Strong First-Order Phase Transitions, Models and Probes

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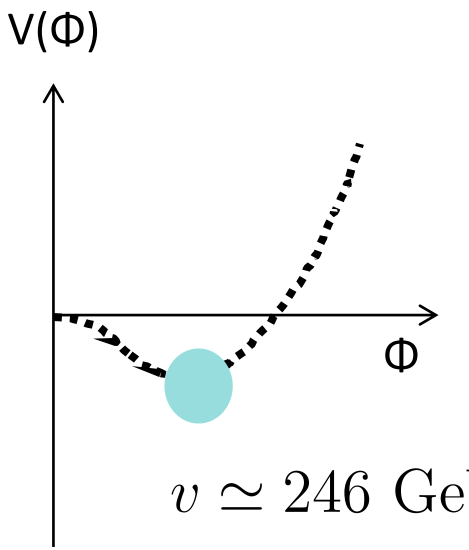
What do we *really* know about the Higgs?

- We have discovered the Higgs boson and measured its properties with precisions.
- However, we know very little about the Higgs potential.



$v \simeq 246$ GeV

vev, measured from G_F

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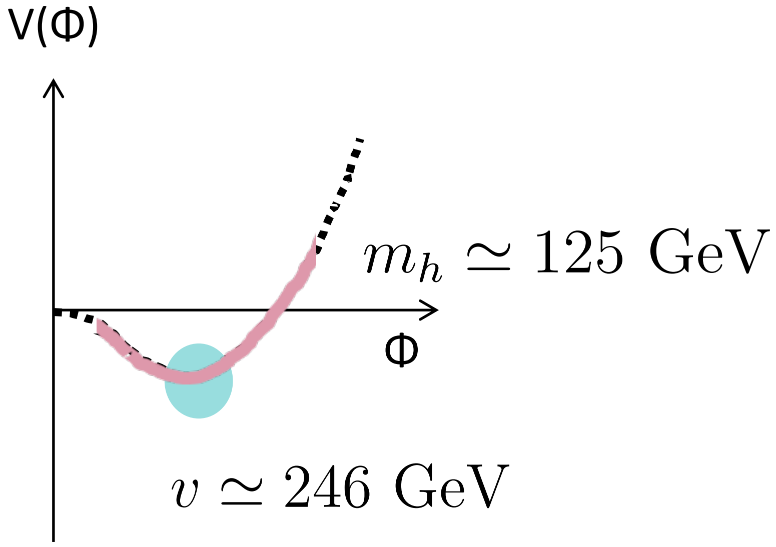

vev, measured from G_F

Higgs mass measured at the LHC

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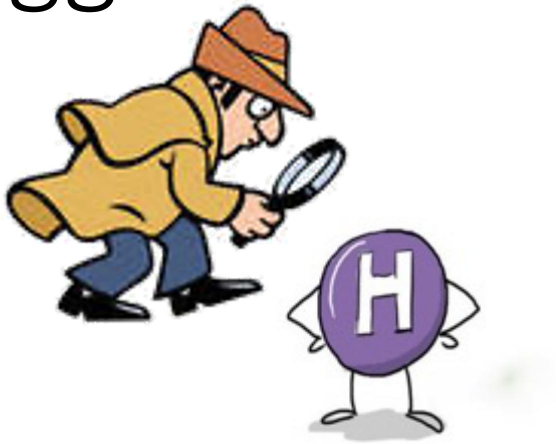

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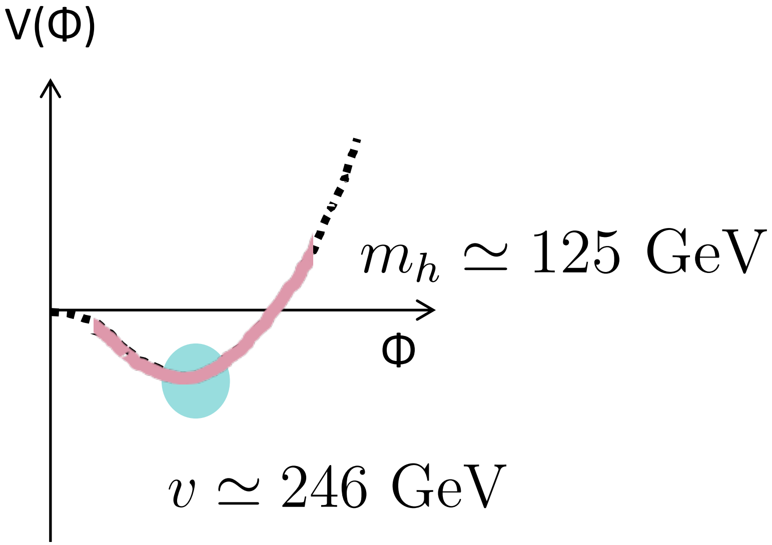

Completely specify the Higgs potential in the SM, but *NOT* directly measured

$$V = -\mu^2 H^\dagger H + \lambda_h (H^\dagger H)^2$$

$$\mu^2 = m_h^2/2 \simeq (88\mathrm{GeV})^2$$

$$\lambda_h = m_h^2/2v^2 \simeq 0.13$$

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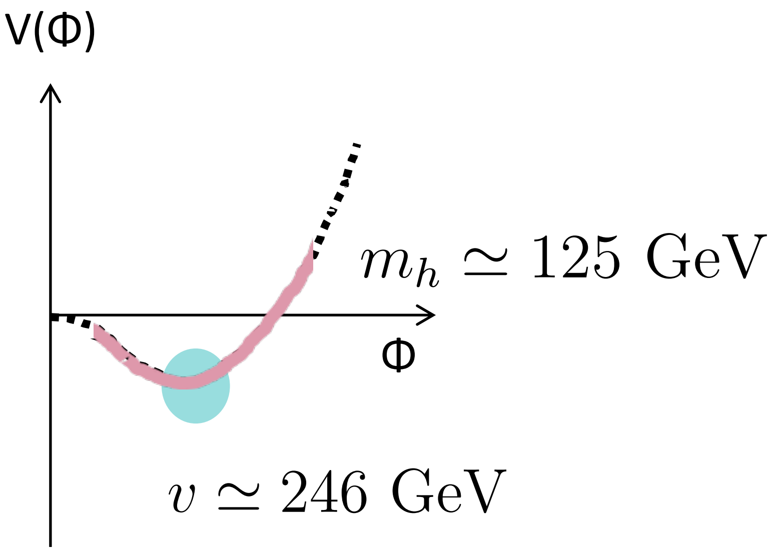
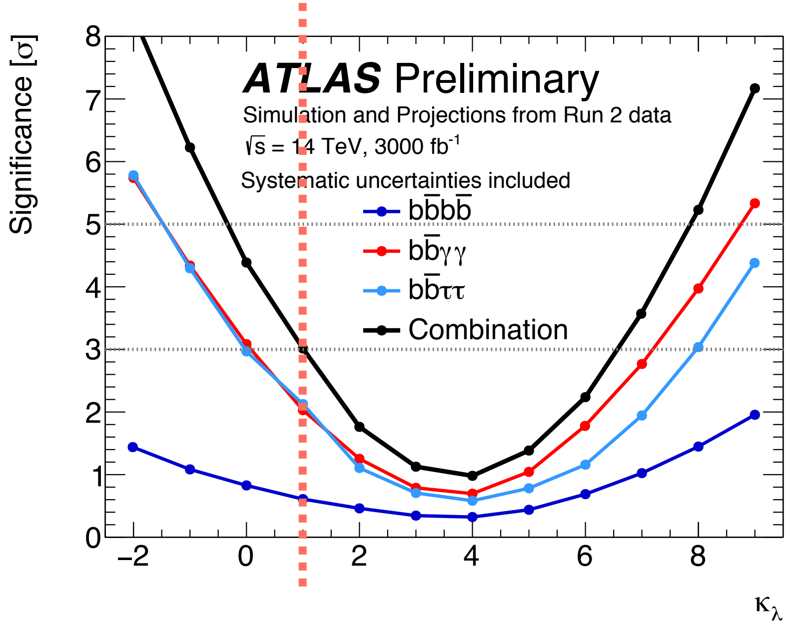
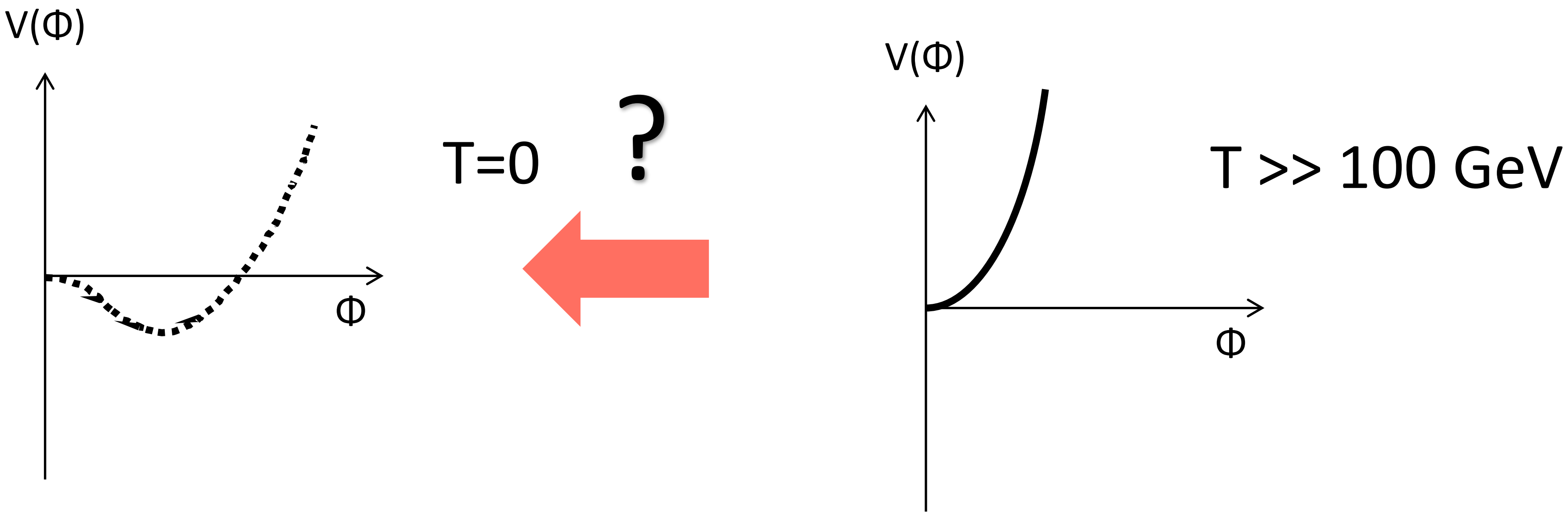




Self coupling, Limited sensitivity at HL-LHC

What do we *want* to know about the Higgs?

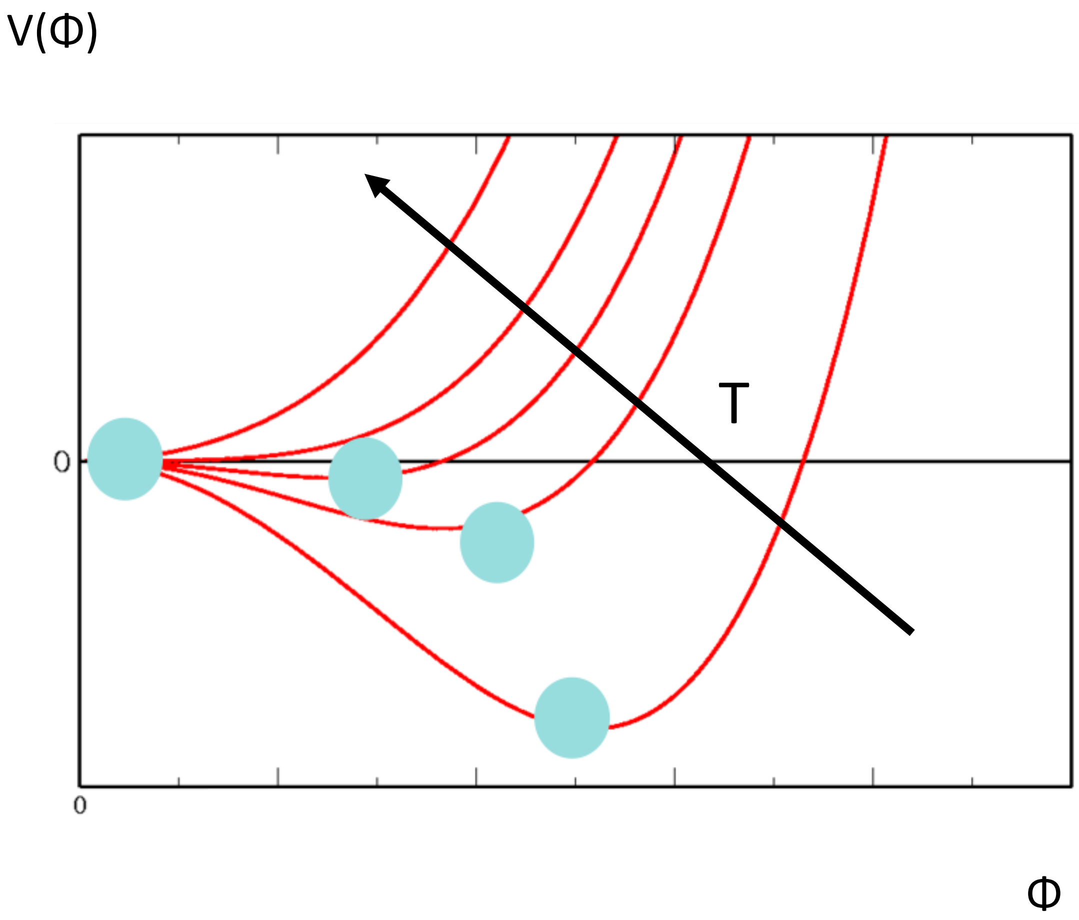
- The shape of the Higgs potential is closely related to the electroweak phase transition.



