The impact of LHC data on the origin of matter

Jing Shu

ITP-CAS

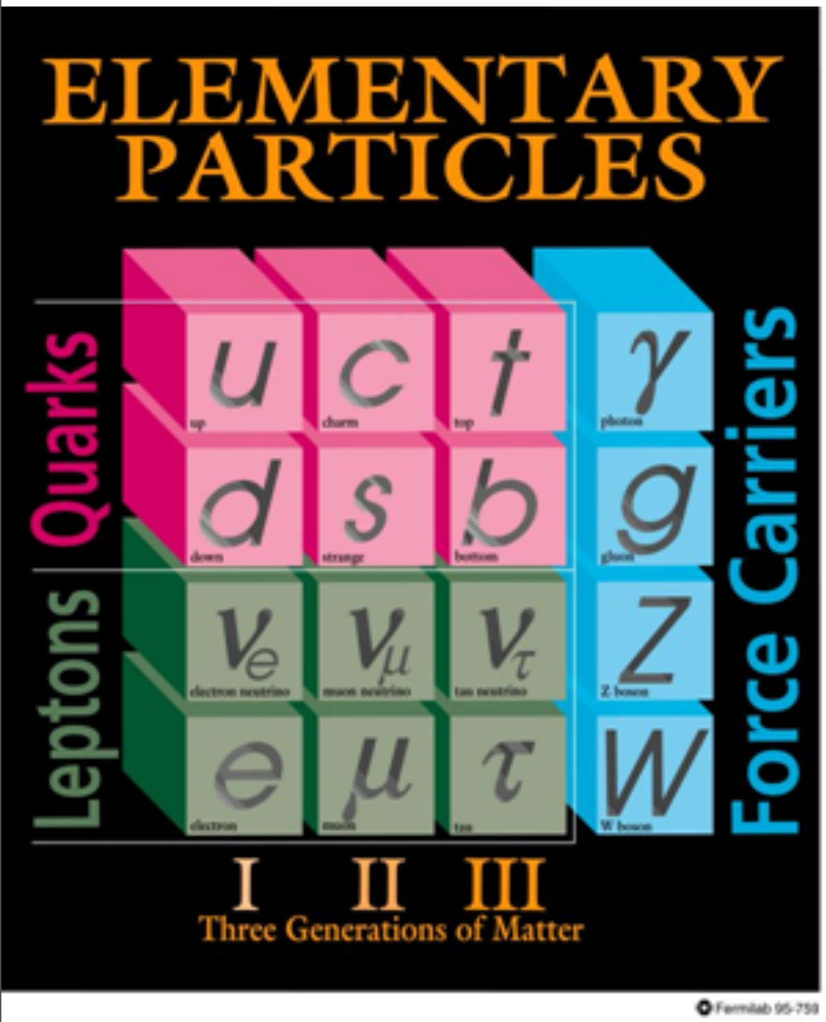
W. Huang, J. S,Y. Zhang, JHEP 1303 (2013) 164

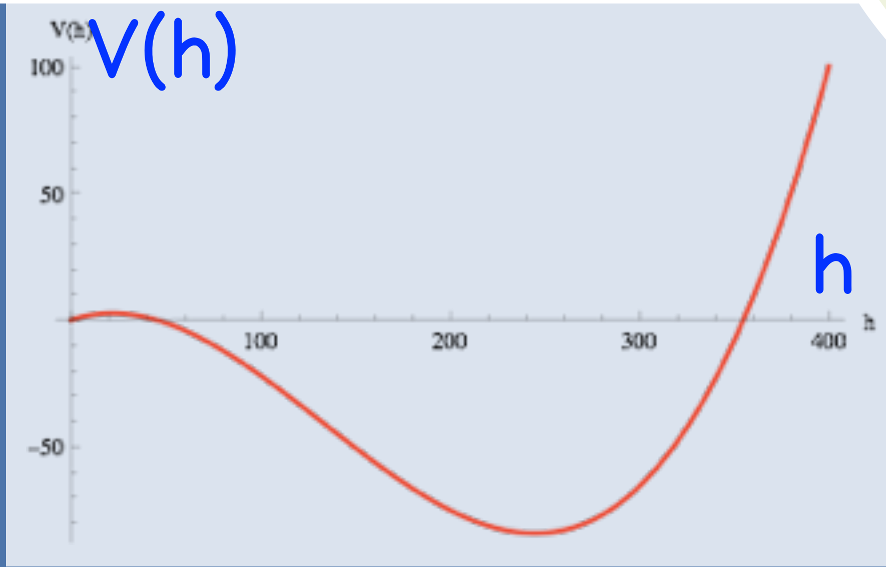
J. S,Y. Zhang, Phys. Rev. Lett. 111 (2013) 091801

Outline

- Overview of the connection between Higgs global fits & BG.
- The electroweak phase transition & Higgs global fits
- CP Violation & Higgs global fits
- Future measurements (CPV, self-coupling) at the LHC
- Summary and outlook.

The origin of mass!





searching for higgs boson

Higgs mechanism

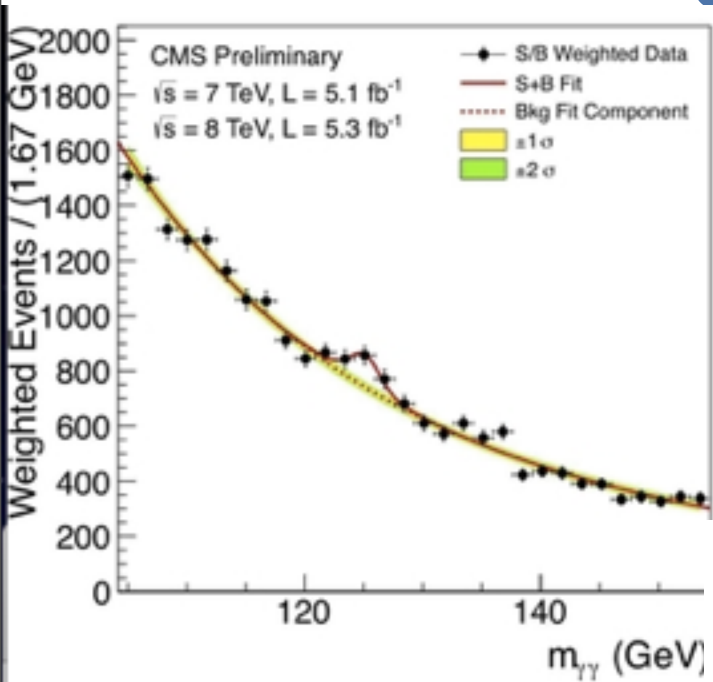
The origin of electroweak symmetry breaking

Higgs ???

