Probing radiative electroweak symmetry breaking with colliders and gravitational waves

Ke-Pan Xie (谢柯盼)
Beihang University

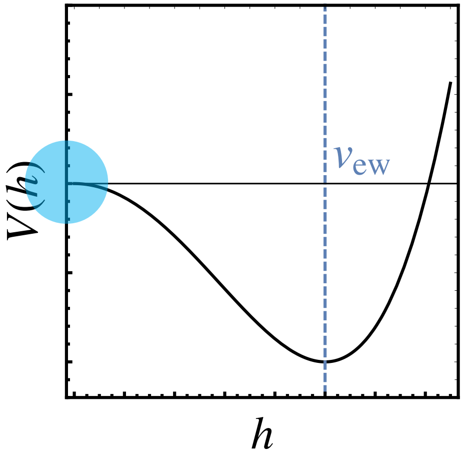
2024.7.13 @第17届粒子物理、核物理和宇宙学交叉学科前沿问题研讨会

with Wei Liu, arXiv: 2407.xxxxx (maybe next week)

Mystery of electroweak symmetry breaking

The Standard Model:

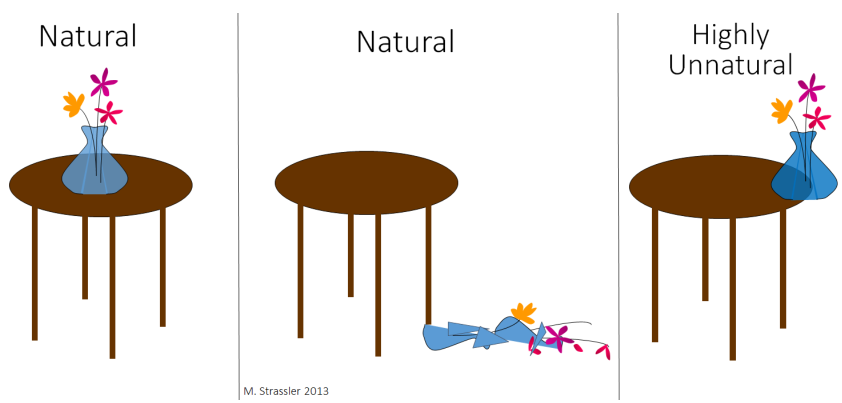
$$V(h) = \frac{\mu_h^2}{2} h^2 + \frac{\lambda_h}{4} h^4$$



Two issues:

1. What is the origin of $\mu_h^2 < 0$?
2. The hierarchy problem

$$\delta m_h^2 \sim \Lambda_{\rm NP}^2 \gg (100\ \mathrm{GeV})^2$$



... the flush toilet in a stately mansion.

S. Glashow

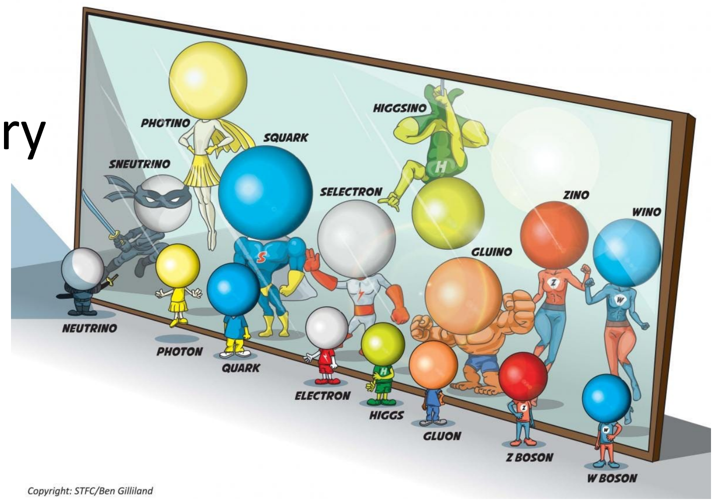
Efforts to solve the mystery

Supersymmetry

Cancellation guaranteed by symmetry

$$\delta\mu_{\mathrm{B}}^2 - \delta\mu_{\mathrm{F}}^2 = 0$$

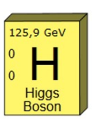
Prediction: *sparticles*



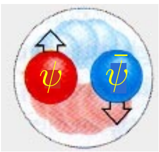
Composite Higgs

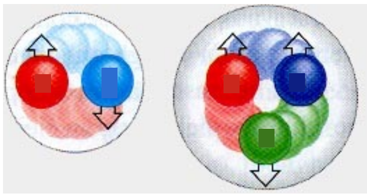
The Higgs boson is a pNGB, like π mesons in the QCD

Fundamental strong dynamics



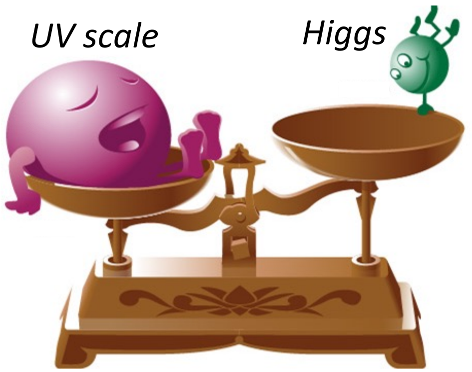
Zoom-in





Vector
??? TeV

Fermion
??? TeV



Prediction: *composite resonances*

Radiative symmetry breaking [This talk]

Radiative symmetry breaking

Originates from Coleman & Weinberg[Phys.Rev.D 7 (1973) 1888-1910]

Example: massless scalar QED

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + D_\mu S^\dagger D^\mu S - \lambda|S|^4$$

$S = (\phi + i\eta)/\sqrt{2}$ and $D_\mu = \partial_\mu + ieA_\mu$

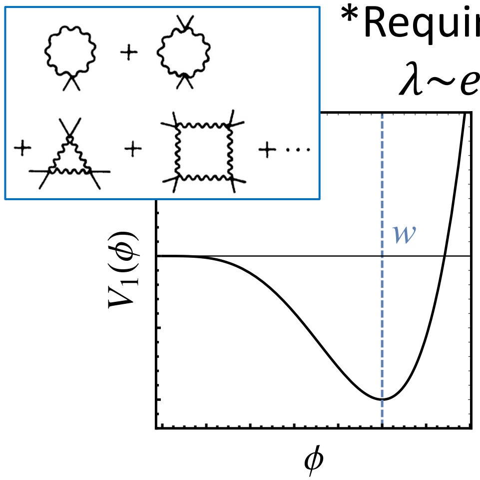
Radiative symmetry breaking

Originates from Coleman & Weinberg[Phys.Rev.D 7 (1973) 1888-1910]

Example: massless scalar QED

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + D_\mu S^\dagger D^\mu S - \lambda|S|^4$$

$S = (\phi + i\eta)/\sqrt{2}$ and $D_\mu = \partial_\mu + ieA_\mu$



*Requires $\lambda \sim e^4$

One-loop level

$$V_1(\phi) = \frac{3e^4}{32\pi^2}\phi^4\left(\log\frac{\phi}{w} - \frac{1}{4}\right)$$

Spontaneous symmetry breaking!

$m_\phi = \sqrt{6}e^2 w/4\pi$ and $m_A = ew$

Radiative symmetry breaking

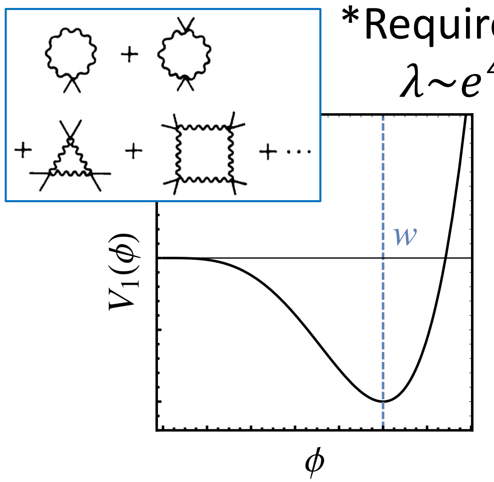
Originates from Coleman & Weinberg[Phys.Rev.D 7 (1973) 1888-1910]

Example: massless scalar QED

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + D_\mu S^\dagger D^\mu S - \lambda|S|^4$$

$S = (\phi + i\eta)/\sqrt{2}$ and $D_\mu = \partial_\mu + ieA_\mu$

*Requires $\lambda \sim e^4$



One-loop level

$$V_1(\phi) = \frac{3e^4}{32\pi^2}\phi^4\left(\log\frac{\phi}{w} - \frac{1}{4}\right)$$

Spontaneous symmetry breaking!

