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Higgs as a portal and BSM Exotic Higgs decays: Testing EWPT

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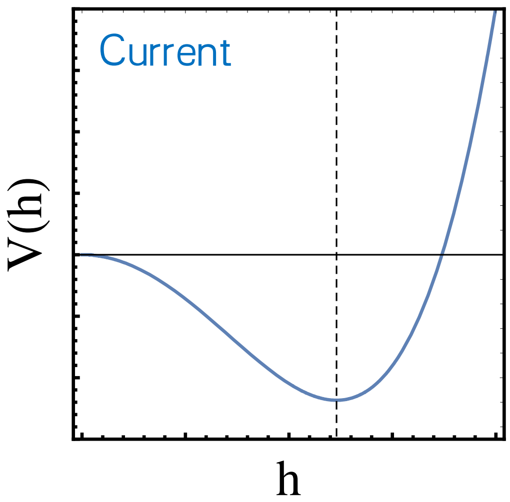
JHEP 04(2021) 015, Phys.Rev.D 105 (2022) 11, 115040
Higgs 2023

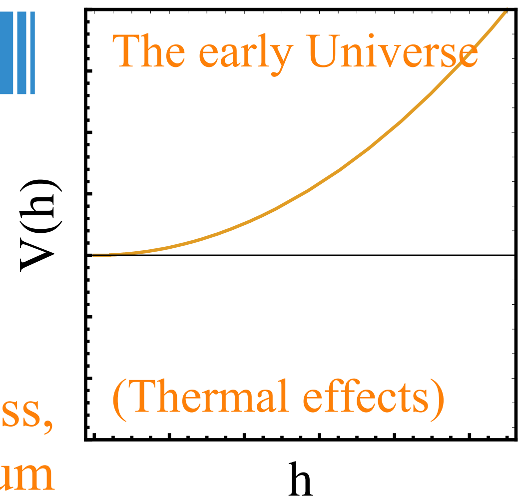
Phase transition in electroweak theory

EW symmetry restoration in the early Universe



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

Phase transition

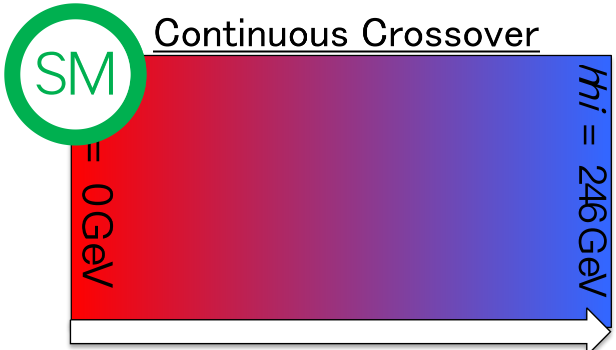


$SU(2)_L$ & $U(1)_Y$ bosons are massless,
True vacuum

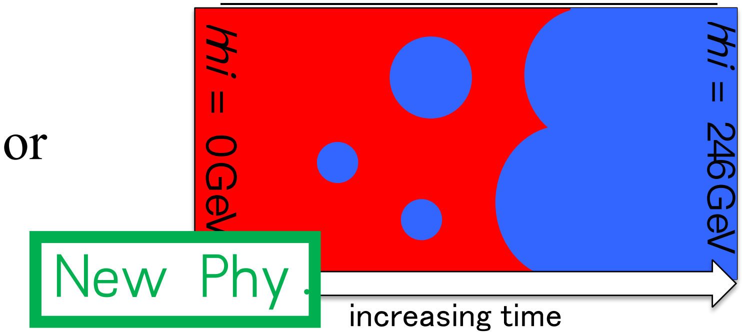
What is the pattern of EW phase transition (PT)?

It could be –

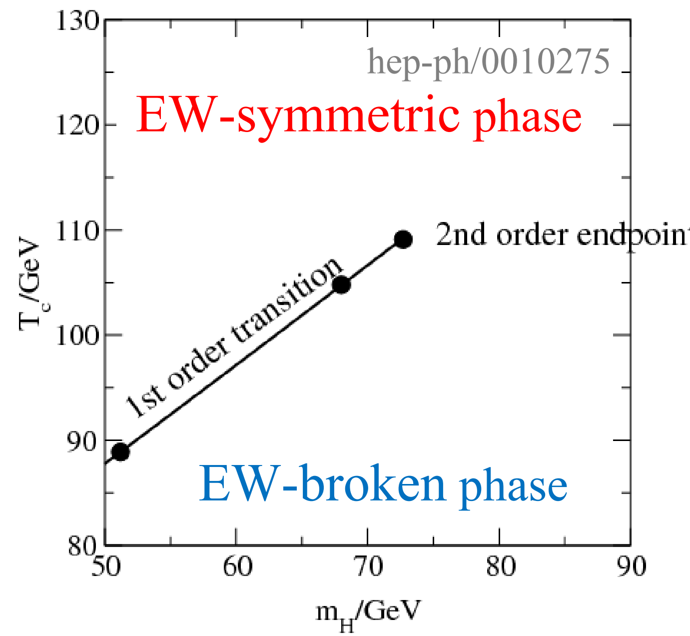
Figure from L.-T. Wang's talk in IHEP workshop



or



Lattice calculation shows the phase diagram ==>



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

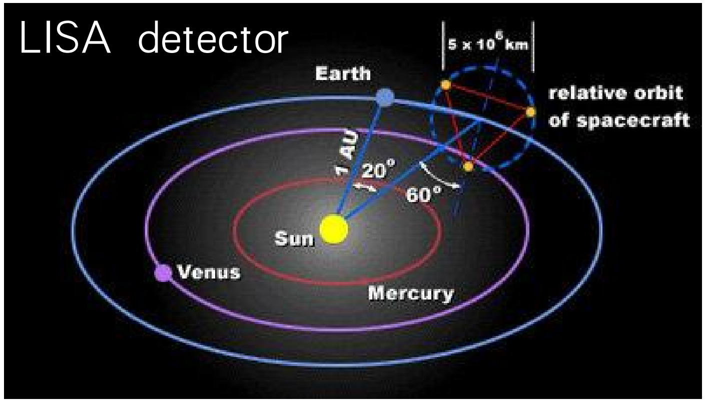
However, a 1st-order EWPT is more interesting.
(Needs new physics)

Why is a 1st-order EWPT interesting?

