Going Beyond a Standard (Model) Higgs

Jose Miguel No
King's College London

BSM Aspects of Higgs Physics & EWSB…

TO DO LIST (Shortcomings of the SM Higgs)

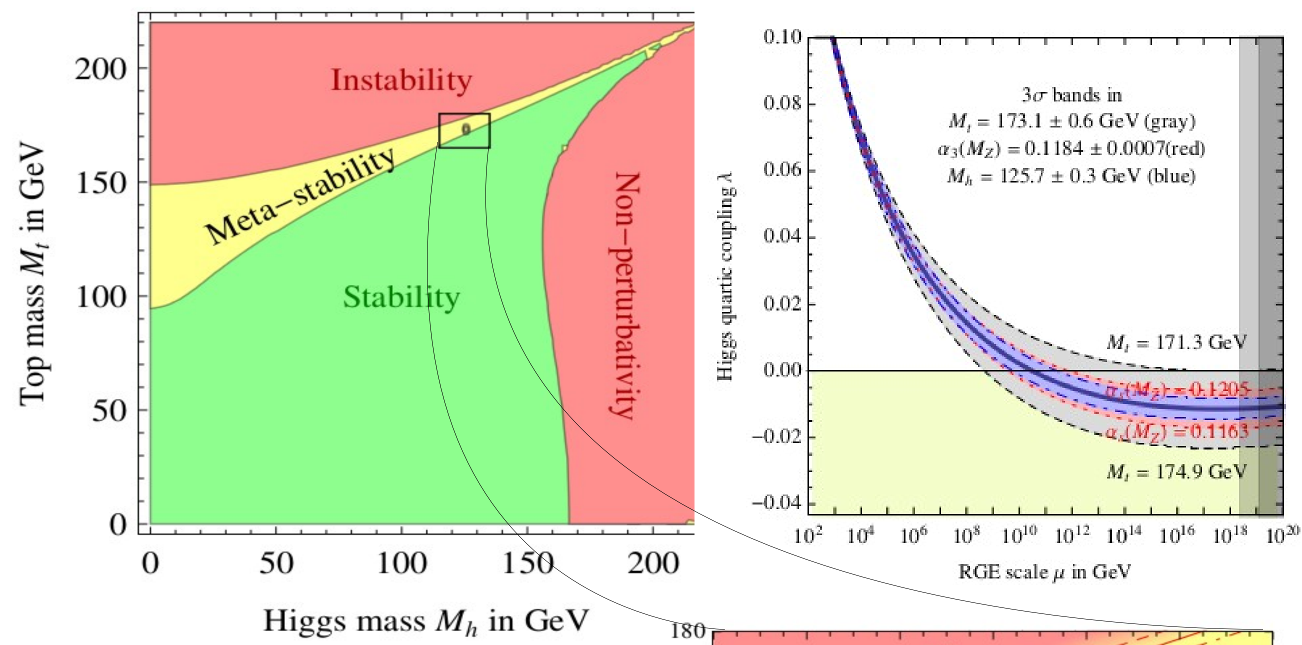
- [ ] Naturalness
- [ ] ...
- [ ]
- [ ]
- [ ]

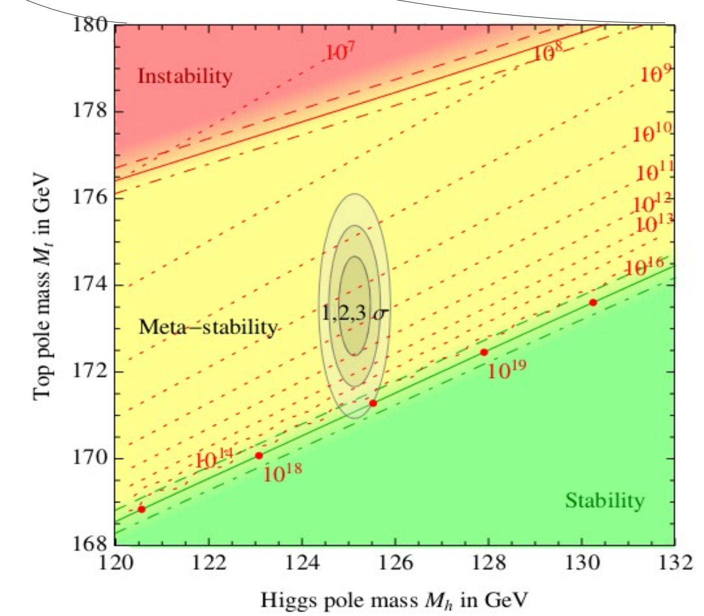
TO DO LIST (Shortcomings of the SM Higgs)

- [ ] Naturalness
- [ ] ...
- [ ] Vacuum Stability in SM
- [ ] ...
- [ ]

*Degrassi, Di Vita, Elias-Miro, Espinosa, Giudice, Isidori, Strumia, JHEP **1208** (2012) 098*

*Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia, JHEP **1312** (2013) 089*





New Scalar(s) Could Alleviate SM Vacuum Stability Problem

e.g. Heavy singlet scalar can provide threshold correction to λ running

$$V_0 = \lambda_H \left(H^\dagger H - v^2/2\right)^2 + \lambda_S \left(S^\dagger S - w^2/2\right)^2 + 2\lambda_{HS}\left(H^\dagger H - v^2/2\right)\left(S^\dagger S - w^2/2\right)$$

$$V_{\rm eff} = \lambda \left(H^\dagger H - \frac{v^2}{2}\right)^2, \qquad \lambda = \lambda_H - \frac{\lambda_{HS}^2}{\lambda_S}$$

*Elias-Miro, Espinosa, Giudice, Lee, Strumia, JHEP **1206** (2012) 031*

*Lebedev, Eur. Phys. J C**72** (2012) 2038*

BSM

TO DO LIST

- ☐ Dark Matter
- ☐ Neutrino Masses
- ☐ Matter-Antimatter Asymmetry
- ☐ Dynamics of Inflation
- ☐ ...

BSM TO DO LIST

- [ ] Dark Matter
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What may we learn by going beyond the Standard (Model) Higgs system?

BSM

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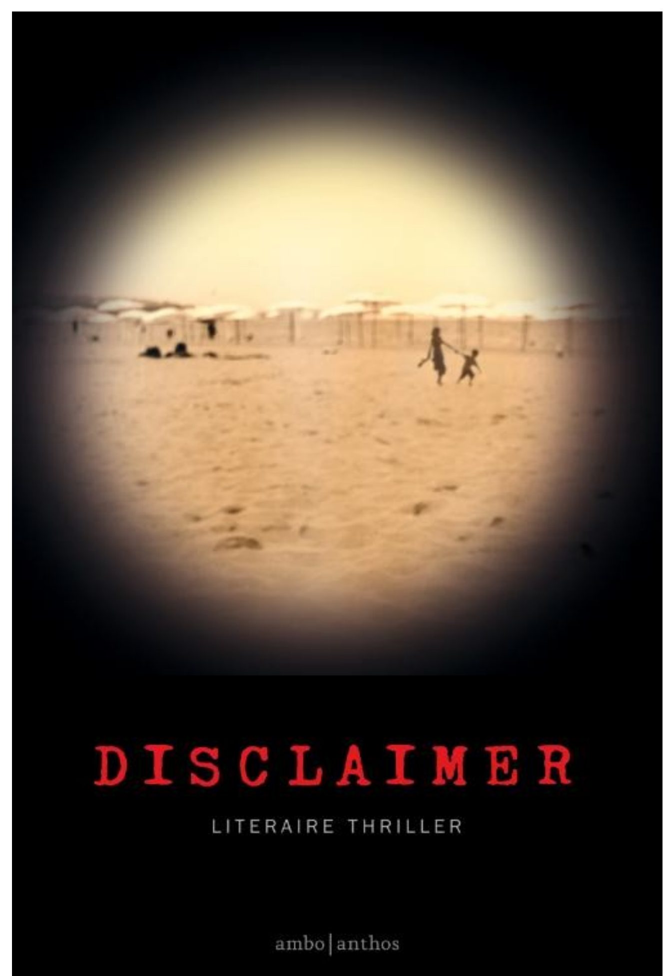


Matter-Antimatter Asymmetry

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

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

Matter-Antimatter Asymmetry

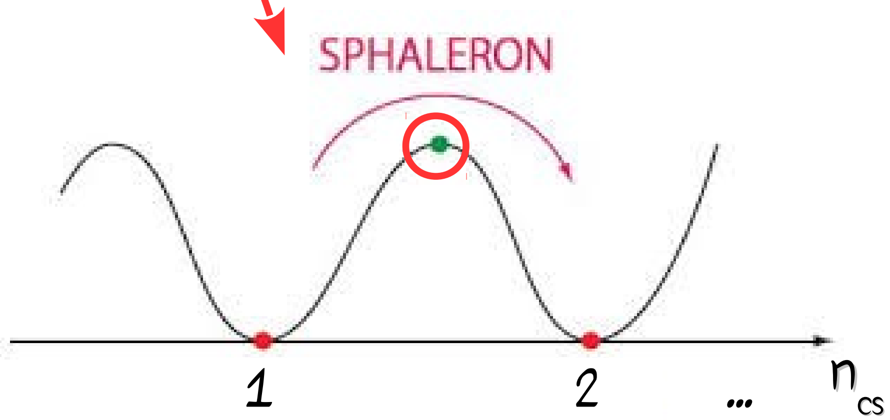
SAKHAROV CONDITIONS *(for dynamical generation of baryon asymmetry)*

B Violation ✓ *Sphalerons*

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

C/CP Violation *CKM*

Departure from Thermal Equilibrium *EW Phase Transition*



Matter-Antimatter Asymmetry

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

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

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*

In the SM (m_h = **125 GeV**) EW Phase Transition Smooth CrossOver

*Kajantie, Laine, Rummukainen, Shaposhnikov, Phys. Rev. Lett. **77** (1996) 2887*

Matter-Antimatter Asymmetry

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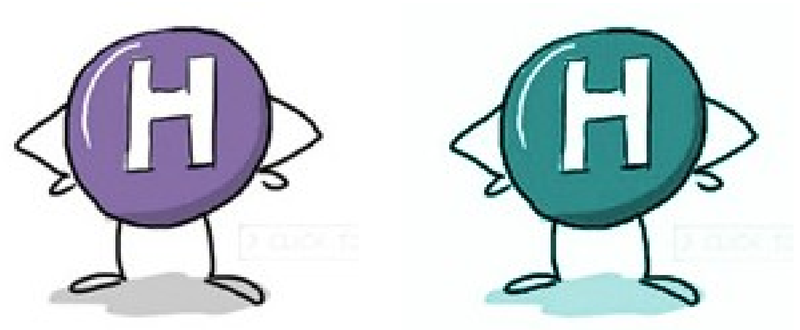
C/CP Violation ? CPV in Scalar Sector

Departure from Thermal Equilibrium ? EW Phase Transition

Beyond **SM** Higgs System

More Higgses Help



....

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Beyond **SM** Higgs System

C/CP Violation **?** CPV in Scalar Sector

Departure from Thermal Equilibrium **?** EW Phase Transition

EDMs

LHC & beyond

TESTABLE

Possible to establish / rule-out EW Baryogenesis in the not-too-distant future

CP Violation (in Scalar Sector)

e.g. 2 Higgs Doublets

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

$$\begin{aligned} V(H_1, H_2) &= \mu_1^2 \left|H_1\right|^2 + \mu_2^2 \left|H_2\right|^2 - \left[\mu^2 H_1^\dagger H_2 + \text{h.c.}\right] \\ &+ \frac{\lambda_1}{2}\left|H_1\right|^4 + \frac{\lambda_2}{2}\left|H_2\right|^4 + \lambda_3 \left|H_1\right|^2 \left|H_2\right|^2 \\ &+ \lambda_4 \left|H_1^\dagger H_2\right|^2 + \frac{1}{2}\left[\lambda_5 \left(H_1^\dagger H_2\right)^2 + \text{h.c.}\right] \end{aligned}$$

e.g. Higgs + Complex Singlet

$$V(H,S) = \mu_H^2 \left|H\right|^2 + \mu_S^2 \left|S\right|^2 + \left[S\left(\kappa_H \left|H\right|^2 + \kappa_S \left|S\right|^2\right) + \text{h.c.}\right] + \ldots$$

Also Possible to Obtain CPV (within non-minimal scalar sector scenarios) from higher-dim. operators

*Espinosa, Gripaios, Konstandin, Riva, JCAP **1201** (2012) 012*

*Chala, Nardini, Sobolev, Phys. Rev. D**94** (2016) 055006*

$$\frac{s}{f} H \bar{Q}_3 (a + i b \gamma_5) t + \text{h.c.}$$

CP Violation (in Scalar Sector)

CPV Induces Electric Dipole Moments (EDMs)

(Measurable for electrons, neutrons & Atomic Nuclei)

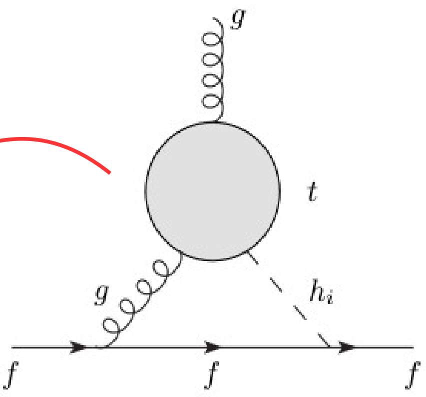
Engel, Ramsey-Musolf, van Kolck, Prog. Part. Nucl. Phys. **71** (2013) 21

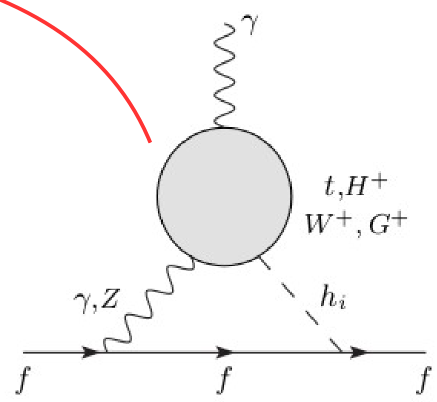
EDM

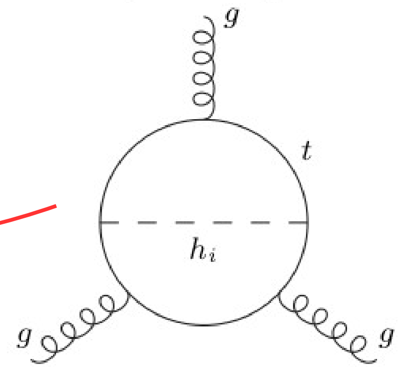
Chromo-EDM

$$\mathcal{L} \supset -\sum_f \frac{d_f}{2}\left(i\bar{f}\sigma_{\mu\nu}\gamma_5 f F^{\mu\nu}\right) - \sum_f \frac{\tilde{d}_f}{2}\left(i g_s \bar{f}\sigma_{\mu\nu}\gamma_5 f T^a G_a^{\mu\nu}\right)$$
$$+ \frac{d_W}{6} f_{abc}\epsilon^{\mu\nu\rho\sigma} G^a_{\mu\lambda} G^{b\ \lambda}_{\nu} G^c_{\rho\sigma},$$

Weinberg Operator







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EDM — Chromo-EDM

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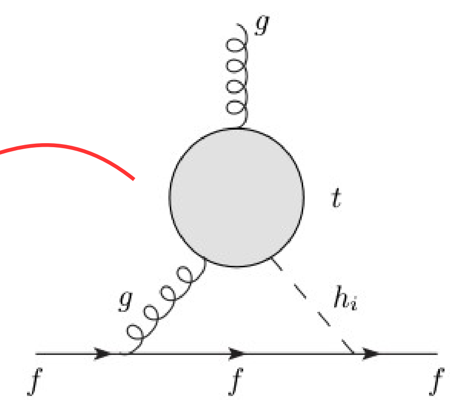
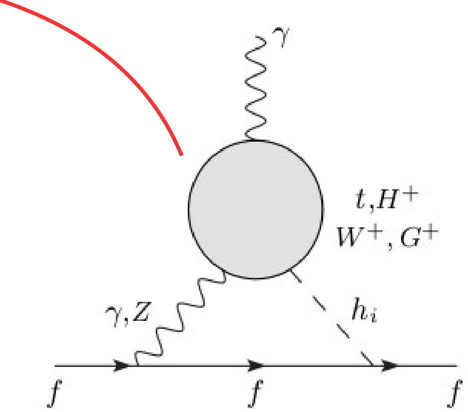
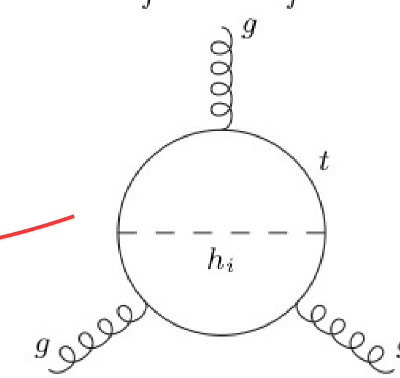
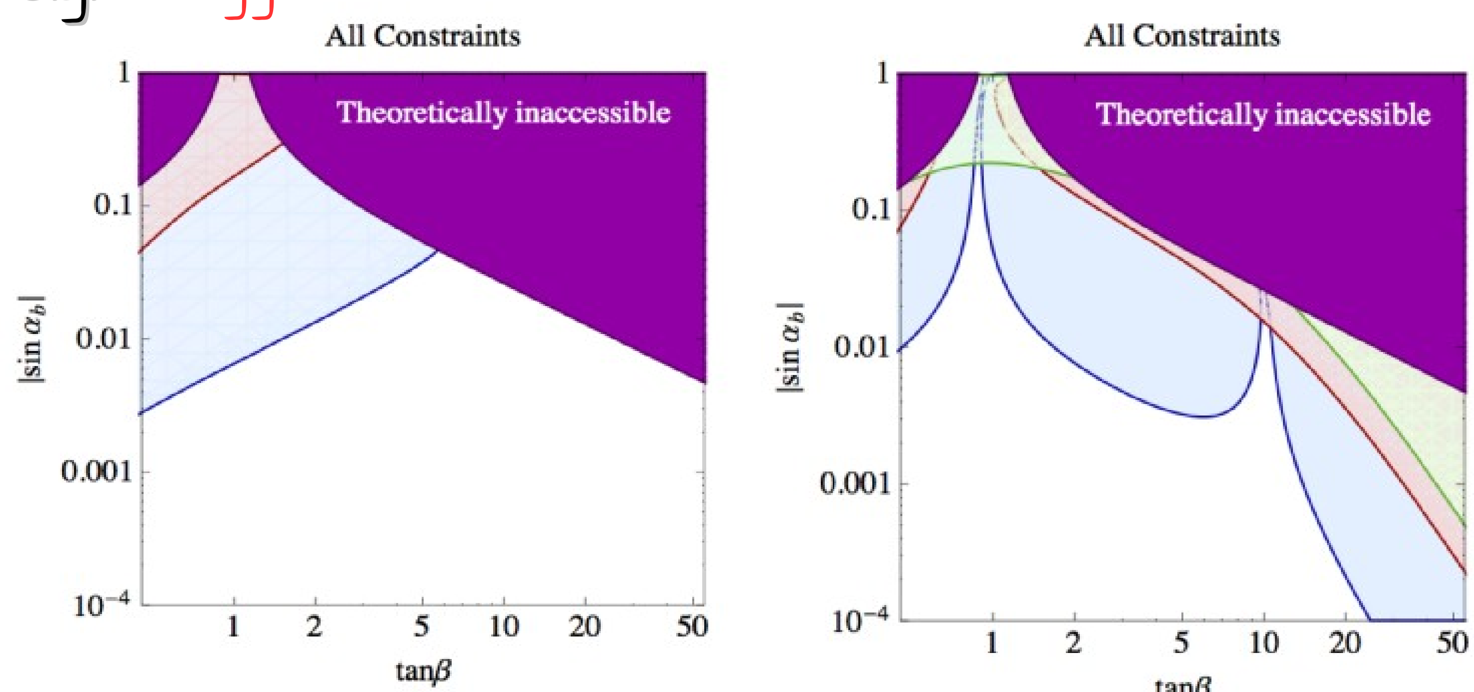






e.g. 2 Higgs Doublets



ACME eEDM Experiment Yields Stringent Bounds on CPV

*Inoue, Ramsey-Musolf, Zhang, Phys.Rev. D**89** (2014) 115023*

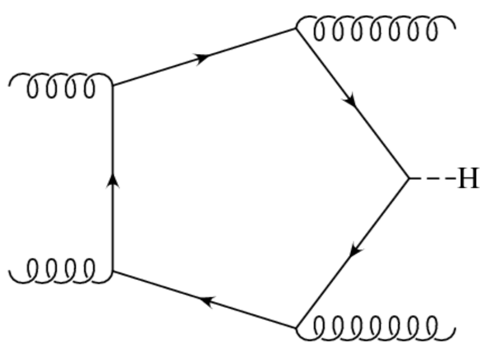
CP Violation (in Scalar Sector)

