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Impact of LHC Higgs physics and EDMs on Baryogenesis in the Standard Model EFT with dim 6 terms

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Outline

- Motivation/Relevant observables
- SM EFT with dim 6 terms
- Basics of EWBG
- EWPT
- EWBG/EDM/Collider Pheno in SMEFT
- Results: single flavor, combined flavors.
- Conclusions

Motivation I

- Observation of asymmetry of matter-antimatter in the Universe.

$$Y_B^{\rm obs} = (8.59 \pm 0.08) \times 10^{-11}$$

Planck

- *How to make a matter filled Universe?*
  - *Baryon number violation*
  - *Departure from thermal equilibrium*
  - *C and CP violation*

Sakharov '67

Motivation II

- High precision, low energy experiments that have strong bounds.
- New CP violating terms have implications in other types of observables such as electric dipole moments.

- ACME bound

$$|d_e^{\mathrm{max}}| = 1.1 \times 10^{-29}\ e\ \mathrm{cm}\ \text{at}\ 90\%\,\mathrm{C.\,L.}$$

Motivation III

- LHC results of Higgs discovery and measurement of physical properties.
  - Scalar particle with SM Higgs boson properties
- No new elementary particles discovered with m ~ 1 TeV
  - New physics scale is high enough to be parametrized via higher dimensional operators.
- New physics via higher dimension operators
  - Use Higgs physics results from LHC to constrain these higher dim terms
  - Consider dimension six terms of Higgs- fermion fields with complex couplings

Constraining SMEFT

- Experimental results can constrain the complex couplings via:
    - New contributions to cosmological observations, Y_B
    - New contributions to Higgs production and decay rates at colliders
    - New contributions to EDMs

SM EFT Framework

- Dim-6 term with real and imaginary Yukawa in Lagrangian:

$$L_{\mathrm{Yuk}} = y_f \overline{F_L} F_R H + \frac{1}{\Lambda^2}(X_R^f + iX_I^f)|H|^2 \overline{F_L} F_R H + \mathrm{h.c.}$$

$$H = \frac{1}{\sqrt{2}}(v + h)$$

- Allows for new CPV interactions
- Changes the fermion mass and the corresponding Yukawa coupling relation.

Parametrize by ratio of dim6 to dim 4 contribution to the fermion mass:

$$T_R^f \equiv \frac{v^2}{2\Lambda^2}\frac{X_R^f}{y_f}, \qquad T_I^f \equiv \frac{v^2}{2\Lambda^2}\frac{X_I^f}{y_f}$$

Parameters in SMEFT

$$\tan\theta_f = \frac{T_I^f}{1 + T_R^f}$$

$$m_f = \frac{y_f v}{\sqrt{2}}\sqrt{(1 + T_R^f)^2 + T_I^{f2}}$$

Mass and Yukawa coupling in real mass basis

$$\lambda_f = \frac{y_f}{\sqrt{2}}\frac{1 + 4T_R^f + 3T_R^{f2} + 3T_I^{f2} + 2iT_I^f}{\sqrt{(1 + T_R^f)^2 + T_I^{f2}}}$$

$$\left(\frac{y_f}{y_f^{\mathrm{SM}}}\right)^2 = \frac{1}{(1 + T_R^f)^2 + T_I^{f2}}$$

Basics of EWBG

Kuzmin, Rubakov, Shaposhnikov ‘85

- Initial hot plasma with zero net baryon number with EW symmetry.
- As Universe expands and cools until EWPT around T ~ 100 GeV
- Bubbles of the broken phase nucleate and expand to fill the Universe.

- Necessary to have new physics
  - CP violation sources: plasma particles CPV interactions with the bubble wall
  - Strong first order phase transition: suppress sphaleron transitions in the broken phase

Electroweak Phase Transition

Assume:

- New degrees of freedom that produce a strong first order EWPT
- These do not affect the CPV interactions with bubble wall we are going to consider.
- No new sources of CPV from these new degrees of freedom.

There are important parameters such as the wall velocity and wall width that need to be obtained In a specific model. We will simply take on some benchmark values for them in this analysis.

Main processes for EWBG

- Charged fermion plasma particles CPV interactions with the bubble wall generate a chiral asymmetry, while CP-conserving interactions wash out the generated asymmetry.
- The strong sphaleron process produces further washout in the quark sector.
- Remaining asymmetry diffuses into the symmetric phase. Diffusion is dominantly affected by gauge interactions, more efficient for leptons than for quarks.
- The weak sphaleron process is efficient only in the symmetric phase, acting on left-handed multiplets and changing baryon number.
- The chemical potential due to the chiral asymmetry induces a preferred direction for the weak sphaleron, thus generating a baryon asymmetry.
- Finally, the bubble wall catches up and freezes in the resulting baryon number density in the broken phase.

SMEFT implications for EW Baryogenesis

Full dynamics given by set of coupled equations:

$$\partial_\mu f^\mu = -\Gamma^f_M \mu^f_M - \Gamma^f_Y \mu^f_Y + \Gamma^f_{ss} \mu_{ss} - \Gamma^f_{ws} \mu^f_{ws} + S_f$$

$$\partial_\mu f^\mu \approx v_w f' - D_f f''$$

SMEFT implications for EW Baryogenesis

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CPV Source term

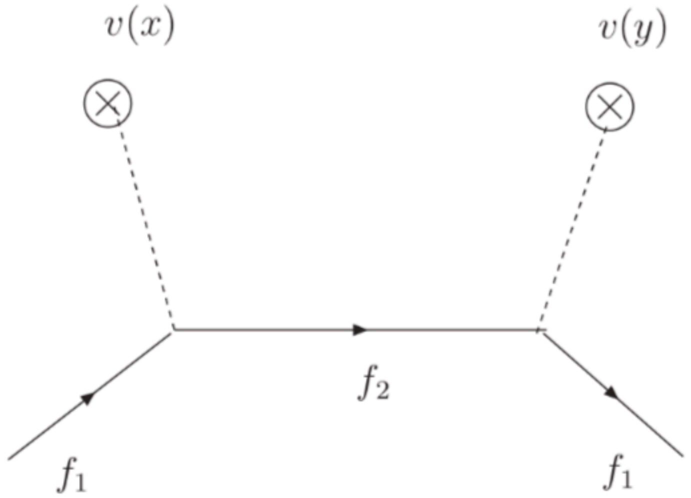
$$\partial_\mu f^\mu \approx v_w f' - D_f f''$$