- It's the essential ingredient of the **EW baryogenesis**, to explain **Baryon Asymmetry**
- Acting as the background of very rich **dark matter** mechanisms
- Sources of the stochastic GWs:

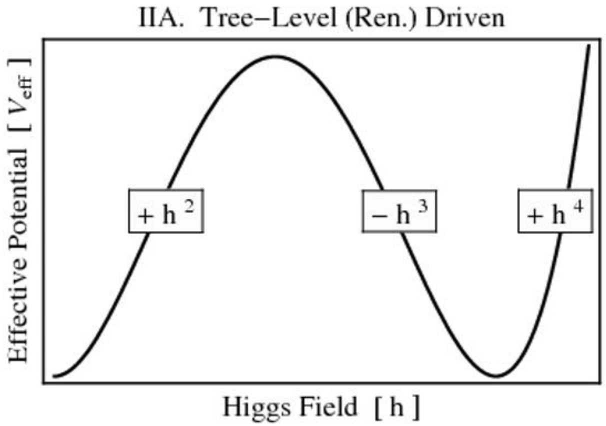
- Collision of the bubbles
- Sound waves in plasma
- Turbulence in plasma

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

$$H = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+h \end{pmatrix}, \quad S = v_s + s,$$

$$h_1 = s\cos\theta + h\sin\theta,$$
$$h_2 = -s\sin\theta + h\cos\theta,$$

Mass eigenstates & the mixing angle.
h_1 is **singlet-like**, h_2 is **SM-like**

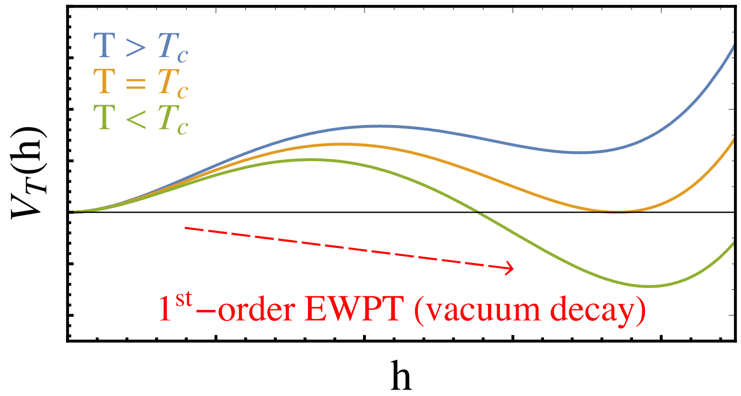
1^{st}-order EWPT in the xSM

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 --

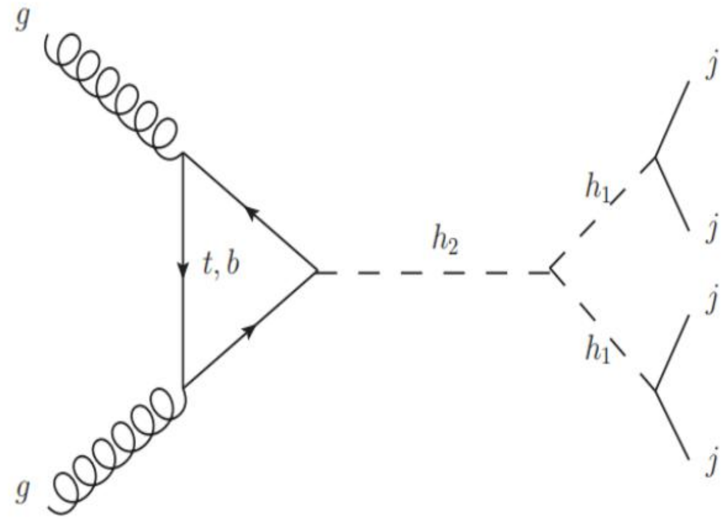


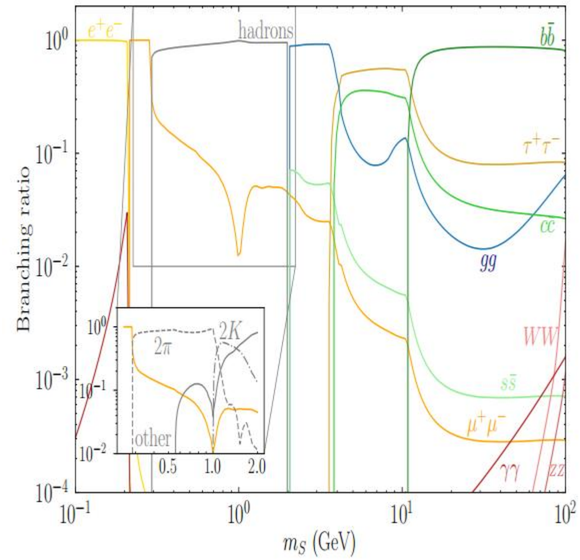
Question:

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

Higgs Exotic Decays

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

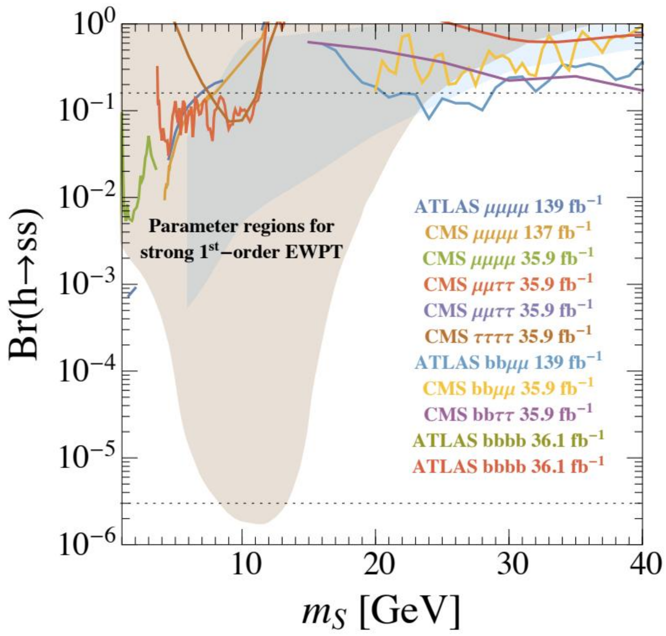


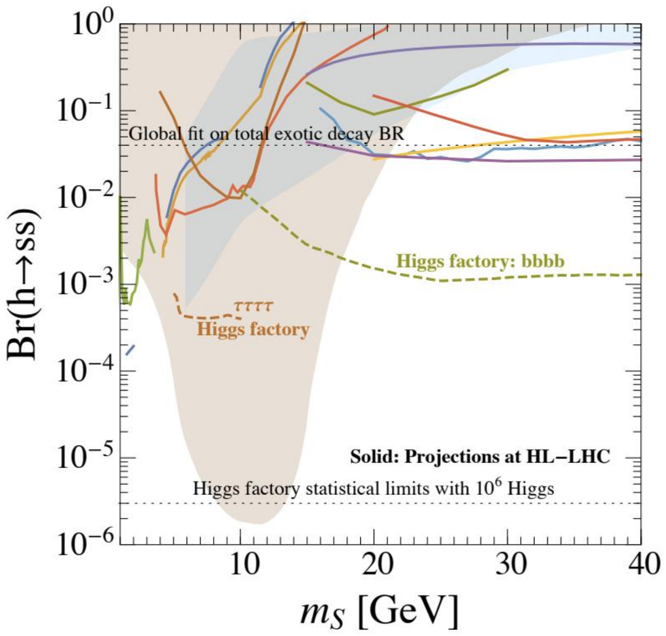


1st-order EWPT leads to large $BR(h_2 \rightarrow h_1 h_1)$.

h_1 decays into jets dominantly.

