A New Look at the Electroweak Baryogenesis in the post-LHC Era.

Jing Shu

ITP-CAS

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

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

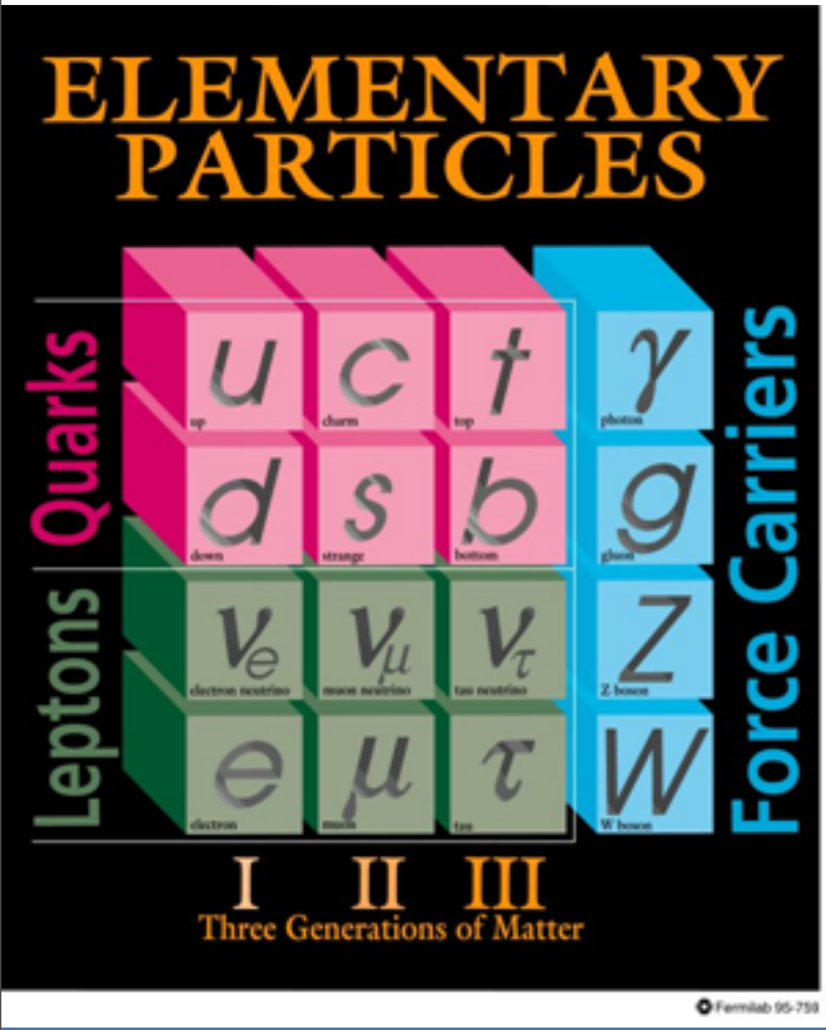
W. Huang, ZF. Kang, J. S, PW. Wu, JM. Yang, 1405.1152

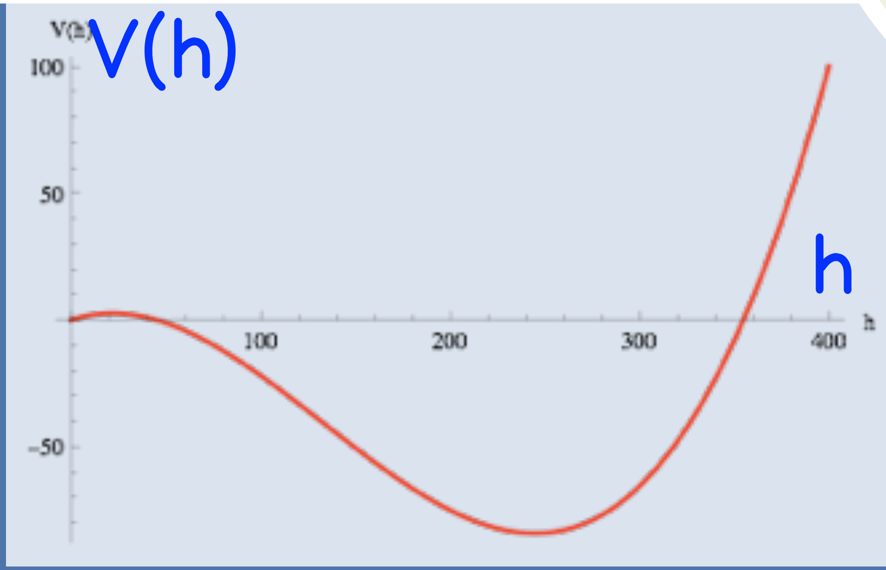
LG. Bian, T. Liu, J. S, in preparation

Outline

- Overview of the connection between Higgs physics & BG (general MI arguments).
- CP Violation & EDM & Higgs global fits
- The electroweak phase transition & Higgs physics
- Future direct measurements.
- Summary and outlook.

The origin of mass!





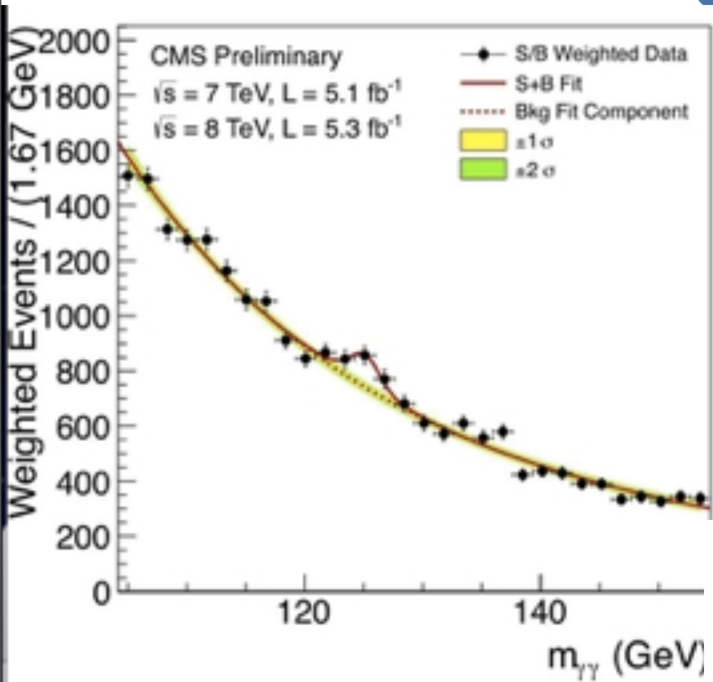
searching for higgs boson

Higgs mechanism

The origin of electroweak symmetry breaking

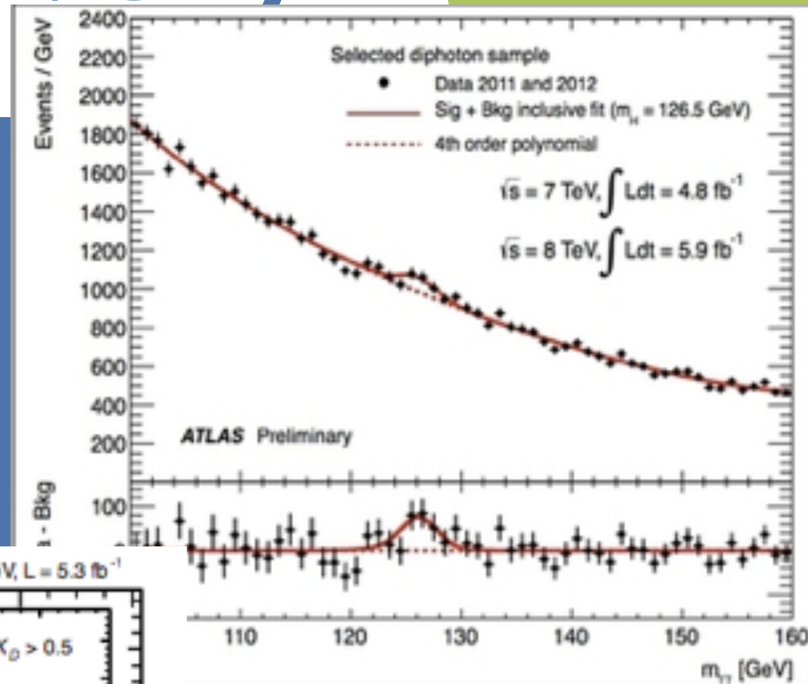
Higgs ???

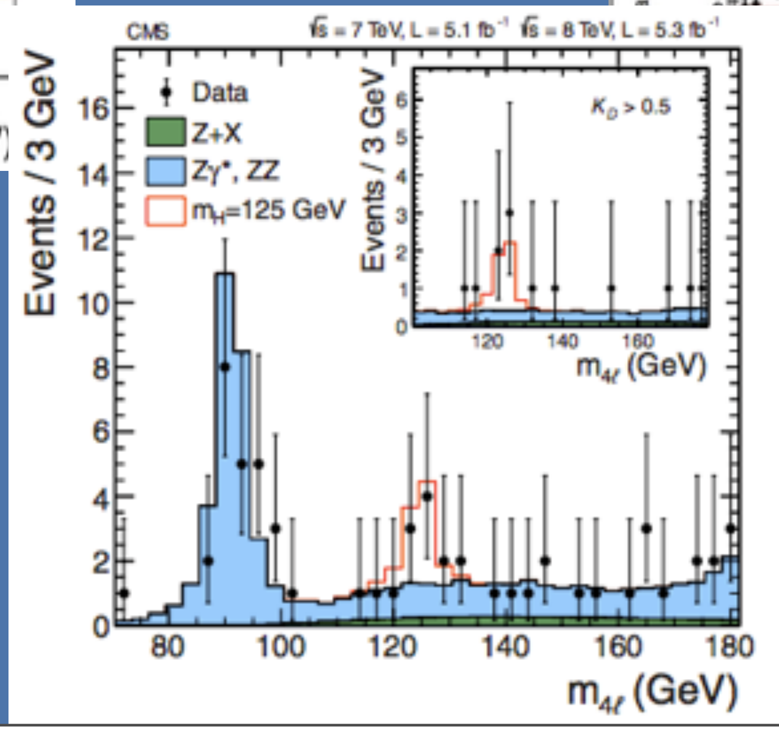
Higgs discovery



July 4th 2012

CMS ZZ

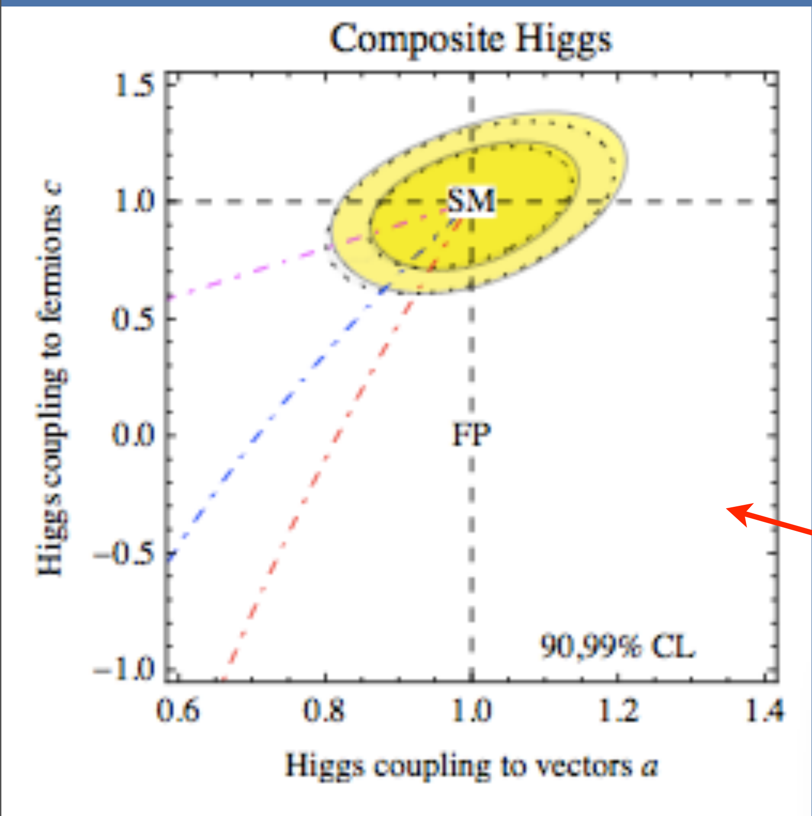




CMS diphoton

ATLAS diphoton

The origin of mass!



P. Giardino, et al, arxiv: 1303.3570

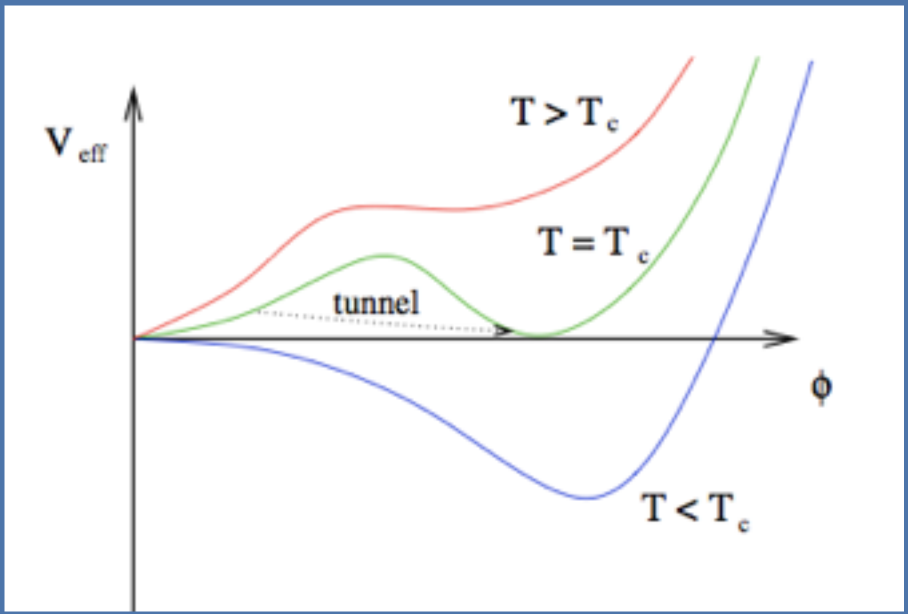
With more and more data, we do learn for sure that we would understand more on electroweak symmetry breaking!

