南京理工大学
NANJING UNIVERSITY OF SCIENCE & TECHNOLOGY

Testing electroweak phase transition at muon colliders

Wei Liu (刘威)
Nanjing University of Science and Technology

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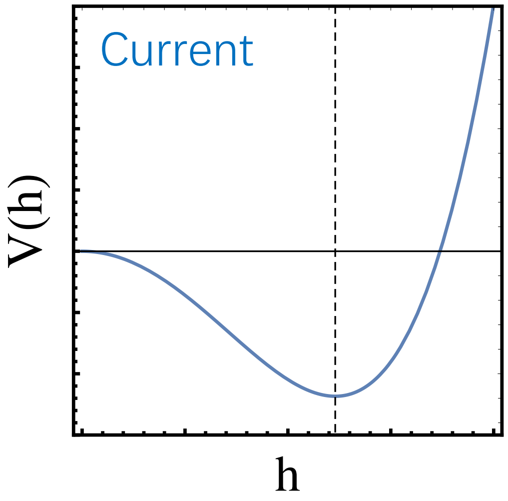
Work in collaboration with Ke-pan Xie

SUSY2021

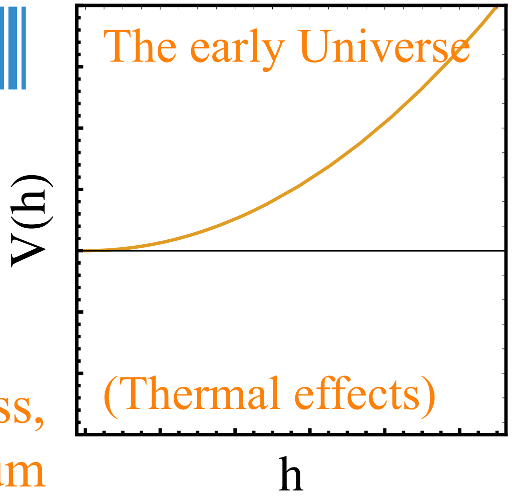
Phase transition in electroweak theory

EW symmetry restoration in the early Universe



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

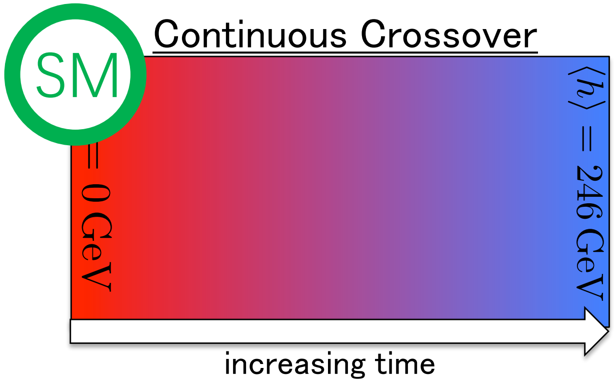
Phase transition



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

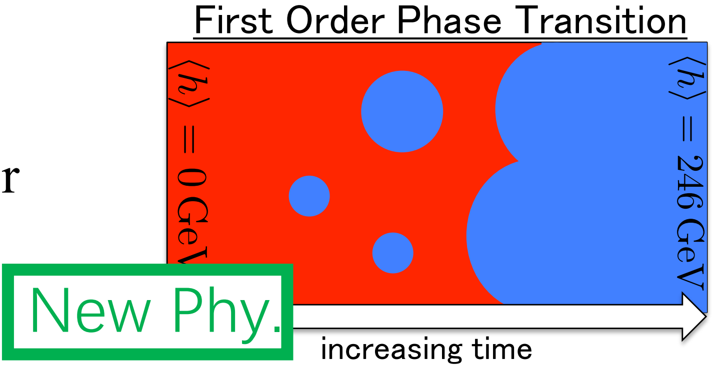
What is the pattern of EW phase transition (PT)?