Current Bounds





- BSM Higgs Exotic Decays can be bounded by **Prompt** Searches at Colliders
- Mapped into the Parameter Space of the **1st-order EWPT**
- **1st-order EWPT** with low $Br(h_2 \to h_1 h_1)$ can not be reached even for Higgs factory
- **Can we reach even lower $Br(h_2 \to h_1 h_1)$?**

Carena, Kozaczuk, Liu, Ou, J.Ramsey-Musolf et al, 2203.08206
Kozaczuk, J.Ramsey-Musolf and Shelton, 1911.10210
Carena, Liu, Wang, 1911.10206

Long-lived Particles (LLP)

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

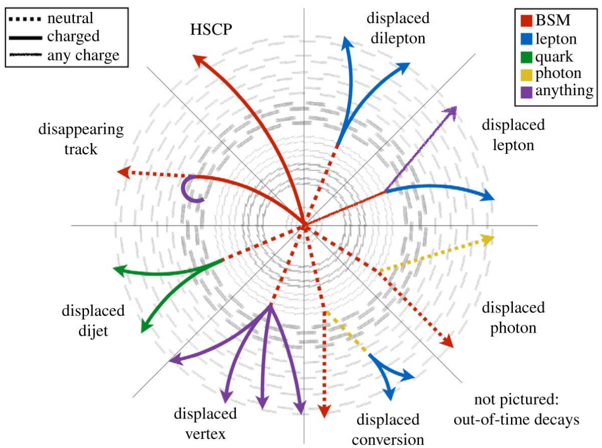


Figure from Albert De Roeck.

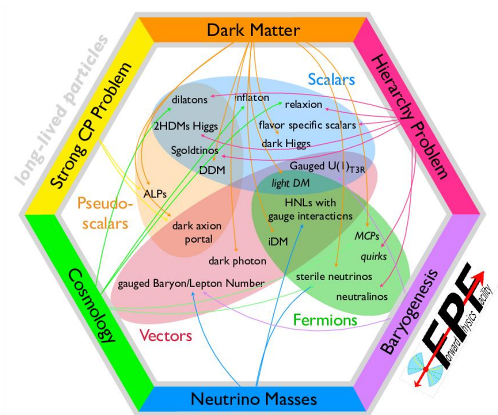
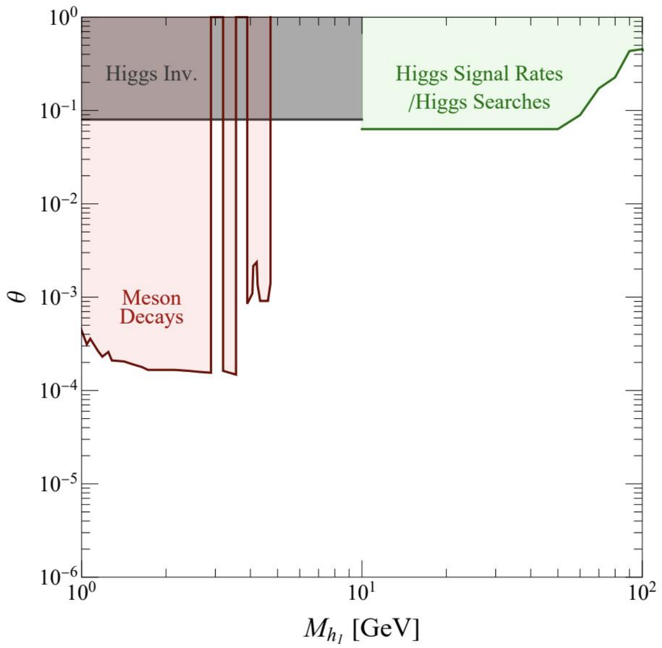


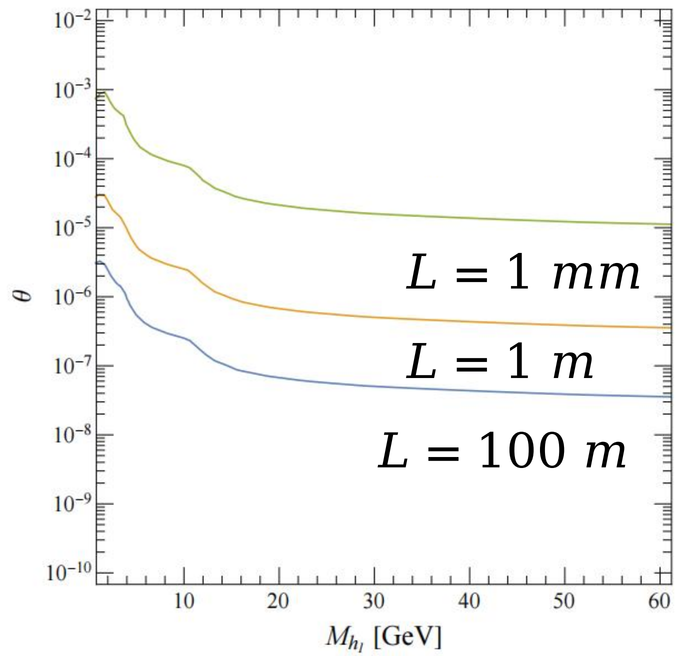
Figure from 2203.05090.

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

Current Limits on Higgs Mixing

The current limits on (M_{h_1}, θ)