Typical fits for models based on EFT

What big questions we may answer 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

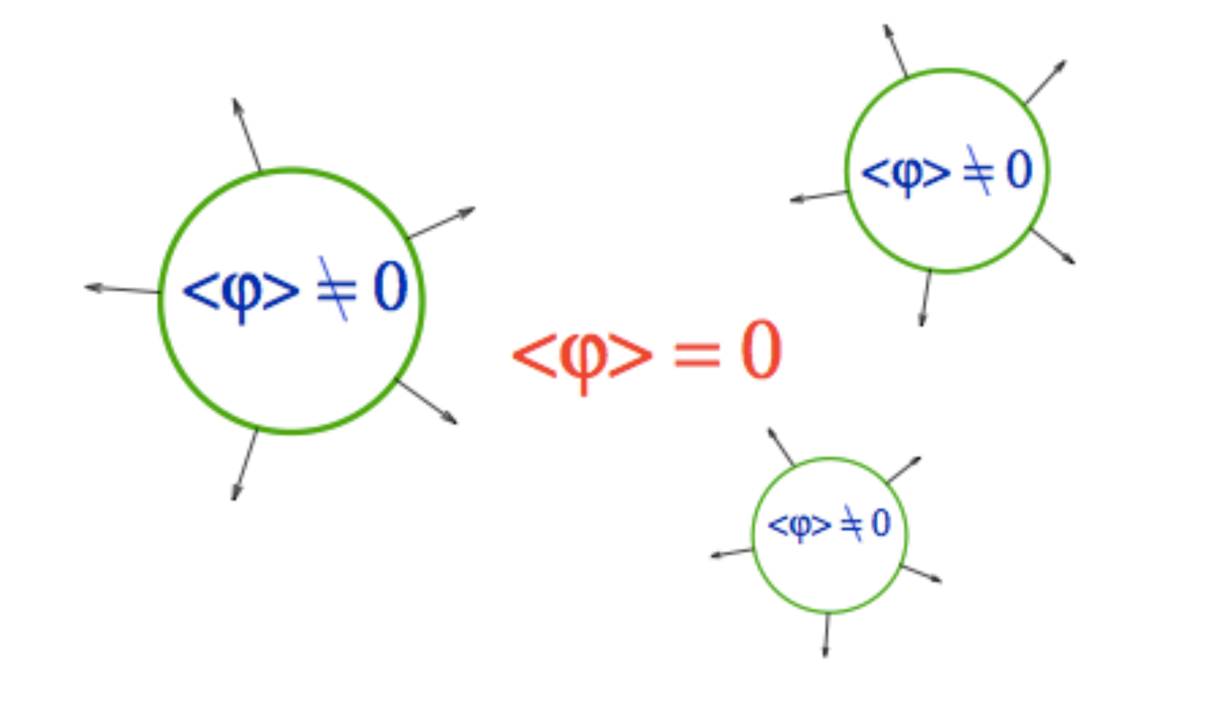
Electroweak baryogenesis: generate baryon asymmetry with particle mass generation at EW scale.

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)

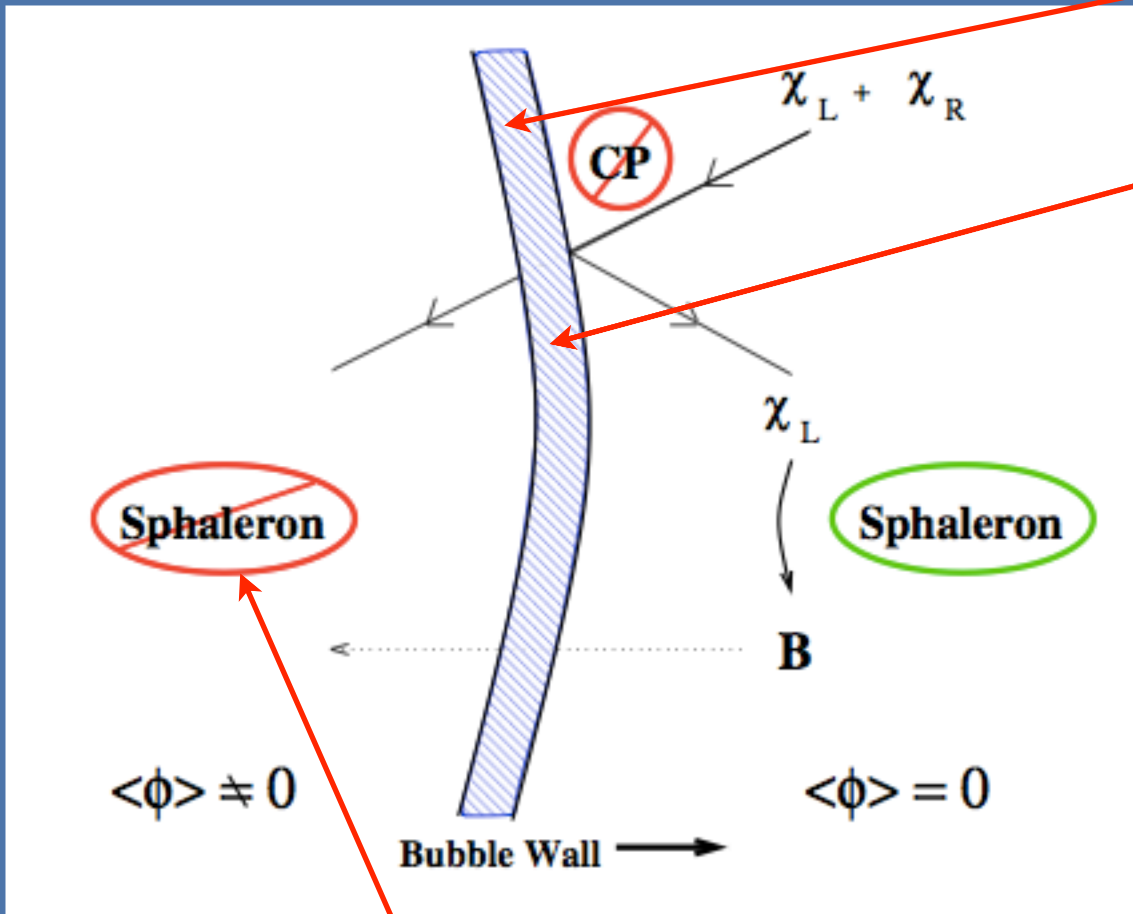
Strongly 1st order PT

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



Strongly first order phase transition

The EWBG



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

$\dot{\theta}$

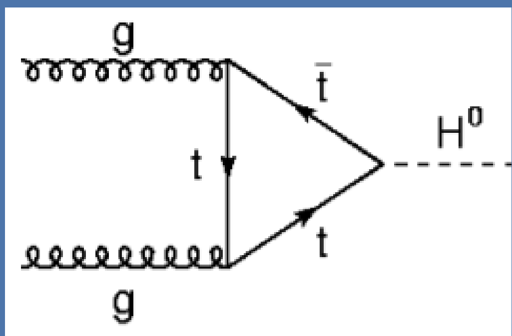
CPV phase jump generate a net chiral charge inside the bubble wall

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

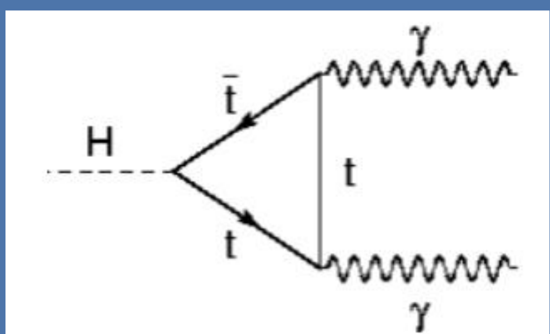
require strongly first order phase transition

Thursday, November 20, 2014

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

There might be more universal results based on LHT.

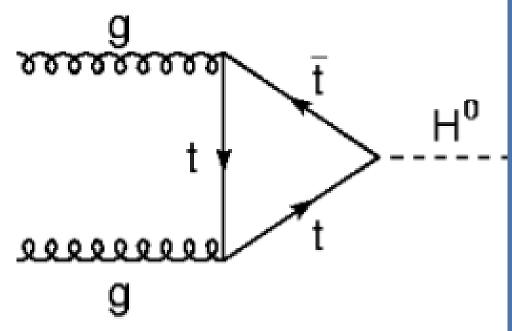
The connection

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

Indirect Higgs global fits tells us on the EWBG mechanism as long as the mediator particle is charged.

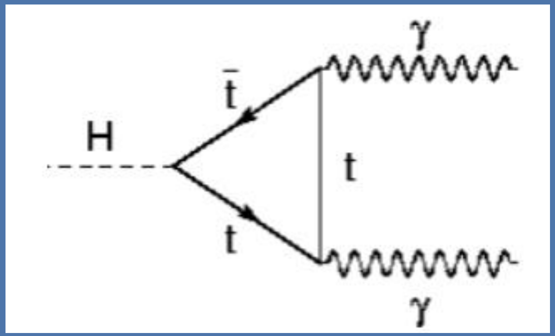
Beyond SM physics: LHC data & CPV source

General connection



$$c_\gamma \frac{\alpha}{\pi v} h F_{\mu\nu} F^{\mu\nu}$$

$$\tilde{c}_\gamma \frac{\alpha}{\pi v} h \tilde{F}_{\mu\nu} F^{\mu\nu}$$

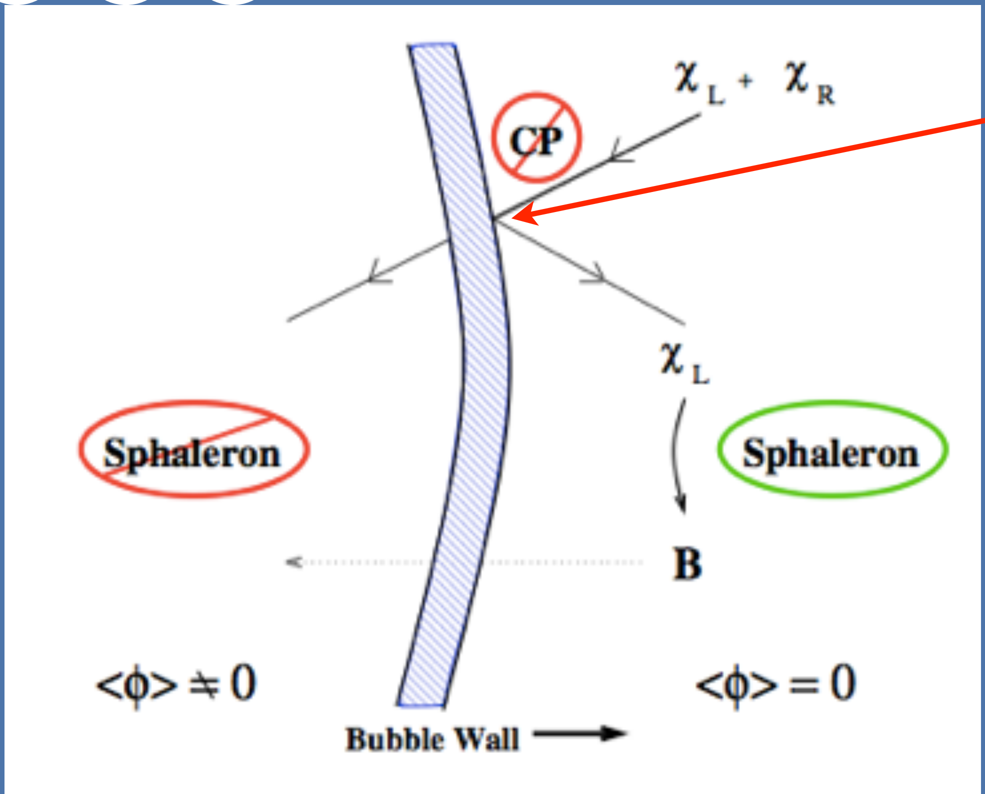


$$c_g \frac{\alpha}{\pi v} h G_{\mu\nu} G^{\mu\nu}$$

$$\tilde{c}_g \frac{\alpha}{\pi v} h \tilde{G}_{\mu\nu} G^{\mu\nu}$$

Fermionic CP Violation

General connection



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

$$\mathcal{L}_X \sim (\partial_\mu \xi) J^\mu_X$$

$$\partial_t \xi = \partial_v \xi (\Delta v) v_w / L_w$$

Behave like a chemical potential term

$$Q_X \sim g_*(\partial_t \xi) T^2/6 \sim (\partial_t \xi) T^2.$$

Converted to B by sphalerons inside the bubble wall

General connection

Consider a fermion mass X with complex mass term (CPV): $m(v)\bar{X}(1+i\xi(v)\gamma_5)X$.

Expanding around v, CP odd term: $im(v)\left\{\xi(v)+\frac{\partial\xi(v)}{\partial\log v}\frac{h}{v}\right\}\bar{X}\gamma_5 X$

An axial rotation of X can remove the 2nd term, results extra terms where F is the gauge field where X is charged.

$\tilde{c}_X\left(\frac{h}{v}\right)F\tilde{F}$

$\tilde{c}_X = v[\partial\xi(v)/\partial v].$

$\sim\left(\xi(v)+\frac{\partial\xi(v)}{\partial\log v}\frac{h}{v}\right)F\tilde{F}$

The CP violating sources from X in EWBG is proportional to the size of the effective operators where X is integrated out.

Stories on CPV

Effective theory parametrization:

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

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

+ gluons

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

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

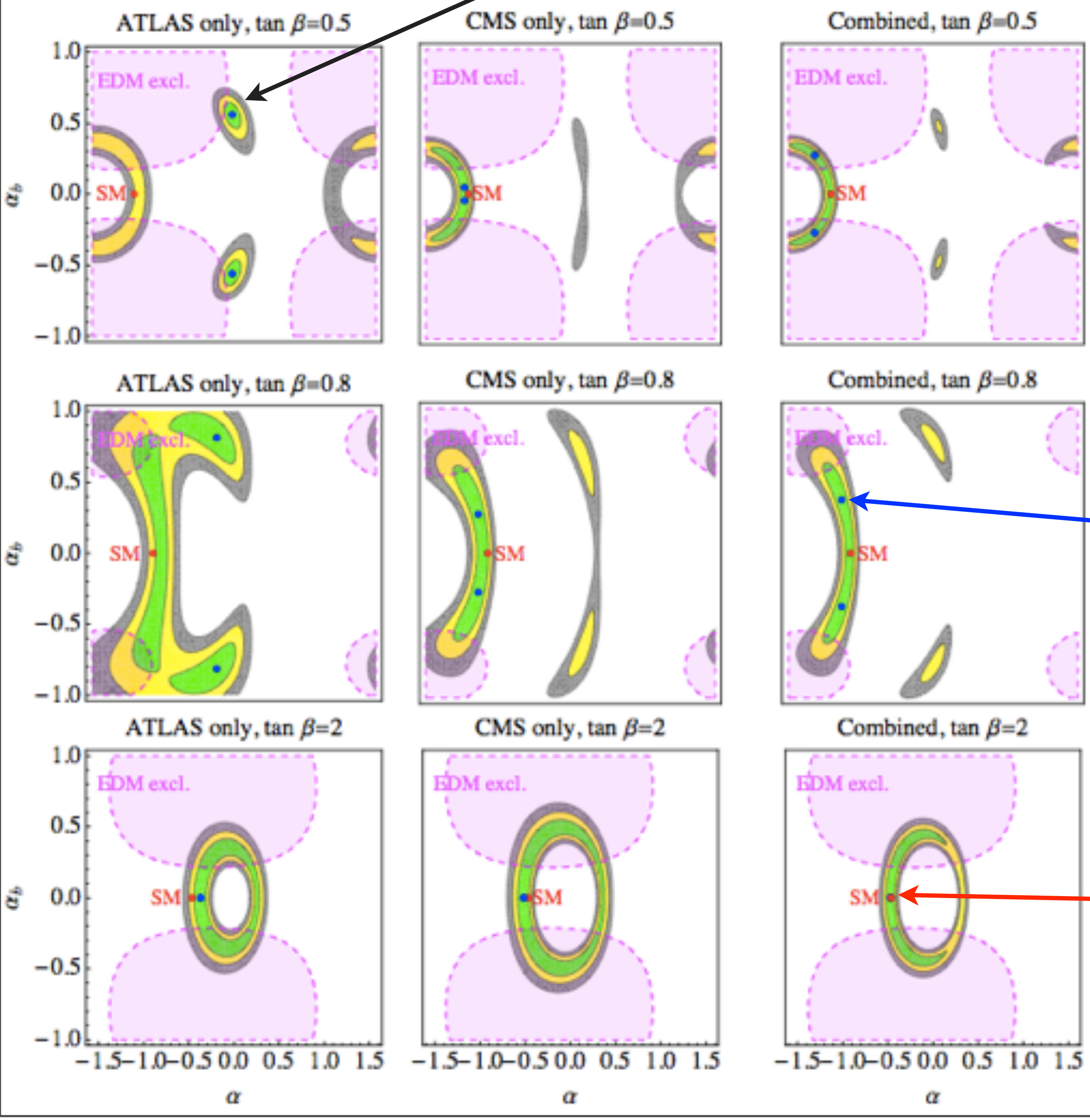
$$\mathcal{L}_{h_1VV} = \cos\alpha_b\sin(\beta-\alpha)\mathcal{L}^{\text{SM}}_{hVV} \equiv a\mathcal{L}^{\text{SM}}_{hVV}$$