$m_\phi = \sqrt{6}e^2 w/4\pi$ and $m_A = ew$

Other perspectives

1. Scale anomaly, or conformal anomaly, or trace anomaly
2. Dimensional transmutation – from λ to w

Application to the EWSB

Get rid of the quadratic divergence

[Bardeen, FERMILAB-CONF-95-391-T; Meissner *et al*, PLB 660 (2008) 260-266]

Can it be **directly** applied to the SM Higgs? **No!**

1. EW W & Z induces: $\frac{m_h^2}{m_W^2} \sim \frac{g_W^2}{16\pi^2} \Rightarrow m_h \lesssim 10\ \mathrm{GeV}$
2. Including t: $V_1(h) \sim B_h h^4 \log h$, with $B_h \sim (9g_W^2 - 48y_t^2) < 0$

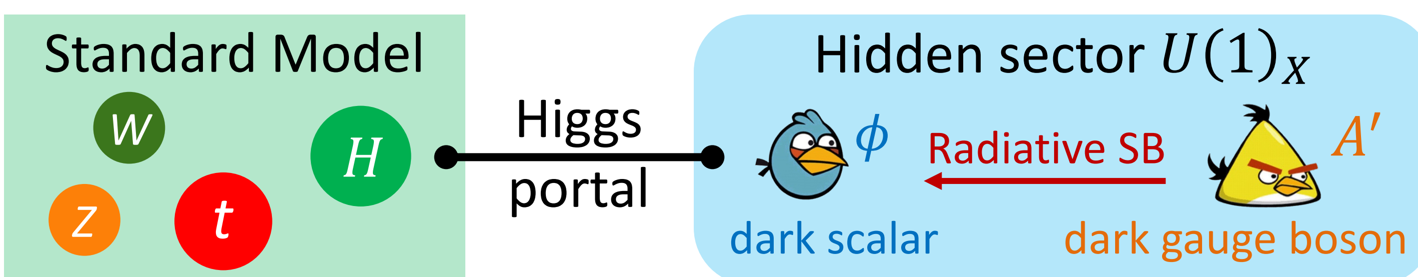
Application to the EWSB

Get rid of the quadratic divergence
[Bardeen, FERMILAB-CONF-95-391-T; Meissner *et al*, PLB 660 (2008) 260-266]

Can it be **directly** applied to the SM Higgs? **No!**

1. EW W & Z induces: $\frac{m_h^2}{m_W^2} \sim \frac{g_W^2}{16\pi^2} \Rightarrow m_h \lesssim 10~\mathrm{GeV}$
2. Including t: $V_1(h) \sim B_h h^4 \log h$, with $B_h \sim (9g_W^2 - 48y_t^2) < 0$

A next-to-minimal approach[Hempfling, Phys.Lett.B 379 (1996) 153-158]



The framework of a realistic model

Tree-level $V_0(H, S) = \lambda_h |H|^4 + \lambda_s |S|^4 - \lambda' |S|^2 |H|^2$
Only dimensionless parameters

The framework of a realistic model

Tree-level $V_0(H,S) = \lambda_h|H|^4 + \lambda_s|S|^4 - \lambda'|S|^2|H|^2$
Only dimensionless parameters

Loop-level, unitary gauge

$$V_1(h,\phi) = \underbrace{\frac{3g_X^4}{32\pi^2}\phi^4\left(\log\frac{\phi}{w_0} - \frac{1}{4}\right)}_{\text{Radiative symmetry breaking at } w_0 \gg 100\text{ GeV via } A'} - \frac{\lambda'}{4}h^2\phi^2 + \frac{\lambda_h}{4}h^4$$

$$\Big\downarrow \langle\phi\rangle \approx w_0$$

$$V_h(h) \approx -\frac{\lambda' w_0^2}{4}h^2 + \frac{\lambda_h}{4}h^4$$

The framework of a realistic model

Tree-level $V_0(H,S) = \lambda_h|H|^4 + \lambda_s|S|^4 - \lambda'|S|^2|H|^2$

Only dimensionless parameters

Loop-level, unitary gauge

$$V_1(h,\phi) = \underbrace{\frac{3g_X^4}{32\pi^2}\phi^4\left(\log\frac{\phi}{w_0} - \frac{1}{4}\right)}_{\text{Radiative symmetry breaking at } w_0 \gg 100\text{ GeV via } A'} - \frac{\lambda'}{4}h^2\phi^2 + \frac{\lambda_h}{4}h^4$$

$$\xrightarrow{\langle\phi\rangle \approx w_0}$$

$$V_h(h) \approx -\frac{\lambda' w_0^2}{4}h^2 + \frac{\lambda_h}{4}h^4$$

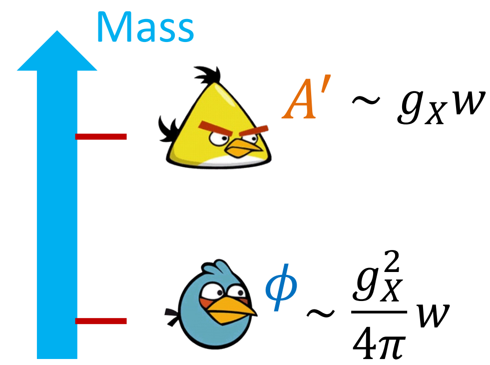
Taking $\lambda' \approx \frac{m_h^2}{w_0^2} \approx 1.6\times10^{-4}\times\left(\frac{10^4\text{ GeV}}{w_0}\right)^2$ and $\lambda_h \approx \frac{m_h^2}{2v_{\rm ew}^2} \approx 0.13$ --

Correct Higgs potential & EWSB get!

The prediction of this mechanism? [This talk]

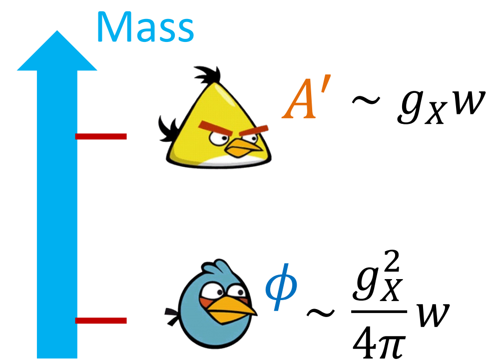
The distinctive feature

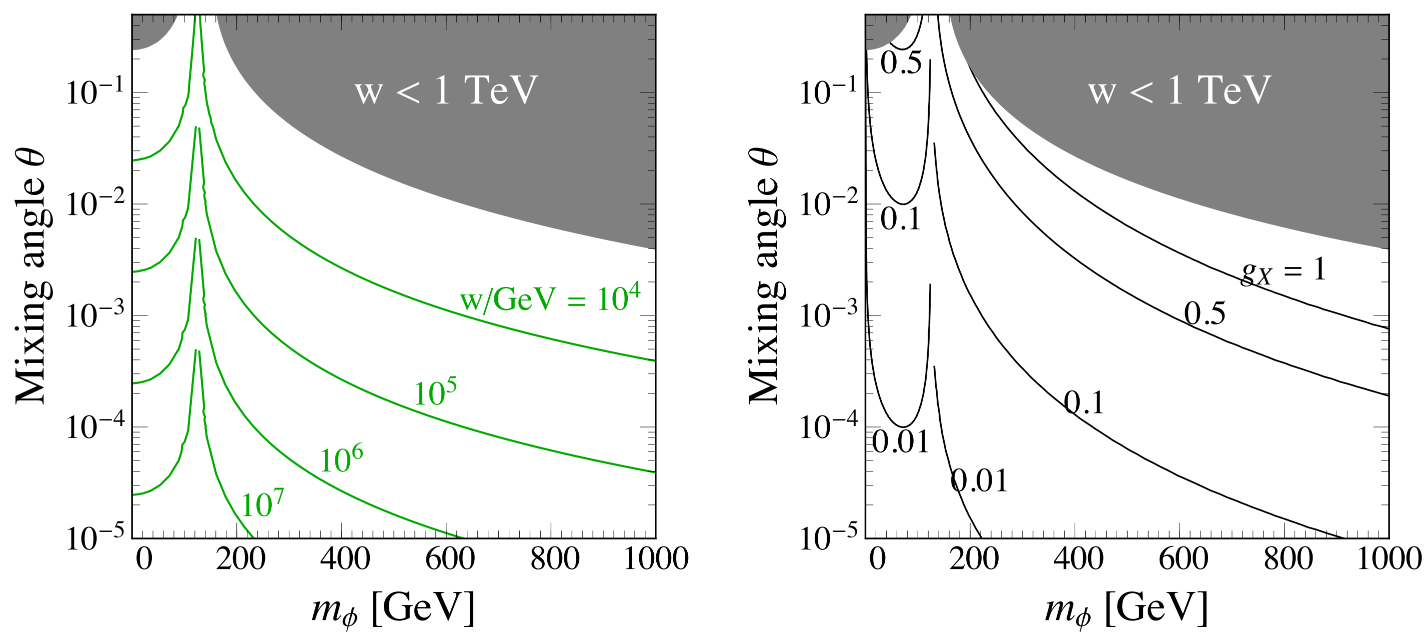
A **light** scalar compared to the NP scale
λ' portal -- h-ϕ **mixing**
Vacuum structure $(h,\phi)=(v_{\rm ew},w)$.
Only two free parameters!