CPV in Scalar Sector Could be Probed @Colliders

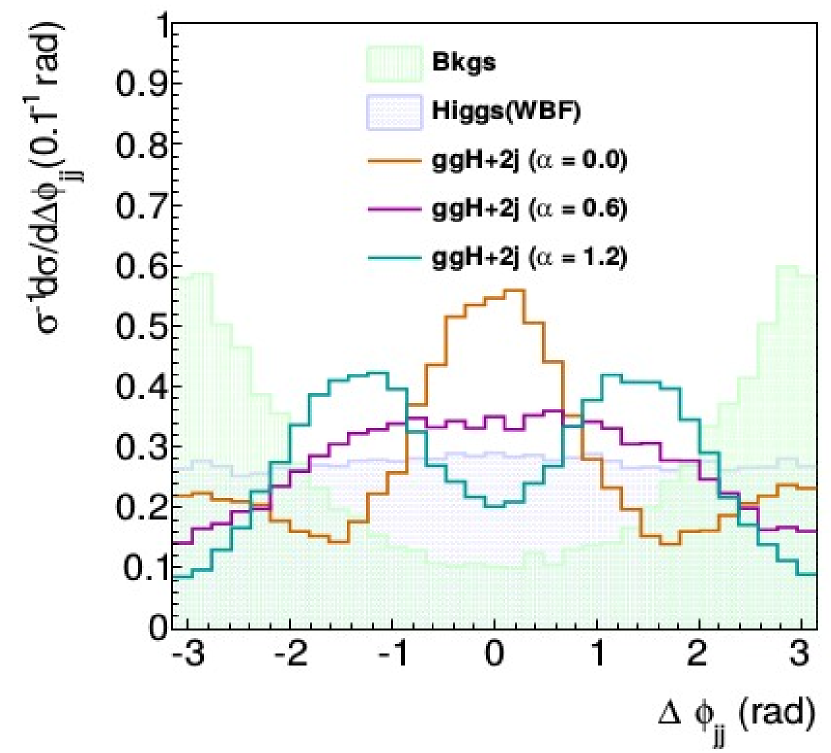
(Higgs CP Properties)

Higgs + 2Jets @LHC

*Dolan, Harris, Jankowiak, Spannowsky, Phys.Rev. D**90** (2014) 073008*

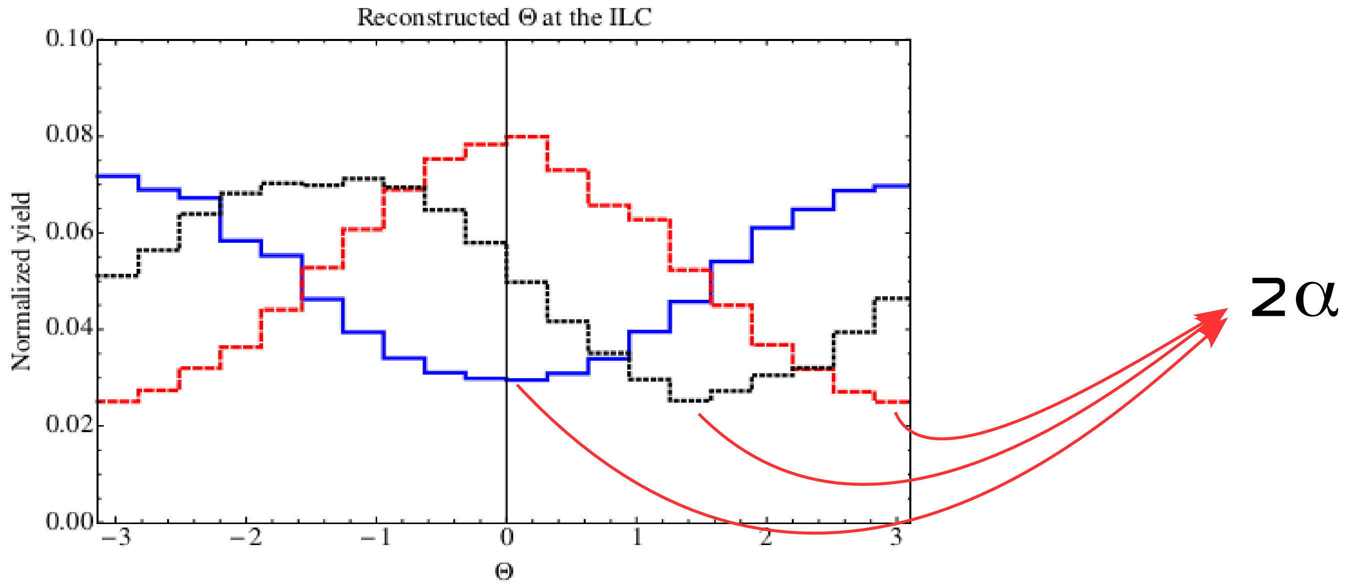


$$\mathcal{L}_{h\bar{f}f} = \cos\alpha\, y_f \bar{\psi}_f \psi_f h + \sin\alpha\, \tilde{y}_f \bar{\psi}_f i\gamma_5 \psi_f h$$



Higgs Decays to Taus @LHC-ILC

*Harnik, Martin, Okui, Primulando, Yu, Phys.Rev. D**88** (2013) 076009*



Others: $t\bar{t}h$, $h \to 4\ell$, $h \to Z\gamma(Z \to \ell^+\ell^-)$ ...

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

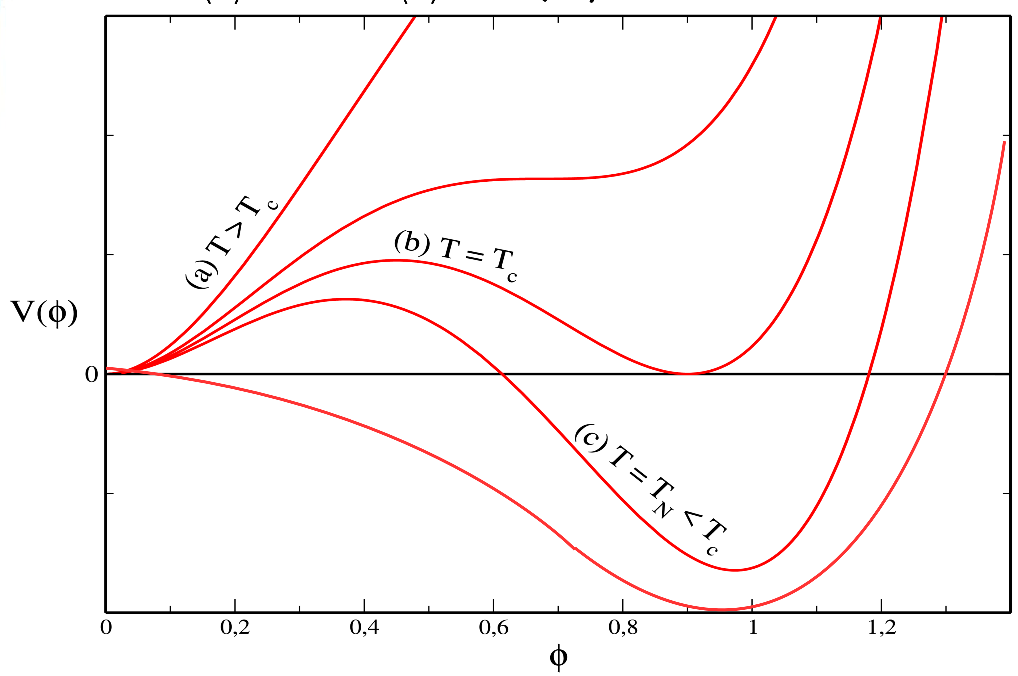
$$\approx (a\,T^2 - \mu^2)\,h^2 - E(T)\,h^3 + \lambda_{eff}(T)\,h^4$$ (High - T expansion)

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

Tree-level potential | Loop corrections | Thermal corrections

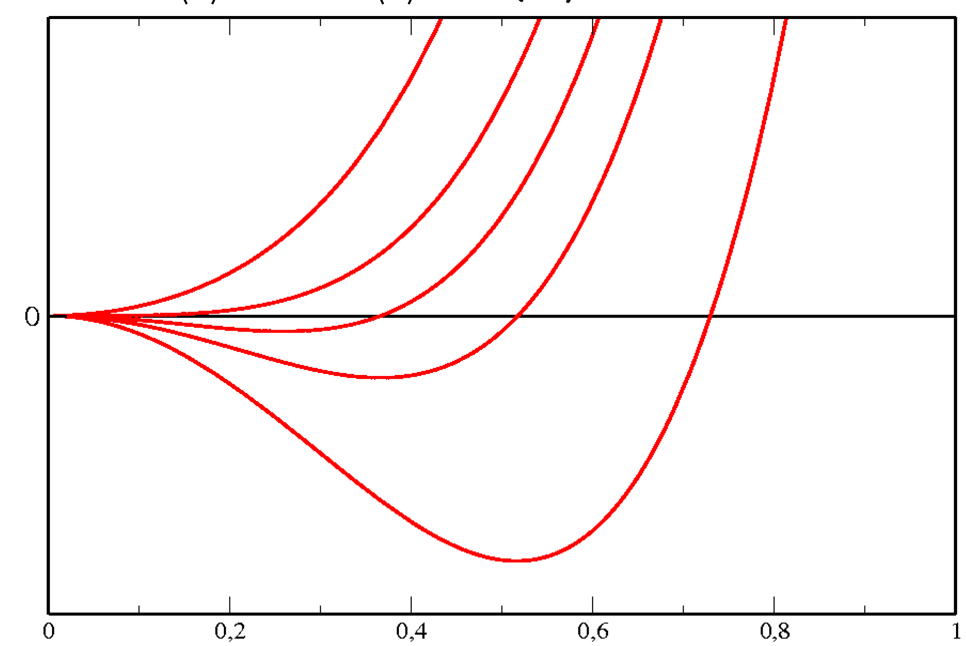
1^{st} Order:

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



2^{nd} Order:

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



EW Phase Transition

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

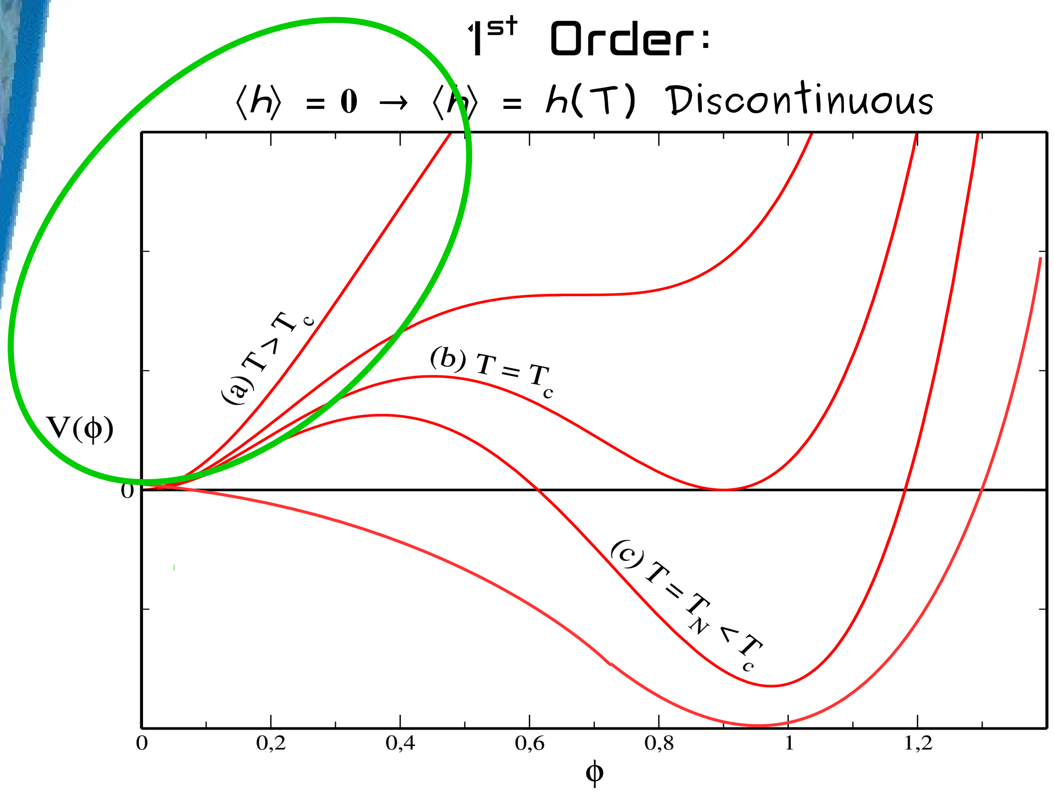
$$V_{\rm eff}(h,T) = V_0(h) + V_0^{\rm loop}(h) + V_T(h,T)$$

Tree-level potential | Loop corrections | Thermal corrections

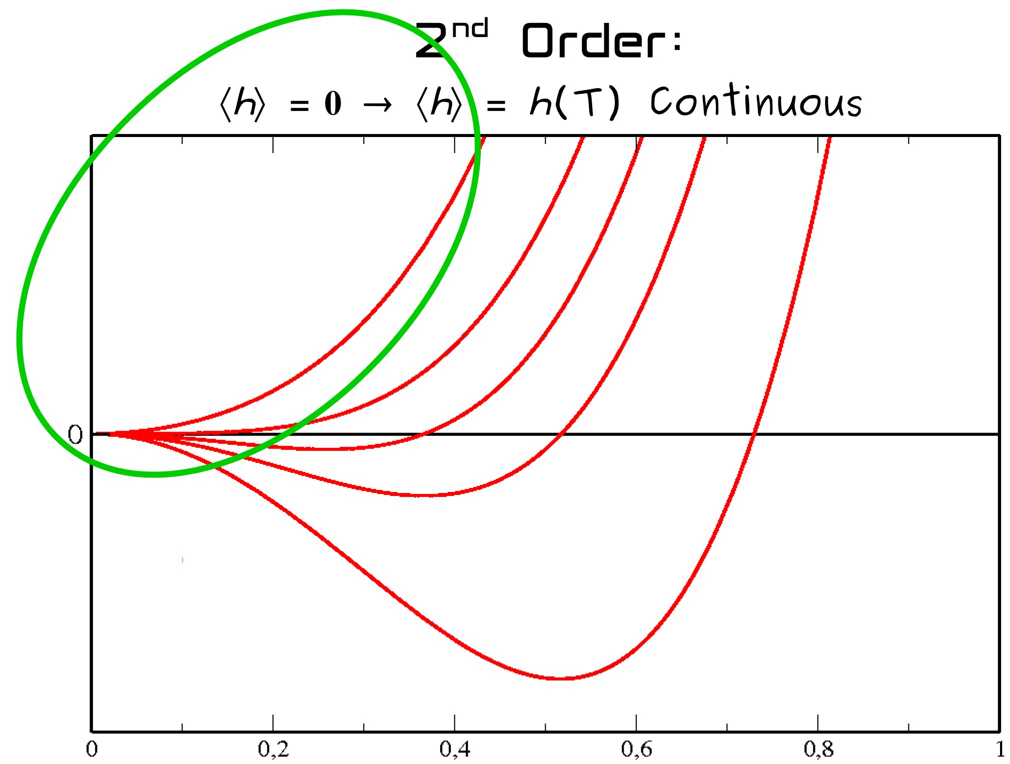
$T \gg v$

EW Symmetry Restoration

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



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



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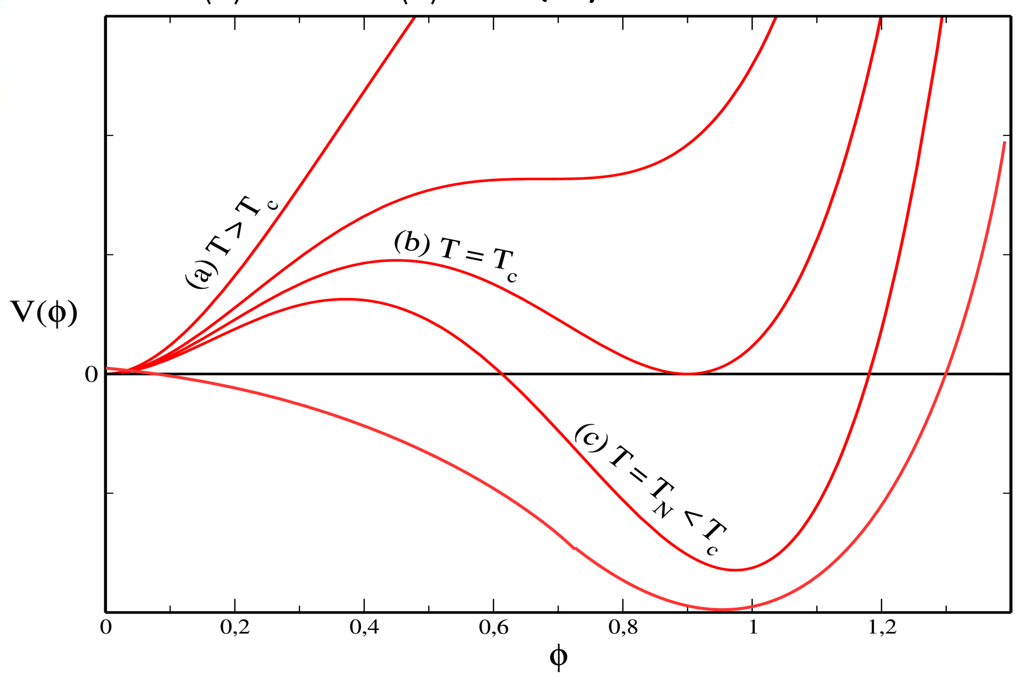
Tree-level potential — Loop corrections — Thermal corrections

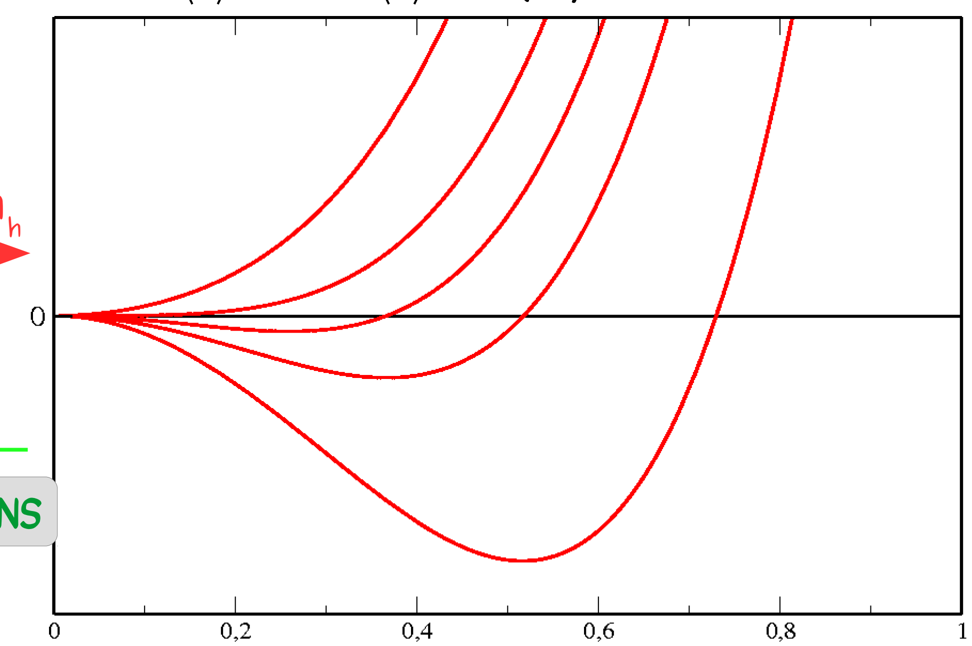
1st Order: $\langle h\rangle = 0 \rightarrow \langle h\rangle = h(T)$ Discontinuous



