A Second Higgs & the Cosmic *Matter / Antimatter* Asymmetry

Work with G. Dorsch, S. Huber and K. Mimasu

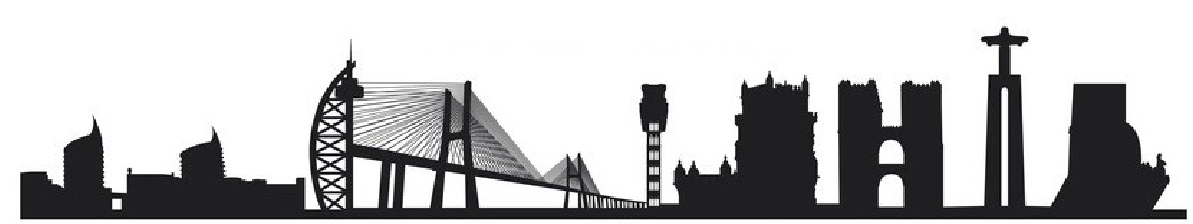
1405.5537 (Phys.Rev.Lett 113, 211802) & 1609.xxxxx

+161x.xxxxx with T. Konstandin

Jose Miguel No

University of Sussex

Multi-Higgs, Lisbon, 09/09/2016



BSM TO DO LIST

- [ ] Dark Matter
- [ ] Neutrino Masses
- [ ] Matter-Antimatter Asymmetry → Baryogenesis
- [ ] ...
- [ ]

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- ☐ Dark Matter
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SAKHAROV CONDITIONS *(for dynamical generation of baryon asymmetry)*

B Violation

C/*CP* Violation

Departure from Thermal Equilibrium

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SAKHAROV CONDITIONS *(for dynamical generation of baryon asymmetry)*

$$\not{C}\!P \sim \frac{\prod_{i\neq j}^{u,c,t} |m_i^2 - m_j^2| \times \prod_{i\neq j}^{d,s,b} |m_i^2 - m_j^2|}{T^{12}} \times J \sim 10^{-20}$$

B Violation ✓ Sphalerons

*Kuzmin, Rubakov, Shaposhnikov, Phys. Lett. B**155** (1985) 36*

C/CP Violation ✗ *not enough*

*Gavela, Hernandez, Orloff, Pene, Quimbay, Nucl. Phys. B**430** (1994) 382*

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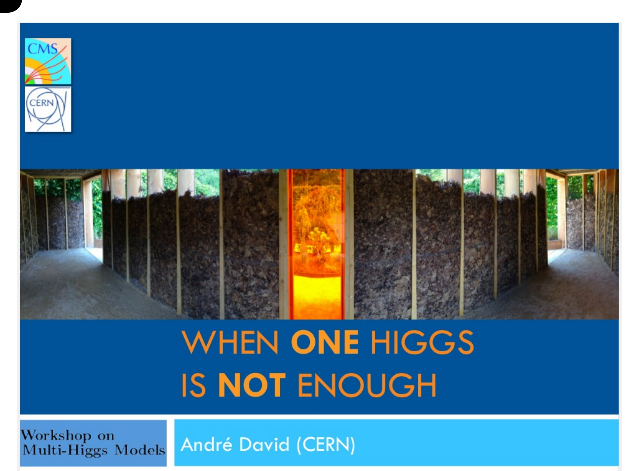
EW Phase Transition Smooth CrossOver

No CPV in Scalar Sector

The SM (1 Higgs) is not Enough



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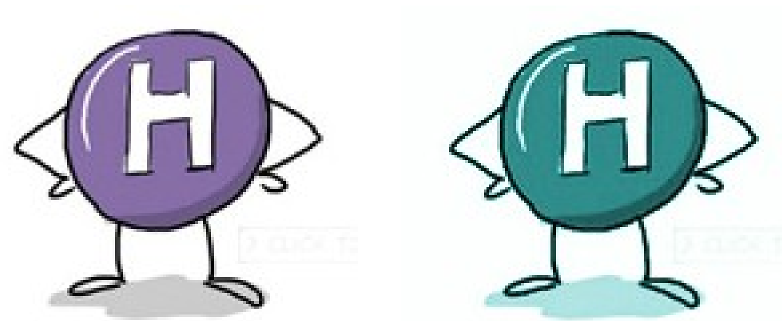
✓

✓

More Higgses Help!



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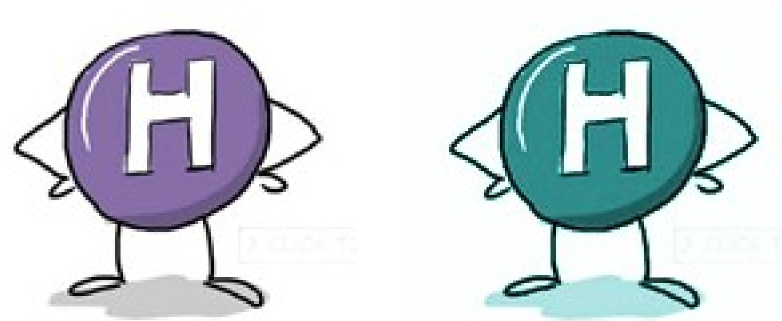

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EW Phase Transition

Universe Expands Adiabatically ⇨ *Equilibrium Thermal Field Theory* ⇨ *Higgs Finite-T Effective Potential*

$$V_{\rm eff}(h,T) = V_0(h) + V_0^{\rm loop}(h) + V_T(h,T)$$

Tree-level potential | Loop corrections | Thermal corrections

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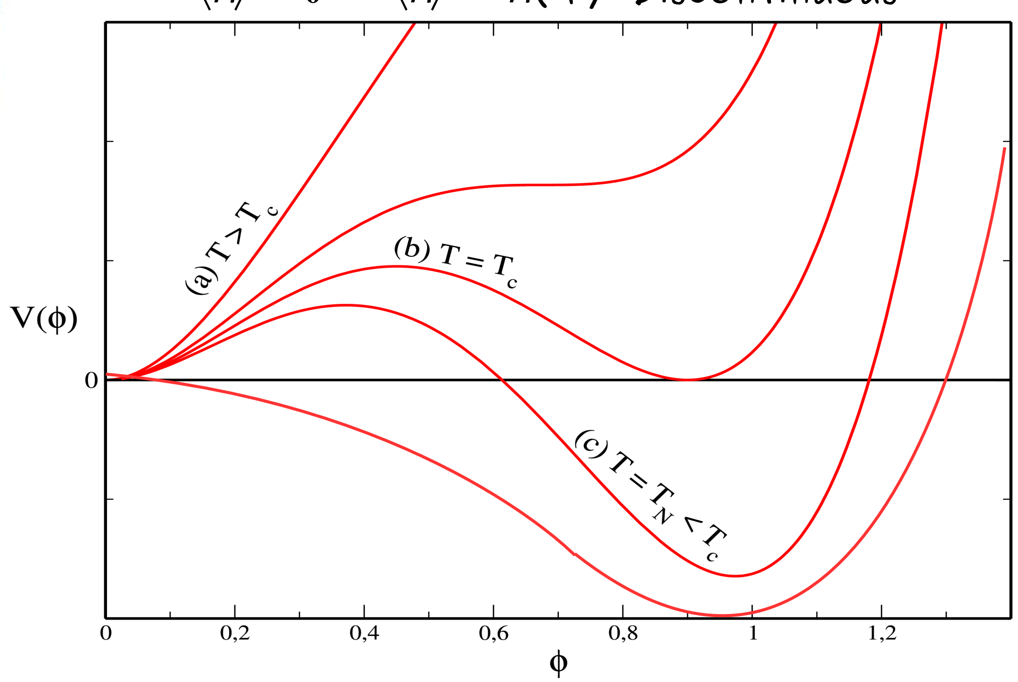
$T \gg v$

$\kappa\, T^2 h^2$

EW Symmetry Restoration

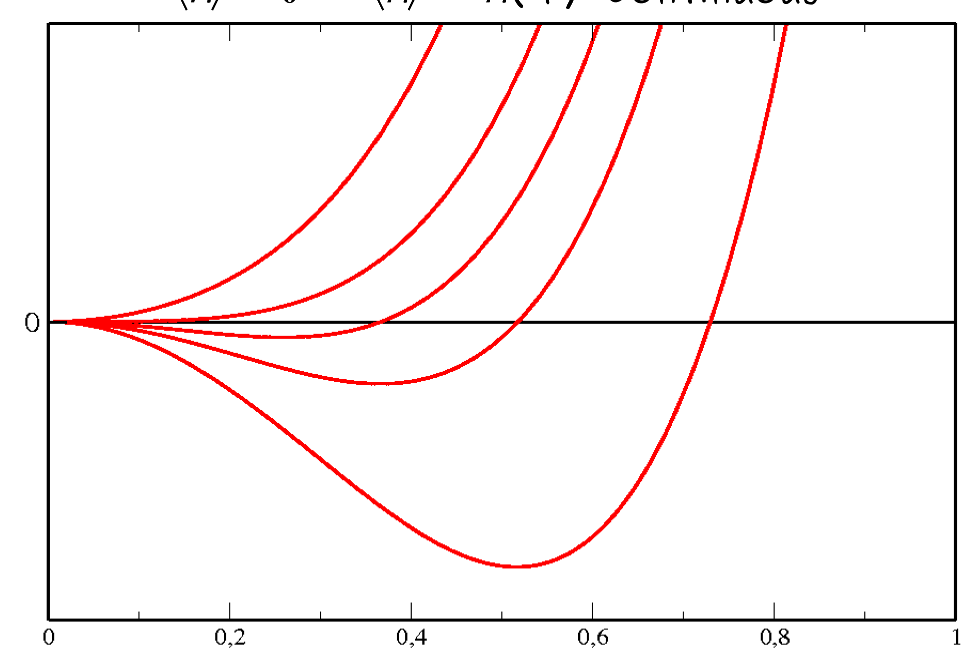
1^{st} Order:

$\langle h \rangle = \mathbf{0} \rightarrow \langle h \rangle = h(T)$ Discontinuous



2^{nd} Order:

