Electroweak phase transition with anomalous Higgs couplings and its cosmological implications

Archil Kobakhidze

CoEPP
ARC Centre of Excellence for
Particle Physics at the Terascale

THE UNIVERSITY OF
SYDNEY

AK, Lei Wu, Jason Yue, JHEP 1604 (2016) 011
AK, Adrian Manning, Jason Yue, to appear

28th Rencontres de Blois on Particle Physics and Cosmology
1 June 2016

Many important properties of the Higgs boson still need to be verified. In particular, precision measurements of the Higgs couplings are important to determine the nature of the electroweak symmetry and of the electroweak phase transition in the early universe.

Parameterizing new physics

- High-dimensional operators consistent with $SU(3) \times SU(2) \times U(1)$ gauge invariance

$$\mathcal{O}_6 = \frac{c_6}{\Lambda^2}(H^\dagger H)^3 \Rightarrow \frac{\sigma}{3}h^3$$

$$\mathcal{O}_{t\bar{t}h} = \frac{c_{t\bar{t}h}}{\Lambda^2}(H^\dagger H)\overline{Q}_L H t_R \ , \Rightarrow y_t \bar{t}th$$

- Non-linear realisation –

$$[SU(3) \times SU(2) \times U(1)] \, / \, [SU(3) \times U(1)_{\mathrm{EM}}]$$

Non-linear realisation

- Parameterize coset with

$$\mathcal{X}(x) = e^{\frac{i}{2}\pi_i(x)T_i} \left(\begin{array}{c} 0 \\ 1 \end{array} \right)$$

- Higgs is residing in a singlet field

$$\rho(x) = h(x) + v$$

- Connection with the SM Higgs doublet

$$H(x) = \frac{\rho(x)}{\sqrt{2}}\mathcal{X}(x)$$

Non-linear realisation

- Many new couplings – constraints from electroweak precision data, flavour data, violation of perturbative unitarity…

- Simplified model – less constrained, relevant for the electroweaak baryogenesis –

$$\mathcal{L}_{\mathrm{H-T}} = -\left[m_t' + Y_t\rho/\sqrt{2}\right]\bar{Q}_L\tilde{\mathcal{X}}t_{\mathrm{R}} + \mathrm{h.c.}\ , \quad Y_t = y_t \mathrm{e}^{i\xi}$$

$$V = \frac{\mu^2}{2}\rho^2 + \frac{\kappa}{3}\rho^3 + \frac{\lambda}{4}\rho^4$$

Non-linear realisation

- Perturbative unitarity – $E \gtrsim 10\ \mathrm{TeV}$

- No 1-loop corrections to S, T, U parameters

- Fermion EDM

$$d_f/\bar{d}_f = \frac{4}{9}\sin\xi\left(\frac{m_t'}{m_t}\right)\left(\frac{y_t v}{\sqrt{2}m_t}\right)\ln\left(\frac{m_t^2}{m_h^2}\right)$$

$$\approx 0.29\sin\xi\left(\frac{y_t}{y_t^{\mathrm{SM}}}\right)\left(\frac{m_t'}{m_t}\right)\ .$$

$$\bar{d}_f = \frac{|Q_f|\alpha m_f}{16\pi^3 v^2}, \quad \bar{d}_e \approx 2.5\cdot 10^{-27}\ e\cdot cm$$

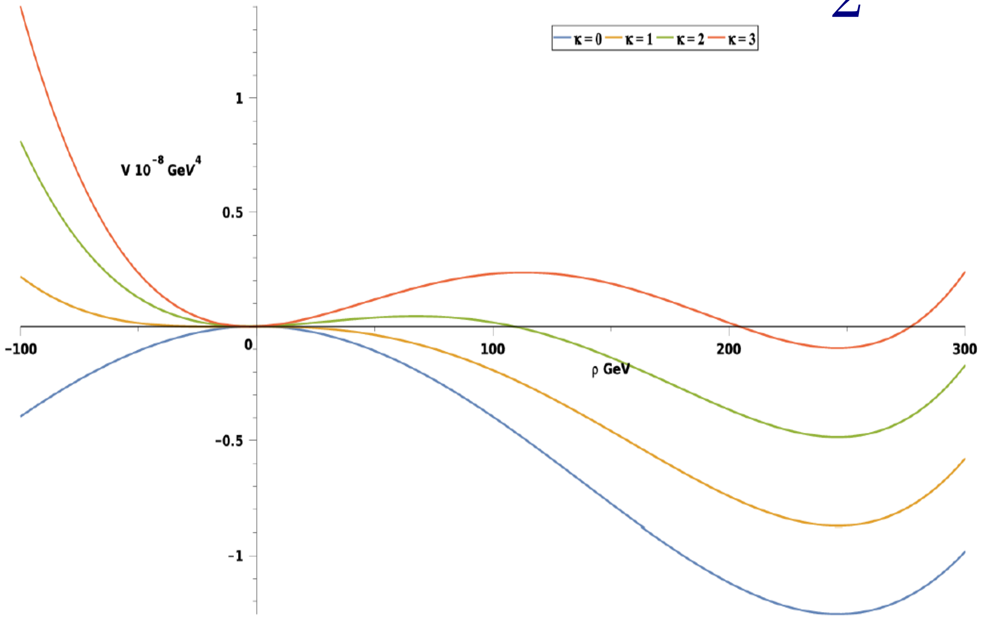
Electroweak Phase transition

- Higgs potential:

$$V(\rho_c, T) = V_c + V_{CW} + V_T$$

- Classical potential at zero temperature :

$$V_c = -\frac{\mu^2}{2}\rho_c + \frac{\lambda}{4}\phi_c^4 + \frac{\kappa}{3}\phi_c^3$$



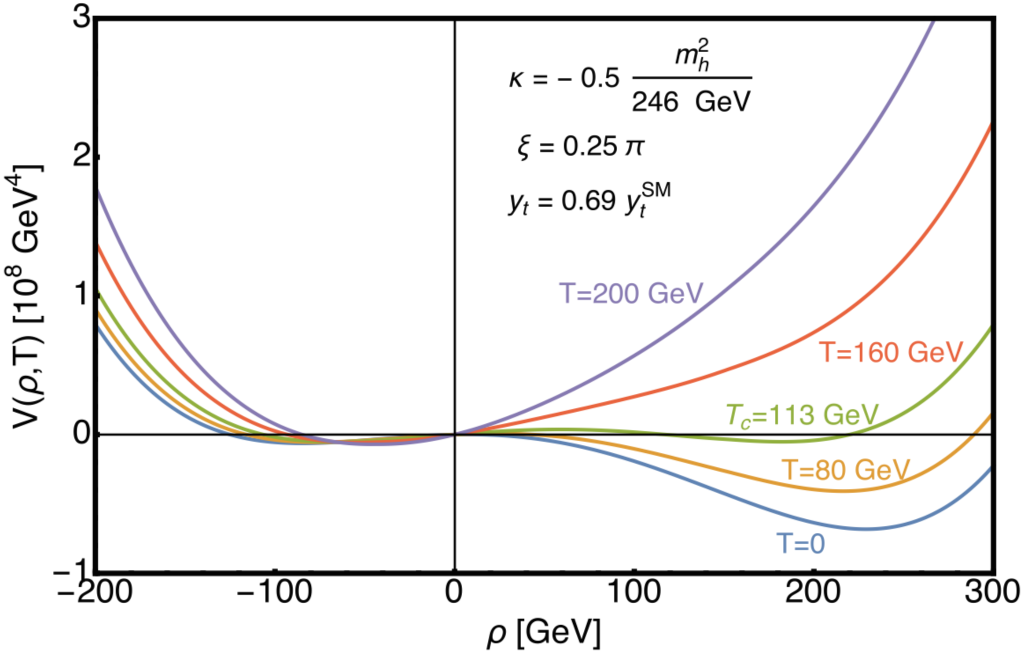
- $\mu^2 < 0$, min [0,v], $-3m_h^2 < v\kappa < -m_h^2$
- $\mu^2 > 0$, min [v',v], $-m_h^2 < v\kappa < 0$
- $\mu^2 = 0$, $v = -\kappa/\lambda$

