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Shedding light on the **electroweak phase transition from exotic Higgs boson decays at the **lifetime frontiers****

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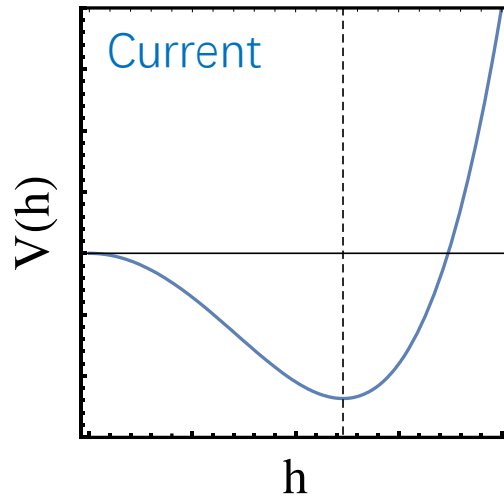
Nanjing University of Science and Technology

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Higgs Potential 2022

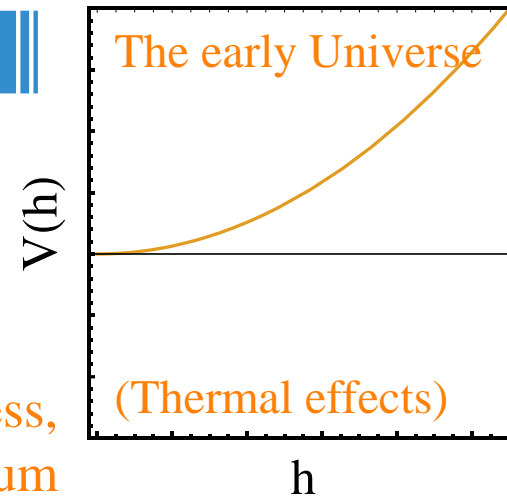
Phase transition in electroweak theory

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 –

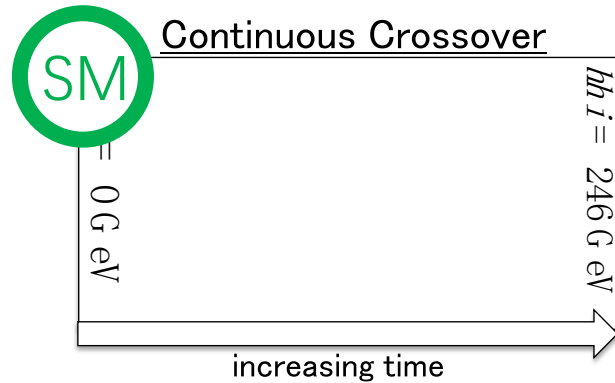
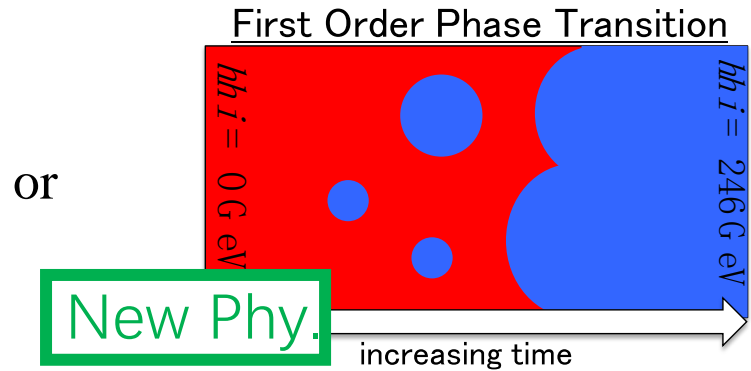