$\langle h \rangle = \mathbf{0} \rightarrow \langle h \rangle = h(T)$ Continuous



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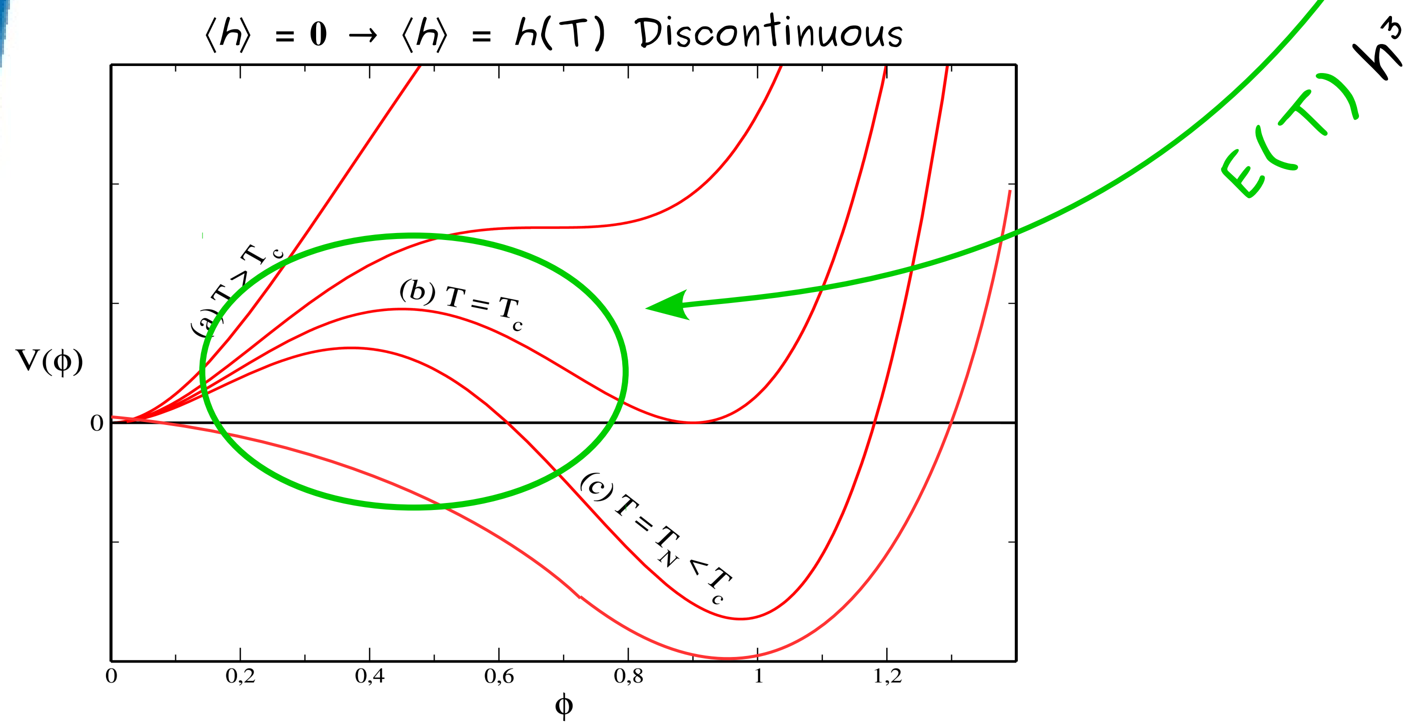

⇨ **Thermal Effects** (In the SM, W, Z gauge bosons → not sufficient)

Add New BOSONS to generate a thermal barrier

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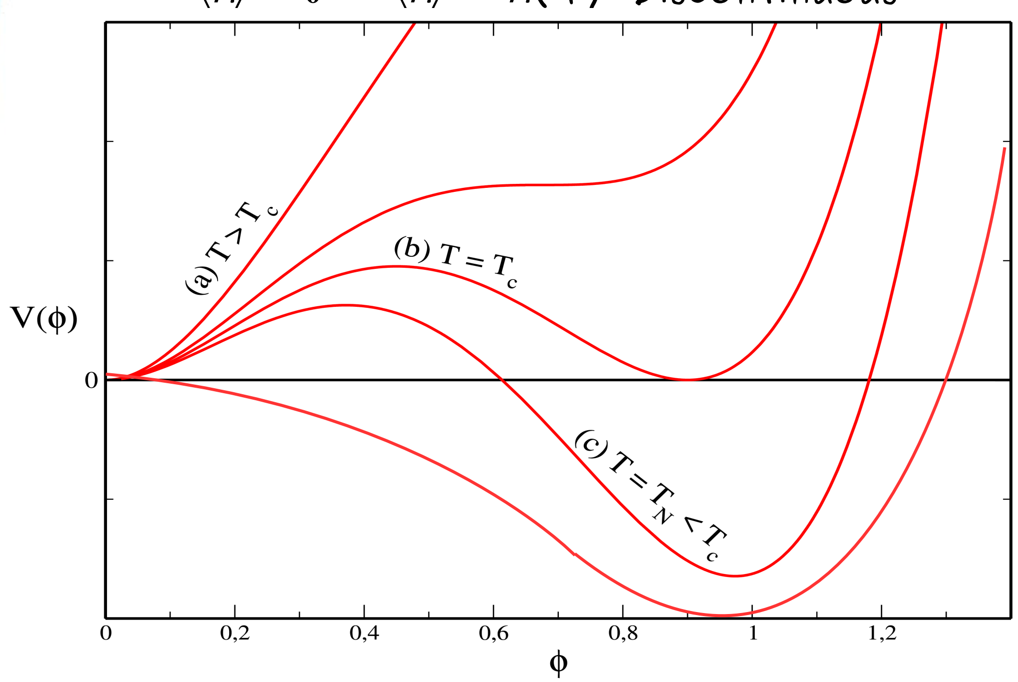

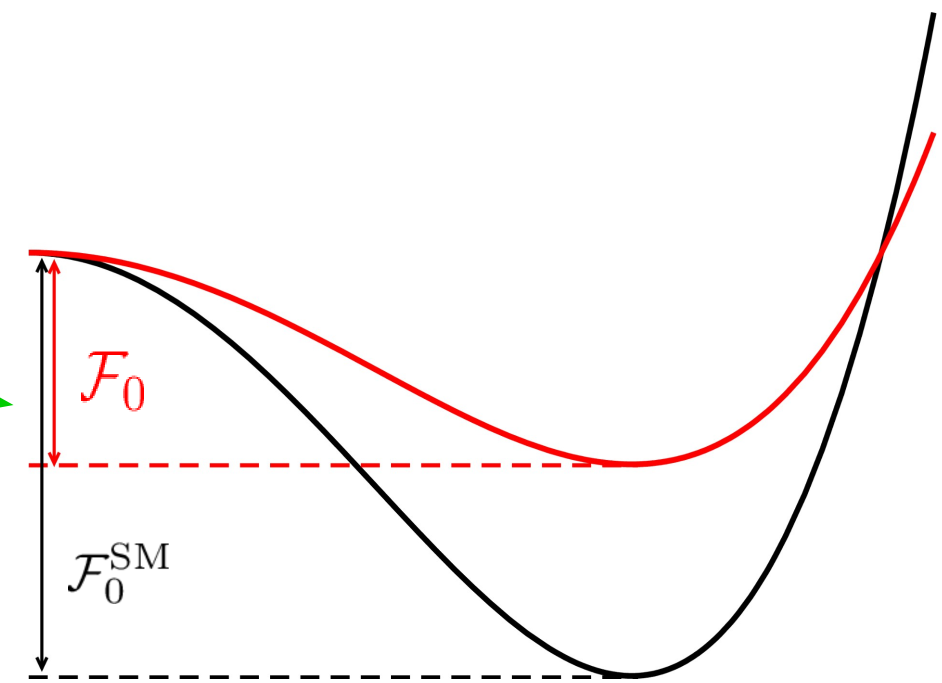

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Add Particles whose loops reduce vacua energy difference.

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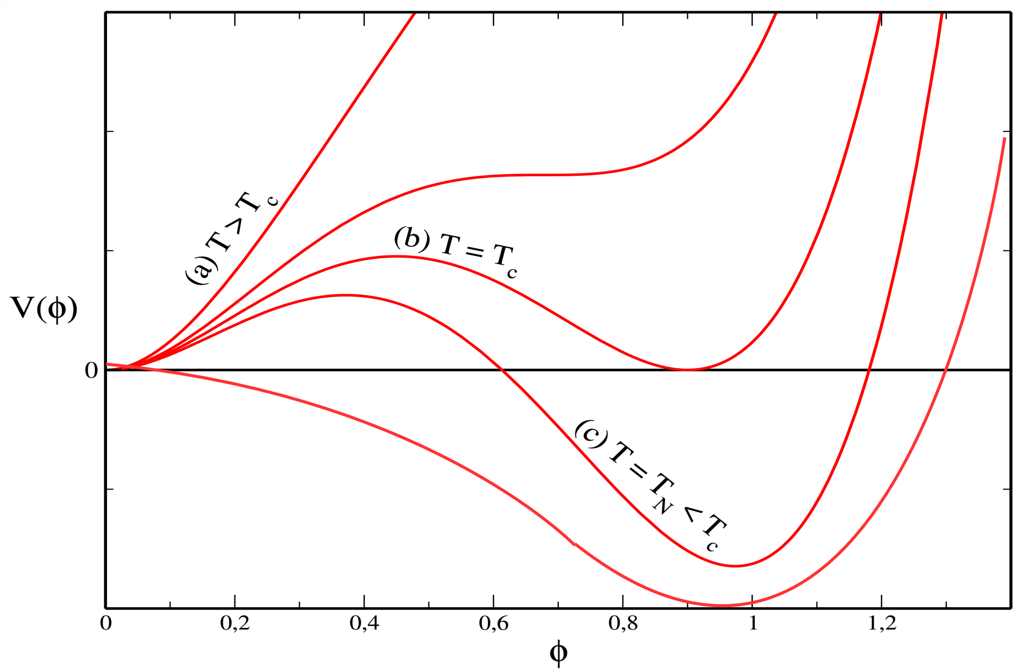

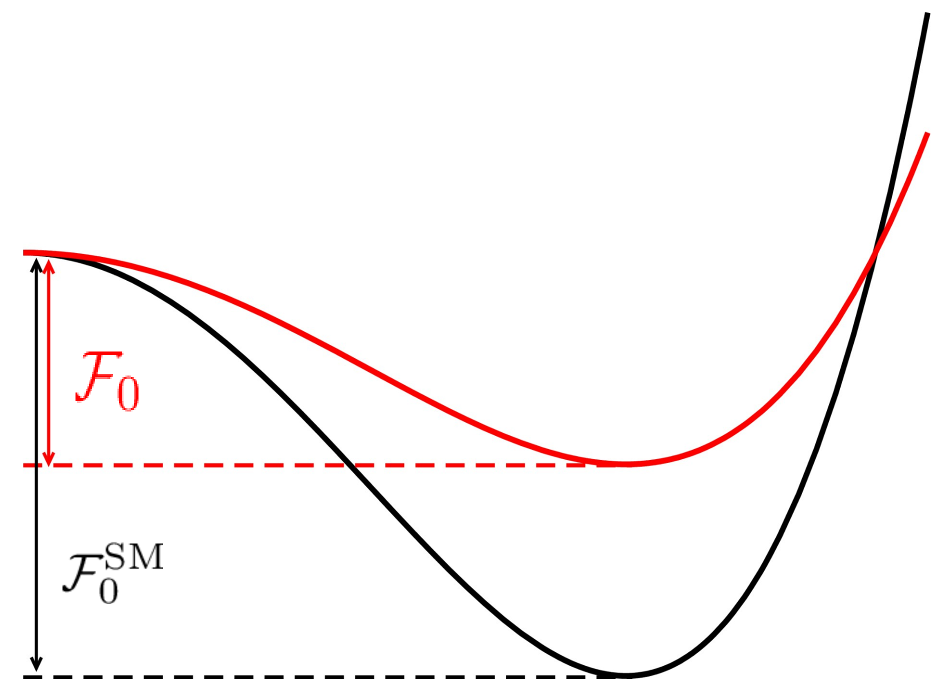

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Add New BOSONS to generate a thermal barrier

