Testing electroweak phase transition at muon colliders

Wei Liu

Nanjing University of Science and Technology

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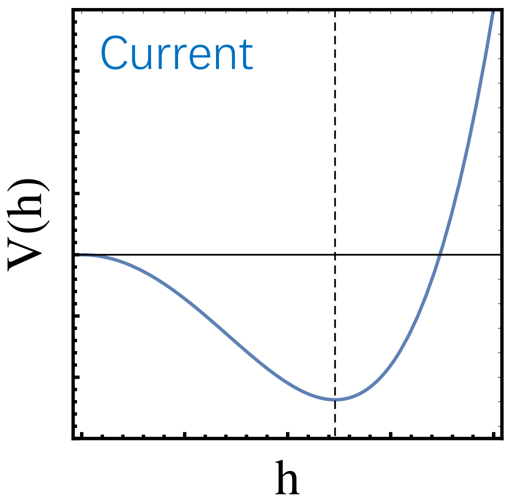
Work in collaboration with Ke-pan Xie

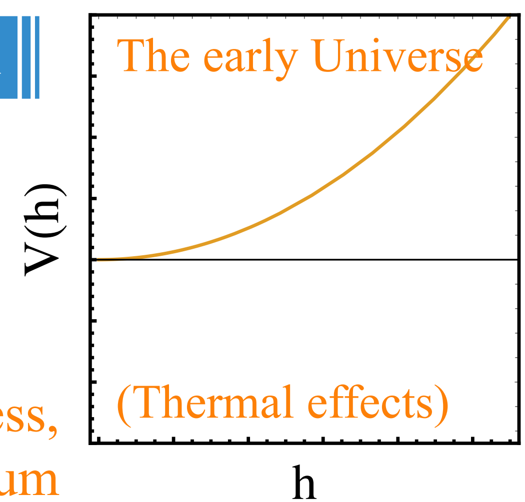
Phase transition in electroweak theory

EW symmetry restoration in the early Universe



W & Z bosons are massive;
Photon is massless,
Mexican-hat like

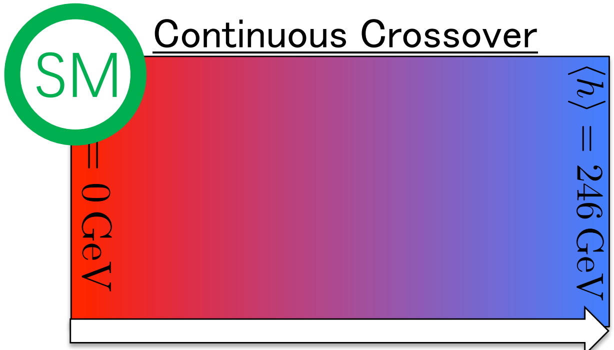
Phase transition



$SU(2)_L$ & $U(1)_Y$ bosons are massless,
True vacuum

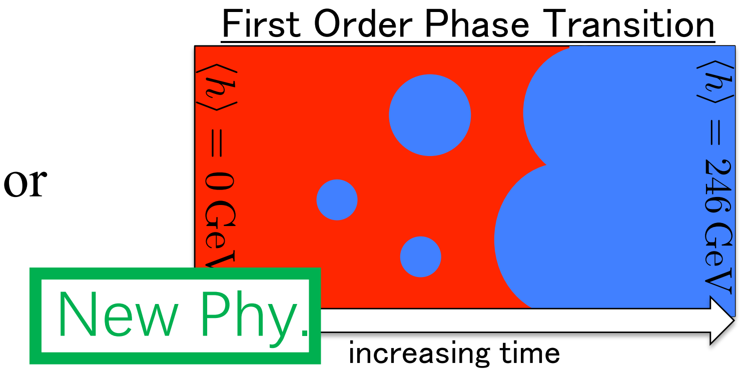
What is the pattern of EW phase transition (PT)?