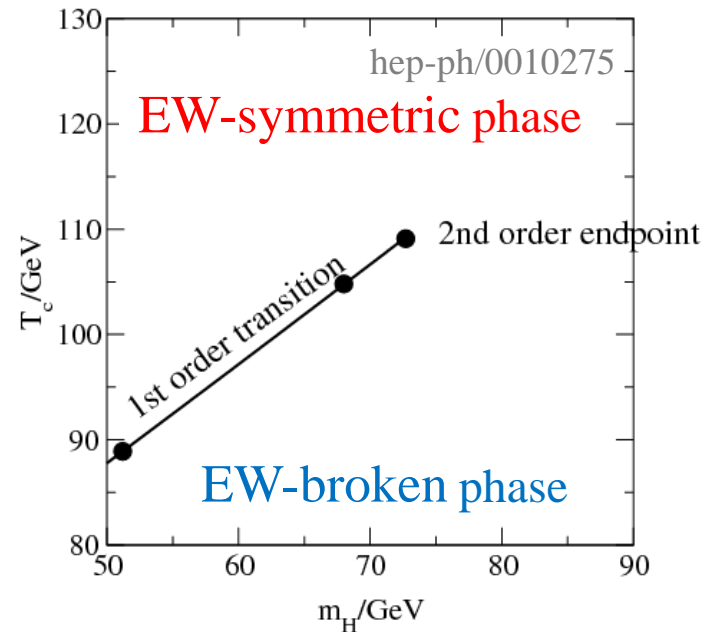
Figure from L.-T. Wang's talk in IHEP workshop



Lattice calculation shows the phase diagram ==>

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

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



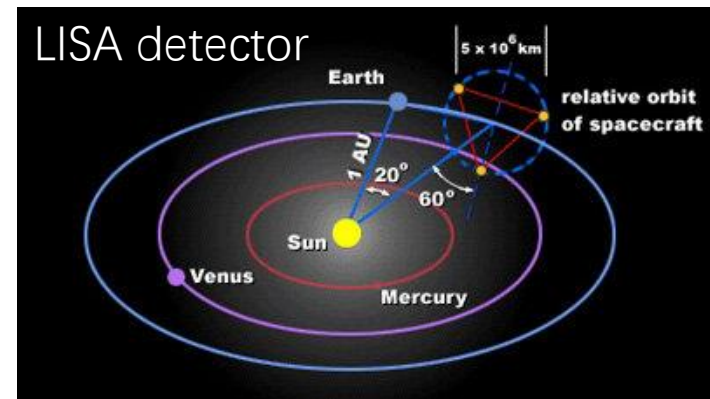
Why is a 1st-order EWPT interesting?

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- 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
- Turbulence in plasma

EWPT GWs typically peak in mHz.



How to achieve a 1st-order EWPT?

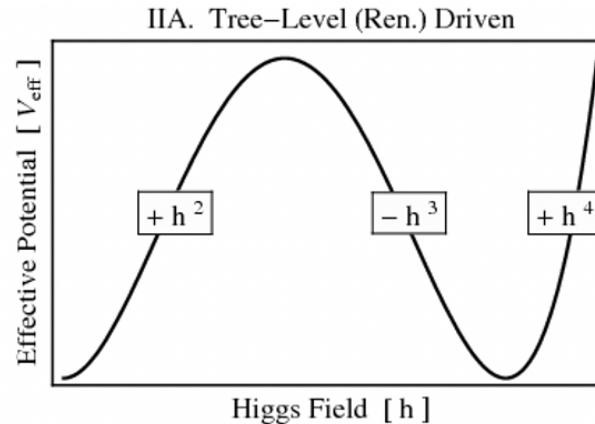
Adding a barrier for the Higgs potential via new physics!

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

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

Mass eigenstates & the mixing angle.