Know nothing beyond v, and m_h

EW symmetry restored

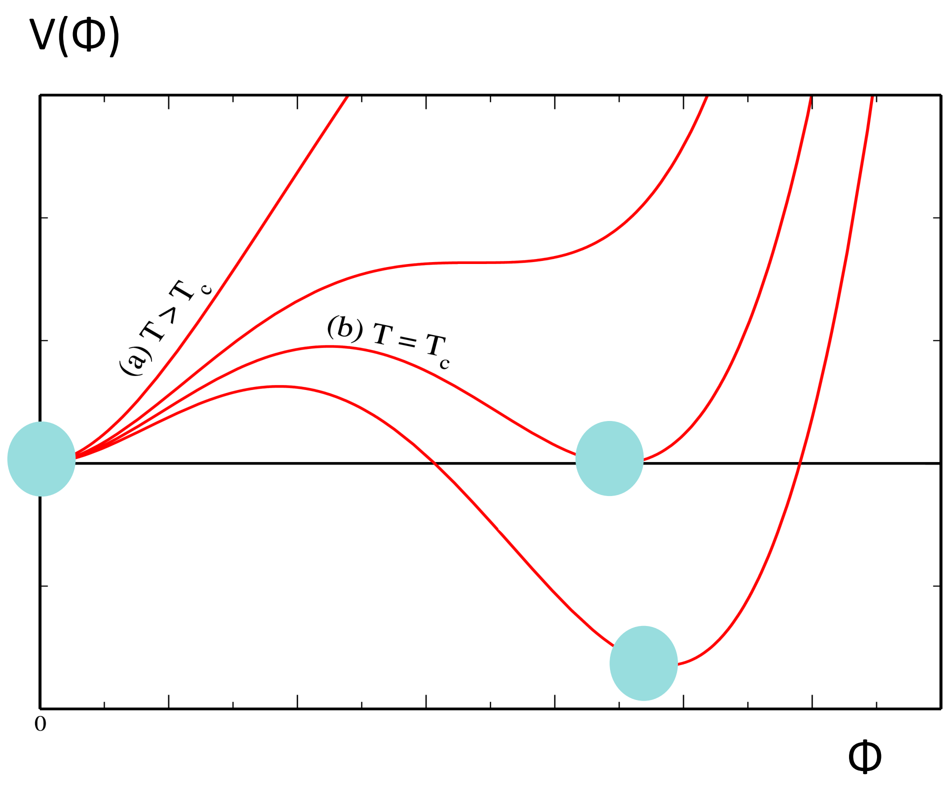
Electroweak Phase Transitions



- First Order?

- In the SM, the EW symmetry is broken by a smooth cross over.
- v (T) changes smoothly
- No energy barrier; no bubbles;
- no cosmological relics

Electroweak Phase Transitions



- First Order Phase Transition
- v is discontinuous
- V_{eff} has a barrier, bubbles nucleated
- Possibly interesting cosmological relics!

New physics to generate a barrier

Outline

How can we probe the new physics?

- Gravitational waves
- Colliders

What kind of models?

- Other model-dependent probes of the new physics?

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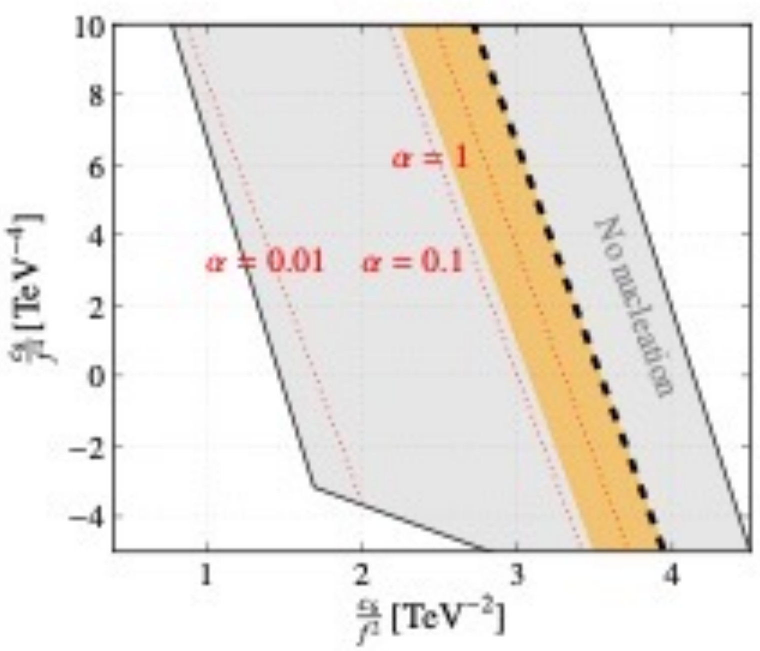
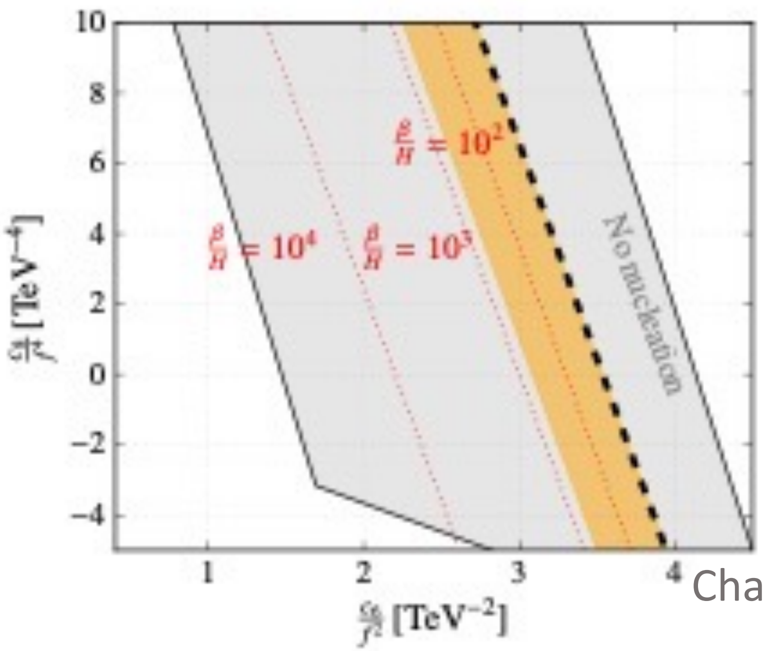
- Gravitational waves





Chala, Krause, and Nardini, 1802.02168

Outline

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What kind of models?

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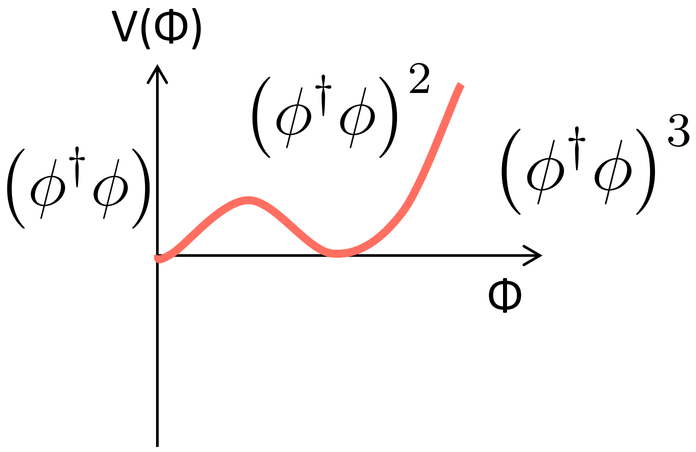
Probes?

Generate the Barrier

$$V(\phi,T)=\frac{m^2+a_0T^2}{2}\left(\phi^\dagger\phi\right)+\frac{\lambda}{4}\left(\phi^\dagger\phi\right)^2+\frac{c_6}{8\Lambda^2}\left(\phi^\dagger\phi\right)^3$$



$$\lambda_3=\frac{\partial^3 V}{\partial\phi^3}\bigg|_{\phi=v}=\frac{3m_h^2}{v}\left(1+\frac{2c_6v^4}{m_h^2\Lambda^2}\right)$$

Critical temperature

$$T_c^2=\frac{3c_6}{4\Lambda^2a_0}\left(v^2-v_c^2\right)\left(v^2-\frac{v_c^2}{3}\right).$$

vev at T_c

$$\left(\phi_c^\dagger\phi_c\right)=v_c^2=-\frac{\lambda\Lambda^2}{c_6}.$$

Requiring first order phase transition

$$\frac{5}{3}\lambda_3^{SM}<\lambda_3<3\lambda_3^{SM}$$

Generate the Barrier – Adding Higher-dim Operators

$$V(\phi,0) = \frac{m^2}{2}(\phi^\dagger\phi) + \frac{\lambda}{4}(\phi^\dagger\phi)^2 + \sum_{n=1}^{\infty} \frac{c_{2n+4}}{2^{(n+2)}\Lambda^{2n}}\left(\phi^\dagger\phi\right)^{n+2}$$

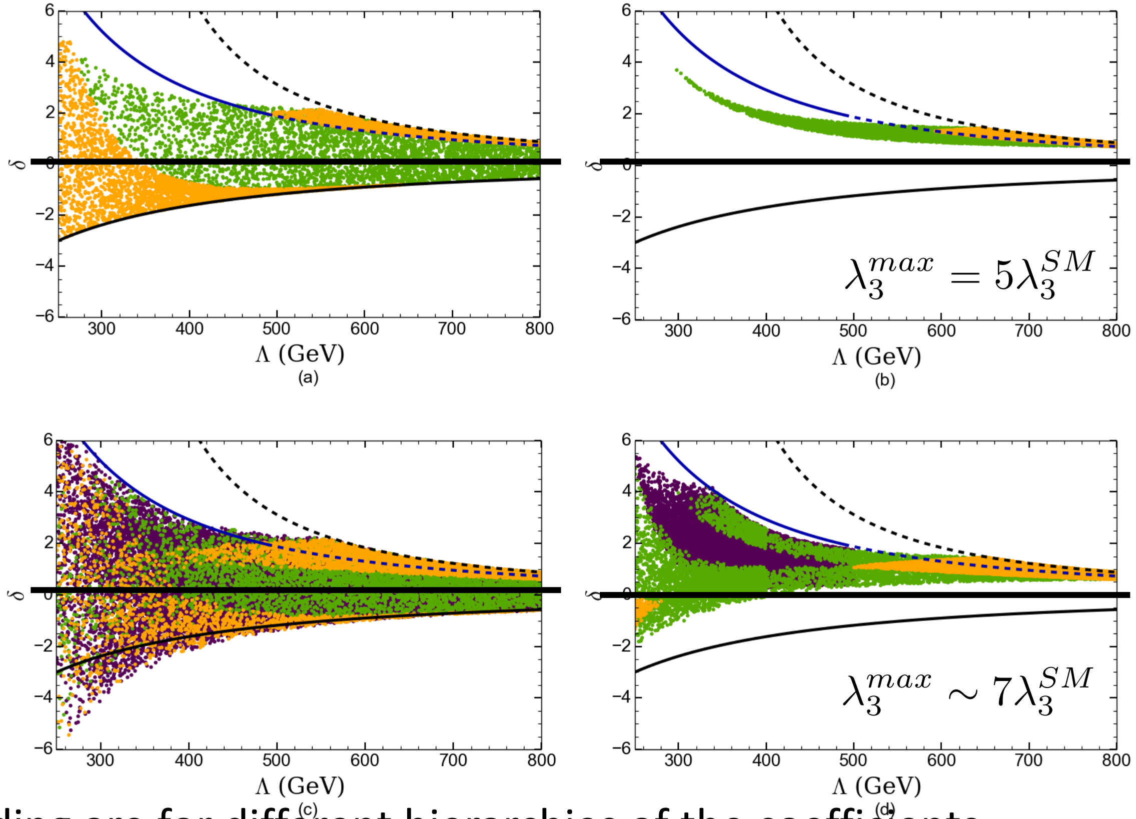
$\delta = \frac{\lambda_3}{\lambda_3^{SM}} - 1$

