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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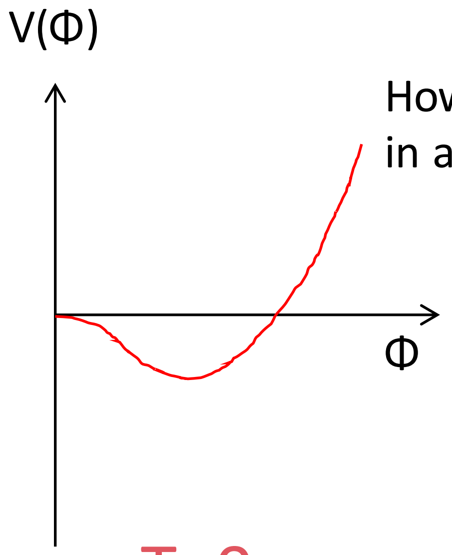
University of Pittsburgh, 05/10/2016

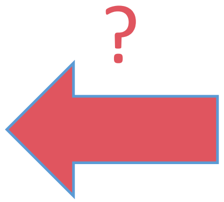
Higgs Potential at High Temperature

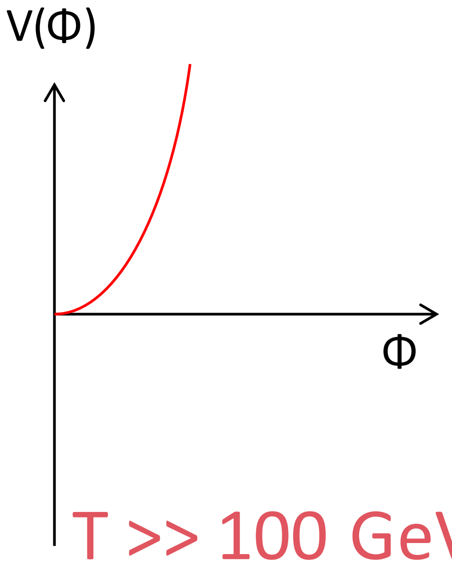
At high temperature, the Electroweak Symmetry is restored



T=0

How does the potential change in a hot environment?



