IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

Higgs Scenario from Peccei-Quinn Mechanism at the LHC

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Outline

- introduction and motivation
- variant axion models
- impact on Higgs boson search
    - h -> $\gamma\gamma$ and production
- Summary

Introduction

strong CP problem (very short review)

$$\mathcal{L}_{QCD} = \mathcal{L}_{pert} + \bar{\theta}\frac{g_s^2}{32\pi^2}G^{a\mu\nu}\tilde{G}_{a\mu\nu}$$

$$\bar{\theta} = \theta + \mathrm{Arg}(\det\mathcal{M}) \quad \tilde{G}_{a\mu\nu} = \frac{1}{2}\varepsilon_{\mu\nu\alpha\beta}G_{a\alpha\beta}$$

from neutron EDM exp → $\bar{\theta} \lesssim \mathcal{O}(10^{-9})$

Harris et al. PRL 82, 904 (1999)

Why so small?

intro. -- PQWW axion

Peccei-Quinn Mechanism and PQWW axion

Peccei and Quinn, PRL 38, 1440 (1977), PRD 16, 1791 (1977);
Weinberg, PRL 40, 223 (1978); Wilczerk, PRL 40, 279 (1978)

an addition global symmetry $U(1)_{PQ}$, SSB @ f_a

a NGB appears -- axion

$$\mathcal{L}_{QCD} = ... + \bar{\theta}\frac{g_s^2}{32\pi^2}G^{a\mu\nu}\tilde{G}_{a\mu\nu} + \xi\frac{a}{f_a}\frac{g_s^2}{32\pi^2}G^{a\mu\nu}\tilde{G}_{a\mu\nu}$$

$$< a >= -\frac{\bar{\theta}f_a}{\xi}$$

θ-term is cancelled!

NOTE

mass of axion, coupling to SM fields ∝ $1/f_a$

intro. -- axion

- original PQWW axion model ($f_a \approx v_{ew}$) was ruled out experimentally by

$$BR(K^+ \to \pi^+ + \text{nothing}) < 3.8\times10^{-8}$$

Y. Asano et al, PLB 107, 159 (1981)

invisible axion

- introduce a SU(2)xU(1) singlet heavy scalar Φ with $f_a = \langle\Phi\rangle \gg v_{ew}$ (KSVZ, DFSZ)

Kim '79, Shifman, Vainshtein, Zakharov '80; Dine, Fischler, Srednicki '81 Zhitnitsky '80

axion: very light, very weakly coupled

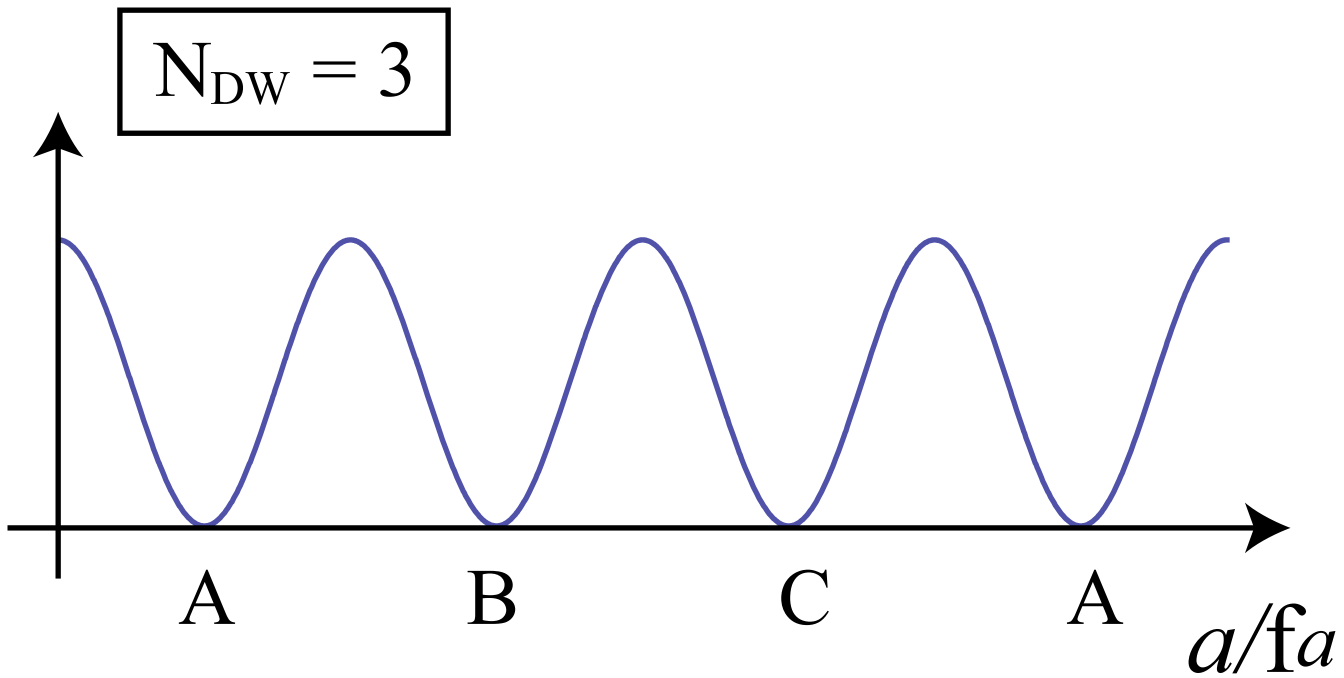
constraints: 10^9 GeV < f_a < 10^{12} GeV

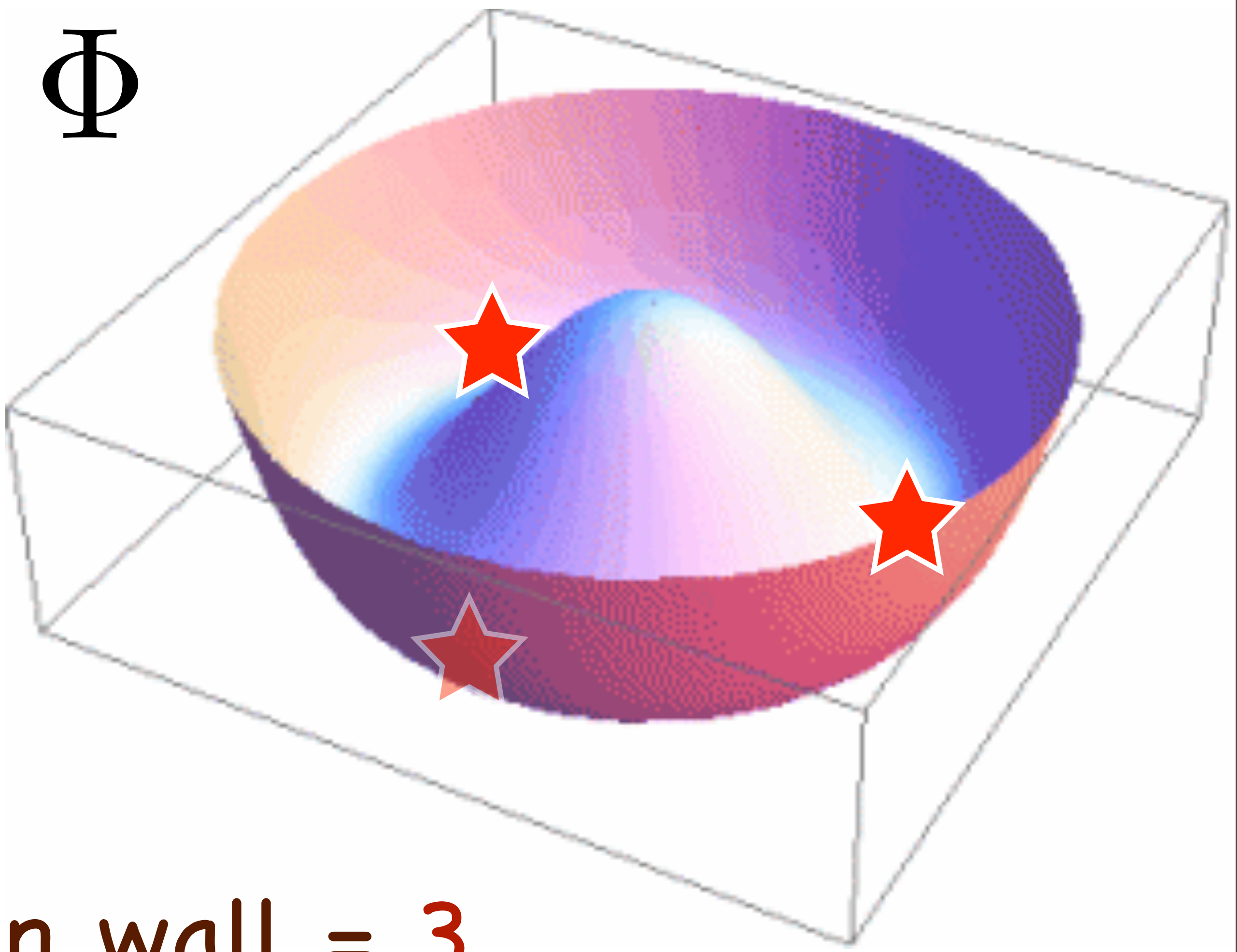
However → domain wall problem

Sikivie, PRL48, 1156 (1982)