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

sweet spot around $\tan\beta \sim 1$

SM

New ACME results

Much Tighter constraints than before:

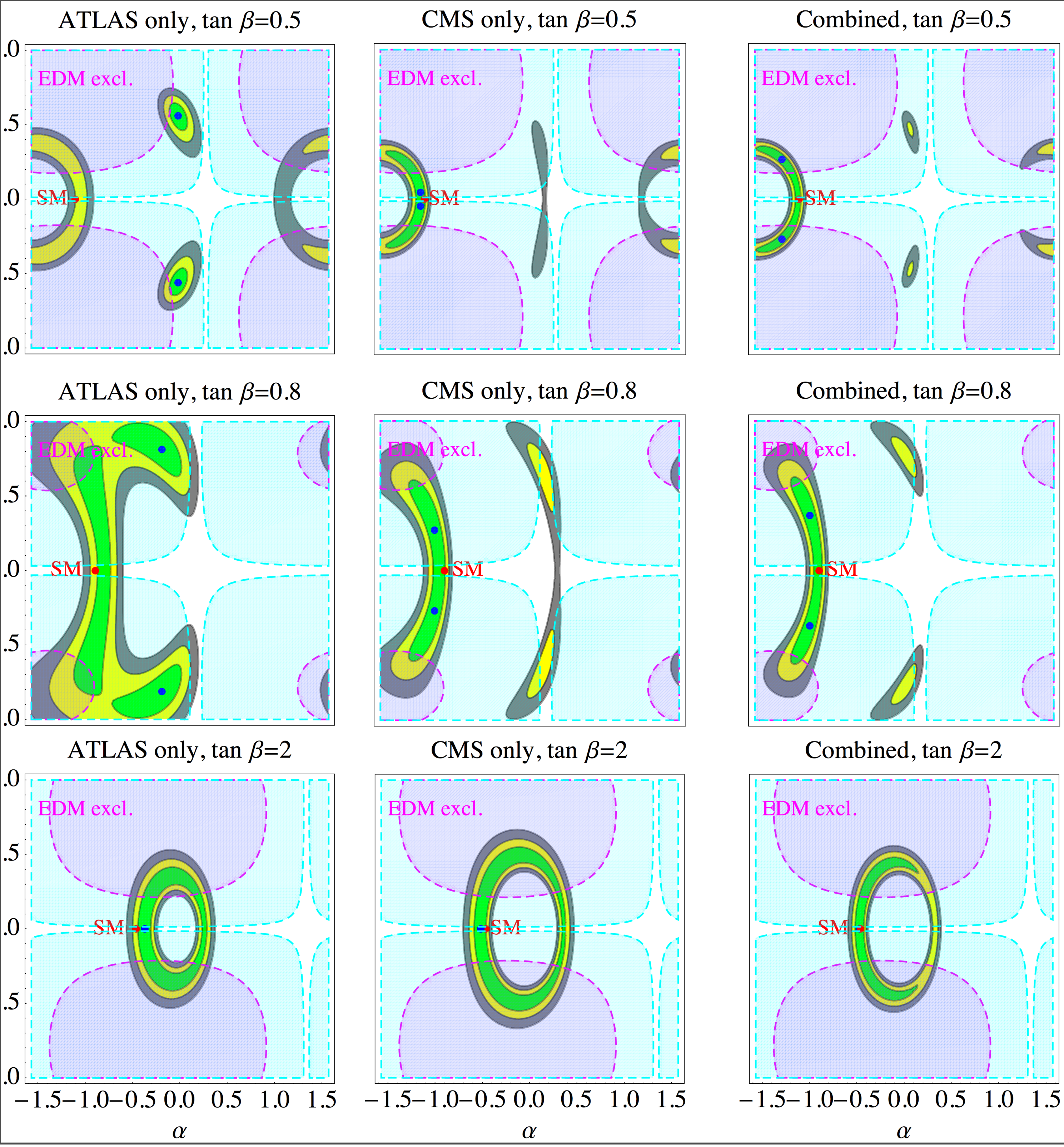
$|d_e| < 8.7 \times 10^{-29} e\text{cm}$ at 90% C. L.

More than one order improvements

Naively constraints $\tilde{c}_\gamma \sim \mathcal{O}(10^{-3})$

But is that really the general case? No need for CPV direct search?

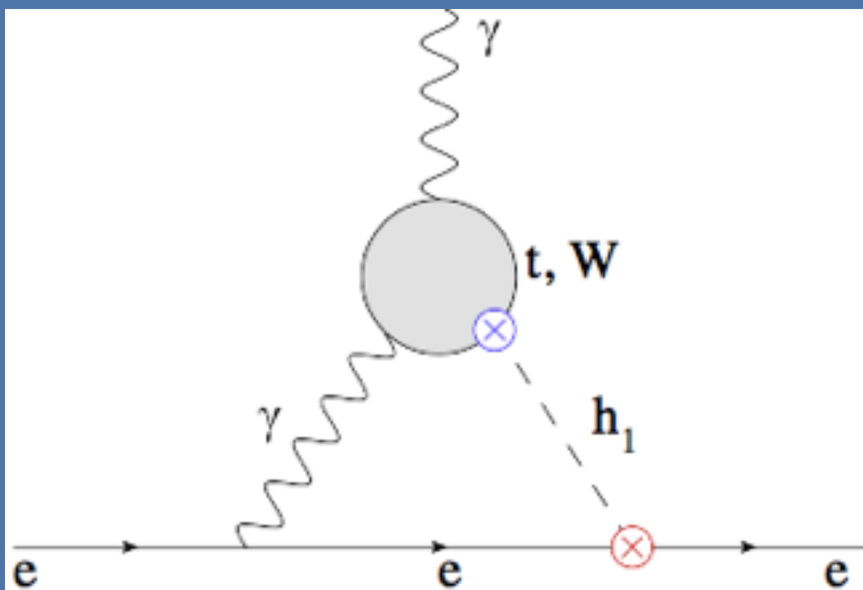
Where are the room for direct CPV searches?



ılts

Much Tightly constrained than before:

Bounds from EDM



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

The same operators would contribute to the EDM or CEDM

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

Naively constraints $\tilde{c}_\gamma$ ~ O(10^{-2})

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

2HDM case

$$\mathcal{L}_{\rm eff} = \frac{m_f}{v} h \bar{f}\left(c_f + i\tilde{c}_f \gamma^5\right) f + \frac{\alpha}{\pi v} h \left(c_\gamma F^{\mu\nu} V_{\mu\nu} + \tilde{c}_\gamma F^{\mu\nu} \tilde{V}_{\mu\nu}\right),$$

$$\mathcal{L}_{\rm eff} = -i d_e \bar{e} \sigma^{\mu\nu} \gamma_5 e \partial_\mu A_\nu$$

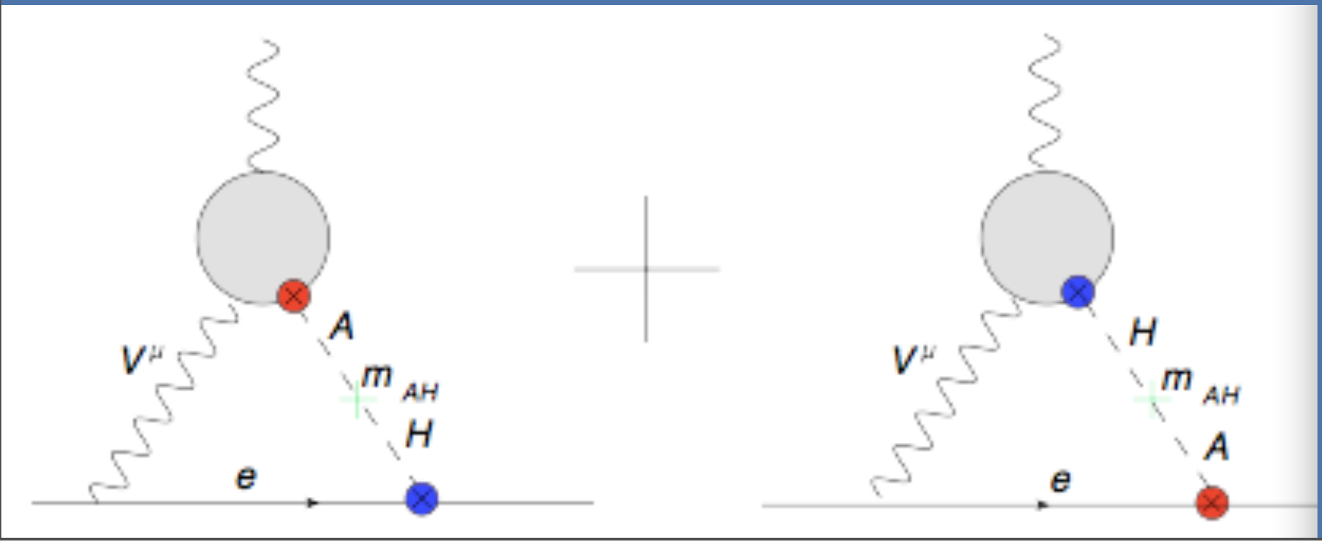
$$\frac{d_e}{e} = \frac{\alpha m_e}{4\pi^3 v^2}\left[-c_e \tilde{c}_\gamma \log\left(\frac{\tilde{\Lambda}^2_{{\rm UV},\, i}}{m^2_{h_i}}\right) + \tilde{c}_e c_\gamma \log\left(\frac{\Lambda^2_{{\rm UV},\, i}}{m^2_{h_i}}\right)\right]$$

EFT only for illustration

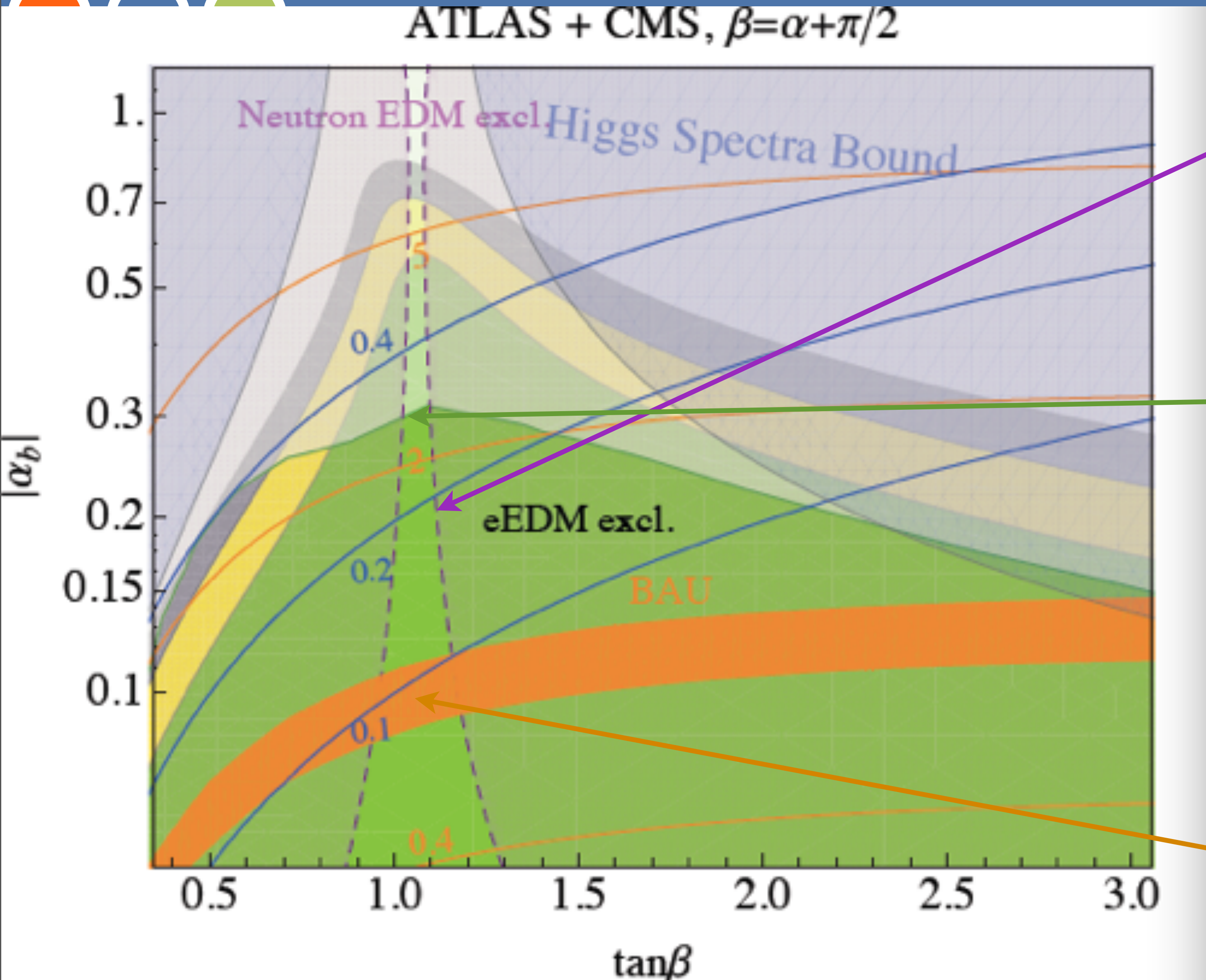
The two pieces can naturally cancel each other

The Higgs is a CP mixture!