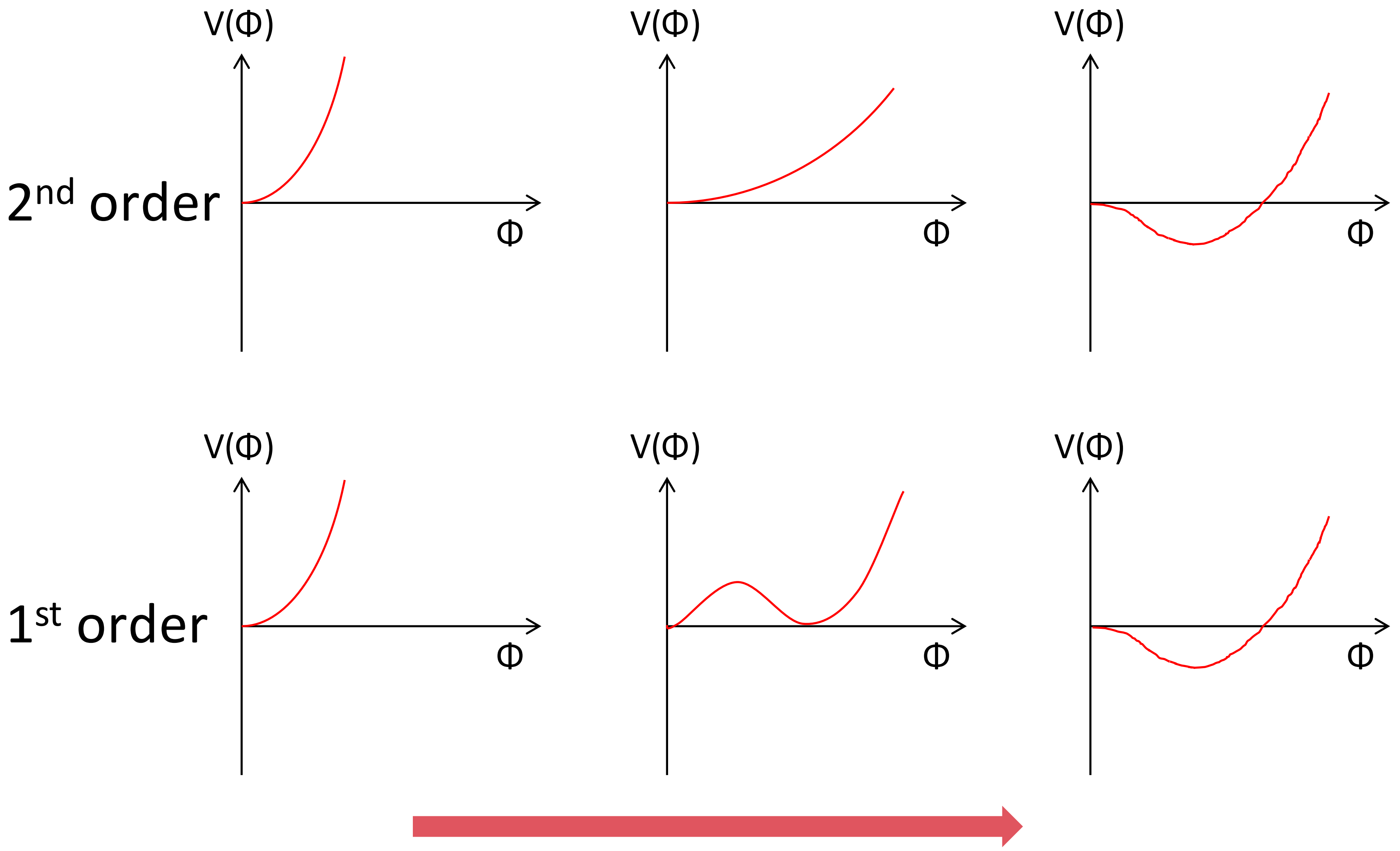


T >> 100 GeV

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 2nd 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

Extend the SM to include a scalar singlet field ϕ_s

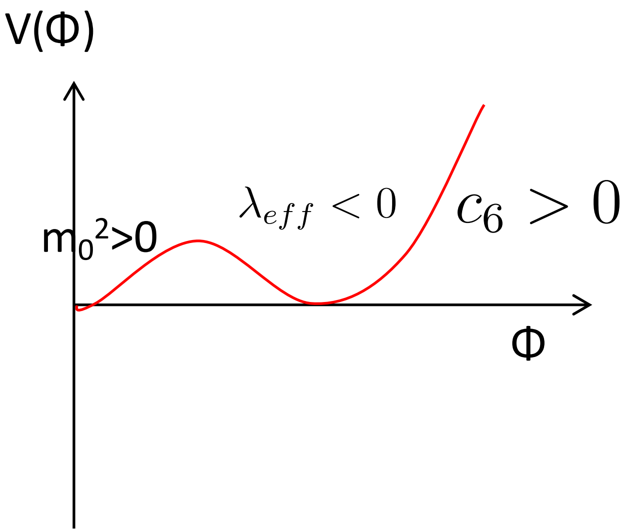
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}(\partial_\mu \phi_s)(\partial^\mu \phi_s) - t_s\phi_s - \frac{m_s^2}{2}\phi_s^2 - \frac{a_s}{3}\phi_s^3 - \frac{\lambda_s}{4}\phi_s^4 - \lambda_{hs}\Phi^\dagger\Phi\phi_s^2 - 2a_{hs}\Phi^\dagger\Phi\phi_s$$

Integrate out the singlet if it is heavy

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

In the high-temperature limit

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



Possible to generate a first order EWPT

What to expect on colliders?

