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Higgs couplings to heavy flavors

Rehovot, 25 June 2014

Plan

Heavy flavors = bottom + charm

- LHC constraints on Higgs couplings to heavy flavors
- Examples of models with modified Higgs couplings to heavy flavors

LHC Constraints

Where do we stand

- Gazillion sigma evidence for a SM-like Higgs boson
- Higgs mass is 125.5 GeV, give or take a few hundred MeV.
- Strong evidence for couplings to SM gauge bosons but also some direct/indirect evidence for couplings to fermions
- Strong evidence for gluon fusion production but also some evidence for vector boson fusion production

Simplified 7 parameter effective Higgs Lagrangian

$$
\begin{aligned}
\mathcal{L}_{h,\mathrm{sim}} = \frac{h}{v}\Big(& \quad 2c_V m_W^2 W_\mu^+ W_\mu^- + c_V m_Z^2 Z_\mu Z_\mu \\
& -c_u \sum_{q=u,c,t} m_q \bar{q} q - c_d \sum_{q=d,s,b} m_q \bar{q} q - c_l \sum_{l=e,\mu\tau} m_l \bar{l} l \\
& + \frac{1}{4} c_{gg} G_{\mu\nu}^a G_{\mu\nu}^a - \frac{1}{4} c_{\gamma\gamma} \gamma_{\mu\nu} \gamma_{\mu\nu} \\
& - \frac{1}{2} c_{WW} W_{\mu\nu}^+ W_{\mu\nu}^- - \frac{1}{4} c_{ZZ} Z_{\mu\nu} Z_{\mu\nu} - \frac{1}{2} c_{Z\gamma} \gamma_{\mu\nu} Z_{\mu\nu} \Big)
\end{aligned}
$$

$$
c_{WW} = c_{\gamma\gamma} + \frac{c_w}{s_w} c_{Z\gamma} \qquad c_{ZZ} = c_{\gamma\gamma} + \frac{c_w^2 - s_w^2}{c_w s_w} c_{Z\gamma}
$$

- Simpler effective theory with 7 free parameters
- Assume flavor blind Higgs couplings + custodial symmetry + no extra particles
- <ALL> 7 parameters are meaningfully constrained by current Higgs data
- Standard Model limit: $c_V = c_f = 1$, $c_{gg} = c_{\gamma\gamma} = c_{Z\gamma} = 0$

7 parameter fit

Central values and 1σ uncertainties

$$c_V = 1.04^{+0.03}_{-0.03}$$

$$c_u = 1.30^{+0.23}_{-0.27}$$

$$c_d = 1.03^{+0.27}_{-0.17}$$

$$c_l = 1.10^{+0.18}_{-0.15}$$

$$c_{gg} = \frac{g_s^2}{16\pi^2}\left(-0.48^{+0.44}_{-0.17}\right)$$

$$c_{\gamma\gamma} = \frac{e^2}{16\pi^2}\left(0.2^{+2.8}_{-3.3}\right)$$

$$c_{Z\gamma} = \frac{e g_L}{\cos\theta_W 16\pi^2}\left(4^{+10}_{-19}\right)$$

using only Higgs data:

$$c_V = 1.03^{+0.08}_{-0.08}$$

Islands of good fit with negative cu, cd, cl ignored here

Belusca-Maito, AA
arXiv: 1311.1113 + updates

$\Delta\chi^2 = \chi^2_{SM} - \chi^2_{min} \approx 5.5$, with 7 d.o.f.
SM hypothesis is a perfect fit :-(((

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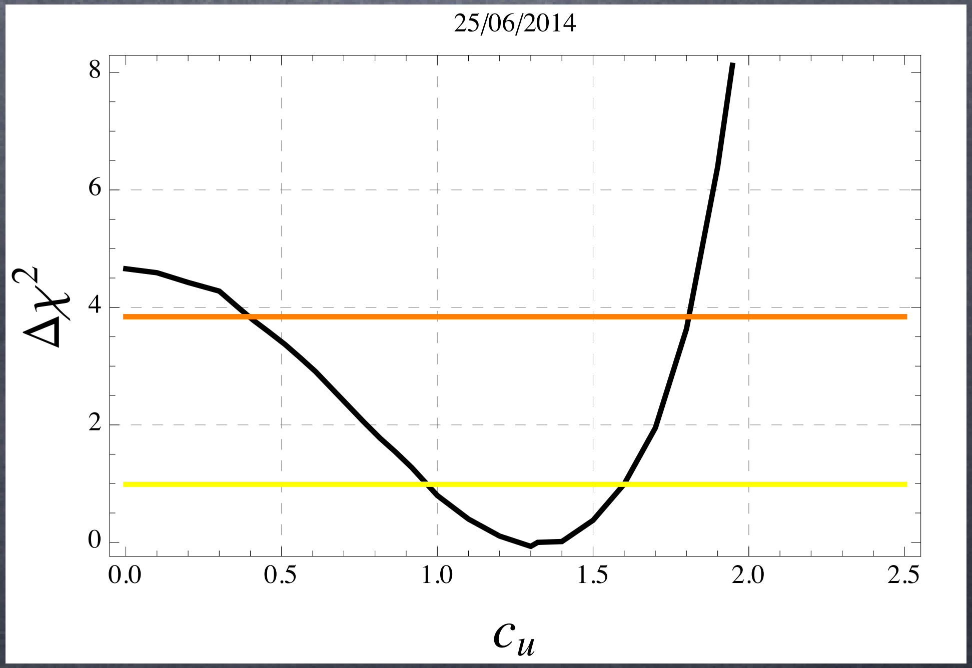
Bounds on cd from bottom mostly via Higgs width

