Center for Theoretical Physics
SEOUL NATIONAL UNIVERSITY

Testing electroweak phase transition at muon colliders

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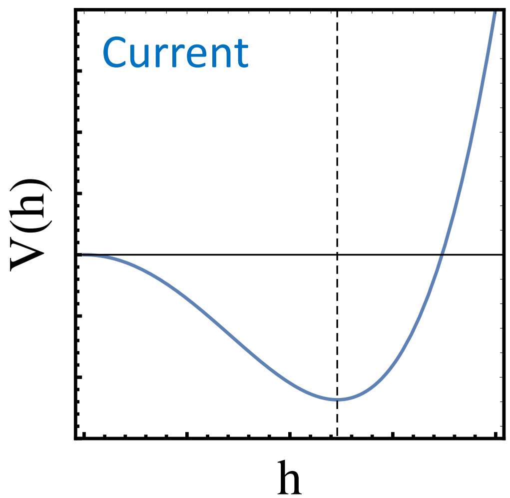
2021.1.14, HKUST-IAS Program on High Energy Physics (remotely)

Mainly based on work with Wei Liu, arXiv:2102.xxxxx

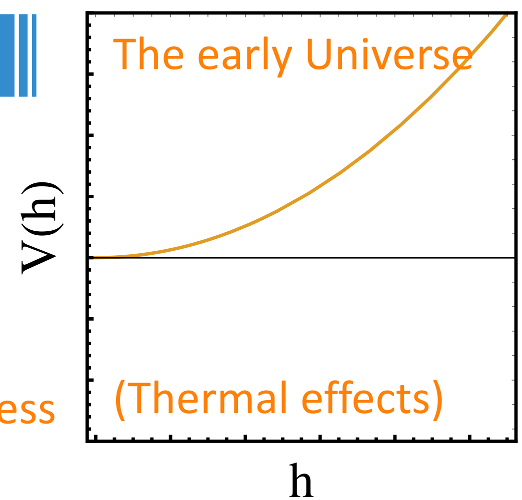
Phase transition in electroweak theory

- EW symmetry restoration in the early Universe



W & *Z* bosons are massive;
Photon is massless

Phase transition



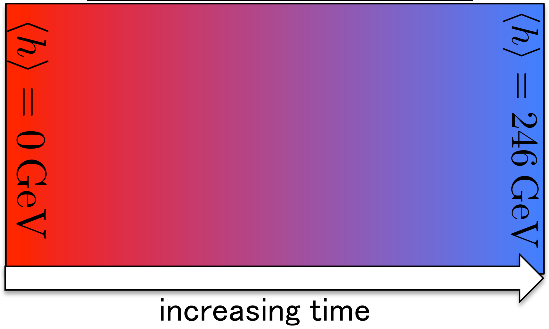
$SU(2)_L$ & $U(1)_Y$ bosons are massless

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

It could be –

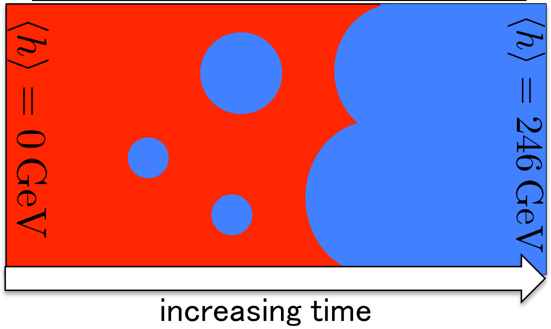
Figure from L.-T. Wang's talk in IHEP workshop

Continuous Crossover



or

First Order Phase Transition



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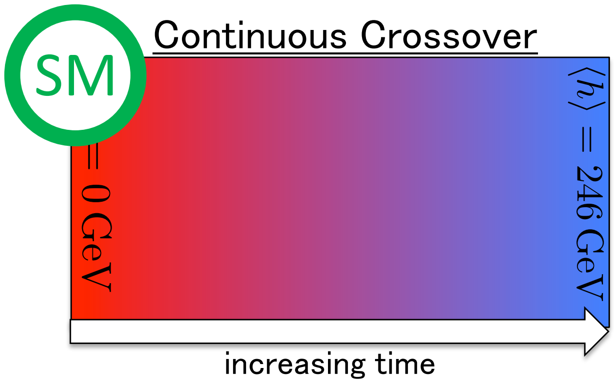
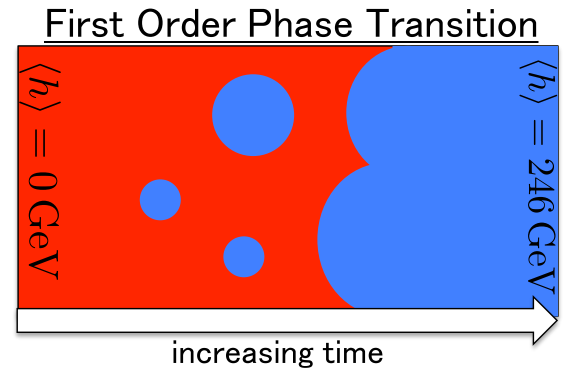
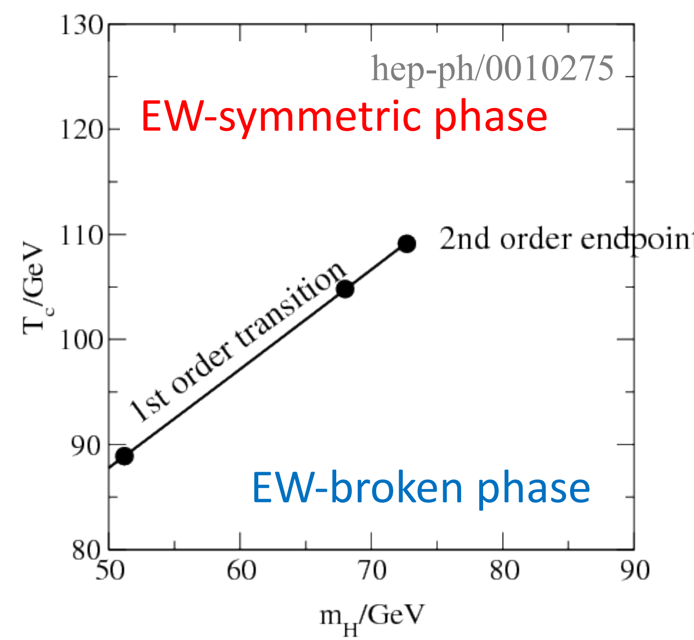


or



Lattice calculation shows the phase diagram ==>

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



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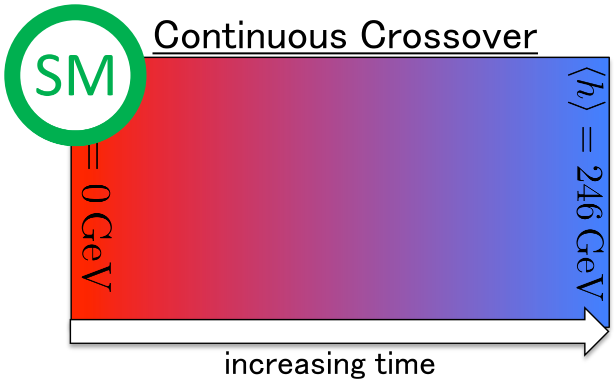

