More Higgses: Dark Matter & Matter/Antimatter Asymmetry

Jose Miguel No
University of Sussex

Padua, INVISIBLES 2016, 16/09/2016

BSM TO DO LIST

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

BSM TO DO LIST

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

Impact of a non-minimal Higgs Sector

BSM TO DO LIST

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

Impact of a non-minimal Higgs Sector

"When ONE Higgs is NOT Enough"

Matter-Antimatter Asymmetry

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

- B Violation
- C/CP Violation
- Departure from Thermal Equilibrium

Matter-Antimatter Asymmetry

<u>SAKHAROV CONDITIONS</u> *(for dynamical generation of baryon asymmetry)*

B Violation ✓ *Sphalerons*

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

C/CP Violation *CKM*

Departure from Thermal Equilibrium *EW Phase Transition*

Matter-Antimatter Asymmetry

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

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

- 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
- Departure from Thermal Equilibrium ✗ *not enough*
  Kajantie, Laine, Rummukainen, Shaposhnikov, Phys. Rev. Lett. **77** (1996) 2887

Matter-Antimatter Asymmetry

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

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

- 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
- Departure from Thermal Equilibrium ✗ *not enough*
  Kajantie, Laine, Rummukainen, Shaposhnikov, Phys. Rev. Lett. **77** (1996) 2887

→ EW Phase Transition Smooth CrossOver

→ No CPV in Scalar Sector

Matter-Antimatter Asymmetry

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

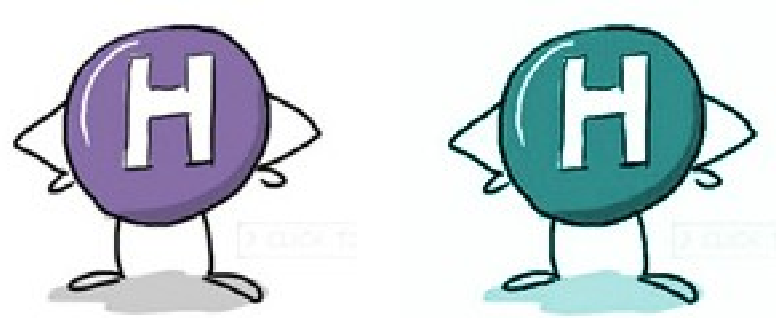
B Violation ✓ **Sphalerons**

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

C/CP Violation ✓

Departure from Thermal Equilibrium ✓

More Higgses Help



....

Scalar-Philic

Matter-Antimatter Asymmetry

<u>SAKHAROV CONDITIONS</u> *(for dynamical generation of baryon asymmetry)*

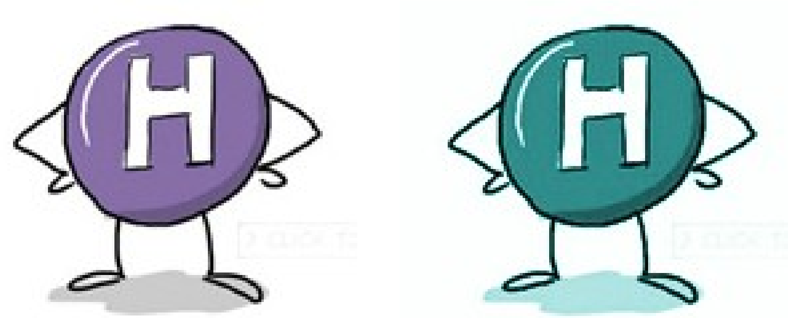
B Violation ✓ **Sphalerons**

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

C/*CP* Violation

Departure from Thermal Equilibrium

✓
✓ **More Higgses Help**



....

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

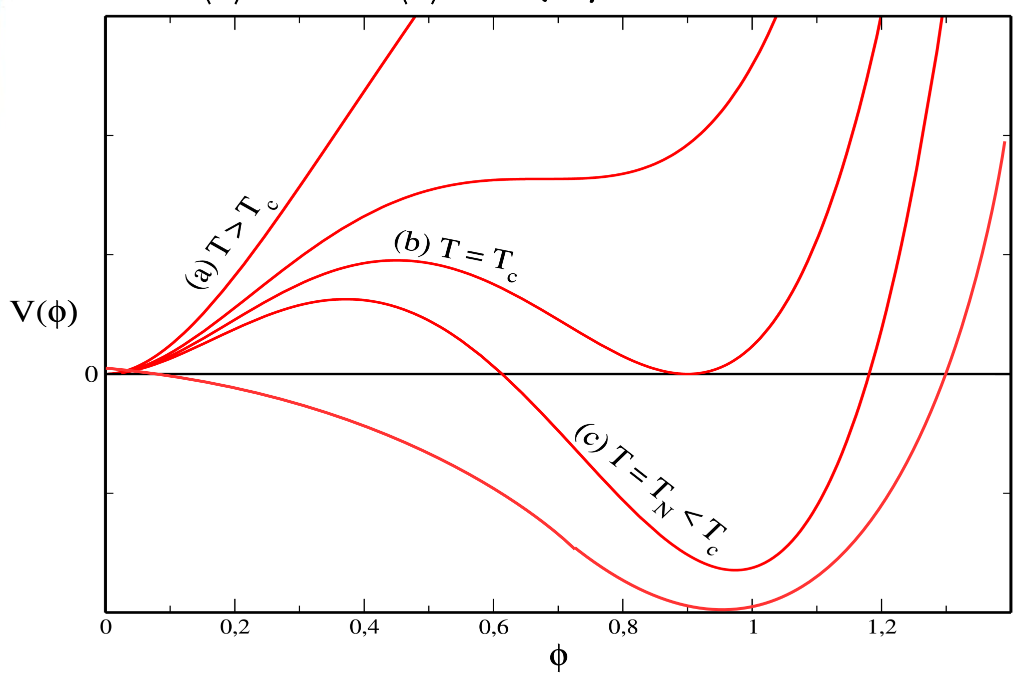
EW Phase Transition

$$\approx (a\,T^2 - \mu^2)\,h^2 - E(T)\,h^3 + \lambda_{eff}(T)\,h^4$$

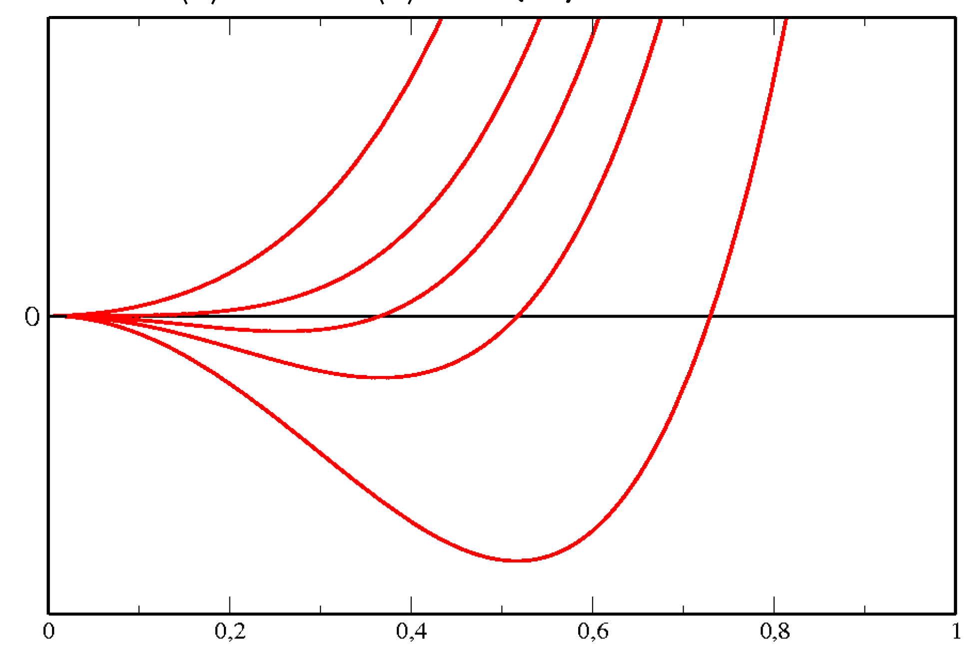
$$\boxed{V_{\rm eff}(h,T) = V_0(h) + V_0^{\rm loop}(h) + V_T(h,T)}$$

Tree-level potential | Loop corrections | Thermal corrections

1st Order: $\langle h \rangle = 0 \rightarrow \langle h \rangle = h(T)$ Discontinuous



2nd Order: $\langle h \rangle = 0 \rightarrow \langle h \rangle = h(T)$ Continuous



EW Phase Transition

$$\approx (a\,T^2 - \mu^2)\,h^2 - E(T)\,h^3 + \lambda_{eff}(T)\,h^4$$

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

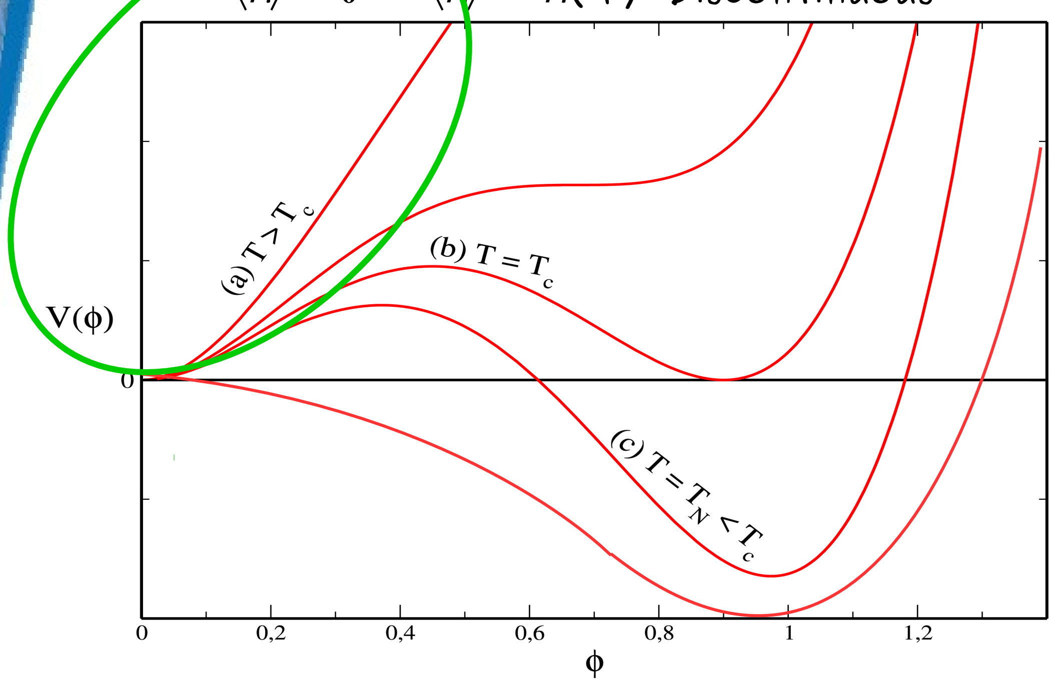
Tree-level potential | Loop corrections | Thermal corrections