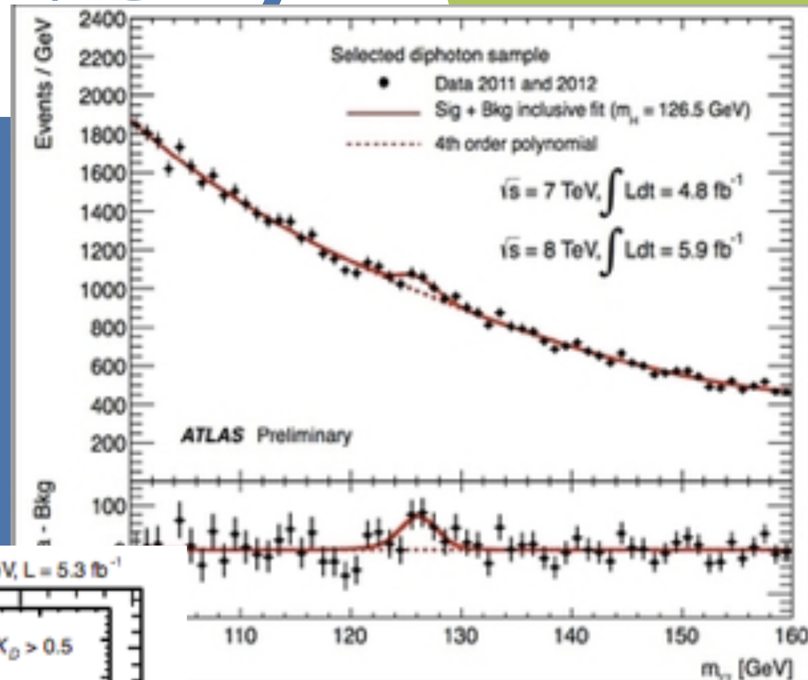
Higgs discovery

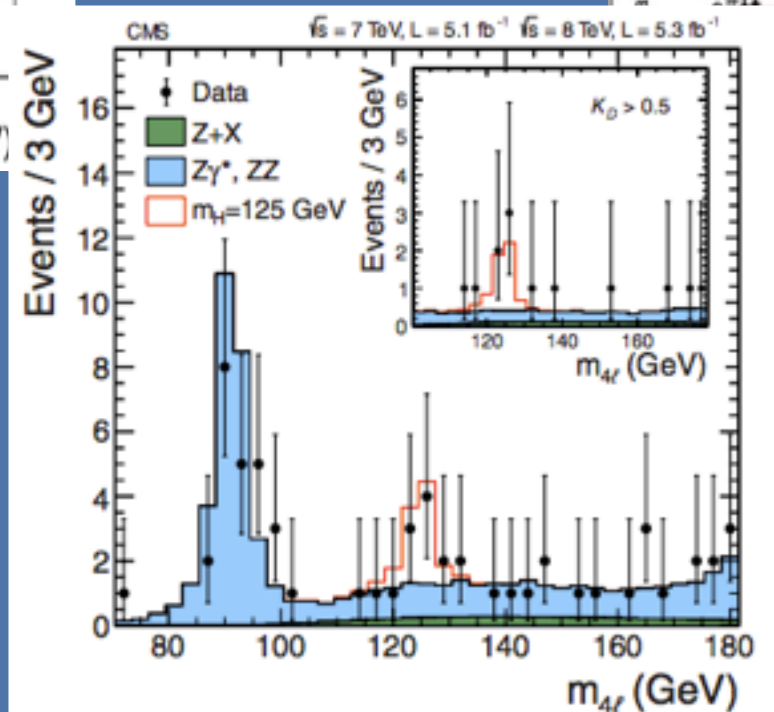
July 4th 2012

CMS ZZ



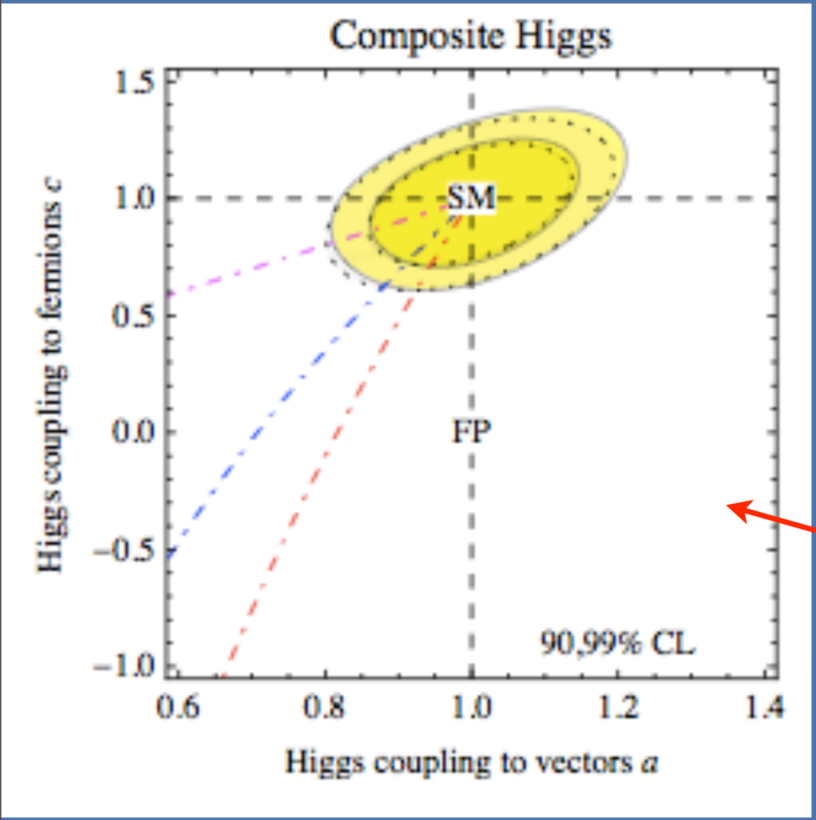
CMS diphoton





ATLAS diphoton

The origin of mass!



P. Giardino, et al, arxiv: 1303.3570

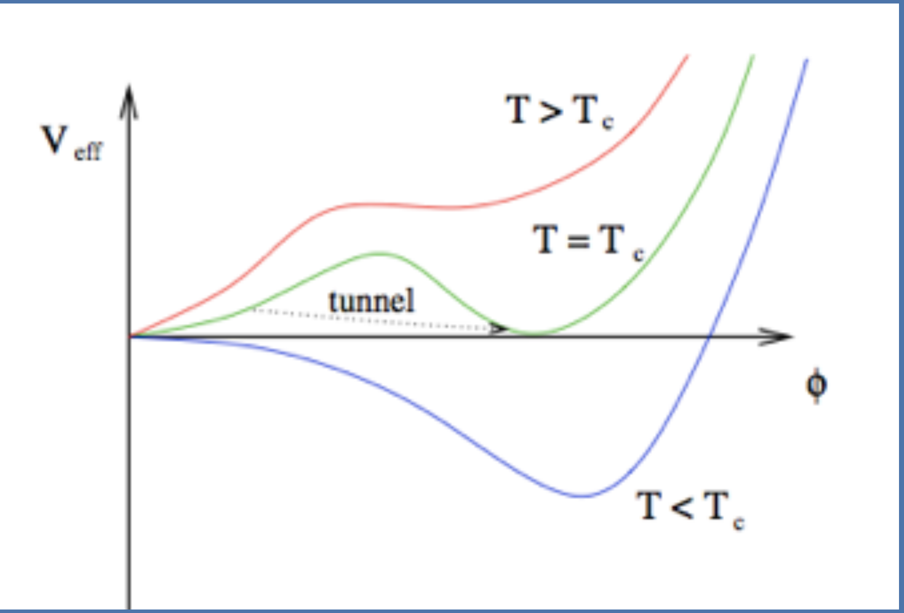
With more and more data, We do learn for sure that we would understand electroweak symmetry breaking!

Typical fits for models based on EFT

What else can we learn from that?

The origin of matter

How mass is generated in our universe?



After the electroweak phase transition, the broken phase, all the masses are turning on.

How "positive" matter is generated in our universe?

Quite interesting if connected to the mass generation.

The EWBG

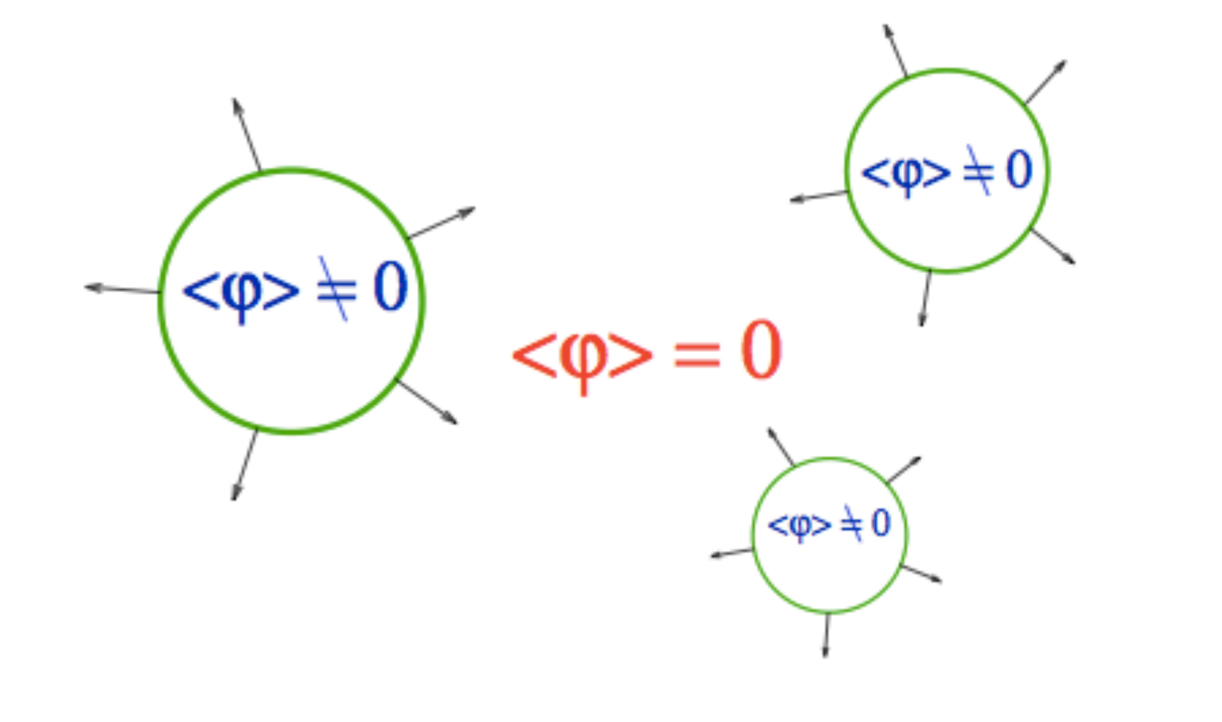
Electroweak baryogenesis: generate baryon asymmetry with particle mass generation at EW scale.