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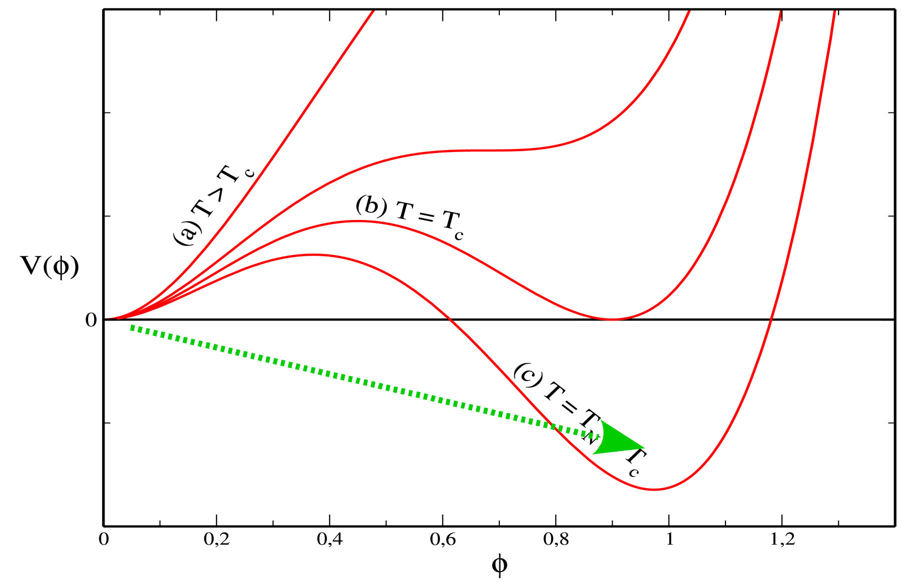
Add Particles whose loops reduce vacua energy difference.

⇨ **Tree-level Effects**

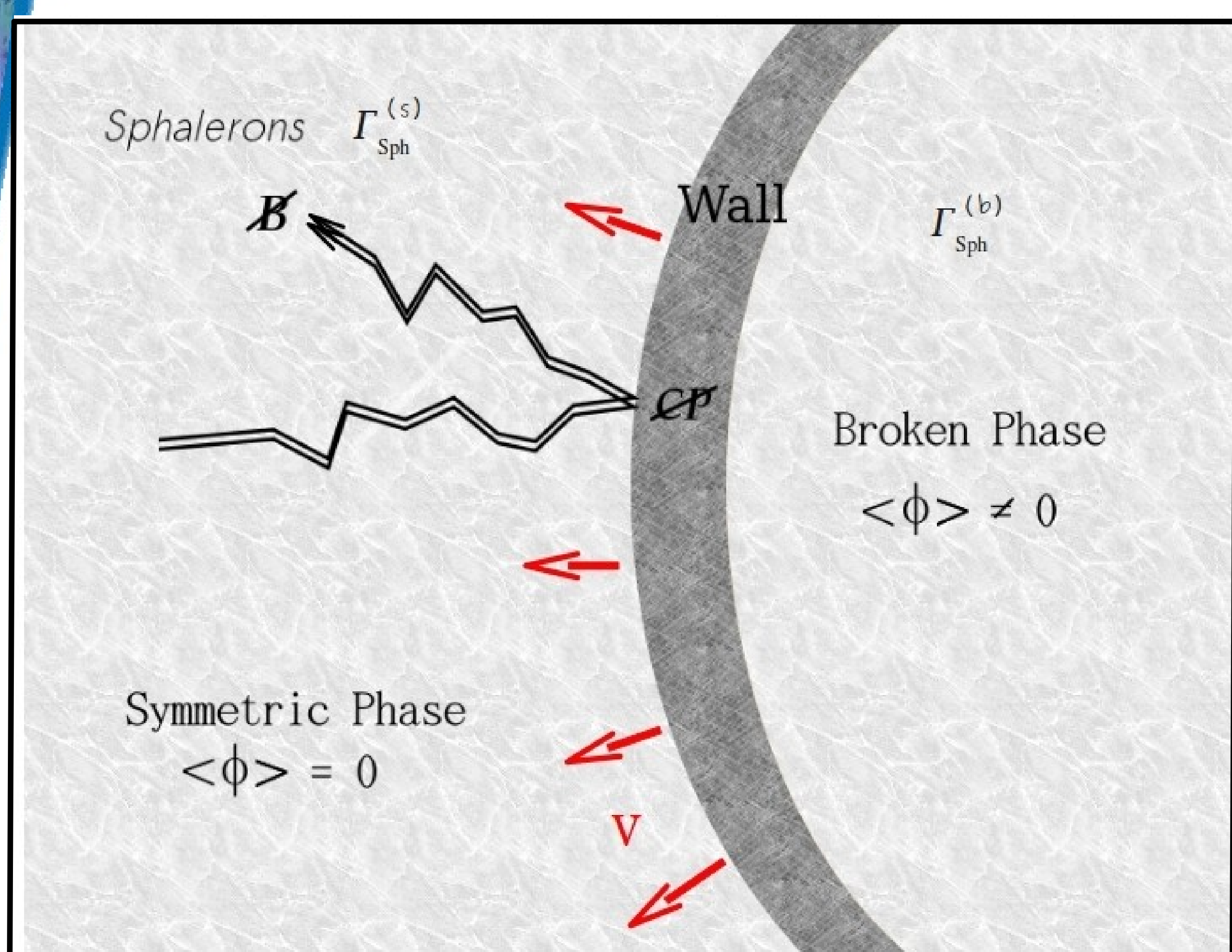
Add scalars that modify the tree-level potential

EW Phase Transition



$\Gamma^{(s)}_{\rm Sph} \sim (\alpha_W\, T)^4$

$\Gamma^{(b)}_{\rm Sph} \sim T^4\, e^{-E_{\rm Sph}/T}$

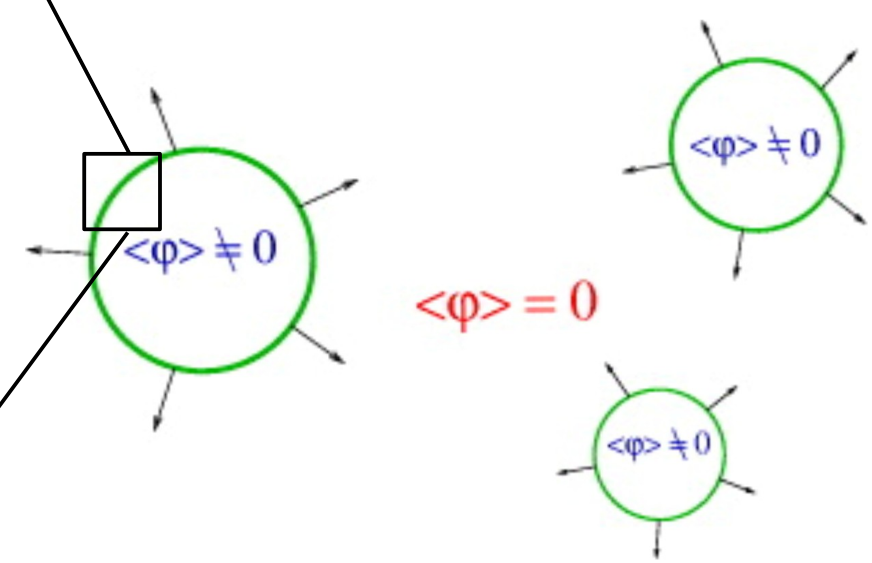


$$E_{\rm Sph} = \kappa \frac{4\pi\langle\phi\rangle}{g}$$

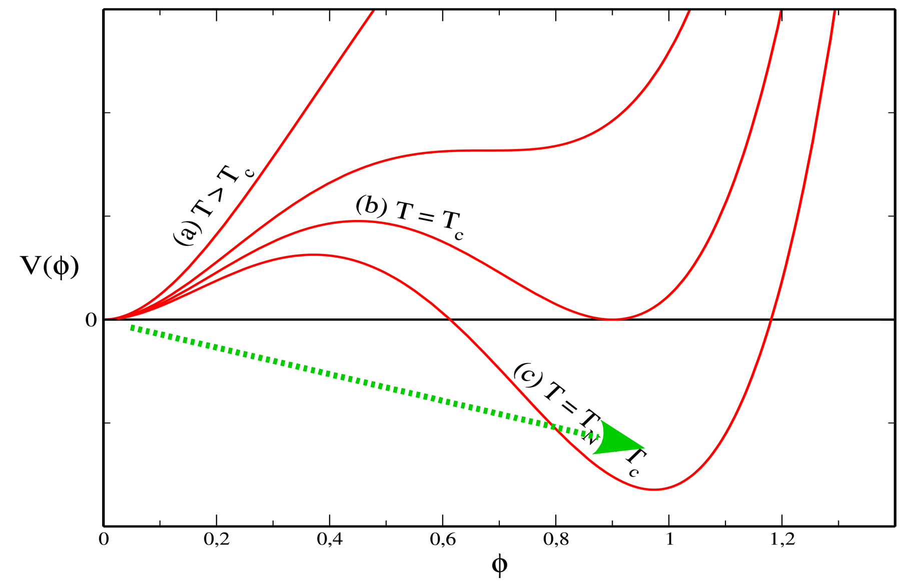
Out of Equilibrium

(SPHALERON SHUT-OFF)