$0.67 \leq c_d \leq 1.64$ @95%CL

Bounds on cu from top via tth constraints

$0.39 \leq c_u \leq 1.81$ @95%CL

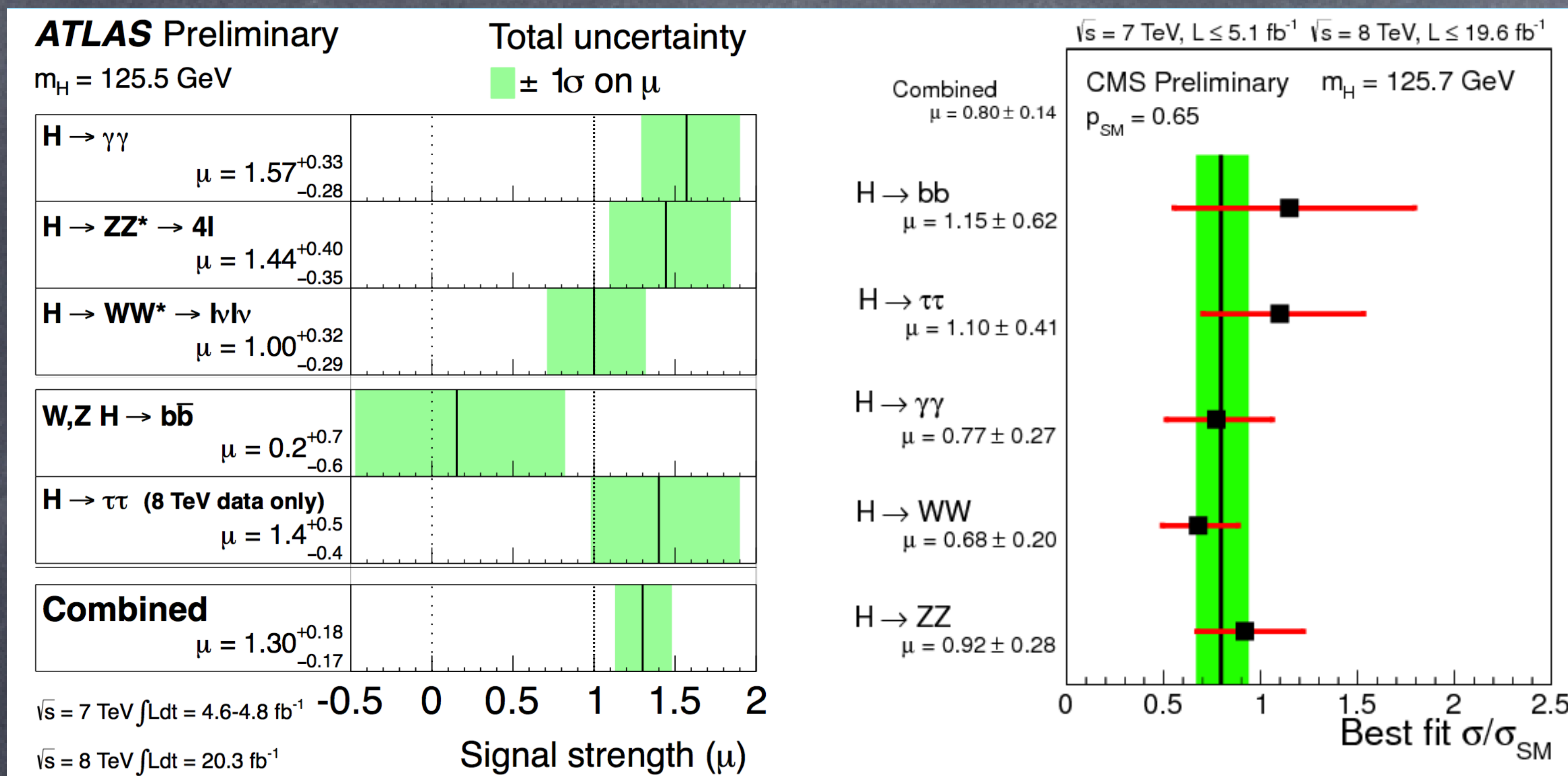


Where do we stand

- Very depressing
- For some couplings, limits strongly depend on assumptions
- Dropping the assumption of flavor blindness gives more wiggle room for Higgs couplings
- Moreover, in the presence of new light particles leading to an extra Higgs width, the limits on Higgs couplings can be relaxed
- Let's look in more detail at constraints on Higgs couplings to heavy flavors...

Constraints on Higgs couplings to bees

- Direct h→bb searches



$$\frac{\Gamma(h \to b\bar{b})}{\Gamma(h \to b\bar{b})_{\rm SM}} \approx c_d^2$$

- Contribution to the total width (indirectly enters all other rates)

$$\frac{\Gamma_h}{\Gamma_{h,\rm SM}} \approx 0.57 c_d^2 + \ldots$$

- Small contribution to gg→h and h → γγ from bottom loop

$$\frac{\Gamma(h \to gg)}{\Gamma(h \to gg)_{\rm SM}} \approx |c_u - (0.03 - 0.04i) c_d + \ldots|^2$$

Higgs couplings to bees

95%CL limits on Higgs couplings to down-type quarks

only c_d free:

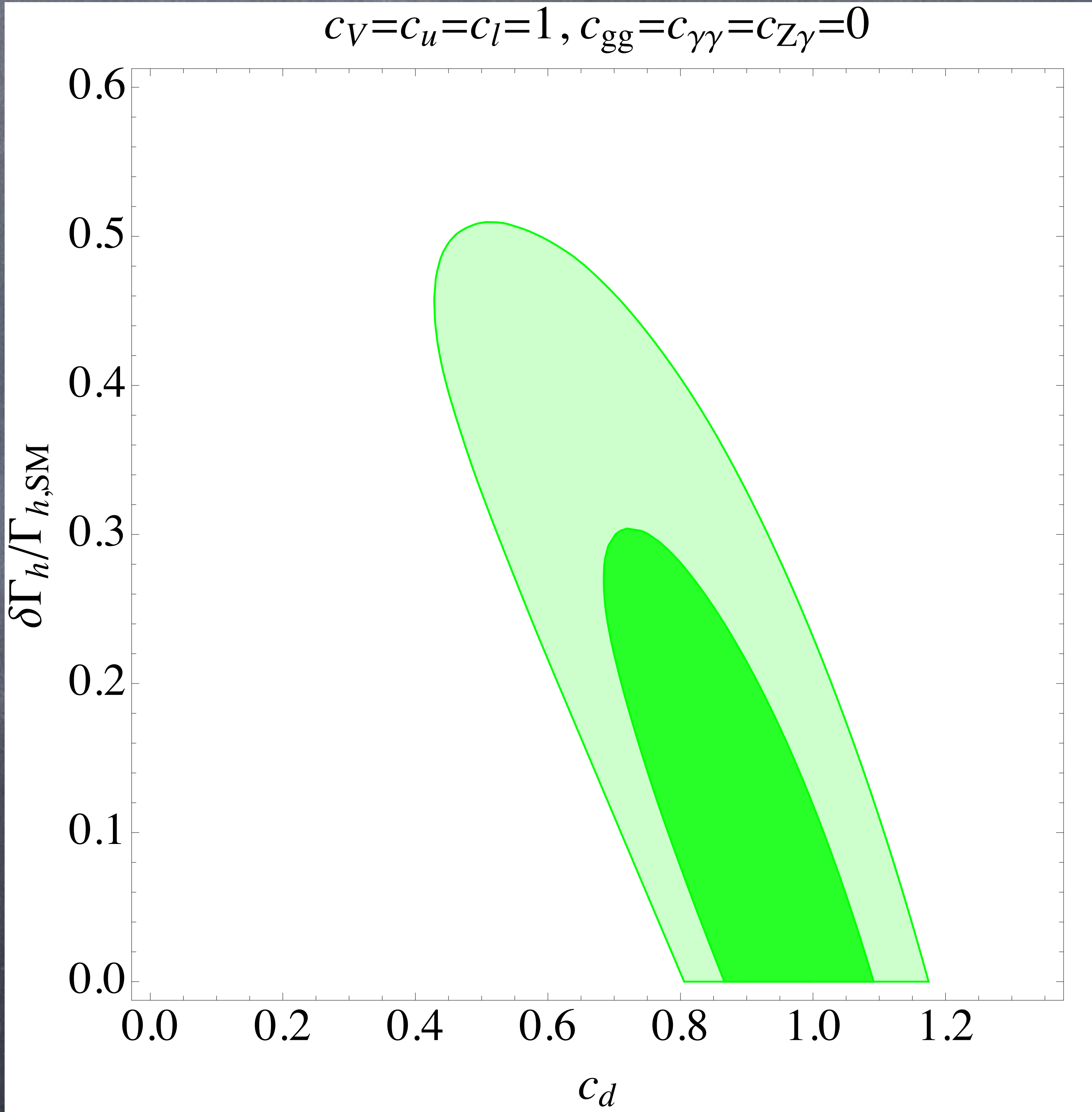
$$0.84 \le c_d \le 1.13$$

c_d + extra width:

$$0.57 \le c_d \le 1.13$$

$c_d + c_{gg}$:

$$0.61 \le c_d \le 1.24$$



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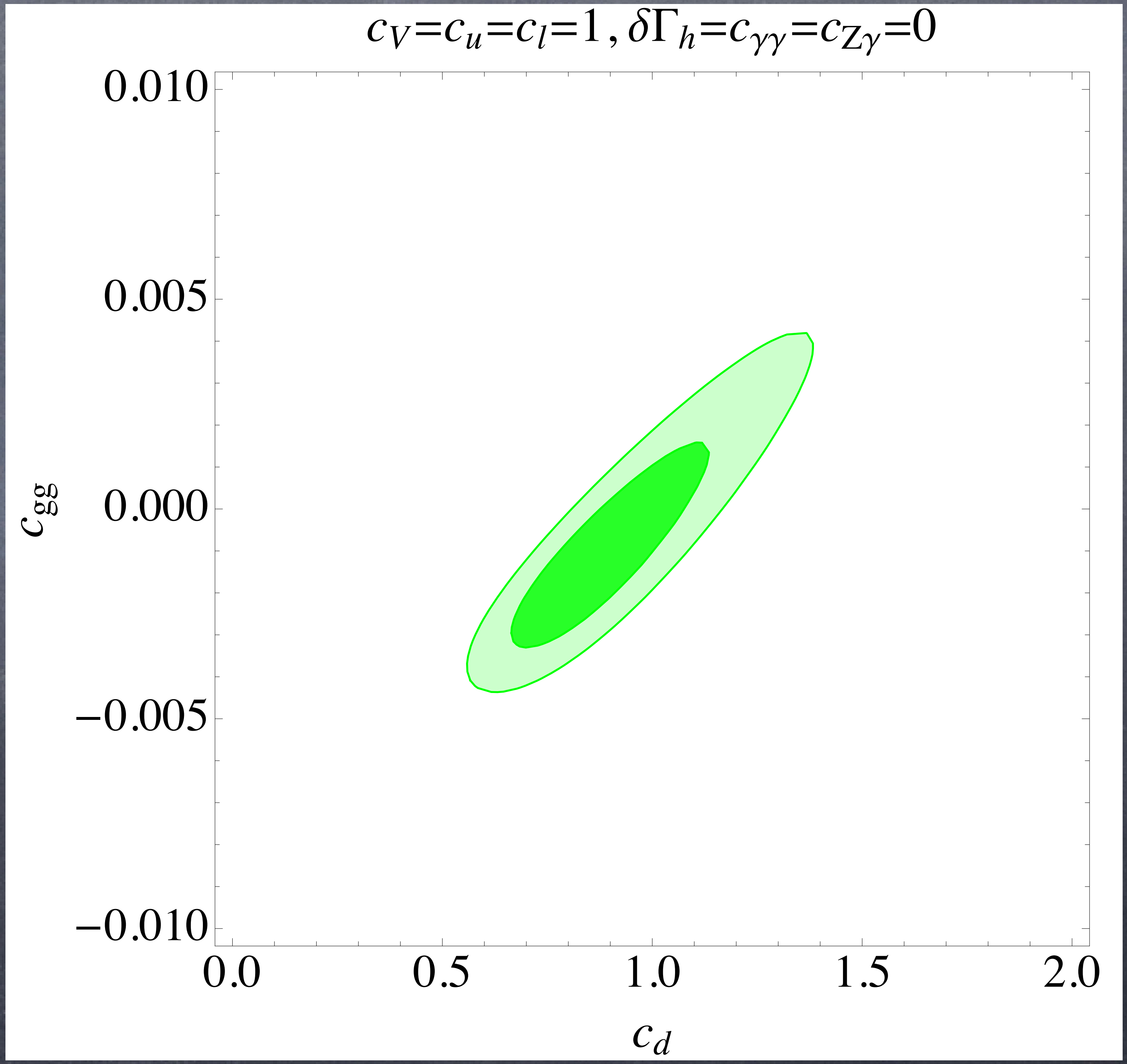
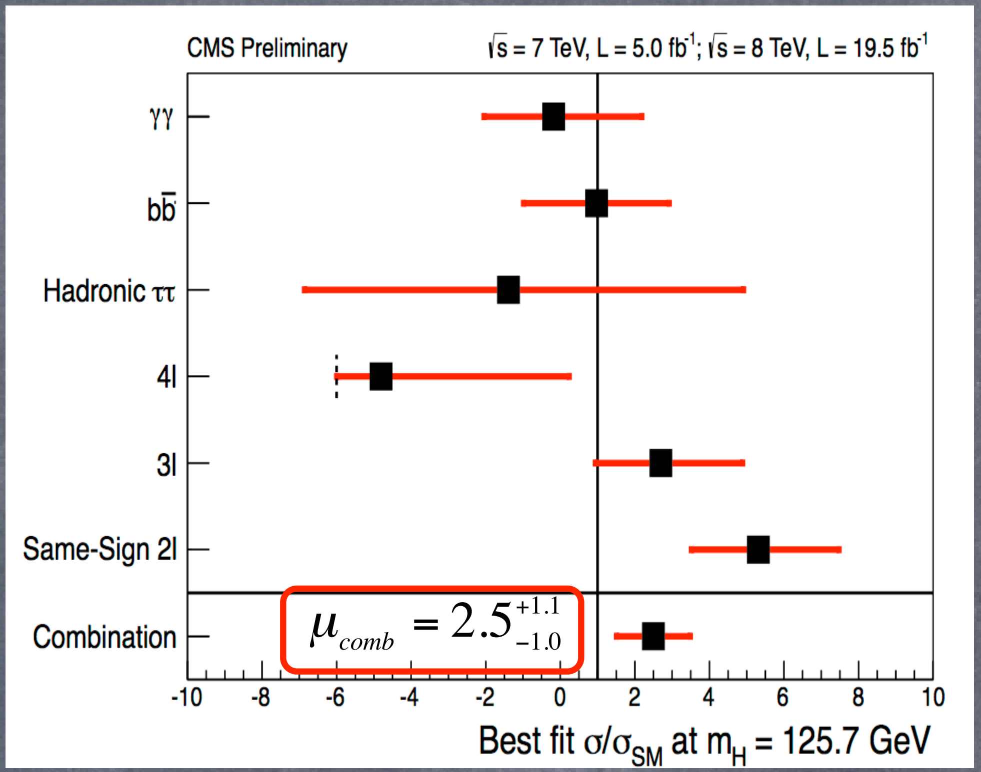
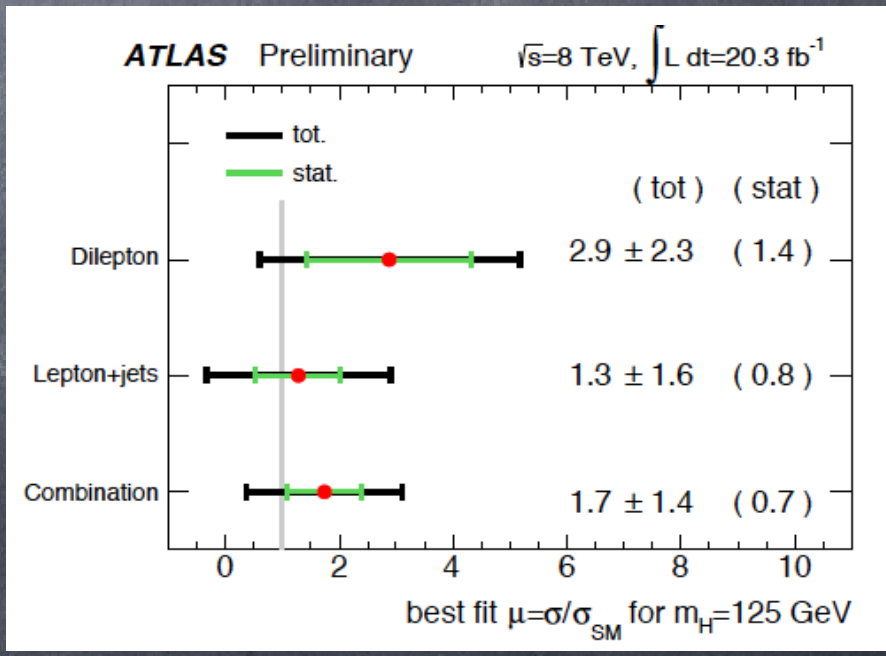