domain wall problem

Multiple degenerate vacua → domain wall may form





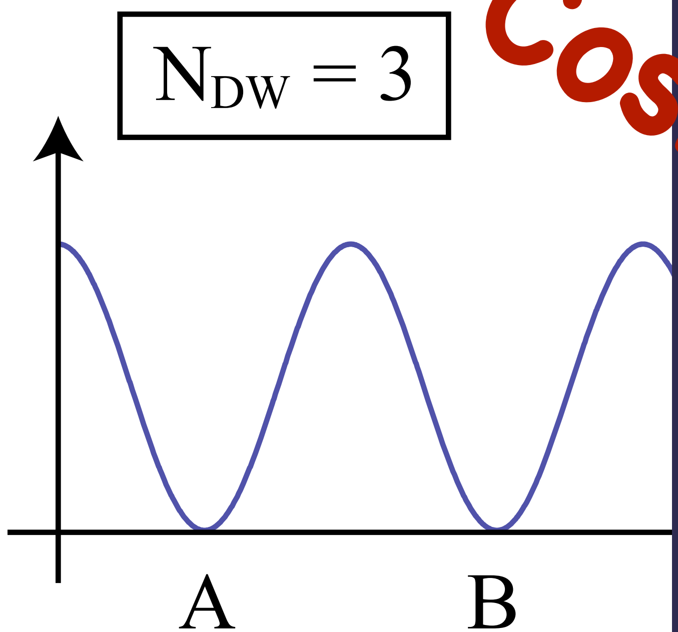
DFSZ model has # of domain wall = 3

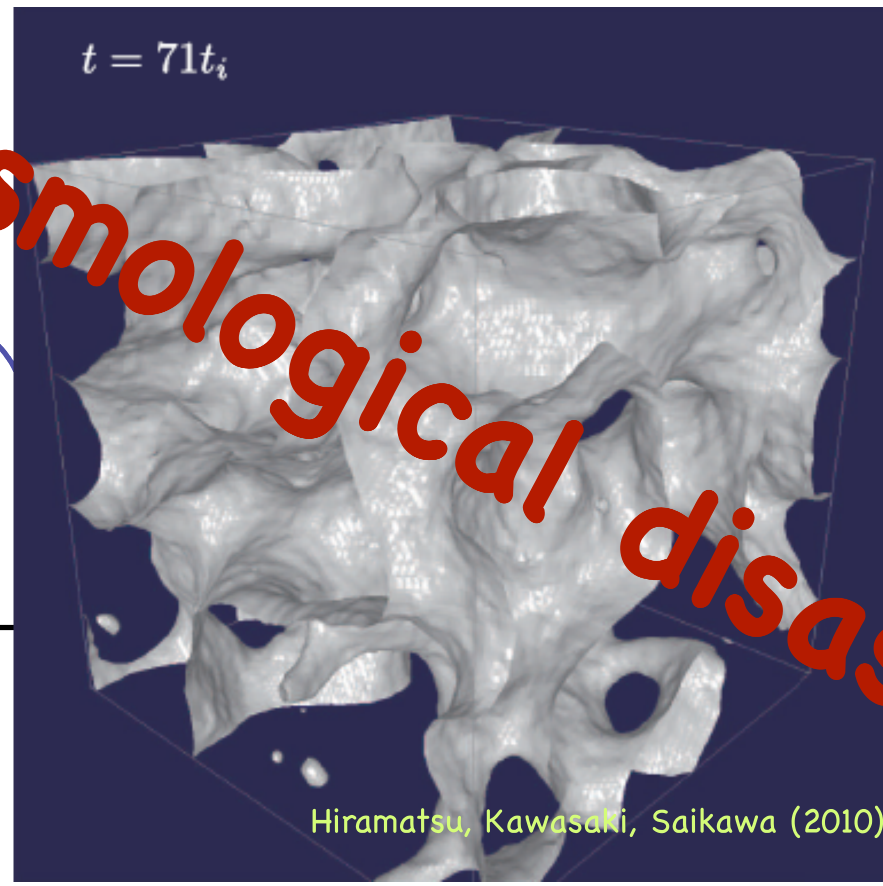
since PQ charges are assigned to 3 generations of quarks

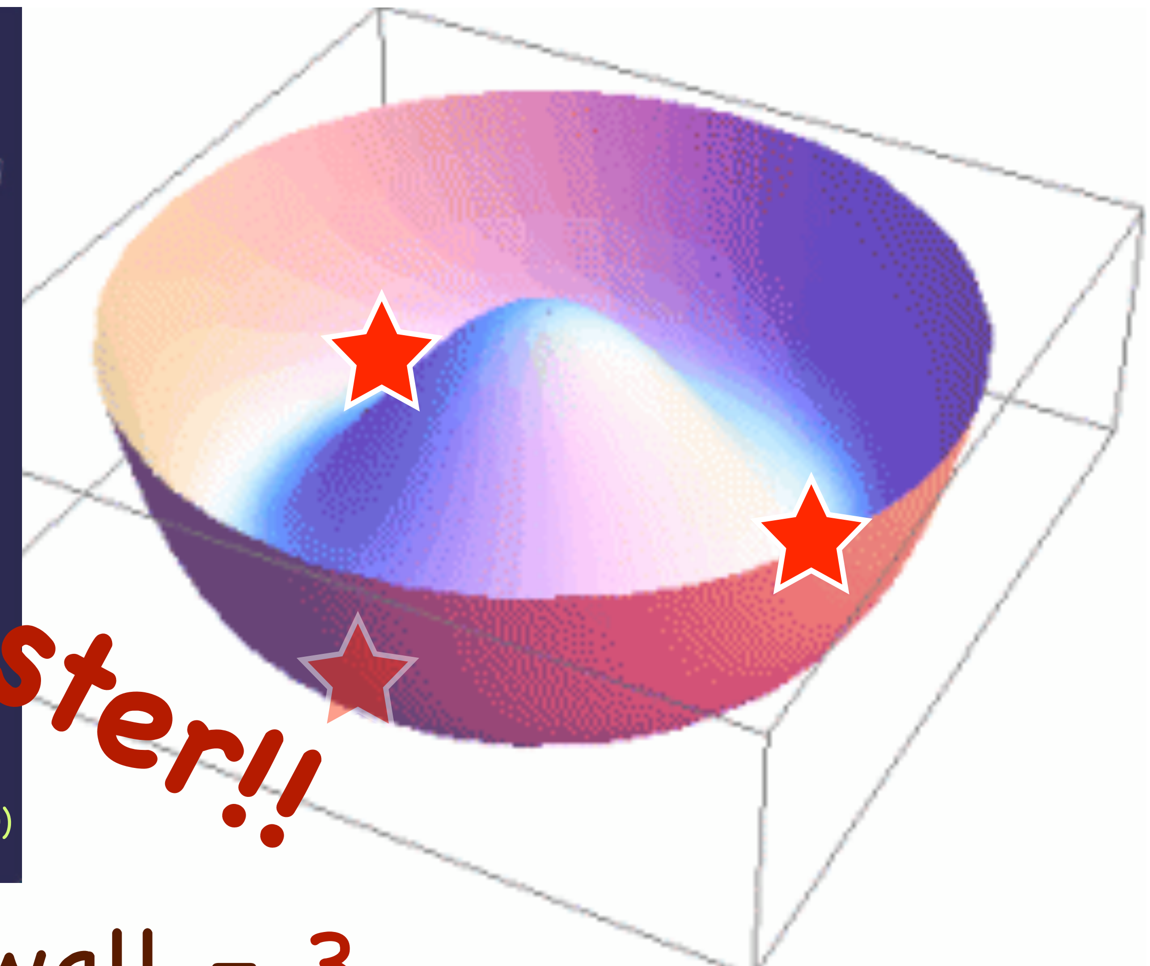
domain wall problem

Multiple degenerate vacua

→ domain wall may form







Cosmological disaster!!