Electroweak Phase transition

- Finite temperature potential (high-T limit):

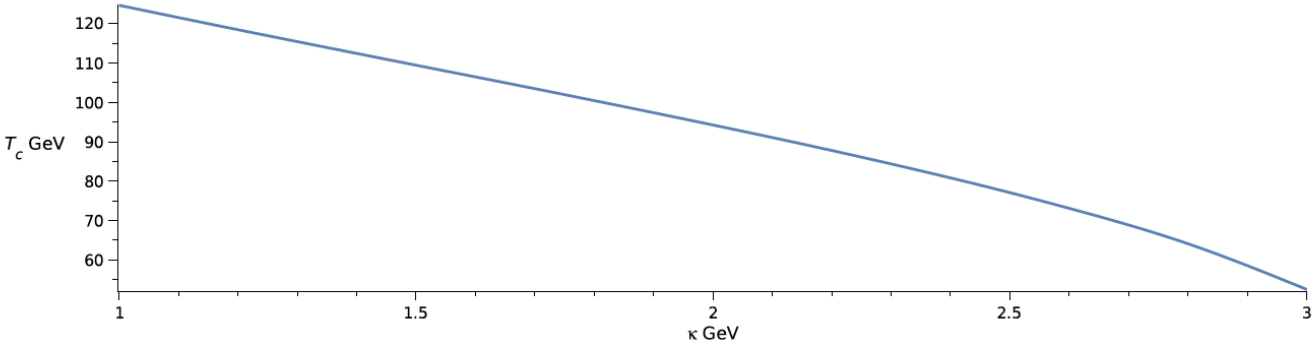
$$V(\phi_c, T) = \frac{\lambda}{4}\phi_c^4 + \frac{\kappa}{3}\phi_c^3 + \phi_c^2\left(-\frac{\mu^2}{2} + \frac{T^2}{32}(3g_2^2 + g_1^2 + 4\lambda + 4y_t^2)\right)$$

$$+ \frac{T^2}{12}(\kappa + 3\sqrt{2}y_t m_t' \cos\xi)\phi_c + \ldots$$



Electroweak Phase transition

- Critical temperature



κ	T_c	Root 1	Root 2
1.0	124.6551514	0.6250000000	174.6093750
1.2	118.4555054	-0.2343750000	188.3203125
1.4	112.4313354	-0.8593750000	199.3750000
1.5	109.4406128	-1.093750000	204.1796875
1.6	106.4712524	-1.289062500	208.5156250
1.8	100.4470824	-1.601562500	216.2500000
2.0	94.25201417	-1.875000000	222.8125000
2.2	87.77923583	-2.109375000	228.4375000
2.4	80.81512452	-2.324218750	233.2617188
2.5	77.07672119	-2.421875000	235.4101563
2.6	73.08197023	-2.519531250	237.4218750
2.8	64.08843995	-2.695312500	240.9179688
3.0	52.48870849	-2.871093750	243.7890625

Electroweak Phase transition

- Bubble nucleation

$$S_3[\rho] = 4\pi \int_0^\infty dr\ r^2 \left[\frac{1}{2} \left(\frac{d\rho}{dr} \right)^2 + V(\rho, T) \right]$$

$$\frac{d^2\rho}{dr^2} + \frac{2}{r}\frac{d\rho}{dr} - \frac{\partial V(\rho, T)}{\partial \rho} = 0$$

$$\left.\frac{d\rho}{dr}\right|_{r=0} = 0, \qquad \rho|_{r=\infty} = v^s_{T_n}$$

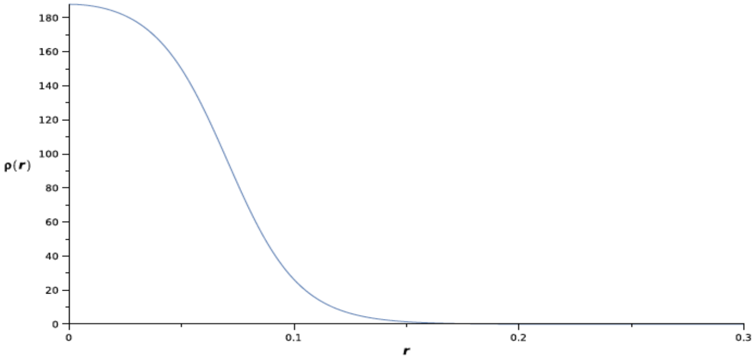


Figure 4: Bubble profile for $\kappa = 1$ at T_n

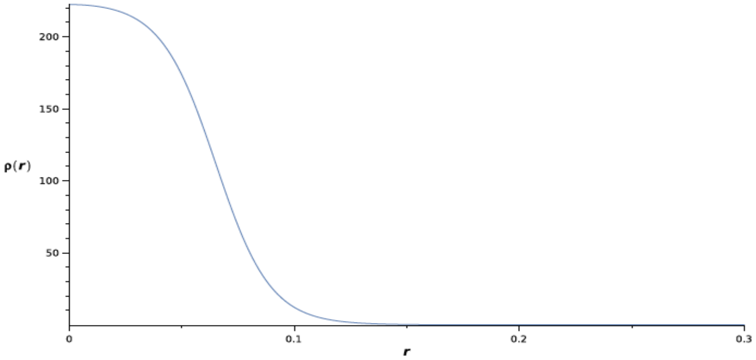
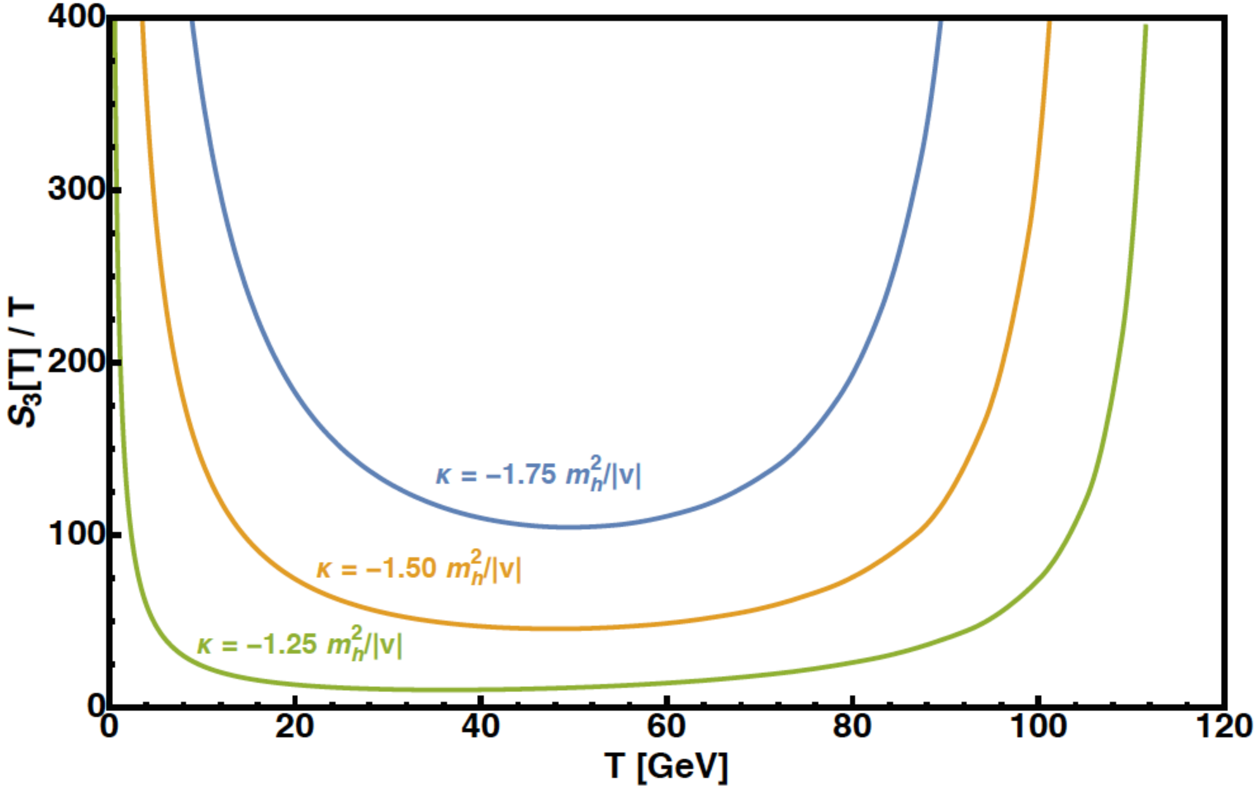