- Singlet can be directly produced on colliders through its mixing with the Higgs
  - m_s = 525 GeV, $\sin^2\theta$ ~ 0.2, σ(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 λ_3^{SM} in such a theory arxiv:1512:00068 PH, A. Joglekar, B. Li, and C. Wagner

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

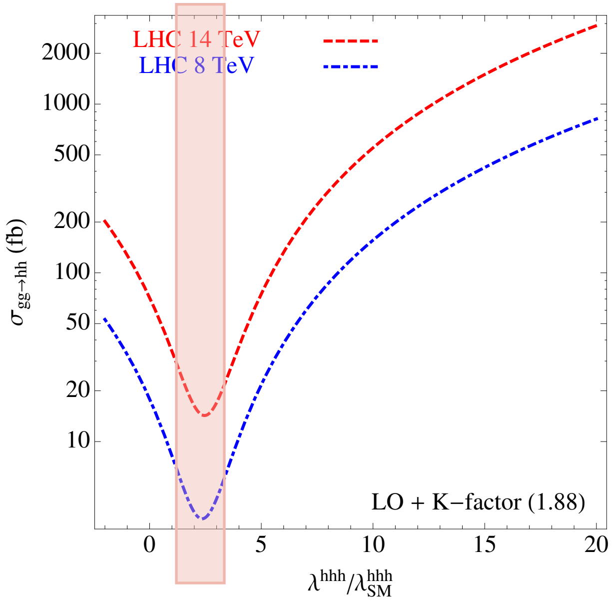
- The singlet kinetic term modifies the wavefunction of the physical Higgs, and therefore shifts all Higgs couplings universally

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

Probe the trilinear coupling at HL-LHC, and the 100 TeV collider

$\lambda^3 < 3\lambda^3_{SM}$, $m_{hh} > 350$ GeV

$\lambda^3 > 3\lambda^3_{SM}$, 250 GeV $< m_{hh} <$ 350 GeV



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

λ_3	λ_3^{SM}	$5\lambda_3^{SM}$	$7\lambda_3^{SM}$	$9\lambda_3^{SM}$	0	$-\lambda_3^{SM}$	$-2\ \lambda_3^{SM}$
$S/\sqrt{B}$	3.3	2.1	6.0	11	4.4	7.5	9.8

5 σ for $\lambda^3 \sim 6.5\lambda^3_{SM}$, or $\lambda^3 \sim -0.2\ \lambda^3_{SM}$

14 TeV and 3000 fb $^{-1}$

λ_3	λ_3^{SM}	$3\ \lambda_3^{SM}$	$5\ \lambda_3^{SM}$
$S/\sqrt{B}$	11	4.5	5.3

100 TeV, 3000 fb^{-1}

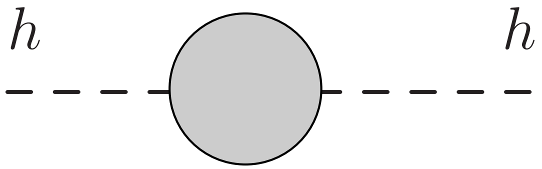
5 σ for $\lambda^3 \sim 5\lambda^3_{SM}$, or $\lambda^3 \sim 1.6\ \lambda^3_{SM}$

arxiv:1512.00068 PH, A. Joglekar, B. Li, and C. Wagner

more analysis on double Higgs production at future colliders, see talk by N. Chen and I. Lewis.

Probe the higgs coupling at HL-LHC

From wavefunction renormalization



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

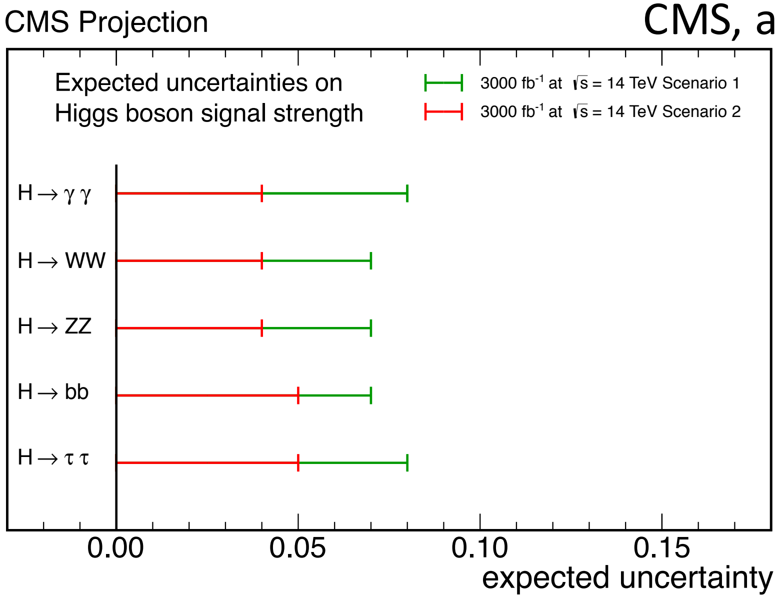
Fractional change in all higgs couplings