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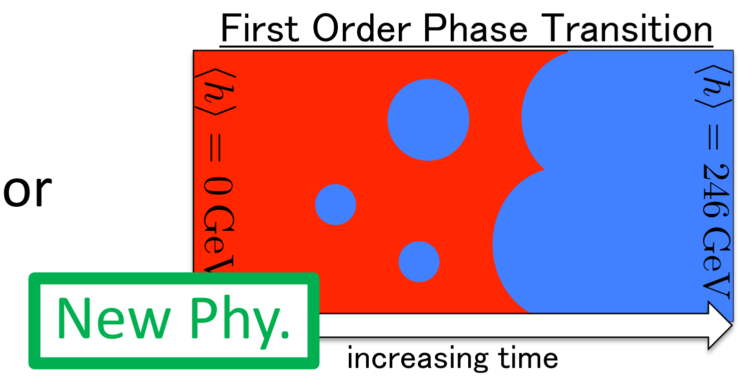
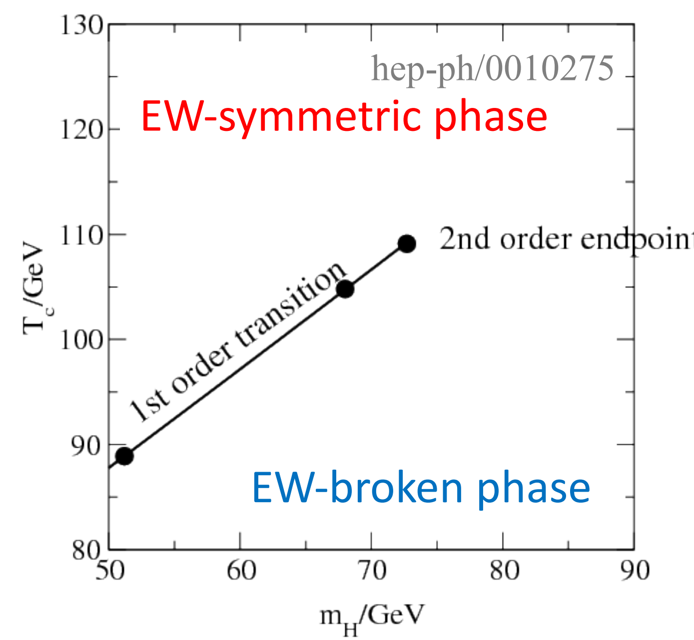
Figure from L.-T. Wang's talk in IHEP workshop



Lattice calculation shows the phase diagram ==>

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

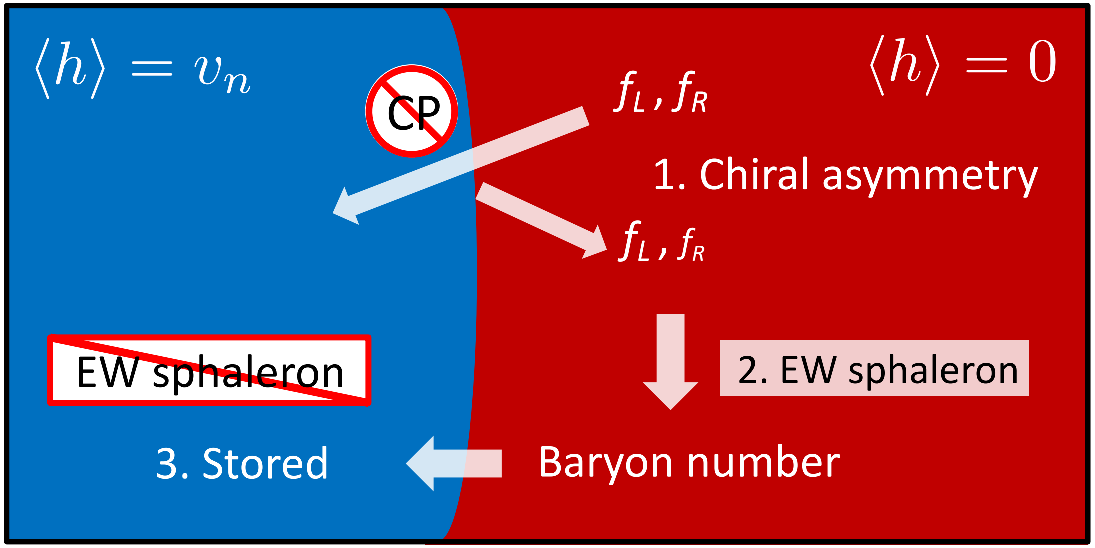
However, a 1st-order EWPT is more interesting.
(Needs new physics)



- ## Why is a 1st-order EWPT interesting?

First, it's the essential ingredient of the EW baryogenesis.

EW baryogenesis (new physics mechanism):
Explaining the matter-antimatter asymmetry of the Universe at EW scale;



1. CP violating collision generates a *chiral asymmetry*;
2. EW sphaleron converts the chiral asymmetry to a net **baryon number**;
3. The baryon number is swept into bubble and survives until today.

Providing the background of the mechanism.

- Why is a 1st-order EWPT interesting?

Second, a 1st-order phase transition itself is more interesting.

Acting as the background of very rich **dark matter** mechanisms

- ❑ Altering the decay of DM;[Baker *et al*, PRL2017]
- ❑ Filtering DM particles to the true vacuum;[Baker *et al*, PRL2020; Chway *et al*, PRD2019]
- ❑ Trapping fermions to form Fermi-balls;[J.-P.Hong, S.Jung and **K.-P.Xie**, PRD2020]
- ❑ Packaging scalar particles into Q-balls;[Krylov *et al*, PRD2013]
- ❑ Confining quarks into DM nuggets;[Witten, PRD1984; Bai *et al*, JHEP2018]
- ❑ ……

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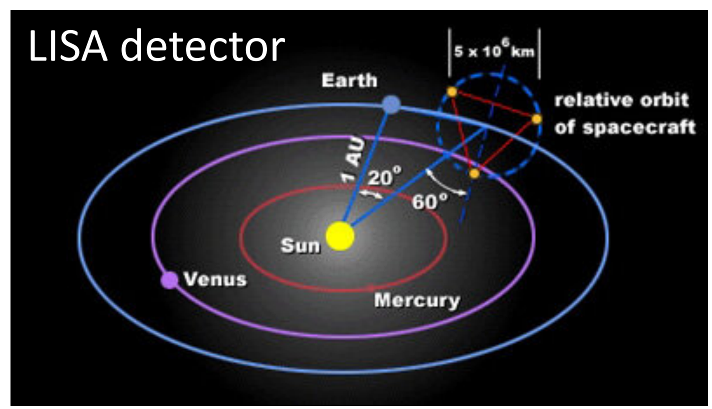
- ❑ ……

Third, it might be detected via gravitational wave (GW) signals.

Sources of the stochastic GWs:

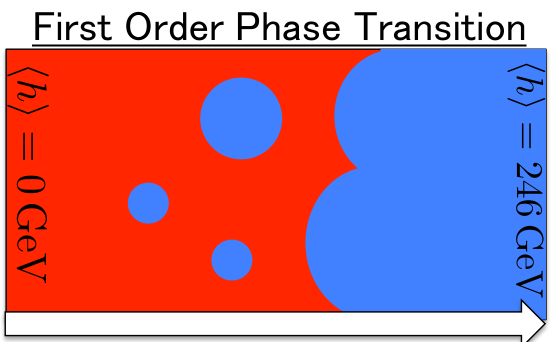
- ✓ Collision of the bubbles
- ✓ Sound waves in plasma
- ✓ Turbulence in plasma

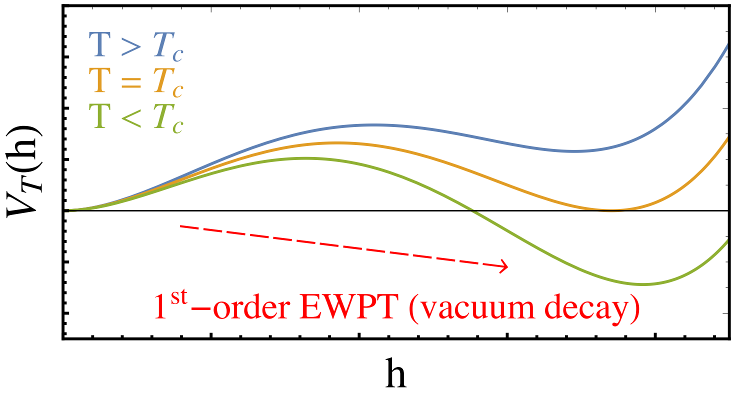
EWPT GWs typically peak in mHz.



- How to achieve a 1st-order EWPT?

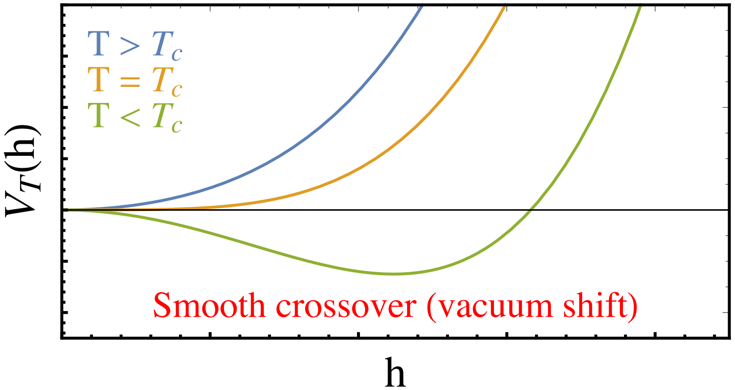
1st-order EWPT:
The decay between two vacua separated by a barrier.
The VEV of the Higgs field *jumps*.