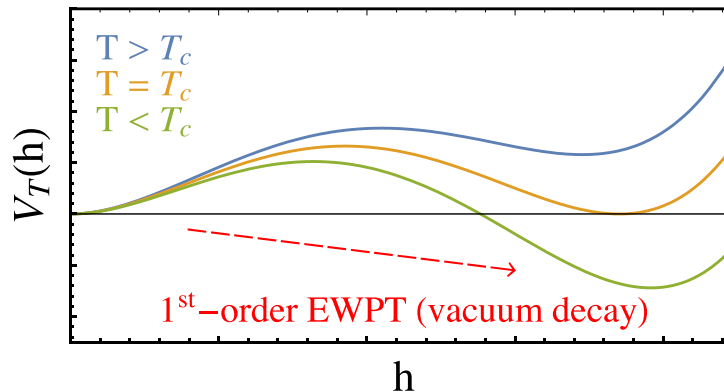
1st-order EWPT in the xSM

At finite temperature:

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

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

An Illustration --



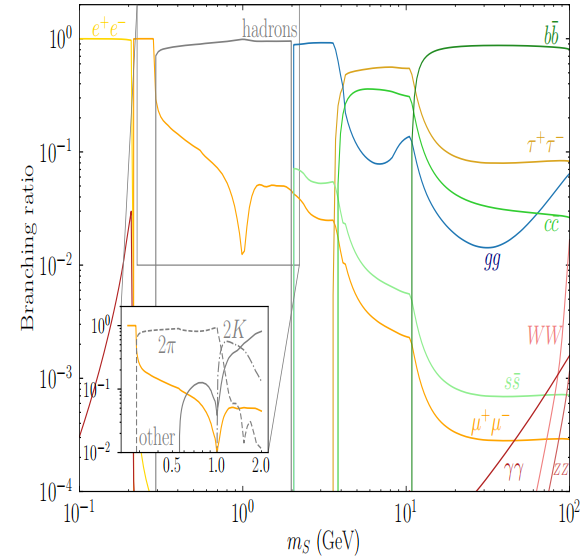
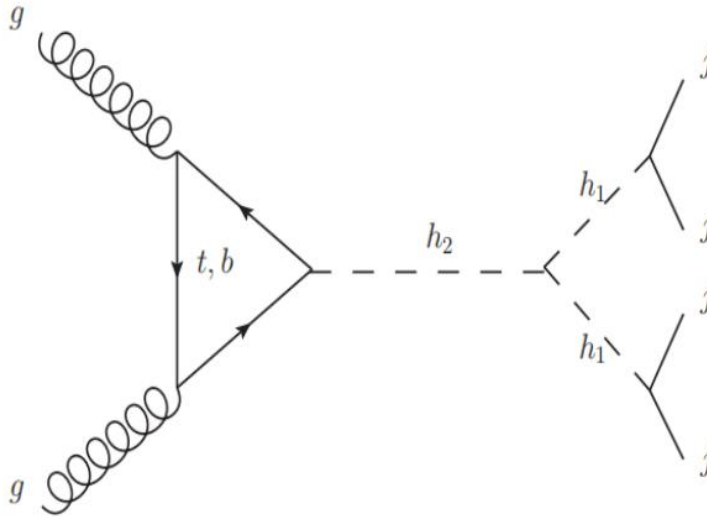
Question:

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

Production processes

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$$gg \rightarrow h_{2(SM)} \rightarrow h_1 h_1 \rightarrow 4j$$

