Testing EWPT at the lifetime and energy frontiers

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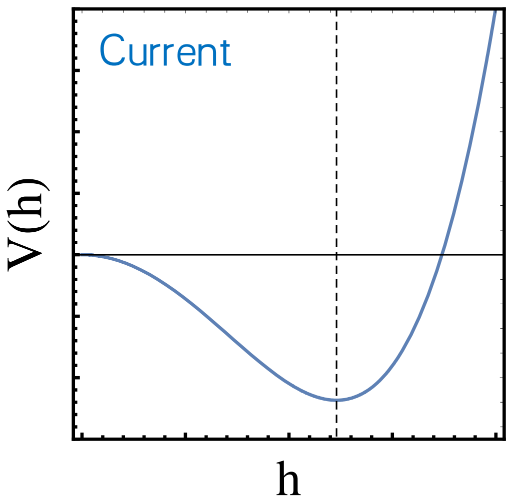
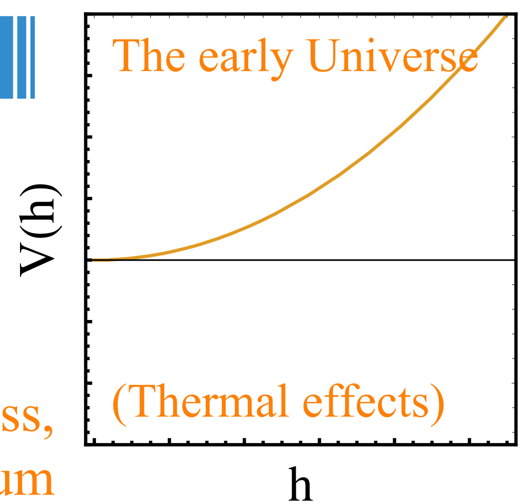
Phase transition in electroweak theory

EW symmetry restoration in the early Universe



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

Phase transition

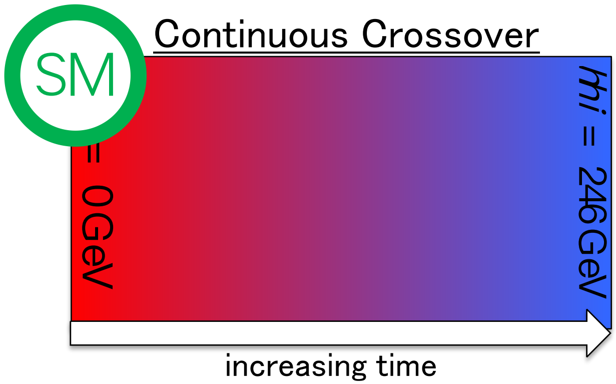


$SU(2)_L$ & $U(1)_Y$ bosons are massless,
True vacuum

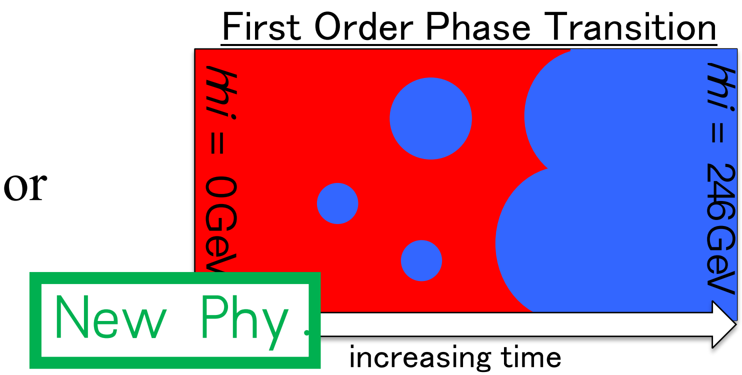
What is the pattern of EW phase transition (PT)?

It could be –

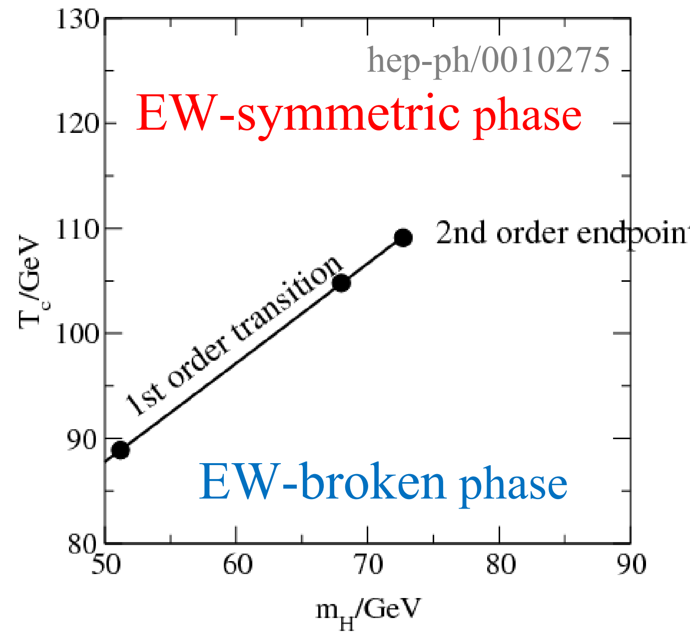
Figure from L.-T. Wang's talk in IHEP workshop