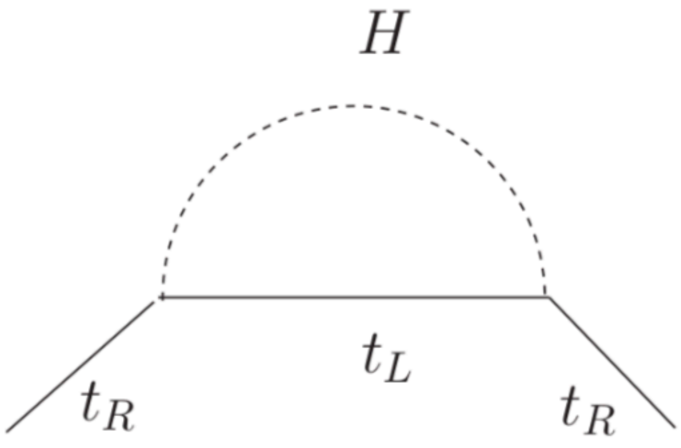
wall velocity

Diffusion constant

Source, relaxation and Yukawa terms

Use vev-insertion approx.





Lee et al

$$S_f \propto \mathcal{I}m(m_f^* m_f') \propto y_f^2 T_I^f$$

SMEFT implications for EW Baryogenesis

Full dynamics given by set of coupled eqns:

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Relaxation terms

Yukawa terms

Strong sphaleron

Weak sphaleron

Changes in CP-even rates

$$\Gamma_M \to \left[\frac{(1 + r_{N0}^2 T_R^f)^2 + (r_{N0}^2 T_I^f)^2}{(1 + T_R^f)^2 + T_I^{f\,2}}\right] \Gamma_M$$

$$\Gamma_Y \to \left[\frac{(1 + 3r_{N0}^2 T_R^f)^2 + (3r_{N0}^2 T_I^f)^2}{(1 + T_R^f)^2 + T_I^{f\,2}}\right] \Gamma_Y$$

Baryon Asymmetry of the Universe

Using benchmark parameters

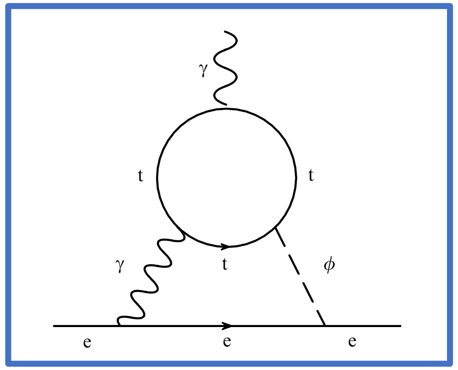
$$T_R^f = 0$$

$$Y_B = 8.6 \times 10^{-11} \times (51\, T_I^t - 23\, T_I^\tau - 0.44\, T_I^b)$$

BAU for values:

$$|T_I^t| = \mathcal{O}(0.02), \quad |T_I^\tau| = \mathcal{O}(0.04), \quad |T_I^b| > 1$$

SMEFT implications for (e)-EDMs



ACME bound $|d_e^{\max}| = 1.1 \times 10^{-29}\ e\ \mathrm{cm}$ at $90\%\ \mathrm{C.L.}$

$$\frac{d_e^{(t)}}{e} \simeq -\frac{32\sqrt{2}}{3}\frac{e^2}{(16\pi^2)^2}\frac{m_e}{v^2}\left[\left(2+\ln\frac{m_t^2}{m_h^2}\right)\left(\frac{y_t}{y_t^{\mathrm{SM}}}\right)^2 T_l^t\right]$$

Panico et al '19

$$\frac{d_e^{(b)}}{e} \simeq -\frac{32\sqrt{2}}{3}\frac{e^2}{(16\pi^2)^2}\frac{m_e}{v^2}\left[\frac{1}{4}\left(\frac{\pi^2}{3}+\ln^2\frac{m_b^2}{m_h^2}\right)\frac{m_b^2}{m_h^2}\left(\frac{y_b}{y_b^{\mathrm{SM}}}\right)^2 T_l^b\right]$$

$$\frac{d_e^{(\tau,\mu)}}{e} \simeq -\frac{32\sqrt{2}}{3}\frac{e^2}{(16\pi^2)^2}\frac{m_e}{v^2}\left[\frac{3}{4}\left(\frac{\pi^2}{3}+\ln^2\frac{m_{\tau,\mu}^2}{m_h^2}\right)\frac{m_{\tau,\mu}^2}{m_h^2}\left(\frac{y_{\tau,\mu}}{y_{\tau,\mu}^{\mathrm{SM}}}\right)^2 T_l^{\tau,\mu}\right]$$

e-EDMs of only third generation fermions

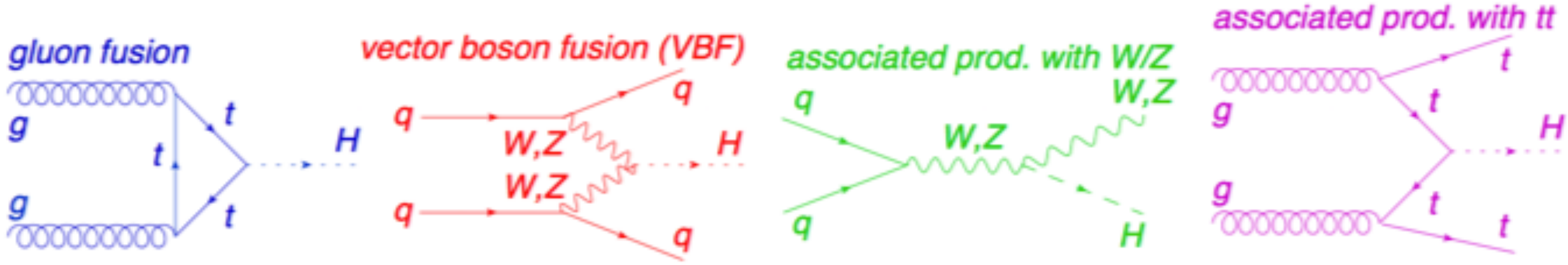
$$d_e \approx |d_e^{\max}| \left[2223 \left(\frac{y_t}{y_t^{\rm SM}}\right)^2 T_l^t + 9.6 \left(\frac{y_\tau}{y_\tau^{\rm SM}}\right)^2 T_l^\tau + 11.6 \left(\frac{y_b}{y_b^{\rm SM}}\right)^2 T_l^b\right]$$

