Correlating new physics searches at colliders with a possible gravitational-wave detection

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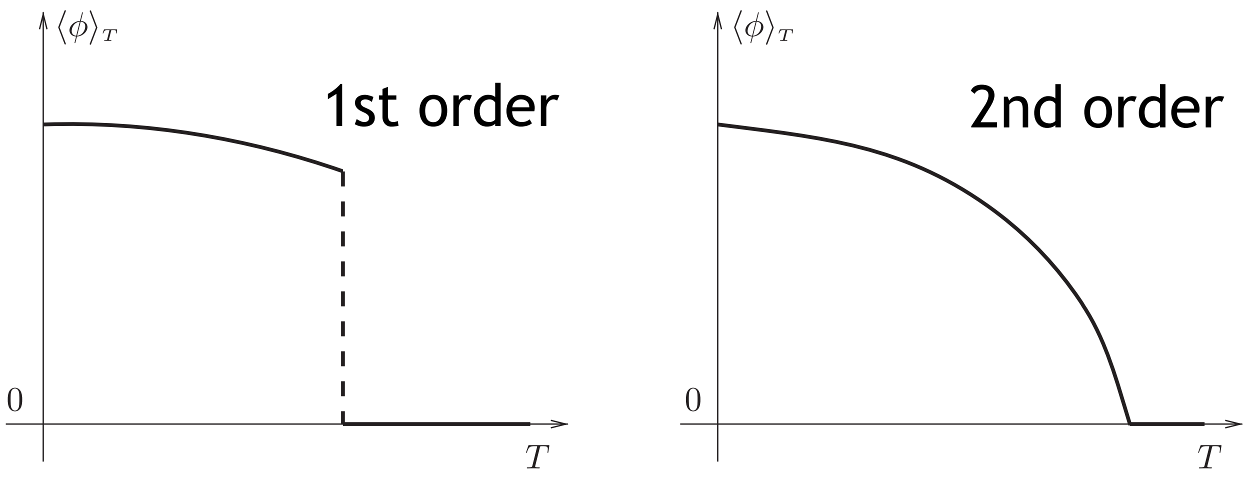
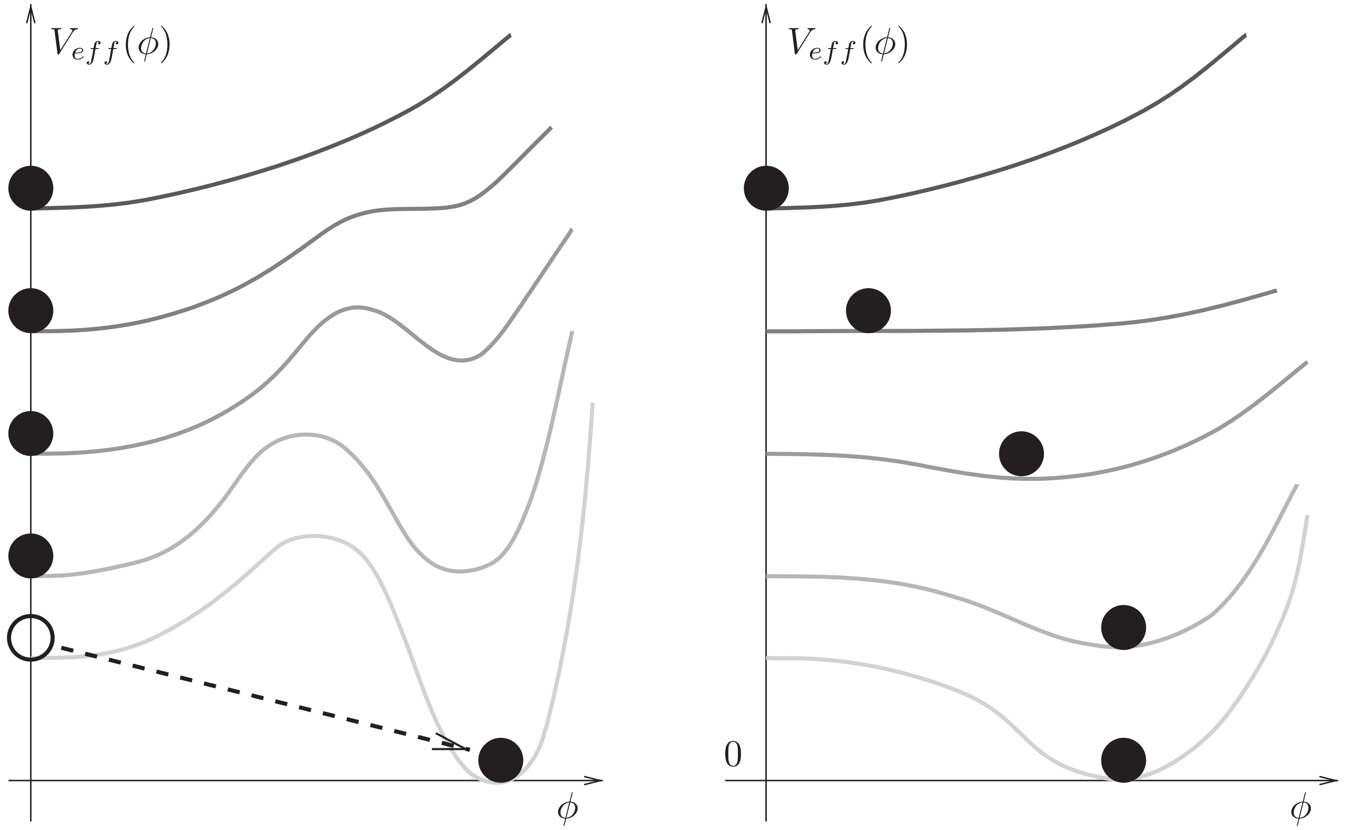
EW phase transitions - why New Physics?





Strong cosmological phase transitions (PTs) →
by expanding and colliding vacuum bubbles of new phase

Stochastic Gravitational Wave (GW) background
as a gravitational probe for New Physics

$$\frac{n_B - n_{\overline{B}}}{s} \sim 10^{-11}$$

Why strong FOPTs?

