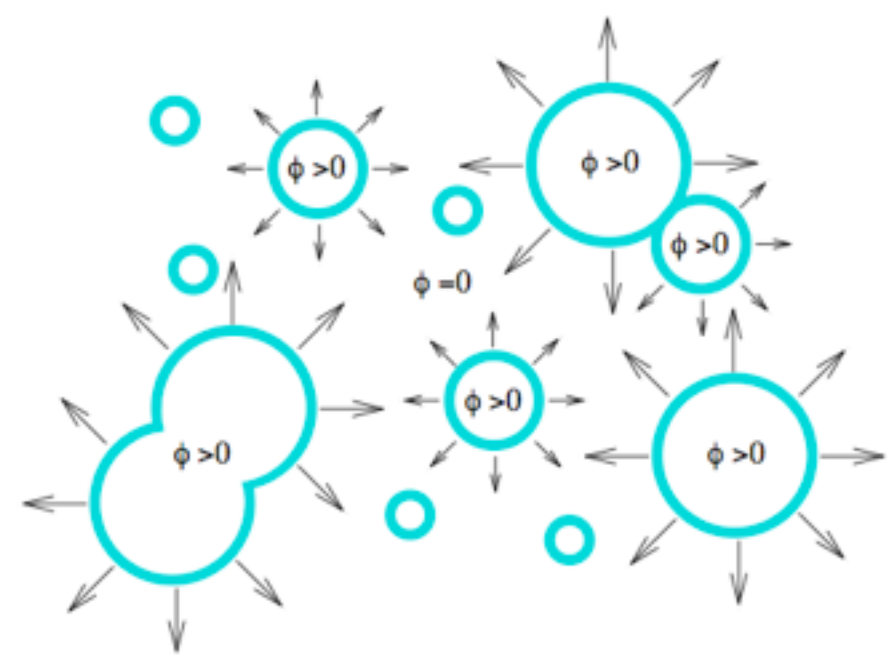
Motivation

- Adding a singlet is the MINIMAL extension of the Higgs sector
- Could help to stabilize the Higgs potential at high energy (~ M_{Planck})
- Could induce a 1st order the Electroweak Phase Transition



Espinosa, Konstandin, Riva 2012



pictures credit: G. Nardini

Introduction

Motivation

- Adding a singlet is the MINIMAL extension of the Higgs sector
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- Could provide masses to right handed neutrinos (Low scale see-saw)

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- Could provide new CP phases
- Could be related to DM
  - Stable if the Lagrangian is invariant under $\Phi \rightarrow -\Phi$
  - Portal to some extra (e.g. new fermion) DM candidate

Introduction

Motivation

- Adding a singlet is the MINIMAL extension of the Higgs sector
- Could help to stabilize the Higgs potential at high energy ($\sim M_{Planck}$)
- Could induce a 1st order the Electroweak Phase Transition
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- Could provide new CP phases
- Could be related to DM
  - Stable if the Lagrangian is invariant under $\Phi \to -\Phi$
  - Portal to some new fermion, DM candidate

$\Rightarrow$ A nice scenario to address different issues !!!

The Model

REAL

- Potential

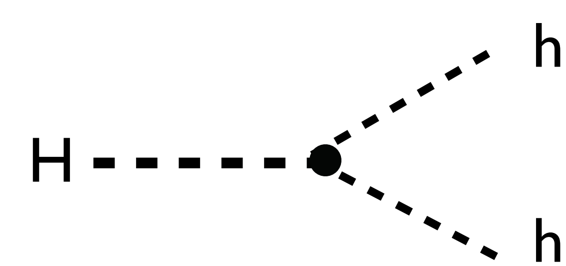
$$V_0(\Phi, S) = -\mu^2(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2 + \frac{1}{2}\mu_S^2 S^2 + \frac{\alpha}{3}S^3 + \frac{\lambda_S}{4}S^4 +$$
$$+ \frac{\omega}{2}(\Phi^\dagger\Phi)S + \frac{\lambda_{\Phi S}}{2}(\Phi^\dagger\Phi)S^2$$

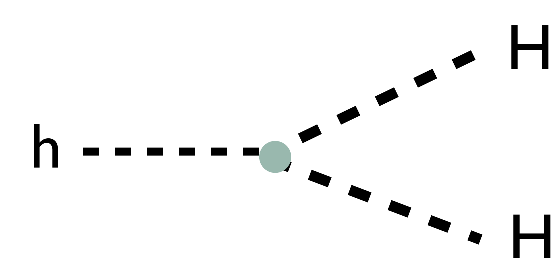
- After the breaking

$$\Phi \equiv \begin{pmatrix} 0 \\ v + h_{SM} \end{pmatrix} \qquad S \equiv s + h_{Singlet}$$

- Mass eigenstates

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h_{SM} \\ h_{Singlet} \end{pmatrix}$$



