EW Phase Transition and Baryogenesis

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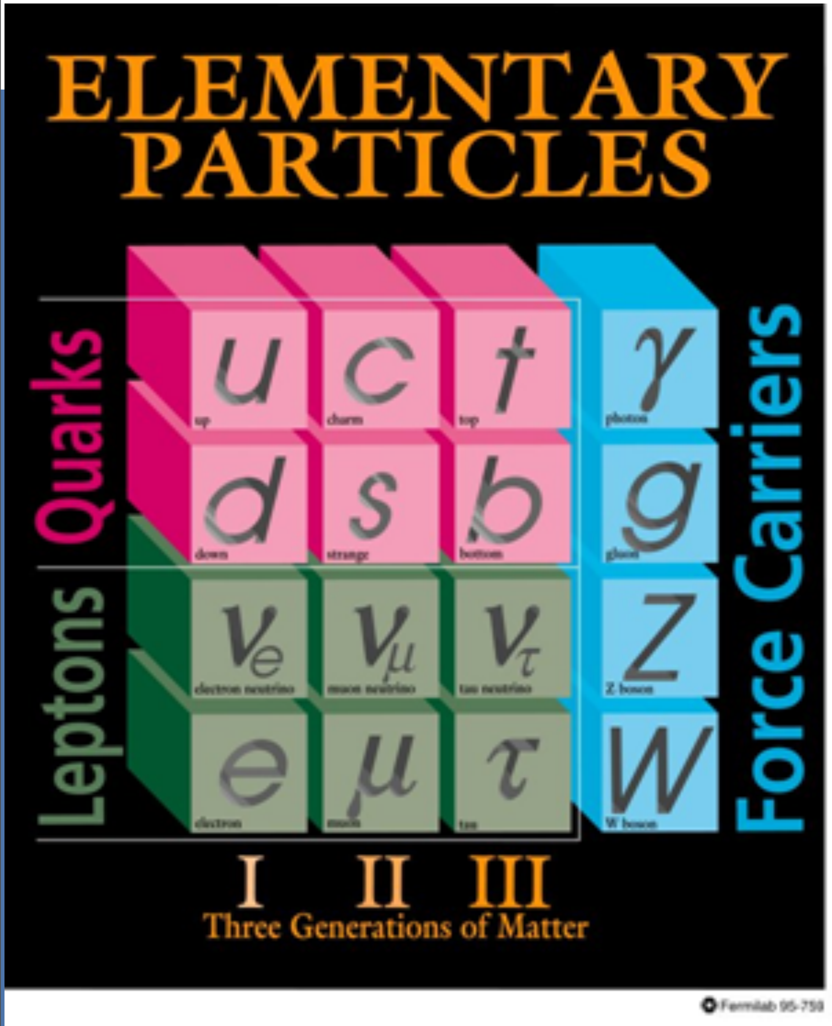
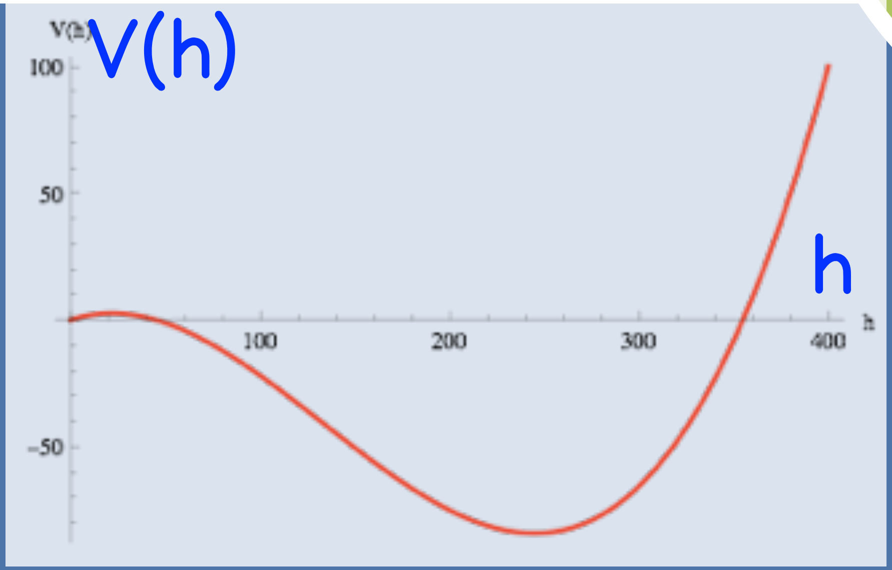
Outline

- The Time to test EWBG (A general overview).
- Electroweak Phase Transition in the post-LHC era.
- Higgs related CP violation and baryon asymmetry generation in the post-LHC era.
- Future prospects of testing EWBG.
- Summary and outlook.

The origin of mass!





Higgs mechanism

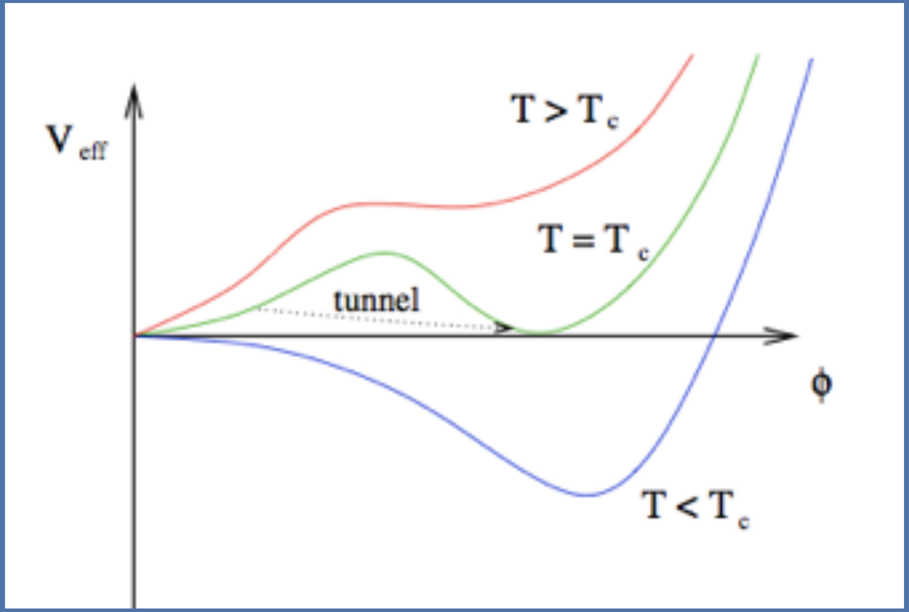
The origin of electroweak symmetry breaking

Higgs ???

What big questions 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

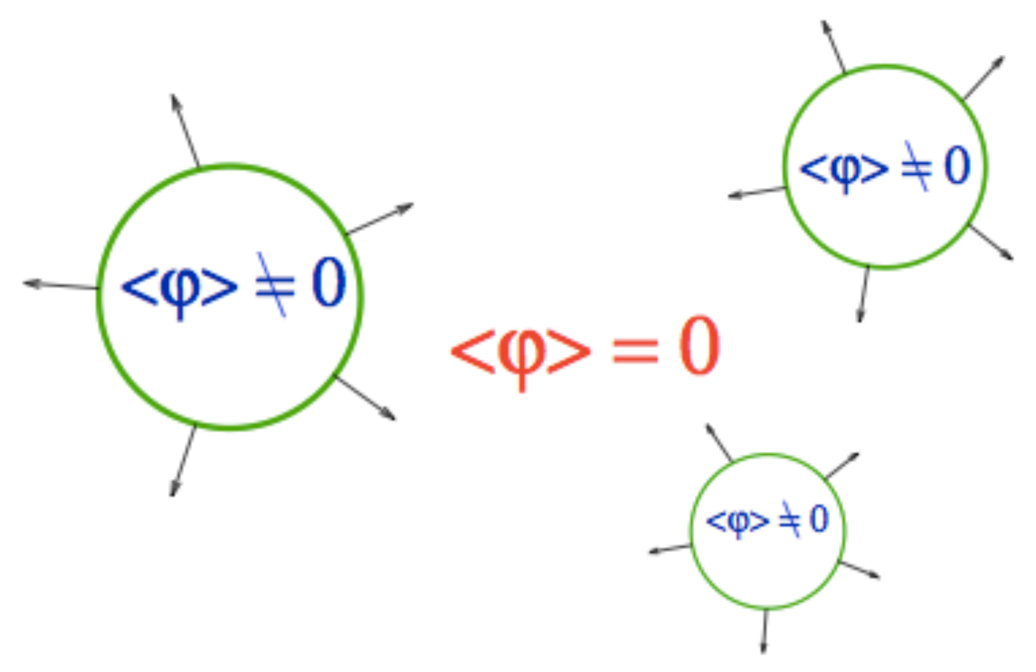
Electroweak baryogenesis: generate baryon asymmetry with particle mass generation at EW scale.

Sakharov's condition (EWBG):

- Baryon number violation (Sphaleron transitions)
- Strongly 1st order PT (SM: crossover) Out of thermal equilibrium
- CP violation (SM CPV too small)

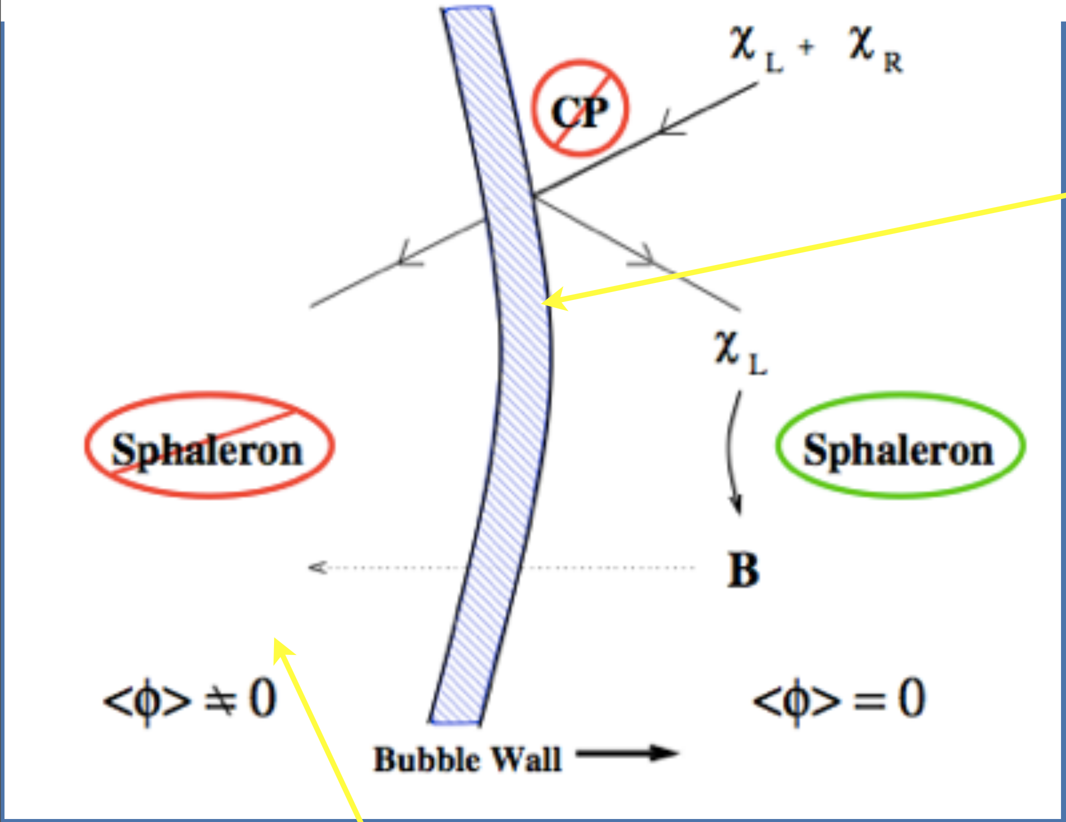
Strongly 1st order PT

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



Strongly first order phase transition

B number generation



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

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

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

Behave like a chemical potential term

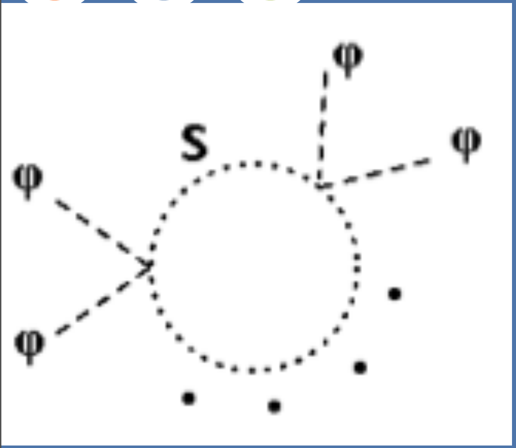
$$Q_X \sim g_* (\partial_t \xi) T^2/6 \sim (\partial_t \xi) T^2.$$