General results

First order Phase Transition

$(\phi^\dagger\phi)^4$

$(\phi^\dagger\phi)^5$



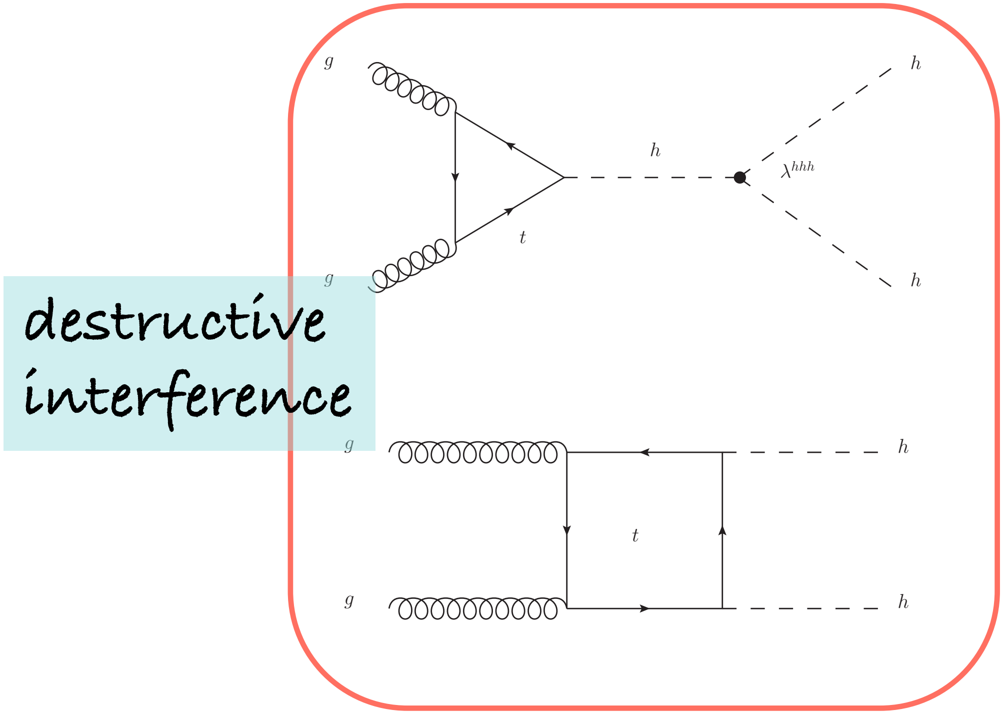
Color coding are for different hierarchies of the coefficients.

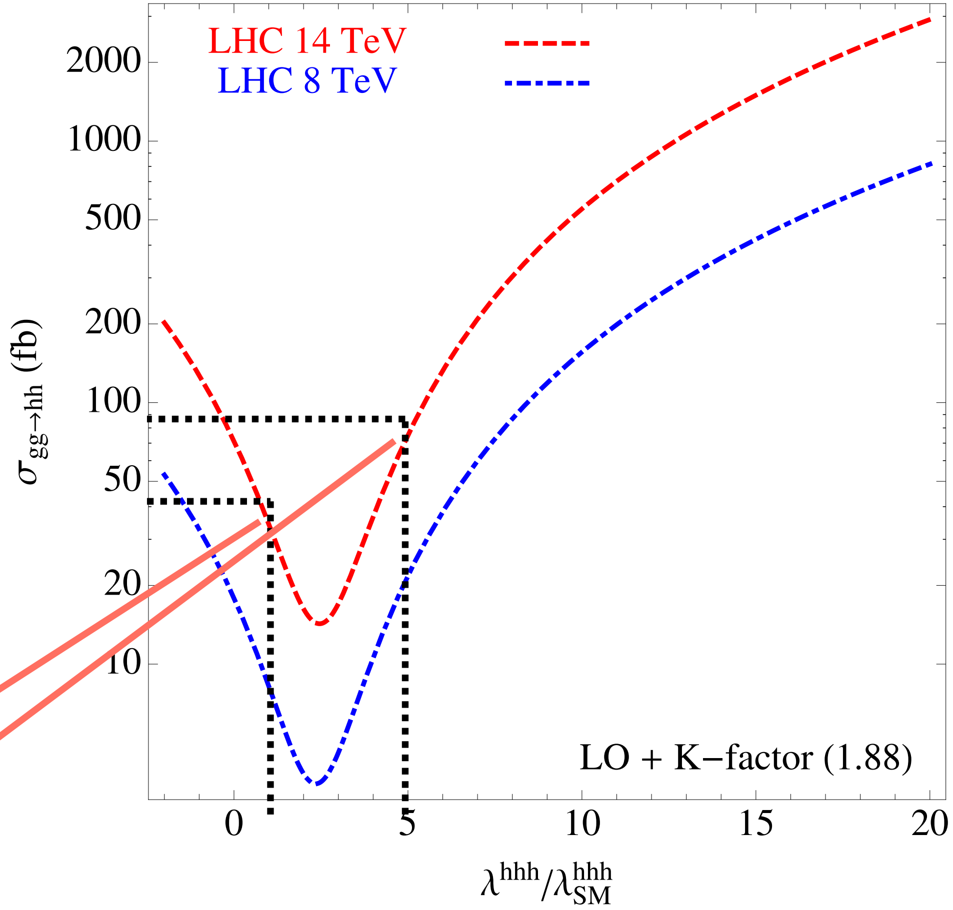
- First order PTs tend to be associated with enhancements in the trilinear coupling, while suppressions tend to be associated with second order PTs.

- The trilinear coupling could deviate significantly from its SM value in the region consistent with a first order EWPT.

arxiv:1512:00068 PH, A. Joglekar, B. Li, and C. Wagner

Collider Probes – Double Higgs Production





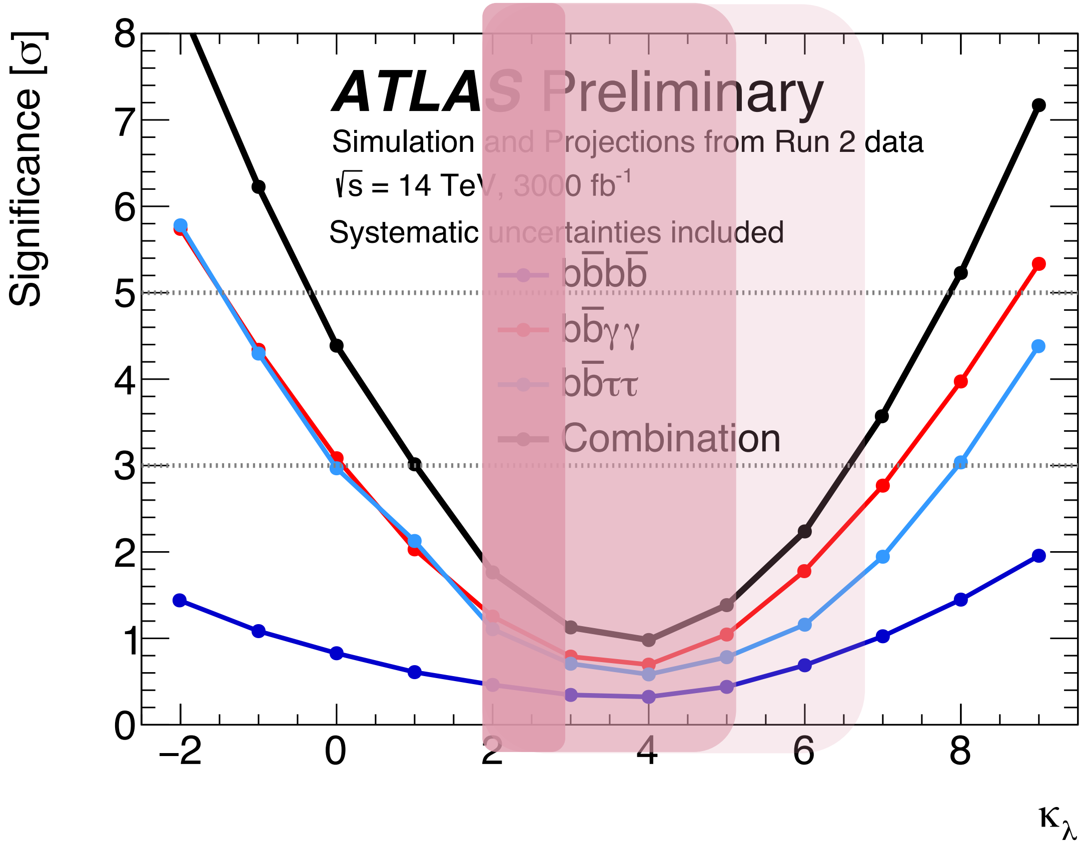
At NNLO, 14 TeV,

- $\lambda^3 = \lambda^3_{SM}$ $\sigma(pp \to hh) = 40$ fb
- $\lambda^3 = 5\lambda^3_{SM}$ $\sigma(pp \to hh) = 100$fb

De Florian and Mazzitelli, Grigo, Melnikov, and Steinhauser

Spira, figure from Barger, Everett, Jackson, and Shaughnessy

Collider Probes – Double Higgs Production



$$V(\phi,T)=\frac{m^2+a_0T^2}{2}\left(\phi^\dagger\phi\right)+\frac{\lambda}{4}\left(\phi^\dagger\phi\right)^2+\frac{c_6}{8\Lambda^2}\left(\phi^\dagger\phi\right)^3$$

$$\frac{5}{3}<\kappa_\lambda<3$$

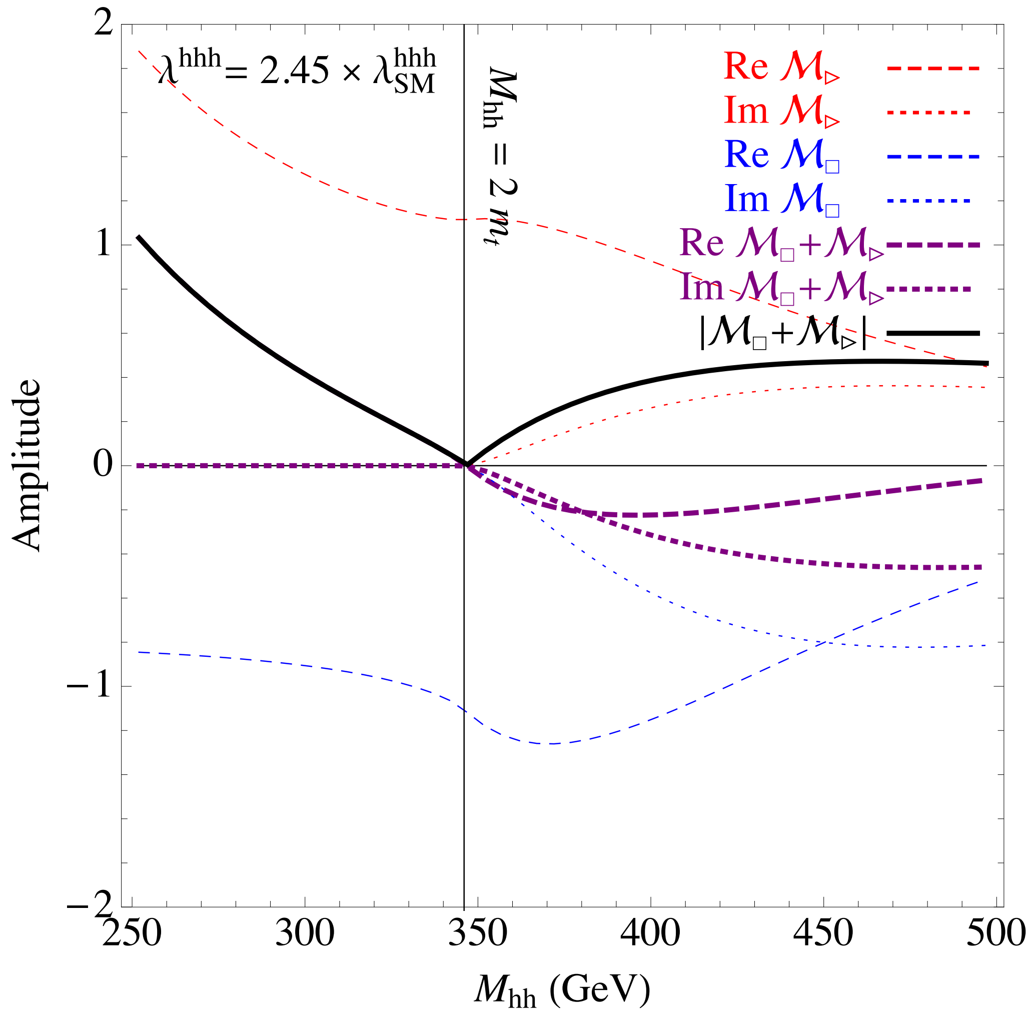
$$V\left(\phi,0\right)=\frac{m^2}{2}(\phi^\dagger\phi)+\frac{\lambda}{4}(\phi^\dagger\phi)^2+\sum_{n=1}^{\infty}\frac{c_{2n+4}}{2^{(n+2)}\Lambda^{2n}}\left(\phi^\dagger\phi\right)^{n+2}$$

$$\lambda_3^{max}\sim 7\lambda_3^{SM}$$

The LHC has a very limited sensitivity in the region where the EWPT can be strongly-first-order.