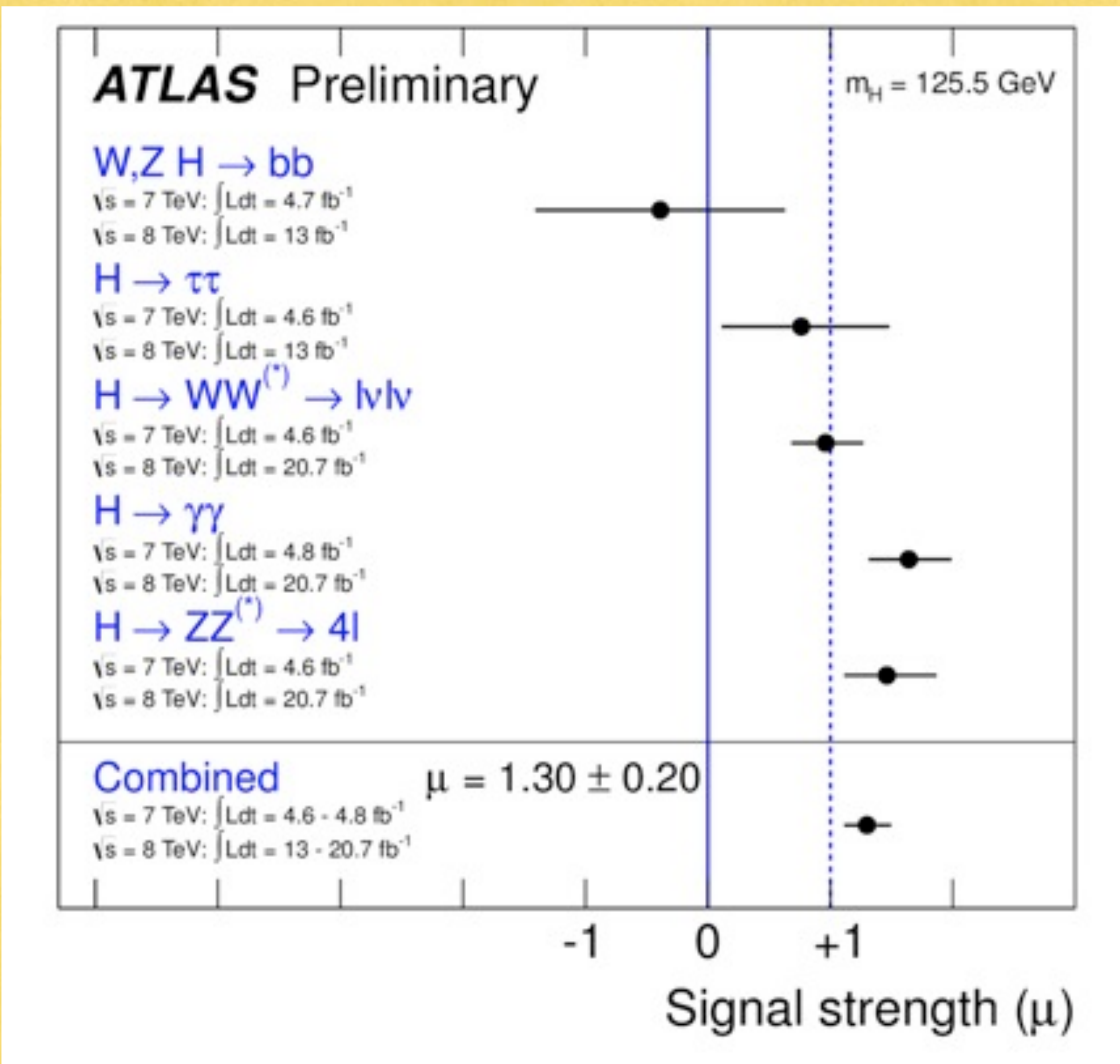


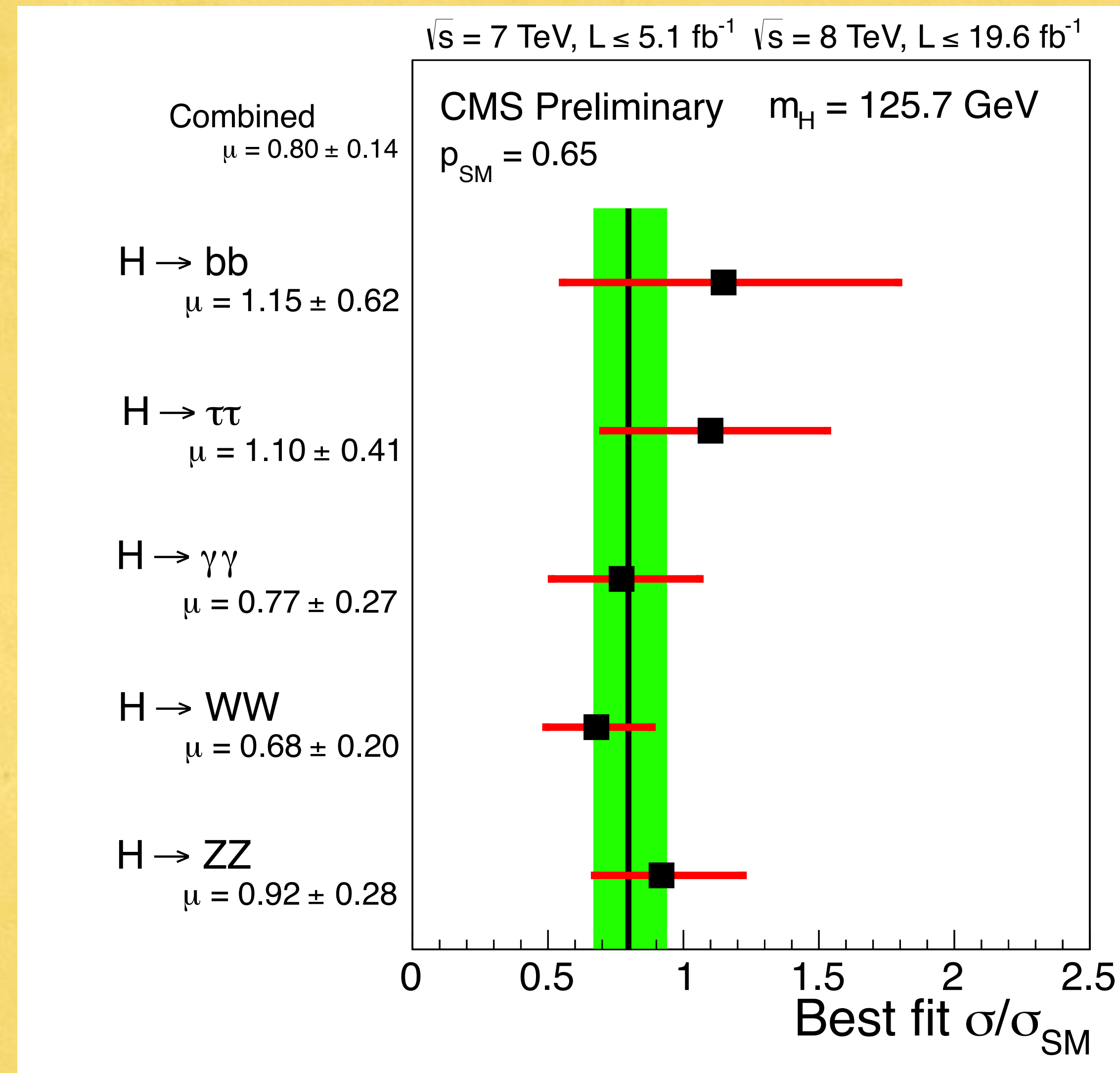
h ≡ Scalar boson discovered at LHC

$(m_h\ ,\ m_H)$ $\quad m_h \approx 126$ GeV

Constraints

From Higgs couplings measurements



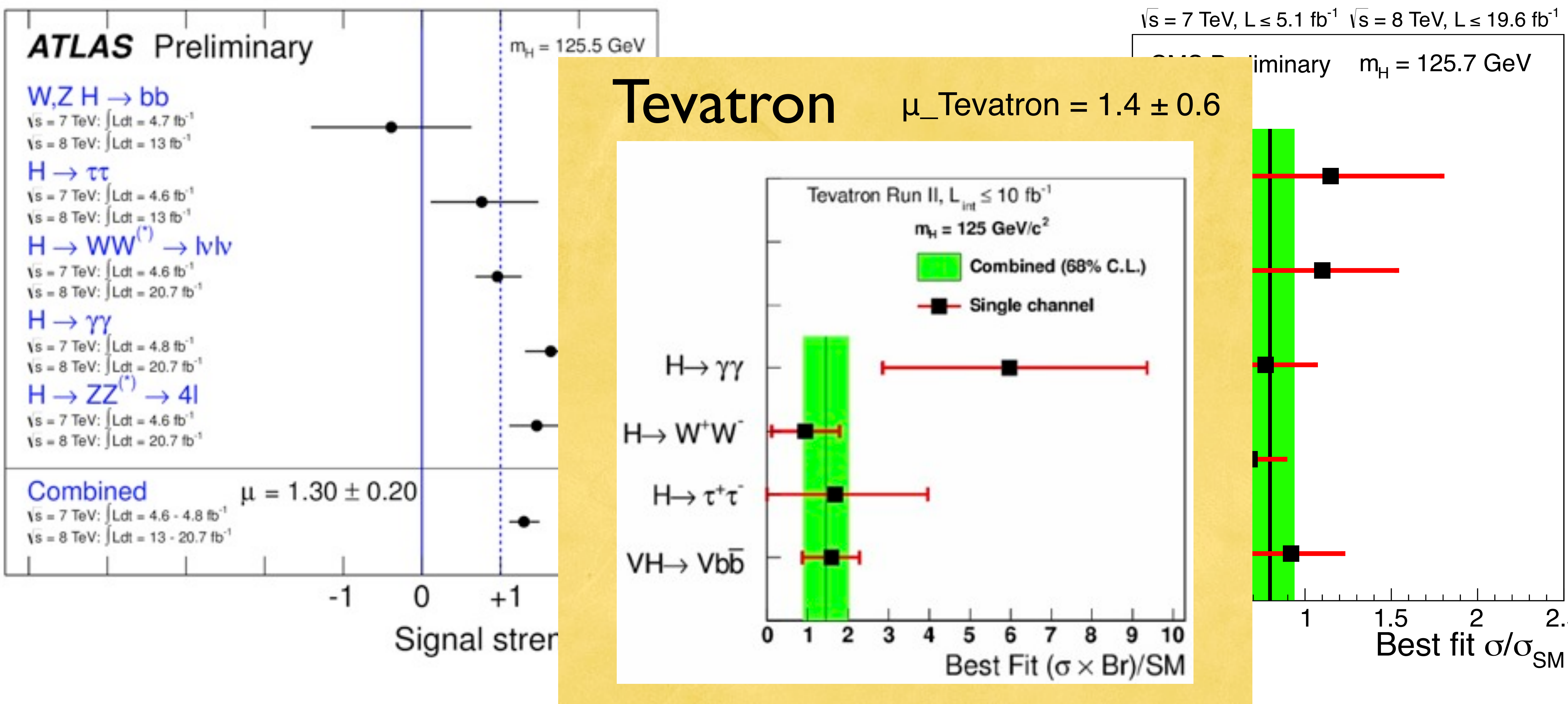


μ_Atlas = 1.30 ± 0.20
μ CMS = 0.80 ± 0.14

μ_Combined = 0.96 ± 0.11

Constraints

From Higgs couplings measurements

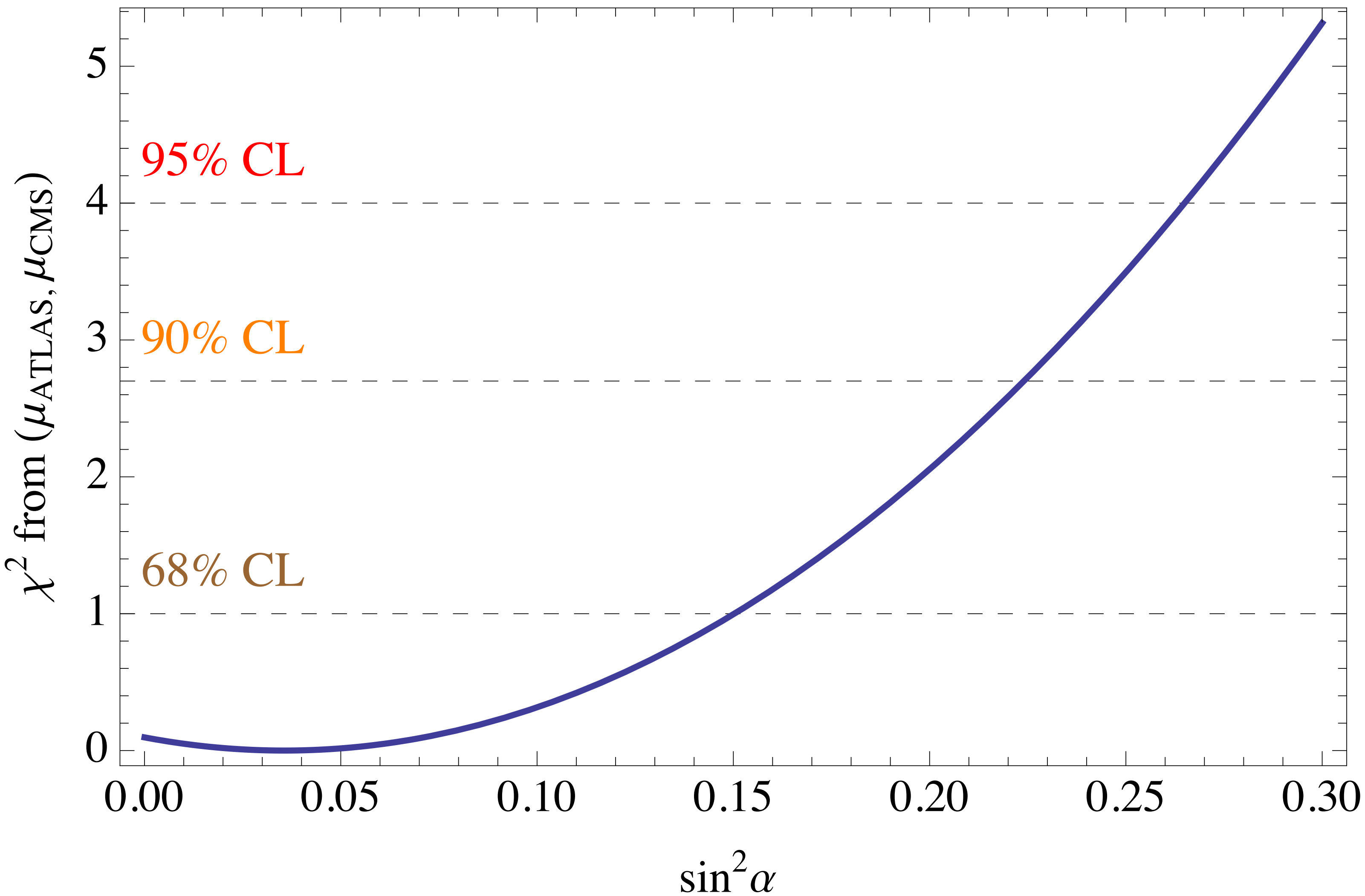


μ_Atlas = 1.30 ± 0.20
μ_CMS = 0.80 ± 0.14
μ_Tevatron = 1.4 ± 0.6

μ_Combined = 0.98 ± 0.11

Constraints

From Higgs couplings measurements



0.26 95% CL

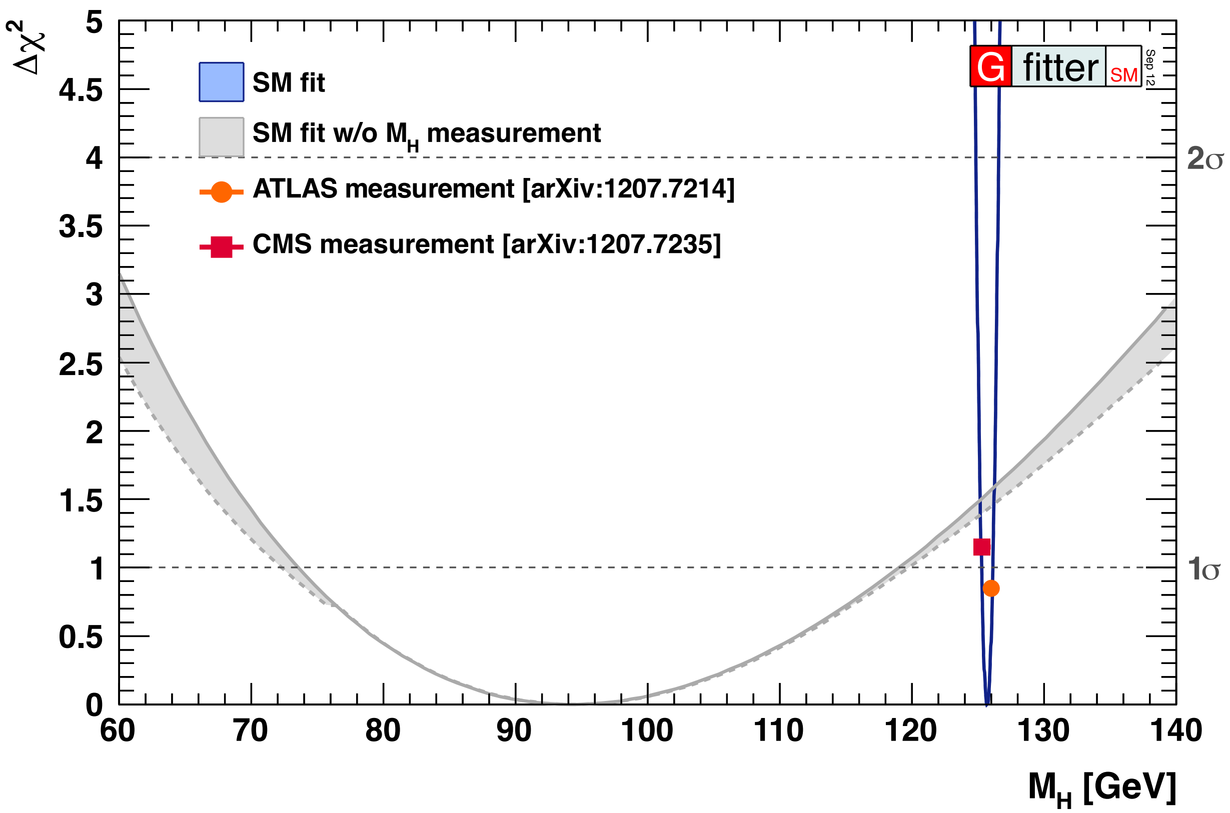
$\sin^2\alpha < 0.22$ 90% CL

0.15 68% CL

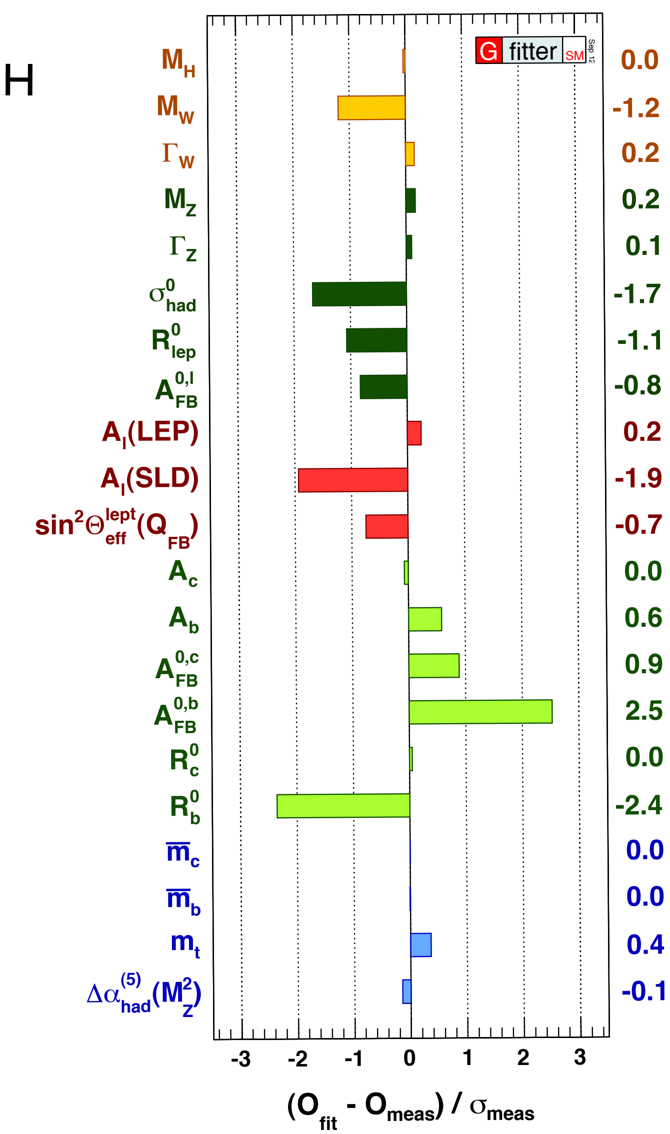
Constraints

From electroweak precision data

- The Higgs boson is involved in 1-loop corrections to the electroweak observables (relevant in order to compare with experimental data)
- These **corrections** are **sensitive** to both the **Higgs mass** and **Higgs couplings**
- In the SM framework (standard Higgs couplings) the fitted m_H value is $\approx 1 - 1.3\ \sigma$ form the ATLAS & CMS measurement



$$m_H = 94^{+25}_{-22}\ GeV$$



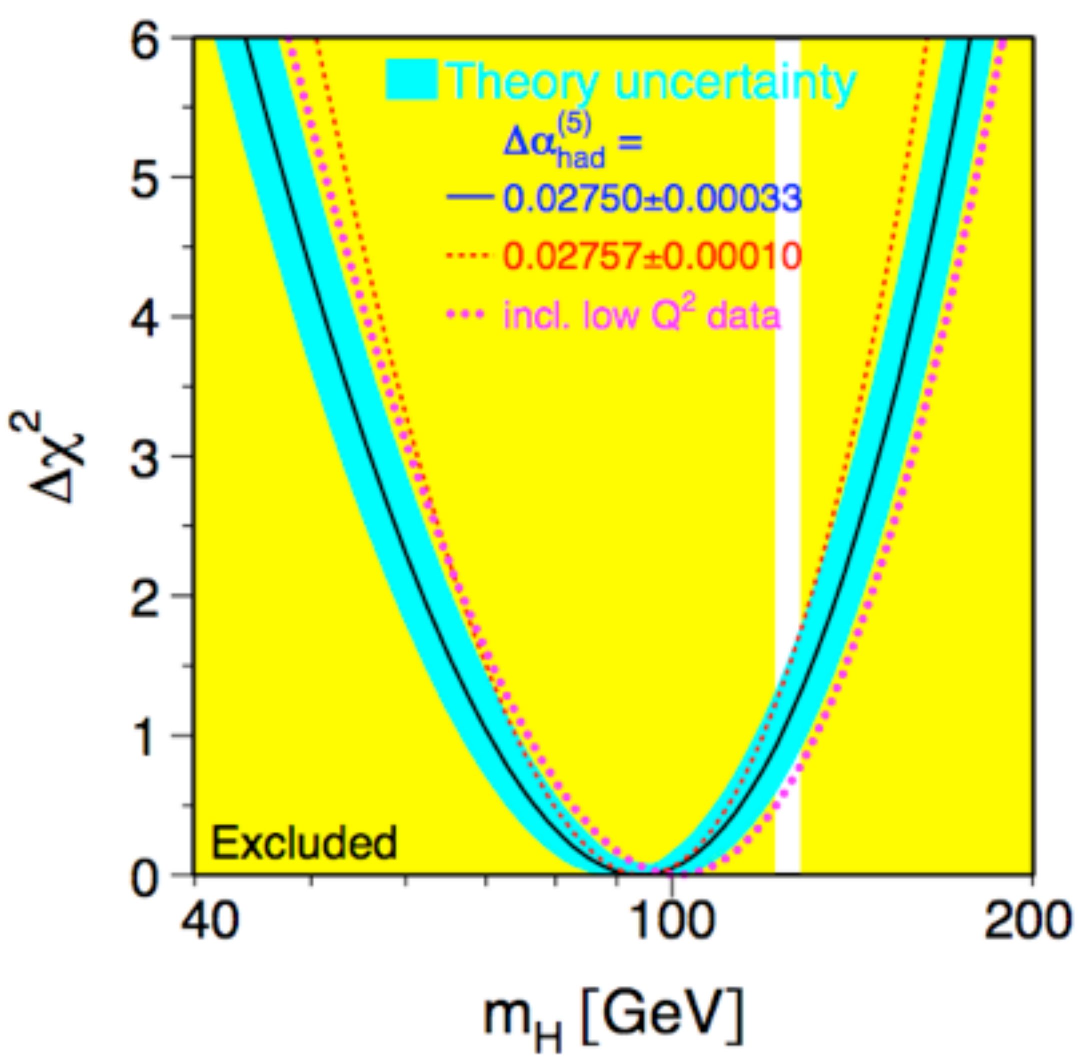
Constraints

From electroweak precision data

The LEP Electroweak Working Group

arXiv:1302.3415

all Z-pole data plus m_t, m_W, Γ_W



$$m_H = 93^{+30}_{-24}\ GeV$$

- LEP EWWG

$$\log_{10} m_H = 1.97^{+0.12}_{-0.13}\ GeV$$

$$m_H = 94^{+25}_{-22}\ GeV$$

- GFITTER

$$m_H = 101^{+25}_{-20}\ GeV$$

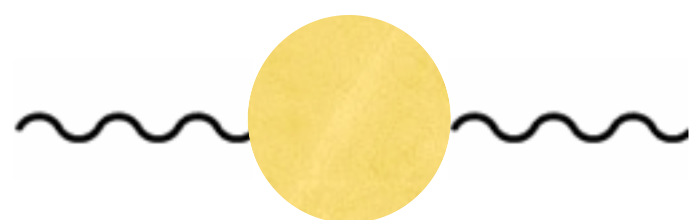
- J. Erler, S. Su

arXiv:1303.5522

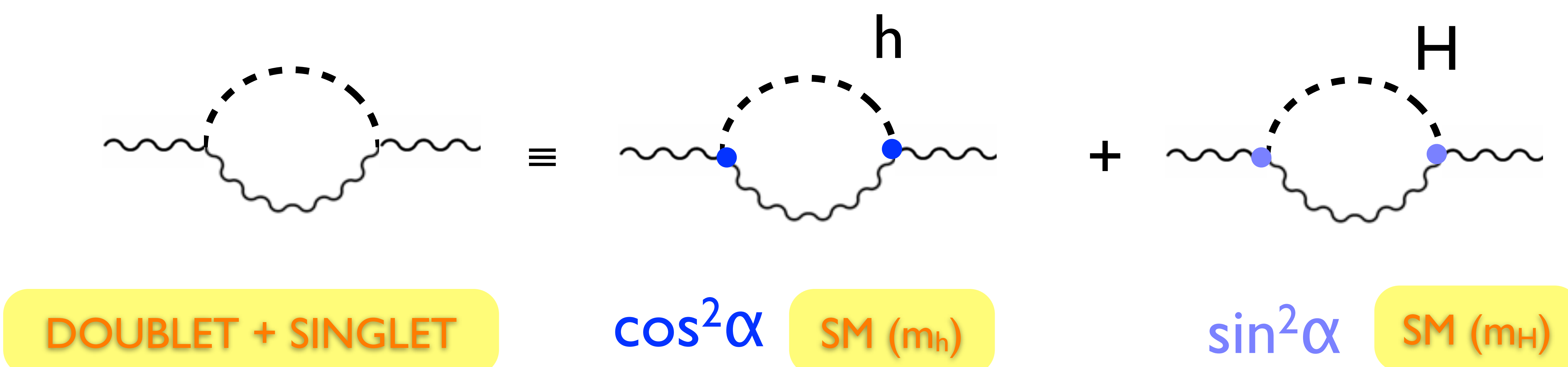
Constraints

From electroweak precision data

- Instead of considering the full set of observables (≈20-40) we will use S,T,U, the oblique parameters, defined in terms of the gauge boson self-energies