CPV phase jump generate a net chiral charge close to the bubble wall

Converted to B by sphalerons inside the bubble wall

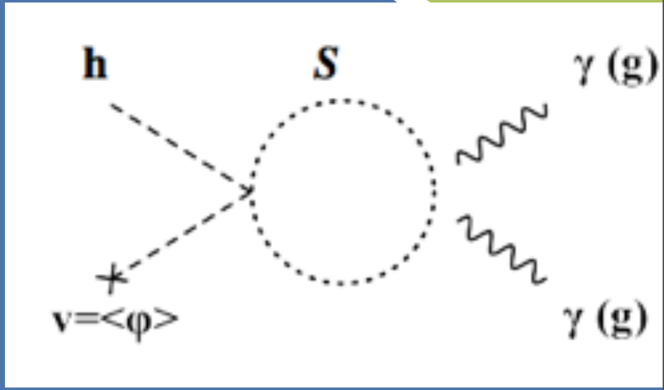
require strongly first order phase transition

Lessons from T=0 Higgs physic



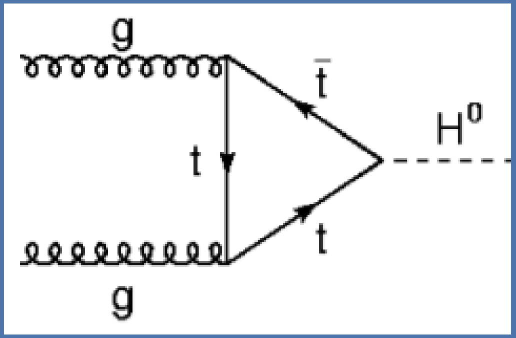
EW Phase Transition:

For any particle S would contribute to the thermal Higgs effective potential



- Charged under SM group: (MSSM stops, 2HDM, etc: LHC Higgs global fits, direct searches on S, etc) A
- Higgs mixture (NMSSM, etc, LHC non-Standard Higgs searches, EW precision, etc) B
- Hidden (EW & Higgs precision, SPPC direct search) C

LHC Higgs data: CPV source



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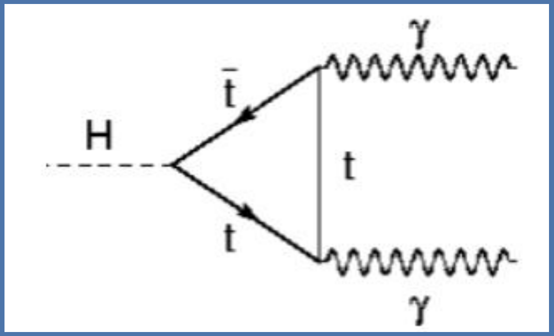


if electric charged

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

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

Lessons from T=0 Higgs physic

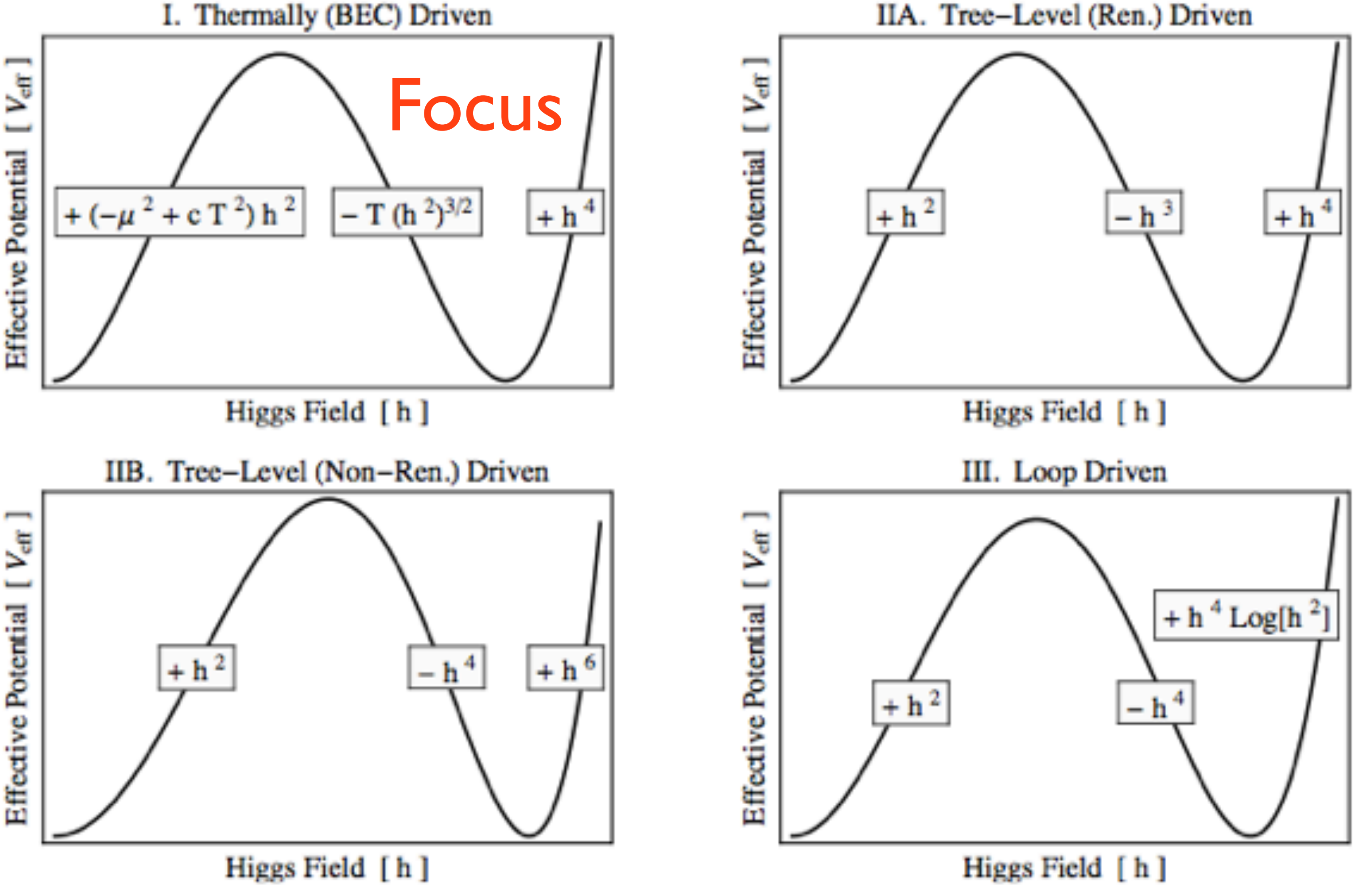
$$m_\chi(v)e^{i\theta(v)}$$

A complex mass term
with vev dependence

- Charged under SM group: (MSSM charginos, stops, 2HDM top quark, etc: LHC Higgs global fits, direct CPV searches.)
- Singlet Higgs mixture (NMSSM, etc: EWBG driven by singlino. Relatively difficult to test)
- Complex Yukawa (vector quarks)?

The EW Phase Transition & Higgs physics

EWPT Classification



Focus

D. Chung, A. Long, L. T. Wang, PRD 87 (2013) 023509

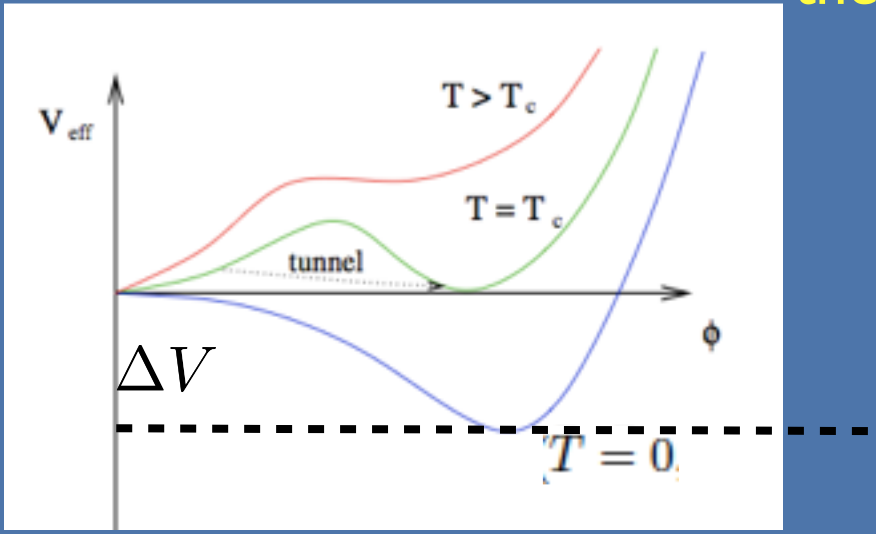
Also may from fermion contributions

M. Carena, A. Megevand, M. Quiros, C. Wagner, NPB 716 (2005) 391-351

H. Davoudiasl, I. Lewis, E. Ponton, PRD 87 (2013) 093001

A Master Formula

For scalar driven 1st order EWPT (focus on thermal driven):



$$\frac{v_c}{T_c} \simeq \frac{v^4 E}{2\Delta V}$$

J. S, private derivations.

Assume $v_c \approx v$,

Better in stronger EWPT

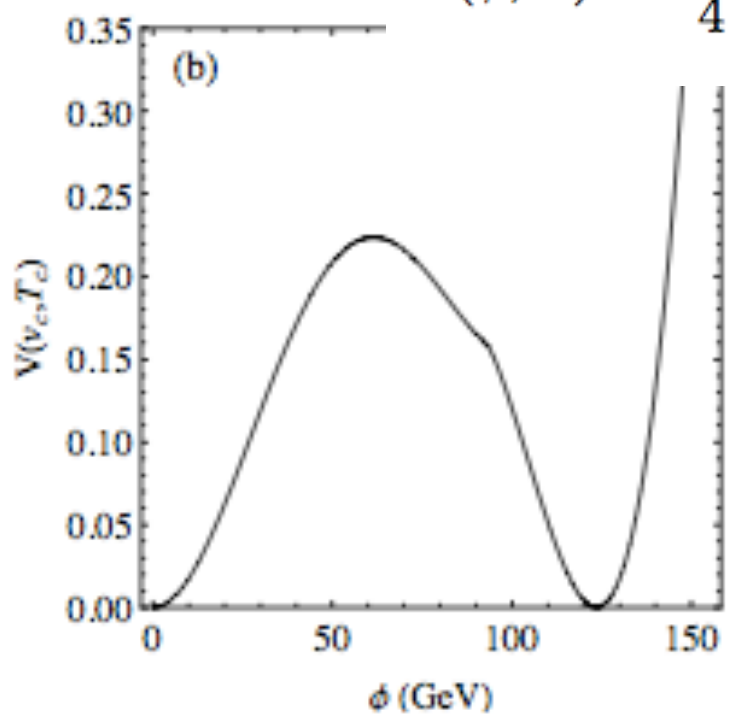
- Increase the thermal cubic term E term (E is the coefficient of $\phi^3 T$)
- Decrease the T=0 energy difference ΔV (Increase the fine tuning of the Higgs potential)

Large E case (No Higgs mixing)

- The 1st case (large E) is indeed the case A & C (The MSSM stops, strongly top Yukawa with N=12 to increase the loop effect)

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

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

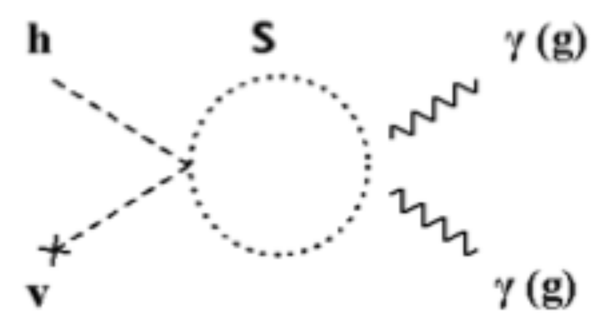


term $-Tm_s^3(\phi,T)$ has to decrease with phi to compete with positive terms such that there is a 1st PT

Therefore for the single scalar, $\alpha > 0$.

Higgs Global Fits

For the positive EWSB mass square $\alpha > 0$, if it is colored or electric charged.



