Probing the Electroweak Phase Transition at the LHC and Future Colliders

Peisi Huang
University of Chicago / Argonne National Laboratory

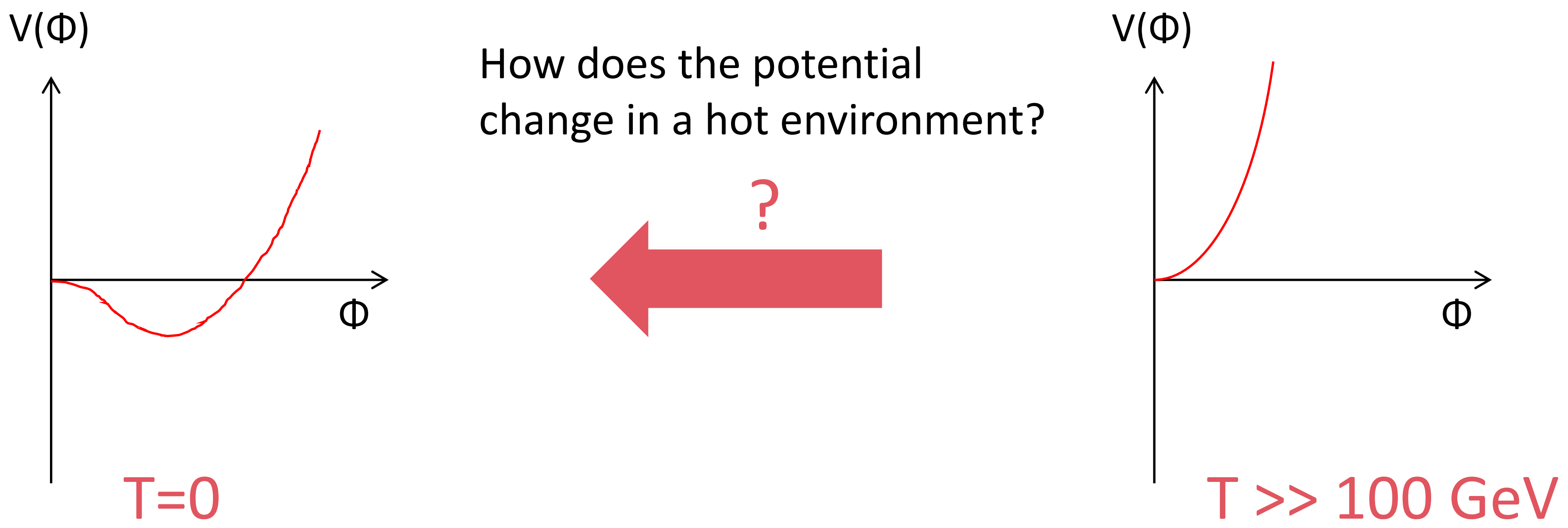
ICHEP 2016

Chicago, IL, 08/06/2016

Work with A. Joglekar, B. Li, and C. Wagner, arxiv:1512.00068
and A. Long and L.T. Wang, 1608:tbd

Higgs Potential at High Temperature

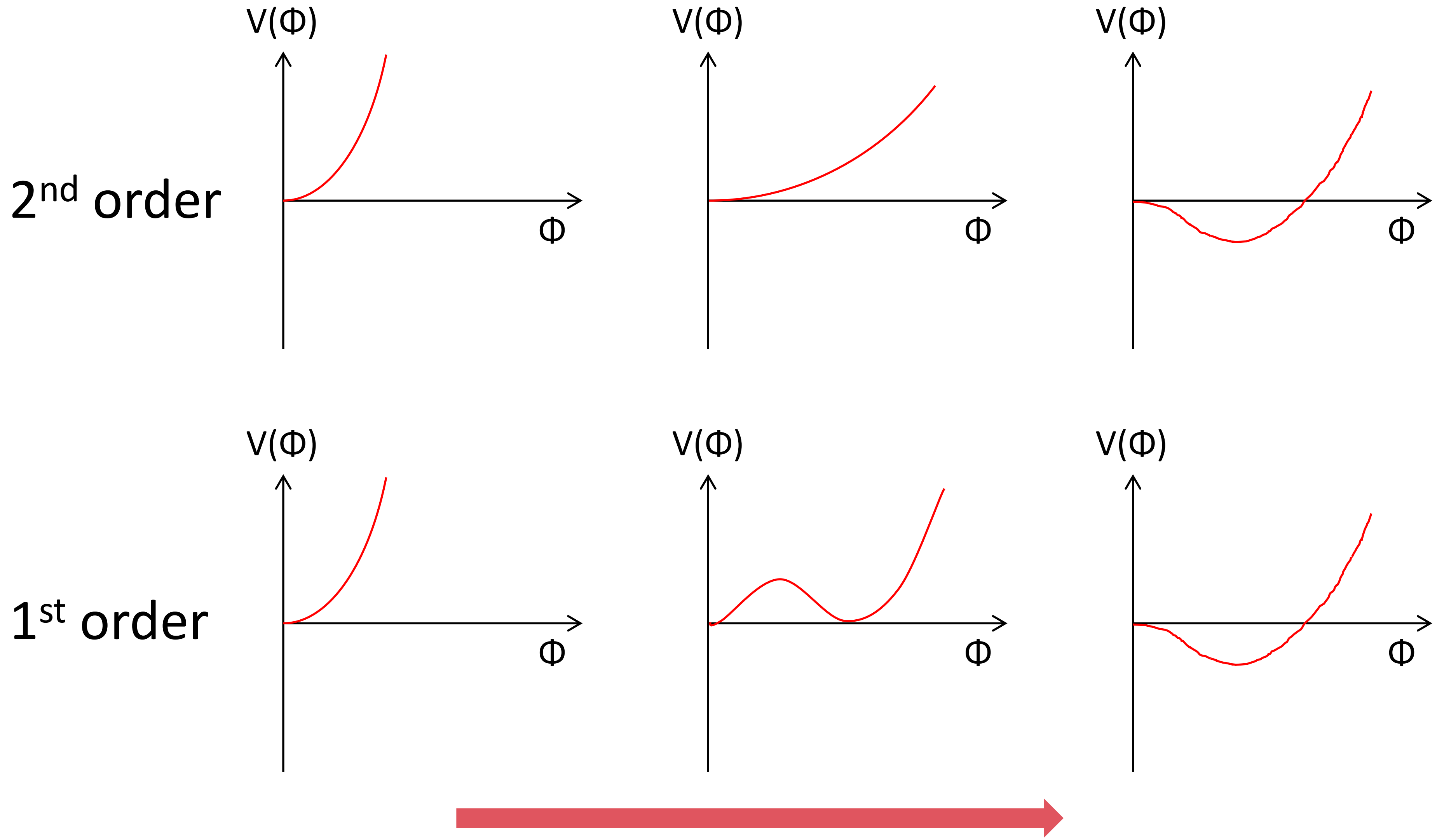
At high temperature, the Electroweak Symmetry is restored