The distinctive feature

A **light** scalar compared to the NP scale
λ' portal -- h-ϕ **mixing**
Vacuum structure $(h, \phi) = (v_{\rm ew}, w)$.
Only two free parameters!
Full expressions in our paper



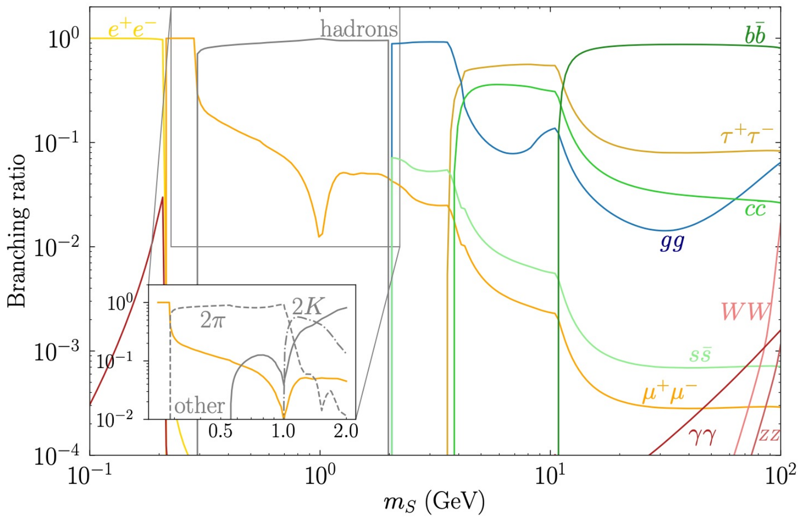


Searching for a singlet scalar mixing with the Higgs boson!

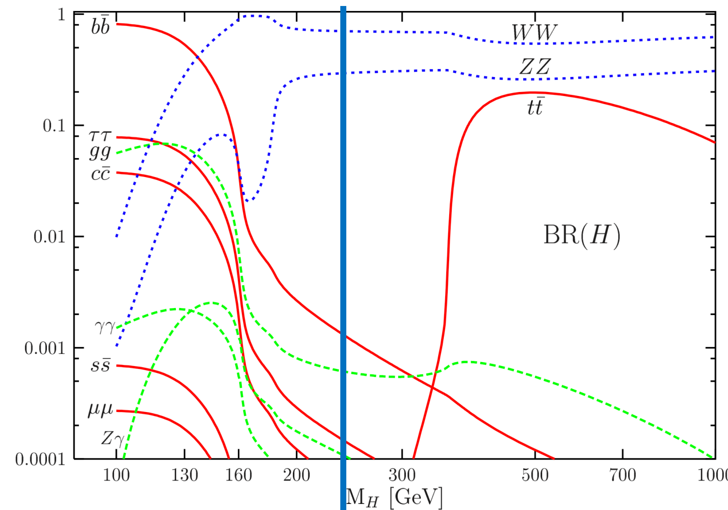
The particle experiment search

The decay branching ratios of ϕ

Gershtein *et al*, Phys.Lett.B 823 (2021) 136758



Djouadi, Phys.Rept. 457 (2008) 1-216



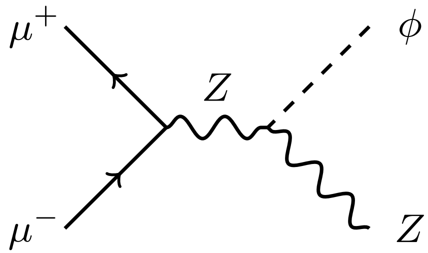
Need to include $\phi \to hh$

Landscape:

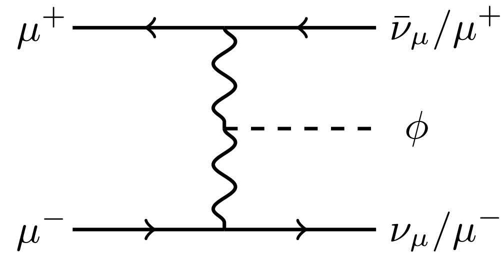
- $m_\phi \lesssim 4$ GeV: mesons, gg
- $4\ \text{GeV} \lesssim m_\phi \lesssim 10\ \text{GeV}$: $\phi \to \tau^+\tau^-$
- $10\ \text{GeV} \lesssim m_\phi \lesssim 160\ \text{GeV}$: $\phi \to b\bar{b}$
- $160\ \text{GeV} \lesssim m_\phi \lesssim 250\ \text{GeV}$: $\phi \to VV$, with $V = W^\pm, Z$
- $m_\phi \gtrsim 250$ GeV: $\phi \to VV$, hh, or even $t\bar{t}$

Simulations at a 10 TeV muon collider

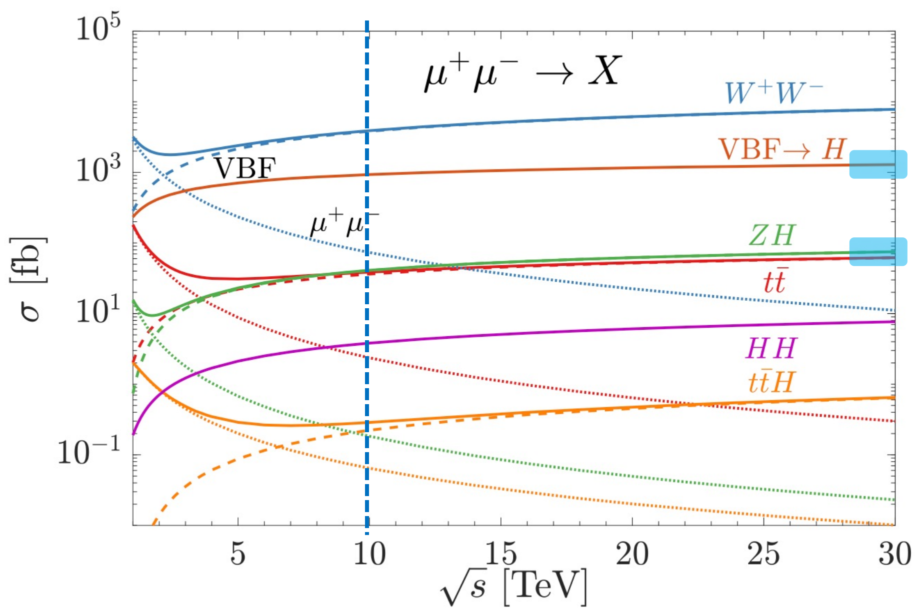
$Z\phi$ associated production



Vector boson fusion (VBF)



Cross section $\sigma = \sin^2\theta \times \sigma_h(m_\phi)$ ⟵ SM-like calculation