DFSZ model has # of domain wall = 3

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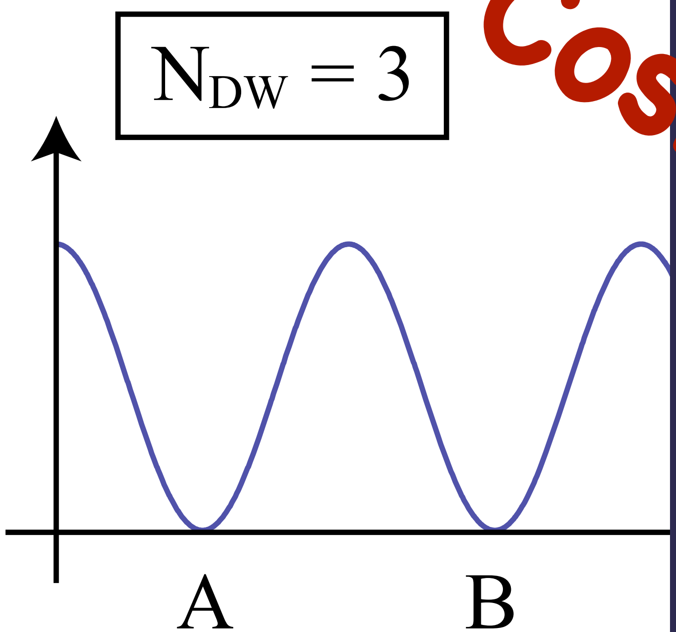
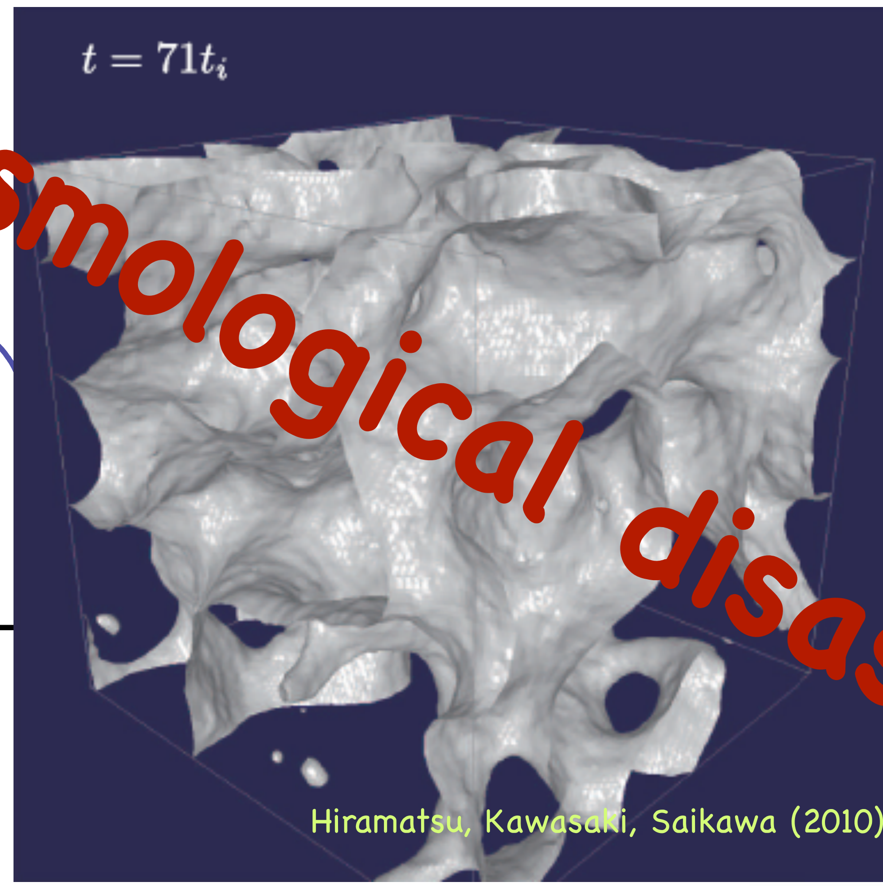
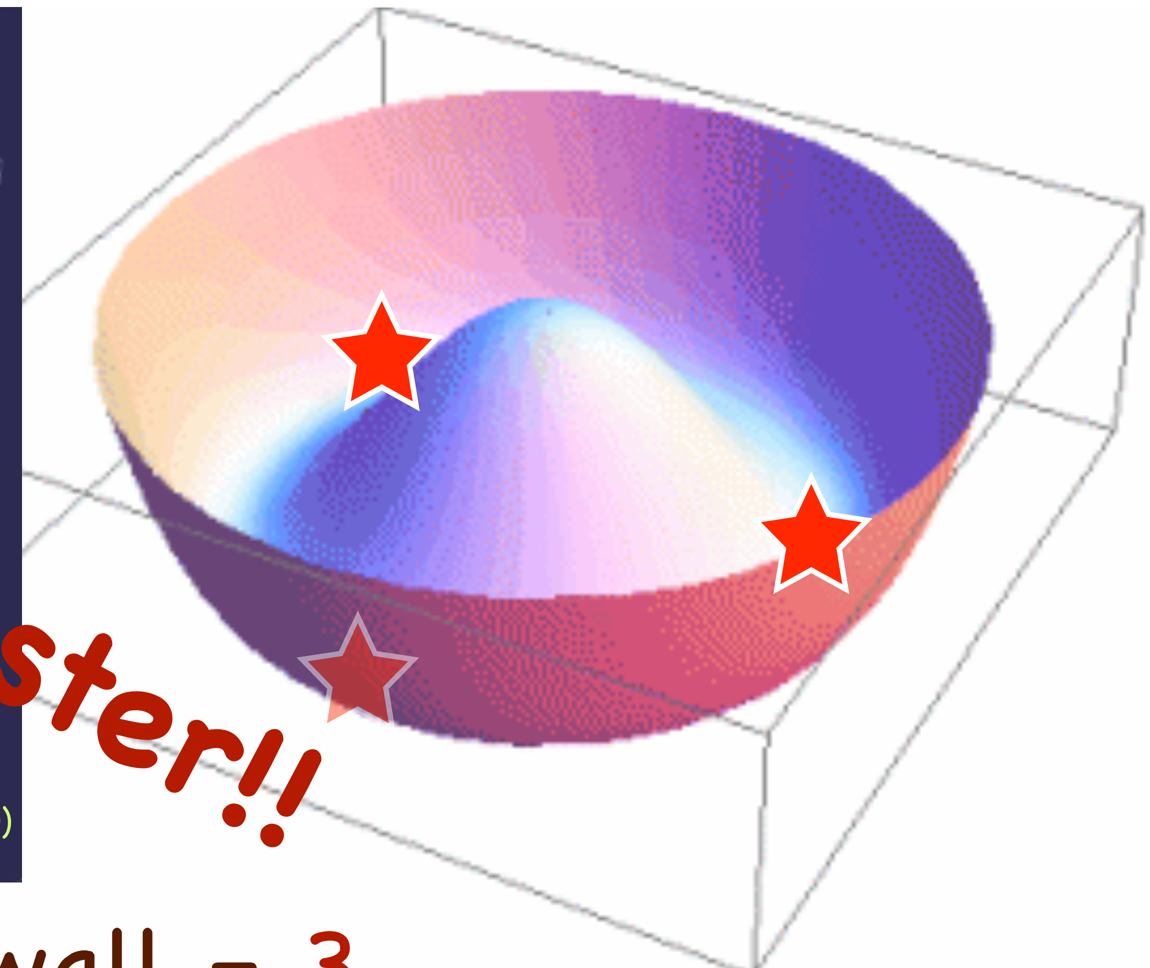
domain wall problem

Multiple degenerate vacua → domain wall may form







Cosmological disaster!!

DFSZ model has # of domain wall = 3

since PQ charges are assigned to 3 generations of quarks

How to avoid DW problem?

1) low inflation scale, 2) explicit PQ symm breaking, 3) # of DW = 1

variant axion models

Peccei, Wu, Yanagida PLB 172, 435 (1986),
Krauss, Wilczek PLB 173, 189 (1986)

- a two Higgs doublets + one singlet scalar (heavy)
  (Φ_1 , Φ_2) (σ)
- Φ_2 couples to only u or c or t quark
  (carries PQ charge)

N_{DW} = 1

NO domain wall problem !!