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

Current LHC limit from the Higgs signal strength $\delta Z_h \lesssim 0.14$

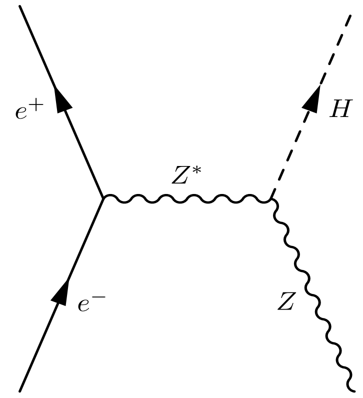
HL-LHC expects to measure the Higgs couplings to percent level. *O*(2-10%)

CMS, arXiv:1307.7135

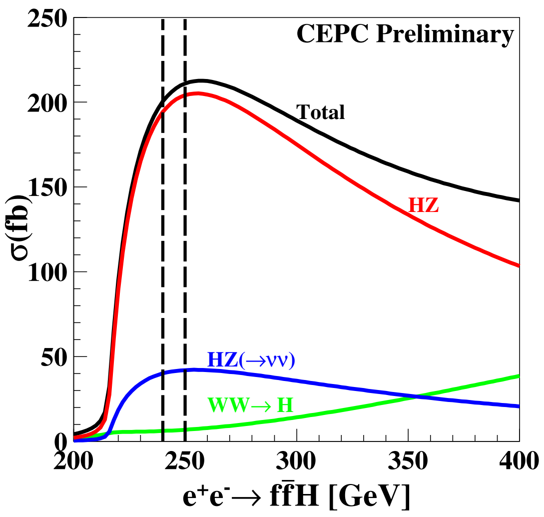


Probe the hZZ coupling at CEPC/FCC-ee

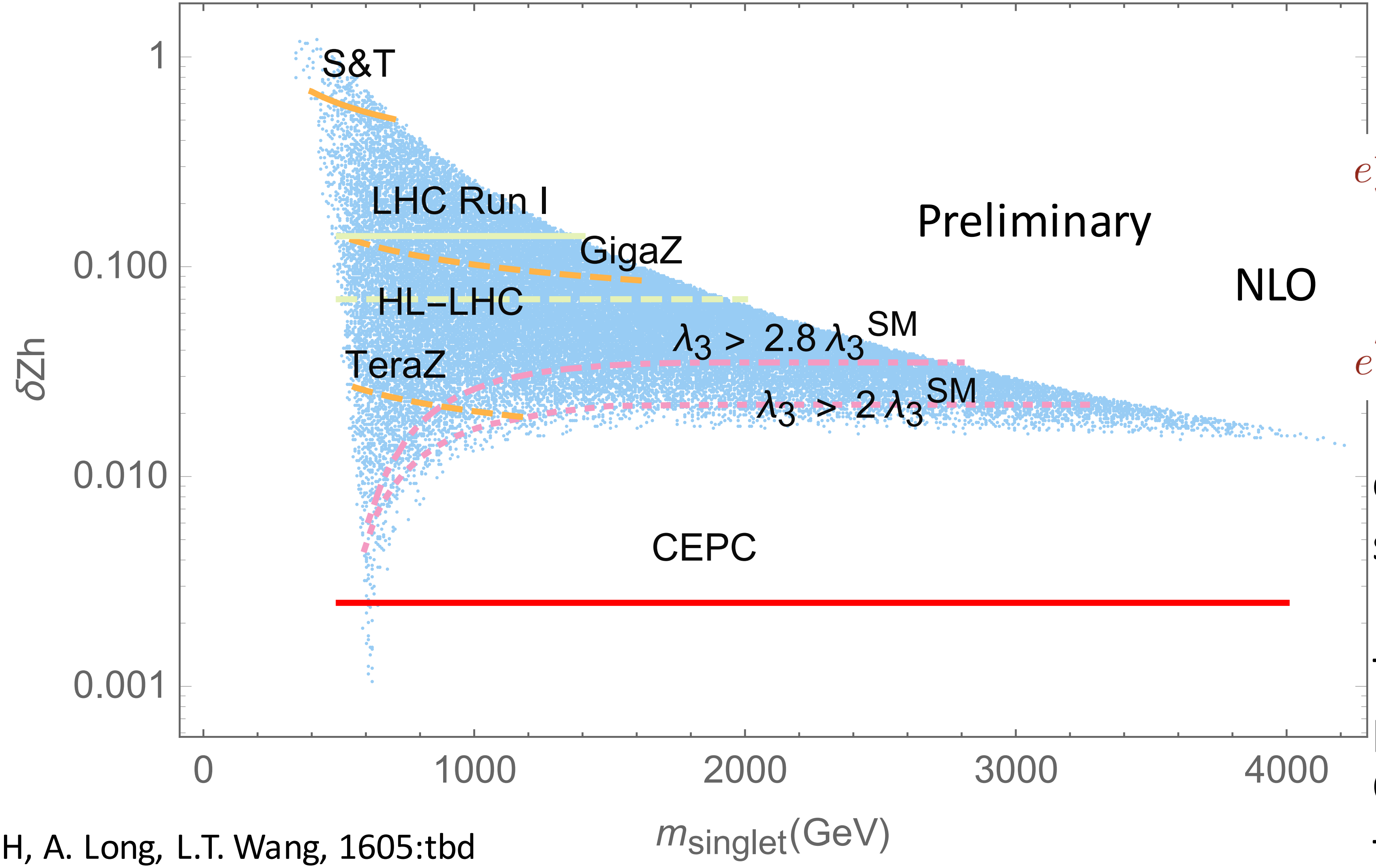
- Lepton colliders are good for precision measurements
  - electroweak production, cross sections are predicted with (sub percent)precision
  - clean events, smaller background
- hZZ coupling can be measured to high precisions with lepton colliders.
  - hZZ coupling can be probed by the Higgsstralung process
  - large production cross section around 240 GeV to 250 GeV ~ 200 fb
  - expect 0.25% precision in hZZ coupling!



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

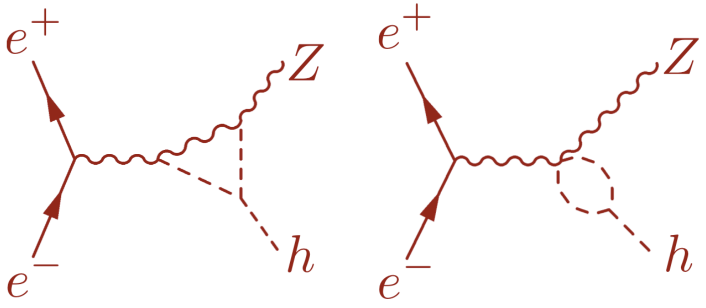


Probe the hZZ coupling at CEPC



LO

NLO



current constraints : Higgs signal strength
HL-LHC can start to probe the hZZ coupling to percent level
CEPC can basically cover the whole region