So for, $y_f = \mathcal{O}(y_f^{\rm SM})$

$$T_l^t = \mathcal{O}(0.0004), \quad T_l^\tau = \mathcal{O}(0.1), \quad T_l^b = \mathcal{O}(0.09)$$

SMEFT implications for Colliders

- Modification of Higgs production and decay modes.



$$\mu_I^F \equiv \frac{\sigma_I(pp \to h) \cdot \Gamma(h \to F)/\Gamma_h}{[\sigma_I(pp \to h) \cdot \Gamma(h \to F)/\Gamma_h]_{\rm SM}}$$

$$r_f \equiv \frac{|\lambda_f|^2/|\lambda_f^{\rm SM}|^2}{|m_f|^2/|m_f^{\rm SM}|^2} = \frac{(1+3T_R^f)^2 + 9T_I^{f\,2}}{(1+T_R^f)^2 + T_I^{f\,2}}$$

Modified Production Rates, Decays and Total Width

Production Rates

$$\sigma_{\rm ggF}/\sigma_{\rm ggF}^{\rm SM} = \sigma_{tth}/\sigma_{tth}^{\rm SM} = r_t$$

$$\sigma_{Vh}/\sigma_{Vh}^{\rm SM} = \sigma_{\rm VBF}/\sigma_{\rm VBF}^{\rm SM} = 1$$

Decay Rates

$$\Gamma(h \to f\bar{f})/[\Gamma(h \to f\bar{f})]^{\rm SM} = r_f \quad (f = b, \tau, \mu)$$

Total Width

$$\Gamma_h/\Gamma_h^{\rm SM} = 1 + {\rm BR}_b^{\rm SM}(r_b - 1) + {\rm BR}_\tau^{\rm SM}(r_\tau - 1) + {\rm BR}_g^{\rm SM}(r_t - 1)$$

LHC Measurements

channel	experiment	$\sqrt{s}$/ TeV	$\mathscr{L}$ / fb^{-1}	comment	μ
$h \to \tau^+\tau^-$	ATLAS+CMS	7+8	$5+20$		$1.11^{+0.24}_{-0.22}$
	ATLAS	13	36.1	ggF, VBF	$1.09^{+0.35}_{-0.30}$
	CMS	13	77	ggF, $\bar{b}b$, VBF, Vh	0.75 ± 0.17
	ATLAS+CMS	7+8+13		all prod., priv. comb.	0.91 ± 0.13
$h \to \mu^+\mu^-$	ATLAS	13	139	upper bound at 95% C.L.	< 1.7
	CMS	13	35.9	upper bound at 95% C.L.	< 2.9
$h \to \bar{b}b$	ATLAS	13	79.8	VBF+VH	1.23 ± 0.26
	ATLAS	13	79.8	$t\bar{t}h + th$	$0.79^{+0.60}_{-0.59}$
	CMS	7+8+13	41.3	VH (0-2ℓ, 2 b-tags+jets)	1.01 ± 0.22
	CMS	7+8+13	41.3	all prod.	1.04 ± 0.2
	ATLAS+CMS	7+8+13		VH, priv. comb.	0.98 ± 0.15
	ATLAS+CMS	7+8+13		all prod., priv. comb.	1.02 ± 0.14

+ all processes with t

Single flavor

$$\mu_f = \frac{r_f}{1 + \mathrm{BR}_f^{\mathrm{SM}}(r_f - 1)}$$

defines a circle in the (T_R, T_I) plane

$${T_I^f}^2 + (T_R^f - T_{R0}^f)^2 = R_T^2$$

For $\mu_f = 1$, can have $T_R^f, T_I^f \neq 0$, independent of $\mathrm{BR}_f^{\mathrm{SM}}$

Combined flavors

σ_I	$\Gamma(h \to F)$	Γ_h	f_1, f_2	process	dependence
SM	f_1	f_1, f_2	τ, b t, τ t, b	any production, $h \to \tau\tau, b\bar{b}$ Vh+VBF, $h \to \tau\tau$ Vh+VBF, $h \to b\bar{b}$	A
f_1	SM	f_1, f_2	$t, b/\tau$	ggF+tth, $h \to VV$	A
f_1	f_2	f_1, f_2	t, τ t, b	ggF+tth, $h \to \tau\tau$ ggF+tth, $h \to b\bar{b}$	B

