Higgs and Extra Sectors

Jonathan J. Heckman

Harvard University

Mainly Based On...

Funparticles

- hep-th/1006.5459 w/ C. Vafa
- hep-th/1009.0017 w/ Y. Tachikawa, C. Vafa, B. Wecht
- hep-th/1103.3287 w/ C. Vafa, B. Wecht

Higgs + Extra

- hep-ph/1108.3849 w/ P. Kumar, C. Vafa, B. Wecht
- hep-ph/1204.3640 w/ P. Kumar, B. Wecht
- hep-ph/1205.5580 w/ L. Bellantoni, J. Erler,
  E. Ramirez-Homs
- hep-ph/1210.???? w/ P. Kumar, B. Wecht

Motivation

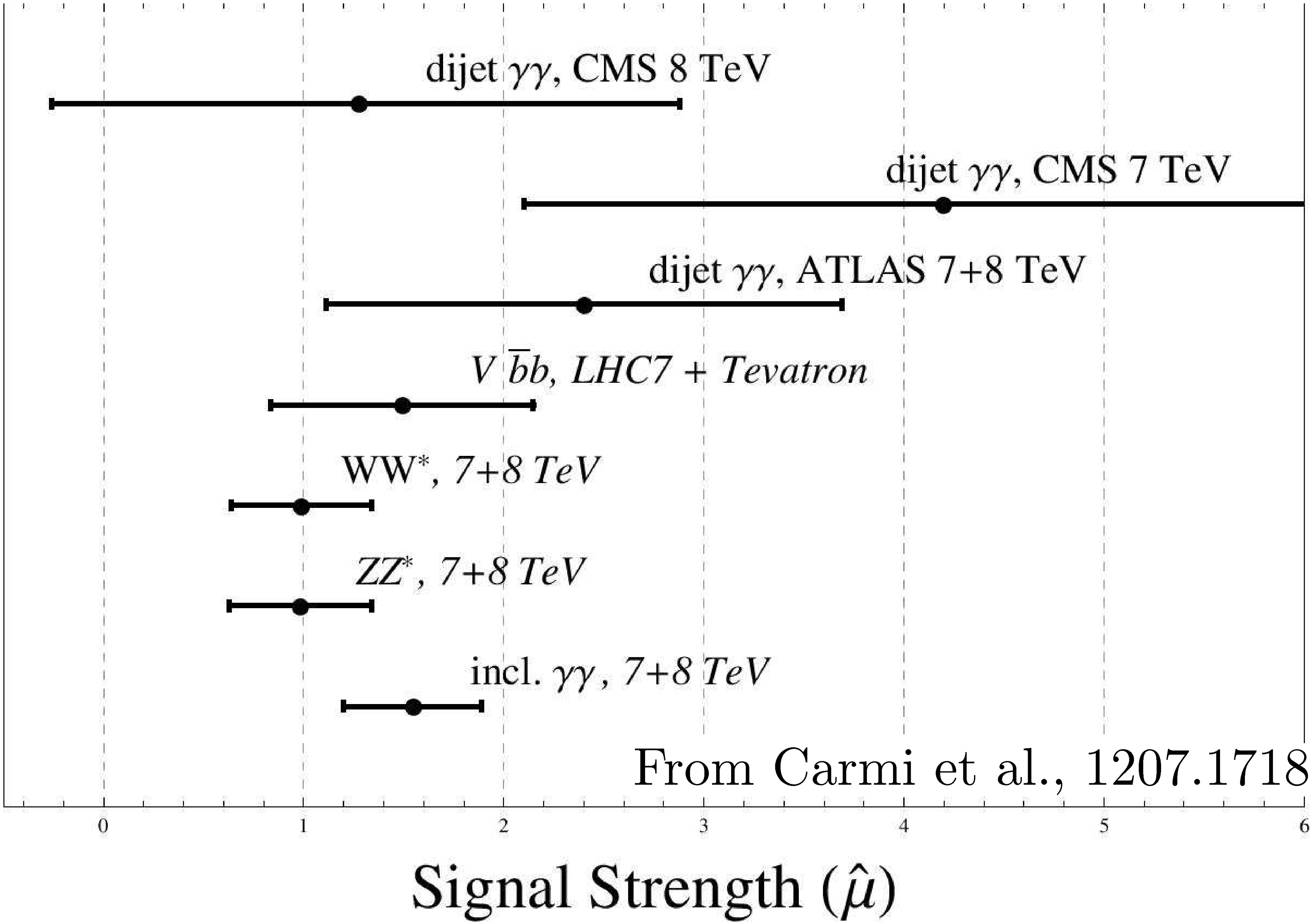
What has the LHC found?

- The Standard Model

- An SM-Like Higgs Boson

  $m_h \sim 125 - 126$ GeV

  (Assume it is a Higgs boson for talk)



dijet $\gamma\gamma$, CMS 8 TeV
dijet $\gamma\gamma$, CMS 7 TeV
dijet $\gamma\gamma$, ATLAS 7+8 TeV
$V\,\bar{b}b$, LHC7 + Tevatron
WW*, 7+8 TeV
ZZ*, 7+8 TeV
incl. $\gamma\gamma$, 7+8 TeV
From Carmi et al., 1207.1718
0
1
2
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4
5
6
Signal Strength ($\hat{\mu}$)

Some Possibilities

- Tuning: The Higgs is it for TeV scale physics
  (current hints in $h^0 \to \gamma\gamma$ may go away...)

- Mini-Tuning: $\sim$ 2 TeV - 10 TeV superpartners?
  (current hints persist, tuned corners of soft param space, risk of destabilized V_{Higgs}...)

- Less Minimal Higgs Sectors

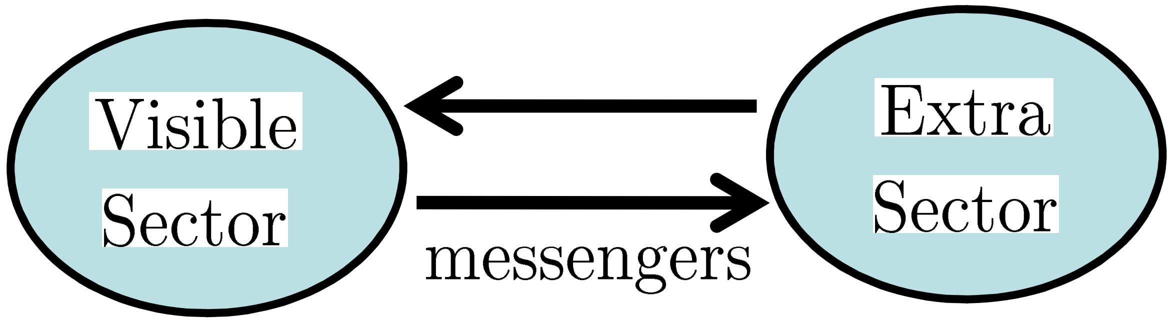
Reducing the Tuning?

Natural to consider mixing with new operators:

Mixing terms: $\int d^2\theta\,(H_u\mathcal{O}_u + H_d\mathcal{O}_d)$

This can naturally raise the Higgs mass
relative to the MSSM
and can also change production and decay...

Effective Theory Picture



Gauge Fields: $\mathcal{L} \supset A_\mu^{vis} \cdot J_\mu^{extra}$

Yukawas: $\mathcal{L} \supset \int d^2\theta \; \Psi_R^{vis} \cdot \mathcal{O}_{\overline{R}}^{extra}$

Possible Extra Sectors?

Range of possibilities:

- Vector-Like Generation(s)
- Strongly Coupled Sectors

(Note: SQCD not the only option...)

Possible Extra Sectors?

Note: SQCD is not the only option!

Issues with SQCD:

- Generically, Large SM / Extra Mixing...
- Low scale Landau Poles for SM couplings

Possible Extra Sectors?

Note: SQCD is not the only option!

Example: Funparticles

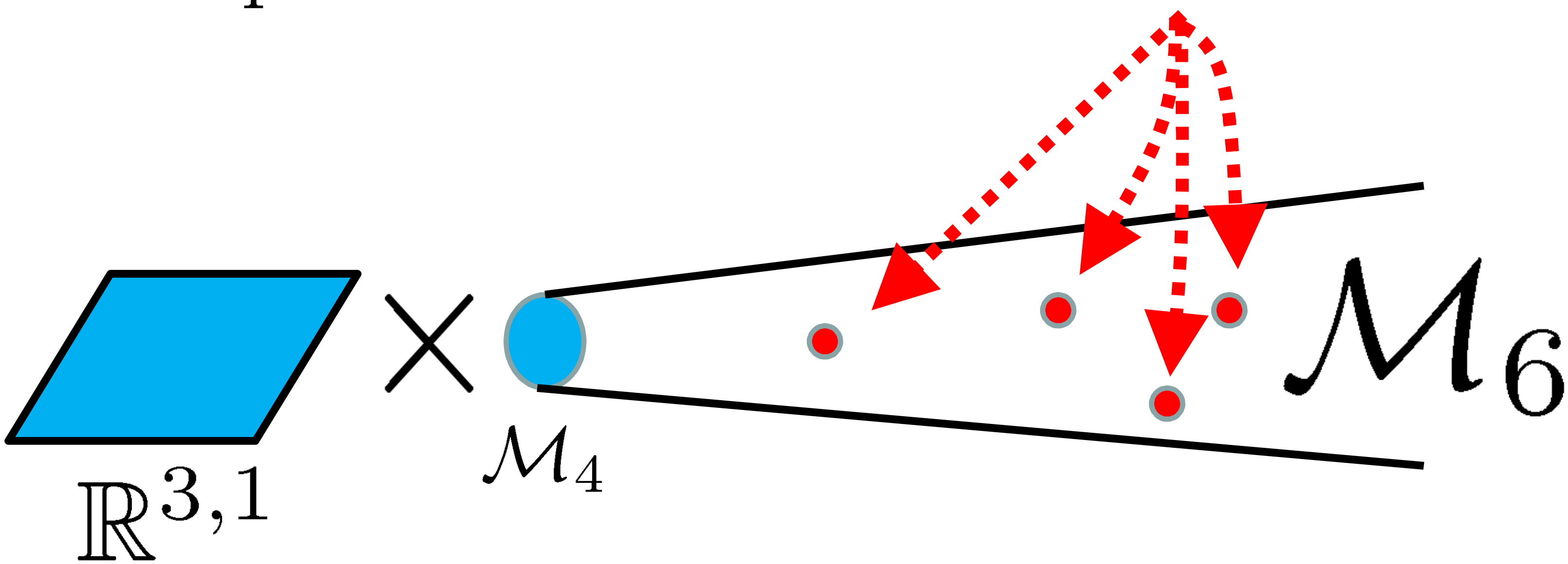
F-theory motivated $\mathcal{N} = 1$ D3-Brane CFTs + mass gap

- Scaling Dimension $\Delta(\Psi^{SM}) = \Delta_{free} + \underbrace{\varepsilon_{SM} + \varepsilon_{D3}}_{\text{similar sizes}}$
- Beta functions: $b_G \sim 2 - 4 \Rightarrow$ Retains Unification

F-theory Scenarios:

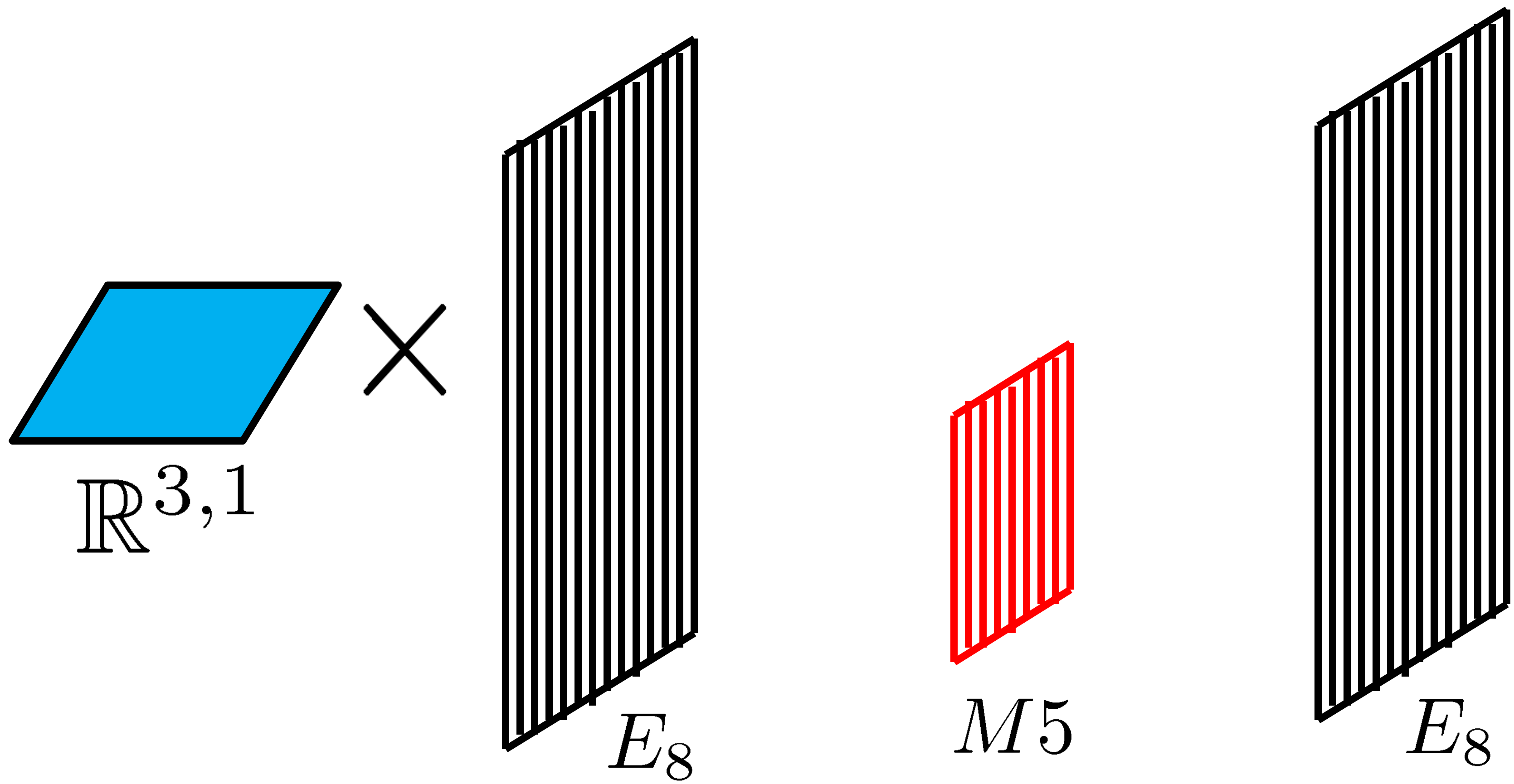
SM: $\cap$7-branes, Extra: D3-branes

10D Tadpole Cancellation $\Rightarrow$ D3-Branes

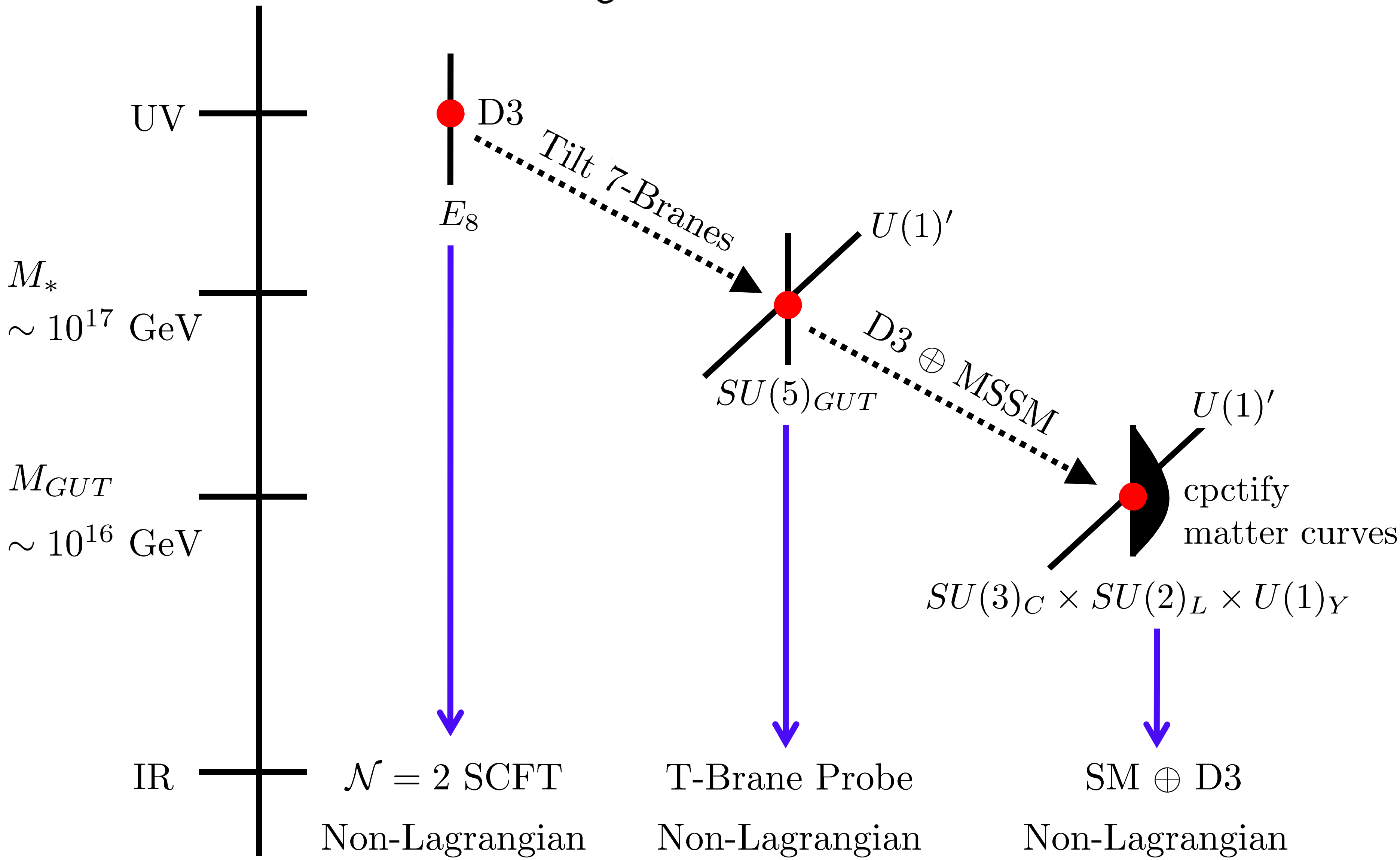


Heterotic Scenarios:

SM: E_8 Wall, Extra: M5-Branes



F-theory Scenarios:



The Extra Sector (I)

Minahan Nemeschansky '96

$\mathcal{N} = 2$ SCFT with E_8 flavor symmetry

dim in UV $= 2$

$$\int d^2\theta \; \mathrm{Tr}_{E_8}(m_{248} \cdot \mathcal{O}_{248})$$

Huge class of $\mathcal{N} = 1$ SCFTs

JJH Tachikawa Vafa Wecht '10

The Extra Sector (II)

Always strongly coupled: $\tau_{D3} \sim \frac{i}{g_s} \sim O(1)$

Low Energy View: Exotic... (not SQCD)

High Energy View: Generic (strong $U(1)$)

Computability

Determine R_{IR} via a-maximization

Intriligator Wecht '03

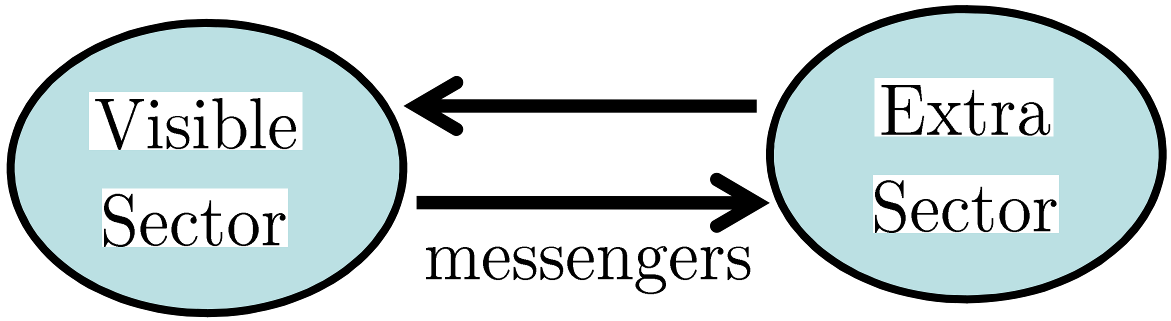
$\Rightarrow$ *Computability* at strong coupling!

- Dimensions: $\Delta(\Psi_{SM}) = \frac{3}{2} R_{IR}(\Psi_{SM})$

- Beta functions: $b_G = -3\mathrm{Tr}(R_{IR} J_G J_G)$

  Anselmi et al. '97

Recap of Setup



SUSY 2HDM + Extra Sector:

Mixing terms: $\int d^2\theta \left(H_u \mathcal{O}_u + H_d \mathcal{O}_d\right)$

Precision Electroweak?

Adding $H \cdot \mathcal{O}$ also compatible with S and T

- Simplest possibility, G_{SM} preserving mass terms:

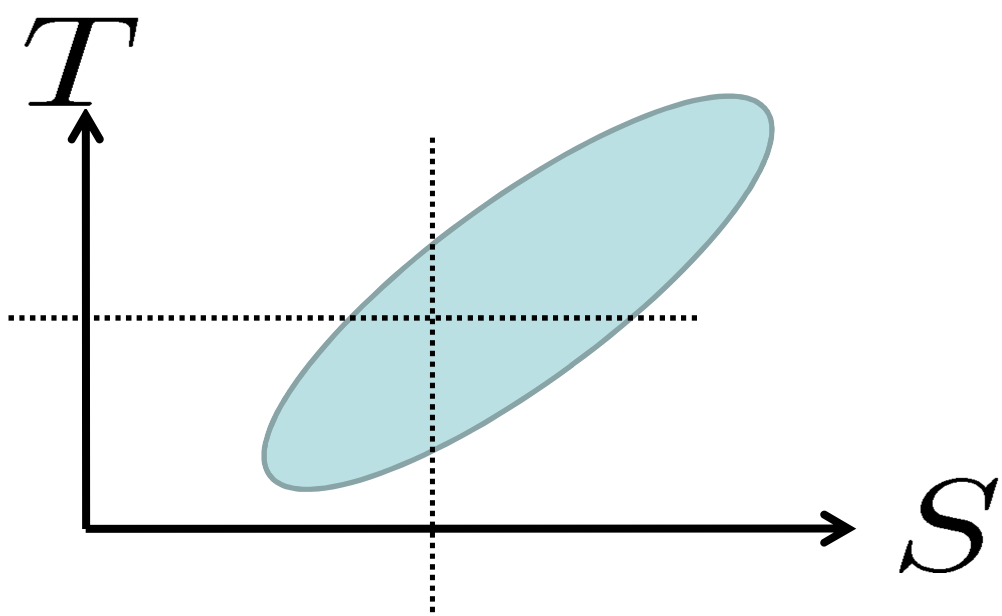
  i.e. "Vector-like" masses, $\Rightarrow \Delta S, \Delta T \sim \frac{v^2}{\Lambda_{vec}^2}$

- Not as simple: Masses mainly from v_u and v_d:

  BUT still possible to make it work

Precision Electroweak?

What About Mixing terms: $\int d^2\theta\,(H_u\mathcal{O}_u + H_d\mathcal{O}_d)$?



(68% confidence)

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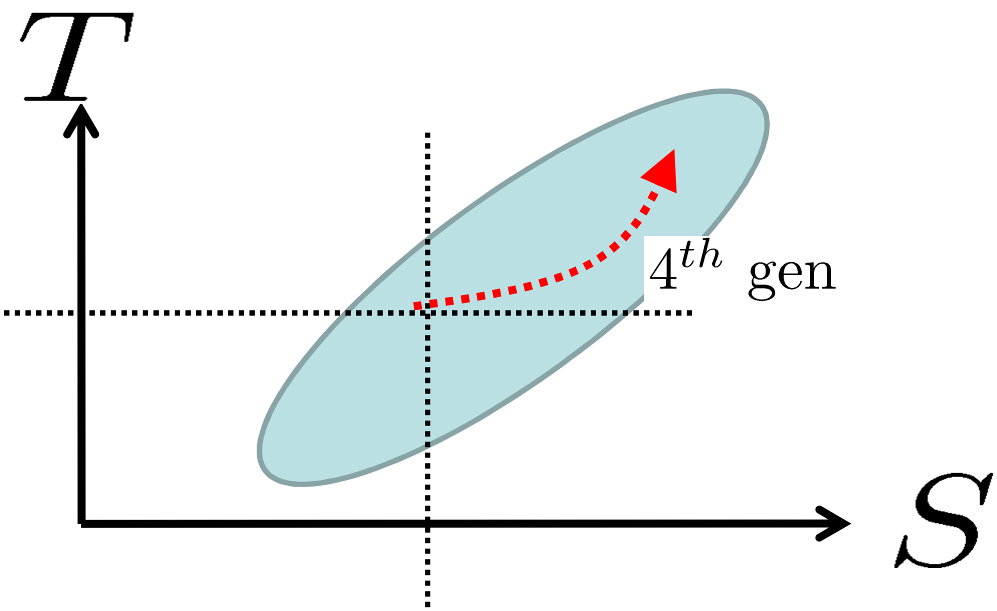

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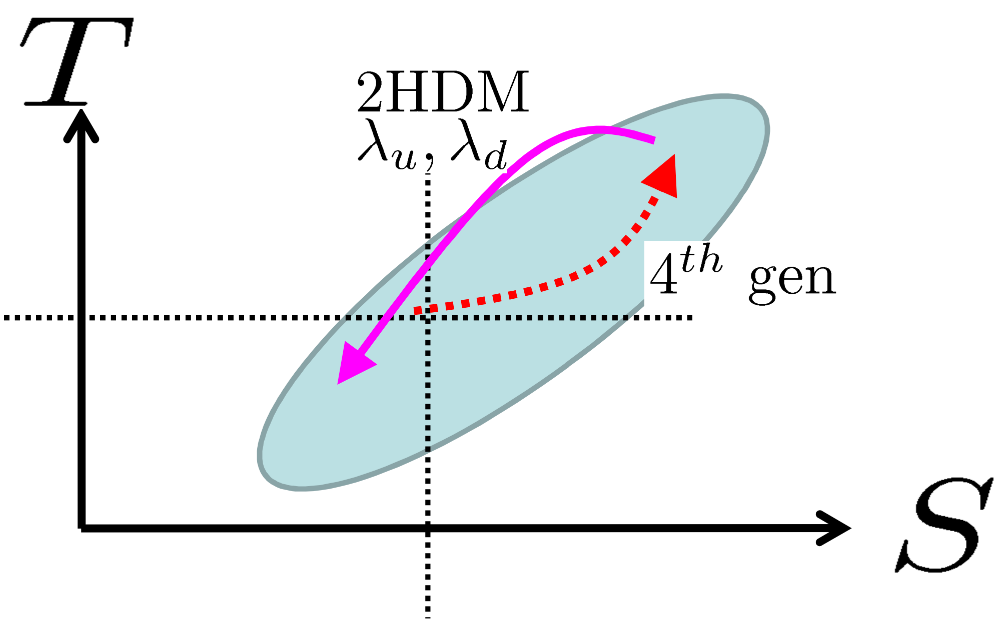
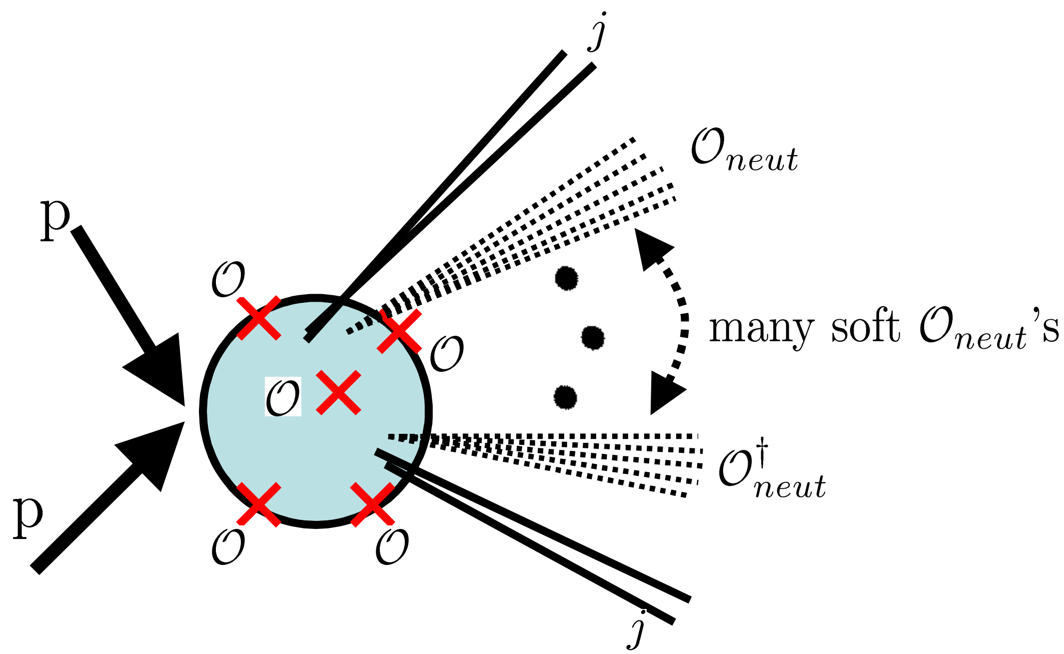


(68% confidence)

Signatures?



p
p
$\mathcal{O}$
$\mathcal{O}$
$\mathcal{O}$
$\mathcal{O}$
$\mathcal{O}$
j
j
$\mathcal{O}_{neut}$
many soft $\mathcal{O}_{neut}$'s
$\mathcal{O}^{\dagger}_{neut}$

?

Model Dependent...

- Hard to study directly...

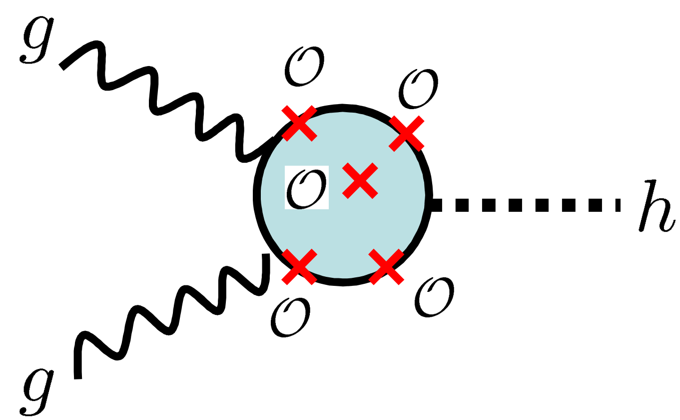
- Also, extra states may be too heavy...

- But they will still enter in loops...