It could be –



or

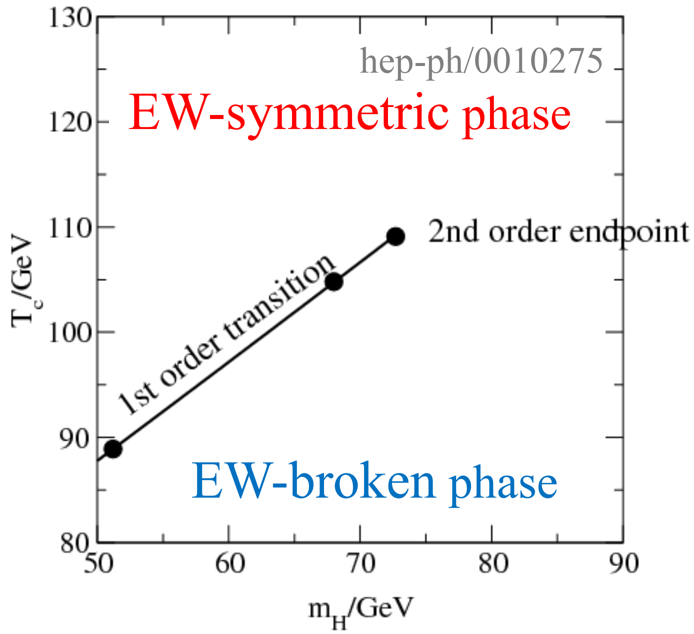
Figure from L.-T. Wang's talk in IHEP workshop



Lattice calculation shows the phase diagram ==>

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

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

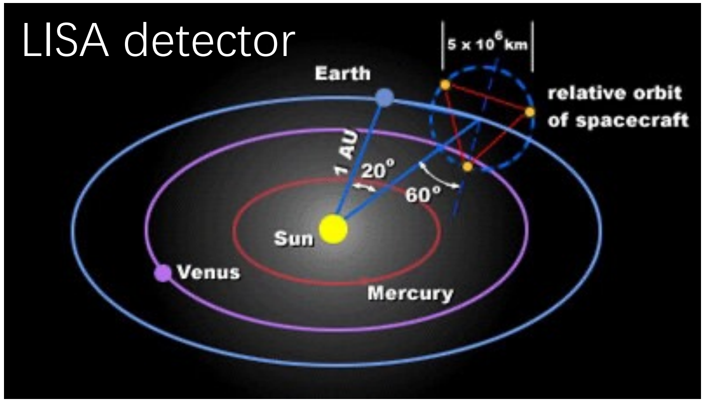


Why is a 1st-order EWPT interesting?

- 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.

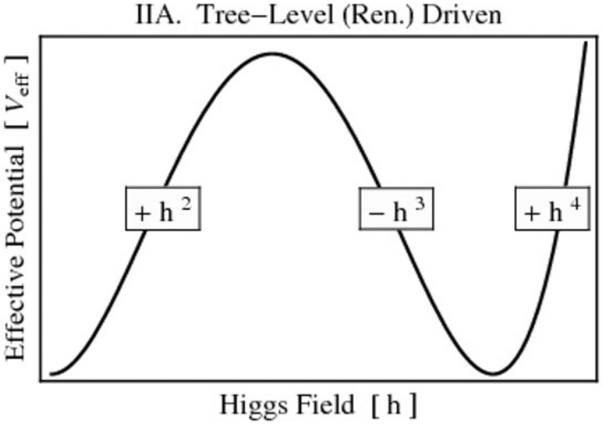

LISA detector

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.

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

Higgs-like, 125 GeV

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

Mass eigenstates & the mixing angle.

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

Can we probe it at colliders?