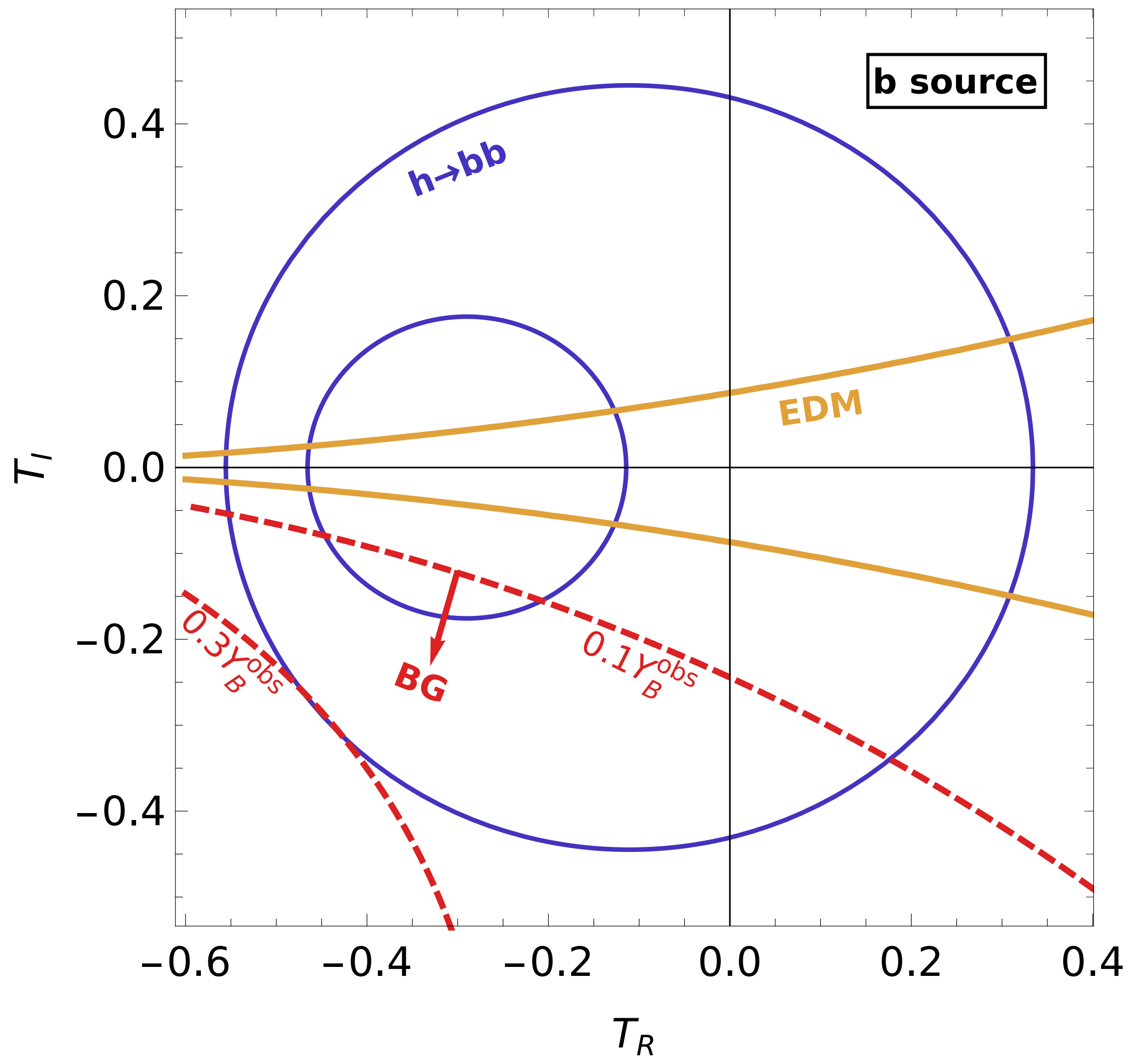
$$\text{A:} \qquad \mu^{f_1}_{\text{SM}} = \mu^{\text{SM}}_{f_1} = \frac{r_{f_1}}{\Gamma_h/\Gamma_h^{\text{SM}}} = \frac{r_{f_1}}{1 + \text{BR}^{\text{SM}}_{f_1}(r_{f_1} - 1) + \text{BR}^{\text{SM}}_{f_2}(r_{f_2} - 1)}$$

$$\text{B:} \qquad \mu^{f_2}_{f_1} = \frac{r_{f_1}\, r_{f_2}}{\Gamma_h/\Gamma_h^{\text{SM}}} = \frac{r_{f_1}\, r_{f_2}}{1 + \text{BR}^{\text{SM}}_{f_1}(r_{f_1} - 1) + \text{BR}^{\text{SM}}_{f_2}(r_{f_2} - 1)}$$

Results: Single flavor features

- $Y_B, |d_e| \propto (y_f/y_f^{SM})^2 T_I^f$, except for the top quark. For $f \neq t$, contours of constant Y_B are also contours of constant d_e.
- Y_B^t is approximately constant in T_R^t due to the large Yukawa coupling contributing to its thermal mass.
- Y_B dependence on T_R^f is mild. Negative values of T_R generate a larger baryon asymmetry.
- $\mu_f = 1$ defines a circle through the SM point $T_I^f = T_R^f = 0$.
- Experimental bounds on μ_f constrain the dim-6 operators of each species to an annulus in the T_R^f, T_I^f plane.