LARGER m_h →

← NEW BOSONS

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



In the SM (m_h = 125 GeV) EW Phase Transition Smooth CrossOver

K. Kajantie, M. Laine, K. Rummukainen, M. Shaposhnikov, Phys. Rev. Lett. ***77*** *(1996) 2887*

Non-analytic term $(m^2)^{3/2}$ in V(h) from Matsubara Zero-modes

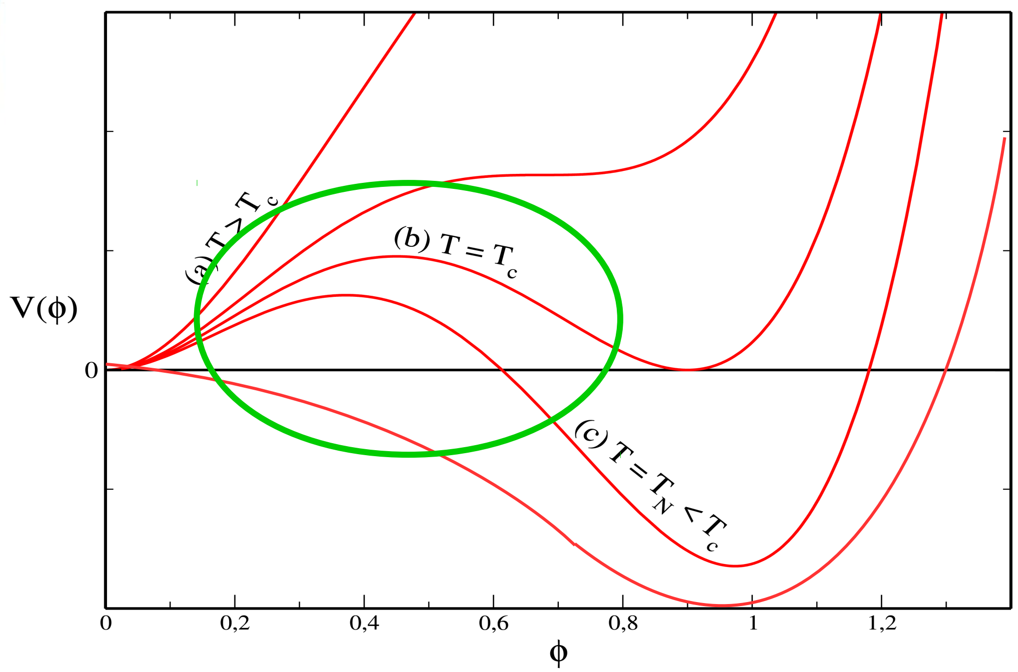
(only present for bosons)

EW Phase Transition

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

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

Tree-level potential | Loop corrections | Thermal corrections



⇨ **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

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

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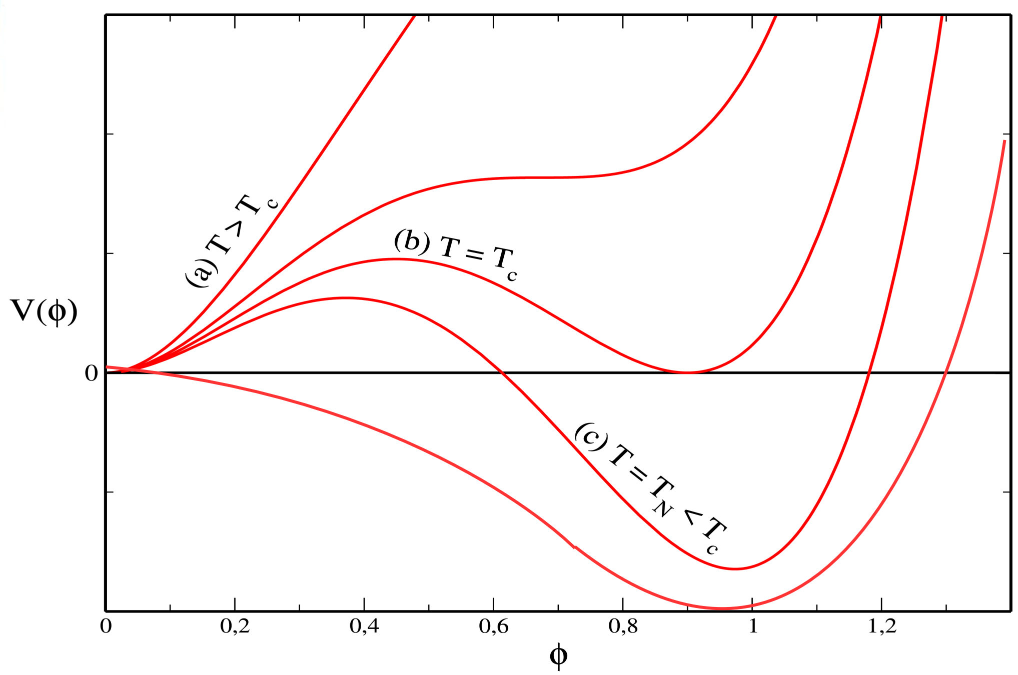
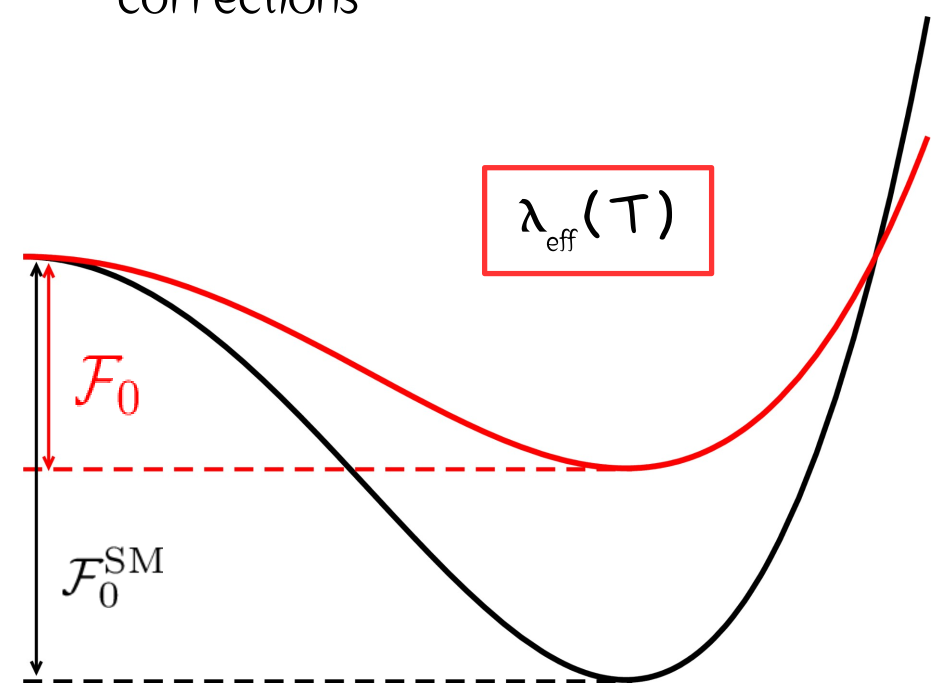
Tree-level potential | Loop corrections | Thermal corrections





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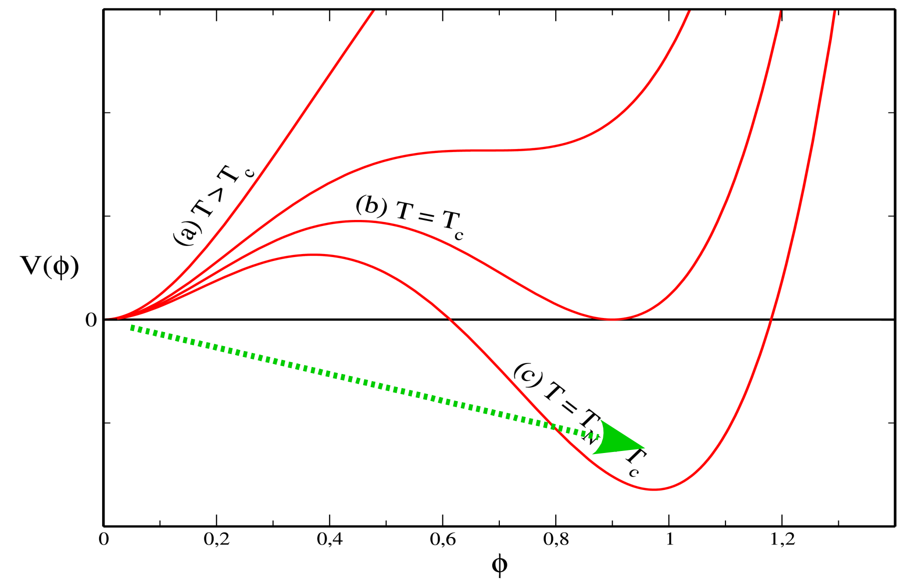
EW Phase Transition



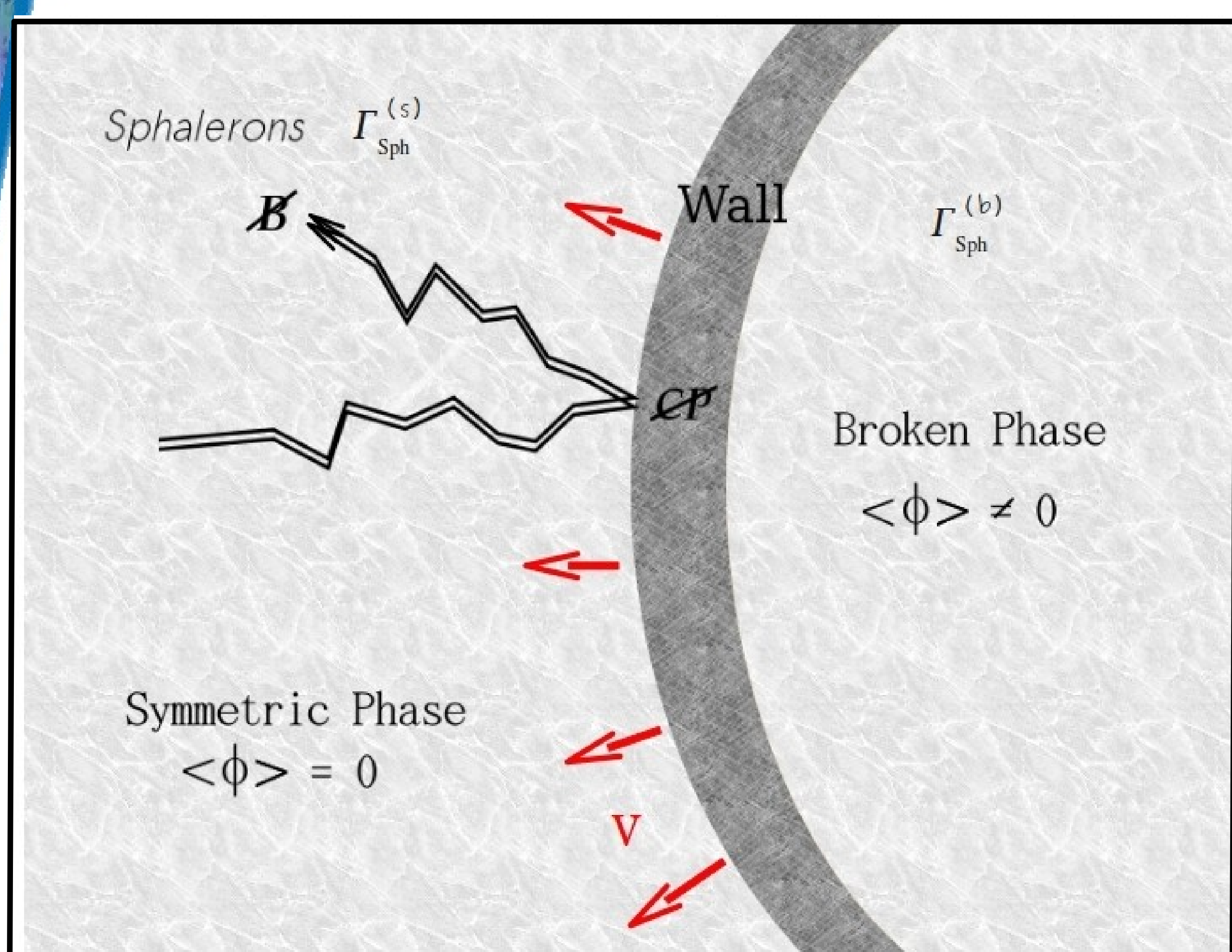
$\Gamma_{\text{Sph}}^{(s)} \sim (\alpha_W T)^4$

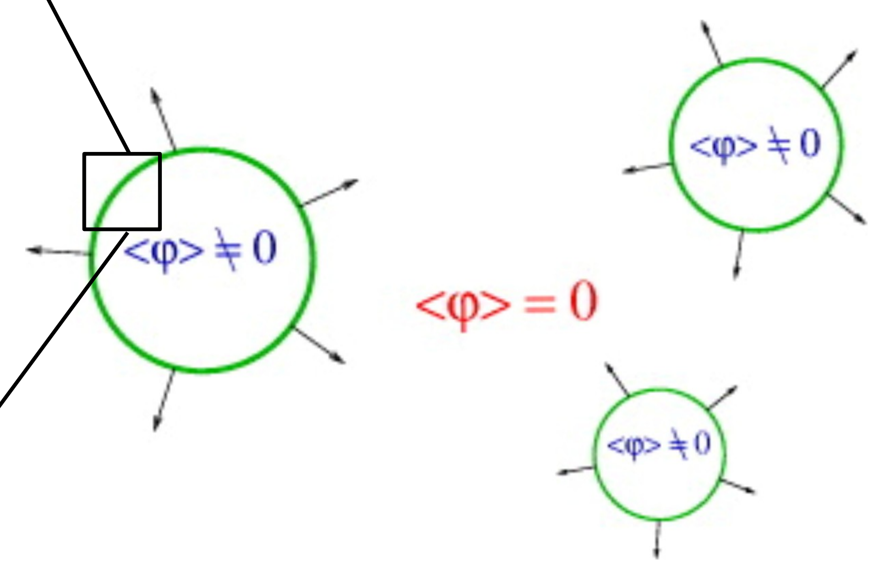
$\Gamma_{\text{Sph}}^{(b)} \sim T^4 \, e^{-E_{\text{Sph}}/T}$

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

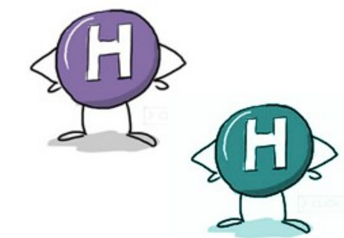
Out of Equilibrium
(SPHALERON SHUT-OFF)

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





Case Study: a Second Higgs



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

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

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

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

2 CP Even States, with

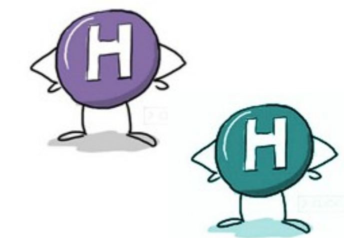
$$m_{H_0} \geq m_h$$

We Assume m_h = 125 GeV

m_{H_0} = 125 GeV Is Also Possible

*Bernon, Gunion, Haber, Jiang, Kraml, Phys. Rev. D**93** (2016) 035027*

Case Study: a Second Higgs



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

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

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

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

h is SM Higgs for $c_{\beta-\alpha} = 0$

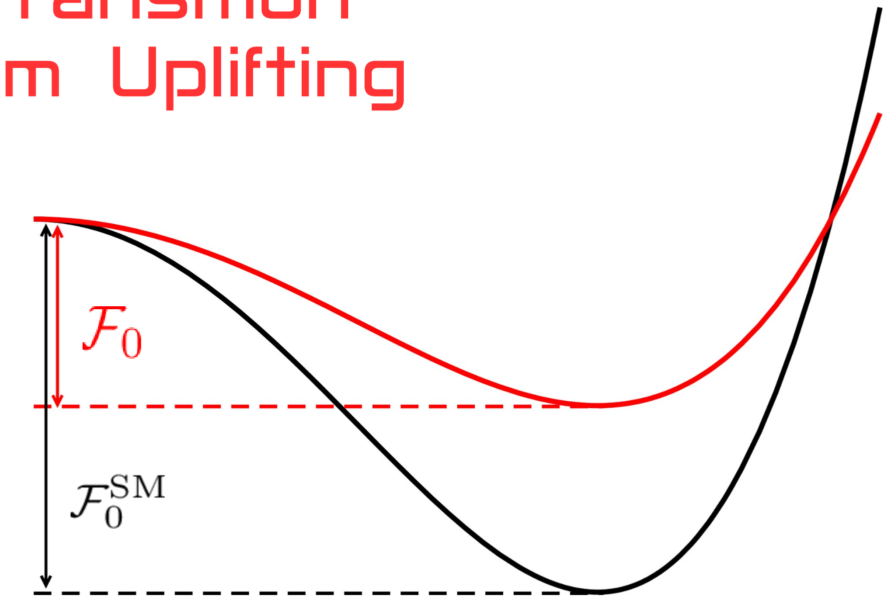
EWPO: $m_{H^\pm} \simeq m_{H_0}$ or $m_{H^\pm} \simeq m_{A_0}$

H_j Couplings to Fermions: Type I , Type II ... choice not Relevant for EW Phase Transition

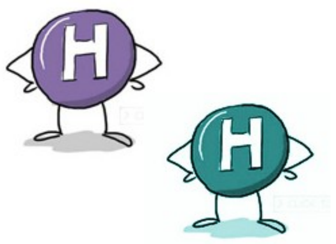
Case Study: a Second Higgs

Strength of 2HDM EW Phase Transition Dominantly Controlled by Vacuum Uplifting

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



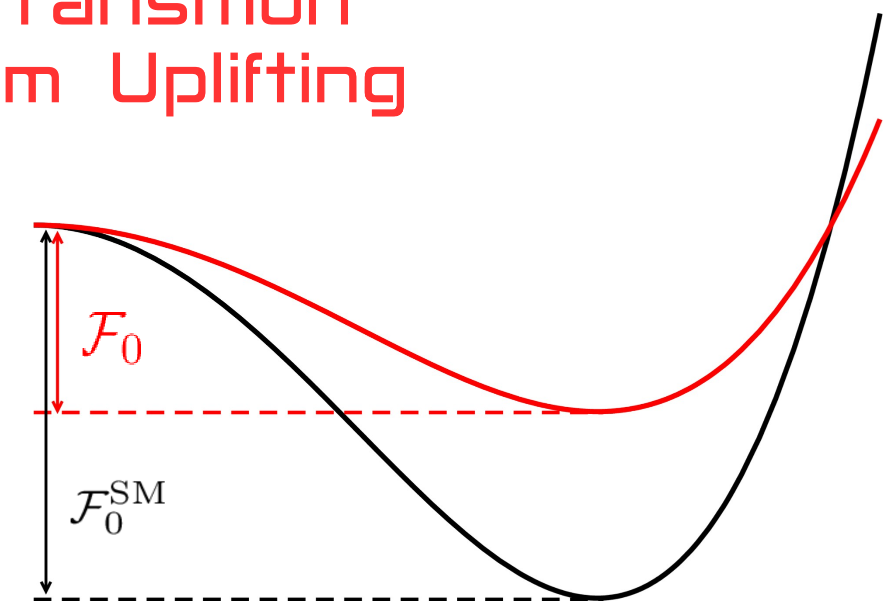
Case Study: a Second Higgs



Strength of 2HDM EW Phase Transition Dominantly Controlled by Vacuum Uplifting

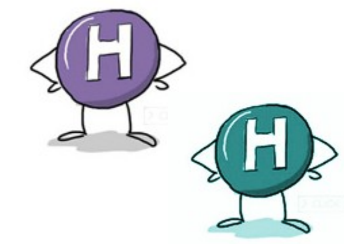
$$\mathcal{F}_0 = V_0(v) + V_0^{\rm loop}(v) - V_0(0) - V_0^{\rm loop}(0)$$