1st-order EWPT in the xSM

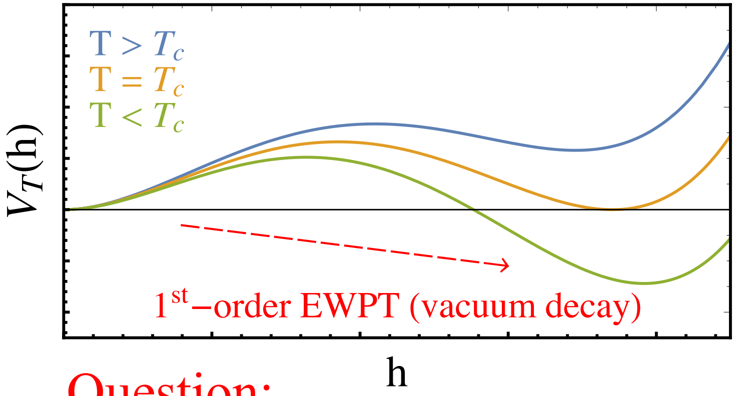
At finite temperature:

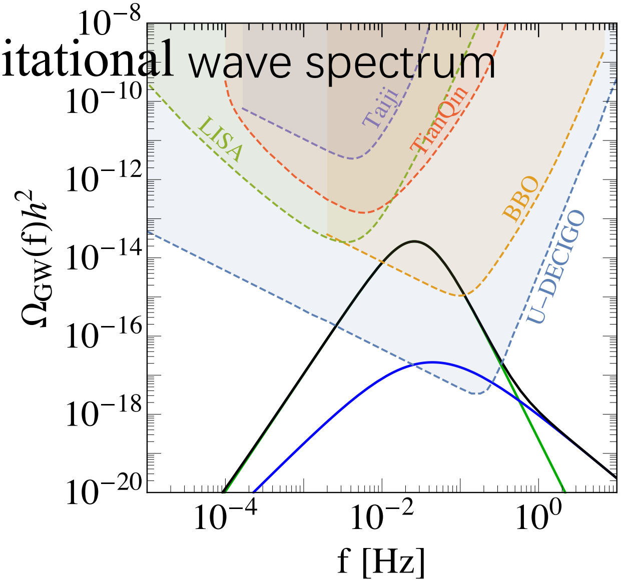
$$V = -\left(\mu^2 - c_H T^2\right)|H|^2 + \lambda |H|^4 + \frac{a_1}{2}|H|^2 S + \frac{a_2}{2}|H|^2 S^2$$

$$+ \left(b_1 + m_1 T^2\right) S + \frac{b_2 + c_S T^2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4$$

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

An Illustration --




Gravitational wave spectrum

Question:

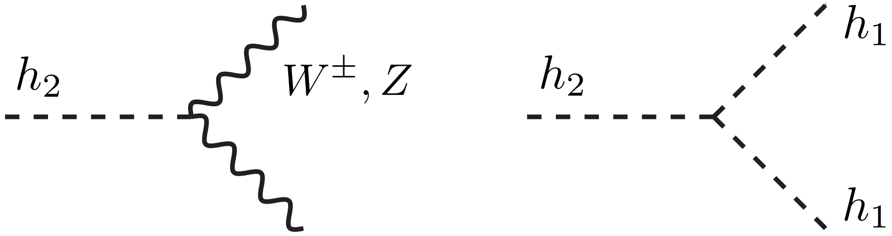
Can collider experiments probe the 1st-order EWPT parameter space?

Probing EWPT of the xSM at colliders

Feature of the xSM

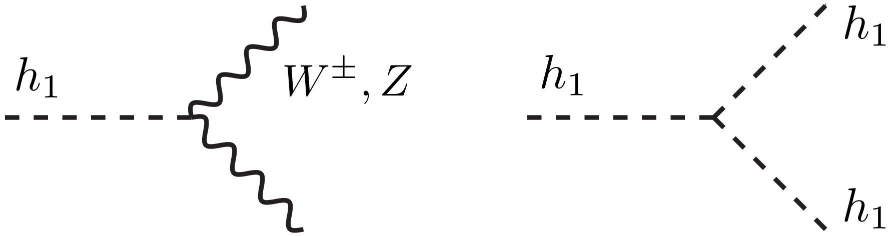
Two neutral scalars: h_1 (Higgs-like) and h_2 (singlet-like, TeV), with mixing angle θ;

$$\boxed{\begin{aligned} g_{h_2VV} &= g_{hVV}^{\mathrm{SM}} \sin\theta \\ g_{h_2f\bar{f}} &= g_{hf\bar{f}}^{\mathrm{SM}} \sin\theta \\ \lambda_{h_2h_1h_1} &\propto \sin\theta \end{aligned}}$$