Sakharov's condition:

- baryon number violation (Sphaleron transitions)
- CP violation (SM CPV too small, Need BSM physics)
- Strongly 1st order PT (SM: crossover, Need BSM physics)

Strongly 1st order PT

When the universe is cooling down, if we have strongly1st order PT, then we have bubble expanding

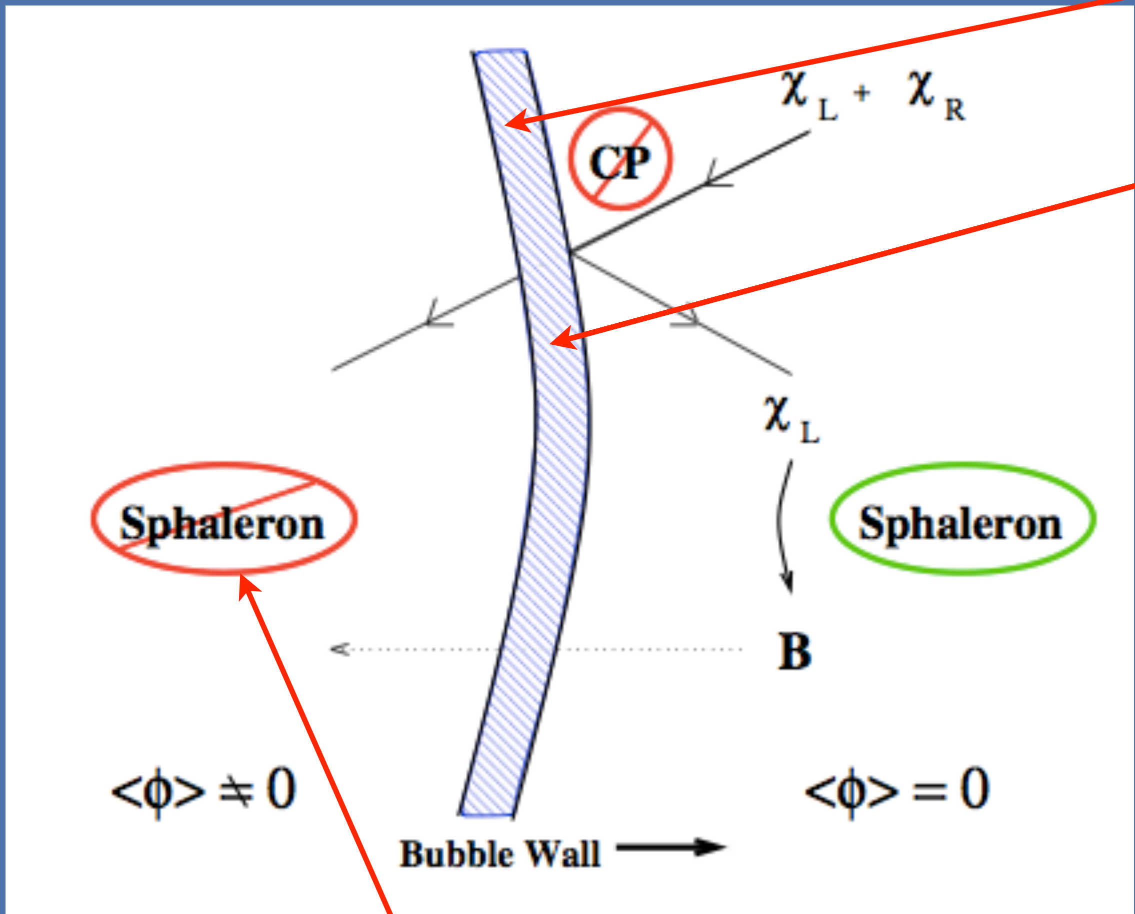


Strongly first order phase transition

The EWBG

$m_\chi(v)e^{i\theta(v)}$

$\dot{\theta}$

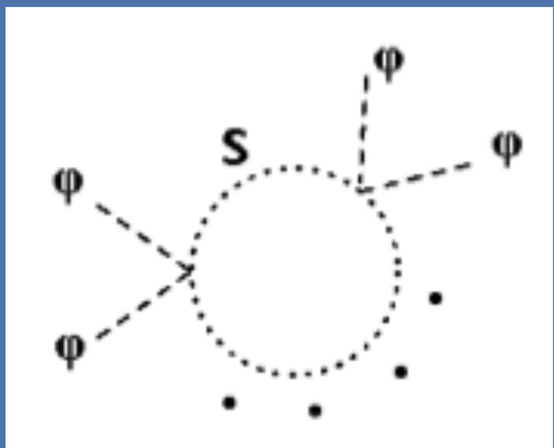


CPV phase jump generate a net chiral charge inside the bubble wall

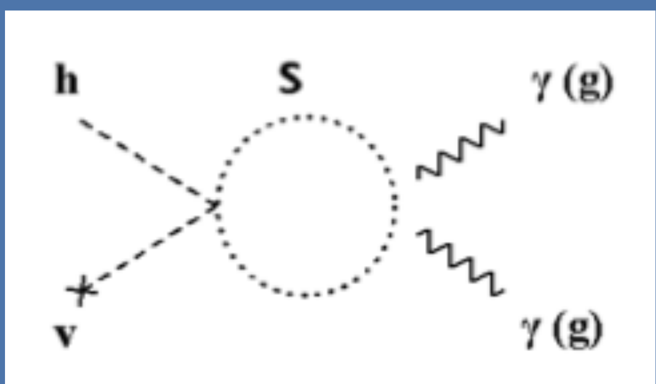
It diffuses into the bubble (broken phase) and then converted into net baryon density.

require strongly first order phase transition

LHC Higgs data & EWPT



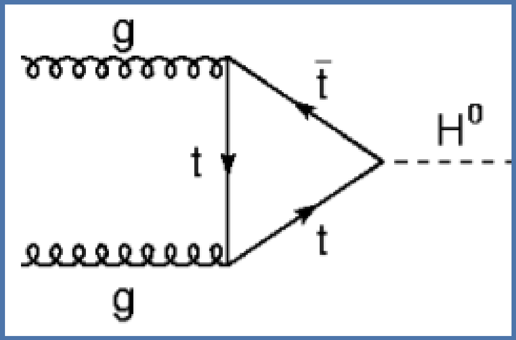
For any particle S would contribute to the Higgs effective potential



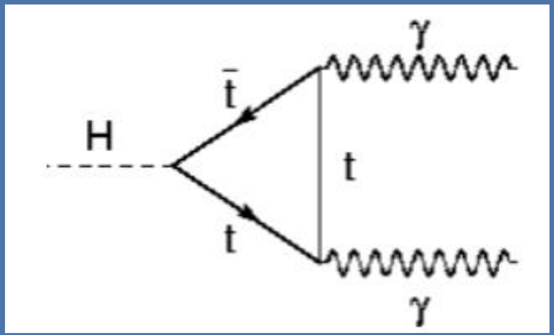
Simultaneously, S would also contribute to hgg and $h\gamma\gamma$. vertex if colored or electric charged.

Well known

LHC Higgs data: CPV source



if colored



if electric charged

χ as top quark

$$m_\chi(v)e^{i\theta(v)}$$

A complex mass term which has vev dependence

suggests that particle χ would contribute to hgg and $h\gamma\gamma$. vertex with CPV

First noticed by me

More universal results based on LHT would not be presented here.

The connection

Since hgg and $h\gamma\gamma$. vertex are so critical in the Higgs global fits

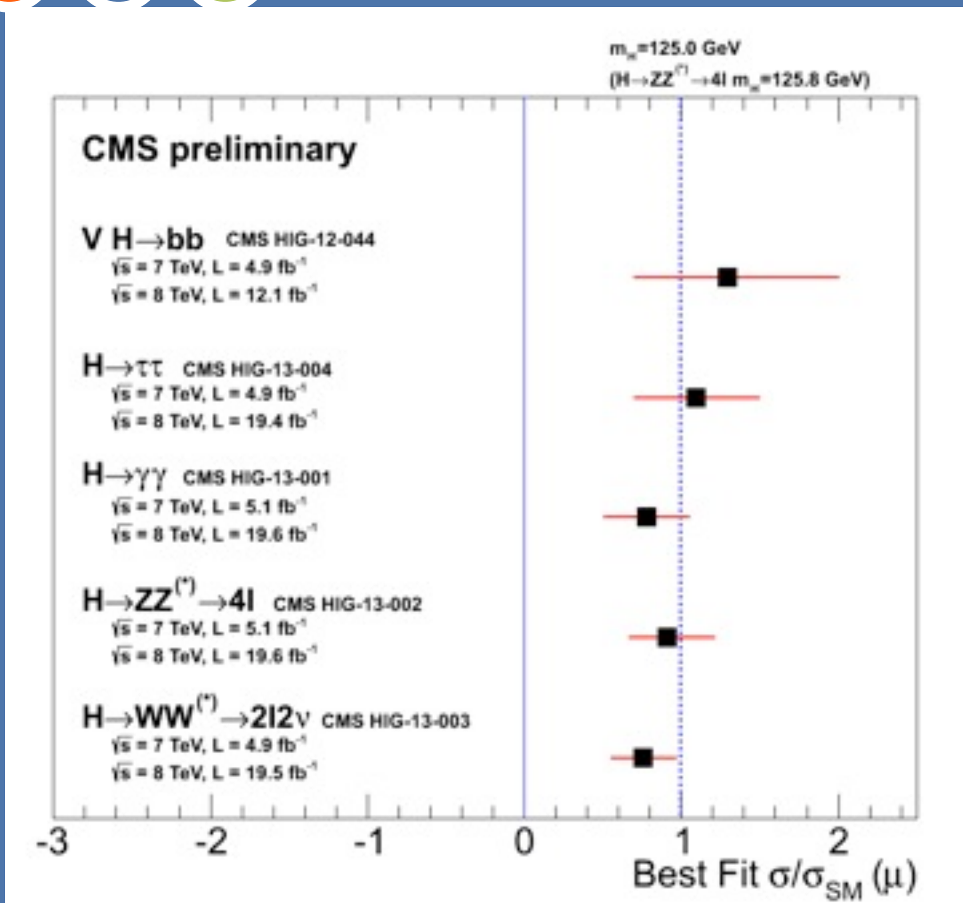
The Higgs global fits would give hints on possible models on strong 1st order PT