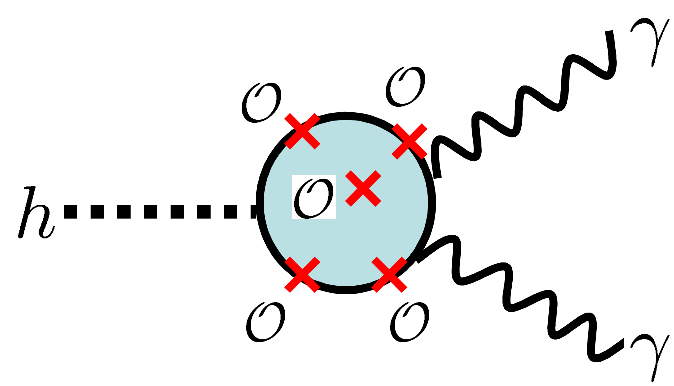
Higgs Signatures

Higgs and Loops

Production: $gg \to h$



Decays: $h \to \gamma\gamma$



Dim 5 Operators

$$H_u \oplus H_d \to h^0, H^0, A^0, H^\pm, G^0, G^\pm$$

$$\mathcal{O}_{h^0 FF} = \frac{b_{h^0}}{32\pi^2} \frac{h^0}{v} \mathrm{Tr}_G F_{\mu\nu} F^{\mu\nu}$$

$$\mathcal{O}_{H^0 FF} = \frac{b_{H^0}}{32\pi^2} \frac{H^0}{v} \mathrm{Tr}_G F_{\mu\nu} F^{\mu\nu}$$

$$\mathcal{O}_{A^0 FF} = \frac{b_{A^0}}{32\pi^2} \frac{A^0}{v} \mathrm{Tr}_G F_{\mu\nu} \widetilde{F}^{\mu\nu}$$

Setup: SUSY 2HDM

$$H_u \oplus H_d \to h^0, H^0, A^0, H^\pm, G^0, G^\pm$$

Dimension 5 operators of interest:

$$\mathcal{O}_{h^0 FF} = \frac{\boxed{b_{h^0}}}{32\pi^2} \frac{h^0}{v} \mathrm{Tr}_G F_{\mu\nu} F^{\mu\nu}$$

$$\mathcal{O}_{H^0 FF} = \frac{\boxed{b_{H^0}}}{32\pi^2} \frac{H^0}{v} \mathrm{Tr}_G F_{\mu\nu} F^{\mu\nu}$$

???

$$\mathcal{O}_{A^0 FF} = \frac{\boxed{b_{A^0}}}{32\pi^2} \frac{A^0}{v} \mathrm{Tr}_G F_{\mu\nu} \widetilde{F}^{\mu\nu}$$

Suppose... (I / III)

- SUSY is not broken (in the extra sector)

- and the extra states had G_{SM} preserving masses

Then, there would be a single term we could write:

$$\mathcal{O}_{HH\mathcal{W}\mathcal{W}} = \frac{b_{eff}}{8\pi^2} \int d^2\theta \frac{H_u H_d}{\Lambda_G^2} \mathrm{Tr}_G \mathcal{W}^\alpha \mathcal{W}_\alpha + c.c.$$

Suppose... (II / III)

Next, expand in a mass eigenstate basis:

$$H_u^0 = \frac{1}{\sqrt{2}}(v \sin\beta + h^0 \cos\alpha + H^0 \sin\alpha + iA^0 \cos\beta) + g.b.s$$

$$H_d^0 = \frac{1}{\sqrt{2}}(v \cos\beta - h^0 \sin\alpha + H^0 \cos\alpha + iA^0 \sin\beta) + g.b.s$$

Suppose... (III / III)

$\Rightarrow$ in SUSY limit, THREE dim 5 operators are correlated:

$$\mathcal{O}_{h^0FF} = \frac{b_G}{16\pi^2}\cos(\alpha+\beta)\left(\frac{v}{\Lambda_G}\right)^2 \frac{h^0}{v}\mathrm{Tr}_G F_{\mu\nu}F^{\mu\nu}$$

$$\mathcal{O}_{H^0FF} = \frac{b_G}{16\pi^2}\sin(\alpha+\beta)\left(\frac{v}{\Lambda_G}\right)^2 \frac{H^0}{v}\mathrm{Tr}_G F_{\mu\nu}F^{\mu\nu}$$

$$\mathcal{O}_{A^0FF} = \frac{b_G}{32\pi^2}\left(\frac{v}{\Lambda_G}\right)^2 \frac{A^0}{v}\varepsilon^{\mu\nu\rho\sigma}\mathrm{Tr}_G F_{\mu\nu}F_{\rho\sigma}$$

b_G and Λ_G?

See Shifman Vainshtein, Voloshin, Zakharov ’79

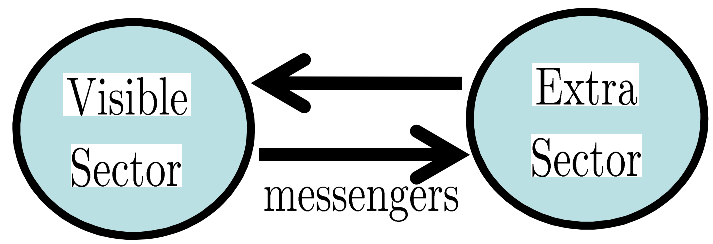
View $\frac{h^0}{v}\mathrm{Tr}_G F^2$ as a threshold correction:

$$\mathcal{L}_{eff} \supset -\frac{1}{2g^2_{eff}(\mu)}\mathrm{Tr}_G F^2$$

$$\frac{1}{g^2_{eff}(\mu)} = \frac{1}{g^2_{eff}(\mu_0)} + \frac{\delta b_{thresh}}{8\pi^2}\log\frac{M(v_{Higgs}+h^0)}{\mu_0}$$

The Coefficient b_G (I / II)

View SM gauge group as a flavor symmetry of extra sector:



$$b_G = -3\mathrm{Tr}(R_{IR} J_G J_G)$$

Flavor symmetry

R-symmetry in CFT limit

(c.f. NSVZ β f^n)

The Coefficient b_G (I / II)

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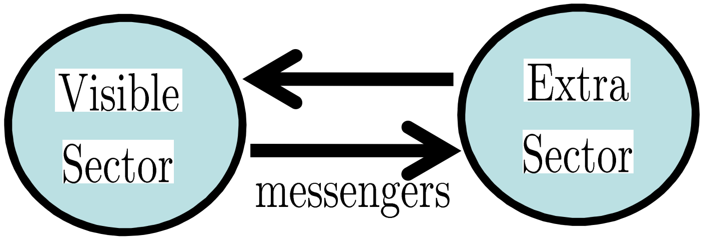
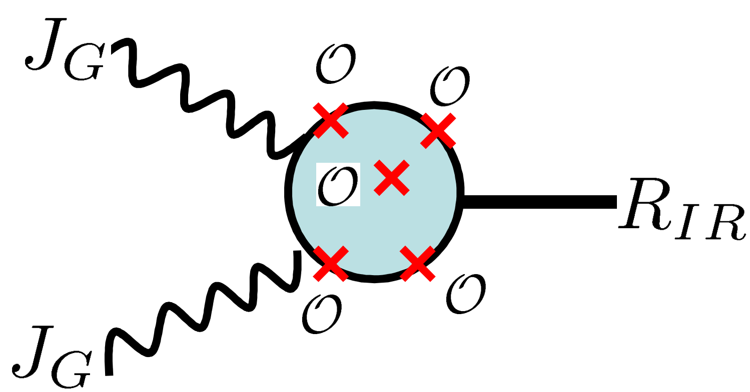


$$b_G = -3\mathrm{Tr}(R_{IR} J_G J_G)$$

This is often calculable via 't Hooft anomaly matching



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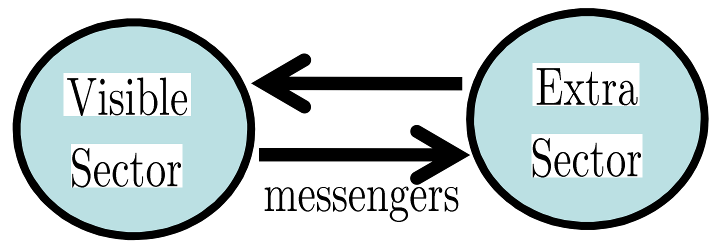

$$b_G = -3\mathrm{Tr}(R_{IR} J_G J_G)$$

NOTE: In a CFT $b_G > 0$

($b_G < 0$ also possible in non-CFTs (c.f. spin 1))

The Coefficient b_G (II / II)

Actually, we can compare two b_G's:

$$b_{UV} \equiv \text{without } H \cdot \mathcal{O}_{extra} \text{ mixing}$$

$$b_{IR} \equiv \text{with } H \cdot \mathcal{O}_{extra} \text{ mixing}$$

F-term approx justified when: $\frac{b_{UV} - b_{IR}}{b_{IR}} \ll 1$

A Good Deal: 3 For 1

One unknown scale: Λ_G

Known: Mixing angle dependence and b_G

$$\mathcal{O}_{h^0FF} = \frac{b_G}{16\pi^2}\cos(\alpha+\beta)\left(\frac{v}{\Lambda_G}\right)^2\frac{h^0}{v}\mathrm{Tr}_G F_{\mu\nu}F^{\mu\nu}$$

$$\mathcal{O}_{H^0FF} = \frac{b_G}{16\pi^2}\sin(\alpha+\beta)\left(\frac{v}{\Lambda_G}\right)^2\frac{H^0}{v}\mathrm{Tr}_G F_{\mu\nu}F^{\mu\nu}$$

$$\mathcal{O}_{A^0FF} = \frac{b_G}{32\pi^2}\left(\frac{v}{\Lambda_G}\right)^2\frac{A^0}{v}\varepsilon^{\mu\nu\rho\sigma}\mathrm{Tr}_G F_{\mu\nu}F_{\rho\sigma}$$

A Very Calculable Limit

IF Higgs sole source of mass for extra sector,
(precision electroweak more tuned in this case...)

Then $\Lambda_G^2 = 2 v_u v_d$, and we have:
(assuming equal b_u and b_d contributions)

$$\boxed{\mathcal{O}_{h^0 FF} = \frac{b_G}{16\pi^2} \frac{\cos(\alpha+\beta)}{\sin 2\beta} \frac{h^0}{v} \mathrm{Tr}_G F_{\mu\nu} F^{\mu\nu}}$$

Comparison With LHC

Comparison With LHC

(Disclaimer I: preliminary # ' s, subject to change...)

Comparison With LHC

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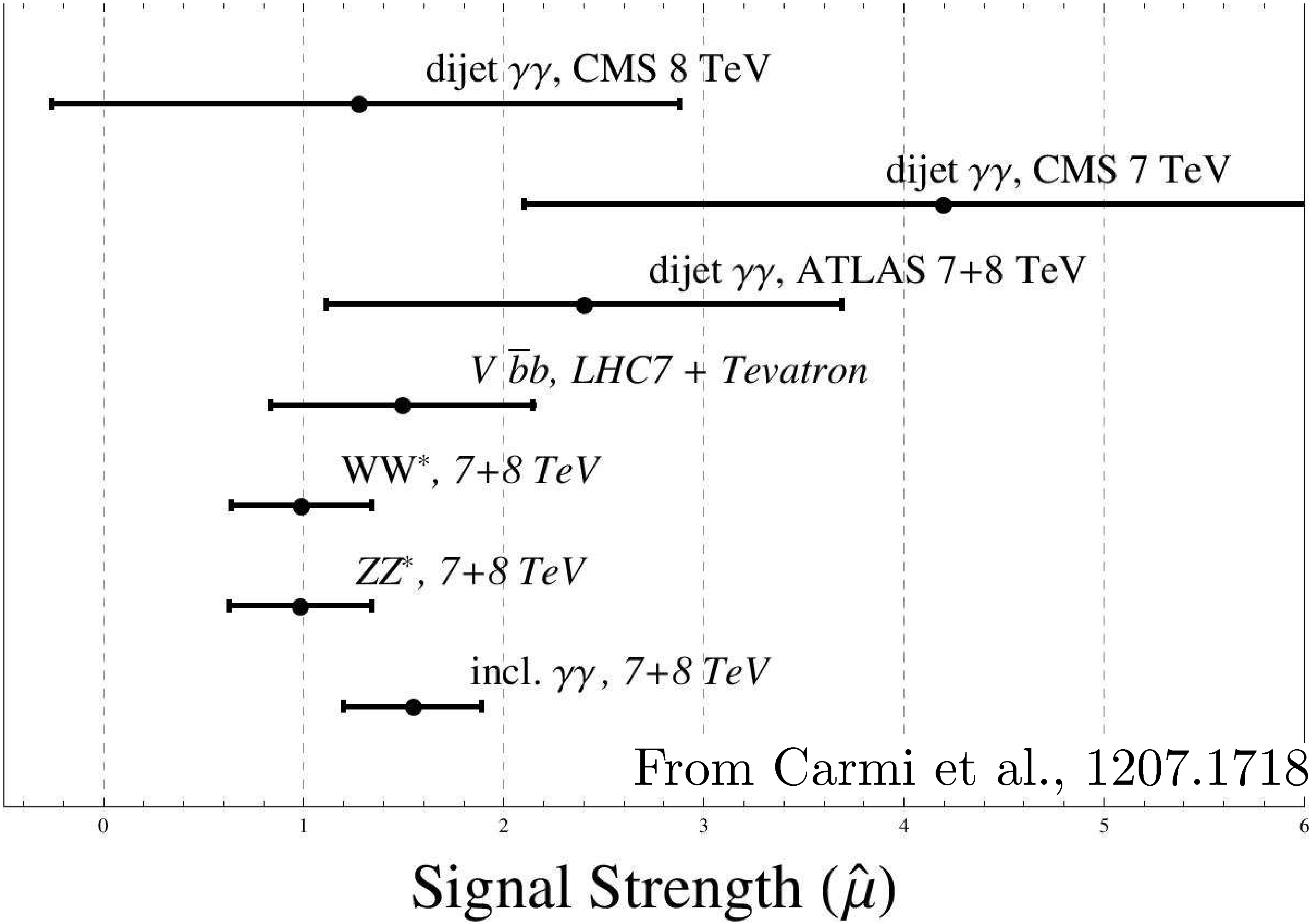
(Disclaimer II: Not doing a Bayesian combination here)



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From Carmi et al., 1207.1718
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Signal Strength ($\hat{\mu}$)

LHC Limits

Compare with expectation for a SM Higgs:

$$\frac{\sigma}{\sigma_{SM}}(h \to \gamma\gamma)_{incl}\colon\ 1.5^{+0.4}_{-0.3}$$

see CMS and ATLAS

Carmi et al. '12

+ many more

$$\frac{\sigma}{\sigma_{SM}}(h \to VV^*)_{incl}\colon\ 1.0^{+0.4}_{-0.4}$$

$$\frac{\sigma}{\sigma_{SM}}(pp \to hjj \to \gamma\gamma jj)\colon\ 2.4^{+1.4}_{-1.2}$$

(some from VBF

and gluon fusion)

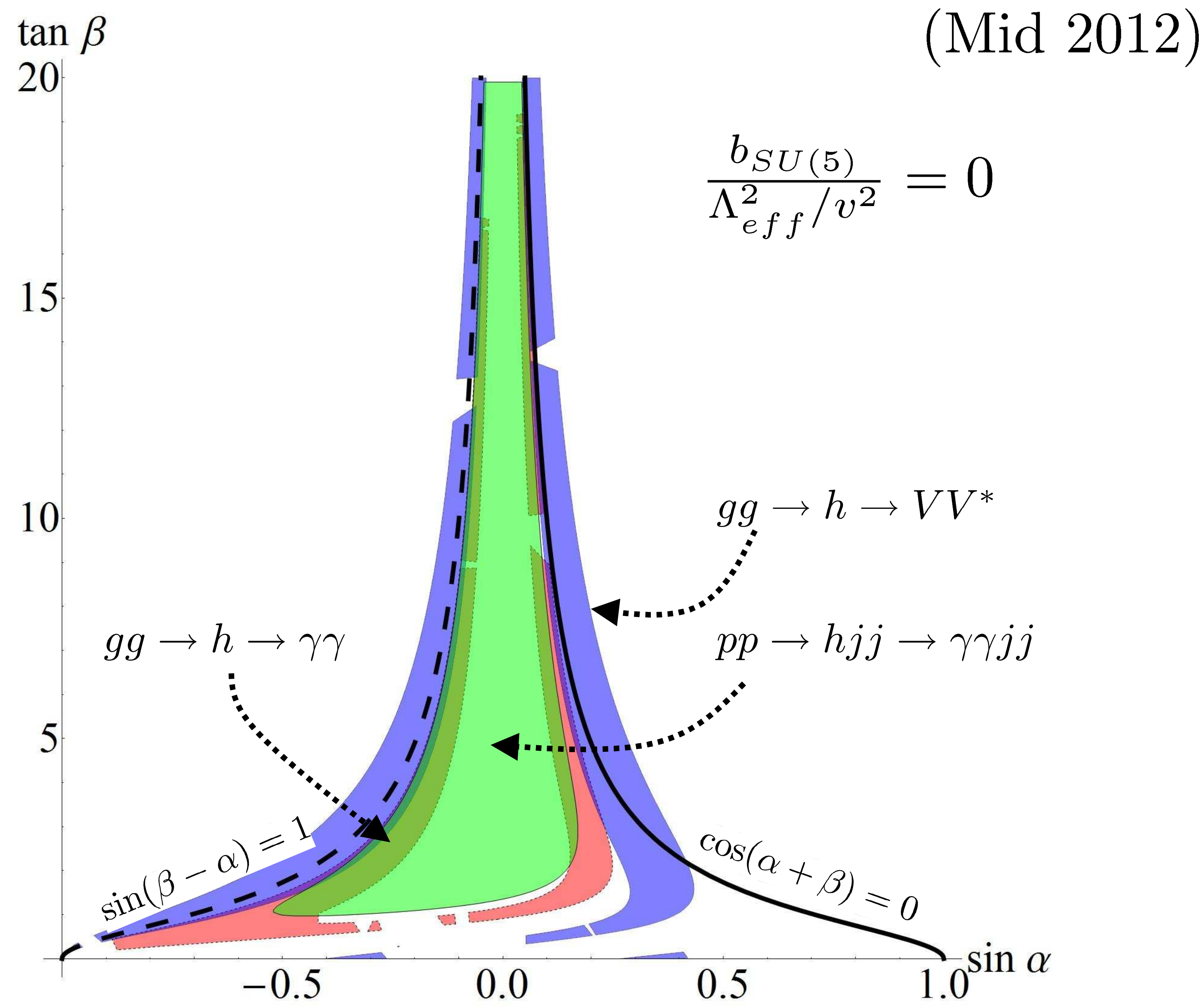
(just using ATLAS)