However, in the SM, we don't have such a barrier in the Higgs potential.

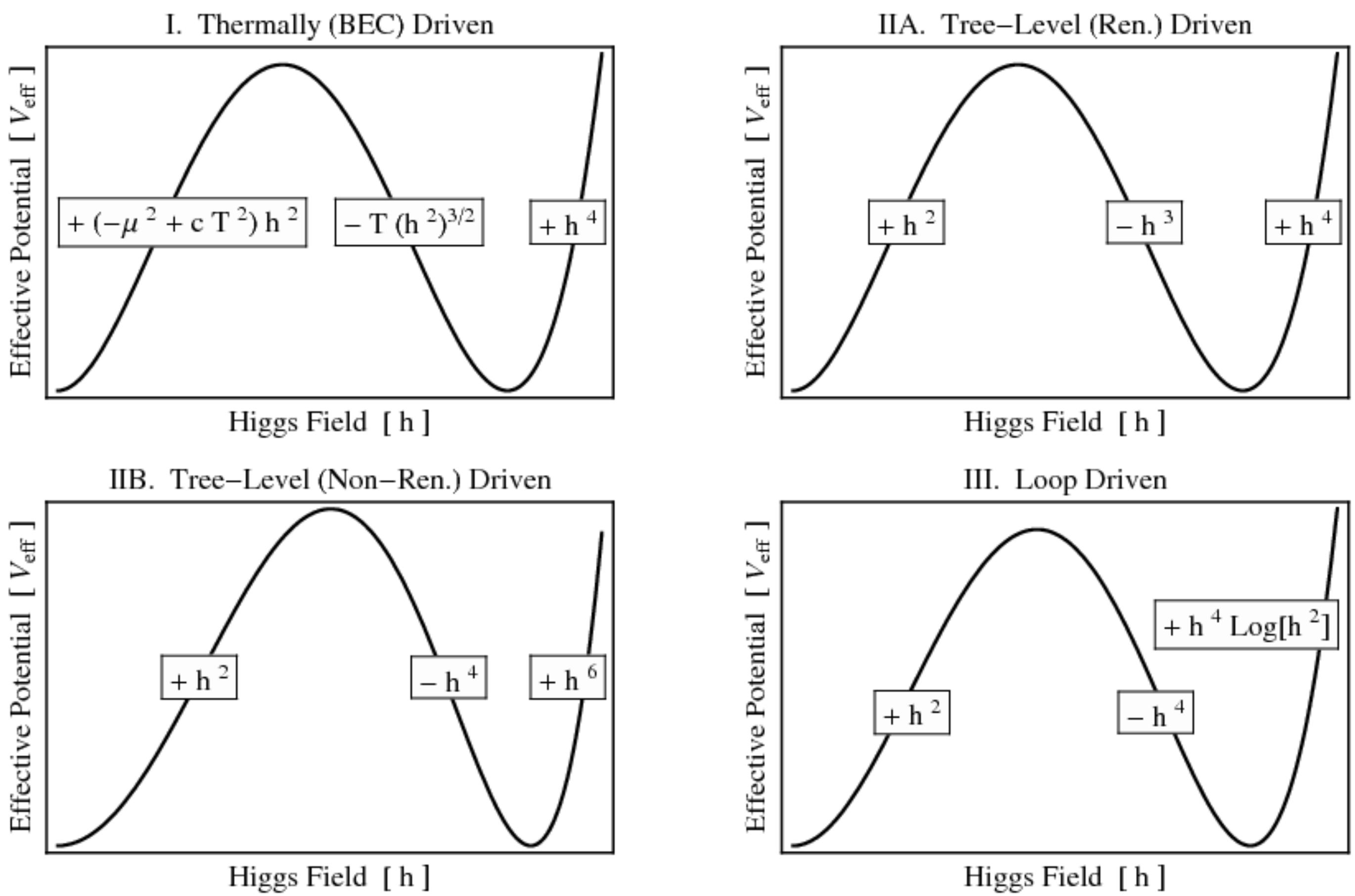
The VEV of Higgs *smoothly* shifts, leaving us a crossover.



- # How to achieve a 1st-order EWPT?

Adding a barrier for the Higgs potential via new physics!

Figure from: Chung, Long and Wang, PRD, arXiv:1209.1819



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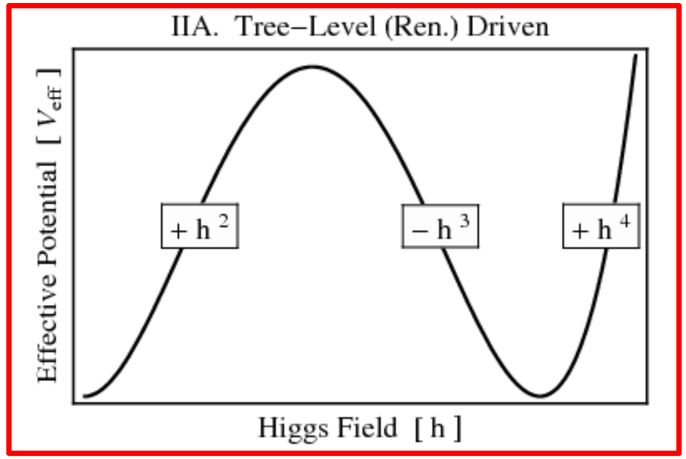


Getting a barrier via the help of additional scalar field(s):

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

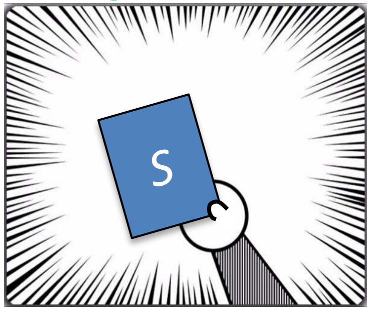
We choose the **xSM** as the benchmark model.

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

EWPT in the xSM (SM + real singlet)

- Setup

The scalar potential of the xSM



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

<u>8 input parameters</u>:
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, *O*(TeV) (h_2)

Mass eigenstates & the mixing angle.

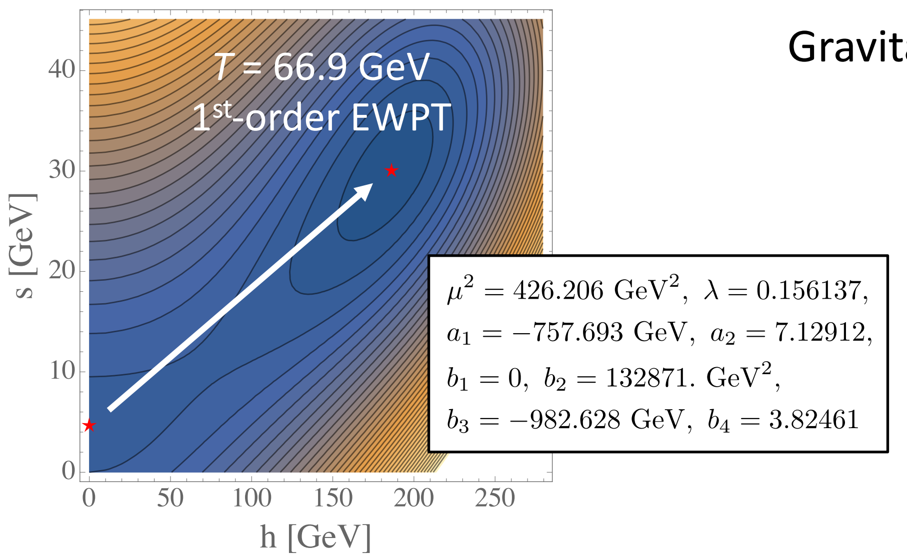
• 1^{st}-order EWPT in the xSM

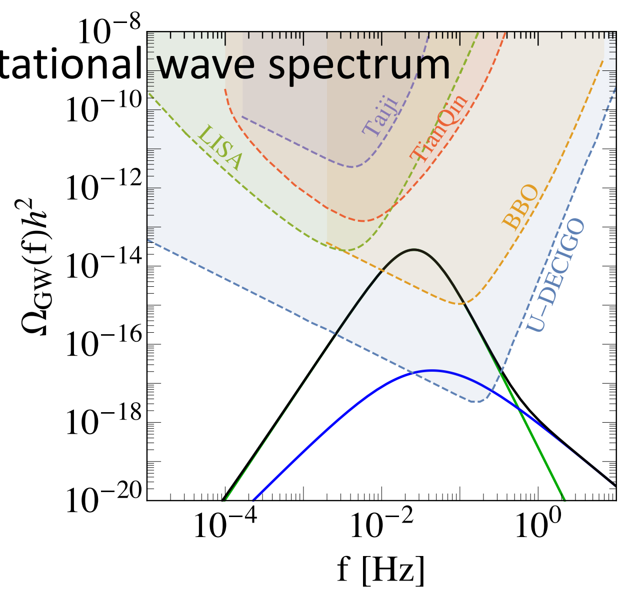
At finite temperature:

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

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

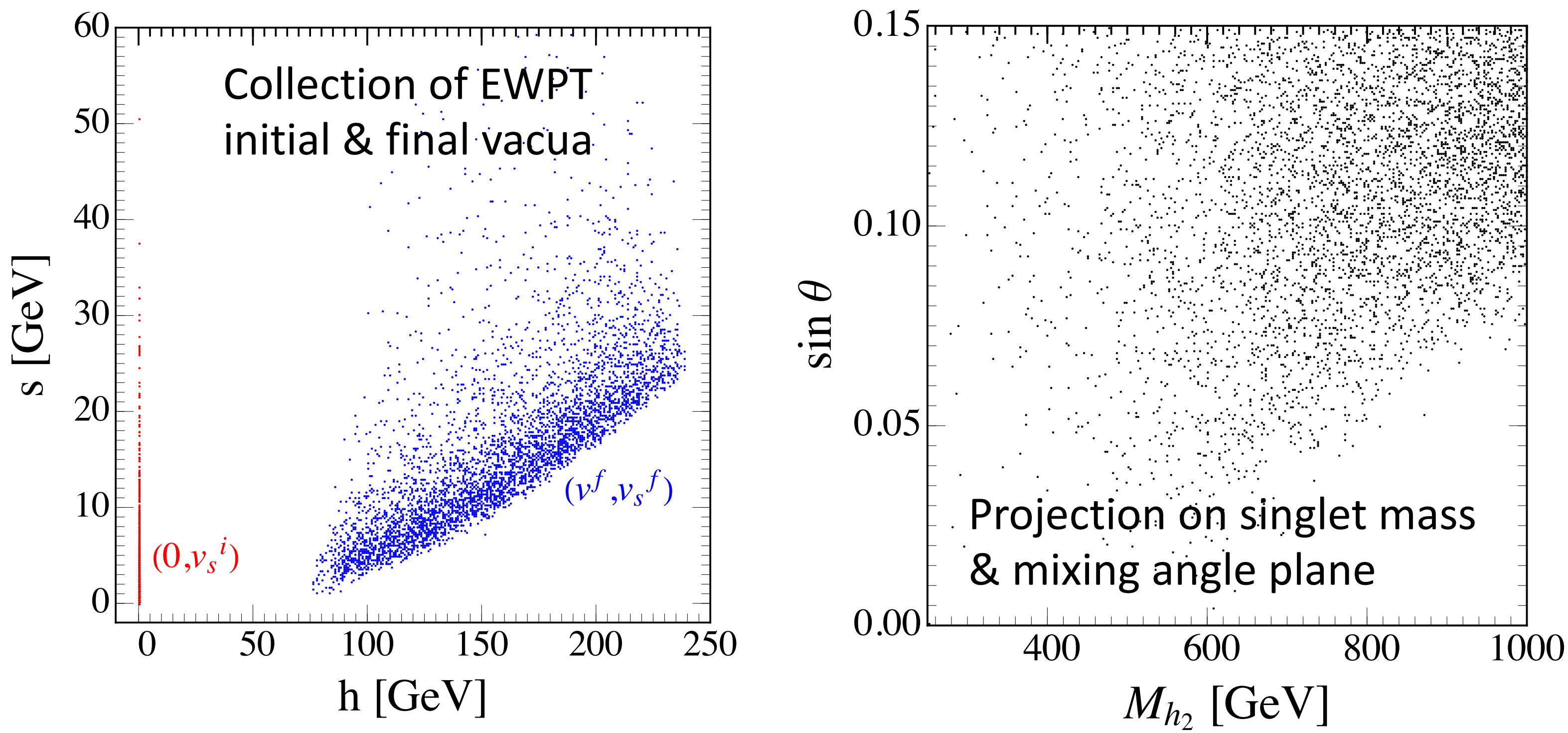
An Illustration --





• 1^{st}-order EWPT in the xSM

Parameter space for 1^{st}-order EWPT



Question:

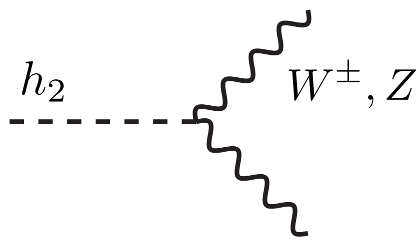
Can <u>collider experiments</u> probe the 1^{st}-order EWPT parameter space?

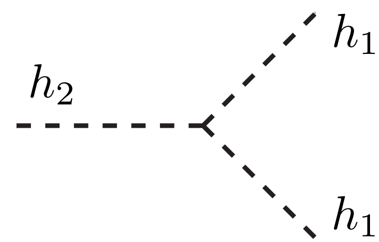
Probing EWPT of the xSM at colliders

- Feature of the xSM

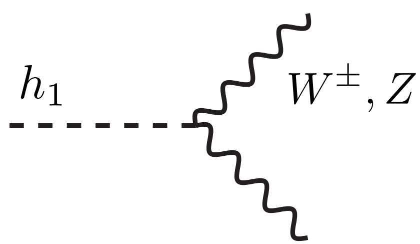
Two neutral scalars: h_1 (Higgs-like) and h_2 (singlet-like, TeV), with mixing angle ϑ;

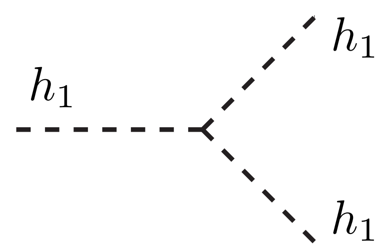
$$
\begin{aligned}
g_{h_2VV} &= g_{hVV}^{\rm SM} \sin\theta \\
g_{h_2f\bar{f}} &= g_{hf\bar{f}}^{\rm SM} \sin\theta \\
\lambda_{h_2h_1h_1} &\propto \sin\theta
\end{aligned}
$$





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

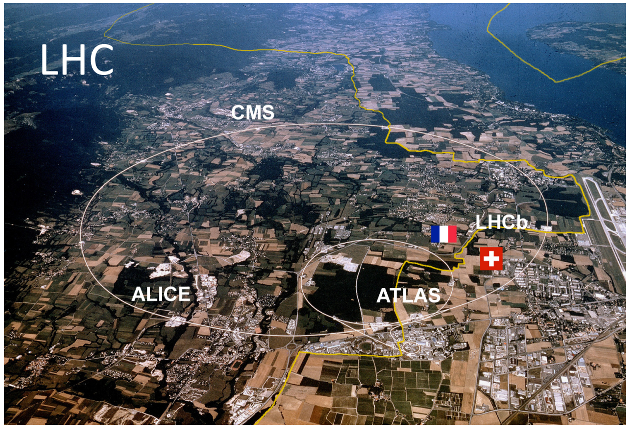




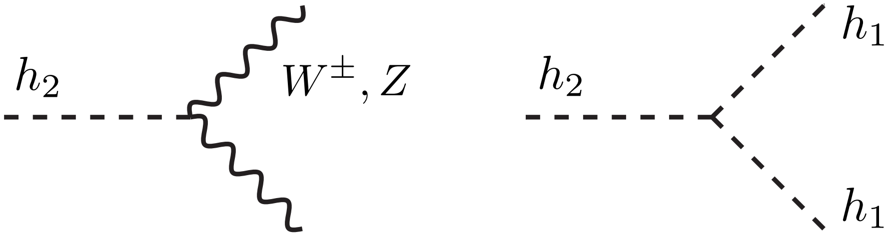
- Basic strategies

Generally speaking:

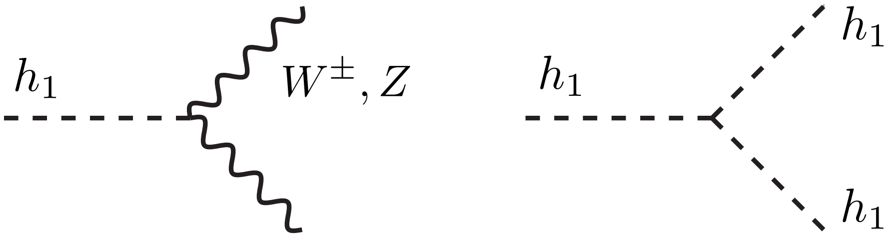
1. *pp* colliders are high-energy but relatively “dirty”;
2. e^+e^- colliders are clean but typically low energy.