$$\langle\phi\rangle/T > 1$$



EW Phase Transition



Issues with Gauge Dependence

Patel, Ramsey-Musolf, JHEP **1107** (2011) 029

Garny, Konstandin, JHEP **1207** (2012) 189

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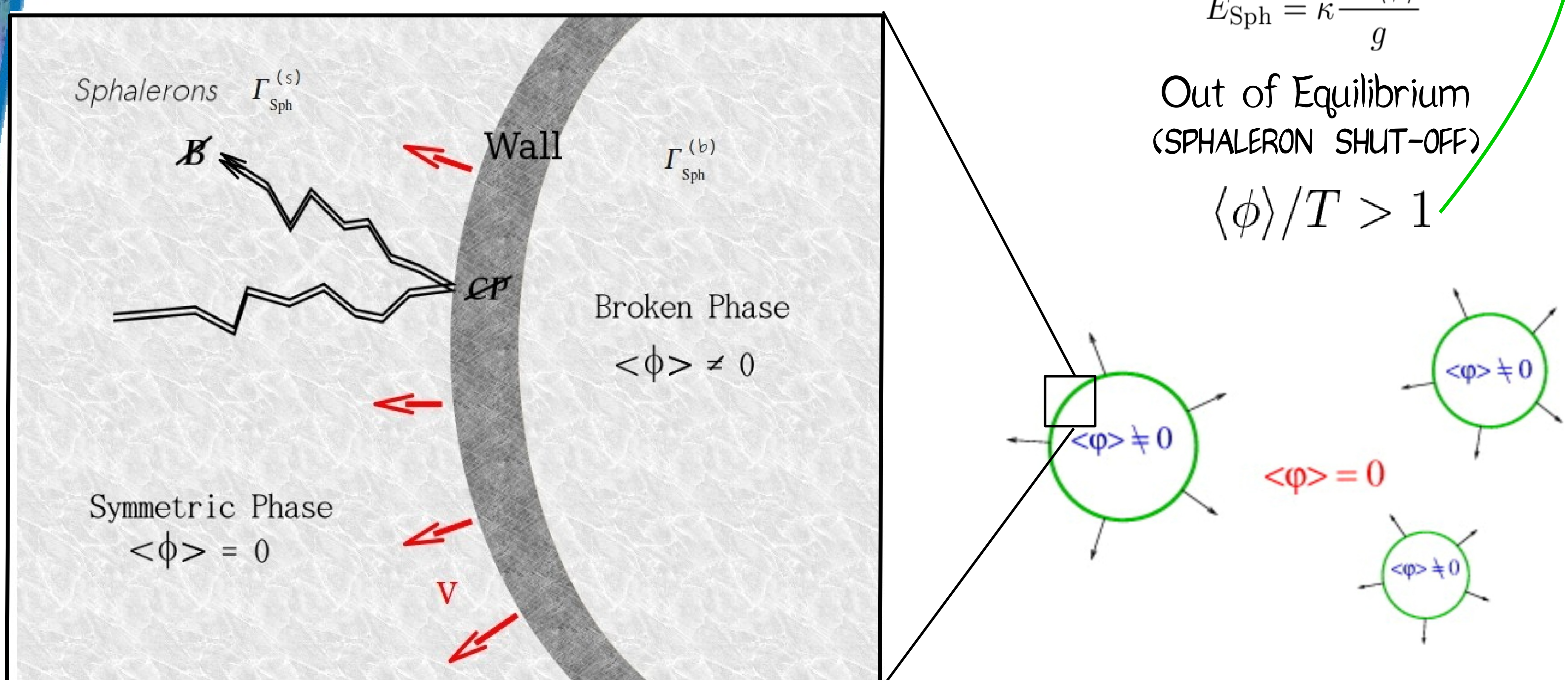

Baryogenesis with a Second Higgs

$$V(H_1,H_2) = \mu_1^2\,|H_1|^2 + \mu_2^2\,|H_2|^2 - \mu^2\left[H_1^\dagger H_2 + \text{h.c.}\right]$$
$$+ \frac{\lambda_1}{2}\,|H_1|^4 + \frac{\lambda_2}{2}\,|H_2|^4 + \lambda_3\,|H_1|^2\,|H_2|^2$$
$$+ \lambda_4\left|H_1^\dagger H_2\right|^2 + \frac{\lambda_5}{2}\left[\left(H_1^\dagger H_2\right)^2 + \text{h.c.}\right]$$

$$H_j = \begin{pmatrix} \phi_j^+ \\ \frac{v_j + h_j + i\,\eta_j}{\sqrt{2}} \end{pmatrix}$$

$$H^\pm = -s_\beta\,\phi_1^\pm + c_\beta\,\phi_2^\pm \qquad A_0 = -s_\beta\,\eta_1 + c_\beta\,\eta_2$$
$$h = -s_\alpha\,h_1 + c_\alpha\,h_2 \qquad H_0 = -c_\alpha\,h_1 - s_\alpha\,h_2$$

ALL Needed Ingredients for EW Baryogenesis: **Out-of-Equilibrium + CPV**

~~Baryogenesis~~ with a Second Higgs

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$$V(H_1,H_2) = \mu_1^2\,|H_1|^2 + \mu_2^2\,|H_2|^2 - \mu^2\left[H_1^\dagger H_2 + \text{h.c.}\right] + \frac{\lambda_1}{2}\,|H_1|^4 + \frac{\lambda_2}{2}\,|H_2|^4 + \lambda_3\,|H_1|^2\,|H_2|^2 + \lambda_4\left|H_1^\dagger H_2\right|^2 + \frac{\lambda_5}{2}\left[\left(H_1^\dagger H_2\right)^2 + \text{h.c.}\right]$$

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ALL Needed Ingredients for EW Baryogenesis: Out-of-Equilibrium + CPV

For Simplicity, let's not consider CPV yet

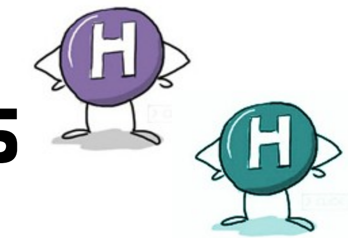
BSM Parameters m_{H_0} m_{A_0} $m_{H^\pm}$ $\tan\beta$ $\cos(\beta-\alpha)$ μ^2

EWPO: $m_{H^\pm} \simeq m_{H_0}$ or $m_{H^\pm} \simeq m_{A_0}$

Choice of H_j Couplings to Fermions not Relevant for EW Phase Transition

Type I , Type II ...

Baryogenesis with a Second Higgs



EW Phase Transition

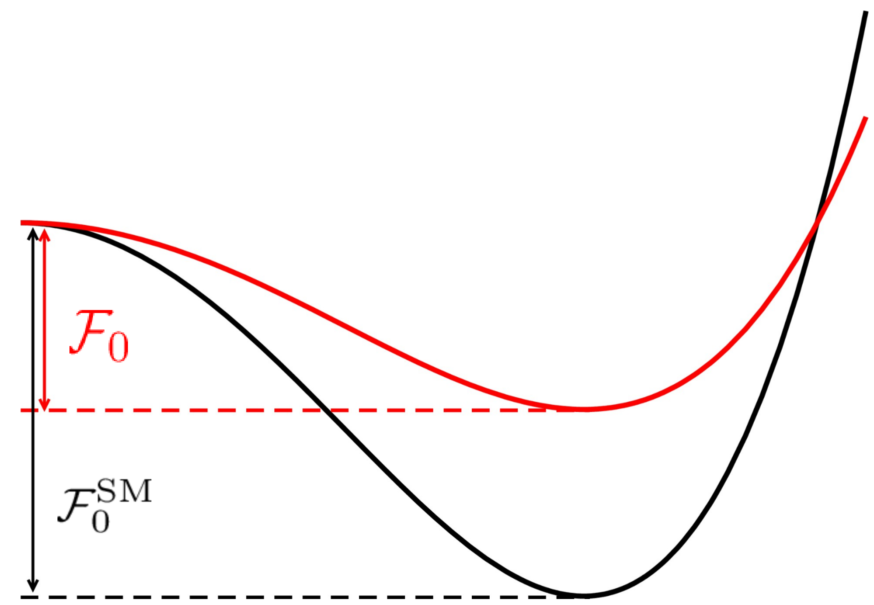
Thermal + Loop + Tree-level Effects

~~Baryogenesis~~ with a Second Higgs

EW Phase Transition

Thermal + Loop + Tree-level Effects

$$\mathcal{F}_0 = V_0(v) + V_0^{\rm loop}(v) - V_0(0) - V_0^{\rm loop}(0)$$



Journal of High Energy Physics
June 2016, 2016:5

Does zero temperature decide on the nature of the electroweak phase transition?

Christopher P.D. Harman, Stephan J. Huber

*Huang, Kang, Shu, Wu, Yang, Phys.Rev. D**91** (2015) 025006*
*Harman, Huber, JHEP **1606** (2016) 005*

Baryogenesis with a Second Higgs

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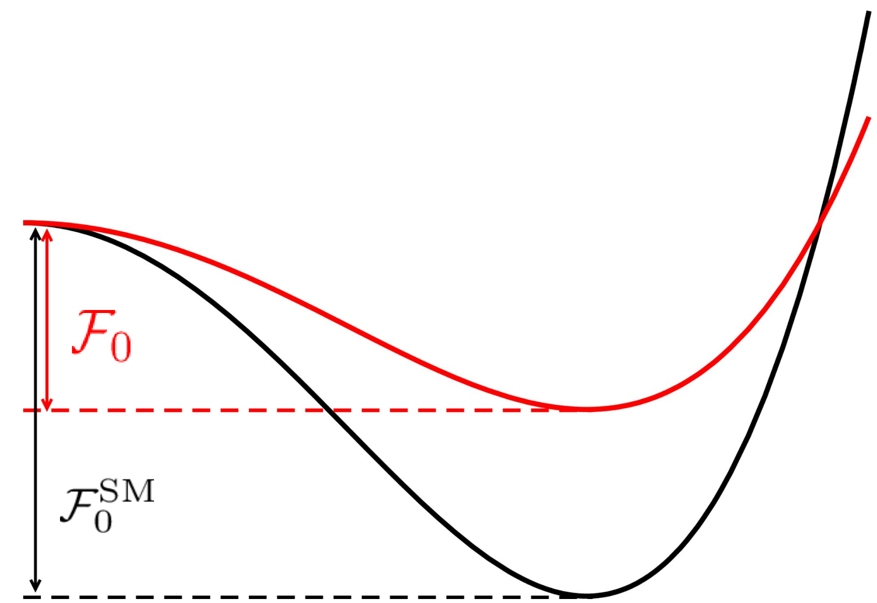

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$$\left[\mathcal{F}_0 - \mathcal{F}_0^{\rm SM}\right]_{\rm tree} = -\frac{v^2}{8} c^2_{\beta-\alpha}(m^2_{H_0} - m^2_h) < 0$$

(Assuming m_h = 125 GeV)