Sakharov'67

(i) B violation

(ii) C and CP violation

(iii) Departure from thermal equilibrium → **strong 1st-order PT**

Nucleation of expanding broken-phase vacuum bubbles → sphaleron suppression

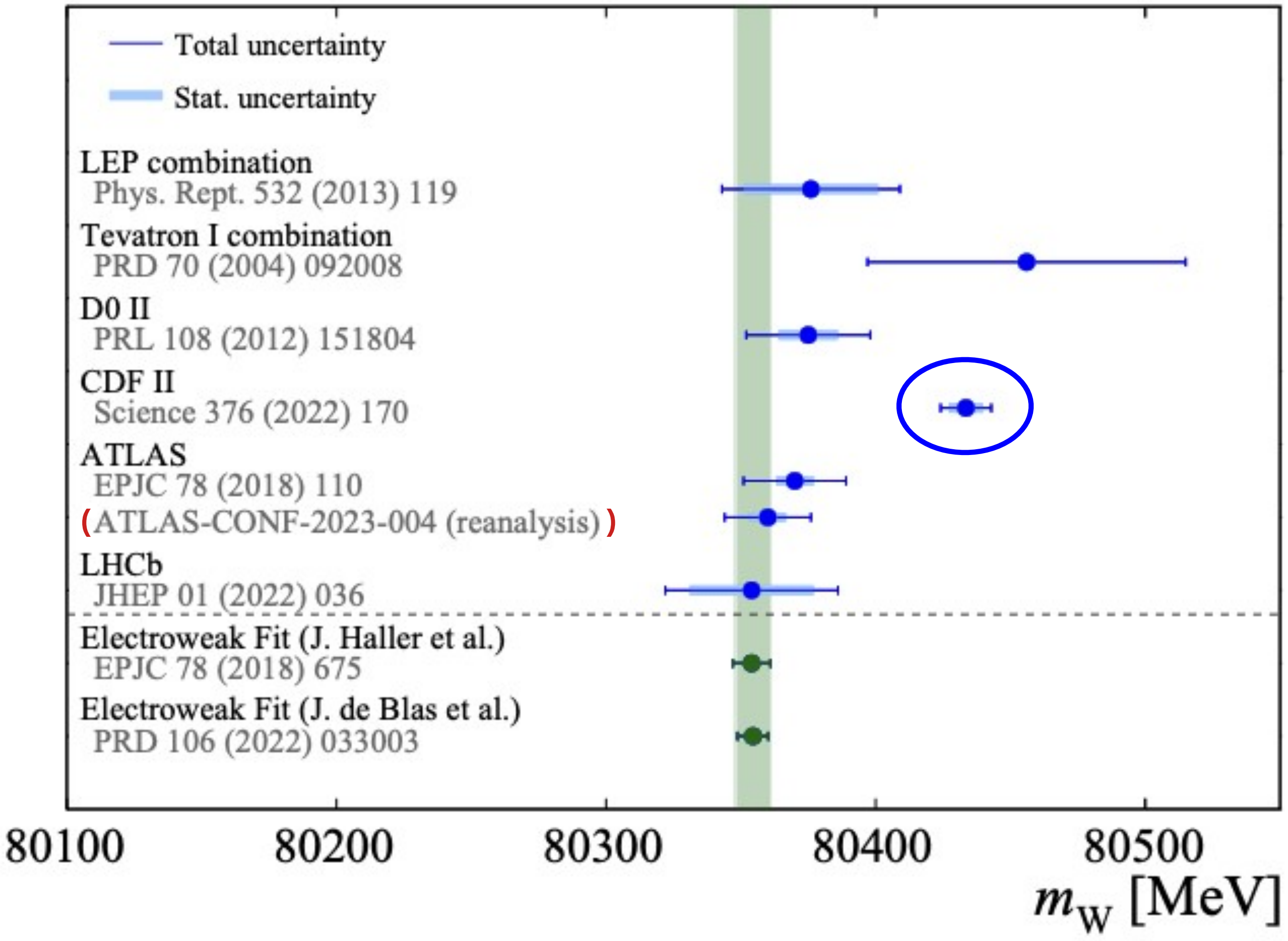
$$\frac{\phi(T_c)}{T_c} \gtrsim 1.1 \qquad \rightarrow \qquad 1^{\text{st}} \text{ order PT}$$

Standard Model (SM) does not explain the BA → **the need to go beyond the SM**

GW/Collider probes for New Physics:

Example I: Triplet-extended SM

How/Where New Physics may show up



credit to Maarten Boonekamp

- Surprising CDF II measurement of W mass lies >7σ away from the Standard Model

- Many scenarios beyond the SM have been deployed in the literature to explain this measurement (over 300 publications so far!)

- A large class of BSM scenarios offering such an explanation features the existence of a new SU(2) adjoint (triplet) scalar which provides a tree-level corrections to the SM W mass value

- Existence of such scalars may impact the Electro Weak phase transition in early Universe, possibly rendering such models testable in future gravitational-wave detectors

EMEFT approach

L. Di Luzio, R. Gröber and P. Paradisi,
"Higgs physics confronts the mW anomaly" Phys.Lett.B 832 (2022) 137250

SMEFT Lagrangian (Warsaw):

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i c_i \mathcal{O}_i$$

Universal "bosonic" operators:

$$\mathcal{O}_{HWB} = (H^\dagger \tau^a H) W^a_{\mu\nu} B^{\mu\nu} \,,$$
$$\mathcal{O}_{HD} = (H^\dagger D_\mu H)((D_\mu H)^\dagger H) \,,$$

Leading EW oblique corrections:

$$\hat{S} \equiv \frac{c_W}{s_W} \Pi'(0)_{W_3 B} = \frac{c_W}{s_W} v^2 c_{HWB} \,,$$
$$\hat{T} \equiv \frac{1}{M_W^2} (\Pi_{W_3 W_3}(0) - \Pi_{W^+ W^-}(0)) = -\frac{v^2}{2} c_{HD} \,,$$

EFT d=6 operator generates W mass shift

A. Strumia, JHEP 08 (2022) 248

W mass anomaly ↔ **Anomaly in T-parameter (assuming U=0)**

$$\hat{T} \simeq (0.84 \pm 0.14) \times 10^{-3}$$
$$c_{HD} \; = \; -(0.17 \pm 0.07/\text{TeV})^2$$

$$\hat{S} \sim 10^{-3} \qquad c_{HWB} \; \sim \; (0.07/\text{TeV})^2$$

compatible with zero

A minimal scalar SU(2) triplet extension

Interaction Lagrangian with Higgs:

$$\mathcal{L}_\Delta^{\rm int} \ni -\kappa_\Delta H^\dagger \Delta^a \sigma^a H - \frac{\lambda_{H\Delta}}{2}(H^\dagger H)\Delta^a\Delta^a$$

$$\Delta = (1,3,0)$$

Integrating out heavy triplet:

$$c_{HD} = -2\frac{\kappa_\Delta^2}{M_\Delta^4}$$

negative effective coupling!

$$\boxed{\hat{T} = \frac{\kappa_\Delta^2 v^2}{M_\Delta^4} = 0.84\times 10^{-3}\left(\frac{|\kappa_\Delta|}{M_\Delta}\right)^2\left(\frac{8.5\,\mathrm{TeV}}{M_\Delta}\right)^2}$$

the same effect in T can be recast in terms of the adjoint VEV

$$\langle\Delta\rangle \equiv v_\Delta = \kappa_\Delta v^2/(2M_\Delta^2)$$

L. Di Luzio, R. Gröber and P. Paradisi, Phys.Lett.B 832 (2022) 137250

Saturating the perturbativity bound $|k_\Delta|/M_\Delta \leq 4\pi$ the mass scale cannot exceed 100 TeV

Effective d=6 Higgs self-interaction

Integrating out heavy new scalar triplet state yields both:
a positive contribution to the T-parameter and a modification of the Higgs potential

Higgs quartic couplings receives a tree-level correction

$$\lambda = \lambda_{\mathrm{bare}} + (k_\Delta / m_\Delta)^2$$

$$\lambda = m^2/2v^2$$

due to an adjoint VEV, we have

$$\lambda_\Delta \mathrm{Tr}[\Delta^\dagger \Delta \Delta^\dagger \Delta] \to \frac{\mu_\Delta}{3}\Delta^3 \qquad \mu_\Delta \sim \lambda_\Delta v_\Delta$$

effective operator below the cutoff scale:

d=6 Higgs self-interaction term:

$$\boxed{c_H (H^\dagger H)^3} \qquad c_H \equiv \frac{\kappa}{\Lambda^2} \sim v_\Delta$$

Other contributions to this operator come from quartics:

$$\frac{k_\Delta^2}{M_\Delta^4}\lambda' \to c_H \qquad \lambda' \equiv 4\lambda - \frac{\lambda_{H\Delta}}{2}$$

$$\mu_\Delta \to 0 \qquad c_H = -4\frac{\hat{T}}{v^2}\left(\frac{\lambda_{H\Delta}}{8} - \lambda\right) \sim v_\Delta^2 \to 0$$

d=6 contribution to the Higgs potential is important for the nature and the strength of the EW phase transition

Finite-T effective potential & EW FOPTs

In unitary gauge, one-loop effective Higgs potential:

$$V_{\rm eff}(T,h) = V_{\rm tree}(h) + V^{(1)}_{T=0}(h) + \Delta V_T(h,T)$$

$$V_{\rm tree}(h) = \frac{1}{2}m^2 h^2 + \frac{\lambda}{4}h^4 + \frac{\kappa}{8\Lambda^2}h^6$$

The dominant thermal correction to the Higgs mass:

$$CT^2/2$$

$$C \simeq \frac{1}{16}\left(g'^2 + 3g^2 + 4y_{\rm t}^2 + 4\frac{m_{\rm h}^2}{v^2} + 36\frac{\kappa v^2}{\Lambda^2}\right)$$

modification of EW parameters

$$m^2 = m_{\rm SM}^2(1-\Lambda_{\rm M}^2/2\Lambda^2) \qquad \Lambda_{\rm M} = \sqrt{3}\Lambda_{\rm m} = \sqrt{3\kappa v^2/m^2}$$

$$\lambda = \lambda_{\rm SM}(1-\Lambda_{\rm M}^2/\Lambda^2) \qquad \Lambda_{\rm m} \leq \Lambda \leq \Lambda_{\rm M}$$

cutoff scale

$$m_{\rm h}^2 = 2\lambda v^2 + 3v^4\kappa/\Lambda^2 \qquad m_{\rm h} = 125\,{\rm GeV}$$