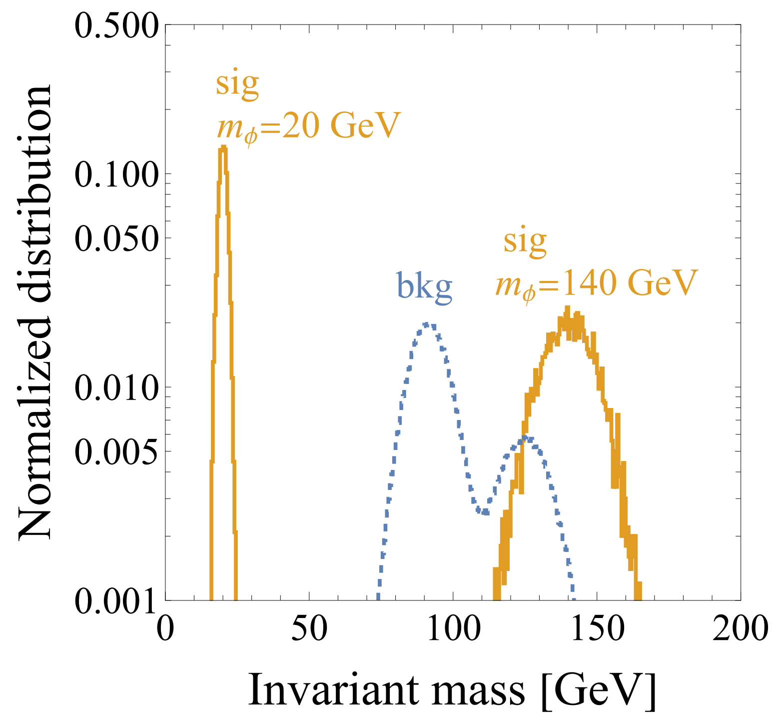


VBF dominates for multi-TeV colliders

Han *et al*, Phys.Rev.D 103 (2021) 3, L031301

The $\phi \to b\bar{b}$ channel

Parton-level simulation =
FeynRules model file +
MadGraph5 event generator +
10% jet energy smearing



Backgrounds

- VBF $\mu^+\mu^- \to jj$
- $\mu^+\mu^- \to Z/\gamma \to jj$ easily removed using $m(jj)$

Cuts:

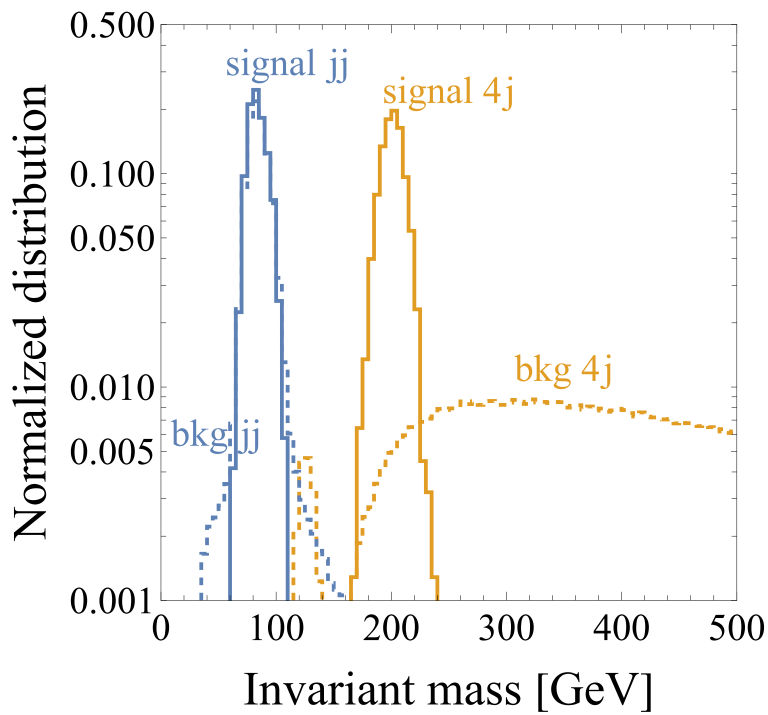
- Two jets with $p_T > 30$ GeV and $|\eta| < 2.43$
- $m_{\text{recoil}} > 200$ GeV
- $|m(jj) - m_\phi| < 0.2 \times m_\phi$

Assuming a 70% b-tagging rate yields similar sensitivity

Similar treatment for $\phi \to \tau^+\tau^-$ with 90% τ-tagging rate

The $\phi \to VV$ channel

Backgrounds
- VBF $\mu^+\mu^- \to VV \to jjjj$
- $\mu^+\mu^- \to jjjj$ easily removed using $m(jjjj)$
- VBF $\mu^+\mu^- \to jjjj$ via QCD splitting negligible after $m(jj)$ selection

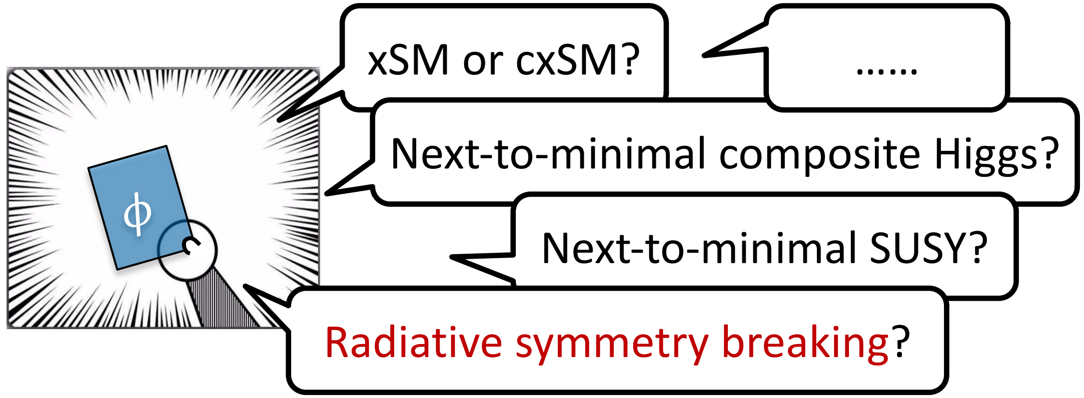


Cuts:
- Four jets with $p_T > 30$ GeV and $|\eta| < 2.43$
- $m_{\text{recoil}} > 200$ GeV
- Pairing jets to have V candidates with $|m(jj) - m_V| < 15$ GeV
- $|m(jjjj) - m_\phi| < 30$ GeV

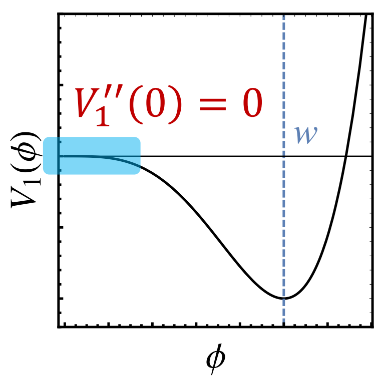
Similar treatment for $\phi \to hh \to b\bar{b}b\bar{b}$ 70% b-tagging rate

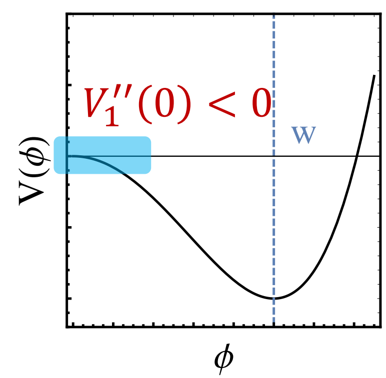
Another distinctive feature

A new scalar can be the consequence of any new physics model!



