# Probe the Electroweak Phase Transition at future colliders

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Work with A. Joglekar, B. Li, and C. Wagner, arxiv:1512.00068 and A. Long and L.T. Wang, 1605:tbd

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# Higgs Potential at High Temperature

At high temperature, the Electroweak Symmetry is restored



As the Universe cools down, the symmetry is broken. The Higgs undergoes a Phase Transition from zero to non-zero VEV What was the phase transition from unbroken phase to the broken phase look like?

### Higgs Potential at Finite Temperature



## Electroweak Phase Transition

- EWPT is difficult to study from cosmology (gravitational waves?)
- EWPT in the SM is 2<sup>nd</sup> order (unless the  $m_h < 40$  GeV)
- New physics is required for a strongly first-order phase transition
- The new physics will alter the finite-temperature Higgs potential
- Higgs couples to SM particles differently, or couples to BSM particles
- Precision Higgs tests at the LHC and future colliders!

### Example: extension with a heavy singlet  $\alpha$ <sup>*x*</sup> $\alpha$ </sub>  $\alpha$ <sup>*n*</sup> which is a cubic polynomial equation in *s*. We are interested in the limit where *as*<sup>2</sup>

Extend the SM to include a scalar singlet field  $\Phi_s$ 

$$
\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{2} \big( \partial_\mu \phi_s \big) \big( \partial^\mu \phi_s \big) - t_s \phi_s - \frac{m_s^2}{2} \phi_s^2 - \frac{a_s}{3} \phi_s^3 - \frac{\lambda_s}{4} \phi_s^4 - \lambda_{hs} \Phi^\dagger \Phi \phi_s^2 - 2 a_{hs} \Phi^\dagger \Phi \phi_s
$$

Integrate out the singlet if it is heavy<br> **Integrate** out the singlet if it is heavy  $\omega$  is the guarantee of  $\omega$  the canonical interest  $\omega$  in the limit  $\omega$  in the limit  $\omega$ the grate out the singlet into sin

$$
V \approx m_0^2 \Phi^\dagger \Phi + \left(\lambda_h - \frac{2 a_{hs}^2}{m_s^2}\right) \left(\Phi^\dagger \Phi\right)^2 + \frac{4 \lambda_{hs} a_{hs}^2}{m_s^4} \left(\Phi^\dagger \Phi\right)^3 \left[1+O(\lambda_{hs} \Phi^\dagger \Phi/m_s^2)\right]
$$

If the singlet is heavy, we can integrate it out. Then *<sup>s</sup>* satisfies @*V /*@*<sup>s</sup>* = 0 or In the high-temperature limit between the <sup>4</sup> and <sup>6</sup> terms. In order to justify dropping the higher order terms, *<sup>|</sup>m*<sup>2</sup>

$$
V_{eff} = \frac{1}{2}(m_0^2 + c_0T^2)\phi_h^2 + \frac{\lambda_{eff}}{4}\phi_h^4 + \frac{c_6}{8\Lambda_{eff}^2}\phi_h^6
$$

*<sup>s</sup> ,* (6)  $m_0^2 > 0$  and  $m_0^2 > 0$ *<sup>s</sup>* + 2*hs† .* (7)  $V(\Psi)$ *<sup>s</sup>| |*2*hs†|*, there must  $\lambda^6$ . Otherwise, the minimum of minimum of minimum occurs at  $\lambda$ . *.* (9)  $V(\Phi)$ Φ  $\lambda_{eff}$  < 0  $\bigg/C_6$  > 0 *<sup>V</sup>ef f* <sup>=</sup> <sup>1</sup> (*m*<sup>2</sup>  $\frac{1}{4}$ **c**e6 →  $\rightarrow$  $c_6 > 0$  $m_0^2 > 0$ 

*<sup>s</sup>* <sup>=</sup> *<sup>t</sup><sup>s</sup>* + 2*ahs†*  $\overline{a}$ @*µ<sup>s</sup>* @*µ<sup>s</sup>* ⇡ *m*<sup>4</sup> *s* Possible to generate a first order EWPT

#### What to expect on colliders? and the trilinear coupling *ahs†<sup>s</sup>* in particular will play an important role. The scalar potential is  $\overline{C}$ *as* 3 3 *<sup>s</sup>* + *s* 4 4