2HDM case



Final Results



ACME bound

Future Neutron EDM bound will probe this region

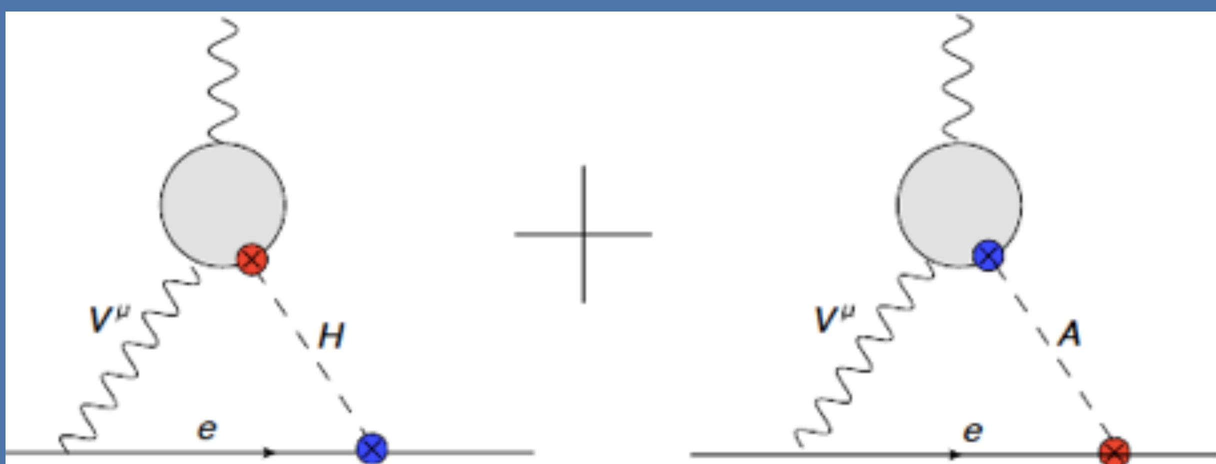
Mercury EDM is weaker

Preferred by EWBG

MSSM case

$$\left[\frac{de}{e}\right] \approx C\tilde{c}_e^A \sum_{j=1,2} \left(c_\gamma^{\tilde{\chi}_j^\pm} \ln \frac{1}{z^A_{\tilde{\chi}_j^\pm}} + c_\gamma^{\tilde{\tau}_j^\pm} \ln \frac{1}{z^A_{\tilde{\tau}_j^\pm}} \right) - C c_e^H \sum_{j=1,2} \tilde{c}_\gamma^{\tilde{\chi}_j^\pm} \ln \frac{1}{z^H_{\tilde{\chi}_j^\pm}}$$

EFT only for illustration



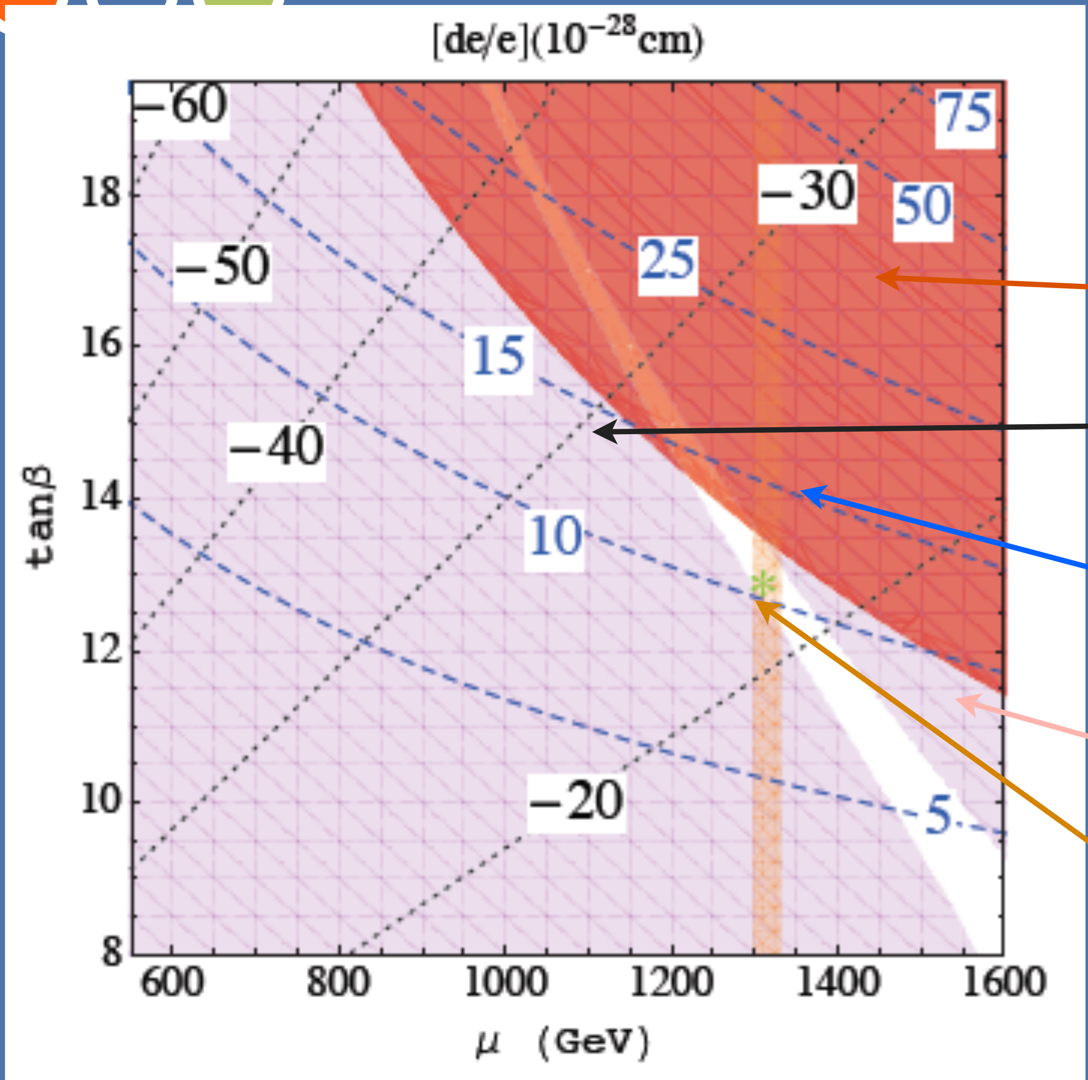
MSSM with chargino & staus

Negligible CPV in the Higgs sector

Heavy Higgs coupling enhanced by tan beta

Non-standard Higgs mediate the cancellation

Change in the CPSuperH



Open the Heavy Higgs CPV search

Mercury exclusion

Chargino contour

Stau contour

ACME exclusion

Preferred by EWBG

Correction in CPSuperH

- A sign mistake in the anomalous D of the di-pole operator (smaller EDMs at low energy).
- No operator mixing effects are considered
- Detailed RG running in the Mercury & other EDMs
- Update the matrix elements
- W boson loop included in the Barr-Zee diagram.

The bounds with QCDs are much weaker

Correction in CPSuperH

$$\gamma_s = \begin{bmatrix} +8C_F & 0 & 0 \\ +8C_F & +16C_F - 4N & 0 \\ 0 & +2N & N + 2n_f + \beta_0 \end{bmatrix}, \quad (36)$$

$$\gamma_f = \left[-12C_F + 6\right], \quad (37)$$

$$\gamma'_f = \begin{bmatrix} -12C_F & 0 \\ 0 & -12C_F \end{bmatrix}, \quad (38)$$

and

$$\gamma_{sf} = \begin{bmatrix} +4 & +4 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \quad (39)$$

where $N = 3$, $C_F = (N^2 - 1)/(2N) = 4/3$, $\beta_0 = (11N - 2n_f)/3$ and n_f is the flavor number.

Now, we explore details of the RG running.

Firstly, we need to use the $n_f = 5$ version of the above RGE for running from Λ(we use M_H in our analysis) to m_b. In which, CP-odd four-fermion operators (33) play a significant role. For our case, we one consider the operators containing the bottom quark for $\tan\beta$ enhancement effects. In addition to coefficients $C_{b(u,d)}$, $C_{(u,d)b}$ that contribute to the light quark CEDM through RGE operator mixing, we also considered the coefficient C_{bb} which mixes with and contributes to the b-quark CEDM. Keeping only the leading logarithmic terms that make additional contributions to the CEDMs of bottom and light quarks at the matching scale $\mu = m_b$, we have

bellow m_c scale we use 3 flavors version of RGE.

After above processes, we have the neutron EDM

$$d_n = \left(e\zeta_n^u\delta_u + e\zeta_n^d\delta_d\right) + \left(e\tilde{\zeta}_n^u\tilde{\delta}_u + e\tilde{\zeta}_n^d\tilde{\delta}_d\right) + \beta_n^G C_{\tilde{G}}\ ,(44)$$

with update hadronic matrix elements $\zeta_n^u = 0.82 \times 10^{-8}$, $\zeta_n^d = -3.3 \times 10^{-8}$, $\tilde{\zeta}_n^u = 0.82 \times 10^{-8}$, $\tilde{\zeta}_n^d = 1.63 \times 10^{-8}$ and $\beta_n^G = 2 \times 10^{-20}\, e\,\mathrm{cm}$ [45].

(2) Mercury EDM

Though the contributions from d_e^E and from the CP-odd electron-nucleon interactions

$$\mathcal{L} = C_S \bar{e} i\gamma_5 e \bar{N} N + C_P\, \bar{e}e\, \bar{N} i\gamma_5 N + C'_P\, \bar{e}e\, \bar{N} i\gamma_5 \tau_3 N\ , \quad (45)$$

are also incorporated in the CPsuperH, the mercury EDM is mainly contributed by the nuclear Schiff moment (S). The Schiff moment is generated by long-range, pion-exchange mediated P- and T-violating nucleon-nucleon interactions,

$$\mathcal{L}_{\pi NN}^{\mathrm{TVPV}} = \bar{N}\left[\bar{g}_\pi^{(0)}\vec{\tau}\cdot\vec{\pi} + \bar{g}_\pi^{(1)}\pi^0 + \bar{g}_\pi^{(2)}(2\tau_3\pi^0 - \vec{\tau}\cdot\vec{\pi})\right] N(46)$$

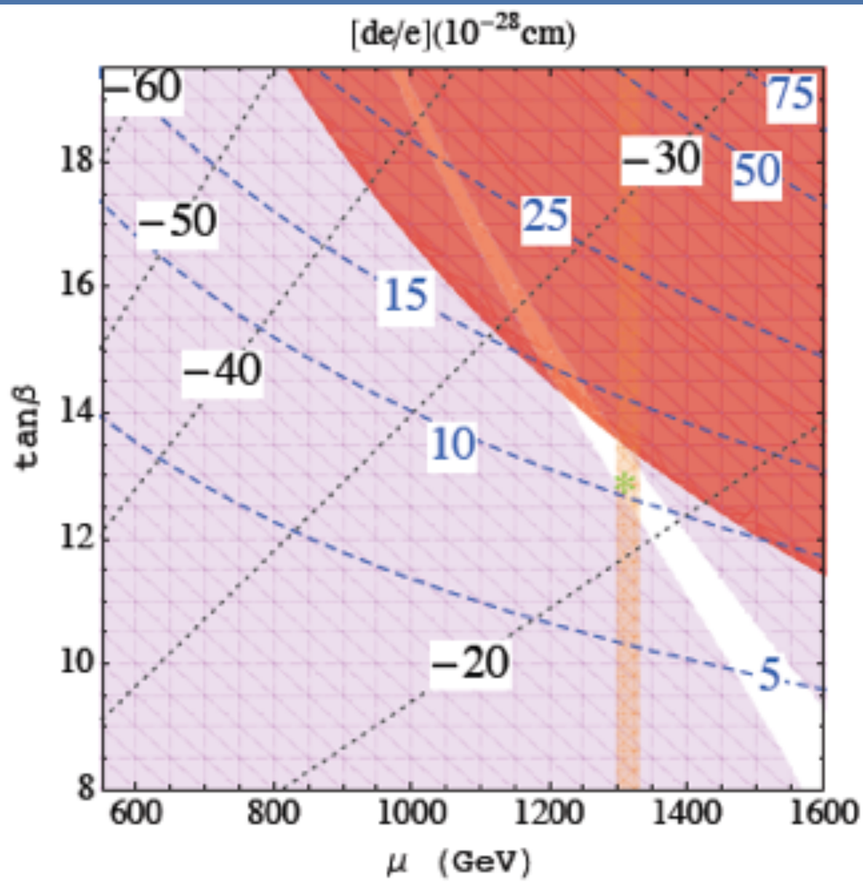
In a general context, the isoscalar and isovector couplings $\bar{g}_\pi^{(0)}$, $\bar{g}_\pi^{(1)}$ are dominant over the isotensor coupling $\bar{g}_\pi^{(2)}$ [45], so the mercury EDM is approximately given by [45],

$$d_{\mathrm{Hg}} = \kappa_S S \approx \kappa_S \frac{2m_N g_A}{F_\pi}\left(a_0\bar{g}_\pi^{(0)} + a_1\bar{g}_\pi^{(1)}\right)\ , \quad (47)$$

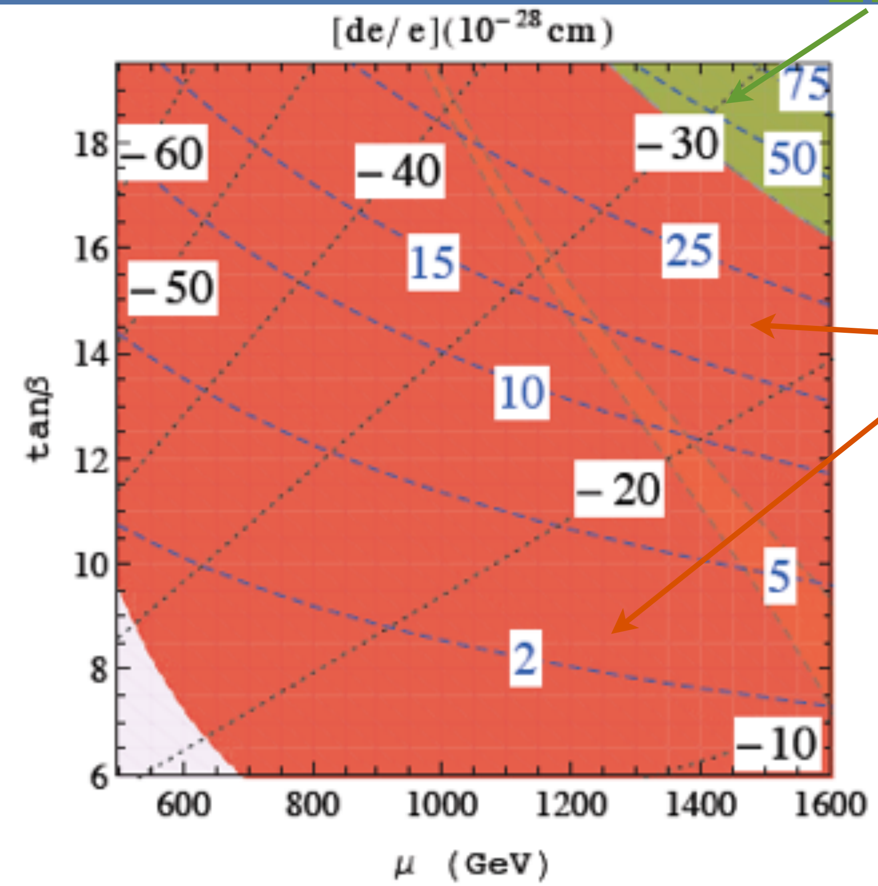
In arxiv soon

Correction in CPSuperH

Before correction:

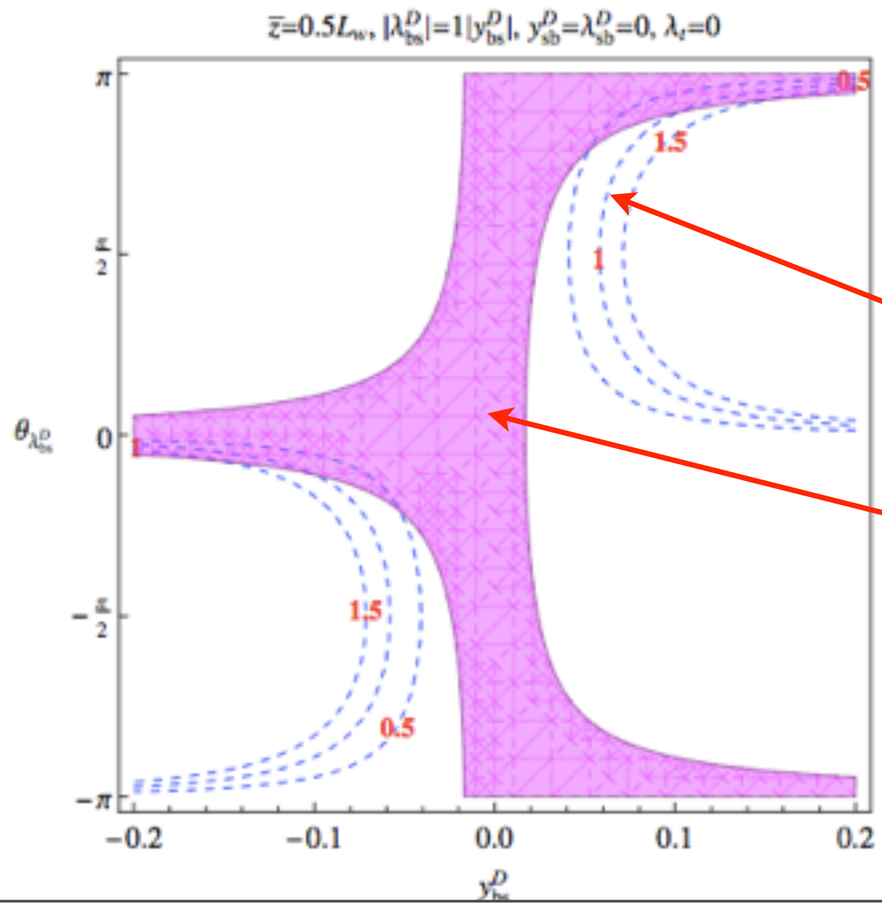


After correction:



Off-diagonal EWBG

The CPV sources may also coming from the off diagonal masses



T. Liu, M. Ramsey-Musolf J. S, Phys. Rev. Lett. 108 (2012) 221301

H. Guo, S. Hong, T. Liu, M. Ramsey-Musolf J. S, in progress

EWBG BAU

b to s gamma bound

The EDM bounds are well smaller than the bounds

Beyond SM physics: LHC data & EWPT

Classifications

- New particles with color or electric charge couples to the 125 GeV Higgs.
- Multi-Higgs!

  G.C. Dorsch, S.J. Huber, J.M. No JHEP 1310 (2013) 29

  G.C. Dorsch, S.J. Huber, K. Mimasu, J.M. No 1405.5537
- New singlet scalars mix with Higgs

  W. Huang, ZF. Kang, J. S, PW. Wu, JM. Yang, 1405.1152
- Singlet scalars couples to the Higgs

  B. Henning, XC. Lu, H. Murayama 1404.1058
- Other possibilities (even worse to detect).

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:

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

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

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

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

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

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

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

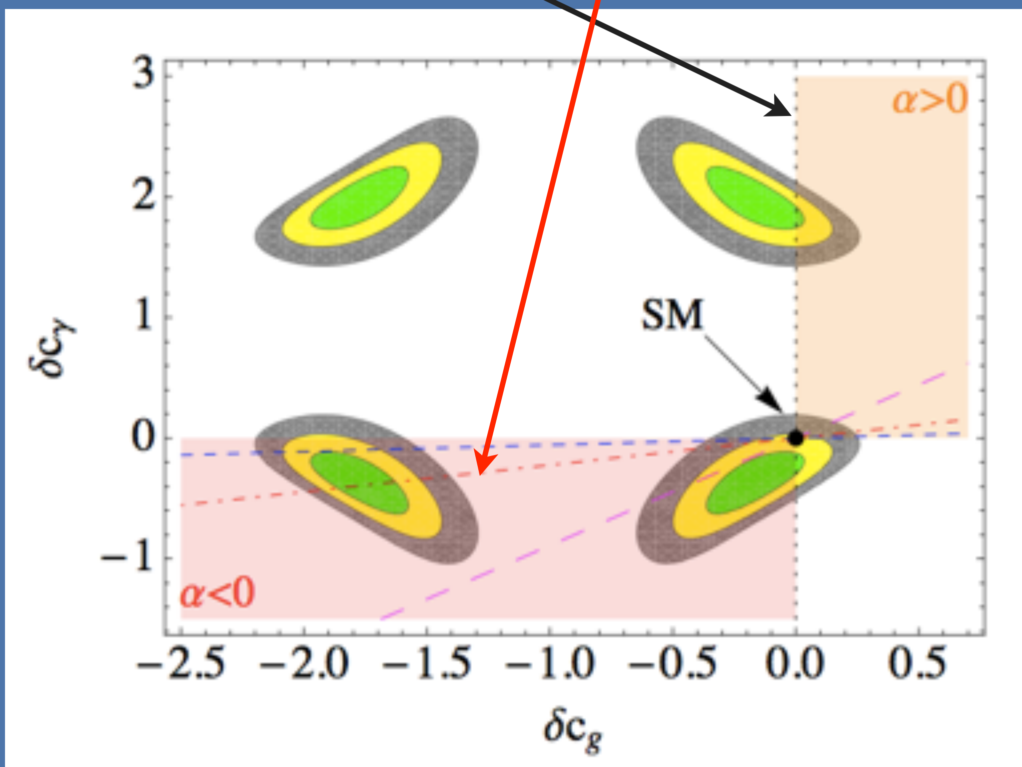
Higgs fits (old data)

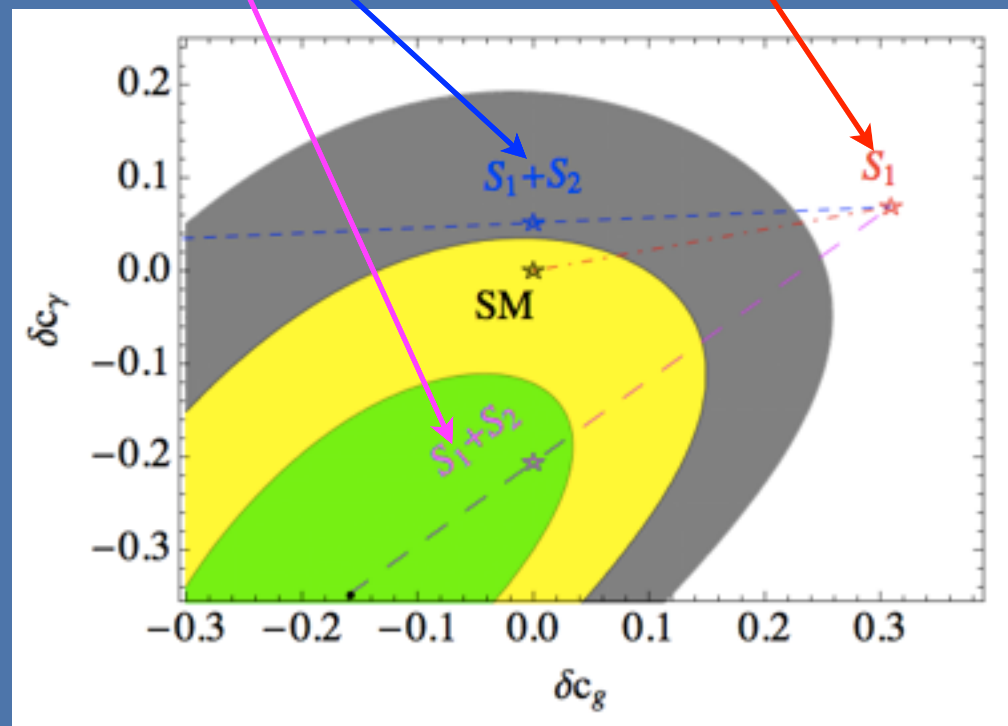
Color singlet

Color triplet with different Qs

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

Stop like state (a>0)

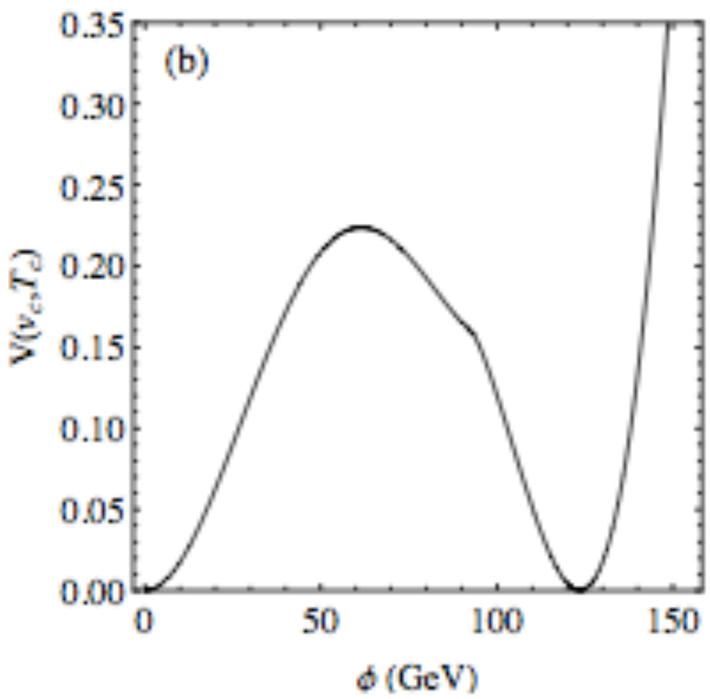




EWPT

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

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



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 $v_c/T_c \gtrsim 0.9$

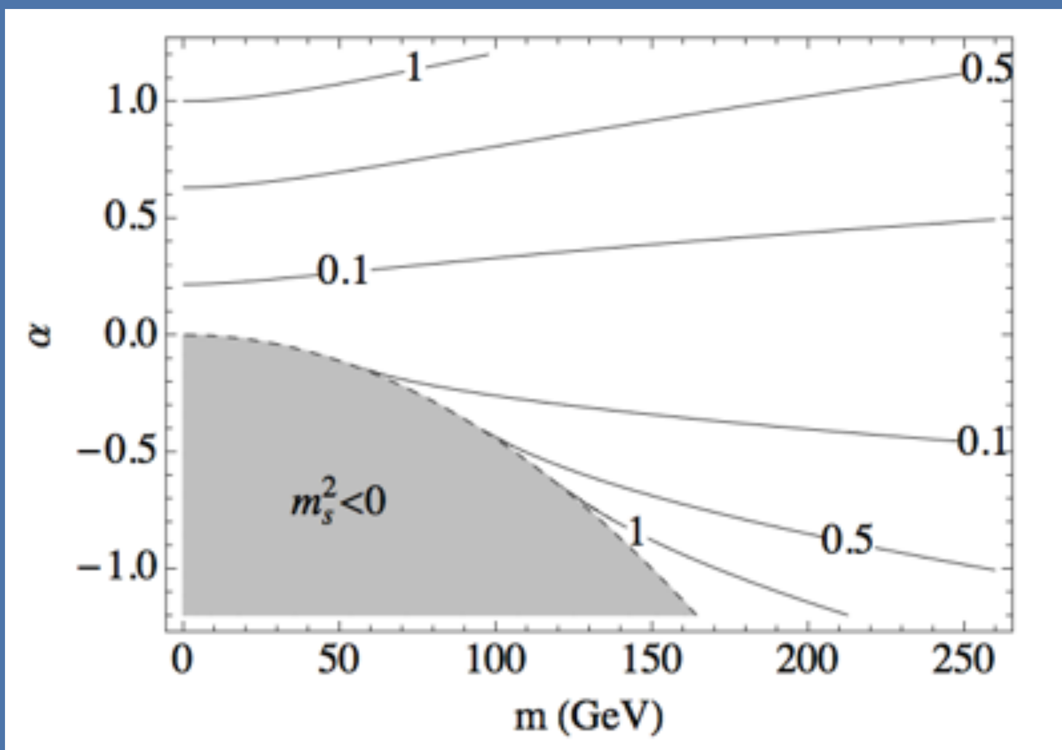
For general mass matrix and arbitrary number of scalars

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

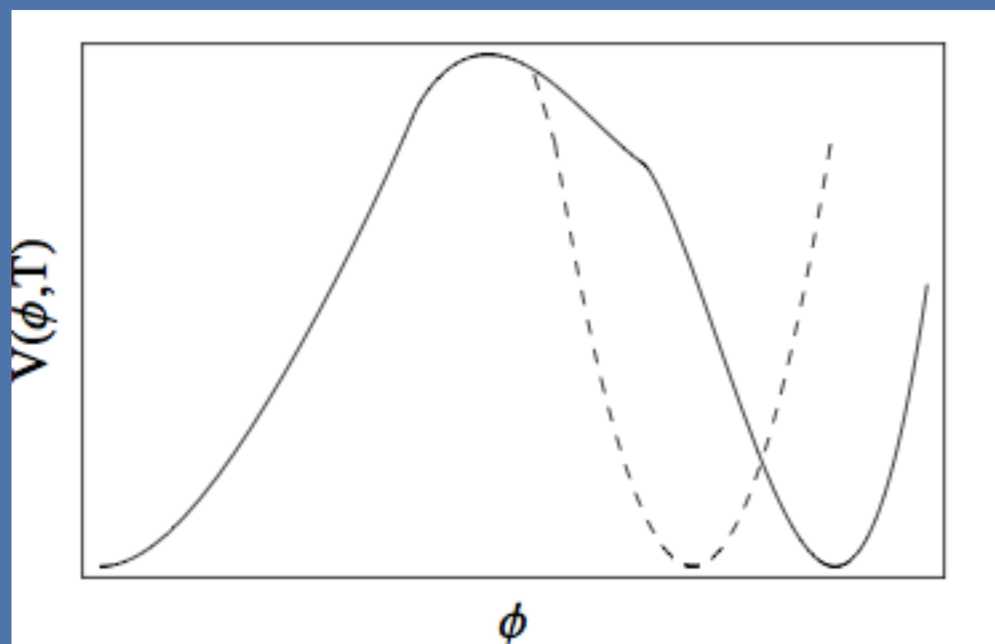
$$F[m_s] \equiv \frac{\partial m_s^3(v_c,T_c)}{\partial v_c} v_c - 2\left[m_s^3(v_c,T_c) - m_s^3(0,T_c) \right].$$