- couple to t (model T)
  PQ charge assignment:

Φ_1	Φ_2	t_R	other q's	σ
0	-1	-1	0	1

variant axion models

- model T

potential

$$V(\Phi_1,\Phi_2,\sigma) = \lambda_1\left(|\Phi_1|^2-\frac{v_1^2}{2}\right)^2+\lambda_2\left(|\Phi_2|^2-\frac{v_2^2}{2}\right)^2+\lambda\left(|\sigma|^2-\frac{v^2}{2}\right)^2$$
$$+a\,|\Phi_1|^2|\sigma|^2+b\,|\Phi_2|^2|\sigma|^2+\left(m\,\Phi_1^\dagger\Phi_2\sigma+\mathrm{h.c.}\right)$$
$$+d\,|\Phi_1^\dagger\Phi_2|^2+e\,|\Phi_1|^2\,|\Phi_2|^2$$

Yukawa

$$-\mathcal{L}_{\mathrm{Yukawa}} = y_{ij}^{(d)}\bar{Q}_{Li}\Phi_1 d_{Rj}+y_i^{(u)}\bar{Q}_{Li}\tilde{\Phi}_1 u_R+y_i^{(c)}\bar{Q}_{Li}\tilde{\Phi}_1 c_R$$
$$+y_i^{(t)}\bar{Q}_{Li}\tilde{\Phi}_2 t_R,$$

VAM avoids DW problem

⇒ Yukawa couplings are different

⇒ can have signal of VAM at LHC??

variant axion models

- model T

Higgs bosons

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + h_1 + i g_1) \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + h_2 + i g_2) \end{pmatrix}$$

$$\Longrightarrow \begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix},$$

$\sin\alpha \to 0$ ⟹ $H \sim h_1, h \sim h_2$

couplings to SM particles

$\tan\beta \equiv v_2/v_1$ ⟹ larger/smaller than 1

variant axion models

- model T

Higgs bosons

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + h_1 + ig_1) \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + h_2 + ig_2) \end{pmatrix}$$

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$\sin\alpha \to 0$ → $H \sim h_1, h \sim h_2$

light

couplings to SM particles

$\tan\beta \equiv v_2/v_1$ → larger/smaller than 1

variant axion models

- model T -- light Higgs couplings

to gauge bosons

$$hVV\ :\ \sin(\beta-\alpha)\ g_{\rm SM}^{hVV}$$ → SM like

tanβ large, sinα≈0

to quarks

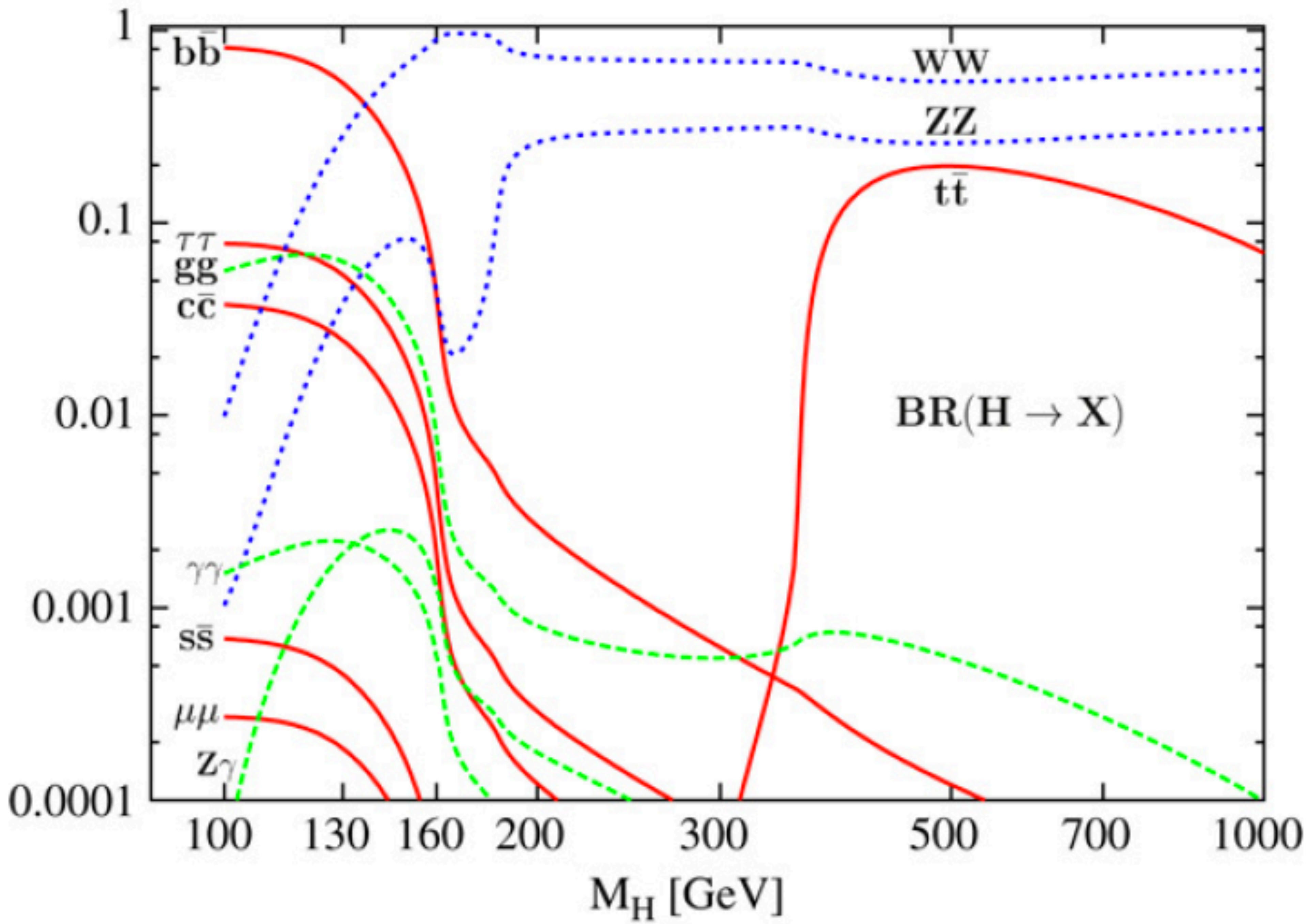
$$hcc\ :\ -\frac{\sin\alpha}{\cos\beta}g_{\rm SM}^{hcc},$$
$$hbb\ :\ -\frac{\sin\alpha}{\cos\beta}g_{\rm SM}^{hbb},$$

