CP Violation
(and Baryogenesis)
in Two Higgs Doublet Models

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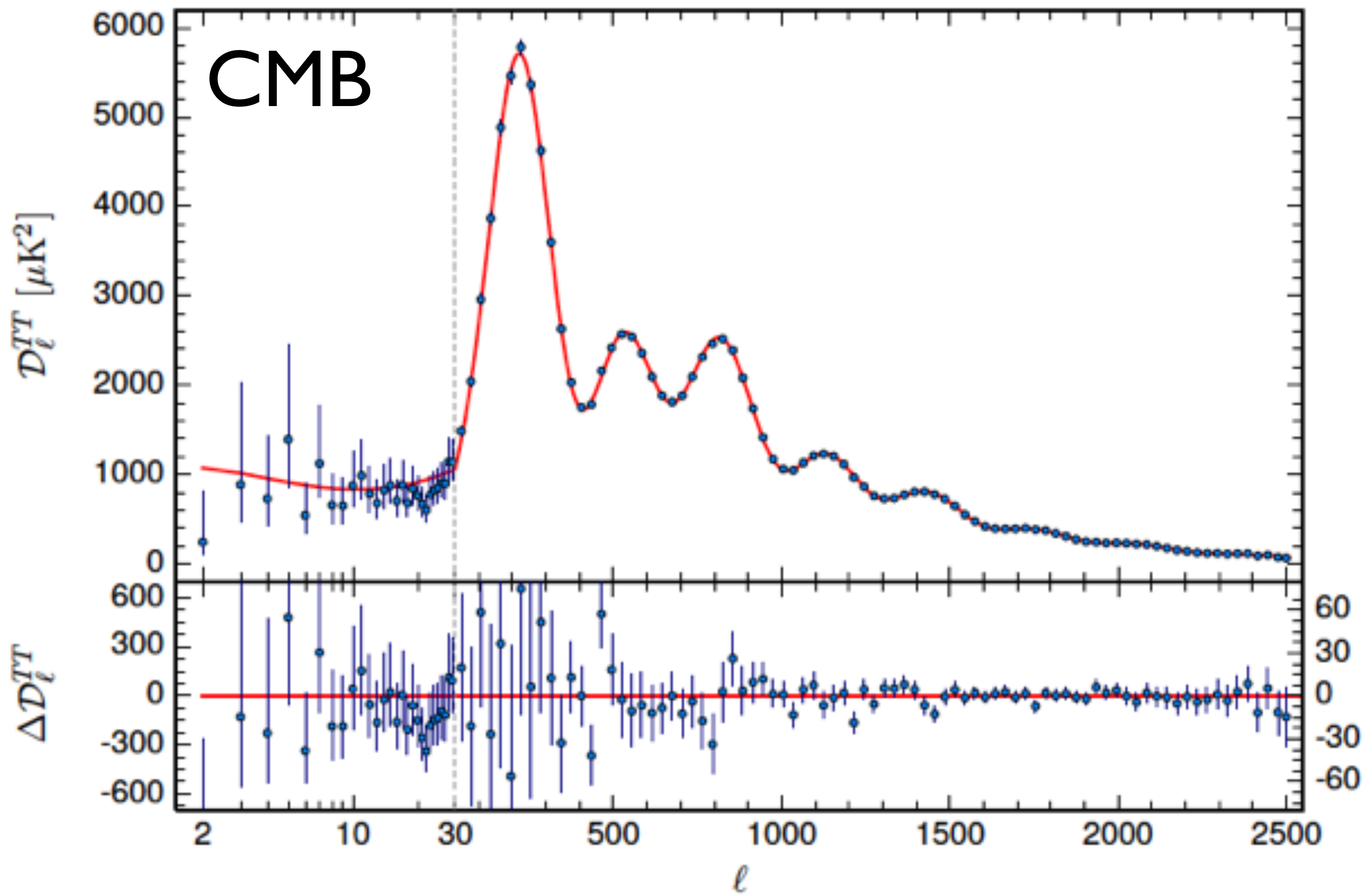
Ipek, *PRD D89 (2014) 073012, arXiv:1310.6790* + work in progress

Sneak peek

- There is more matter than antimatter - *baryogenesis*
- SM cannot explain this:
  - There is baryon number violation
  - Not enough CP violation
  - No out-of-equilibrium processes
- Solution: Two Higgs Doublet Model (2HDM)
- Constraints on CP violation: EDM experiments
- Small CP violation gives an “easy”, perturbative approach
- Study the phase structure of CP violating 2HDM?

There is more matter than antimatter

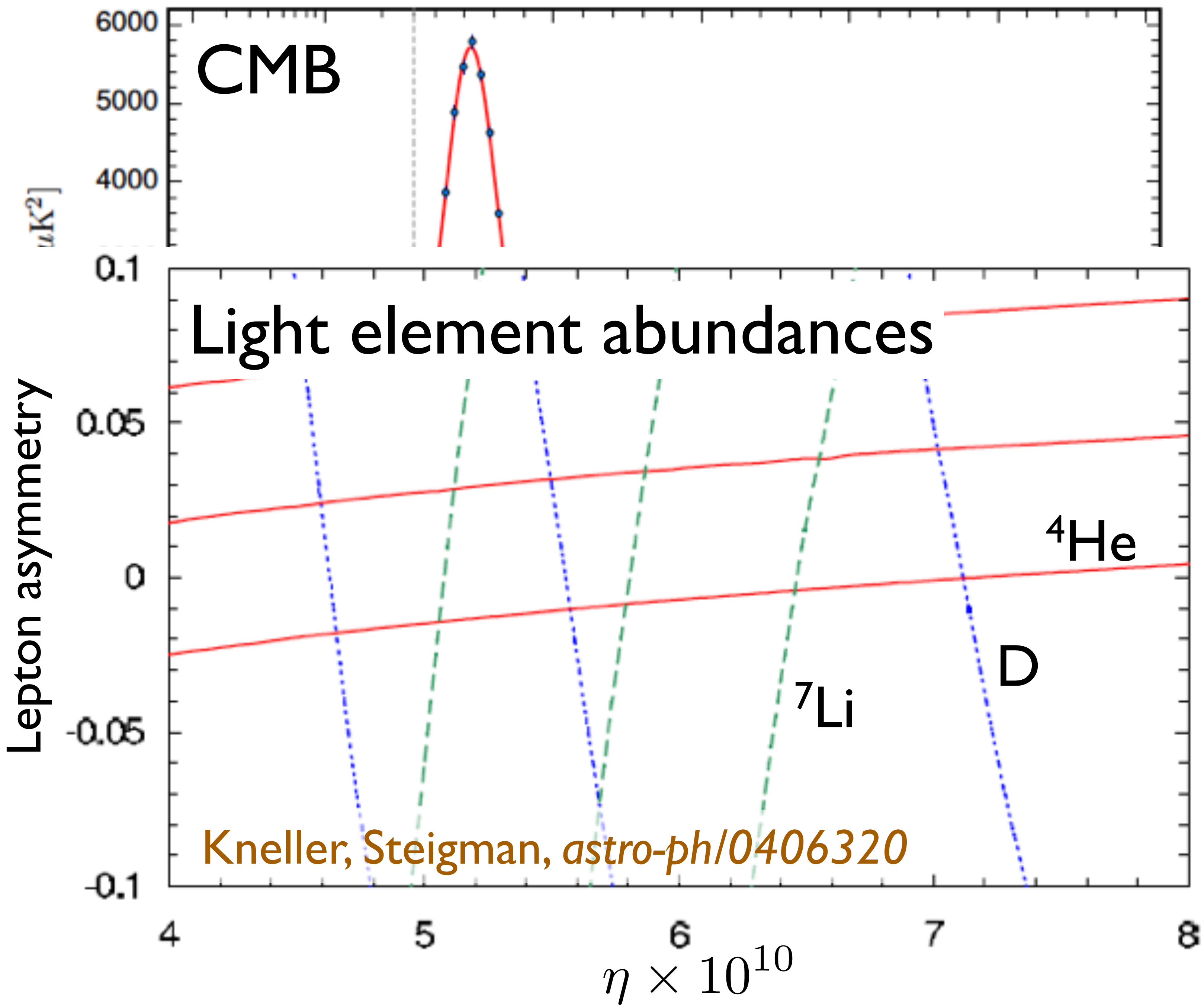


$$\Omega_\Lambda \sim 0.69$$
$$\Omega_{\rm DM} \sim 0.27$$
$$\Omega_{\rm B} \sim 0.04$$

number of baryons:

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma}$$
$$\simeq 6 \times 10^{-10}$$

There is more matter than antimatter



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$$\simeq 6 \times 10^{-10}$$

Sakharov Conditions

Sakharov, *JETP Lett. 5, 24 (1967)*

Need to produce 1 extra quark for every 10 billion antiquarks!

But how?