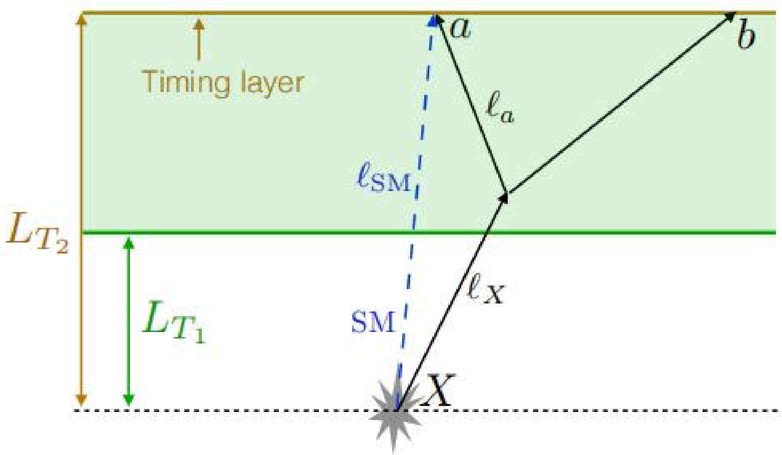


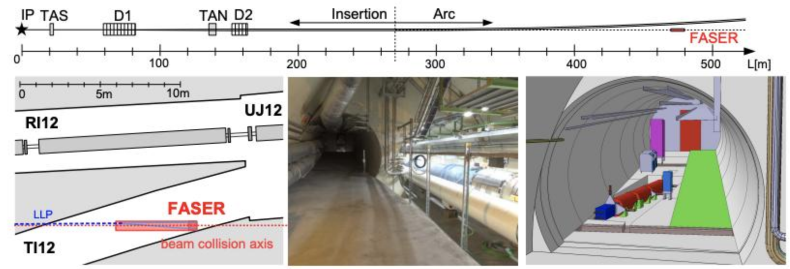


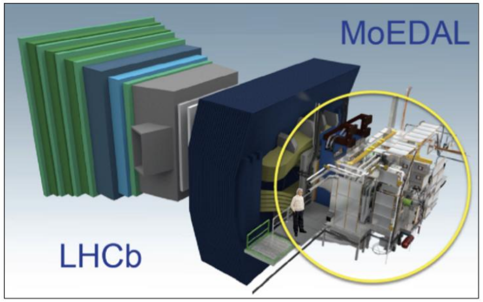
- For $M_{h_1} < 10$ GeV, the current limits from rare meson decays at the LHCb, leads to h_1 as a **long-lived particle** (LLP).

Detectors for LLPs

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





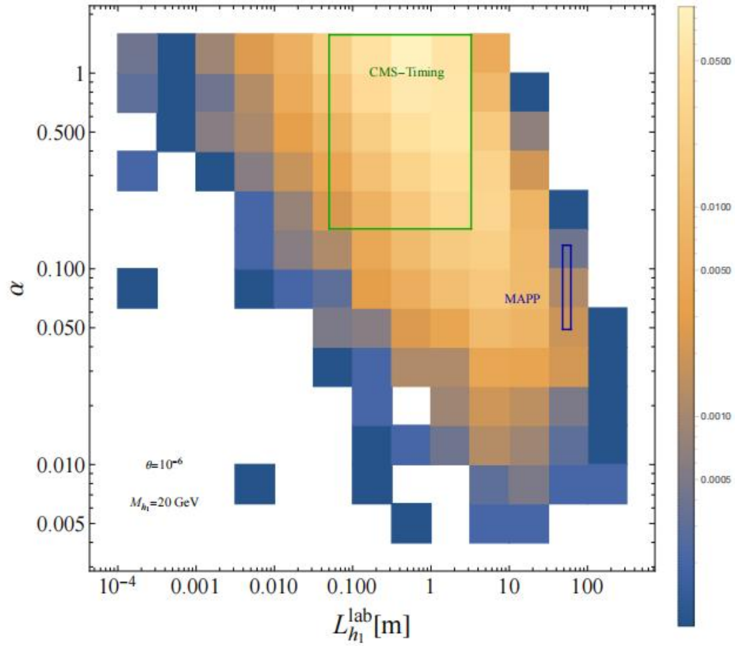


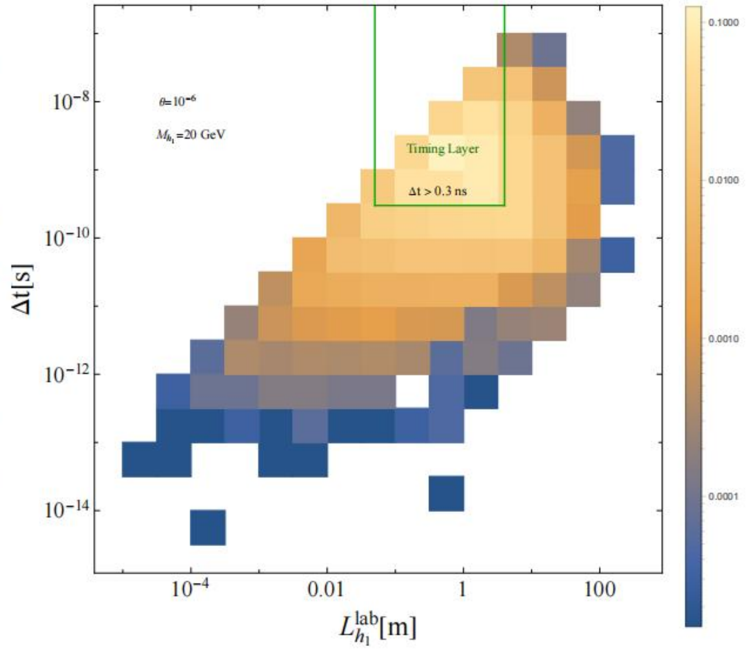
Many others, e.g. MATHUSLA and CODEX-b are in discussions.