or



Lattice calculation shows the phase diagram ==>



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

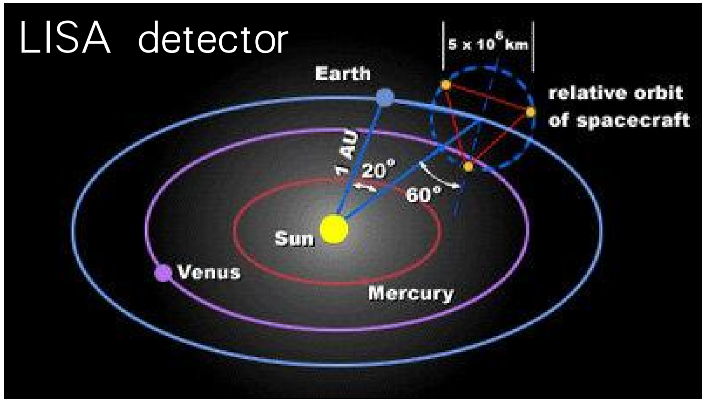
However, a 1st-order EWPT is more interesting.
(Needs new physics)

Why is a 1st-order EWPT interesting?

- 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.

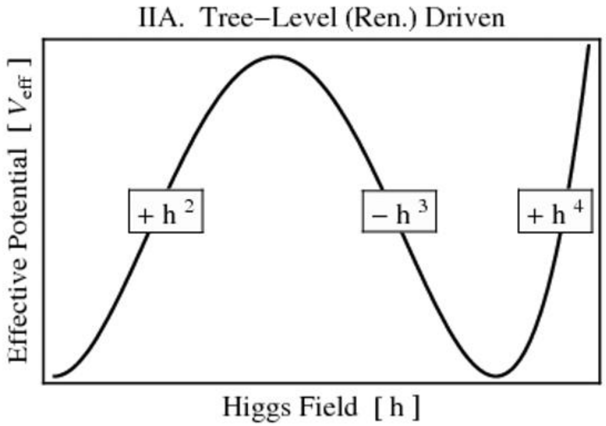


How to achieve a 1st-order EWPT?

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

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

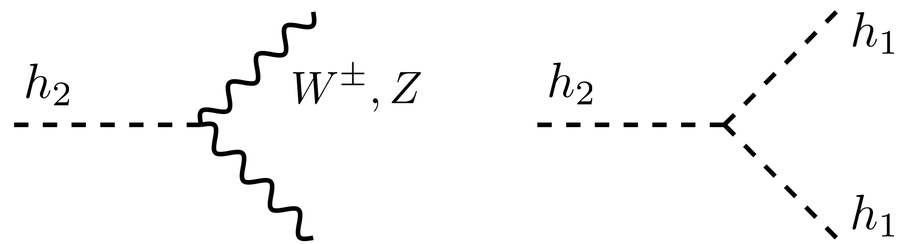
Mass eigenstates & the mixing angle.

Probing EWPT of the xSM at colliders

Feature of the xSM

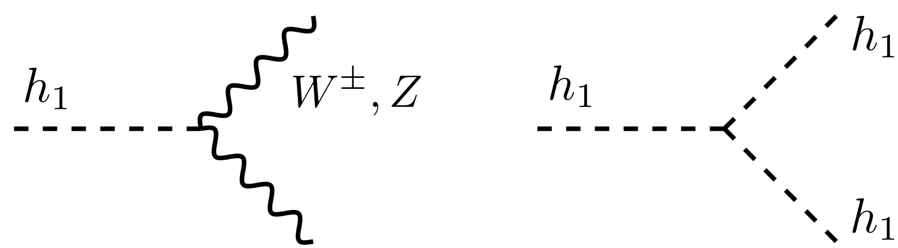
Two neutral scalars: h_1 (Higgs-like) and h_2 (singlet-like, TeV), with mixing angle θ;

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



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

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!

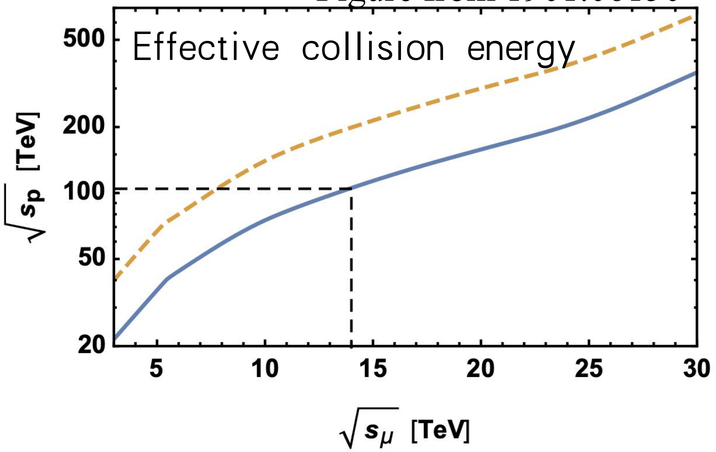
Compared to the e^+e^- machine:

- 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:

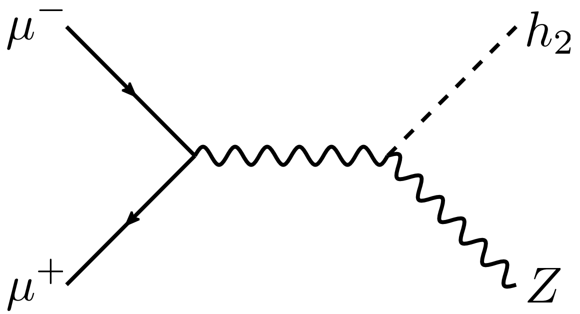
- The entire collision energy can be used to probe hard process;
- Much cleaner due to the small QCD background.