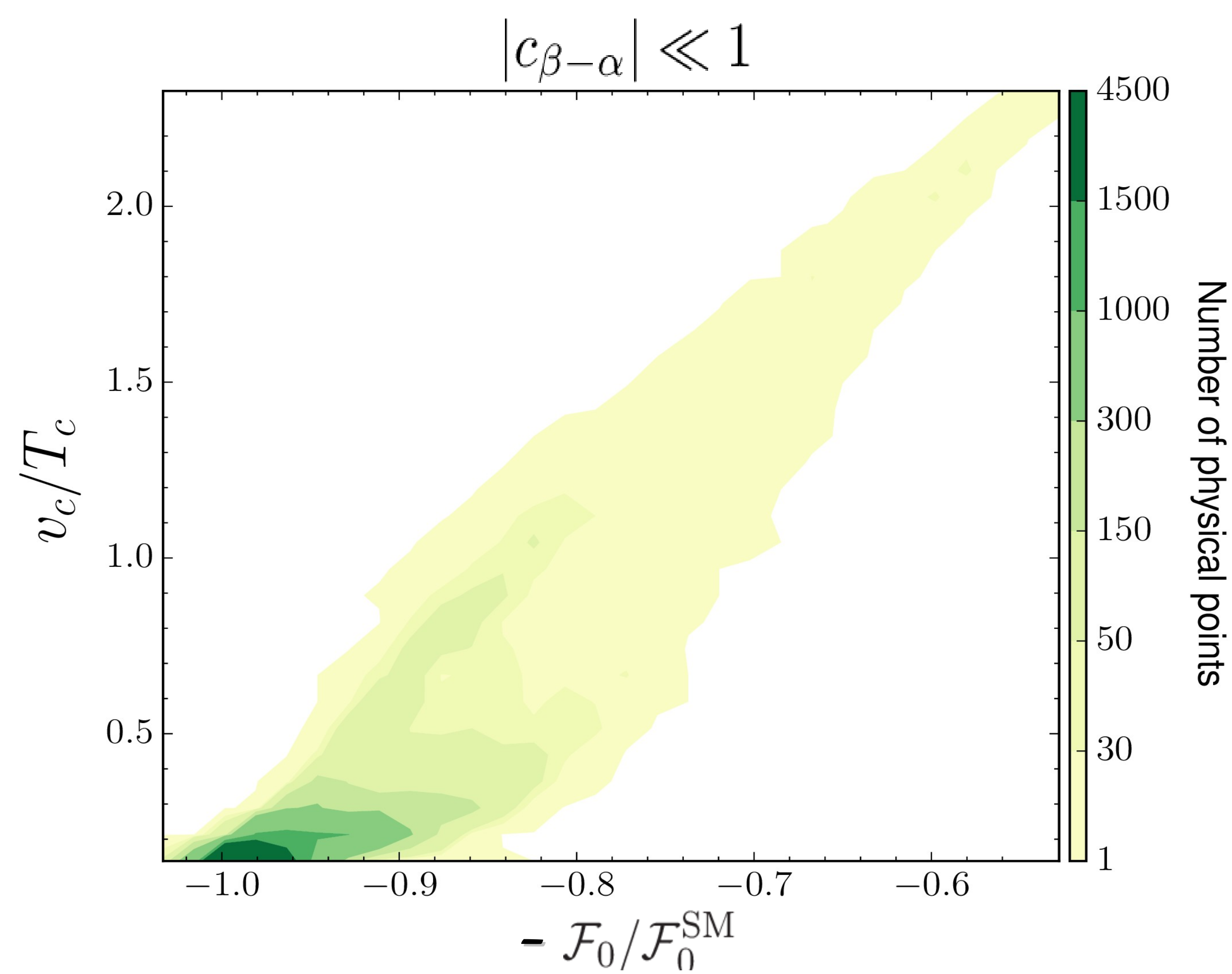
Baryogenesis with a Second Higgs

EW Phase Transition

LET'S LOOK (FIRST) AT THE ALIGNMENT LIMIT:

$$\mathcal{F}_0 - \mathcal{F}_0^{\rm SM} = \frac{1}{64\,\pi^2}\left[\left(2M^2 - m_h^2\right)^2\left(\frac{3}{2}+\frac{1}{2}\log\left[\frac{4\,m_{A_0}\,m_{H_0}\,m_{H^\pm}^2}{\left(2M^2-m_h^2\right)^2}\right]\right)\right.$$
$$\left. + \frac{1}{2}\left(m_{A_0}^4 + m_{H_0}^4 + 2\,m_{H^\pm}^4\right) - \left(2M^2 - m_h^2\right)\left(m_{A_0}^2 + m_{H_0}^2 + 2\,m_{H^\pm}^2\right)\right]$$

$$M^2 = \mu^2/(s_\beta c_\beta)$$



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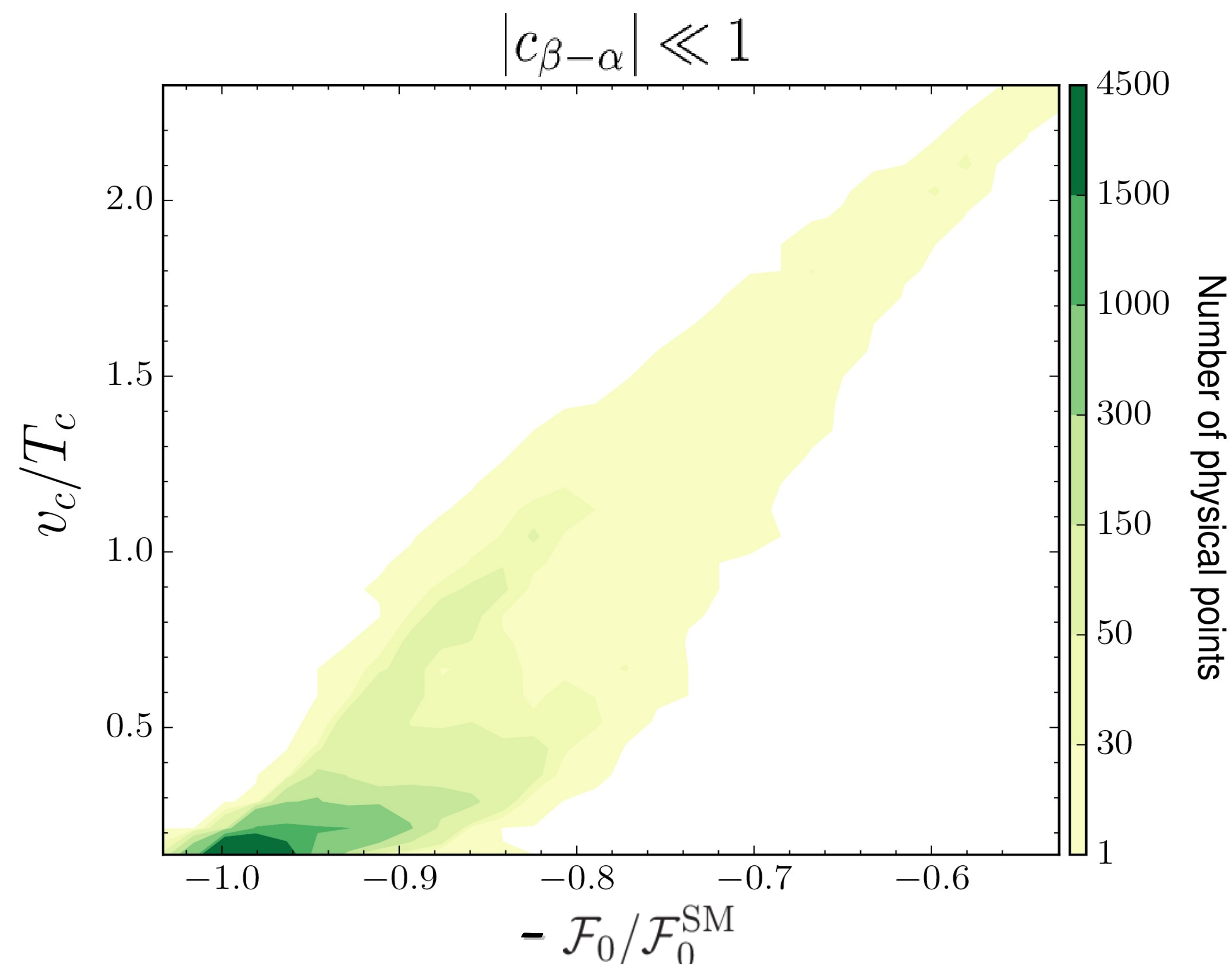
$$M^2 = \mu^2/(s_\beta c_\beta)$$

Combine with (tree-level)

Vacuum Stability and Unitarity

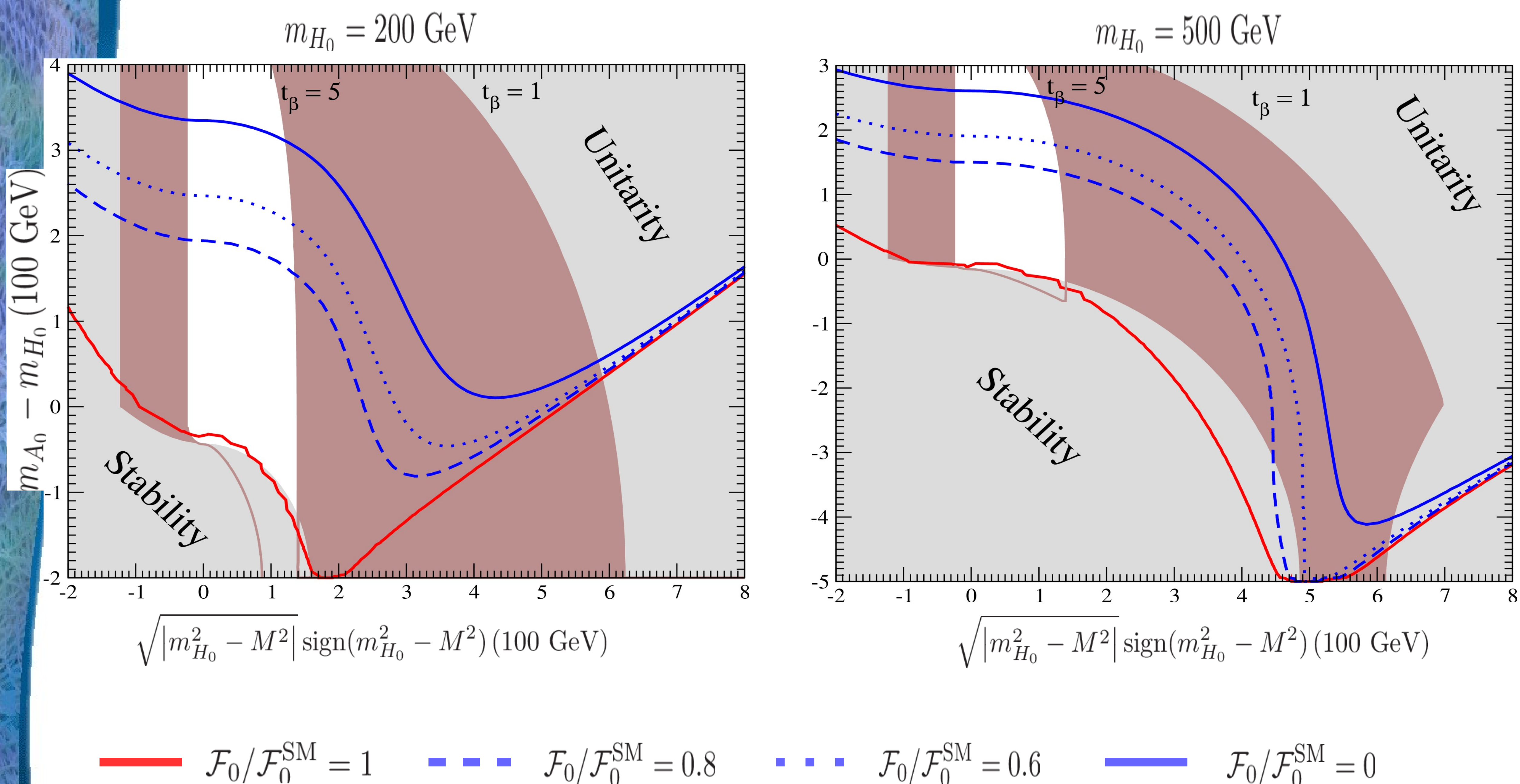
*Gunion, Haber, Phys.Rev. D**67** (2003) 075019*
*Ginzburg, Ivanov, Phys.Rev. D**72** (2005) 115010*
*Barroso, Ferreira, Ivanov, Santos, JHEP **1306** (2013) 045*