Limit on the d=6 operator imposed by the strongly 1st order EW phase transition requirement yields:

$$\boxed{480\,{\rm GeV} \lesssim \frac{1}{\sqrt{|c_H|}} \lesssim 840\,{\rm GeV}}$$

F. Huang et al, Phys. Rev. D94 (2016) 041702 [arXiv:1601.01640 [hep-ph]]

$$v(T_{\rm c})/T_{\rm c} > 1$$

Gravitational-wave power spectrum

- GW energy density per logarithmic frequency

$$h^2\Omega_{\rm GW} \equiv \frac{h^2}{\rho_c}\frac{d\rho_{\rm GW}}{d\log f} \simeq h^2\Omega_{\rm col} + \boxed{h^2\Omega_{\rm sw}} + h^2\Omega_{\rm MHD}$$

$\alpha,\ \beta/H,\ T_* \longrightarrow$ **calculated from a given BSM theory, used as inputs to obtain the GW power spectrum**

$$h^2\Omega_{\rm GW} = h^2\Omega_{\rm GW}^{\rm peak}\left(\frac{4}{7}\right)^{-\frac{7}{2}}\left(\frac{f}{f_{\rm peak}}\right)^3\left[1+\frac{3}{4}\left(\frac{f}{f_{\rm peak}}\right)\right]^{-\frac{7}{2}}$$

Peak amplitude

Spectral function

$$h^2\Omega_{\rm GW}^{\rm peak}(f_{\rm peak}) = 7.835\times10^{-17} f_{\rm peak}^{-2}\left(\frac{100}{g_*}\right)^{2/3}\left(\frac{T_*}{100}\right)^2\frac{K^{\frac{3}{2}}}{c_s} \quad \text{for} \quad \mathrm{H}\tau_{\rm sh} = \frac{2}{\sqrt{3}}\frac{\mathrm{HR}}{\mathrm{K}^{1/2}} < 1$$

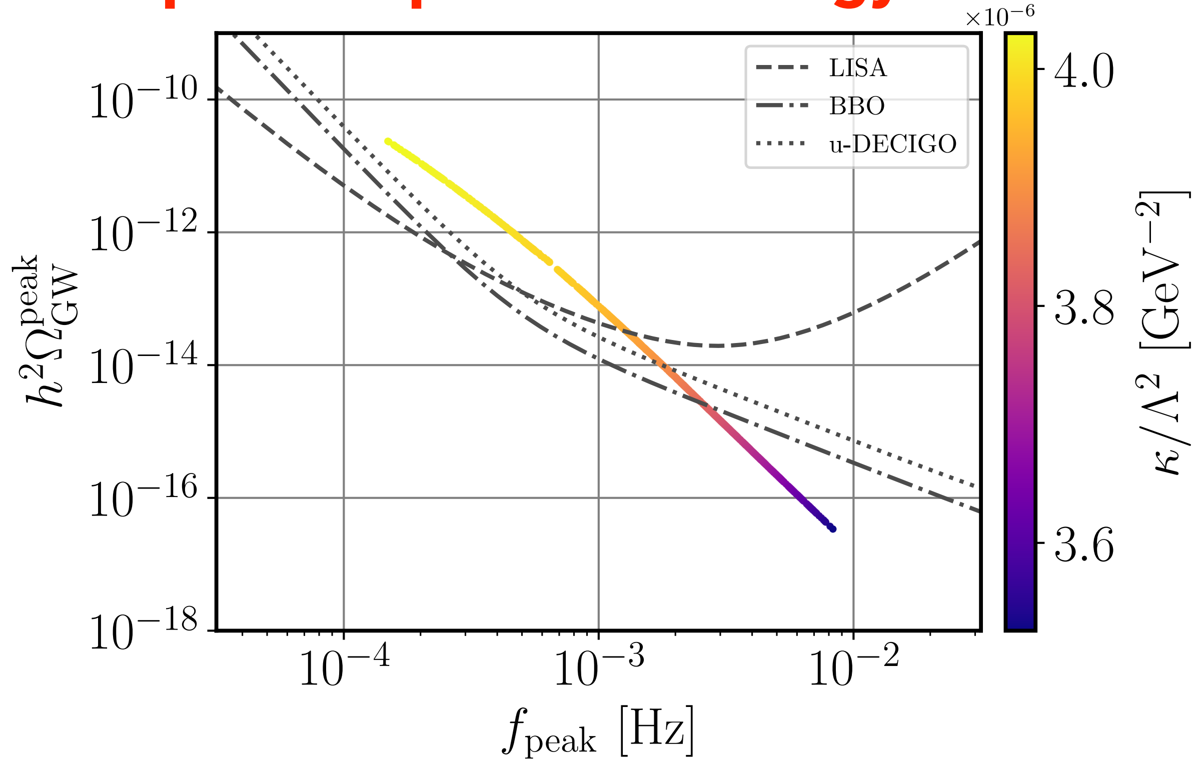
$$h^2\Omega_{\rm GW}^{\rm peak}(f_{\rm peak}) = 7.835\times10^{-17} f_{\rm peak}^{-2}\left(\frac{100}{g_*}\right)^{2/3}\left(\frac{T_*}{100}\right)^2\frac{K^2}{c_s^2} \quad \text{for} \quad \mathrm{H}\tau_{\rm sh} = \frac{2}{\sqrt{3}}\frac{\mathrm{HR}}{\mathrm{K}^{1/2}} \simeq 1\,;$$

$$f_{\rm peak} = 26\times10^{-6}\left(\frac{1}{HR}\right)\left(\frac{T_*}{100}\right)\left(\frac{g_*}{100\ \mathrm{GeV}}\right)^{\frac{1}{6}}\mathrm{Hz} \qquad HR = \frac{H}{\beta}(8\pi)^{\frac{1}{3}}\max(v_b, c_s) \qquad K = \frac{\kappa\alpha}{1+\alpha}$$

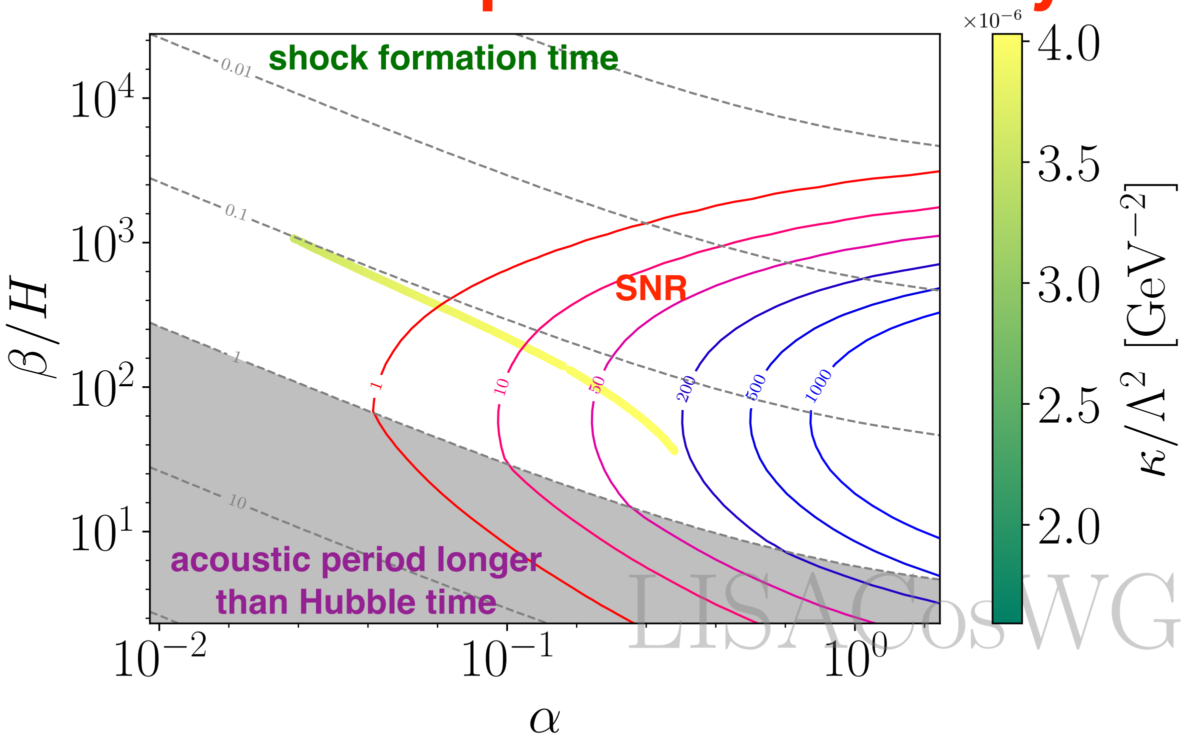
We use the templates for SW peak in [Caprini et al. JCAP 03 (2020) 024]