Comparing with the Limits

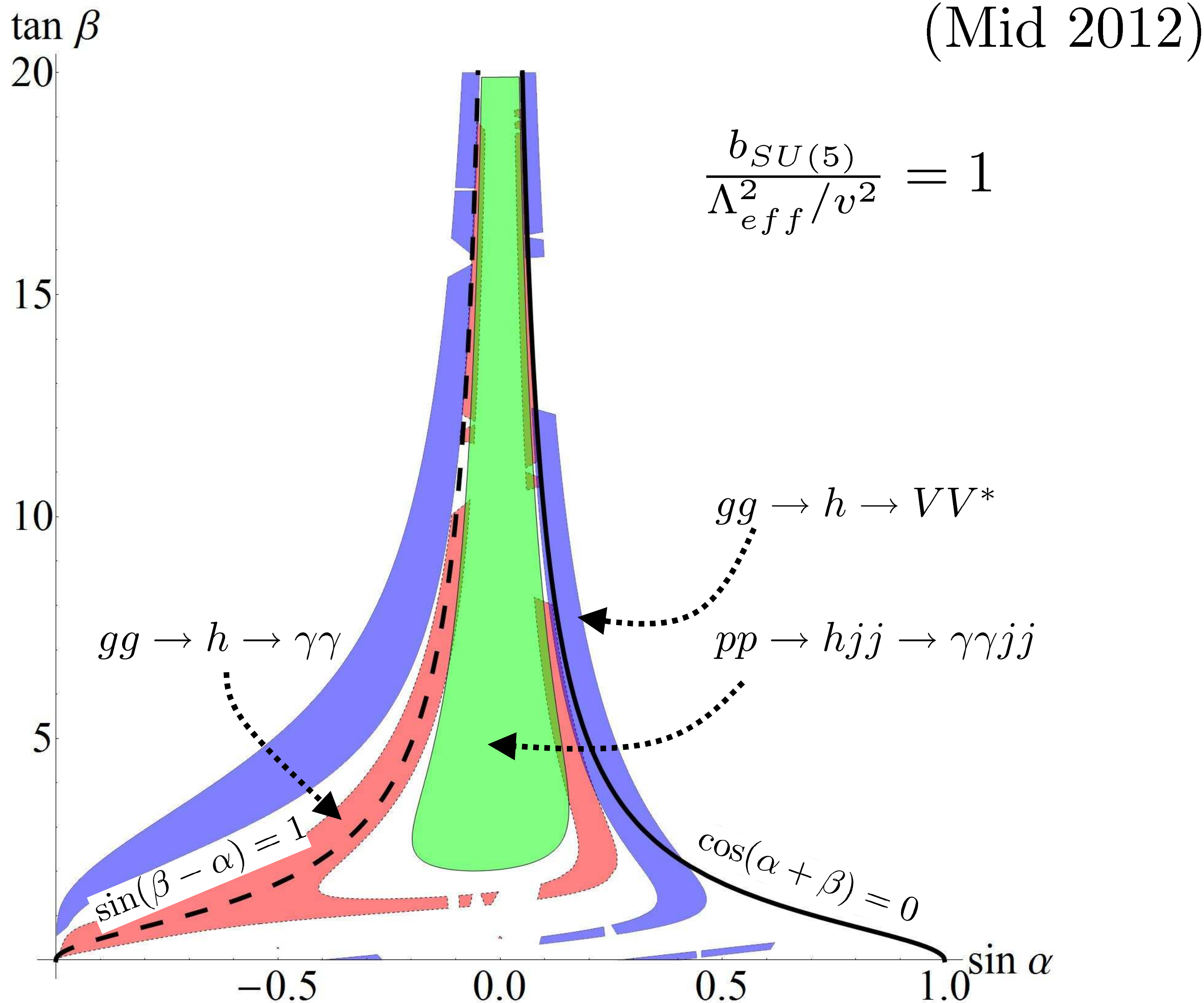
Plot in limit of 2HDM + Extra, i.e.,

Assume superpartners decoupled

to order $\frac{v^2}{M_{SUSY}^2}$



tan β
(Mid 2012)
$\frac{b_{SU(5)}}{\Lambda_{eff}^2/v^2} = 0$
20
15
10
5
$gg \to h \to VV^*$
$pp \to hjj \to \gamma\gamma jj$
$gg \to h \to \gamma\gamma$
$\sin(\beta - \alpha) = 1$
$\cos(\alpha + \beta) = 0$
−0.5
0.0
0.5
1.0
$\sin\alpha$



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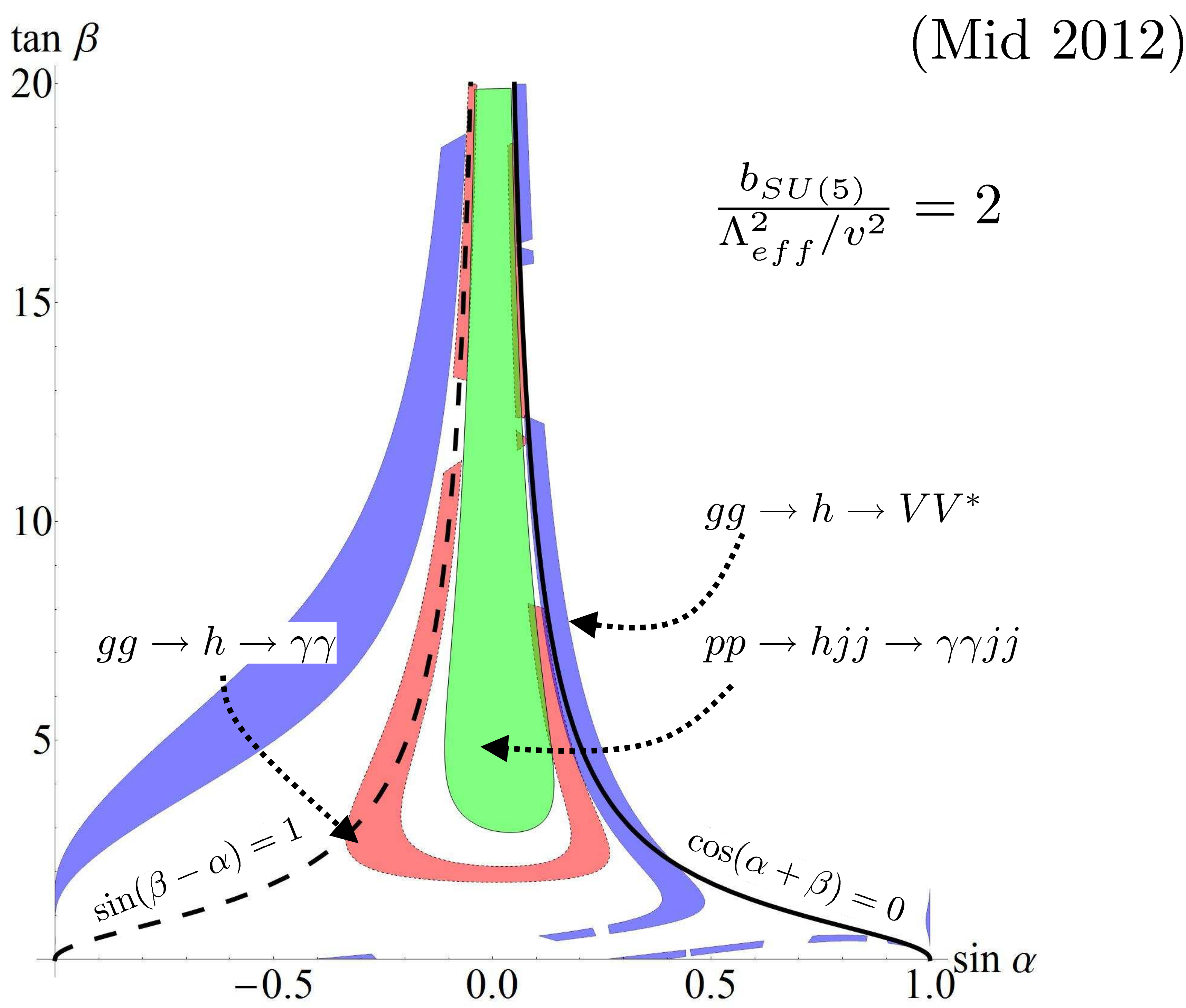

(Mid 2012)
$\tan\beta$
$\frac{b_{SU(5)}}{\Lambda^2_{eff}/v^2} = 2$
$gg \to h \to VV^*$
$pp \to hjj \to \gamma\gamma jj$
$gg \to h \to \gamma\gamma$
$\sin(\beta - \alpha) = 1$
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$\sin\alpha$
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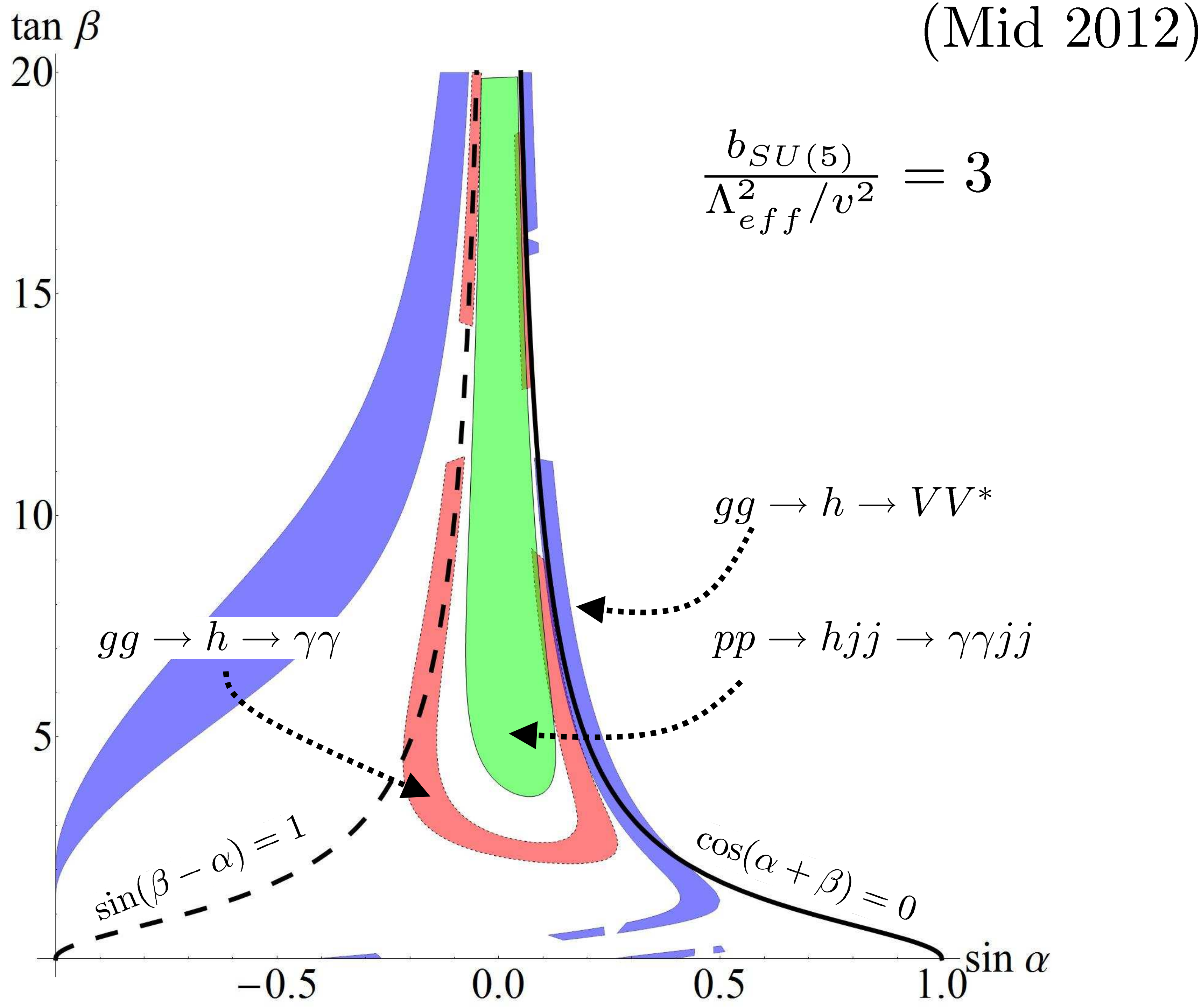