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

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

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

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

Enhanced Higgs production

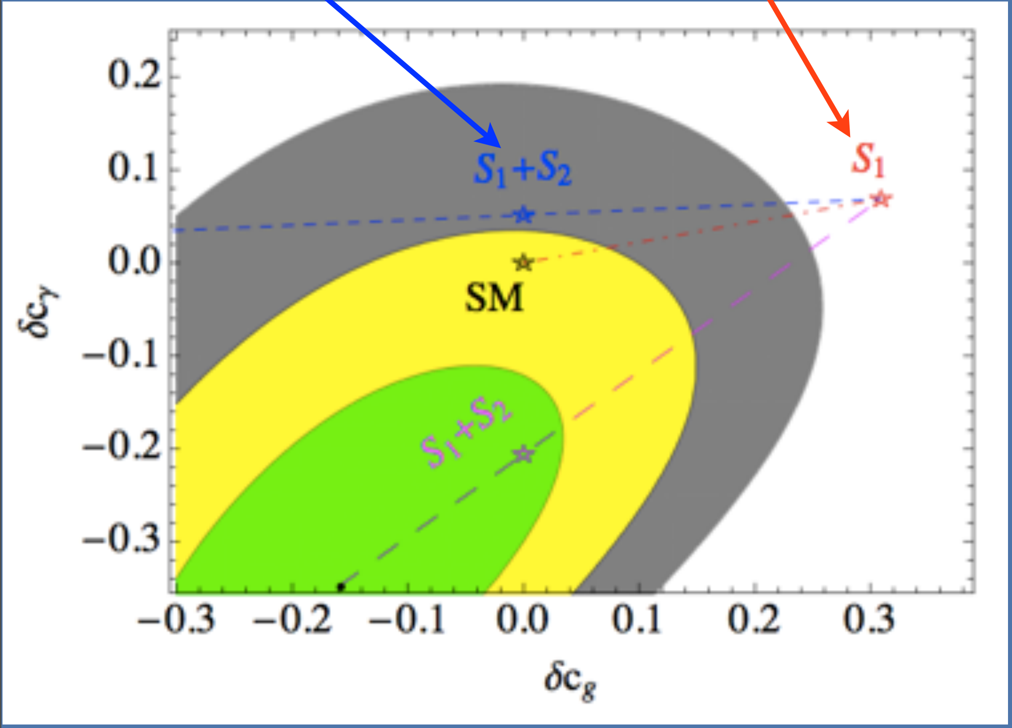
Suppressed Higgs di-photon BR

W. Huang, J. S, Y. Zhang, JHEP 1303 (2013) 164
D. Chung, A. Long, L. T. Wang, PRD 87 (2013) 023509

The MSSM case

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

Stop like state (a>0)



- For MSSM stops, it requires small stop mass ~ 100GeV and large Yukawa couplings to Higgs so it is ruled out by the experiments.

D. Curtin, P. Jaiswall, P. Meade, JHEP 1208 (2012) 005

T. Cohen, D. Morrissey, A. Pierce, PRD 86 (2012) 013009

Adding the light sbottom into the spectra can enhance the EWPT strength and cancel the effects from stop on Higgs global fits

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

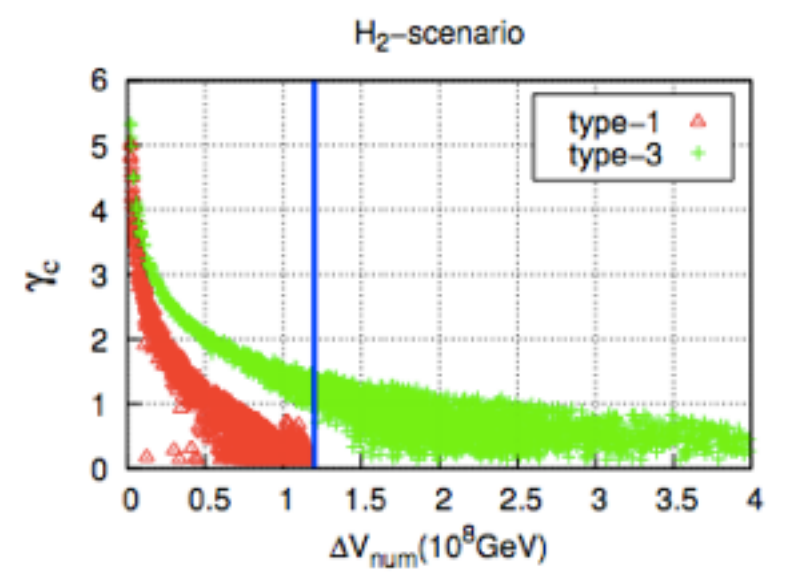
Decrease ΔV.

Higgs + singlet (NMSSM)

- The 2nd case (decrease the ΔV) is the case B, which involves Higgs singlet mixing (Higgs/2HDM + singlet, the NMSSM, etc)

$$\frac{v_c}{T_c} \simeq \frac{v^4 E}{2\Delta V}$$

Big PT strength with small T=0 potential difference ΔV .



W-c. Huang, Z-f. Kang, J. S, P.-w Wu, J-m.Yang, Phys. Rev. D. (2015) 2 025006

Other aspects NMSSM EWBG:

J. Kozaczuk, S. Profumo, L.S.Haskins, C.Wainwright, JHEP, 1501 (2015) 144
C. Balazs, A. Mazumdar, E.Pukartas, G.White, JHEP, 1401 (2014) 073

Tuning of the potential

$$\frac{v_c}{T_c} \simeq \frac{v^4 E}{2\Delta V}$$

The natural size of ΔV is $\lambda v^4/2$

λ ~ order 0.1 for 125GeV Higgs

The E is a one-loop effect, ~ 0.01 for EW couplings

The tuning of the Higgs potential is roughly the order E/λ .

Higgs + Singlet

$$\Delta V = \frac{v^4}{2}\left(\tilde{\lambda} - \frac{2\tilde{a}^2 m_s^2}{(m_s^2 + \lambda^2 v^2)^2}\right)$$

M. Carena, N. Shah, C. Wagner,
Phys. Rev. D. (2015) 85 036003

Weak coupling strength, more than 10% of tunning

NMSSM PT Patterns

Decoupled Stop, Phase Transition Triggered by the Higgs-singlet sector

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 III PT: One step PT.
- H1 scenario: 125 GeV Higgs is the lightest
- H2 scenario: 125 GeV Higgs is the 2nd lightest

NMSSM

The question is now to understand the parameter dependence of ΔV .

PT parameter

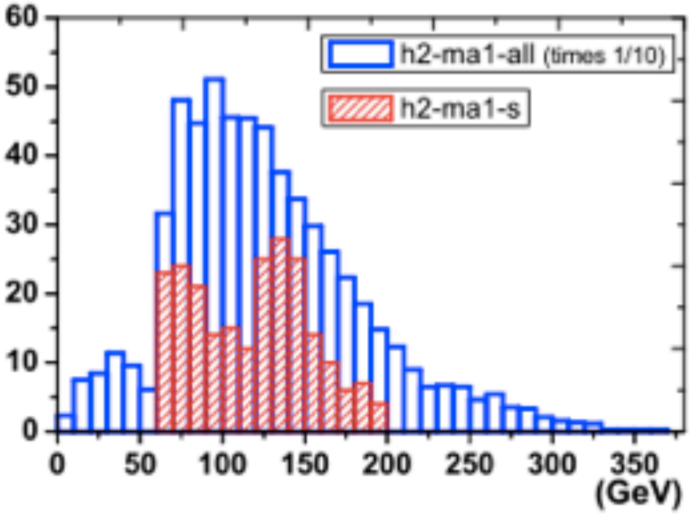
$$R_\kappa \equiv \frac{4\kappa v_s}{A_\kappa}$$

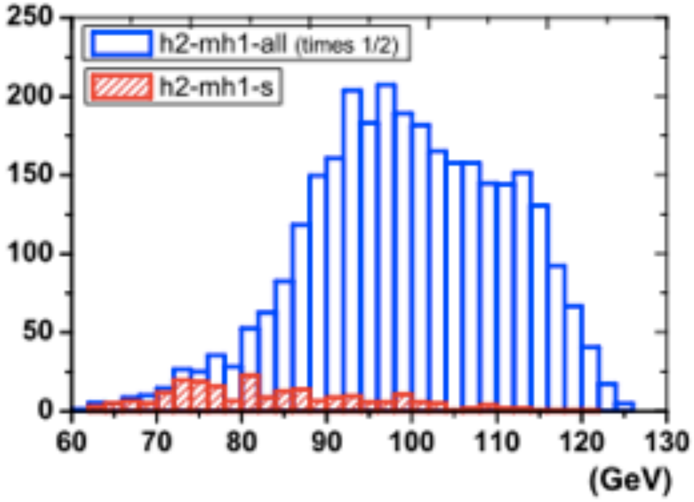
For the 1st time, EWPT in NMSSM is understood semi-analytically!

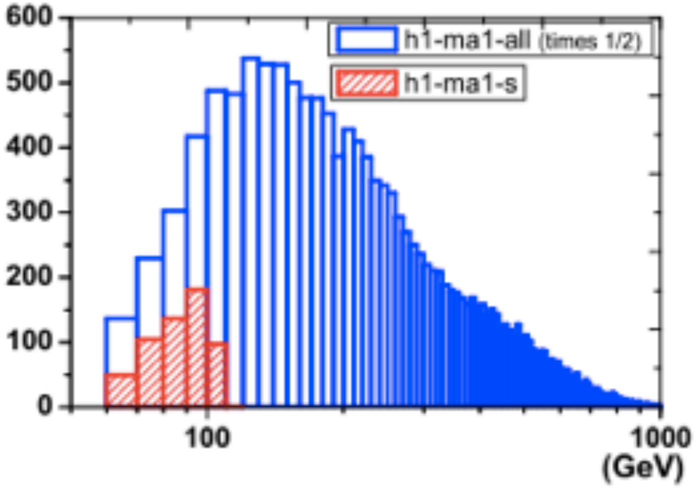
More details on other parameter dependence see the paper

- Type III PT (H1) SFEWPT requires $R_\kappa \subset (5, 30)$
- Type III PT (H2): SFEWPT suggests $R_\kappa \sim -1$ and $R_\kappa \subset (2, 10)$.
- Type III PT (H2): SFEWPT suggests $R_\kappa \sim -4/3$.

Overall Spectra



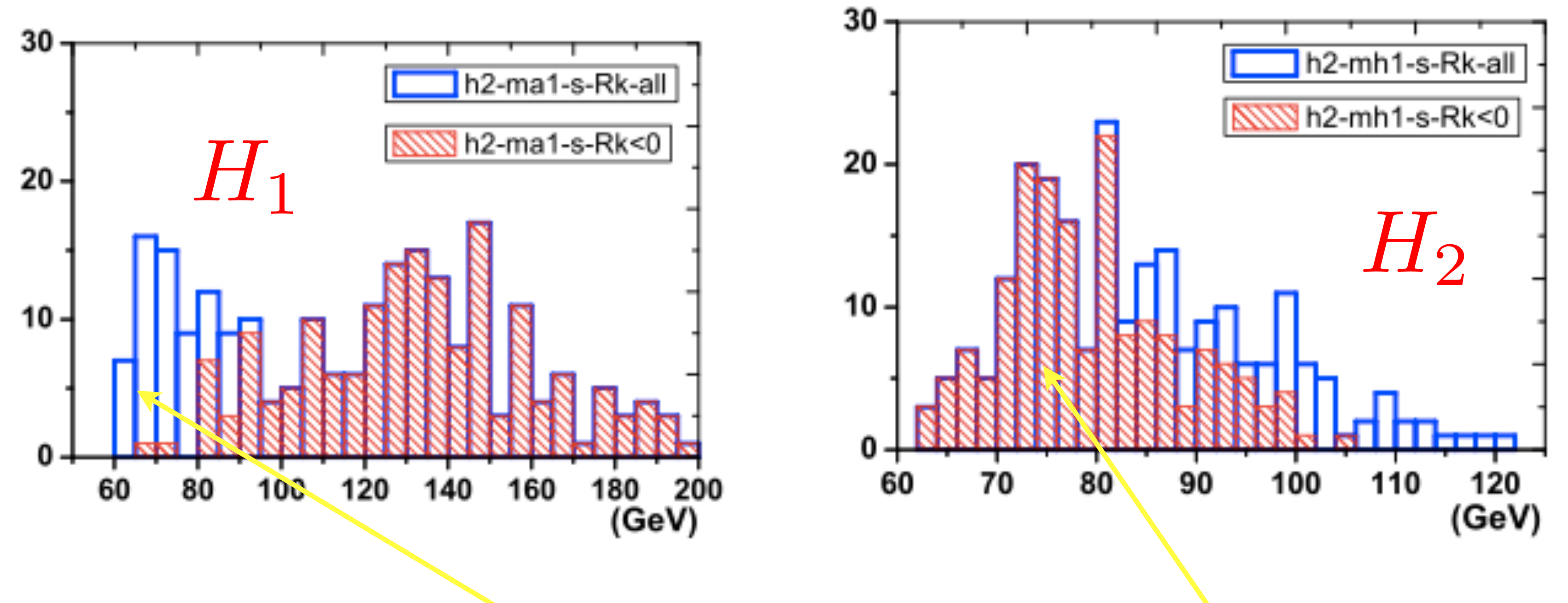




Strong 1st PT suggest light Higgs spectra

No PQ limit since the stops are decoupled

Overall Spectra



W-c. Huang, Z-f. Kang, J. S, P.-w Wu, J-m.Yang, Phys. Rev. D. (2015) 2 025006

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?
Or other non-Standard Higgs search channels?