Primordial GWs in a minimal triplet model

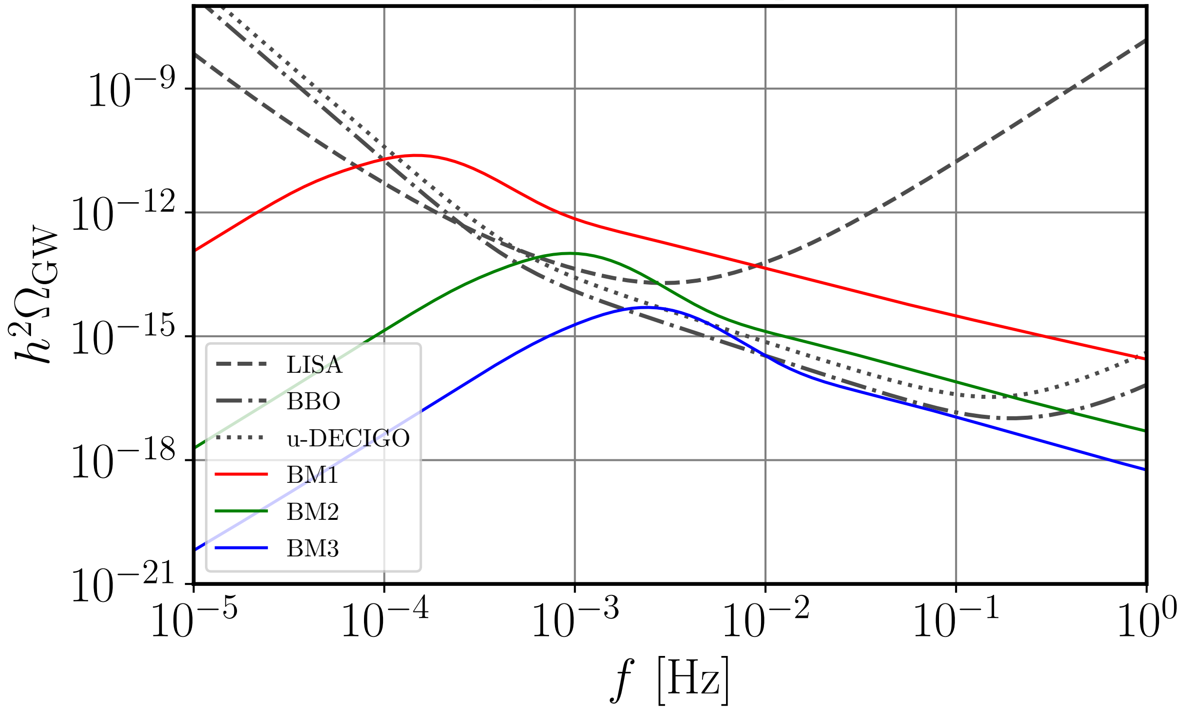
peak-amplitude vs energy scale



duration & SNR for points detectable by LISA



GWs power spectrum



Benchmarks:

T_*(GeV)	α	β/H_*	$\kappa^{-1/2}\Lambda$(GeV)	$\delta_{\sigma_{hz}}$(%)
43.8	0.30	36.37	498.12	1.8
55.6	0.12	180.94	502.40	2.1
64.2	0.07	394.14	508.38	2.2

- Consistent with LHC bounds
- Can be probed in future measurements of trilinear Higgs coupling:

$$\lambda_{3h} = -(1+\delta_h)\frac{Ah^3}{6} \qquad A = 3m_h^2/v$$

$$\delta_h = 2\Lambda_m/\Lambda \in (2/3, 2) \qquad \delta_{\sigma_{hZ}} = \delta\sigma_{hZ}/\sigma_{hZ} \simeq 1.6\%\ \delta_h \text{ at } \sqrt{s} = 240 \text{ GeV}$$

CEPC collider: $10\ \text{ab}^{-1} \qquad \delta_{\sigma_{hZ}} \sim 0.4\% \qquad |\delta_h| \sim 25\%$

GW/Collider probes for New Physics:

Example II: Dynamical EWSB

Dynamical EWSB

Many attractive features….

- ✓ **EWSB is triggered by a new strongly-coupled dynamics (more than one confinement scale in Nature?)**
- ✓ **No fundamental scalars (composite Higgs?)**
- ✓ **No hierarchy problem, no fine-tuning (best alternative to SUSY?)**
- ✓ **A plenty of new hadron-like objects, difficult to find/treat though (composite Dark Matter? LHC phenomenology?)**

Evolutions of DEWSB ideas/realizations….

Technicolor

Extended TC

Walking TC

Bosonic TC

Composite Higgs…

???

Hill & Simmons, Phys. Rept. 381, 235 (2003)
Sannino, Acta Phys. Polon. B40, 3533 (2009), etc

Toy-model of DEWSB: SU(2)$_{\rm L}$xSU(2)$_{\rm R}$ LσM

Techniquark weak-SU(2) doublet: $\tilde{Q} = \begin{pmatrix} \tilde{U} \\ \tilde{D} \end{pmatrix}$

the source term

$$-g_{\rm TC}\bar{Q}(S + i\gamma_5 P^a)Q \qquad \rightarrow \qquad -g_{\rm TC}\Big(\langle\bar{Q}Q\rangle S + \bar{Q}(S + i\gamma_5 P^a \tau^a)Q\Big)$$

scalar T-sigma
(singlet rep.)

lightest
T-glueball

pseudoscalar T-pions
(adjoint rep.)

collective excitation
of T-quark condensate

QGC formation

$$\bar{Q}Q \rightarrow \langle\bar{Q}Q\rangle + \bar{Q}Q$$

$$S = u + \sigma$$

T-pion mass

global chiral SSB

$$m_Q \ll m_\pi = -\frac{g_{\rm TC}\langle\bar{\tilde{Q}}\tilde{Q}\rangle}{u} \qquad SU(2)_{\rm L} \otimes SU(2)_{\rm R} \rightarrow SU(2)_{\rm V\equiv L+R} \qquad \mu_{\rm S,H} \ll m_{\tilde{\pi}}$$