Figure 5: Bubble profile for $\kappa = 1.5$ at T_n

Electroweak Phase transition

- Bubble nucleation



- Nucleation probability - $P \sim \int_0^{t_*} \Gamma \mathcal{V}_H \, dt \sim \int_{T_n}^{T_c} \left(\sqrt{\frac{45}{4\pi^3 g_*}}\,\frac{M_P}{T}\right)^4 e^{-S_3/T}\,\frac{dT}{T}$

Electroweak Phase transition

- Nucleation temperature

$$P \sim \int_0^{t_*} \Gamma \mathcal{V}_H dt \sim \int_{T_n}^{T_c} \left(\sqrt{\frac{45}{4\pi^3 g_*}} \frac{M_P}{T} \right)^4 e^{-S_3/T} \frac{dT}{T} \sim \mathcal{O}(1)$$

κ	T_n GeV	T_* GeV	T_c GeV
1.0	114.81	114.81	124.66
1.25	106.06	110.82	116.94
1.5	91.85	101.65	109.44
1.75	72.03	91.3	101.96
2.0	-	79.0	94.25
2.5	-	44.72	77.08

Cosmological baryogenesis at the electroweak scale

$$\eta_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 6 \cdot 10^{-10}$$

(nucleosynthesis, CMBR+LSS)

Sakharov's conditions are met within the SM:

- CP violation – Kobayashi-Maskawa mechanism
- B-violation – nonperturbative sphaleron effects
- Non-equilibrium – electroweak phase transition

Phase transition

$$V(H) = m_H^2 |H|^2 + \lambda |H|^4$$

$$V_T(H) = (m_H^2 + \alpha T^2)|H|^2 + \beta T |H|^3 + \lambda_T |H|^4$$

Cosmological baryogenesis at the electroweak scale

- SM fails to reproduce the desired asymmetry,

$$\eta_B^{SM} \sim 10^{-20} <<< \eta_B$$

for 2 reasons:

(i) Not enough CP-violation;

(ii) The phase transition is not enough strongly 1st order

- Anomalous trilinear Higgs coupling may enhance the 1st order phase transition
- Anomalous Higgs-top coupling may contain additional CP violation

Electroweak Baryogenesis: Baryon number

$$D_q n_B''(z) - v_w n_B'(z) - 3\Gamma_{ws}(z) n_L(z) = 0$$

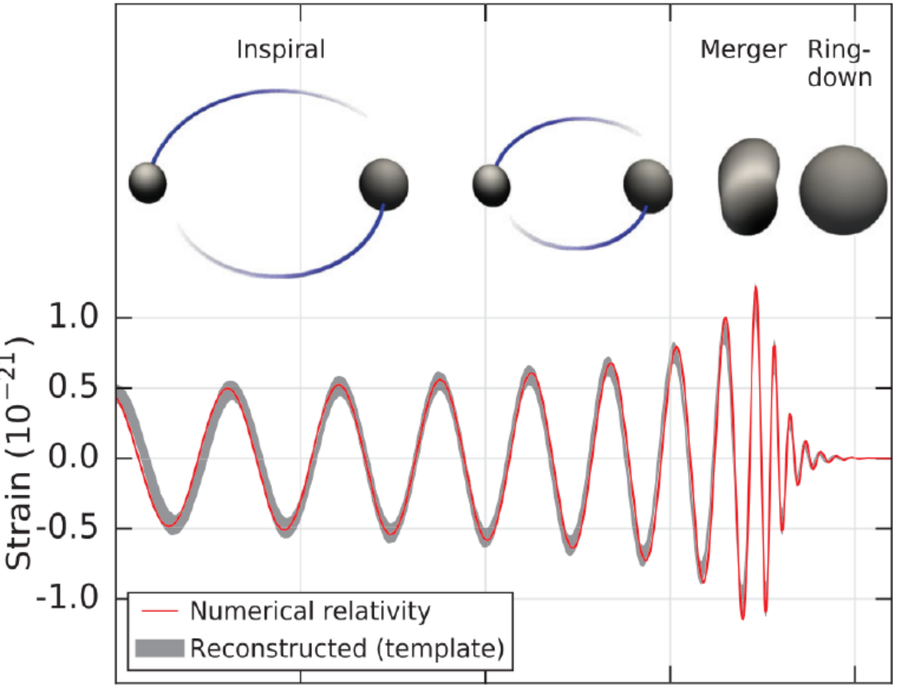
$$n_B(z > 0) \approx -\frac{3\Gamma_{ws}}{v_w} \int_{-\infty}^{0} dz_0 \; n_L(z_0)$$

	$\kappa \left[\frac{m_h^2}{\lvert v \rvert}\right]$	$\xi = 0.25\pi$		
		$y_t = 0.62 y_t^{SM}$	$y_t = 0.69 y_t^{SM}$	$y_t = 0.76 y_t^{SM}$
n_B/s	-0.5	9.28×10^{-10}	3.41×10^{-9}	2.41×10^{-8}
	-2.0	2.02×10^{-5}	1.92×10^{-5}	1.38×10^{-5}
	0.5	8.31×10^{-10}	3.98×10^{-9}	3.35×10^{-8}
	2.0	6.18×10^{-6}	1.00×10^{-5}	1.01×10^{-5}

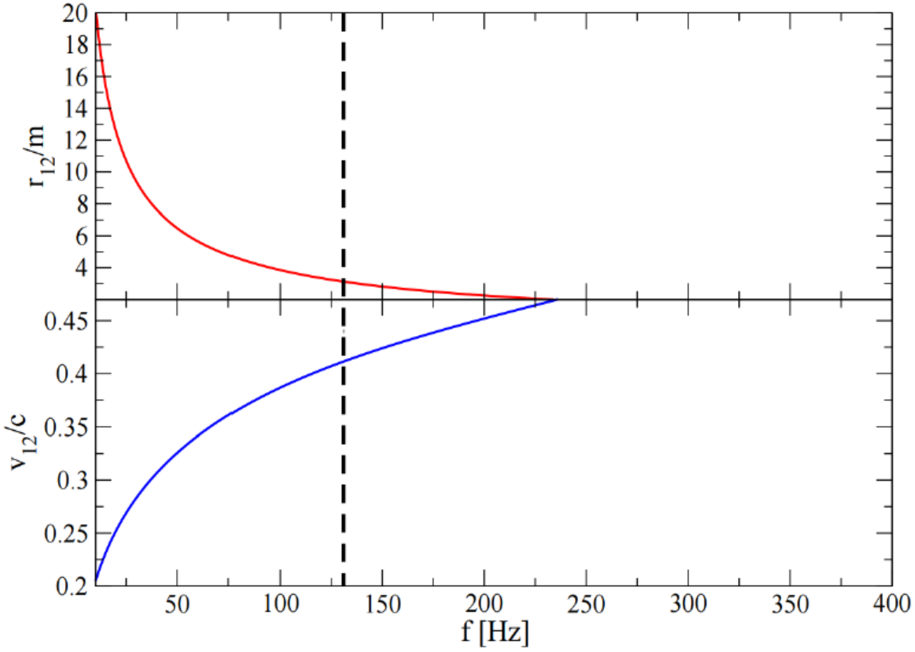
Electroweak Baryogenesis: Baryon number

	$\kappa\left[\frac{m_h^2}{\lvert v\rvert}\right]$	$\xi = 0.5\pi$		
		$y_t = 0.46 y_t^{SM}$	$y_t = 0.52 y_t^{SM}$	$y_t = 0.57 y_t^{SM}$
n_B/s	-1.5	1.14×10^{-6}	1.72×10^{-6}	1.59×10^{-6}
	-2.0	8.02×10^{-8}	3.48×10^{-8}	1.24×10^{-8}
	-2.5	2.10×10^{-12}	5.71×10^{-10}	1.21×10^{-8}

The LIGO detectors observed a binary black hole merger, with masses of $36^{+5}_{-4} M_{\odot}$ and $29^{+4}_{-4} M_{\odot}$. Observed frequencies ranging from 35 to 250 Hz and speeds of up to $\sim 0.5c$.