EWPT

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

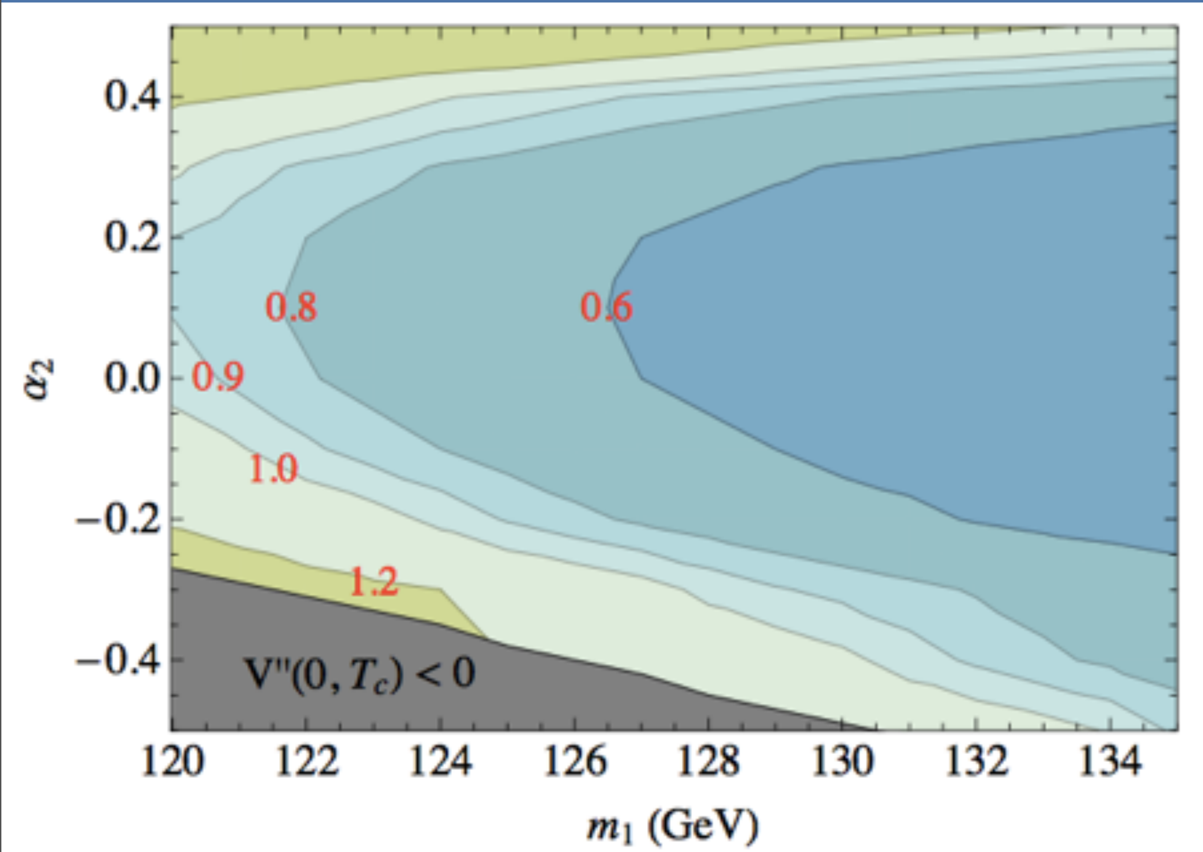


Adding another scalar with a<0 would make phi larger



EWPT

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



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 → 150 GeV light stop, 200 GeV light sbottom

Perhaps not so live now.

- 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.

SFOEWPT in NMSSM

The mixing case

What if it is not the higgs portal case?

- Another generic possibility is that the Higgs actually mixes with other scalars 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 and scale invariant):

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

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

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

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

NMSSM setup

Goldstone basis:
S2 SM like

$$H_u^0 = v_u + \frac{1}{\sqrt{2}}(S_1\cos\beta + S_2\sin\beta) + \frac{i}{\sqrt{2}}(P_1\cos\beta + G^0\sin\beta),$$
$$H_d^0 = v_d + \frac{1}{\sqrt{2}}(-S_1\sin\beta + S_2\cos\beta) + \frac{i}{\sqrt{2}}(P_1\sin\beta - G^0\cos\beta),$$
$$S = v_s + \frac{S_3 + iP_2}{\sqrt{2}},$$

$$(M_S^2)_{11} = M_A^2 + (m_Z^2 - \lambda^2 v^2)\sin^2 2\beta,$$
$$(M_S^2)_{12} = -\frac{1}{2}(m_Z^2 - \lambda^2 v^2)\sin 4\beta,$$
$$(M_S^2)_{13} = -(M_A^2\sin 2\beta + 2\lambda\kappa v_s^2)\cos 2\beta\frac{v}{v_s},$$
$$(M_S^2)_{22} = m_Z^2\cos^2 2\beta + \lambda^2 v^2\sin^2 2\beta,$$
$$(M_S^2)_{23} = \frac{1}{2}(-M_A^2\sin^2 2\beta + 4\lambda^2 v_s^2 - 2\lambda\kappa v_s^2\sin 2\beta)\frac{v}{v_s},$$
$$(M_S^2)_{33} = \frac{1}{4}M_A^2\sin^2 2\beta\left(\frac{v}{v_s}\right)^2 + 4\kappa^2 v_s^2 + \kappa A_\kappa v_s - \frac{1}{2}\lambda\kappa v^2\sin 2\beta.$$

P1 eaten by the W, Z

$$(\mathcal{M}_P^2)_{11} = M_A^2,$$
$$(\mathcal{M}_P^2)_{22} = \frac{1}{4}M_A^2\sin^2 2\beta\left(\frac{v}{v_s}\right)^2 - \frac{3}{2}\lambda\kappa v^2\sin 2\beta - \frac{12\kappa^2 v_s^2}{R_\kappa}$$
$$(\mathcal{M}_P^2)_{12} = \frac{1}{2}M_A^2\sin 2\beta\left(\frac{v}{v_s}\right),$$

$$M_{23}^2 = 2C_A\lambda\mu v$$

$$C_A \equiv 1 - A_\lambda\sin 2\beta/2\mu - \kappa\sin 2\beta/\lambda$$

$$M_A^2 = 2\lambda v_s(A_\lambda + \kappa v_s)/\sin 2\beta$$

C_A always small for 125GeV SM Higgs

Critical mass

$$R_\kappa \equiv \frac{4\kappa v_s}{A_\kappa}$$

$$\begin{aligned}(M_S^2)_{33} &= \frac{1}{4}M_A^2 \sin^2 2\beta \left(\frac{v}{v_s}\right)^2 + 4\kappa^2 v_s^2 \left(1 + \frac{1}{R_\kappa}\right) - \frac{1}{2}\lambda\kappa v^2 \sin 2\beta, \\ &= -\frac{1}{2}(M_S^2)_{23}\left(\frac{v}{v_s}\right) + 4\kappa^2 v_s^2 \left(1 + \frac{1}{R_\kappa}\right) + \lambda^2 v^2 - \lambda\kappa v^2 \sin 2\beta\end{aligned}$$

$$(\mathcal{M}_P^2)_{22} = \frac{1}{4}M_A^2 \sin^2 2\beta \left(\frac{v}{v_s}\right)^2 - \frac{3}{2}\lambda\kappa v^2 \sin 2\beta - \frac{12\kappa^2 v_s^2}{R_\kappa} \; ,$$

Patterns

As our universe cools down

- Type I PT: it first goes to the S-breaking, EW symmetric phase, then to the EW breaking phase.
- Type II PT: Intermediate phase is the EW-breaking, S-conserving phase. Large <S> does not prefer this case.
- Type III PT: One step PT.

More patterns

Together with two different Higgs spectra pattern

- H1 scenario: 125 GeV Higgs is the lightest
- H2 scenario: 125 GeV Higgs is the 2nd lightest

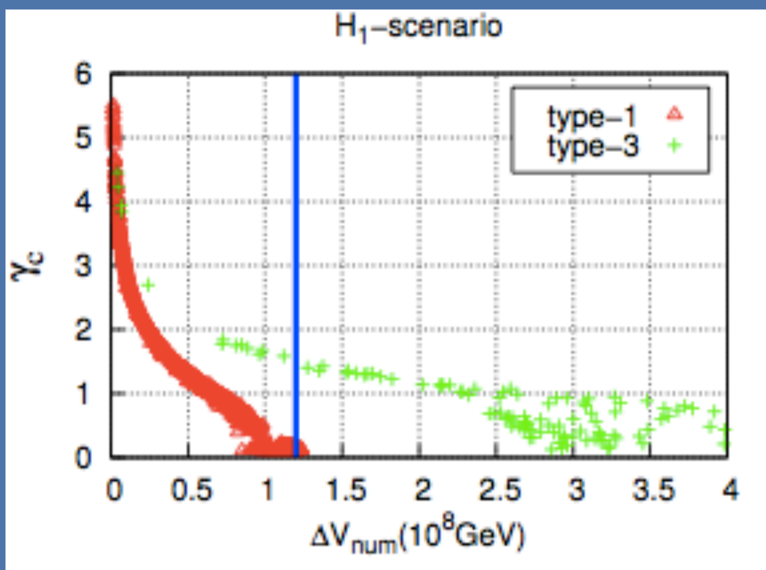
What can we learn from that?

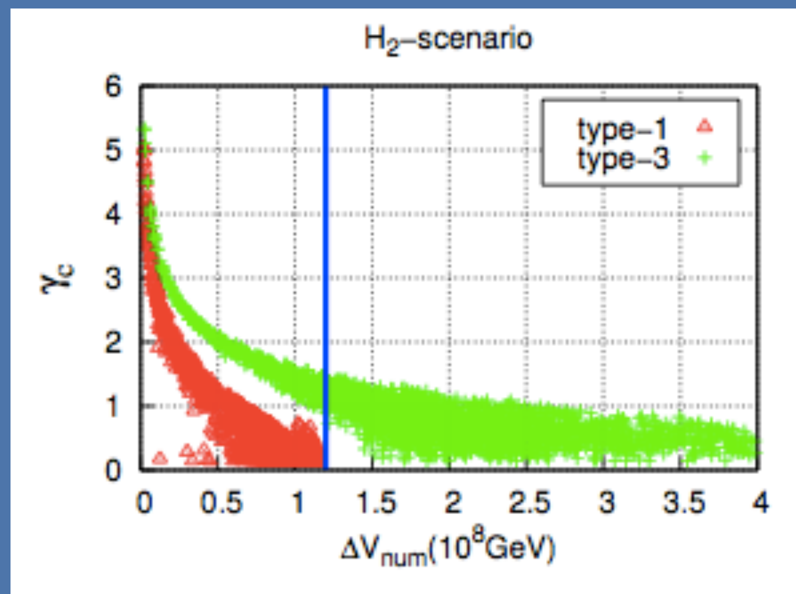
Measure of PT strength

Better approximated if the PT is stronger

$$\begin{aligned}\Delta V &= \left(V_{\rm sym} - V_{\rm EW}(v_0)\right)|_{T=0} \\ &\simeq V_{\rm sym}(T_c) - V_{\rm EW}(T=0, v_0) \\ &= V_{\rm EW}(T_c, v_c) - V_{\rm EW}(T=0, v_0) \\ &\simeq T_c \frac{\partial V}{\partial T}(T=T_r, v_0)\end{aligned}$$

$$\frac{v_c}{T_c} \simeq \left(v \frac{\partial V}{\partial T}\Big|_{T=T_c} \right) \frac{1}{\Delta V}$$





Type-I PT

$$
\begin{aligned}
\Delta V_{\text{tree}} =& V_S - V_{\text{EW}}^S - V_{\text{EW}}^{HS} - V_{\text{EW}}^H \\
\simeq& \frac{v^2 m_h^2}{4} - C_A \lambda^2 v^2 (u_s^2 - v_s^2) + \kappa^2 (v_s^2 - u_s^2)^2 \\
&+ \frac{1}{3}\kappa A_\kappa \left[2u_s^2(u_s - v_s) + v_s(v_s^2 - u_s^2)\right] \\
\approx& 4\delta^2 \kappa^2 \left(1 + 1/R_\kappa\right) v_s^4 - 2\delta\, C_A v^2 \mu^2 + \frac{v^2 m_h^2}{4},
\end{aligned}
$$

$$R_\kappa \equiv \frac{4\kappa v_s}{A_\kappa}$$

$$u_s = (1+\delta) v_s$$

S-direction (EW conserving) singlet vev

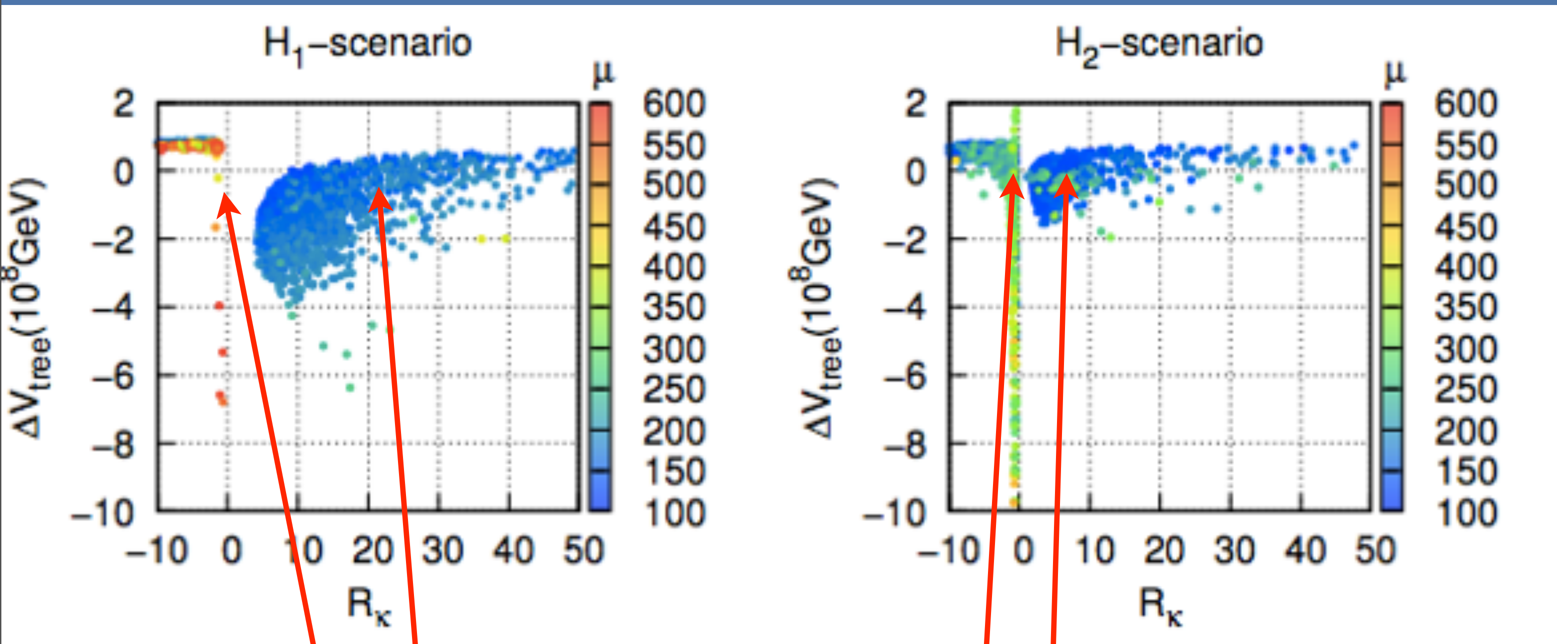
$$|R_\kappa| \to \infty \qquad \delta \to 0$$

$$
u_s \approx \begin{cases} -v_s(1 + 2/R_\kappa) + \mathcal{O}(C_A) & \text{if } R_\kappa \gtrsim -1; \\ v_s + \mathcal{O}(C_A) & \text{if } R_\kappa \lesssim -1. \end{cases}
$$