~~Baryogenesis~~ with a Second Higgs

EW Phase Transition

$$m_{H^\pm} \simeq m_{A_0}$$



Dorsch, Huber, Mimasu, JMN, arXiv:1609.xxxxx

Baryogenesis with a Second Higgs

EW Phase Transition

- ⇒ EW Phase Transition Favours 2HDM Alignment or $m_{H_0} \sim m_h$
- ⇒ EW Phase Transition Favours $m_{A_0} - m_{H_0} \sim v$ (> m_Z)

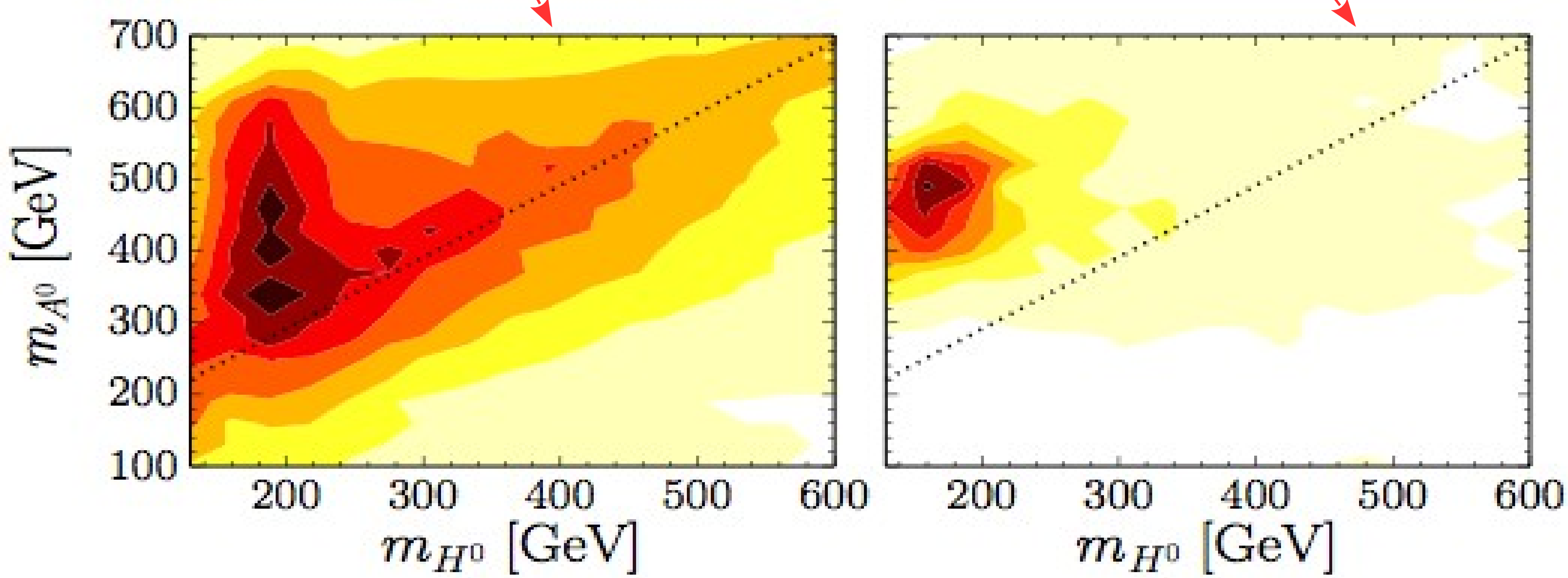
Baryogenesis with a Second Higgs

EW Phase Transition

⇒ EW Phase Transition Favours 2HDM Alignment or $m_{H_0} \sim m_h$

⇒ EW Phase Transition Favours $m_{A_0} - m_{H_0} \sim v$ (> m_Z)

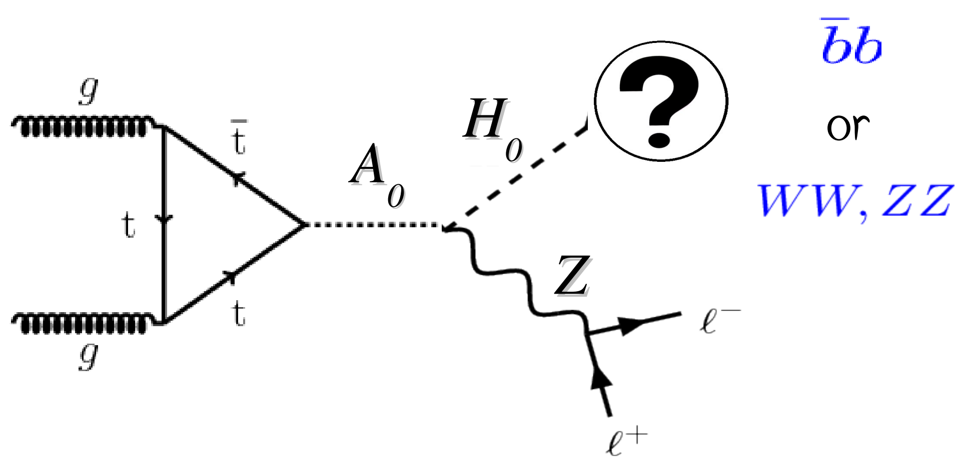
Physically Allowed ⊃ EW Phase Transition



EW Phase Transition SIGNATURE

$$A_0 \rightarrow H_0\, Z$$

Dorsch, Huber, Mimasu, JMN, Phys. Rev. Lett. **113** (2014) 211802



Baryogenesis with a Second Higgs

EW Phase Transition

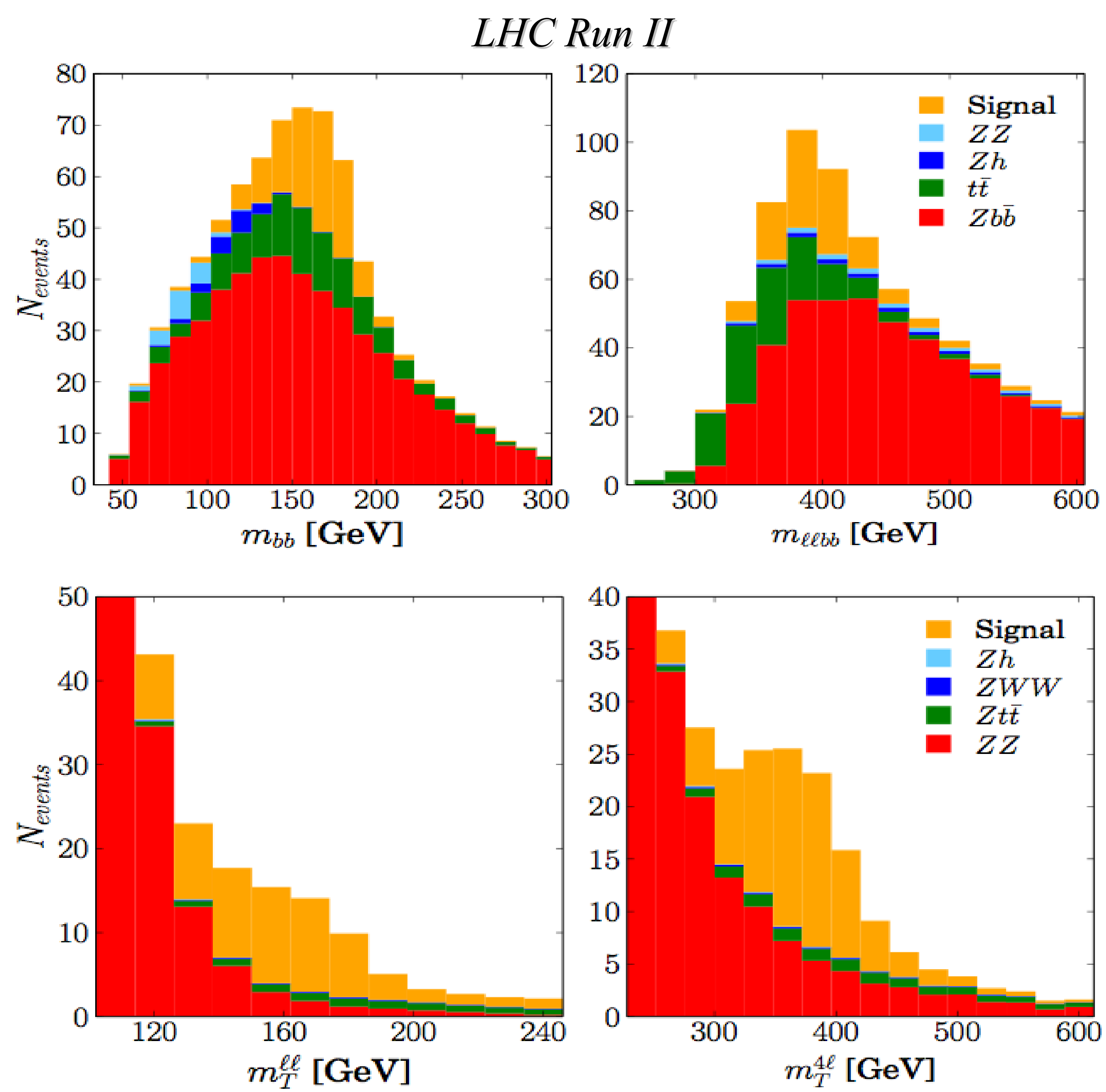
@ LHC

$$A_0 \to H_0\, Z \to \bar{b}b\, \ell\ell$$

$$A_0 \to H_0\, Z \to W^+W^-\ell\ell$$

$$(m_T^{\ell\ell})^2 = \left(\sqrt{p_{T,\ell\ell}^2 + m_{\ell\ell}^2} + \not{p}_T\right)^2 - \left(\vec{p}_{T,\ell\ell} + \vec{\not{p}}_T\right)^2$$

$$m_T^{4\ell} = \sqrt{p_{T,\ell'\ell'}^2 + m_{\ell'\ell'}^2} + \sqrt{p_{T,\ell\ell}^2 + (m_T^{\ell\ell})^2}$$