Constraints on Higgs couplings to charm (flavor blind)

- For flavor blind Higgs couplings, same coupling c_u to top and charm quark.
- Then, model independently, strongest constraints from tth searches
- If c_{gg} is absent, strongest constraints via top loop contributions to $gg \to h$ and $h \to \gamma\gamma$





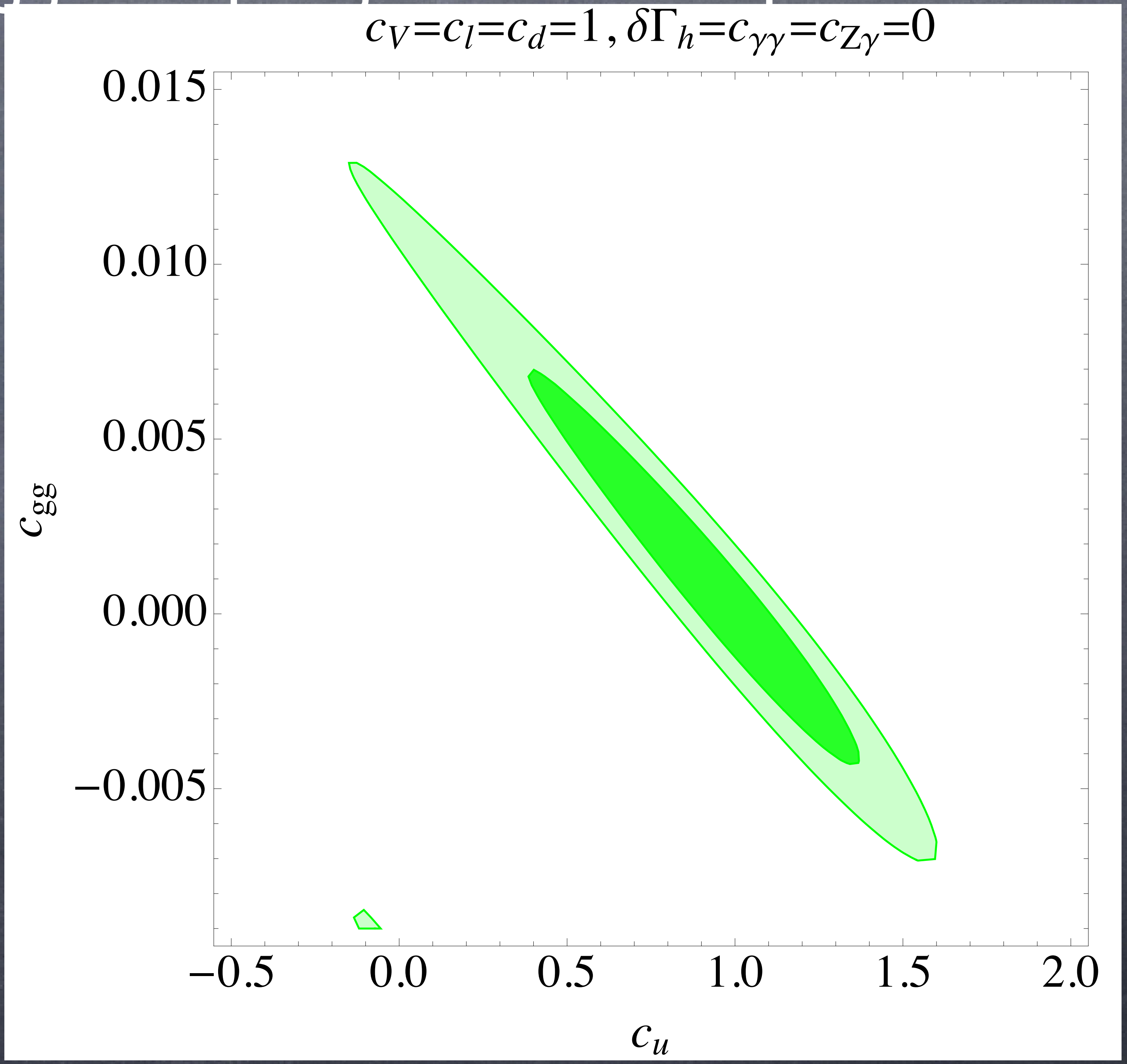
$$\frac{\Gamma(h \to gg)}{\Gamma(h \to gg)_{\rm SM}} \approx \left| c_u + 80 c_{gg} + \ldots \right|^2$$

Higgs couplings to charm (flavor blind)

95%CL limits on Higgs couplings to charm quarks

- if only c_u free:

$$0.85 \leq c_u \leq 1.14$$



- if c_u and c_{gg} free:

$$0.15 \leq c_u \leq 1.48$$

Constraints on Higgs couplings to charm

- Leakage of $h \to cc$ into $h \to bb$ (not taken into account here)
- Contribution to the total Higgs width (indirectly enters all other rates)
- Tiny contribution to $gg \to h$ and $h \to \gamma\gamma$ from charm loop