Third generation quarks --bottom

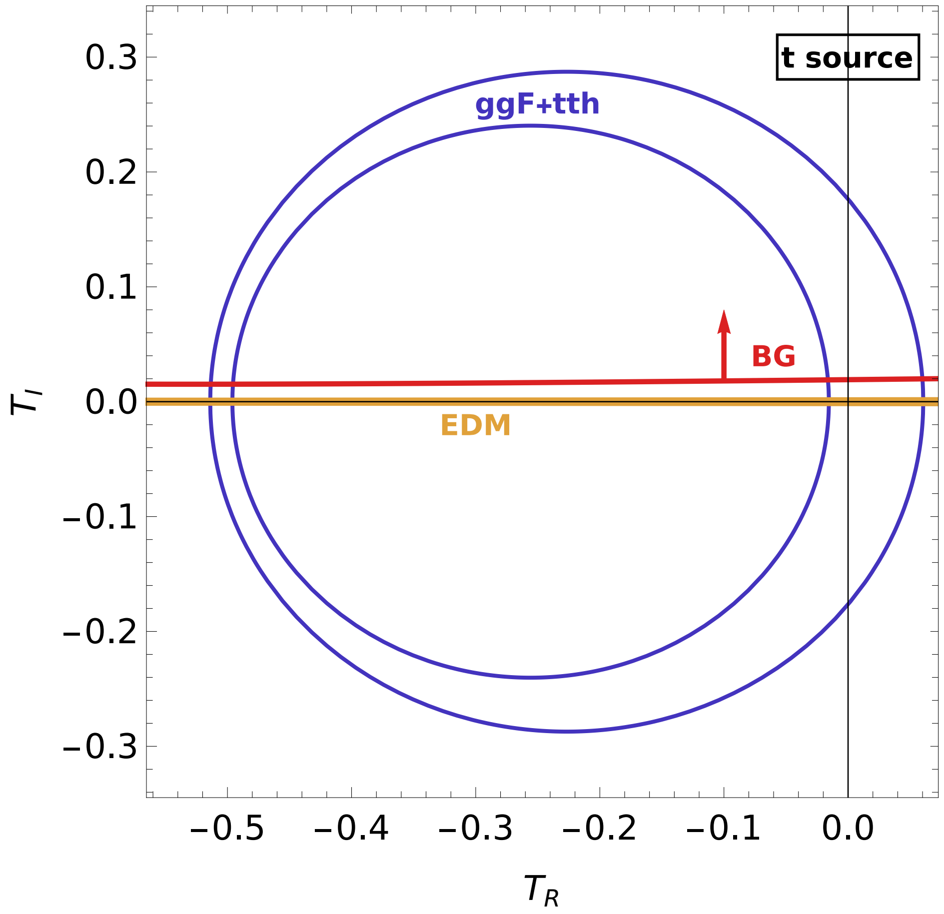


All production modes combined

$$\mu_{b\bar{b}} = 1.02 \pm 0.14$$

dominated by μ_{Vh}^{bb}

Third generation quarks -- top

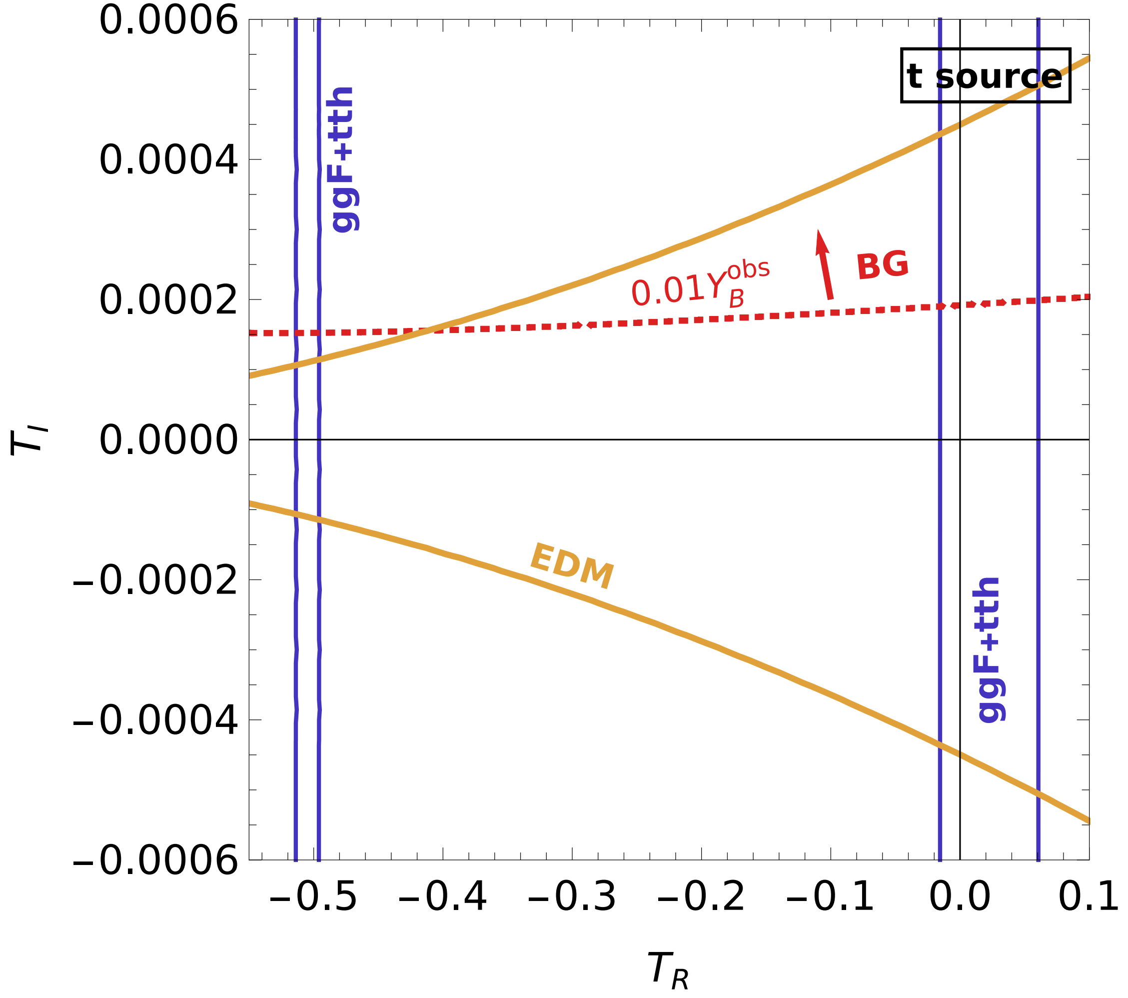


Constrained by μ_{ggF}, μ_{tth} and $\mu_{\gamma\gamma}$

all decays

$$\mu_{\mathrm{ggF}+t\bar{t}h} = 1.09 \pm 0.08$$

Third generation quarks –top (zoomed)



Constrained by μ_{ggF}, μ_{tth} and $\mu_{\gamma\gamma}$

$$\mu_{\mathrm{ggF}+t\bar{t}h} = 1.09 \pm 0.08$$

Leptons --muon

$$\frac{Y_B^{(\mu)}}{8.6 \times 10^{-11}} = \frac{d_e^{(\mu)}}{4.1 \times 10^{-30}\ e\ \mathrm{cm}}$$

$$\mu_{\mu^+\mu^-} = \frac{\Gamma(h \to \mu^+\mu^-)}{[\Gamma(h \to \mu^+\mu^-)]_{\mathrm{SM}}} \qquad \mu_{\mu^+\mu^-} = \frac{(1 + 3T_R^{\mu})^2 + 9T_I^{\mu 2}}{(1 + T_R^{\mu})^2 + T_I^{\mu 2}}$$

$$\mu_{\mu^+\mu^-}^{\mathrm{CMS}} < 2.9 \text{ at } 95\% \text{ C.L.}$$

$$\mu_{\mu^+\mu^-}^{\mathrm{ATLAS}} < 1.7 \text{ at } 95\% \text{ C.L.}$$

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$$\mu_{\mu^+\mu^-} = \frac{\Gamma(h \to \mu^+\mu^-)}{[\Gamma(h \to \mu^+\mu^-)]_{\rm SM}}$$