It could be –

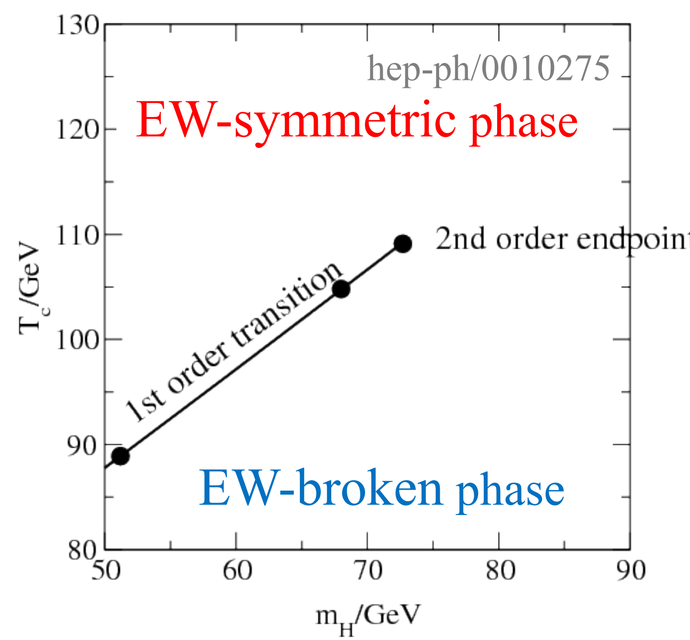


or

Figure from L.-T. Wang's talk in IHEP workshop



Lattice calculation shows the phase diagram ==>



Thus in the SM it is a crossover, since M_h = 125 GeV > 75 GeV;

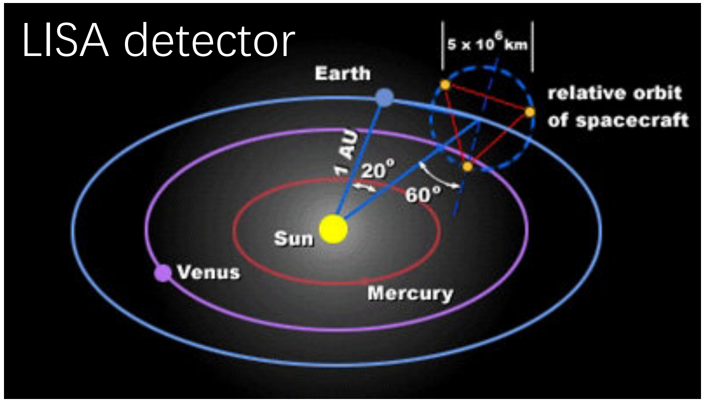
However, a 1st-order EWPT is more interesting.
(Needs new physics)

Why is a 1^{st}-order EWPT interesting?

- It's the essential ingredient of the EW baryogenesis.
- Acting as the background of very rich **dark matter** mechanisms
- Sources of the stochastic GWs:

- Collision of the bubbles
- Sound waves in plasma
- Turbulance in plasma

EWPT GWs typically peak in mHz.



EWPT in the xSM (SM + real singlet)

We choose the **xSM** as the benchmark model.
It's simple, but has captured the most important feature of EWPT.

The scalar potential of the xSM

$$V = -\mu^2|H|^2 + \lambda|H|^4 + \frac{a_1}{2}|H|^2 S + \frac{a_2}{2}|H|^2 S^2 + b_1 S + \frac{b_2}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4$$

8 input parameters:
1 unphysical, 2 fixed by Higgs mass & VEV; 5 *free* parameters.

Expansion around the VEV

$$H = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+h \end{pmatrix}, \quad S = v_s + s, \quad \begin{pmatrix} h \\ s \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}\begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$$

Higgs-like, 125 GeV (h_1)

Singlet-like, $\mathcal{O}$(TeV) (h_2)

Mass eigenstates & the mixing angle.

Can we probe it at colliders?

Muon collider!

Precision and Energy Frontier!

A high-energy muon collider is able to execute both the

- **direct search**
- **indirect search**

strategies for EWPT in xSM!