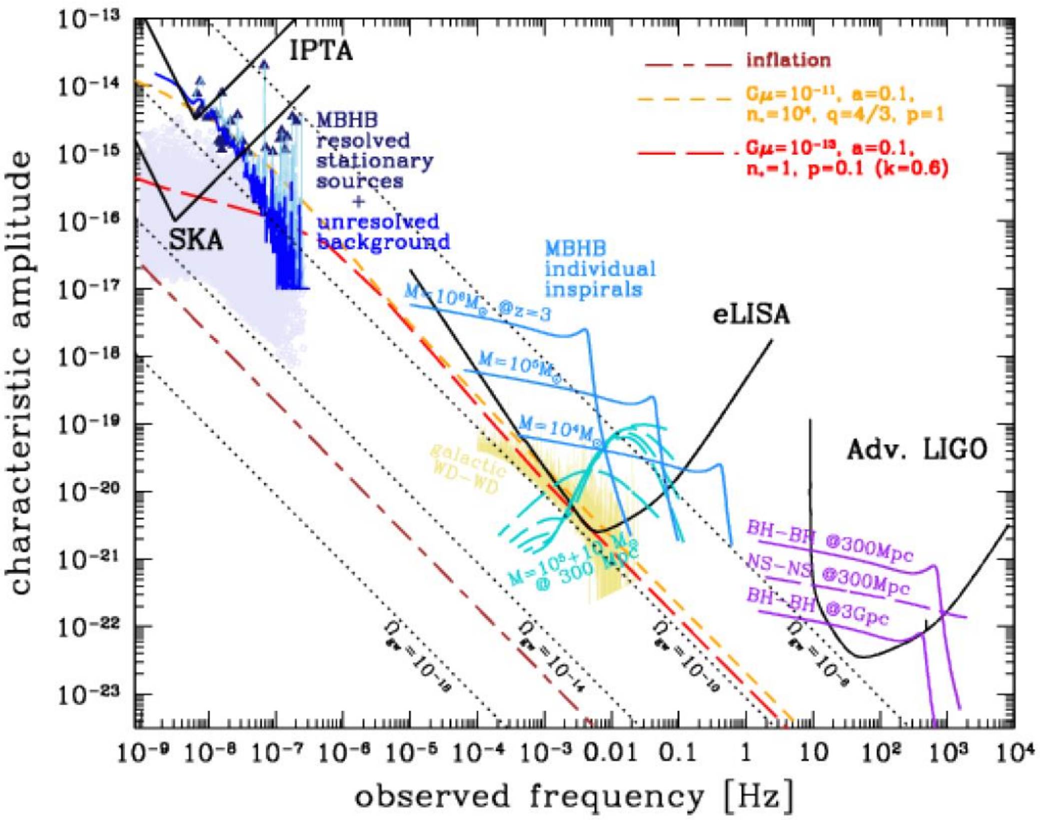
[Phys. Rev. Lett. 116 (2016) 061102]



[arXiv:1603.08955]

Gravitational waves from EWPT

- Bubble collisions
- Sound waves
- Turbulence



G. Janssen et al, 1501.00127

Gravitational waves from EWPT

- Latent heat

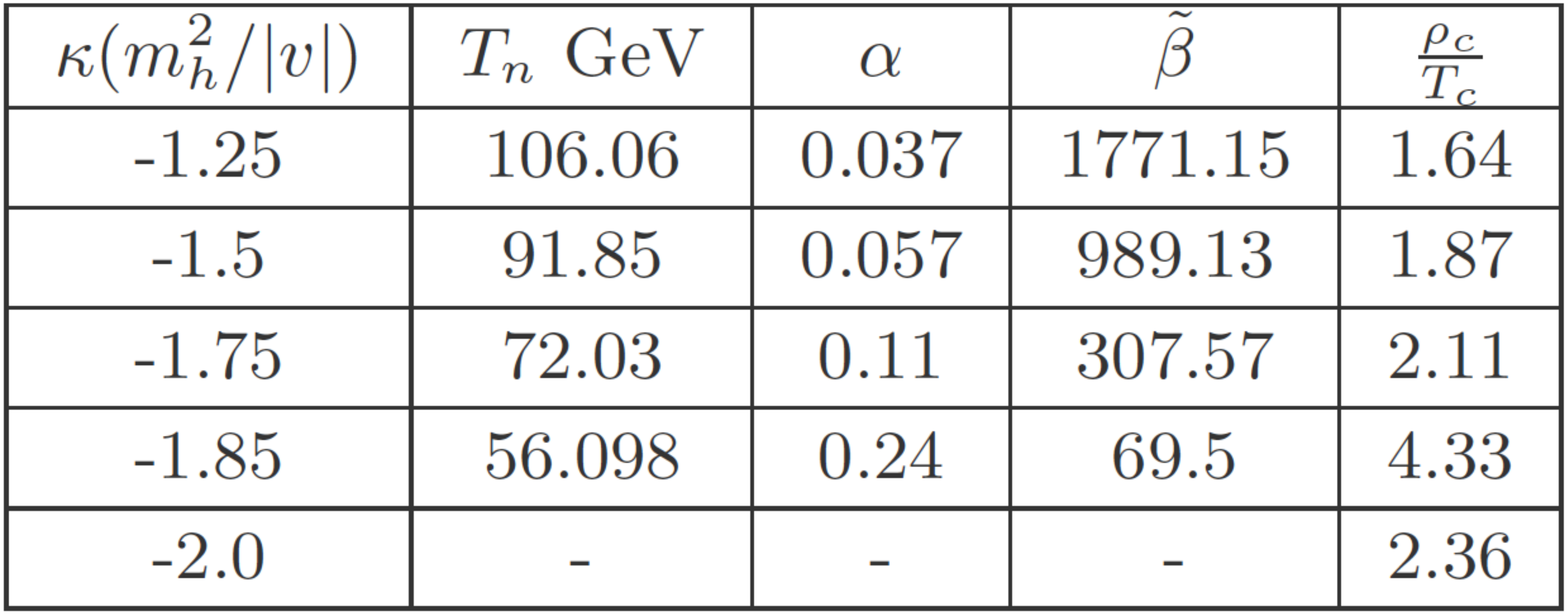
$$\alpha = \frac{\varepsilon_n}{\rho_{rad}} = \frac{1}{\frac{\pi^2}{30} g_n T_n^4} (-\Delta V - T \Delta s)$$