$$\mu^{\rm CMS}_{\mu^+\mu^-} < 2.9 \text{ at } 95\% \text{ C.L.}$$
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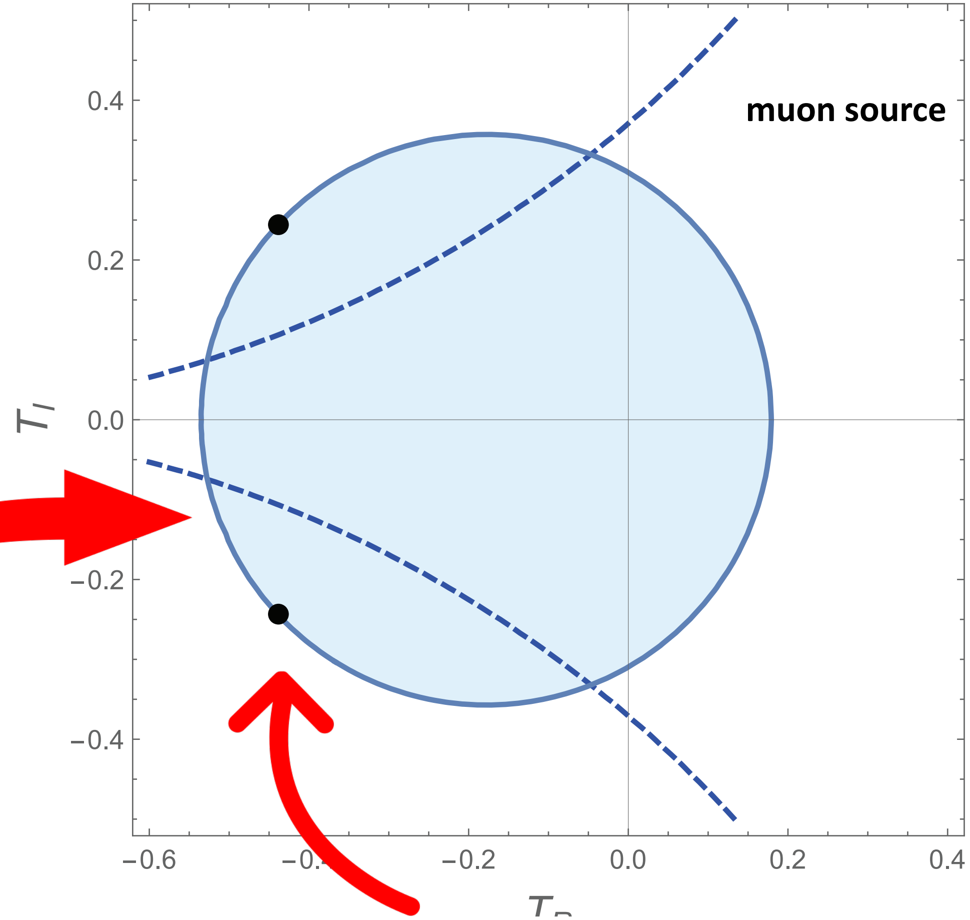


$$|Y_B^{(\mu)}|_{\max} = 1.4 \times 10^{-11}$$
$$|d_e^{(\mu)}|_{\max} = 6.5 \times 10^{-31}\ e\ \text{cm}$$

Leptons --muon

$\mu_{\mu^+\mu^-}$ CP-even observable

- The effective muon Yukawa coupling is not dominated by contributions from non-renormalizable terms.
- Is constraining a CP-odd observable, the baryon asymmetry, which is not dominated by a complex muon Yukawa coupling

$$|Y_B^{(\mu)}|_{\max}$$

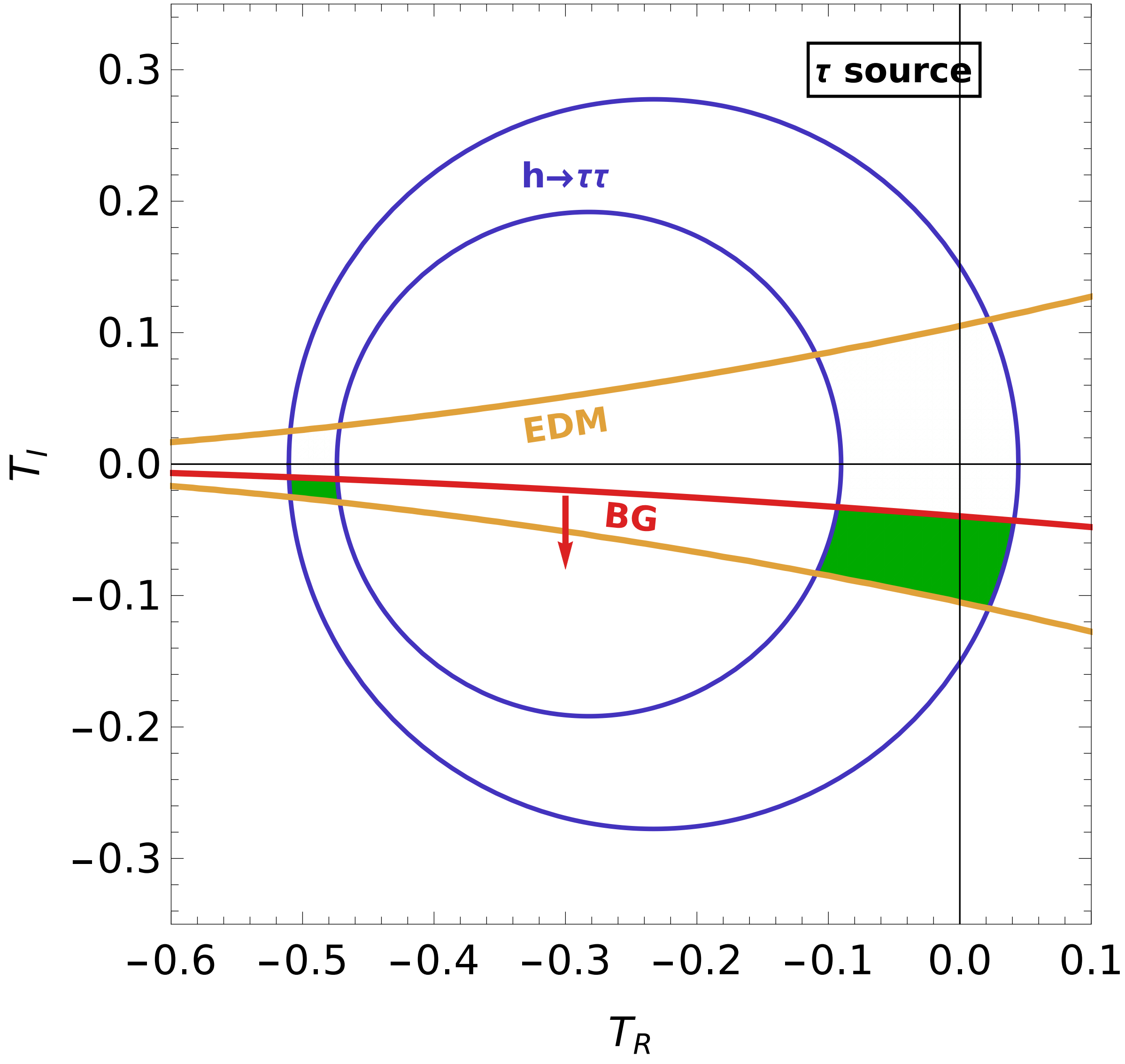
- A complex muon coupling could account for as much as 16% of Y_B, from current collider constraints.