	ε(B)	R(c)	R(light)
MV1	80%	~3	~27
	70%	~5.0	~150
	60%	~8.0	~650
	50%	~14	~2500
	30%	~78	~40k

$$\frac{\Gamma_h}{\Gamma_{h,\text{SM}}} \approx 0.57 c_d^2 + \cdots + 0.03 c_c^2 + \ldots$$

$$\frac{\Gamma(h \to gg)}{\Gamma(h \to gg)_{\text{SM}}} \approx |c_u - (0.003 - 0.003i) c_c + \ldots|^2$$

Higgs couplings to charm

95%CL limits on Higgs couplings to charm quarks

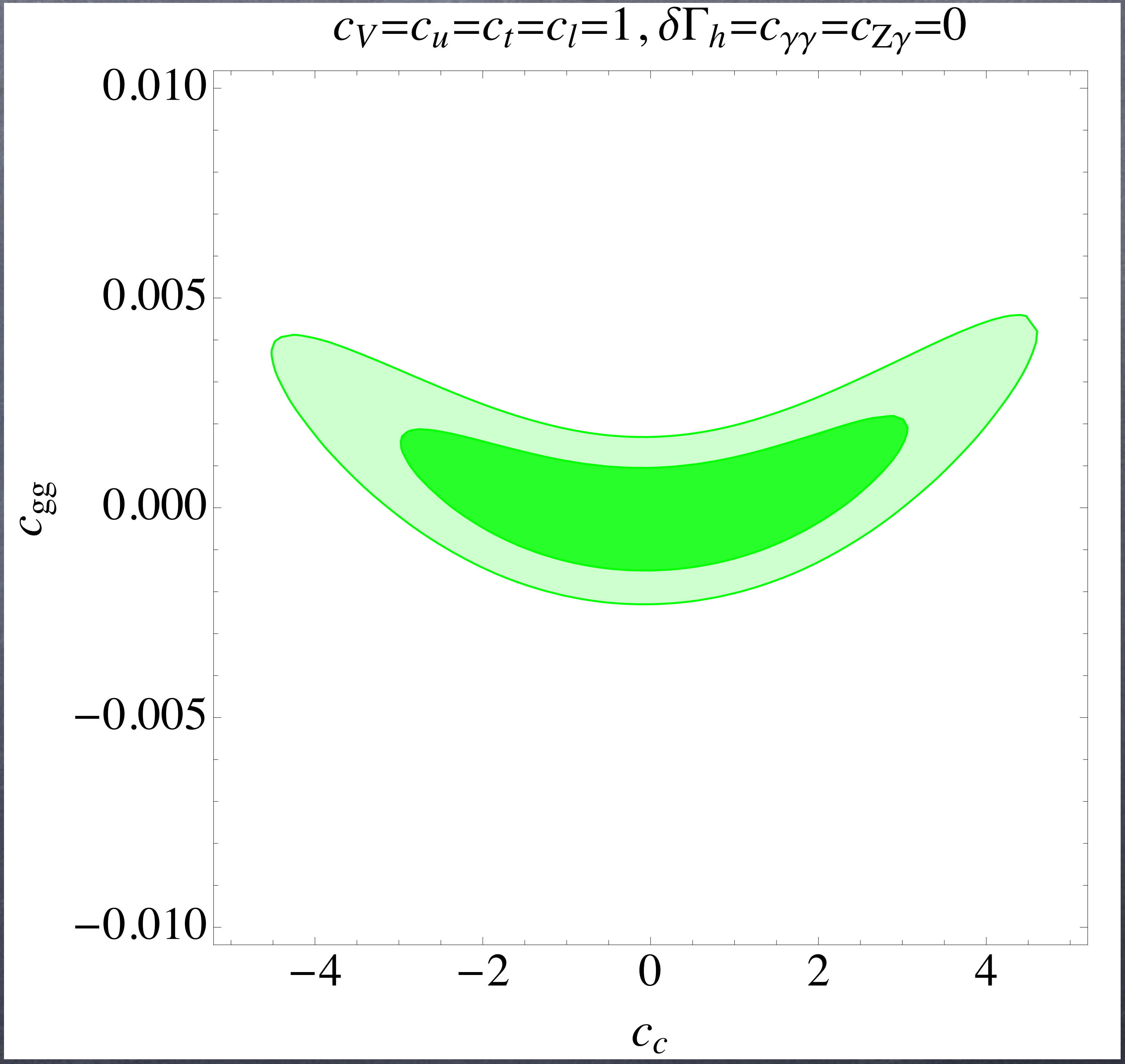
- if only c_c free:

$$|c_c| \leq 2.7$$

- if c_c and c_{gg} free:

$$|c_c| \leq 3.8$$

- extra width has no important effect



Delaunay et al 1310.7029: $|c_c| < 3.7$ (7.3)