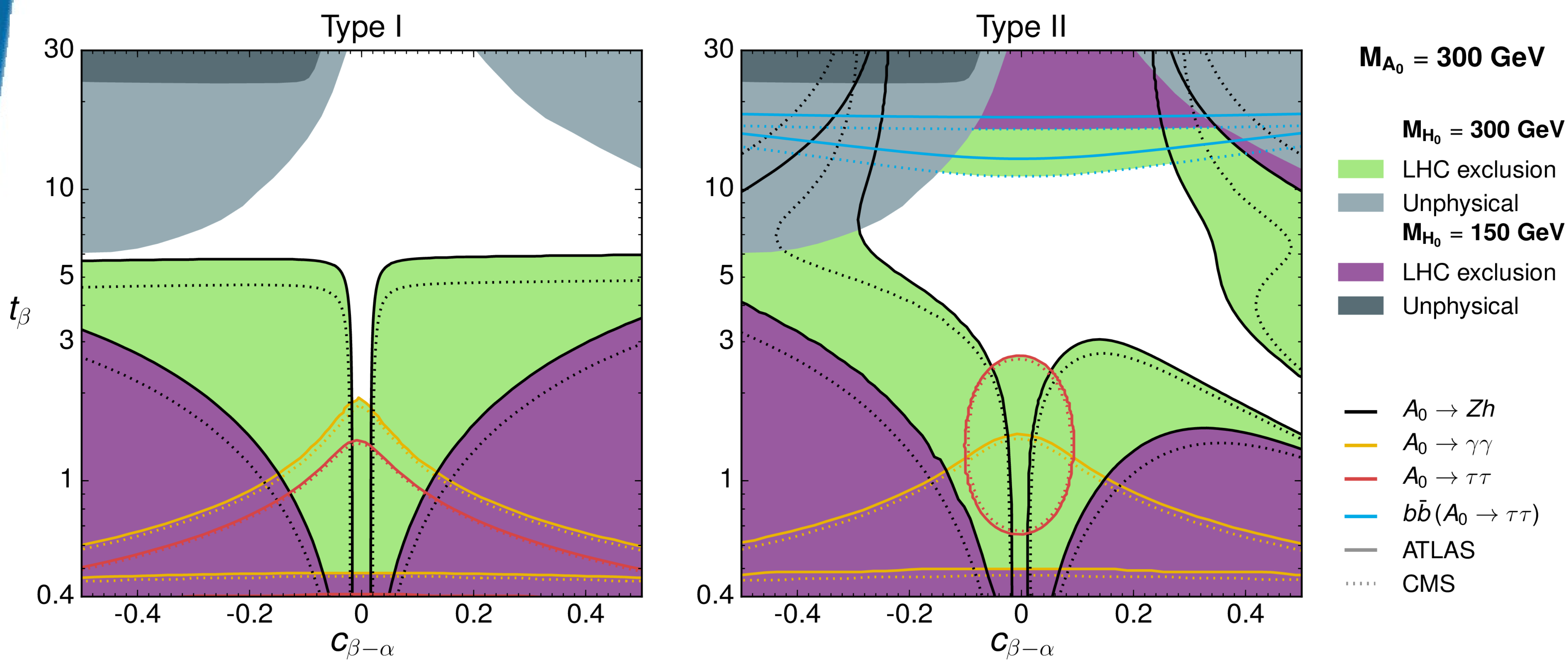


Baryogenesis with a Second Higgs

EW Phase Transition

@ LHC

$A_0 \to H_0\, Z$ channel Open → BR to other decay channels drastically reduced



*Dorsch, Huber, Mimasu, JMN, Phys. Rev. D**93** (2016) 115033*

CMS-PAS-HIG-15-001

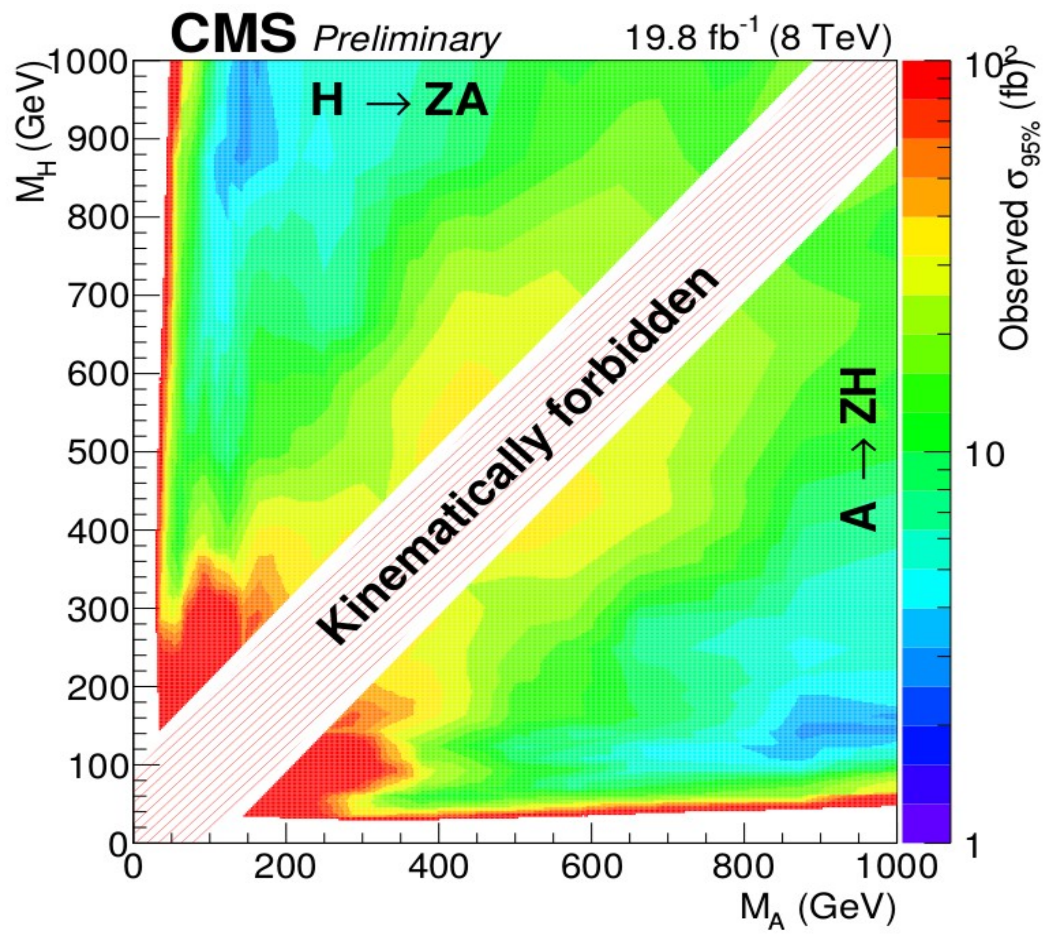
Phys. Lett. B759 (2016) 369 (ArXiv:1603.02991)

Search for H/A decaying into Z and A/H, with Z→ $\ell\ell$ and A/H→ bb or A/H→ $\tau\tau$

The CMS Collaboration

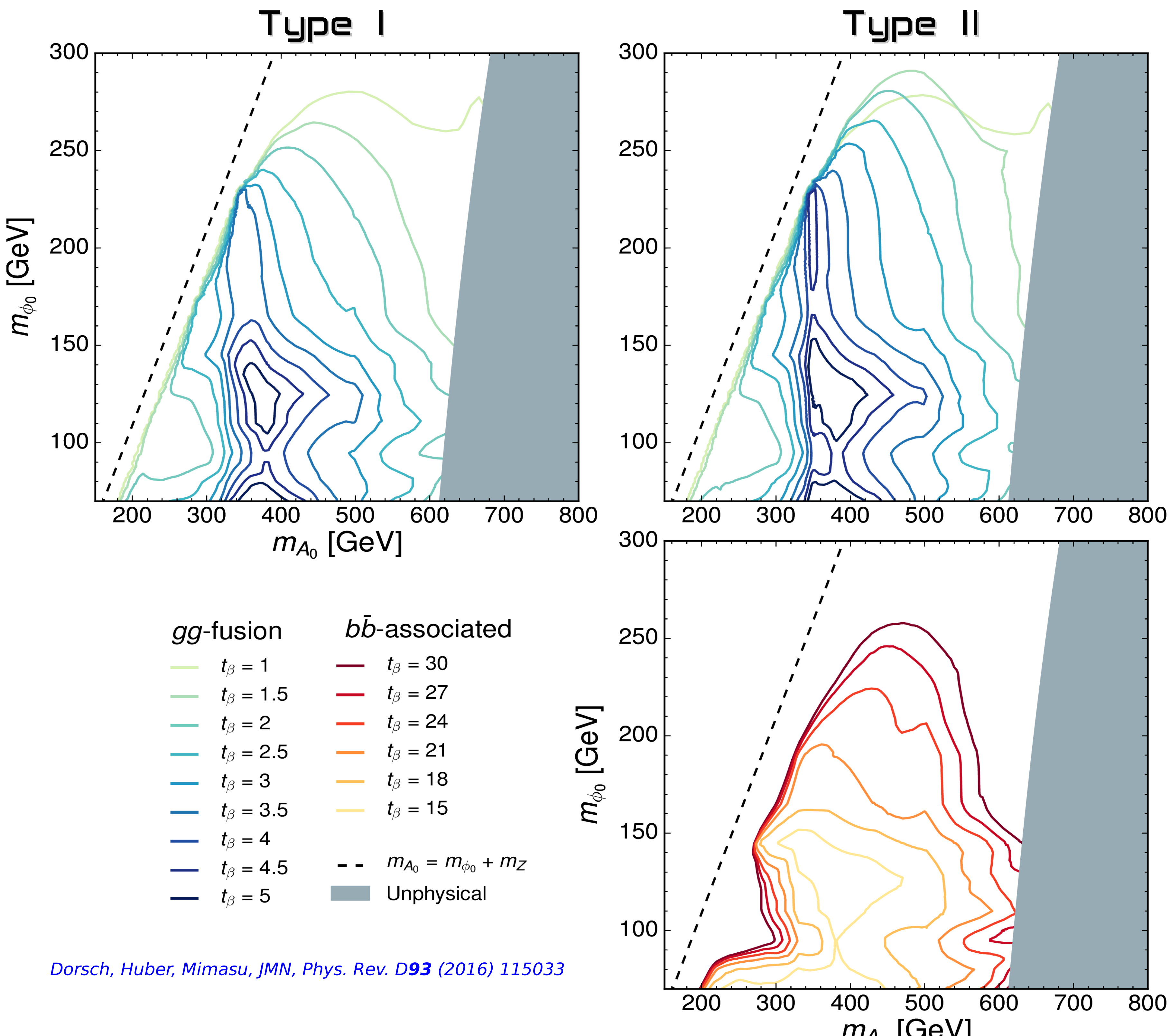
One important motivation for 2HDMs is that these models provide a way to explain the asymmetry between matter and anti-matter observed in the Universe [4, 5]. Another important motivation is Supersymmetry [6], which is a theory that falls in the broad class of 2HDMs. Axion models [7], which would explain how the strong interaction does not violate the CP symmetry, would give rise to an effective low-energy theory with two Higgs doublets. Finally, it has also been recently noted [8] that certain realizations of 2HDMs can accommodate the muon $g-2$ anomaly [9] without violating the present theoretical and experimental constraints.