Potential

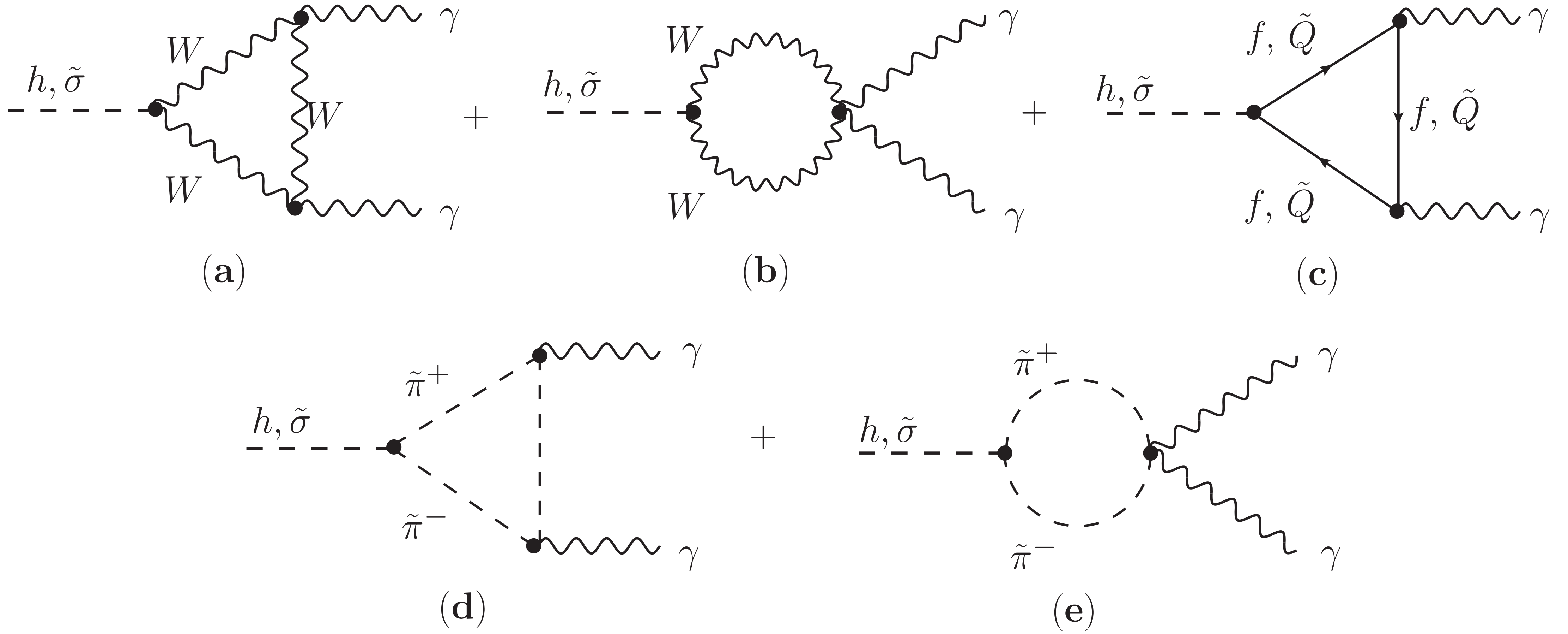
$$\frac{1}{2}\mu_{\rm S}^2(S^2 + P^2) + \mu_{\rm H}^2\mathcal{H}^2 - \frac{1}{4}\lambda_{\rm TC}(S^2 + P^2)^2 - \lambda_{\rm H}\mathcal{H}^4 + \boxed{\lambda\mathcal{H}^2(S^2 + P^2)}$$

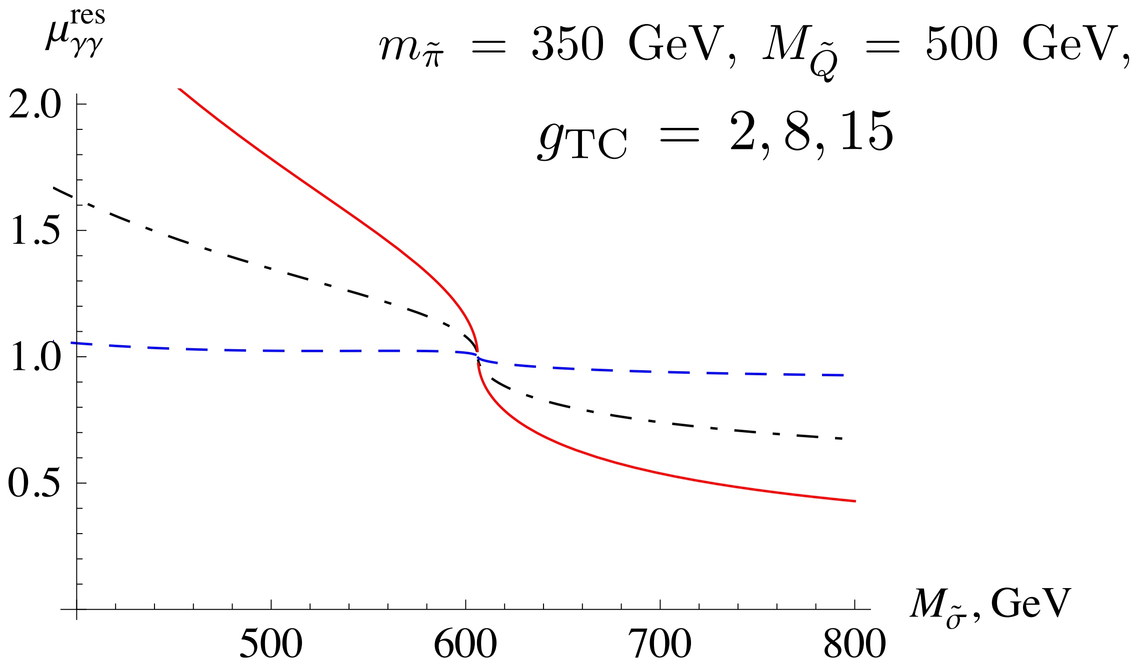
$$\langle\mathcal{H}\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \end{pmatrix} \qquad u = \left(\frac{\lambda_{\rm H}}{\delta}\right)^{1/3} g_{\rm TC}^{-1/3}\,, \qquad v = \left(\frac{\xi\lambda}{\lambda_{\rm H}}\right)^{1/2}\left(\frac{\lambda_{\rm H}}{\delta}\right)^{1/3} g_{\rm TC}^{-1/3}$$

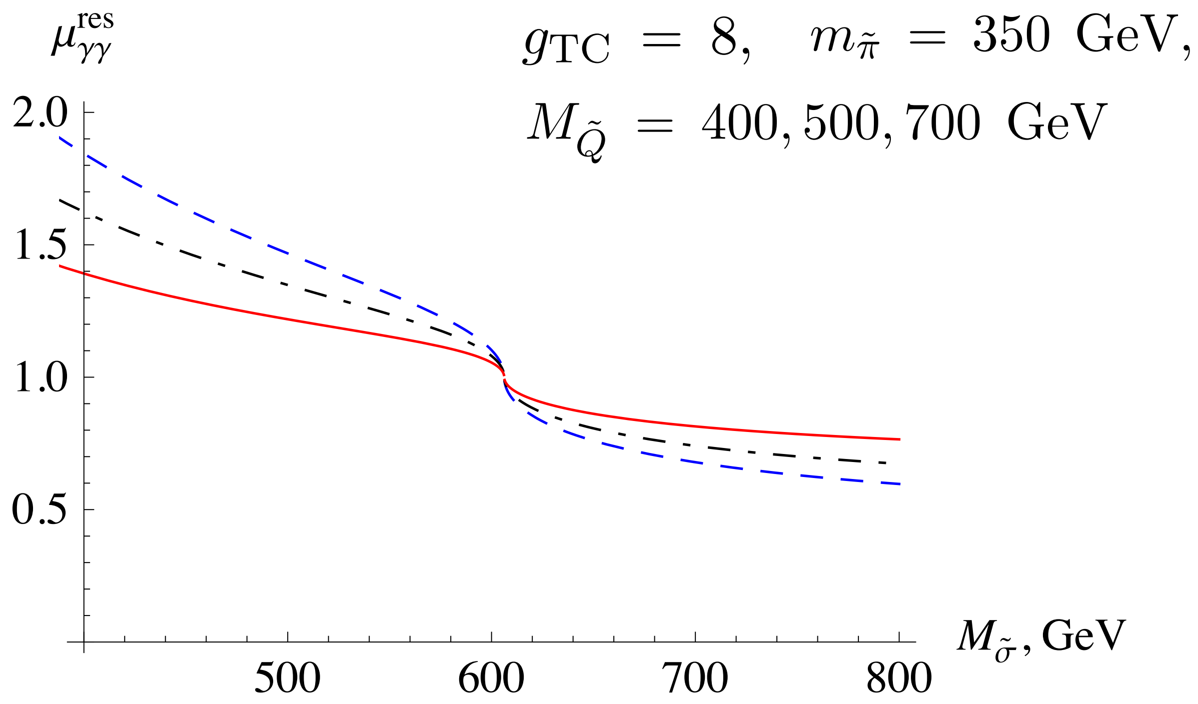
Spontaneous
EWSB

- *Both chiral and EW SSB are dynamically linked to T-quark condensate*
- *T-pion gets mass via T-sigma interaction with T-quark condensate*
- *T-pions remain physical, the Higgs-like mechanism becomes effective*