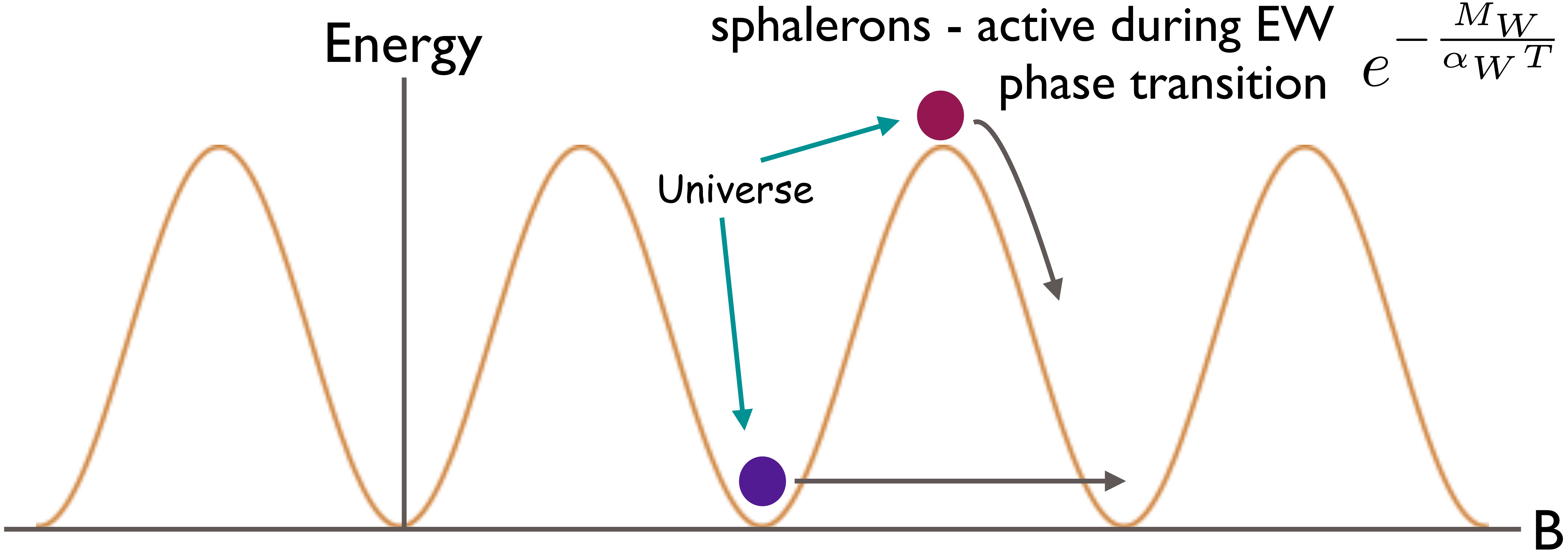
Three conditions must be satisfied:

1) Baryon number (B) must be violated
   can't have a baryon asymmetry w/o violating baryon number!
2) C and CP must be violated
   a way to differentiate matter from antimatter
3) B and CP violating processes must happen out of equilibrium
   equilibrium destroys the produced baryon number

1) SM violates baryon number ✔

Baryon number is anomalously violated

high temperature:
sphalerons - active during EW phase transition $e^{-\frac{M_W}{\alpha_W T}}$



low temperature:
tunneling - exponentially suppressed $e^{-4\pi/\alpha_W}$

2) SM has CP violation ✗

But not enough!

Only source of CP violation: quark mixing matrix:

$$-\frac{g}{\sqrt{2}}(\bar{u}\ \bar{c}\ \bar{t})\,\gamma^\mu W_\mu^+ \underbrace{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}}_{V_{\mathrm{CKM}}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

3 mixing angles + 1 phase ➡ CP violation!

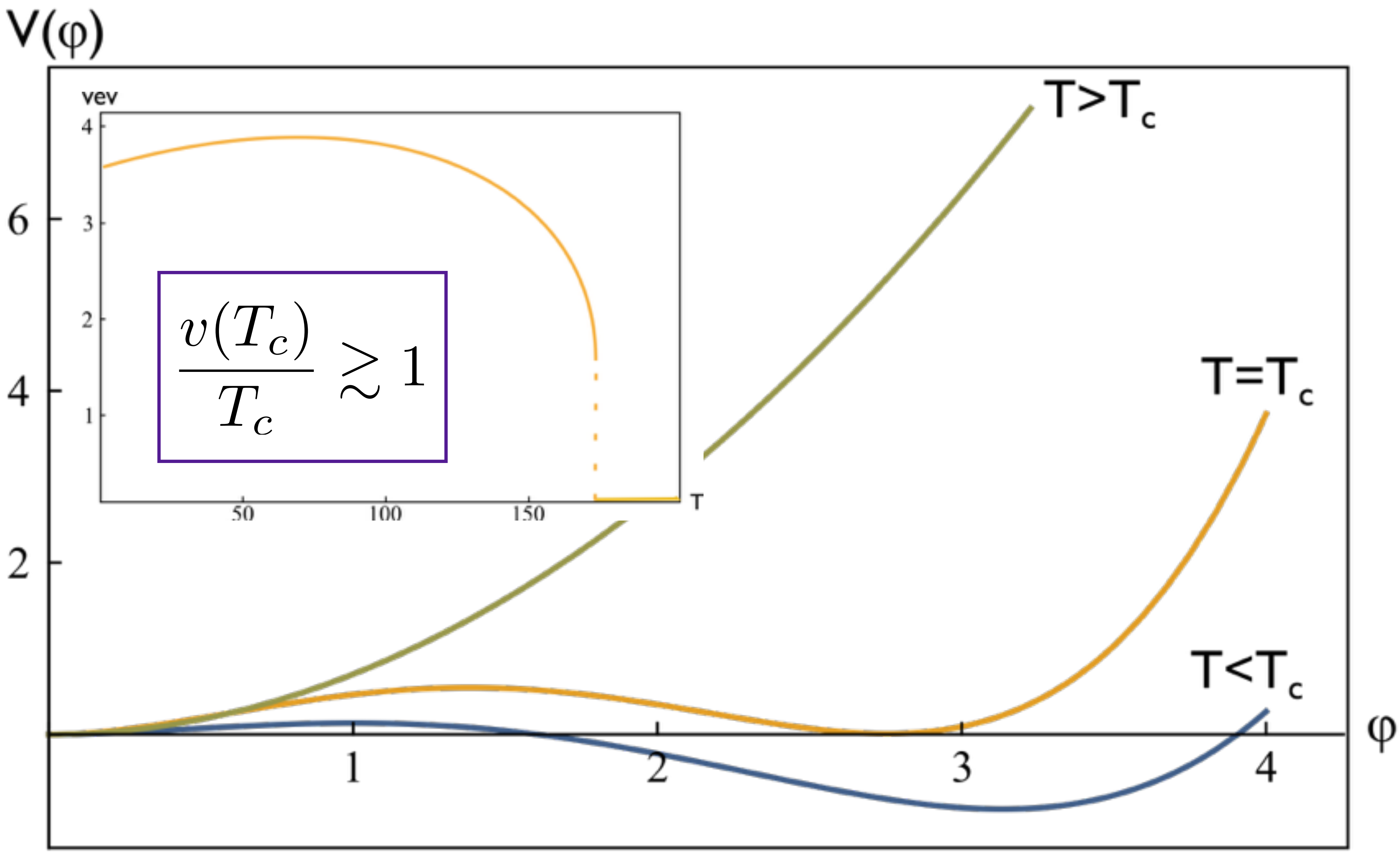
BUT

too small + gets suppressed by small Yukawa's

➡ $\eta \sim 10^{-20}$ ✗

3) SM has EW phase transition ✘

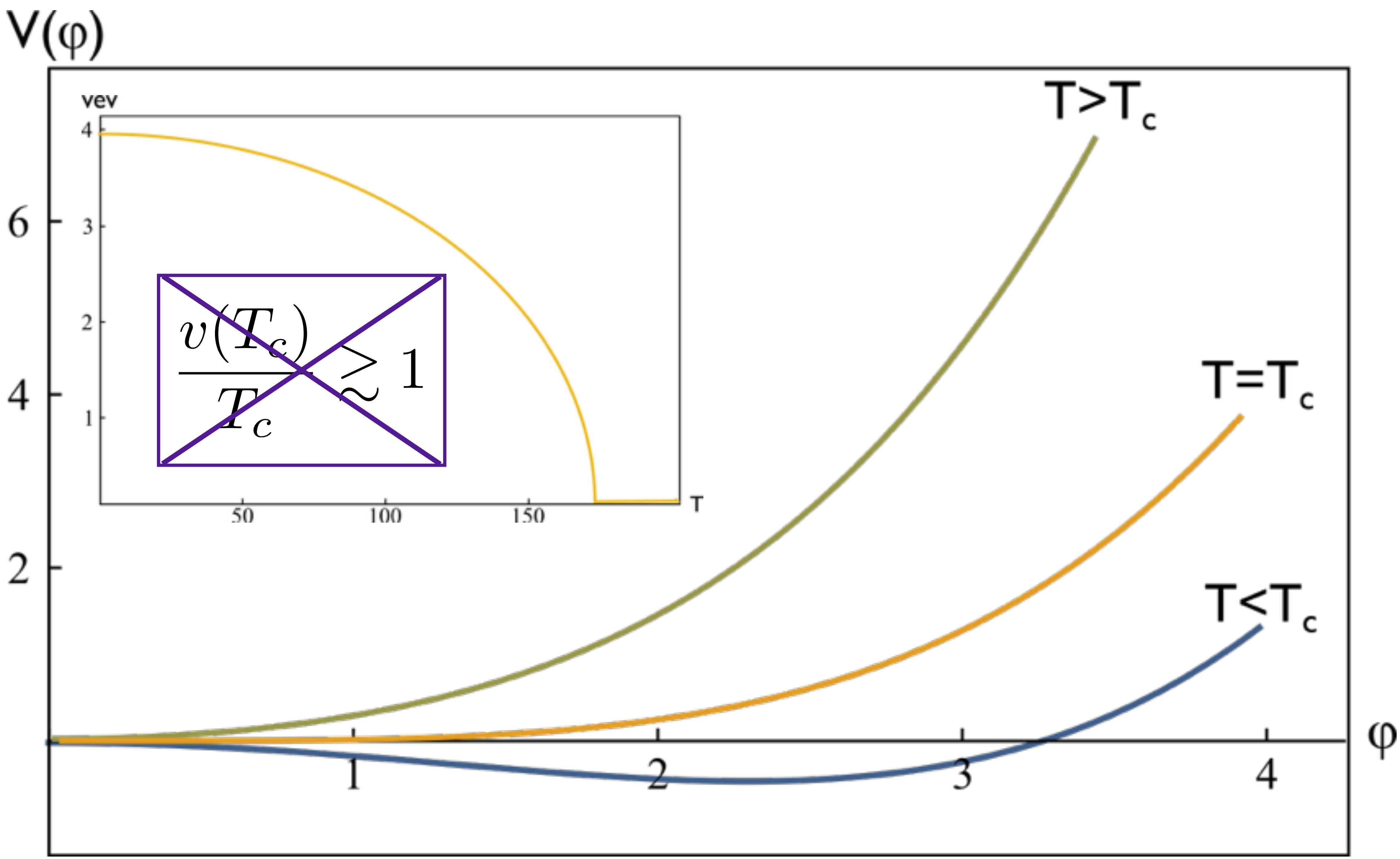
But not out-of-equilibrium!