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

Detector efficiency

Detector efficiency is a function of geometrical coverage,

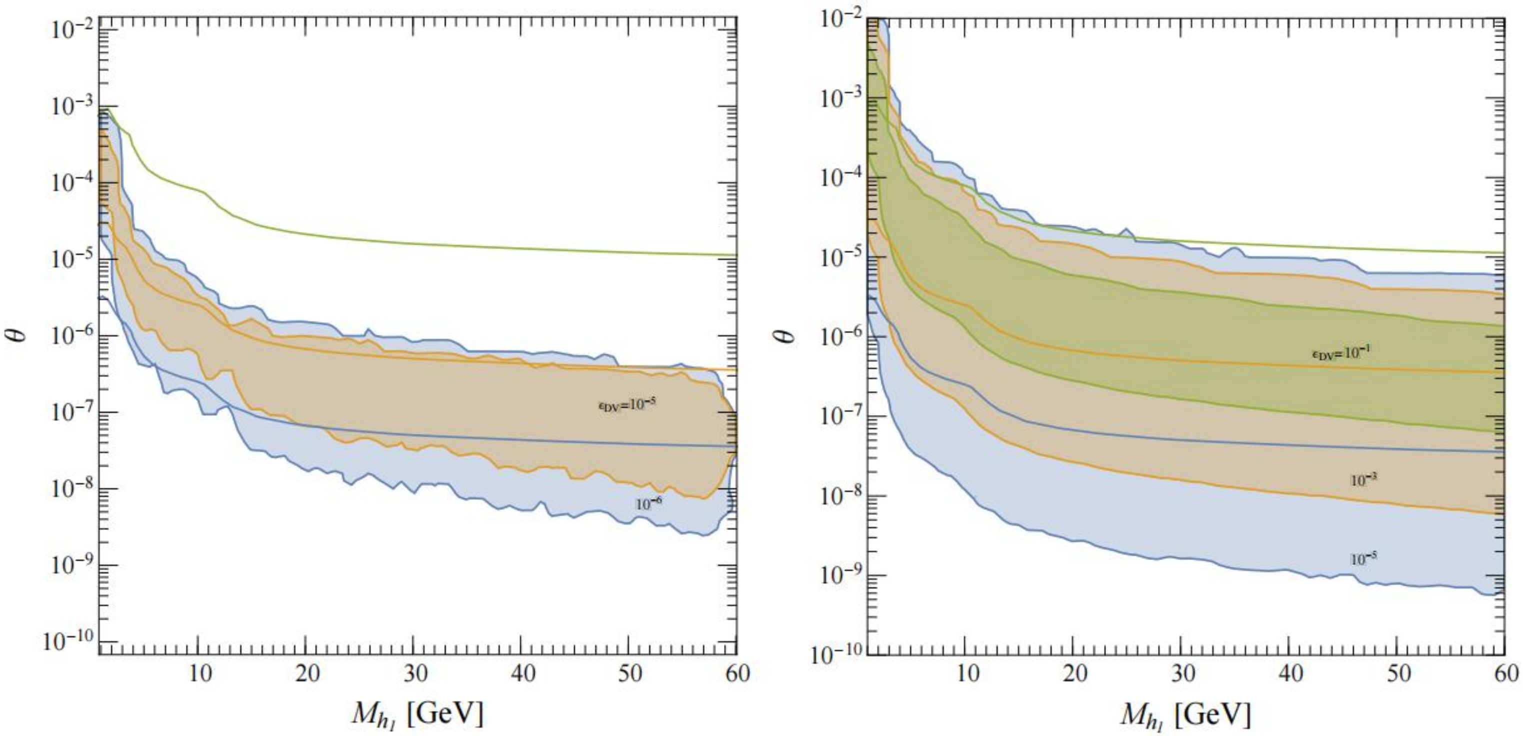




and resolution in time for timing detector.
CMS-Timing has large coverage, and good resolution.
MAPP has small coverage,
while negligible for FASER.

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.

1^{st}-order EWPT parameter space

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From J. Kozaczuk, M. Ramsey-Musolf, J. Shelton, 1911.10210

The Higgs mixing is small

Approximate **Z_2 symmetry**

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

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

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

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

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

Connects to 1st-order EWPT

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

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

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

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

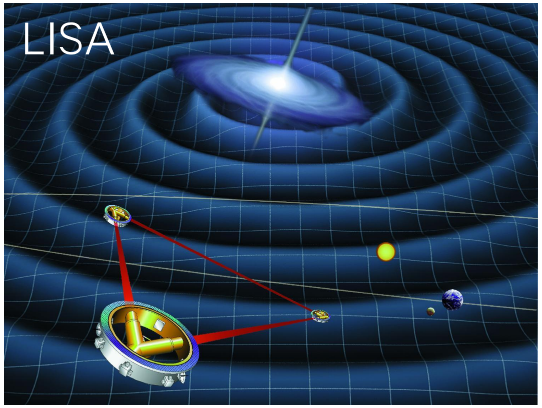
- LLP events are sensitive to $|H|^2 S^2$ couplings to trigger 1st-order EWPT.