Higgs signal rates

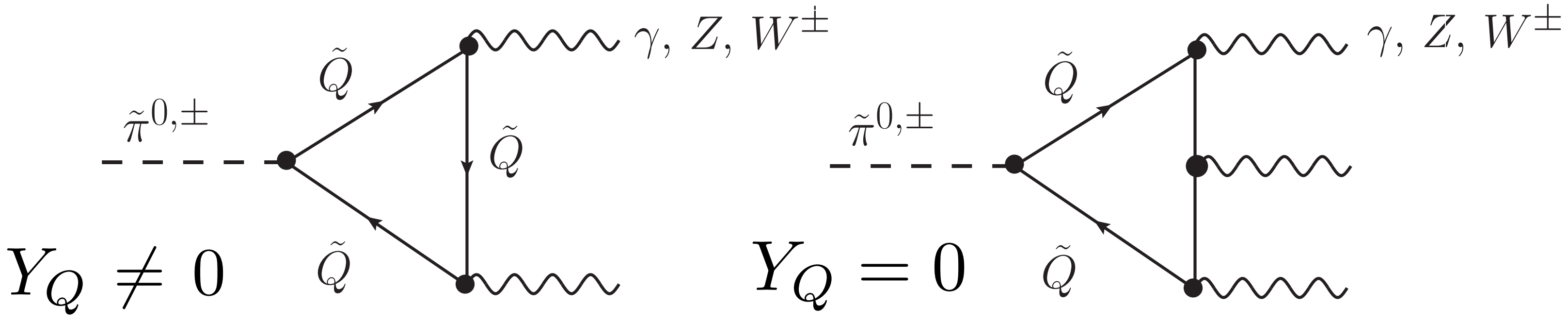


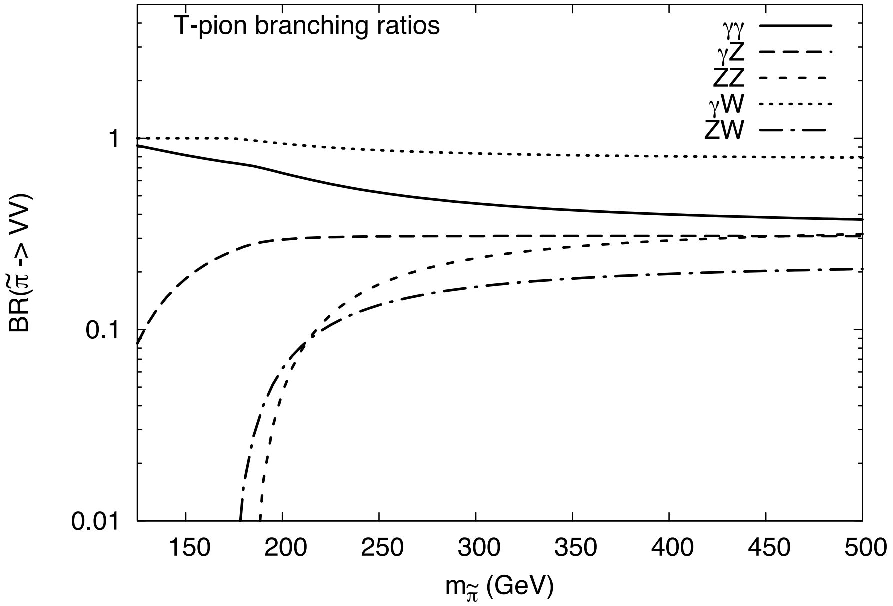

$m_{\tilde\pi} = 350$ GeV, $M_{\tilde Q} = 500$ GeV,
$g_{\mathrm{TC}} = 2, 8, 15$


$g_{\mathrm{TC}} = 8$, $m_{\tilde\pi} = 350$ GeV,
$M_{\tilde Q} = 400, 500, 700$ GeV

Search for T-pions

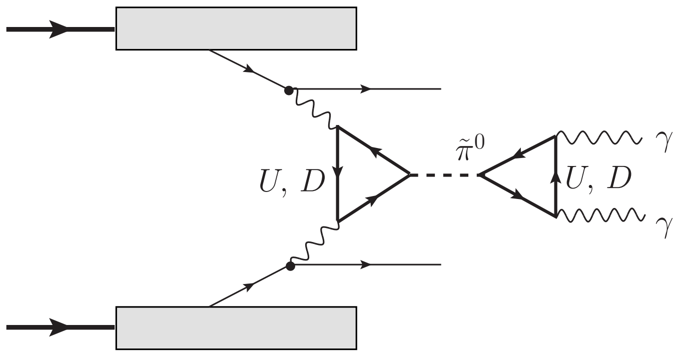
T-pion decay

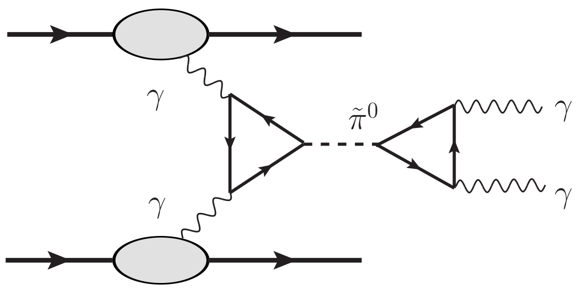




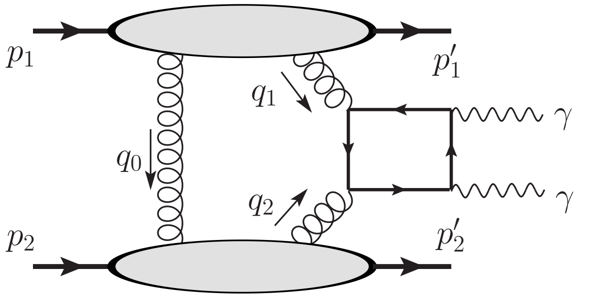
RP et al,
NP881, 288 (2014)