Higgs couplings to charm

95%CL limits on Higgs couplings to charm quarks

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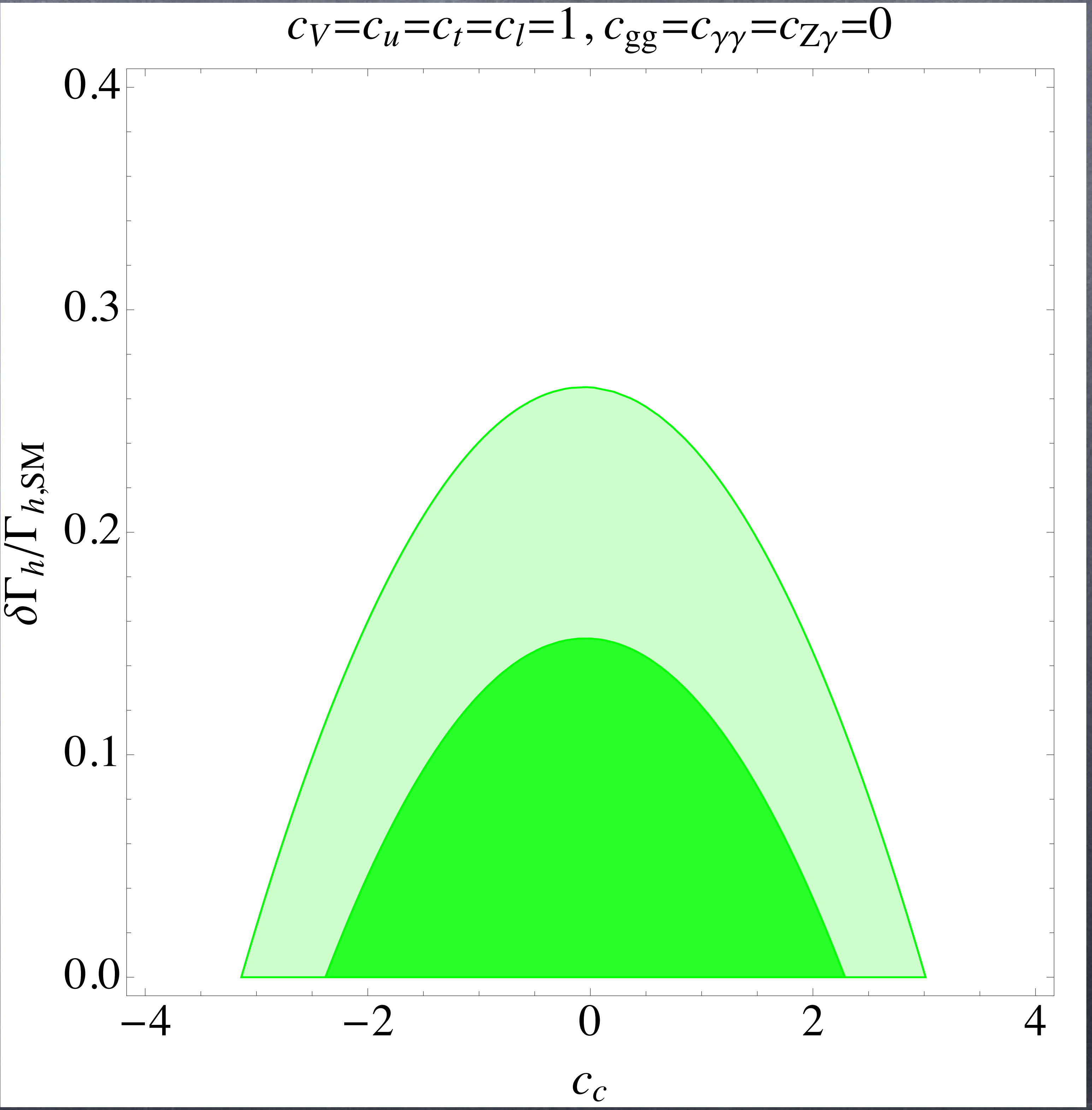


Models

Effective Theory

Effective Theory

$$\mathcal{L}^{D=6} \supset -\frac{1}{\Lambda^2}\left(H^\dagger H - v^2/2\right)\left[Hq\tilde{Y}_u u^c + H^\dagger q\tilde{Y}_d d^c\right] + \text{h.c.}$$

$$\Delta\mathcal{L}_{\text{higgs}} = -\frac{3}{2\sqrt{2}}\frac{v^2}{\Lambda^2}\frac{h}{v}\left[u\tilde{Y}_u u^c + d\tilde{Y}_d d^c\right]$$

- Anything goes
- Dimension 6 operators shifting Higgs couplings to quarks

$$\tilde{Y}_q = \tilde{c}_q Y_q \Rightarrow c_q = \frac{3\tilde{c}_q}{2}\frac{v^2}{\Lambda^2}$$

- If dimension 6 Yukawas aligned with SM ones, flavor blind corrections to Higgs quark couplings


2HDM

2HDM

Two SM SU(2) doublets that get a vev

$$\Phi_j = \begin{pmatrix} \phi_j^+ \\ (v_j + \rho_j + i\eta_j)/\sqrt{2} \end{pmatrix},$$

see e.g. Branco et al 1106.0034

CP-even neutral Higgs sector customarily described by 2 masses m_h, m_H and 2 angles α,β.

$$\begin{aligned} h &= \rho_1 \sin\alpha - \rho_2 \cos\alpha, \\ H &= -\rho_1 \cos\alpha - \rho_2 \sin\alpha. \end{aligned}$$

$$\tan\beta = v_2/v_1$$

$$\beta \in [0, \pi/2]$$

Two Higgs doublet models predict light Higgs h couplings c_V to WW and ZZ are suppressed:

$$c_v = \sin(\beta - \alpha)$$

2HDM

Two Higgs doublet models predict Higgs couplings c_V to WW and ZZ are suppressed:

$$c_v = \sin(\beta - \alpha)$$

Fermion couplings in general arbitrary.
But to avoid FCNC in natural way, one needs discrete symmetry such that only one Higgs doublet couples to ups, downs, and lepton.

4 possibilities

	Type I	Type II	Lepton-specific	Flipped
c_u	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
c_d	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
c_ℓ	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$

2HDM

Two Higgs doublet models predict Higgs couplings c_V to WW and ZZ are suppressed:

$$c_v \approx 1 - \frac{1}{2}\delta^2$$

$$\alpha = \beta - \pi/2 - \delta, \qquad |\delta| \ll 1$$

Fermion couplings in general arbitrary.
But to avoid FCNC in natural way, one needs discrete symmetry such that only one Higgs doublet couples to ups, downs, and lepton.

4 possibilities

	Type I	Type II	Lepton Specific	Flipped
c_u	$1-\delta\cot\beta$	$1-\delta\cot\beta$	$1-\delta\cot\beta$	$1-\delta\cot\beta$
c_d	$1-\delta\cot\beta$	$1+\delta\tan\beta$	$1-\delta\cot\beta$	$1+\delta\tan\beta$
c_ℓ	$1-\delta\cot\beta$	$1+\delta\tan\beta$	$1+\delta\tan\beta$	$1-\delta\cot\beta$

2HDM

Two Higgs doublet models predict Higgs couplings c_V to WW and ZZ are suppressed:

$$c_v \approx 1 - \frac{1}{2}\delta^2$$

$$\alpha = \beta - \pi/2 - \delta, \qquad |\delta| \ll 1$$

- deviation in fermionic Higgs coupling larger than in bosonic ones (O(δ) vs O(δ^2))
- possible to enhance only one coupling (only bottom or only top/charm)

	Type I	Type II	Lepton Specific	Flipped
c_u	$1-\delta\cot\beta$	$1-\delta\cot\beta$	$1-\delta\cot\beta$	$1-\delta\cot\beta$
c_d	$1-\delta\cot\beta$	$1+\delta\tan\beta$	$1-\delta\cot\beta$	$1+\delta\tan\beta$
c_ℓ	$1-\delta\cot\beta$	$1+\delta\tan\beta$	$1+\delta\tan\beta$	$1-\delta\cot\beta$

2HDM

- So, in flavor blind scenario large deviations of Higgs couplings to heavy flavors trivially realized in 2HDM
- What about splitting top and charm couplings?
- 2HDM + MFV studied in Dery et al 1304.6727

$$
\begin{aligned}
c_t &\simeq A_S^U + B_S^U y_t^2 + C_S^U y_b^2 \left|V_{tb}\right|^2 , \\
c_c &\simeq A_S^U + B_S^U y_c^2 + C_S^U \left(y_b^2 \left|V_{cb}\right|^2 + y_s^2 \left|V_{cs}\right|^2 \right)
\end{aligned}
$$

With some cancelation between O(1) coefficients A and B one can get c_c order few

Composite Higgs

Composite Higgs Model

Like QCD: (techni)quarks, strong dynamics, global symmetry

New "quarks"