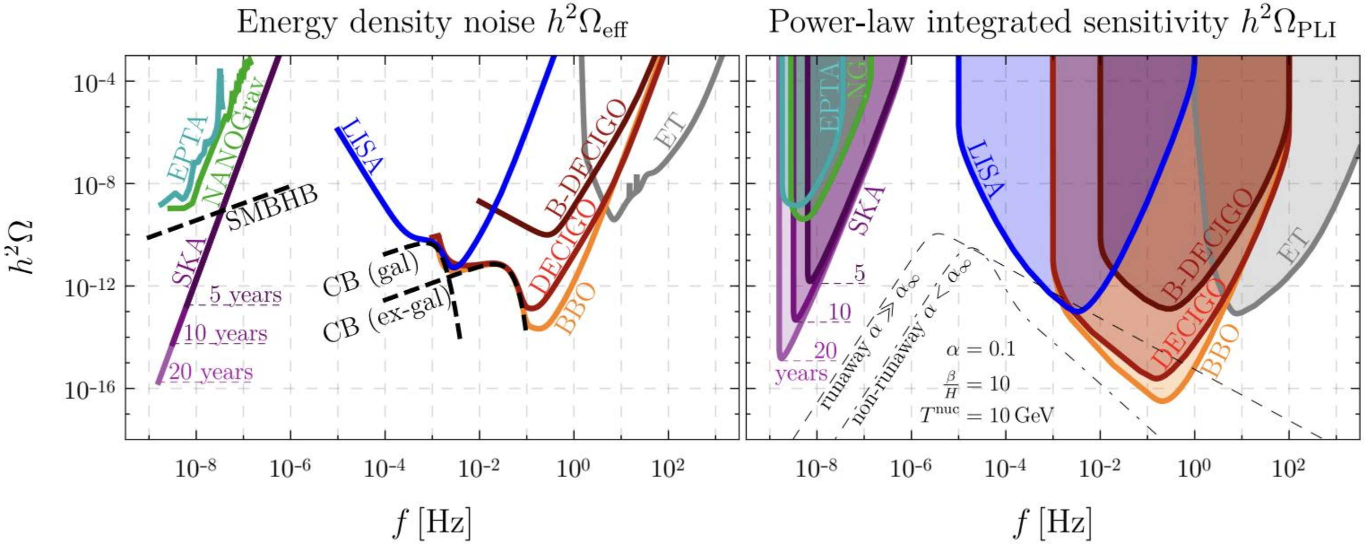
GW Signal

1st-order EWPT can lead to **Primodial GW signal**

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

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

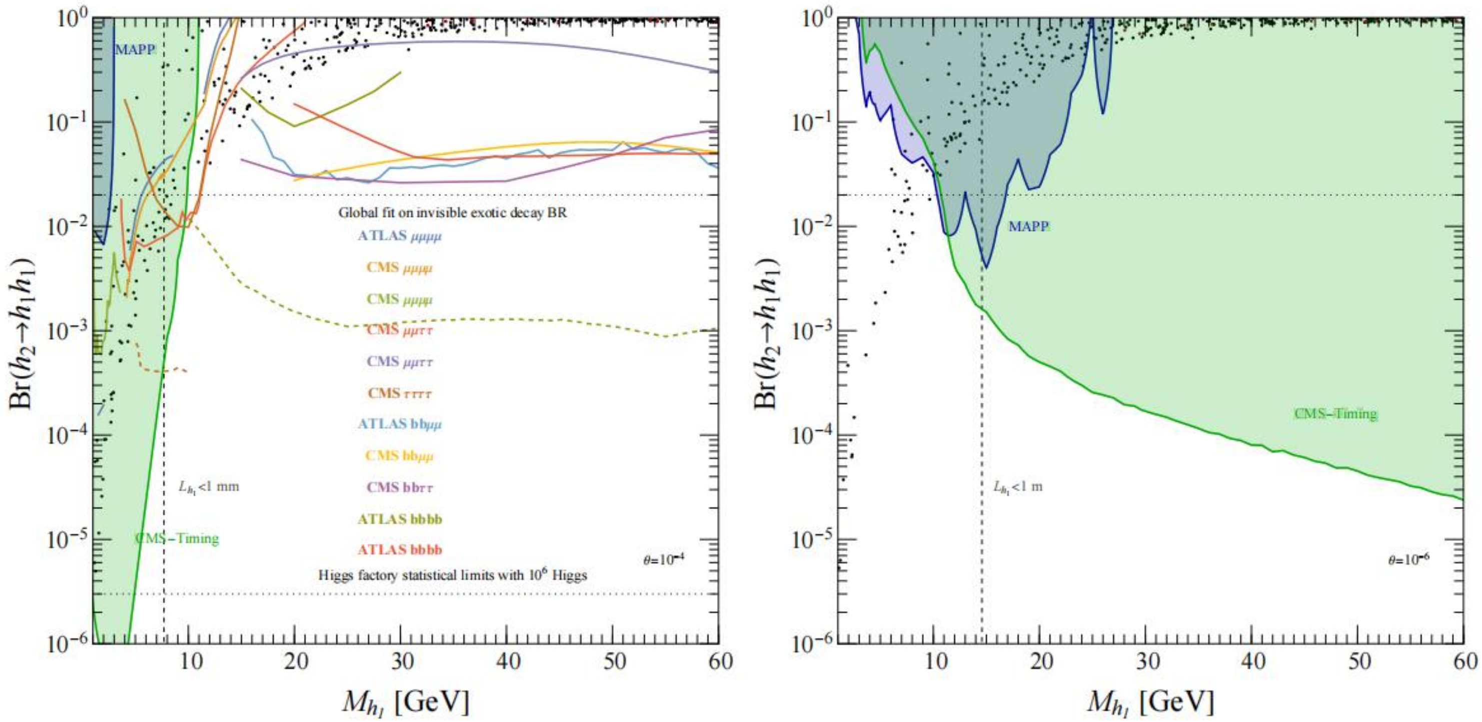




Breitbach, Kopp, Madge, Opferkuch, Schwaller, 1811.11175

Sensitivity

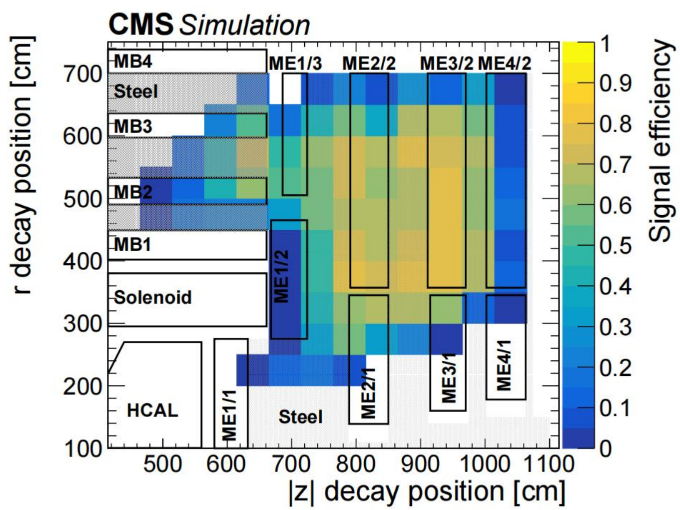
Fixed $\theta = 10^{-4}(left),\ 10^{-6}(right).$

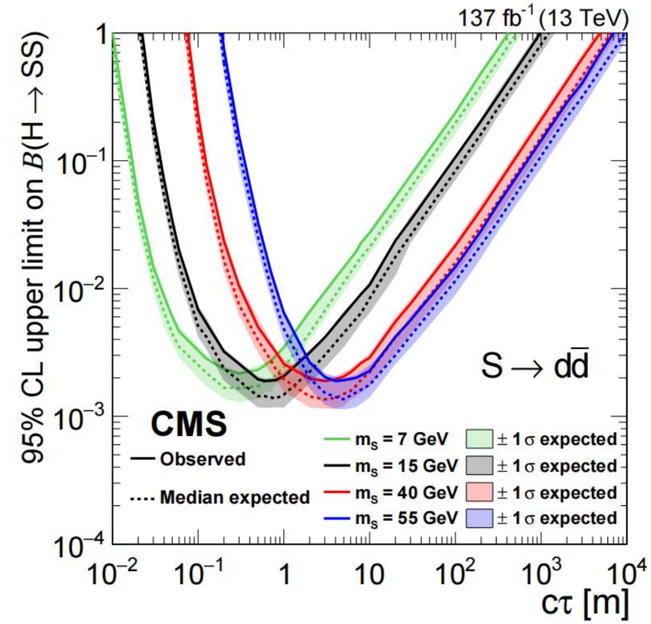


- No FASER sensitivity, No Enough Higgs from Meson decay
- **CMS-Timing** can probe large parameter space where the searches for **promptly Higgs exotic decays** can not reach.
- **MAPP** can only probe small parameter space
- No **GW signals!**
- **W.L., A.Y. and H. S., Phys.Rev.D 105 (2022) 11, 115040**

An Existing Search at the CMS

CMS-EXO-20-015





- Search for LLPs in the CMS endcap muon detectors
- Can be **recast** to test **1st-order EWPT,** **to be done**

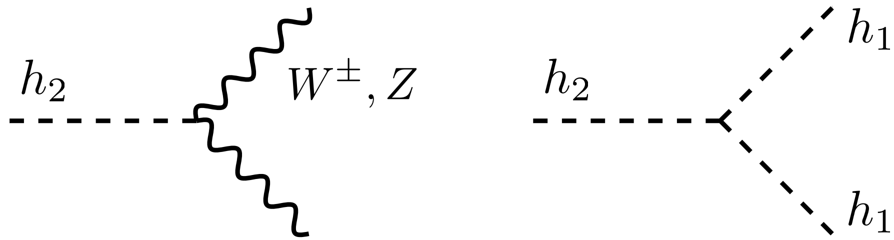
CMS Collaboration, 2107.04838

BSM Scalar Decays

Feature of the xSM

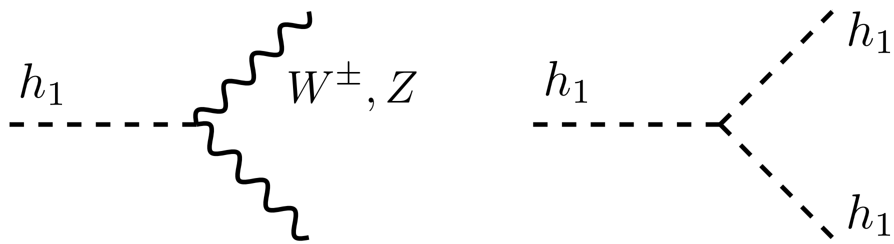
Two neutral scalars: h_1 (Higgs-like) and h_2 (singlet-like, TeV), with mixing angle θ;

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



Direct searches at the *pp* colliders

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



Indirect searches at the e^+e^- colliders

Muon collider!

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Precision and Energy Frontier!