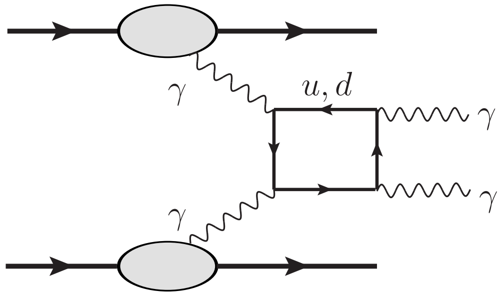
Signal

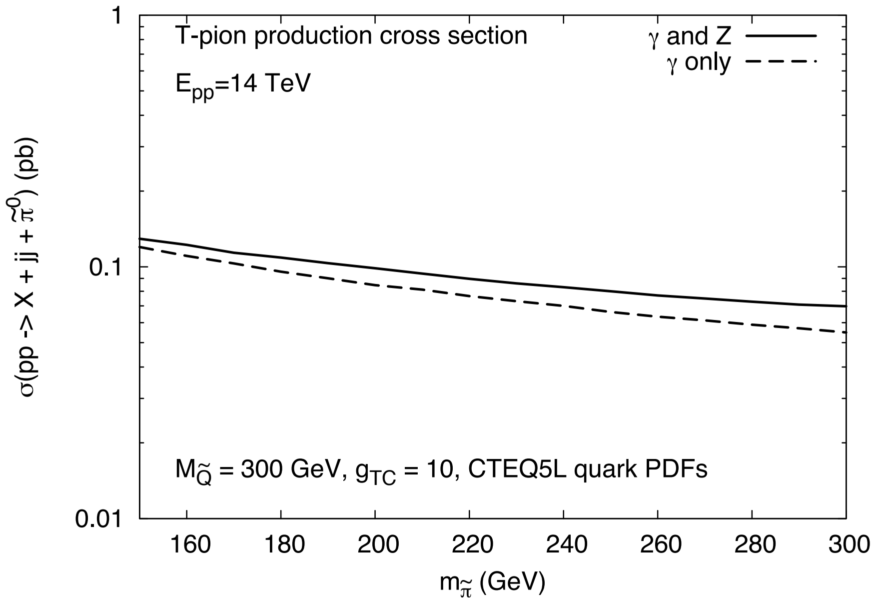


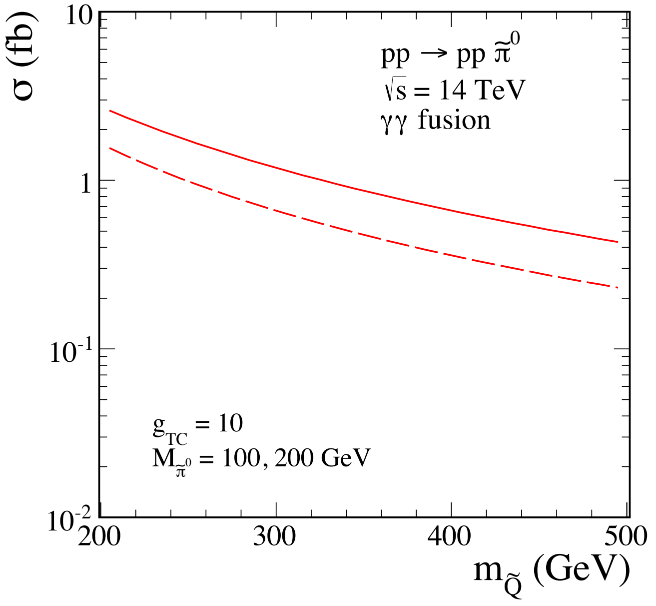


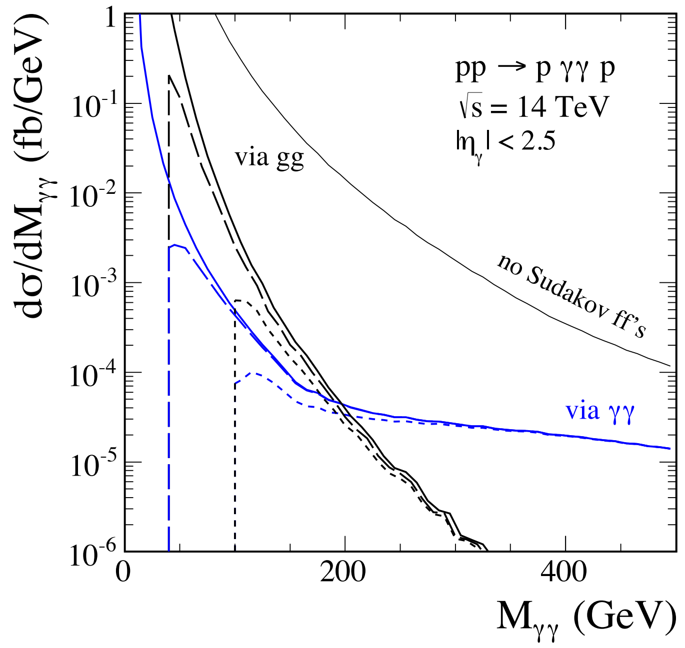
Background











Thermal masses and renormalisation conditions

Thermal corrections

$$\mu_\alpha^2(T) = \mu_\alpha^2 + c_\alpha T^2$$

In analogy to QCD:

$$\left\langle \bar{\tilde{Q}}\tilde{Q} \right\rangle_T = \left\langle \bar{\tilde{Q}}\tilde{Q} \right\rangle \left[1 - \frac{1}{4f_{\tilde{\pi}}^2}T^2 - \frac{1}{96 f_{\tilde{\pi}}^4}T^4\right]$$

$$f_{\tilde{\pi}}^2 = -\frac{(m_{\tilde{U}} + m_{\tilde{D}})\left\langle \bar{\tilde{Q}}\tilde{Q} \right\rangle}{m_{\tilde{\pi}}^2}$$

Counterterm potential:

$$\begin{aligned} V_{\rm ct} =& \frac{1}{2}\delta\mu_S^2\phi_{\tilde{\sigma}}^2 + \frac{1}{2}\delta\mu_H^2\phi_h^2 \\ &+ \frac{1}{4}\delta\lambda_{\rm TC}\phi_{\tilde{\sigma}}^4 + \frac{1}{4}\delta\lambda_H\phi_h^4 - \frac{1}{2}\delta\lambda\phi_h^2\phi_{\tilde{\sigma}}^2 , \end{aligned}$$

$$\begin{aligned} \delta\mu_H^2 =& \frac{1}{2}\left\langle \frac{\partial^2 V_{\rm CW}^{(1)}}{\partial\phi_h^2} \right\rangle_{\rm vac} - \frac{3}{2v}\left\langle \frac{\partial V_{\rm CW}^{(1)}}{\partial\phi_h} \right\rangle_{\rm vac} \\ &+ \frac{u}{2v}\left\langle \frac{\partial^2 V_{\rm CW}^{(1)}}{\partial\phi_h\partial\phi_{\tilde{\sigma}}} \right\rangle_{\rm vac} , \\ \delta\mu_S^2 =& \frac{1}{2}\left\langle \frac{\partial^2 V_{\rm CW}^{(1)}}{\partial\phi_{\tilde{\sigma}}^2} \right\rangle_{\rm vac} - \frac{3}{2u}\left\langle \frac{\partial V_{\rm CW}^{(1)}}{\partial\phi_{\tilde{\sigma}}} \right\rangle_{\rm vac} \\ &+ \frac{v}{2u}\left\langle \frac{\partial^2 V_{\rm CW}^{(1)}}{\partial\phi_h\partial\phi_{\tilde{\sigma}}} \right\rangle_{\rm vac} , \end{aligned}$$

$$\begin{aligned} c_H =& \frac{1}{2}\lambda_H - \frac{1}{3}\lambda + \frac{3}{16}g^2 + \frac{1}{16}g'^2 \\ &+ \frac{1}{4}(y_t^2 + y_b^2 + y_c^2 + y_s^2 + y_u^2 + y_d^2) \\ &+ \frac{1}{12}(y_\tau^2 + y_e^2 + y_\mu^2) , \\ c_S =& \frac{1}{2}\lambda_{\rm TC} - \frac{1}{3}\lambda + \frac{2}{3}\mathcal{Y}_{\rm TC}^2 , \end{aligned}$$

$$\left\langle \frac{\partial V_{\rm eff}}{\partial\phi_\alpha} \right\rangle_{\rm vac} = \left\langle \frac{\partial V_0}{\partial\phi_\alpha} \right\rangle_{\rm vac} , \left\langle \frac{\partial^2 V_{\rm eff}}{\partial\phi_\alpha^2} \right\rangle_{\rm vac} = \left\langle \frac{\partial^2 V_0}{\partial\phi_\alpha^2} \right\rangle_{\rm vac}$$

$$\left\langle \frac{\partial^2 V_{\rm eff}}{\partial\phi_h\partial\phi_{\tilde{\sigma}}} \right\rangle_{\rm vac} = \left\langle \frac{\partial^2 V_0}{\partial\phi_h\partial\phi_{\tilde{\sigma}}} \right\rangle_{\rm vac}$$

$$\delta\lambda_H = -\frac{1}{2v^2}\left\langle \frac{\partial^2 V_{\rm CW}^{(1)}}{\partial\phi_h^2} \right\rangle_{\rm vac} + \frac{1}{2v^3}\left\langle \frac{\partial V_{\rm CW}^{(1)}}{\partial\phi_h} \right\rangle_{\rm vac}$$

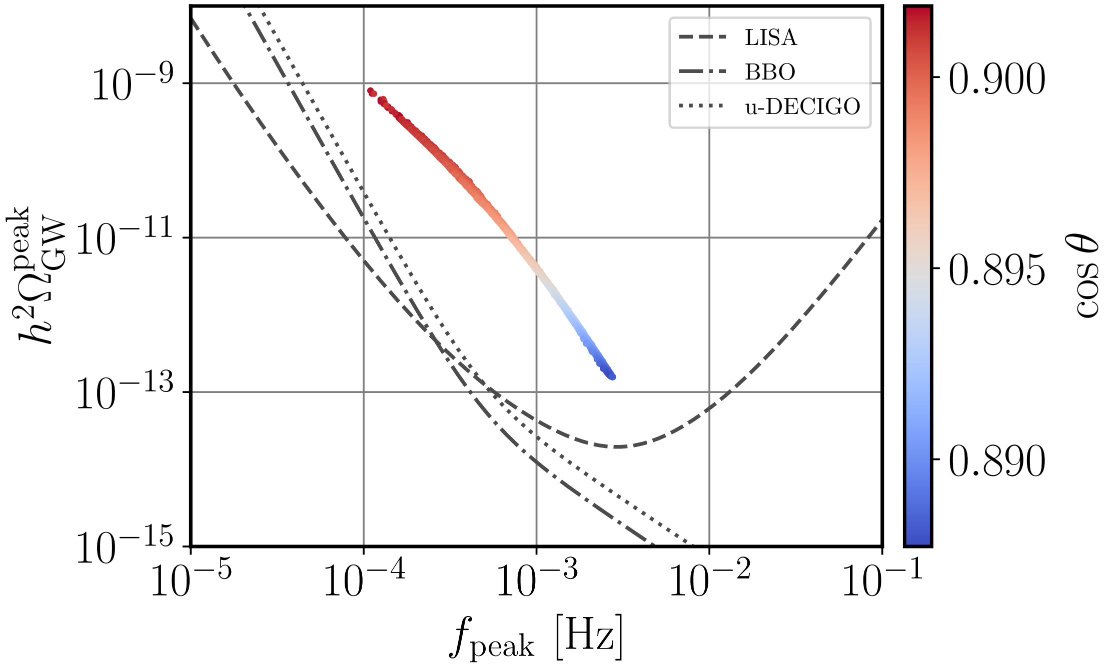
$$\delta\lambda_{\rm TC} = -\frac{1}{2u^2}\left\langle \frac{\partial^2 V_{\rm CW}^{(1)}}{\partial\phi_{\tilde{\sigma}}^2} \right\rangle_{\rm vac} + \frac{1}{2u^3}\left\langle \frac{\partial V_{\rm CW}^{(1)}}{\partial\phi_{\tilde{\sigma}}} \right\rangle_{\rm vac}$$

