# CDF II W-mass anomaly faces first-order electroweak phase transition

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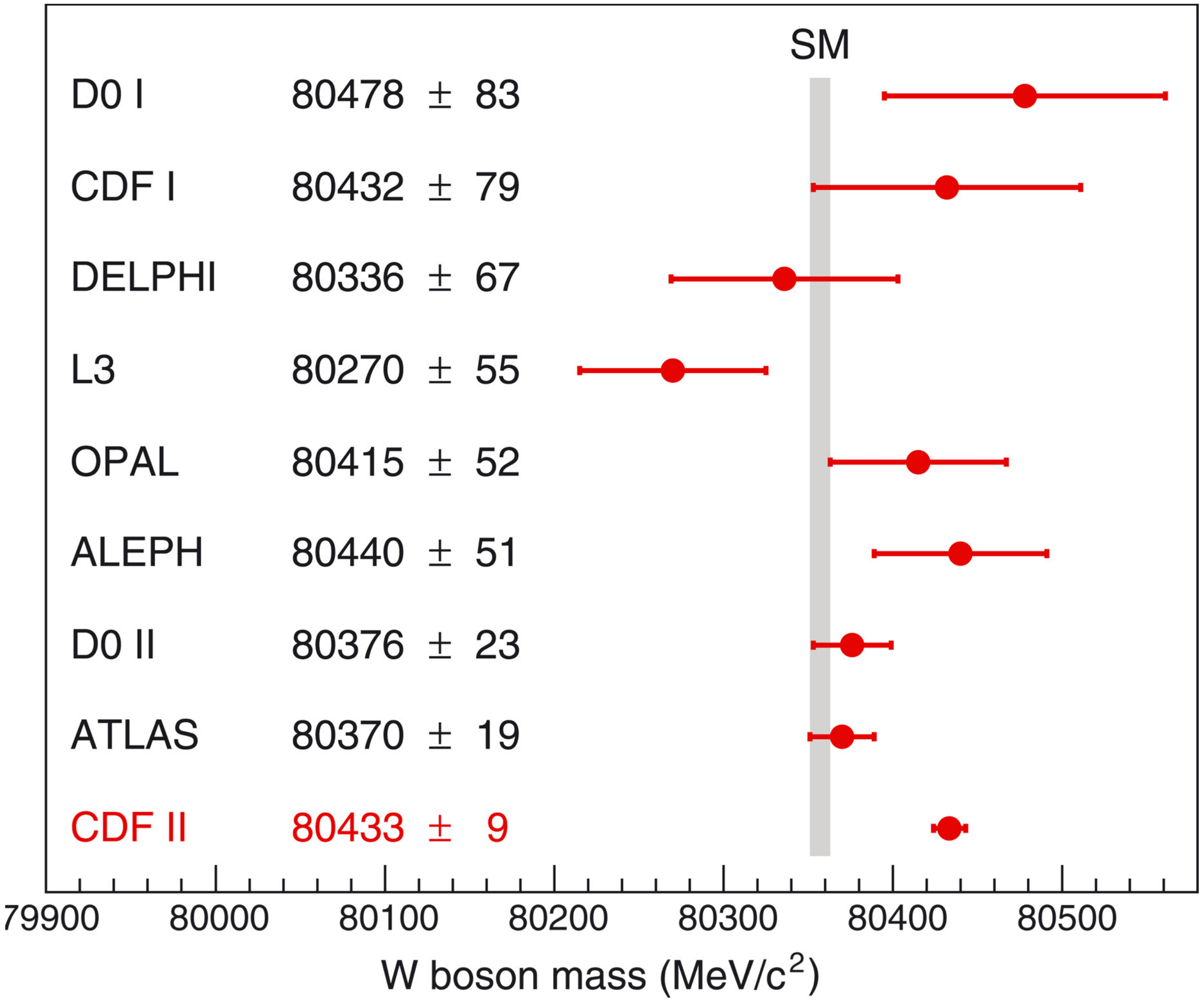
**Based on:**
A. Addazi, A. Marciano, A. Morais, RP, H. Yang
arXiv: 2204.10315

**Fysikdagarna, June 15th 2022**

# W mass anomaly

CDF II Collaboration,
Science 376, 170 (2022)



- Surprising CDF II measurement of W mass lies 7.6σ away from the Standard Model
- Many scenarios beyond the SM have been deployed in the literature to explain this measurement (over 100 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