PH, A. Long, L.T. Wang, 1605:tbd

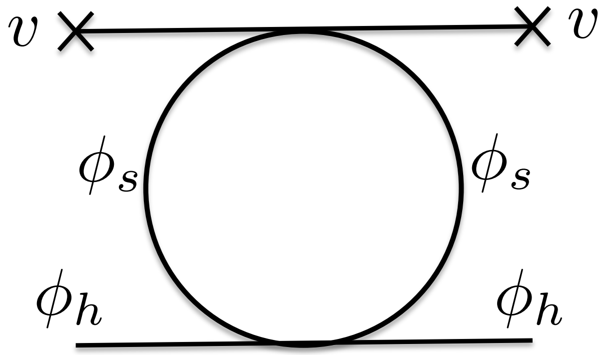
Even in the Z_2 limit, CEPC can start to probe the nature of the EWPT

$$\mathcal{L}_{\text{int}} = -\lambda_{hs}\Phi^\dagger\Phi\phi_s^2$$

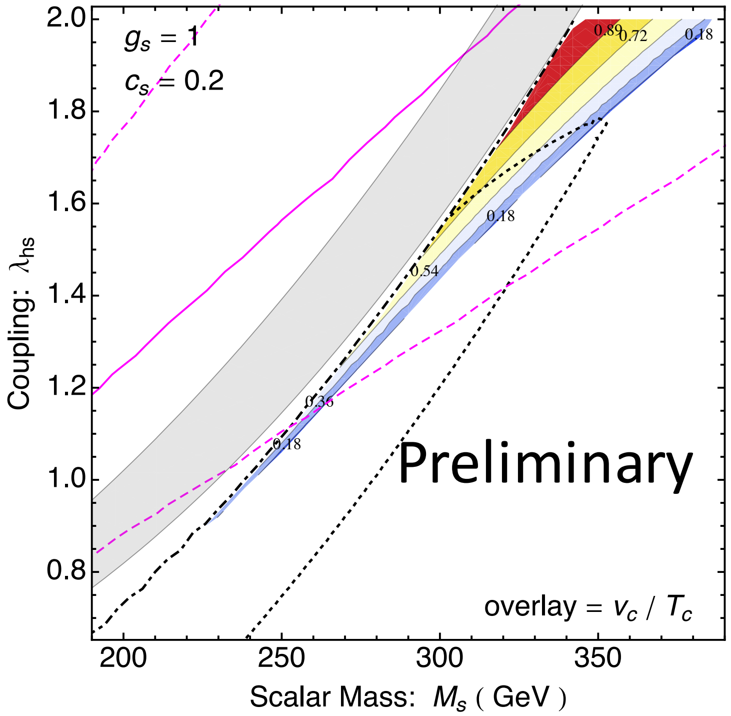
Nightmare scenario, Curtain, Meade, and Yu, 2014.

Largest deviation for the trilinear coupling from its SM value is about 18%, Gupta, Rzehak, and Wells, 2013

The portal coupling leads to a wavefunction renormalization of the Higgs field at 1-loop order



$$\delta Z_h = \frac{1}{2}\frac{|\lambda_{hs}|^2}{16\pi^2}\frac{v^2}{M_h^2}\left[1 + F(\tau_\phi)\right]$$