M_{PL}

Hierarchy

Global symmetry

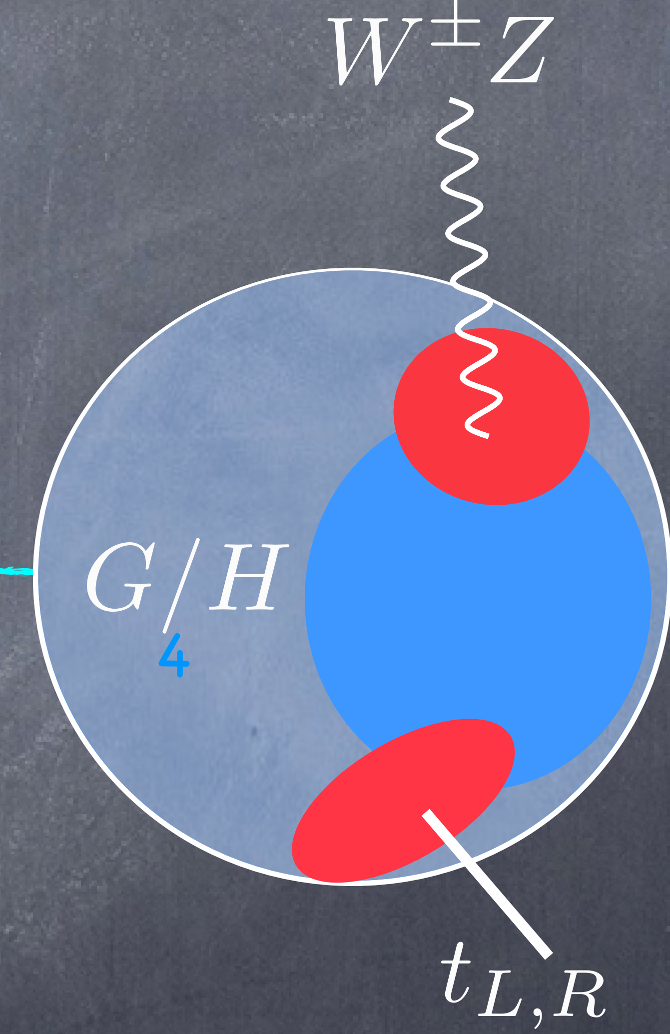
$G = SO(5)$ 10

dynamically generated

f=TeV

Composite states (incl. scalars)

$H = SO(4)$ 6



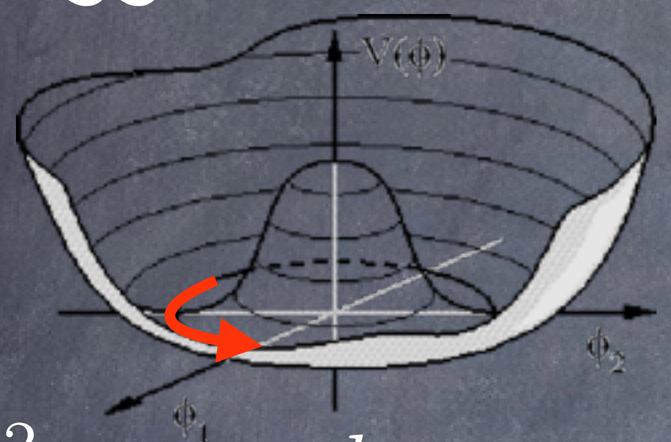
4 naturally light

composite PseudoGoldstone bosons = Higgs doublet

Kaplan,Georgi,Dimopoulos,Dugan,Galison '84; Agashe,Contino,DaRold,Pomarol '05 -'07

Composite Higgs Model

Higgs = Goldstone Boson of SO(5)/SO(4)



described by angular variable $\sin\frac{h}{f}$

$$\frac{g^2}{4} f^2 \sin^2\frac{h}{f} W_\mu W^\mu \overset{h \to \langle h \rangle + h}{=} \frac{g^2}{4} \underbrace{f^2 \sin\frac{\langle h \rangle}{f}^2}_{v^2} W_\mu W^\mu$$

$$+\frac{g^2}{2} f \sin\frac{\langle h \rangle}{f}\sqrt{1-\sin^2\frac{\langle h \rangle}{f}}\, hW_\mu W^\mu + ..$$

$$c_V = \sqrt{1-\frac{v^2}{f^2}}$$

Coupling to W and model independent

$$c_f = \frac{1+2m-(1+2m+n)v^2/f^2}{\sqrt{1-v^2/f^2}}$$

Coupling to fermions model dependent $m_t \sim \sin^{2m+1}\left(\frac{h}{f}\right)\cos^n\left(\frac{h}{f}\right)$

Pomarol,Riva,'12

Slide stolen from Francesco Riva

Composite Higgs Model

- Higgs couplings to heavy flavors depend on how quarks are embedded into representations of global symmetry
- Current limits on f typically exclude large effects
- But for non-minimal representations one can realize large corrections