$T \gg v$

EW Symmetry Restoration

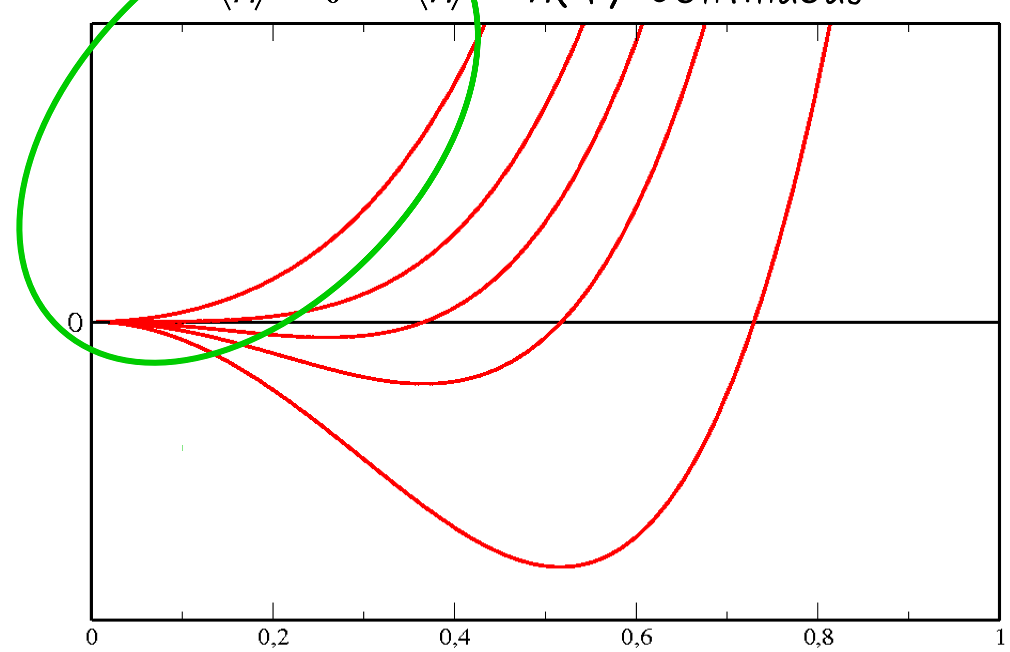
1^{st} Order:

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



2^{nd} Order:

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



EW Phase Transition

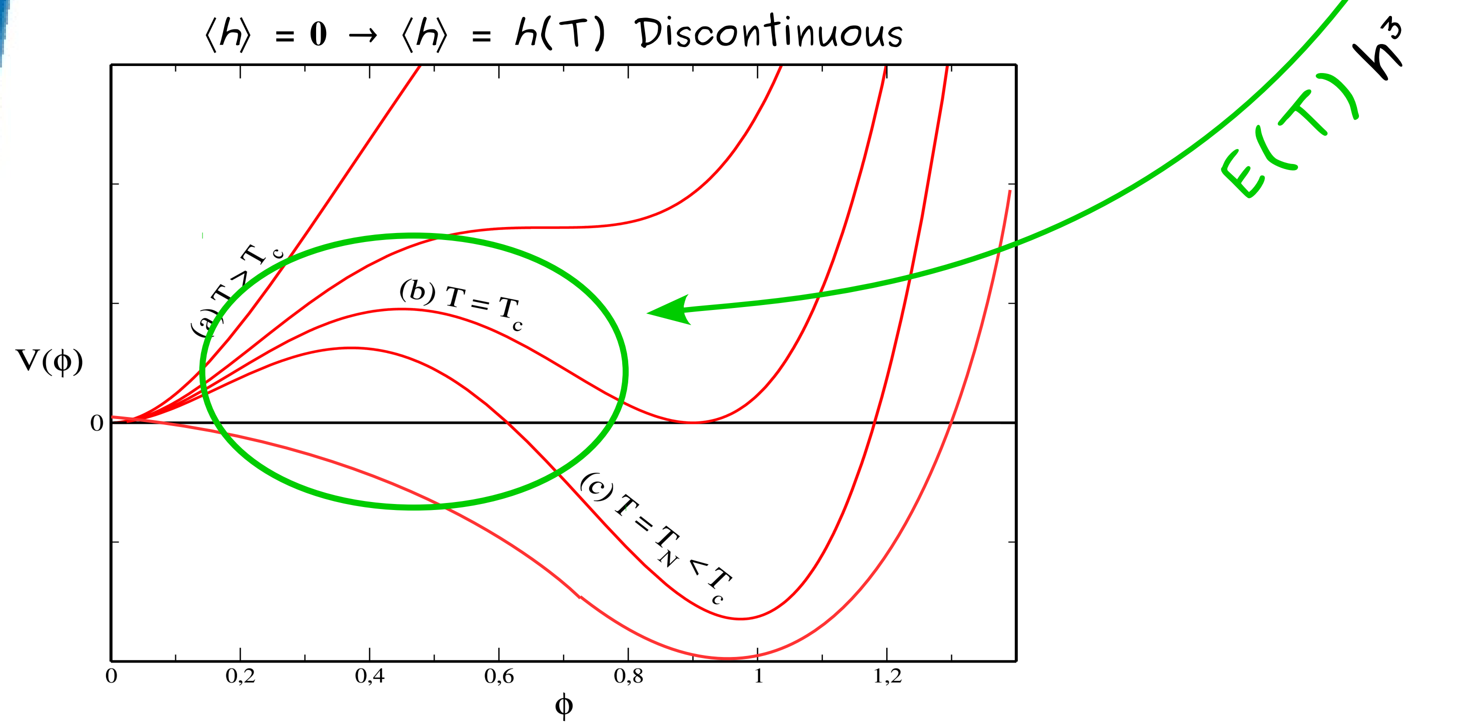
$$\approx (a\,T^2 - \mu^2)\,h^2 - E(T)\,h^3 + \lambda_{eff}(T)\,h^4$$

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

Tree-level potential | Loop corrections | Thermal corrections

1^{st} Order:

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



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

Add New BOSONS to generate a thermal barrier

EW Phase Transition

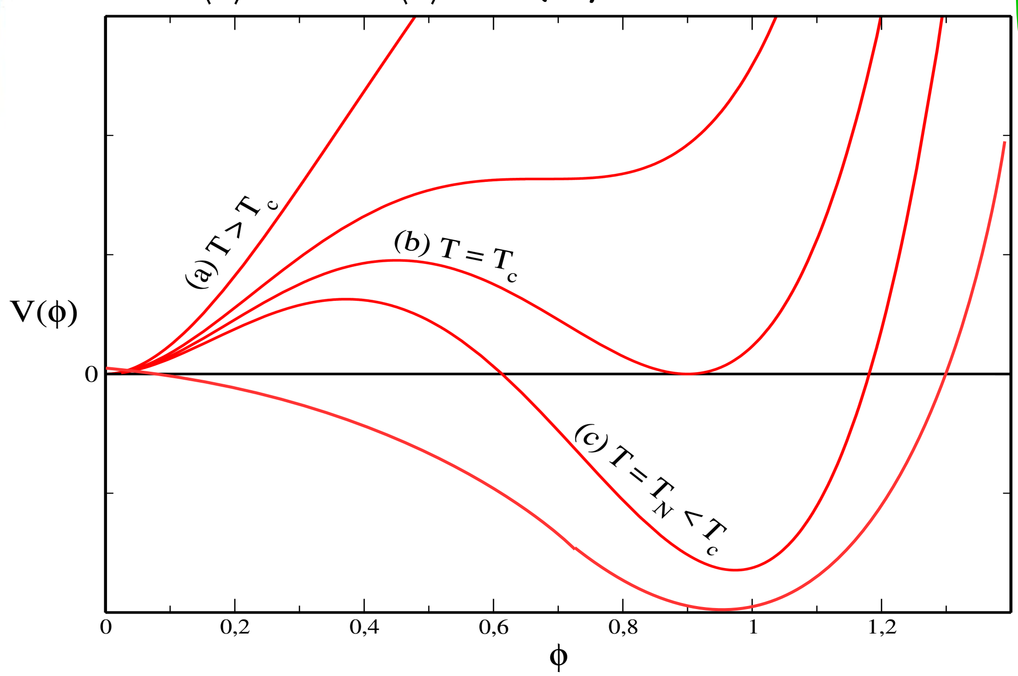
$$\approx (a\,T^2 - \mu^2)\,h^2 - E(T)\,h^3 + \lambda_{eff}(T)\,h^4$$

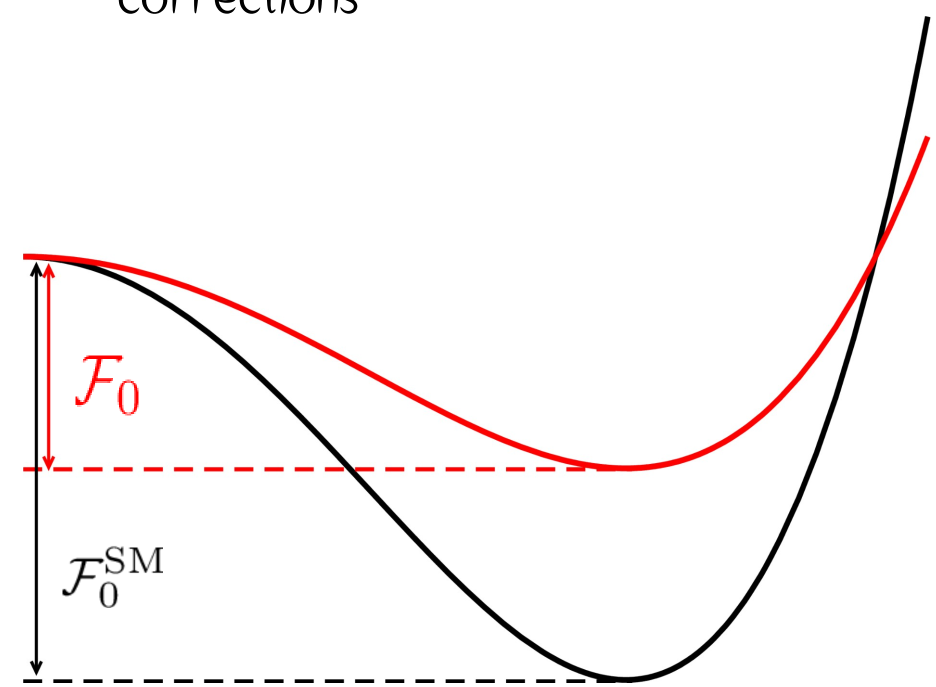
$$V_{\rm eff}(h,T) = V_0(h) + V_0^{\rm loop}(h) + V_T(h,T)$$

Tree-level potential | Loop corrections | Thermal corrections

1^{st} Order:

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





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

Add New BOSONS to generate a thermal barrier

⇨ **Loop Effects**

Add Particles whose loops reduce vacua energy difference.

EW Phase Transition

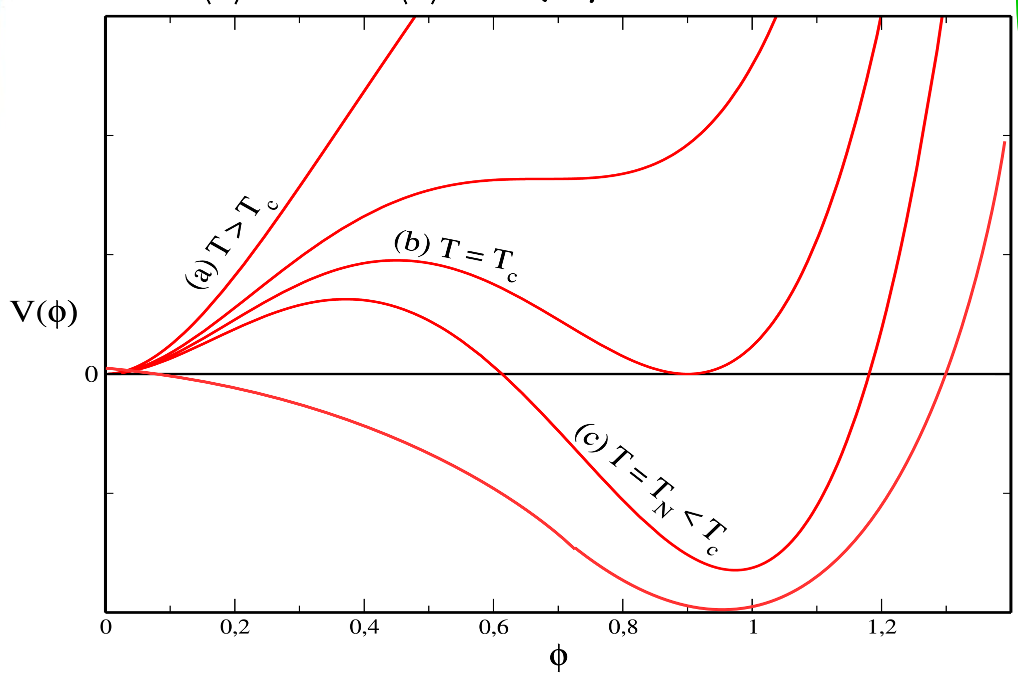
$$\approx (a\,T^2 - \mu^2)\,h^2 - E(T)\,h^3 + \lambda_{eff}(T)\,h^4$$