} suppressed if |sinα| < cotβ

$$htt\ :\ \frac{\cos\alpha}{\sin\beta}g_{\rm SM}^{htt}.$$ → SM like

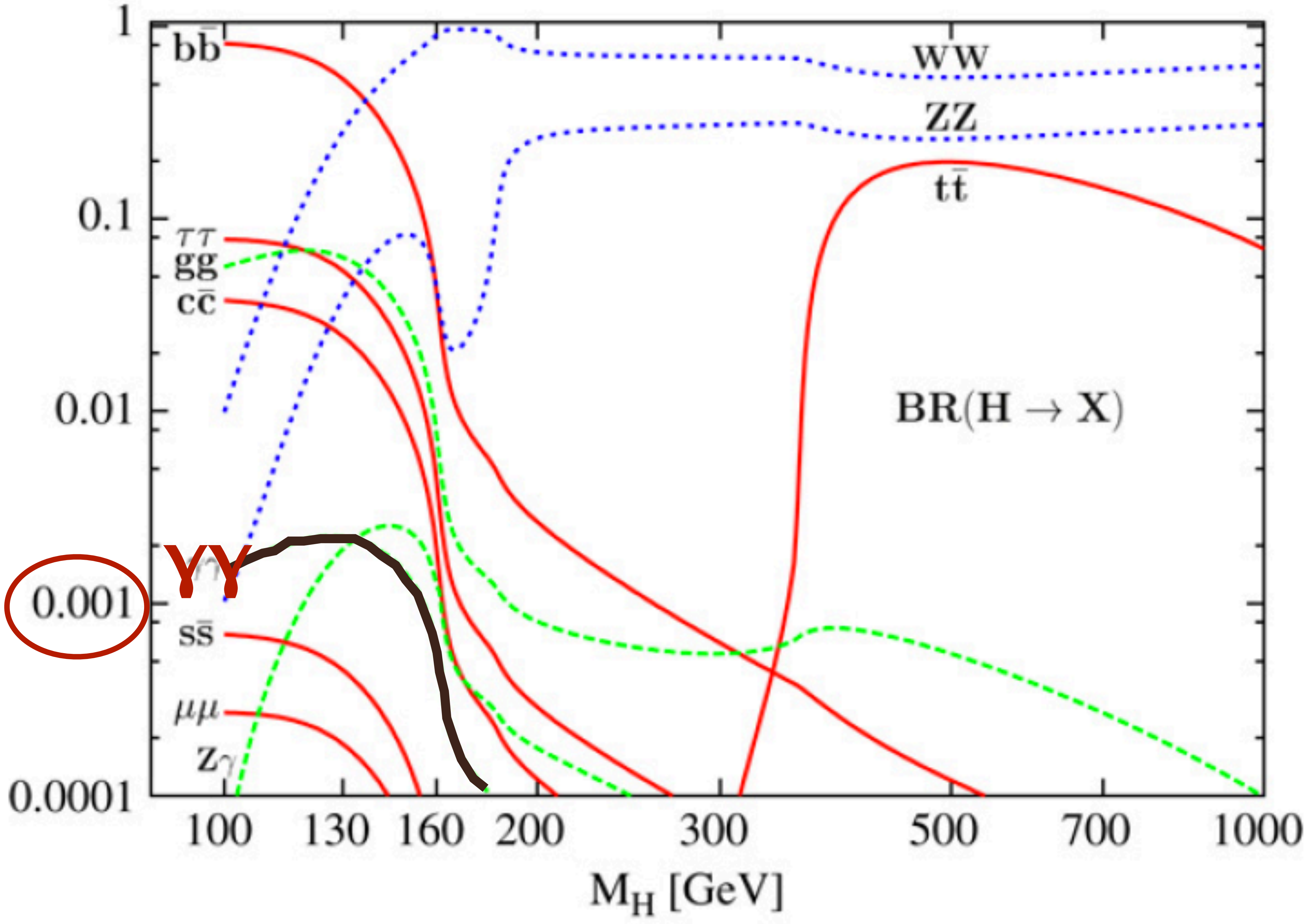
Higgs search

decay BRs in SM



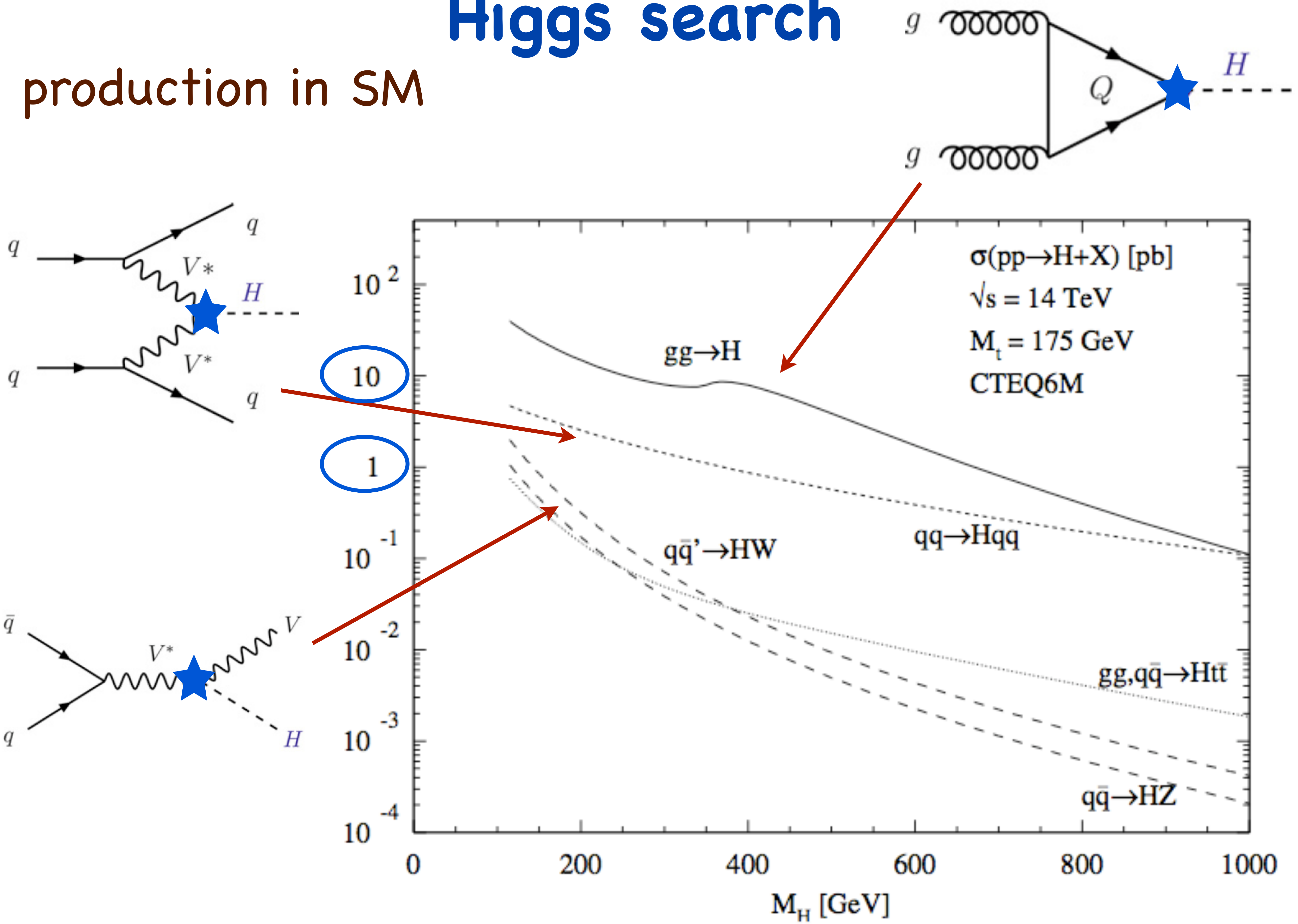
Higgs search

decay BRs in SM



Higgs search

production in SM



Model U

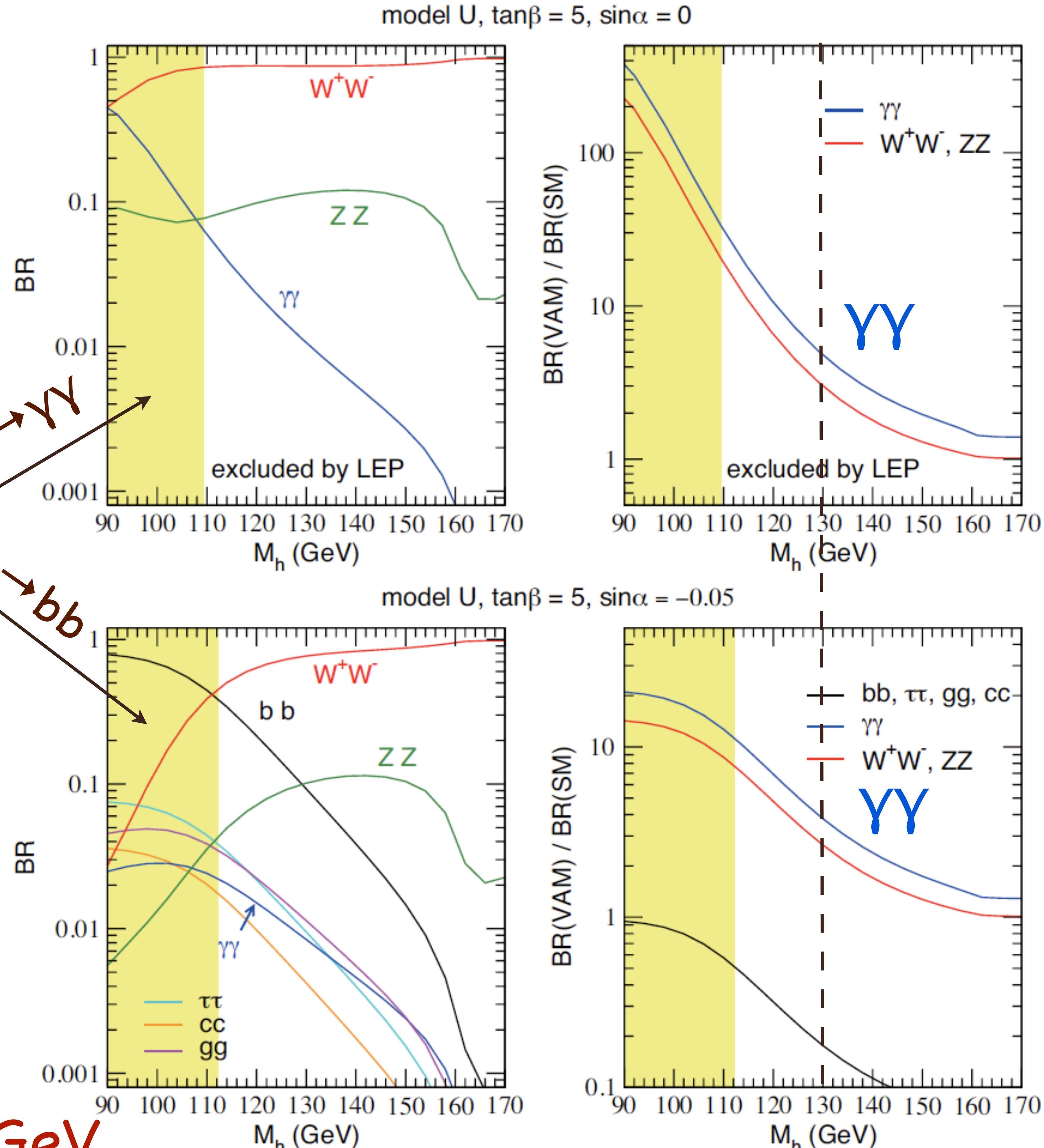
$\tan\beta = 5$

$\sin\alpha = 0$

constrained by LEP

$h \to \gamma\gamma$

$h \to bb$



$\sin\alpha = -0.05$

a factor of $5 \sim 30$ enhancement for $M_h \lesssim 130$ GeV