(Mid 2012)
$\tan\beta$
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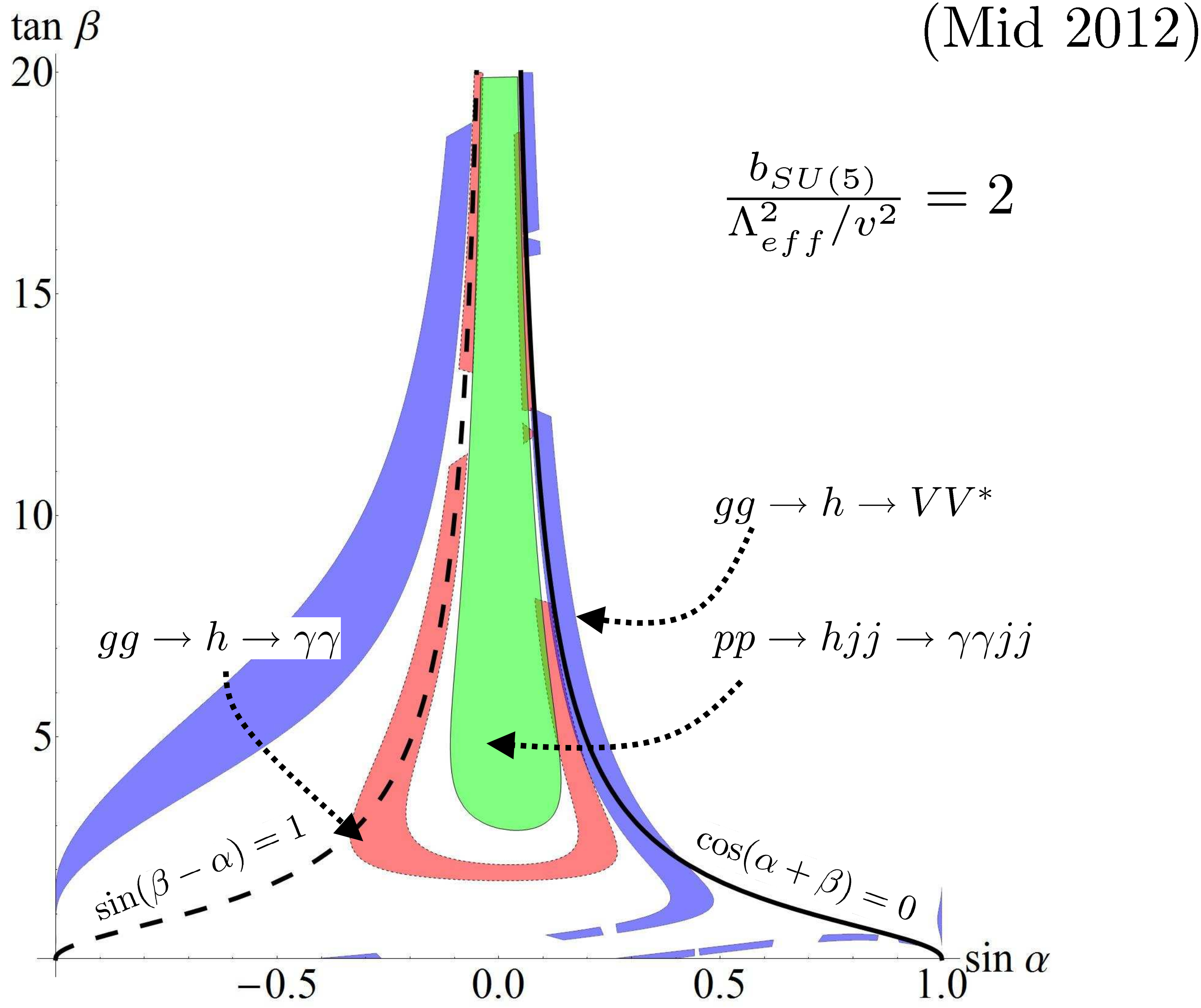
-0.5
0.0
0.5
1.0
$\sin\alpha$
$\frac{b_{SU(5)}}{\Lambda^2_{eff}/v^2} = 3$
$gg \to h \to VV^*$
$pp \to hjj \to \gamma\gamma jj$
$gg \to h \to \gamma\gamma$
$\sin(\beta-\alpha)=1$
$\cos(\alpha+\beta)=0$



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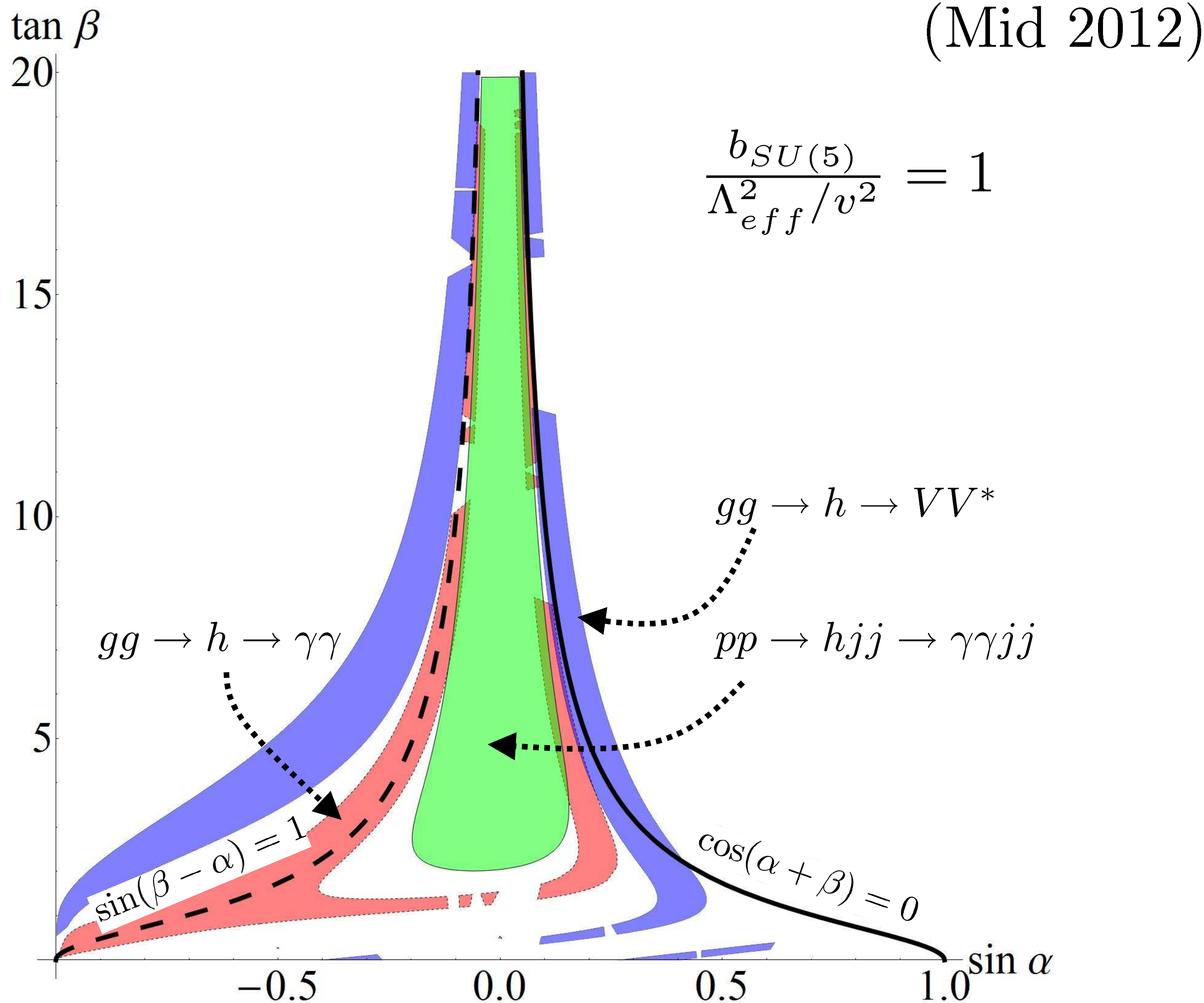

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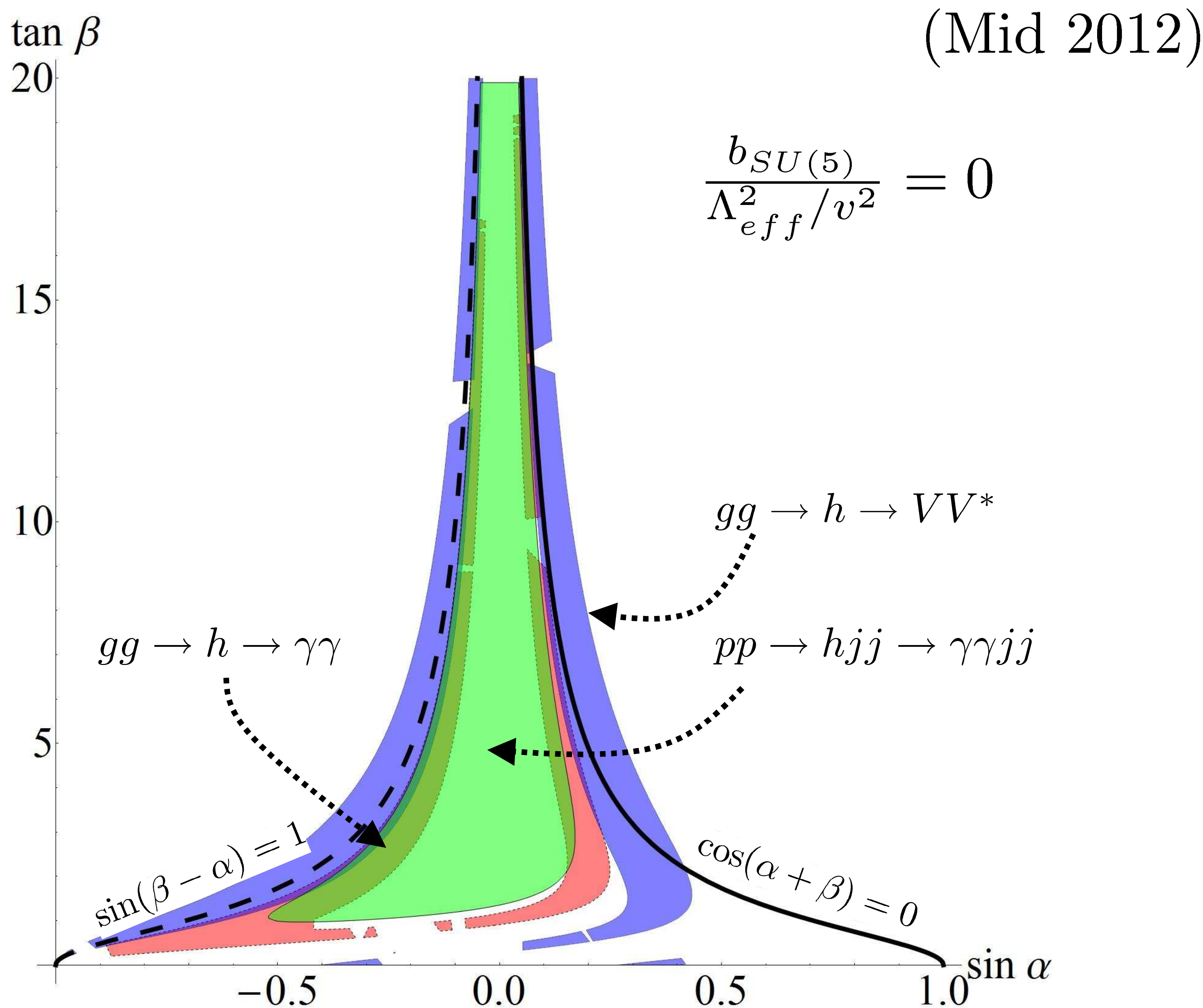

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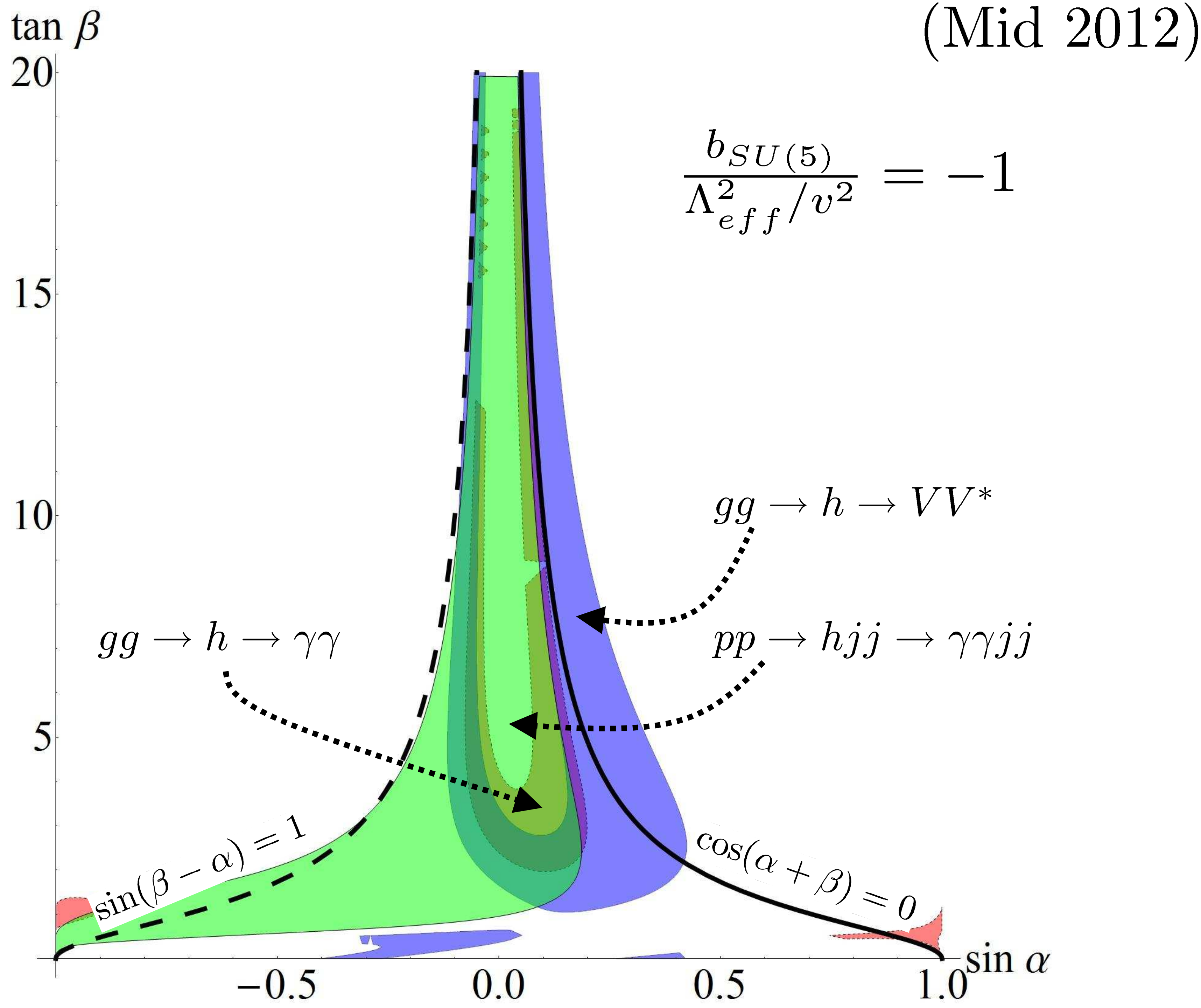

(Mid 2012)
$\tan\beta$
$\frac{b_{SU(5)}}{\Lambda^2_{eff}/v^2} = -1$
$gg \to h \to VV^*$
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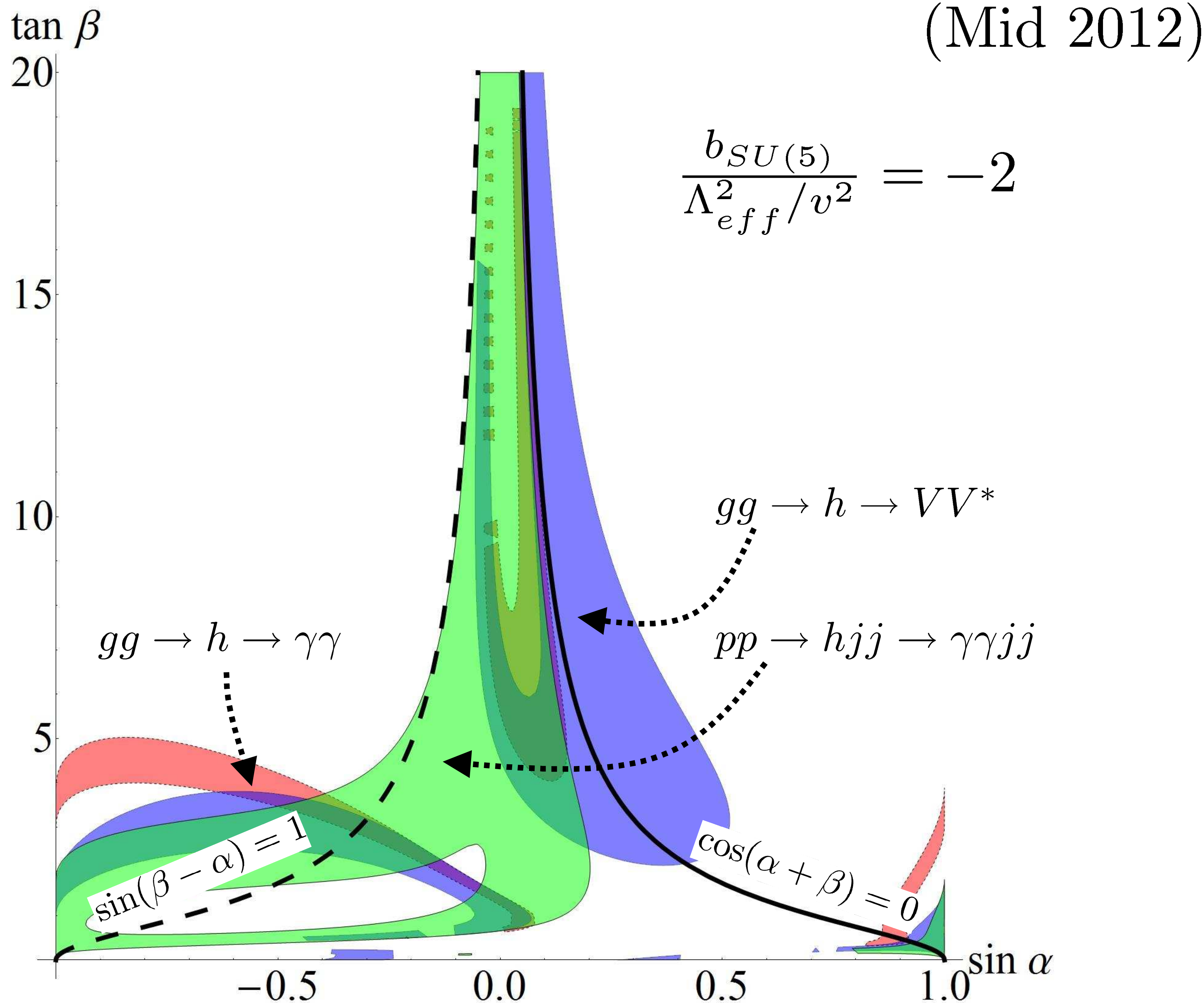