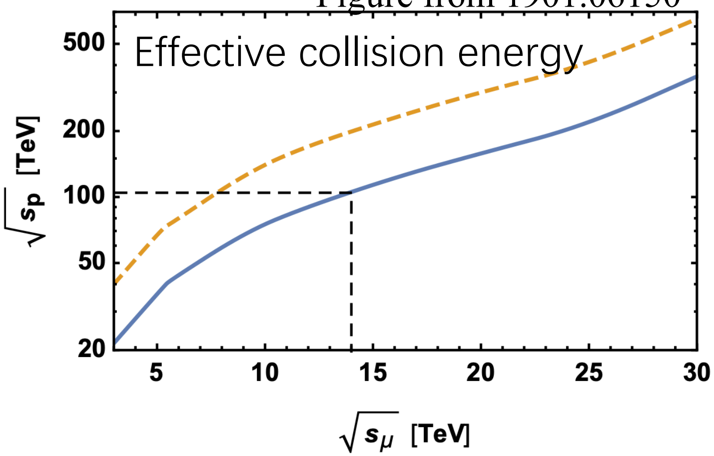
Compared to the e^+e^- machine:

- Synchrotron radiation is suppressed by 10^9 since $M_\mu >> M_e$, hence the collision energy can reach O(10) TeV;
- Also very clean, as long as the beam-induced-background is controllable (main challenge).

Compared to the *pp* machine:

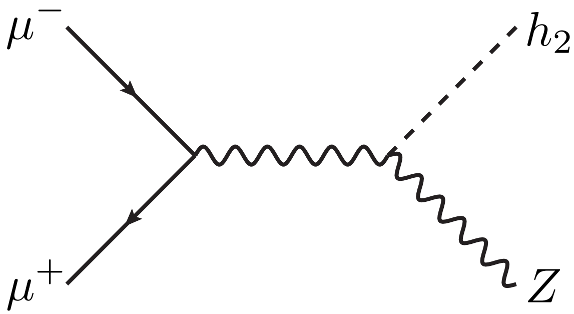
- The entire collision energy can be used to probe hard process;
- Much cleaner due to the small QCD background.

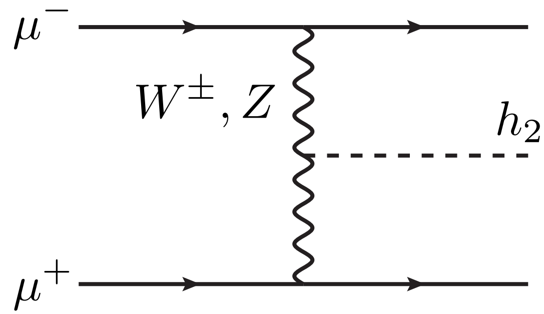
Figure from 1901.06150



Muon collider: direct search

Producing the h_2 at a muon collider

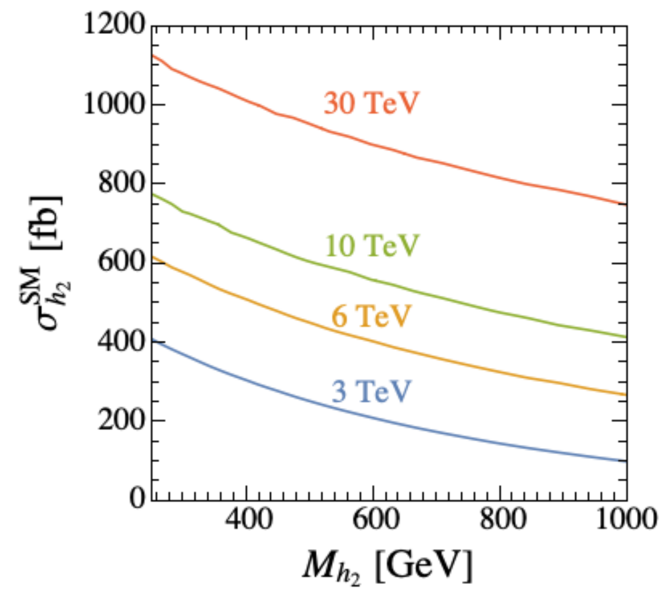




Zh_2 associated production & Vector Boson Fusion (VBF).