Model C

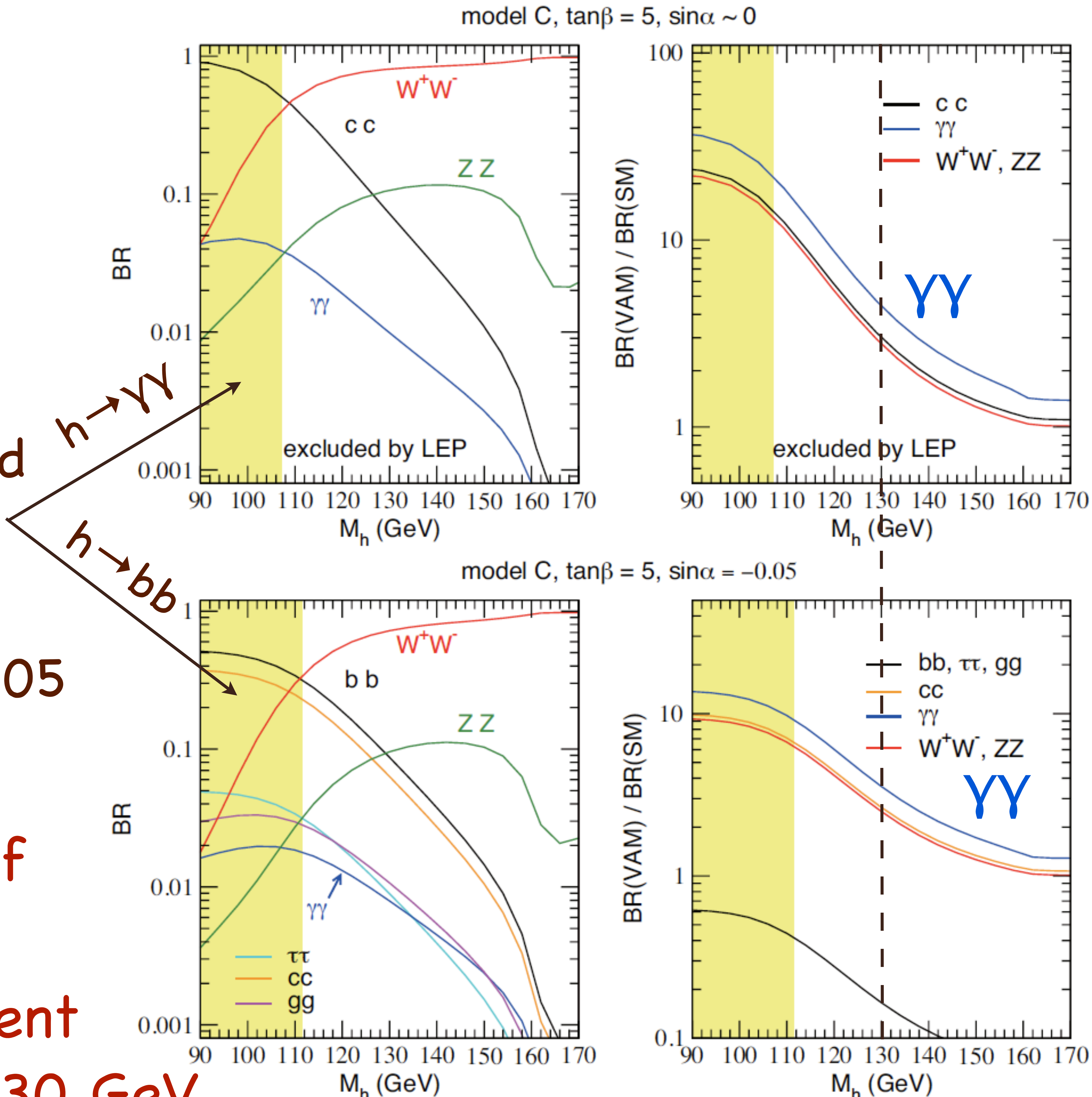
$\tan\beta = 5$

$\sin\alpha = 0$

constrained by LEP

$\sin\alpha = -0.05$

a factor of $4 \sim O(10)$ enhancement for $M_h \lesssim 130$ GeV



Model T

$\tan\beta = 5$

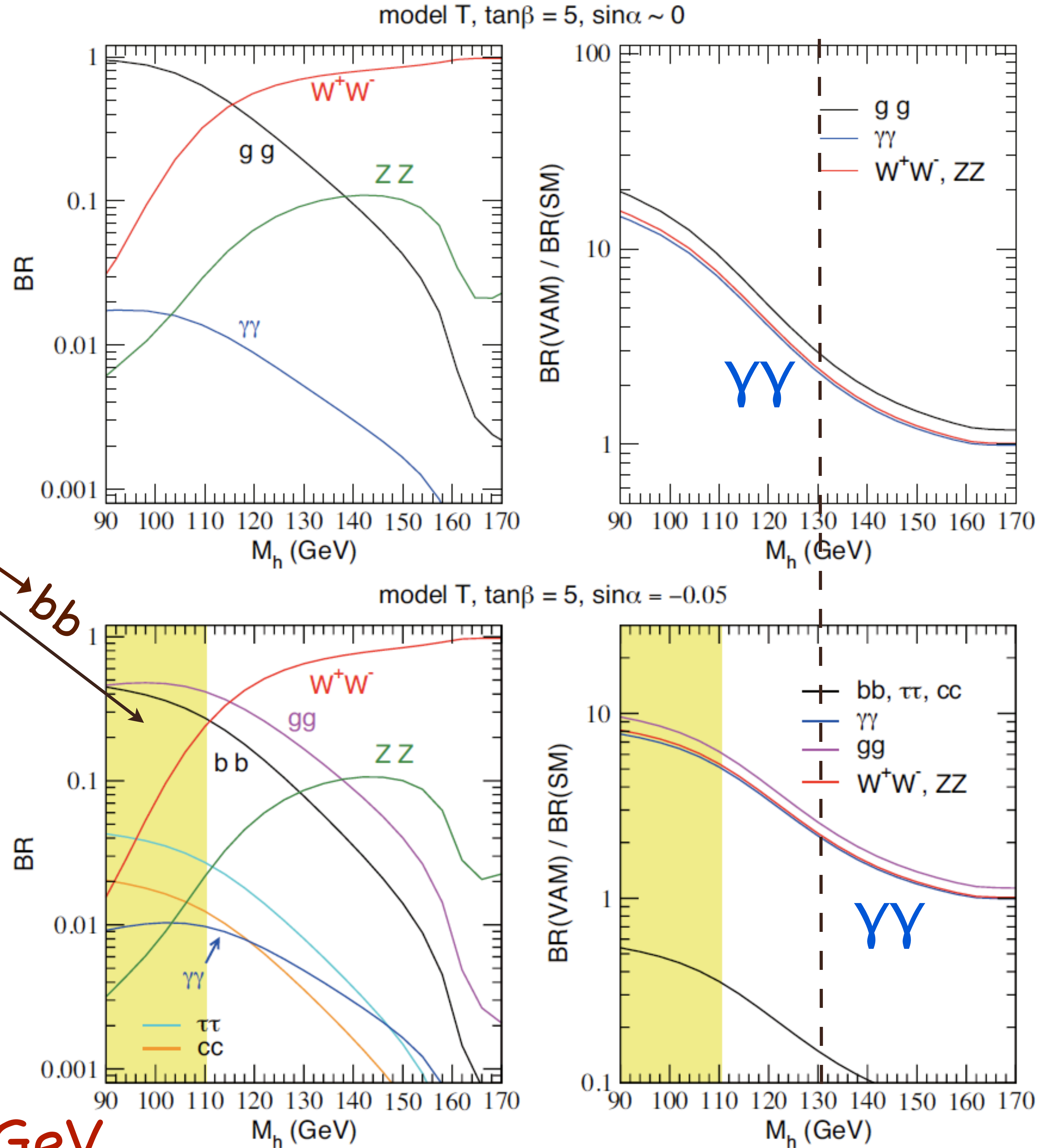
$\sin\alpha = 0$

constrained by LEP

$h \to bb$

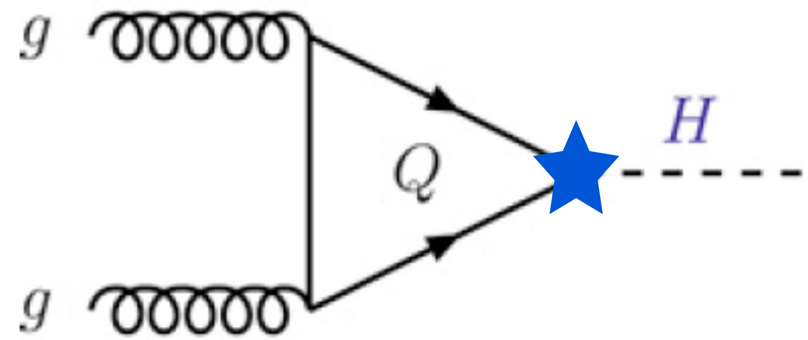
$\sin\alpha = -0.05$

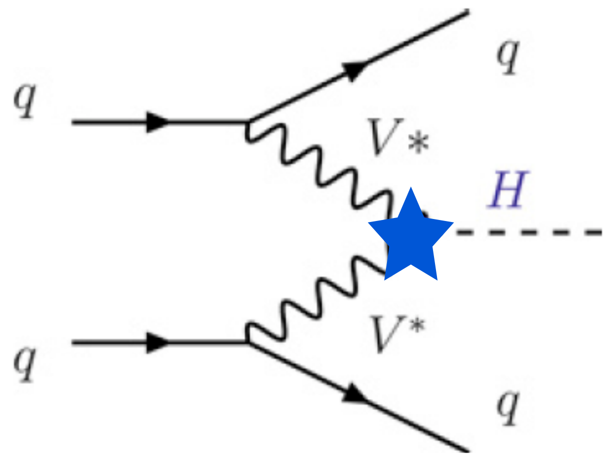
a factor of $2 \sim O(10)$ enhancement for $M_h \lesssim 130$ GeV