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, see A. Long's talk)
- EWPT in the SM is not 1^{st} order
- 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

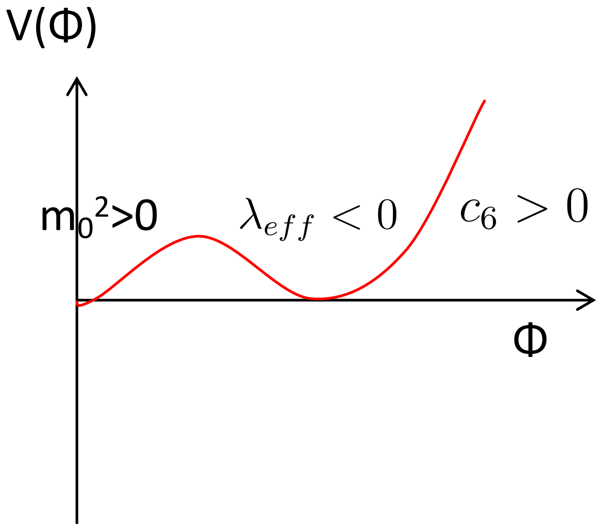
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}(\partial_\mu \phi_s)(\partial^\mu \phi_s) - t_s\phi_s - \frac{m_s^2}{2}\phi_s^2 - \frac{a_s}{3}\phi_s^3 - \frac{\lambda_s}{4}\phi_s^4 - \lambda_{hs}\Phi^\dagger\Phi\phi_s^2 - 2a_{hs}\Phi^\dagger\Phi\phi_s$$

Integrate out the singlet if it is heavy

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

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

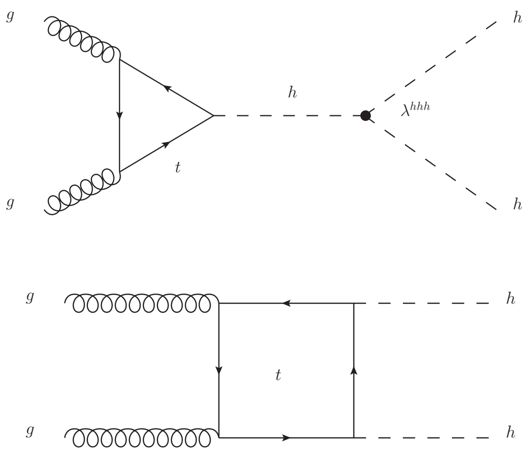
$$\frac{1}{2}(\partial_\mu \phi_s)(\partial^\mu \phi_s) \approx \frac{2a_{hs}^2}{m_s^4}\left(\Phi^\dagger\partial_\mu\Phi + \mathrm{h.c.}\right)^2\left[1 + O(\lambda_{hs}\Phi^\dagger\Phi/m_s^2)\right]$$

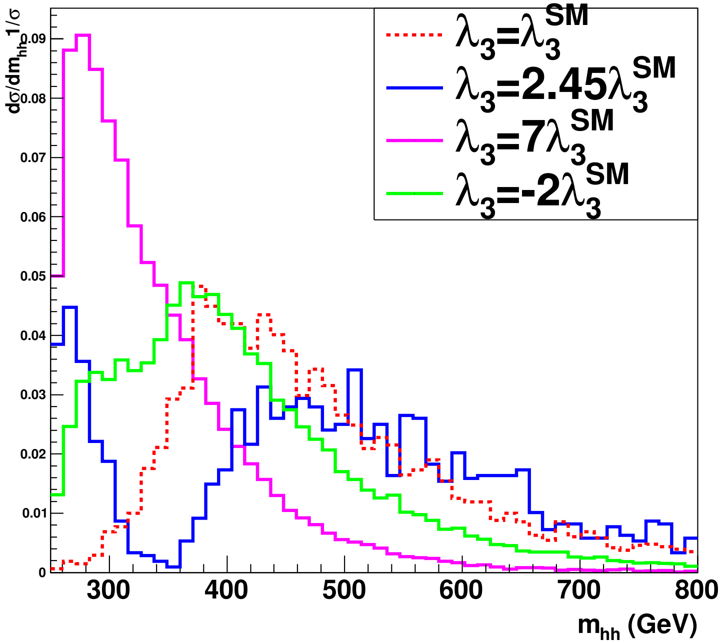
Probe the Trilinear Coupling at HL-LHC and the 100 TeV Collider