More evidences? The special shape of potential

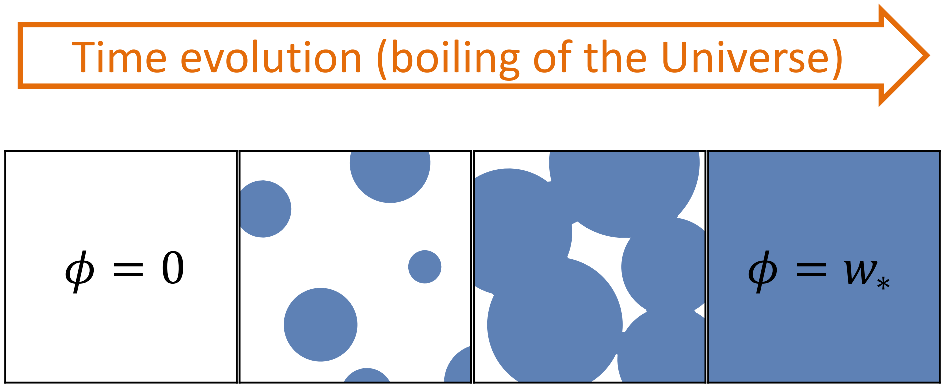


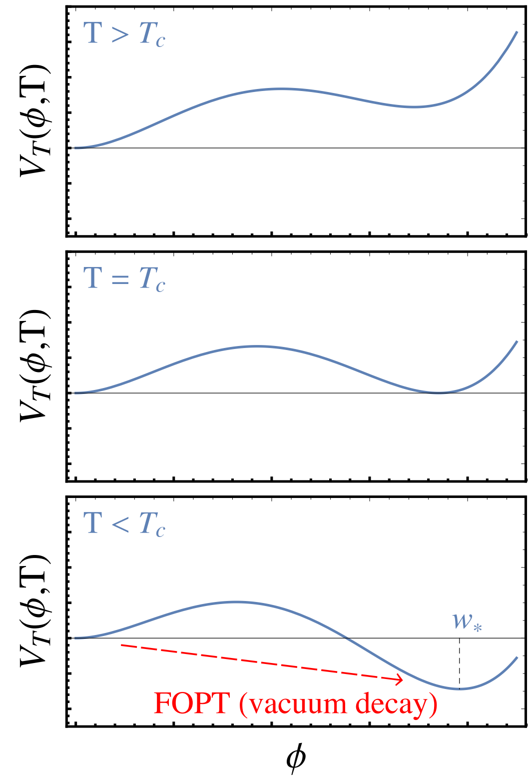


$$V(\phi) \sim \frac{B}{4}\phi^4\left(\log\frac{\phi}{w} - \frac{1}{4}\right)$$

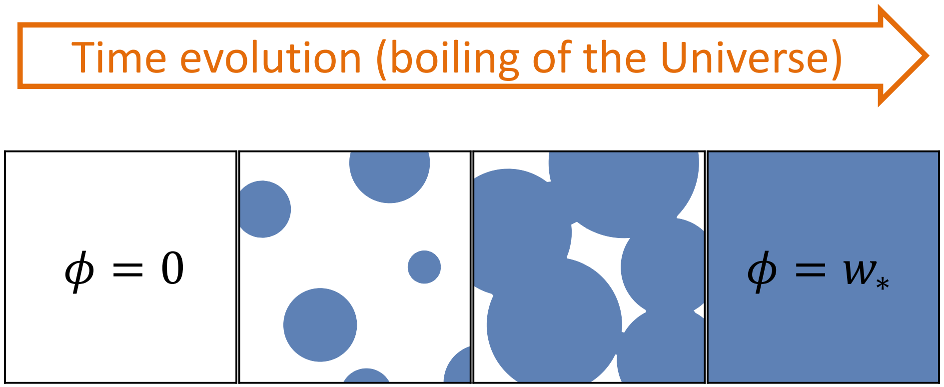
$$V(\phi) \sim \frac{\mu^2}{2}\phi^2 + \frac{\lambda}{4}\phi^4$$

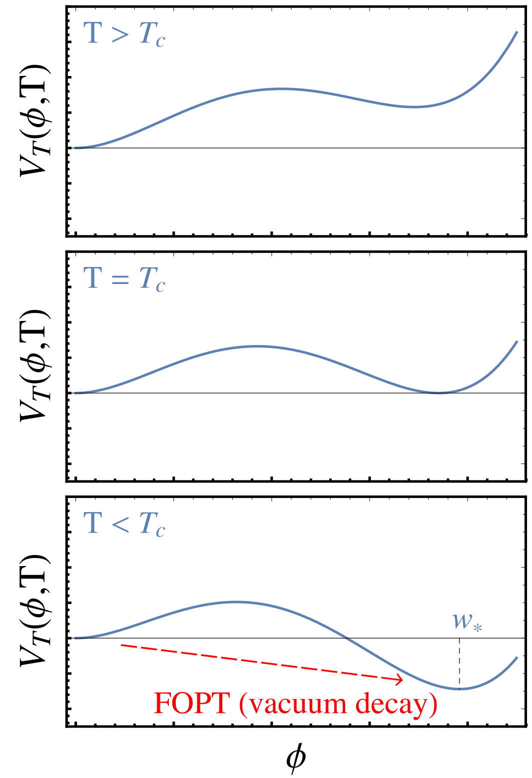
First-order phase transitions



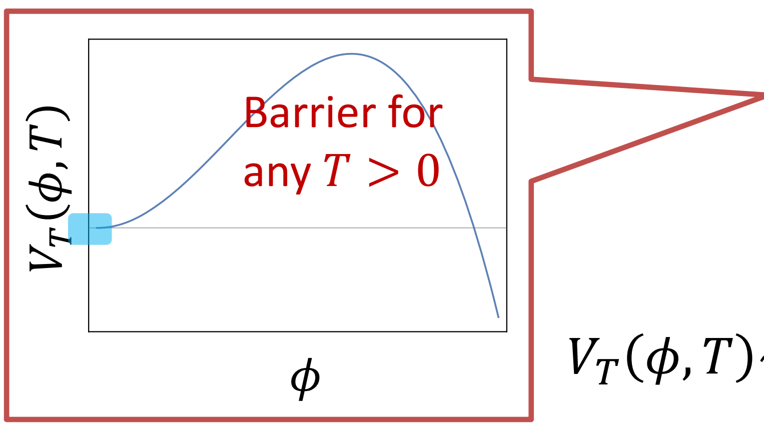


First-order phase transitions





The necessary **barrier** is easily obtained in a classically conformal theory



$$V_T(\phi,T) \sim \frac{g_X T^2}{8}\phi^2 + V_1(\phi)$$

Vacuum decay rate $\sim e^{-1/g_X^3}$, when $g_X \downarrow$, FOPT temperature $T_p \downarrow$

Thermal history: normal pattern

$$V_T(h,\phi,T) \approx \frac{3g_X^4}{32\pi^2}\phi^4\left(\log\frac{\phi}{w}-\frac{1}{4}\right)+\underbrace{\frac{g_X^2T^2}{8}}_{\text{Dark } A'}\phi^2-\frac{\lambda'}{4}h^2\phi^2+\frac{\lambda_h}{4}h^4+\underbrace{\frac{c_hT^2}{2}}_{\text{SM particle}}h^2$$

1. At T_p, the $U(1)_X$ FOPT occurs via $\phi: 0 \to w_*$
2. Then $V_T(h,\phi,T) \to V_T(h) \approx \frac{c_hT^2-m_h^2/2}{2}h^2+\frac{\lambda_h}{4}h^4$

Define $T_{\rm ew}=\frac{m_h}{\sqrt{2c_h}} \sim 140\ \mathrm{GeV}$

Thermal history: normal pattern

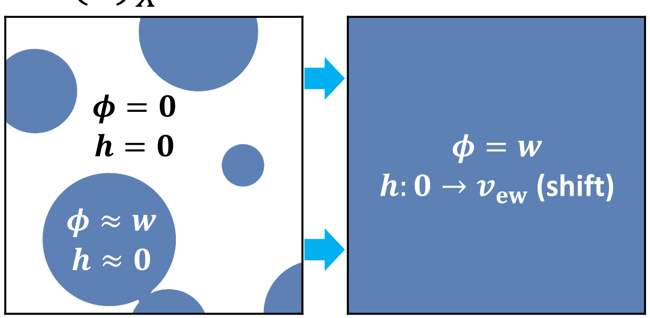
$$V_T(h,\phi,T) \approx \frac{3g_X^4}{32\pi^2}\phi^4\left(\log\frac{\phi}{w}-\frac{1}{4}\right)+\underbrace{\frac{g_X^2T^2}{8}}_{\text{Dark } A'}\phi^2-\frac{\lambda'}{4}h^2\phi^2+\frac{\lambda_h}{4}h^4+\underbrace{\frac{c_hT^2}{2}}_{\text{SM particle}}h^2$$

1. At T_p, the $U(1)_X$ FOPT occurs via ϕ: $0 \to w_*$
2. Then $V_T(h,\phi,T) \to V_T(h) \approx \frac{c_hT^2-m_h^2/2}{2}h^2+\frac{\lambda_h}{4}h^4$