$$\frac{v(T_c)}{T_c} \gtrsim 1$$

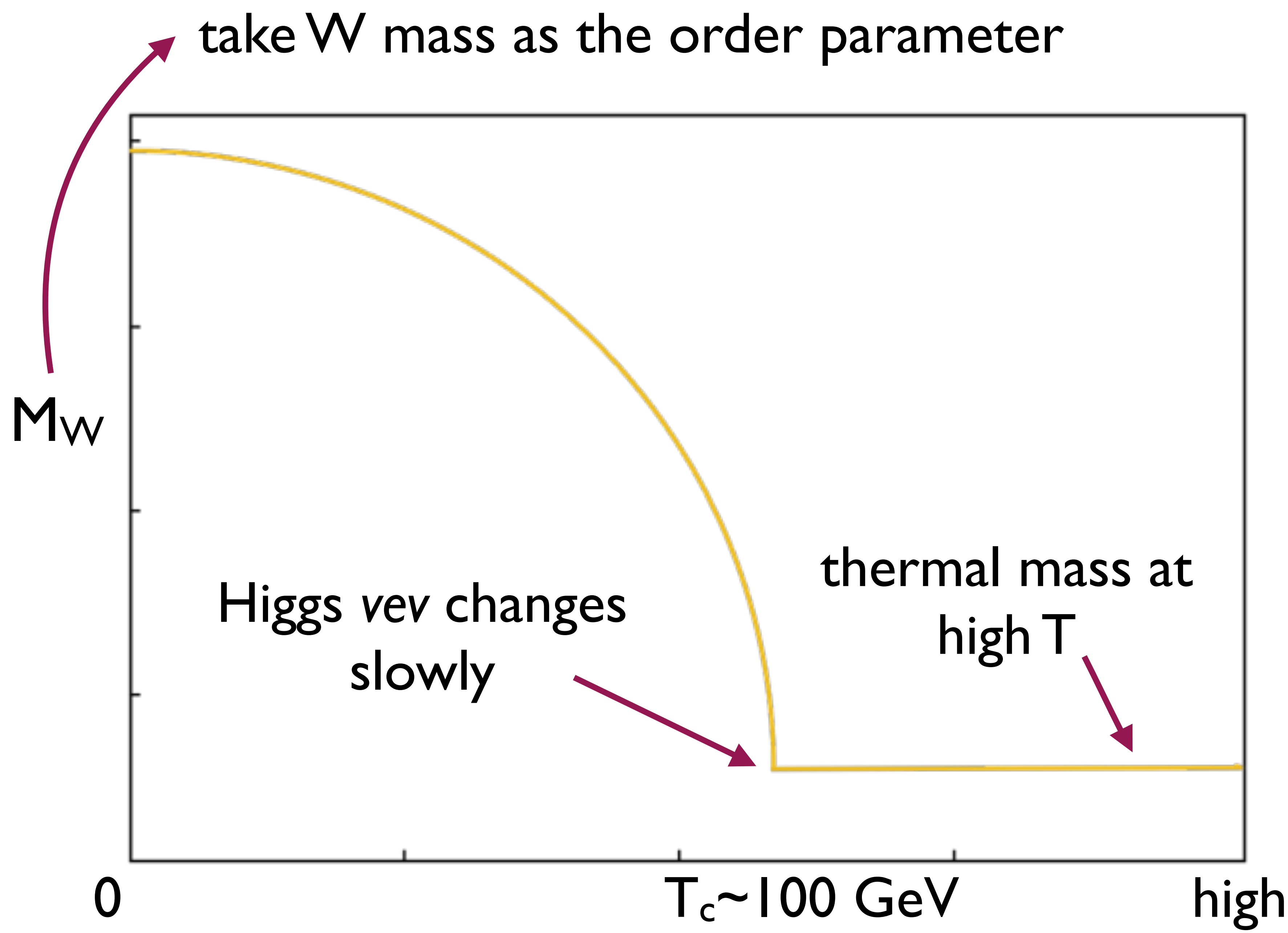
3) SM has EW phase transition ✗

But not out-of-equilibrium!



3) SM has EW phase transition ✗

But not out-of-equilibrium!