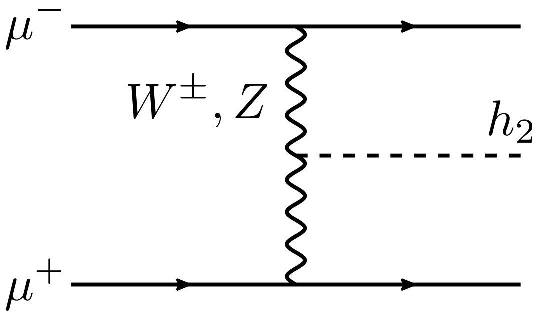
Figure from 1901.06150



Muon collider: direct search

Producing the h_2 at a muon collider

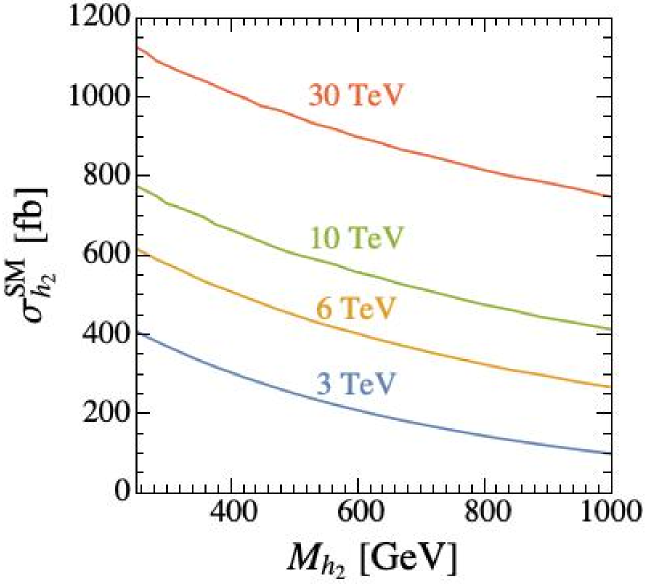




Zh_2 associated production & Vector Boson Fusion (VBF).

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)

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

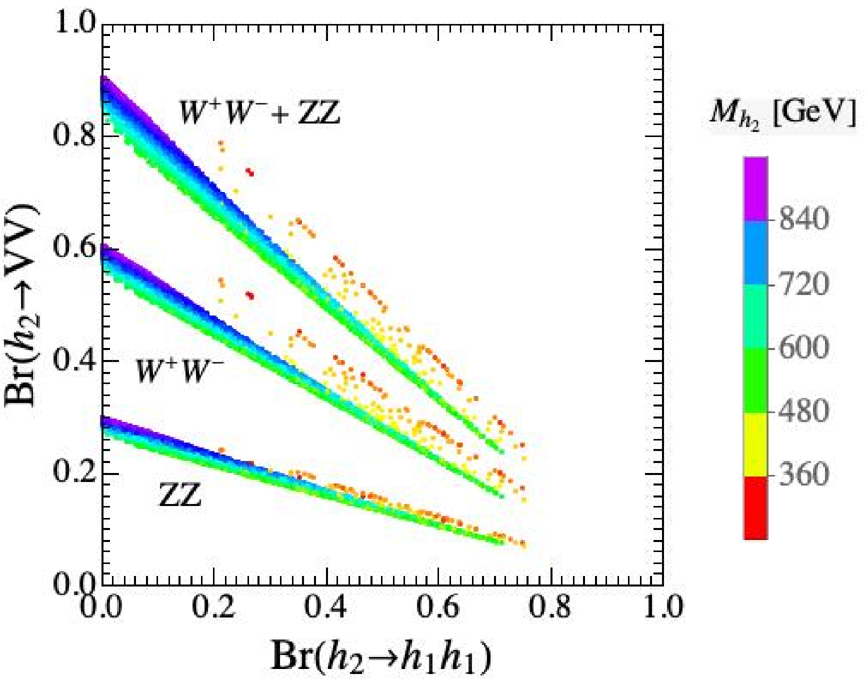
Dominant channels: di-boson (W^+W^-, ZZ), tt, and h_1h_1.

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.