Direct searches at the *pp* colliders (LHC, HE-LHC, SppC FCC-hh):
1701.08774, 1812.09333, 1808.08974, 2007.15654, 2010.00597, …



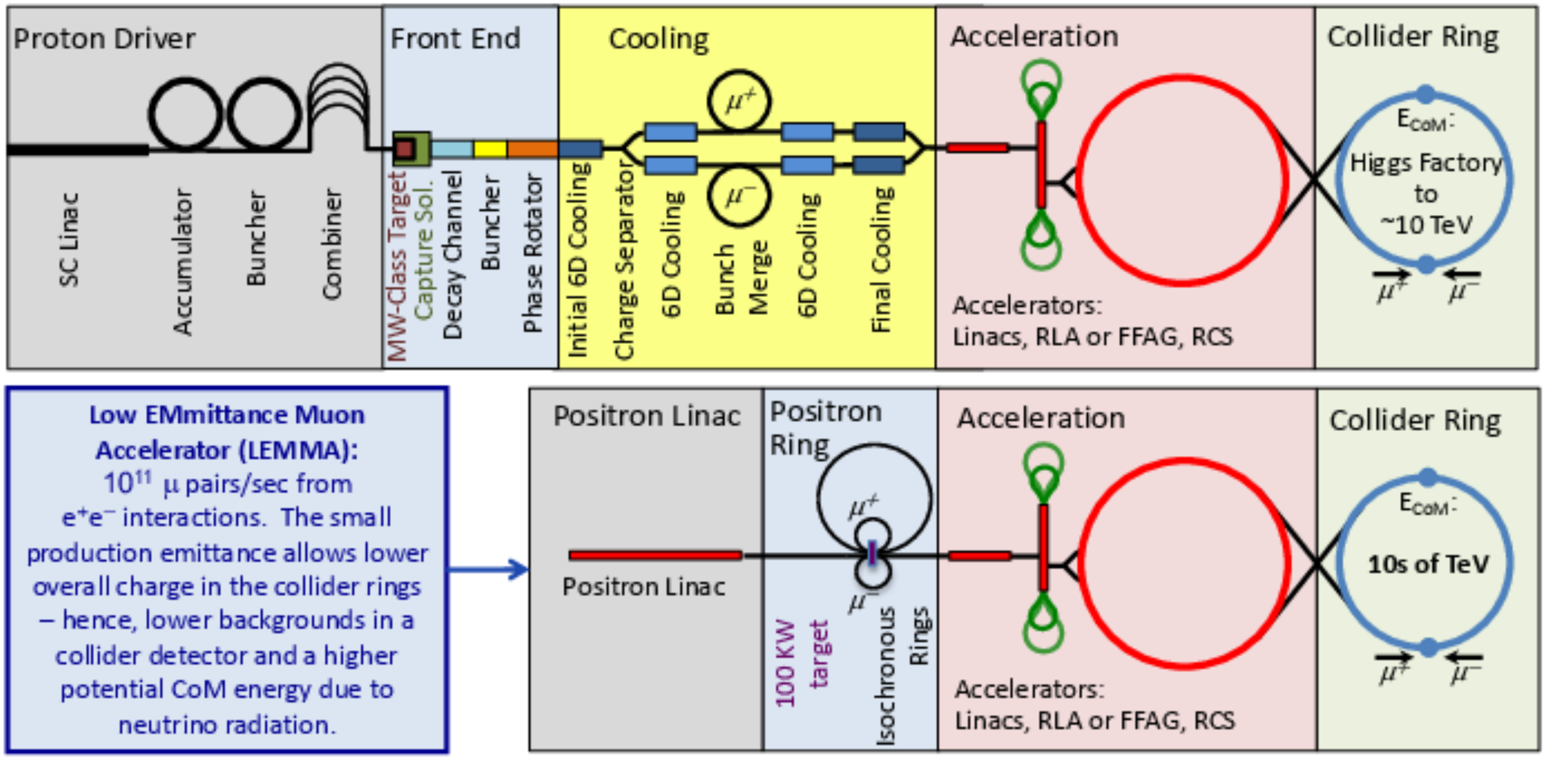
Indirect searches at the e^+e^- colliders (CEPC, ILC, CLIC, FCC-ee):
1407.5342, 1608.06619 , 1708.04737, 1807.04284, …



- How about the muon collider?

A high-energy muon collider has been discussed since 1980's; and it receives a renewed interest recently.

Figure from 1901.06150



(I'm not an experimentalist; please refer to 1901.06150 for the details of the machine.)

- How about the muon collider?

A high-energy muon collider is able to execute both the **direct** and **indirect** strategies for EWPT in xSM!

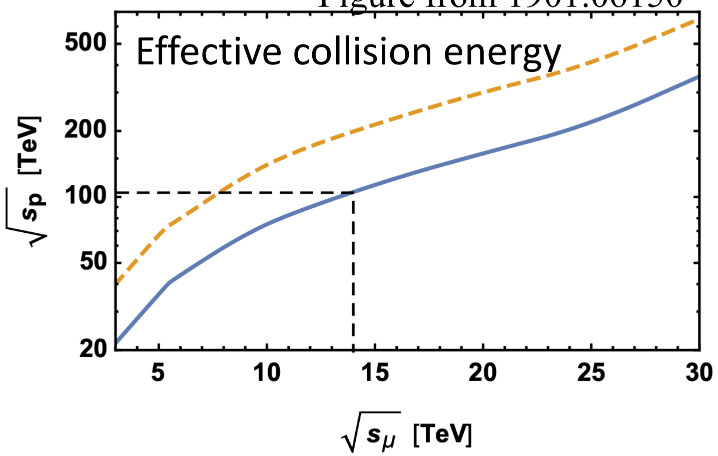
Compared to the e^+e^- machine:

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

Compared to the *pp* machine:

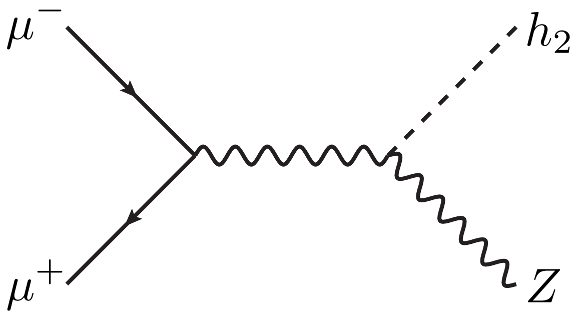
1. The entire collision energy can be used to probe hard process;
2. Much cleaner due to the small the QCD background.