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

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

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





0.7 σ for $\lambda^3 \sim 5\lambda^3_{SM}$ if using the cut $m_{hh} > 350$ GeV

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

14 TeV, 3000 fb^{-1}

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

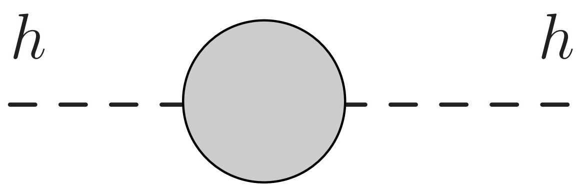
100 TeV, 3000 fb^{-1}

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

Modification in the Higgs Couplings

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



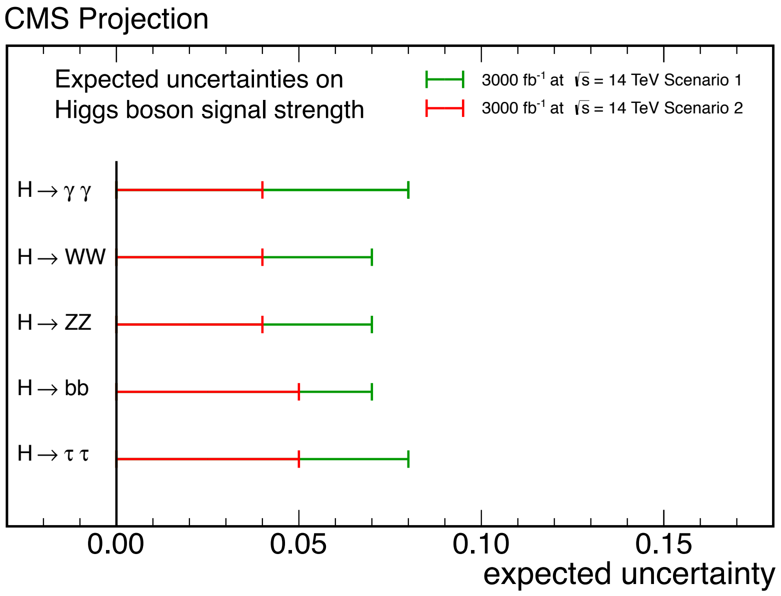
$$\frac{1}{2}(\partial_\mu\phi_s)(\partial^\mu\phi_s) \approx \frac{2a_{hs}^2}{m_s^4}(\Phi^\dagger\partial_\mu\Phi + \text{h.c.})^2\left[1 + O(\lambda_{hs}\Phi^\dagger\Phi/m_s^2)\right]$$

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 $\delta Z_h \lesssim 0.14$

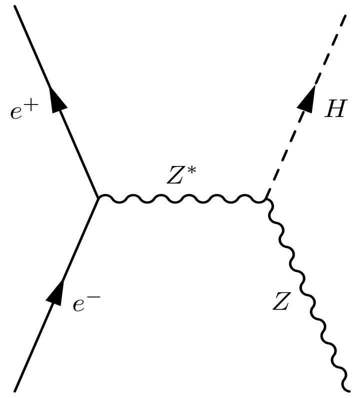
HL-LHC expects to measure the Higgs couplings to percent level. *O*(2-10%)



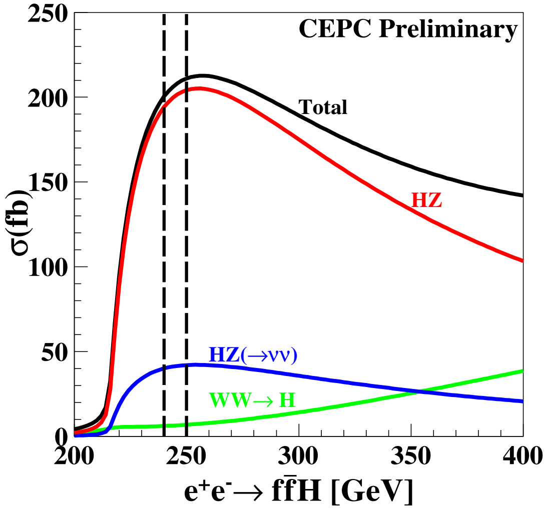
CMS, arXiv:1307.7135

Probe the hZZ Coupling at CEPC/ILC/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 CEPC/ILC!