- Inverse time duration of PT

$$\frac{\beta}{H_*} = T_* \left. \frac{dS_4}{dT_*} \right|_{T=T_*}$$

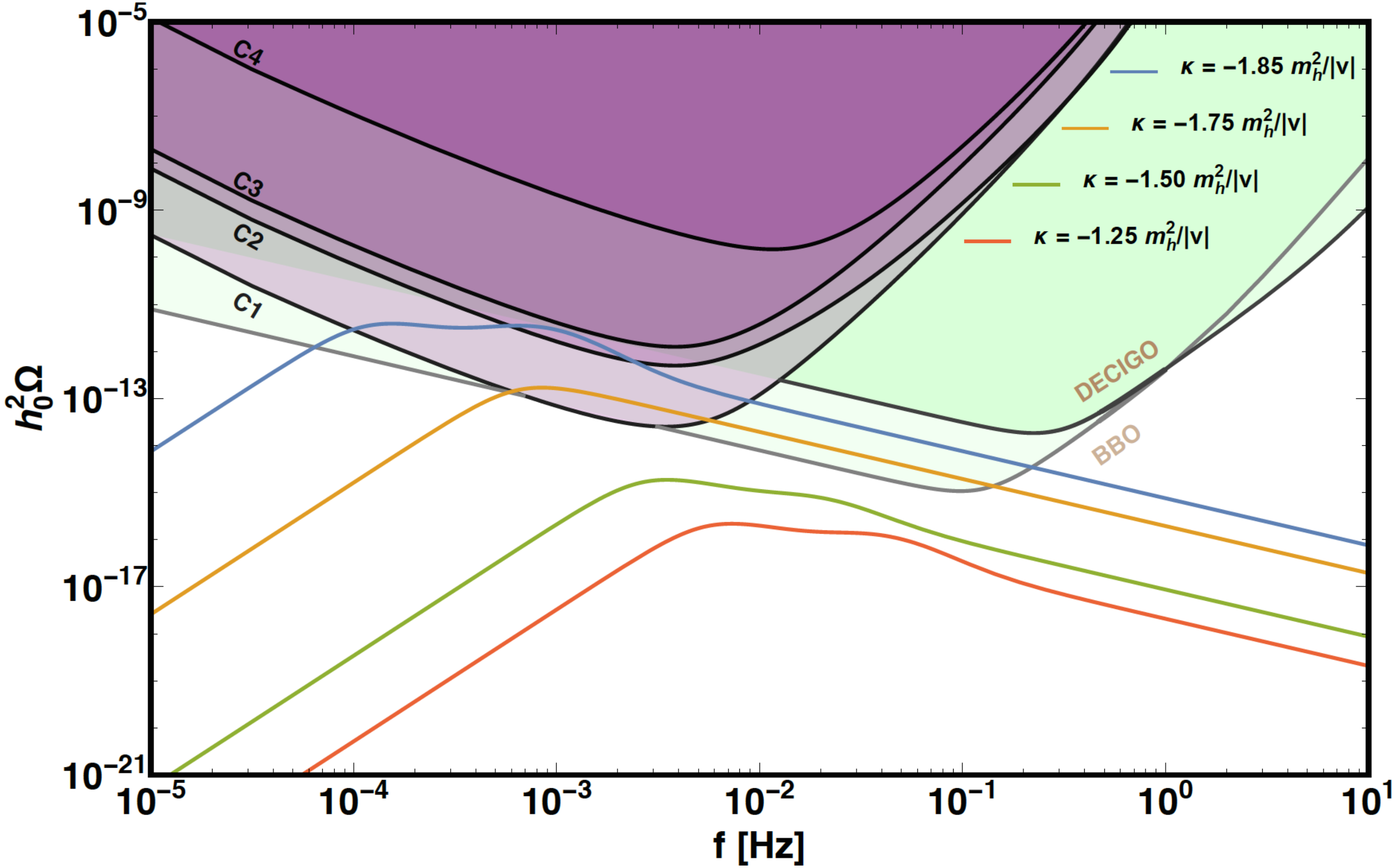
Gravitational waves from EWPT

Typical parameters



$\kappa(m_h^2/\|v\|)$	T_n GeV	α	$\tilde{\beta}$	$\frac{\rho_c}{T_c}$
-1.25	106.06	0.037	1771.15	1.64
-1.5	91.85	0.057	989.13	1.87
-1.75	72.03	0.11	307.57	2.11
-1.85	56.098	0.24	69.5	4.33
-2.0	-	-	-	2.36

Gravitational waves from EWPT



Conclusion

- The discovery of the Higgs boson is an important milestone in particles physics. However, the nature of the electroweak symmetry breaking still needs to be clarified
- Important goal – precise measurement of Higgs couplings, especially Higgs-top and trilinear Higgs couplings, which may shed light on the nature of electroweak symmetry and phase transition in the early universe
- Successful electroweak baryogenesis is still a viable option within the effective SM with nonlinearly realised electroweak symmetry
- Gravitational waves from the electroweak phase transition – new probe of BSM physics

Anomalous Higgs-Top interactions

[A.K., L. Wu, J. Yue, JHEP 1410 (2014) 100 [arXiv:1406.1961]]

$$\mathcal{L}_{\mathrm{Higgs-Top}} = -\frac{y_t^{SM}}{\sqrt{2}}\bar{t}\left(C_s + \gamma^5 C_p\right) th$$

$$C_s = y_t \cos\xi / y_t^{SM}$$

$$C_p = y_t \sin\xi / y_t^{SM}$$

Anomalous Higgs-Top interactions

[A.K., L. Wu, J. Yue, JHEP 1410 (2014) 100 [arXiv:1406.1961]]