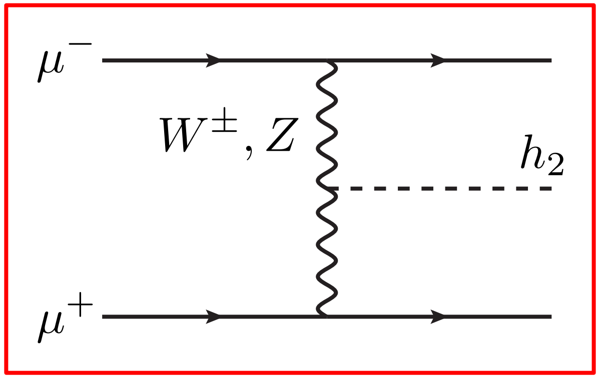
Figure from 1901.06150



- Muon collider: direct search

Producing the h_2 at a muon collider

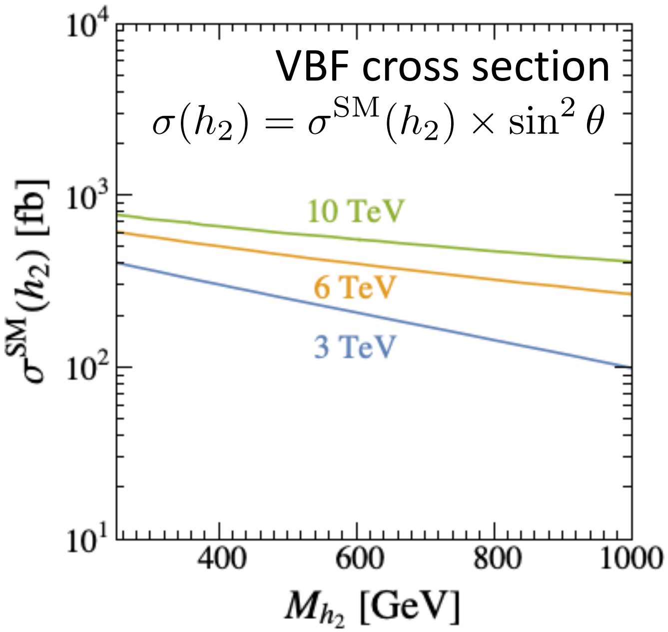




Zh_2 associated production & Vector Boson Fusion (VBF).

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)

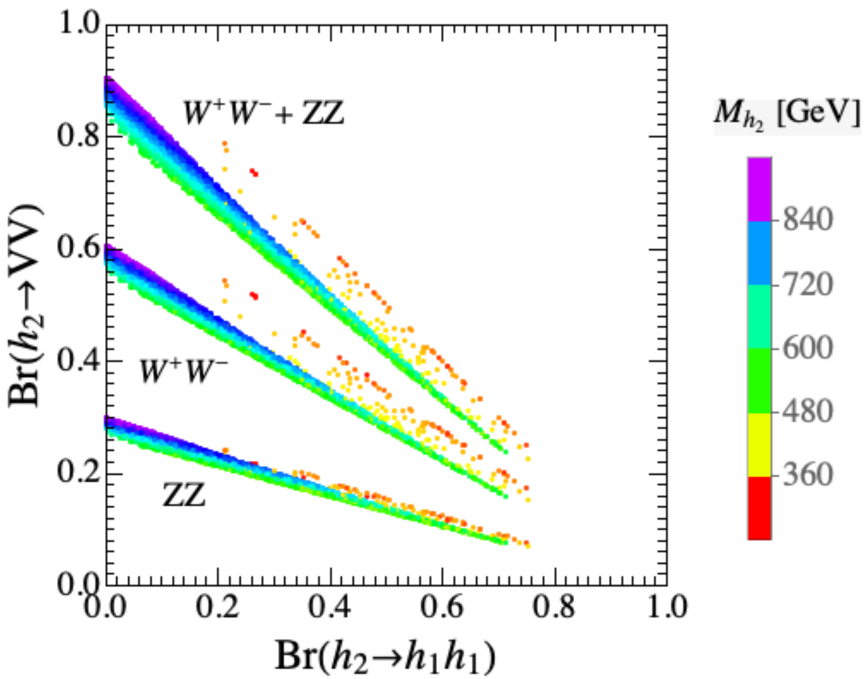
$$\Gamma(h_2 \to XX) = \sin^2\theta \times \Gamma^{\rm SM}(h_2 \to XX),$$
$$\Gamma(h_2 \to h_1 h_1) \propto \lambda^2_{h_2 h_1 h_1}$$

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
$h_2 \to ZZ \to l^+l^-l^+l^-$
$h_2 \to h_1h_1 \to bbbb$
for a detailed simulation.



• Muon collider: direct search – diHiggs channel

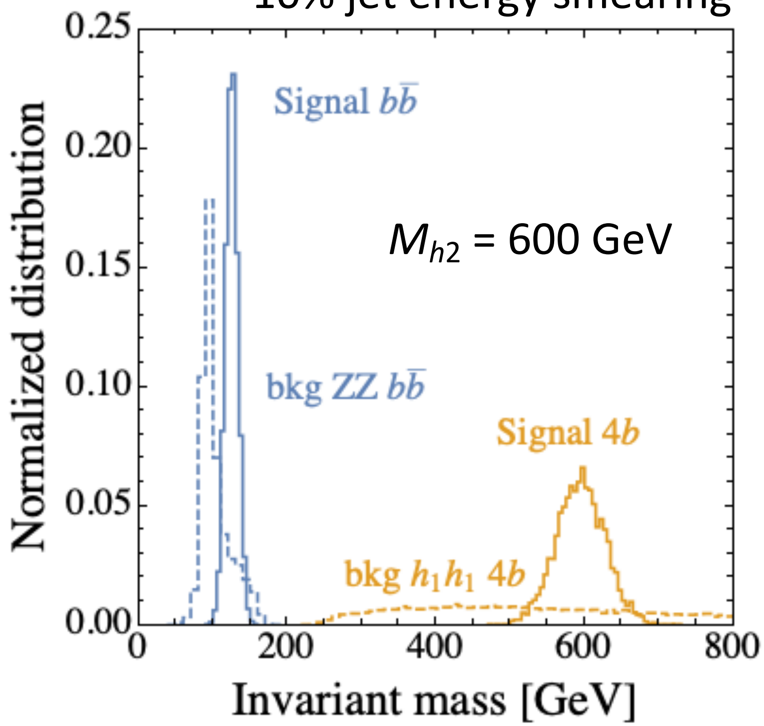
The h_2 -> $h_1 h_1$ -> *bbbb* channel:

Main background:

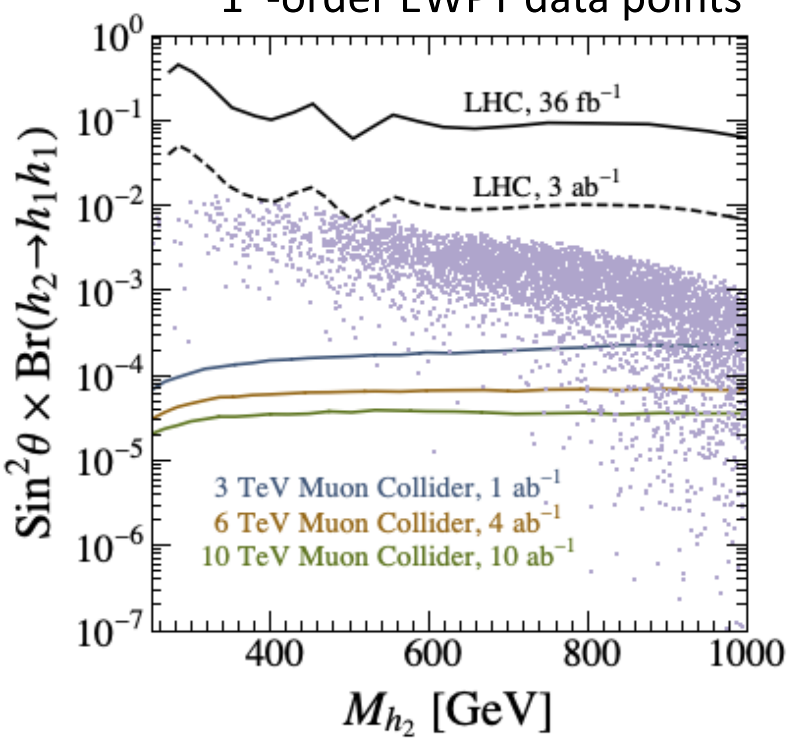
✓ Vector Boson Scattering *ZZ* -> *bbbb* and $h_1 h_1$ -> *bbbb*.