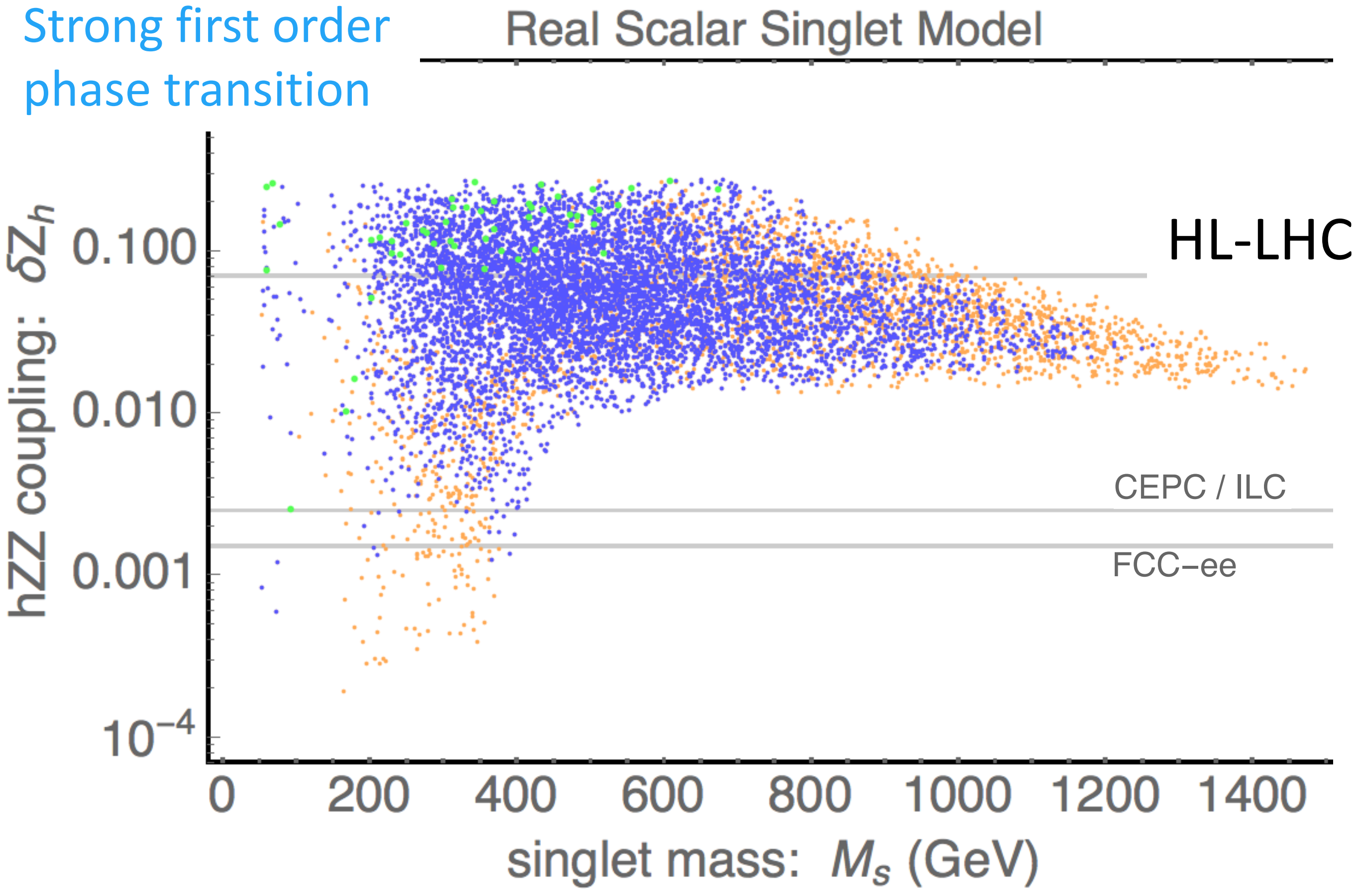
5 ab $^{-1}$ CEPC pre-CDR

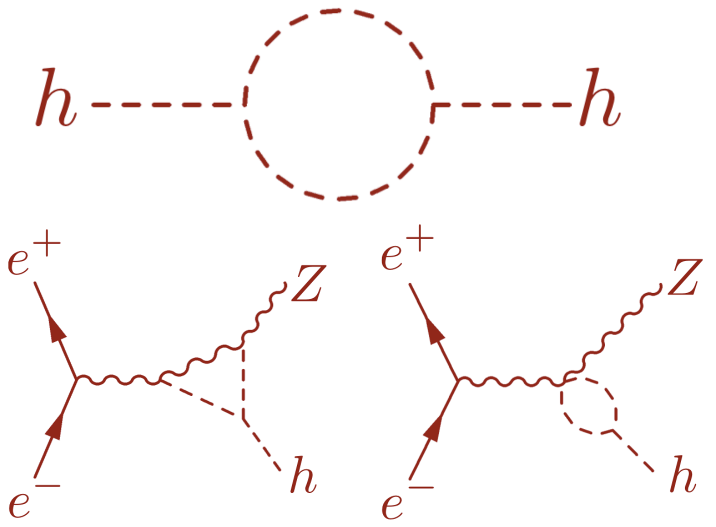
Probe the hZZ Coupling at Lepton Colliders