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



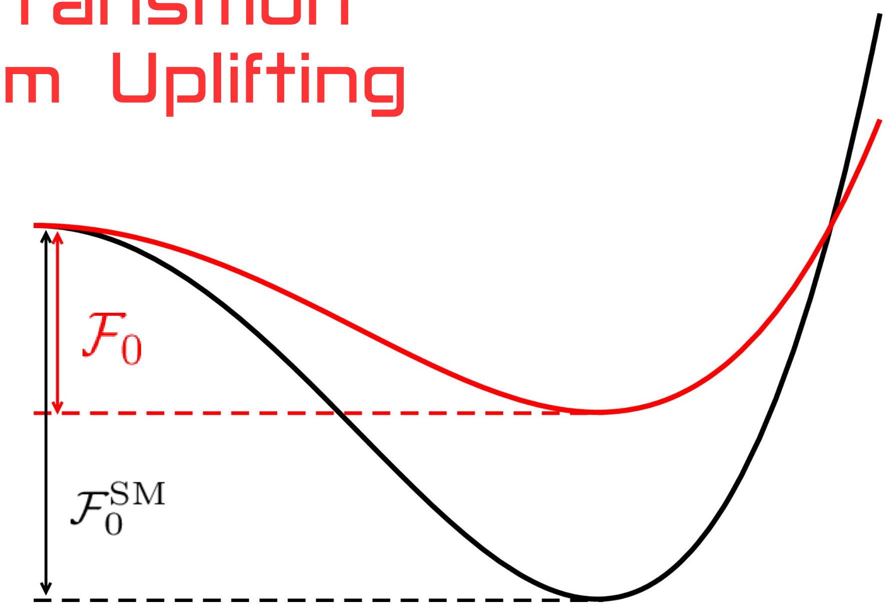
⇒ EW Phase Transition Favours 2HDM Alignment or $m_{H_0} \gtrsim m_h$

Case Study: a Second Higgs



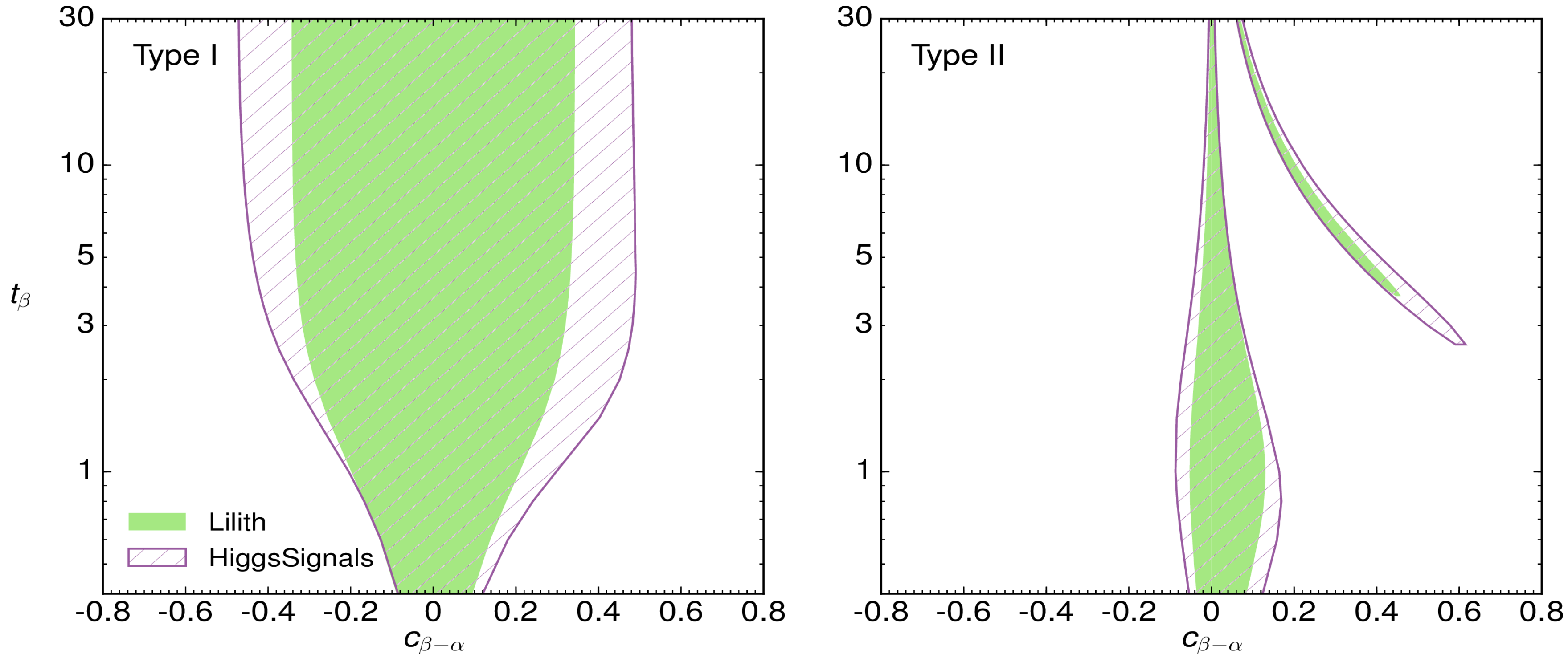
Strength of 2HDM EW Phase Transition Dominantly Controlled by Vacuum Uplifting

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



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

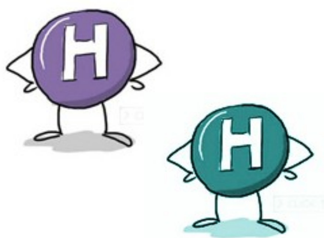
$\Rightarrow$ EW Phase Transition Favours 2HDM Alignment or $m_{H_0} \gtrsim m_h$



Higgs Signal Strengths (LHC Run 1)

Dorsch, Huber, Mimasu, JMN, Phys. Rev. D ***93*** *(2016) 115033*
+ Many Other Refs!

Case Study: a Second Higgs



Strength of 2HDM EW Phase Transition
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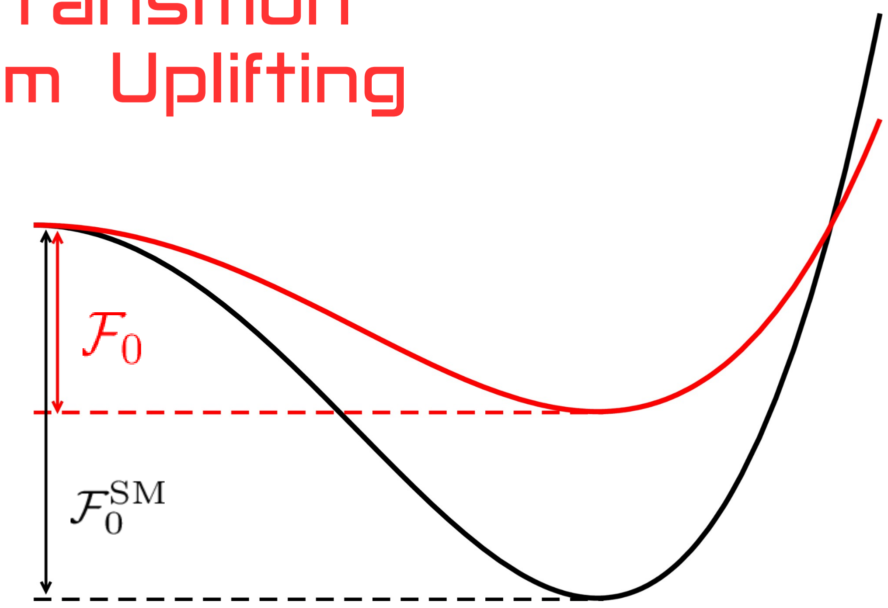

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$\Rightarrow$ EW Phase Transition Favours 2HDM Alignment or $m_{H_0} \gtrsim m_h$

ALIGNMENT LIMIT $c_{\beta-\alpha} = 0$

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

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

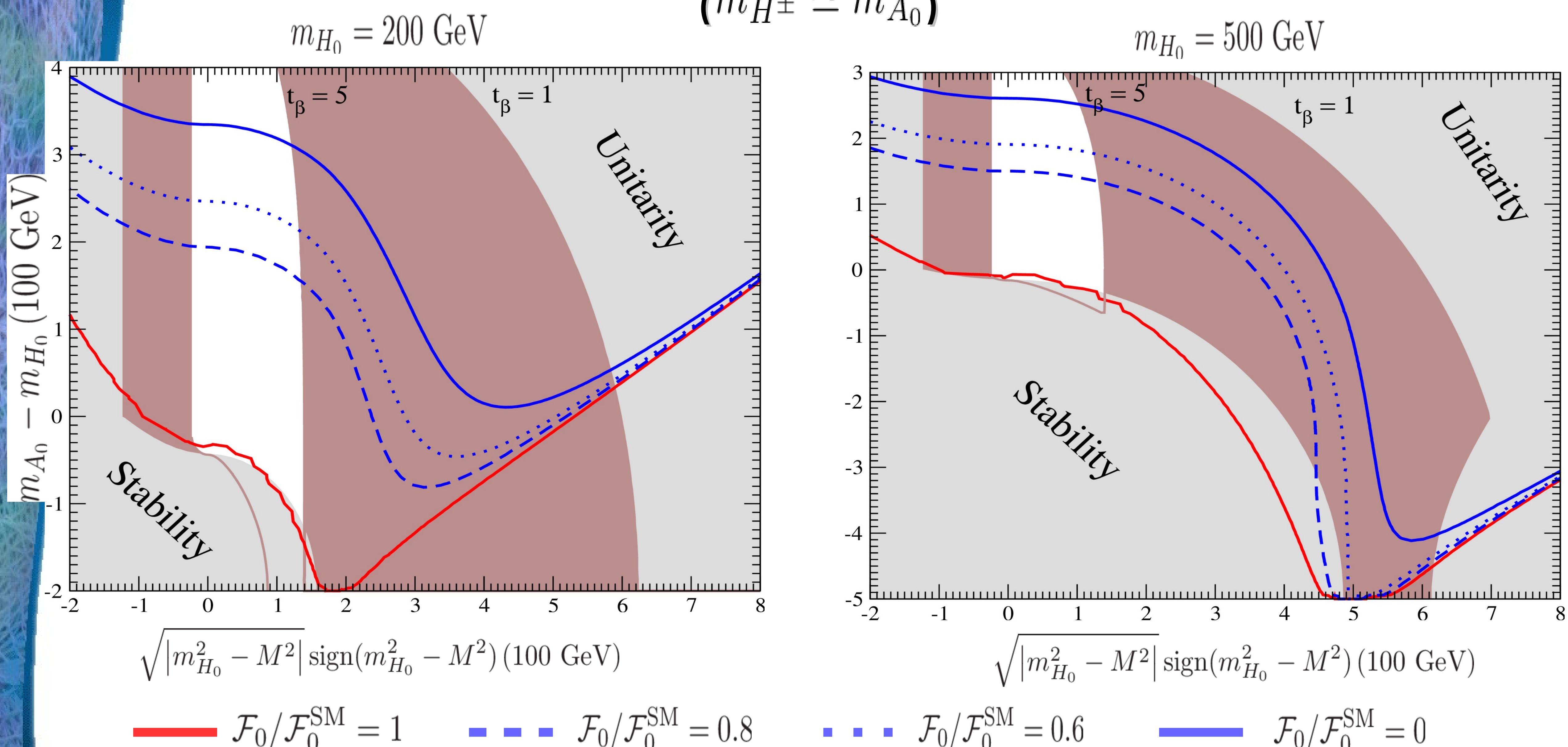
Case Study: a Second Higgs

Combine with 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

Preliminary

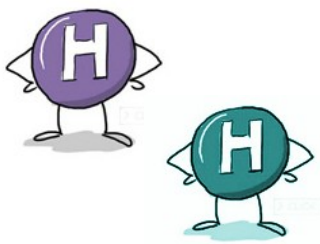
$(m_{H^\pm} \simeq m_{A_0})$



Dorsch, Huber, Mimasu, JMN, arXiv:1612.xxxxx

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

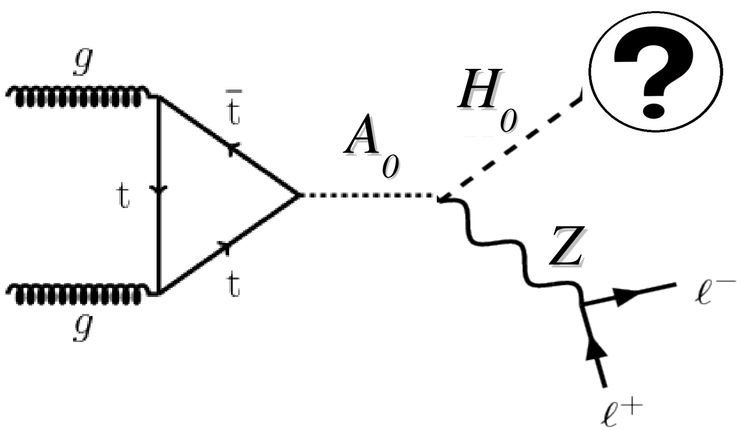
Case Study: a Second Higgs



EW Phase Transition Signature

$$A_0 \to H_0\, Z$$

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



$\bar{b}b$

or

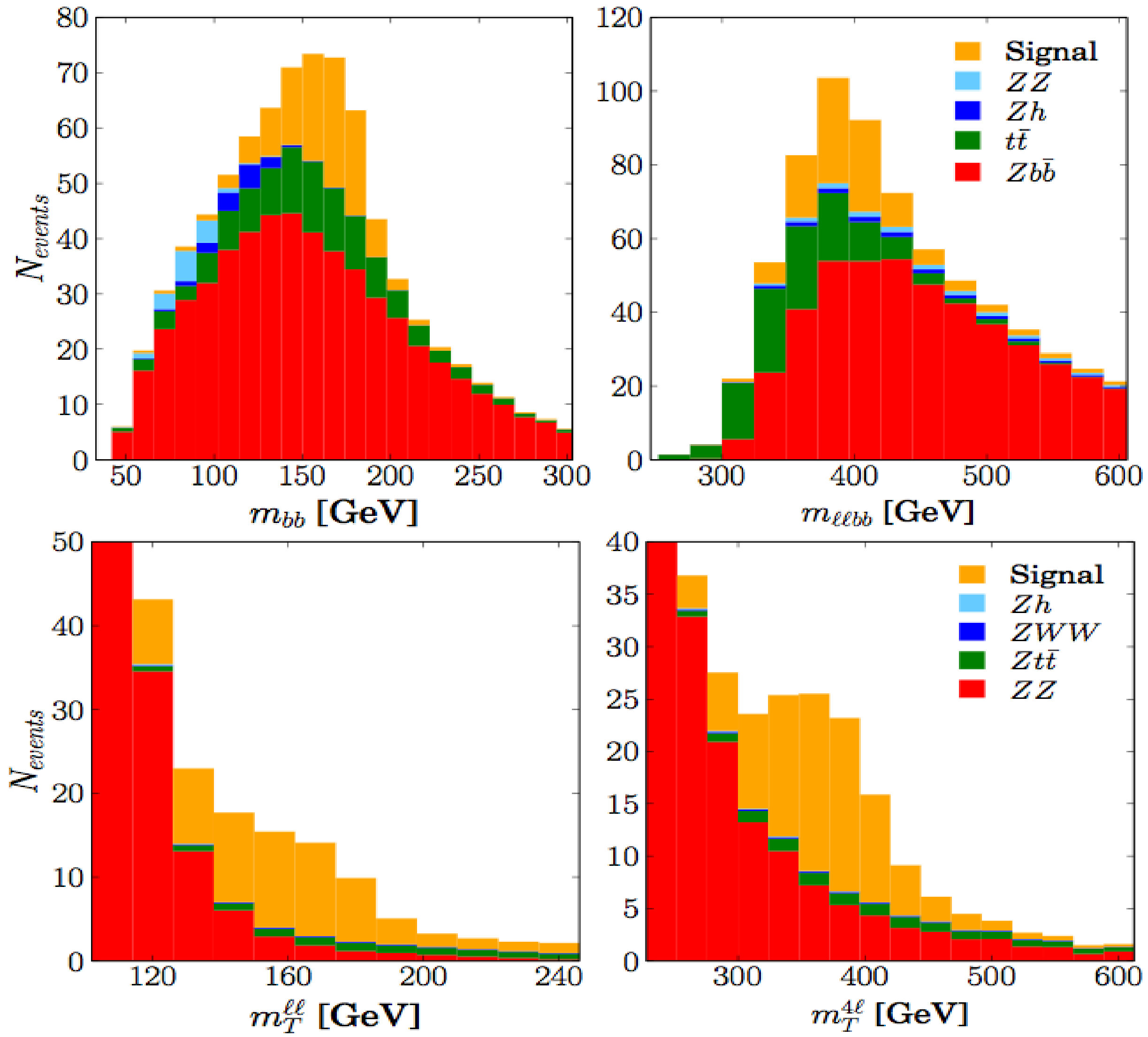
WW, ZZ

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

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

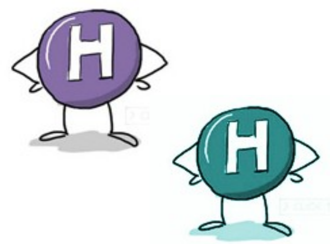
$$(m_T^{\ell\ell})^2 = \left(\sqrt{p_{T,\ell\ell}^2 + m_{\ell\ell}^2} + \not{p}_T\right)^2 - \left(\vec{p}_{T,\ell\ell} + \vec{\not{p}}_T\right)^2$$

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



LHC 13 TeV with ~100 fb^{-1}
Shall Have a Final Word
on this Scenario

Case Study: a Second Higgs



CMS-PAS-HIG-15-001

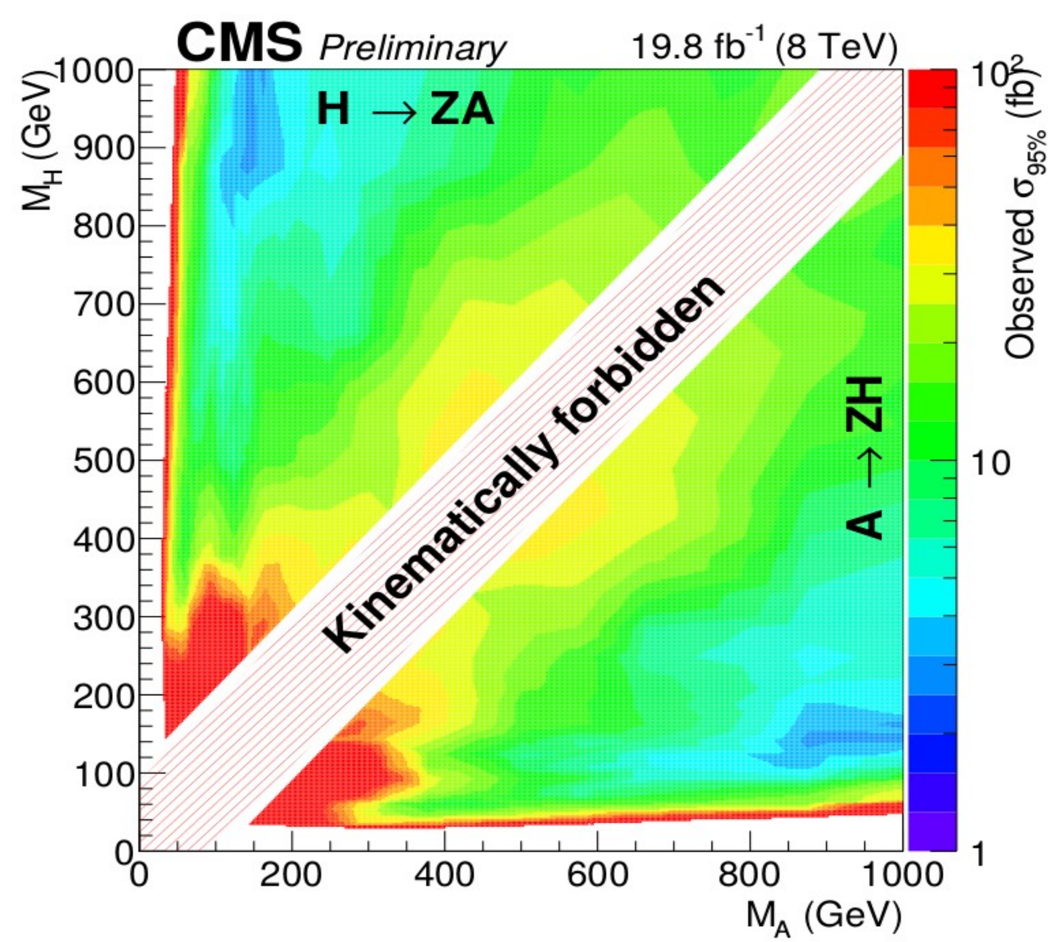
Phys. Lett. B759 (2016) 369 (ArXiv:1603.02991)

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.