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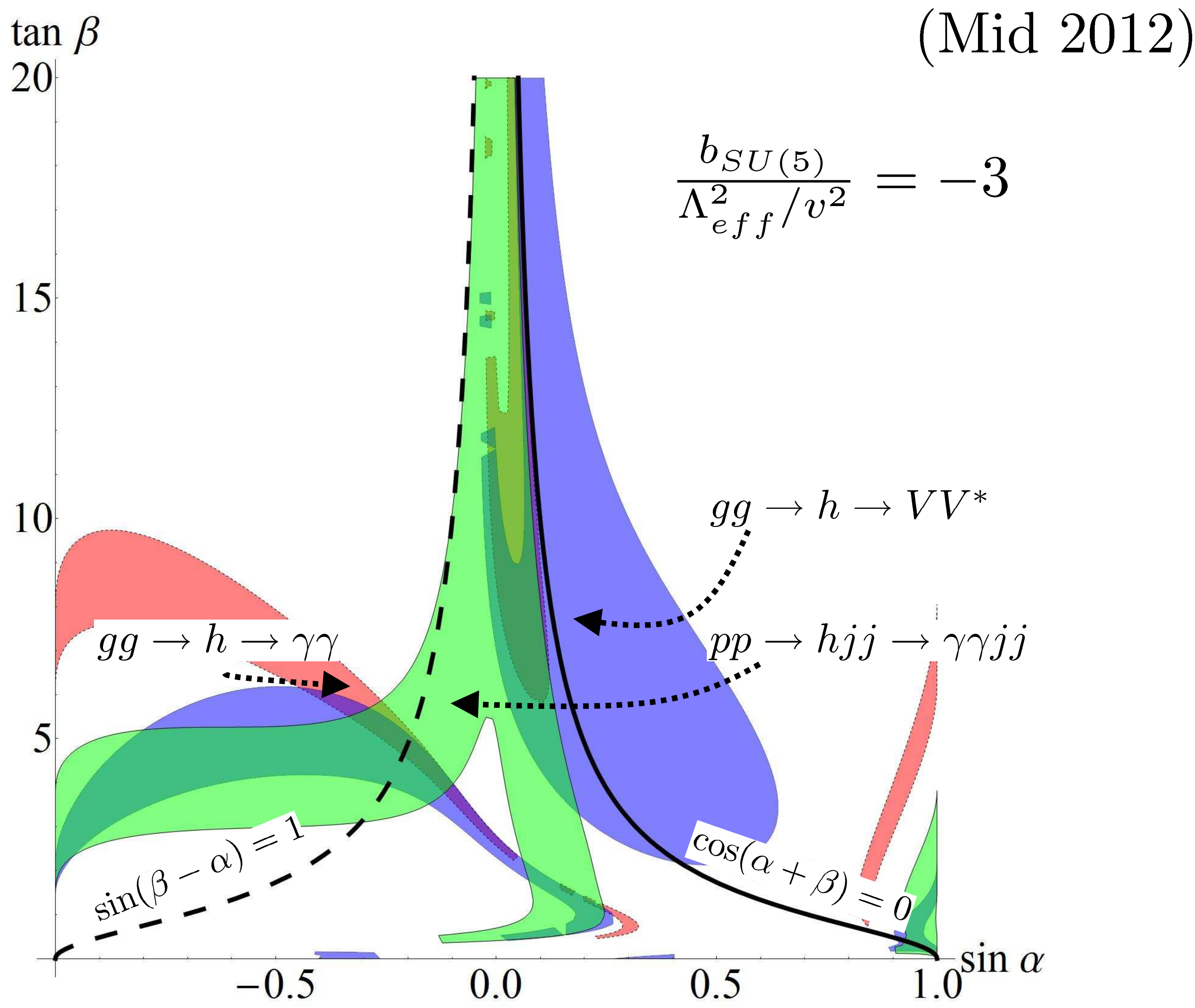
$\cos(\alpha+\beta)=0$



(Mid 2012)
$\tan\beta$
20
15
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5
$\frac{b_{SU(5)}}{\Lambda_{eff}^2/v^2} = -3$
$gg \to h \to VV^*$
$gg \to h \to \gamma\gamma$
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$\sin(\beta - \alpha) = 1$
$\cos(\alpha + \beta) = 0$
-0.5
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0.5
1.0
$\sin\alpha$

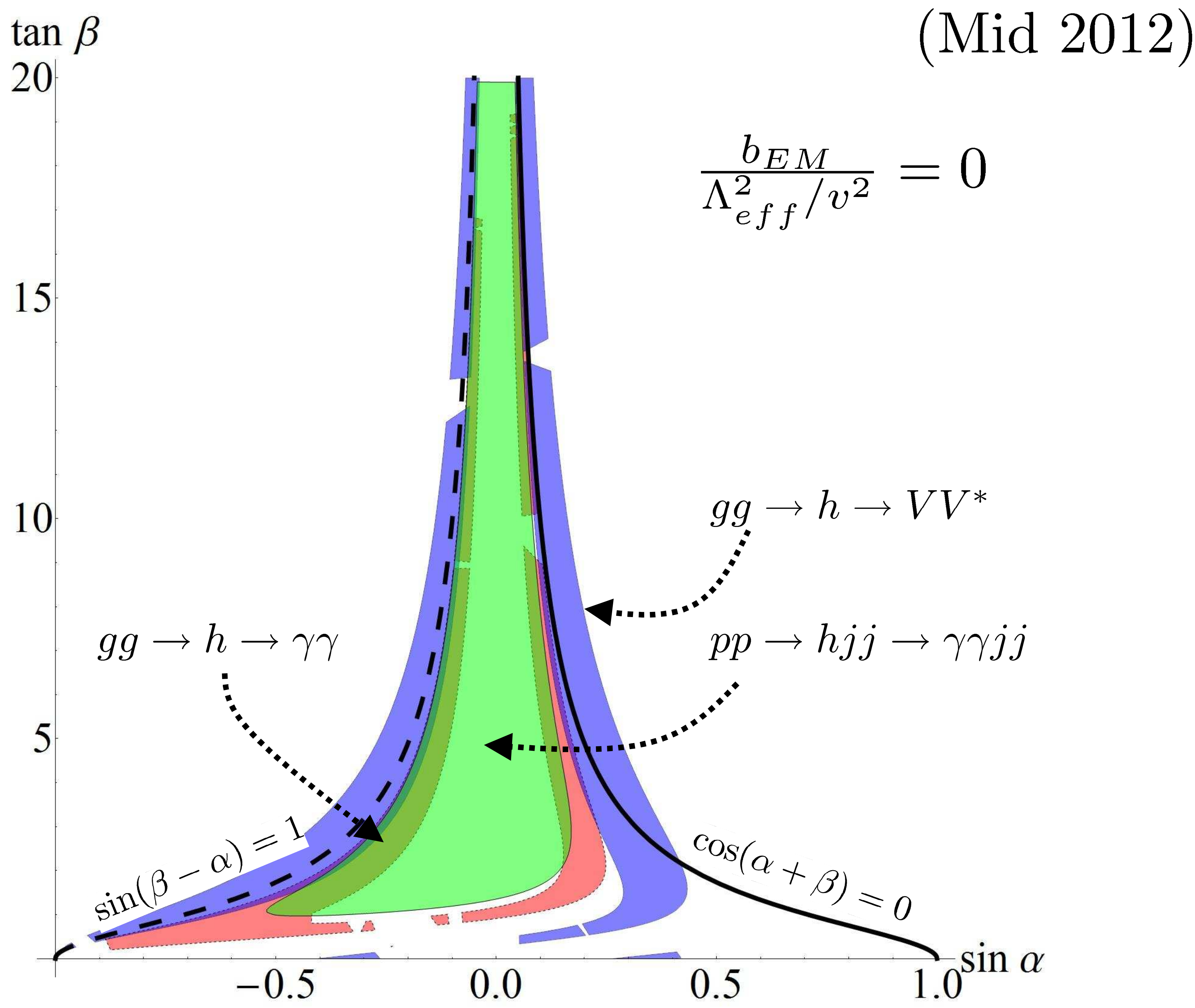
Also Possible:

Decouple Extra $SU(3)$ Colored States

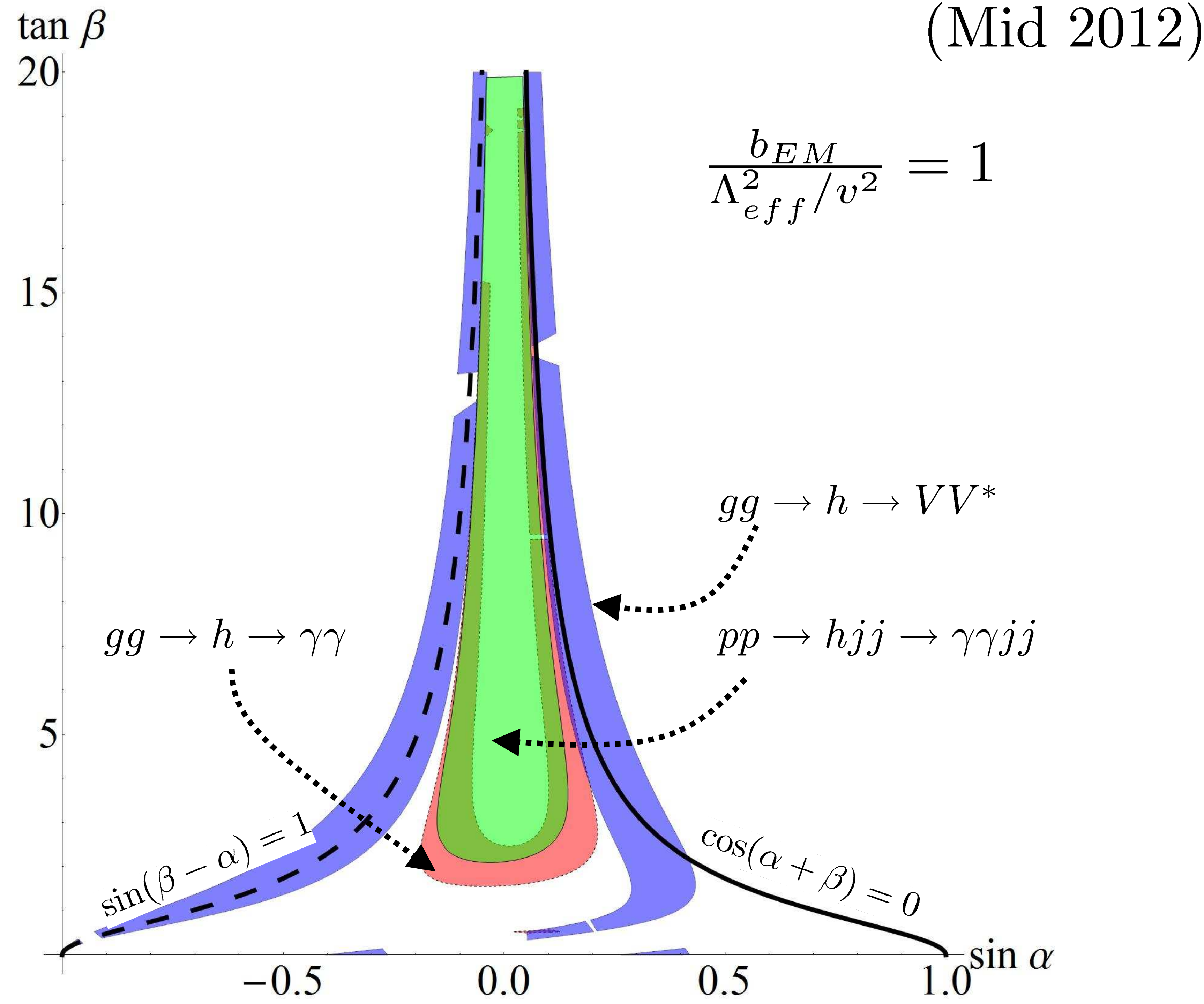
This is in principle compatible with unif^n

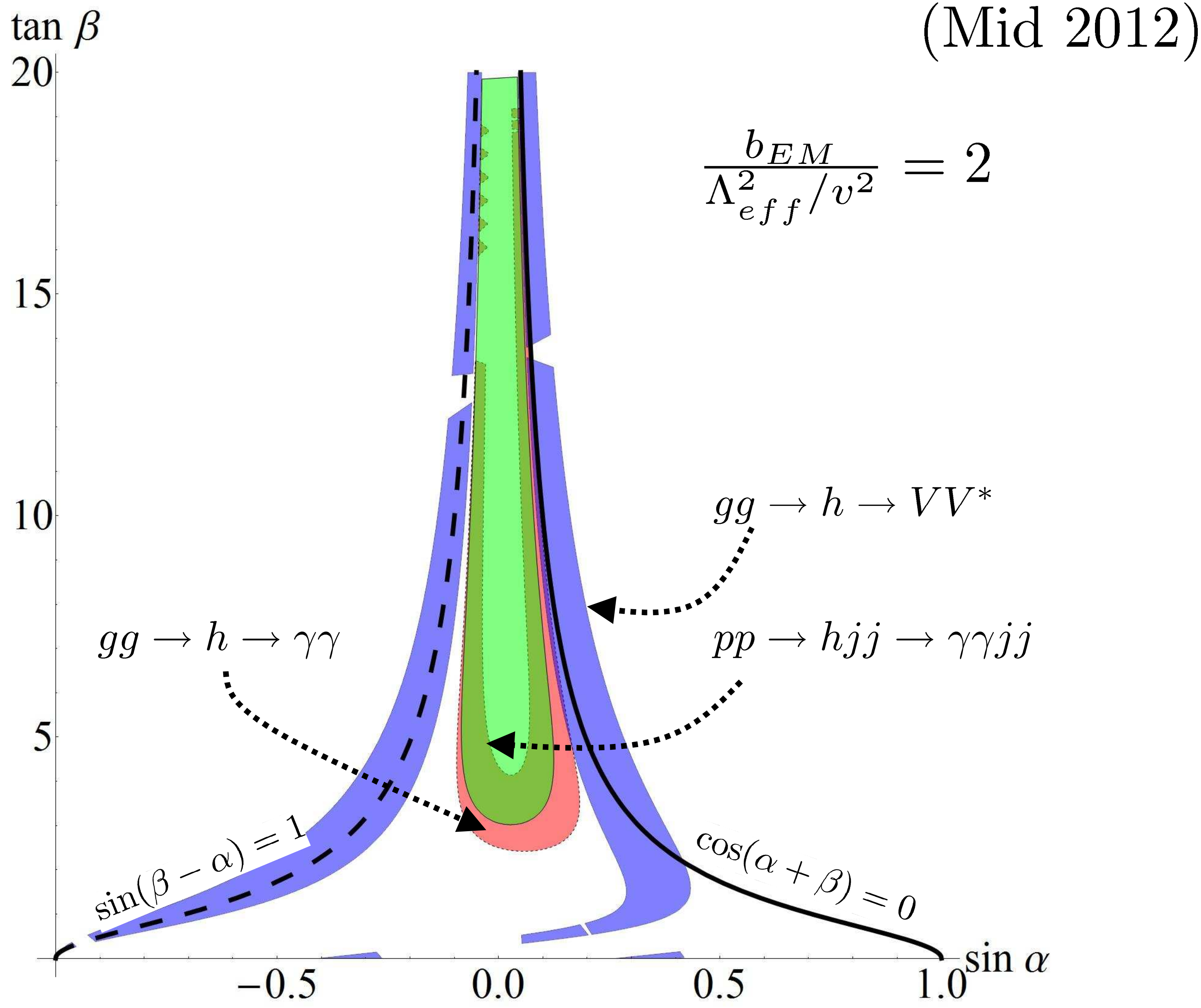
(These states can decouple as v^2/Λ^2_{eff})