- They can be easily evaluated in this framework



Constraints

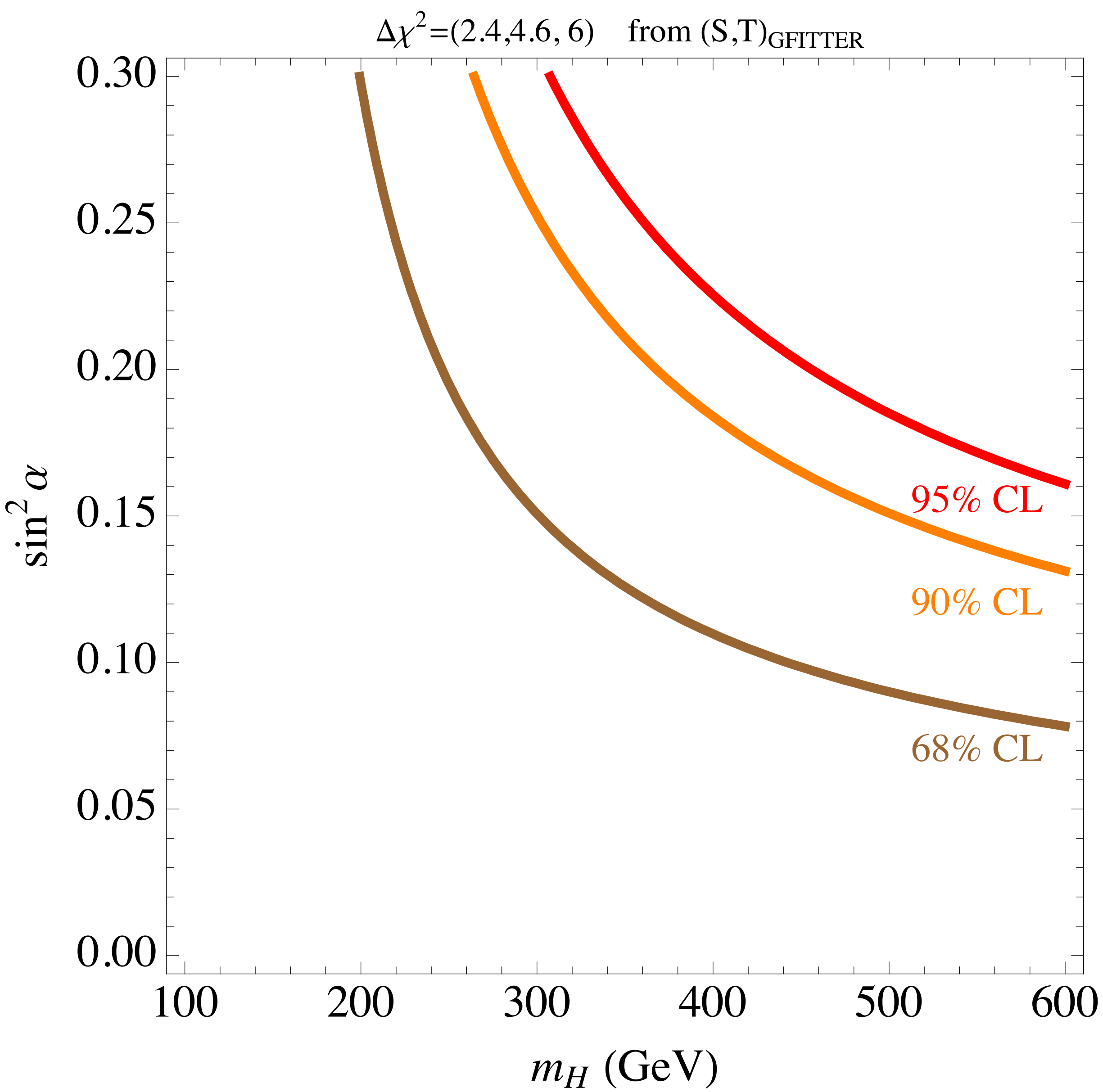
From electroweak precision data

- Using (S,T) GFITTER data:

  S = 0.05 ±0.09

  T = 0.08 ±0.07

  (correlation 0.91)



(see also S. Baek, P. Ko, W. Park arXiv:1112.1847)

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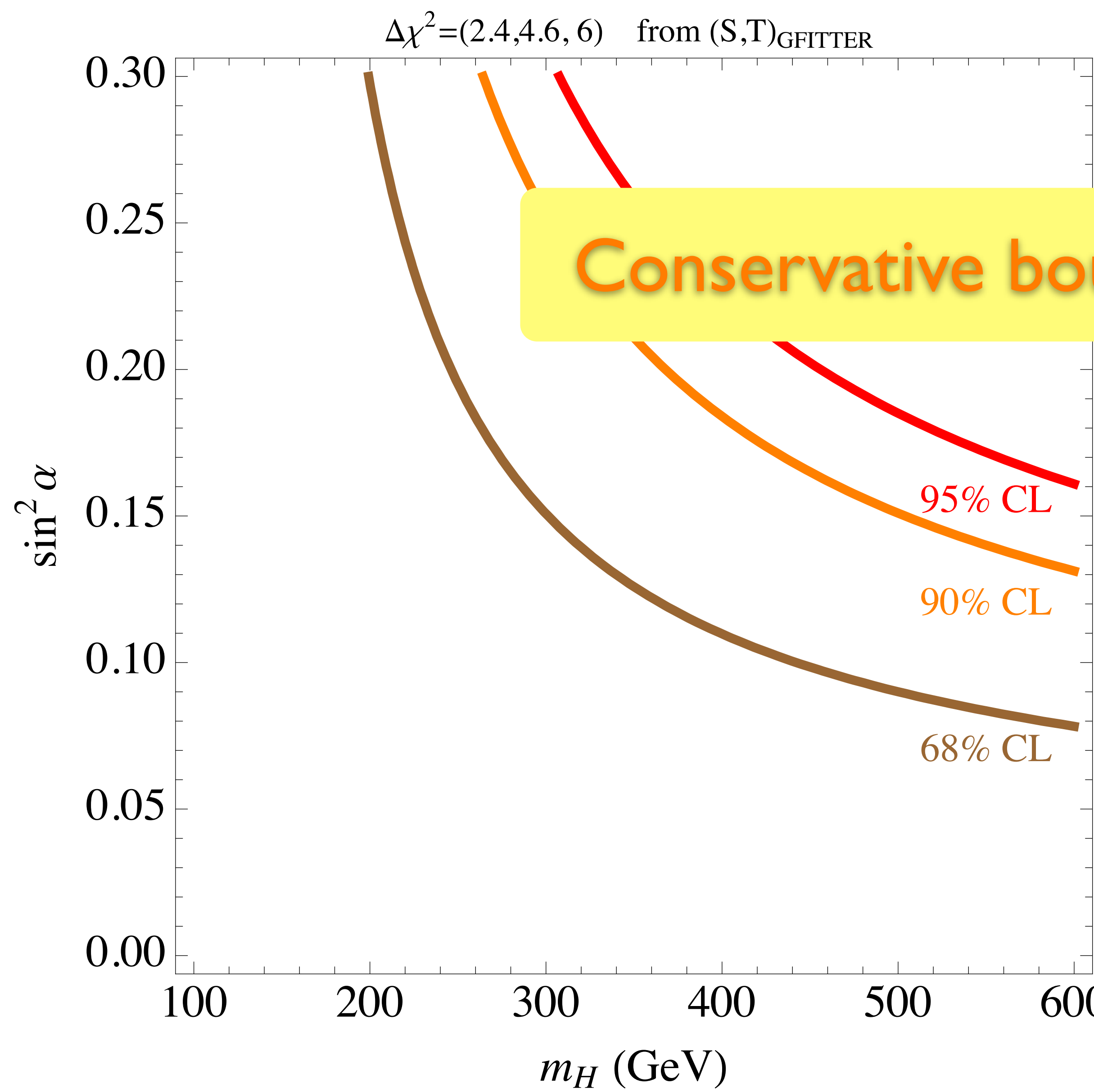


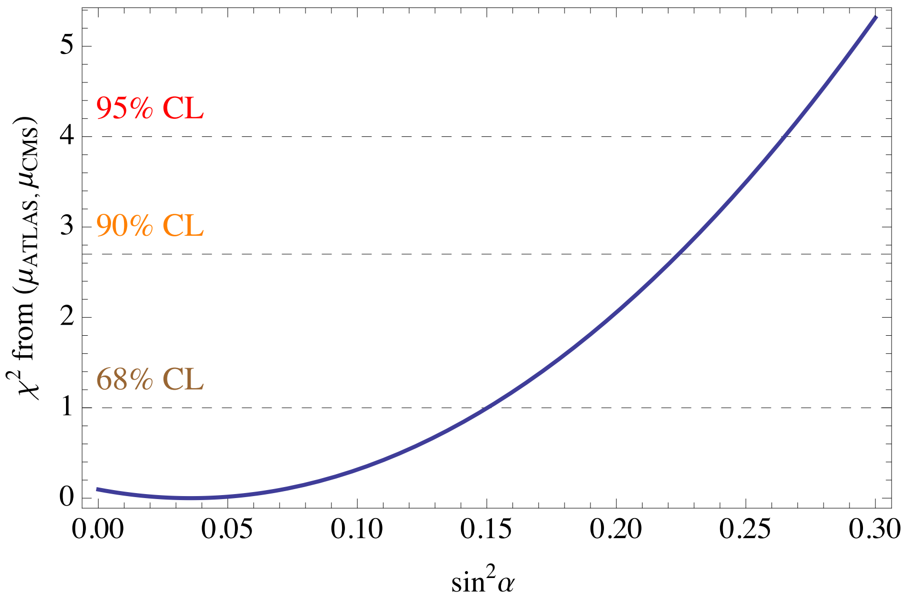
Conservative bounds

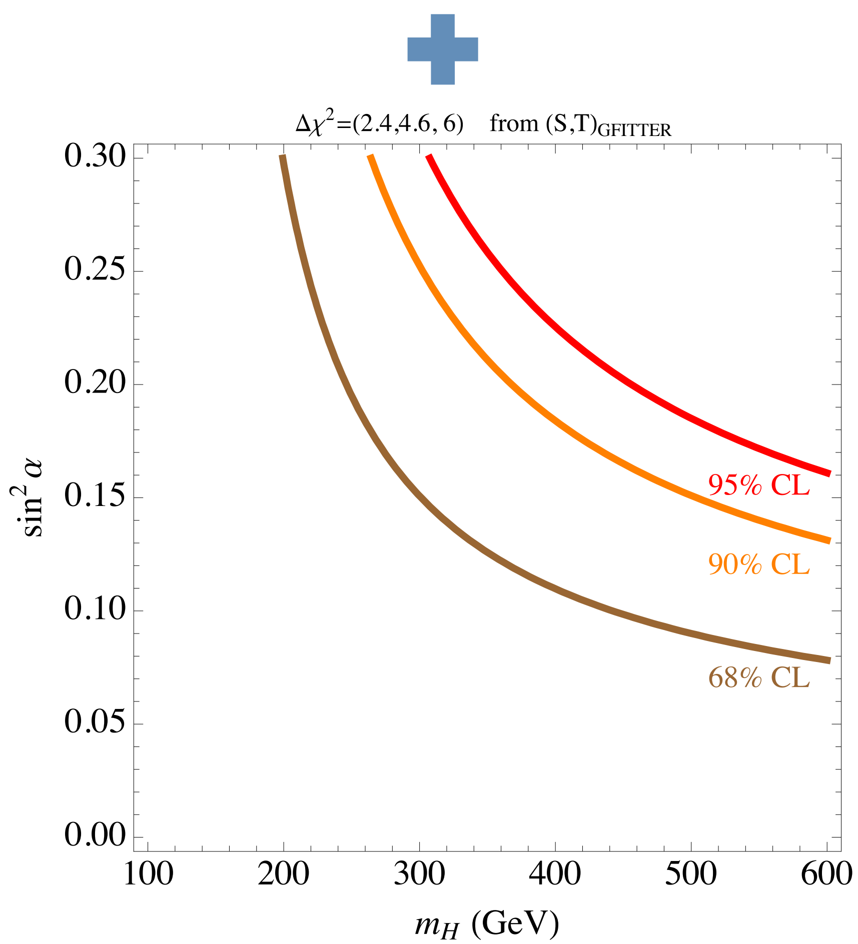
NOTE

- We are including only one loop effects
- We are not using the whole information (all EW precision test variables)

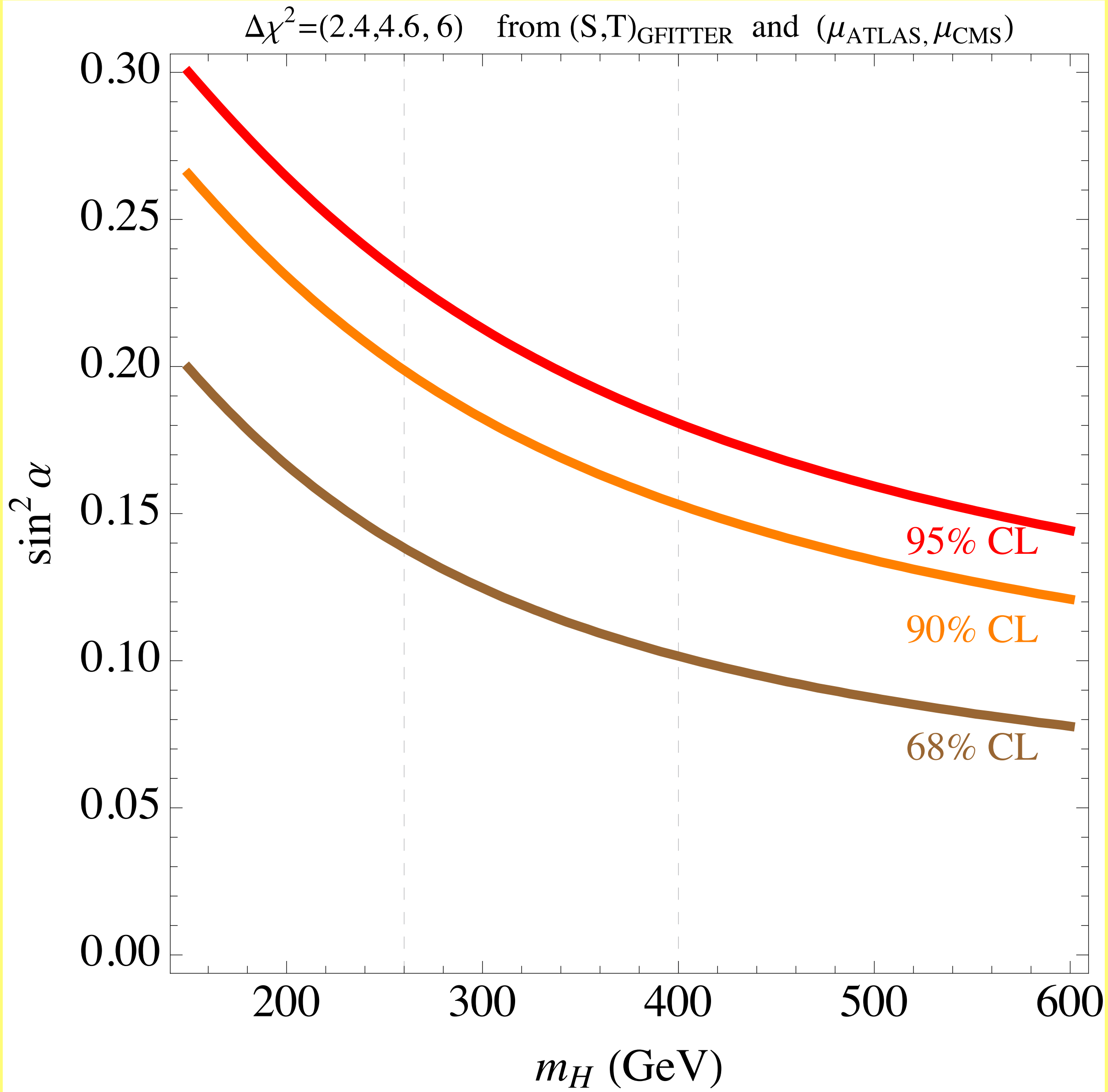
As a consequence, we are **overestimating bounds on** Higgs couplings (ie, on $\mathbf{\sin^2 \alpha}$)

Constraints





Combining
electroweak precision data +
LHC Higgs couplings



Constraints

Until now we have considered indirect bounds from modification of the SM like Higgs (h) couplings.