125 GeV Higgs

SM *phase transition* is a crossover

We need New Physics

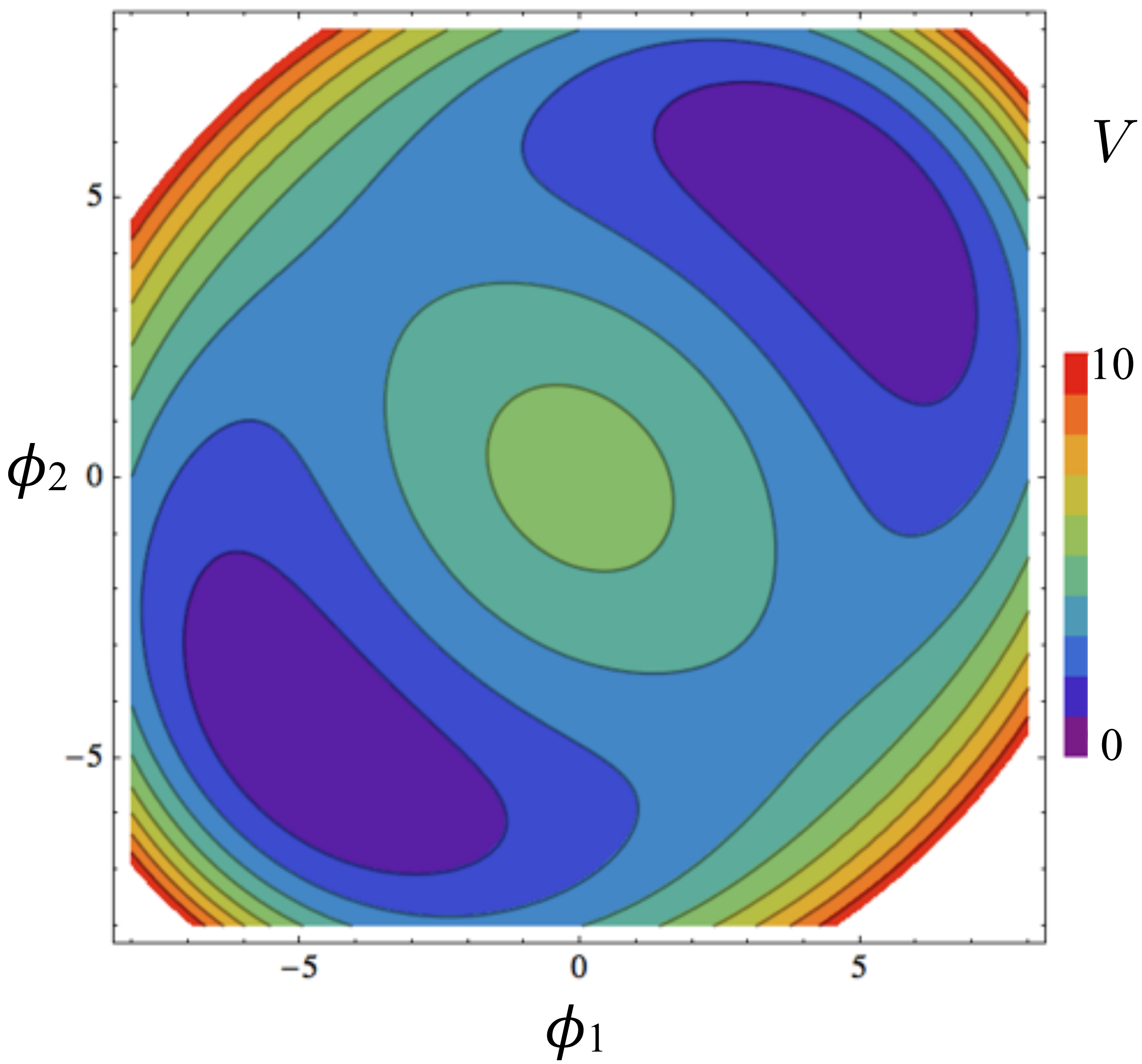
Couple to the SM

Extra CP violation

New light scalars can give a first order phase transition

→ Two Higgs Doublet Model

Two is better than one



$$V = h_1\left(\Phi_1^\dagger\Phi_1 - \frac{v_1^2}{2}\right)^2 + h_2\left(\Phi_2^\dagger\Phi_2 - \frac{v_2^2}{2}\right)^2$$
$$+ h_3\left[\left(\Phi_1^\dagger\Phi_1 - \frac{v_1^2}{2}\right) + \left(\Phi_2^\dagger\Phi_2 - \frac{v_2^2}{2}\right)\right]^2$$
$$+ h_4\left[(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) - (\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)\right]$$
$$+ h_5\left(\mathrm{Re}(\Phi_1^\dagger\Phi_2) - \frac{v_1 v_2}{2}\cos\xi\right)^2$$
$$+ h_6\left(\mathrm{Im}(\Phi_1^\dagger\Phi_2) - \frac{v_1 v_2}{2}\sin\xi\right)^2$$

minimum at: $\langle\Phi_1\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_1\end{pmatrix} \quad \langle\Phi_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_2 e^{i\xi}\end{pmatrix}$

$\sqrt{v_1^2 + v_2^2} = 246\ \mathrm{GeV}$

CP violation!

There are 5 Higgs bosons

2 Higgs doublets

$$\Phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1^+ \\ v_1 + \rho_1 + i\eta_1 \end{pmatrix} \qquad \Phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_2^+ \\ v_2 e^{i\xi} + \rho_2 + i\eta_2 \end{pmatrix}$$

→ 8 degrees of freedom —W, Z→ 5 Higgs bosons

2 charged Higgses: $H^\pm = -\sin\beta\phi_1^\pm + \cos\beta\phi_2^\pm$

$$\tan\beta = \frac{v_2}{v_1}$$

Assume no CP violation ξ=0, 3 neutral Higgses:

$$A^0 = -\sin\beta\,\eta_1 + \cos\beta\,\eta_2$$ — CP odd

$$H^0 = \cos\alpha\,\rho_1 + \sin\alpha\,\rho_2$$

125 GeV Higgs → $$h^0 = -\sin\alpha\,\rho_1 + \cos\alpha\,\rho_2$$

CP even

New Higgs couplings

Assume no CP violation, ξ=0

Type II 2HDM: Φ_1 couples to down-type quarks and leptons
Φ_2 couples to up-type quarks,

Higgs boson(s) couplings in units of 125 GeV Higgs couplings:

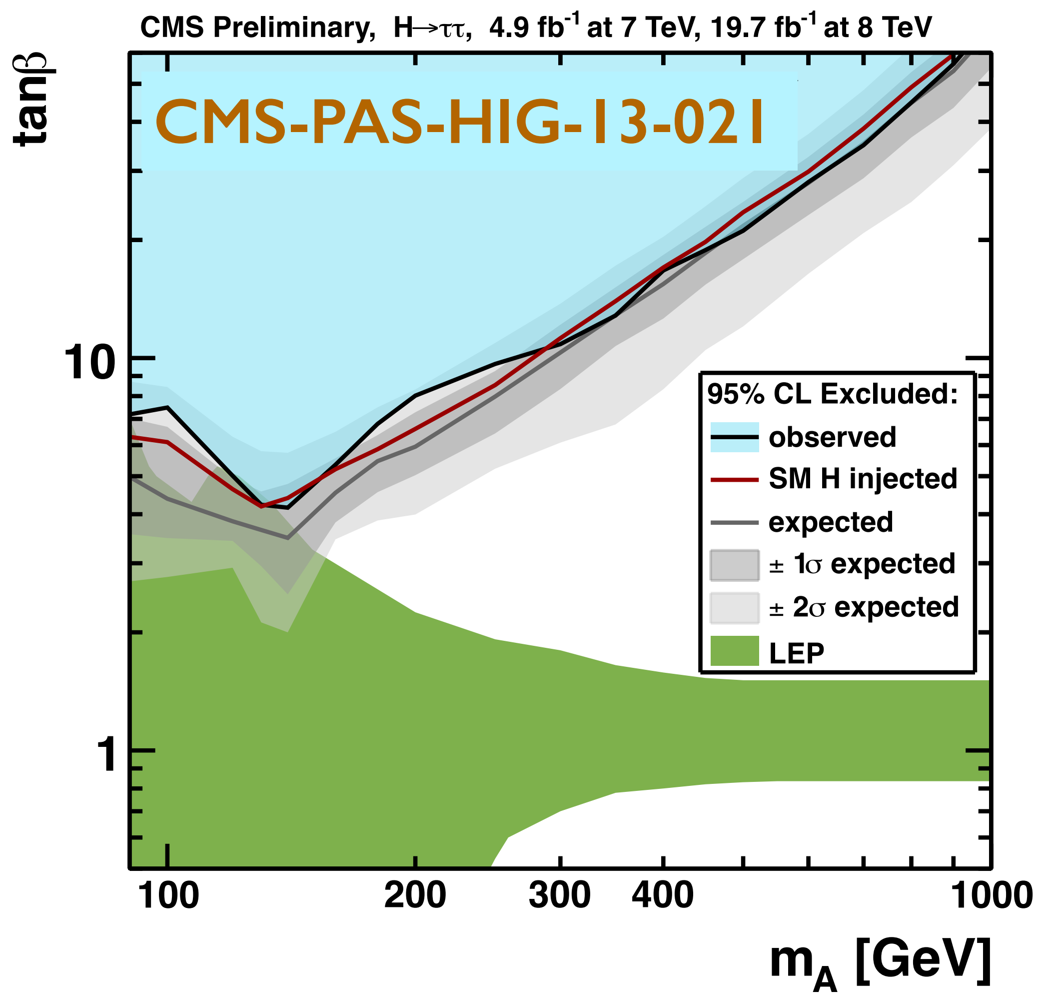
	h^0	H^0	A^0
χ_u	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$-\cot\beta$
$\chi_{d,e}$	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$-\tan\beta$
χ_V	$\sin(\beta-\alpha)$	$\cos(\beta-\alpha)$	✗

alignment limit: $\beta - \alpha = \frac{\pi}{2} \longrightarrow$ h^0 couplings are SM-like