Direct searches at the *pp* colliders

$$\boxed{\begin{aligned} g_{h_1VV} &= g_{hVV}^{\mathrm{SM}} \cos\theta \\ g_{h_1f\bar{f}} &= g_{hf\bar{f}}^{\mathrm{SM}} \cos\theta \\ \lambda_{h_1h_1h_1} &= \lambda_{hhh}^{\mathrm{SM}} f(\theta) \end{aligned}}$$



Indirect searches at the e^+e^- 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!

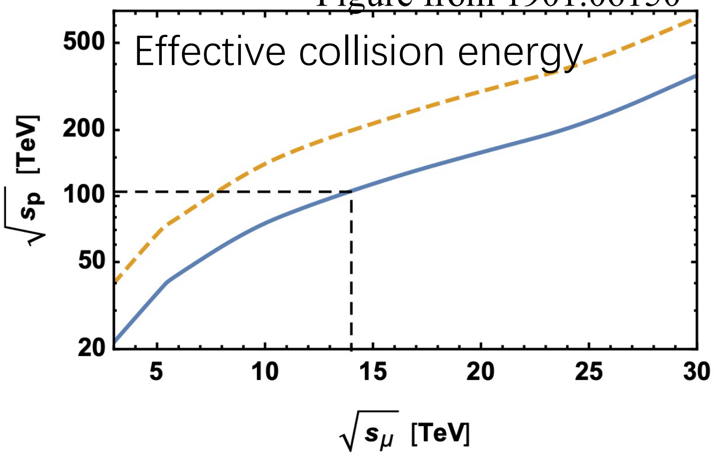
Compared to the e^+e^- machine:

- 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:

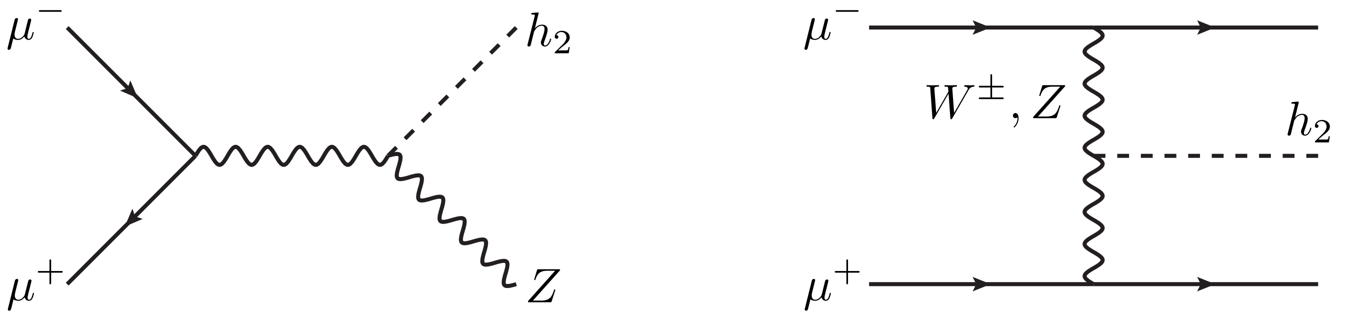
- The entire collision energy can be used to probe hard process;
- Much cleaner due to the small QCD background.