.. what about direct production and decay of the new scalar boson ?

- **Production:** $\sigma(pp \rightarrow H)$ will depend on $(m_H, \sin^2\alpha)$
- **Decay:** We have to consider a new parameter $BR(H \rightarrow hh)$. Assuming no new matter content

$$BR(H \rightarrow \text{SM particles}) + BR(H \rightarrow hh) = 1$$

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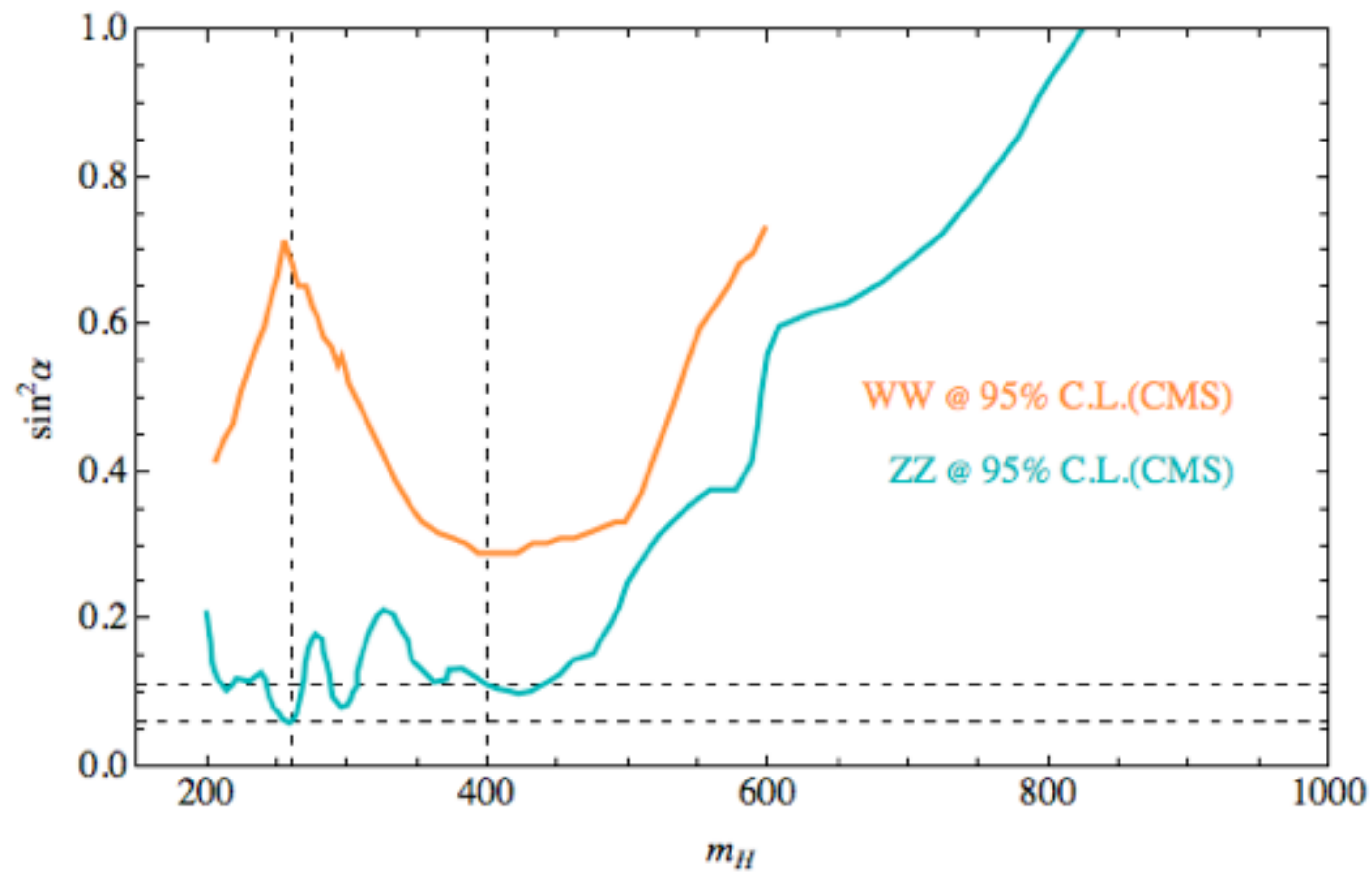
$BR(H \to$ SM particles$) = 1$

Bounds on $(m_H,\ \sin^2\alpha)$ obtained from SM-like Higgs searches @LHC



..easily reescaled for $BR \neq 1$

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- **Production:** $\sigma(pp \to H)$ will depend on $(m_H, \sin^2\alpha)$
- **Decay:** We have to consider a new parameter $BR(H \to hh)$. Assuming no new matter content, and $m_H > 2\, m_h$

$BR(H \to hh) = 1$

Same signature than $h^* \to hh$ in the SM

Prospects for $\sqrt{s}$ = 14 TeV ?

Double Higgs production ($H \to hh$)

Decay signature

- The dominant decay is $H \to hh \to b\bar{b}\, b\bar{b}$
  Issues:
    - A four jet final state has a large background
    - Poor reconstruction efficiency

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- The subleading decay is $H \rightarrow hh \rightarrow b\bar{b}\ WW^*$
  Depending on the Ws decays:
  - Fully hadronic decay: reconstruction + background issues.
  - Semileptonic: the Higgs mass cannot be reconstructed (ν) although the ν four-momentum can be obtained assuming that we know m_H

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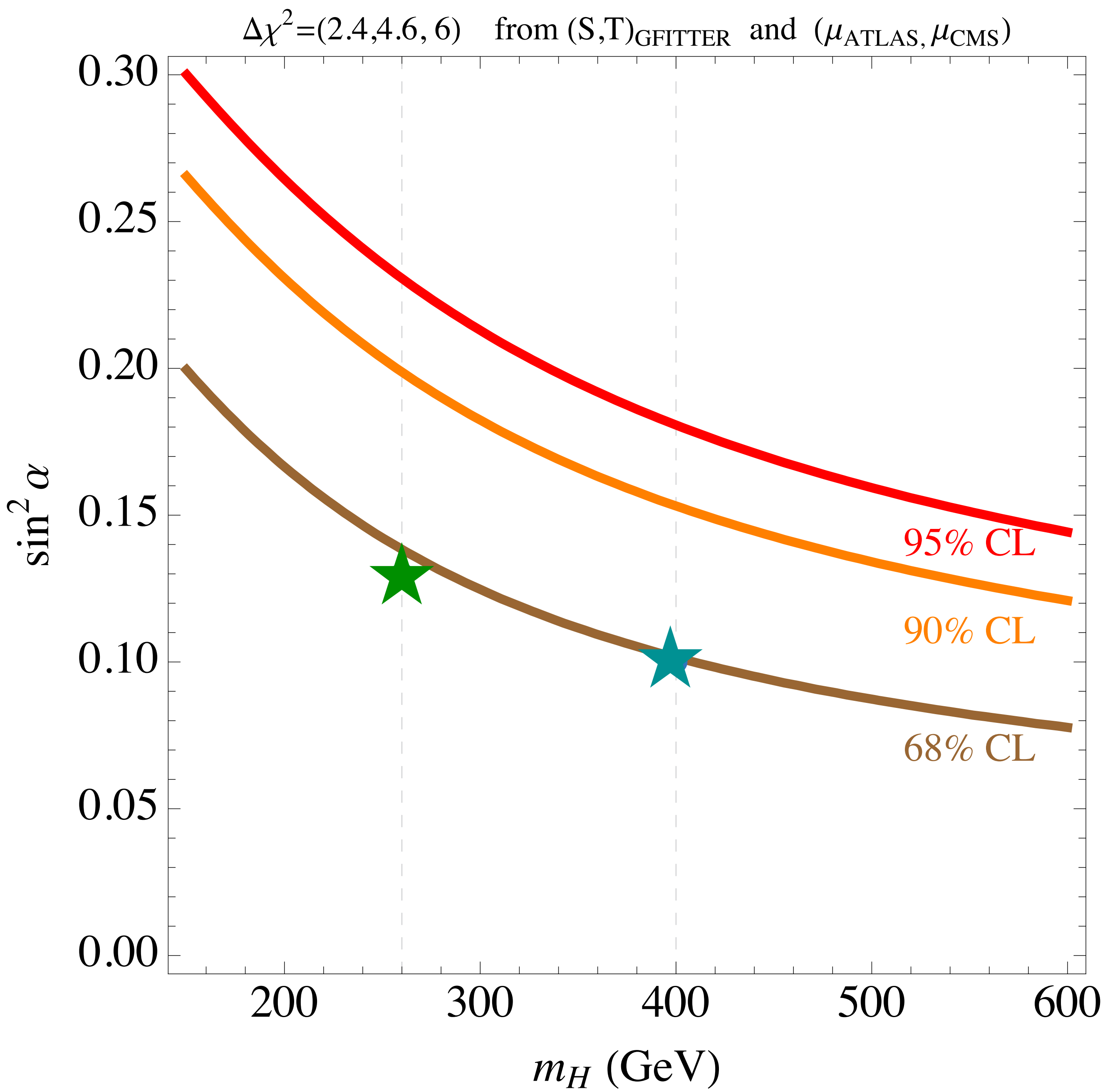
- Dileptonic decay mode:
  - ✔ less vulnerable concerning jet reconstruction.
  - ✖ more challenging (selection cuts, kinematic variables)

Double Higgs production (H→hh)

Benchmark points



★ m_H = 260 GeV, $\sin^2\alpha$ =0.13

★ m_H = 400 GeV, $\sin^2\alpha$ =0.10

Double Higgs production ($H \to hh$)

Signal

★ m_H = 400 GeV, $\sin^2\alpha$ =0.10

★ m_H = 260 GeV, $\sin^2\alpha$ =0.13

BR($H \to hh$) = 100%

For the numerical analysis we have generate events using PHYTIA 8 interfaced with CT10 parton distribution function at $\sqrt{s}$=14 TeV

Process	Cross section
$H \to hh$ ($m_H = 400$ GeV)	1.09 (pb)
$H \to hh$ ($m_H = 260$ GeV)	1.71

Parton showering and hadronization: PHYTIA 8; hadron level data processed with DELPHES (ATLAS detector card) . Includes FASTJET 3 to reconstruct jets (anti-k_T jet clustering algorithm with a radius parameter 0.5)

$b\bar{b}\, l^+ l^-\, \not{E}_T$

We assume a b-tagging efficiency of 70% for p_T > 30 GeV and $|\eta|$<2.5. Misstagging efficiency: 10% for c-jet, 1% light flavour & g

Isolated electrons (muons) p_T > 13 (10) GeV

We require $\Delta R_{lj} \equiv \sqrt{\Delta\Phi_{lj}^2 + \eta_{lj}^2}$ < 0.4 for a jet with p_T > 30 GeV to remove fake leptons from decays of hadrons

We reject events containing the tau jet with p_T > 10 GeV for maintaining a good level of purity of the leptonic signal events

Double Higgs production (H→hh)

Background

★ m_H = 400 GeV, $\sin^2\alpha$ =0.10

★ m_H = 260 GeV, $\sin^2\alpha$ =0.13

BR(H→hh) = 100%

Dileptonic tt	Same final state ⇒ the main background TOP ++ 1.4 (@ next-to-leading order)
Drell-Yan	PHYTHIA 8
hh	Modified PHYTHIA 6 with matrix elements from HPAIR
Rest	PHYTHIA 8

Process	Cross section
$H \to hh$ ($m_H = 400$ GeV)	1.09 (pb)
$H \to hh$ ($m_H = 260$ GeV)	1.71
$t\bar{t}$	844.43
GGF h	50.35
VBF h	4.17
hW/Z	2.39
$ht\bar{t}$	0.61
hh	0.033
DY	91130.0
Di-boson	121.0

Double Higgs production (H→hh)

(I) Basic selection cuts

- At least two isolated, opposite-sign leptons e^+e^-, $\mu^+\mu^-$, and $e^\pm\mu^\mp$. We further require that one of them must have $p_T > 20$ GeV,

- At least two b-tagged jets with $p_T > 30$ GeV,

- Missing energy $\not{E}_T > 20$ GeV,

- For the opposite-sign same-flavor leptons, the event is rejected if $m_{\ell\ell} < 12$ GeV to avoid the leptons produced from the hadrons, and a Z-veto condition, which discards events containing $|m_{\ell\ell} - m_Z| < 15$ GeV, is imposed.