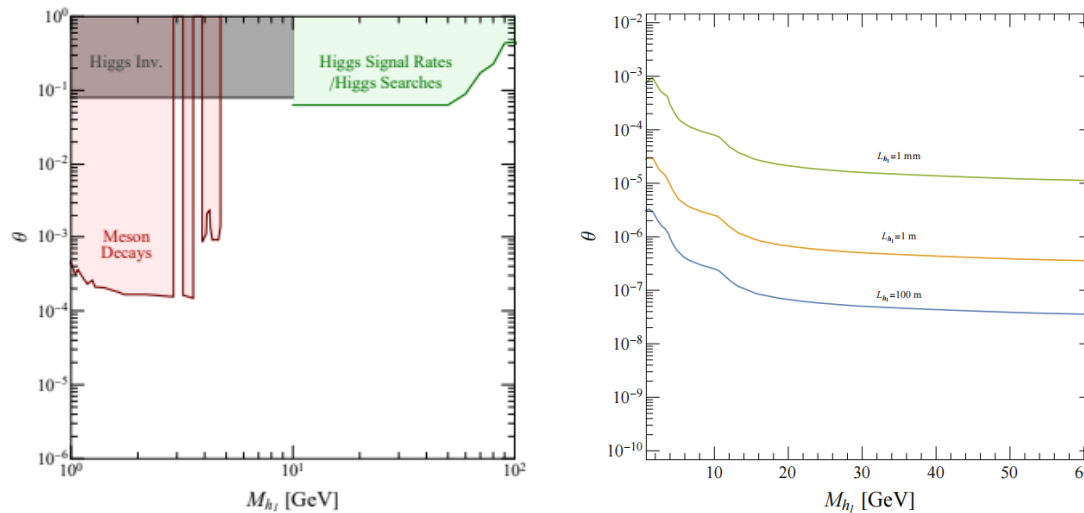


1st-order EWPT leads to large $BR(h_2 \rightarrow h_1 h_1)$.
 h_1 decays into jets dominantly.

Long-lived Particles

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The current limits on (M_{h_1}, θ)



For $M_{h_1} < 10$ GeV, the current limits from rare meson decays at the LHCb, leads to h_1 as a long-lived particle (LLP).

Long-lived Particles

LLP is widely searched, of great interests experimentally and theoretically.

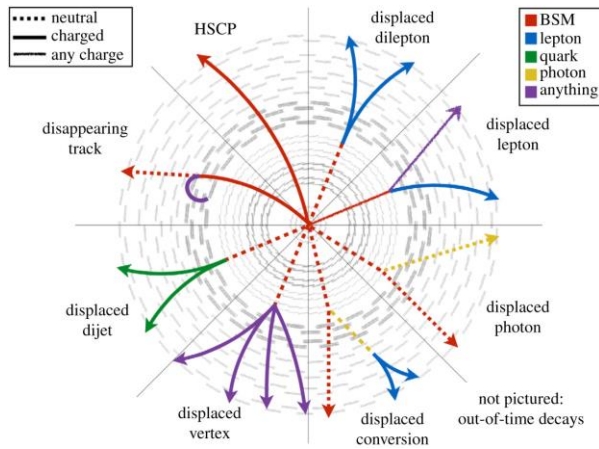


Figure from Albert De Roeck.