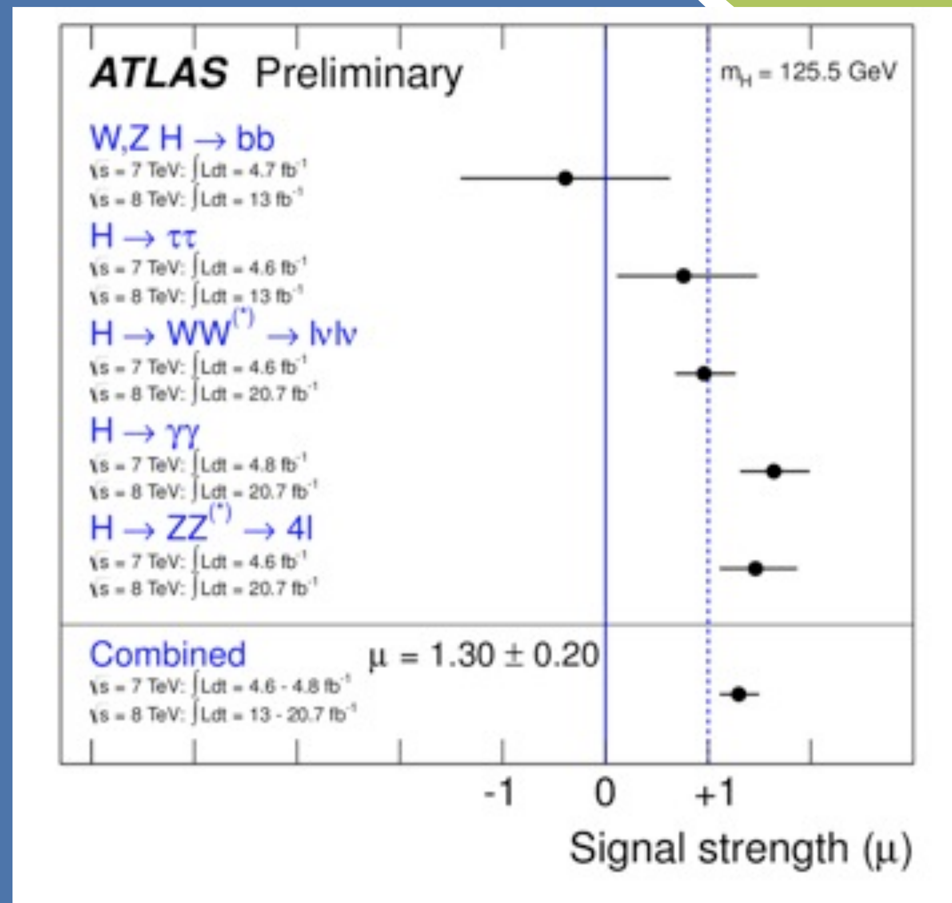
The global fits with CPV would suggest the possible model parameter regions on the baryon asymmetry number

For hgg and $h\gamma\gamma$

Notice CP odd and even operator have no interference with each other.

Higgs global fits





What can we learn from that?

Beyond SM physics: LHC data & CPV source

Stories on CPV

Effective theory parametrization:

$$\mathcal{L}_{\rm eff} = c_V \frac{2m_W^2}{v} h W_\mu^+ W_\mu^- + c_V \frac{m_Z^2}{v} h Z_\mu Z_\mu + c'_\gamma \frac{\alpha}{\pi v} h F_{\mu\nu} F^{\mu\nu} + c_{Z\gamma} \frac{\alpha}{\pi v} h F^{\mu\nu} \partial_\mu Z_\nu$$
$$+ \epsilon^{\mu\nu\alpha\beta} \left[\tilde{c}_\gamma \frac{\alpha}{\pi v} h F_{\mu\nu} F_{\alpha\beta} + \tilde{c}_{ZZ} \frac{\alpha}{\pi v} h \partial_\mu Z_\nu \partial_\alpha Z_\beta + \tilde{c}_{Z\gamma} \frac{\alpha}{\pi v} h F_{\mu\nu} \partial_\alpha Z_\beta \right].$$

$$\mathcal{L}_{\rm int} = -\sum_f c_f \frac{m_f}{v} h \bar{f} f - \sum_f i \tilde{c}_f \frac{m_f}{v} h \bar{f} \gamma_5 f.$$

Certainly I can do a global fits
based on the above EFT

Global fits based on CPV EFT

Global fits based on EFT, only central values (best points) are shown here.

	$\gamma\gamma$	WW	ZZ	Vbb	$\tau\tau$
ATLAS	1.6 ± 0.3	1.5 ± 0.4	1.4 ± 0.4	-0.4 ± 1.0	0.8 ± 0.7
CMS	0.8 ± 0.3	0.8 ± 0.2	0.9 ± 0.2	1.1 ± 0.5	0.9 ± 0.5

	α	$\lvert\alpha_b\rvert$	c_t / $R_{\gamma\gamma}$	$\tilde{c}_t$ / R_{WW}	c_b / R_{ZZ}	$\tilde{c}_b$ / R_{Vbb}	a / $R_{\tau\tau}$
ATLAS	-0.19	0.81	1.08	-0.91	0.17	-0.58	0.52
			1.35	1.28	1.28	0.47	1.71
CMS	-1.00	0.27	0.83	-0.33	1.04	-0.21	0.96
			0.91	0.83	0.83	0.93	1.02
Combined	-0.99	0.37	0.82	-0.45	1.00	-0.29	0.93
			1.05	0.86	0.86	1.02	1.18

TABLE I: Best fit points with $\tan\beta = 0.8$. ATLAS: $\chi^2_{\rm min} - \chi^2_{\rm SM} = -3.27$. CMS: $\chi^2_{\rm min} - \chi^2_{\rm SM} = -1.74$. Combined: $\chi^2_{\rm min} - \chi^2_{\rm SM} = -0.39$.

2HDM

In order to make a connection with baryogenesis, I must make a model.

$$V = \frac{\lambda_1}{2}(\phi_1^\dagger\phi_1)^2 + \frac{\lambda_2}{2}(\phi_2^\dagger\phi_2)^2 + \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2)$$
$$+ \ \lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) + \frac{1}{2}\left[\lambda_5(\phi_1^\dagger\phi_2)^2 + \text{h.c.}\right]$$
$$- \ \frac{1}{2}\left\{m_{11}^2(\phi_1^\dagger\phi_1) + \left[m_{12}^2(\phi_1^\dagger\phi_2) + \text{h.c.}\right] + m_{22}^2(\phi_2^\dagger\phi_2)\right\}.$$

There are two independent phases from m_{12} and λ_5.

$$\mathcal{L}_Y = \bar{Q}_L Y_D \phi_1 D_R + \bar{Q}_L Y_U (i\tau_2)\phi_2^* U_R + \bar{L}_L Y_E \phi_1 E_R$$

$$\langle\phi_1\rangle = \begin{pmatrix} 0 \\ v\cos\beta/\sqrt{2} \end{pmatrix}, \quad \langle\phi_2\rangle = \begin{pmatrix} 0 \\ v\sin\beta e^{i\xi}/\sqrt{2} \end{pmatrix}$$

Mass eigenstates:

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = \begin{pmatrix} -s_\alpha c_{\alpha_b} & c_\alpha c_{\alpha_b} & s_{\alpha_b} \\ s_\alpha s_{\alpha_b} s_{\alpha_c} - c_\alpha c_{\alpha_c} & -s_\alpha c_{\alpha_c} - c_\alpha s_{\alpha_b} s_{\alpha_c} & c_{\alpha_b} s_{\alpha_c} \\ s_\alpha s_{\alpha_b} c_{\alpha_c} + c_\alpha s_{\alpha_c} & s_\alpha s_{\alpha_c} - c_\alpha s_{\alpha_b} c_{\alpha_c} & c_{\alpha_b} c_{\alpha_c} \end{pmatrix} \begin{pmatrix} H_1 \\ H_2 \\ A \end{pmatrix}$$

2HDM

In order to make a connection with baryogenesis, I must make a model.

Higgs coupling

$$c_t = \frac{\cos\alpha}{\sin\beta}\cos\alpha_b\ , \quad c_b = -\frac{\sin\alpha}{\cos\beta}\cos\alpha_b$$
$$\tilde{c}_t = -\cot\beta\sin\alpha_b\ , \quad \tilde{c}_b = -\tan\beta\sin\alpha_b$$