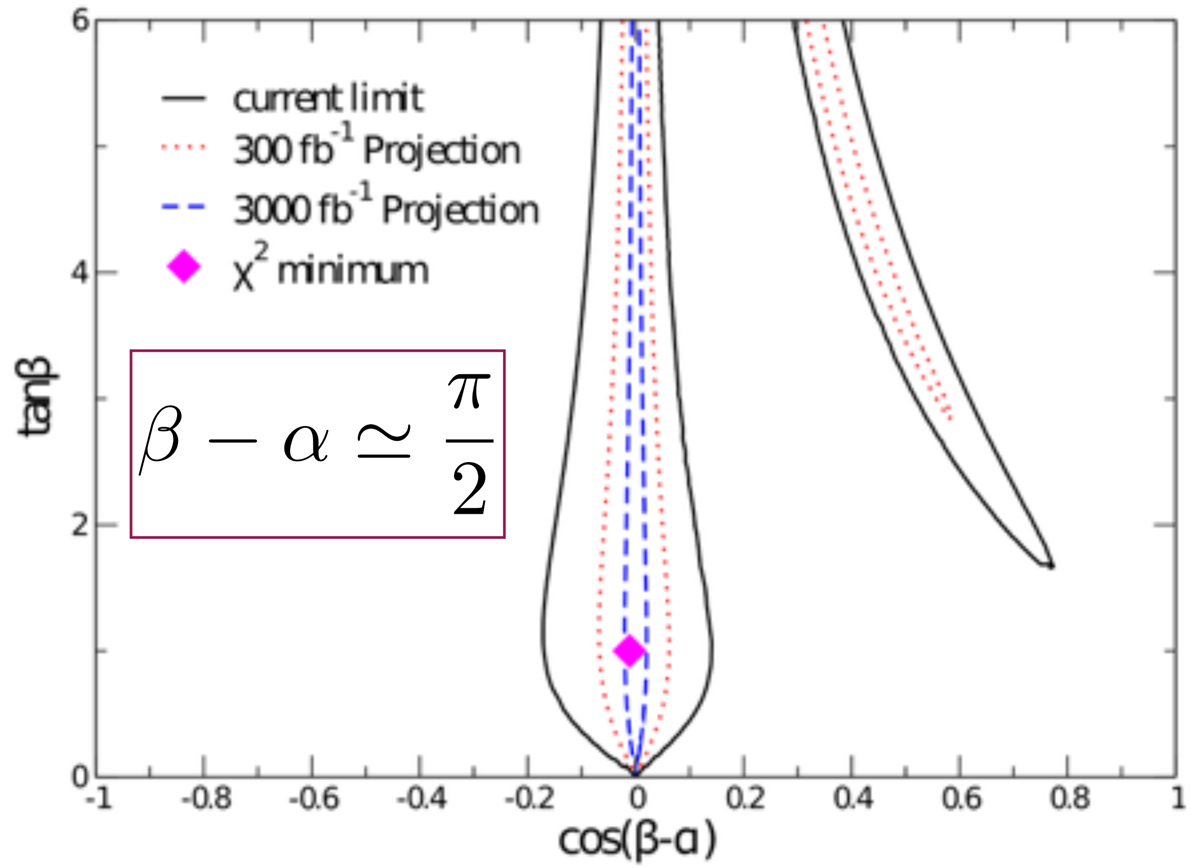
How to find Heavy Higgses

Assume no CP violation, ξ=0

- Heavy Higgs decays: $H \to \tau\tau$



- Deviations from SM Higgs couplings Chen, Dawson, *arxiv: 1305.1624*



$$\beta - \alpha \simeq \frac{\pi}{2}$$

- Electroweak precision parameters

$$M_{H^\pm} \simeq M_{A^0/H^0/h^0}$$

Grimus, *et al, arxiv: 0711.4022*

- $\bar{B} \to X_s \gamma$ decays:

$$M_{H^\pm} \geq 380 \text{ GeV}$$

Hermann, *et al, arxiv: 1208.2788*

New Higgs potential at high T

Assume no CP violation, ξ=0

Consider the zero temperature 2HDM potential:

simplified

$$V_0 = -\mu_1^2\Phi_1^\dagger\Phi_1 - \mu_2^2\Phi_2^\dagger\Phi_2 + \lambda_1(\Phi_1^\dagger\Phi_1)^2 + \lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \frac{\lambda_5}{2}\left[(\Phi_1^\dagger\Phi_2)^2 + (\Phi_2^\dagger\Phi_1)^2\right]$$

At finite temperature, Coleman-Weinberg type loop expansion:

over simplified

e.g. light Higgses $\lambda \ll g_W^2$

$$V_T = \mu^2 T^2 v^2 - \delta T v^3 + V_0(v_1, v_2)$$

μ^2: $g_W^2 + \left(\frac{v_2}{v} y_t\right)^2$

δ: $g_W^3 + \left(\frac{v_2}{v} y_t\right)^3$

* Top-Yukawa is the most important one

competition between T^2v^2 and Tv^3 terms → order of the phase transition

New Higgs potential at high T

Assume no CP violation, ξ=0

In general, with a softly broken Z_2:

$$V = -\mu_1^2\Phi_1^\dagger\Phi_1 - \mu_2^2\Phi_2^\dagger\Phi_2 - \frac{\mu^2}{2}\left(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1\right) + \lambda_1(\Phi_1^\dagger\Phi_1)^2 + \lambda_2(\Phi_2^\dagger\Phi_2)^2$$
$$+ \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \frac{\lambda_5}{2}\left[(\Phi_1^\dagger\Phi_2)^2 + (\Phi_2^\dagger\Phi_1)^2\right]$$

We have $m_{H^\pm}, m_{h^0} \gg M_W$ not simple!

Finite T potential depends on:

- 2 mixing angles
- μ
- 5 Higgs masses

- W/Z masses
- Top-quark mass

we know

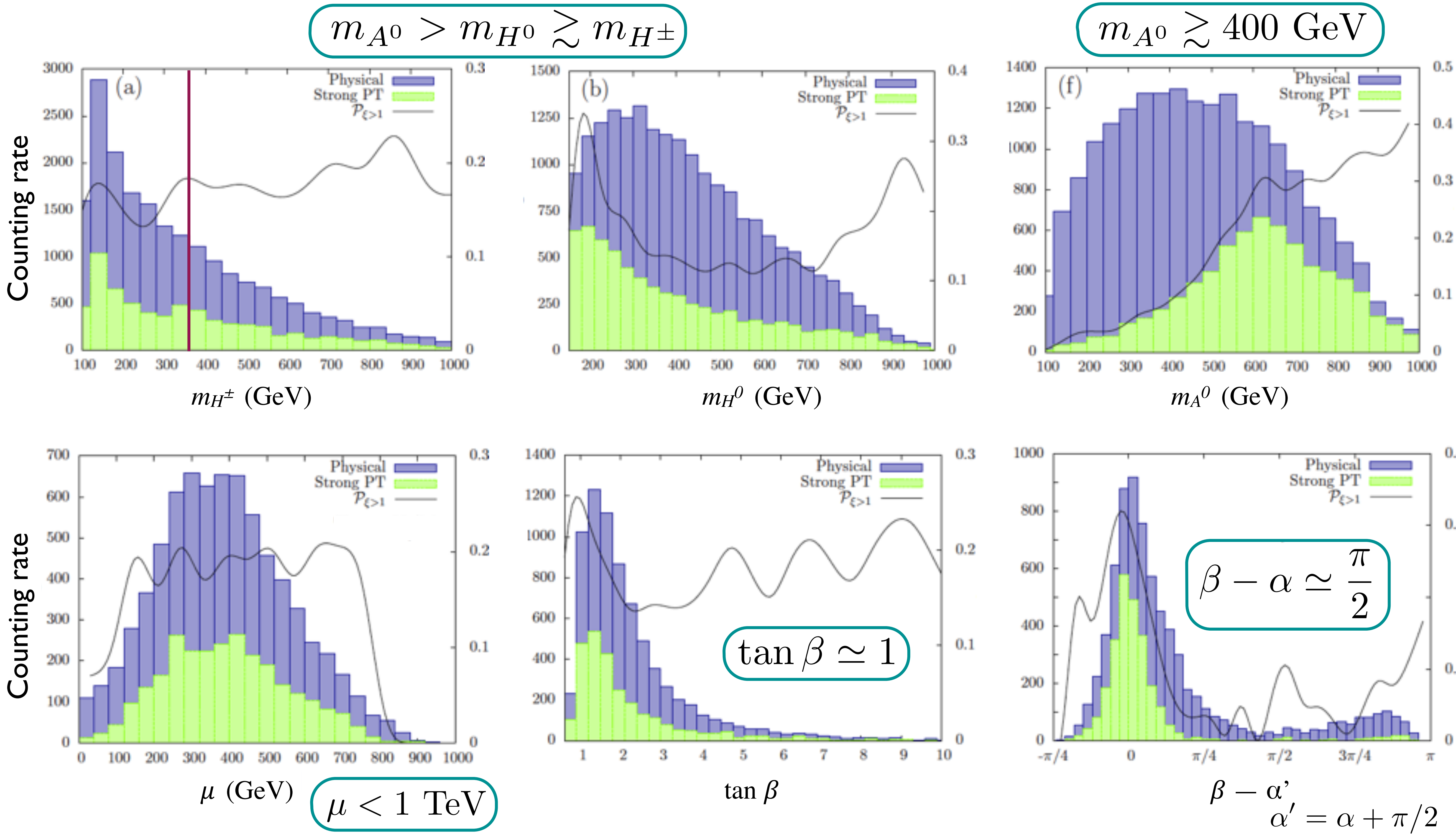
set $m_{h^0} = 125$ GeV

➡ Left with: $m_{A^0}, m_{H^0}, m_{H^\pm}, \mu, \beta, \alpha$

First order phase transition ✔

Assume no CP violation, ξ=0

Dorsch, Huber, No, *arxiv: 1305.6610*



We also need CP violation

2HDMs can have a first order EW phase transition → Provides out-of-equilibrium conditions

First order phase transition is awesome, but not enough!

We also need extra CP violation

↕

2HDMs can have CP violation in the Higgs sector

But complicated…

CP violation mixes 3 Higgses

There is CP violation: ξ≠0

$$V = h_1\left(\Phi_1^\dagger\Phi_1 - \frac{v_1^2}{2}\right)^2 + h_2\left(\Phi_2^\dagger\Phi_2 - \frac{v_2^2}{2}\right)^2 + h_3\left[\left(\Phi_1^\dagger\Phi_1 - \frac{v_1^2}{2}\right) + \left(\Phi_2^\dagger\Phi_2 - \frac{v_2^2}{2}\right)\right]^2$$
$$+ h_4\left[(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) - (\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)\right]$$
$$+ h_5\left(\mathrm{Re}(\Phi_1^\dagger\Phi_2) - \frac{v_1 v_2}{2}\cos\xi\right)^2 + h_6\left(\mathrm{Im}(\Phi_1^\dagger\Phi_2) - \frac{v_1 v_2}{2}\sin\xi\right)^2$$