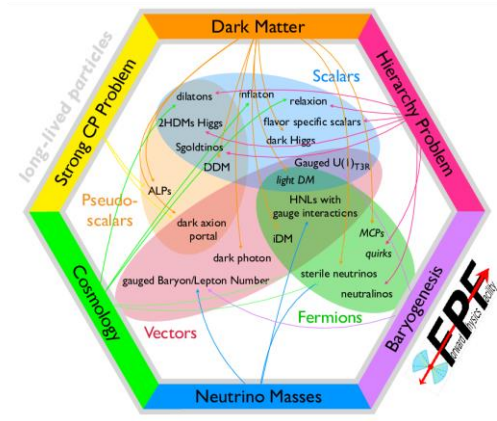
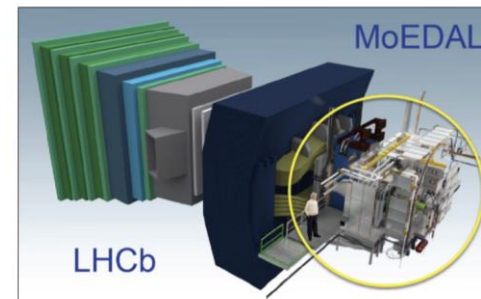
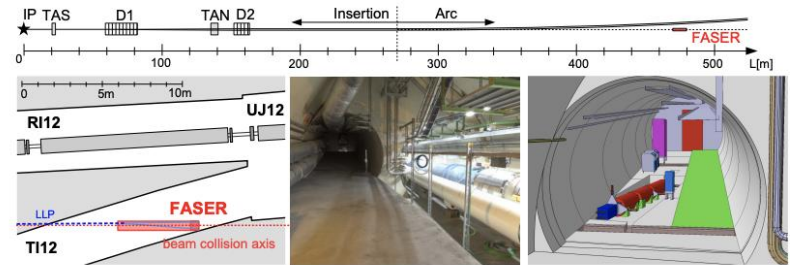
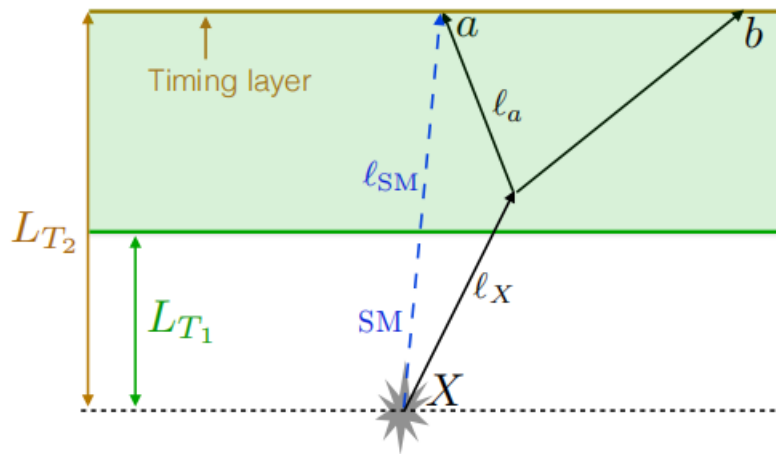


Figure from 2203.05090.

Light weakly-coupled particles as LLPs, are strongly motivated, including the light scalar responsible for 1st-order EWPT in the xSM.

Detectors for LLPs

CMS-Timing, FASER, MoEDAL-MAPP are to be operated at Run 3.

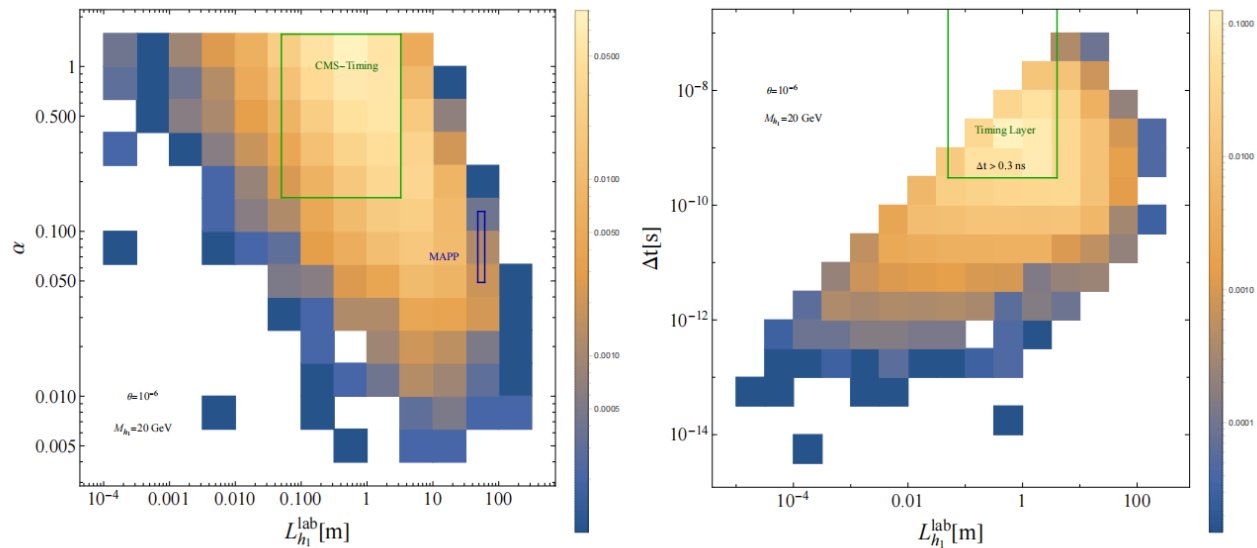


Many others, e.g. MATHUSLA and CODEX-b are in discussions.