Kinematic distribution

10% jet energy smearing



1st-order EWPT data points



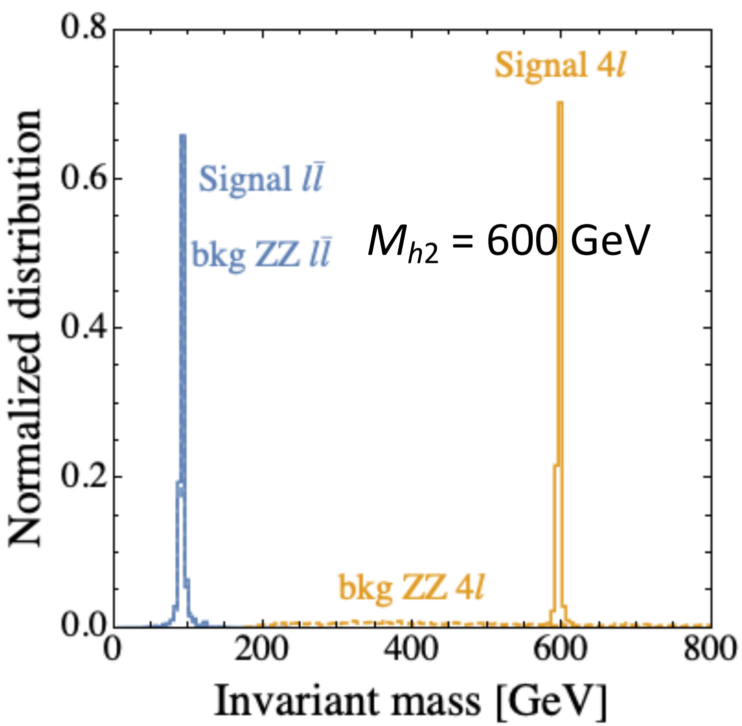
• Muon collider: direct search – diboson channel

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

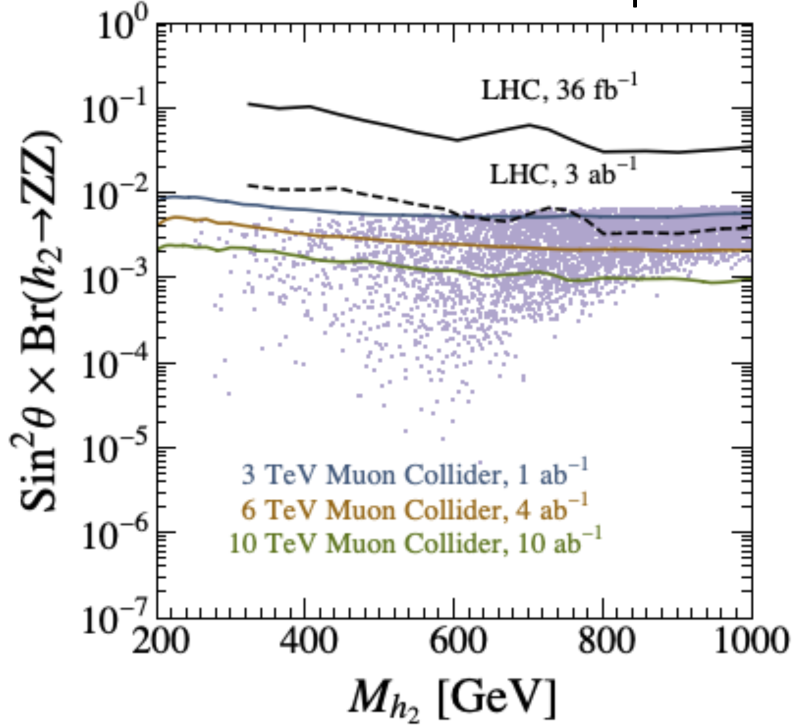
Main background:

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

Kinematic distribution



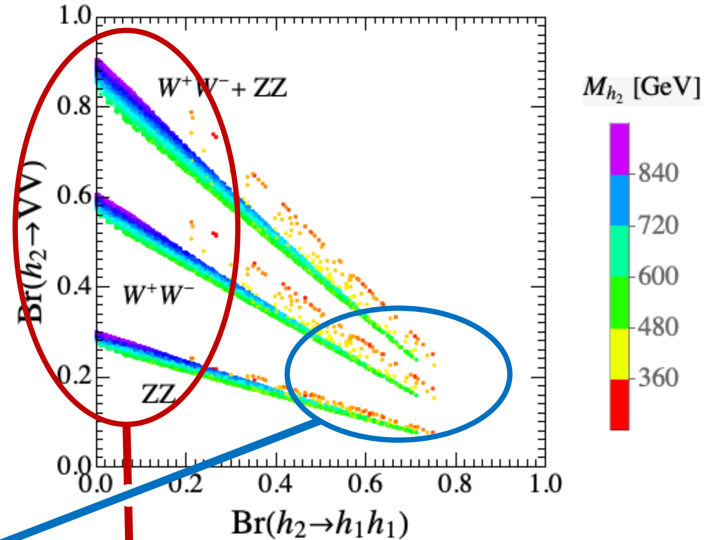
1st-order EWPT data points

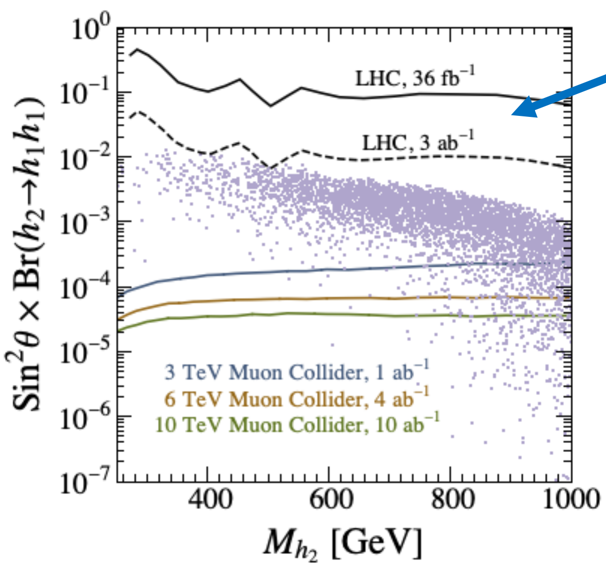


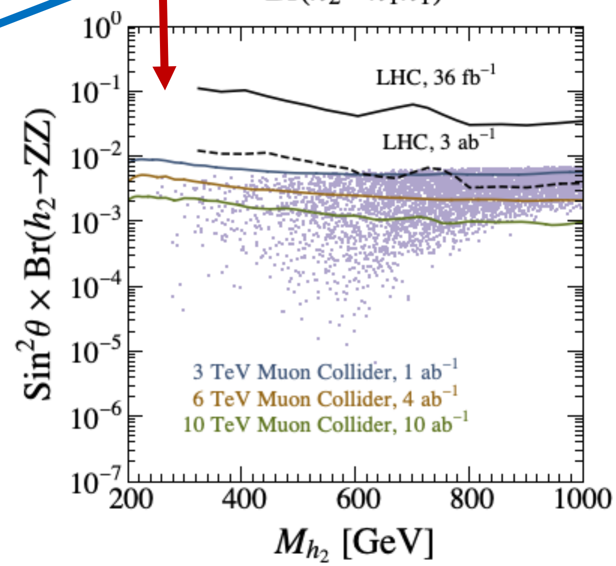
• Muon collider: direct search

The diHiggs & diboson channels are complementary

Thanks to the high accuracy of the muon collider, the reach is typically higher than the HL-LHC!

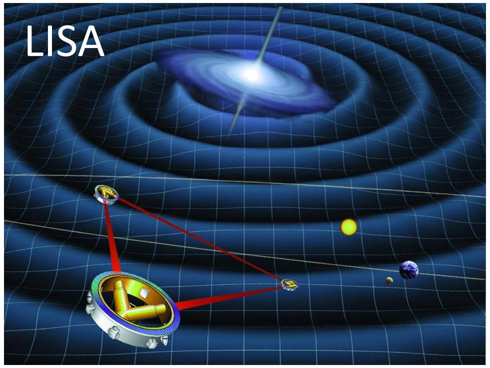






• Muon collider: direct search

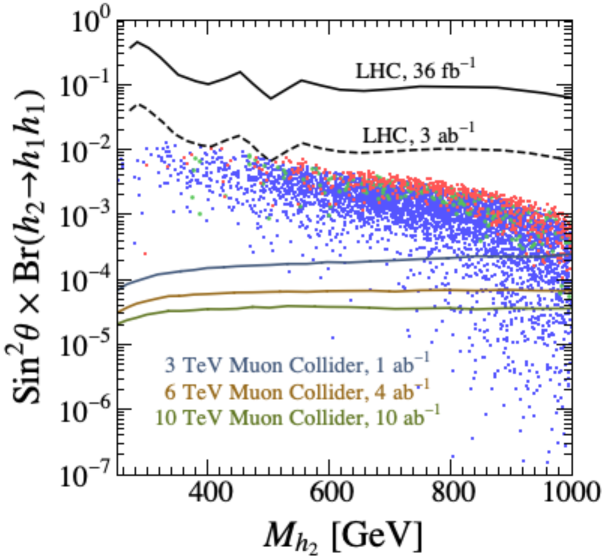
The collider search and gravitational wave detection are complementary as well!