Hidden Models (C)

Real singlet with no vevs only couples with the Higgs

Direct and indirect searches at the future colliders

- Future Z pole precision measurements (Two loop effects)

B. Henning, X-c. Lu,
H. Murayama, 1404.1058

- ILC + CEPC / FCC-ee indirect probe of Higgs-self couplings or hZZ, etc.

A. Katz, M. Perelstein,
JHEP 1407 (2014), 108

- SPPC direct production!

D. Curtin, P. Meade, C-T. Yu
JHEP 1411 (2014) 127

Higgs self interactions

Higgs self-interaction is believed to be a very good probe of the strongly 1st order EWPT.

A. Nobel, M. Perelstein, Phys. Rev. D. 78 (2008) 063518

Large deviations in general are expected with some exceptional cases with small deviation

A. Katz, M. Perelstein, JHEP 1407 (2014), 108

- Indirect search of Higgs self-coupling at the future lepton collider

M. McCullough, Phys. Rev. D 90 (2014), 1, 015001

- Di-Higgs production at the HL--LHC or SPPC / FCC-hh (Higgs-self couplings)

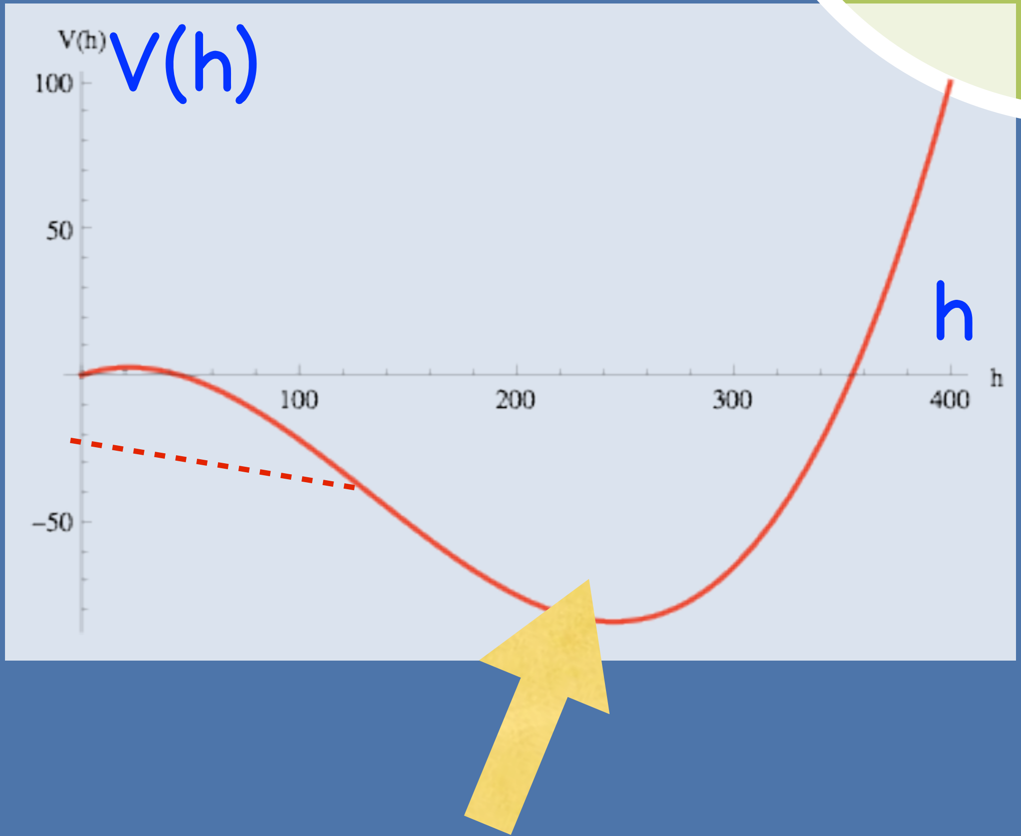
S. Profumo, M. Ramsey-Musolf, C. Wainwright, P. Winslow Phys. Rev. D 91 (2015), 3, 035018

D. Curtin, P. Meade, C-T. Yu JHEP 1411 (2014) 127

Other aspects!

The two curves here would results very different EWPT.

Need knowledge of global behavior of Higgs potential in principle

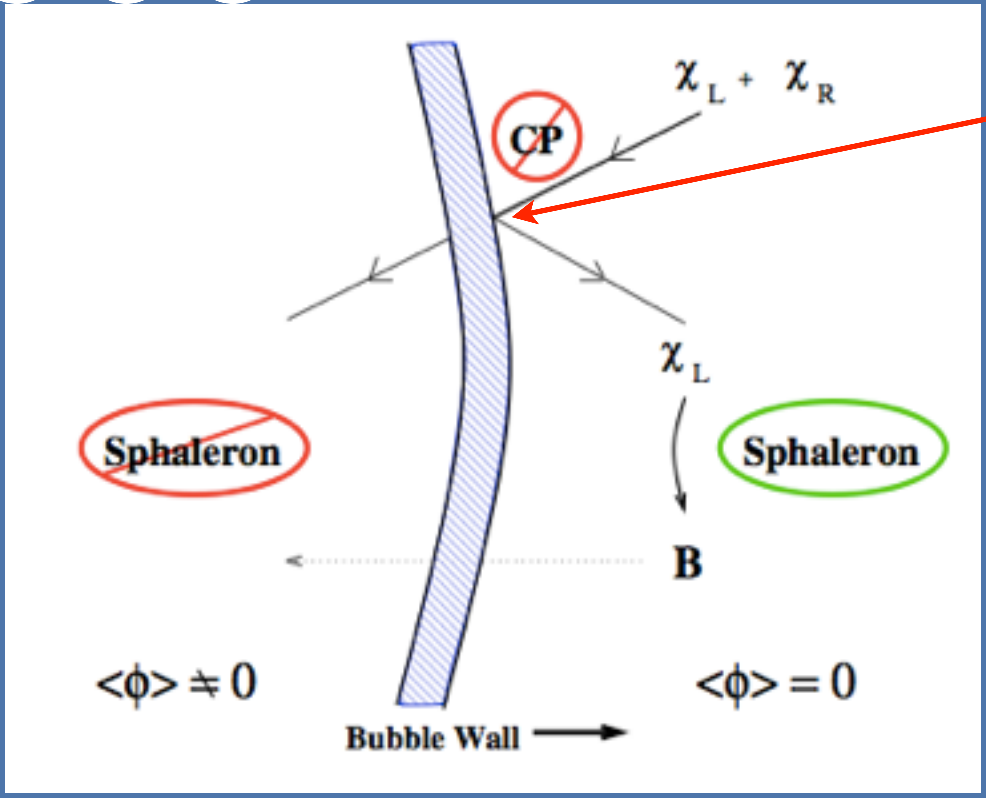


Colliders can only probe the local behavior.

Maybe future gravitational detection ?

CP Violation & EDM & Higgs Physics

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.

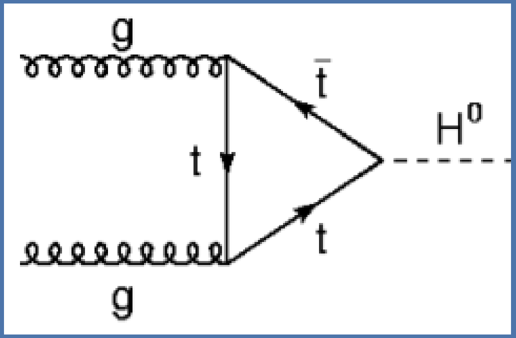
$$\tilde{c}_X\left(\frac{h}{v}\right)F\tilde{F}$$

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

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

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

Affect the Higgs global fits



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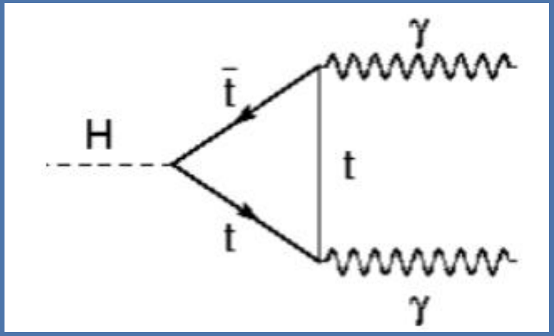


if electric charged

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 Higgs low energy theorem.

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

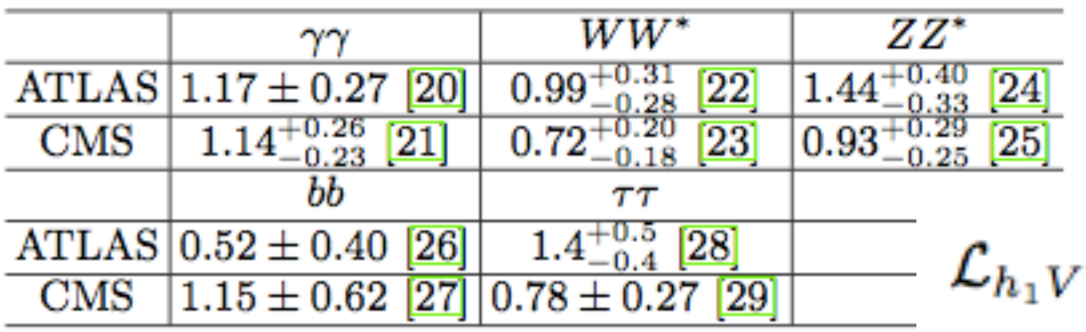
2HDM example

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.

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

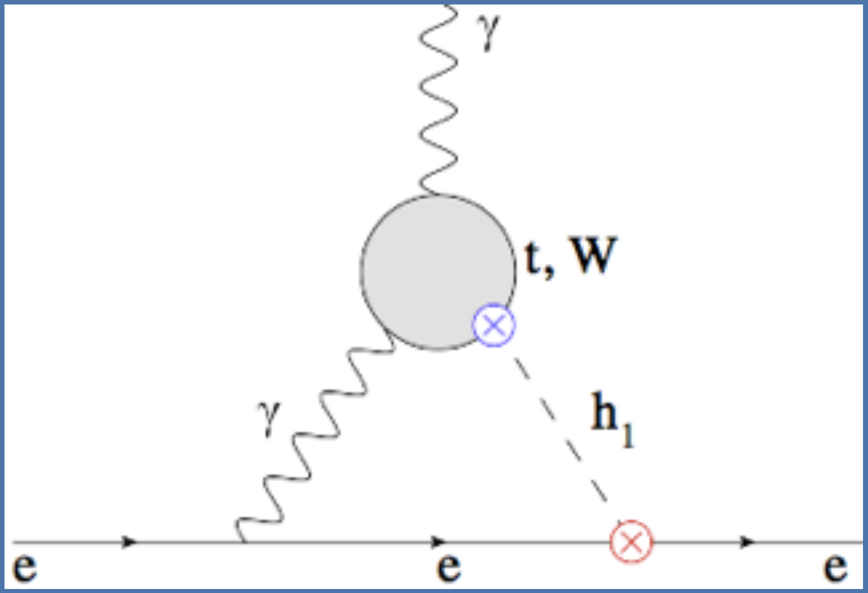


	$\gamma\gamma$	WW^*	ZZ^*
ATLAS	1.17 ± 0.27 [20]	$0.99^{+0.31}_{-0.28}$ [22]	$1.44^{+0.40}_{-0.33}$ [24]
CMS	$1.14^{+0.26}_{-0.23}$ [21]	$0.72^{+0.20}_{-0.18}$ [23]	$0.93^{+0.29}_{-0.25}$ [25]
	bb	$\tau\tau$	
ATLAS	0.52 ± 0.40 [26]	$1.4^{+0.5}_{-0.4}$ [28]	
CMS	1.15 ± 0.62 [27]	0.78 ± 0.27 [29]	