CMS-Timing detector using the **time-delayed leptons/jets** as signals, while the other detectors using displaced vertex.

Detector efficiency

Detector efficiency is a function of geometrical coverage,



and resolution in time for timing detector.

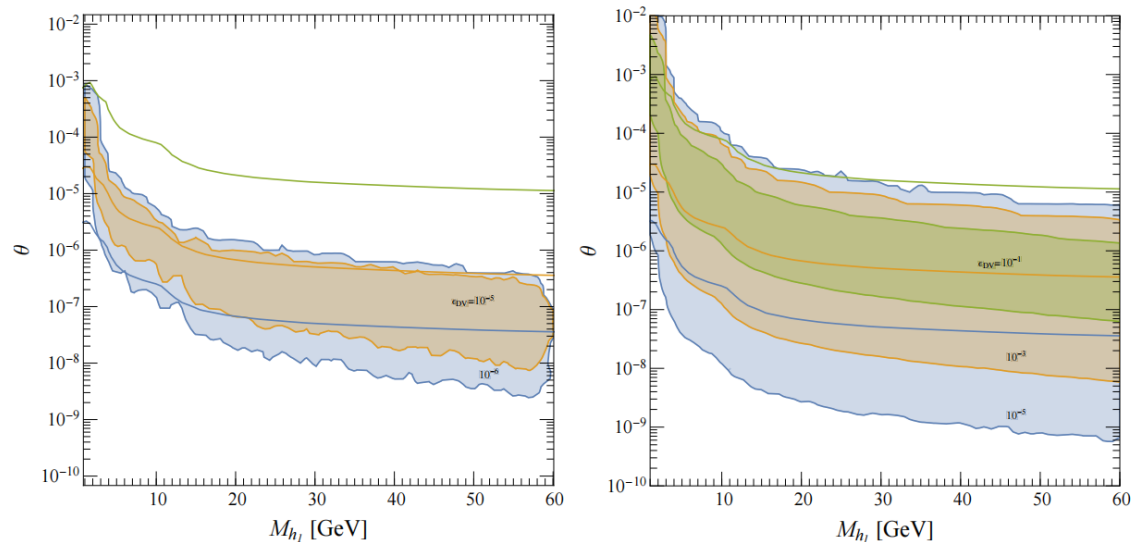
CMS-Timing has large coverage, and good resolution.

MAPP has small coverage,

while negligible for FASER.

Detector efficiency

Detector efficiency is a function of geometrical coverage,



CMS-Timing has efficiency up to 10^{-1} .
MAPP has 10^{-4} ,
while negligible for FASER.

Connects to 1st-order EWPT

Link between the number of events and 1st-order EWPT

$$\begin{aligned} N_{signal} &= \sigma_{pp \rightarrow h_2} \times L \times BR_{h_2 \rightarrow h_1 h_1}(a_2, M_{h_1}) \\ &\times BR_{h_1 \rightarrow jj}^2(M_{h_1}) \times \epsilon_{kin}(M_{h_1}) \times \epsilon_{geo}(M_{h_1}, \theta) \end{aligned}$$