# A minimal scalar SU(2) triplet extension

**Let us focus on a simplified framework that relates the characteristics of EW phase transitions to a possible explanation of the W mass anomaly**

The model by: L. Di Luzio, R. Gröber and P. Paradisi,
"Higgs physics confronts the $m_W$ anomaly"
[arXiv:2204.05284 [hep-ph]]

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

$$\hat{T} \simeq (0.84 \pm 0.14) \times 10^{-3}$$

A. Strumia, [arXiv:2204.04191 [hep-ph]]

**Effective Field Theory d=6 operator generates this anomaly**

$$c_{\mathrm{HD}} \mathcal{O}_{\mathrm{HD}} = c_{\mathrm{HD}} (H^\dagger D_\mu H)((D_\mu H)^\dagger H)$$

$$\hat{T} = -\frac{v^2}{2} c_{\mathrm{HD}}$$

**A new heavy state that generates this operator**

$$\Delta = (1, 3, 0) \qquad \mathcal{L}_{\mathrm{T}} = -k_\Delta H^\dagger \Delta \cdot \sigma H + \mathrm{h.c.}$$

$$\boxed{c_{\mathrm{HD}} = -2 \frac{k_\Delta^2}{M_\Delta^4}}$$

**negative effective coupling!**

# Scale of New Physics

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

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

**consistent with the observed shift in W mass for a TeV-scale scalar triplet state!**

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

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

**Higgs quartic couplings receives a tree-level correction**

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

$m^2$ Higgs mass parameter

$v \simeq 246\ \mathrm{GeV}$ Higgs VEV

$$\frac{\mu_\Delta}{3}\Delta^3 + \mathrm{h.c.} \qquad \Delta^3 \equiv (\Delta\cdot\sigma)(\Delta\cdot\sigma)(\Delta\cdot\sigma)$$

**d=6 Higgs self-interaction term is induced as well**

**crucial contribution to the Higgs potential that determines the nature and the strength of the EW phase transition**

$$\frac{\kappa}{\Lambda^2}(H^\dagger H)^3 + \mathrm{h.c.}$$

**cutoff scale**

$$\frac{\Lambda}{\sqrt{\kappa}} = \frac{\sqrt{3}M_\Delta^3}{\sqrt{\mu_\Delta}k_\Delta^{3/2}}$$

$$\kappa \lesssim 4\pi$$

# Dynamics of EWPTs

- High $T$ → classical motion in Euclidean space described by action $\hat{S}_3$

$$\hat{S}_3 = 4\pi \int_0^\infty \mathrm{d}r\, r^2 \left\{ \frac{1}{2} \left( \frac{\mathrm{d}\hat{\phi}}{\mathrm{d}r} \right)^2 + V_{\text{eff}}(\hat{\phi}) \right\} ,$$

- Effective potential: loop and thermal corrections

$$\begin{aligned} V_{\text{eff}}^{(1)}(\hat{\phi}) &= V_{\text{tree}} + V_{\text{CW}} + \Delta V^{(1)}(T) \\ V_{\text{CW}} &= \sum_i (-1)^F n_i \frac{m_i^4}{64\pi^2} \left( \log\left[ \frac{m_i^2(\hat{\phi}_\alpha)}{\Lambda^2} \right] - c_i \right) \\ \Delta V^{(1)}(T) &= \frac{T^4}{2\pi^2} \left\{ \sum_b n_b J_B \left[ \frac{m_b^2(\hat{\phi}_\alpha)}{T^2} \right] - \sum_f n_f J_F \left[ \frac{m_f^2(\hat{\phi}_\alpha)}{T^2} \right] \right\} , \end{aligned}$$

- $\hat{\phi}$ → solution of the e.o.m. found by the path that minimizes the energy.

$$\Delta V^{(1)}(T)|_{\text{L.O.}} = \frac{T^2}{24} \left\{ \text{Tr}\left[ M_{\alpha\beta}^2(\phi_\alpha) \right] + \sum_{i=W,Z,\gamma} n_i m_i^2(\phi_\alpha) + \sum_{i=t,b,\tau} \frac{n_i}{2} m_i^2(\phi_\alpha) \right\}$$