PH, A. Joglekar, B. Li, and C. Wagner. 2015

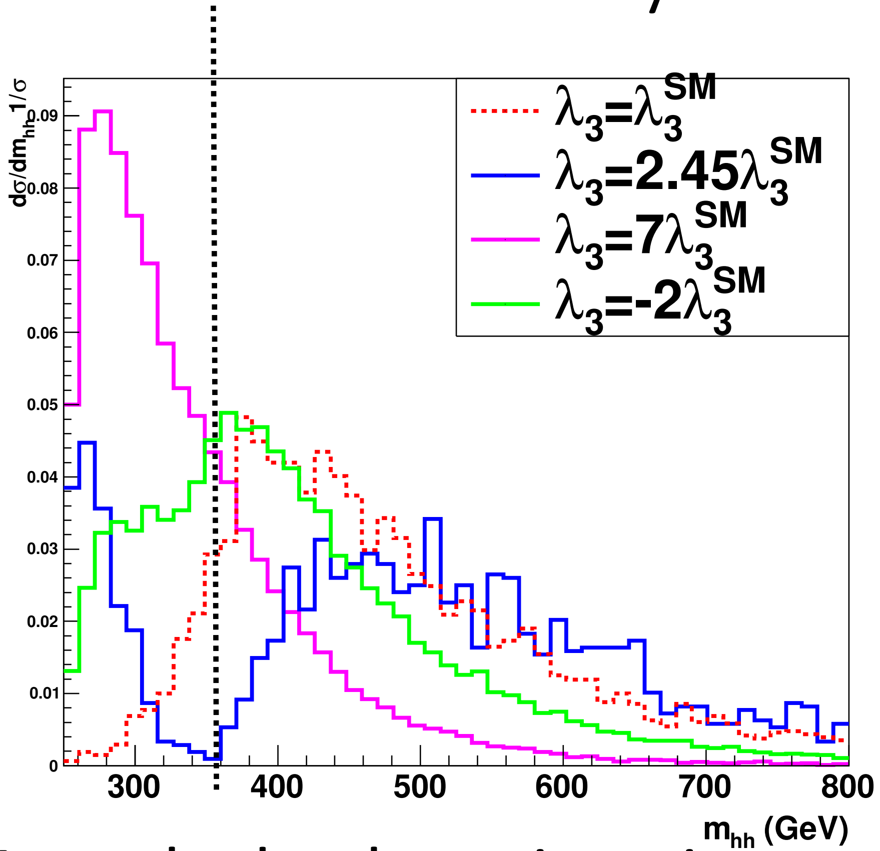
Limited sensitivity with large λ_3



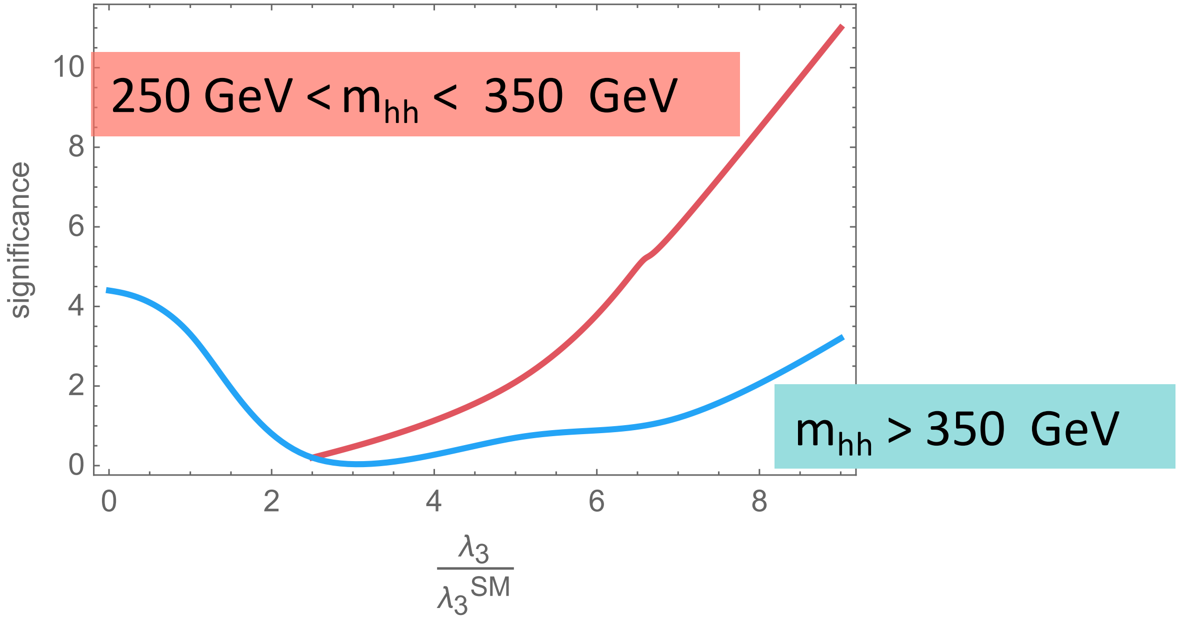
- The destructive interference occurs between the real part of the triangle and the box diagrams
- Above the tt threshold, the amplitudes develop imaginary parts, the cancellation does not occur
- When λ_3 increases, the amplitudes increases more below the tt threshold than above the threshold
- m_{hh} *shifts to smaller value for large* λ_3

Barger, Everett, Jackson, and Shaughnessy

Limited sensitivity with large λ_3



14 TeV and 3000 fb^{-1}



Big Improvement for New Physics!

SM: peaked at large invariant mass. A cut of $m_{hh} > 2m_{top}$ or something equivalent is currently used in both experimental and phenomenology studies.

$\lambda_3 > 3\lambda_3^{SM}$, m_{hh} distribution is much softer than the SM case

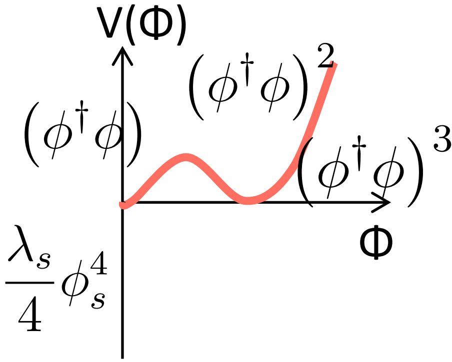
PH, Joglekar, Li, and Wagner, arxiv:1512.00068

How can we probe the new physics?

- Gravitational waves
- Collider
  - The trilinear coupling deviates significantly from the SM
  - Need to change the m_{hh} cut

Models

Heavy Scalar Singlet



$$V(\phi_h,\phi_s,T)=\frac{m_0^2+a_0T^2}{2}\phi_h^2+\frac{\lambda_h}{4}\phi_h^4+a_{hs}\phi_s\phi_h^2+\frac{\lambda_{hs}}{2}\phi_s^2\phi_h^2+t_s\phi_s+\frac{m_s^2}{2}\phi_s^2+\frac{a_s}{3}\phi_s^3+\frac{\lambda_s}{4}\phi_s^4$$

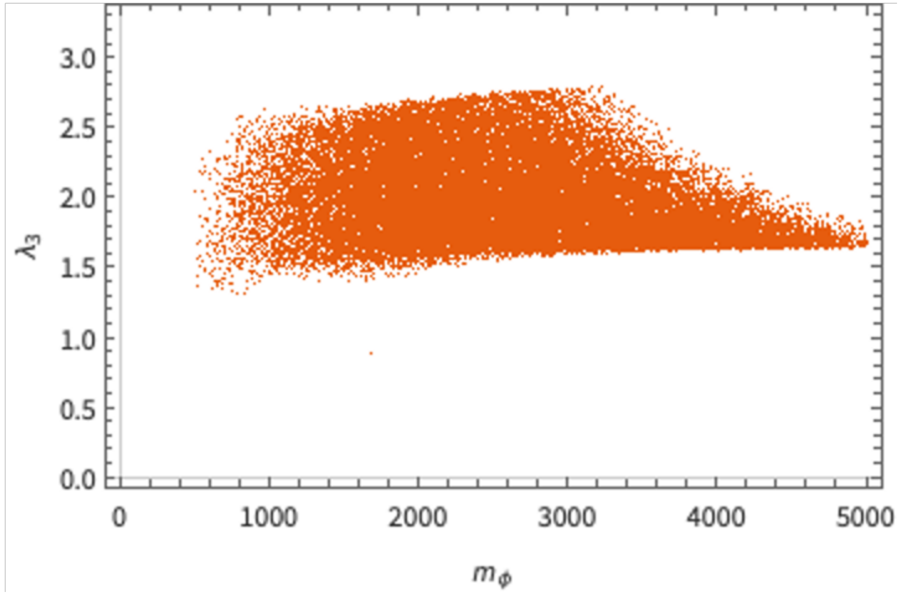
Integrate out the singlet,

$y=v^2/m_s^2.$

$$z=\frac{(am_s^2-t\lambda_{hs})^2v^2}{m_s^8}$$

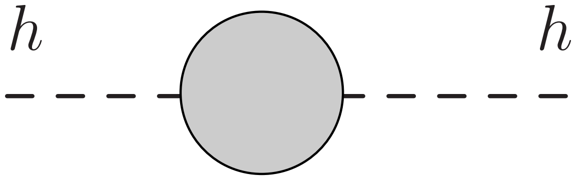
$$V_{eff}(H,T)=\frac{m_0^2+a_0T^2}{2}H^2+\left(\frac{\lambda_h}{4}-\frac{z}{2y}-\frac{2m^2z}{3v^2}\right)H^4+\left(\frac{8z^2-4yz\lambda_h+3yz\lambda_{hs}}{6v^2y}\right)H^6.$$

- Collider probes/constraints
  - Higgs signal strength
  - Resonance decaying to vector bosons and Higgs bosons
  - Electroweak precision observables

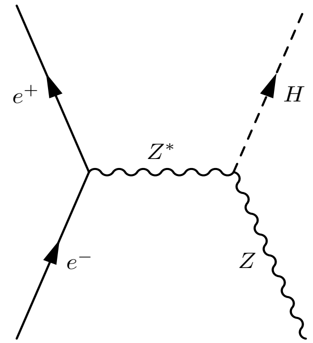


PH, A. Joglekar, B. Li, and C. Wagner, arxiv:1512.00068
PH, A. Hooper, and C. Wagner, work in progress

Heavy Scalar Singlet, Lepton Collide



The singlet kinetic term modifies the wave function of the physical and therefore shifts all Higgs couplings universally

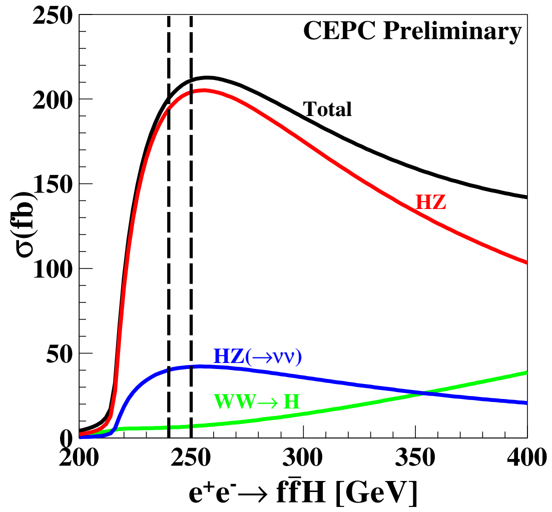


$$\frac{1}{2}(\partial_\mu \phi_s)(\partial^\mu \phi_s) \approx \frac{2a_{hs}^2}{m_s^4}(\Phi^\dagger \partial_\mu \Phi + \text{h.c.})^2 \left[1 + O(\lambda_{hs}\Phi^\dagger\Phi/m_s^2)\right]$$

HL-LHC expects to measure the Higgs couplings to percent level. *O*(2-10%)

hZZ coupling can be measured to high precisions with lepton colliders.