(II) Reducing the leptonic background

$h \to WW^*$: due to spin correlations the leptons are collinear. Cuts:

$$|\Delta\Phi_{\ell\ell}|, \quad \Delta R_{\ell\ell}$$

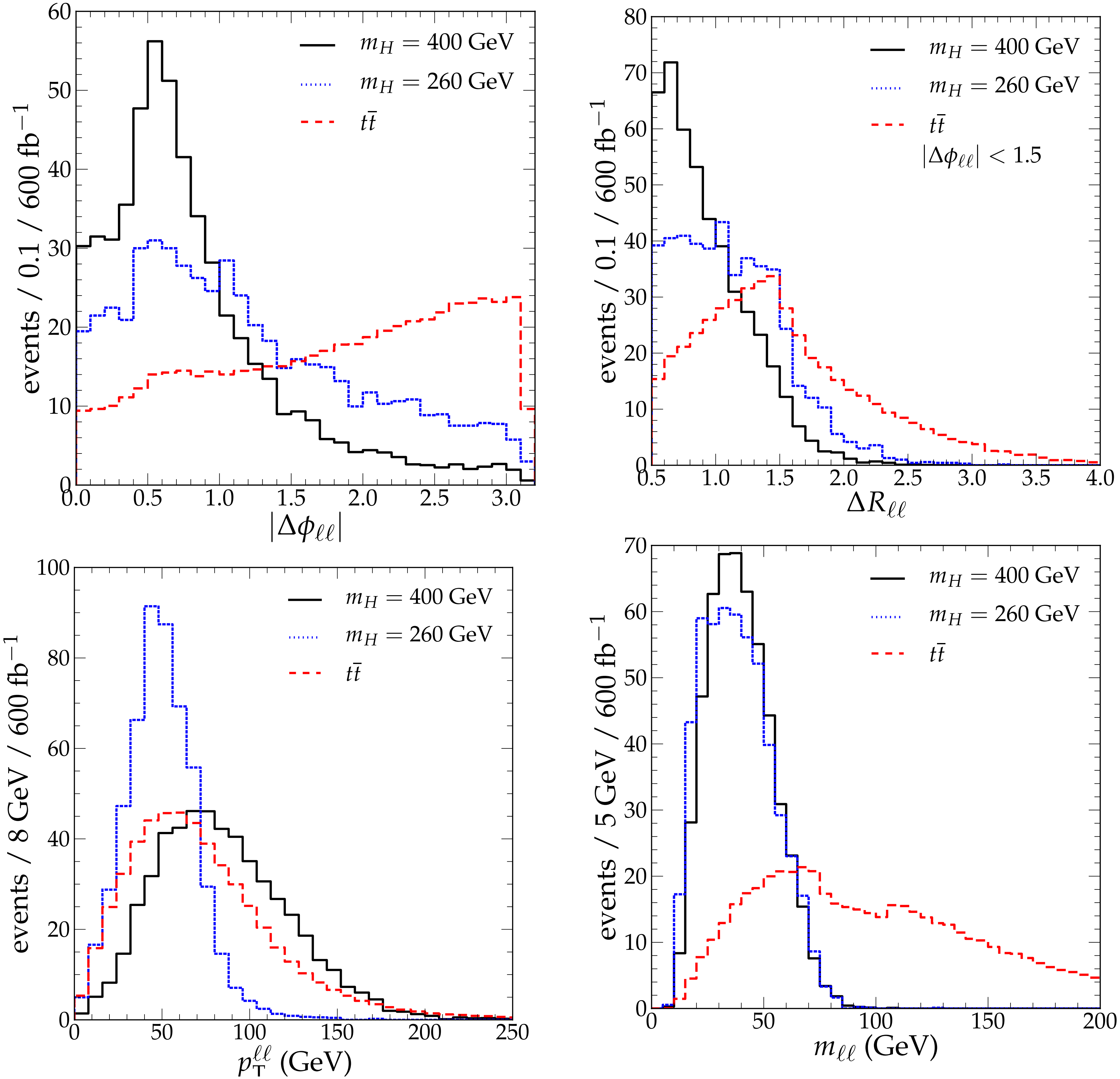
$$\Delta R_{ll} \equiv \sqrt{\Delta\Phi_{ll}^2 + \eta_{ll}^2}$$

Also on

$$p_T^{\ell\ell} = |\mathbf{p}_T^\ell + \mathbf{q}_T^\ell| \qquad m_{\ell\ell}$$

Kinematic variables

$\vec{\ell}\,\vec{\ell}$



$|\Delta\Phi_{\ell\ell}| < 1.32$ (1.57) $m_H = 400$ (260) GeV
$\Delta R_{\ell\ell} < 1.34$ (1.58) $m_H = 400$ (260) GeV

$p_T^{\ell\ell}$ > 42 (25) GeV
$m_{\ell\ell}$ > 60 (47) GeV

Detector-level distributions of the kinematic variables for the two charged leptons. The upper frames are (Left panel) the azimuthal angular separations and (Right panel) the $\Delta R_{\ell\ell}$ when applying the azimuthal angular cut has been imposed. The lower frames are (Left panel) the sum of transverse momenta $p^{\ell\ell}_T$ and (Right panel) the invariant mass $m_{\ell\ell}$ distributions. Basic selection cuts are applied and all the distributions are normalized for an illustration.

Double Higgs production ($H \rightarrow hh$)

(III) Cuts on b-tagged objects

Butterworth, A. R. Davison, M. Rubin and G. P. Salam

Idea:

If the Higgs is substantially boosted, the jets produced from the Higgs can be considered very often as a fat jet, whose mass is around m_h . For very high p^T_{h}, it is possible to estimate $\Delta R_{bb} \cong 2 m_h / p^T_h$

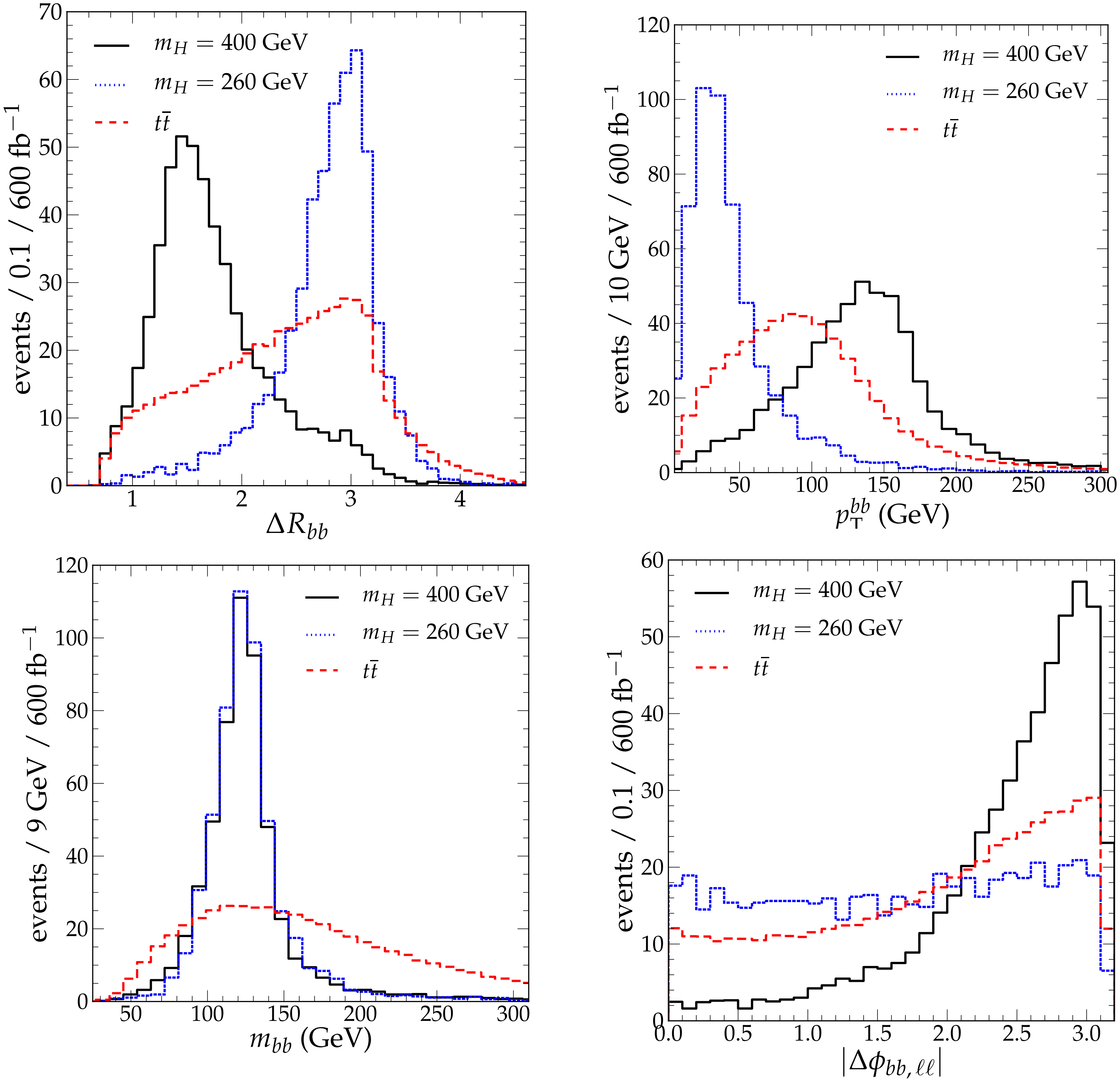
... but boosted Higgses imply $m_H \geq 490$ Ge, not valid in our benchmark points

Conventional cuts

ΔR_{bb} , p^T_{bb} , m_{bb}

Kinematic variables

$b\bar{b}$



m_H =400GeV

$\Delta R_{bb} < 2.25$, $p^T_{bb} > 105$GeV
115 GeV < m_{bb} < 146 GeV

m_H = 260GeV

$\Delta R_{bb} > 2.56$
94 GeV < m_{bb} < 135 GeV

Detector-level distributions of the kinematic variables for the two b-tagged jets. The upper frames are (Left panel) ΔR_{bb} and (Right panel) the transverse momentum p^T_{bb} . The lower frames are (Left panel) the di-b-jet invariant mass and (Right panel) the azimuthal angular separation between bb and l^+l^- systems. Basic selection cuts are applied and all the distributions are normalized for an illustration.

Double Higgs production ($H \to hh$)

(IV) Cuts based on MT2 and MAOS

A. Barr, C. Lester and P. Stephens

- The MT2 variable can be used to reconstruct events involving two invisible particles from the decay of two parent ones (as is our case with W and νs)

- It provides information even in the case where the parent particles are off-shell

W. S. Cho, K. Choi, Y. G. Kim and C. B. Park

- It can be generalized by adding information from on the shell equations (MAOS)

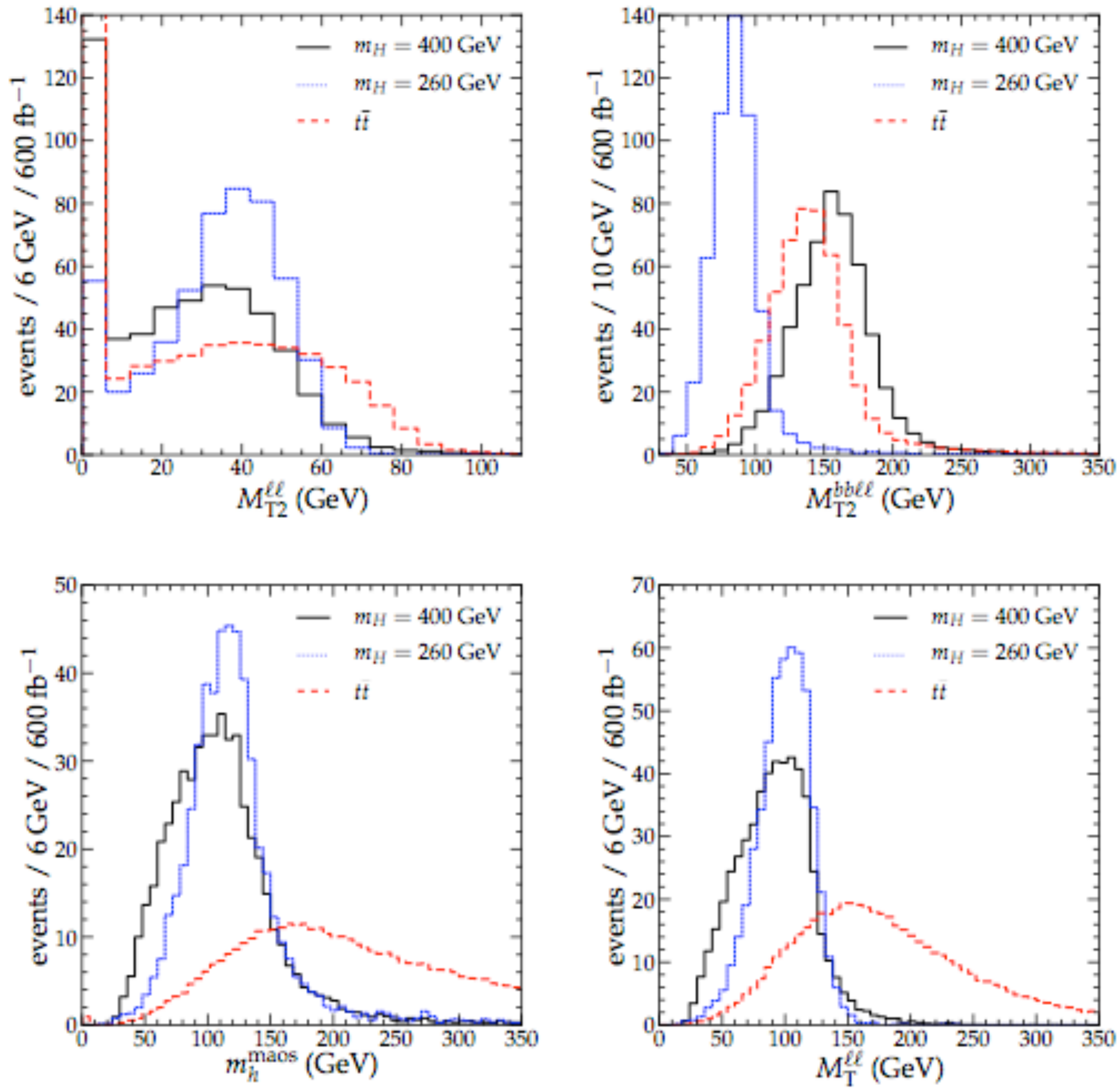


Figure 4: The upper frames are detector-level $M_{\rm T2}$ distributions for (Left panel) the $2\ell + \not{E}_{\rm T}$ and (Right panel) $2b + 2\ell + \not{E}_{\rm T}$ systems. The lower frame are (Left panel) $m_h^{\rm maos}$ and (Right panel) $M_{\rm T}^{\ell\ell}$ distributions for detector-level signals and backgrounds. Basic selection cuts are applied and all the distributions are normalized for an illustration.

Double Higgs production ($H \to hh$)

m_H = 400

Significance (600 fb^{-1})

2.30 $\sin^2 \alpha$ =0.10

3.10 $\sin^2 \alpha$ =0.15

Selection cuts	$H \to hh$	$t\bar{t}$	GGF h	$ht\bar{t}$	hh	DY	VV	$\hat{\sigma}_{600}$
Basic selection	0.90	3560.36	0.15	0.072	0.024	272.41	0.90	0.36
$\Delta\phi_{\ell\ell}$, $\Delta R_{\ell\ell}$, $p_T^{\ell\ell}$	0.67	562.02	0.11	0.015	0.019	33.56	0.047	0.67
$m_{\ell\ell}$, $M_{T2}^{\ell\ell}$	0.60	314.95	0.097	0.009	0.017	11.20	0.0	0.81
$m_h^{\rm maos}$, $M_T^{\ell\ell}$	0.55	237.96	0.097	0.007	0.015	11.20	–	0.85
ΔR_{bb}, p_T^{bb}	0.39	73.03	0.008	0.002	0.012	3.73	–	1.09
m_{bb}	0.24	16.24	0.0	$\simeq 0.0$	0.007	0.0	–	1.45
$\Delta\phi_{bb,\ell\ell}$, $m_{bb\ell\ell}$	0.21	11.99	–	–	0.005	–	–	1.48
$M_{T2}^{bb\ell\ell}$	0.098	1.31	–	–	0.004	–	–	2.07
Signal region	0.080	0.70	–	–	$\simeq 0.0$	–	–	2.30

Table 2: Cut flow of signals for $m_H = 400$ GeV and the main backgrounds in fb. See the text for detailed description of the event selection cuts applied. VV denotes the di-boson processes ($V = W, Z$). $\hat{\sigma}_{500}$ is the signal significance calculated with a Poisson probability at 600 fb^{-1} integrated luminosity. The signal region is defined by 345 GeV $< M_T^{bb\ell\ell} <$ 425 GeV and 350 GeV $< m_H^{\rm maos} <$ 430 GeV.