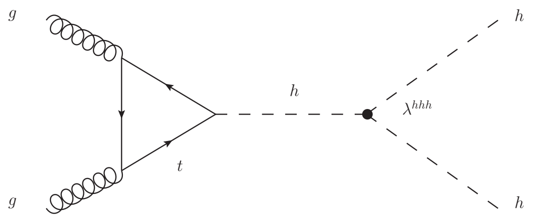
PH, A. Long, L.T. Wang, 1605:tbd

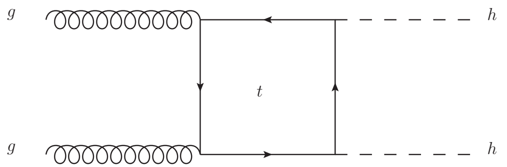
conclusion

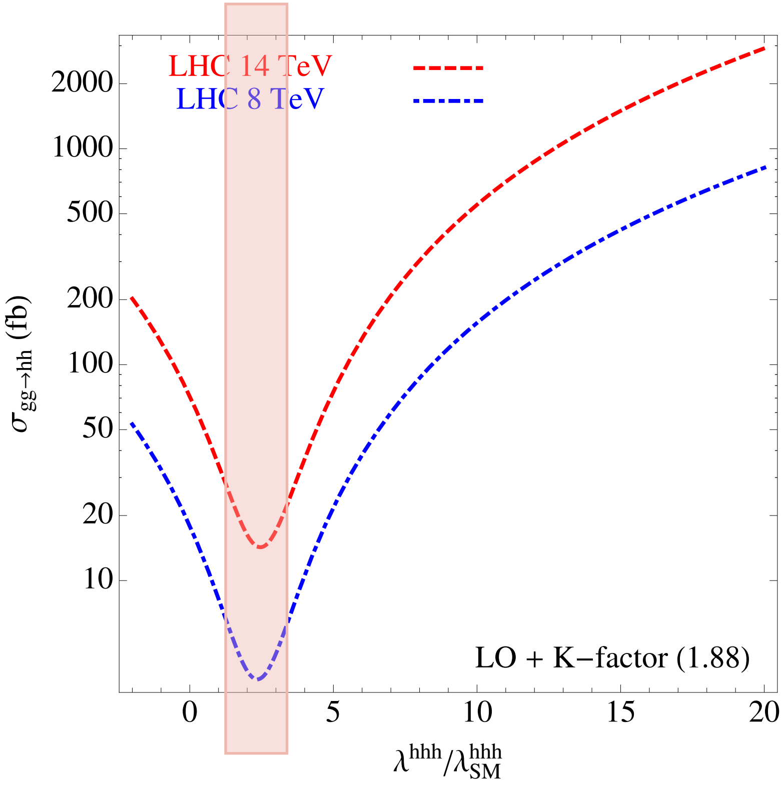
- In models exhibit a strong first order phase transition, modifications in the Higgs trilinear coupling and the hZZ coupling are expected
- It is very challenging to probe the trilinear coupling at the LHC
- hZZ coupling can be measured very well at lepton colliders, CEPC is almost able to cover the 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!

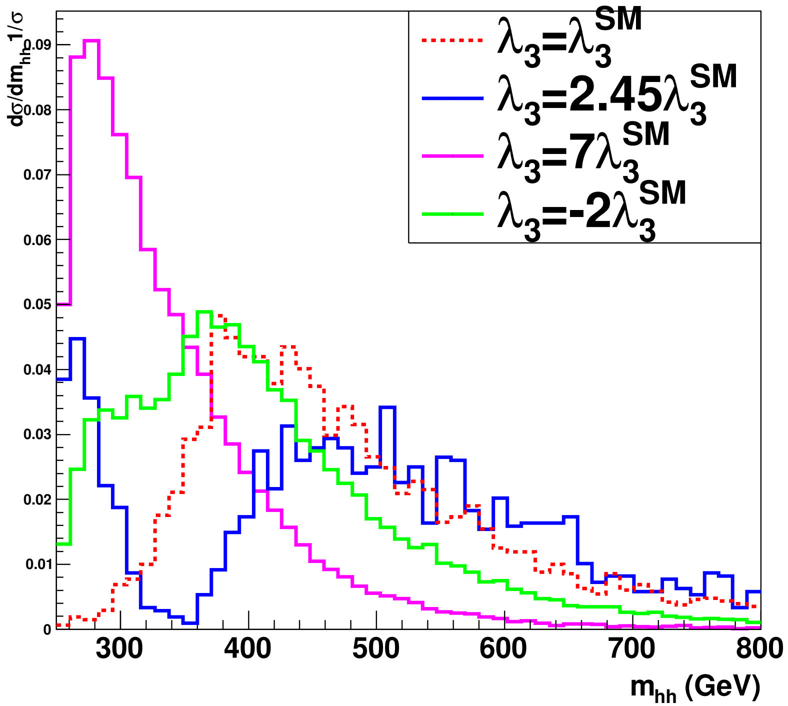
- BACK UP SLIDES

Probe the trilinear coupling at HL-LHC, and the 100 TeV collider – double Higgs production