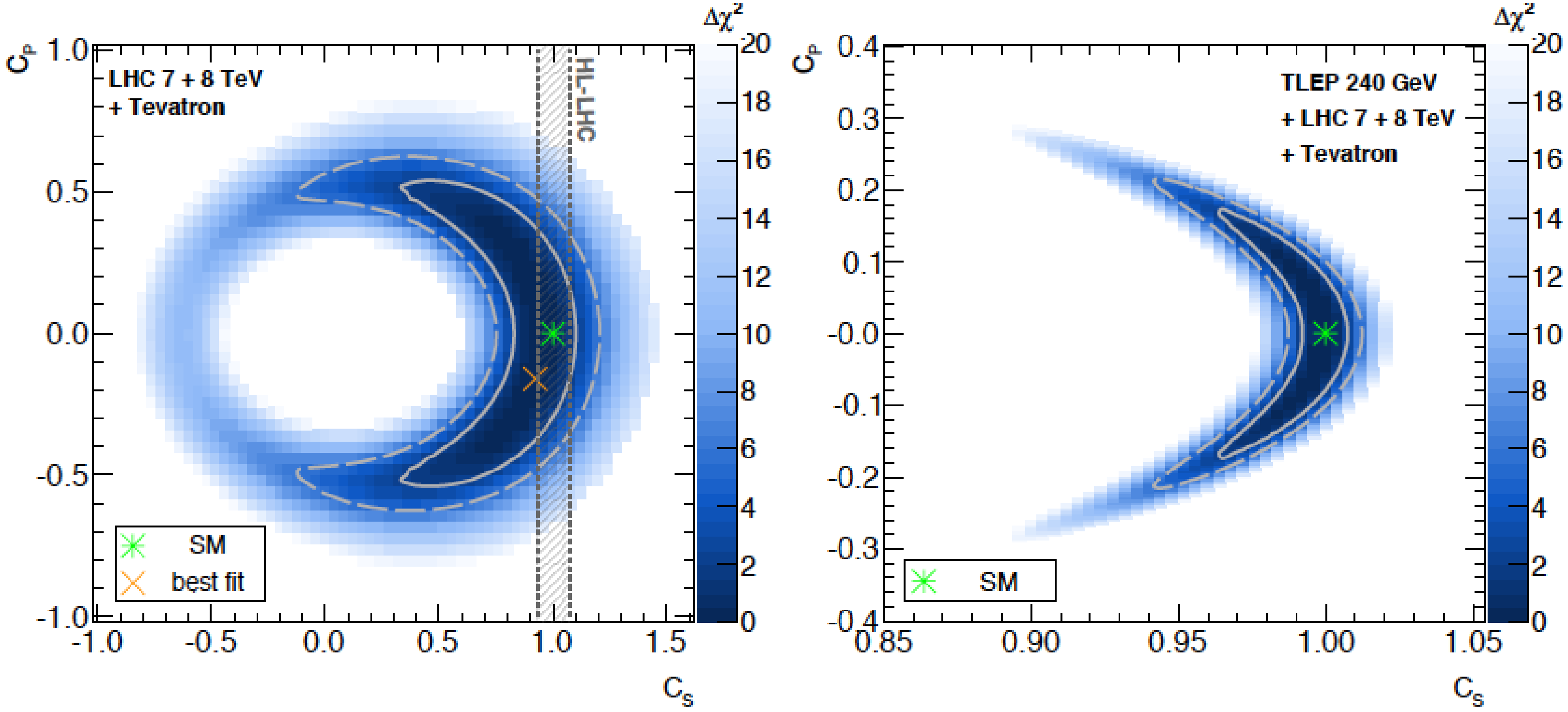
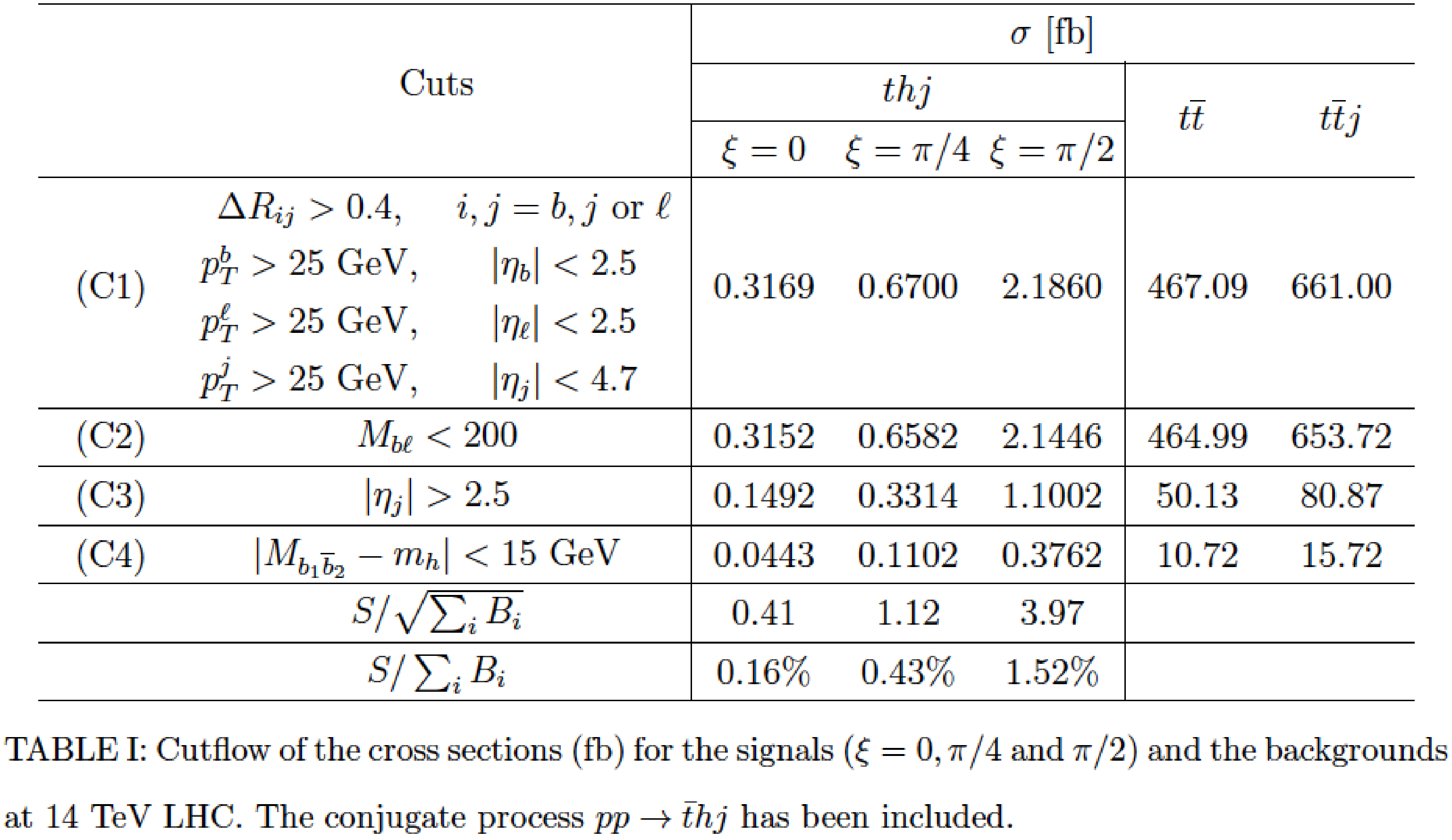


FIG. 1: The Higgs data constraints on the anomalous couplings C_S and C_P at the LHC and the expected sensitivity of these couplings at 240 GeV TLEP. The solid and dashed lines correspond to 68% and 95% C.L. respectively. The shadowed region represents the expected measurement uncertainty at HL-LHC.

Anomalous Higgs-Top interactions

[A.K., L. Wu, J. Yue, JHEP 1410 (2014) 100 [arXiv:1406.1961]]

$$pp \to thj \to bl^+\nu b\bar{b}j$$



	Cuts	σ [fb]				
		thj			$t\bar{t}$	$t\bar{t}j$
		$\xi = 0$	$\xi = \pi/4$	$\xi = \pi/2$		
(C1)	$\Delta R_{ij} > 0.4, \quad i, j = b, j \text{ or } \ell$ $p_T^b > 25$ GeV, $\quad \lvert\eta_b\rvert < 2.5$ $p_T^\ell > 25$ GeV, $\quad \lvert\eta_\ell\rvert < 2.5$ $p_T^j > 25$ GeV, $\quad \lvert\eta_j\rvert < 4.7$	0.3169	0.6700	2.1860	467.09	661.00
(C2)	$M_{b\ell} < 200$	0.3152	0.6582	2.1446	464.99	653.72
(C3)	$\lvert\eta_j\rvert > 2.5$	0.1492	0.3314	1.1002	50.13	80.87
(C4)	$\lvert M_{b_1\bar{b}_2} - m_h\rvert < 15$ GeV	0.0443	0.1102	0.3762	10.72	15.72
	$S/\sqrt{\sum_i B_i}$	0.41	1.12	3.97		
	$S/\sum_i B_i$	0.16%	0.43%	1.52%		

TABLE I: Cutflow of the cross sections (fb) for the signals ($\xi = 0, \pi/4$ and $\pi/2$) and the backgrounds at 14 TeV LHC. The conjugate process $pp \to \bar{t}hj$ has been included.

Anomalous Higgs-Top interactions

[A.K., L. Wu, J. Yue, JHEP 1410 (2014) 100 [arXiv:1406.1961]]