- Charged Higgses are the same with mass $\frac{h_4}{2}v^2$
- Neutral Higgses are a mixture of CP-odd (A^0) and CP-even (ρ_1 and ρ_2) states:

$$\begin{pmatrix} \tilde{h} \\ \tilde{H} \\ \tilde{A} \end{pmatrix} = \begin{pmatrix} -s_\alpha c_{\alpha_b} & c_\alpha c_{\alpha_b} & s_{\alpha_b} \\ s_\alpha s_{\alpha_b} s_{\alpha_c} + c_\alpha c_{\alpha_c} & s_\alpha c_{\alpha_c} - c_\alpha s_{\alpha_b} s_{\alpha_c} & c_{\alpha_b} s_{\alpha_c} \\ s_\alpha s_{\alpha_b} c_{\alpha_c} - c_\alpha s_{\alpha_c} & -s_\alpha s_{\alpha_c} - c_\alpha s_{\alpha_b} c_{\alpha_c} & c_{\alpha_b} c_{\alpha_c} \end{pmatrix} \begin{pmatrix} \rho_1 \\ \rho_2 \\ A^0 \end{pmatrix}$$

Mass states are a mess

There is CP violation: $\xi \neq 0$

Mass^2 matrix in the basis $(\rho_1,\ \rho_2,\ A^0)^{\mathrm{T}}$

$$M^2 = v^2 \begin{pmatrix} 2(h_1+h_3)c_\beta^2 + \frac{1}{2}(h_5 c_\xi^2 + h_6 s_\xi^2)s_\beta^2 & \left[2h_3 + \frac{1}{2}(h_5 c_\xi^2 + h_6 s_\xi^2)\right] s_\beta\, c_\beta & \frac{1}{2}(h_6 - h_5) s_\beta\, c_\xi\, s_\xi \\ \left[2h_3 + \frac{1}{2}(h_5 c_\xi^2 + h_6 s_\xi^2)\right] s_\beta\, c_\beta & 2(h_2+h_3)s_\beta^2 + \frac{1}{2}(h_5 c_\xi^2 + h_6 s_\xi^2)c_\beta^2 & \frac{1}{2}(h_6 - h_5) c_\beta\, c_\xi\, s_\xi \\ \frac{1}{2}(h_6 - h_5) s_\beta\, c_\xi\, s_\xi & \frac{1}{2}(h_6 - h_5) c_\beta\, c_\xi\, s_\xi & \frac{1}{4}(h_5 + h_6 + (h_6 - h_5)c_{2\xi}) \end{pmatrix}$$

If $h_5 = h_6$ ➡ No dependence on ξ !

Diagonalize to find the mass eigenstates with:

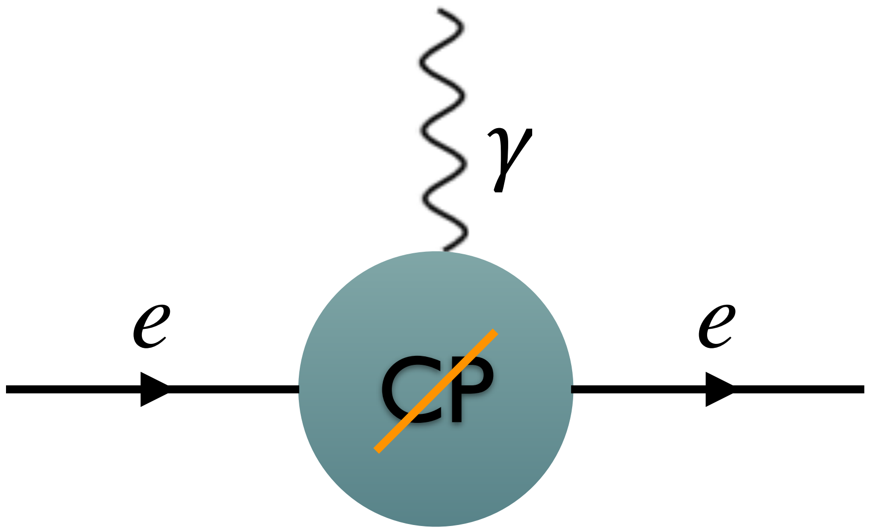
$$R = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha_c & \sin\alpha_c \\ 0 & -\sin\alpha_c & \cos\alpha_c \end{pmatrix} \begin{pmatrix} \cos\alpha_b & 0 & \sin\alpha_b \\ 0 & 1 & 0 \\ -\sin\alpha_b & 0 & \cos\alpha_b \end{pmatrix} \begin{pmatrix} -\sin\alpha & \cos\alpha & 0 \\ \cos\alpha & \sin\alpha & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

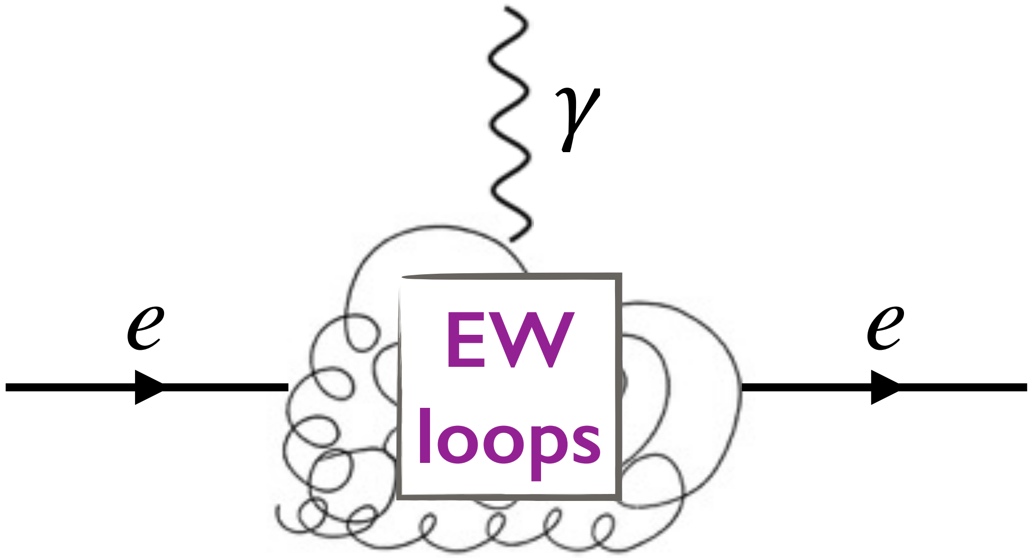
2 new angles

In general, it is a mess!

CP violation shows up in EDMs

Electric Dipole Moments are a good measure of CP violation





SM prediction for electron EDM is very small:

$$d_e < 10^{-38}\ e\cdot\text{cm}$$

10 orders of magnitude!
But still very small

Experimental bound: $d_e < 0.87\times 10^{-28}\ e\cdot\text{cm}$

ACME, *Science, 343* (2014)

We expect *small* CP violation

Let's do some estimates

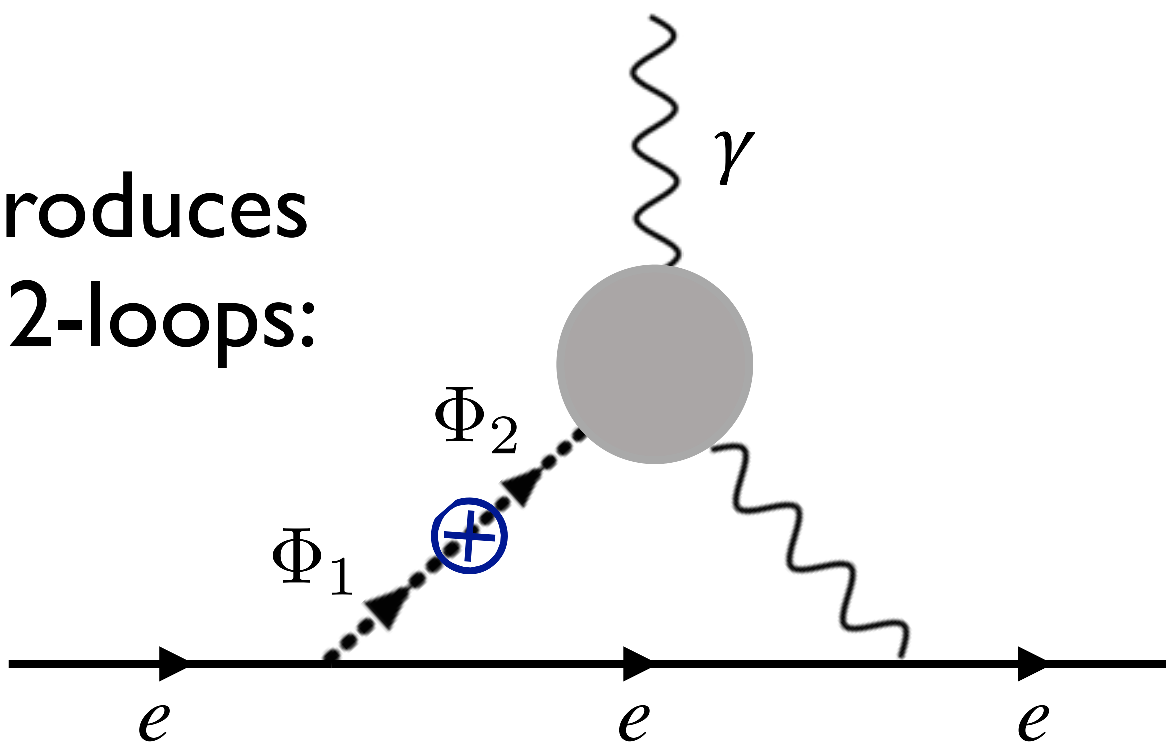
Experiment says: $d_e < 0.87 \times 10^{-28}\ e \cdot \mathrm{cm}$