- hZZ coupling can be probed by the Higgsstralung process
- Large production cross section around 240 GeV to 250 GeV ~ 200 fb
- Expect 0.25% precision in hZZ coupling at future lepton colliders!

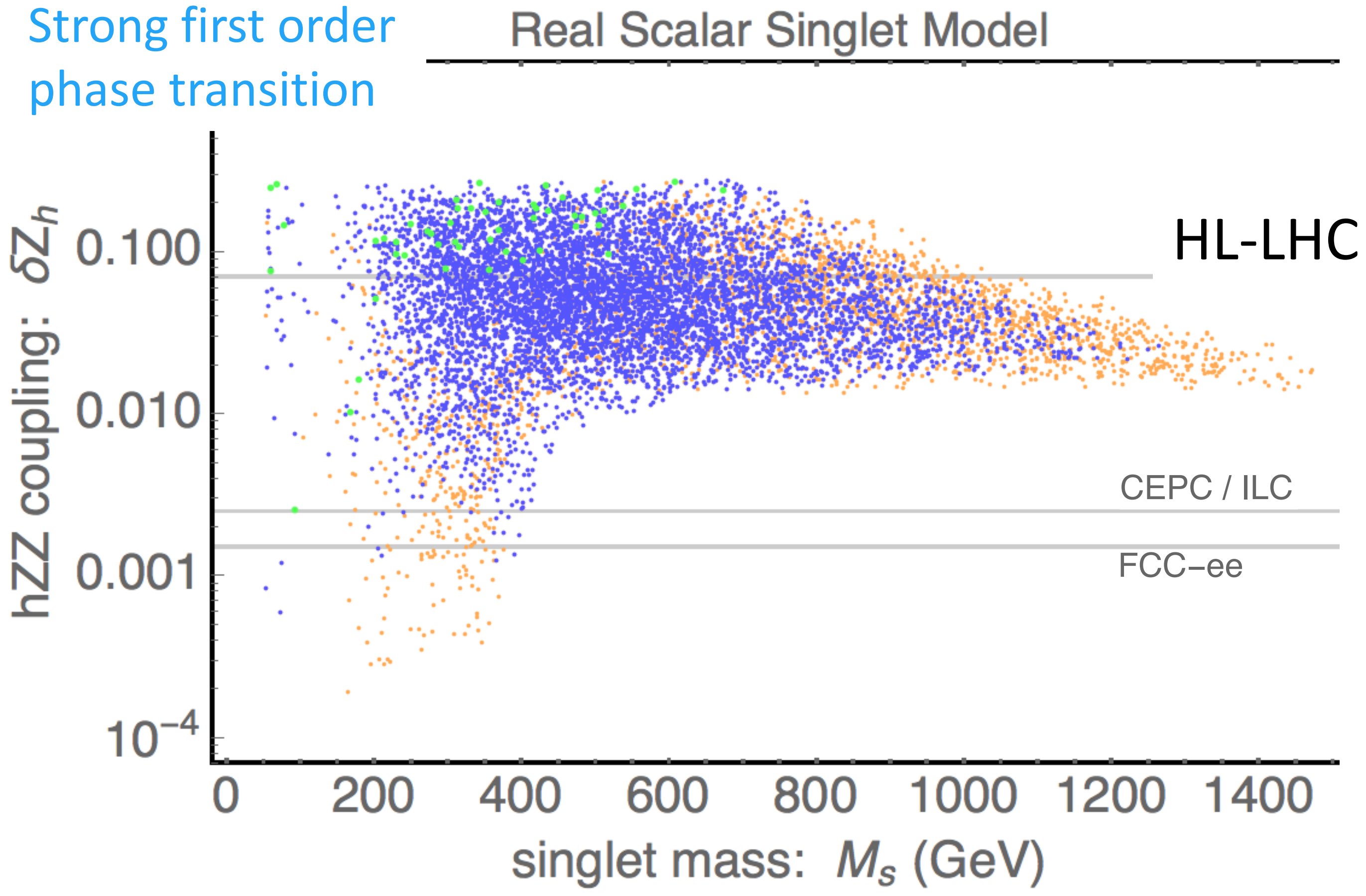


5 ab $^{-1}$ CEPC pre-CDR

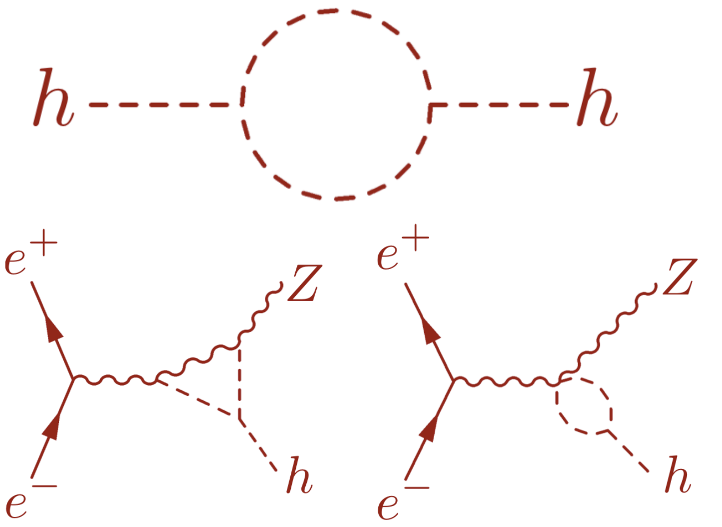
Heavy Scalar Singlet, Lepton Colliders, GWs

1st order phase transition

Strong first order phase transition



PH, A. Long, L.T. Wang, arXiv:1608.06619



Current constraints: Higgs signal strength

HL-LHC can start to probe the hZZ coupling to percent level

Next generation lepton colliders can basically cover the whole region

Scalar Doublets

$$\tilde{Q} \sim (\mathbf{1}, \mathbf{2}, 1/3) \times 3 \text{ flavor}$$
$$\tilde{U} \sim (\mathbf{1}, \mathbf{1}, 4/3) \times 3 \text{ flavor}$$

$$\begin{aligned} V = & \frac{1}{2} m_0^2 \phi_h^2 + \frac{\lambda_h}{4} \phi_h^4 \\ & + m_Q^2 \big(|\tilde{u}|^2 + |\tilde{d}|^2\big) + m_U^2 |\tilde{U}|^2 + \lambda_Q \big(|\tilde{u}|^2 + |\tilde{d}|^2\big)^2 + \lambda_U \big(|\tilde{U}|^2\big) \\ & + \lambda_{QU} \big(|\tilde{u}|^2 + |\tilde{d}|^2\big) |\tilde{U}|^2 + \frac{\lambda_{hU}}{2} \phi_h^2 |\tilde{U}|^2 \\ & + \frac{\lambda_{hQ}}{2} \big(|\tilde{u}|^2 + |\tilde{d}|^2\big) \phi_h^2 + \frac{\lambda'_{hQ}}{2} |\tilde{u}|^2 \phi_h^2 + \frac{\lambda''_{hQ}}{2} |\tilde{d}|^2 \phi_h^2 \\ & + \Big[\frac{a_{hQU}}{\sqrt{2}} \tilde{u} \phi_h \tilde{U}^* + \text{h.c.} \Big] \ . \end{aligned}$$

For simplicity, consider

$$\langle \tilde{Q} \rangle = (0\,,\,0) \qquad \text{and} \qquad \langle \tilde{U} \rangle = 0$$

$$\lambda_Q = \lambda_U = \lambda_{QU} = \lambda_{hU} = \lambda_{hQ} = \lambda'_{hQ} = \lambda''_{hQ} \equiv \lambda$$

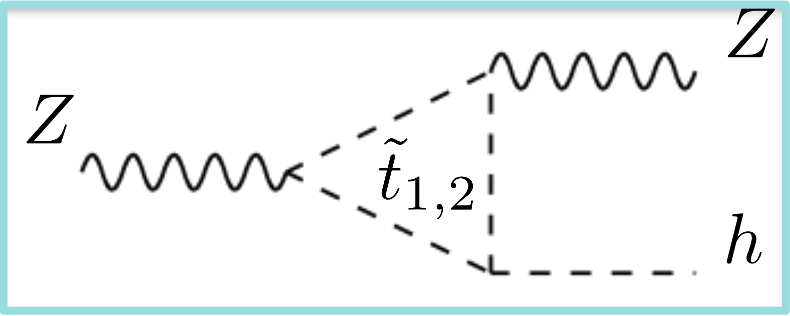
$$M_{\tilde{t}}^2 = \begin{pmatrix} m_Q^2 + \frac{1}{2}\big(\lambda_{hQ} + \lambda'_{hQ}\big) v^2 & \frac{a_{hQU} v}{\sqrt{2}} \\ \frac{a_{hQU} v}{\sqrt{2}} & m_U^2 + \frac{1}{2} \lambda_{hU} v^2 \end{pmatrix} \qquad m_{\tilde{b}}^2 = m_Q^2 + \frac{1}{2}\big(\lambda_{hQ} + \lambda''_{hQ}\big) v^2$$

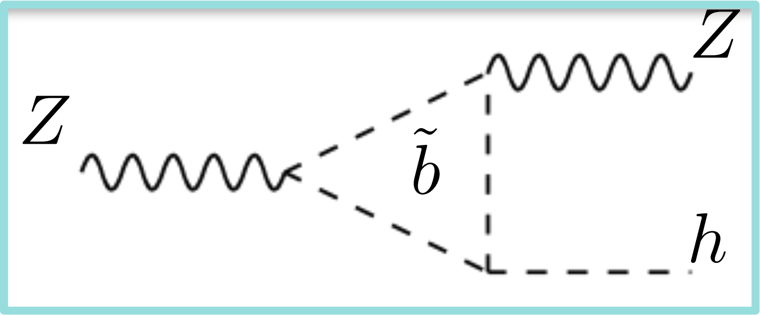
Scalar Doublets, Collider Probes

Modified hZZ couplings,

$$\delta Z_h = 3 \sum_{i,j=1}^{2} \frac{|g_{h\tilde{t}_i\tilde{t}_j}|^2 v^2}{32\pi^2} I(m_h^2; m_{\tilde{t}_i}^2, m_{\tilde{t}_j}^2) + 3 \frac{|g_{h\tilde{b}\tilde{b}}|^2 v^2}{32\pi^2} I(m_h^2; m_{\tilde{b}}^2, m_{\tilde{b}}^2)$$

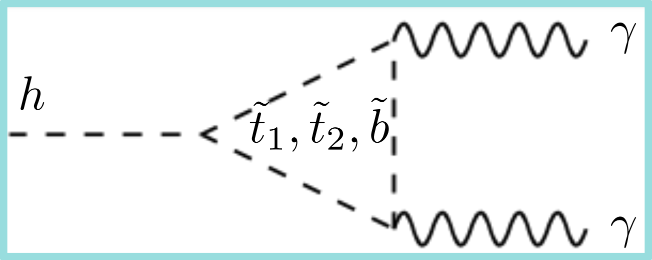
Fan, Reece, Wang. 2014





PH, A. Long, L.T. Wang, arXiv:1608.06619

Scalar Doublet, Modified di-photon coupling



$$\Gamma_{h\to\gamma\gamma} = G_F\,\alpha^2 \frac{M_h^3}{128\sqrt{2}\pi^3}\left|A_W + A_t + A_{\tilde{t}} + A_{\tilde{b}}\right|^2$$

$$A_W = F_1\big(M_h^2/4M_W^2\big)$$

$$A_t = \frac{4}{3}F_{1/2}\big(M_h^2/4M_t^2\big)$$

$$A_{\tilde{t}} = \sum_{i=1,2} 3\left(\frac{2}{3}\right)^2 g_{h\tilde{t}_i\tilde{t}_i}\frac{v^2}{M_{\tilde{t}_i}^2}F_0\big(M_h^2/4M_{\tilde{t}_i}^2\big)$$

$$A_{\tilde{b}} = -3\left(\frac{1}{3}\right)^2 g_{h\tilde{b}\tilde{b}}\frac{v^2}{M_{\tilde{b}}^2}\,F_0\big(M_h^2/4M_{\tilde{b}}^2\big)$$