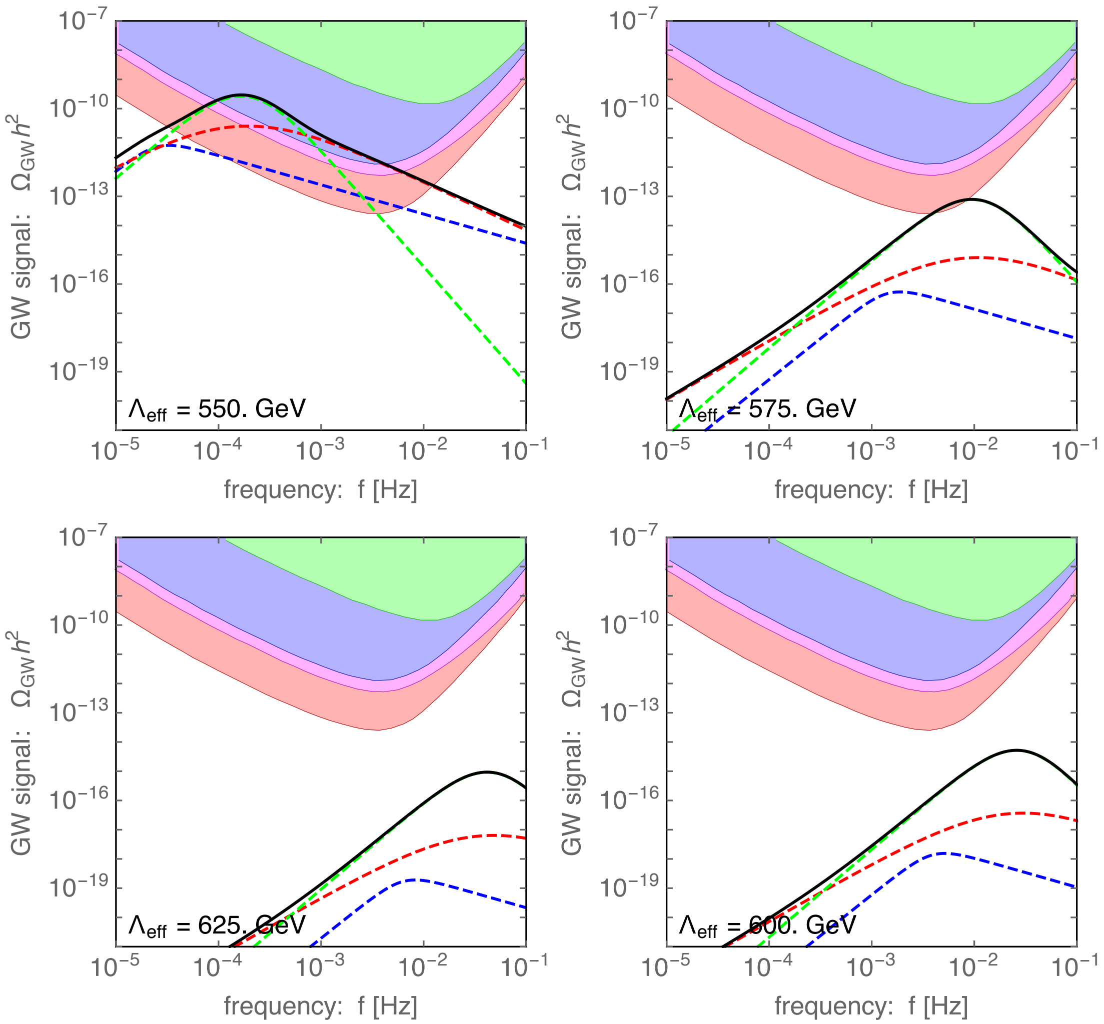




- The box and the triangle diagram interfere with each other destructively in SM
- The strongest cancellation is around ~$2.5\lambda_3^{SM}$, the cross section is suppressed in the region consistent with a first order phase transition
- The m_{hh} distribution shifts to lower values for large λ_3, expect more background

arxiv:1512.00068 PH, A. Joglekar, B. Li, and C. Wagner

Gravitational Waves probes



preliminary

CEPC event rate