Double Higgs production ($H \to hh$)

$m_H = 260$

Significance: (800 fb^{-1})

2.28 $\sin^2\alpha = 0.13$

3.10 $\sin^2\alpha = 0.18$

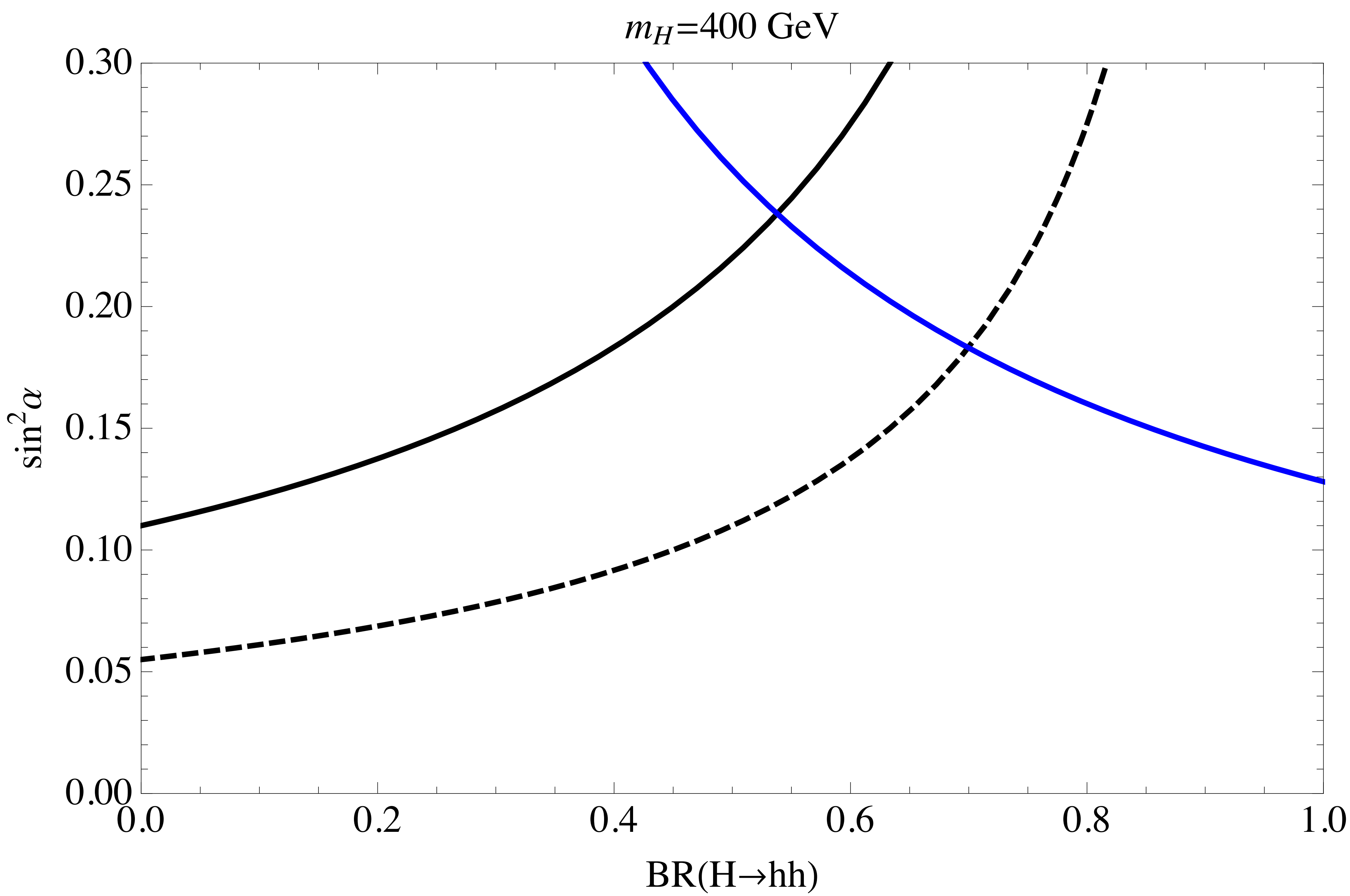
Selection cuts	$H \to hh$	$t\bar{t}$	GGF h	$ht\bar{t}$	hh	DY	VV	$\hat{\sigma}_{800}$
Basic selection	0.69	3560.36	0.15	0.072	0.024	272.41	0.90	0.32
$\Delta\phi_{\ell\ell}$, $\Delta R_{\ell\ell}$, $p_T^{\ell\ell}$	0.40	818.01	0.15	0.020	0.022	48.51	0.095	0.38
$m_{\ell\ell}$, $M_{T2}^{\ell\ell}$	0.30	206.23	0.11	0.006	0.007	0.0	0.0	0.59
$m_h^{\rm maos}$, $M_T^{\ell\ell}$	0.27	140.69	0.08	0.004	0.005	–	–	0.64
ΔR_{bb}, m_{bb}	0.15	6.65	0.008	$\simeq 0.0$	$\simeq 0.0$	–	–	1.64
$m_{bb\ell\ell}$	0.13	3.03	0.008	–	–	–	–	2.09
$M_{T2}^{bb\ell\ell}$	0.12	2.29	0.0	–	–	–	–	2.22
Signal region	0.12	2.19	–	–	–	–	–	2.28

Table 3: Cut flow of signals for $m_H = 260$ GeV and the main backgrounds in fb. See the text for detailed description of the event selection cuts applied. $\hat{\sigma}_{800}$ is the signal significance calculated with a Poisson probability at 800 fb^{-1} integrated luminosity. The signal region is defined by 180 GeV $< M_T^{bb\ell\ell} <$ 265 GeV and 185 GeV $< m_H^{\rm maos} <$ 305 GeV.

Double Higgs production (H→hh)

Detectability m_H = 400

600 fb^{-1}



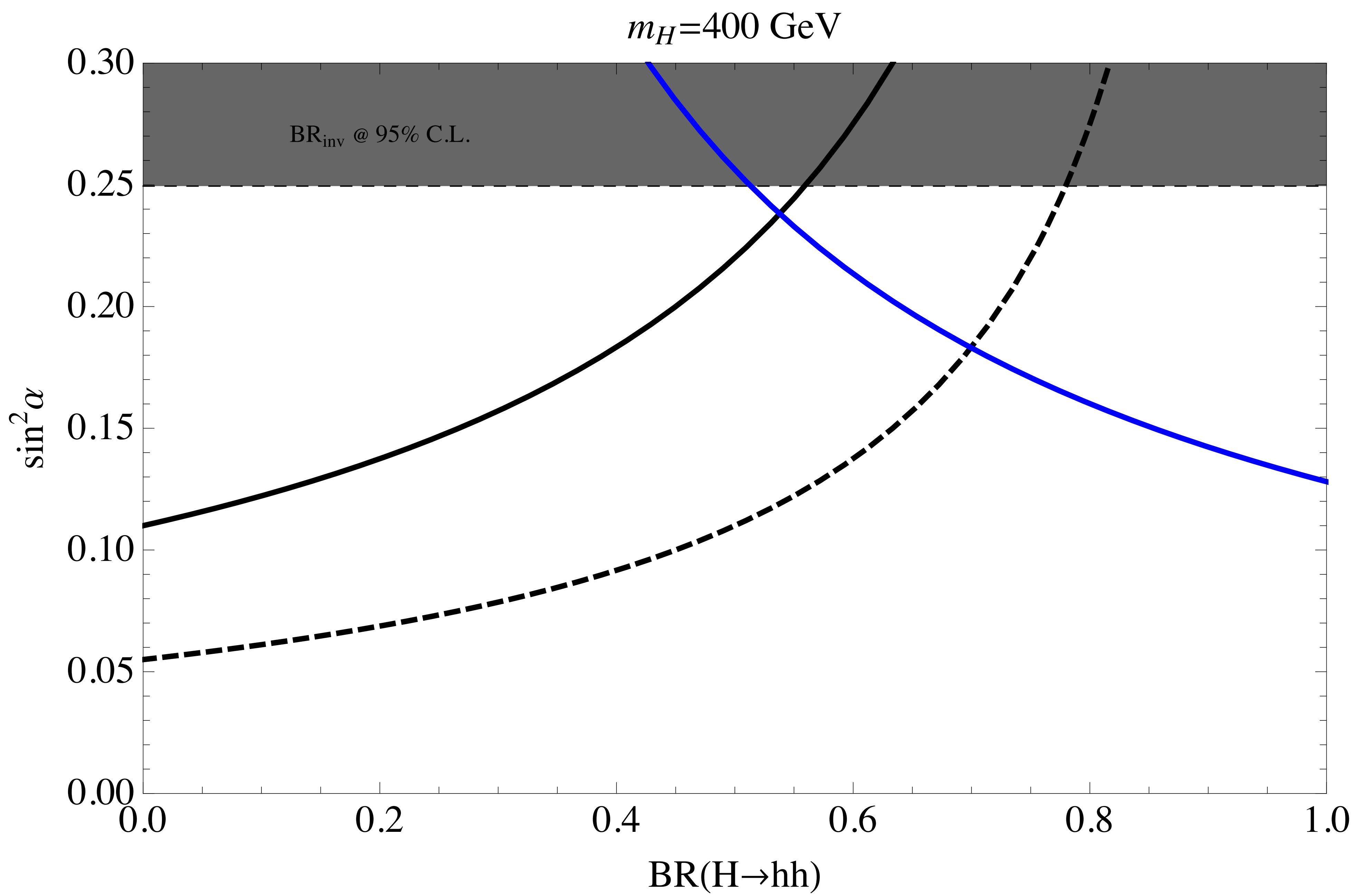
H→hh

(significance 3)

Double Higgs production (H→hh)

Detectability m_H = 400

600 fb^{-1}



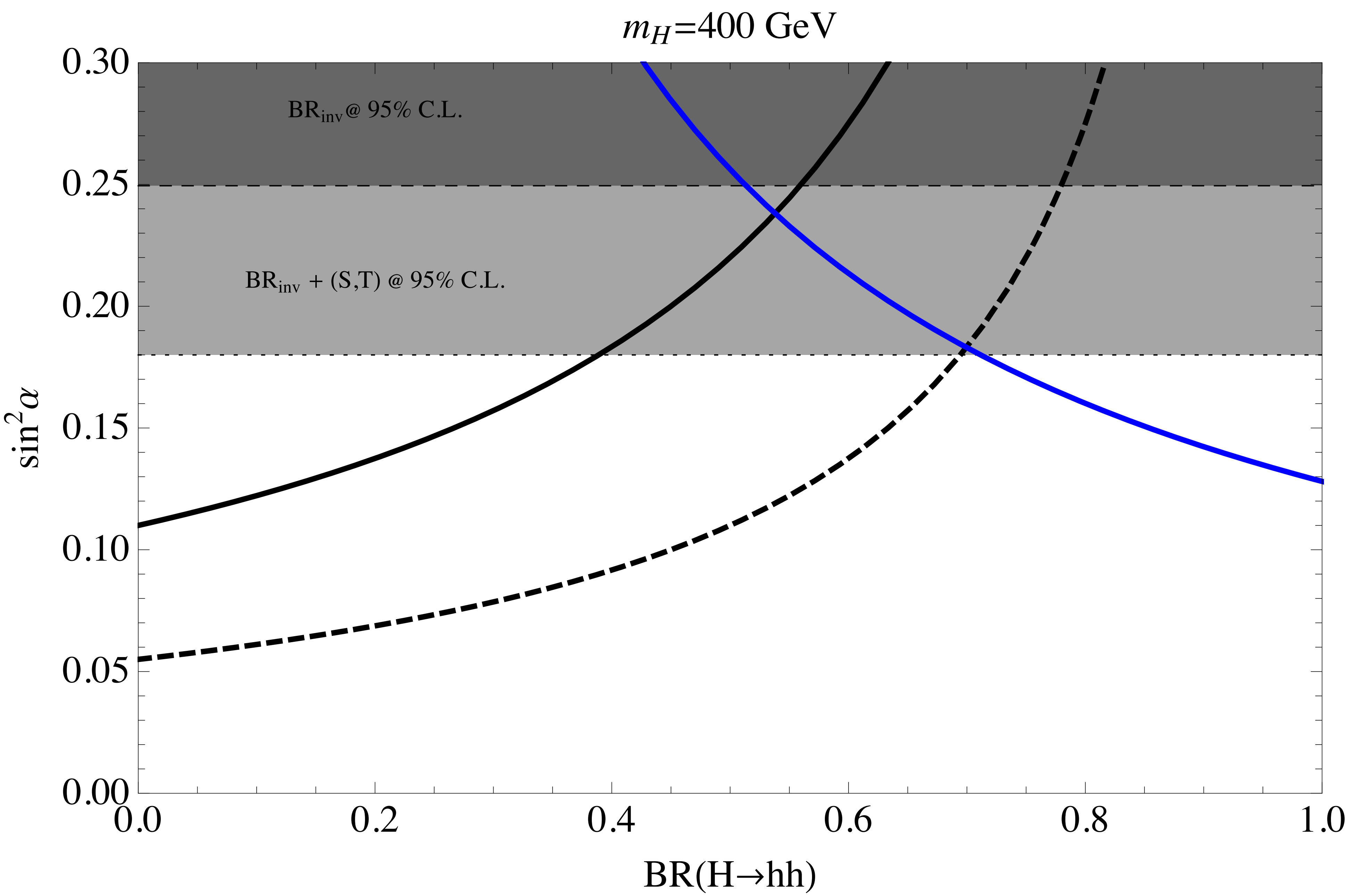
H→hh

(significance 3)

Double Higgs production (H→hh)

Detectability m_H = 400

600 fb^{-1}



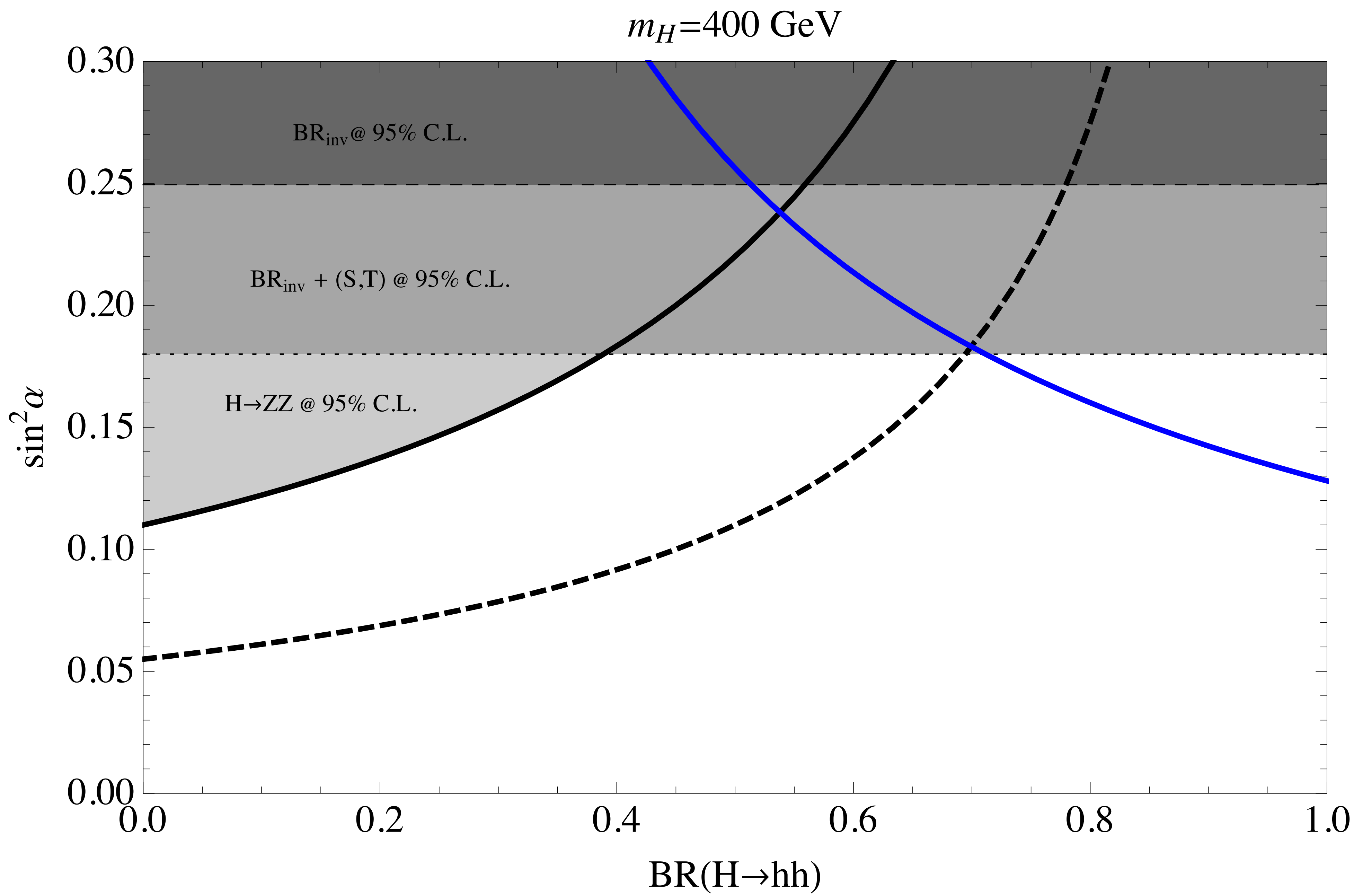
H→hh

(significance 3)