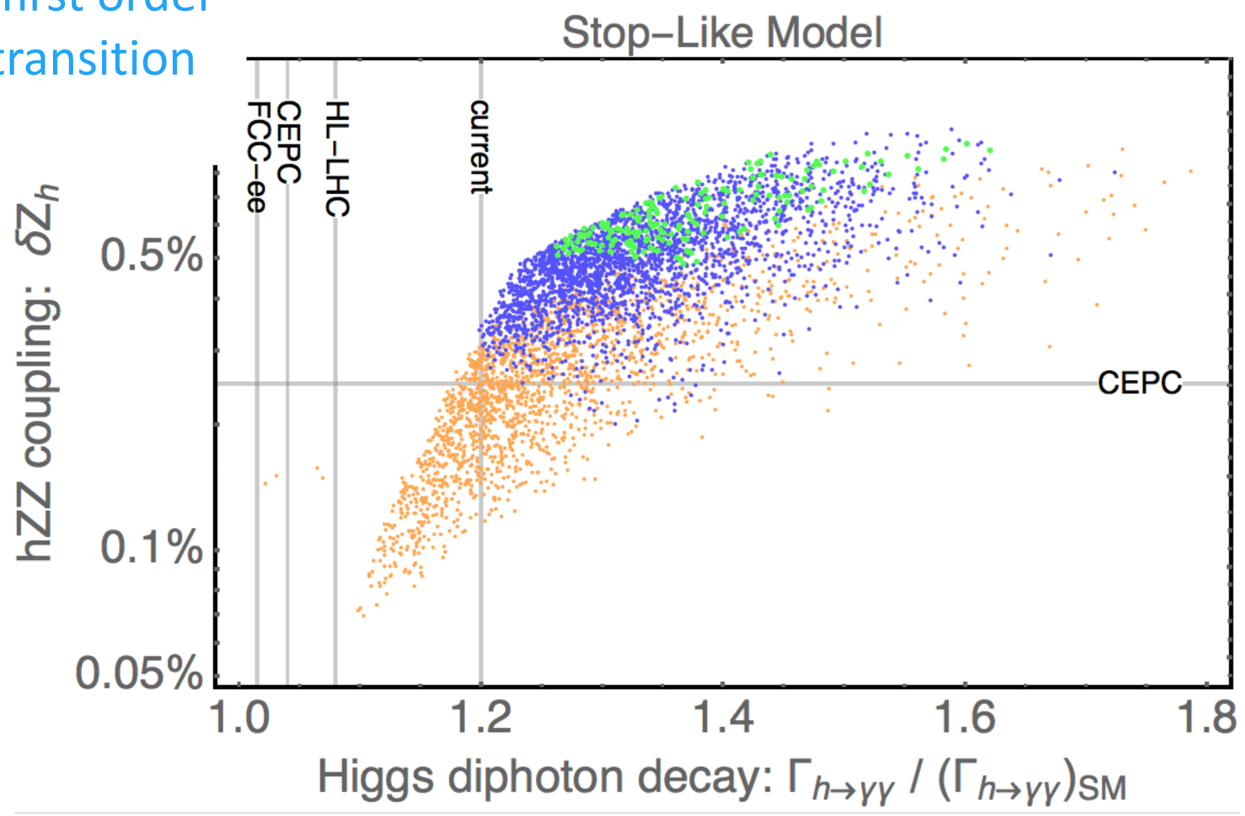
Djouadi, Driesen,Hollik,Illana, 2005

Scalar Doublets

1st order phase transition

Strong first order phase transition

Lisa



In the region where the EWPT is strongly first-order, hZZ and Higgs diphoton couplings deviate significantly from the SM.
Will be fully tested by HL-LHC.

PH, A. Long, L.T. Wang, arXiv:1608.06619

Fermions?

Integrating out new fermions?

Take a general vector-like fermion model,

$$\mathcal{L}_{VLL} = \overline{L}(i\gamma_\mu D_L^\mu - m_L)L + \overline{E}'(i\gamma_\mu D_E^\mu - m_E)E' + \overline{N}'(i\gamma_\mu D_N^\mu - m_N)N'$$
$$- \left[\overline{L}\, H\, (y_{E_L}\mathbb{P}_L + y_{E_R}\mathbb{P}_R)\, E' + \overline{L}\, \widetilde{H}\, (y_{N_L}\mathbb{P}_L + y_{N_R}\mathbb{P}_R)\, N' + \text{h.c.}\right],$$

$$L_{L,R} = \begin{pmatrix} N \\ E \end{pmatrix}_{L,R} \sim (1,2,Y), \quad N'_{L,R} \sim (1,1,Y+\frac{1}{2}), \quad E'_{L,R} \sim (1,1,Y-\frac{1}{2}),$$

$$16\pi^2 \mathcal{L}_H^{\text{CP}} \supset + \left(-\frac{4}{3} + 2\log\frac{\mu^2}{m^2}\right)\left(|y_N|^2 + |y_E|^2\right)|D_\mu H|^2$$
$$- \left(1 + 3\log\frac{\mu^2}{m^2}\right)\left(|y_N|^2 + |y_E|^2\right) m^2\, |H|^2$$
$$+ \left(\frac{16}{3} + 2\log\frac{\mu^2}{m^2}\right)\left(|y_N|^4 + |y_E|^4\right)|H|^4\,,$$

$$-\frac{2\left(|y_N|^6 + |y_E|^6\right)}{15 m^2}\mathcal{O}_6$$

Does not have the barrier we want as in the singlet extension.

A. Angelescu, PH 2006.16532
S. Ellis, J. Quevillon, P. Vuong, T. You, and Z. Zhang 2006.16260

Possible to have a barrier from fermions?

Low T, scalars and fermions contribute equally

$$-\frac{T^2 m^2(\phi)}{2\pi^2} K_2\left(m(\phi)/T\right) + \mathcal{O}\left(T^2 m(\phi)^2 e^{-2m(\phi)/T}\right)$$

Consider the possibility of generating a barrier through fermions

A Minimal Vector-Like Lepton (VLL) Model

- Fermion models for strong first order phase transitions?
  - Strong couplings to the Higgs!
- To avoid large mixing between the VLLs and SM leptons, and large contributions to the T parameter, we add

$$L_{L,R} = \begin{pmatrix} N \\ E \end{pmatrix}_{L,R} \sim (1,2)_{-1/2}, \quad N'_{L,R} \sim (1,1)_0, \quad E'_{L,R} \sim (1,1)_{-1}$$

- The most general Lagrangian is,

$$\begin{aligned} -\mathcal{L}_{VLL} = & \, y_{N_R} \overline{L}_L \tilde{H} N'_R + y_{N_L} \overline{N}'_L \tilde{H}^\dagger L_R + y_{E_R} \overline{L}_L H E'_R + y_{E_L} \overline{E}'_L H^\dagger L_R \\ & + m_L \overline{L}_L L_R + m_N \overline{N}'_L N'_R + m_E \overline{E}'_L E'_R + \text{h.c.} \, , \end{aligned}$$

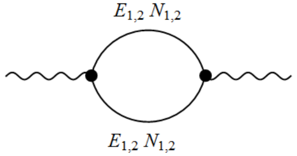
A Minimal Vector-Like Lepton (VLL) Model

$$-\mathcal{L}_{VLL} = y_{N_R}\overline{L}_L\tilde{H}N'_R + y_{N_L}\overline{N}'_L\tilde{H}^\dagger L_R + y_{E_R}\overline{L}_L H E'_R + y_{E_L}\overline{E}'_L H^\dagger L_R$$
$$+ m_L\overline{L}_L L_R + m_N\overline{N}'_L N'_R + m_E\overline{E}'_L E'_R + \text{h.c.}\ ,$$

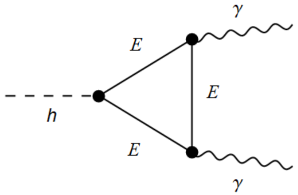
- 2 neutral and 2 charged VLLs
- Ranges of the parameters considered,

$$m_L, m_N, m_E \in [500, 1500]\ \text{GeV}, \qquad y_{N_{L,R}}, y_{E_{L,R}} \in [2, \sqrt{4\pi}].$$

- Constraints:



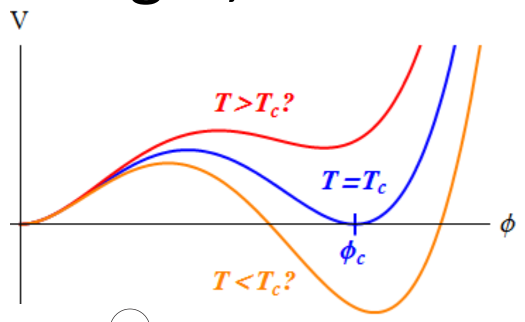
  - S & T parameters
  - Diphoton signal strength, $0.71 < \mu_{\gamma\gamma} < 1.29$ ATLAS, 1802.04146
  - Masses of the lighter states, $m_{E_1} > 100$ GeV and $m_{N_1} > 90$ GeV



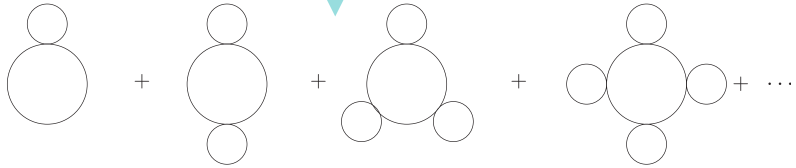
LEP2, Phys Rept 427(2006)257-454

Thermal Evolution of the Effective Potential

- For each surviving point, calculate the phase transition strength, $\xi = \phi_c/T_c$



$$V(\phi,T) = V_{tree}^{SM}(\phi) + V_{1-loop}^{SM}(\phi,T) + V_{1-loop}^{VLL}(\phi,T) + V_{Daisy}(\phi,T)$$



- Benchmark A,

$$y_{N_L} \simeq 3.40,\ y_{N_R} \simeq 3.49,\ y_{E_L} \simeq 3.34,\ y_{E_R} \simeq 3.46,$$

$$m_L \simeq 1.06 \text{ TeV},\ m_N \simeq 0.94 \text{ TeV},\ m_E \simeq 1.34 \text{ TeV}.$$

$$\mu_{\gamma\gamma} = 1.28,\ \Delta\chi^2(S,T) = 1.33,\ m_{N_1} = 400 \text{ GeV},\ m_{E_1} = 592 \text{ GeV}.$$

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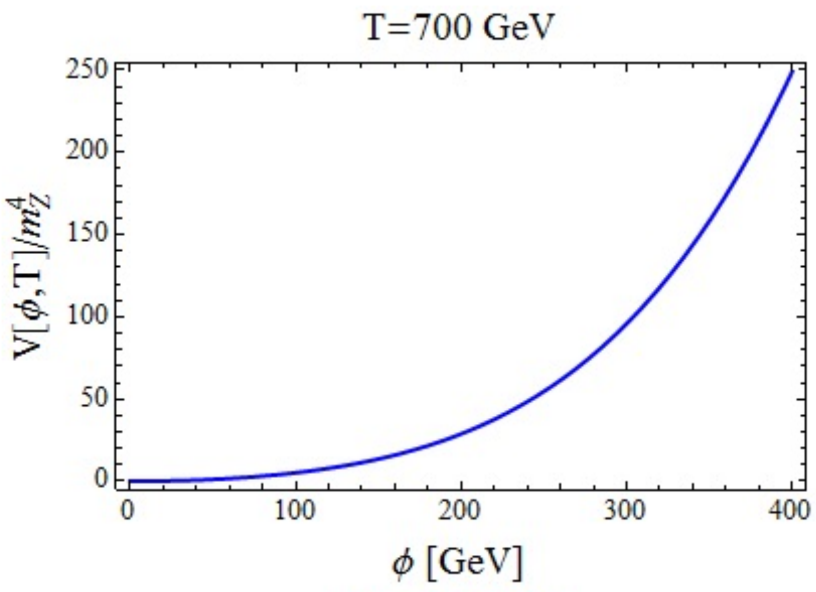
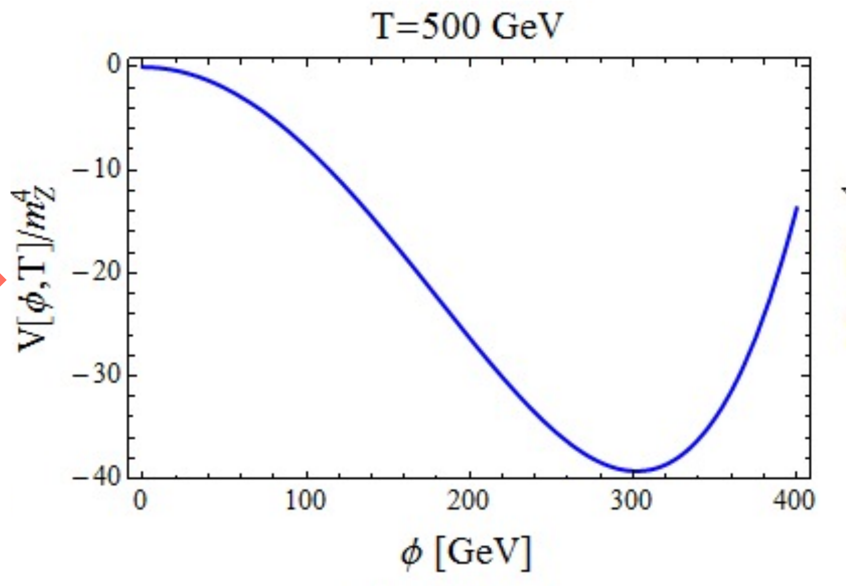
Thermal Evolution of the Effective Potential