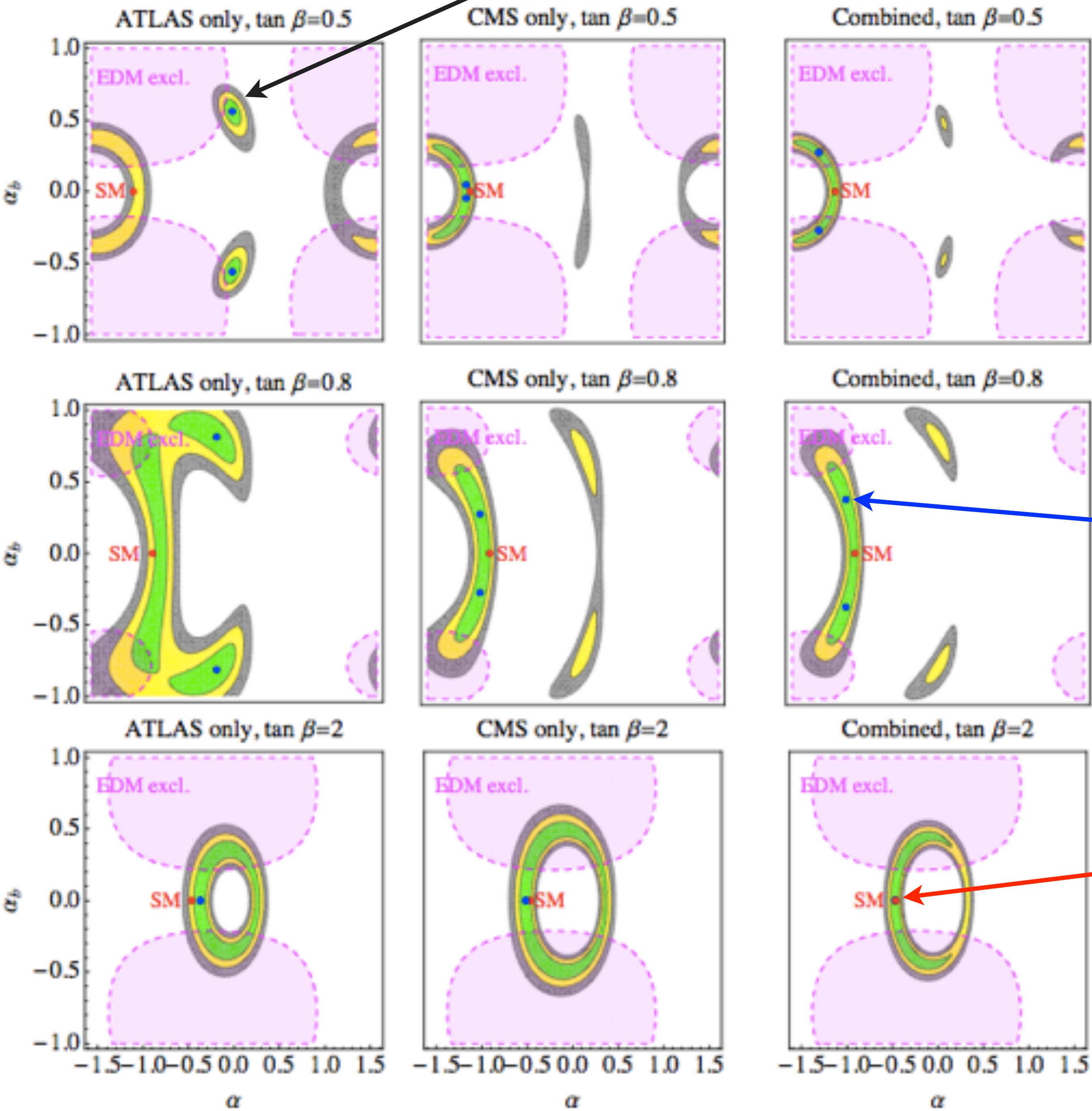
$$\mathcal{L}_{h_1VV} = \cos\alpha_b\sin(\beta-\alpha)\mathcal{L}^{SM}_{hVV} \equiv a\mathcal{L}^{SM}_{hVV}$$

α_b measures the CPV

$$\tan\alpha_b \approx \frac{-\lambda_5\sin 2\xi\, v^2}{m^2_{h^+} + (\lambda_4 - \lambda_5\cos 2\xi)v^2/2} \lesssim \xi$$

include: 1) enhanced effective hgg coupling r_g, 2) suppressed $\tilde{c}_t$, $\tilde{c}_b$, a couplings, and the effective $h\gamma\gamma$ coupling r_g, 3) reduced Higgs total width. These effects are

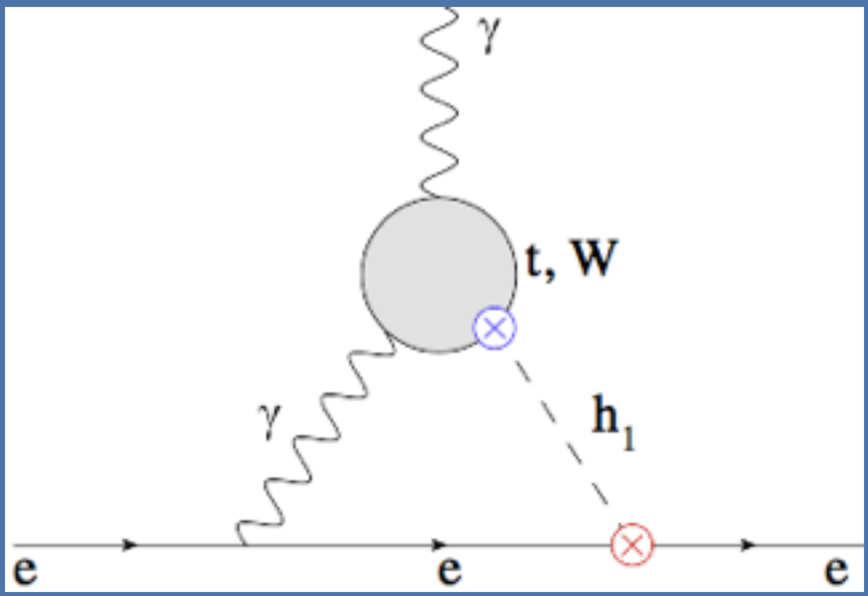
Second region



Blue points: best fits

SM

Bounds from EDM



D. McKeen, M. Pospelov, A. Ritz, PRD, 86, 113004 (2012)

When there is a CP odd operator contributes to hgg or $h\gamma\gamma$.

The same operators would contribute to the EDM or CEDM

Additional Higgs rather than 125 GeV can also contribute

Bounds from neutron EDM and chromo-EDM (CEDM) are much weaker due to small u, d quark charge and Wilson coefficient in RG running.

Formulars

$$\left[\frac{d_e}{e}\right]_t = \frac{16\sqrt{2}\alpha G_F m_e}{3(4\pi)^3} \times \left(f\left(z_t\right)\tan^2\beta \mathrm{Im}Z_2 - g\left(z_t\right)\cot^2\beta \mathrm{Im}Z_1\right),$$

$$\left[\frac{d_e}{e}\right]_w = \frac{2\sqrt{2}\alpha G_F m_e}{(4\pi)^3}\left(3f\left(z_w\right)+5g\left(z_w\right)\right) \times \left(\sin^2\beta\tan^2\beta \mathrm{Im}Z_2 + \cos^2\beta \mathrm{Im}Z_1\right),$$

$$f(z) = \frac{z}{2}\int_0^1 \frac{1-2x(1-x)}{x(1-x)-z}\ln\frac{x(1-x)}{z},$$

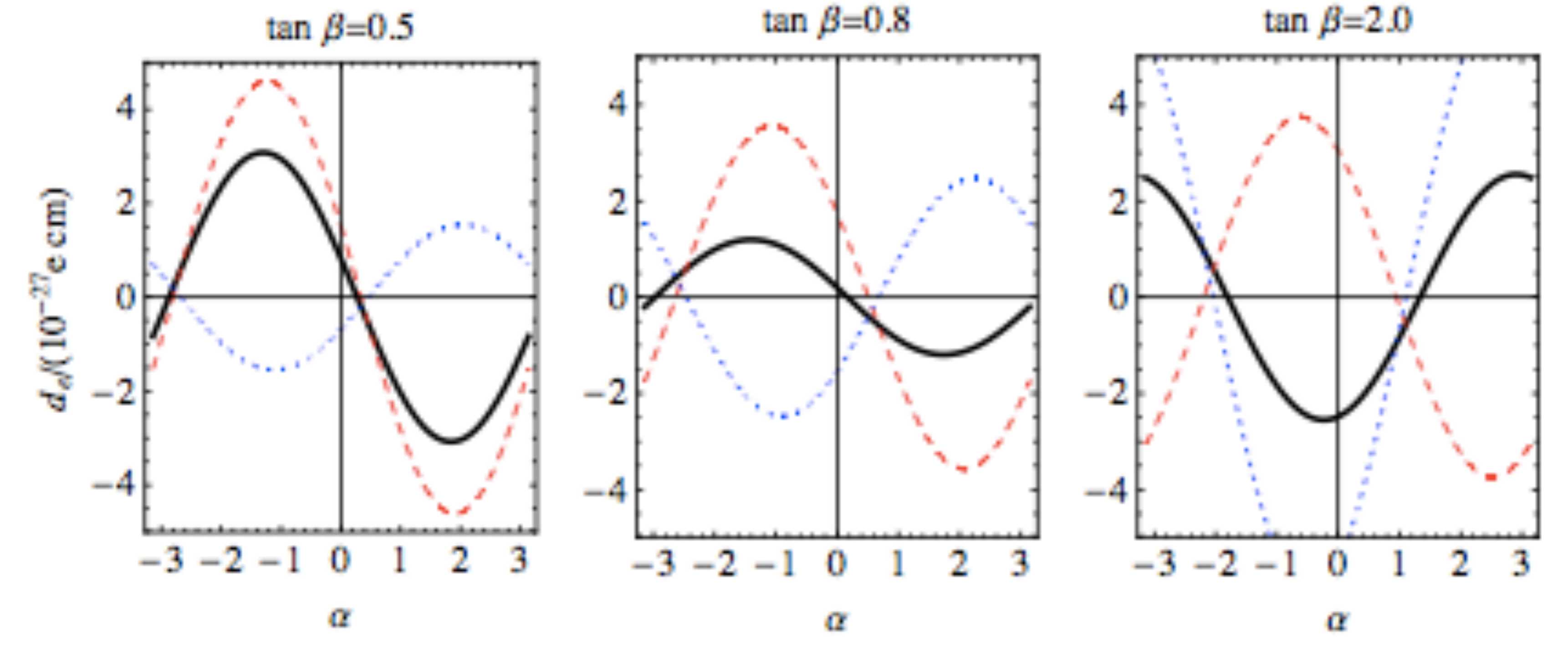
$$g(z) = \frac{z}{2}\int_0^1 \frac{1}{x(1-x)-z}\ln\frac{x(1-x)}{z}.$$

$$\tan^2\beta \mathrm{Im}\, Z_2 = -\tilde{c}_b c_t ,$$

$$\cot^2\beta \mathrm{Im}\, Z_1 = \tilde{c}_t c_b ,$$

$$\left(\sin^2\beta\tan^2\beta \mathrm{Im}Z_2 + \cos^2\beta \mathrm{Im}Z_1\right) = a\,\tilde{c}_b ,$$

Bounds from EDM



Top & W loop contribution cancel
depends on different beta

neutron EDM and CEDM are considerably small due to small d electric charge and Wilson coefficient.