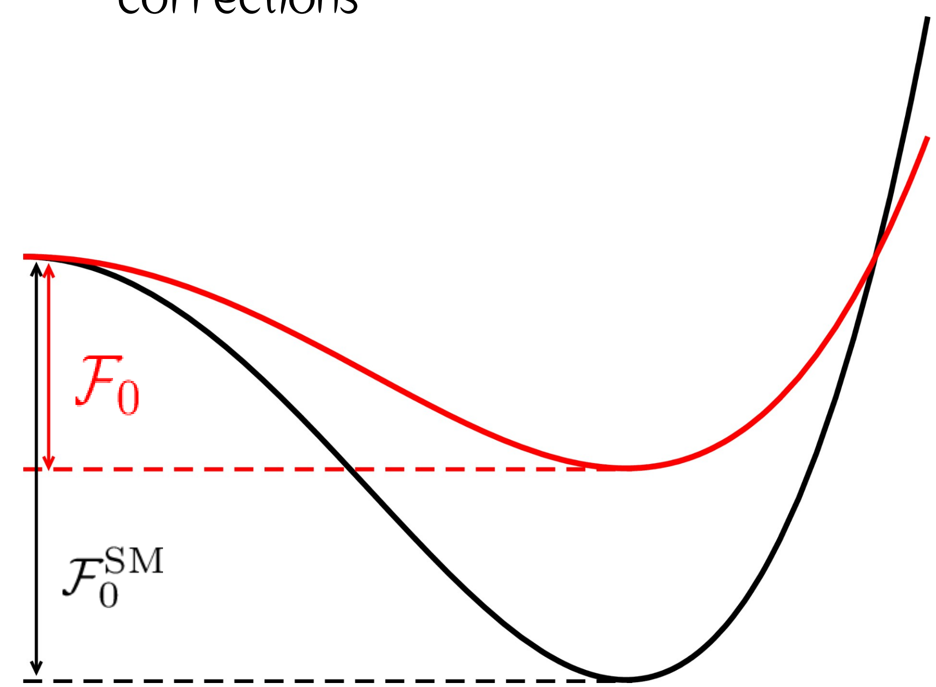
$$V_{\rm eff}(h,T) = V_0(h) + V_0^{\rm loop}(h) + V_T(h,T)$$

Tree-level potential | Loop corrections | Thermal corrections

1^{st} Order:

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





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

Add New BOSONS to generate a thermal barrier

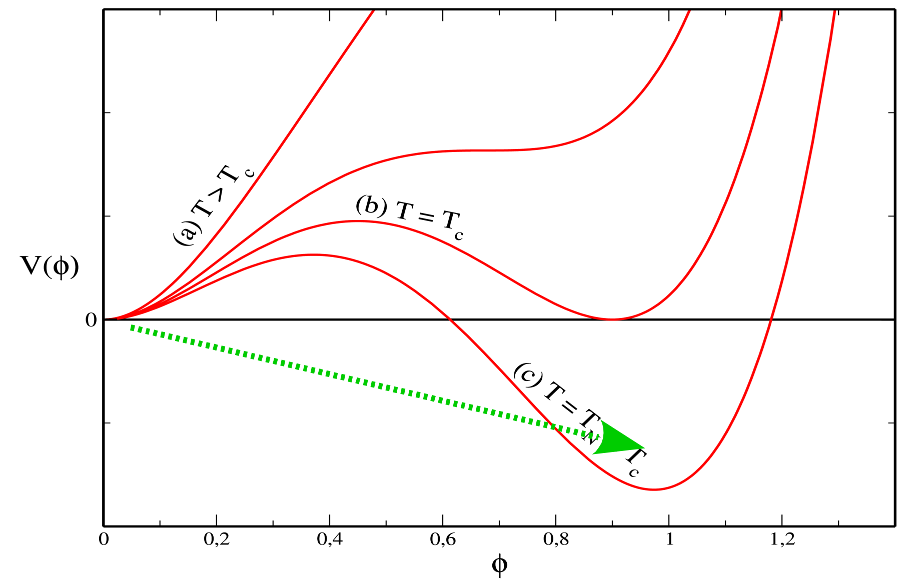
⇨ **Loop Effects**

Add Particles whose loops reduce vacua energy difference.

⇨ **Tree-level Effects**

Add scalars that modify the tree-level potential

EW Phase Transition



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

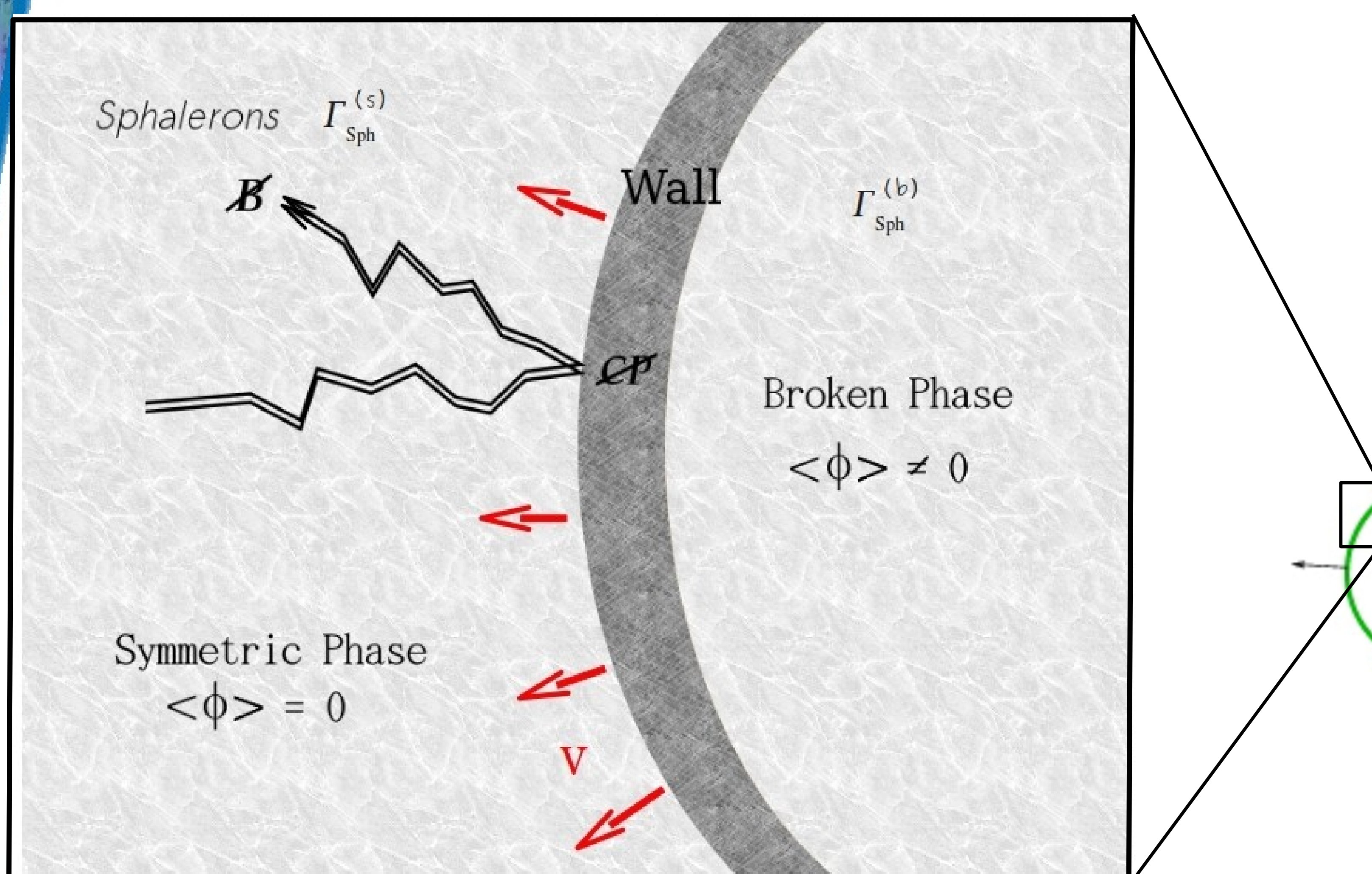
$\Gamma^{(b)}_{\rm Sph} \sim T^4\, e^{-E_{\rm Sph}/T}$

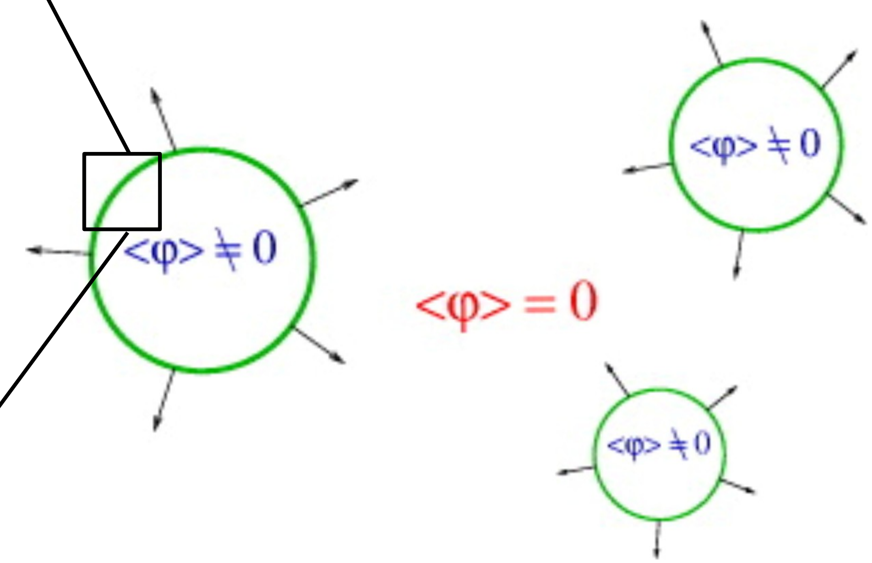
$E_{\rm Sph} = \kappa \frac{4\pi\langle\phi\rangle}{g}$

Out of Equilibrium

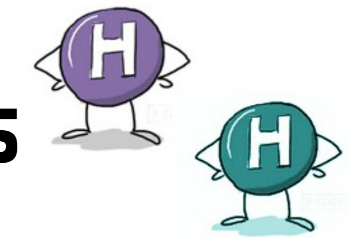
(SPHALERON SHUT-OFF)

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





Baryogenesis with a Second Higgs



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

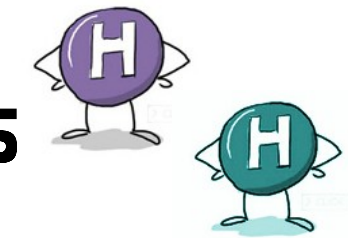
$$
H_j = \begin{pmatrix} \phi_j^+ \\ \frac{v_j + h_j + i\,\eta_j}{\sqrt{2}} \end{pmatrix}
$$

$$
H^\pm = -s_\beta\,\phi_1^\pm + c_\beta\,\phi_2^\pm \qquad A_0 = -s_\beta\,\eta_1 + c_\beta\,\eta_2
$$

$$
h = -s_\alpha\,h_1 + c_\alpha\,h_2 \qquad H_0 = -c_\alpha\,h_1 - s_\alpha\,h_2
$$