New Physics gives: $d_e \sim \left(\frac{\alpha_e}{4\pi}\right)^n \frac{m_e}{\Lambda^2} \sin\xi$

n: number of loops

Λ: scale of NP

2HDM produces EDMs in 2-loops:



For $\Lambda \sim O(100\ \mathrm{GeV})$

$\sin\xi < 0.1$

Perturbative mass matrix

$\sin\xi < 0.1$

Ipek, *PRD D89 (2014) 073012, arXiv:1310.6790*

CP conserving mass^2 matrix

$$M^2 \simeq v^2 \begin{pmatrix} 2(h_1+h_3)c_\beta^2 + \frac{h_5}{2}s_\beta^2 & \frac{1}{4}(4h_3+h_5)s_{2\beta} & 0 \\ \frac{1}{4}(4h_3+h_5)s_{2\beta} & 2(h_2+h_3)c_\beta^2 + \frac{h_5}{2}s_\beta^2 & 0 \\ 0 & 0 & \frac{h_6}{2} \end{pmatrix}$$

$$+ \frac{h_6 - h_5}{2} v^2 \begin{pmatrix} \xi^2 s_\beta^2 & \frac{1}{2}\xi^2 s_{2\beta} & \xi s_\beta \\ \frac{1}{2}\xi^2 s_{2\beta} & \xi^2 c_\beta^2 & \xi c_\beta \\ \xi s_\beta & \xi c_\beta & -\xi^2 \end{pmatrix}$$

Perturbation due to CP violation, mixing

Expansion works when

$$C \equiv \frac{h_6 - h_5}{2} \simeq \frac{m_{A^0}^2}{v^2} - \frac{\mu^2}{v^2 \sin(2\beta)}$$: not too large

Perturbative mass eigenstates

Use **non-degenerate** perturbation theory

$m_{A^0} \neq m_{H^0}, m_{h^0}$ these are neutral Higgs masses when $\xi = 0$

eigenstates	masses
$\tilde{h} \simeq h^0 - \xi\, a \cos\gamma\, A^0$	$m^2_{\tilde{h}} \simeq m^2_{h^0} + \xi^2 C v^2 \cos^2\gamma (1-a)$
$\tilde{H} \simeq H^0 + \xi\, b \sin\gamma A^0$	$m^2_{\tilde{H}} \simeq m^2_{H^0} + \xi^2 C v^2 \sin^2\gamma (1-b)$
$\tilde{A} \simeq A^0 + \xi\, a \cos\gamma\, h^0$	$m^2_{\tilde{A}} \simeq m^2_{A^0} - \xi^2\, C v^2\, \sin^2\gamma (1-b)$
$- \xi\, b \sin\gamma\, H^0$	$- \xi^2\, C v^2\, \cos^2\gamma (1-a)$

$$a \equiv \frac{Cv^2}{m^2_{A^0} - m^2_{h^0}}, \quad b \equiv \frac{Cv^2}{m^2_{A^0} - m^2_{H^0}}, \quad Cv^2 \simeq m^2_{A^0} - \frac{\mu^2}{\sin(2\beta)}, \quad \gamma \equiv \alpha + \beta$$

Perturbative rotation matrix

$$R = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha_c & \sin\alpha_c \\ 0 & -\sin\alpha_c & \cos\alpha_c \end{pmatrix} \begin{pmatrix} \cos\alpha_b & 0 & \sin\alpha_b \\ 0 & 1 & 0 \\ -\sin\alpha_b & 0 & \cos\alpha_b \end{pmatrix} \begin{pmatrix} -\sin\alpha & \cos\alpha & 0 \\ \cos\alpha & \sin\alpha & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

diagonalizes mass^2 matrix $R\, M^2 R^{-1}$

New mixing angles:

- $\sin\alpha_b \simeq -\xi \dfrac{m_{A^0}^2 - \bar{\mu}^2}{m_{A^0}^2 - m_{h^0}^2} \sin\gamma$
- $\sin\alpha_c \simeq \xi \dfrac{m_{A^0}^2 - \bar{\mu}^2}{m_{A^0}^2 - m_{H^0}^2} \cos\gamma$

$$\bar{\mu}^2 \equiv \frac{\mu^2}{\sin(2\beta)}$$

$$\gamma \equiv \alpha + \beta$$

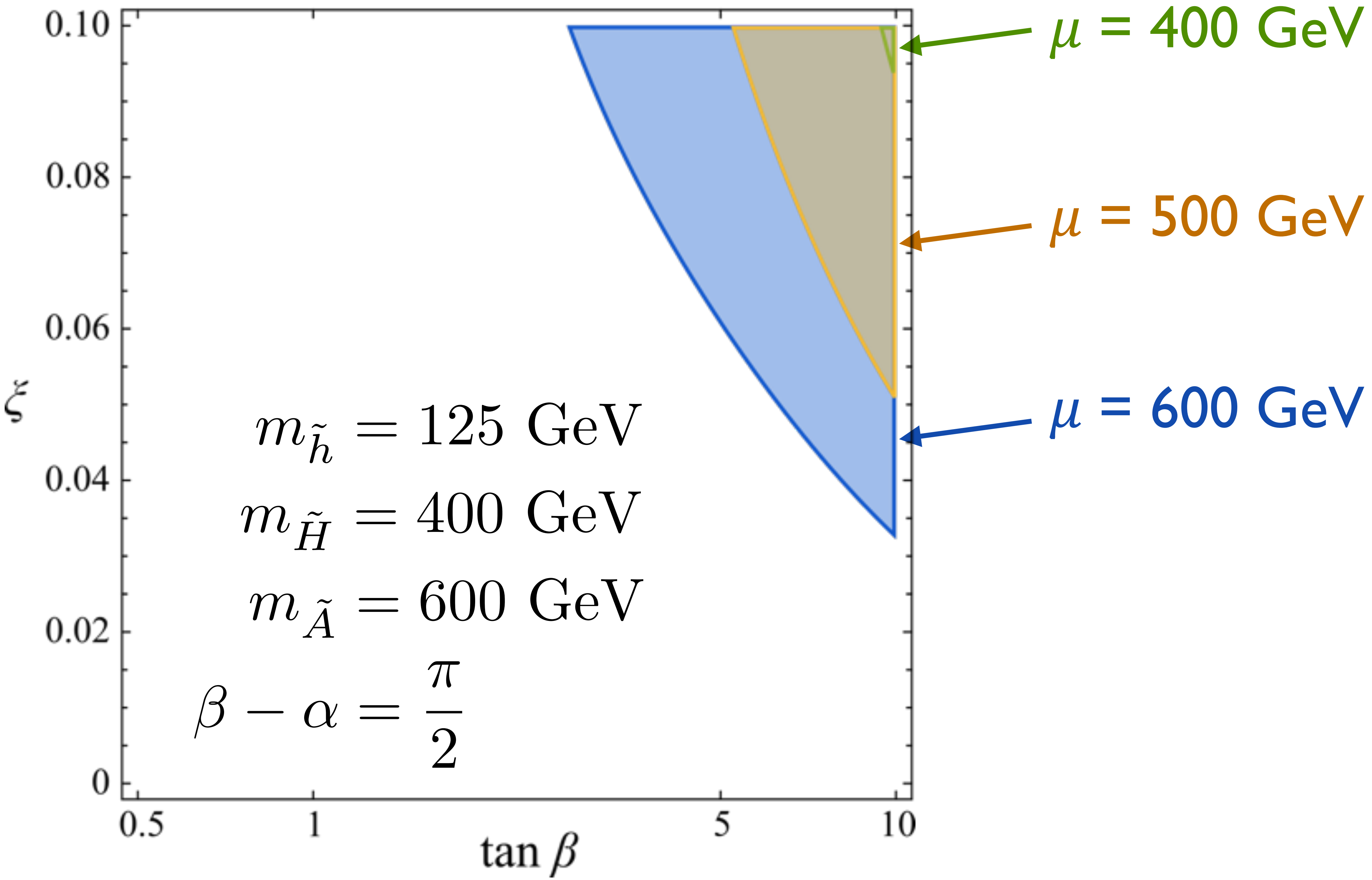
New mass eigenstates:

★ $\tilde{h} \simeq h^0 + \sin\alpha_b\, A^0$ ★ $\tilde{H} \simeq H^0 + \sin\alpha_c\, A^0$

★ $\tilde{A} \simeq A^0 - \sin\alpha_b\, h^0 - \sin\alpha_c\, H^0$

How good is it?