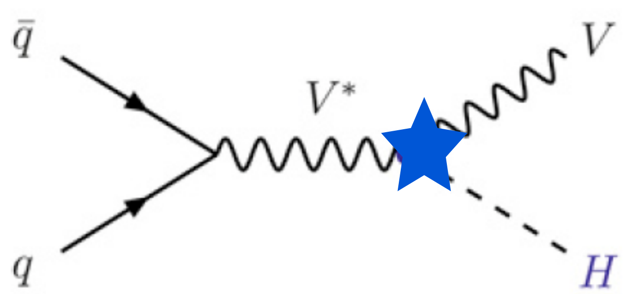


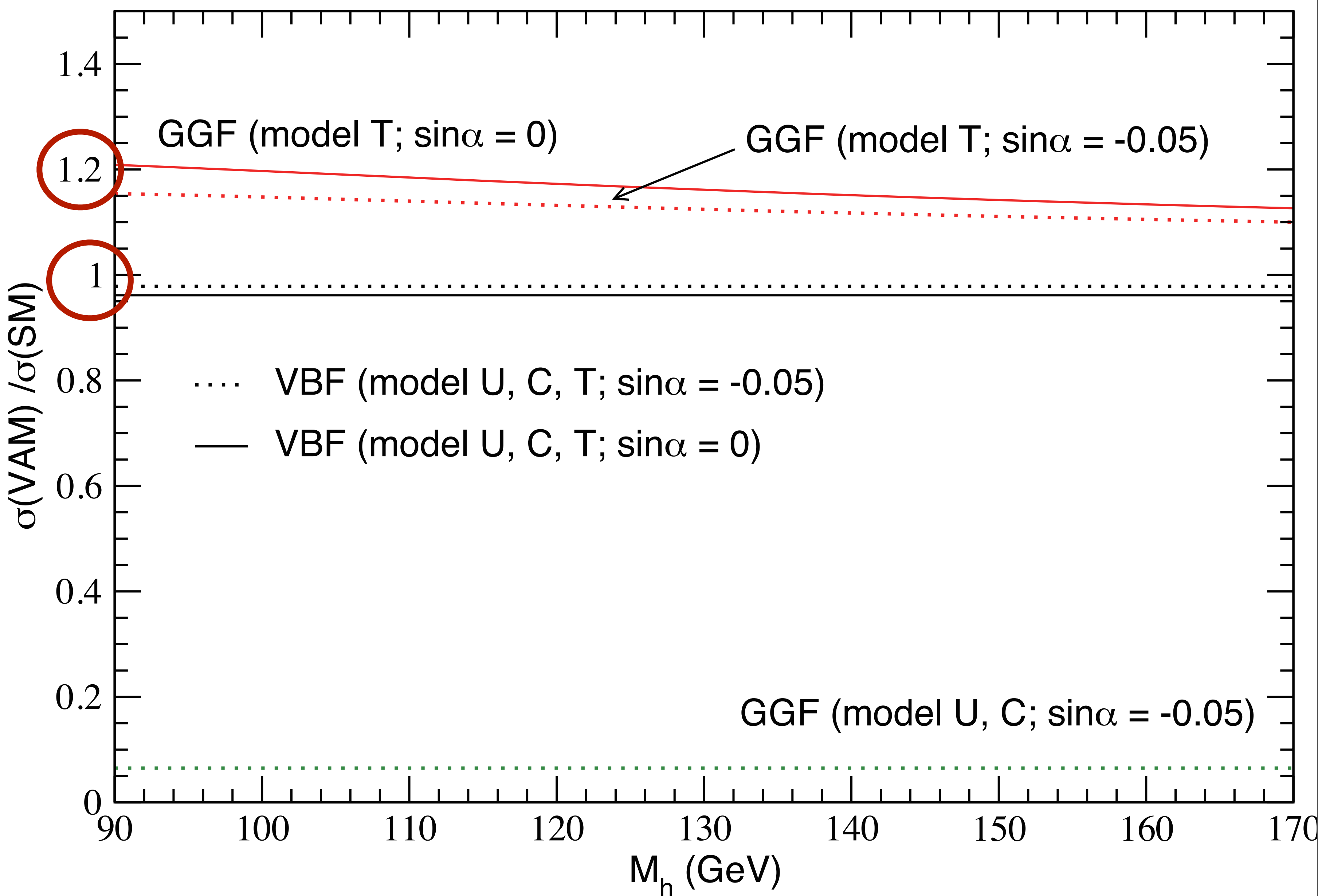
Higgs search

production cross sections









model U and C

→ VBF & VH

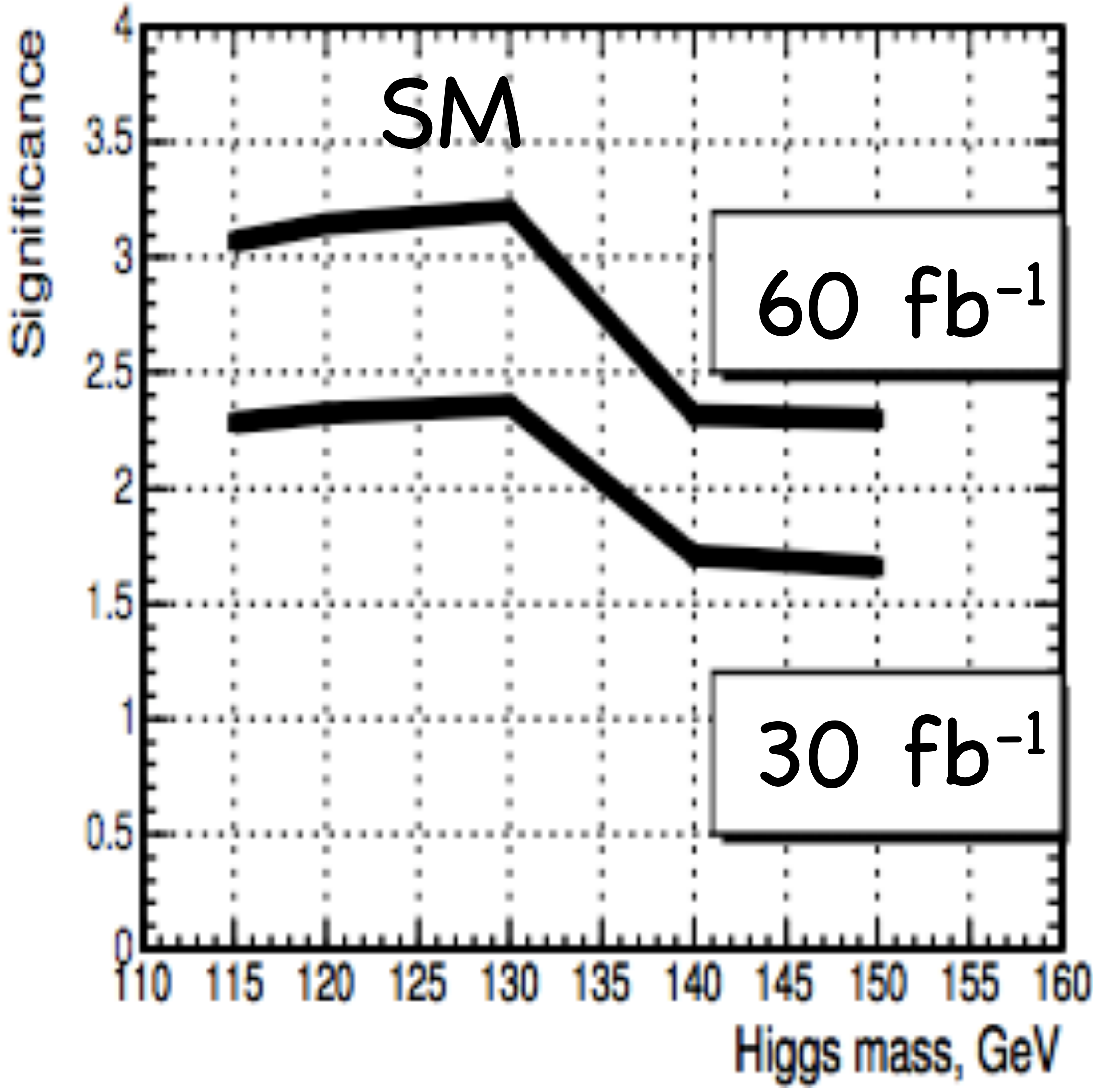
model T → GGF, VBF, VH

Higgs search

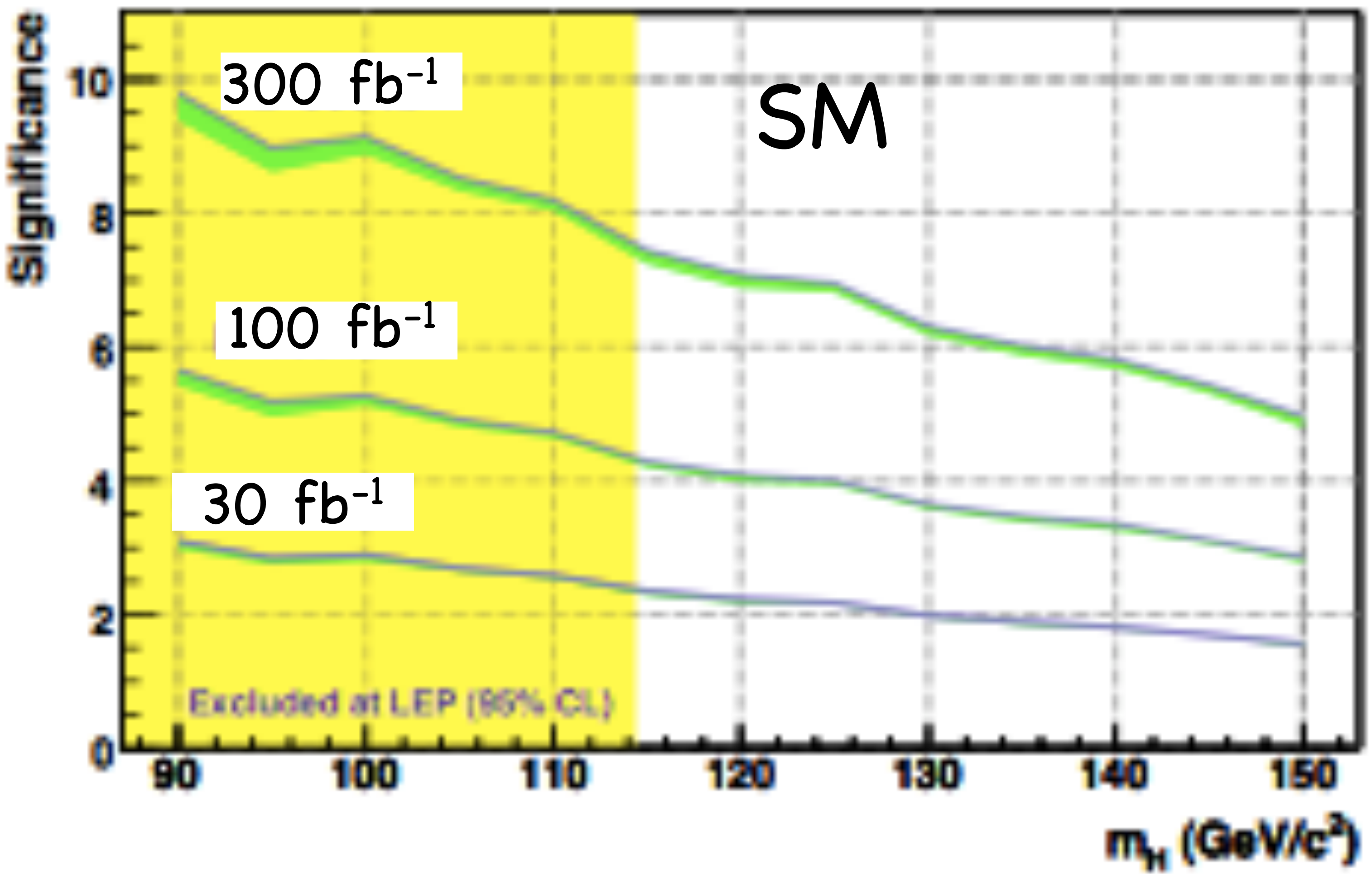
impacts

VBF, $h \to \gamma\gamma$

CMS, TDR



Vh, $h \to \gamma\gamma$



model U, C $\xrightarrow[M_h\,=\,120\text{ GeV}]{5\sigma\text{ w/}}$ ~3 fb^{-1} for $\sin\alpha = 0$

~10 fb^{-1} for $\sin\alpha = -0.05$

Higgs search

impacts

model T

same production Xsection

⊕

larger BR($h \to \gamma\gamma$)