1st order phase transition

Strong first order phase transition

Preliminary





Current constraints: Higgs signal strength

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

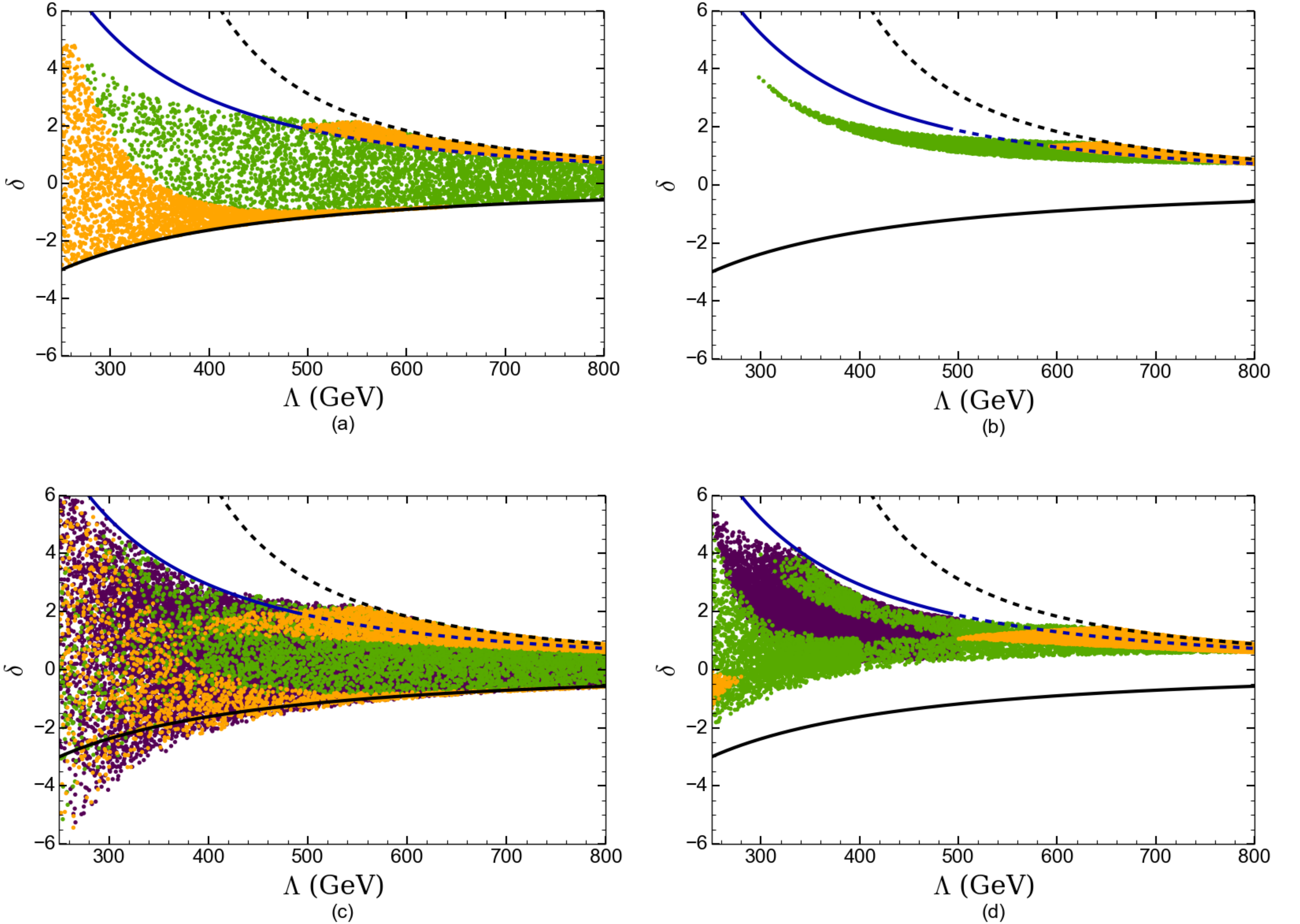
Next generation lepton colliders can basically cover the whole region