# Finite-T effective potential & EW FOPTs

**In unitary gauge, one-loop effective Higgs potential:**

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

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

**The dominant thermal correction to the Higgs mass:**

$$CT^2/2$$

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

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

**zero-T Higgs mass**

$$m_{\rm h} \;=\; 125\,{\rm GeV}$$

**Limit on the cutoff scale imposed by the strongly 1st order EW phase transition requirement yields:**

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

$$480\,{\rm GeV} \lesssim \frac{\sqrt{3}M_\Delta^3}{\sqrt{\mu_\Delta}k_\Delta^{3/2}} \lesssim 840\,{\rm GeV}$$

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

**For saturated perturbativity**

$|k_\Delta|/M_\Delta \simeq 4\pi$ and $|\mu_\Delta|/M_\Delta \simeq 4\pi$

→

**The EW FOPT bound:**

$$M_\Delta \simeq 5 \div 10\,{\rm TeV}$$

# EW FOPTs & GWs characteristics

**Inverse time-scale of the PTs:**

$$\frac{\beta}{H} = T_* \frac{\partial}{\partial T}\left(\frac{\hat{S}_3}{T}\right)\Bigg|_{T_*}$$

**Relative latent heat (PT strength):**

$$\alpha = \frac{1}{\rho_\gamma}\left[V_i - V_f - \frac{T_*}{4}\left(\frac{\partial V_i}{\partial T} - \frac{\partial V_f}{\partial T}\right)\right]$$

$$\rho_\gamma = g_* \frac{\pi^2}{30} T_*^4$$

**Probability to find a point in the false vacuum:**

$$P(T) = e^{-I(T)},$$

$$I(T) = \frac{4\pi v_b^3}{3} \int_T^{T_c} \frac{\Gamma(T')dT'}{T'^4 H(T')} \left(\int_T^{T'} \frac{d\tilde{T}}{H(\tilde{T})}\right)^3$$