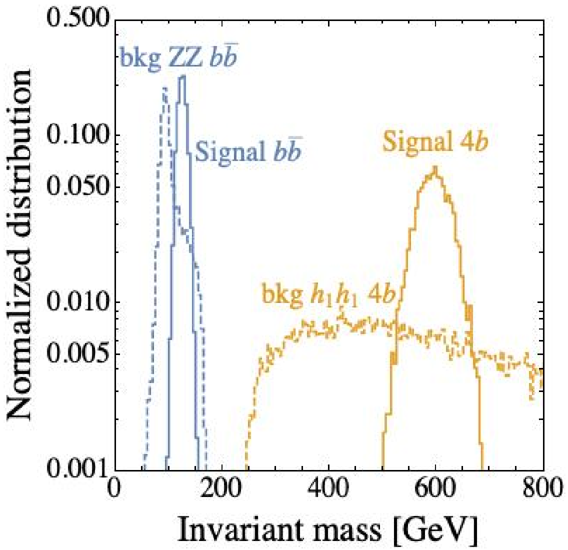
Muon collider: direct search

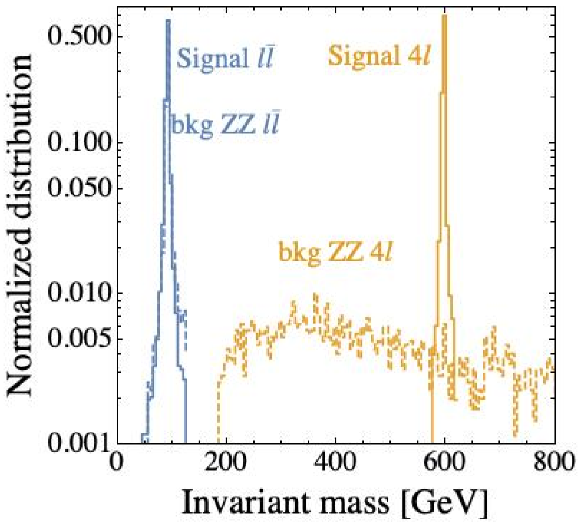
The h_2 -> $h_1 h_1$ -> *bbbb* channel:
Main background:

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

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

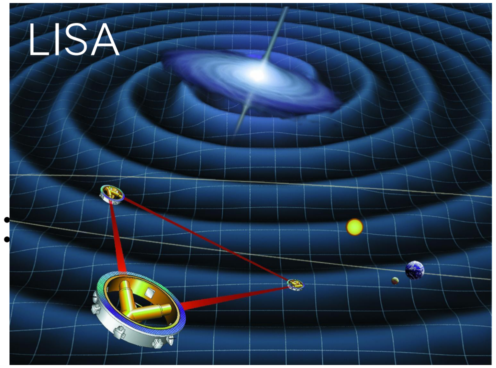
- Vector Boson Scattering *ZZ* -> $l^+l^-l^+l^-$.





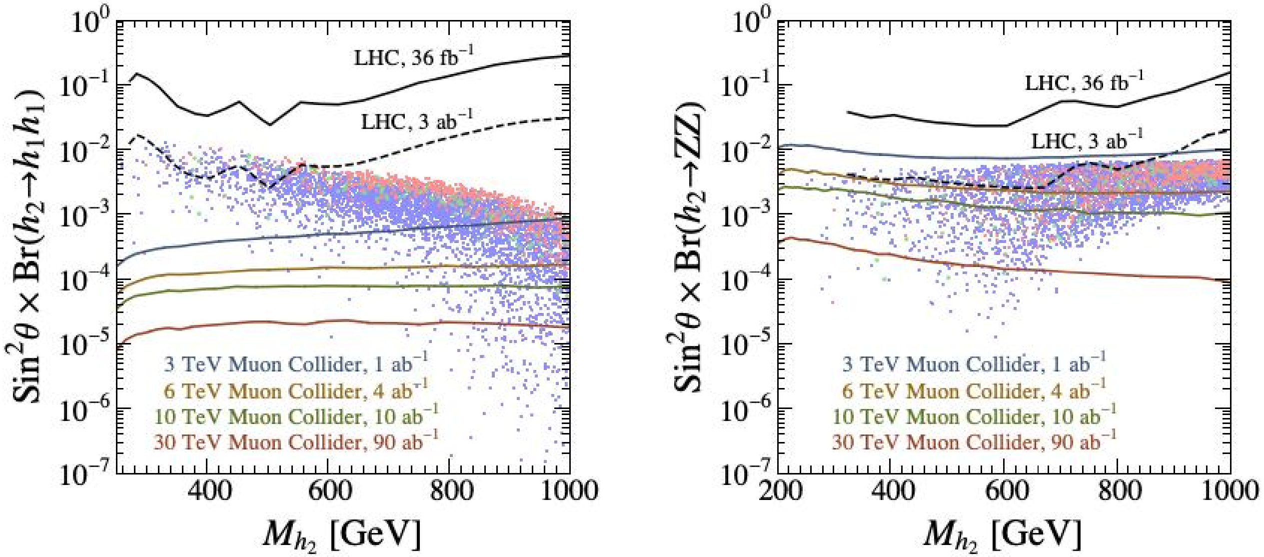
Muon collider: direct search

The collider search and gravitational wave detection are complementary!



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

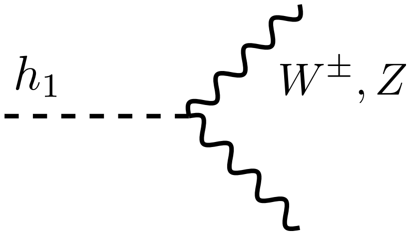
$$\mathrm{SNR} = \sqrt{\mathcal{T}\int_{f_{\min}}^{f_{\max}} df \left(\frac{\Omega_{\mathrm{GW}}(f)}{\Omega_{\mathrm{LISA}}(f)}\right)^2}$$