Figure from 1901.06150



Muon collider: direct search

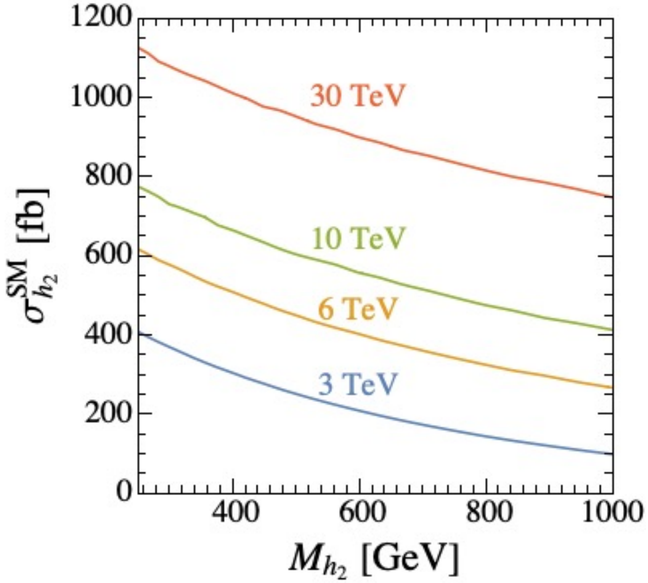
Producing the h_2 at a muon collider



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

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

$$\Gamma(h_2 \to XX) = \sin^2\theta \times \Gamma^{\text{SM}}(h_2 \to XX),$$

$$\Gamma(h_2 \to h_1 h_1) \propto \lambda^2_{h_2 h_1 h_1}$$

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

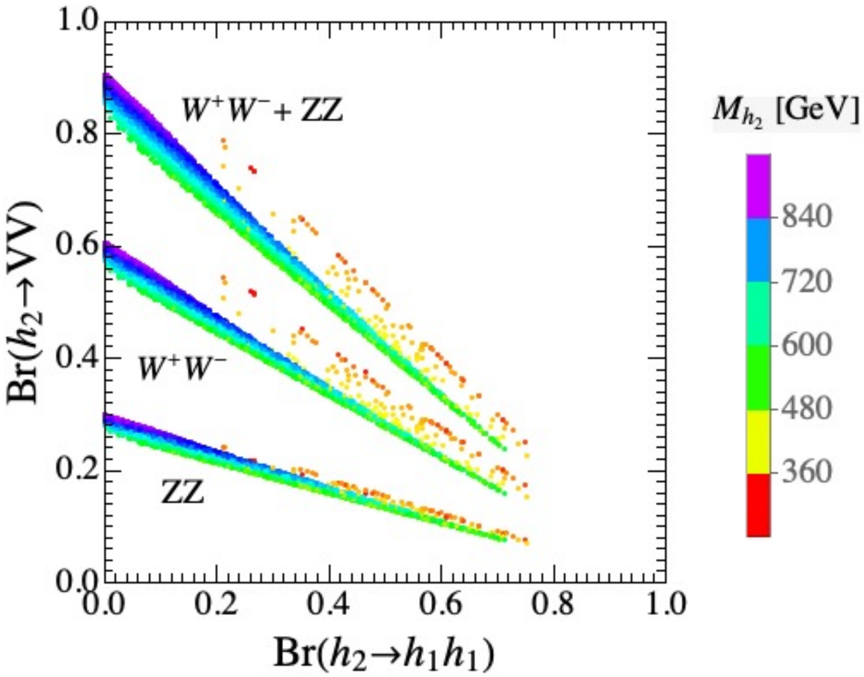
The h_1h_1 channel can reach a branching ratio of 80%;

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.