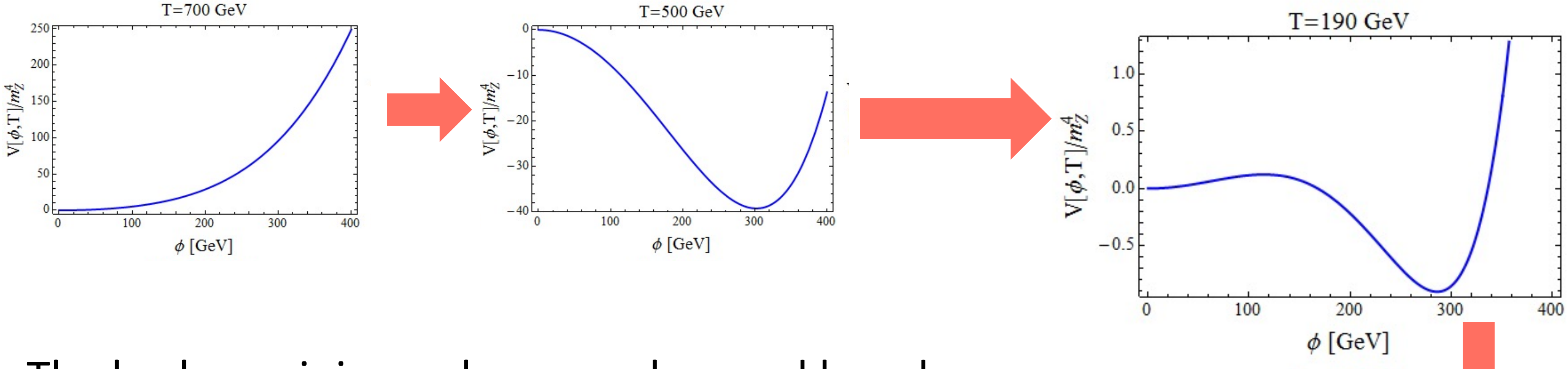
Cross over



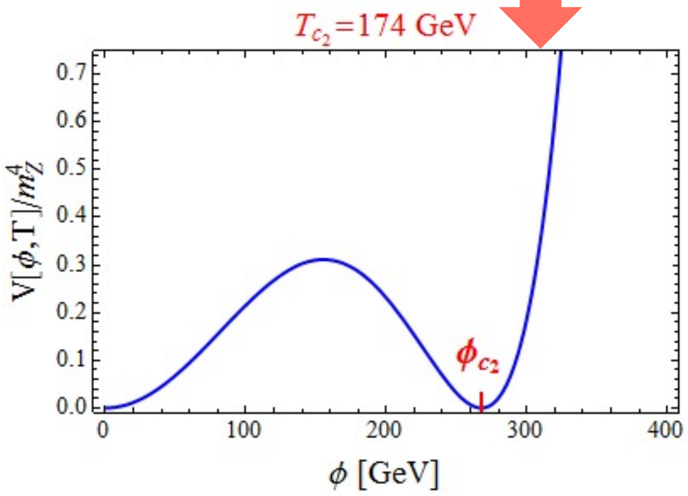
Early universe, symmetric

EWSB

Thermal Evolution of the Effective Potential

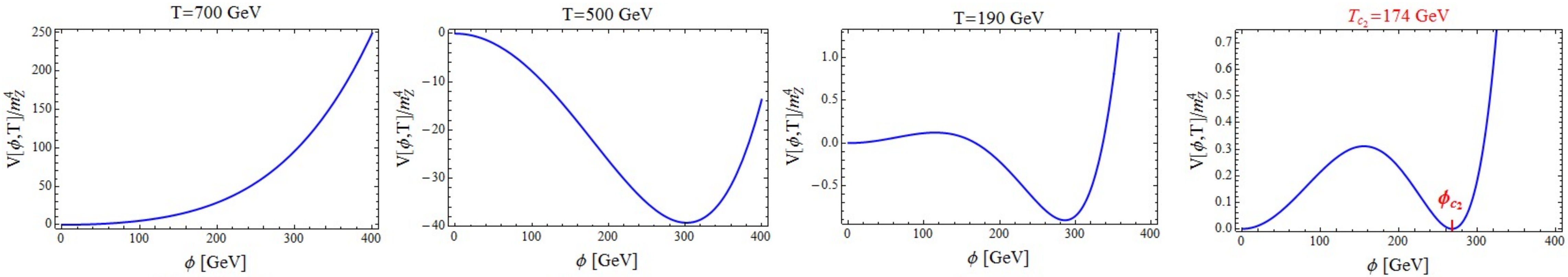


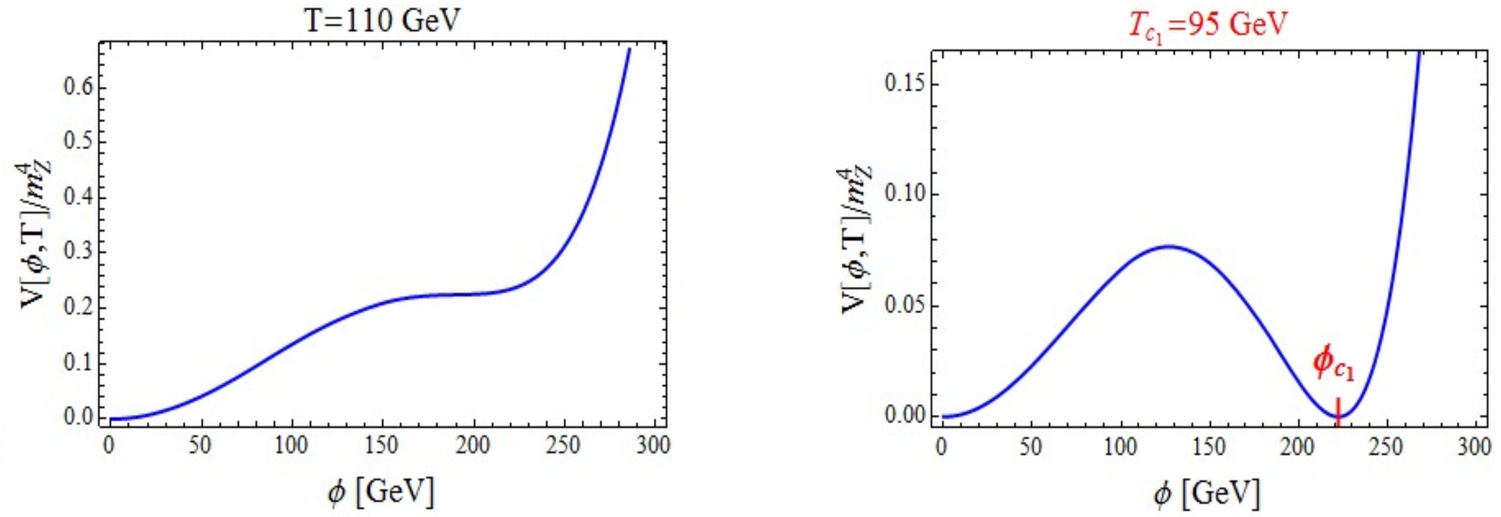
- The broken minimum becomes less and less deep
- A potential barrier starts developing between the symmetric phase and the broken phase
- At T_{c2} , a strong first order phase transition
- The universe tunnels back to the symmetric phase



EW symmetry restored

Thermal Evolution of the Effective Potential





EWSB again through a strongly first order phase transition, at T_{c1}

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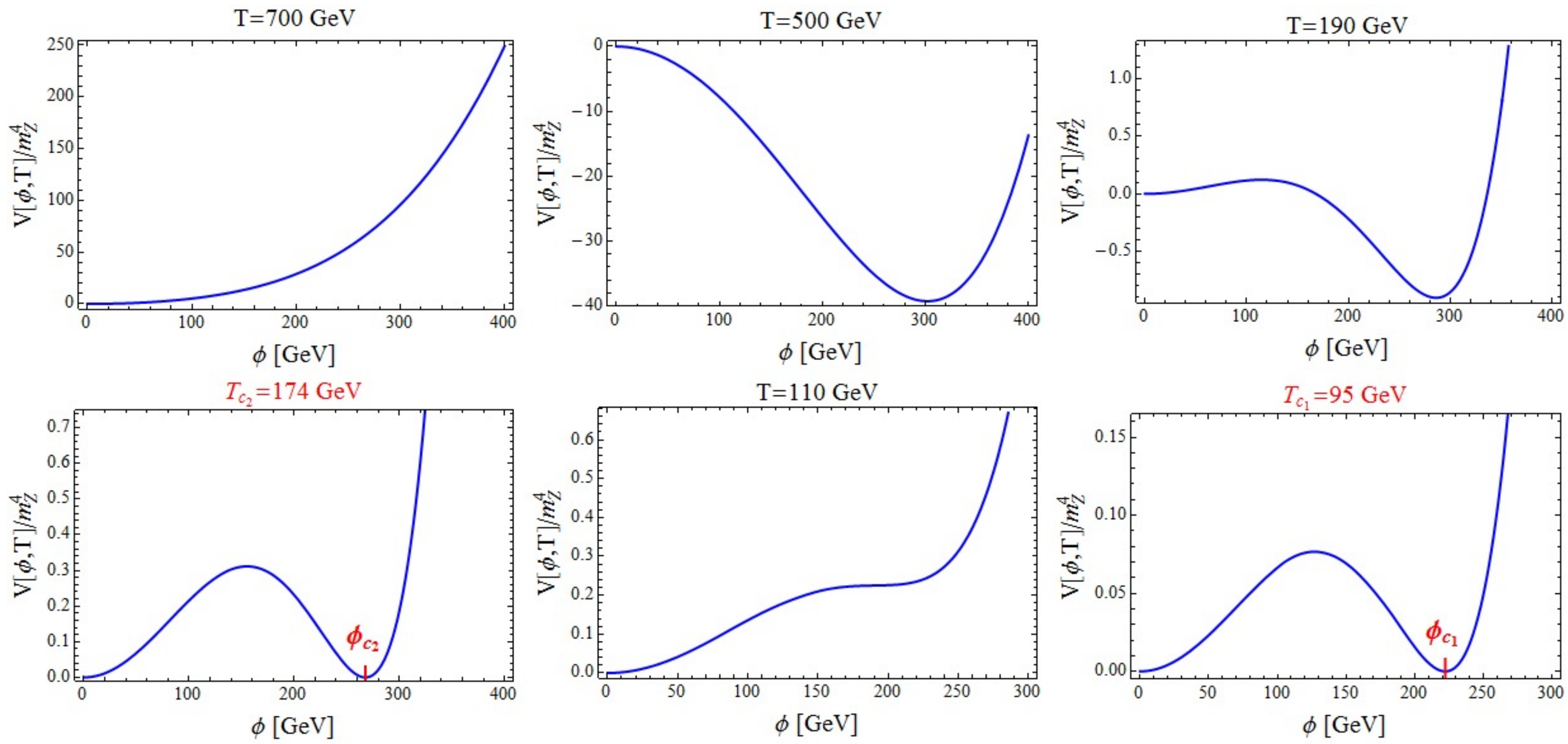
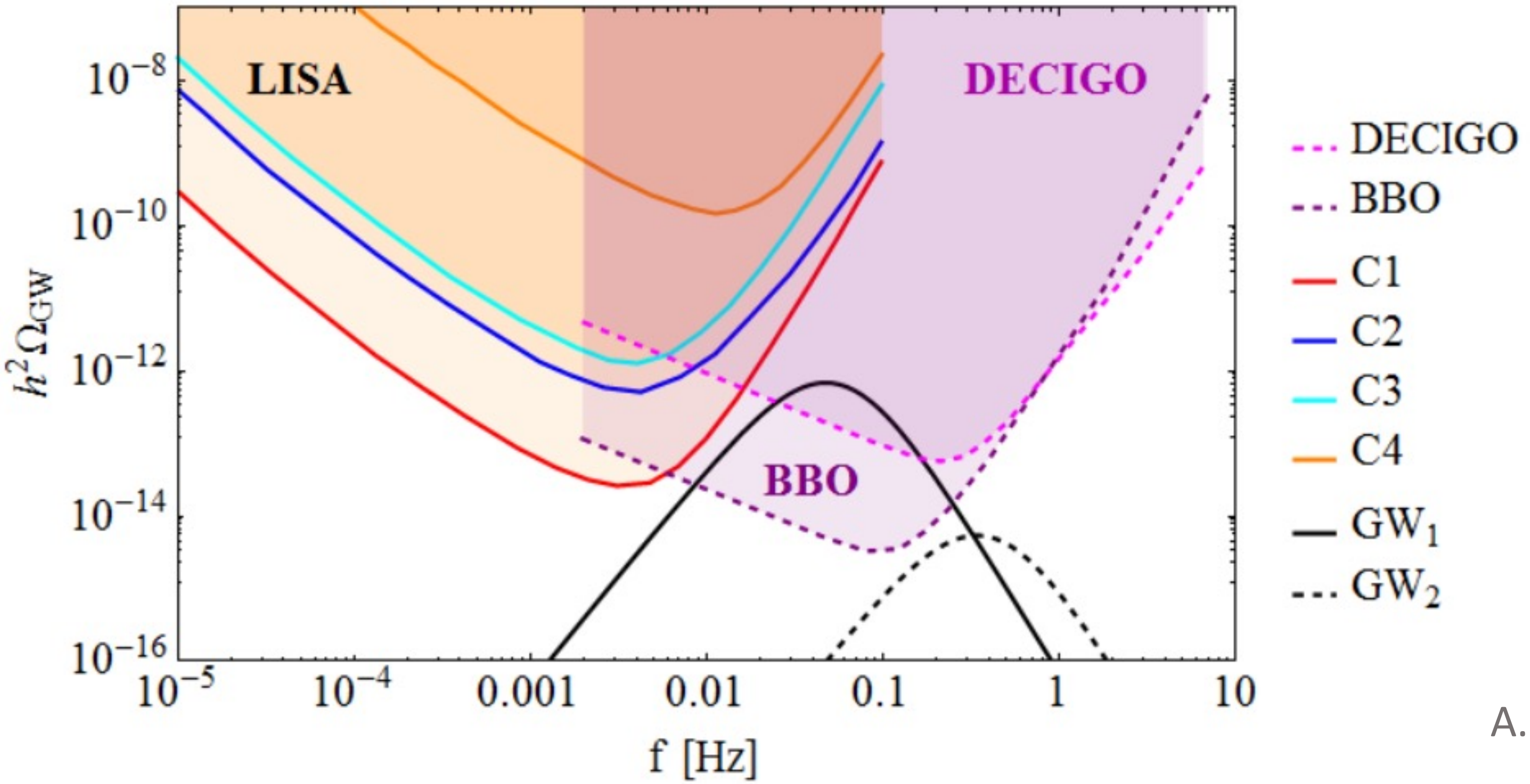
Thermal Evolution of the Effective Potential