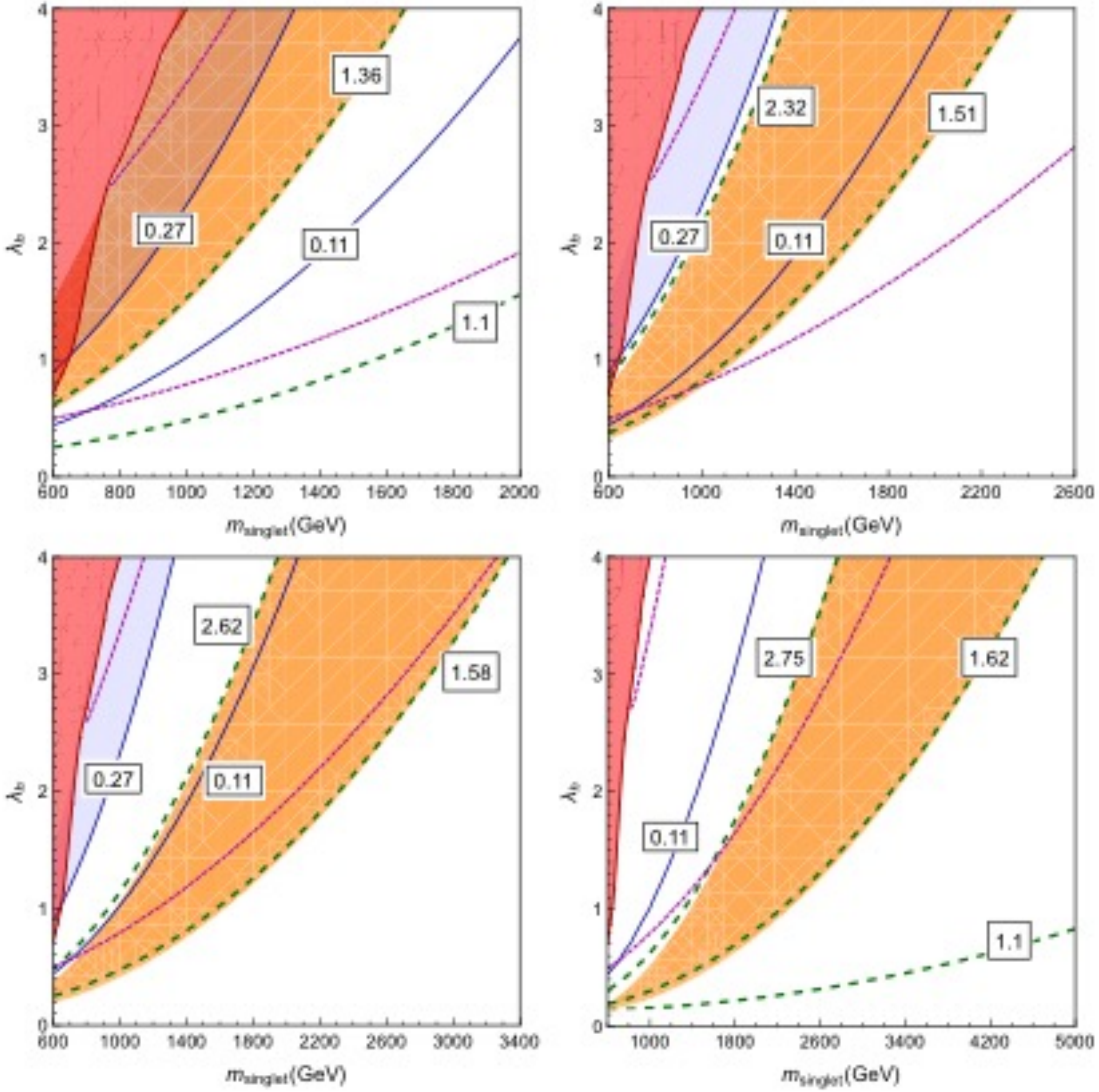
PH, A. Long, L.T. Wang, 1608:tbd

Conclusion

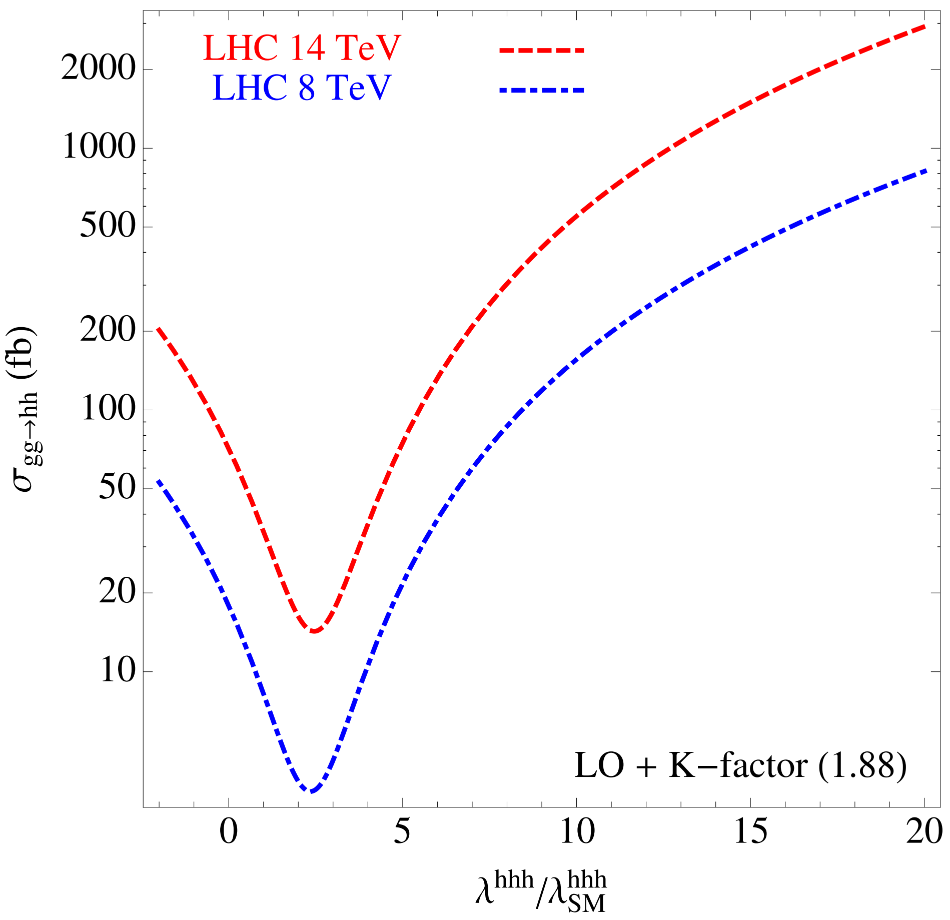
- In models exhibit a strong first order phase transition, modifications in the Higgs trilinear coupling and the hZZ coupling are expected
- It is very challenging to probe the trilinear coupling at the LHC
- hZZ coupling can be measured very well at lepton colliders, CEPC is almost able to cover the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