Leptons- tau

$\Gamma(h \to \tau^+\tau^-)$ and Γ_h

All production modes

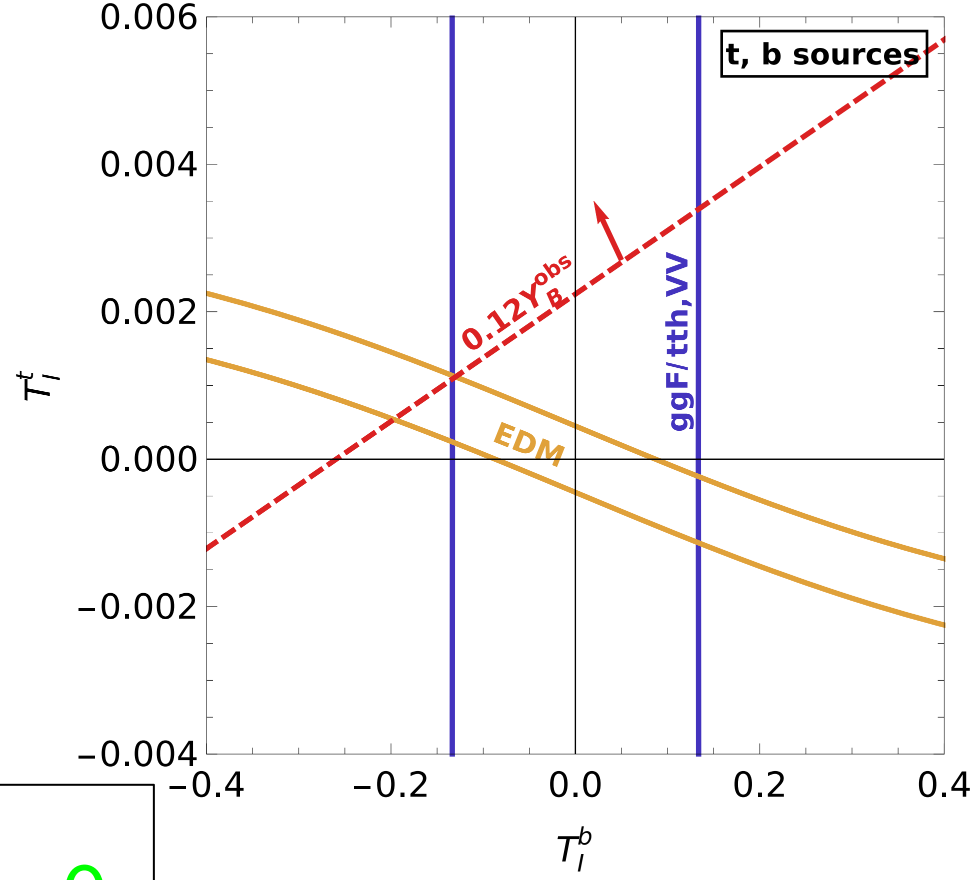
$$\mu_{\tau^+\tau^-} = 0.91 \pm 0.13$$

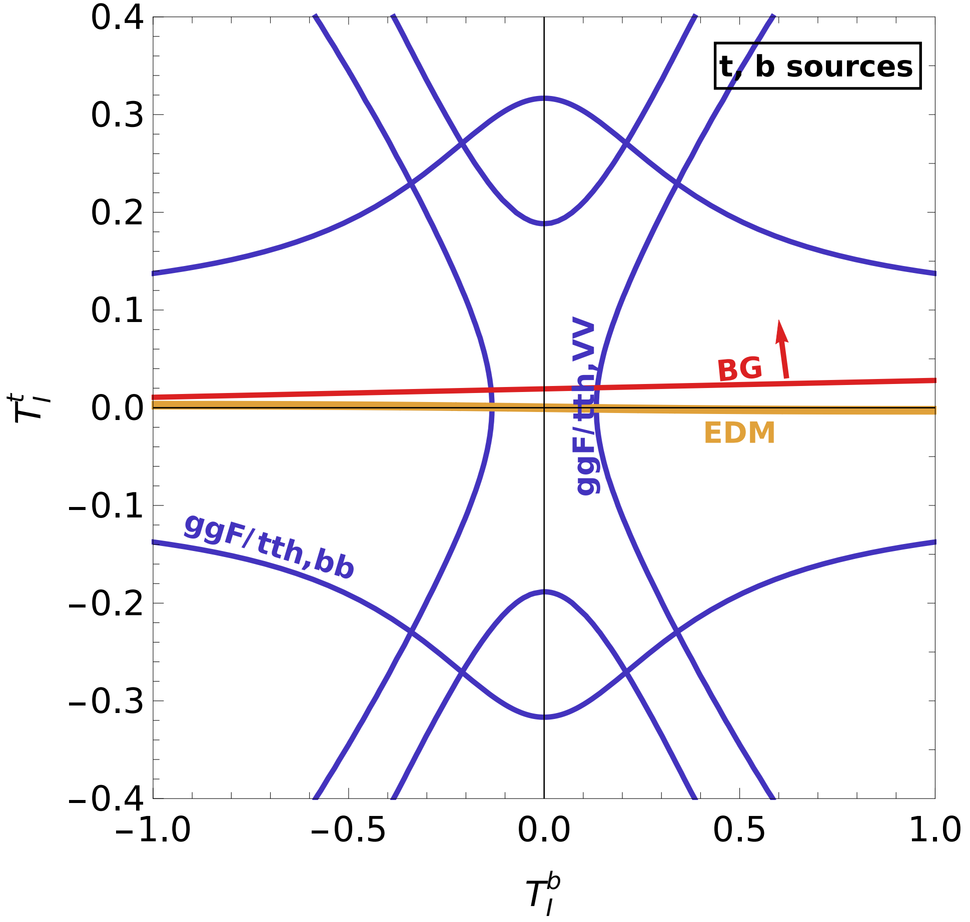


Combined Sources t-b

$$\mu^{b\bar{b}}_{t\bar{t}h+ggF} = 0.88 \pm 0.43$$
$$\mu^{bb}_{VH} = 0.98 \pm 0.15$$
$$\mu^{VV}_{\mathrm{ggF}+tth} = 1.08 \pm 0.08$$