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

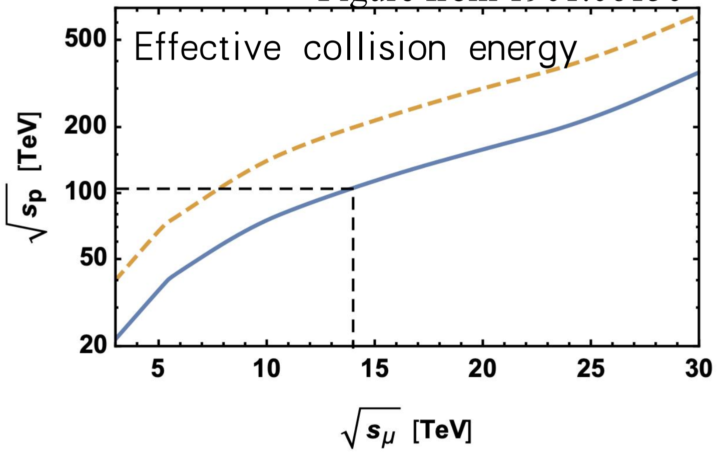
- **direct search**
- **indirect search**

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).

Figure from 1901.06150

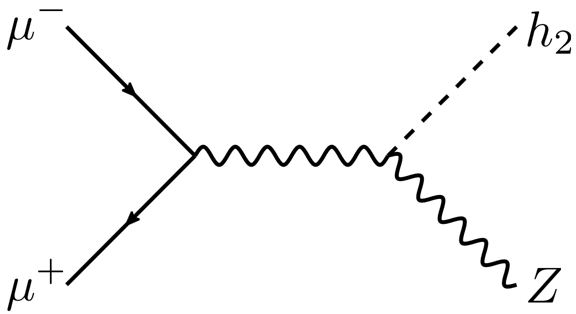


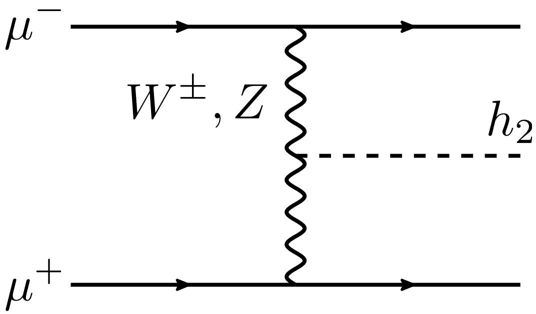
Compared to the pp machine:

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

Muon collider: direct search

Producing the h_2 at a muon collider

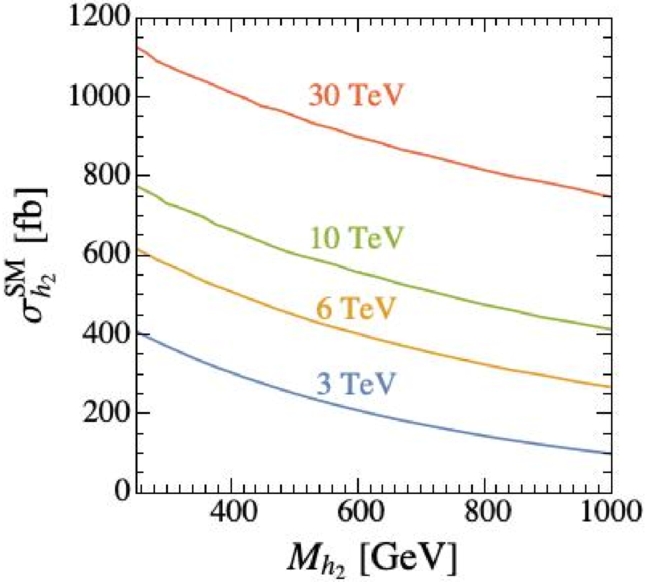




Zh_2 associated production & Vector Boson Fusion (VBF).

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

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



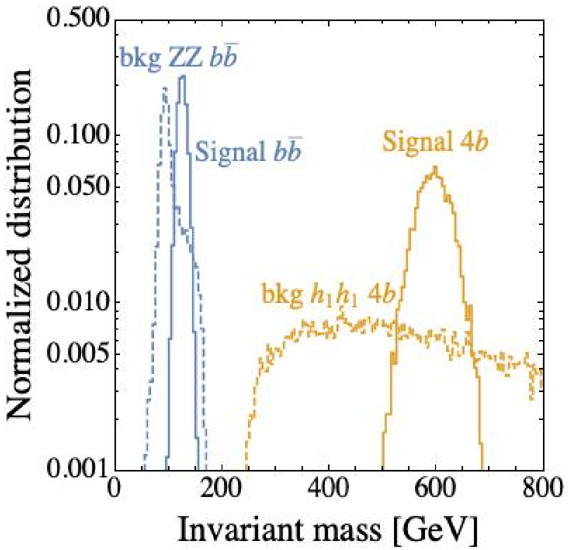
Muon collider: direct search

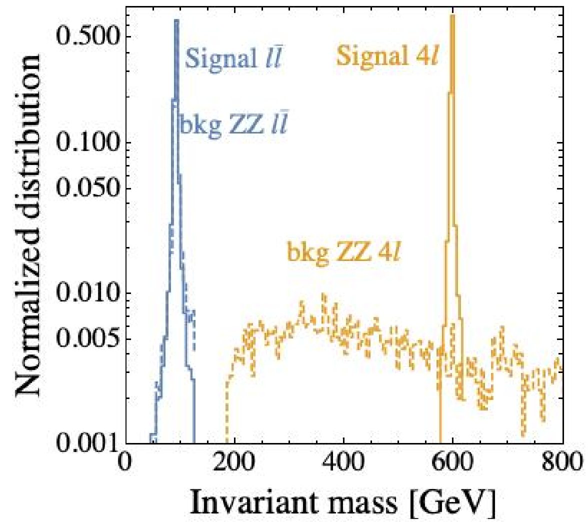
The h_2 -> $h_1 h_1$ -> *bbbb* channel:
Main background:

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

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

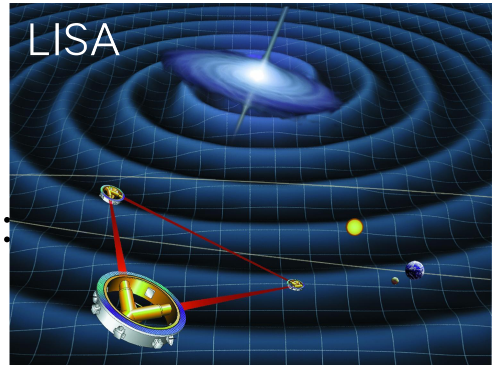
- Vector Boson Scattering *ZZ* -> $l^+l^-l^+l^-$.