EW Baryogenesis

Standard results for 2HDM: Thick wall case.

CP violating source:

$$S_t(z) \approx \frac{3}{2\pi^2}\left(\frac{m_t}{v\sin\beta}\right)^2 v_T^2(z)\theta'(z)v_w T$$

Chiral charge density:

$$n_L(z<0) \approx -\frac{27}{2}\frac{v_w^2}{\Gamma_{ss}\bar{D}}\left(1-\frac{D_q}{\bar{D}}\right)\mathcal{A}e^{v_w z/\bar{D}}$$

Net baryon number density:

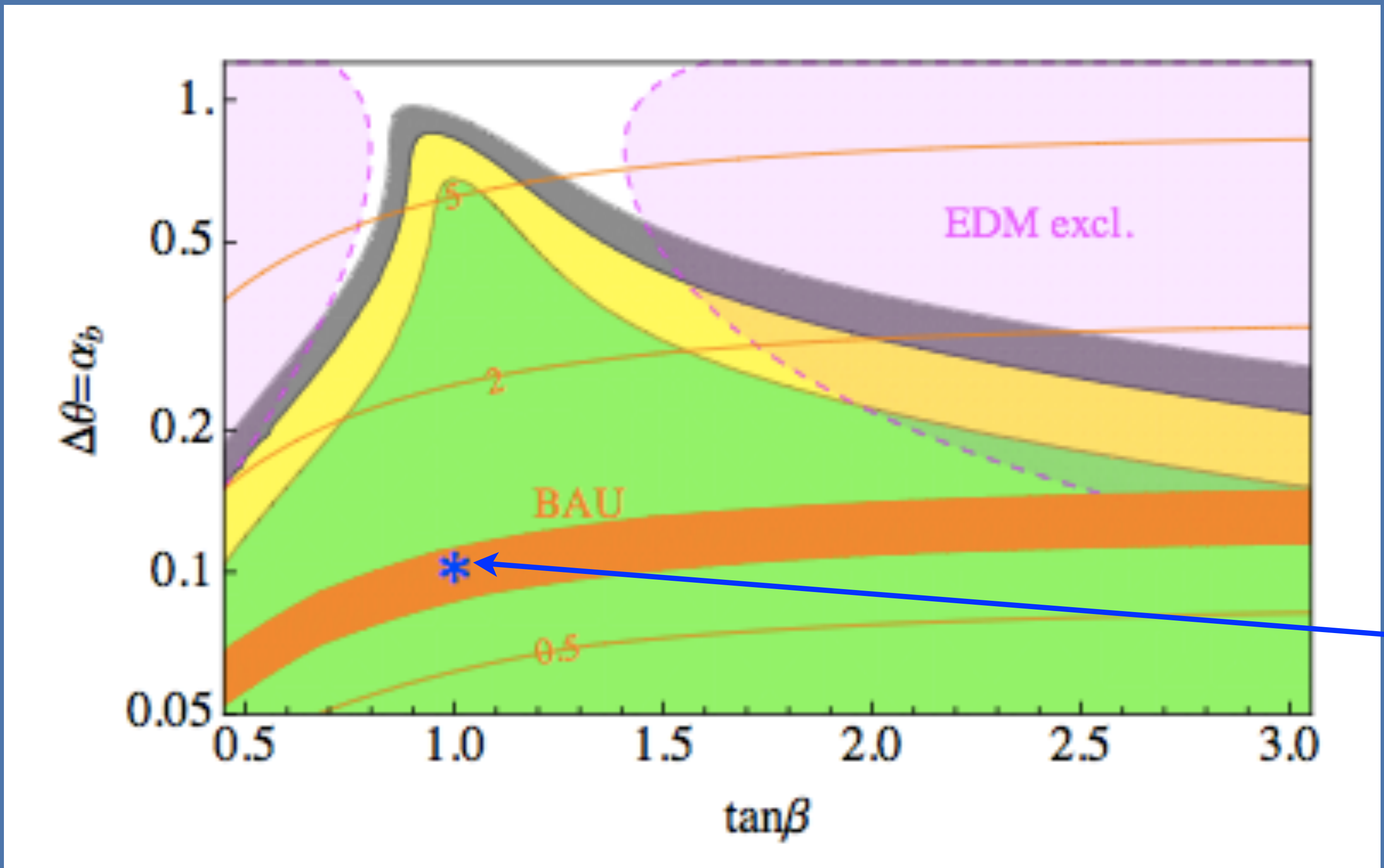
$$n_b = -\frac{3\Gamma_{ws}}{2v_w}\int_{-\infty}^{0} n_L(z)e^{15\Gamma_{ws}z/(4v_w)}dz\,.$$

P. Huet, A. Nelson, PRD, 53, 4578, (1996)

C. Lee, V. Cirigliano, M. Ramsey-Musolf, PRD, 71 (2005) 075010

J. Cline, et al, PRD, 54, 2451, (1996)

Final Results



Benchmark point consistent with detailed phase transition calculation

Beyond SM physics: LHC data & EWPT

Higgs fits

Consider a Higgs portal model that S is scalar with color 8, 3, 1 representation (no vev)

$$m_s^2(\phi, T) = m^2 + \Pi_s(T) + \alpha\phi^2$$

Fits parameterization based on EFT:

$$\frac{\sigma(gg \to h)}{\sigma(gg \to h)_{\rm SM}} = \frac{\Gamma(h \to gg)}{\Gamma(h \to gg)_{\rm SM}} = \frac{\hat{c}_{g,\rm SM} + \delta c_g}{\hat{c}_{g,\rm SM}}$$

$$\frac{\Gamma(h \to \gamma\gamma)}{\Gamma(h \to \gamma\gamma)_{\rm SM}} = \frac{\hat{c}_{\gamma,\rm SM} + \delta c_\gamma}{\hat{c}_{\gamma,\rm SM}}$$

$$\delta c_g = \frac{C(r_s)}{2} \frac{\alpha v^2}{m_s^2} A_s(\tau_s)$$

$$\delta c_\gamma = \frac{N(r_s) Q_s^2}{24} \frac{\alpha v^2}{m_s^2} A_s(\tau_s)$$

$$f(\tau) = \begin{cases} \arcsin^2(\sqrt{\tau}), & \tau \leq 1 \\ -\frac{1}{4}\left[\ln\left(\frac{\sqrt{\tau}+\sqrt{\tau-1}}{\sqrt{\tau}-\sqrt{\tau-1}}\right) - i\pi\right]^2, & \tau \geq 1 \end{cases}$$