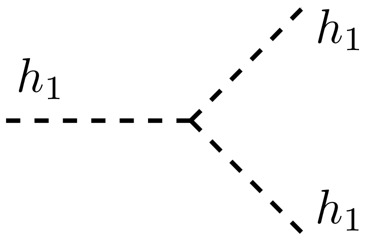


The diHiggs & diboson channels are complementary as well

Muon collider: indirect search

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



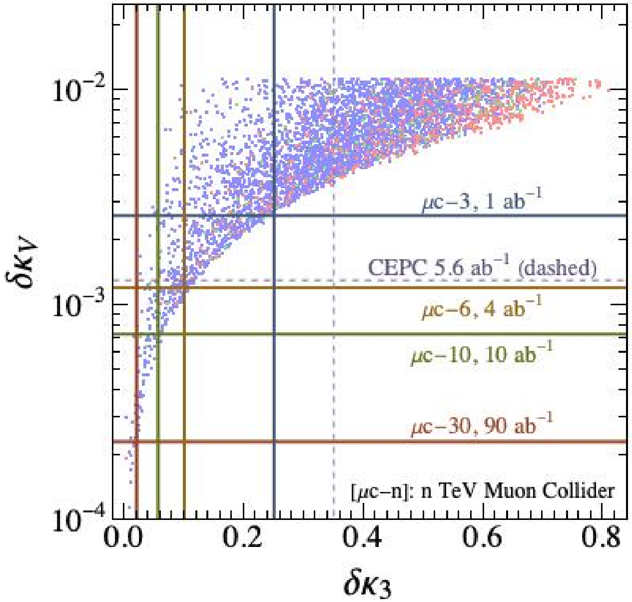


Defining deviations

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

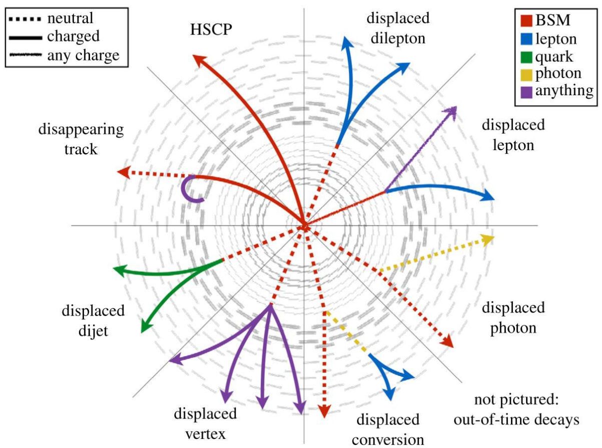
$$\delta\kappa_3 = \frac{\lambda_{h_1h_1h_1}}{\lambda^{\rm SM}_{h_1h_1h_1}} - 1$$

We can obtain the projections.



Long-lived Particles

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



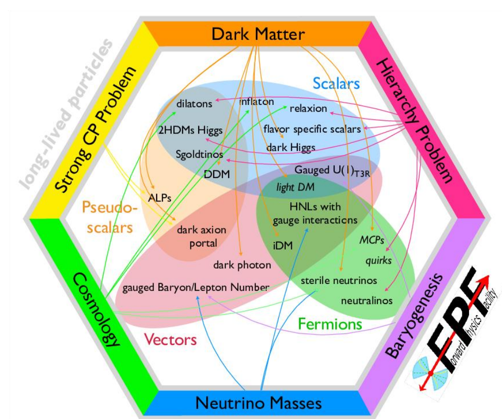


Figure from Albert De Roeck.

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.

LLP EWPT

From J. Kozaczuk, M. Ramsey-Musolf, J. Shelton, Phys.Rev.D 101 (2020) 11, 115035

The Higgs mixing is small

Approximate ***Z_2* symmetry**

EWPT can happen as **two-step transition**

$$(h = 0, s \simeq 0) \to (h = 0, s \neq 0) \to (h \neq 0, s \simeq 0),$$

There are analytical bounds from two-step transition

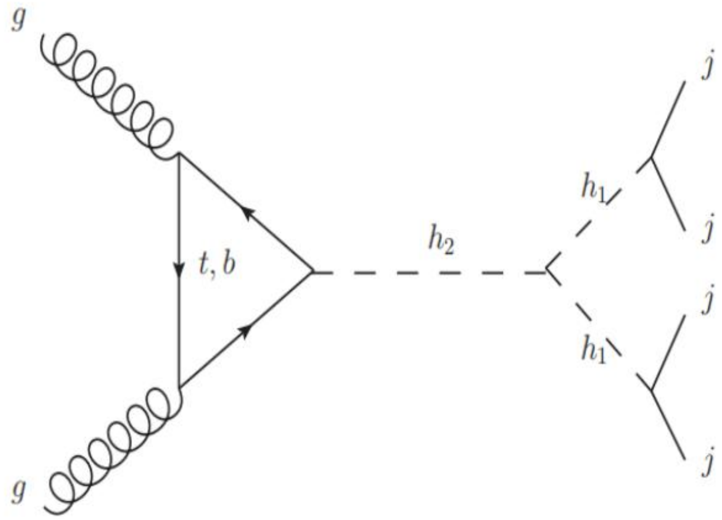
$$a_2 \gtrsim \frac{m_{h_1}^2}{4v^2}\frac{\Delta}{1-\Delta},$$