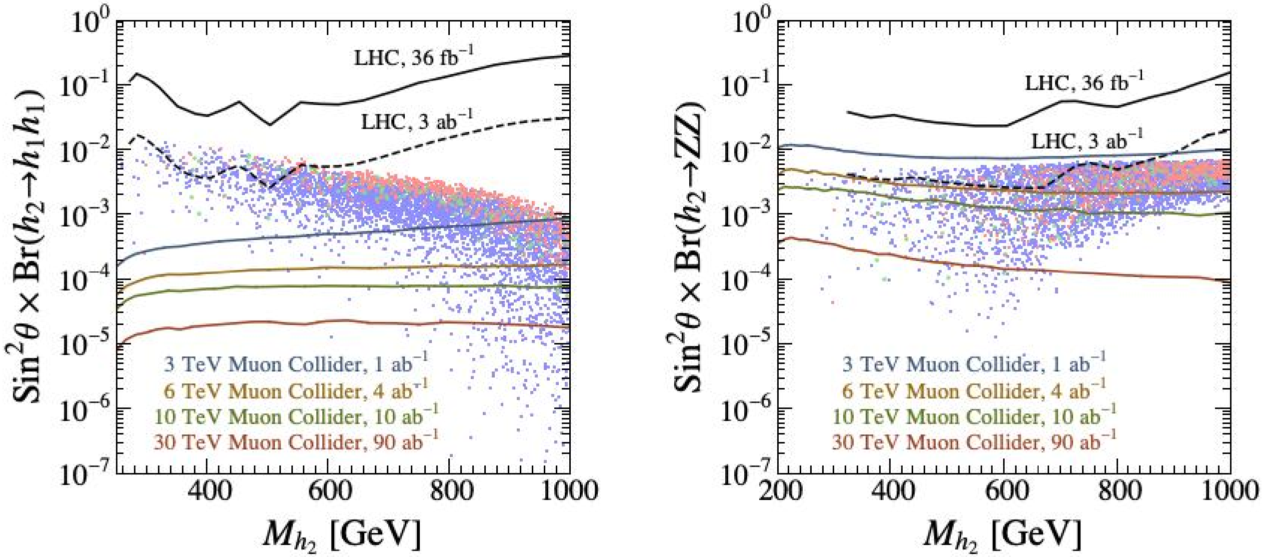
Muon collider: direct search

The collider search and gravitational wave detection are complementary!



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

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

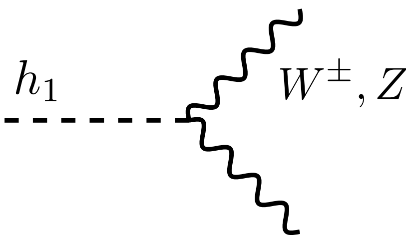


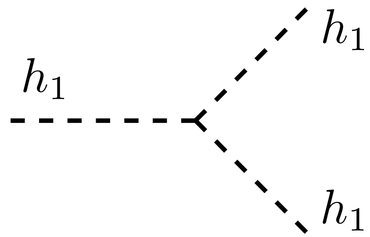
The diHiggs & diboson channels are complementary as well

W.L., K.X., JHEP 04(2021) 015

Muon collider: indirect search

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

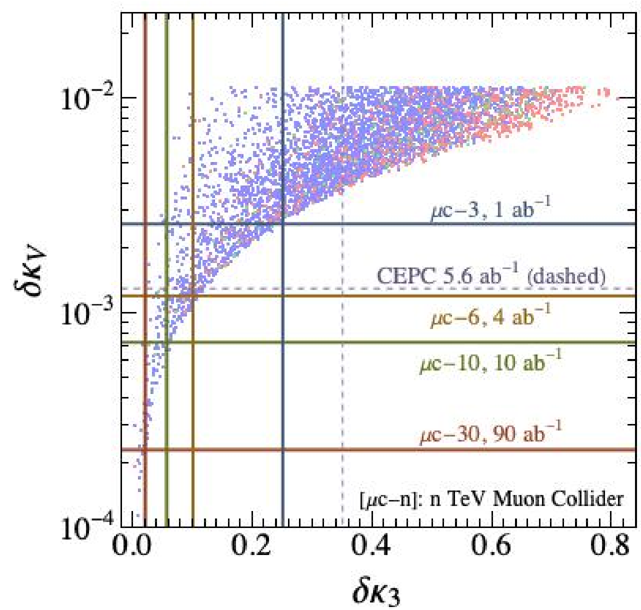




Defining deviations

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

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



We can obtain the projections.

W.L., K.X., JHEP 04(2021) 015

Conclusion

1st-order EW phase transition is interesting:

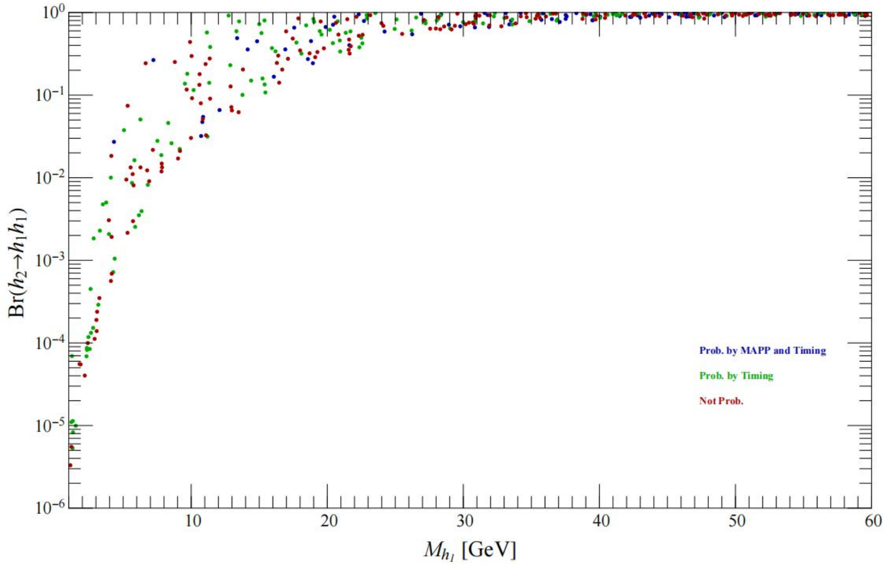
- Theoretically, it is the essential ingredient of EW baryogenesis, and can trigger very rich dark matter mechanisms;
- Experimentally, it yields detectable gravitational waves.

For **light, weakly coupled scalar corresponding to 1st-order EWPT,** we search for **Higgs Exotic decays to LLP signatures,** but **no detectable gravitational waves**.

For **heavy, strongly coupled scalar corresponding to 1st-order EWPT,** we search for **BSM Scalar Decays to direct and indirect signals** at the muon colliders**, and complementary GW signals**.

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.

Muon collider: direct search

Main background:

✓ Vector Boson Scattering *ZZ* -> *bbbb* (*llll*)and h_1h_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: $|M_{1234} - M_{h_2}| < 30(20)\ GeV,$

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

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.