$$\tau_i = m_h^2/4m_i^2$$

$$A_s(\tau) = 3[f(\tau)\tau^{-2} - \tau^{-1}]$$

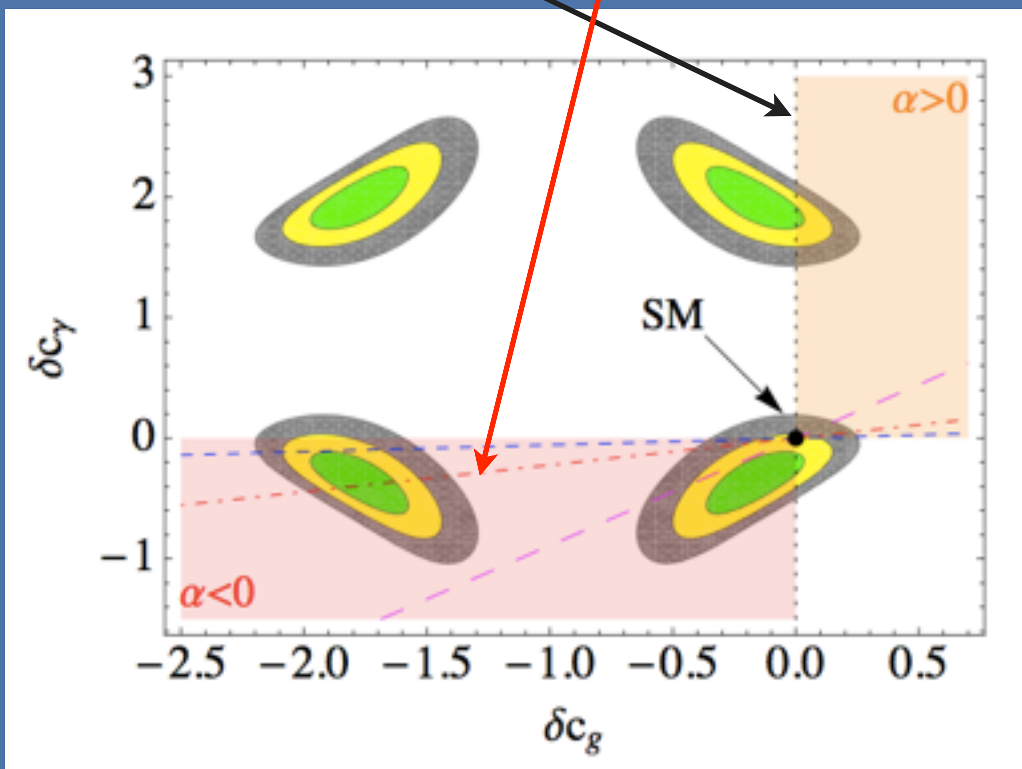
Higgs fits

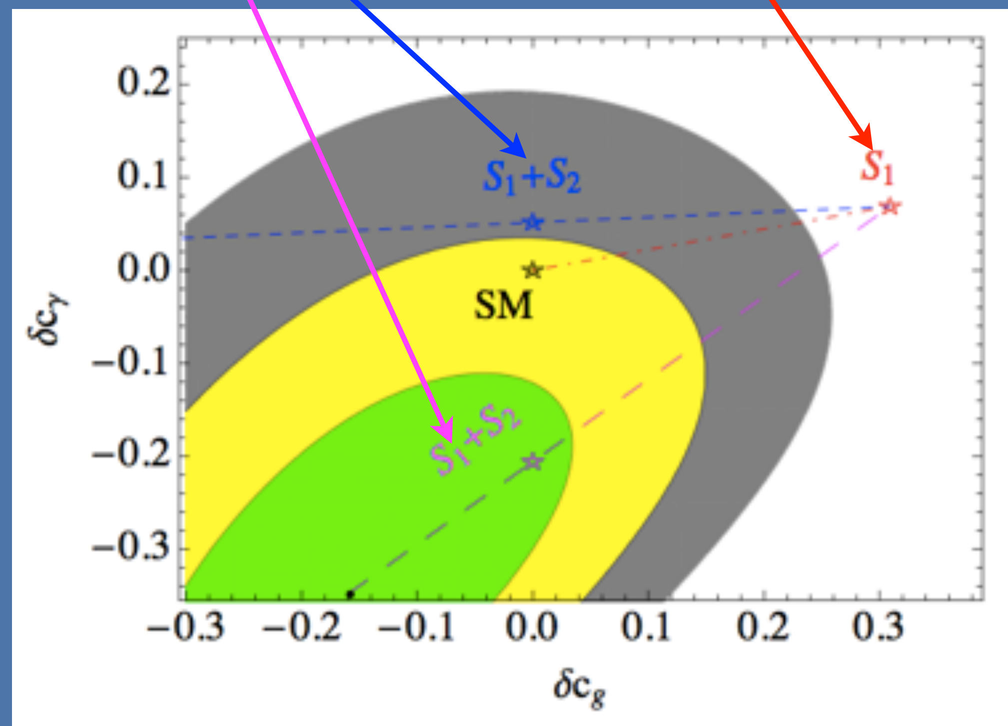
Color singlet

Color triplet with different Qs

Stop (a>0) & sbottom(a<0)

Stop like state (a>0)

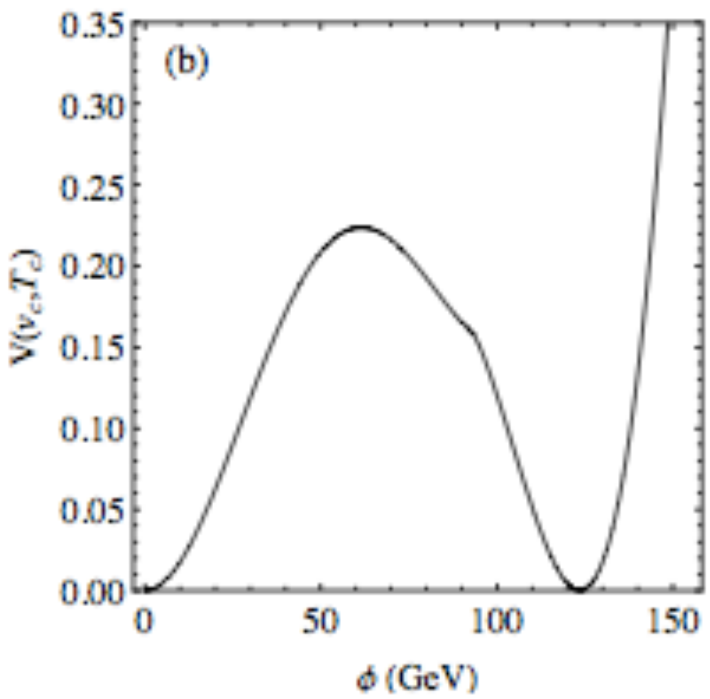




EWPT

$$V(\phi,T) \approx \frac{1}{4}\lambda\phi^4 + \frac{1}{2}\left[-\mu^2+\epsilon_h T^2\right]\phi^2 - T\left[E_{\rm SM}\phi^3 + 2N(r_s)\frac{m_s^3(\phi,T)}{12\pi}\right]$$

$$m_s^2(\phi,T) = m^2 + \alpha\phi^2 + \Pi_s(T)$$



term $-Tm_s^3(\phi,T)$ has to decrease with phi to compete with positive terms such that there is a 1st PT

If there is only one single particle S, then it must be a >0.

EWPT

Critical condition: $V(0,T) = V(\phi,T)$ $V'(\phi,T) = 0.$

$$\frac{N(r_s)}{6\pi} T_c \left[m_s^3(v_c,T_c) - m_s^3(0,T_c) \right] + \frac{1}{4}\lambda v_c^4 = \frac{1}{2} T_c E_{\rm SM} v_c^3 + T_c \frac{N(r_s)}{12\pi} \frac{\partial m_s^3(v_c,T_c)}{\partial v_c} v_c$$

Strong 1st order PT condition $v_c/T_c \gtrsim 0.9$

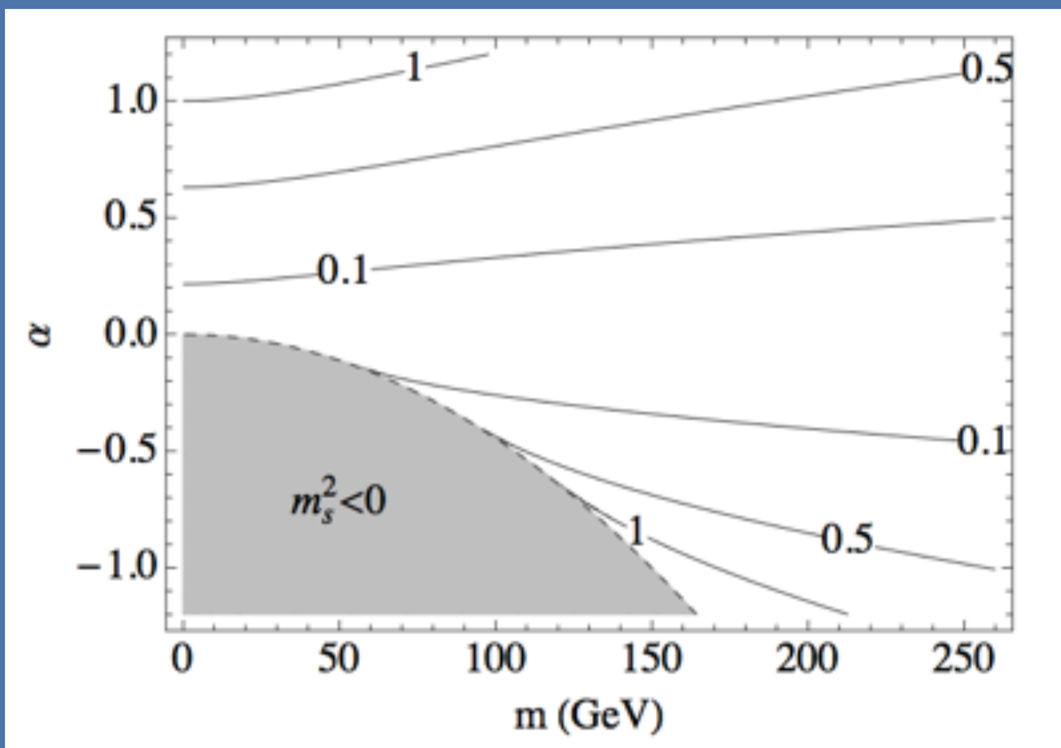
For general mass matrix and arbitrary number of scalars

$$\frac{\mathrm{Tr}\left[N(r_s) F[m_s]\right]}{v_c^3} \gtrsim 1.2 \left(\frac{m_h}{125\,\mathrm{GeV}} \right)^2$$