Define $T_{\rm ew} = \frac{m_h}{\sqrt{2c_h}} \sim 140$ GeV

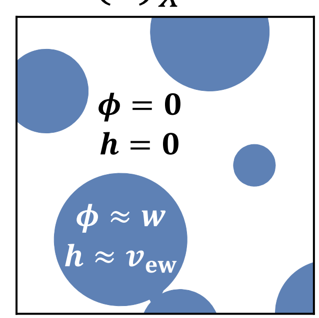
- If $T_p > T_{\rm ew}$

$U(1)_X$ FOPT　　EW crossover



- If $T_p < T_{\rm ew}$

Joint $U(1)_X$-EW FOPT



Thermal history: inverted pattern

1. Even at $T_{\rm QCD} \approx 85$ MeV, $U(1)_X$ & EW still not transition
2. QCD FOPT occurs at $T_{\rm QCD}$ with 6 massless quarks
3. Top Yukawa $-\frac{y_t}{\sqrt{2}}\langle \bar{t}t\rangle h$ induces $\langle h\rangle = v_{\rm QCD} \approx 100$ MeV
4. $V_T(h,\phi,T) \to V_T(\phi) \approx \frac{3g_X^4}{32\pi^2}\phi^4\left(\log\frac{\phi}{w}-\frac{1}{4}\right)+\frac{g_X^2T^2-2\lambda' v_{\rm QCD}^2}{8}\phi^2$

Define $T_{\rm roll} = \sqrt{2\lambda'}\frac{v_{\rm QCD}}{g_X} \approx 1.8\,{\rm MeV}\times\left(\frac{10^4\,{\rm GeV}}{g_X w}\right)$

Witten, NPB 177, 477 (1981); Iso *et al*, PRL 119 (2017) 14, 141301

Thermal history: inverted pattern

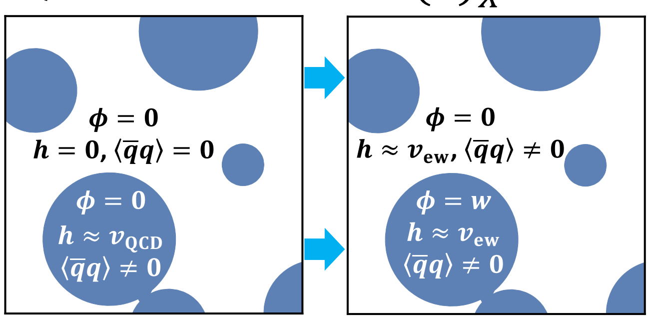
1. Even at $T_{\text{QCD}} \approx 85$ MeV, $U(1)_X$ & EW still not transition
2. QCD FOPT occurs at T_{QCD} with 6 massless quarks
3. Top Yukawa $-\frac{y_t}{\sqrt{2}}\langle \bar{t}t\rangle h$ induces $\langle h\rangle = v_{\text{QCD}} \approx 100$ MeV
4. $V_T(h,\phi,T) \to V_T(\phi) \approx \frac{3g_X^4}{32\pi^2}\phi^4\left(\log\frac{\phi}{w}-\frac{1}{4}\right)+\frac{g_X^2T^2-2\lambda' v_{\text{QCD}}^2}{8}\phi^2$

Define $T_{\text{roll}} = \sqrt{2\lambda'}\frac{v_{\text{QCD}}}{g_X} \approx 1.8\ \text{MeV}\times\left(\frac{10^4\ \text{GeV}}{g_X w}\right)$

Witten, NPB 177, 477 (1981); Iso *et al*, PRL 119 (2017) 14, 141301

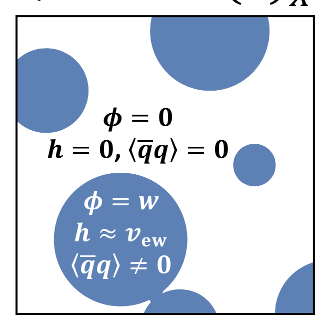
- If $T_{\text{QCD}} > T_{\text{roll}}$

QCD-EW FOPT $\qquad$ $U(1)_X$ FOPT



- If $T_{\text{QCD}} < T_{\text{roll}}$

Joint QCD-EW-$U(1)_X$ FOPT



The consequence of FOPTs

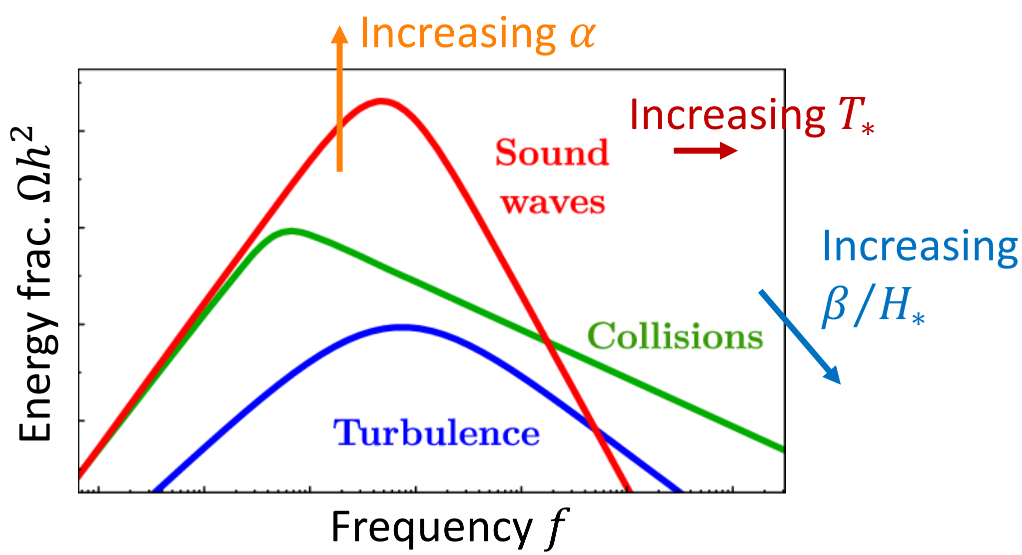
Stochastic gravitational waves[Caprini *et al*, JCAP 1604 (2016) 001]

1. Bubble collision
2. Sound waves in plasma
3. Turbulence in plasma

$$f_{\rm peak} \sim 10^{-3}\,{\rm Hz} \times \left(\frac{1}{v_w}\right)\left(\frac{\beta/H_*}{10}\right)\left(\frac{T_*}{\rm TeV}\right)$$

Two important parameters:

- α -- latent heat over radiation energy
- β/H_* -- <u>inverse</u> ratio of FOPT duration to Hubble time



Our calculations

Resolve the FOPT dynamics using full one-loop finite temperature field theory, optimize calculation at extremely low temperatures

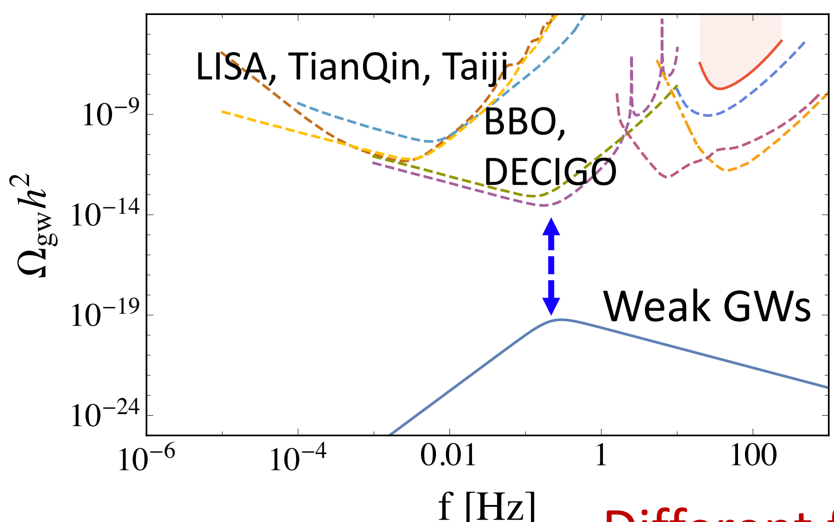
New

One example:

m_ϕ	θ	g_X	w	T_p	α	β/H_*	$T_{\rm rh}$	T_Λ
0.79 GeV	10^{-6}	1.3×10^{-4}	2.5×10^{8} GeV	0.56 MeV	5.2×10^{27}	4.9×10^{6}	1.7 GeV	4.7×10^{3} GeV