At a multi-TeV collider, the dominant channel is VBF, in which W^+W^- fusion dominates (90%);

$\sigma^{SM}(h_2)$: rate obtained by assuming a Higgs-like coupling for the h_2.



Muon collider: direct search

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Decay of h_2 to SM particles (X = vector boson or fermion)

$$\Gamma(h_2 \to XX) = \sin^2\theta \times \Gamma^{\rm SM}(h_2 \to XX),$$
$$\Gamma(h_2 \to h_1 h_1) \propto \lambda^2_{h_2 h_1 h_1}$$

Dominant channels: di-boson (W^+W^-, ZZ), tt, and h_1h_1.

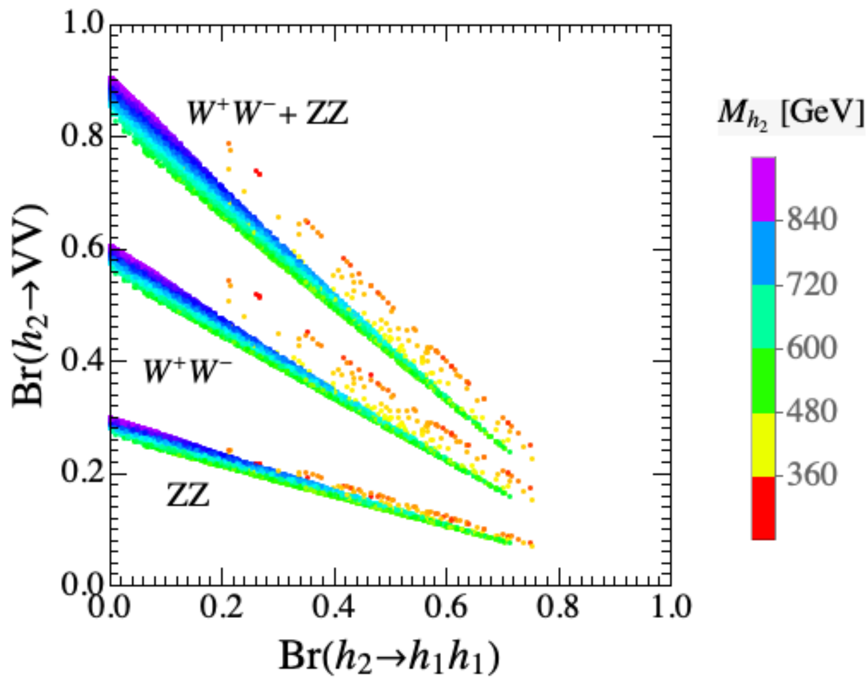
The h_1h_1 channel can reach a branching ratio of 80%;

For heavy h_2, the VV channel dominates;

We choose

- h_2 -> ZZ -> $l^+l^-l^+l^-$
- h_2 -> h_1h_1 -> $bbbb$

for a detailed simulation.