(Take GUT normalization of b_{EM})

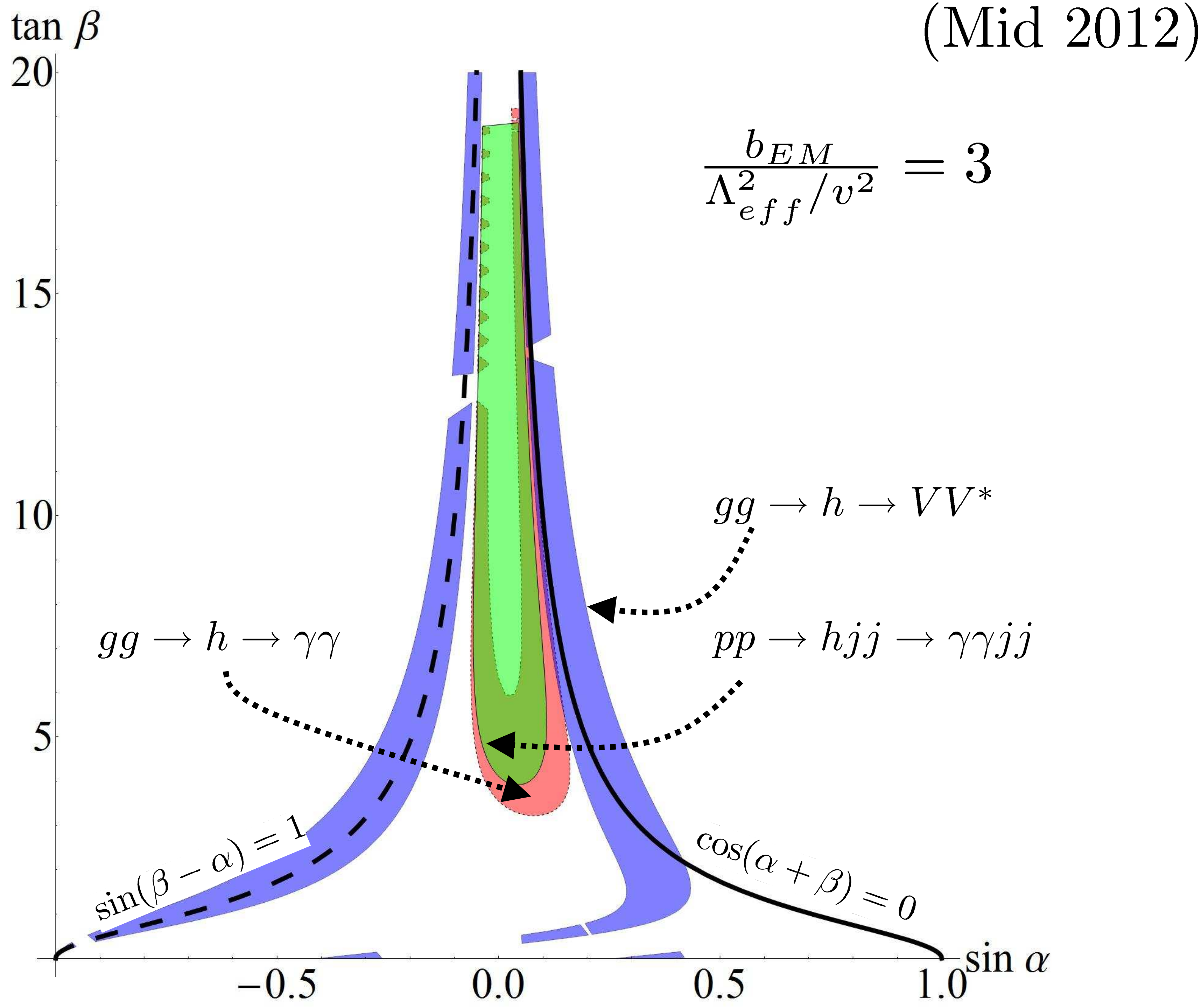


(Mid 2012)
$\tan\beta$
20
15
10
5
$\frac{b_{EM}}{\Lambda^2_{eff}/v^2} = 0$
$gg \to h \to VV^*$
$gg \to h \to \gamma\gamma$
$pp \to hjj \to \gamma\gamma jj$
$\sin(\beta-\alpha) = 1$
$\cos(\alpha+\beta) = 0$
-0.5
0.0
0.5
1.0
$\sin\alpha$

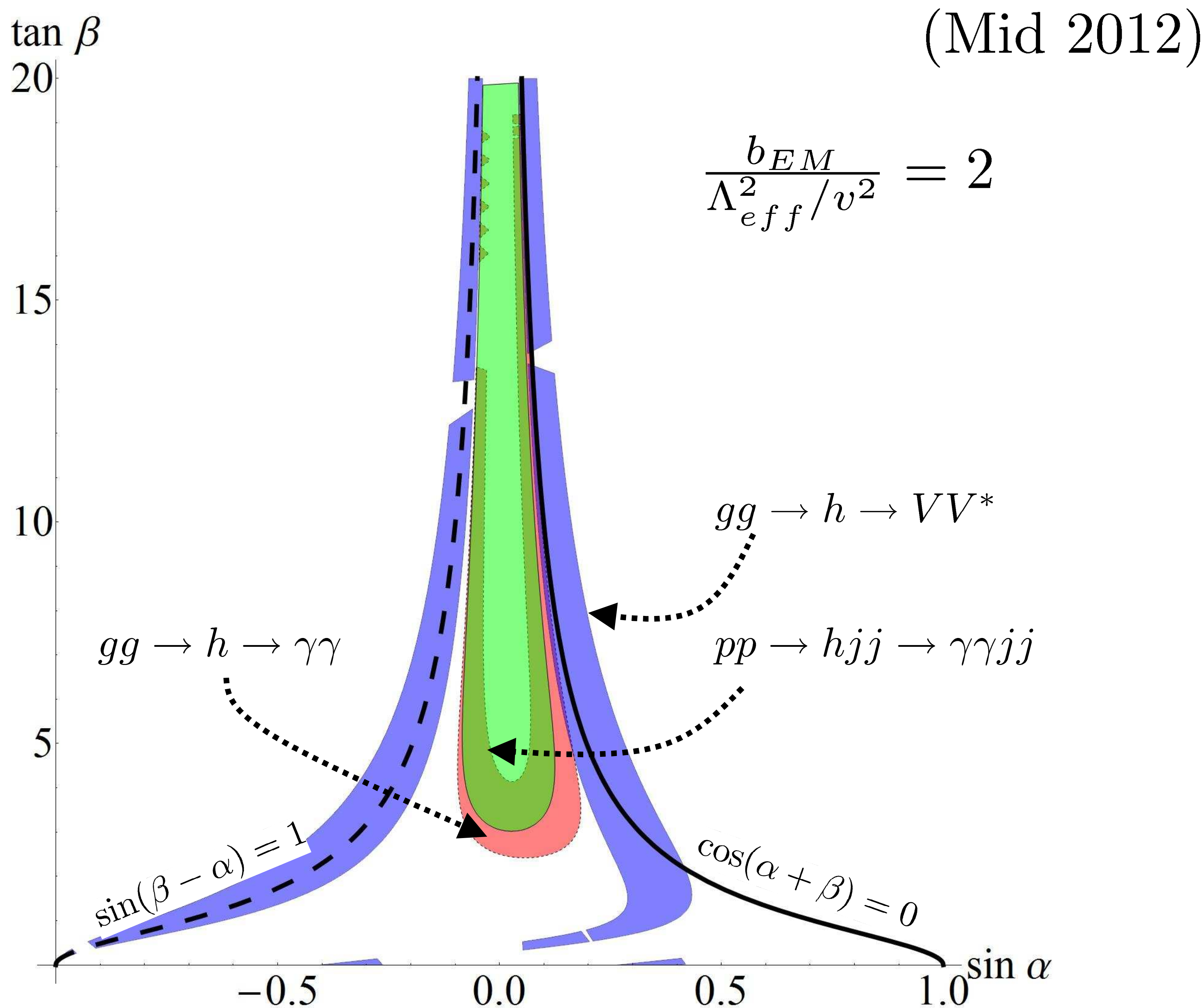

(Mid 2012)
tan β
$\frac{b_{EM}}{\Lambda^2_{eff}/v^2} = 1$
$gg \to h \to VV^*$
$pp \to hjj \to \gamma\gamma jj$
$gg \to h \to \gamma\gamma$
$\sin(\beta - \alpha) = 1$
$\cos(\alpha + \beta) = 0$
$\sin\alpha$
20
15
10
5
−0.5
0.0
0.5
1.0

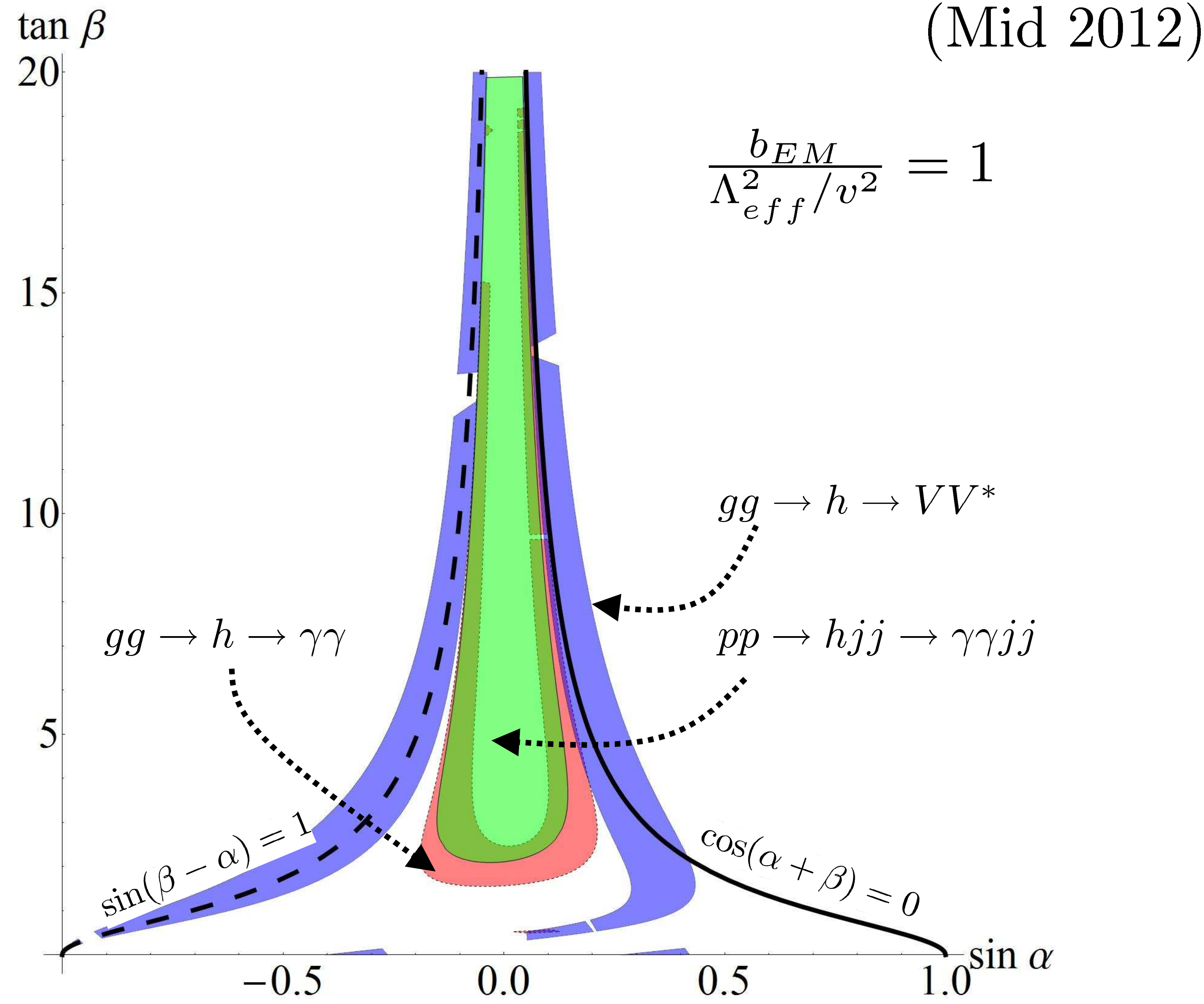


(Mid 2012)
$\tan\beta$
$\sin\alpha$
20
15
10
5
−0.5
0.0
0.5
1.0
$\frac{b_{EM}}{\Lambda^2_{eff}/v^2} = 2$
$gg \to h \to VV^*$
$pp \to hjj \to \gamma\gamma jj$
$gg \to h \to \gamma\gamma$
$\sin(\beta - \alpha) = 1$
$\cos(\alpha + \beta) = 0$

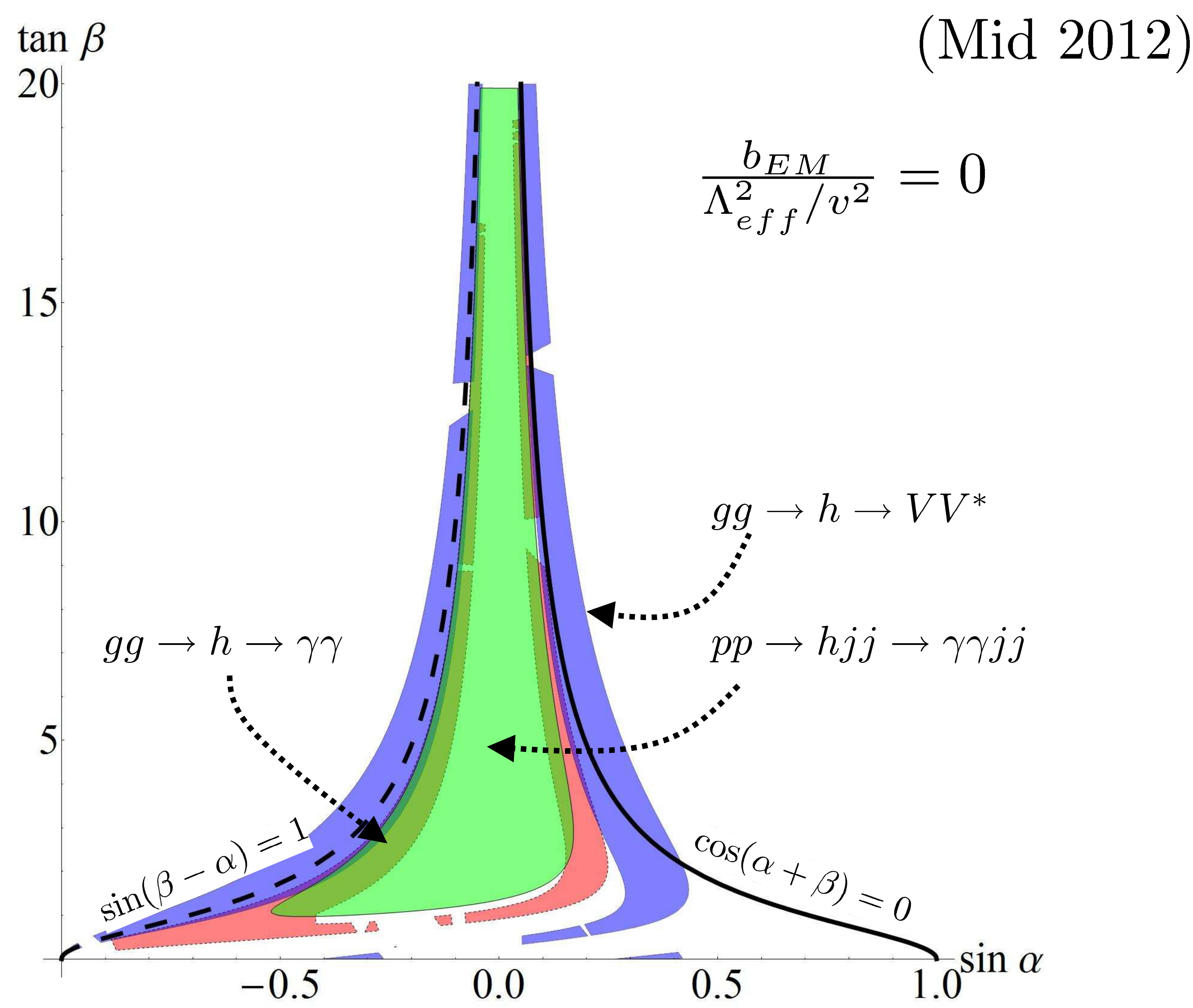


(Mid 2012)
$\tan\beta$
$\frac{b_{EM}}{\Lambda^2_{eff}/v^2} = 3$
$gg \to h \to VV^*$
$gg \to h \to \gamma\gamma$
$pp \to hjj \to \gamma\gamma jj$
$\sin(\beta-\alpha)=1$
$\cos(\alpha+\beta)=0$
$\sin\alpha$
20
15
10
5
−0.5
0.0
0.5
1.0