Extremely strong! “Thermal inflation” below T_Λ

But very *prompt*: a **strong** but **fast** FOPT

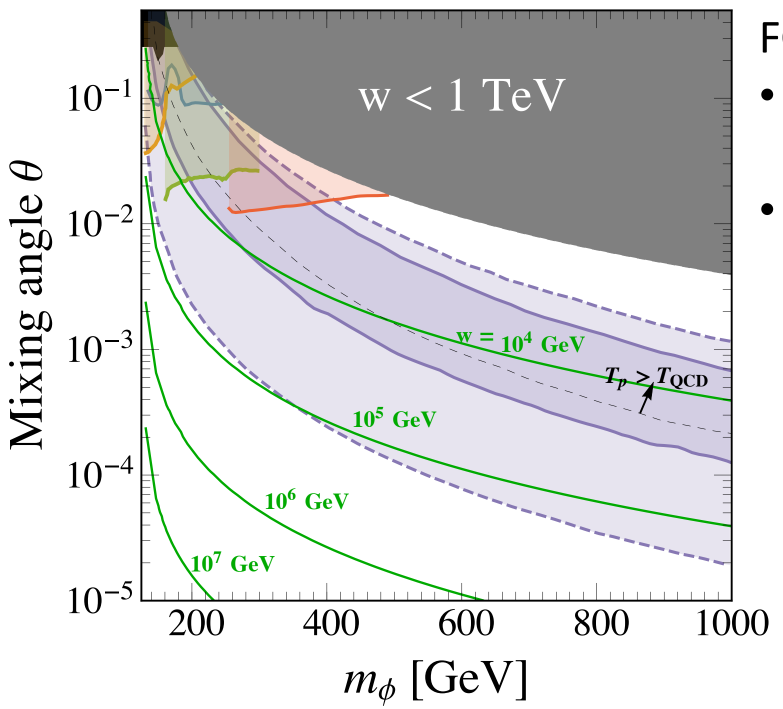


Different from naïve estimate

Combined results (1)

The heavy singlet scenario $m_\phi > m_h$

- Collider: HL-LHC $pp \to \phi \to ZZ$; 10 TeV $\mu^+\mu^- \to \phi \to b\bar{b}, VV, hh$
- GWs: [LISA, TianQin, Taiji] and [BBO, DECIGO]



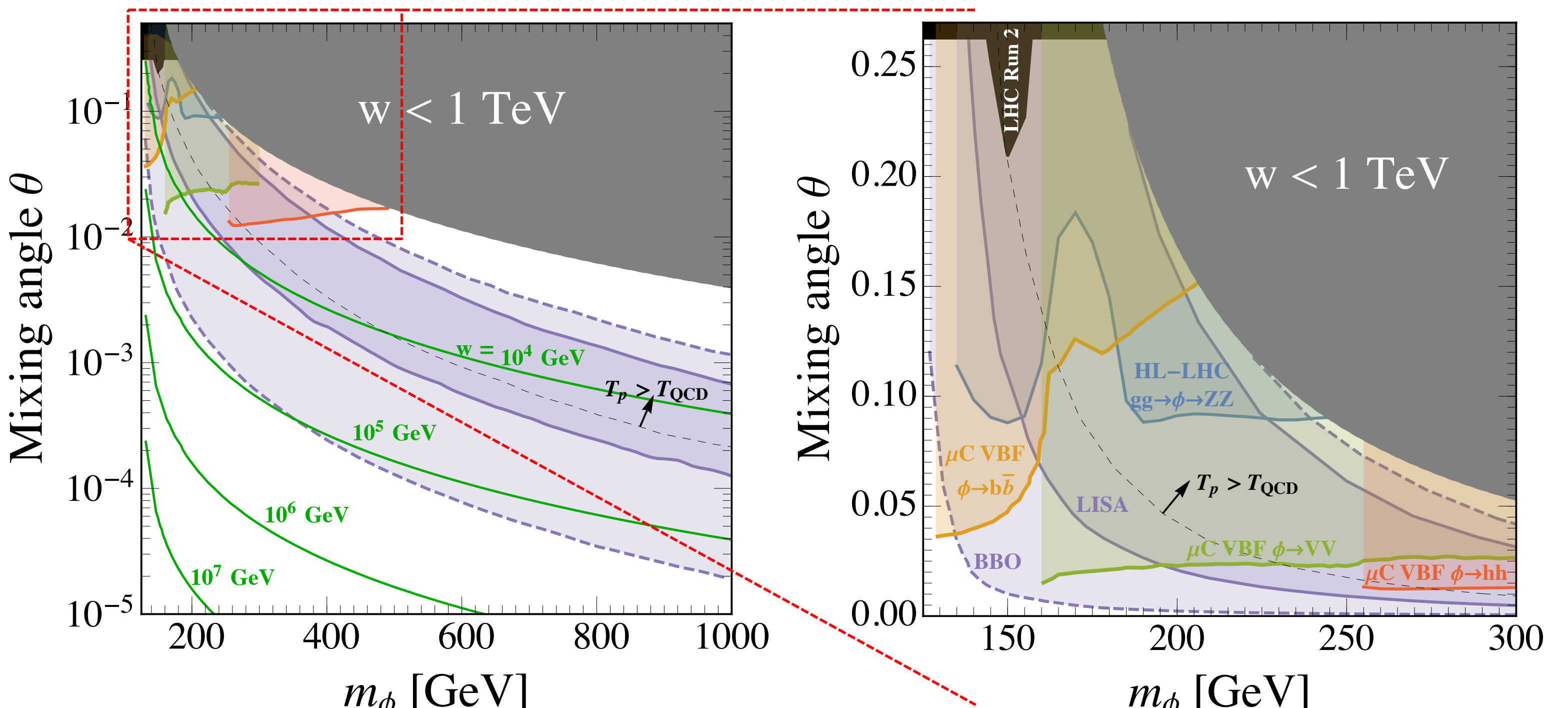
FOPT pattern:

- $U(1)_X$ FOPT + EW crossover or $U(1)_X$-EW FOPT
- $U(1)_X$ transition after the QCD-EW transition

Combined results (1)

The heavy singlet scenario $m_\phi > m_h$

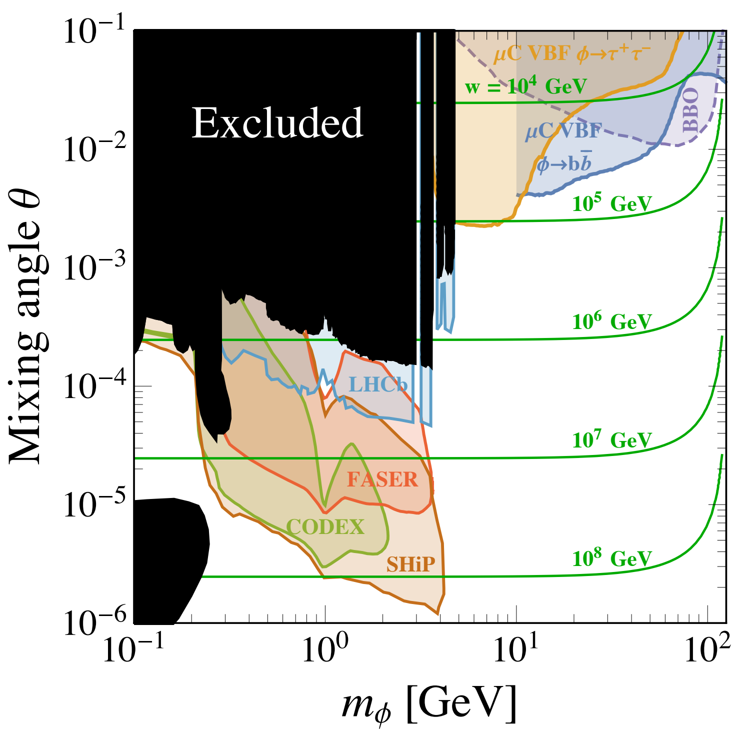
- Collider: HL-LHC $pp \to \phi \to ZZ$; 10 TeV $\mu^+\mu^- \to \phi \to b\bar{b}, VV, hh$
- GWs: [LISA, TianQin, Taiji] and [BBO, DECIGO]



Combined results (2)

The light singlet scenario $m_\phi < m_h$

- Collider: LLP searches; 10 TeV $\mu^+\mu^- \to \phi \to \tau^+\tau^-, b\bar{b}$
- GWs: [BBO, DECIGO]