$$c_f = \frac{1+2m-(1+2m+n)v^2/f^2}{\sqrt{1-v^2/f^2}}$$

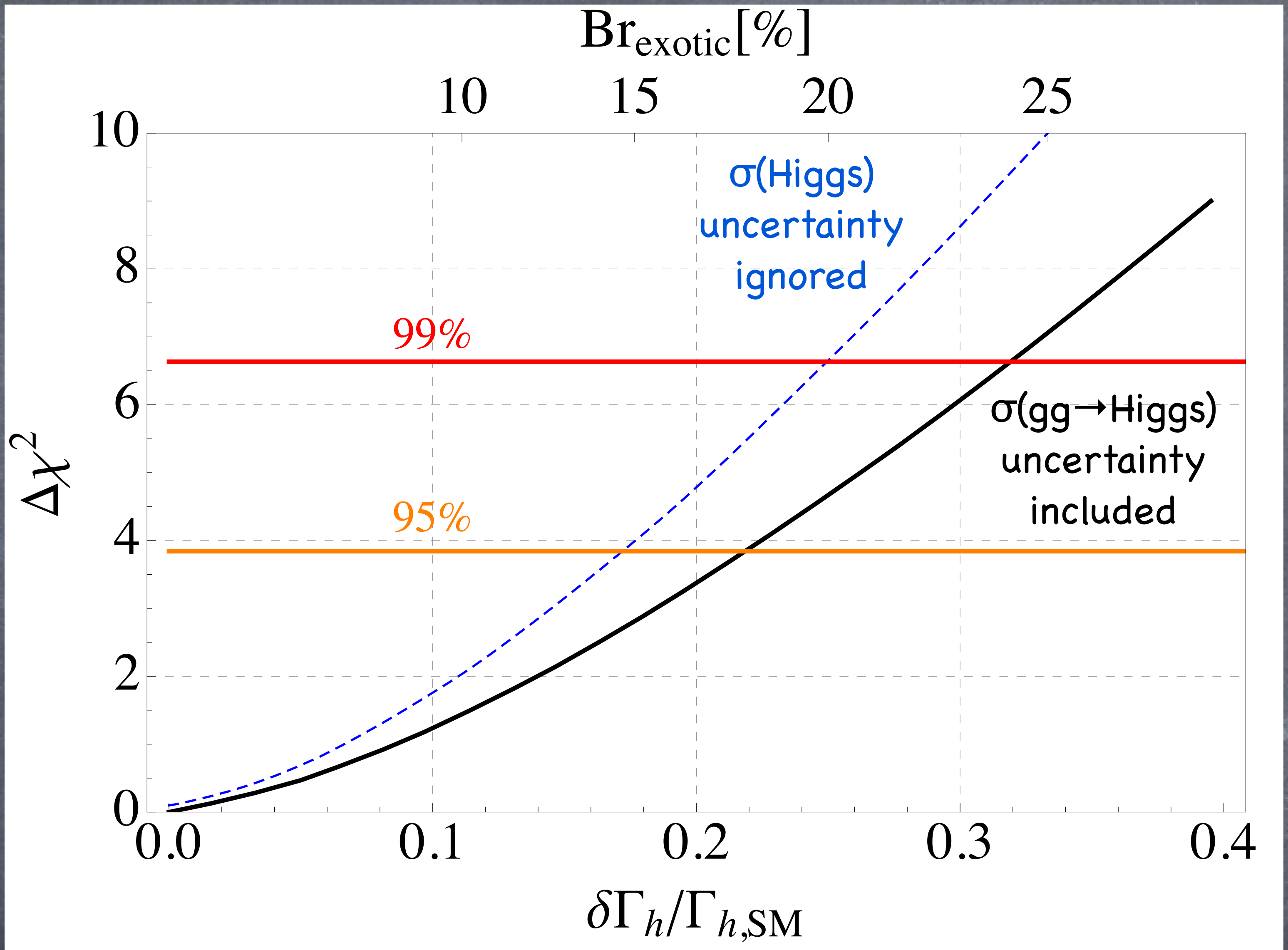
$\mathbf{r_L} \diagdown \mathbf{r_R}$	**1**	**5**	**10**	**14**
5	$m=n=0$	$m=0,\ n=1$	$m=n=0$	$m=n=0$
10	–	$m=n=0$	$(i)\ m=0,\ n=1$ $(ii)\ m=n=0$	$m=0,\ n=1$
14	$m=0,\ n=1$	$(i)\ m=n=0$ $(ii)\ m=0,\ n=2$	$m=0,\ n=1$	$(i)\ m=0,\ n=1$ $(ii)\ m=1,\ n=1$

Take-away

- Higgs couplings to heavy flavors generically constrained to be close to SM, however there are loopholes.
- It is fairly straightforward to modify the coupling to bottom quarks by a large amount (e.g 2HDM).
- Modifying the coupling to charm quarks by a large amount requires more model gymnastics but is possible.

Limits on exotic Higgs branching fraction

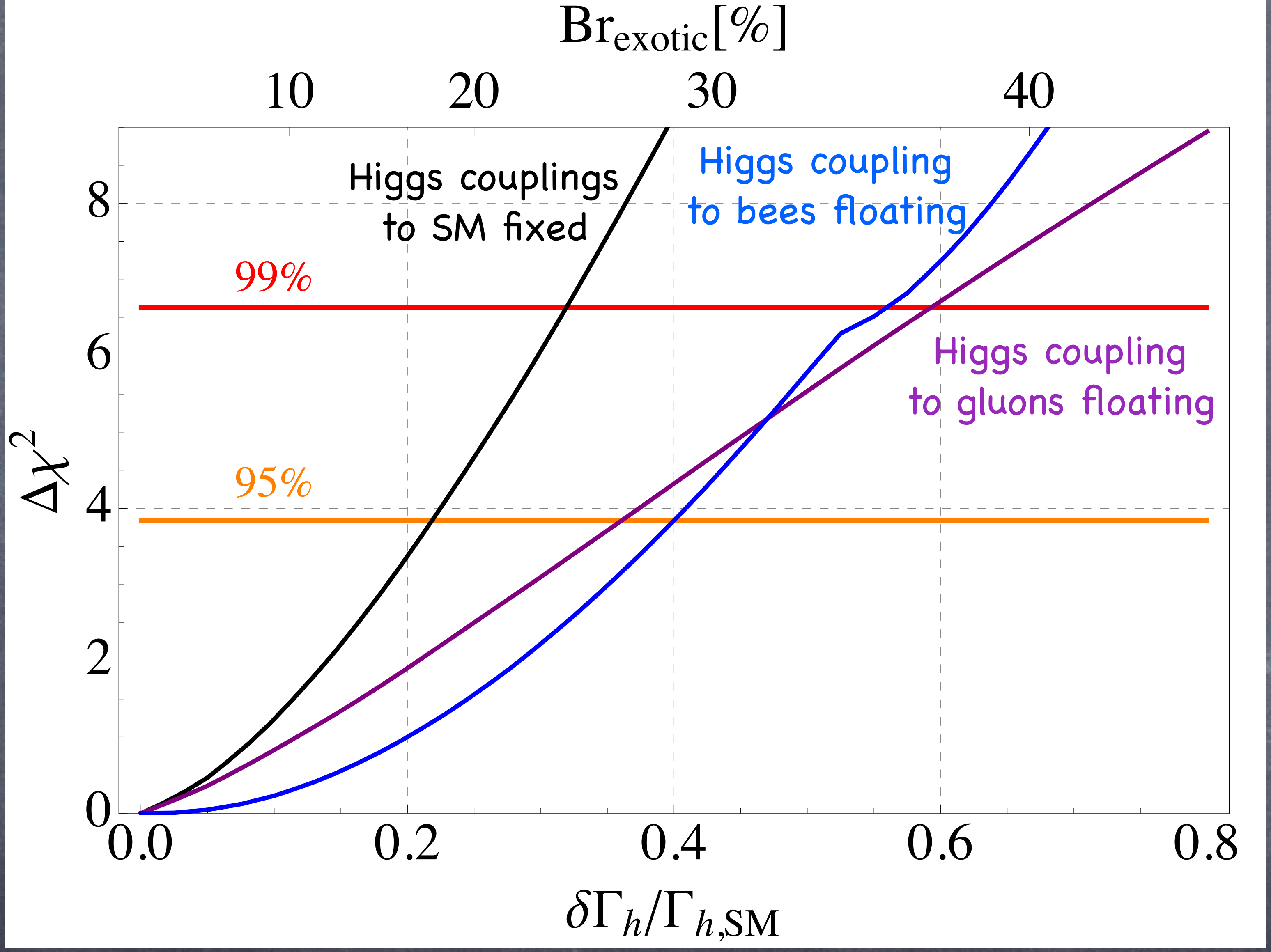
Assuming Higgs couplings to SM fixed



Br(h→exotic) ≲ 18% at 95% CL

Limits on exotic Higgs branching fraction

Allowing some Higgs couplings to SM to float



Br(h→exotic) $\lesssim$ 30% at 95% CL