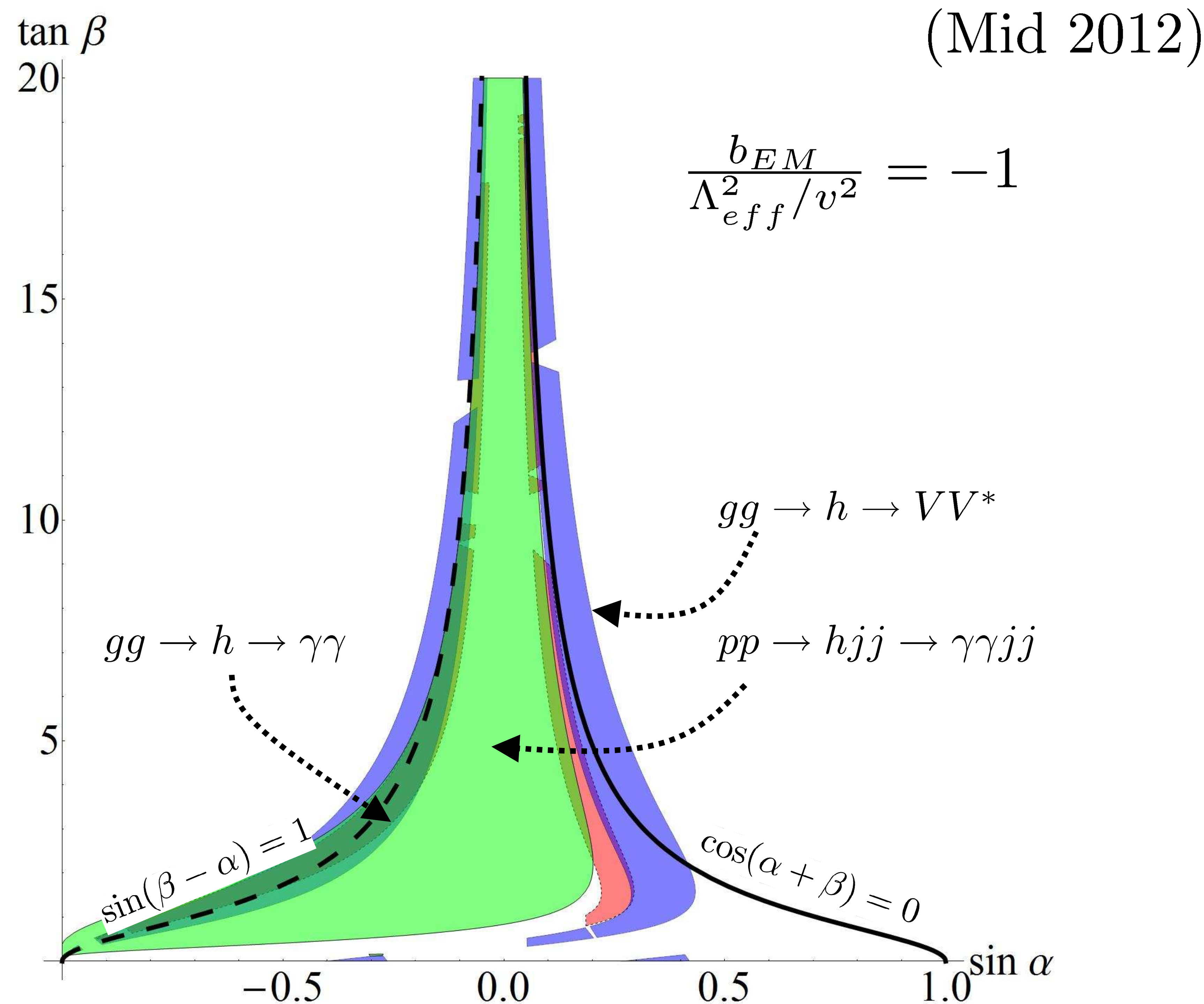

(Mid 2012)
$\tan\beta$
$\frac{b_{EM}}{\Lambda^2_{eff}/v^2} = 2$
$gg \to h \to VV^*$
$gg \to h \to \gamma\gamma$
$pp \to hjj \to \gamma\gamma jj$
$\sin(\beta - \alpha) = 1$
$\cos(\alpha + \beta) = 0$
$\sin\alpha$
20
15
10
5
−0.5
0.0
0.5
1.0



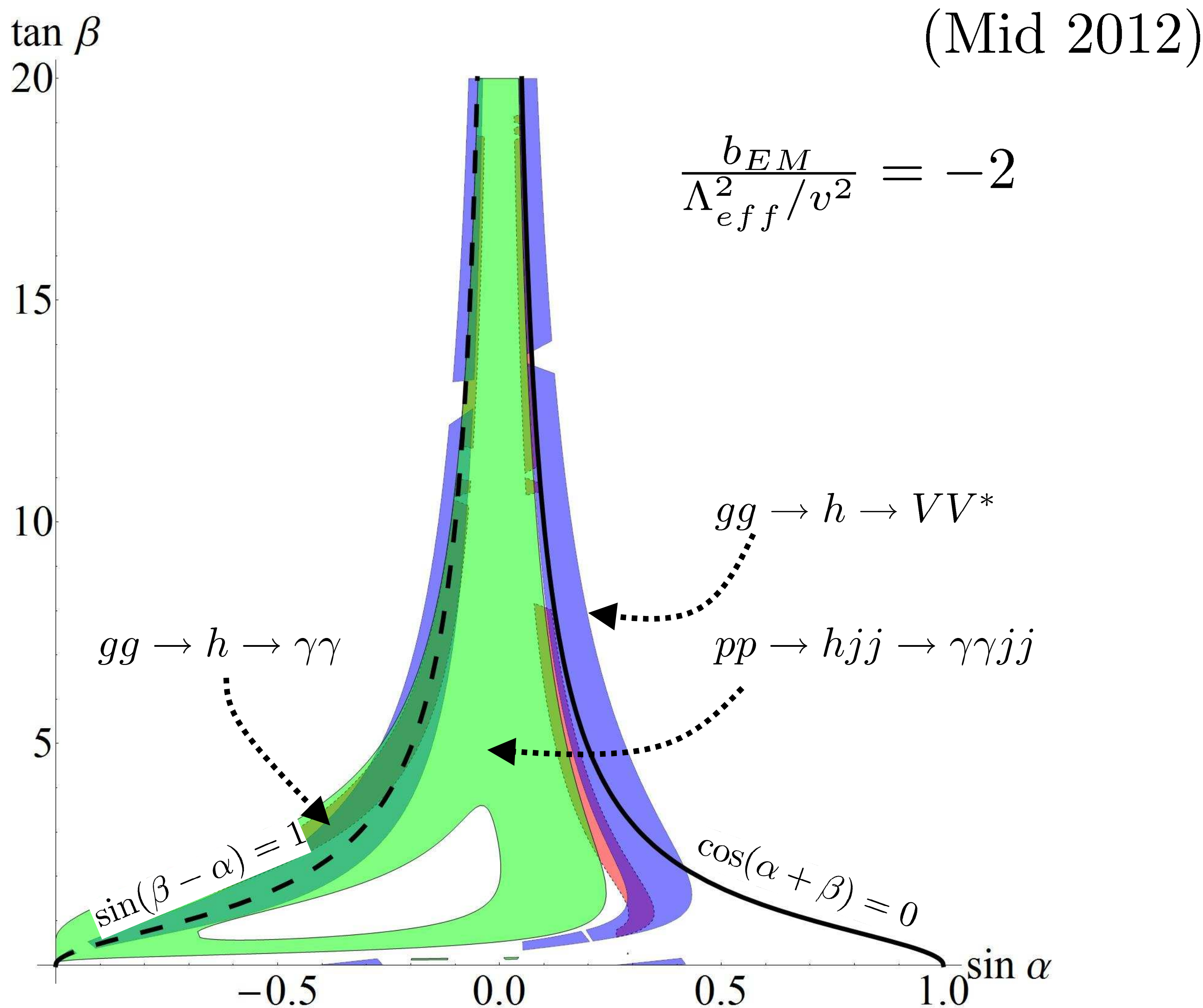
(Mid 2012)
$\tan\beta$
20
15
10
5
$\frac{b_{EM}}{\Lambda^2_{eff}/v^2} = 1$
$gg \to h \to VV^*$
$pp \to hjj \to \gamma\gamma jj$
$gg \to h \to \gamma\gamma$
$\sin(\beta - \alpha) = 1$
$\cos(\alpha + \beta) = 0$
−0.5
0.0
0.5
1.0
$\sin\alpha$



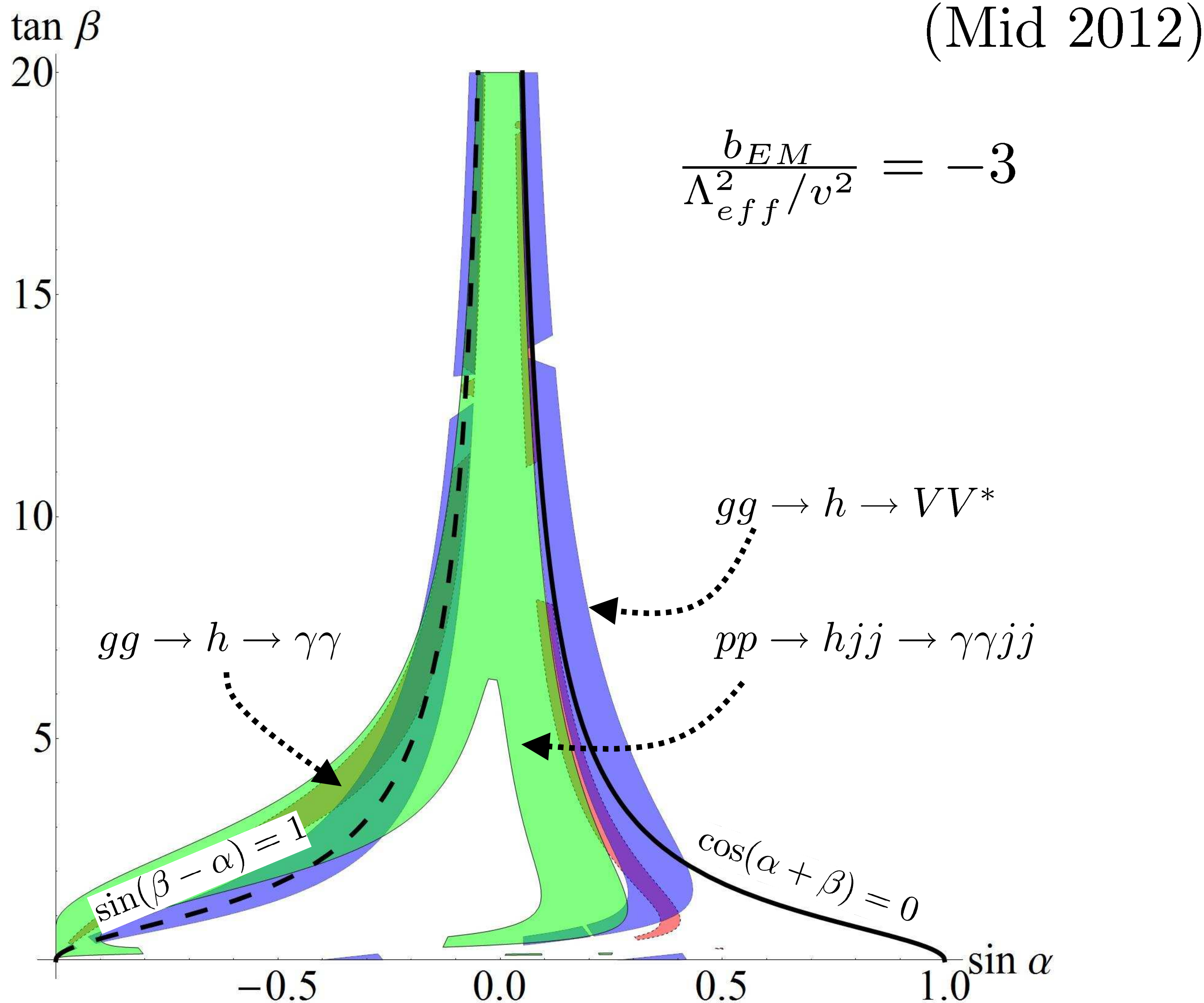
(Mid 2012)
$\tan\beta$
20
15
10
5
$\frac{b_{EM}}{\Lambda^2_{eff}/v^2} = 0$
$gg \to h \to VV^*$
$gg \to h \to \gamma\gamma$
$pp \to hjj \to \gamma\gamma jj$
$\sin(\beta - \alpha) = 1$
$\cos(\alpha + \beta) = 0$
-0.5
0.0
0.5
1.0
$\sin\alpha$



(Mid 2012)
$\tan\beta$
20
15
10
5
-0.5
0.0
0.5
1.0
$\sin\alpha$
$\frac{b_{EM}}{\Lambda^2_{eff}/v^2} = -1$
$gg \to h \to VV^*$
$pp \to hjj \to \gamma\gamma jj$
$gg \to h \to \gamma\gamma$
$\sin(\beta-\alpha) = 1$
$\cos(\alpha+\beta) = 0$



(Mid 2012)
$\tan\beta$
20
15
10
5
-0.5
0.0
0.5
1.0
$\sin\alpha$
$\frac{b_{EM}}{\Lambda^2_{eff}/v^2} = -2$
$gg \to h \to VV^*$
$pp \to hjj \to \gamma\gamma jj$
$gg \to h \to \gamma\gamma$
$\sin(\beta-\alpha) = 1$
$\cos(\alpha+\beta) = 0$



(Mid 2012)
$\tan\beta$
20
15
10
5
$\frac{b_{EM}}{\Lambda^2_{eff}/v^2} = -3$
$gg \to h \to VV^*$
$gg \to h \to \gamma\gamma$
$pp \to hjj \to \gamma\gamma jj$
$\sin(\beta - \alpha) = 1$
$\cos(\alpha + \beta) = 0$
−0.5
0.0
0.5
1.0
$\sin\alpha$

Basic Point

Still preliminary, but Higgs physics
is becoming a good probe
of such scenarios

Summary / Conclusions

Summary

- SM $\subset$ Strings $\Rightarrow$ Extra Sectors
- Higgs / Extra Mixing is *Calculable*
- Use Higgs as a window to BSM
- Probe directly?