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

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

Bounds from EDM



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

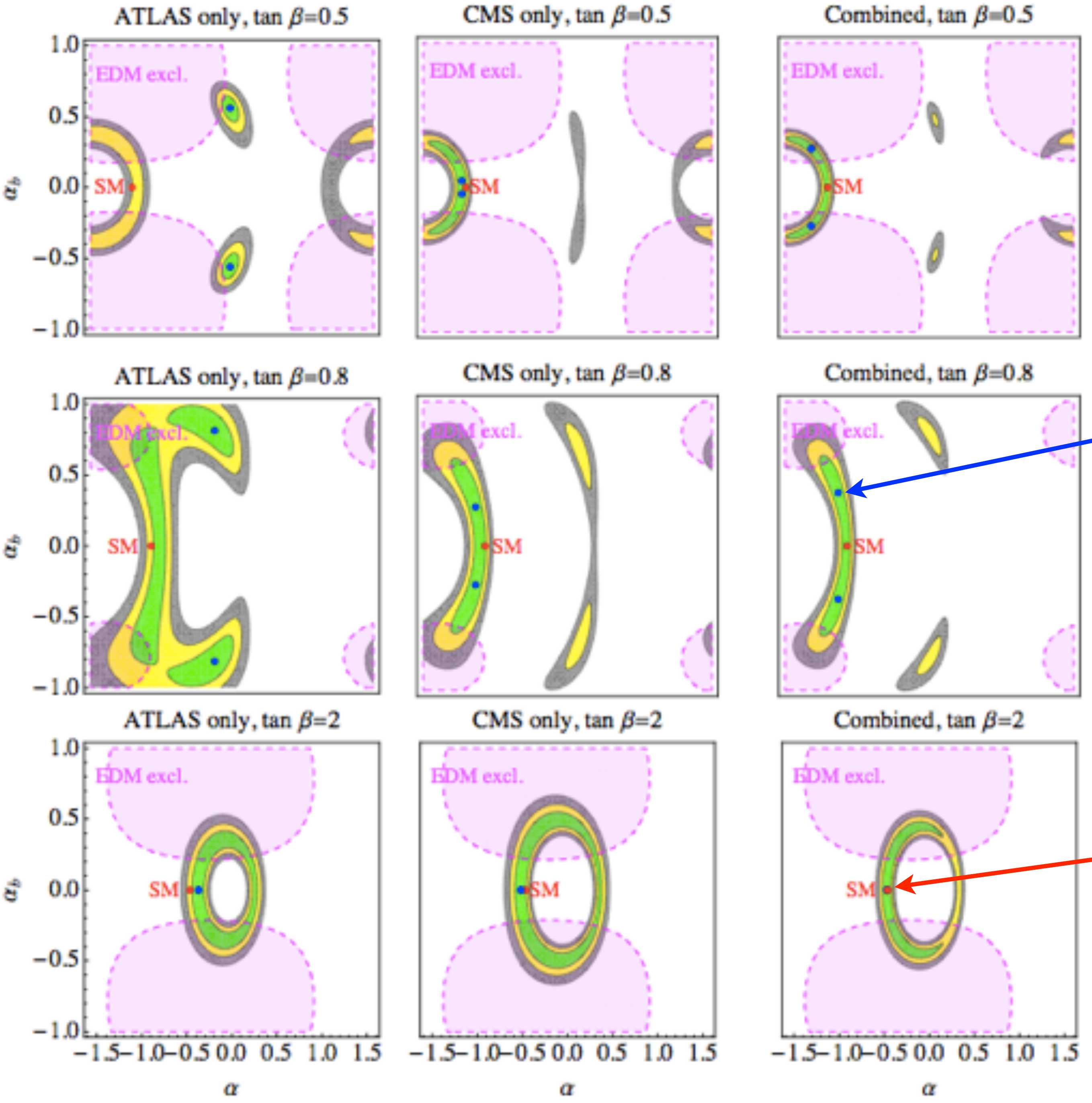
The same operators would contribute to the EDM or CEDM

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

$$\tilde{c}_\gamma \sim \mathcal{O}(10^{-1}) - \mathcal{O}(10^{-2})$$

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

Second region



Blue points:
best fits

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

SM

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

New ACME results

Much Tighter constraints than before:

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

More than one order improvements

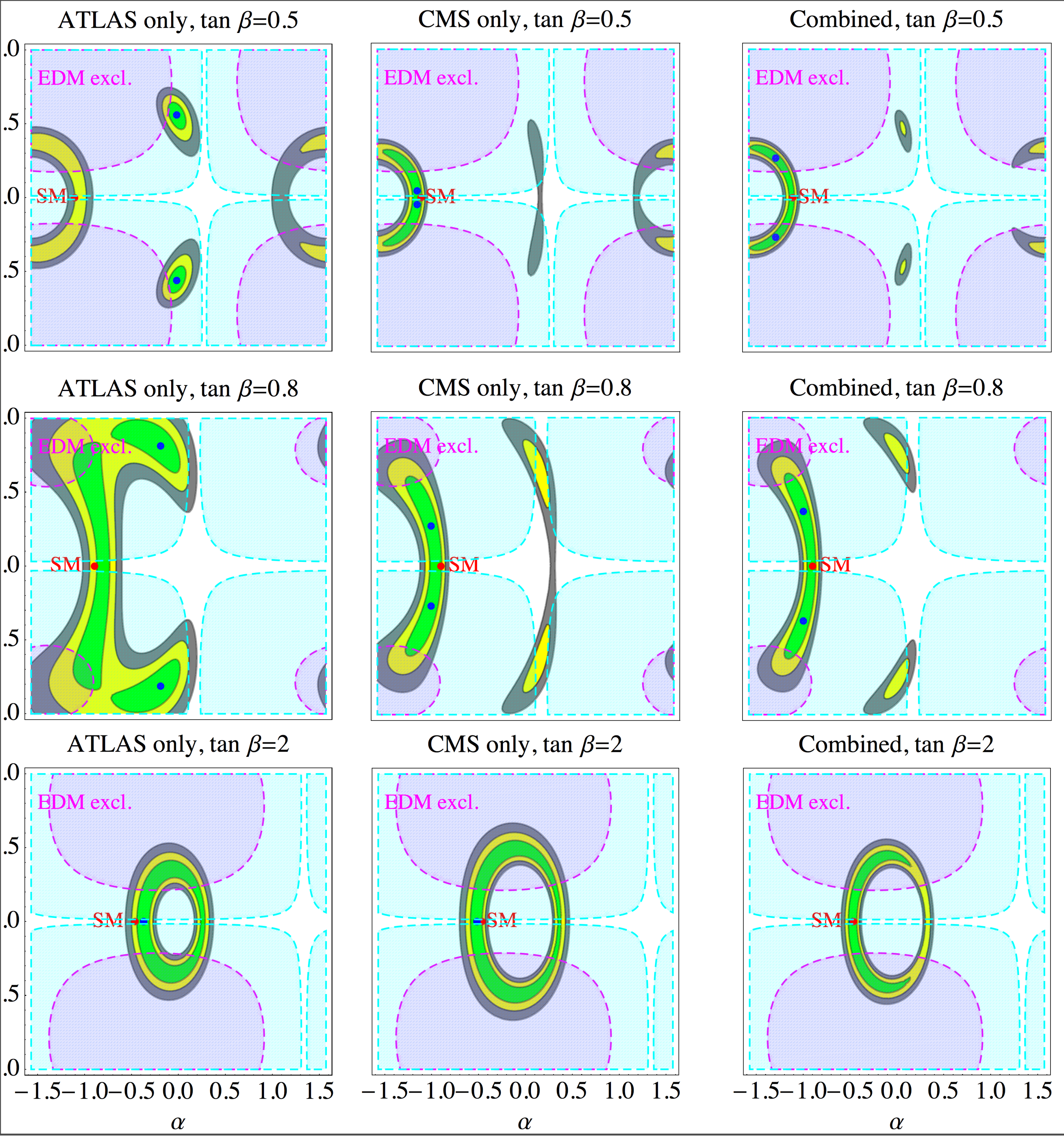
Naively constraints $\tilde{c}_\gamma \sim \mathcal{O}(10^{-2}) - \mathcal{O}(10^{-3})$

J. Brod; U. Haisch and J. Zupan, JHEP, 1311, 180 (2013)

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

Where are the room for direct CPV searches?

lts


ATLAS only, tan β=0.5

CMS only, tan β=0.5

Combined, tan β=0.5

ATLAS only, tan β=0.8

CMS only, tan β=0.8

Combined, tan β=0.8

ATLAS only, tan β=2

CMS only, tan β=2

Combined, tan β=2

Much Tightly constrained than before:

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

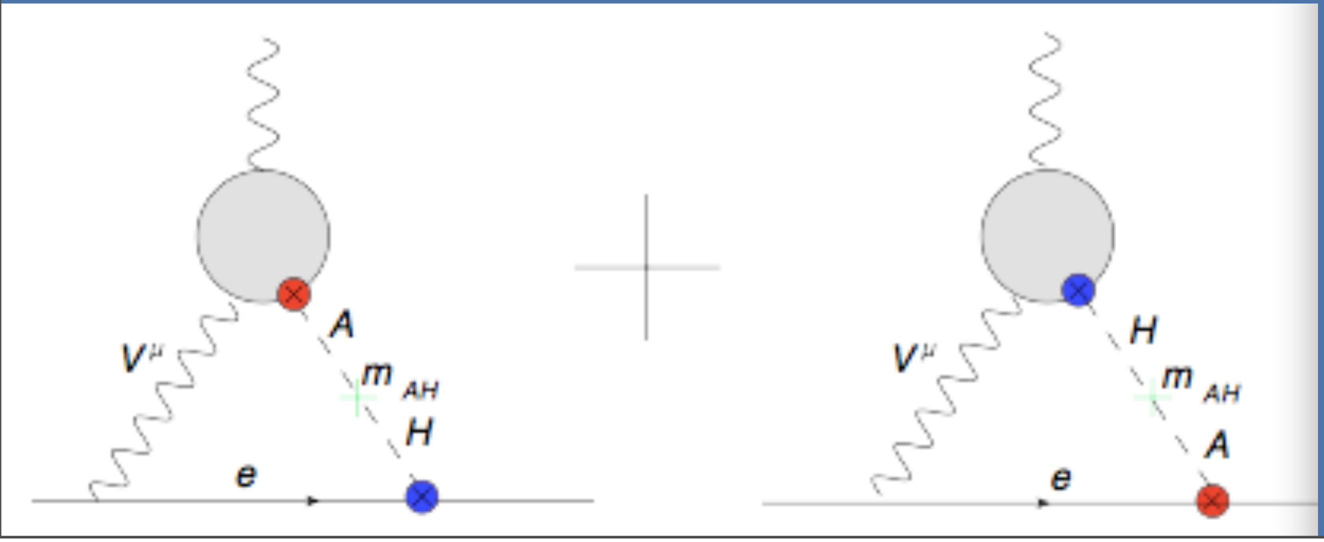
2HDM case

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

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

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

EFT only for illustration

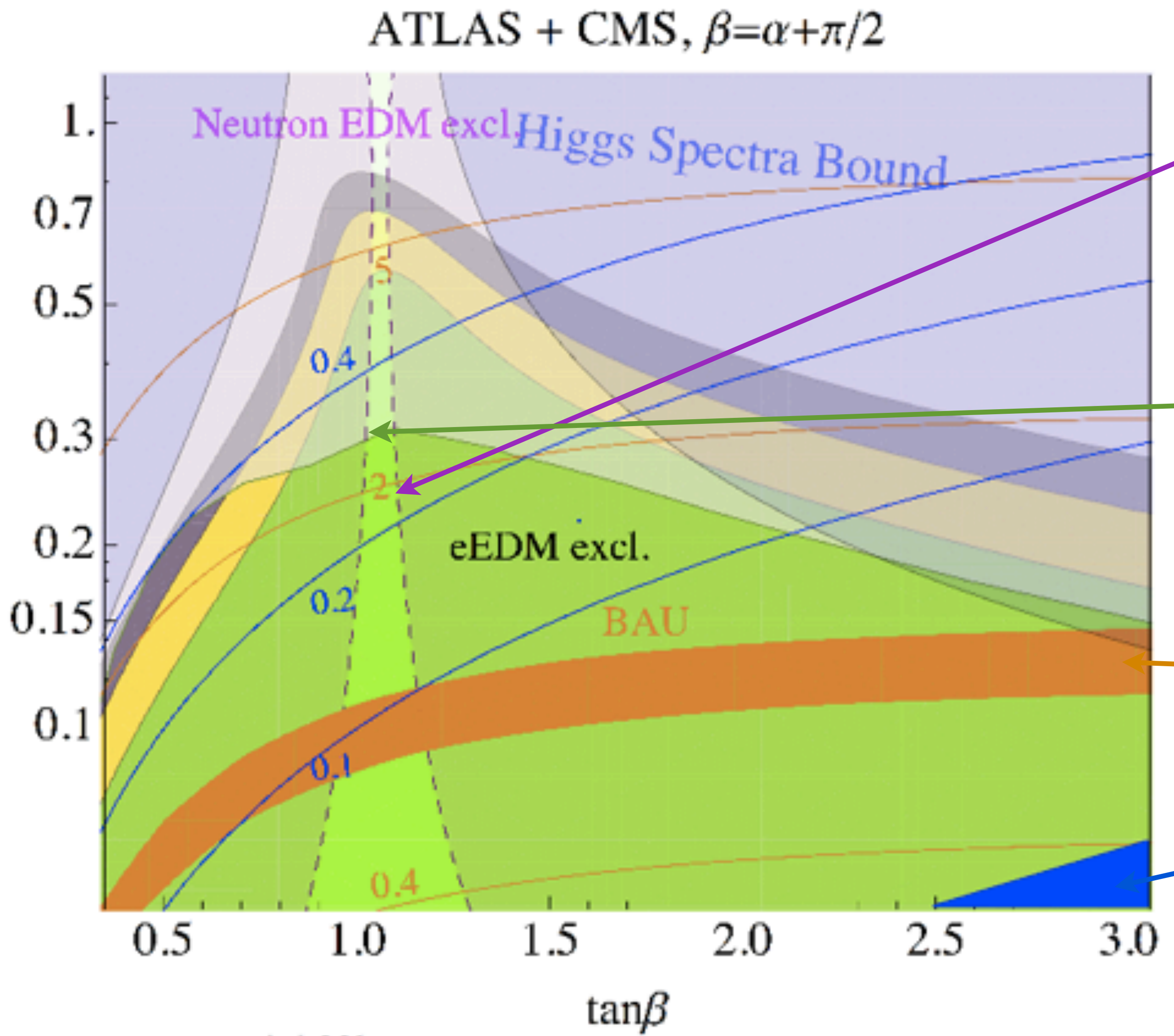


The two pieces can naturally cancel each other

The Higgs is a CP mixture!