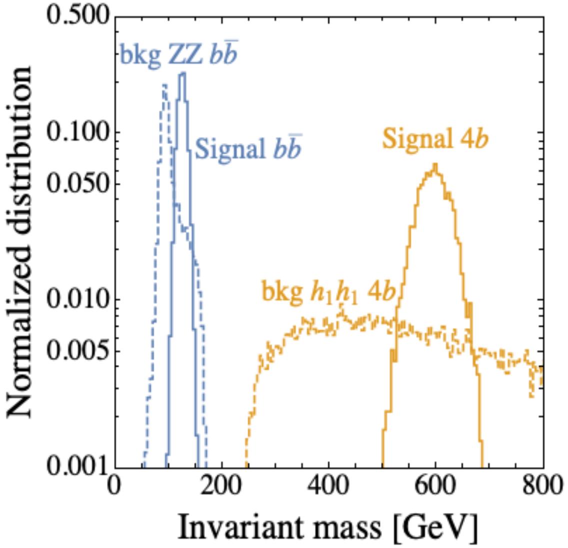
Muon collider: direct search

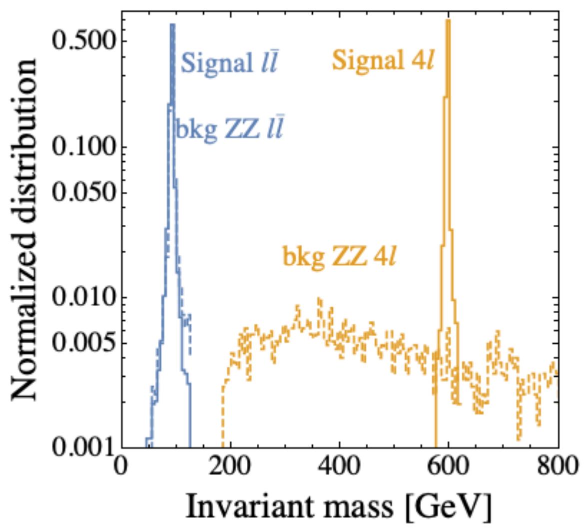
The h_2 -> $h_1 h_1$ -> *bbbb* channel:
Main background:

- Vector Boson Scattering *ZZ* -> *bbbb*
- $h_1 h_1$ -> *bbbb*.

The h_2 -> *ZZ* -> $l^+l^-l^+l^-$ channel:
Main background:

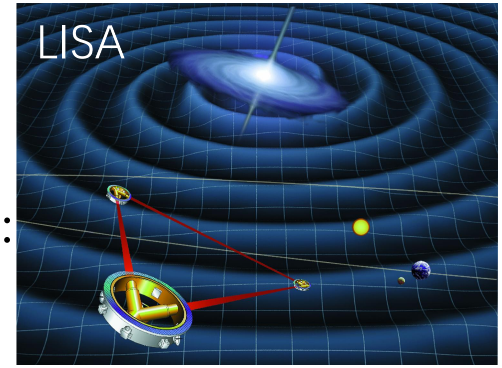
- Vector Boson Scattering *ZZ* -> $l^+l^-l^+l^-$.