**Percolation temperature**

**(temperature at which at least 34% of the false vacuum has tunnelled into the true vacuum)**

$$I(T_*) = 0.34$$

J. Ellis, M. Lewicki, and V. Vaskonen, Journal of Cosmology and Astroparticle Physics **2020**, 020–020 (2020).

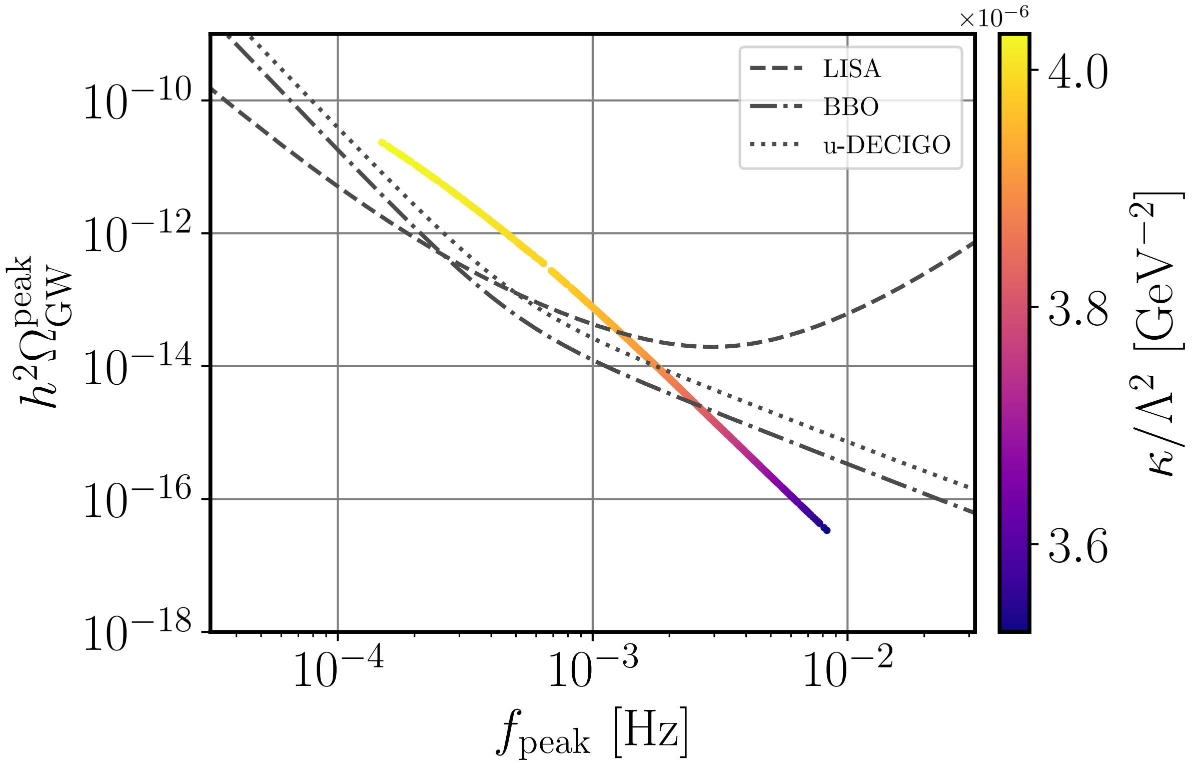
**Primordial GWs power spectrum:**

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

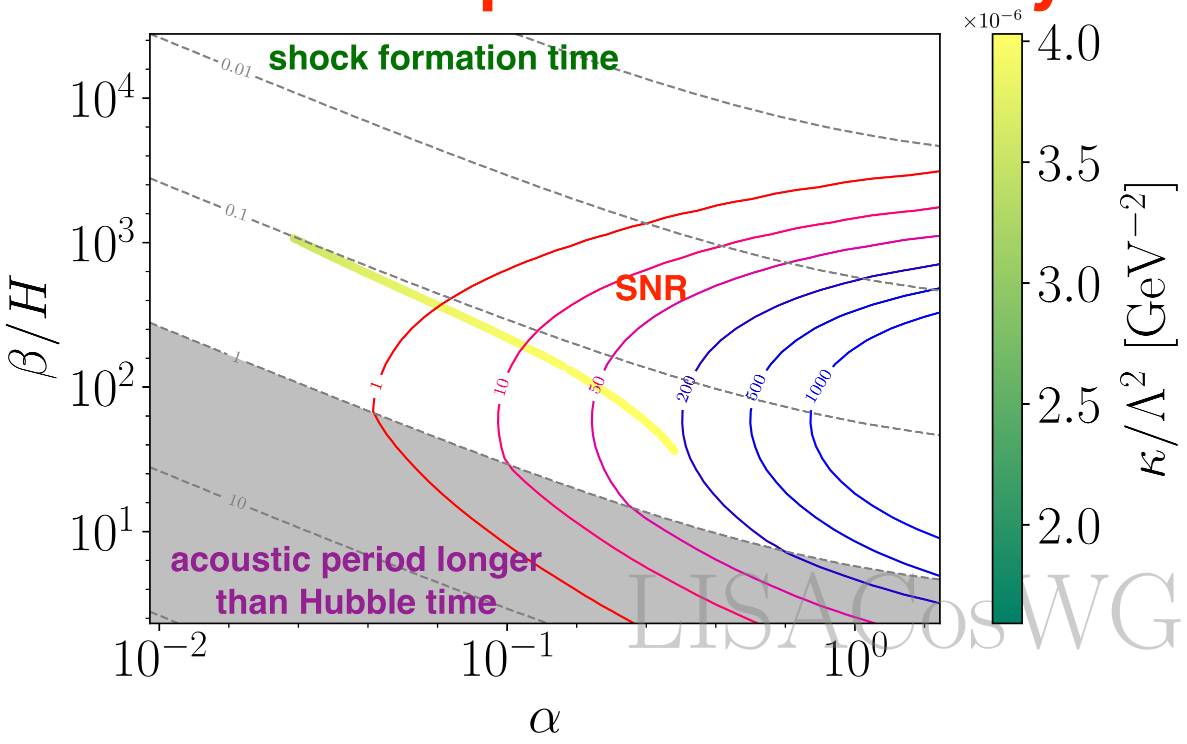
C. Caprini *et al.*, JCAP **2003**, 024 (2020), 1910.13125