Double Higgs production (H→hh)

Detectability m_H = 400

600 fb^{-1}



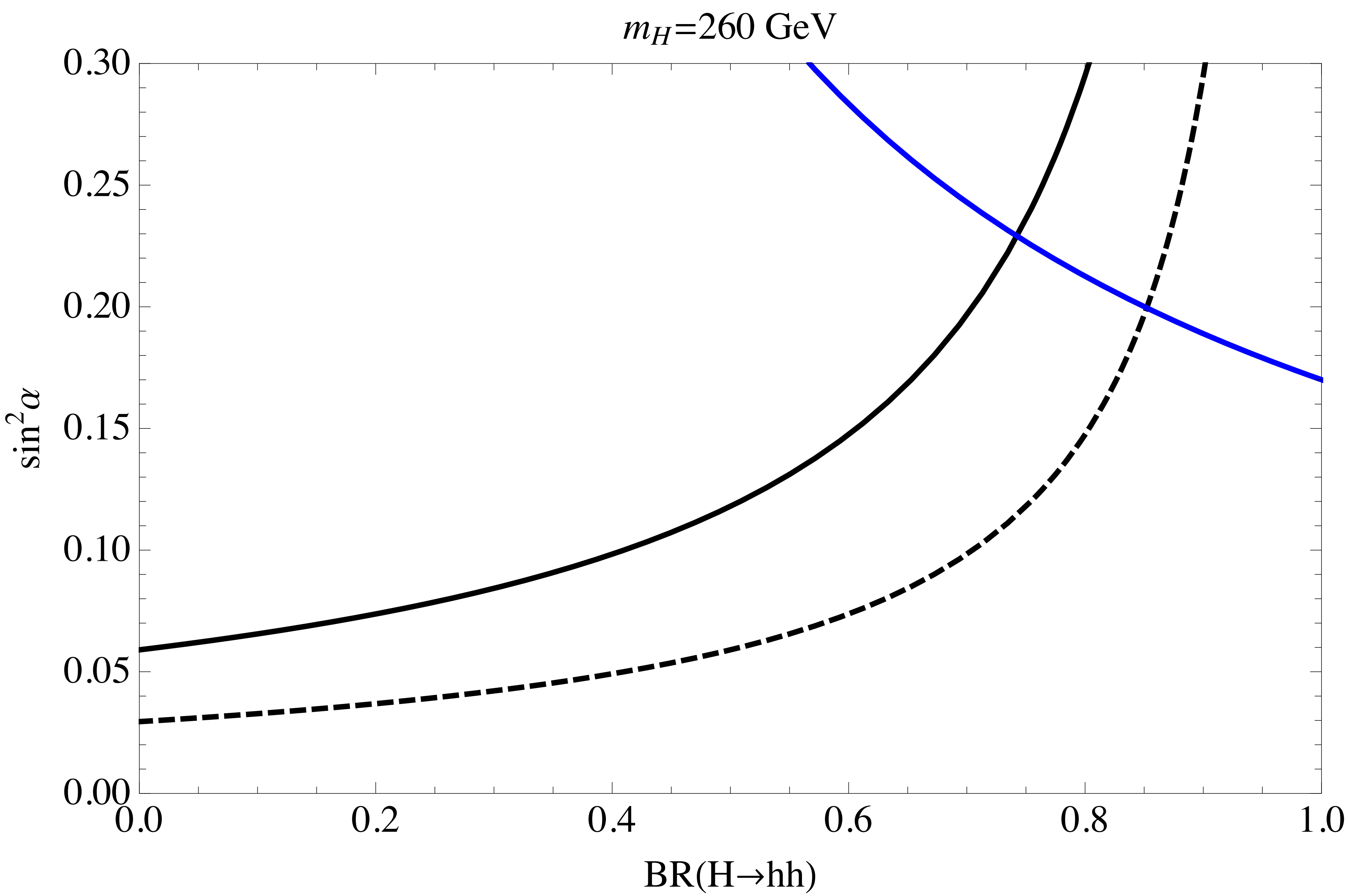
H→hh

(significance 3)

Double Higgs production (H→hh)

Detectability m_H = 260

800 fb^{-1}



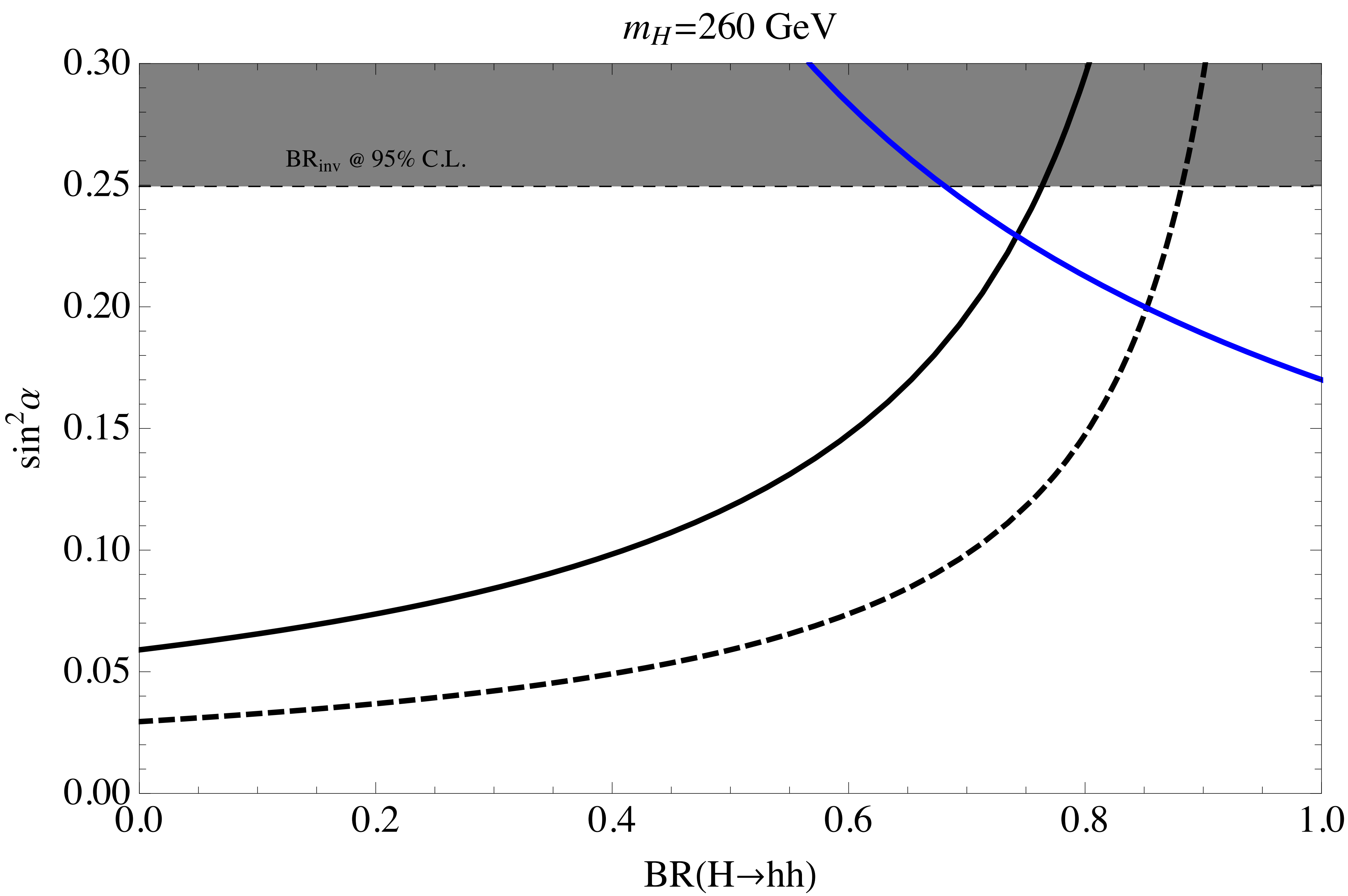
H→hh

(significance 3)

Double Higgs production (H→hh)

Detectability m_H = 260

800 fb^{-1}



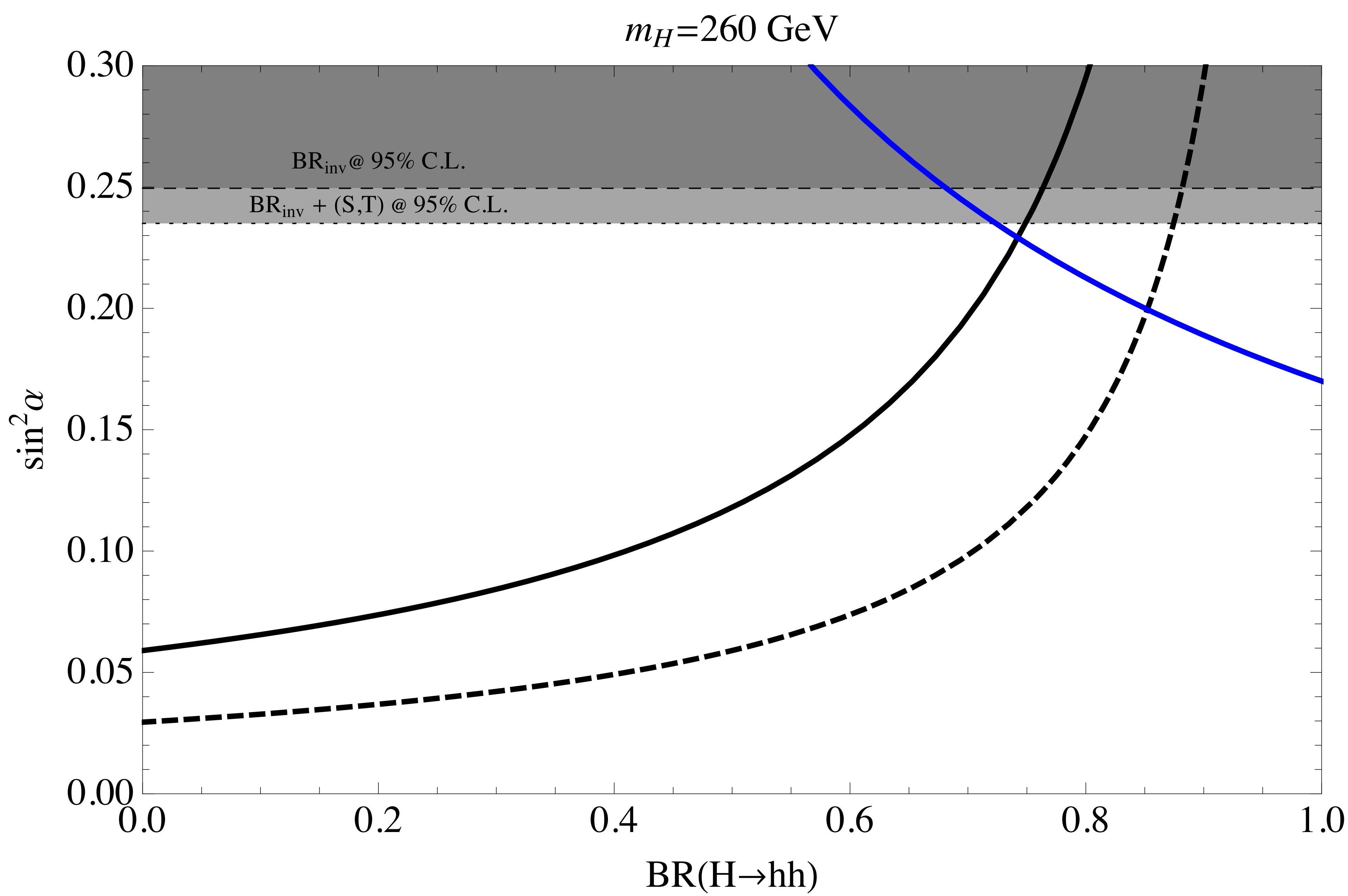
H→hh

(significance   3)

Double Higgs production (H→hh)

Detectability m_H = 260

800 fb^{-1}



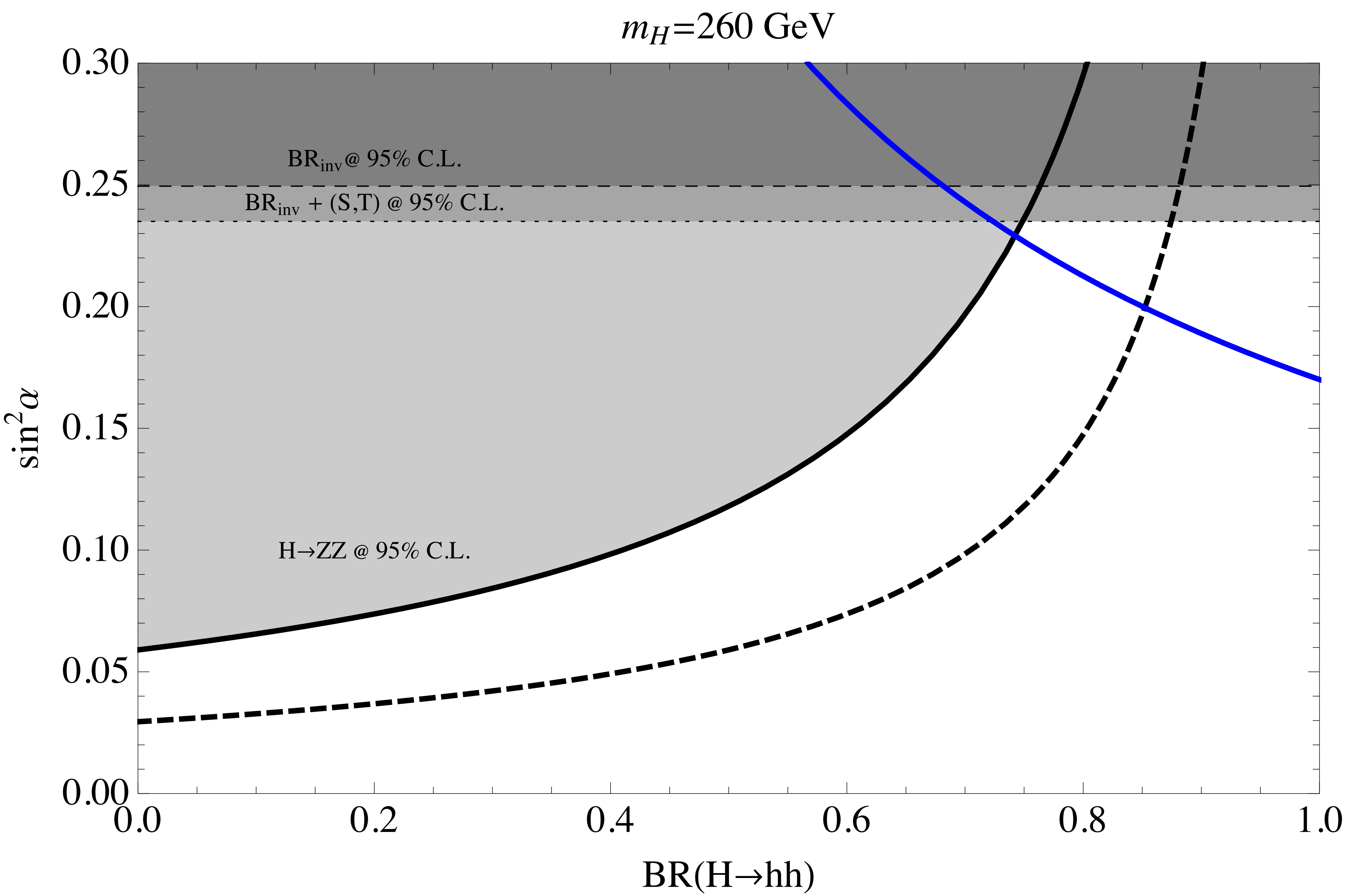
H→hh

(significance   3)