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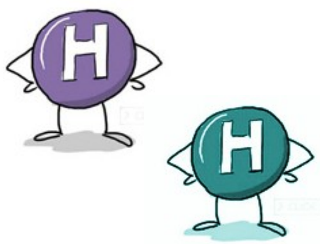
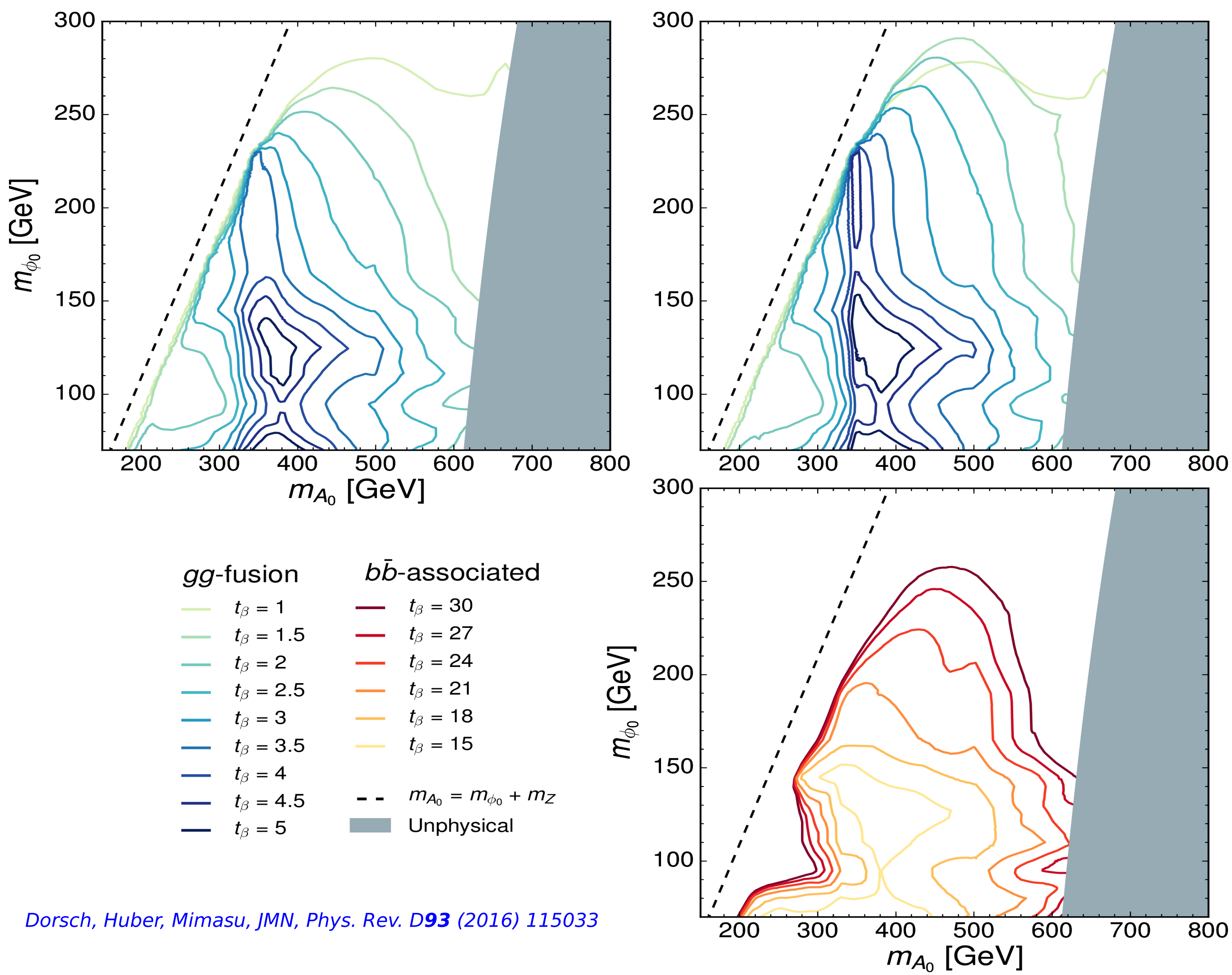
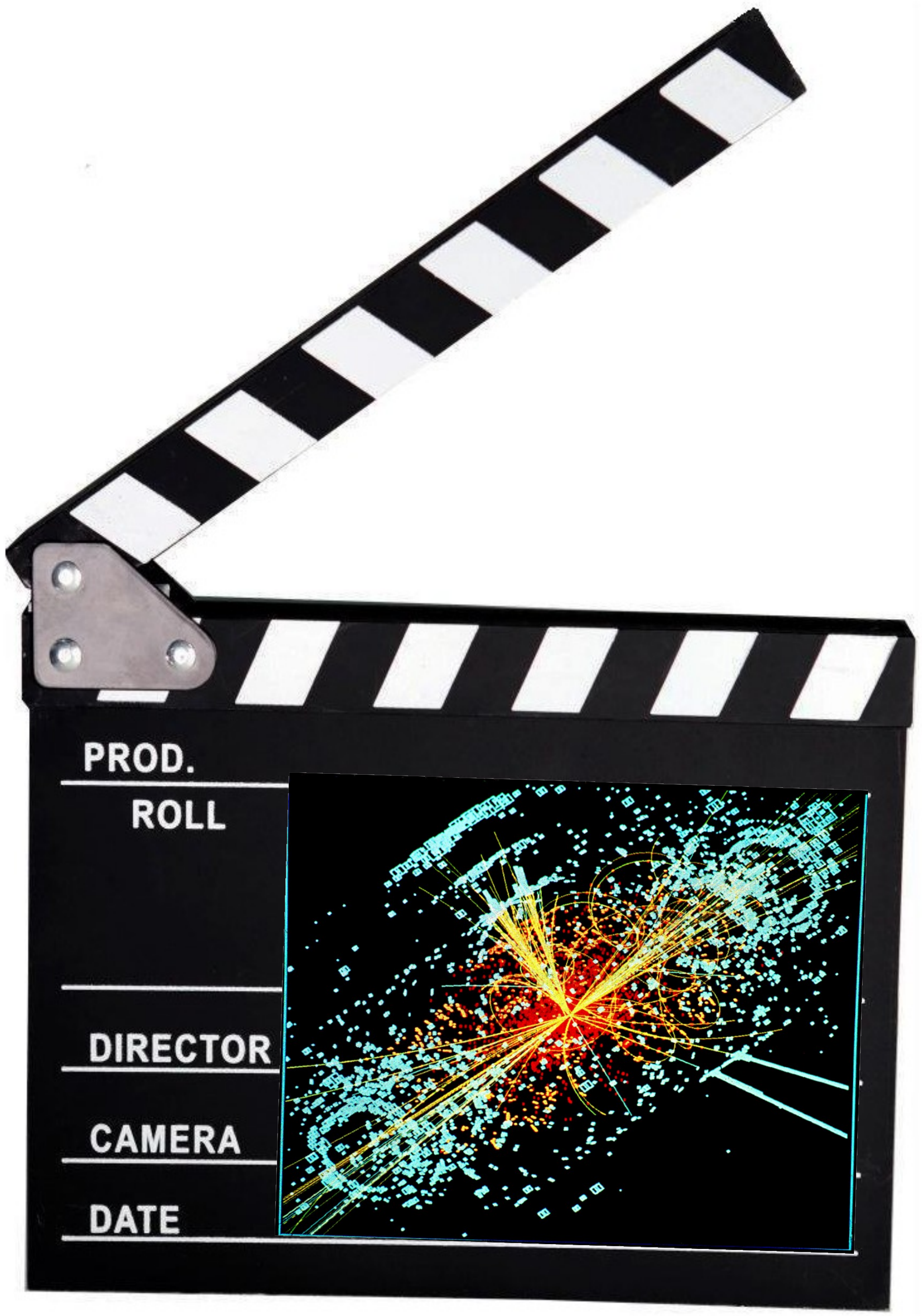


Meaningful LHC Run 1 Constraints

(Assume 2HDM Alignment)



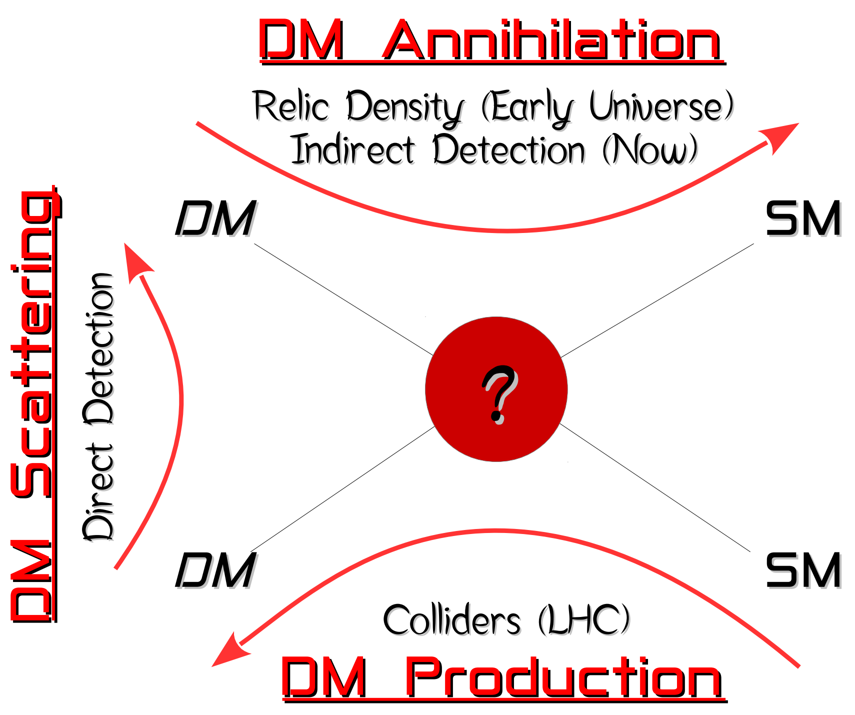
*Dorsch, Huber, Mimasu, JMN, Phys. Rev. D**93** (2016) 115033*


PROD.
ROLL
DIRECTOR
CAMERA
DATE

Higgs & Dark Matter

Assume: DM with Relic Density via Thermal Freeze-Out in Early Universe

Nature of DM-SM Interactions??



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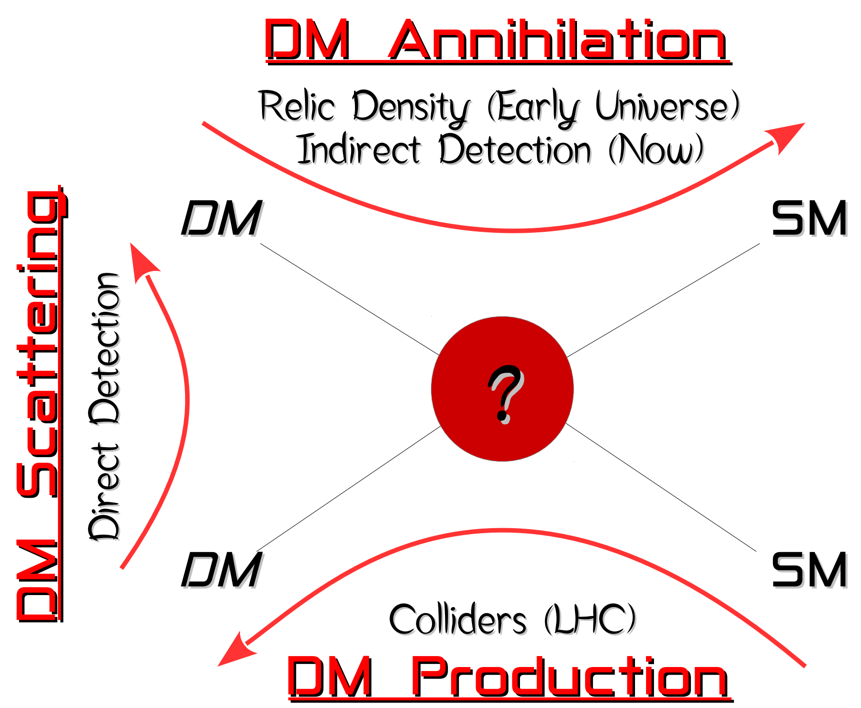

"Dark Matter Complementarity"

Higgs & Dark Matter

DM may feel $SU(2)_{\mathrm{L}} \times U(1)_{\mathrm{Y}}$ gauge interactions

e.g. "Minimal Dark Matter"

*Cirelli, Fornengo, Strumia, Nucl. Phys. B**753** (2006) 178*

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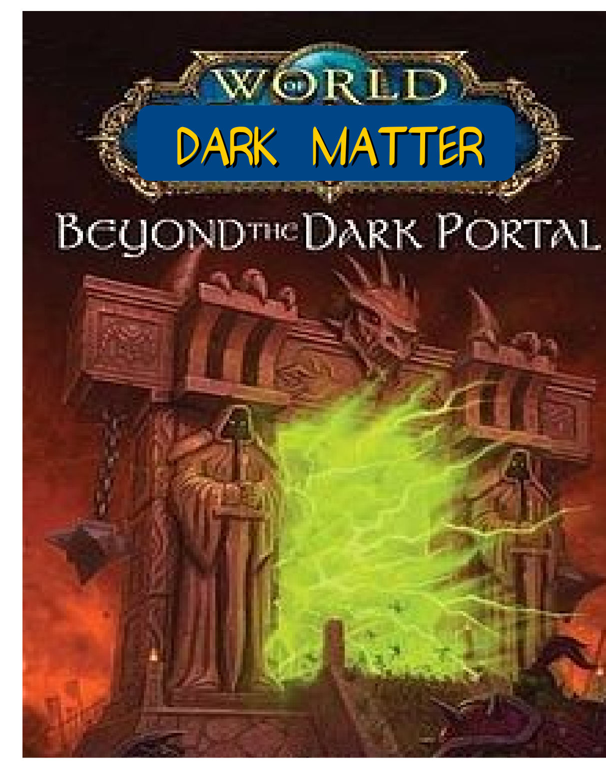
or... DM may belong to a Dark Sector

Need "Portal" Interaction(s) between SM and DS

Standard Model ⟷ (Portal) ⟷ **Dark Sector**



e.g. SM Higgs portal: $H^\dagger H\, O_s$

B.Patt, F. Wilczek, hep-ph/0605188

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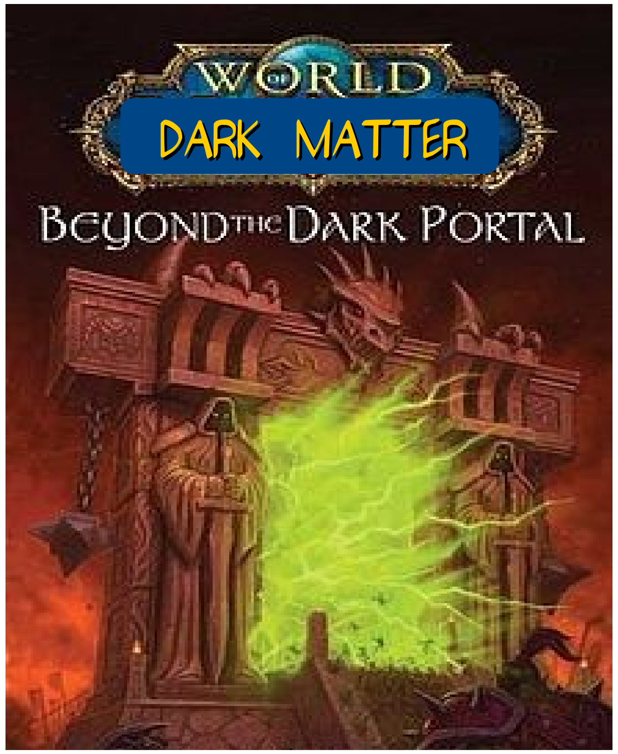
Portal



e.g. SM Higgs portal: $H^\dagger H \, \mathcal{O}_S$

B.Patt, F. Wilczek, hep-ph/0605188

Singlet scalar DM $\lambda_S S^2 H^\dagger H$

The SM Higgs Mediates Interactions of Dark Matter with the SM

The EWSB Sector, Well-Motivated SM-DM Portal

Higgs & Dark Matter

Consider Fermion DM + Spin - 0 Mediator

Higgs & Dark Matter

Consider Fermion DM + Spin - 0 Mediator

Interactions DM-SM may be characterized via Simplified Model (s)

*Shoemaker, Vecchi, Phys. Rev. D**86** (2012) 015023*

*Frandsen, Kahlhoefer, Preston, Sarkar, Schmidt-Hoberg, JHEP**07** (2012) 123*

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

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

Scalar Mediator

$$\begin{aligned}\mathcal{L}_s &= \bar{\chi}(i\partial\!\!\!/ - m_\chi)\chi + \frac{1}{2}(\partial_\mu s)^2 - \frac{m_s^2}{2}s^2 \\ &- g_\chi\, s\,\bar{\chi}\chi - g_{\rm SM}\, s\sum_q \frac{y_q}{\sqrt{2}}\,\bar{q}q\end{aligned}$$

Pseudoscalar Mediator

$$\begin{aligned}\mathcal{L}_a &= \bar{\chi}(i\partial\!\!\!/ - m_\chi)\chi + \frac{1}{2}(\partial_\mu a)^2 - \frac{m_a^2}{2}a^2 \\ &- ig_\chi\, a\,\bar{\chi}\gamma^5\chi - ig_{\rm SM}\, a\sum_q \frac{y_q}{\sqrt{2}}\,\bar{q}\gamma^5 q\end{aligned}$$