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

~~Baryogenesis~~ with a Second Higgs



EW Phase Transition

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

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

$$
H^\pm = -s_\beta\,\phi_1^\pm + c_\beta\,\phi_2^\pm \qquad A_0 = -s_\beta\,\eta_1 + c_\beta\,\eta_2
$$

$$
h = -s_\alpha\,h_1 + c_\alpha\,h_2 \qquad H_0 = -c_\alpha\,h_1 - s_\alpha\,h_2
$$

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

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

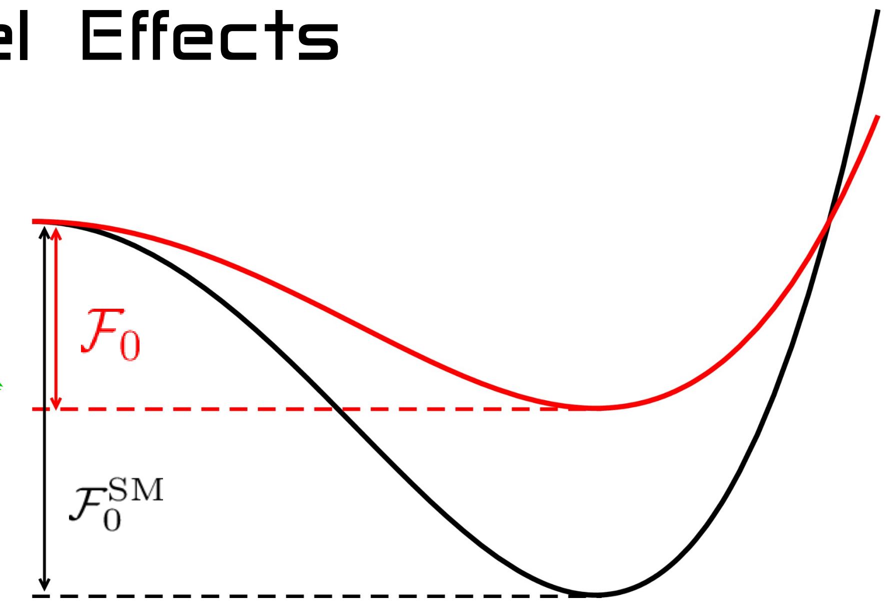
$$\mathcal{F}_0 = V_0(v) + V_0^{\mathrm{loop}}(v) - V_0(0) - V_0^{\mathrm{loop}}(0)$$


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

EW Phase Transition

Thermal + Loop + Tree-level Effects

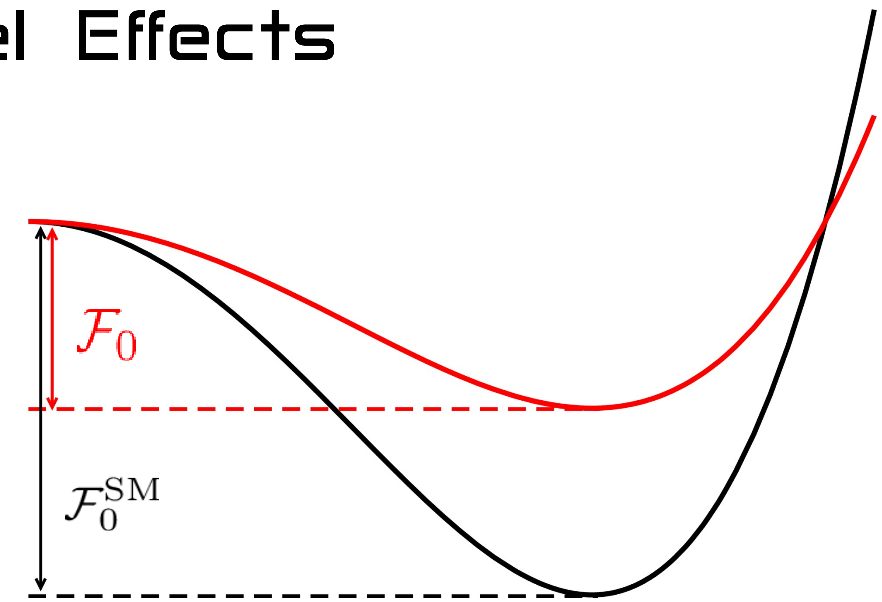
$$\mathcal{F}_0 = V_0(v) + V_0^{\text{loop}}(v) - V_0(0) - V_0^{\text{loop}}(0)$$


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*

$$\left[\mathcal{F}_0 - \mathcal{F}_0^{\text{SM}}\right]_{\text{tree}} = -\frac{v^2}{8} c_{\beta-\alpha}^2 (m_{H_0}^2 - m_h^2) < 0$$

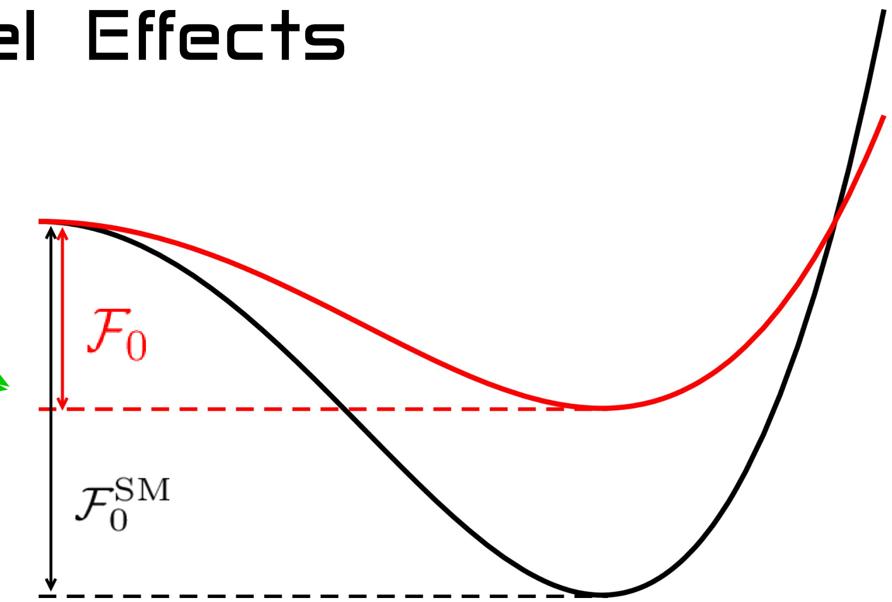
(Assuming m_h = 125 GeV)

~~Baryogenesis~~ with a Second Higgs

EW Phase Transition

Thermal + Loop + Tree-level Effects

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



JHEP Journal of High Energy Physics

Journal of High Energy Physics
June 2016, 2016:5

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

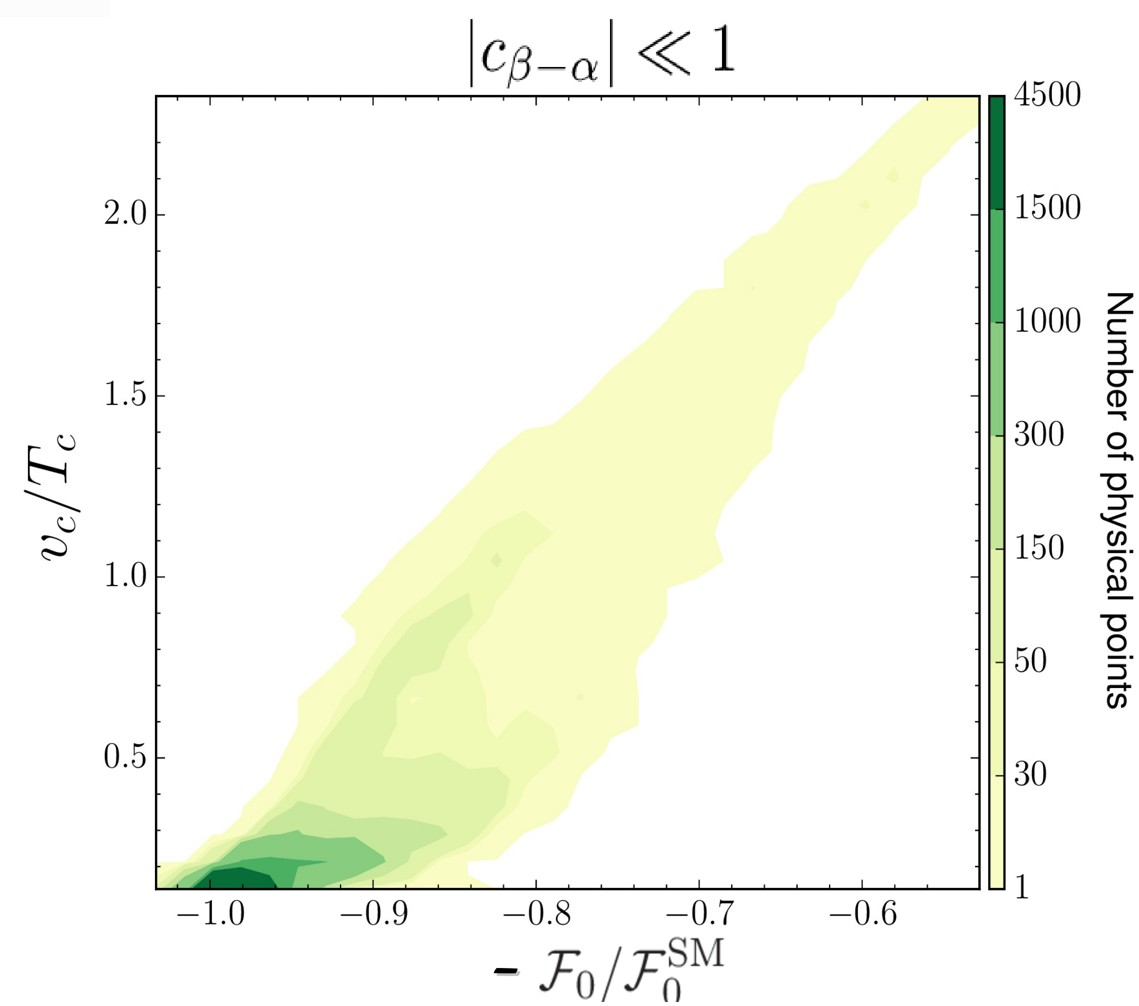
Christopher P.D. Harman, Stephan J. Huber

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

LET'S LOOK AT THE ALIGNMENT LIMIT:

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

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



~~Baryogenesis~~ with a Second Higgs

EW Phase Transition

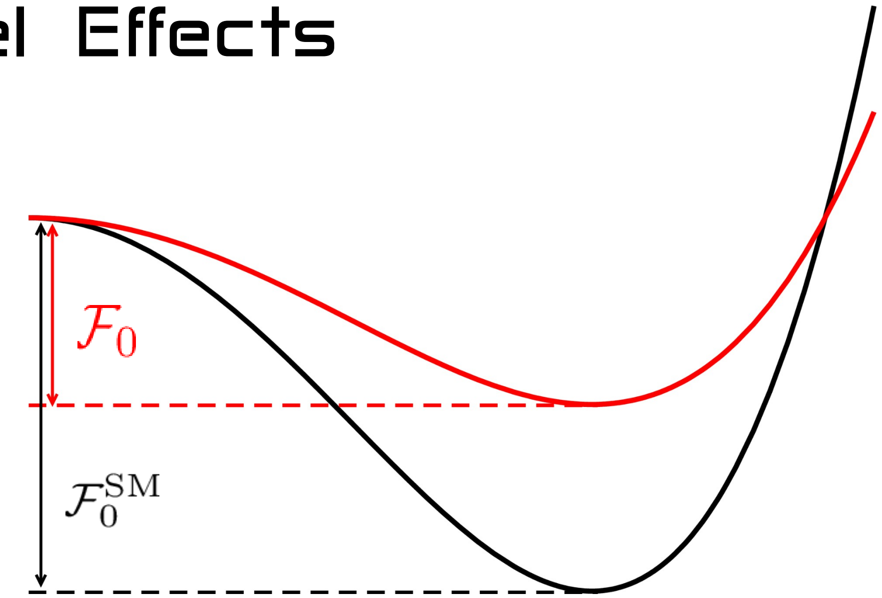
Thermal + Loop + Tree-level Effects

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


Journal of High Energy Physics
June 2016, 2016:5

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

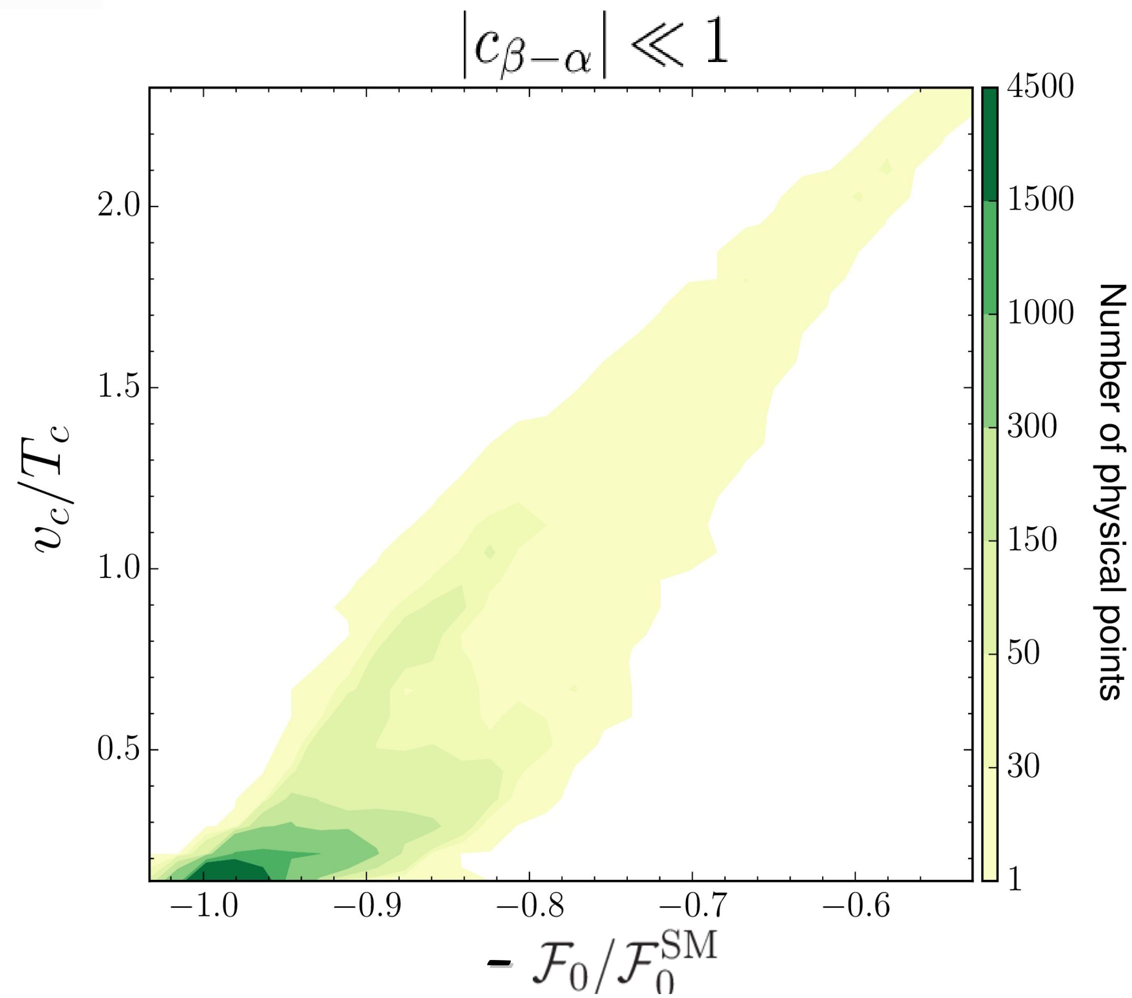
Christopher P.D. Harman, Stephan J. Huber



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

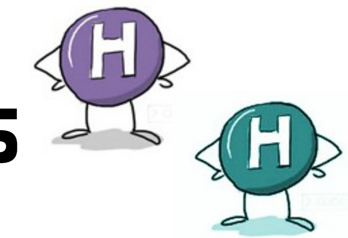
LET'S LOOK AT THE ALIGNMENT LIMIT:

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



Combine with (tree-level)
Vacuum Stability and Unitarity

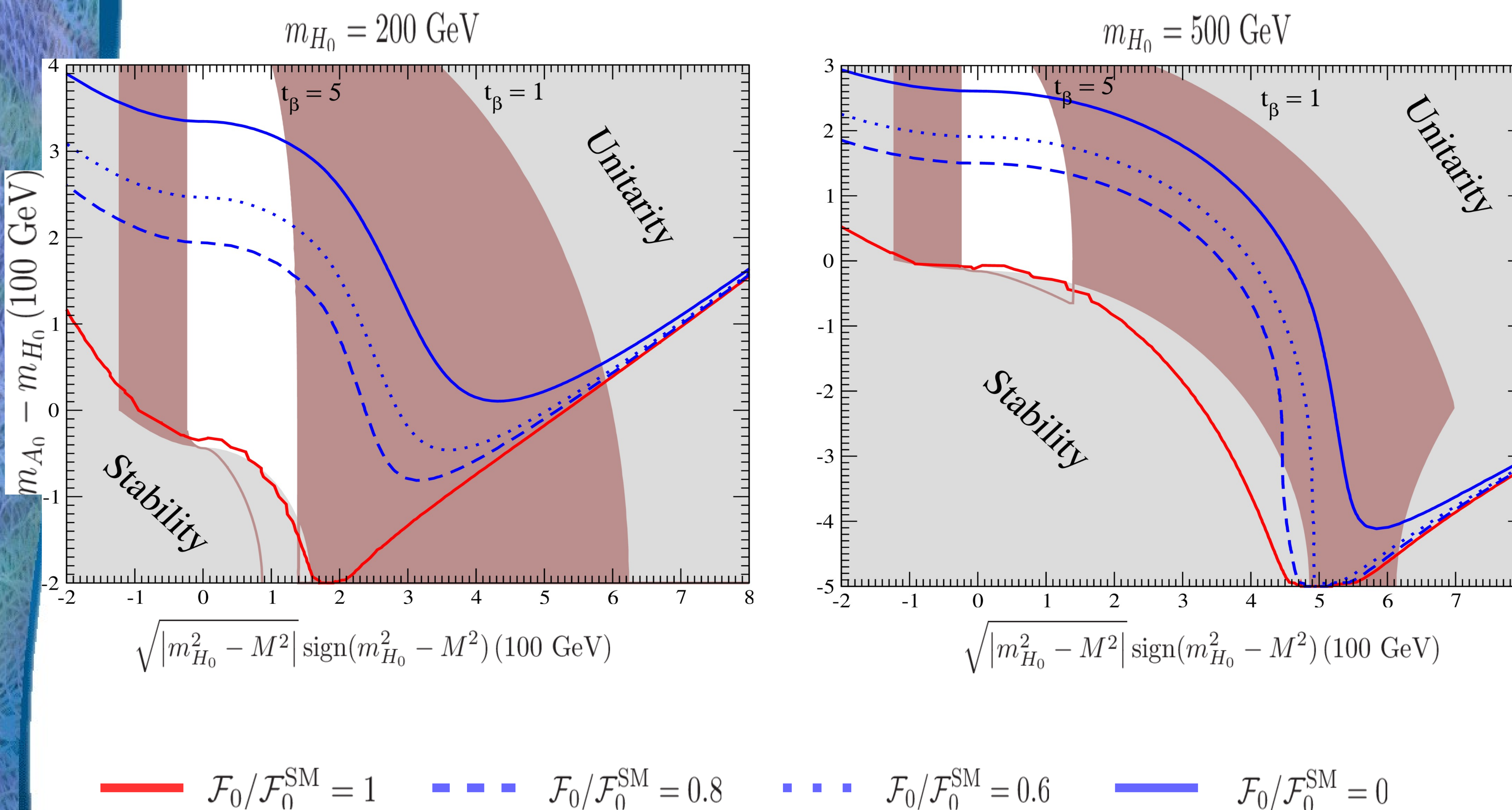
*Gunion, Haber, Phys.Rev. D**67** (2003) 075019*
*Ginzburg, Ivanov, Phys.Rev. D**72** (2005) 115010*
*Barroso, Ferreira, Ivanov, Santos, JHEP **1306** (2013) 045*