2HDM case

Final Results



ACME bound

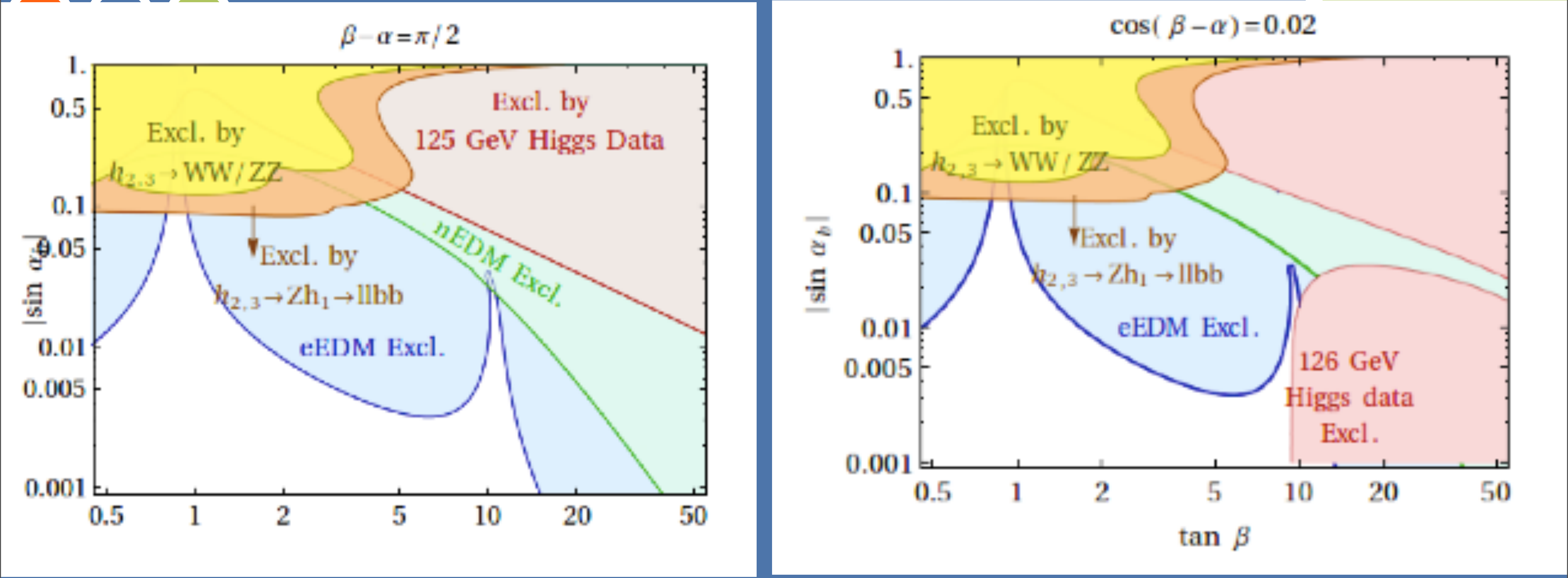
Future Neutron EDM bound will probe this region

Preferred by EWBG

$$\tilde{c}_t \sim \mathcal{O}(10^{-2})$$

J. Brod; U. Haisch and J. Zupan, JHEP, 1311, 180 (2013)

Heavy Higgs Searches



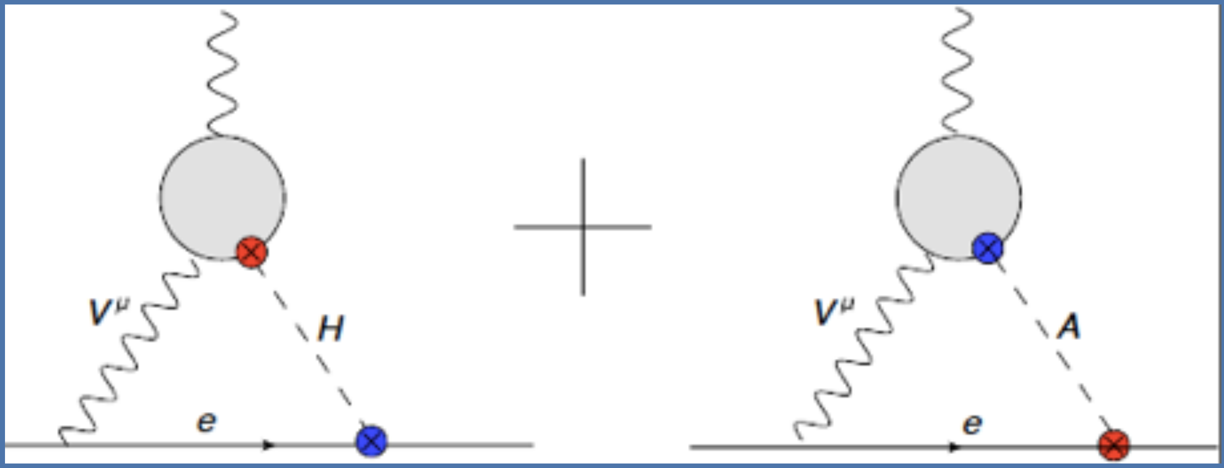
C-Y. Chen, S. Dawson, Y. Zhang, JHEP 1508 (2015) 058

There are also heavy Higgs searches bound (strong in the cancellation region)

MSSM case

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

EFT only for illustration



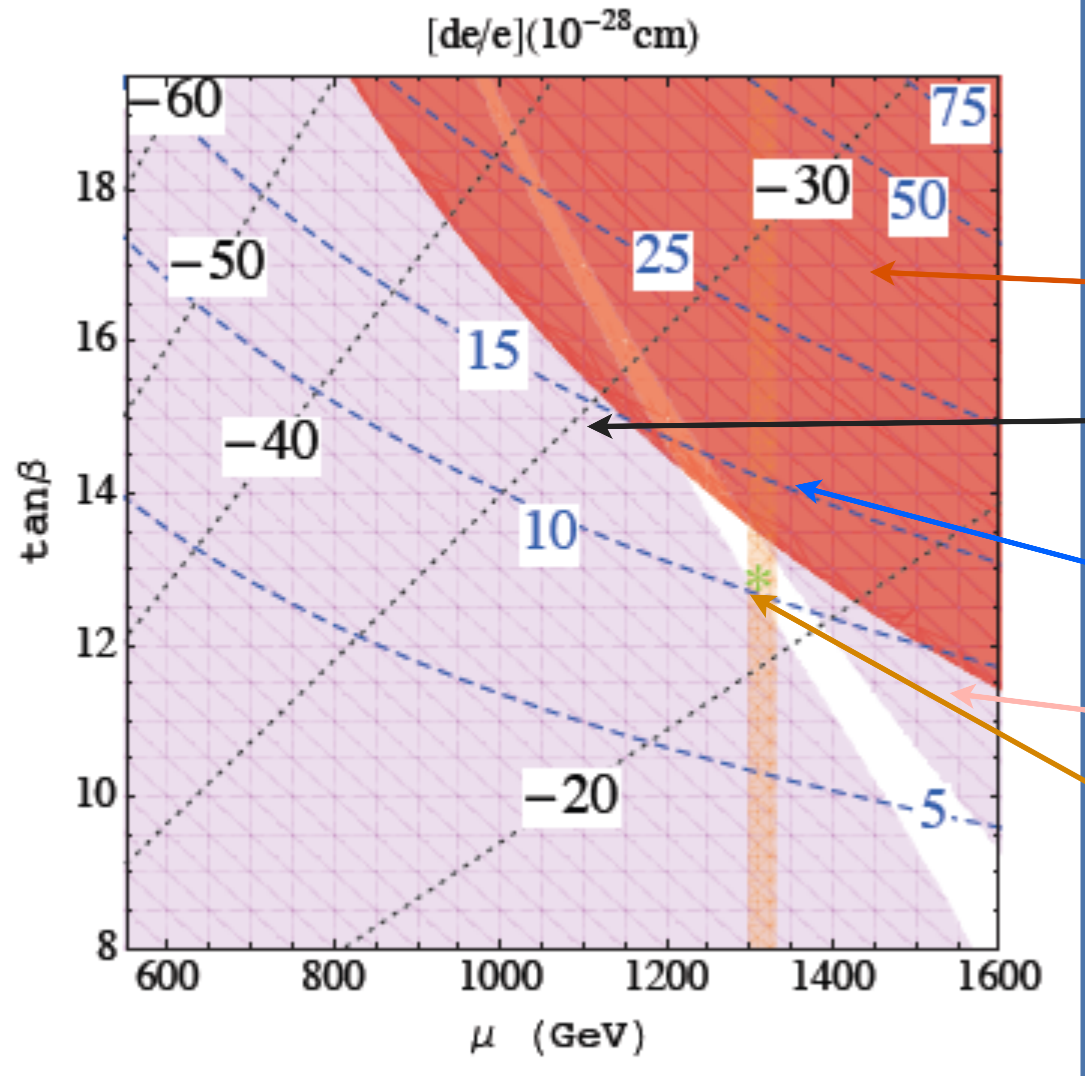
MSSM with chargino & staus

Negligible CPV in the Higgs sector

Heavy Higgs coupling enhanced by tan beta

Non-standard Higgs mediate the cancellation

Allowed CPV for MSSM



Open the Heavy Higgs CPV search

Mercury exclusion

Chargino contour

Stau contour

ACME exclusion

Preferred by EWBG

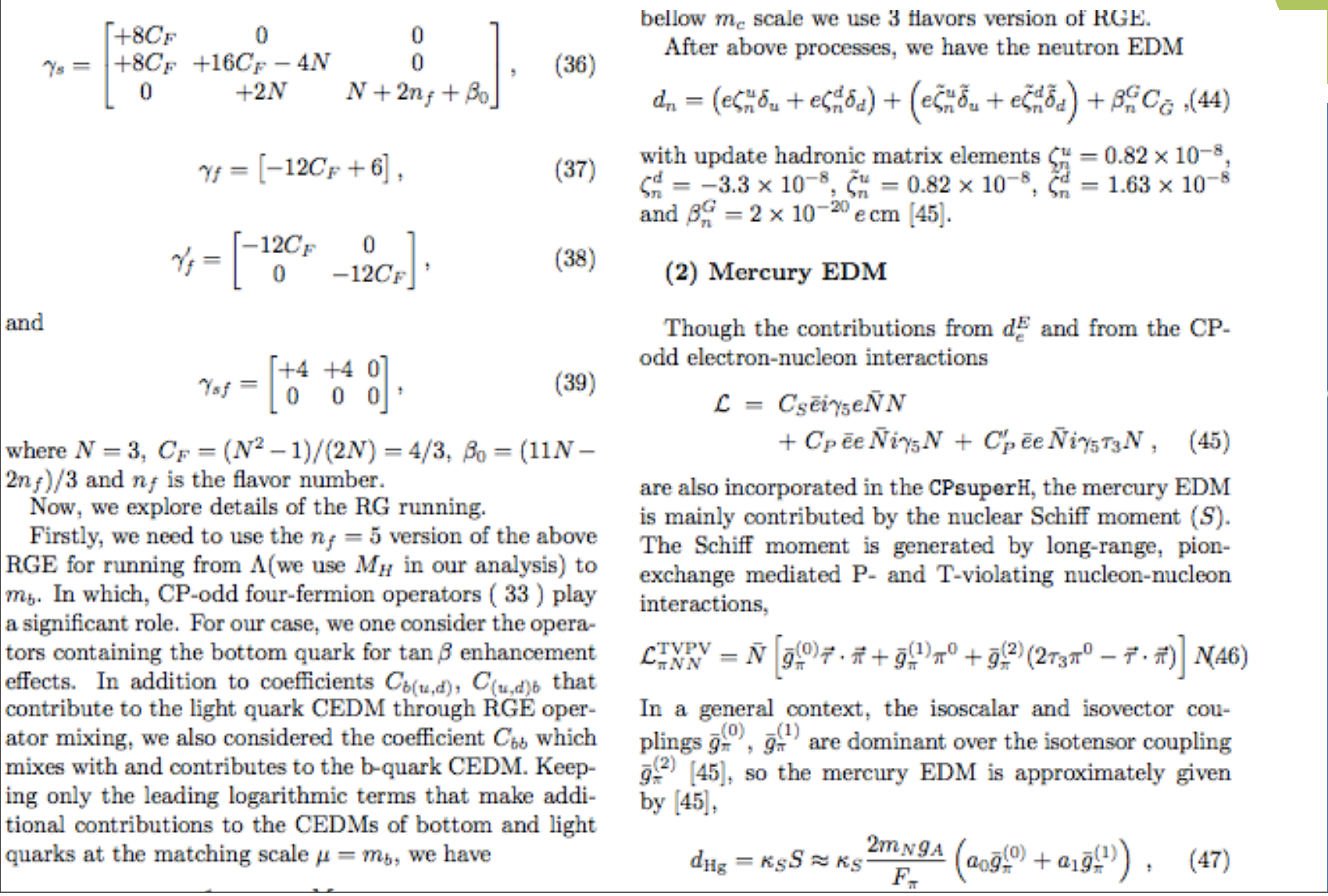
L-g, Bian, T. Liu, J. S, Phys. Rev. Lett. 115 (2015) 021801