GWs from dynamical EWSB

Scan parameters

$$m_{\tilde\sigma}\,, \qquad m_{\tilde\pi}\,, \qquad m_{\tilde Q}\,, \qquad \mathcal{Y}_{\rm TC}\,, \qquad \theta$$

Example of a one-parametric scan:



$$m_{\tilde\sigma} = 702.0{\rm GeV},\ m_{\tilde\pi} = 347.1{\rm GeV},$$

$$m_{\tilde Q} = 466.6{\rm GeV},\ \mathcal{Y}_{\rm TC} = 2.86.$$

Benchmark points:

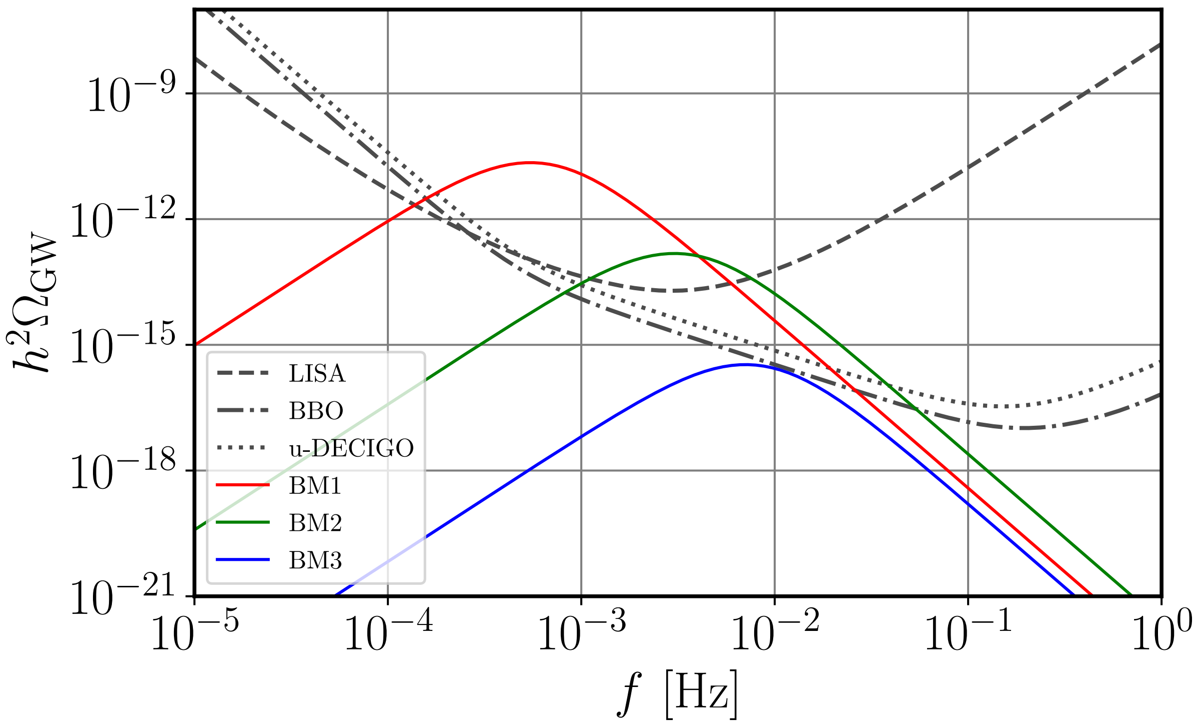
	Color	T_p	α	β/H	$\Delta v/T_p$	$\Delta u/T_p$
BM1	Red	46.36	1.23	124.50	5.47	1.86
BM2	Green	73.15	0.30	439.10	3.54	1.37
BM3	Blue	107.10	0.04	698.24	2.36	0.98

	Color	$m_{\tilde\sigma}$	$m_{\tilde\pi}$	$m_{\tilde Q}$	$\mathcal{Y}_{\rm TC}$	$\cos\theta$	u
BM1	Red	785.4	239.9	591.8	2.85	0.884	207.9
BM2	Green	744.3	303.7	470.3	2.85	0.859	165.0
BM3	Blue	626.2	291.1	490.5	2.38	0.859	206.4

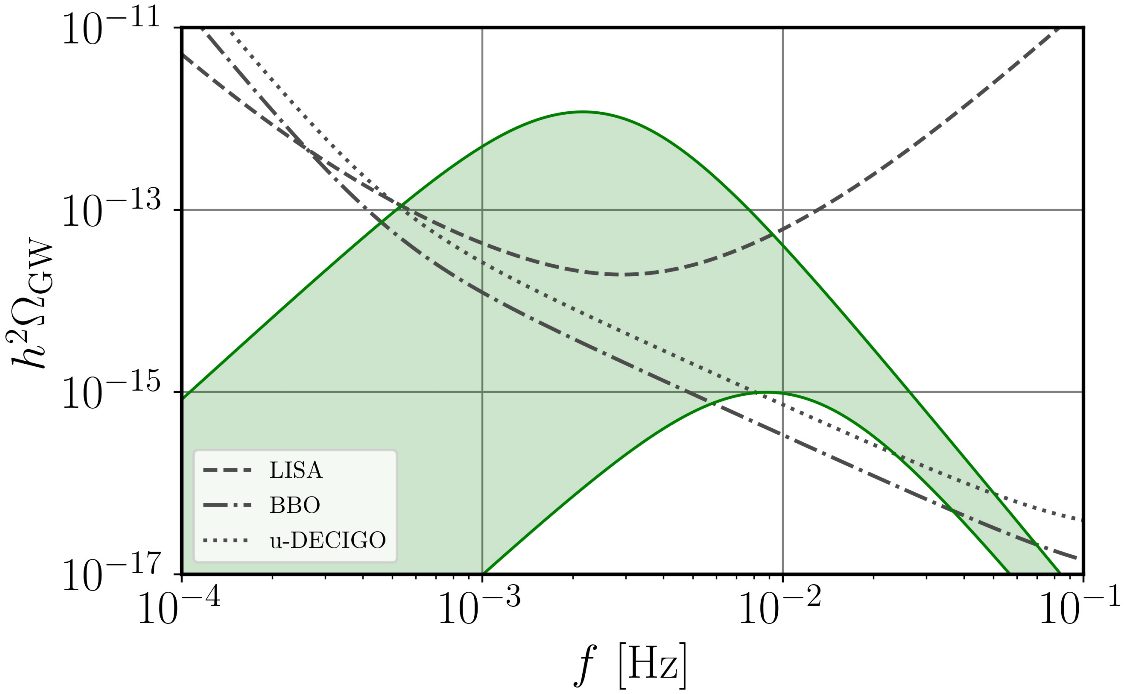
Limits on physical parameters:

$$m_{\tilde\pi} \gtrsim 140{\rm GeV}\,,\ m_{\tilde\sigma} \gtrsim 500{\rm GeV}\,,\ m_{\tilde Q} \gtrsim 300{\rm GeV}$$

GW spectra for benchmark points



Uncertainties



Summary

- Primordial gravitational waves represent a complimentary source of information to the collider measurements
- Combining collider constraints, future measurements (such as the triple Higgs coupling) with a possible observation of primordial GWs provides new opportunities for probing “simple” BSM scenarios such as scalar extensions and Technicolor