No SFOEWPT

Type-I PT

$\kappa : (0.01,\, 0.5),\quad \lambda : (0.3,\, 0.8),\quad \tan\beta : (1.5,\, 10),$
$A_\lambda : (200,\, 2000)\,\mathrm{GeV},\quad A_\kappa : (-1000,\, 1000)\,\mathrm{GeV},\quad \mu : (100,\, 600)\,\mathrm{GeV}.$



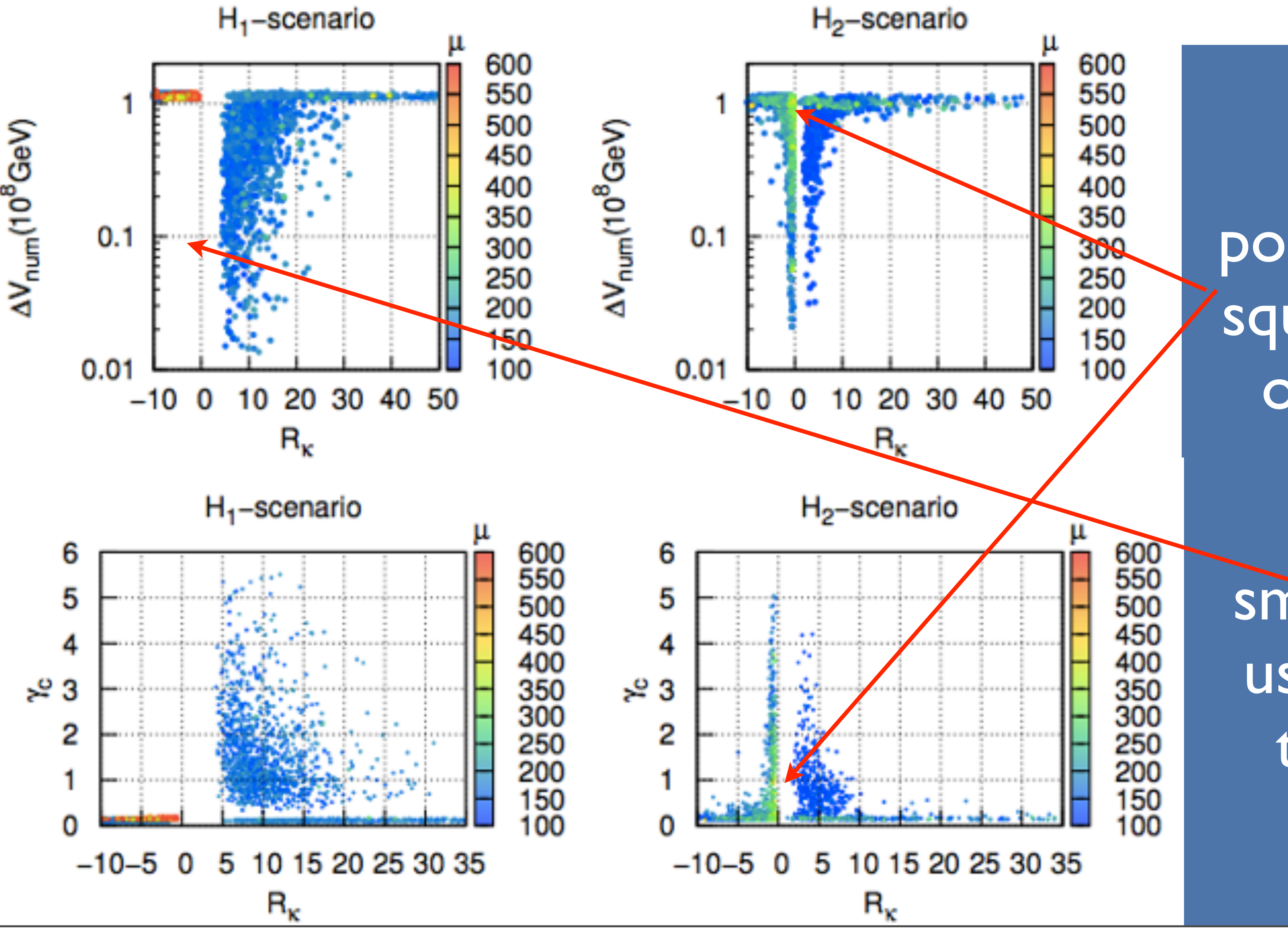
NMSSM tools
+ Higgs fits

Finite δ makes ΔV_{tree} small
or even negative

$R_\kappa \sim -1$

R_κ positive

Type-I PT



positive mass square of CP odd Higgs

Has the smallest M33, usually make the points H2S

Type-I PT

PT parameter

$$R_\kappa \equiv \frac{4\kappa v_s}{A_\kappa}$$

For the 1st time, EWPT in NMSSM is understood semi-analytically!

- H1 scenario: SFEWPT requires $R_\kappa \subset (5, 30)$
- H2 scenario: SFEWPT suggests $R_\kappa \sim -1$ and $R_\kappa \subset (2, 10)$.

More details on other parameter dependence see the paper

Type-III PT

$$\Delta V_{tree} = -V_{\rm EW}^{H} - V_{\rm EW}^{HS} - V_{\rm EW}^{S}$$
$$\simeq \frac{v^2 m_h^2}{4} + C_A \mu^2 v^2 + \kappa^2 v_s^4 \left(\frac{4}{3R_\kappa} + 1\right)$$

$|R_\kappa| \to \infty \quad \delta \to 0$

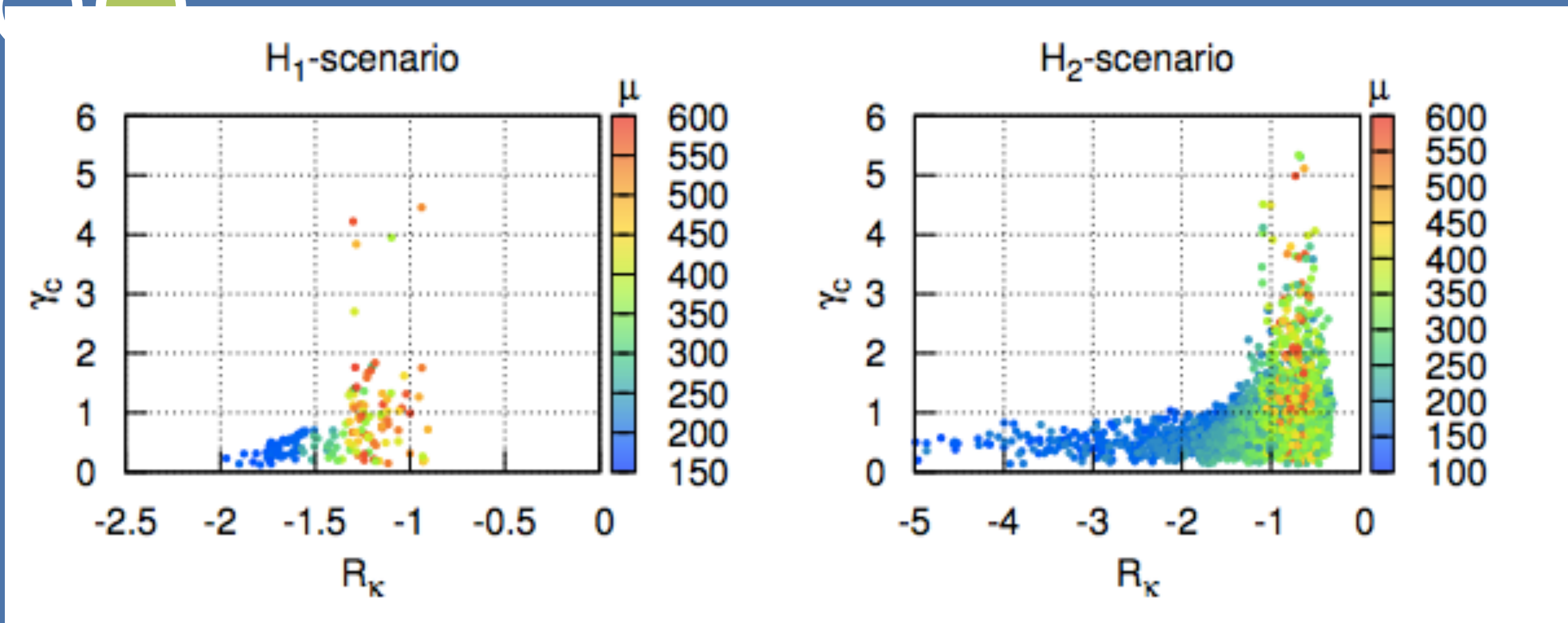
No SFOEWPT

$-4/3 \lesssim R_\kappa < 0.$

a negative C_A

large A_λ.

Type-III PT

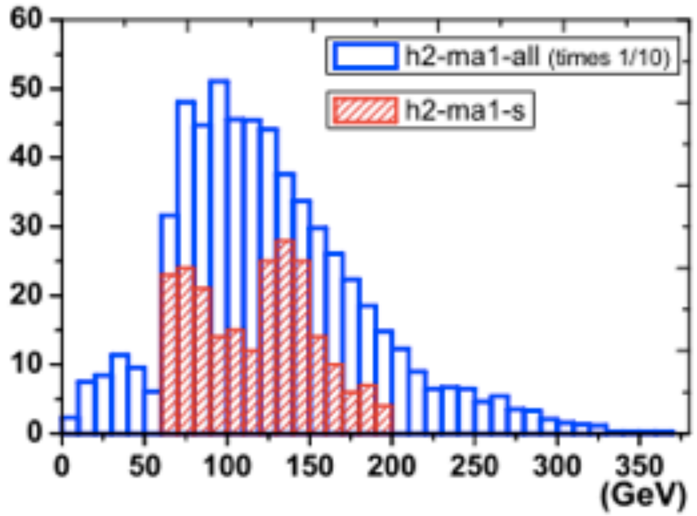


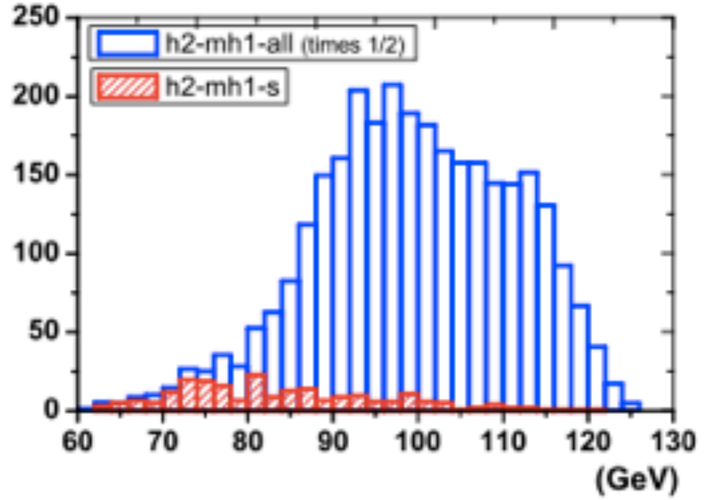
Positive R_κ make the S vev steep and PT Type-I.

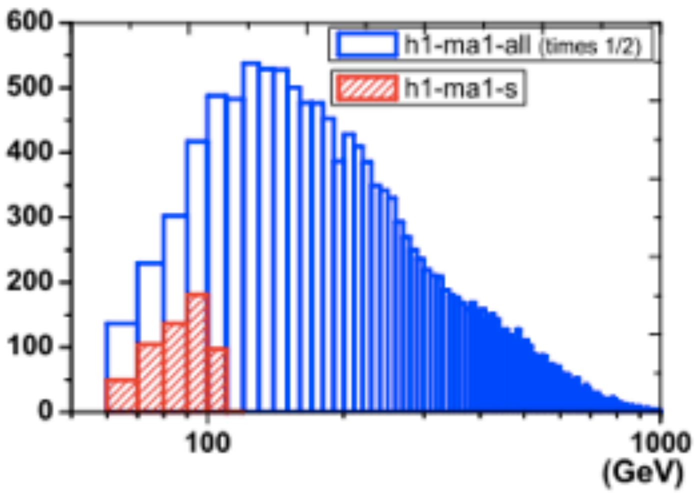
$R_\kappa \sim -4/3$

Almost all SFOEWPT points are in the H2S.