Correction in CPSuperH

- A sign mistake in the anomalous D of the dipole operator (smaller EDMs at low energy).
- No operator mixing effects are considered
- Detailed RG running in the Mercury & other EDMs
- Update the matrix elements (factor of 10 difference)
- W boson loop included in the Barr-Zee diagram.

The bounds with EDM with colored objects 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

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

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 $\beta_n^G = 2 \times 10^{-20}\, e\,\text{cm}$ [45].

(2) Mercury EDM

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

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

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,

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

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],

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

L-g, Bian, T. Liu, J. S, Phys. Rev. Lett. 115 (2015) 021801

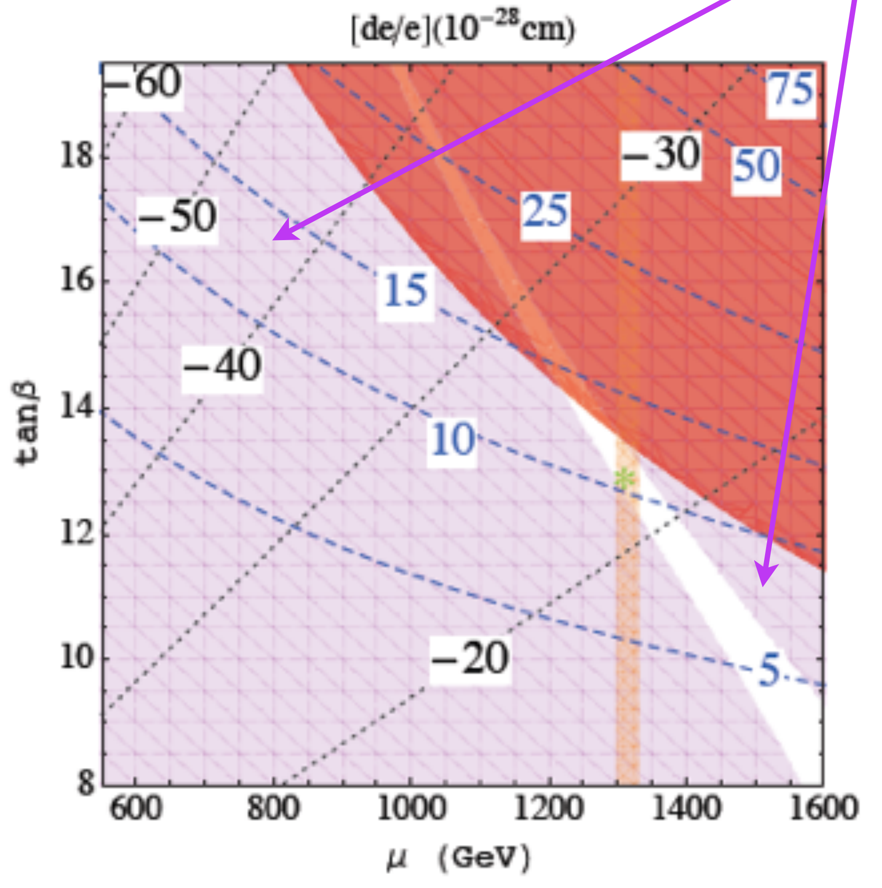
Codes will be updated in the web soon

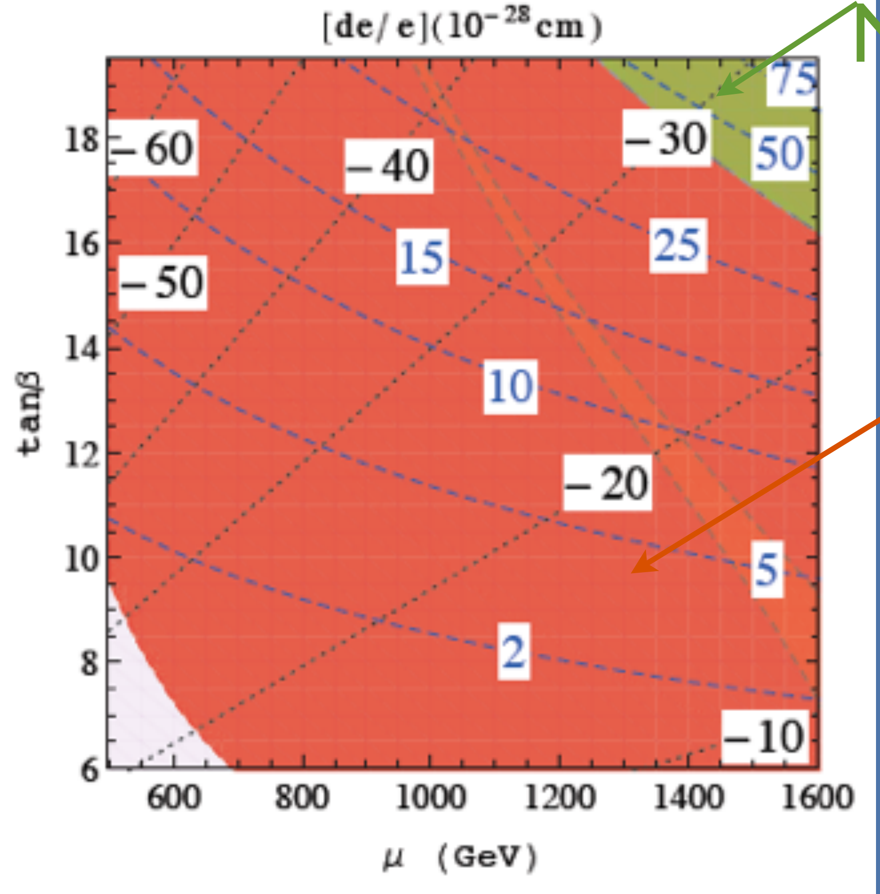
Correction in CPSuperH

After correction:

ACME

Before correction:



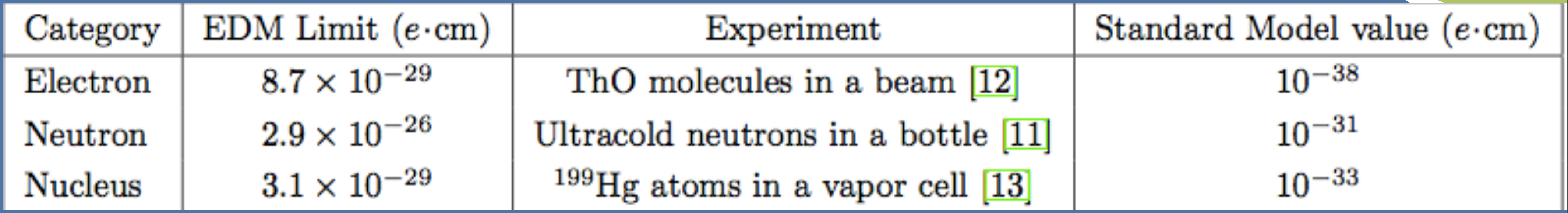


Neutron EDM bound:

Mercury

L-g, Bian, T. Liu, J. S, Phys. Rev. Lett. 115 (2015) 021801

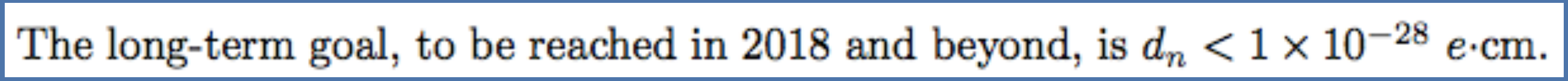
Something is up in the air?



Category	EDM Limit ($e\cdot$cm)	Experiment	Standard Model value ($e\cdot$cm)
Electron	8.7×10^{-29}	ThO molecules in a beam [12]	10^{-38}
Neutron	2.9×10^{-26}	Ultracold neutrons in a bottle [11]	10^{-31}
Nucleus	3.1×10^{-29}	^{199}Hg atoms in a vapor cell [13]	10^{-33}

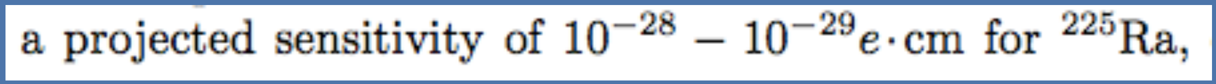
K Kumar, Z-T. Lu, M. R-Musolf 1312.5416

TRIUMF:

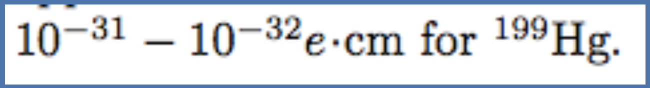


The long-term goal, to be reached in 2018 and beyond, is $d_n < 1 \times 10^{-28}$ $e\cdot$cm.

Proton ring: $\sim 1 \times 10^{-29} e \cdot cm$



a projected sensitivity of $10^{-28} - 10^{-29} e\cdot$cm for ^{225}Ra, $\sim$



$10^{-31} - 10^{-32} e\cdot$cm for ^{199}Hg.

3 orders of magnitude, close the cancellation region

Think more!

If one of those experiments are before the end of LHC (including HL-LHC)

Do we need direct LHC CPV searches?

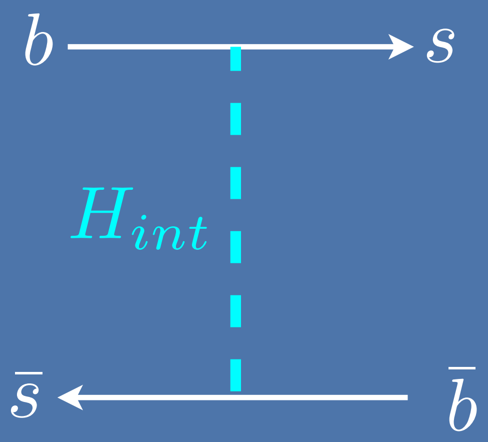
or even CPV searches in the future lepton colliders such as CEPC in China?

One possible solution is that we search for CPV in b systems, (LHCb!)

Electroweak Beautygenesis

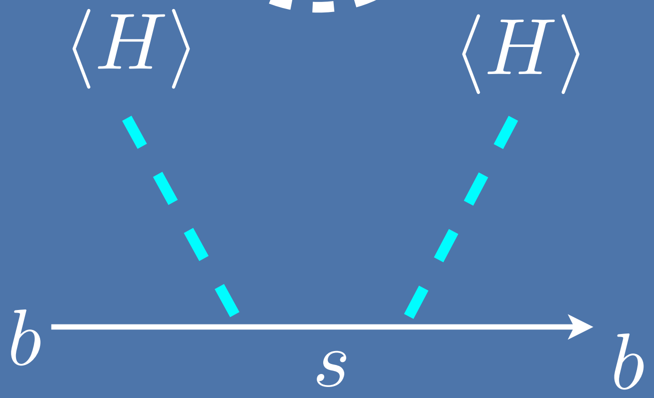
The key idea is to consider extra inert scalars which dominantly couples to b and s with CPV.

New source for CPV in Bs mixing



An extra scalar triggers 1st order EWPT.