Regions of $\tan\beta - \xi$ space where corrections are larger than 10%



Perturbative Yukawa couplings

Coupling constants in units of 125 GeV Higgs couplings

	h^0	H^0	A^0
χ_u	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	
$\tilde{\chi}_u$			$-\cot\beta$
$\chi_{d,e}$	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\cos\beta}$	
$\tilde{\chi}_{d,e}$			$-\tan\beta$
χ_V	$\sin(\beta-\alpha)$	$\cos(\beta-\alpha)$	

Perturbative Yukawa couplings

Coupling constants in units of 125 GeV Higgs couplings

	$\tilde{h}$	$\tilde{H}$	$\tilde{A}$
χ_u	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\xi}{\sin\beta}(a\cos\gamma\cos\alpha + b\sin\gamma\sin\alpha)$
$\tilde{\chi}_u$	$\xi\, a\cos\gamma\cot\beta$	$-\xi\, b\sin\gamma\cot\beta$	$-\cot\beta$
$\chi_{d,e}$	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$\frac{\xi}{\cos\beta}(b\sin\gamma\cos\alpha - a\cos\gamma\sin\alpha)$
$\tilde{\chi}_{d,e}$	$\xi\, a\cos\gamma\tan\beta$	$-\xi\, b\sin\gamma\tan\beta$	$-\tan\beta$
χ_V	$\sin(\beta-\alpha)$	$\cos(\beta-\alpha)$	$\xi\,(a\cos\gamma\sin(\beta-\alpha) + b\sin\gamma\cos(\beta-\alpha))$

$$+O(\xi^2)$$

Only one extra parameter

CP violating Higgs potential:

$$V = -\mu_1^2 \Phi_1^\dagger \Phi_1 - \mu_2^2 \Phi_2^\dagger \Phi_2 - (\mu^2 \Phi_1^\dagger \Phi_2 + \text{h.c.}) + \lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 |\Phi_1^\dagger \Phi_2|^2 + \frac{\lambda_5}{2} \left[(\Phi_1^\dagger \Phi_2)^2 + (\Phi_2^\dagger \Phi_1)^2 \right]$$

Finite T potential depends on:

- 2 mixing angles
- μ
- 5 Higgs masses

set $m_{h^0} = 125 \text{ GeV}$

- W/Z masses
- Top-quark mass

we know

➡ Left with: $m_{A^0}, m_{H^0}, m_{H^\pm}, \mu, \beta, \alpha$

+ ξ

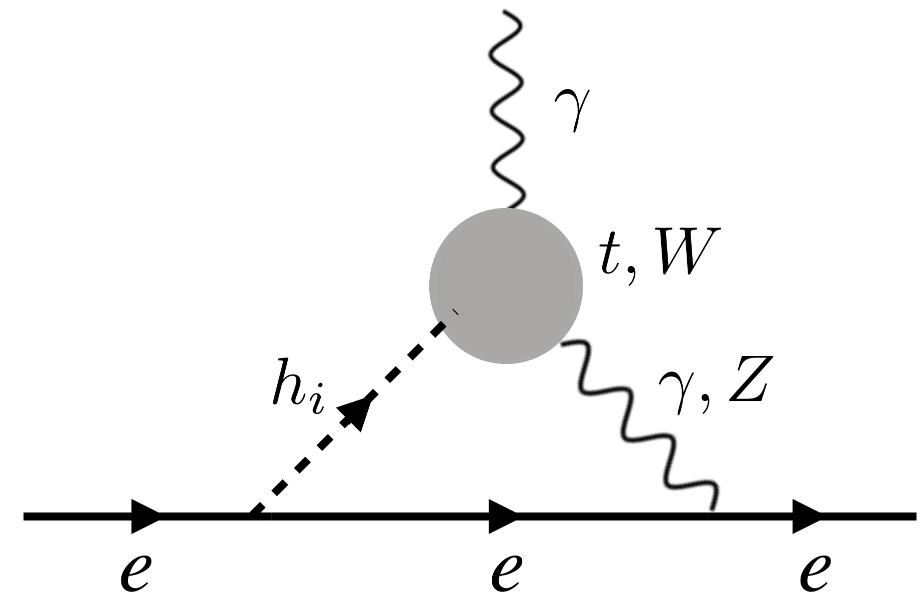
Constraints from EDMs

Inoue, Ramsey-Musolf, Zhang, *arxiv: 1403.4257*
Chen, Dawson, Zheng, *arxiv: 1503.01114*
…

$$d_e < 0.87 \times 10^{-28}\ e\cdot\text{cm}$$

All of the Higgses have CP-odd couplings to electrons

There are a quite a few Barr-Zee diagrams, and more!

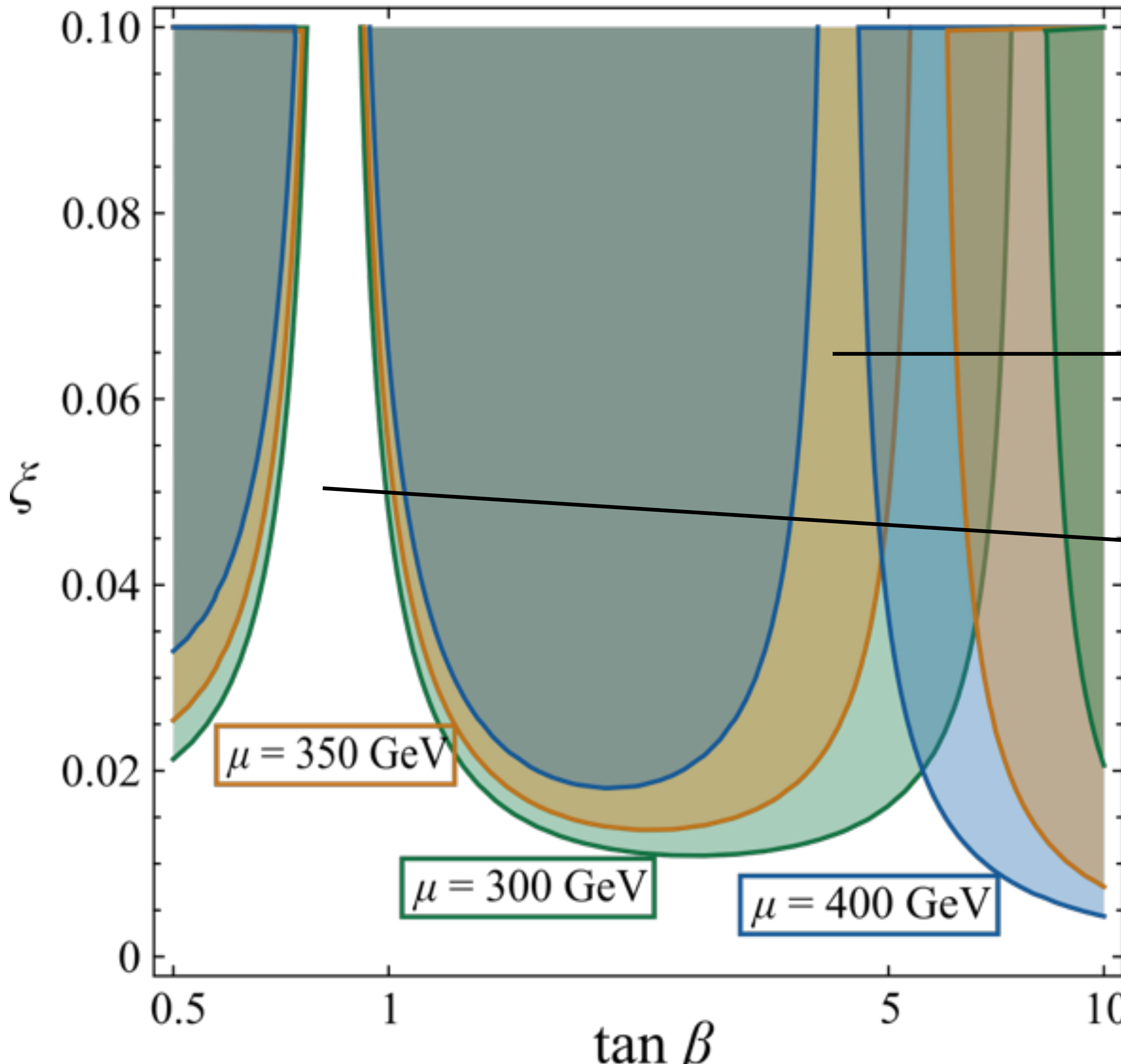


There are other EDMs too, e.g. neutron

Complicated problem with all the new angles and the mixings

But at the end: $d_e \propto \xi(m_A^2 - \bar{\mu}^2)\, F(\text{masses, etc})$

Constraints from EDMs



$$d_e \propto \xi(m_A^2 - \bar{\mu}^2)$$
$$< 10^{-28} e\cdot\text{cm}$$

cancellation between m_A and μ

cancellation between top and W diagrams

$$m_{\tilde{h}} = 125 \text{ GeV}$$
$$m_{\tilde{H}} = 400 \text{ GeV}$$
$$m_{\tilde{A}} = 600 \text{ GeV}$$
$$\beta - \alpha = \frac{\pi}{2}$$

Constraints from Higgs searches

SM Higgs couplings change for $\beta - \alpha \neq \frac{\pi}{2}$

Chen, Dawson, Zheng, *arxiv: 1503.01114*

Also with $\xi \neq 0$ ⟶ $\frac{\Gamma(\tilde{h} \to bb)}{\Gamma_{\rm SM}} \sim 1 + O(\xi^2)$

too small!

New vector boson couplings for $\xi \neq 0$

Summary

- We should be able to explain baryogenesis
- Progress has been made in finding a first-order phase transition in 2HDMs
- CP violation is crucial but complicated in 2HDM
- EDM constraints allow for a small CP-violating phase
- Would also affect Higgs measurements
- Perturbatively including CP violation in baryogenesis studies?