Baryogenesis with a Second Higgs

EW Phase Transition

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

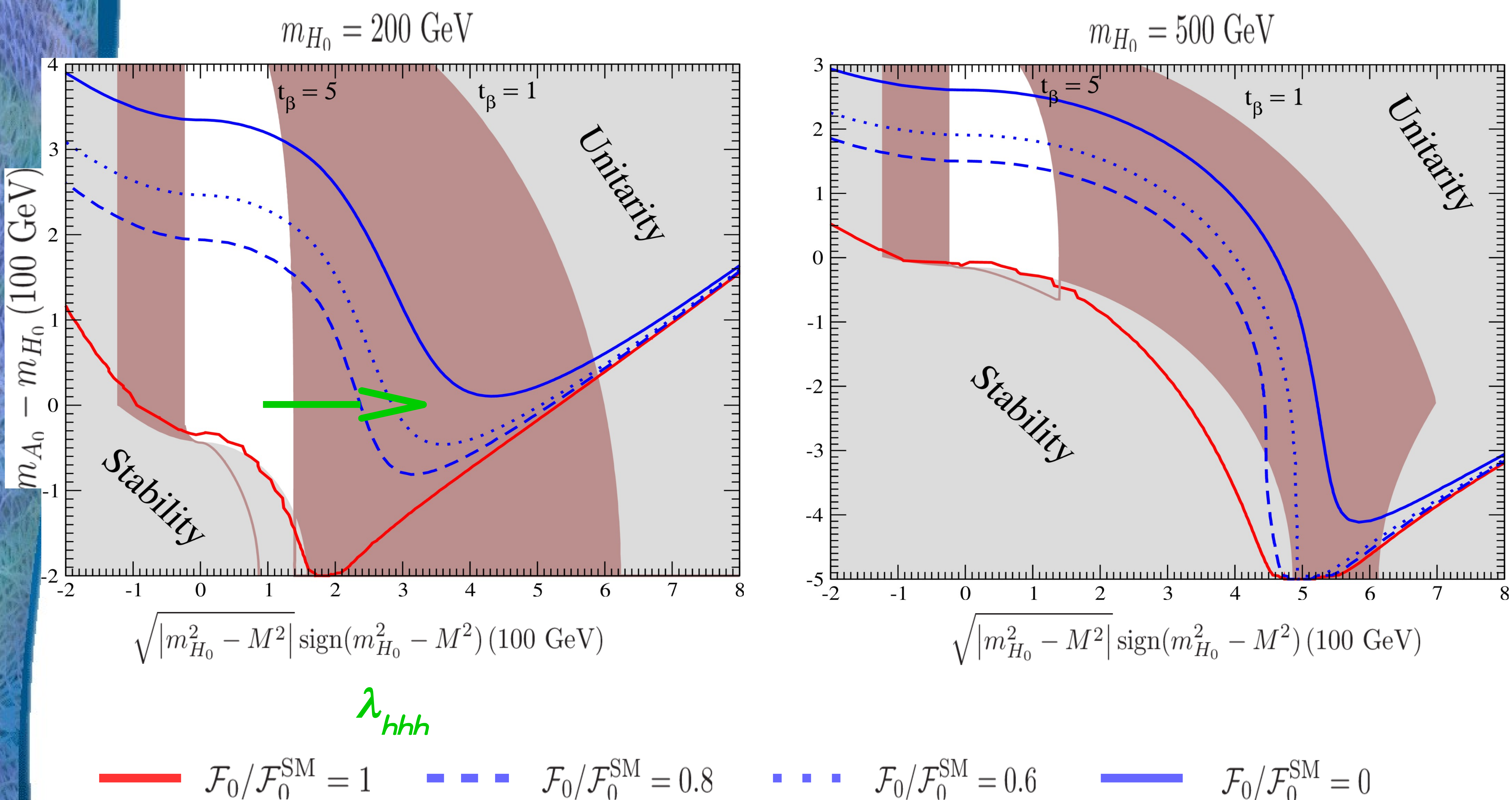


Dorsch, Huber, Mimasu, JMN, arXiv:1609.xxxxx

~~Baryogenesis~~ with a Second Higgs

EW Phase Transition

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



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

Baryogenesis with a Second Higgs

EW Phase Transition

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

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

Baryogenesis with a Second Higgs @ LHC

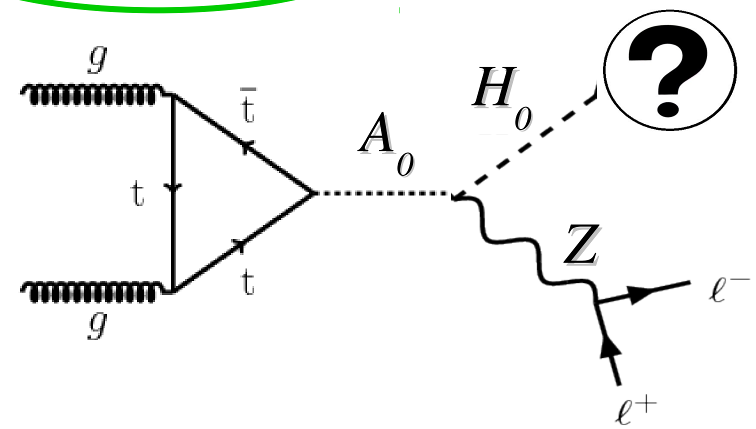
EW Phase Transition

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

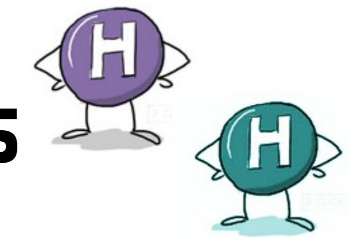
EW Phase Transition SIGNATURE

$$A_0 \rightarrow H_0\, Z$$

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



~~Baryogenesis~~ with a Second Higgs @ LHC



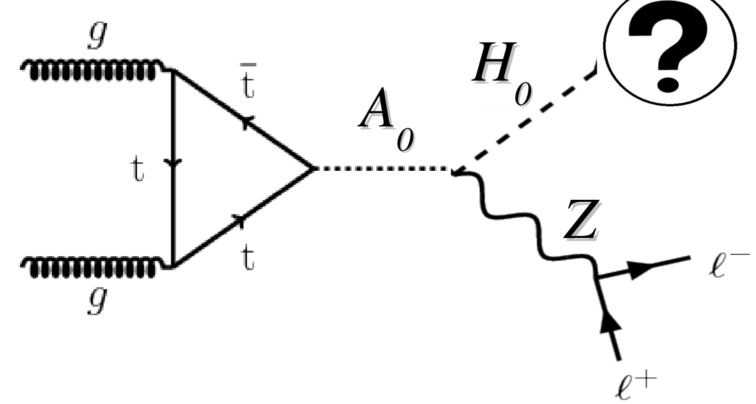
EW Phase Transition

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

EW Phase Transition SIGNATURE

$$A_0 \to H_0\, Z$$

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

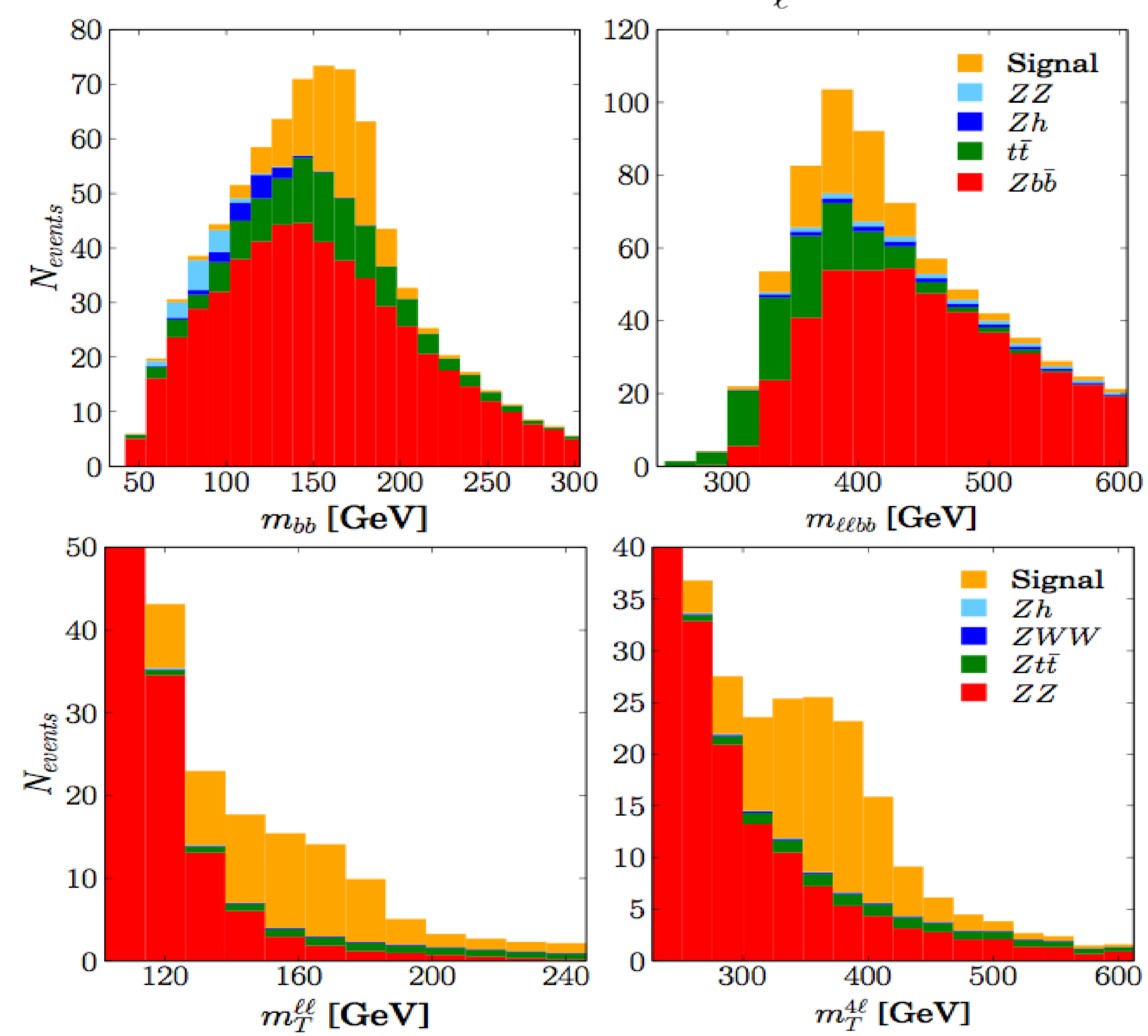


$$A_0 \to H_0\, Z \to \bar{b}b\,\ell\ell$$

$$A_0 \to H_0\, Z \to W^+W^-\ell\ell \to 4\ell + 2\nu$$

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

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



CMS-PAS-HIG-15-001

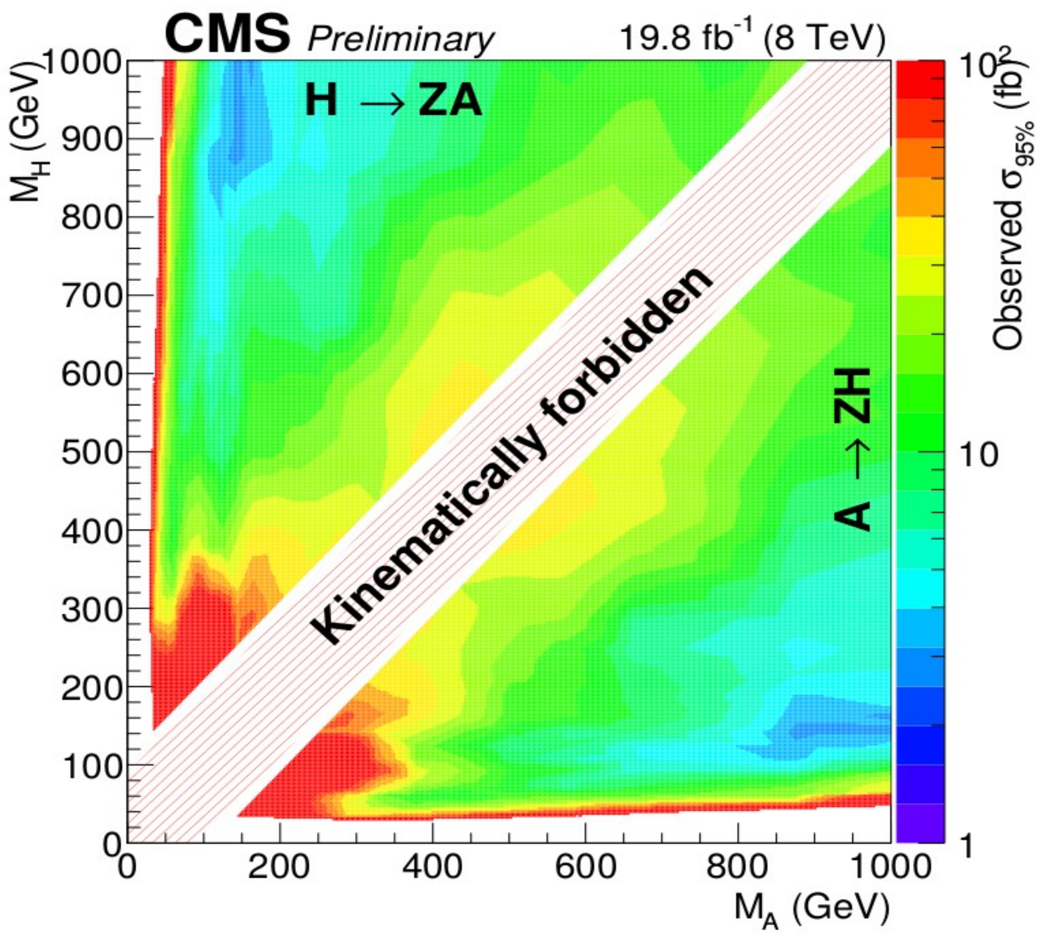
Phys. Lett. B759 (2016) 369 (ArXiv:1603.02991)