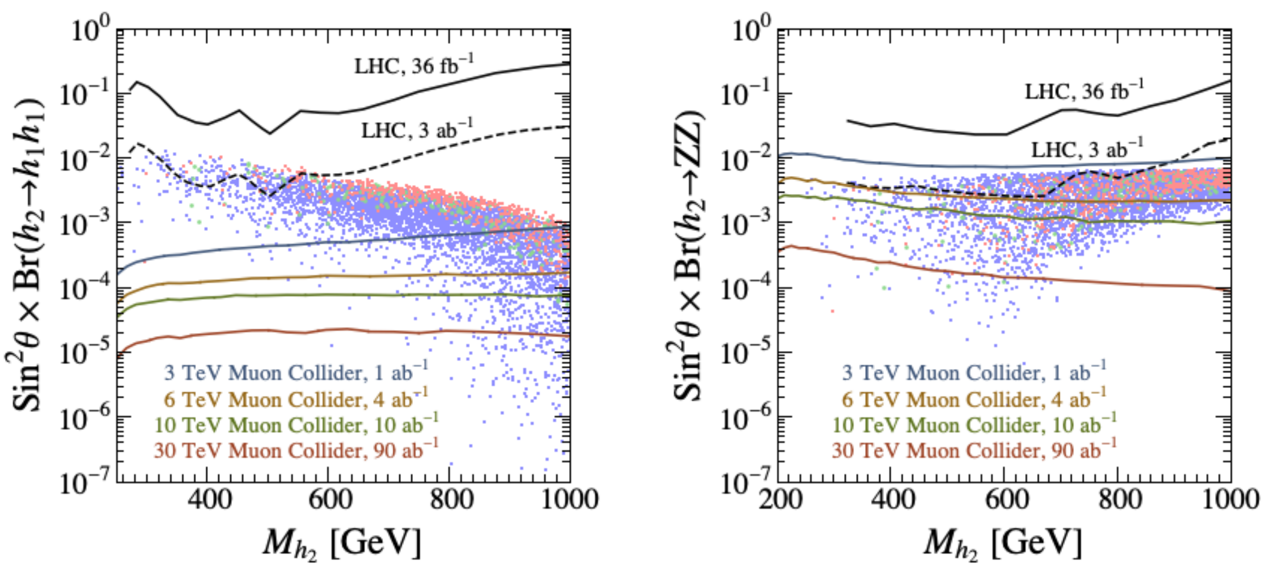
Muon collider: direct search

The collider search and gravitational wave detection are complementary!



For the LISA detector, signal-to-noise ratio (SNR):

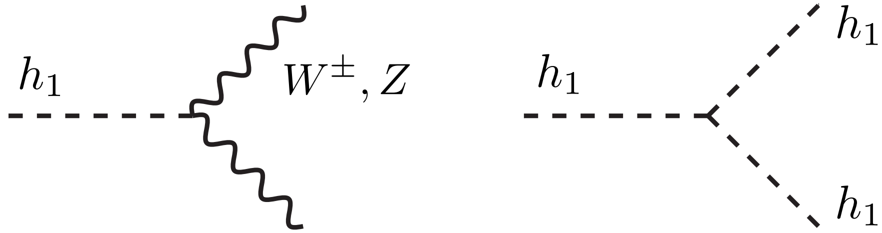
$$\mathrm{SNR} = \sqrt{\mathcal{T} \int_{f_{\min}}^{f_{\max}} df \left(\frac{\Omega_{\mathrm{GW}}(f)}{\Omega_{\mathrm{LISA}}(f)} \right)^2}$$



The diHiggs & diboson channels are complementary as well

Muon collider: indirect search

The gauge boson coupling & triple Higgs coupling. Making use of the results in [Han, Liu, Low and Wang, 2008.12204].

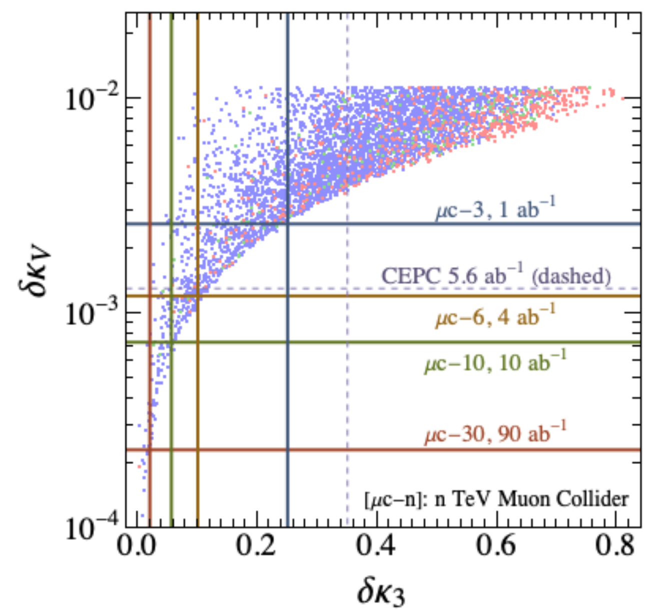


Defining deviations

$$\delta\kappa_V = \left| \frac{g_{h_1 VV}}{g^{\rm SM}_{h_1 VV}} - 1 \right|,$$

$$\delta\kappa_3 = \frac{\lambda_{h_1 h_1 h_1}}{\lambda^{\rm SM}_{h_1 h_1 h_1}} - 1$$

We can obtain the projections.