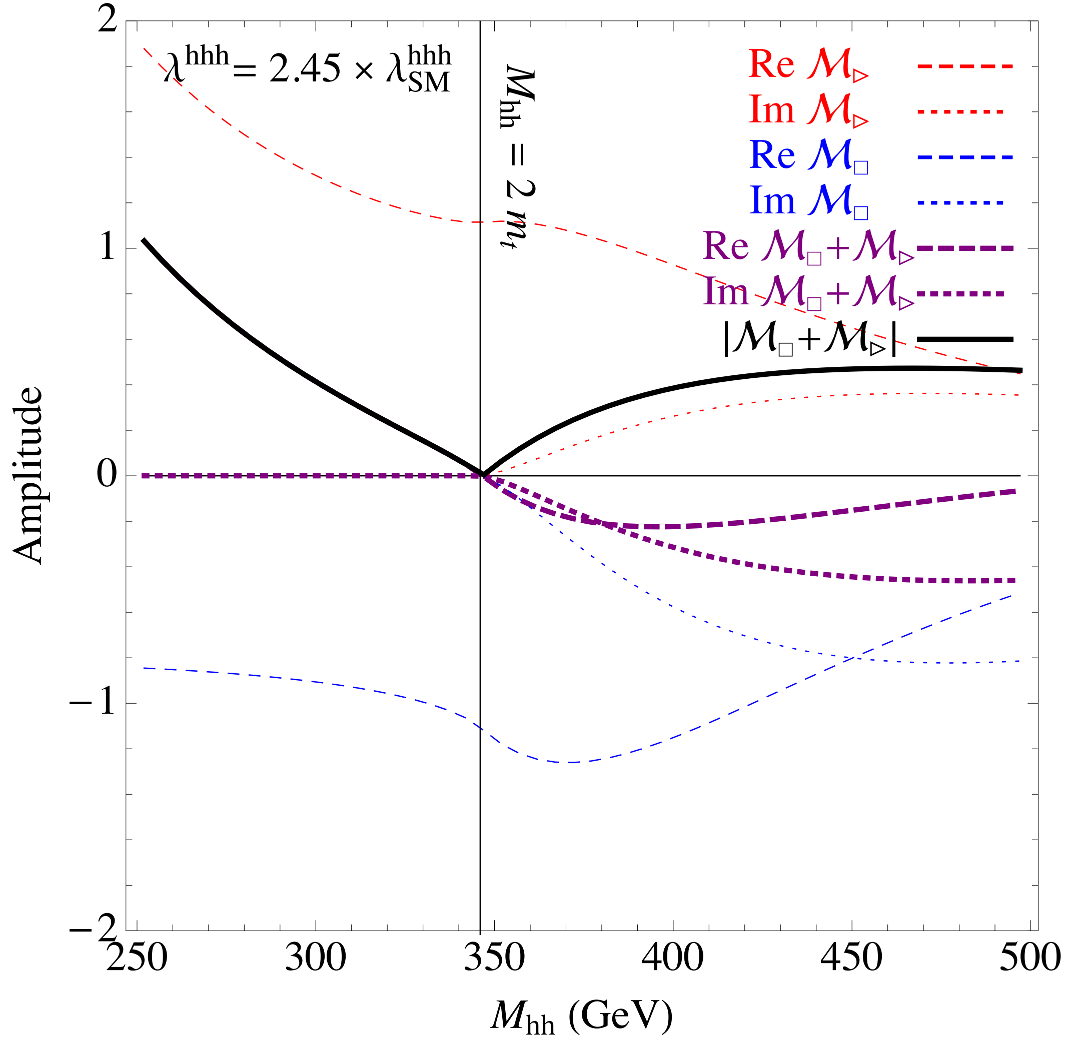
Backup Slides


δ
Λ (GeV)
(a)
(b)
(c)
(d)

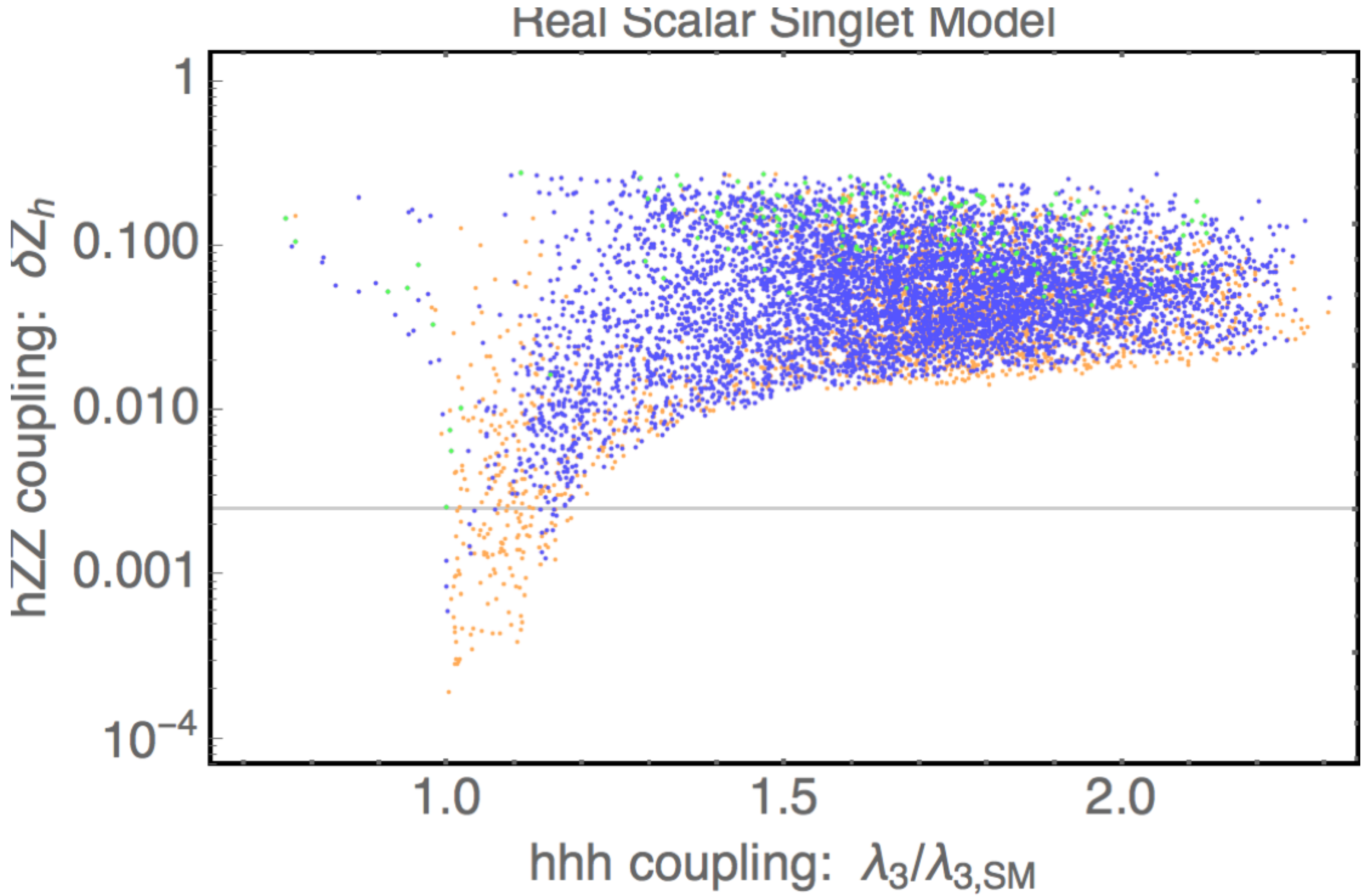


1.36
0.27
0.11
1.1
2.32
0.27
0.11
1.51
2.62
0.27
0.11
1.58
2.75
0.11
1.62
1.1
λ_b
$m_{singlet}$(GeV)