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

The CMS Collaboration

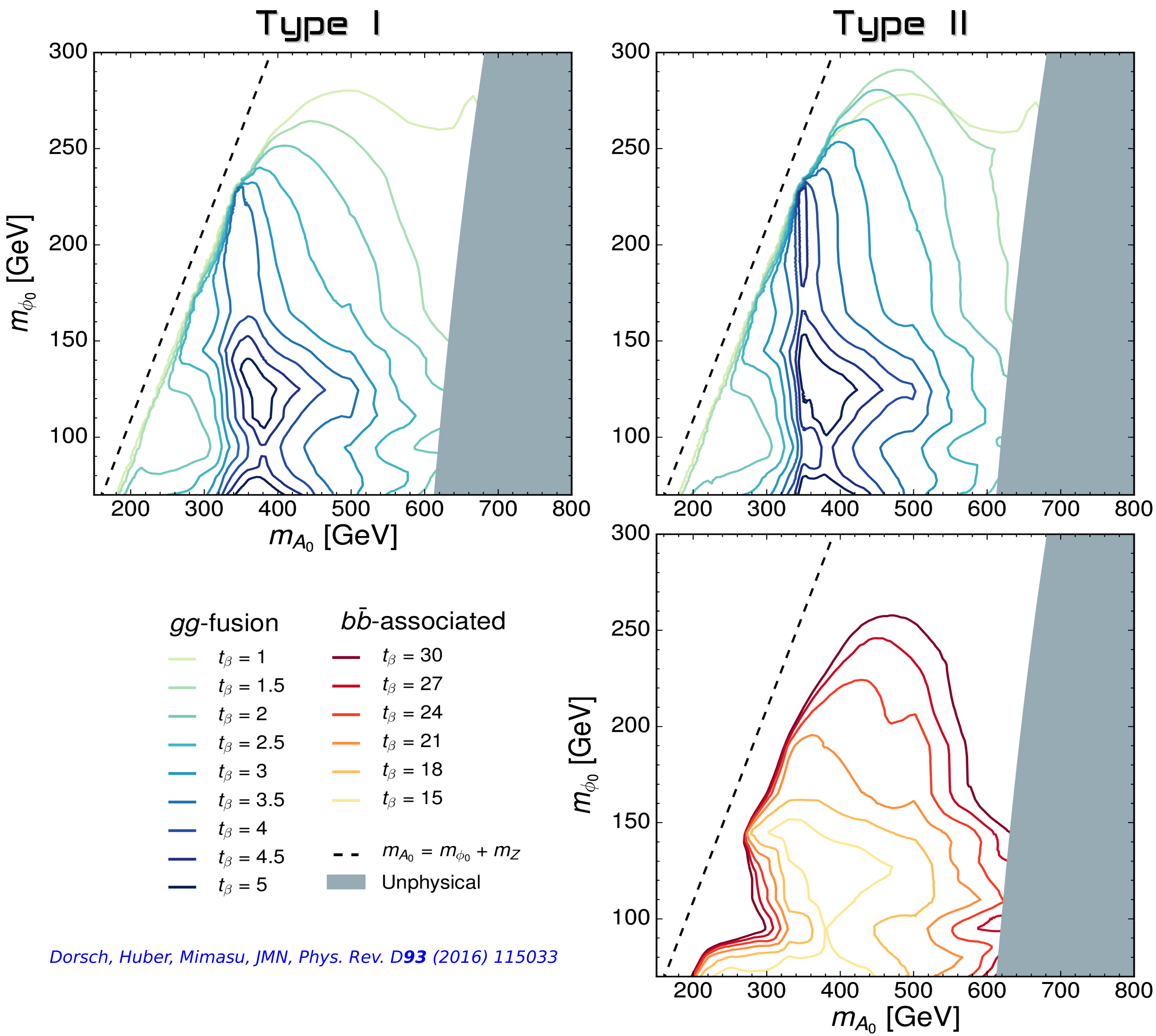
One important motivation for 2HDMs is that these models provide a way to explain the asymmetry between matter and anti-matter observed in the Universe [4, 5]. Another important motivation is Supersymmetry [6], which is a theory that falls in the broad class of 2HDMs. Axion models [7], which would explain 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$\to$ZH.



Meaningful Constraints from LHC Run 1

(Assume 2HDM Alignment)



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

Baryogenesis with a Second Higgs

A Second Higgs
can provide an EW Origin
for the Baryon Asymmetry

There are Observable Signatures

$$A_0 \to H_0 \, Z$$

$$\lambda_{hhh}$$

Dark Matter & More Higgses

➪ Consider DM (fermionic) in a HIDDEN SECTOR

→ DM without SM Gauge Interactions

Dark Matter & More Higgses

- Consider DM (fermionic) in a HIDDEN SECTOR → DM without SM Gauge Interactions

- HIDDEN SECTOR - VISIBLE SECTOR Interactions via a MEDIATOR

Dark Matter & More Higgses

➪ Consider DM (fermionic) in a HIDDEN SECTOR

→ DM without SM Gauge Interactions

➪ HIDDEN SECTOR - VISIBLE SECTOR Interactions via a MEDIATOR

Consider Pseudo-scalar MEDIATOR a_0

(DM Direct Detection as a Possible Motivation...)

$$V_{\text{Dark}} = \frac{m_{a_0}^2}{2} a_0^2 + m_\psi \bar{\psi}\psi + g_\psi \, a_0 \, \bar{\psi} i \gamma^5 \psi$$

Dark Matter & More Higgses

- Consider DM (fermionic) in a HIDDEN SECTOR

  → DM without SM Gauge Interactions

- HIDDEN SECTOR - VISIBLE SECTOR Interactions via a MEDIATOR

  Consider Pseudo-scalar MEDIATOR a_0

  (DM Direct Detection as a Possible Motivation...)

$$V_{\rm Dark} = \frac{m_{a_0}^2}{2} a_0^2 + m_\psi \bar{\psi}\psi + g_\psi\, a_0\, \bar{\psi} i \gamma^5 \psi$$

- Simplified Model:

  *Buckley, Feld, Goncalves, Phys. Rev. D**91** (2015) 015017*

  *De Simone, Jacques, Eur. Phys. J. C**76** (2016) 7, 367*

$$\begin{aligned} \mathcal{L}_a &= \bar{\psi}(i\partial\!\!\!/ - m_\psi)\psi + \frac{1}{2}(\partial_\mu a_0)^2 - \frac{m_{a_0}^2}{2} a_0^2 \\ &- i g_\psi\, a_0\, \bar{\psi}\gamma^5\psi - i g_{\rm SM}\, a_0 \sum_f \frac{y_f}{\sqrt{2}}\, \bar{f}\gamma^5 f \end{aligned}$$

Dark Matter & More Higgses

⇨ Consider DM (fermionic) in a HIDDEN SECTOR

→ DM without SM Gauge Interactions

⇨ HIDDEN SECTOR - VISIBLE SECTOR Interactions via a MEDIATOR

Consider Pseudo-scalar MEDIATOR a_0

(DM Direct Detection as a Possible Motivation...)

$$V_{\rm Dark} = \frac{m_{a_0}^2}{2} a_0^2 + m_\psi \bar{\psi}\psi + g_\psi\, a_0\, \bar{\psi} i \gamma^5 \psi$$

⇨ Simplified Model:

*Buckley, Feld, Goncalves, Phys. Rev. D**91** (2015) 015017*

*De Simone, Jacques, Eur. Phys. J. C**76** (2016) 7, 367*

$$\begin{aligned} \mathcal{L}_a &= \bar{\psi}(i\partial\!\!\!/ - m_\psi)\psi + \frac{1}{2}(\partial_\mu a_0)^2 - \frac{m_{a_0}^2}{2} a_0^2 \\ &- i g_\psi\, a_0\, \bar{\psi}\gamma^5\psi - i g_{\rm SM}\, a_0 \sum_f \frac{y_f}{\sqrt{2}}\, \bar{f}\gamma^5 f \end{aligned}$$

⇨ Gauge Invariant, Renormalizable Model:

Dark Matter & More Higgses

- Consider DM (fermionic) in a HIDDEN SECTOR

  → DM without SM Gauge Interactions

- HIDDEN SECTOR - VISIBLE SECTOR Interactions via a MEDIATOR

  Consider Pseudo-scalar MEDIATOR a_0

  (DM Direct Detection as a Possible Motivation...)

$$V_{\rm Dark} = \frac{m_{a_0}^2}{2} a_0^2 + m_\psi \bar{\psi}\psi + g_\psi\, a_0\, \bar{\psi} i \gamma^5 \psi$$

- Simplified Model:

  *Buckley, Feld, Goncalves, Phys. Rev. D**91** (2015) 015017*

  *De Simone, Jacques, Eur. Phys. J. C**76** (2016) 7, 367*

$$\begin{aligned}\mathcal{L}_a &= \bar{\psi}(i\partial\!\!\!/ - m_\psi)\psi + \frac{1}{2}(\partial_\mu a_0)^2 - \frac{m_{a_0}^2}{2} a_0^2 \\ &- i g_\psi\, a_0\, \bar{\psi}\gamma^5\psi - i g_{\rm SM}\, a_0 \sum_f \frac{y_f}{\sqrt{2}}\, \bar{f}\gamma^5 f\end{aligned}$$

- Gauge Invariant, Renormalizable Model:

DM through the "Axion" Portal

*Nomura, Thaler, Phys. Rev **D79** (2009) 075008*

$$V_{\rm portal} = i\,\kappa\, a_0\, H_1^\dagger H_2 + \text{h.c.}$$

→ Requires 2 Higgs Doublets

Pseudo-scalar Portal to DM

Ipek, McKeen, Nelson, Phys. Rev **D90** (2014) 055021

$$V_{\rm Dark} = \frac{m_{a_0}^2}{2} a_0^2 + m_\psi \bar{\psi}\psi + g_\psi\, a_0\, \bar{\psi} i\gamma^5 \psi$$

$$V_{\rm portal} = i\,\kappa\, a_0\, H_1^\dagger H_2 + {\rm h.c.}$$

$$\begin{aligned} V_{\rm 2HDM} &= \mu_1^2 \left|H_1\right|^2 + \mu_2^2 \left|H_2\right|^2 - \mu^2 \left[H_1^\dagger H_2 + {\rm h.c.}\right] \\ &+ \frac{\lambda_1}{2} \left|H_1\right|^4 + \frac{\lambda_2}{2} \left|H_2\right|^4 + \lambda_3 \left|H_1\right|^2 \left|H_2\right|^2 \\ &+ \lambda_4 \left|H_1^\dagger H_2\right|^2 + \frac{\lambda_5}{2} \left[\left(H_1^\dagger H_2\right)^2 + {\rm h.c.}\right] \end{aligned}$$

Pseudo-scalar Portal to DM

*Ipek, McKeen, Nelson, Phys. Rev **D90** (2014) 055021*

$$V_{\rm Dark} = \frac{m_{a_0}^2}{2} a_0^2 + m_\psi \bar\psi \psi + g_\psi \, a_0 \, \bar\psi i \gamma^5 \psi$$

$$V_{\rm portal} = i \, \kappa \, a_0 \, H_1^\dagger H_2 + {\rm h.c.}$$

Mixing

Physical States

$$A = c_\theta \, A_0 + s_\theta \, a_0 \quad , \quad a = c_\theta \, a_0 - s_\theta \, A_0$$

$$\begin{aligned} V_{\rm 2HDM} &= \mu_1^2 \, |H_1|^2 + \mu_2^2 \, |H_2|^2 - \mu^2 \left[H_1^\dagger H_2 + {\rm h.c.} \right] \\ &+ \frac{\lambda_1}{2} \, |H_1|^4 + \frac{\lambda_2}{2} \, |H_2|^4 + \lambda_3 \, |H_1|^2 \, |H_2|^2 \\ &+ \lambda_4 \left| H_1^\dagger H_2 \right|^2 + \frac{\lambda_5}{2} \left[\left(H_1^\dagger H_2 \right)^2 + {\rm h.c.} \right] \end{aligned}$$

$$V_{\rm Dark} \supset g_\psi \left(c_\theta \, a + s_\theta \, A \right) \bar\psi i \gamma^5 \psi$$

$$\begin{aligned} V_{\rm portal} &= \frac{\left(m_A^2 - m_a^2 \right) s_{2\theta}}{2 \, v} \left(c_{\beta-\alpha} \, H_0 - s_{\beta-\alpha} \, h \right) \\ &\times \left[aA \left(s_\theta^2 - c_\theta^2 \right) + \left(a^2 - A^2 \right) s_\theta c_\theta \right] \end{aligned}$$