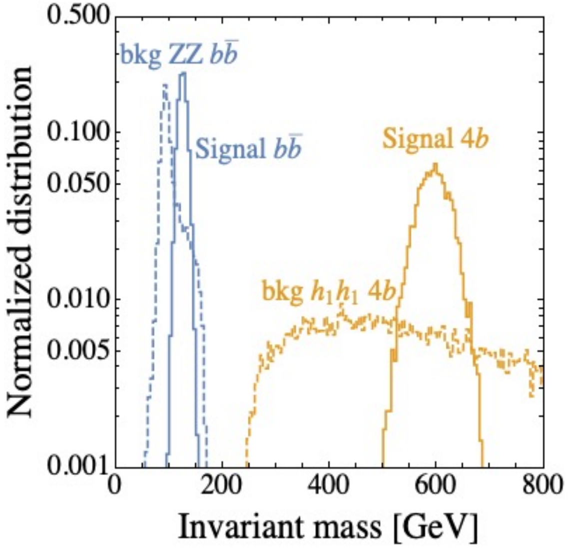


Muon collider: direct search

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

Main background:

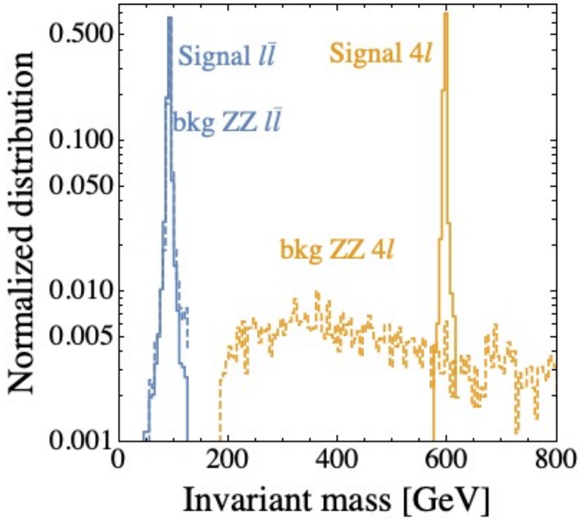
- Vector Boson Scattering *ZZ* -> *bbbb*
- $h_1 h_1$ -> *bbbb*.



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

Main background:

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



Muon collider: direct search

Main background:

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

Kinematic Cuts:

Cut I: $\boldsymbol{p_T}$ **> 30 GeV, |η| < 2.43,** $\boldsymbol{M_{recoil}}$ **> 200 GeV, (Cut I)**

Cut II: minimizing $\boldsymbol{\chi^2 = (M_{12}-M_h)^2 + (M_{34}-M_h)^2}$

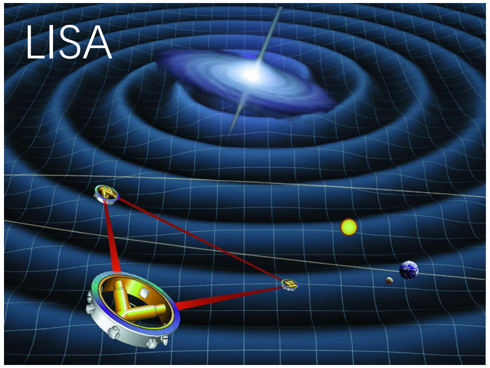
$\boldsymbol{|M_{12} - M_h| < 15(10)\ GeV, |M_{34} - M_h| < 15(10)\ GeV}$