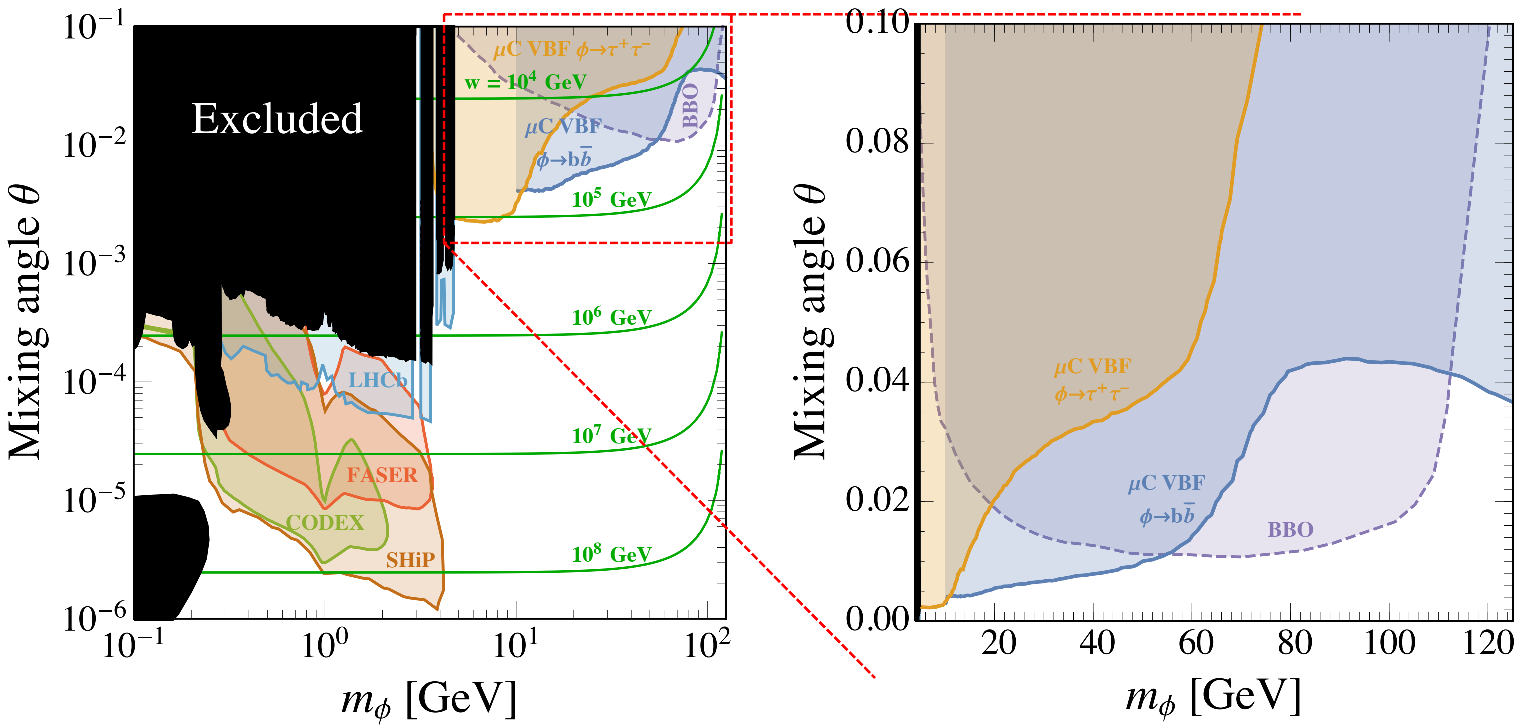


FOPT pattern: $U(1)_X$ transition after the QCD-EW transition

Combined results (2)

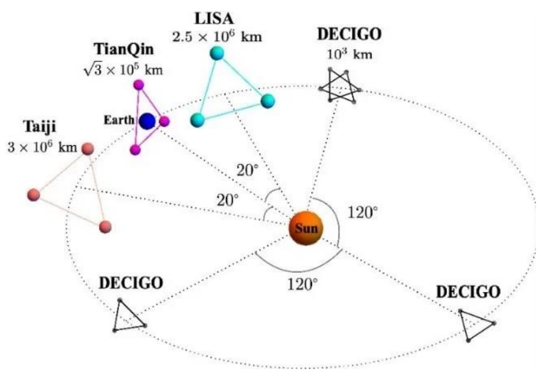
The light singlet scenario $m_\phi < m_h$

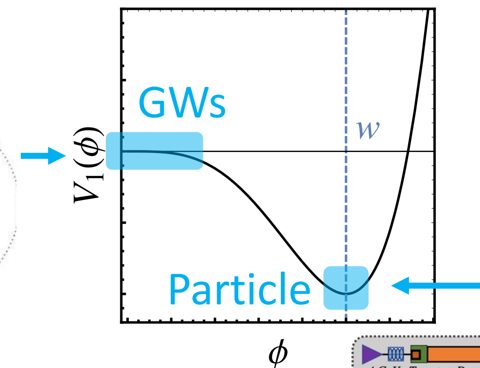
- Collider: LLP searches; 10 TeV $\mu^+\mu^- \to \phi \to \tau^+\tau^-, b\bar{b}$
- GWs: [BBO, DECIGO]

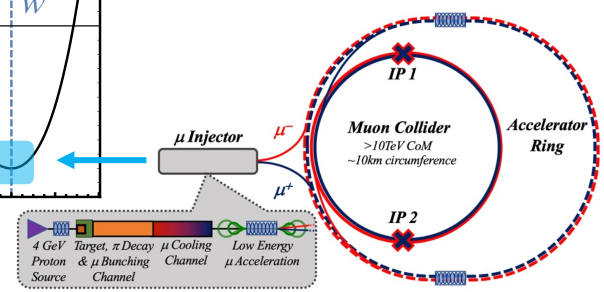


Closing remarks

Radiative symmetry breaking can be efficiently probed by combining the particle and GWs





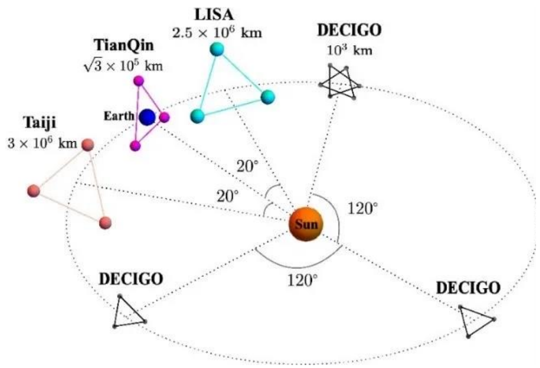


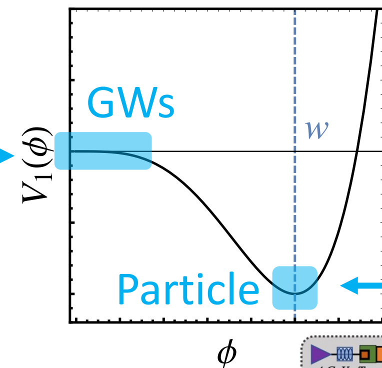
Distinctive features

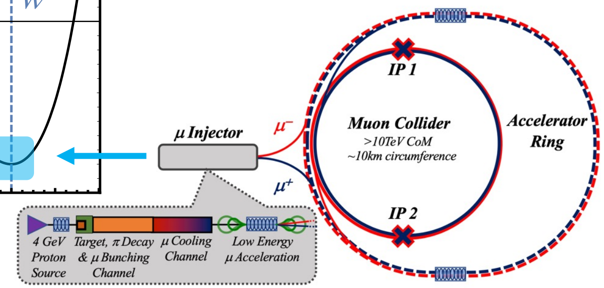
- A relatively light singlet scalar $m_\phi \ll w$
- A supercooled FOPT $T_p \ll w$

Closing remarks

Radiative symmetry breaking can be efficiently probed by combining the particle and GWs







Distinctive features

- A relatively light singlet scalar $m_\phi \ll w$
- A supercooled FOPT $T_p \ll w$

Future research

Exotic thermal history for dark matter,[1805.01473, 2304.00908] primordial black holes,[2311.13640, 2312.04628, 2401.09411] and baryogenesis.[2206.04691, 2305.10759]

Thank you!