Conclusion

1st-order EW phase transition is interesting:

- Theoretically, it is the essential ingredient of EW baryogenesis, and can trigger very rich dark matter mechanisms;
- Experimentally, it yields detectable gravitational waves.

We propose strategies to probe 1st-order EWPT at a high-energy muon collider:

- Direct detection: the resonant production of the new scalar;
- Indirect detection: the deviation of Higgs couplings.

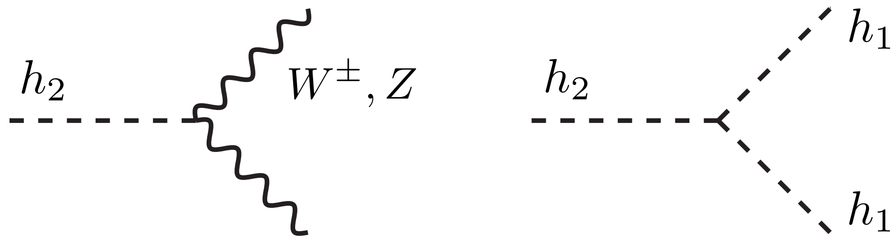
Collider search is complementary to the gravitational waves detection!

Probing EWPT of the xSM at colliders

Feature of the xSM

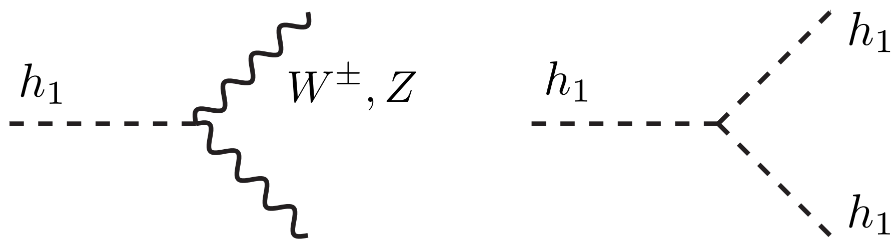
Two neutral scalars: h_1 (Higgs-like) and h_2 (singlet-like, TeV), with mixing angle θ;

$$g_{h_2VV} = g_{hVV}^{\rm SM} \sin\theta$$
$$g_{h_2f\bar{f}} = g_{hf\bar{f}}^{\rm SM} \sin\theta$$
$$\lambda_{h_2h_1h_1} \propto \sin\theta$$



Direct searches at the *pp* colliders

$$g_{h_1VV} = g_{hVV}^{\rm SM} \cos\theta$$
$$g_{h_1f\bar{f}} = g_{hf\bar{f}}^{\rm SM} \cos\theta$$
$$\lambda_{h_1h_1h_1} = \lambda_{hhh}^{\rm SM} f(\theta)$$