Double Higgs production (H→hh)

Detectability m_H = 260

800 fb^{-1}



H→hh

(significance   3)

A short comment on Dark Matter

S. Baek, P. Ko, W. Park

- Dark matter can be incorporated into the model using the singlet as a portal and imposing a discrete symmetry (eg Z_2)

$$\mathcal{L}_\psi = \bar{\psi}(i\partial\!\!\!/ - m_0)\psi + \lambda_\psi S \bar{\psi}\psi$$

A short comment on Dark Matter

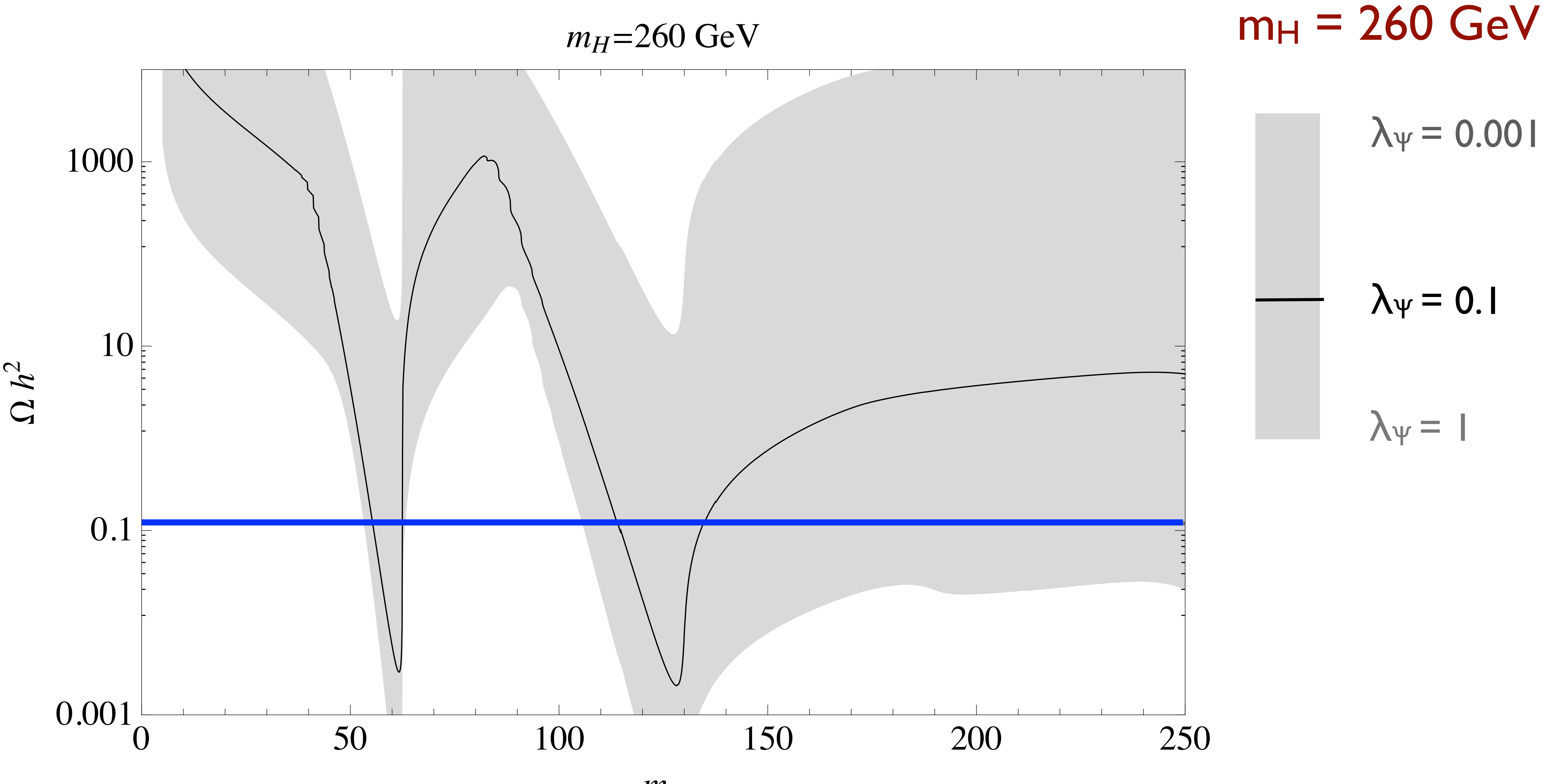
S. Baek, P. Ko, W. Park

- Dark matter can be incorporated into the model using the singlet as a portal and imposing a discrete symmetry (eg Z_2)

$$\mathcal{L}_\psi = \bar{\psi}(i\partial\!\!\!/ - m_0)\psi + \lambda_\psi S\bar{\psi}\psi$$

- Getting the correct amount of DM imposes relations between the two parametes: mass (m) of the fermion and coupling to the singlet (λ_Ψ)

A short comment on Dark Matter

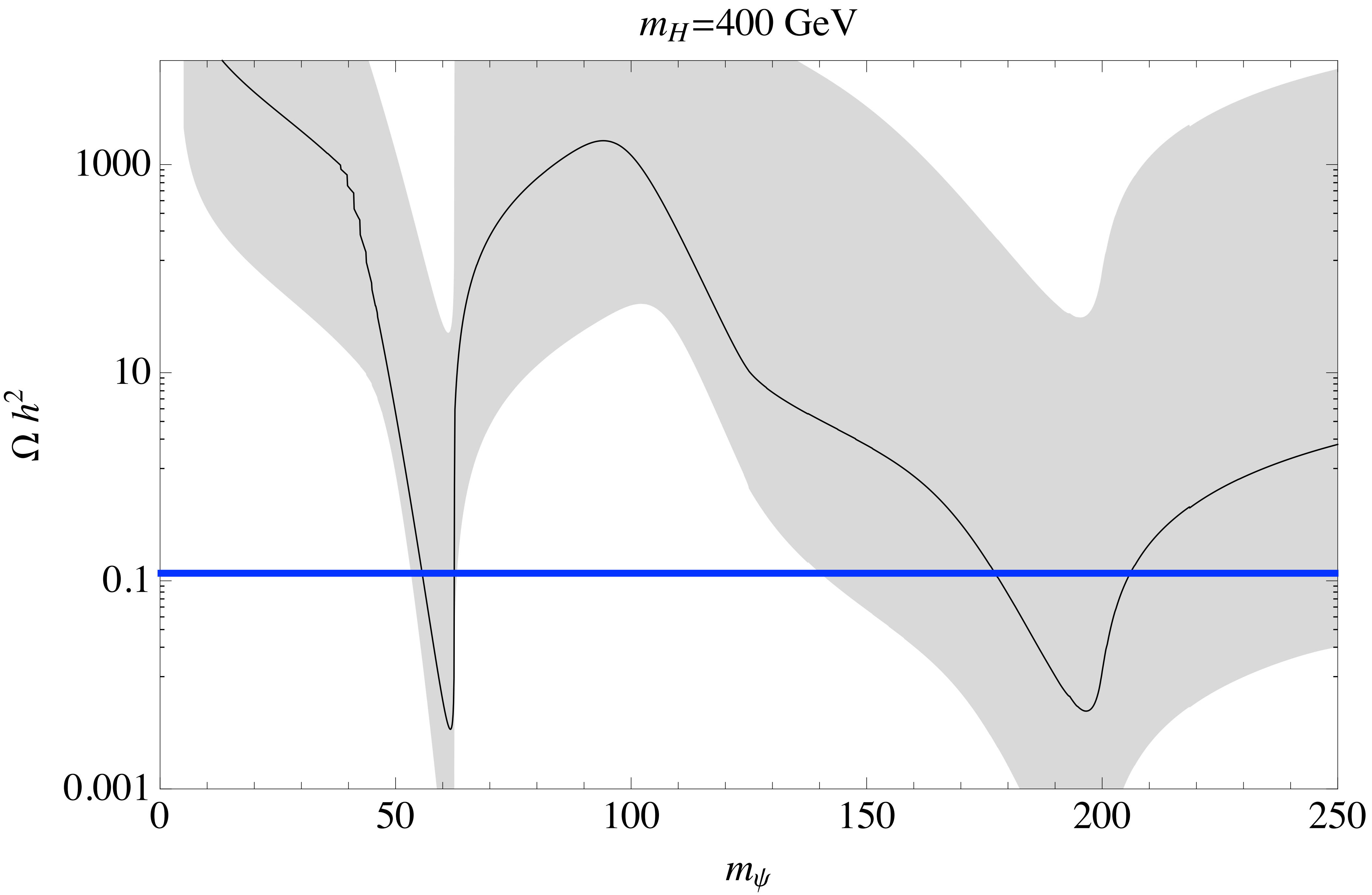


$BR(h \to \bar{\psi}\psi) \neq 0$ →|

$BR(H \to \bar{\psi}\psi) \neq 0$ → |

Resonance areas: $2m_\Psi \approx m_h$, m_H

A short comment on Dark Matter



m_H = 400 GeV

λ_ψ = 0.001

λ_ψ = 0.1

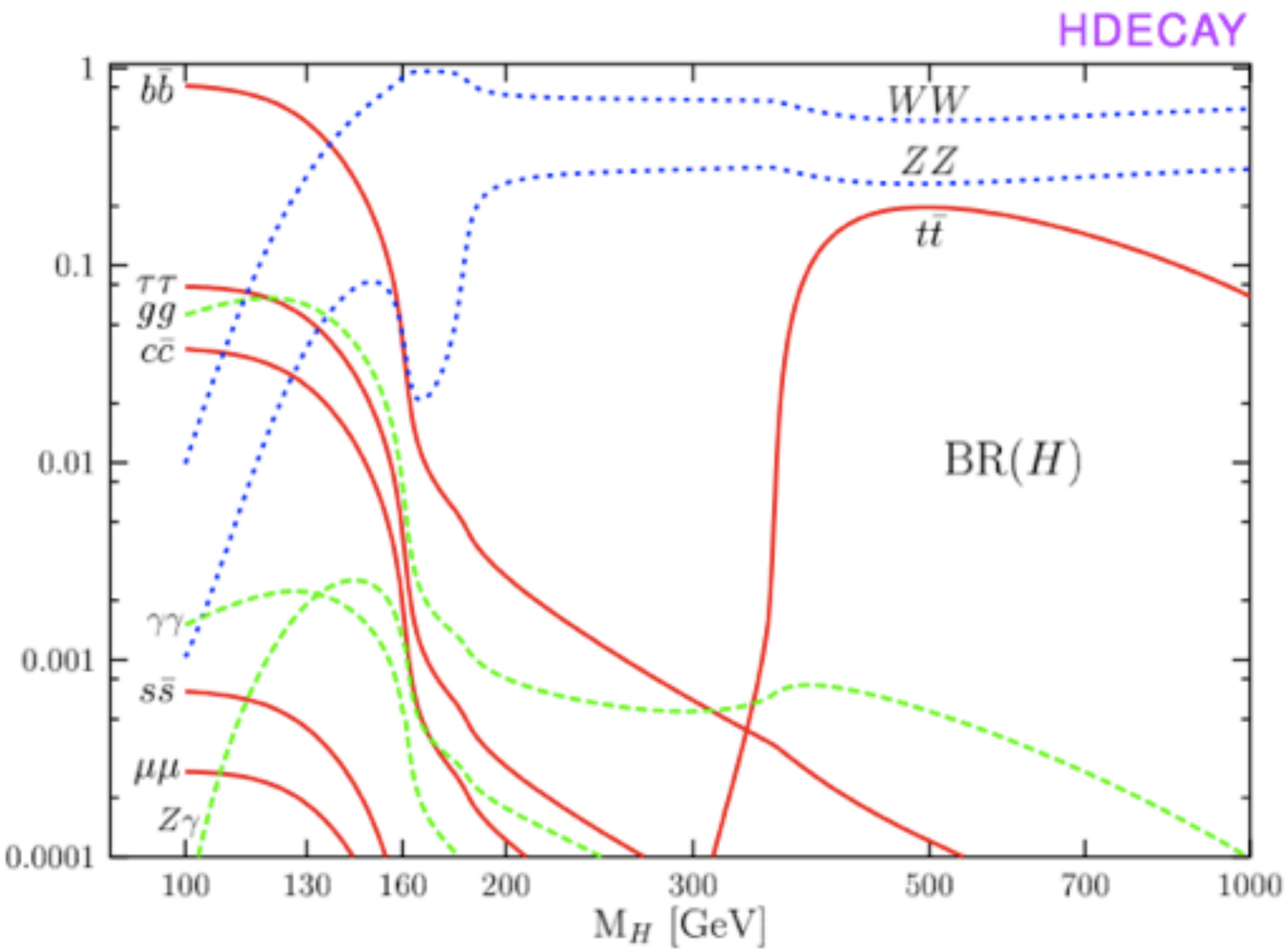
λ_ψ = 1

Conclusion

- Higgs couplings from latest LHC data are compatible with the minimal extension of the Higgs sector ($\sin^2\alpha < 0.22$ @90% CL)
- Electroweak precision data provide additional constraints for $m_H \geq 250$ GeV
- The $H \to hh$ decay offers an opportunity to test this model at the LHC
- The di-leptonic channel $H \to hh \to bb\ W^+W^-$ is quite promising but also challenging. We have analyzed it in detail using different kinematic variables (MT2, MAOS)
- Using proper cuts, a significance ≈ 3 for 600/800 fb^{-1} can be achieved at the $\sqrt{s} = 14$ TeV LHC if the mixing is close to its present limit & $BR(H \to hh) \approx 1$
  A larger significance would require combining different hh decay channels
- Nice complementarity between $H \to hh$ and $H \to ZZ$ channels

Adding dark matter does not necessarily change these conclusions

THANK YOU !


HDECAY
$b\bar{b}$
WW
ZZ
$t\bar{t}$
$\tau\tau$
gg
$c\bar{c}$
$\gamma\gamma$
$s\bar{s}$
$\mu\mu$
$Z\gamma$
BR(H)
1
0.1
0.01
0.001
0.0001
100
130
160
200
300
500
700
1000
M_H [GeV]