Responsible for the BAU

Signatures – Gravitational Waves



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- Peak frequency beyond Lisa (*f*~ 0.01 -1 Hz is typical for VLL models)
- DECIGO, BBO, and AION are sensitive to the later phase transition
- The earlier one is too weak.

Signatures – Colliders, Direct Production

- N_1 can not be dark matter candidate – some mixing required.

$$-\mathcal{L}_{\rm mix} = y_1\,\overline{L}_L H \tau_R + y_2\,\overline{L}^3_L H E'_R + {\rm h.c.}\,,$$

- From $W\tau\nu$ and $Z\tau\tau$ measurements, take $y_1 = y_2 = 0.05$
- The SM fermion + VLL production is suppressed by the mixing
- The dominant production mode is the pair production of VLLs, the typical production cross section is around 0.1 to 0.4 fb.
- Direct searches at the LHC very challenging.

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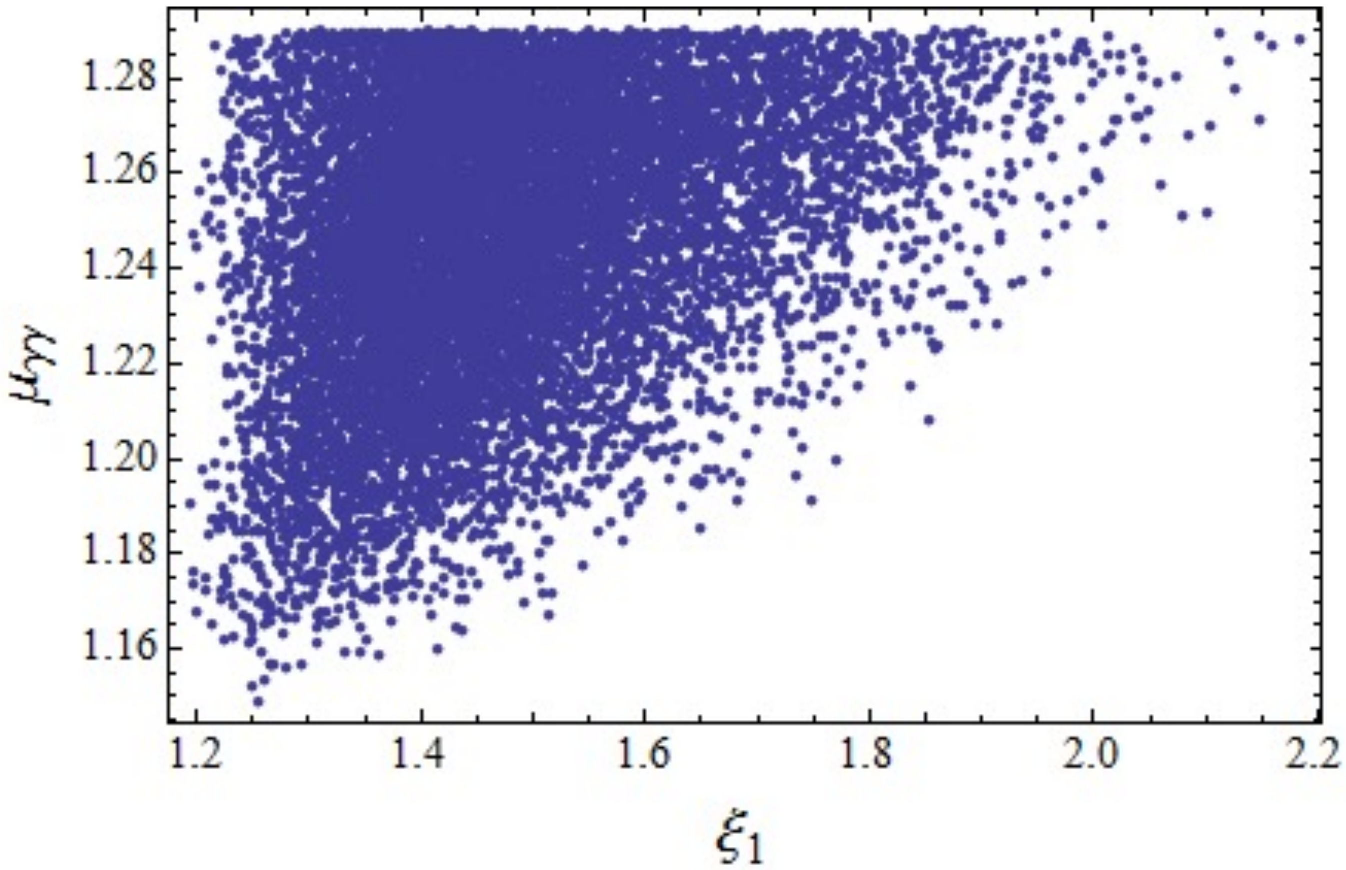
Signatures – Colliders, Indirect Searches



- At least 15% enhancement for the diphoton signal.
- Wil be fully tested at the HL-LHC.

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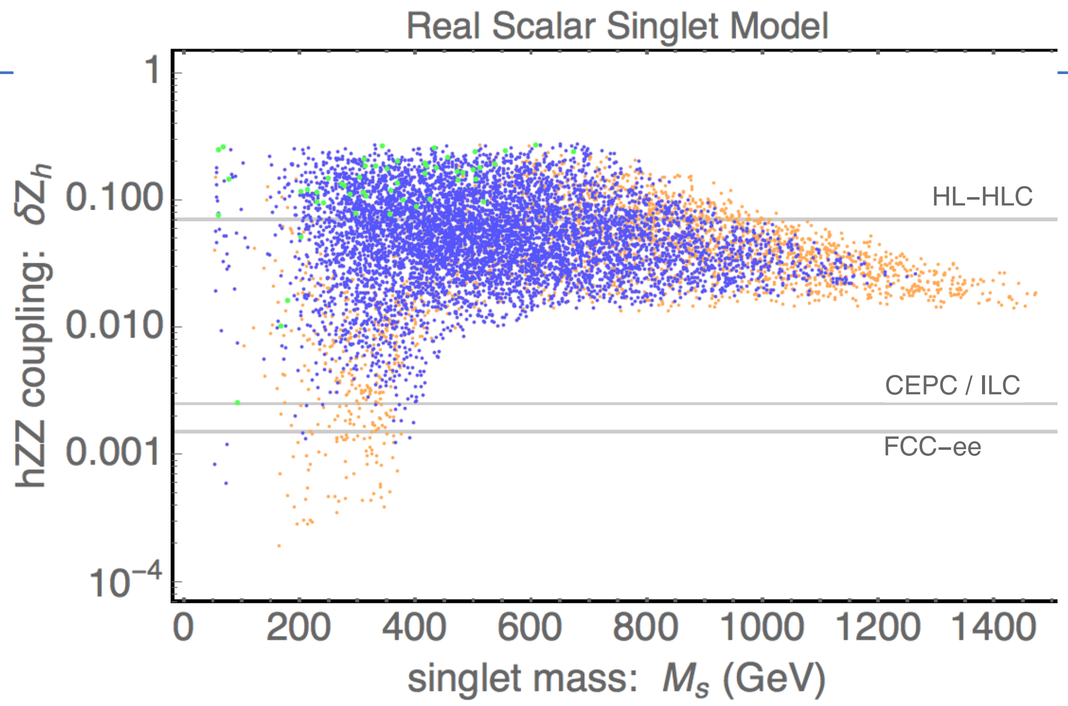
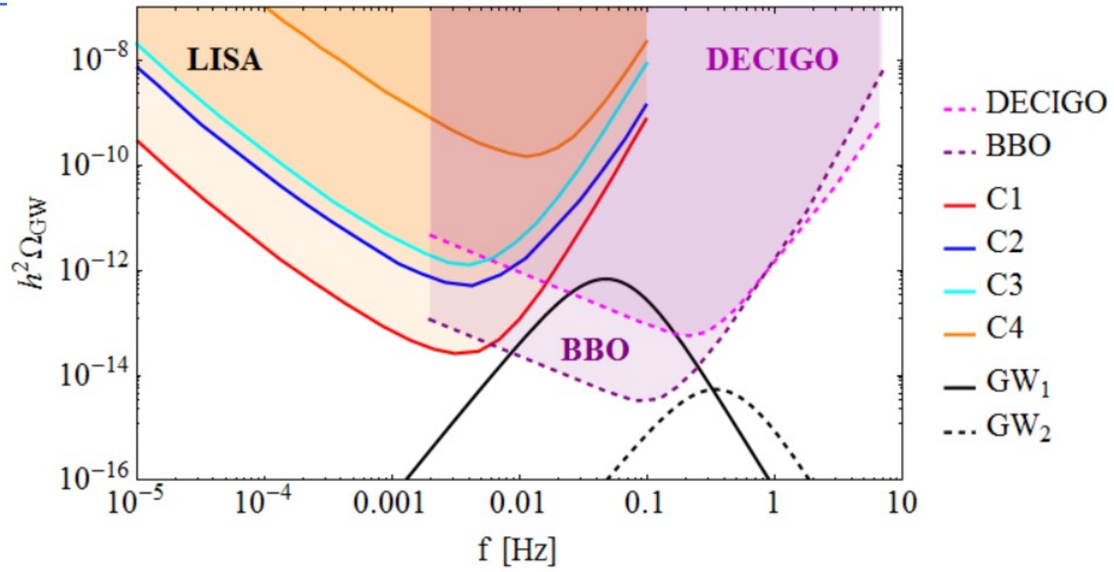
Conclusion

How can we probe the new physics?





Conclusion

What kinds of models ?

- Scalar Singlets
- Scalar Doublets
- Fermions
- Many More!