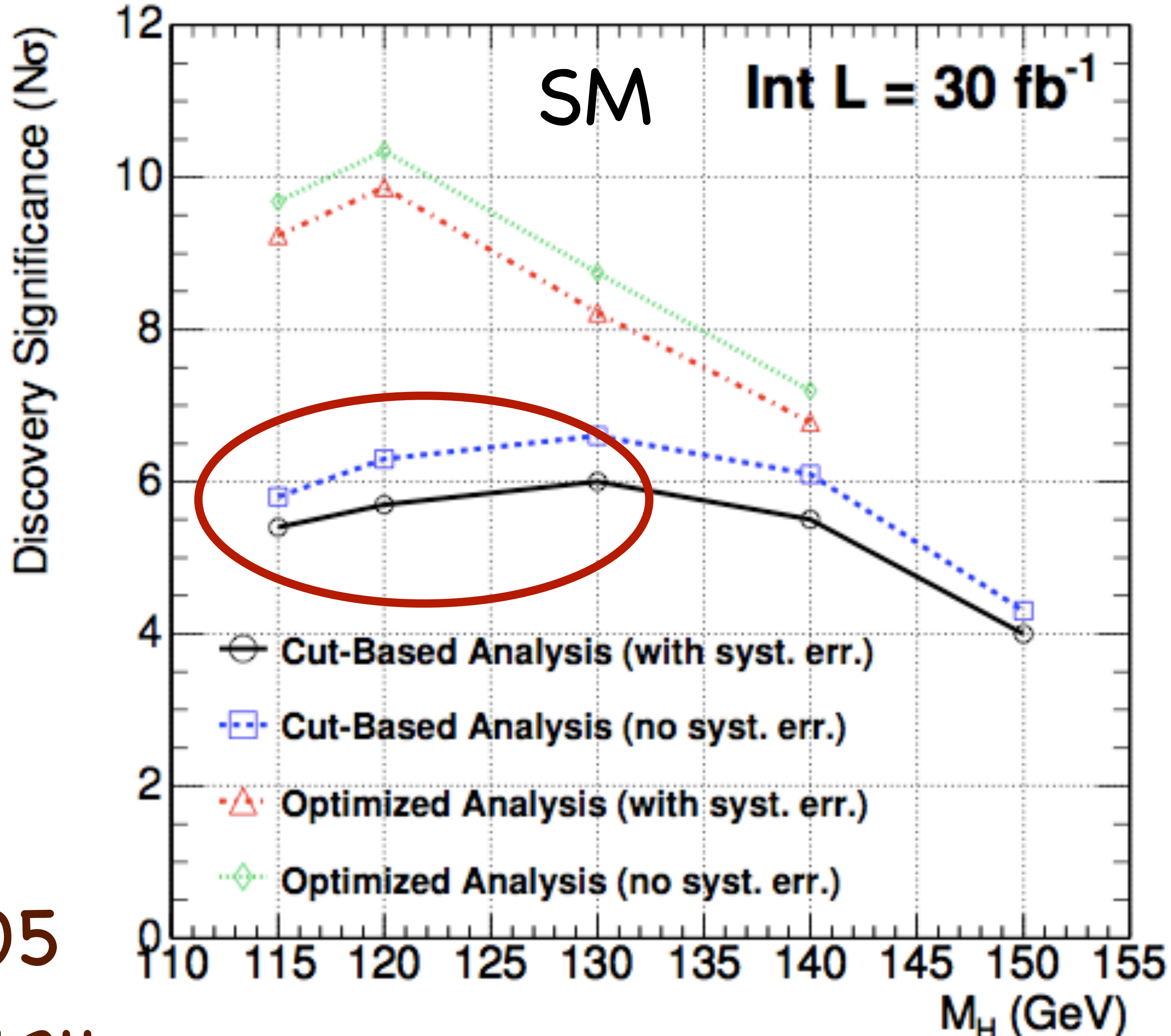
can reach

3σ for $\sin\alpha = 0$

2σ for $\sin\alpha = -0.05$

w/ 7 TeV, 1 fb^{-1} LHC!!

inclusive $h \to \gamma\gamma$ CMS, TDR



Summary

In variant axion models, which avoids the domain wall problem,

- branching ratio of light Higgs boson to two photons can be significantly enhanced.
- gluon-gluon fusion can be suppressed or enhanced, VBF and VH are similar to SM
- VBF, VH + $h \to \gamma\gamma$ may be important at LHC
- in model T (PQ Higgs couples to top only), LHC w/ 7 TeV may have evidence of the existence of light Higgs boson