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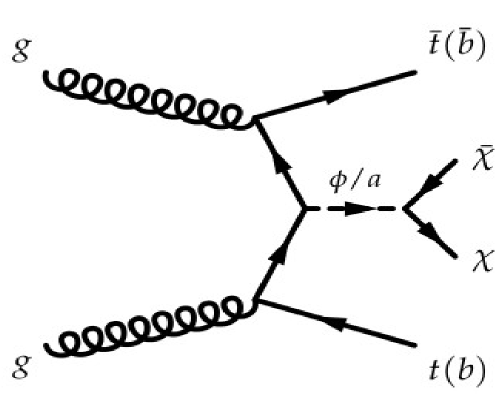
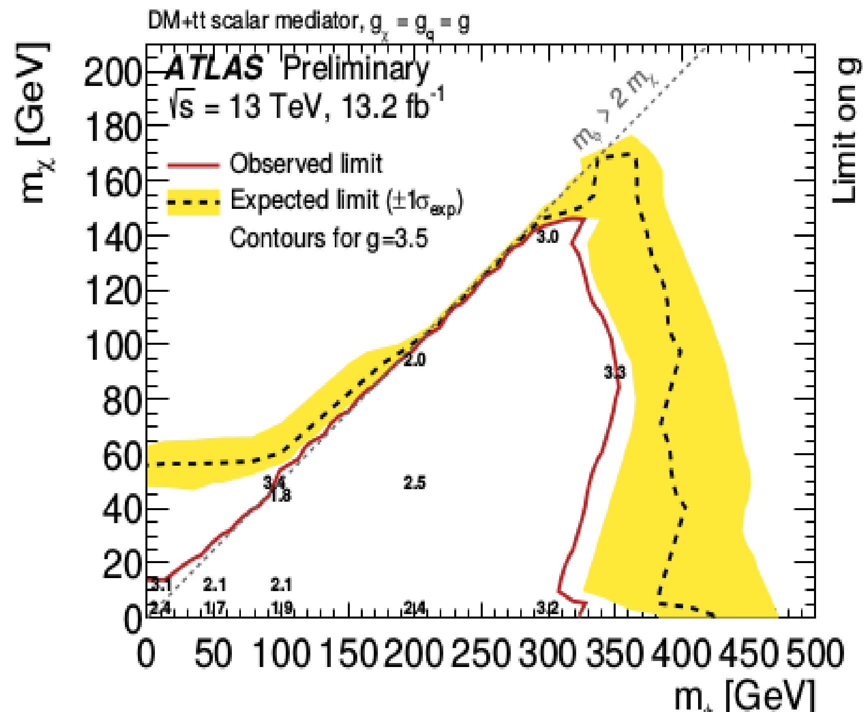
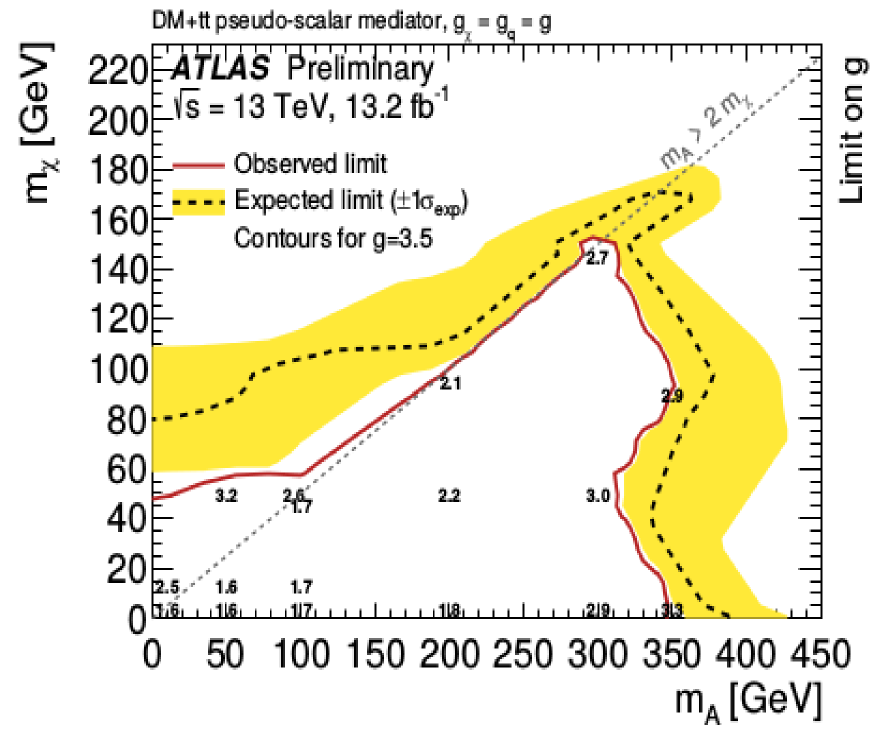
Seem Useful to Interpret LHC Searches







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Seem Useful for DM Complementarity

For Scalar Mediator

Spin-Independent DM Direct Detection (tree-level) MUCH MORE SENSITIVE than LHC

For Pseudoscalar Mediator

Spin Dependent @ Tree-level
Spin Independent @ One-loop

DM Direct Detection MUCH LESS SENSITIVE than LHC

Both very suppressed

Higgs & Dark Matter

The Problem is $SU(2)_{\rm L} \times U(1)_{\rm Y}$ Gauge (non) Invariance

$$\mathcal{L}_a = \bar{\chi}(i\partial\!\!\!/ - m_\chi)\chi + \frac{1}{2}(\partial_\mu a)^2 - \frac{m_a^2}{2}a^2 - ig_\chi\, a\,\bar{\chi}\gamma^5\chi - ig_{\rm SM}\, a \sum_q \frac{y_q}{\sqrt{2}}\,\bar{q}\gamma^5 q$$

Higgs & Dark Matter

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Higgs & Dark Matter

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A Consistent "Completion" of the Simplified Pseudoscalar Portal to DM Goes Beyond the Standard Higgs System

$$V_{\rm Dark} = m_\chi\bar\chi\chi + \frac{1}{2}(\partial_\mu a_0)^2 + \frac{m_{a_0}^2}{2}a_0^2 + i g_\chi\, a_0\,\bar\chi\gamma^5\chi$$

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

2 Higgs Doublets!

Allows Coupling of (singlet) a_0 to SM fermions

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

Higgs & Dark Matter

The Problem is $SU(2)_{\rm L}\times U(1)_{\rm Y}$ Gauge (non) Invariance

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Mixing

Physical States

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

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

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

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

Higgses & Dark Matter

SM + DM + a_0 mediator + NEW STATES

- A New (heavier) Mediator
- $H^{\pm}$ H_0 New States (Mediator Gauge Partners)

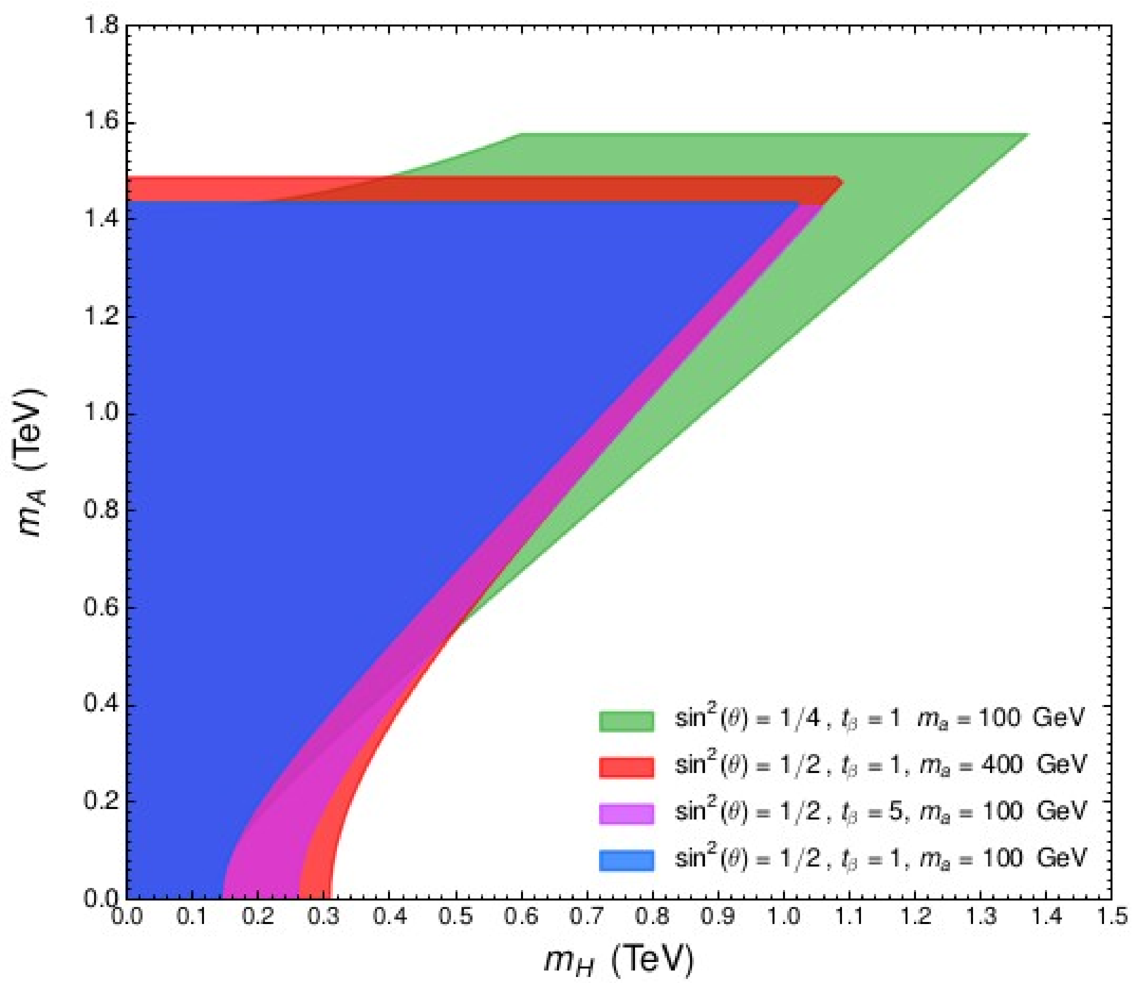
Higgses & Dark Matter

SM + DM + a_0 mediator + NEW STATES

- A New (heavier) Mediator
- $H^{\pm}$ H_0 New States (Mediator Gauge Partners)

NEW STATES DO NOT DECOUPLE (If DM-SM Portal is Active)

Unitarity



Goncalves, Machado, JMN, ArXiv:1611.04593

$$[\, c_{\beta-\alpha} = 0 \qquad m_{H^\pm} = m_{H_0} \,]$$

$$\Delta_a^2 \equiv m_A^2 - m_a^2 \qquad \Delta_H^2 = M^2 - m_{H^\pm}^2 + 2m_W^2 - m_h^2/2$$

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

$$\Lambda_\pm = \left[\frac{\Delta_H^2}{v^2} - \frac{\Delta_a^2\,(1-c_{4\theta})}{8\,v^2} \pm \sqrt{\frac{\Delta_H^4}{v^4} + \frac{\Delta_a^4\,(1-c_{4\theta})}{8\,v^4}}\,\right]$$

$$|\Lambda_\pm| \leq 8\pi$$

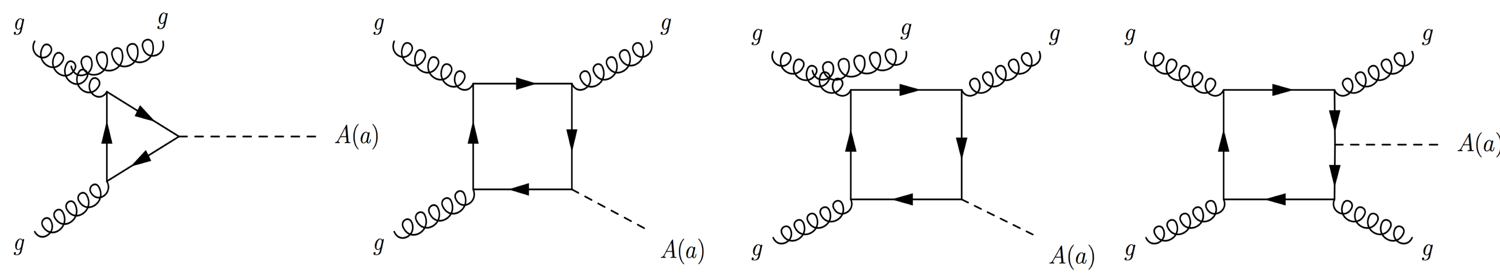
Higgses & Dark Matter

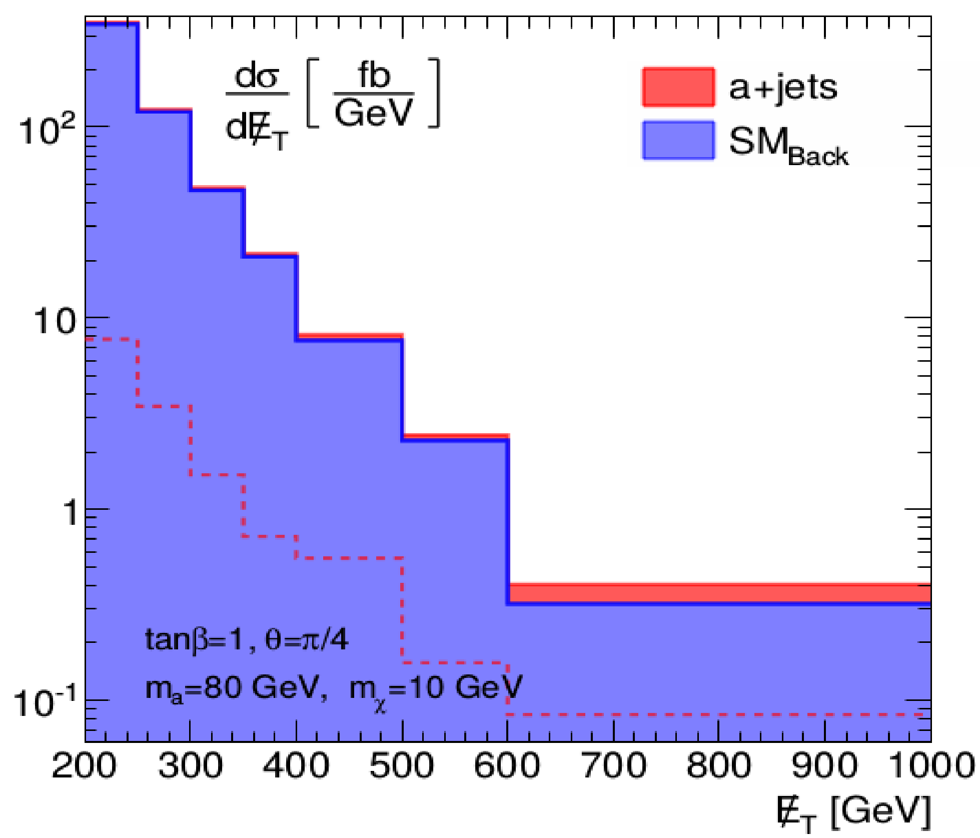
SM + DM + a_0 mediator + NEW STATES → A New (heavier) Mediator; → $H^{\pm}$ H_0 New States (Mediator Gauge Partners)

NEW STATES DO NOT DECOUPLE

Impact on LHC (Simplified Model vs Consistent Completion):

$\mathrm{Jets} + \not{E}_T$





Higgses & Dark Matter

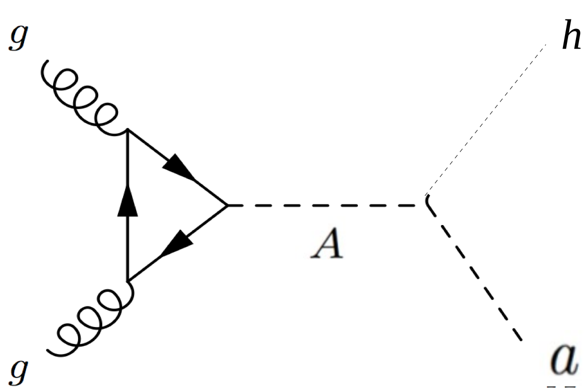
SM + DM + a_0 mediator + NEW STATES

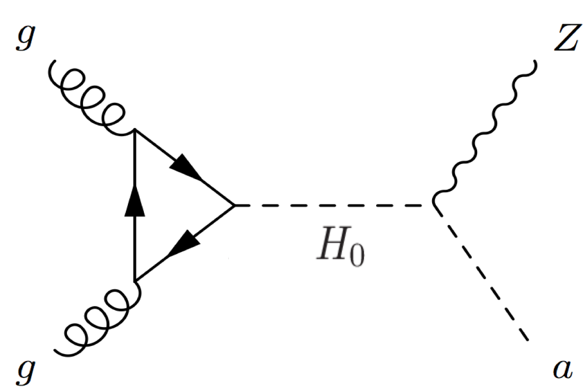
- A — New (heavier) Mediator
- $H^{\pm}$ H_0 — New States (Mediator Gauge Partners)

NEW STATES DO NOT DECOUPLE

Impact on LHC (Simplified Model *vs* Consistent Completion):

$m_A > m_a + m_h$ $\qquad$ $m_{H_0} > m_a + m_Z$





e.g. mono-h

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

"New" Searches: (Resonant) mono-h / mono-Z

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

Higgses & Dark Matter

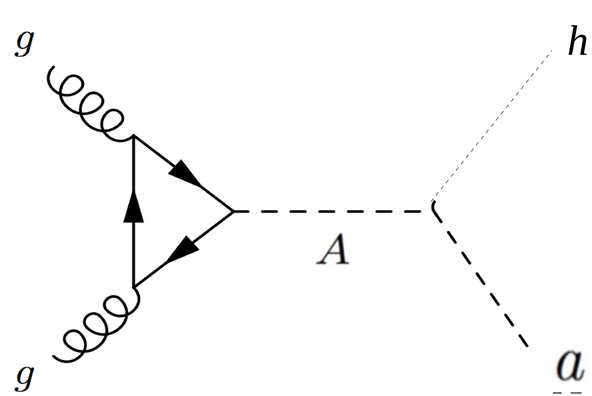
SM + DM + a_0 mediator + NEW STATES

- A — New (heavier) Mediator
- $H^\pm$ H_0 — New States (Mediator Gauge Partners)

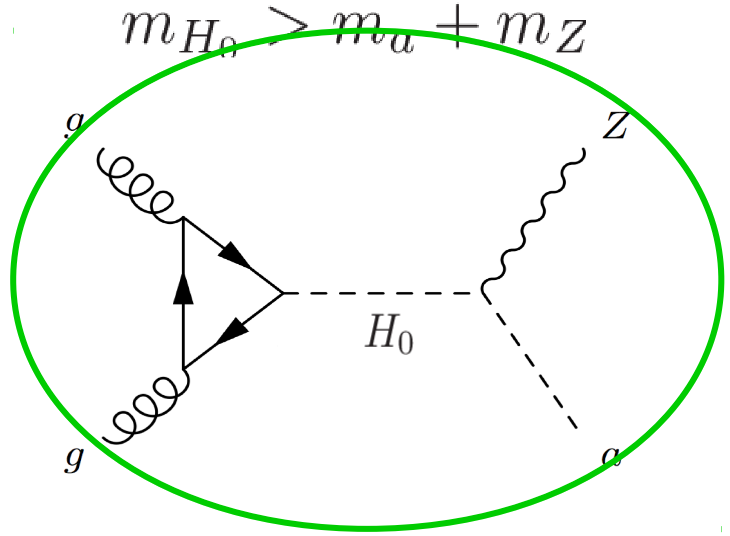
NEW STATES DO NOT DECOUPLE

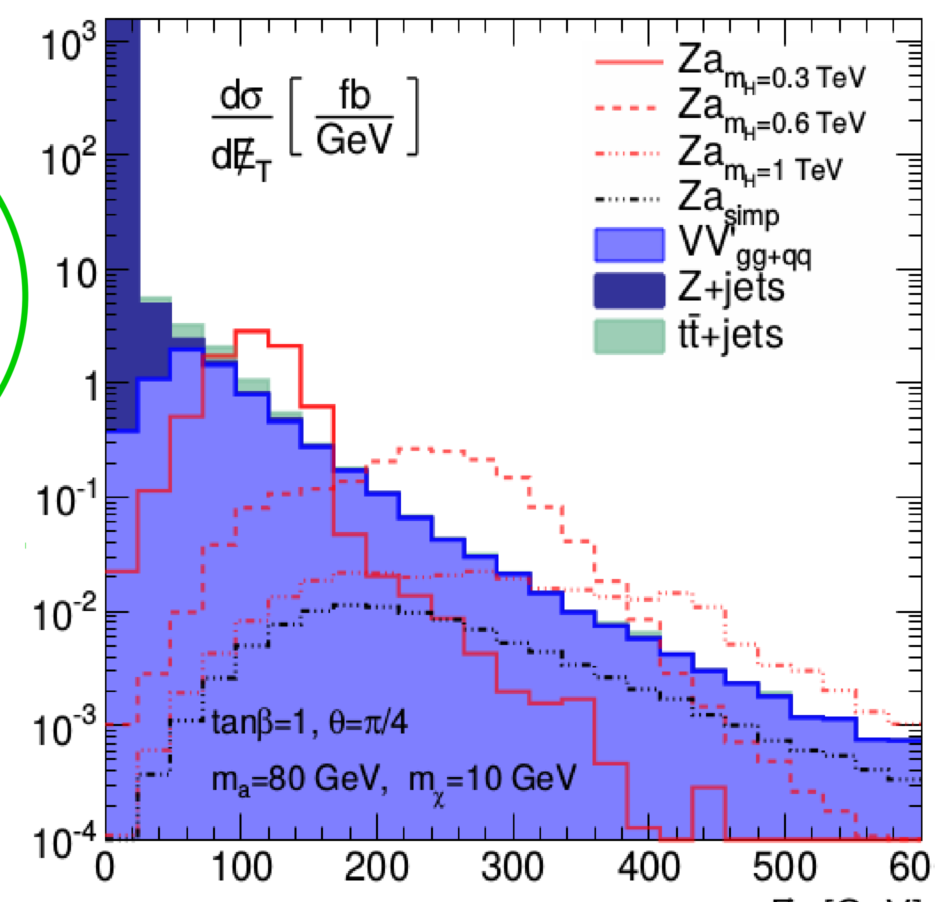
Impact on LHC (Simplified Model vs Consistent Completion):