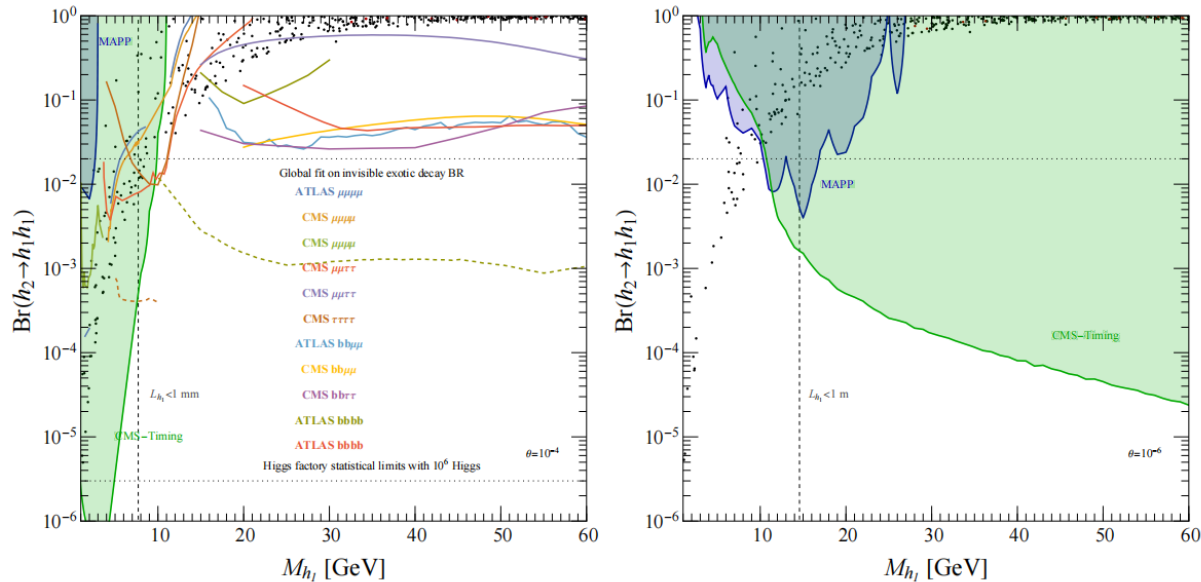
$$BR_{h_2 \rightarrow h_1 h_1}(a_2, M_{h_1}) = \frac{\Gamma_{h_2 \rightarrow h_1 h_1}}{\Gamma_{h_2}^{SM} + \Gamma_{h_2 \rightarrow h_1 h_1}}$$

$$\Gamma_{h_2 \rightarrow h_1 h_1} \propto (a_2 v)^2$$

LLP events are sensitive to $|H|^2 S^2$ couplings.

Sensitivity

Fixed $\theta = 10^{-4}$ (left), 10^{-6} (right).

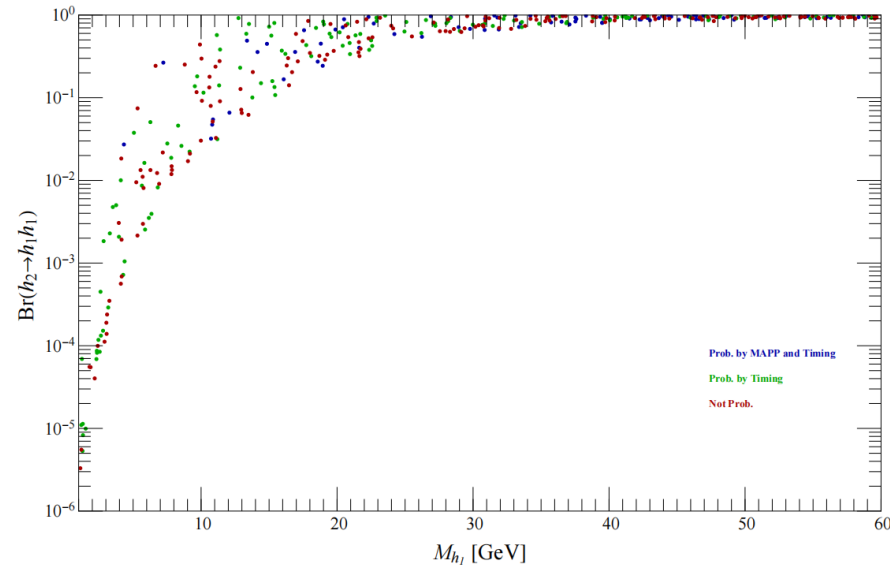


CMS-Timing can probe large parameter space where the **searches for promptly exotic Higgs decays can not reach.**

MAPP can only probe small parameter space, while none for FASER.