Cut III: $\boldsymbol{|M_{1234} - M_{h_2}| < 30(20)\ GeV,}$

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

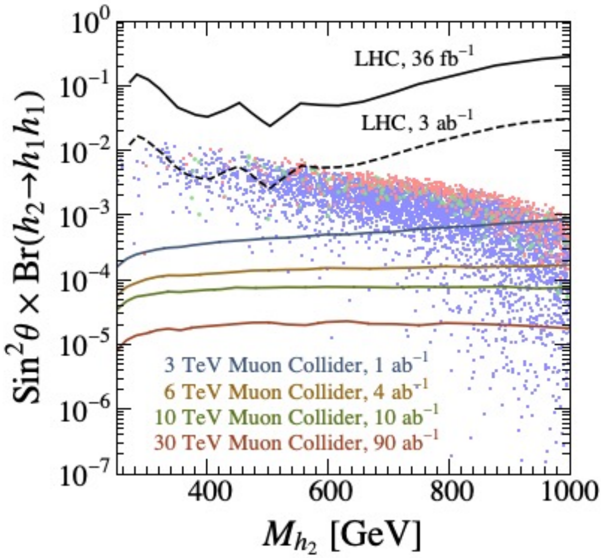
Muon collider: direct search

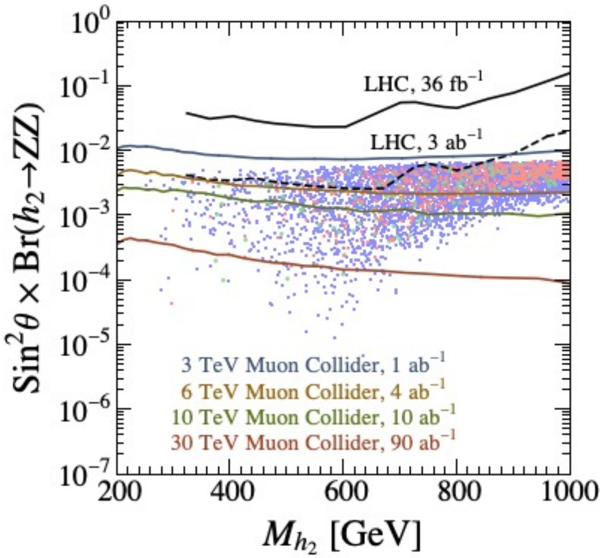
The collider search and gravitational wave detection are complementary!



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

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

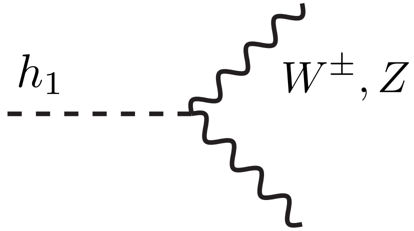


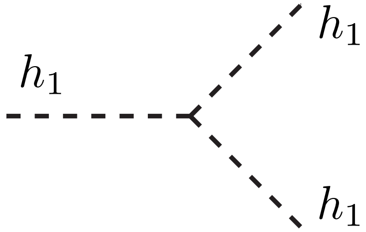


The diHiggs & diboson channels are complementary as well

Muon collider: indirect search

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



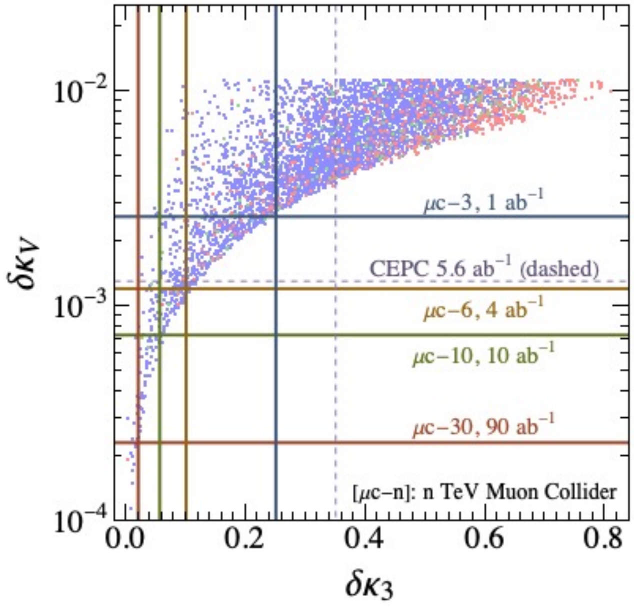


Defining deviations

$$\delta\kappa_V = \left| \frac{g_{h_1VV}}{g^{\rm SM}_{h_1VV}} - 1 \right| ,$$

$$\delta\kappa_3 = \frac{\lambda_{h_1h_1h_1}}{\lambda^{\rm SM}_{h_1h_1h_1}} - 1$$

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!