Indirect searches at the e^+e^- colliders

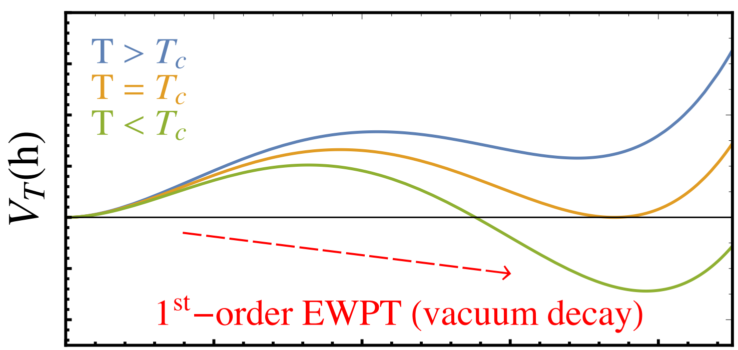
1^{st}-order EWPT in the xSM

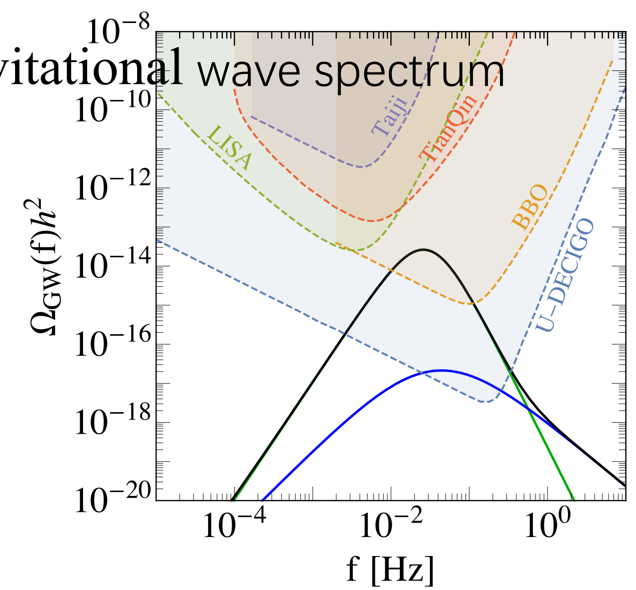
At finite temperature:

$$V = -\left(\mu^2 - c_H T^2\right)|H|^2 + \lambda |H|^4 + \frac{a_1}{2}|H|^2 S + \frac{a_2}{2}|H|^2 S^2$$
$$+\left(b_1 + m_1 T^2\right) S + \frac{b_2 + c_S T^2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4$$

$$c_H = \frac{3g^2 + g'^2}{16} + \frac{y_t^2}{4} + \frac{\lambda}{2} + \frac{a_2}{24}, \quad c_S = \frac{a_2}{6} + \frac{b_4}{4}, \quad m_1 = \frac{a_1 + b_3}{12}$$

An Illustration --



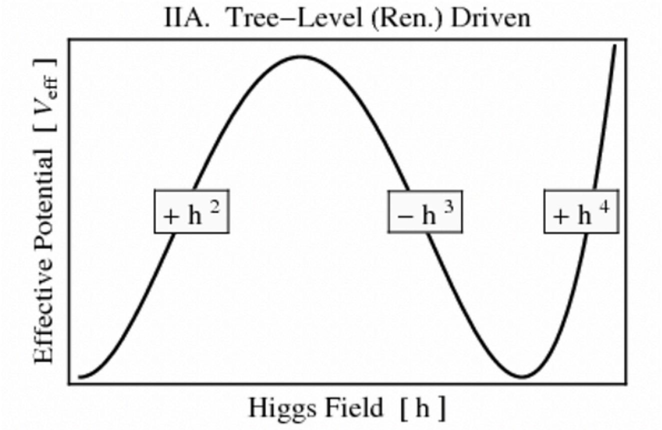


Question:

Can collider experiments probe the 1^{st}-order EWPT parameter space?

How to achieve a 1st-order EWPT?

Adding a barrier for the Higgs potential via new physics!
The decay between two vacua separated by a barrier.
The VEV of the Higgs field *jumps*.



Getting a barrier via the help of additional scalar field(s):

- SM + real singlet (xSM);
- 2HDM;
- Georgi-Machacek model;
- ……

We choose the **xSM** as the benchmark model.

- It's simple, but has captured the most important feature of EWPT;
- It can be treated as the prototype of many new physics EWPT models.

Back Up

The h_2 -> h_1h_1 -> *bbbb* channel:

Main background:

✓ Vector Boson Scattering ZZ -> *bbbb* and h_1h_1 -> *bbbb*.

Kinematic Cuts:

Cut I: pjT > 30 GeV, |ηj| < 2.43, Mrecoil > 200 GeV, (Cut I)

Cut II: minimizing $\chi_j^2 = (M_{j_1j_2} - M_h)^2 + (M_{j_3j_4} - M_h)^2$

$|M_{j_1j_2} - M_h| < 15\ GeV, |M_{j_3j_4} - M_h| < 15\ GeV$

Cut III: $|M_{4j} - M_{h_2}| < 30\ GeV,$

$\Delta E/E = 10\%, \varepsilon_{b-tag} = 70\%$