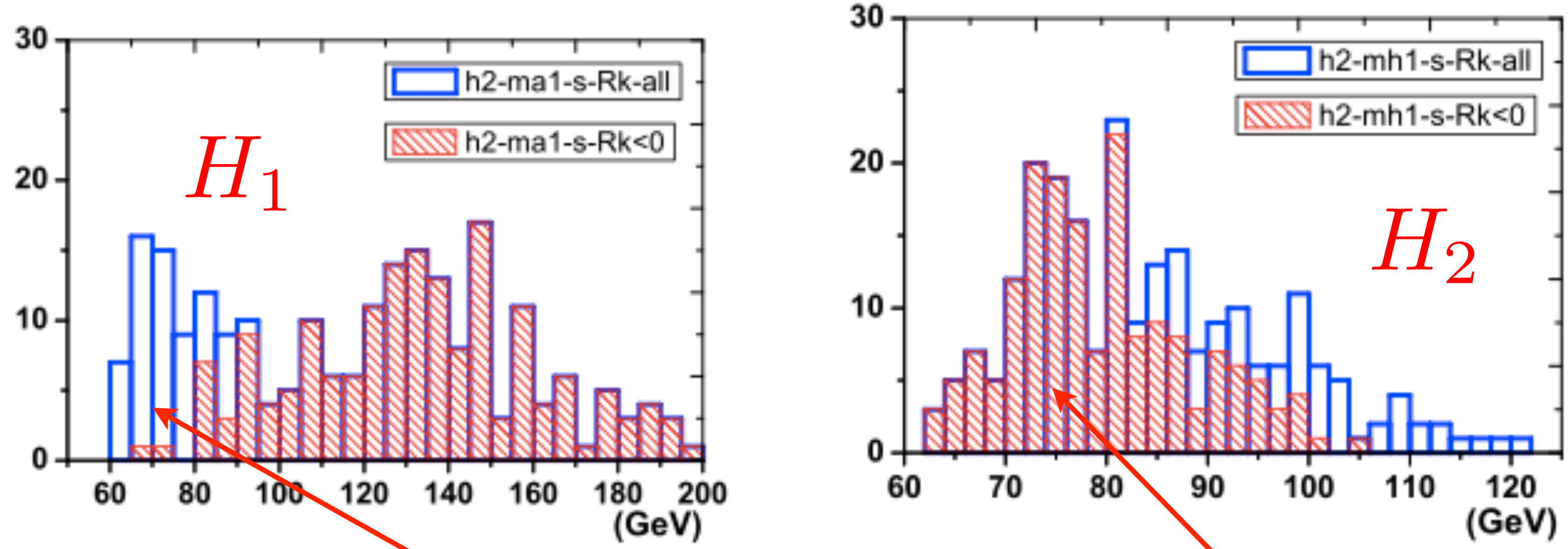
Overall Spectra







Overall Spectra



Either Light CP odd Higgs or light CP even Higgs

$$(\mathcal{M}_P^2)_{22} = \frac{1}{4} M_A^2 \sin^2 2\beta \left(\frac{v}{v_s}\right)^2 - \frac{3}{2}\lambda\kappa v^2 \sin 2\beta - \frac{12\kappa^2 v_s^2}{R_\kappa},$$

$$(M_S^2)_{33} = 4\kappa^2 v_s^2 \left(1 + \frac{1}{R_\kappa}\right) + \cdots,$$

Challenge in searches, may be ttbar h/A channel?

Higgs-singlet protal, ILC, TLEP

Higgs singlet portal

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2}m_S^2 S^2 - A|H|^2 S - \frac{1}{2}k|H|^2 S^2 - \frac{1}{3!}\mu S^3 - \frac{1}{4!}\lambda_S S^4.$$

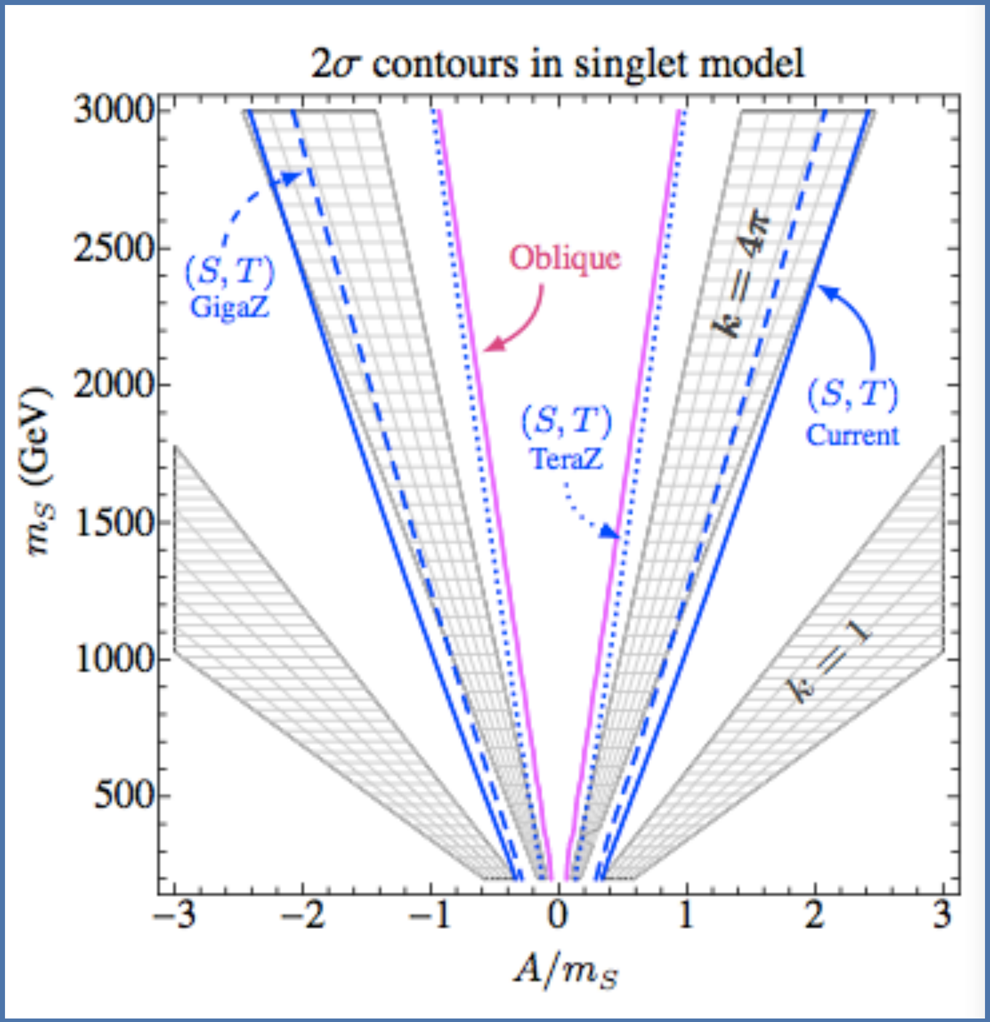
$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \frac{A^2}{2m_S^2}|H|^4 + \frac{A^2}{m_S^4}\mathcal{O}_H - \left(\frac{A^2 k}{m_S^4} - \frac{A^3\mu}{m_S^6}\right)\mathcal{O}_6.$$

Essentially a two loop effects:

$$S = \frac{1}{6\pi}\left[\frac{2v^2}{m_S^2}c_H(m_S)\right]\log\frac{m_S}{m_W},$$

$$T = -\frac{3}{8\pi\cos^2\theta_W}\left[\frac{2v^2}{m_S^2}c_H(m_S)\right]\log\frac{m_S}{m_W}.$$

Higgs singlet portal



Higgs potential

$$V_H \sim a_2 |H|^2 - a_4 |H|^4 + a_6 |H|^6 ,$$

SFOEWPT

$$\frac{4v^4}{m_H^2} < \frac{2m_s^4}{kA^2} < \frac{12v^4}{m_H^2} ,$$

Overview and Outlook

Prospects

EWBG & Higgs physics: Collider Searches

DM & WIMPs, Direct Collider Searches

Low energy CPV experiments

DM Direct detection

Gravitational Waves

DM Indirect Searches.

Many inputs from the astrophysics side has to be well understood

Much fun to explore

Just comments

- CPV in h to massive gauge boson coupling: CP odd is dim5, always small (hard to measure).

- Measure CPV in gamma gamma or Z gamma requires information in photon polarization.

G.C. F. F. Bishara, Y. Grossman, R. Harnik, D. Robinson, J.S. J. Zupan. JHEP 1404 (2014) 084; Y. Chen, A. Falkowski, I. Low, R. Vega-Morales 1405.6723

- Top CPV promising: in ggjj--> h + 2j or ttbar Higgs

- Other CPV fermion couplings

R. Harnik, A. Martin, T. Okui, R. Primulando, F. Yu, PRD, 88 (2013) 7, 076009

CPV in ttbar higgs production

$$b_4 = \frac{p_z^t p_z^{\bar{t}}}{|\vec{p^t}|\,|\vec{p^{\bar{t}}}|}$$

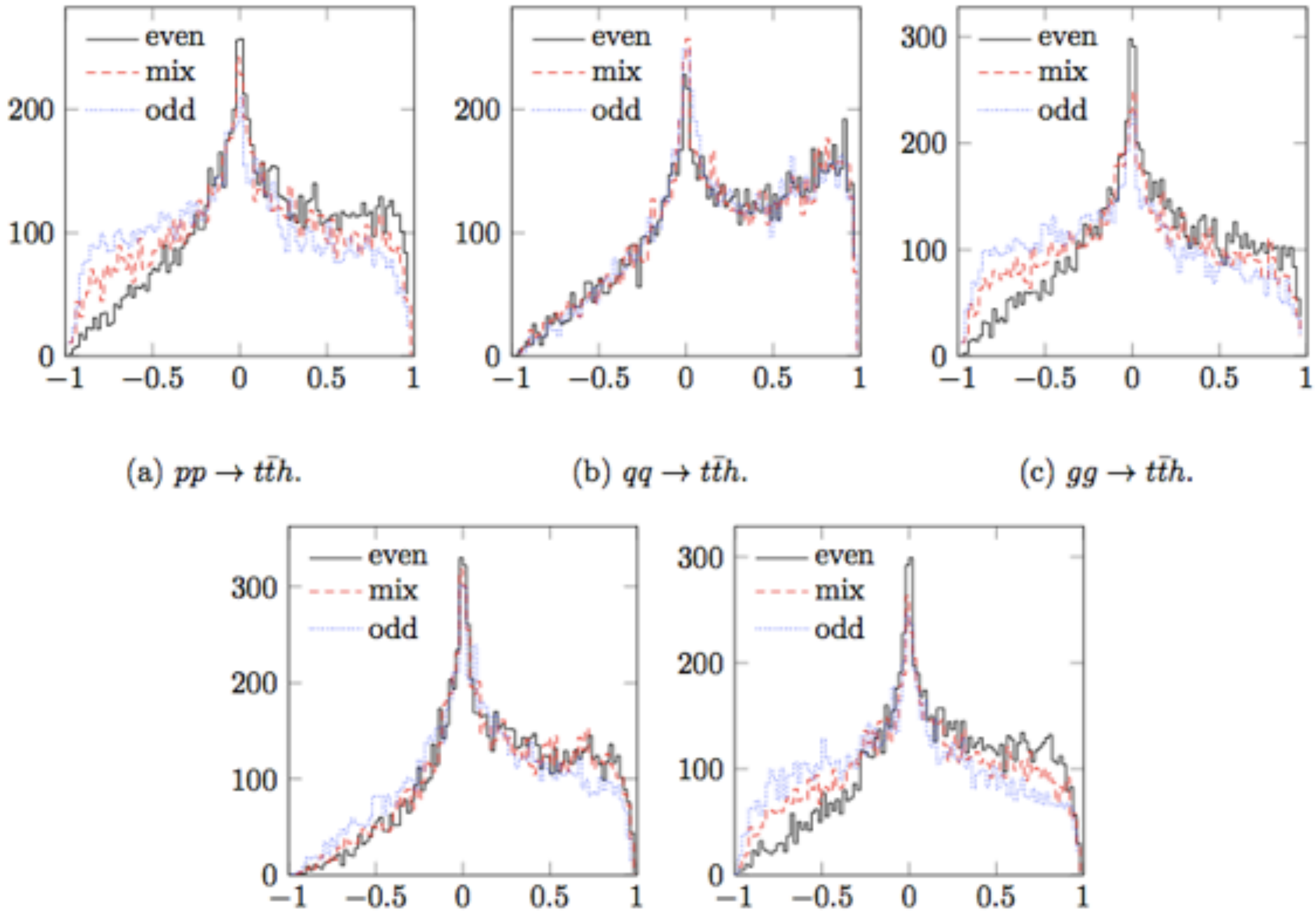
$$\alpha = \int \frac{\mathcal{O}_{CP}}{\sigma} \frac{d\sigma}{dPS} dPS$$

$$\delta\alpha_S = \frac{1}{\sqrt{S}} \sqrt{\beta_S - \alpha_S^2 + \frac{B}{S}\left(\beta_B - 2\alpha_B\alpha_S + \alpha_S^2\right)}\ .$$

$$\beta = \int \frac{\mathcal{O}_{CP}^2}{\sigma} \frac{d\sigma}{dPS} dPS$$

process	CP higgs			difference
	even	mix	odd	
pp	0.146	0.048	-0.028	0.174
qq	0.225	0.216	0.218	0.007
gg	0.114	0.013	-0.062	0.176
gg S	-0.220	-0.191	-0.086	0.134
gg T	0.152	0.055	-0.028	0.180

CPV in ttbar higgs production



(a) $pp \to t\bar{t}h$. (b) $qq \to t\bar{t}h$. (c) $gg \to t\bar{t}h$.

(d) $gg \to t\bar{t}h$ S-channel. (e) $gg \to t\bar{t}h$ T-channel.

Beating down the backgrounds is a difficult task

Summary on the CPV & BG

- There is indeed a natural connection between BAU in EWBG and CPV in the Higgs sector.
- After the ACME results, still a lot of room for large CPV effects, which could be tested in the future EDM experiments.
- Direct CPV at the LHC is still worth to look for and it is difficult to measure.

EWPT !

- T=0 EWSB determines the finite T EWPT.
- Realistically, many different categories on how new physics affects the Higgs physics & the EWPT.
- Future Z factory or the Higgs factory would help us to know more. But not sure if that can let us know

High-Energy Particle Theory (AJO-3258)

Beijing, Inst. Theor. Phys. - Postdoc

Field of Interest: hep-ph
Deadline: 2014-05-30 (PASSED)
Region: Asia

Job description:

The Institute of Theoretical Physics, Chinese Academy of Sciences (ITP-CAS) has several openings for postdoctoral associates in the area of High-Energy Particle Theory, especially related to the models of Electroweak Symmetry Breaking, Collider Phenomenology (with simulation studies) and related subjects on Neutrinos, Dark Matter and Baryogenesis.

The particle theory group of Institute of Theoretical Physics has six other active faculties in this area and many postdocs and graduate students. The Institute of Theoretical Physics, Chinese Academy of Sciences (ITP-CAS) is the basis for the Kavili Institute for Theoretical Physics in China (KITPC), which is the largest platform for all activities of theoretical physics in China and the State Key Laboratory of Theoretical Physics (SKLTP) which is the only National Key Laboratory in Theoretical Physics.

The positions are financially supported by the program "1000 Young Talents" and are guaranteed for at least two years (Very possibly extend to three years). Candidates should send the following things

1): CV.
2): Research Statement.
3): Three Reference Letters.
4): List of Publications.

to jshu@itp.ac.cn with email-title of "PD_ITP/CAS". Any questions should also be addressed to the same email address.

More information: https://academicjobsonline.org/ajo/jobs/3258

I am also welcome for undergraduate student to join ITP.