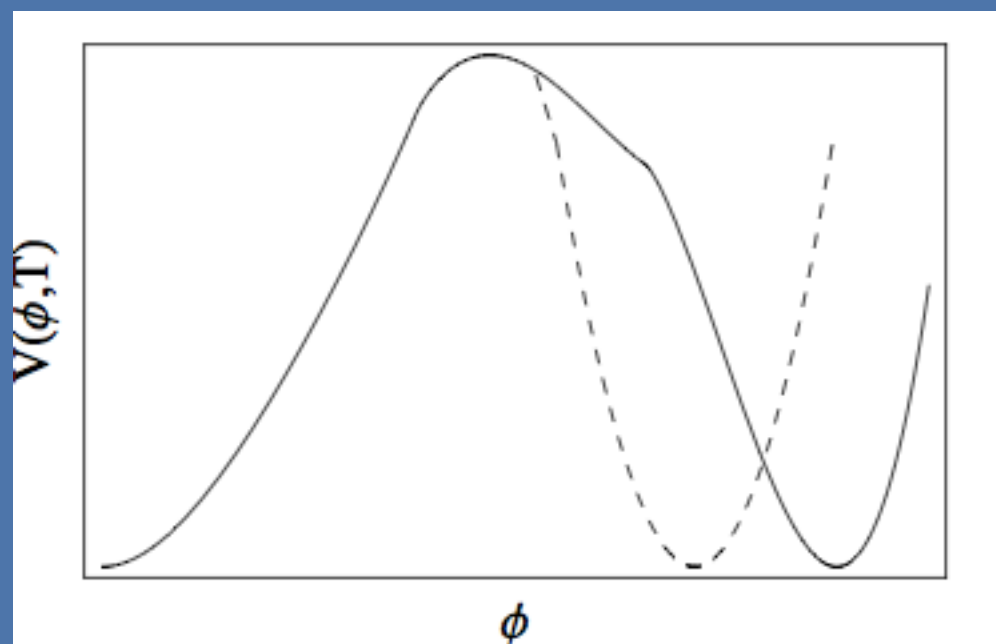
$$F[m_s] \equiv \frac{\partial m_s^3(v_c,T_c)}{\partial v_c} v_c - 2 \left[m_s^3(v_c,T_c) - m_s^3(0,T_c) \right].$$

EWPT

Function F(ms) could be positive for both a>0, a<0; which means that both would enhance the PT strength.

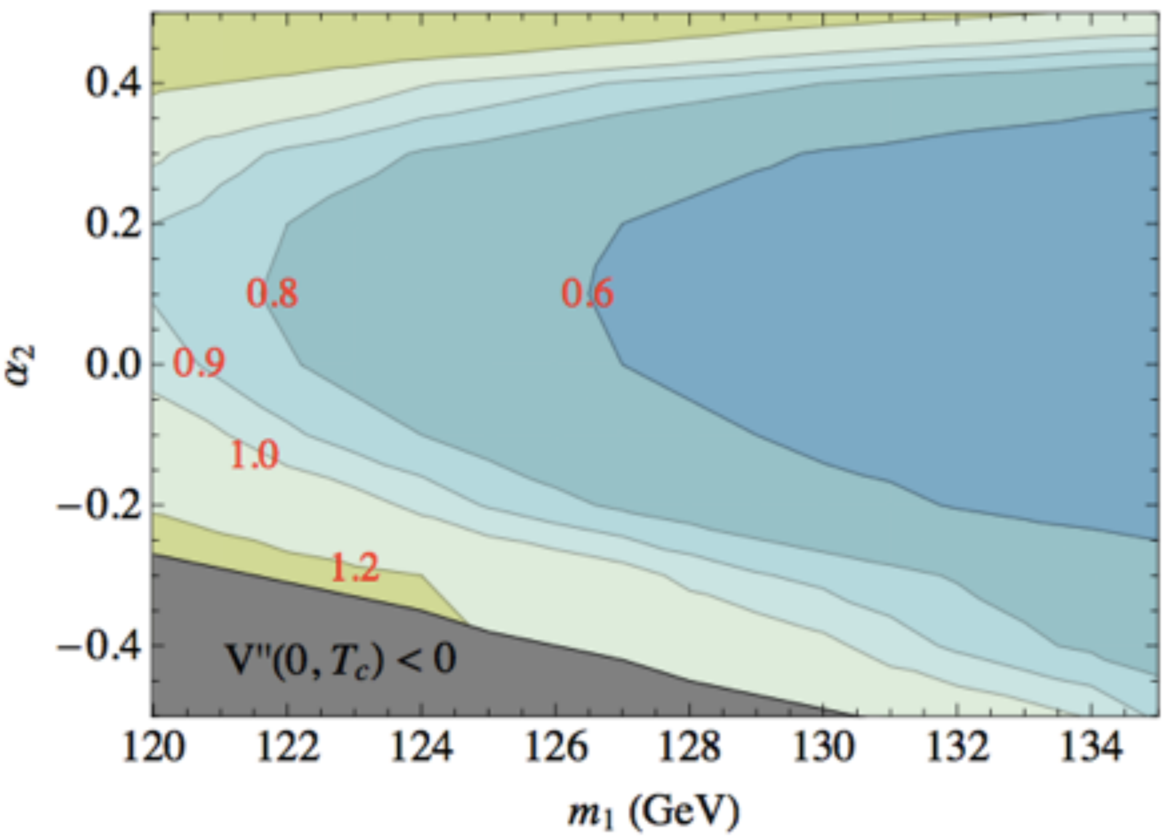


Adding another scalar with a<0 would make phi larger



EWPT

$\alpha_1 = 0.5,\ m_{s_2} = 130\,\text{GeV}$



Adding a second scalar with a<0 would enhance the PT strength and improve the Higgs fits

Reopen BG in MSSM

This is indeed the case for light stop & light sbottom

90GeV light stop with no way to fits Higgs data → 200 GeV light stop, 150 GeV light sbottom

- There are vacuum instability and color breaking problems if one want to get the 125GeV Higgs mass from stop loop.
- One add vector quarks or extend the gauge group, so MSSM is only the low energy description.

The mixing case

What if it is not the higgs portal case?

- Another generic possibility is that the Higgs actually mixes with other scalars which trigger a TREE level $\phi^3 T$ necessary for strong 1st PT.

A very simple but generic realization is that Higgs mix with a singlet after EWSB.

This is indeed the case in many models beyond SM, especially SUSY models.

NMSSM

Let's consider the case for NMSSM(viable among many SUSY models):

$$W_{\text{Higgs}} = \lambda \widehat{S}\, \widehat{H}_u \cdot \widehat{H}_d + \frac{\kappa}{3}\widehat{S}^3$$

$$\begin{aligned} V_0 &= \left|\lambda H_u \cdot H_d - \kappa S^2\right|^2 + |\lambda S|^2 \left(H_d^\dagger H_d + H_u^\dagger H_u\right) \\ &+ \frac{\bar{g}^2}{8}(H_u^\dagger H_u - H_d^\dagger H_d)^2 + \frac{g_2^2}{2}\left|H_d^\dagger H_u\right|^2 \\ &+ m_{H_d}^2 H_d^\dagger H_d + m_{H_u}^2 H_u^\dagger H_u + m_S^2 |S|^2 \\ &+ \left(\lambda A_\lambda H_u \cdot H_d S + \frac{1}{3}\kappa A_\kappa S^3 + \text{h.c.}\right) \end{aligned}$$

Mixture term after EWSB gives a tree level term in the potential.

$$\begin{aligned} V_0(\varphi_1, \varphi_2, \varphi_S) &= m_{H_d}^2 \varphi_1^2 + m_{H_u}^2 \varphi_2^2 + m_S^2 \varphi_S^2 + \frac{2}{3}\kappa A_\kappa \varphi_S^3 - 2\lambda A_\lambda \varphi_1 \varphi_2 \varphi_S \\ &+ \lambda^2 \varphi_1^2 \varphi_2^2 + \frac{\bar{g}^2}{8}\left(\varphi_2^2 - \varphi_1^2\right)^2 + \kappa^2 \varphi_S^4 - 2\lambda\kappa \varphi_1 \varphi_2 \varphi_S^2 \\ &+ \lambda^2 \varphi_S^2 (\varphi_2^2 + \varphi_1^2) \end{aligned}$$

NMSSM

What are the interesting prospects in this case in terms of 125 Higgs data?

Well, this case is much more complicated (mutiple-dimensional PT, many mass spectra)

Nevertheness, there are also much more fruitful structure and correlations

More patterns

For the Higgs fits and spectra:
we have two different patterns

- Case 1: 125GeV Higgs is the second lightest Higgs bosons: 125 GeV Higgs is Hd like, k small, S vev small.
- Case 2: 125 GeV Higgs is the lightest Higgs bosons: 125 GeV like Higgs is Hu like, k large, S large.

More patterns

When the universe is cooling down,

- A: The broken phase first jumps to $\langle S \rangle \neq 0$, then true EWSB vev, but k>0
- B: The broken phase first jumps to $\langle S \rangle \neq 0$, then true EWSB vev, but k<0
- C: The broken phase first jumps to $\langle H \rangle \neq 0$, then true EWSB vev.
- D: The broken phase directly jumps to the true EWSB vev.

More patterns

The interesting connection is that:

- For the case 1: The phase transition patterns can only have B, D in the Higgsino dominated case
- For the case 2: The phase transition patterns can only have A, D in the Higgsino dominated case

The case C can happen in the stop dominated case.

More scanned results need to be understood

Prospects

- Future extensions in Higgs + singlet scalar with vev for phase transition.
- More related to the Higgs self-interaction (Higgs factory?).
- CPV in h to massive gauge boson coupling meaningless: CP odd is dim5, always small.
- Measure CPV in gamma gamma or Z gamma requires information in photon polarization, Bethe-Heitler conversion is very difficult!
- Top CPV promising: in ggjj--> h + 2j or ttbar Higgs

Summary

- We are not dead! Still a lot of interesting things to do. It is only the beginning of the story.
- Much more questions should be raised on the impact of Higgs data.
- Just like stories on DM, BG is another important aspects that closely testable at the LHC era.
- Critical test: Higgs self-interaction (general case) and CPV at the LHC (Maybe future Higgs factory)