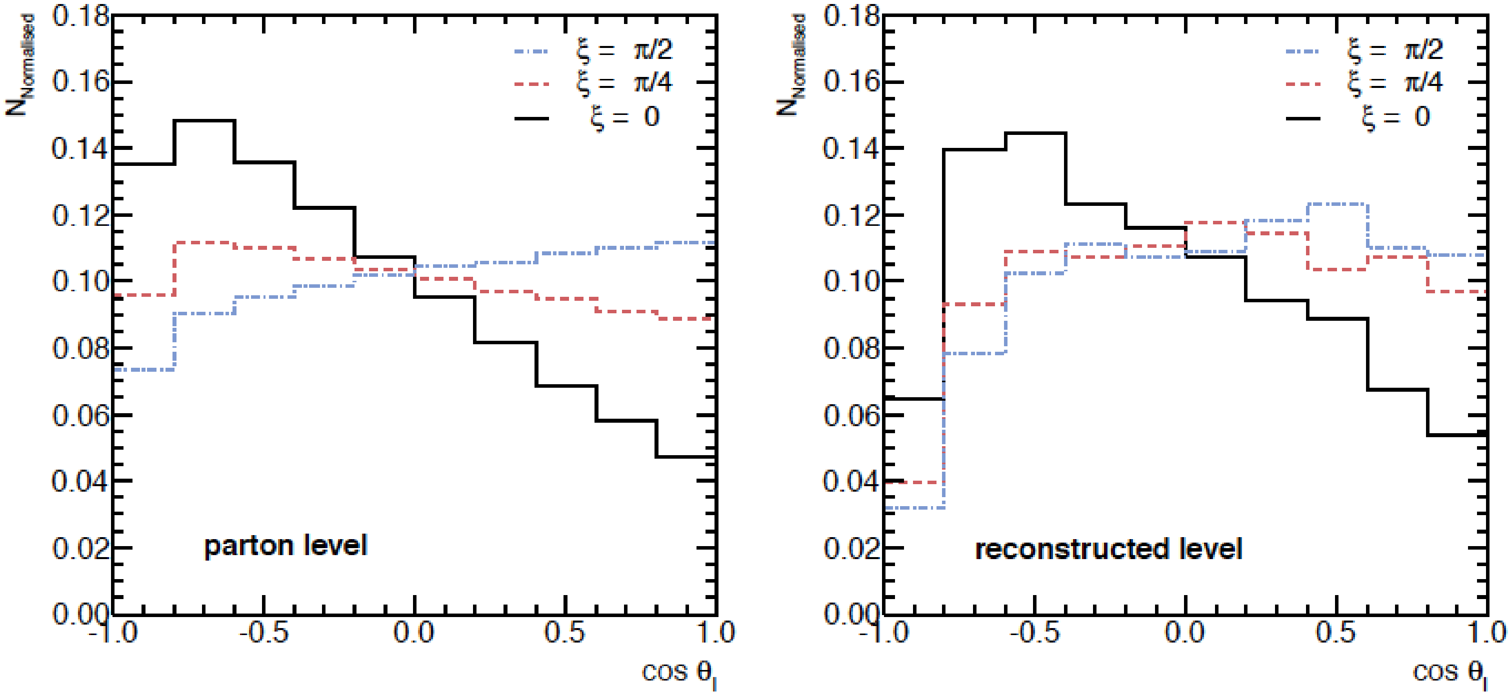


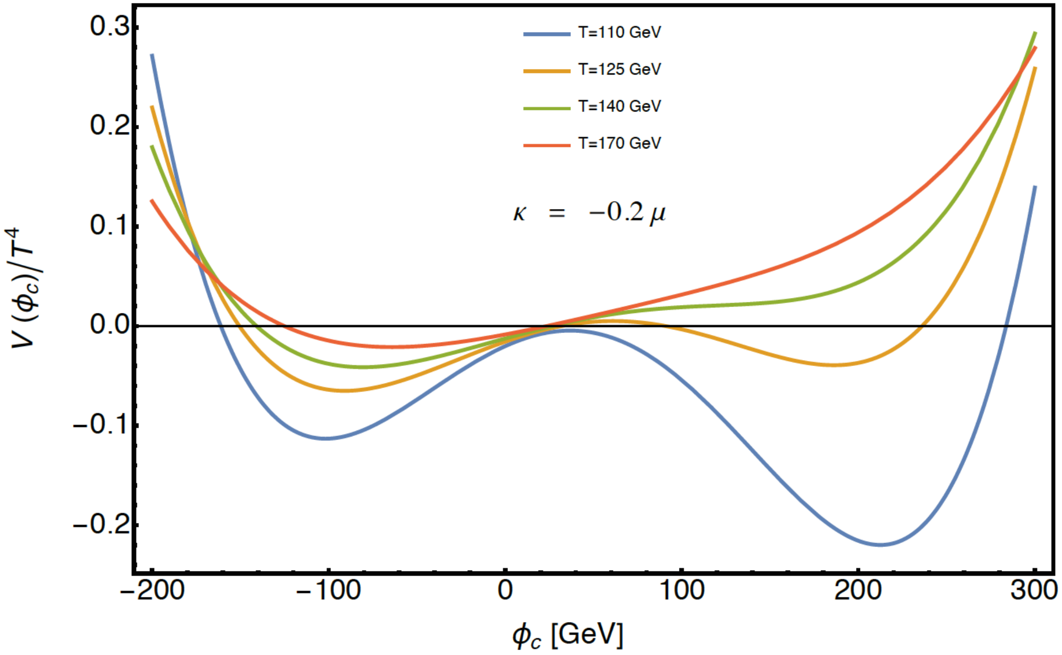
FIG. 7: The angular distributions of the lepton from the top quark decay in the signal $pp \to t(\to \ell^+\nu_\ell b)h(\to b\bar{b})j$ at parton level (left panel) and reconstruction level (right panel) after the cuts.

Cosmological baryogenesis at the electroweak scale

- Finite temperature potential:

$$V(\phi_c, T) = \frac{\lambda}{4}\phi_c^4 + \frac{\kappa}{3}\phi_c^3 + \phi_c^2\left(-\frac{\mu^2}{2} + \frac{T^2}{32}(3g_2^2 + g_1^2 + 4\lambda + 4y_t^2)\right)$$

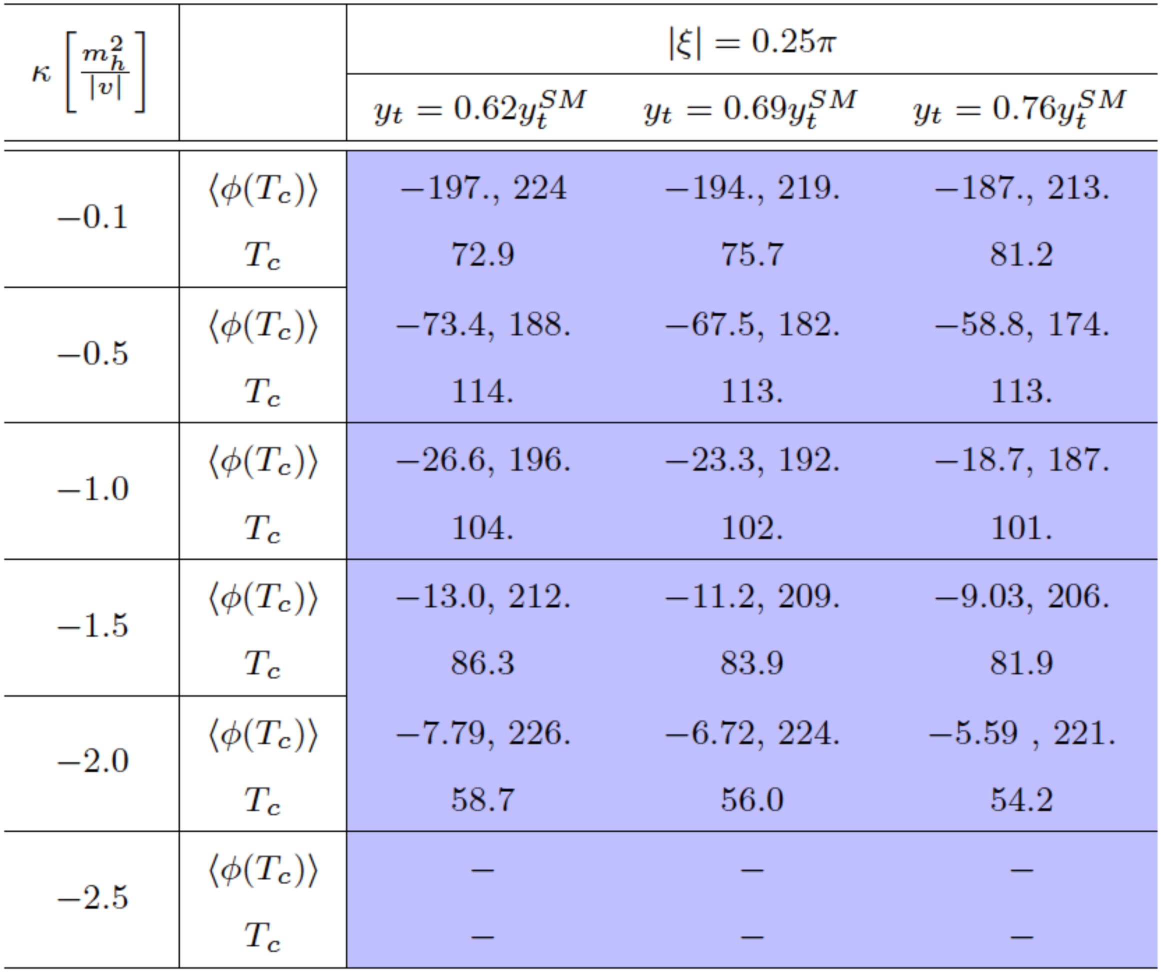
$$+\frac{T^2}{12}(\kappa + 3\sqrt{2}y_t m_t' \cos\xi)\phi_c + \ldots$$