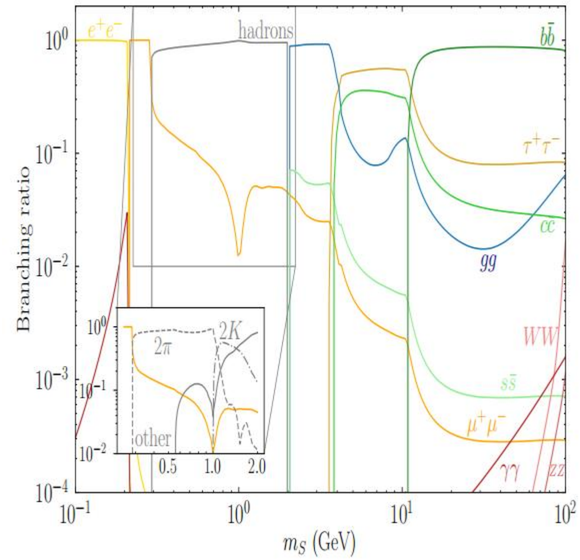
$$|b_3| > \sqrt{\frac{9}{4}b_4(2m_{h_1}^2 - a_2 v^2 + 2T_{\rm EW}^2\beta)},$$

$$b_4 \gtrsim \frac{m_{h_1}^4 \Delta}{4\lambda v^4(1-\Delta)},$$

Production processes

$$gg \to \mathrm{h}_{2(SM)} \to \mathrm{h}_1\mathrm{h}_1 \to 4j$$



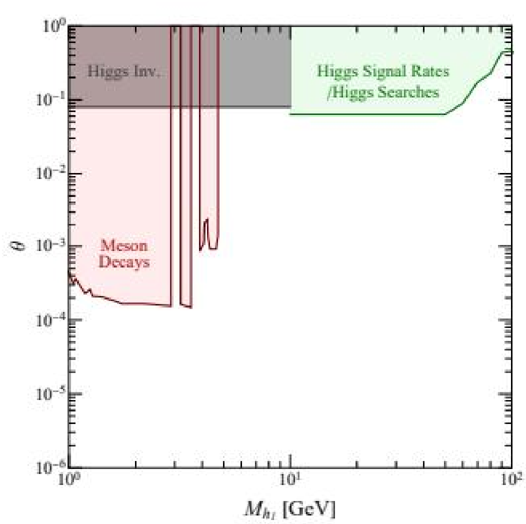


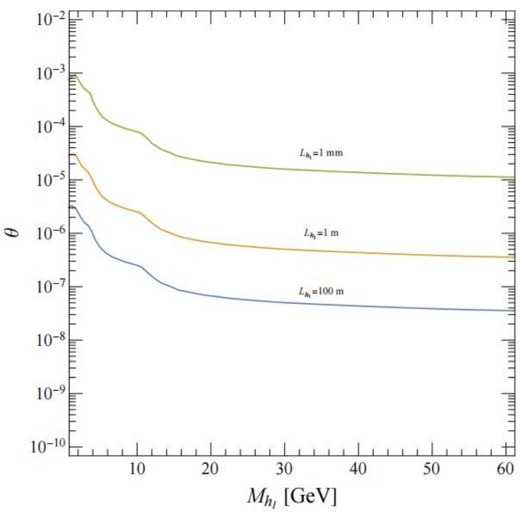
1st-order EWPT leads to large $BR(\mathrm{h}_2 \to \mathrm{h}_1\mathrm{h}_1)$.

h_1 decays into jets dominantly.

Long-lived Particles

The current limits on (M_{h_1},θ)

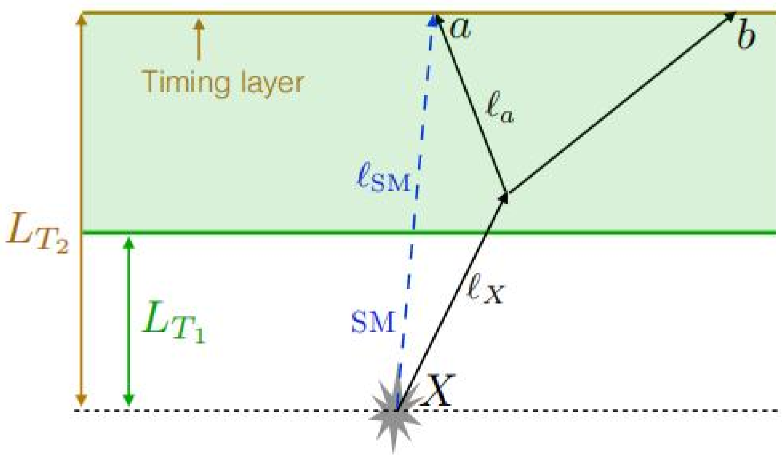


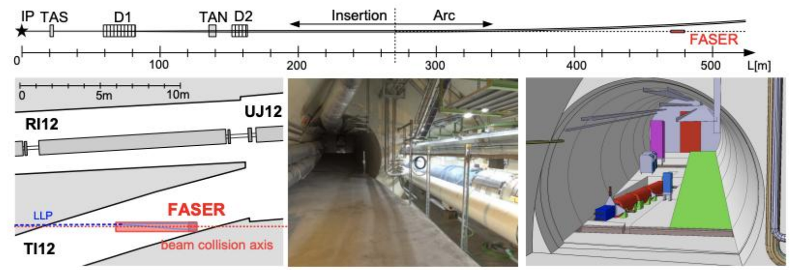


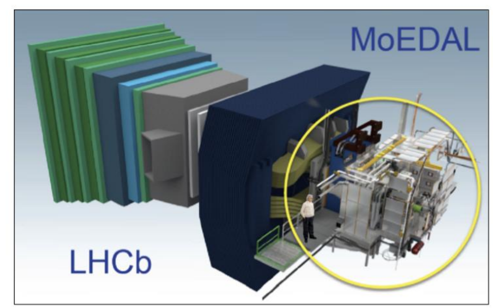
For M_{h_1}< 10 GeV, the current limits from rare meson decays at the LHCb, leads to h_1 as a long-lived particle (LLP).