In the most general case 14 parameters are necessary to describe the scalar sector in a 2HDM. However, only 6 free parameters remain once the so-called Z_2 symmetry is imposed to suppress flavor changing neutral currents, in agreement with experimental observations, and the values of the mass of the recently discovered Higgs boson (125 GeV) and the electroweak vacuum expectation value (246 GeV) are assumed. The compatibility of a 125 GeV SM-like Higgs boson with 2HDMs is possible in the so-called alignment limit. In such a limit, one of the CP-even scalars, h or H, is identified with the 125 GeV Higgs boson and the condition $cos(\beta-\alpha)\approx 0$ or $sin(\beta-\alpha)\approx 0$ is satisfied, where $\tan\beta$ and α are, respectively, the ratio of the vacuum expectation values, and the mixing angle of the two Higgs doublets. A recent theoretical study [5] has shown that, in this limit, a large mass splitting (>100 GeV) between the A and H bosons would favor the electroweak phase transition that would be at the origin of the baryogenesis process in the early Universe, thus explaining the currently observed matter-antimatter asymmetry in the Universe. In such a scenario, the most frequent decay mode of the pseudoscalar A boson would be A→ZH.



Meaningful Constraints from LHC Run 1

(Assume 2HDM Alignment)



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Baryogenesis with a Second Higgs

Out-of-Equilibrium ✓
(EW Phase Transition)

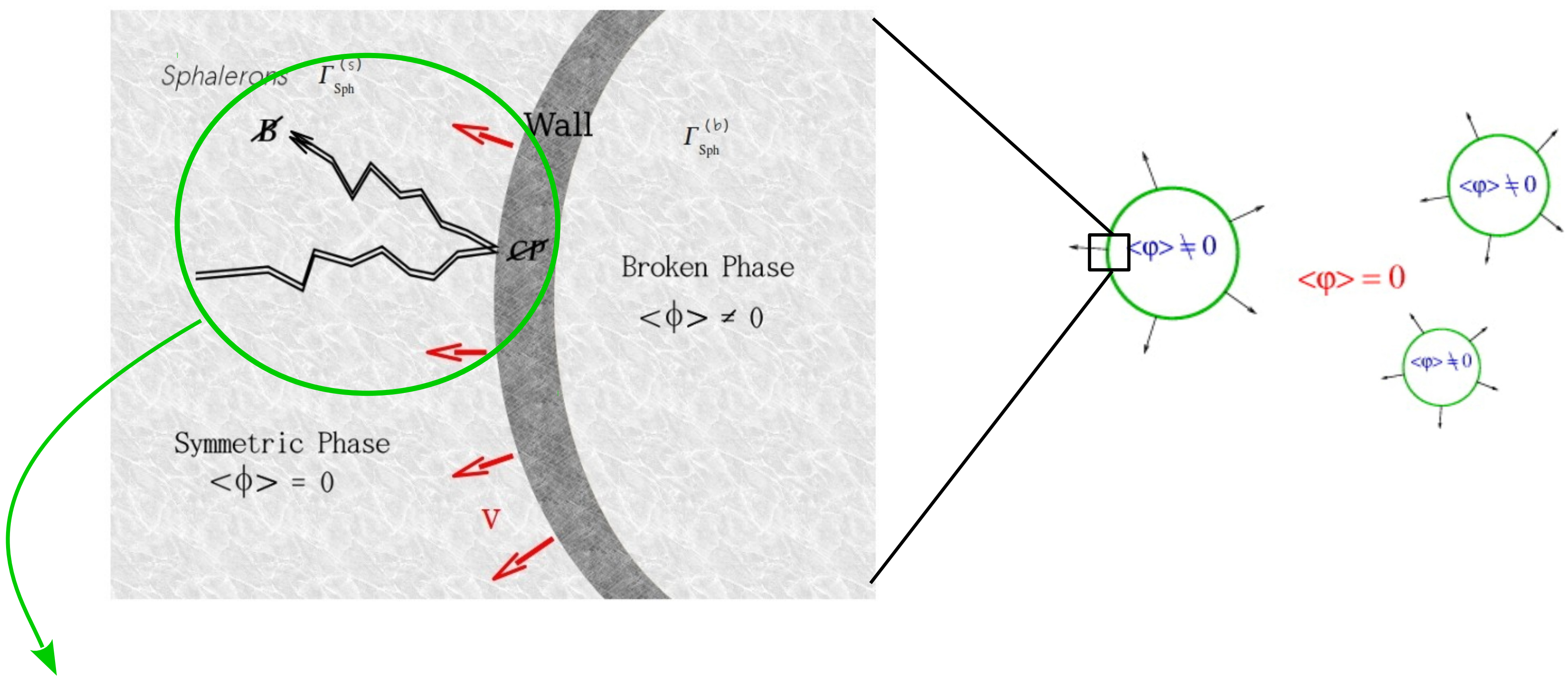
CPV: Baryogenesis vs EDMs

Baryogenesis with a Second Higgs

Out-of-Equilibrium ✓
(EW Phase Transition)

CPV: Baryogenesis vs EDMs

But before that... an Equally Important Issue



The Bubble Wall Velocity is Key for Successful Baryogenesis

$$\partial_\mu \partial^\mu \phi + \frac{\partial \mathcal{F}}{\partial \phi} - \mathcal{K}(\phi) = 0 \qquad \mathcal{K}(\phi) = -\sum_i \frac{dm_i^2}{d\phi} \int \frac{d^3p}{(2\pi)^3 2E_i} \delta f_i(p)$$

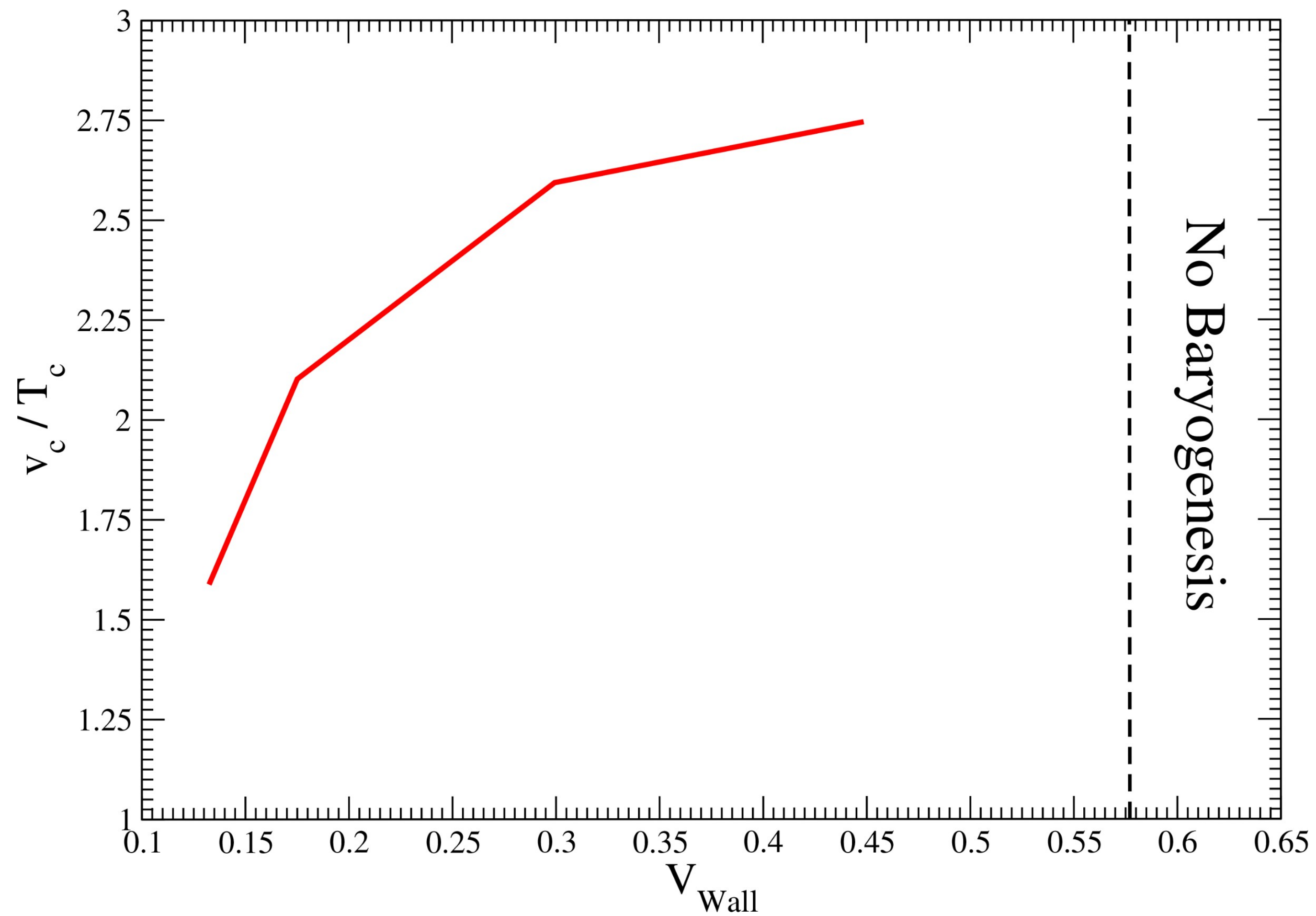
$$F_\eta(v_w) = \int_{-\infty}^{\infty} dz \, \frac{d\phi}{dz} \sum_i \frac{dm_i^2}{d\phi} \int \frac{d^3p}{(2\pi)^3 2E_i} \delta f_i(p) \simeq \eta \, v_w$$

Baryogenesis with a Second Higgs

Out-of-Equilibrium ✓
(EW Phase Transition)

CPV: Baryogenesis vs EDMs

But before that... an Equally Important Issue



Towards a Global Picture of Baryogenesis in the 2HDM

Dorsch, Huber, Konstandin, JMN, arXiv:16xx.xxxxx

Before I Conclude... (in 30s)

Introducing a new 2HDM Public Code → **py2HDM**
(soon to be!)
G. Dorsch, K. Mimasu, (JMN)

⇒ The Usual Things:

Theoretical Constraints: Vacuum Stability, Perturbativity, Unitarity. EWPO. Scalar BRs.

⇒ + CP Violation (Scalar BRs & EDMs) → 2-loop Running of Quartics

+ EW Phase Transition

Modular & "Pure-Execution" Modes

(since not everyone will be interested in computing EDMs or the strength of the EW Phase Transition!)

We would be very happy to get your feedback!


KEEP
CALM
AND FIND THE
HIGGS
BOSONs