- . Singlet can be directly produced on colliders through its mixing with the **Higgs**  $\mathcal{S}$  small (over the equation becomes linear, and its solution is solution is solution is solution is solution is so If the singlet is heavy, we can integrate it out. Then *<sup>s</sup>* satisfies @*V /*@*<sup>s</sup>* = 0 or
	- $\bullet$  m<sub>s</sub> = 525 GeV, sin<sup>2</sup> $\theta$  ~ 0.2,  $\sigma$ (pp -> S) ~ 0.9pb
	- can be searched from the heavy Higgs search channels at HL-LHC.
- The Higgs trilinear coupling will be modified. The range of the trilinear coupling that can be consistent with a first-order phase transition is about  $1.3 - 2.8 \lambda_3$ <sup>SM</sup> in such a SM in such a theory arxiv:1512:00068 PH, A. Joglekar, B. Li, and C. Wagner without complete with the information of the large of the trimited in the limit of the limit  $t$ the small ratio. The equipolent w *mounted.* The range of the trim<br>**b** a first arder phase transition  $\lambda_2$ <sup>SM</sup> in such a theory arxiv:1512:0  $\sim$  The effective potential becomes potential becomes,  $\sim$

$$
V \approx m_0^2 \Phi^{\dagger} \Phi + \left(\lambda_h - \frac{2a_{hs}^2}{m_s^2}\right) \left(\Phi^{\dagger} \Phi\right)^2 + \frac{4\lambda_{hs}a_{hs}^2}{m_s^4} \left(\Phi^{\dagger} \Phi\right)^3 \left[1 + O(\lambda_{hs} \Phi^{\dagger} \Phi/m_s^2)\right]
$$

singlet kinetic term modifies the wavefunction of the physical Higg be a tuning between *<sup>h</sup>* and 2*a*<sup>2</sup> *hs/m*<sup>2</sup> *<sup>s</sup>* such that *<sup>|</sup>*e↵*<sup>|</sup>* ⌧ *<sup>|</sup>h<sup>|</sup>* ⇡ *<sup>|</sup>*2*a*<sup>2</sup> *hs/m*<sup>2</sup> *<sup>s</sup>|*. Otherwise, the minimum occurs at *†* ⇠ *<sup>m</sup>*<sup>2</sup> *<sup>s</sup>/hs*, where the approximation breaks down. The kinetic term gives a derivative self-interaction at kingtic term modifies the wavefunction of the physical between the <sup>4</sup> and <sup>6</sup> terms. In order to justify dropping the higher order terms, *<sup>|</sup>m*<sup>2</sup> *<sup>s</sup>| |*2*hs†|*, there must therefore shifts all Higgs couplings universally • The singlet kinetic term modifies the wavefunction of the physical Higgs, and

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

### اب المسابق الم<br>المسابق المسابق الم Probe the trilinear coupling at HL-LHC, and the 100 TeV collider *<sup>b</sup>*¯*bjj* 7.51⇥10<sup>9</sup> 5.34⇥10<sup>4</sup> 6.47 ⇥10<sup>4</sup>



with p<sub>s</sub>  $\frac{1}{2}$  TeV. and Shaughnessy Spria, figure from Barger, Everett, Jackson,

Spria, figure from Barger, Everett, Jackson.  $5\ \sigma$  for  $\lambda^3 \simeq 5 \lambda^3$  cm  $\lambda$  or  $\lambda^3 \simeq 1.6\ \lambda^3$  cm  $\mathcal{L}$  by  $\mathcal{S}(\mathcal{N})$  for  $\mathcal{N}$  are two detectors. Spria, figure from Barger, Everett, Jackson,  $5\ \sigma$  for  $\lambda^3$   $\sim$   $5\lambda^3_{\rm SM}$  , or  $\lambda^3$   $\sim$   $1.6$   $\lambda^3_{\rm SM}$ *hhh/hhh* SM = 1,2,3.

arxiv:1512.00068 PH, A. Joglekar, B. Li, and C. Wagner<br>Analysis on developing analystics of future colliders, ass talk by N. Ghan and L. Lovis is found to be present in the *p<sup>T</sup>* (*h*) distribution.

more analysis on double Higgs production at future colliders, see talk by N. Chen and I. Lewis. Re M<sup>É</sup> Ie H Re MÉ+M@ For the Higgs decays, we consider the , ⌧ ⌧ , and *b*¯*b* tion at future colliders, see talk by N.