Signatures at Colliders

Running θ

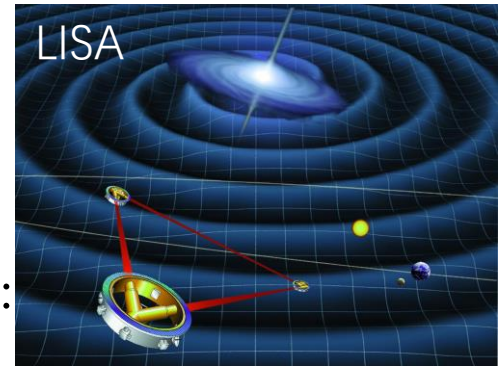


Green points are probed by CMS-Timing, but not by MAPP.

CMS-Timing can probe **a lot more** 1st-order EWPT points. There are still appreciable points not probed by any of LLP detectors.

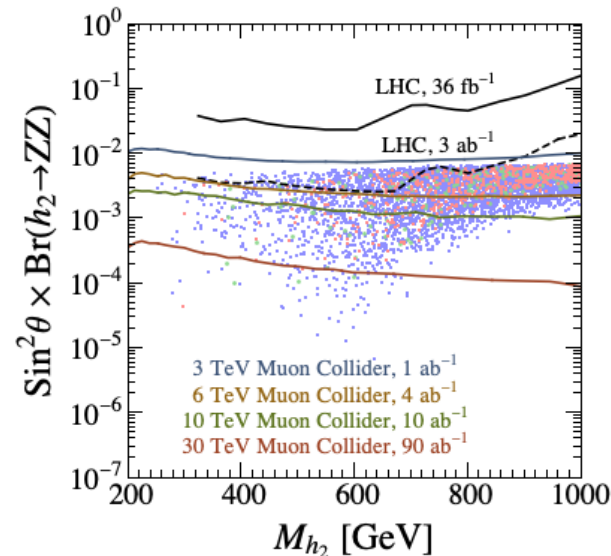
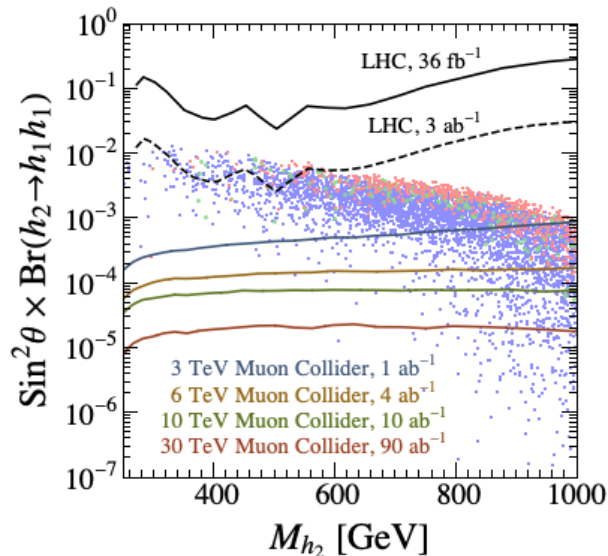
What if there is a TeV h_2 ?

1st-order EWPT can lead to **gravitational wave**, and diHiggs & diboson final states especially at **muon colliders!**



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

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



Wei Liu, Ke-pan Xie, *JHEP* 04 (2021) 015.

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** from LLP signatures at the HL-LHC.

For light, weakly coupled scalar corresponding to **1st-order EWPT**, it can lead to **LLP signatures**, but no detectable gravitational waves.

LLP search is **complementary** to the searches for promptly exotic Higgs decays!