# Primordial GWs in a minimal triplet model

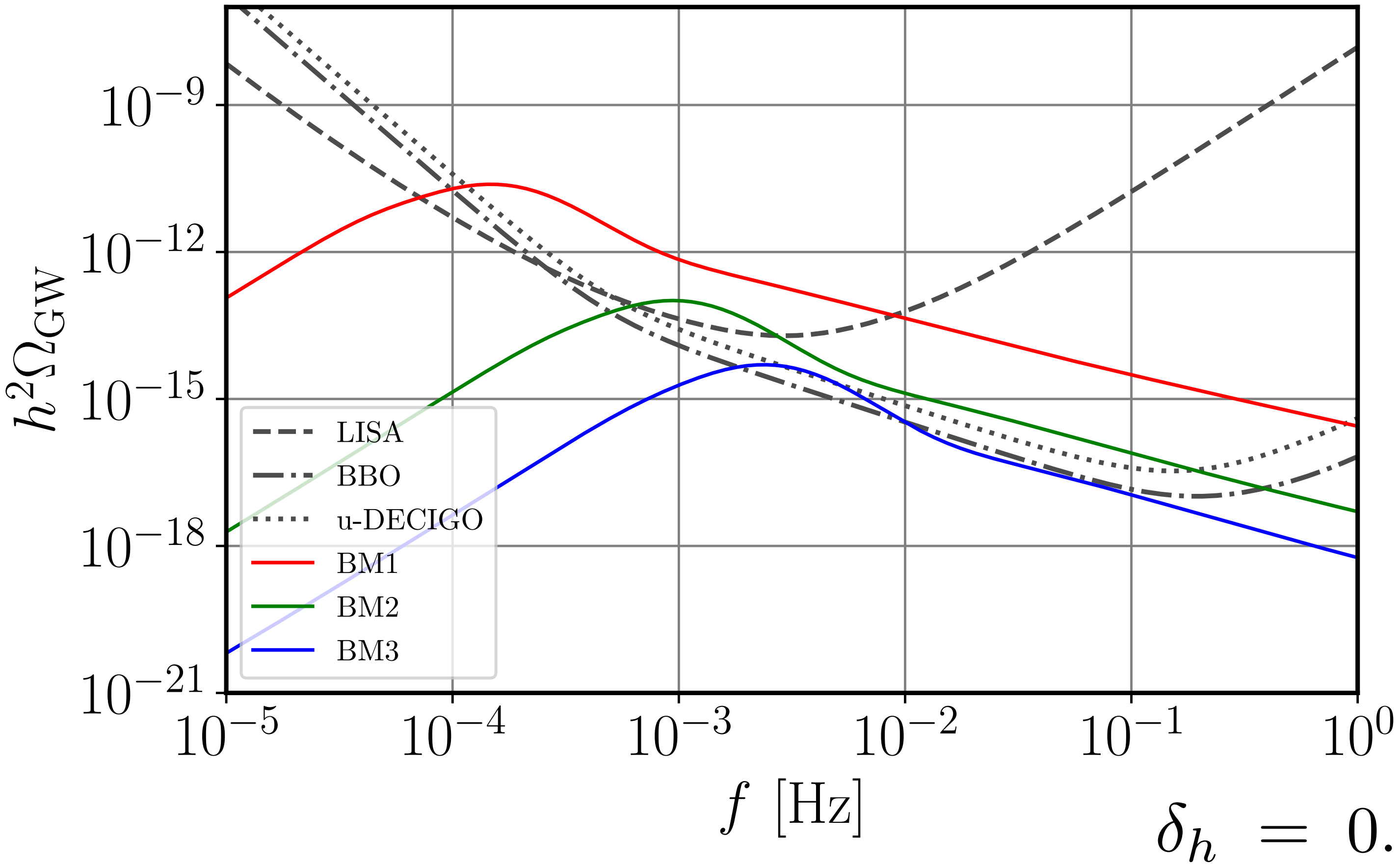
## peak-amplitude vs energy scale



## duration & SNR for points detectable by LISA



## GWs power spectrum



## Benchmarks:

| $T_*$(GeV) | $\alpha$ | $\beta/H_*$ | $\kappa^{-1/2}\Lambda$(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:

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

$$\delta_h = 0.66 \div 2 \qquad \leftrightarrow \qquad \delta_{\sigma_{hZ}} = \delta\sigma_{hZ}/\sigma_{hZ}$$

# Summary

- Recent W mass measurement offers new opportunities for New Physics searches

- A simple model with heavy scalar triplet provides potentially observable new signatures (W mass correction, triple-Higgs coupling, FOPTs & GWs) and addresses some of the fundamental questions (e.g. neutrino mass)

- Primordial gravitational waves represent a complimentary source of information to the collider measurements (such as HE-LHC and Circular e+e- Collider)

- Combining W mass, future measurements of triple Higgs coupling and primordial GWs would provide strong case of probing such a class of models BSM