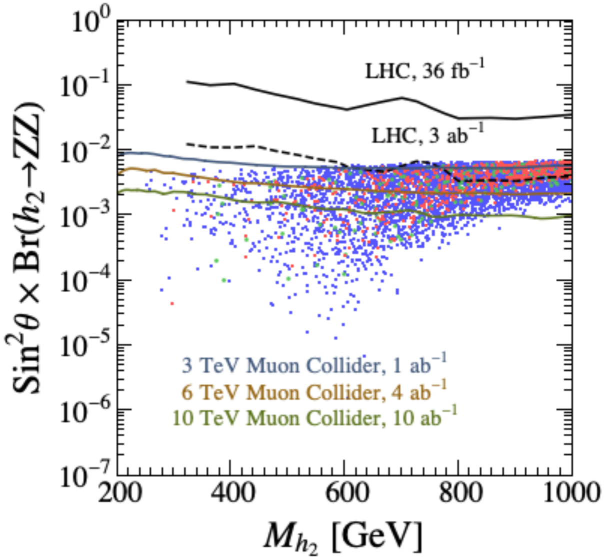


For the LISA detector, signal-to-noise ratio (SNR):

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

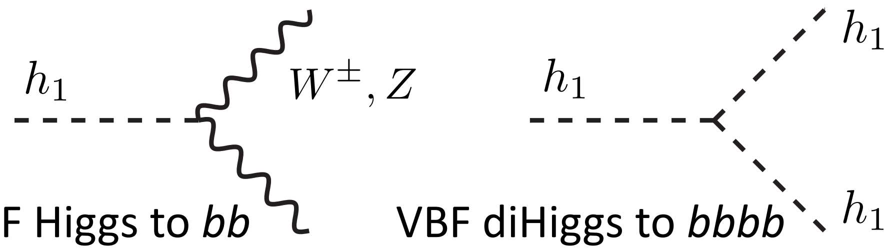
Detectable threshold: SNR > 50 (red)





- # Muon collider: indirect search

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



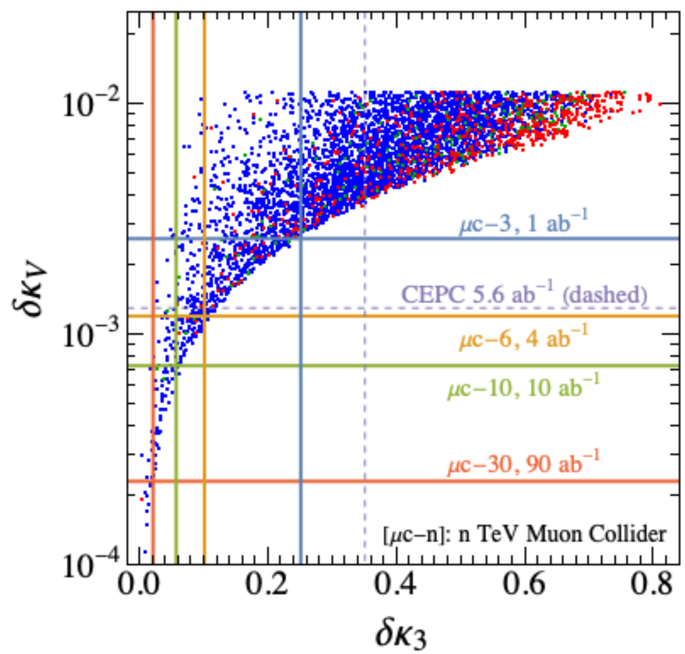
VBF Higgs to *bb*   VBF diHiggs to *bbbb*

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.

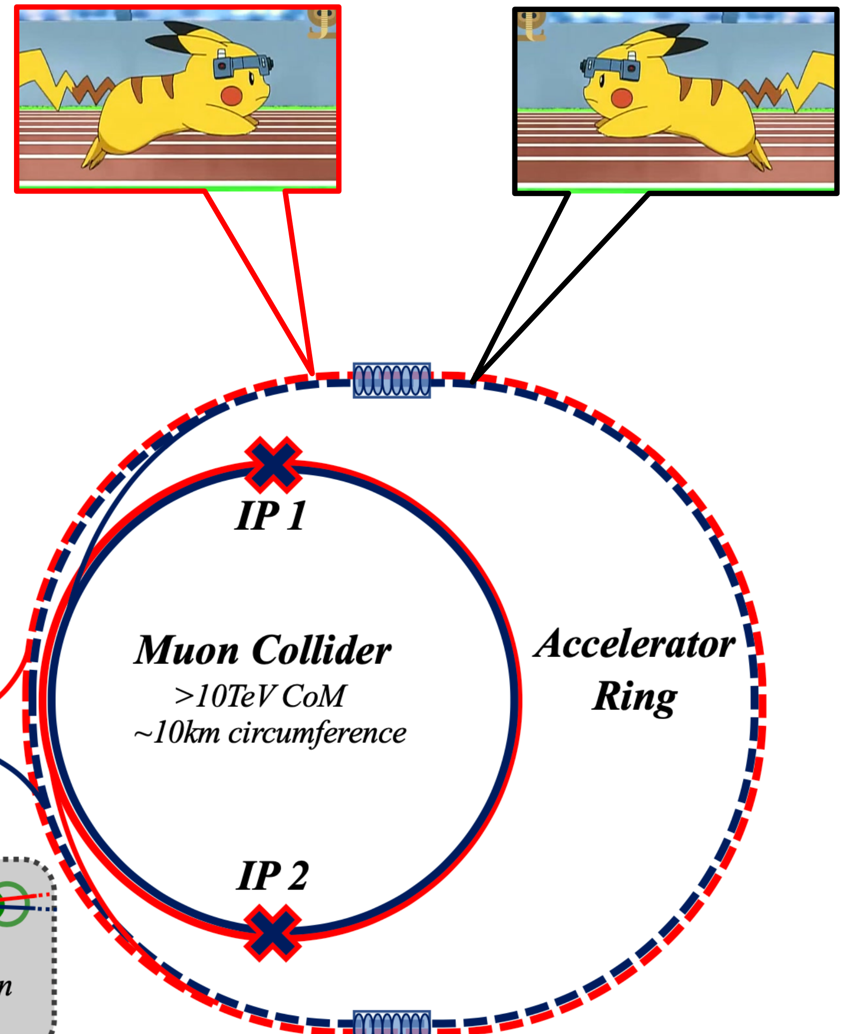
We propose strategies to probe 1st-order EWPT at a high-energy muon collider:

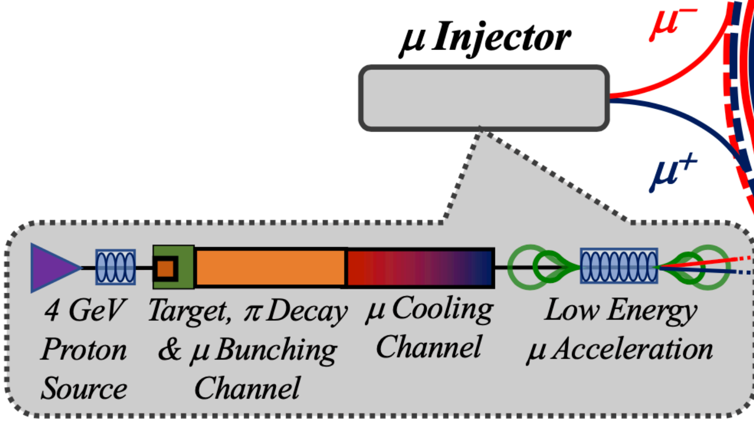
1. Direct detection: the resonant production of the new scalar;
2. Indirect detection: the deviation of Higgs couplings.

Collider search is complementary to the gravitational waves detection!

Thank you!

Let's look forward to a muon collider!





Sketch of Muon Collider: from A.Wulzer's talk in PITT PACC Workshop