Sphaleron rate –

$$\Gamma \propto \left(\frac{\phi_c}{T}\right)^7 \exp\left(-E_{sph}/T\right)$$

Electroweak Baryogenesis: Phase transition



$\kappa\left[\frac{m_h^2}{\lvert v\rvert}\right]$		$\lvert\xi\rvert = 0.25\pi$		
		$y_t = 0.62 y_t^{SM}$	$y_t = 0.69 y_t^{SM}$	$y_t = 0.76 y_t^{SM}$
-0.1	$\langle\phi(T_c)\rangle$	$-197., 224$	$-194., 219.$	$-187., 213.$
	T_c	72.9	75.7	81.2
-0.5	$\langle\phi(T_c)\rangle$	$-73.4, 188.$	$-67.5, 182.$	$-58.8, 174.$
	T_c	$114.$	$113.$	$113.$
-1.0	$\langle\phi(T_c)\rangle$	$-26.6, 196.$	$-23.3, 192.$	$-18.7, 187.$
	T_c	$104.$	$102.$	$101.$
-1.5	$\langle\phi(T_c)\rangle$	$-13.0, 212.$	$-11.2, 209.$	$-9.03, 206.$
	T_c	86.3	83.9	81.9
-2.0	$\langle\phi(T_c)\rangle$	$-7.79, 226.$	$-6.72, 224.$	$-5.59\ , 221.$
	T_c	58.7	56.0	54.2
-2.5	$\langle\phi(T_c)\rangle$	$-$	$-$	$-$
	T_c	$-$	$-$	$-$

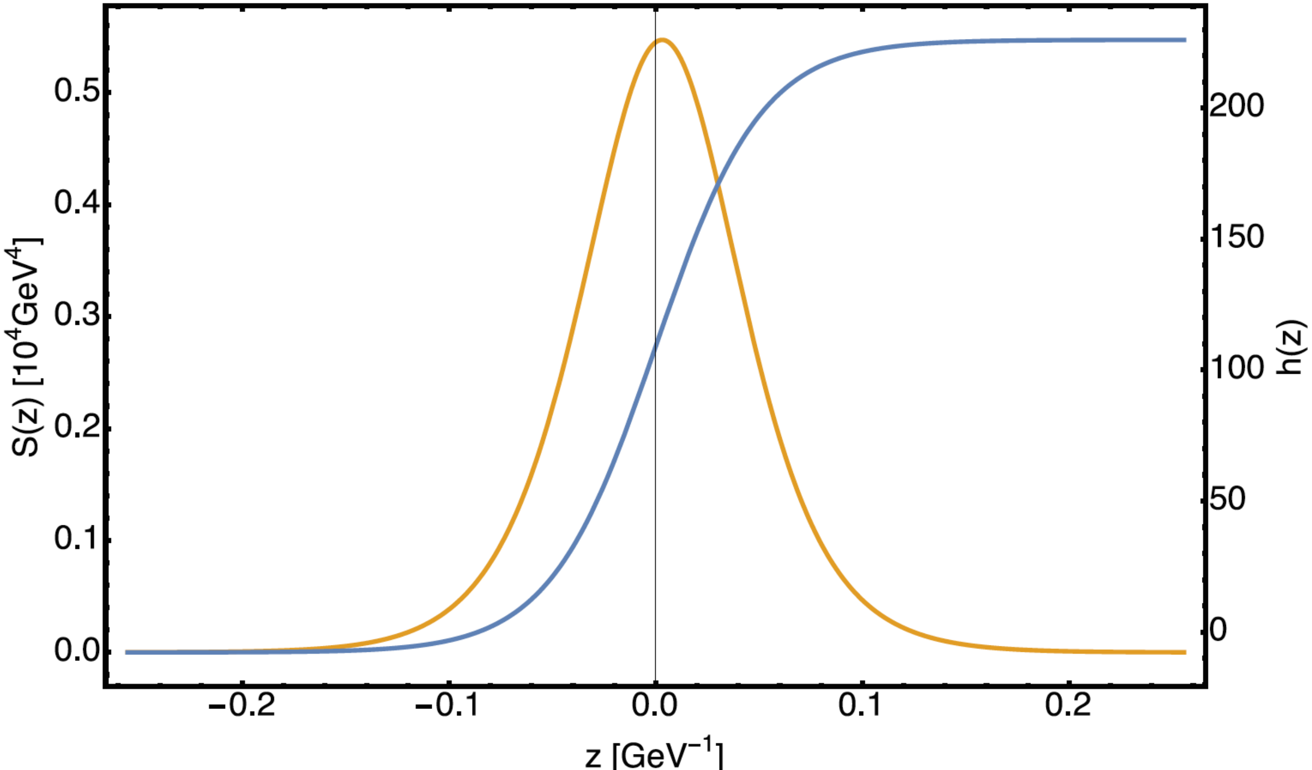
$\xi = 0.25\pi$ with ${m'}_t^{(+)}$, no first order phase transition found for ${m'}_t^{(-)}$

Electroweak Baryogenesis: CP-violation

$$M_t(z) = m_t(z) e^{i\theta_t(z)}$$

$$m_t(z) = \sqrt{\left(m_t' + \frac{y_t}{\sqrt{2}} h(z)\cos\xi\right)^2 + \left(\frac{y_t}{\sqrt{2}} h(z)\sin\xi\right)^2}$$

$$\tan\theta_t(z) = \frac{y_t h(z)\sin\xi}{\sqrt{2}m_t' + y_t h(z)\cos\xi}$$



Gravitational waves from EWPT

Bubble collisions

$$h^2\Omega_{\rm env}(f) \;=\; 1.67\times 10^{-5}\left(\frac{H_*}{\beta}\right)^2\left(\frac{\kappa\alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*}\right)^{\frac{1}{3}}\left(\frac{0.11\,v_w^3}{0.42+v_w^2}\right)S_{\rm env}(f)$$

$$S_{\rm env}(f)=\frac{3.8\,(f/f_{\rm env})^{2.8}}{1+2.8\,(f/f_{\rm env})^{3.8}}$$

$$f_{\rm env}=16.5\times 10^{-3}\,{\rm mHz}\left(\frac{f_*}{\beta}\right)\left(\frac{\beta}{H_*}\right)\left(\frac{T_*}{100\,{\rm GeV}}\right)\left(\frac{g_*}{100}\right)^{\frac{1}{6}}$$

Gravitational waves from EWPT

Sound waves

$$h^2\Omega_{\rm sw}(f) = 2.65 \times 10^{-6} \left(\frac{H_*}{\beta}\right) \left(\frac{\kappa_v \alpha}{1+\alpha}\right)^2 \left(\frac{100}{g_*}\right)^{\frac{1}{3}} v_w \, S_{\rm sw}(f)$$

$$S_{\rm sw}(f) = (f/f_{\rm sw})^3 \left(\frac{7}{4+3\,(f/f_{\rm sw})^2}\right)^{7/2}$$

$$f_{\rm sw} = 1.9 \times 10^{-2}\,{\rm mHz}\,\frac{1}{v_w} \left(\frac{\beta}{H_*}\right) \left(\frac{T_*}{100\,{\rm GeV}}\right) \left(\frac{g_*}{100}\right)^{\frac{1}{6}}$$

Gravitational waves from EWPT

Turbulence

$$h^2\Omega_{\rm turb}(f) = 3.35\times 10^{-4}\left(\frac{H_*}{\beta}\right)\left(\frac{\kappa_{\rm turb}\,\alpha}{1+\alpha}\right)^{\frac{3}{2}}\left(\frac{100}{g_*}\right)^{1/3} v_w\, S_{\rm turb}(f)$$

$$S_{\rm turb}(f) = \frac{(f/f_{\rm turb})^3}{[1+(f/f_{\rm turb})]^{\frac{11}{3}}\,(1+8\pi f/h_*)}\,.$$

$$f_{\rm turb} = 2.7\times 10^{-2}\,{\rm mHz}\,\frac{1}{v_w}\left(\frac{\beta}{H_*}\right)\left(\frac{T_*}{100\,{\rm GeV}}\right)\left(\frac{g_*}{100}\right)^{\frac{1}{6}}\,.$$