$m_A > m_a + m_h$



$m_{H_0} > m_a + m_Z$





Goncalves, Machado, JMN, ArXiv:1611.04593

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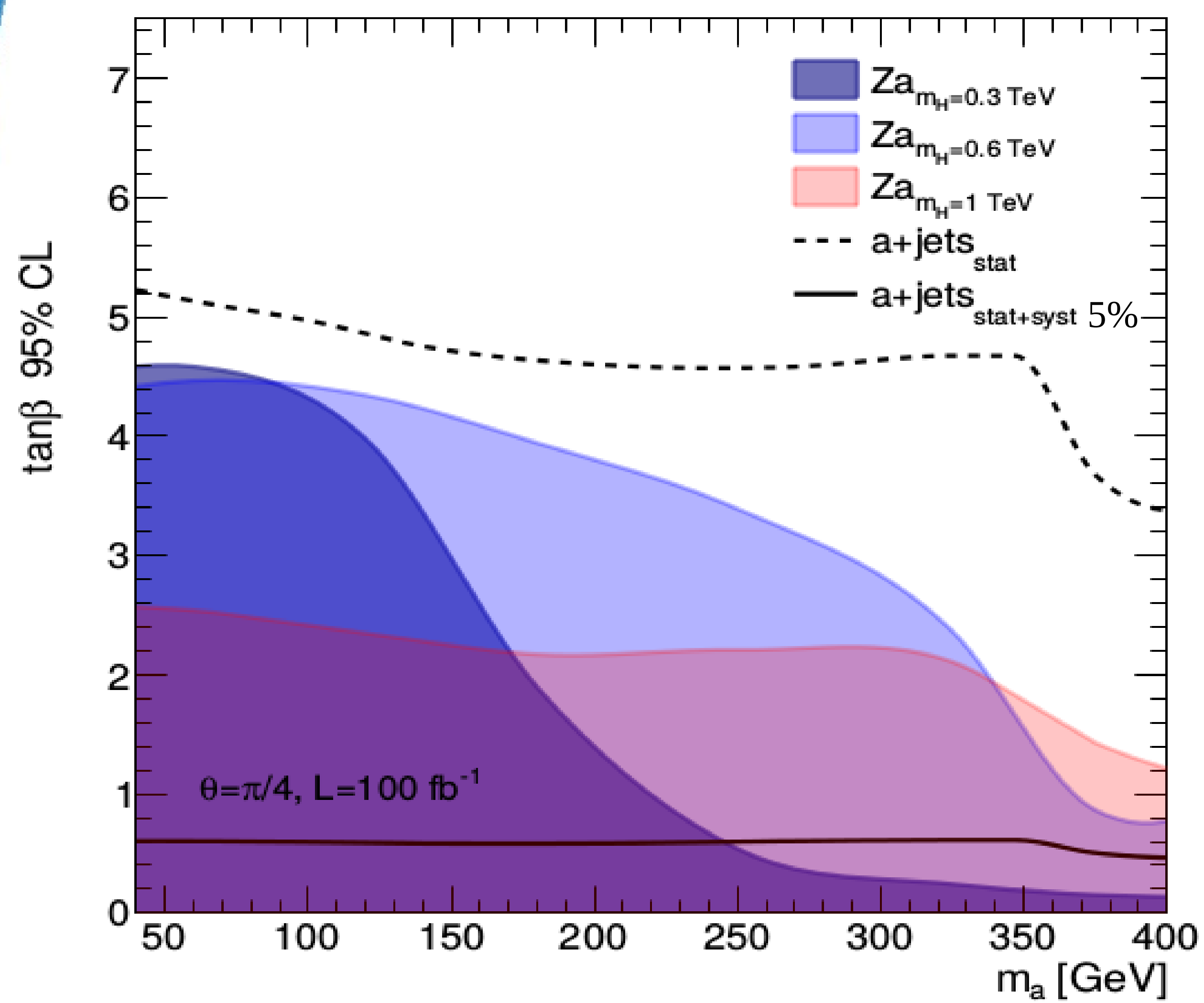


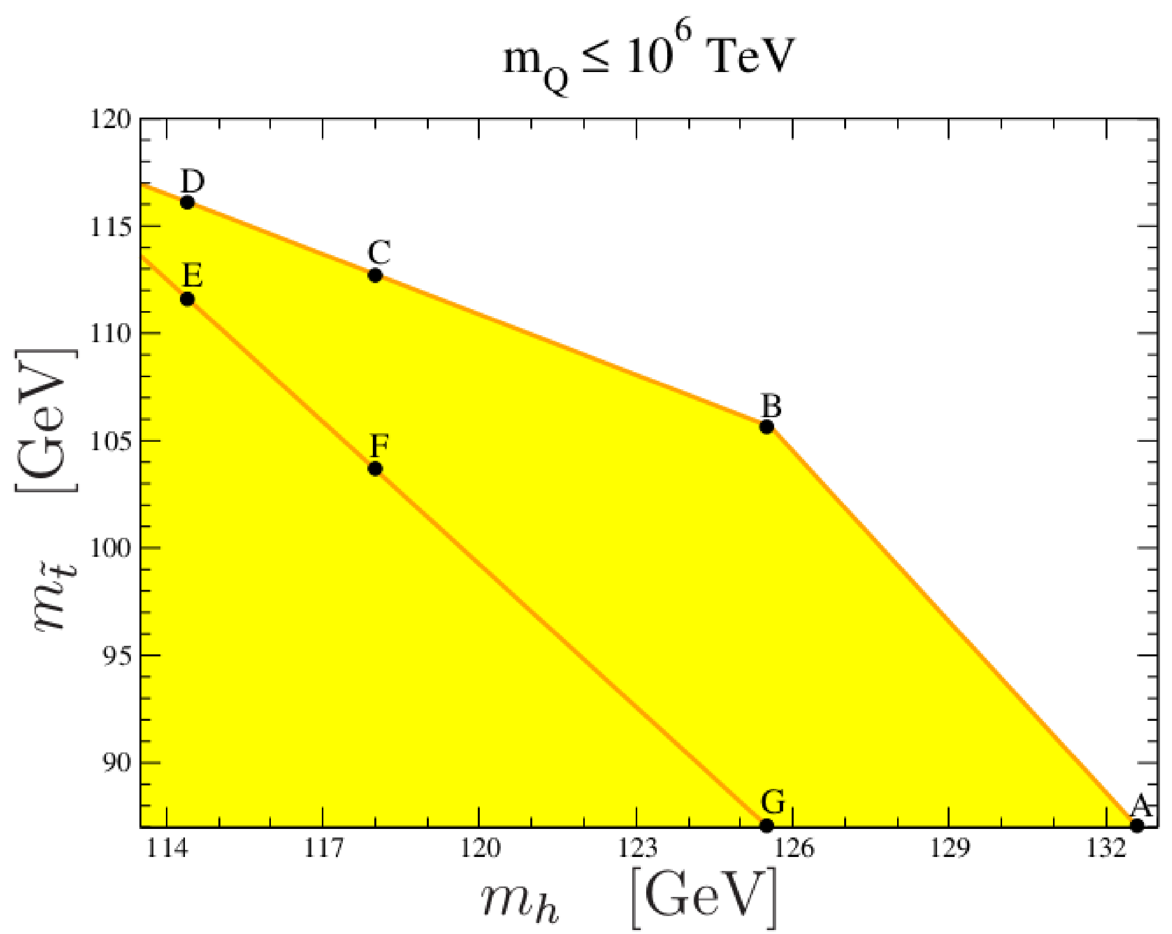
LHC Picture for Consistent DM-SM Pseudoscalar Portal
Very Different from Simplified Model


KEEP
CALM
AND FIND THE
HIGGS
BOSONs


KEEP
CALM
AND
BACKUP
YOUR
WORK

EW Phase Transition @ LHC

MSSM (Most Studied EWBG Scenario)



MSSM Baryogenesis Window

*Carena, Nardini, Quiros, Wagner, Nucl. Phys. B**812** (2009) 243*

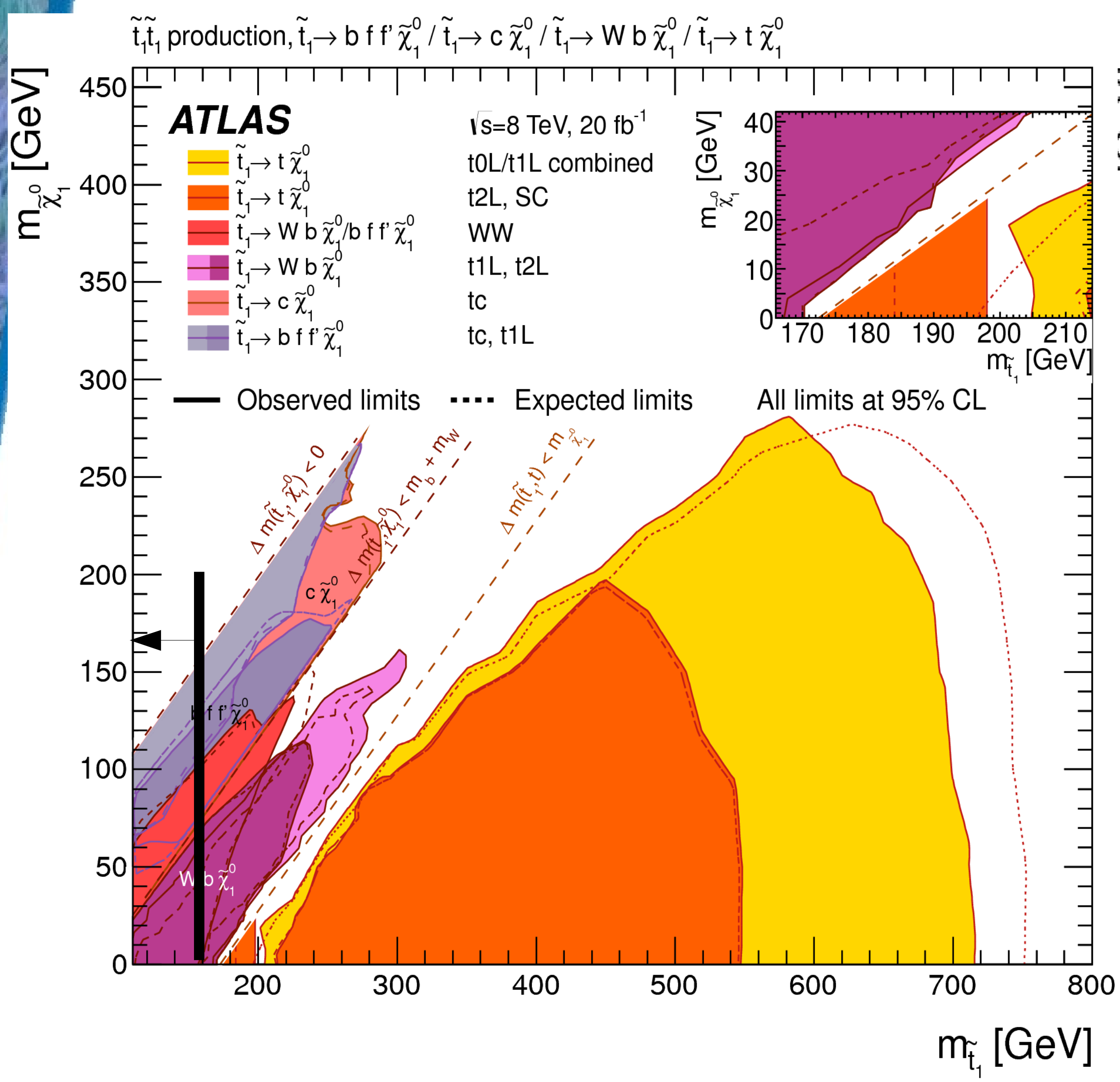
$$m_{\tilde{t}} < 110 \text{ GeV}$$

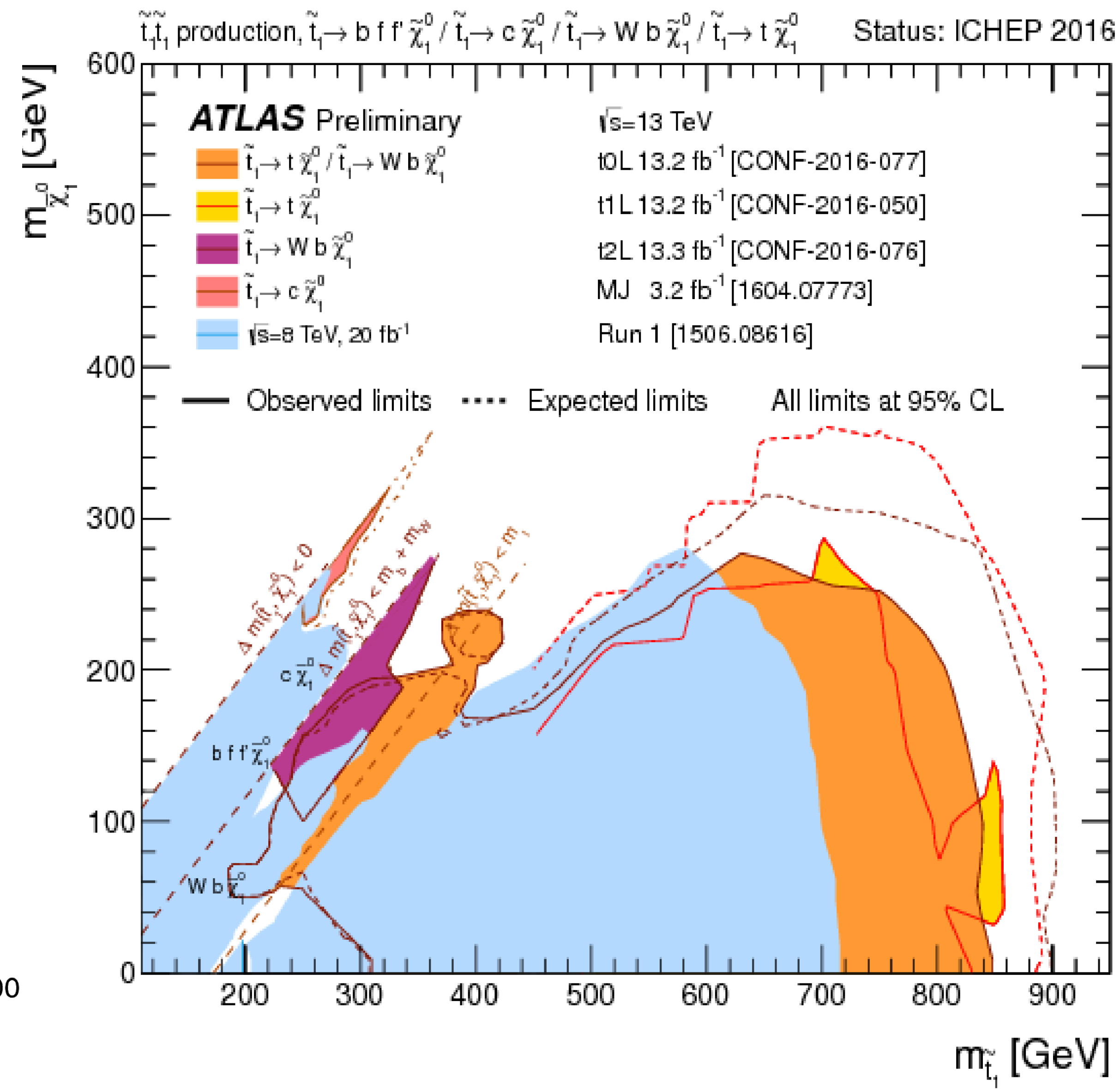
Lattice studies suggest there may be a SEWPT for $m_{\tilde{t}} < 150 - 160$ **GeV**

*Laine, Nardini, Rummukainen, JCAP **1301** (2013) 011*

EW Phase Transition @ LHC

MSSM (Most Studied EWBG Scenario)

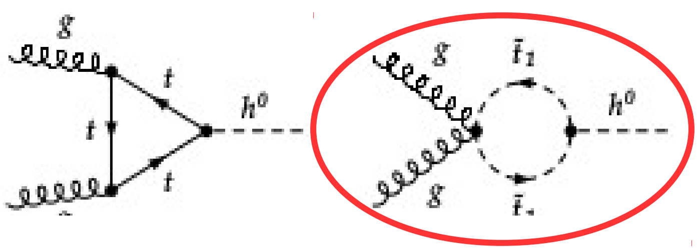


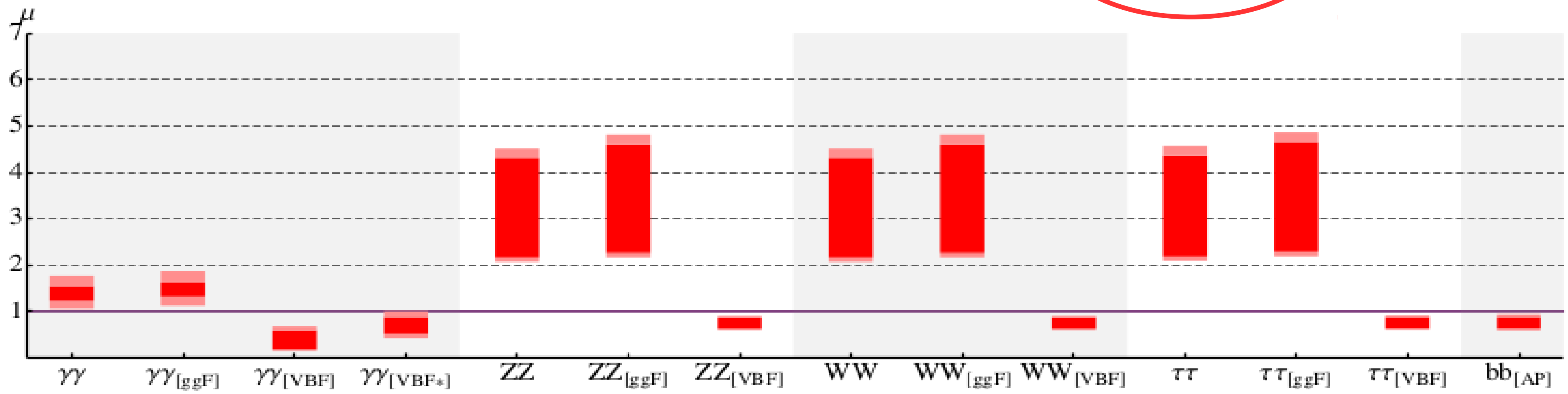


EW Phase Transition @ LHC

MSSM (Most Studied EWBG Scenario)