Pseudo-scalar Portal to DM

*Ipek, McKeen, Nelson, Phys. Rev **D90** (2014) 055021*

$$V_{\rm Dark} = \frac{m_{a_0}^2}{2} a_0^2 + m_\psi \bar\psi\psi + g_\psi\, a_0\, \bar\psi i\gamma^5\psi$$

$$V_{\rm portal} = i\,\kappa\, a_0\, H_1^\dagger H_2 + {\rm h.c.}$$

Mixing

Physical States

$$A = c_\theta\, A_0 + s_\theta\, a_0 \quad , \quad a = c_\theta\, a_0 - s_\theta\, A_0$$

$$\begin{aligned} V_{\rm 2HDM} &= \mu_1^2 \left|H_1\right|^2 + \mu_2^2 \left|H_2\right|^2 - \mu^2 \left[H_1^\dagger H_2 + {\rm h.c.}\right] \\ &+ \frac{\lambda_1}{2}\left|H_1\right|^4 + \frac{\lambda_2}{2}\left|H_2\right|^4 + \lambda_3 \left|H_1\right|^2\left|H_2\right|^2 \\ &+ \lambda_4 \left|H_1^\dagger H_2\right|^2 + \frac{\lambda_5}{2}\left[\left(H_1^\dagger H_2\right)^2 + {\rm h.c.}\right] \end{aligned}$$

$$V_{\rm Dark} \supset g_\psi \left(c_\theta\, a + s_\theta\, A\right) \bar\psi i\gamma^5\psi$$

$$\begin{aligned} V_{\rm portal} &= \frac{\left(m_A^2 - m_a^2\right) s_{2\theta}}{2\,v}\left(c_{\beta-\alpha}\, H_0 - s_{\beta-\alpha}\, h\right) \\ &\times \left[aA\left(s_\theta^2 - c_\theta^2\right) + \left(a^2 - A^2\right) s_\theta c_\theta\right] \end{aligned}$$

New States (beyond Simplified Pseudo-scalar Portal) $H^\pm \quad H_0 \quad A$

NEW STATES DO NOT DECOUPLE (If Portal is Active ⇨ $s_\theta \neq 0$)

Goncalves, Machado, JMN, ArXiv:1609.xxxxx

Unitarity of $AA,\, aA,\, aa \to W^+W^-$ Scattering

Pseudo-scalar Portal to DM

*Ipek, McKeen, Nelson, Phys. Rev **D90** (2014) 055021*

If
- ⇨ a decays mainly into the Hidden Sector (here, $a \to \psi\psi$)
- ⇨ $m_A > m_a + m_h$ and/or $m_{H_0} > m_a + m_Z$

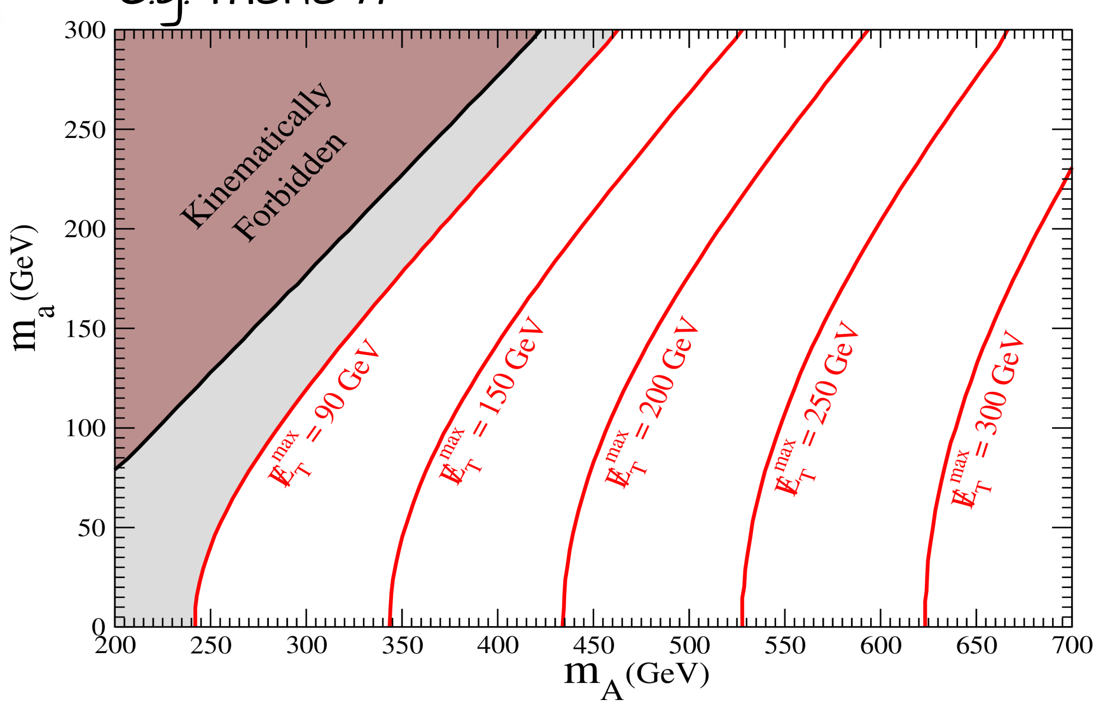
Pseudo-scalar Portal to DM

Ipek, McKeen, Nelson, Phys. Rev **D90** (2014) 055021

If ⇨ a decays mainly into the Hidden Sector (here, $a \to \psi\psi$)

⇨ $m_A > m_a + m_h$ and/or $m_{H_0} > m_a + m_Z$

e.g. mono-h



$$\not{E}_T^{\max} = \frac{1}{2\, m_A}\sqrt{(m_A^2 - m_h^2 - m_a^2)^2 - 4\, m_h^2\, m_a^2}$$

Peak in MET Spectrum

JMN, Phys. Rev **D93** (2016) 031701

Resonant mono-h / mono-Z

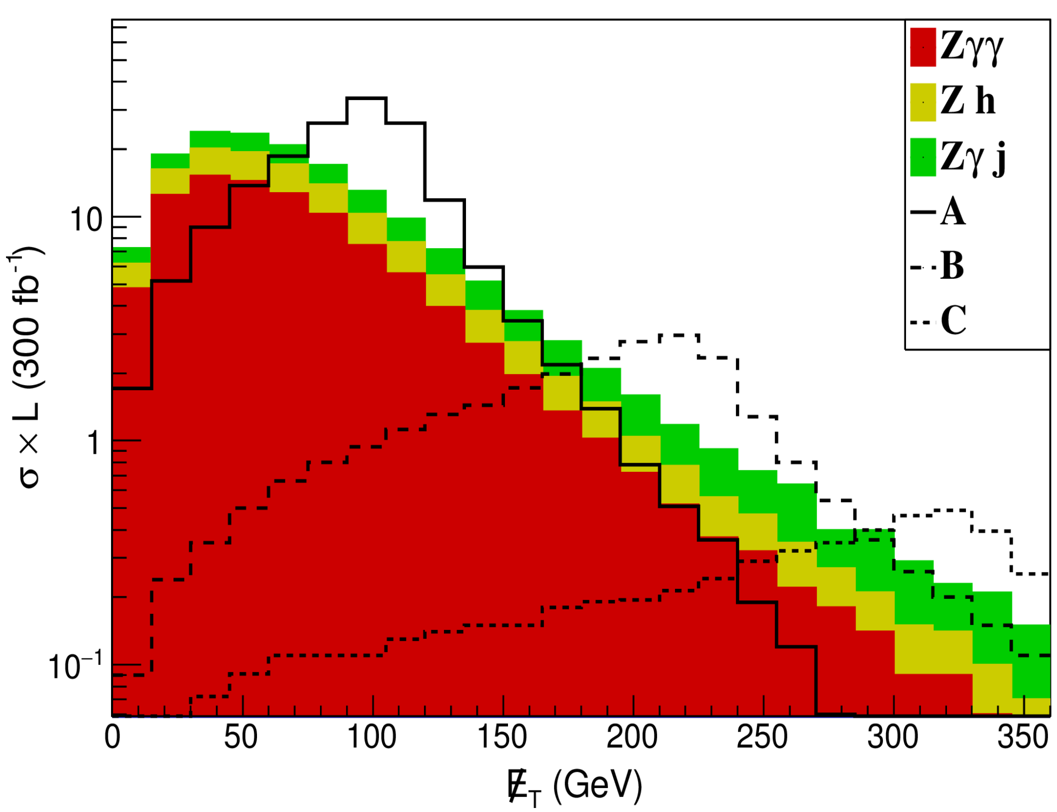
Pseudo-scalar Portal to DM

Ipek, McKeen, Nelson, Phys. Rev ***D90*** *(2014) 055021*

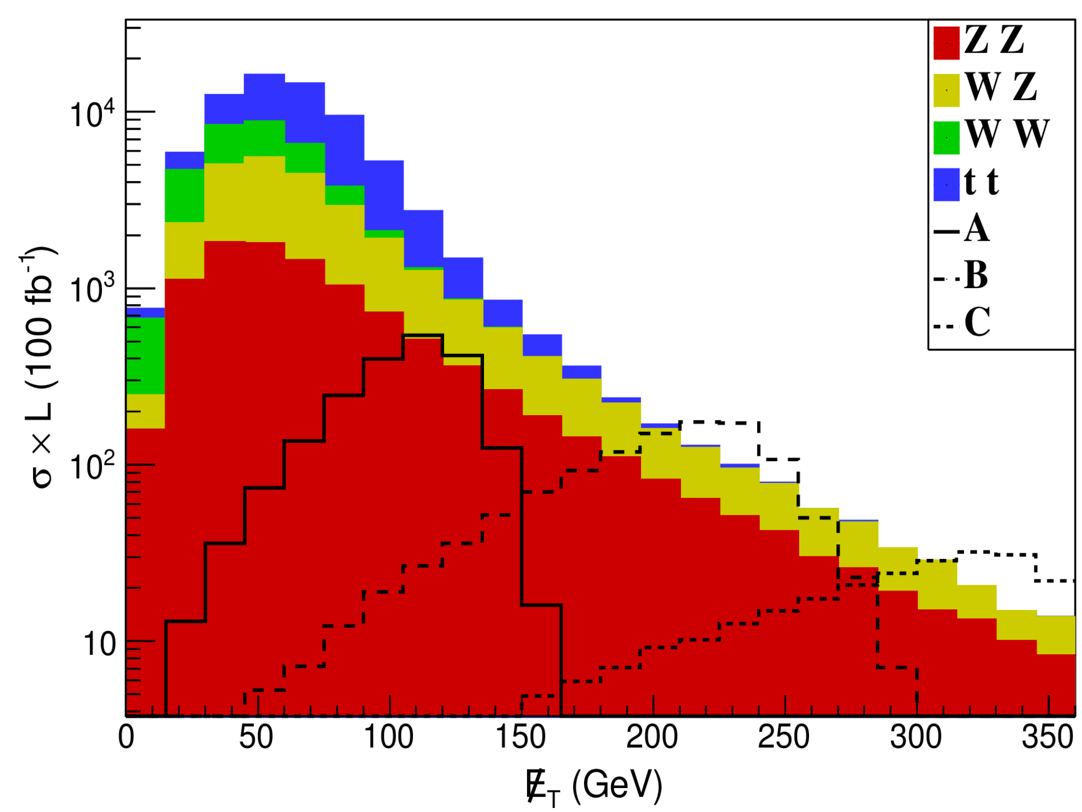
If ⇨ a decays mainly into the Hidden Sector (here, $a \to \psi\psi$)

⇨ $m_A > m_a + m_h$ and/or $m_{H_0} > m_a + m_Z$

mono-h



mono-Z



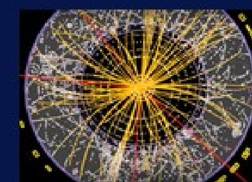
	A	B	C
$m_A = m_{H0} = m_{H+}$ =	300 GeV	500 GeV	700 GeV

m_a = 80 GeV m_ψ = 30 GeV

Dark Matter with a Second Higgs

A Second Higgs
Is needed for a Pseudo-scalar
Portal to Dark Matter

Distinctive LHC Phenomenology:
Resonant Mono-Higgs & Mono-V



KEEP
CALM
AND FIND THE
HIGGS
BOSONs