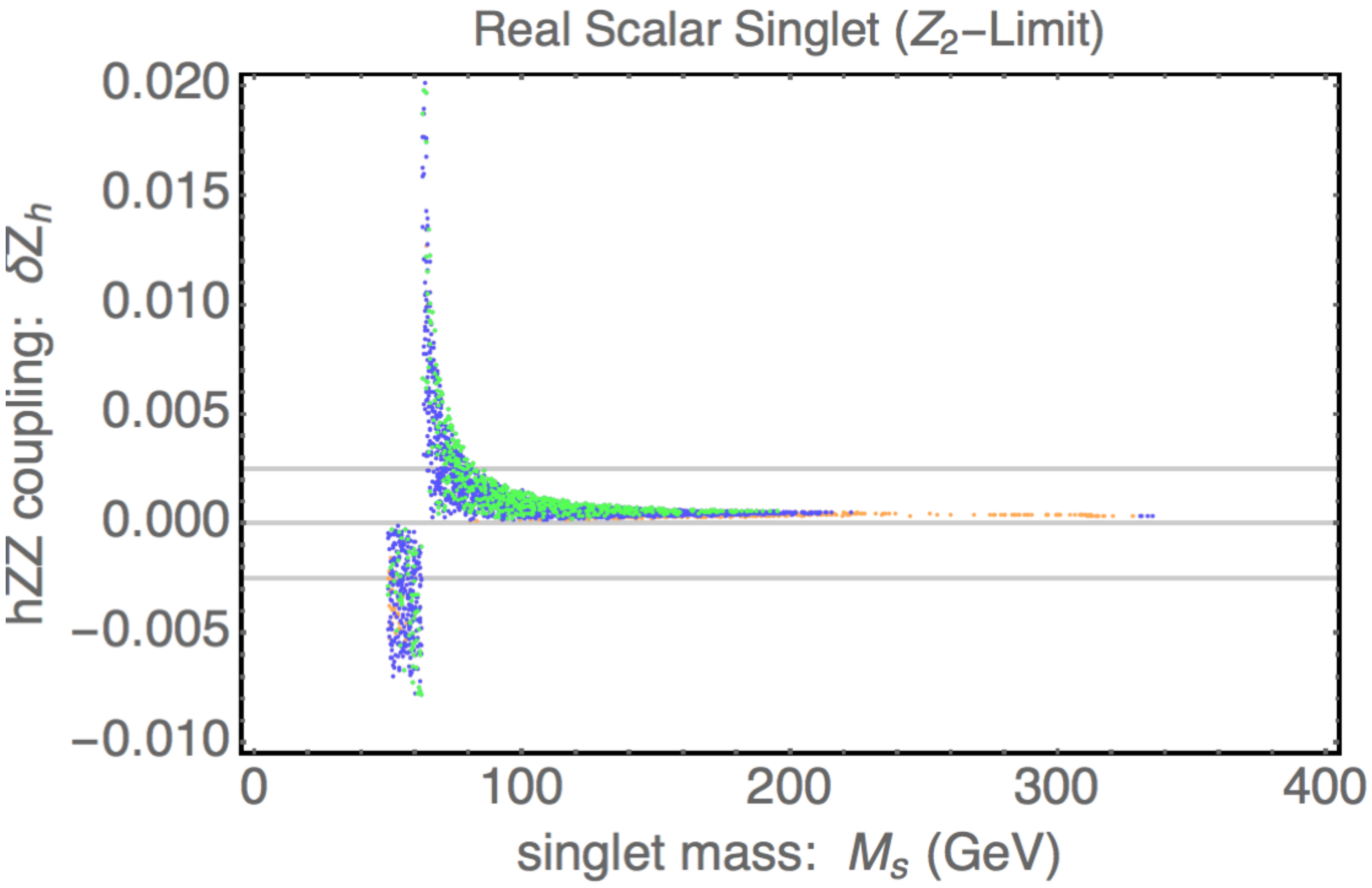




Barger, Everett, Jackson, and Shaughnessy



Real Scalar Singlet Model
hZZ coupling: δZ_h
1
0.100
0.010
0.001
10^{-4}
1.0
1.5
2.0
hhh coupling: $\lambda_3/\lambda_{3,\mathrm{SM}}$


Real Scalar Singlet (Z_2–Limit)
0.020
0.015
0.010
0.005
0.000
−0.005
−0.010
hZZ coupling: δZ_h
0
100
200
300
400
singlet mass: M_s (GeV)

How do interferometers probe the EWPT?

A first order phase transition is a mess!

➔ "Bubbles" of Higgs phase nucleate
➔ They expand … pushing their way through the plasma
➔ Eventually, the bubbles collide

Gravitational waves arise from bubble collisions, as well as turbulence and sound waves in the plasma.

$$f_{\rm gw} \simeq (0.3\,{\rm mHz}) \left(\frac{d_H(a_{\rm PT})}{\lambda_{\rm gw}(a_{\rm PT})} \right) \left(\frac{T_{\rm PT}}{100\,{\rm GeV}} \right) \left(\frac{g_{*,{\rm PT}}}{106.75} \right)^{1/6}$$

GW frequency controlled by size of horizon at time of PT
➔ fairly model-independent

$$\Omega_{\rm gw} h^2 \simeq (1.6 \times 10^{-5}) \left(\frac{g_{*,{\rm PT}}}{106.75} \right)^{-1/3} \Omega_{\rm gw}(a_{\rm PT})$$

GW energy depends on latent heat & efficiency of energy transfer to plasma
➔ very model-dependent