Deviations in Higgs Couplings from SM
due to Light Stops





Curtin, Jaiswal, Meade, JHEP ***1208*** *(2012) 005*

EW Phase Transition @ LHC

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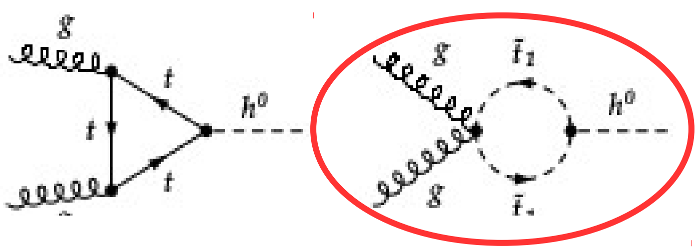
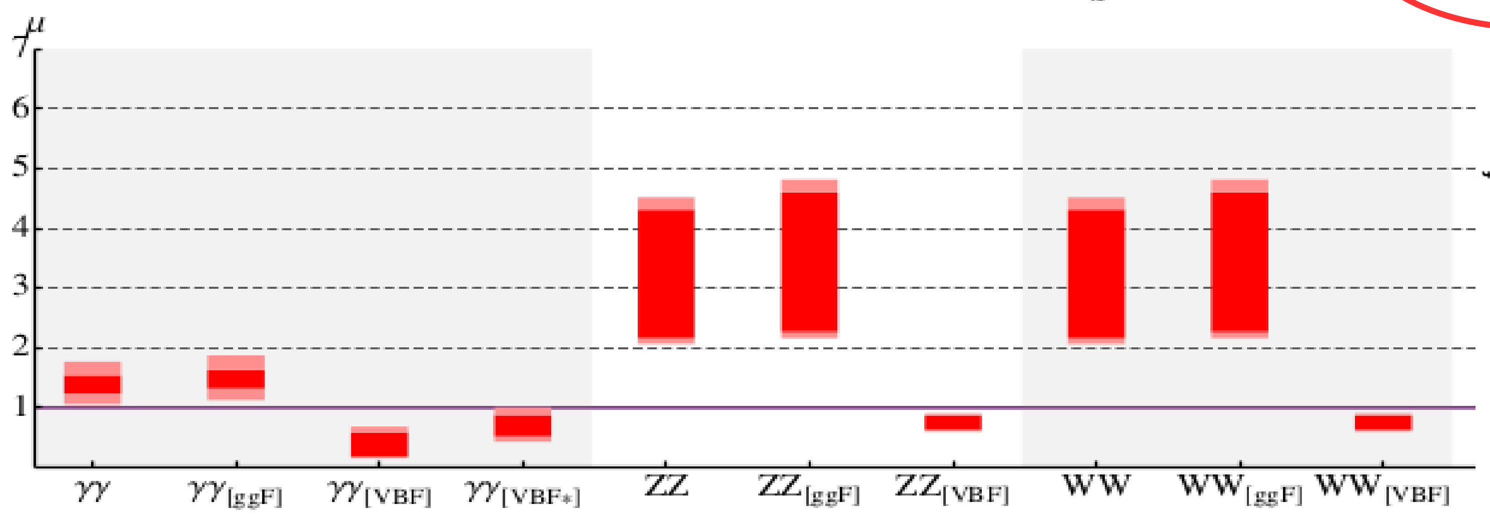
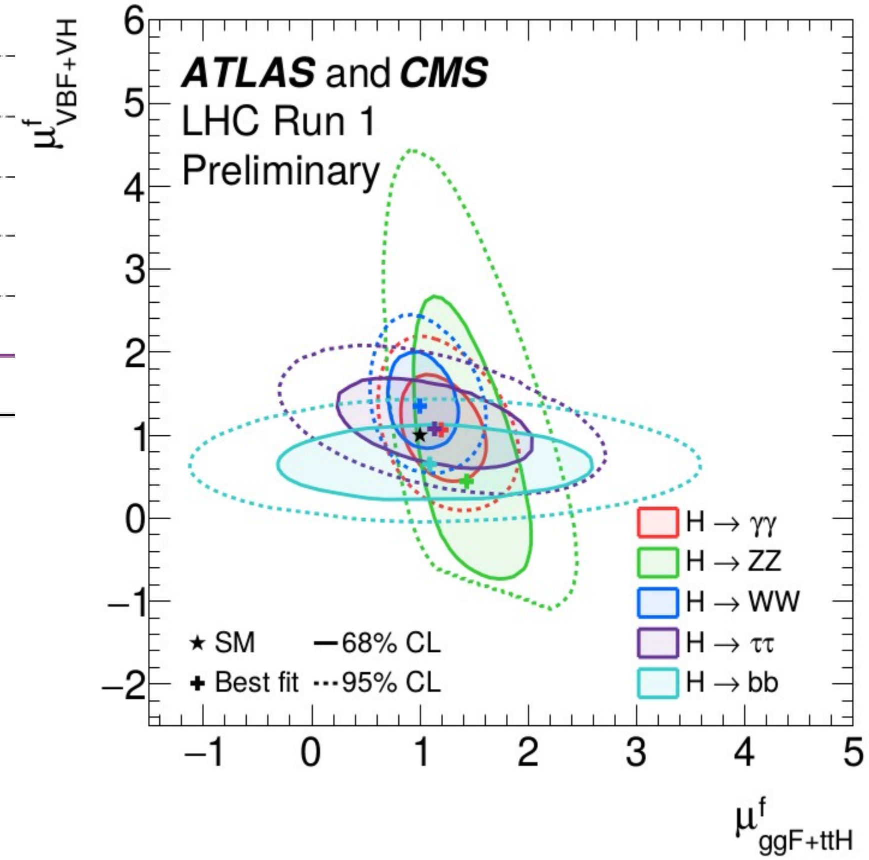




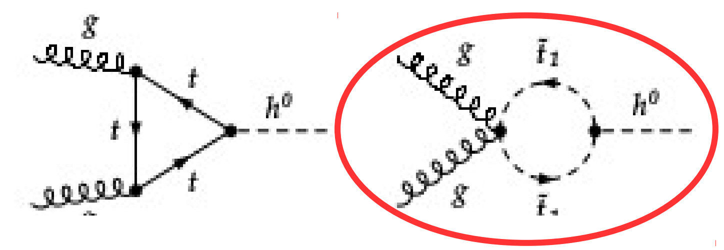
Curtin, Jaiswal, Meade, JHEP ***1208*** *(2012) 005*

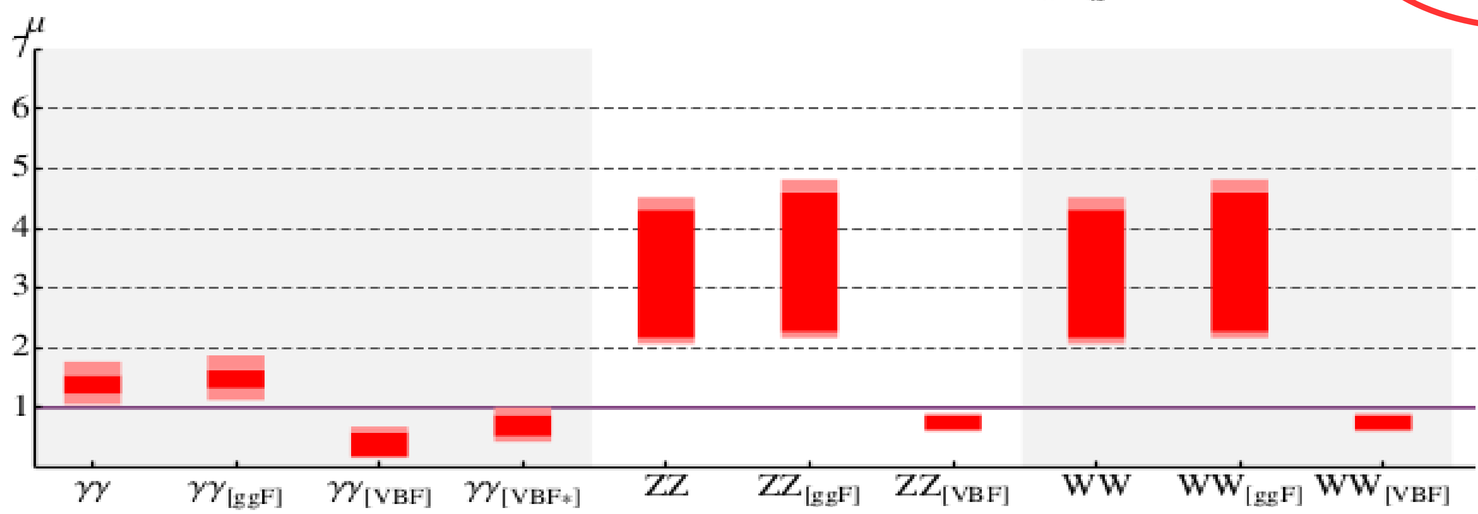


EW Phase Transition @ LHC

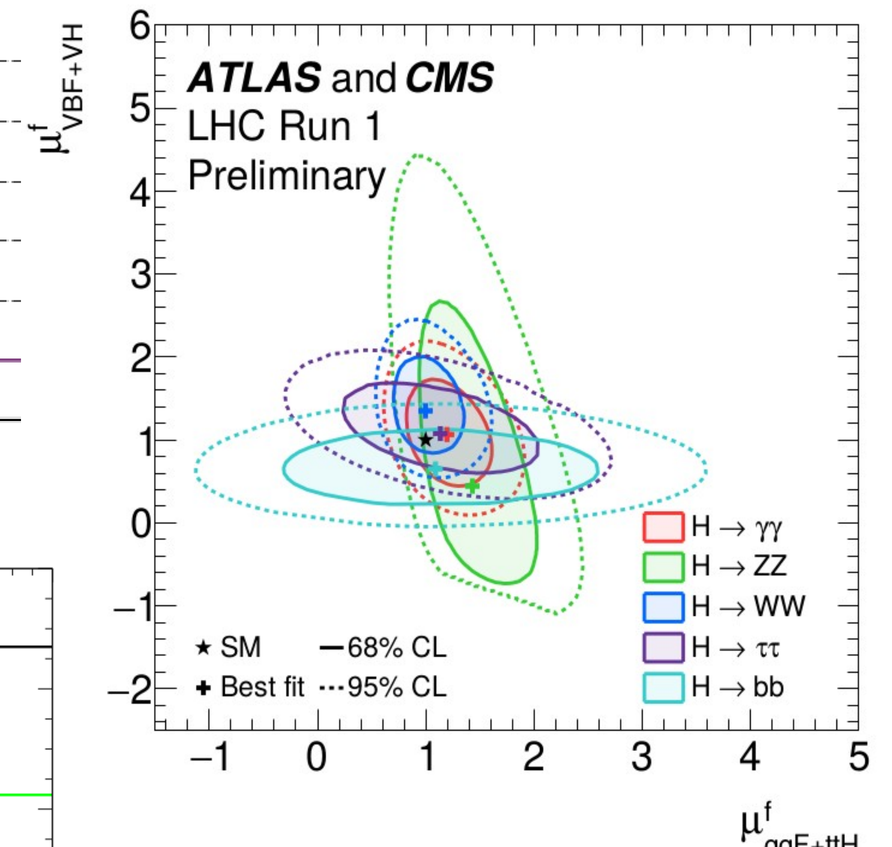
MSSM (Most Studied EWBG Scenario)

Deviations in Higgs Couplings from SM due to Light Stops





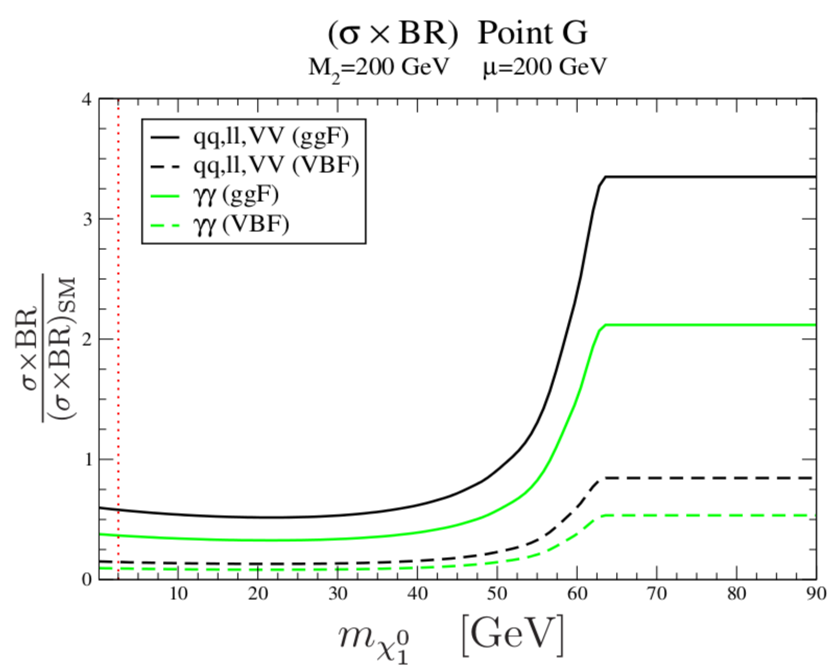
*Curtin, Jaiswal, Meade, JHEP **1208** (2012) 005*



A way out?

Higgs Invisible Width

*Carena, Nardini, Quiros, Wagner, JHEP **1302** (2013) 001*



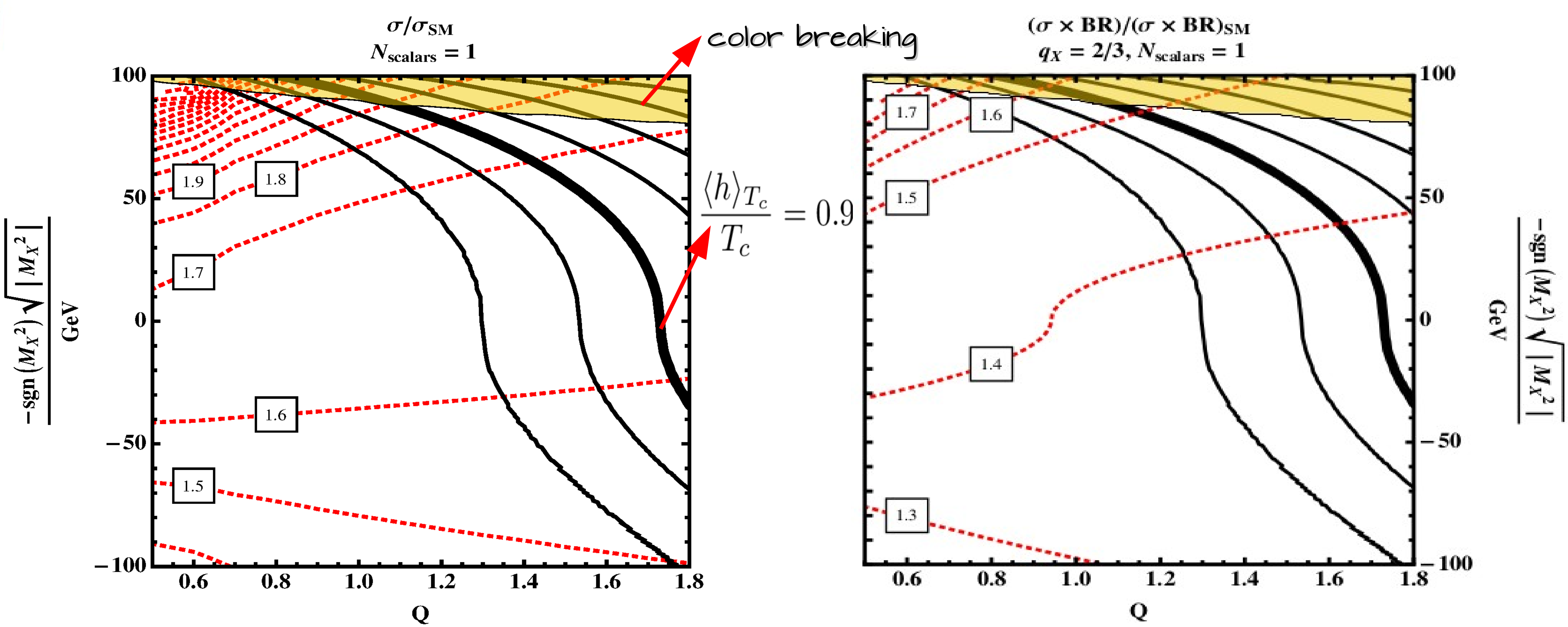
EW Phase Transition @LHC

The MSSM Baryogenesis Window Seems to be Closed

SEWPT via colored states is disfavoured

Cohen, Morrissey, Pierce, Phys. Rev. D**86** (2012) 013009

$$V = M_X^2|X|^2 + \frac{K}{6}|X|^4 + Q\,|H|^2|X|^2$$

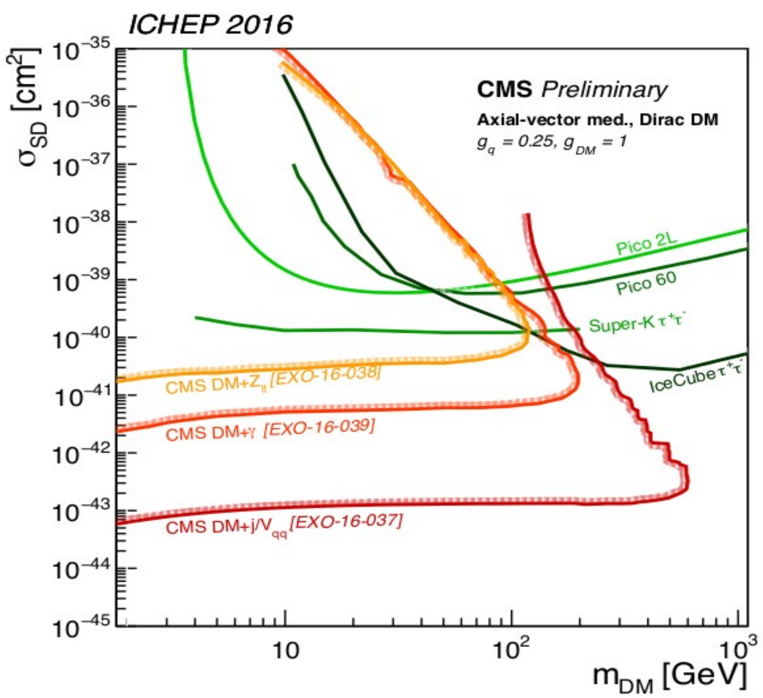


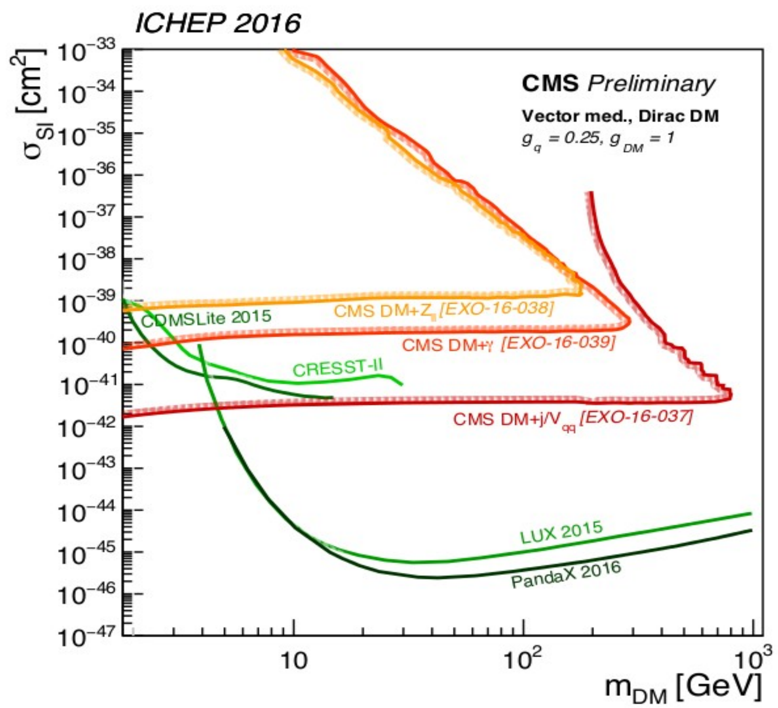
Higgs & Dark Matter

DM Complementarity

$$\mathcal{L}_V \supset V_\mu \left(\sum_q \bar{q}\gamma^\mu (g^V_{\rm SM} + g^A_{\rm SM}\gamma^5) q + \bar{\chi}\gamma^\mu (g^V_\chi + g^A_\chi \gamma^5)\chi \right)$$

Note: Plots for Spin - 1 Mediator





Was unable to find the Spin - 0 ones! (if they exist)

Argument Holds