#### Probe the higgs coupling at HL-LHC *DE LITE INSES COUPHING ALTILELIC* tated by symmetries of the full theory. To a certain exthe the high d fermions, however the Standard Constantine of the Standard  $mmin_{\sigma}$  of  $\Box$  in  $\Box$ coupling at HE-LITC  $\frac{1}{2}$  is a shift in the wave-function renormalization ren and potential of the Higgs doublet *H* as well as operators of dimension six and higher. Most of these shifts

**h** and 2<sup>*m*</sup> such that *h*  $\frac{h}{2}$ *Vef f* = *Promy* ์<br>ล vefunction renorr *ef f* hization<br>A dard Model gauge representations of top partners are not necessarily fixed by the cancellation of  $\mathbf r$ *Zh, m*<sup>2</sup>



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

Fractional change in all higgs couplings  $\delta Z_h \approx \frac{2 a_{hs}^2 v^2}{4}$ supersymmetry [4] the scalar top partners are neutral under der Godinal change in d

s couplings 
$$
\delta Z_h \approx \frac{2a_{hs}^2v^2}{m_s^4}
$$

*z*<sub>reak</sub> | HC limit from the Current LHC limit from the Higgs signal  $\delta Z_h \leq 0.14$ strength  $C_{11}$ uno pet $\Box C$ lino it from curient Life mint non likely strength broad  $\delta Z_h$  : *n||*

 $\mathbf{P}$ HL-LHC expects to measure the Higgs couplings to percent level. *O*(2-10%)



### Probe the hZZ coupling at CEPC/FCC-ee **56** HIGGS PHYSICS AT CEPC **56** HIGGS PHYSICS AT CEPC

- Lepton colliders are good for precision measurements
	- electroweak production, cross sections are predicted with (sub percent)precision
	- clean events, smaller background
- 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  $\sim$  200 fb
	- expect 0.25% precision in hZZ coupling! 5 ab <sup>-1</sup> CEPC pre-CRD







Even in the  $Z_2$  limit, CEPC can start to probe the nature of the EWPT state  $\sim$ *F*<sup>1</sup>  $\alpha$ <sup>2</sup> limit CFPC can start to probe  $\overline{1}$ Squared Coupling: *n*

 $\mathcal{L}_{\text{int}} = -\lambda_{hs} \Phi^\dagger \Phi \phi_s^2.$ Nightmare scenario, Curtain, Meade, and Yu, 2014.

Largest deviation for the trilinear coupling from its SM value is about  $18\%$ , Gupta, Rzehak, and Wells, 2013  $\frac{2.0 \int_{\text{gas}} 1 \times \text{cos} \sqrt{1 - \left(1 - \frac{1}{2} \right)} \cdot \frac{1}{2} \cdot \$ 2.0

> The portal coupling leads to a wavefunction the singlet model,  $\mathbb{Z}_2$ renormalization of the Higgs field at 1-loop order

> > $\delta Z_h = \frac{1}{2}$

2

 $|\lambda_{hs}|^2$ 

 $v^2$ 

 $\left[1 + F(\tau_{\phi})\right]$ 

 $M_h^2$ 

 $16\pi^2$ 





 $\sigma$ <sup> $\Gamma$ </sup> N/ $\sigma$ <sup>*n* $\sigma$ </sub> 1605.  $\mu$ bd</sup> PH, A. Long, L.T. Wang, 1605:tbd

## conclusion

- In models exhibit a strong first order phase transition, modifications in the Higgs trilinear coupling and the hZZ coupling are expected
- It is very challenging to probe the trilinear coupling at the LHC
- hZZ coupling can be measured very well at lepton colliders, CEPC is almost able to cover the whole region consistent with a first order phase transition, in the models with a mix-in singlet
- A 100 TeV collider can measure the Higgs trilinear coupling, and can be complementary to a lepton collider.
- We may have an answer for the nature of the EWPT in 20 years!

### **• BACK UP SLIDES**

#### Probe the trilinear coupling at HL-LHC, and the 100 TeV collider - double Higgs production  $\blacksquare$ the triscalar coupling from its SM value and study the e↵ects of this coupling on the *hh* cross-section and distributions with cut-based and multivariate methods. Our fit to the *hh* production matrix element at LHC(14) with 3 abit 3 a  $\mathsf{P}_{\mathsf{A}}$  $\bigcap_{n=1}^{\infty}$   $\bigcap_{n=1}^{\infty}$  $\Box$  in the beginning the beginning of a new era in particle structure. physics. The next experimental challenge is the measure-*h*



- in SM The box and the triangle diagram interfere with each other destructively
- The strongest cancellation is around  $\sim$ 2.5 $\lambda_{3}^{\rm SM}$  , the cross section is suppressed in the region consistent with a first order phase transition
- The  $m_{hh}$  distribution shifts to lower values for large  $\lambda_{3}$  expect more background

FIG. 4: The di↵erential cross section versus *Mhh* for arxiv:1512.00068 PH, A. Joglekar, B. Li, and C. Wagner

### **Gravitational Waves probes**



### preliminary

### CEPC event rate