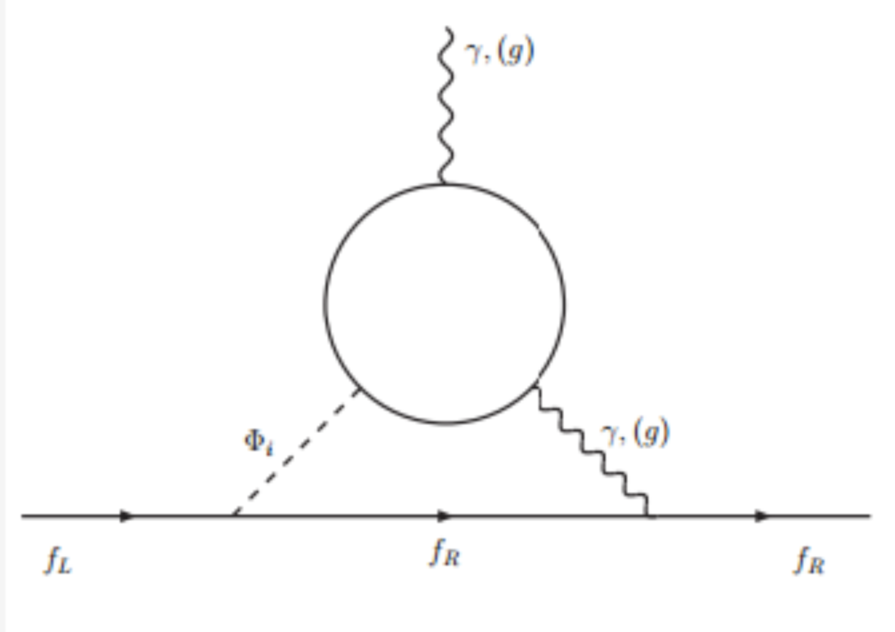
CPV in b,s in the Higgs background

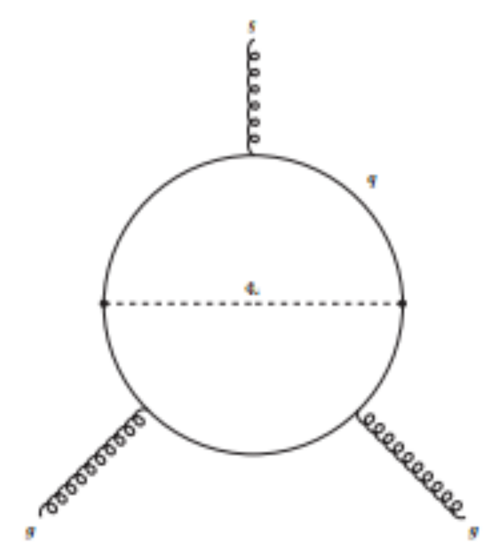


T. Liu, M. Ramsey-Musolf J. S, Phys. Rev. Lett. 108 (2012) 221301

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

EDMs





No direct Barr-Zee diagram contributions

Weinberg operator contributions are small due to small bottom quark mass

Comments on CPV channels

- 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

  M. Dolan, P. Harris, M. Jankowiak, M. Spannowsky, PRD, 90 (2014), 073008
- Other CPV fermion couplings

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

Various New Ideas

- Electroweak Cogenesis (asymmetric DM and B generation at the weak scale).

  C, Cheung, Y. Zhang, JHEP 1309 (2013) 002

- Electroweak baryogenesis from exotic electroweak symmetry breaking.

  N. Blinov, J. Kozaczuk, D. Morrissey, C. Wagner, Phys. Rev. D (2015) 035012

- Electroweak baryogenesis from a early time phase transition.

  J.S, T. Tait, C. Wagner, Phys. Rev. D (2007) 063510

- Electroweak baryogenesis from Randall Sundrum models.

  P. Creminelli, A. Nicolis, R. Rattazzi, JHEP 0203 (2002) 051
  G. Nardino, M. Quiros, A. Wulzer, JHEP 0709 (2007) 077

Some models missing.........

Summary & Outlook

- A natural connection between EWPT and Higgs physics. Strongly1st order tells you: strong coupling or shallow potential at T=0.
- Future lepton and hadron colliders greatly help this aspect.
- A natural connection between BAU in EWBG and CPV in the Higgs sector (EDMs are more sensitive than colliders).
- After the ACME results, large CPV effects are possible due to cancellation, future EDMs will soon recover those region.
- Direct CPV at the LHC or future colliders are worth to look even after future EDMs. Great for both LHC & LHCb!

Prospects: BG versus DM

EWBG & Higgs physics: Collider Searches

Low energy CPV experiments

Gravitational Waves

DM & WIMPs, Direct Collider Searches

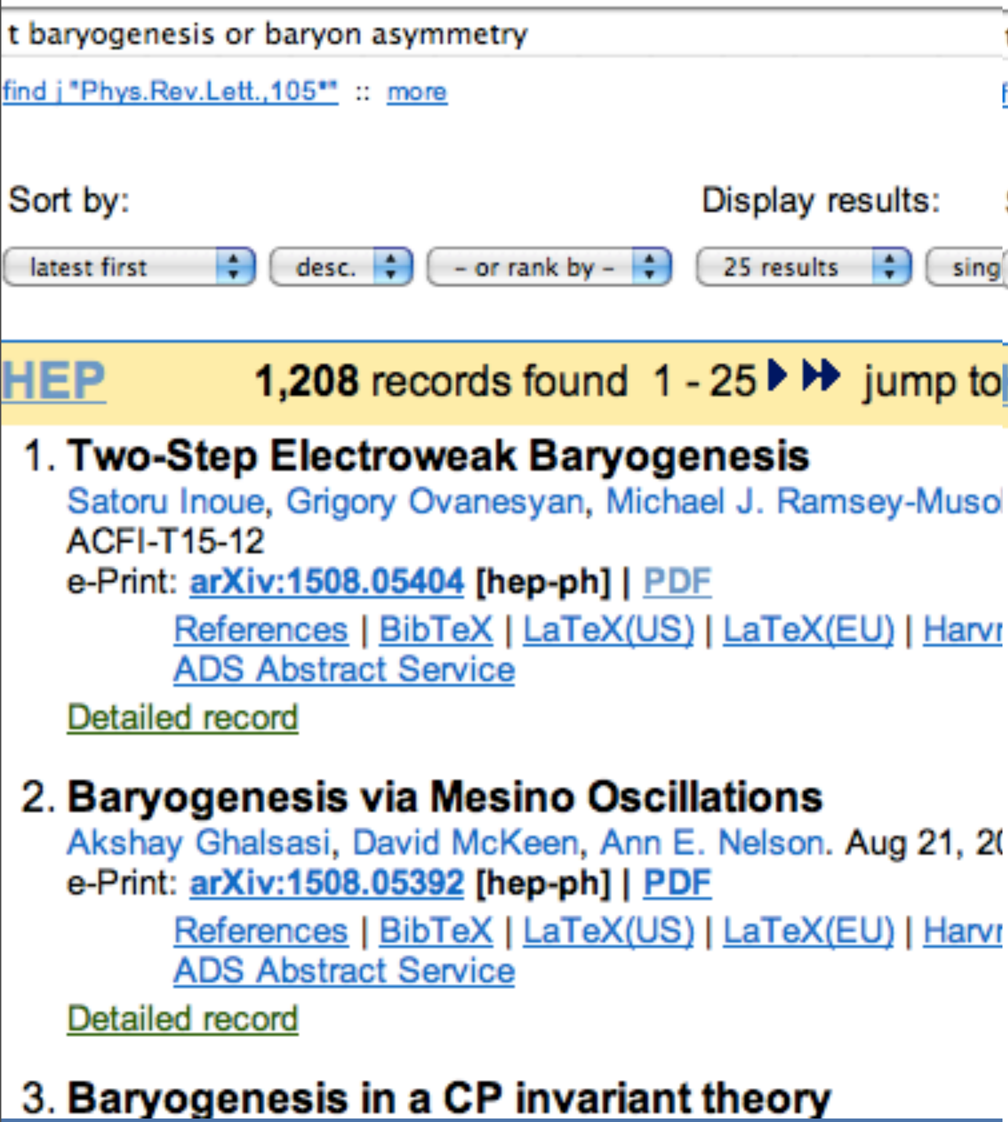
DM Direct detection

DM Indirect Searches.

Many inputs from the astrophysics and nuclear physics has to be well understood

Fun to explore

Prospects: BG versus DM



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Satoru Inoue, Grigory Ovanesyan, Michael J. Ramsey-Muso
ACFI-T15-12
e-Print: **arXiv:1508.05404 [hep-ph]** | PDF
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Akshay Ghalsasi, David McKeen, Ann E. Nelson. Aug 21, 2
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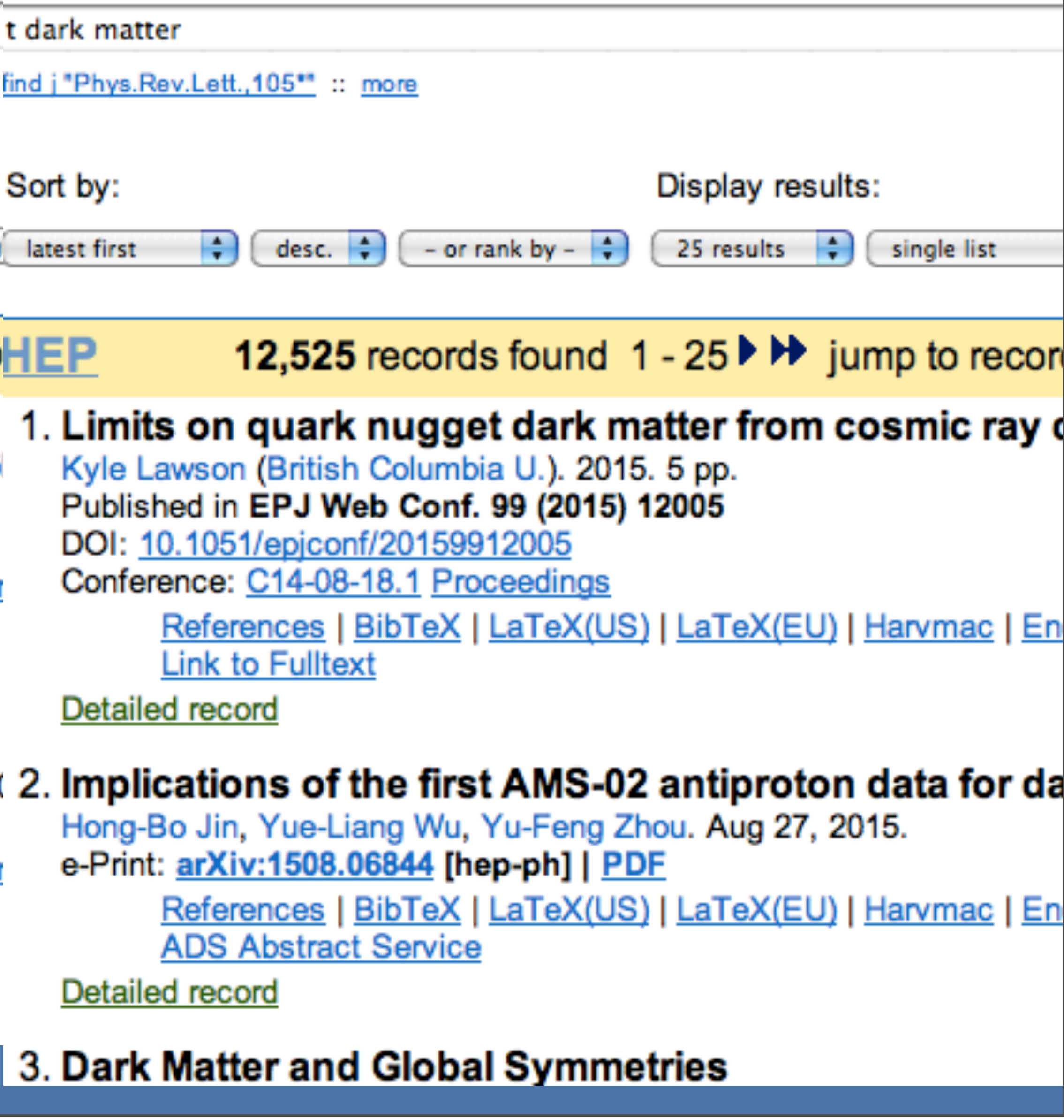

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Kyle Lawson (British Columbia U.). 2015. 5 pp.
Published in **EPJ Web Conf. 99 (2015) 12005**
DOI: 10.1051/epjconf/20159912005
Conference: C14-08-18.1 Proceedings
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Hong-Bo Jin, Yue-Liang Wu, Yu-Feng Zhou. Aug 27, 2015.
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