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.

Connects to 1st-order EWPT

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

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

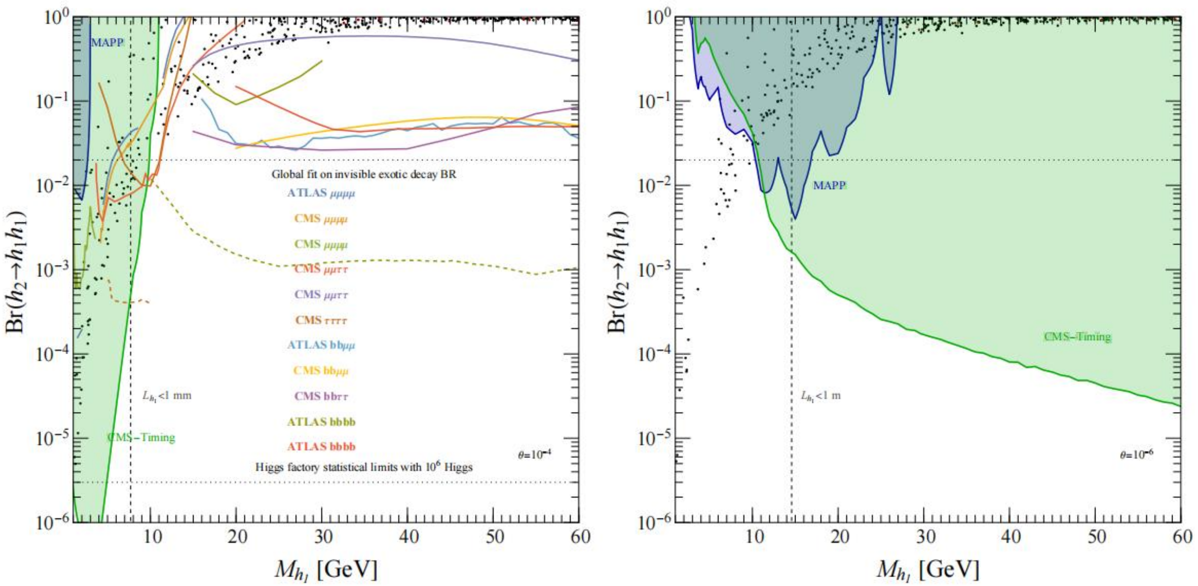
$$BR_{h_2\to h_1 h_1}(a_2, M_{h_1}) = \frac{\Gamma_{h_2\to h_1 h_1}}{\Gamma_{h_2}{}^{SM} + \Gamma_{h_2\to h_1 h_1}}$$

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

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

Sensitivity

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



No FASER sensitivity, too forward

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.

Conclusion

1^{st}-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 1^{st}-order EWPT from LLP signatures at the HL-LHC, and at a high-energy muon collider.

For heavy, strongly coupled scalar corresponding to 1^{st}-order EWPT, it can lead to direct and indirect signals at the muon colliders, and complementary GW signals.

For light, weakly coupled scalar corresponding to 1^{st}-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!

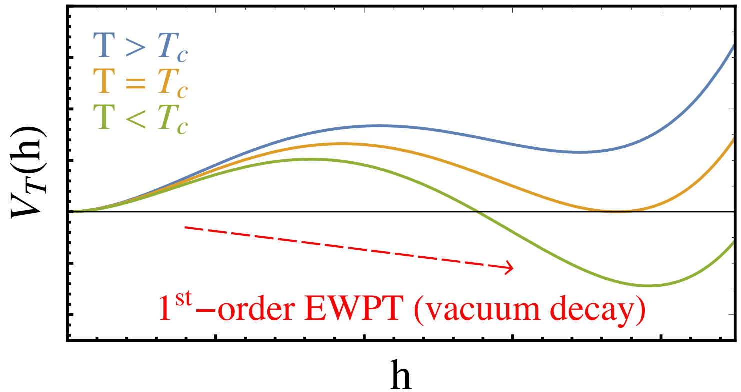
1st-order EWPT in the xSM

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?

Muon collider: direct search

Main background:

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

Kinematic Cuts:

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

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

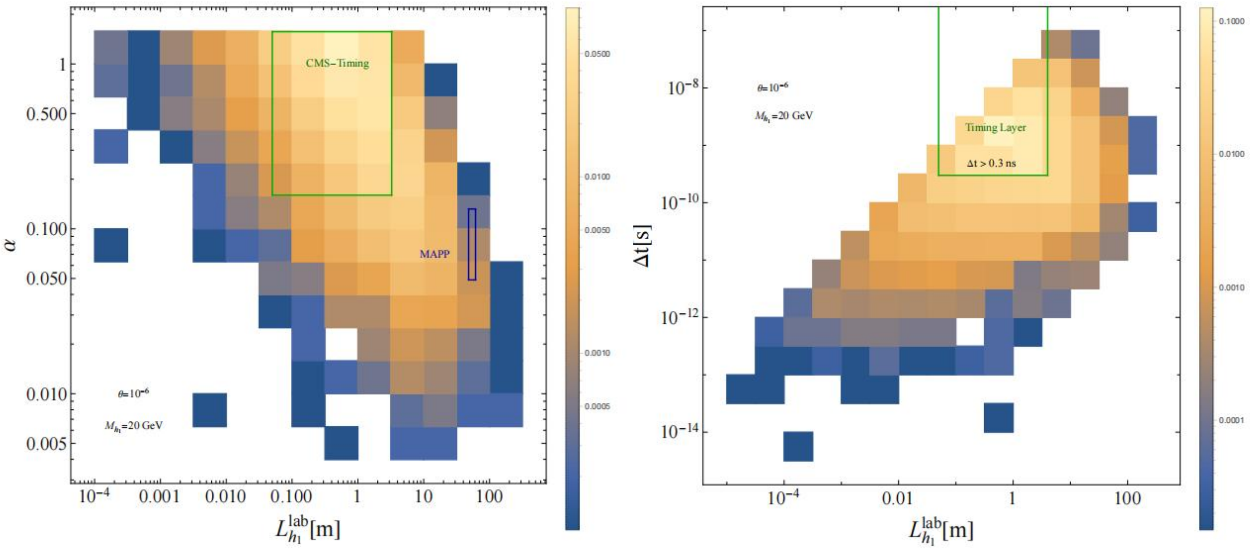
$$|M_{12} - M_h| < 15(10)\ GeV,\ |M_{34} - M_h| < 15(10)\ GeV$$

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

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

Detector efficiency

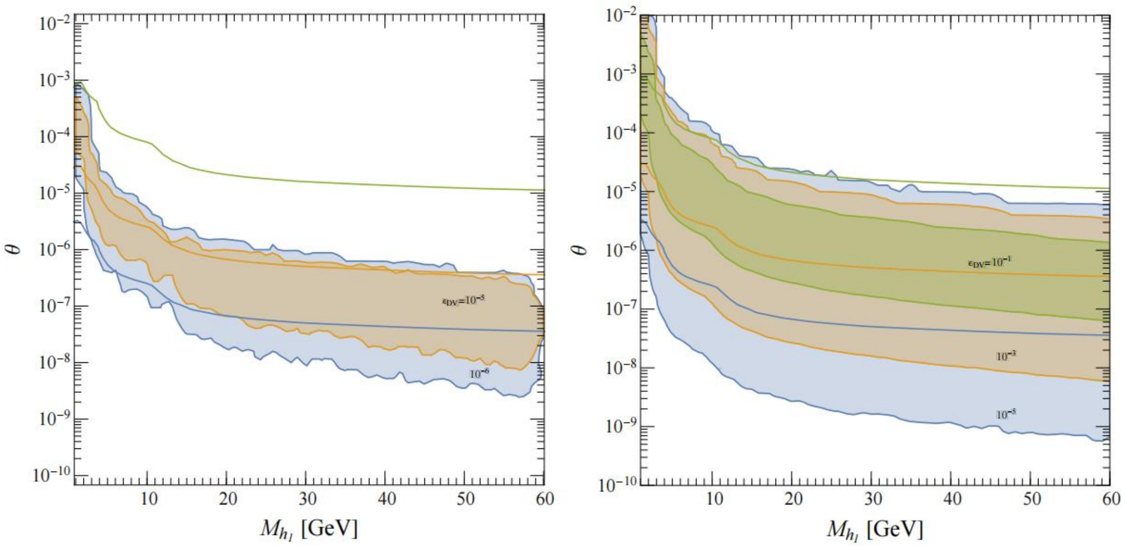
Detector efficiency is a function of geometrical coverage,



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,



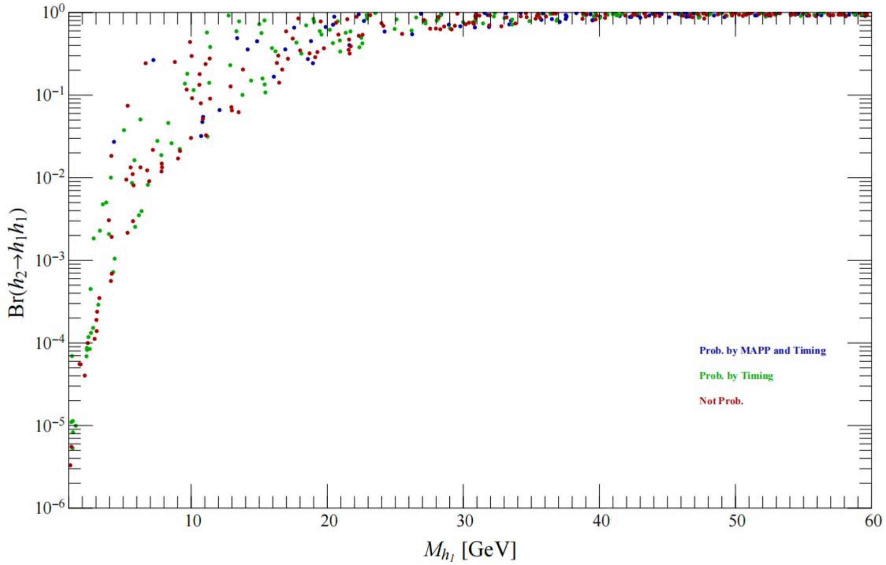
CMS-Timing has efficiency up to 10^{-1}.

MAPP has 10^{-4},

while negligible for FASER.

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.