$$Y_B^{(t+b)} \lesssim 0.12 Y_B^{\mathrm{obs}}$$





$$T_R^f = 0$$

Combined Sources tau- b

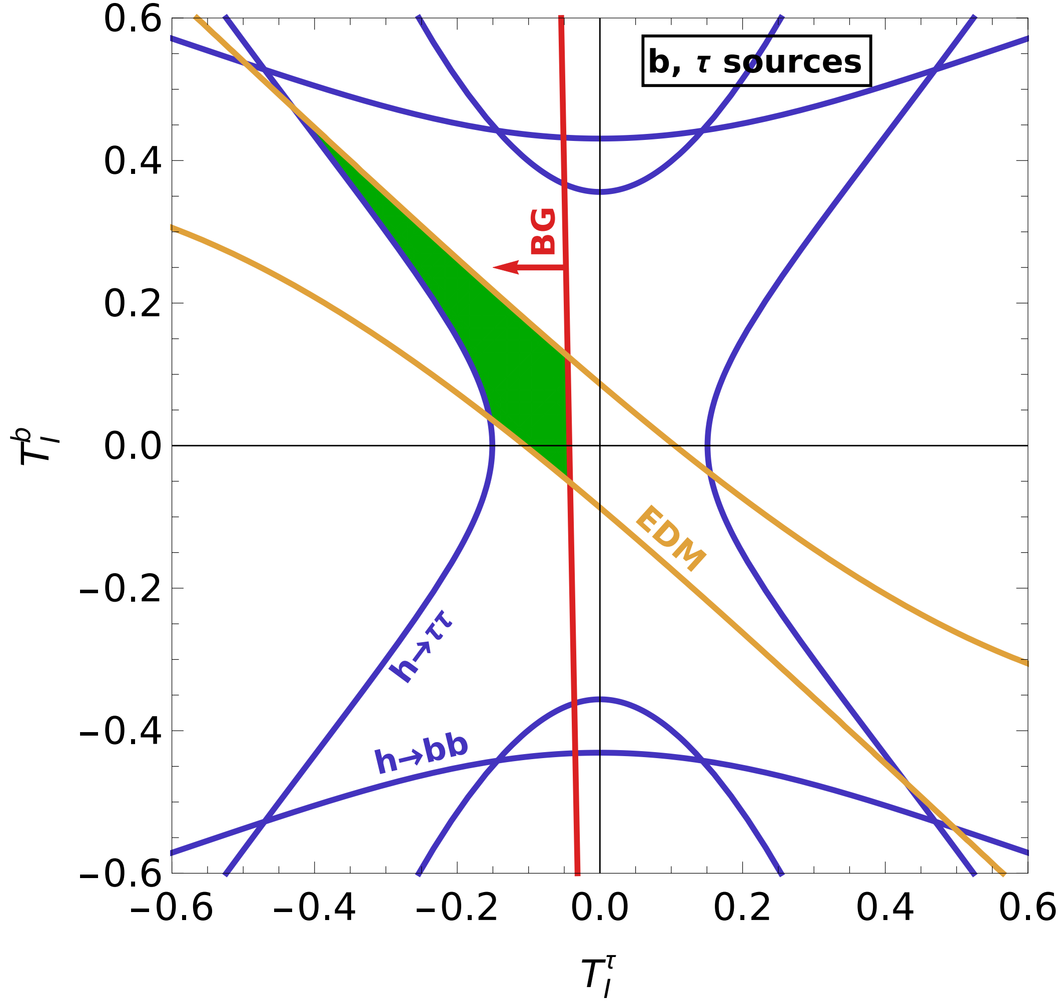
No modification to production rates

$\mu_{\tau^+\tau^-}$

$\mu_{b\bar{b}}$

Only Constraints

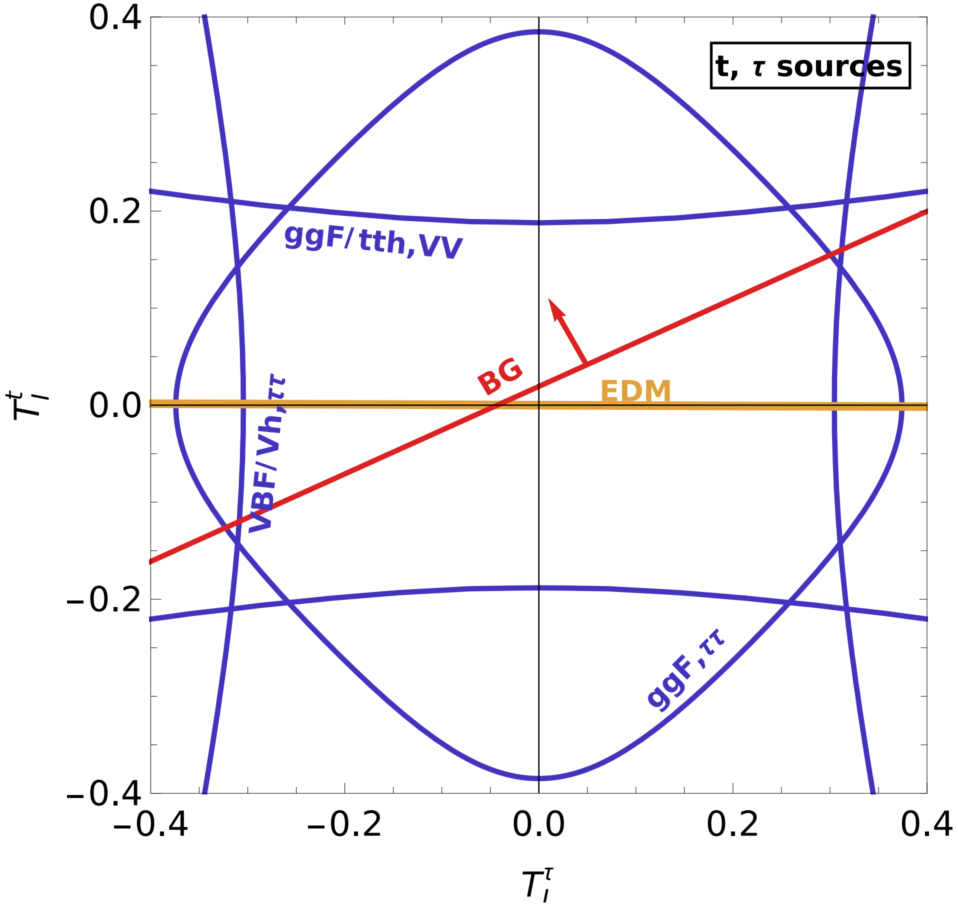
$$Y_B^{b+\tau,\mathrm{max}}(T_I^\tau = -0.4,\, T_I^b = +0.4) \simeq 7.8\, Y_B^{\mathrm{obs}}$$

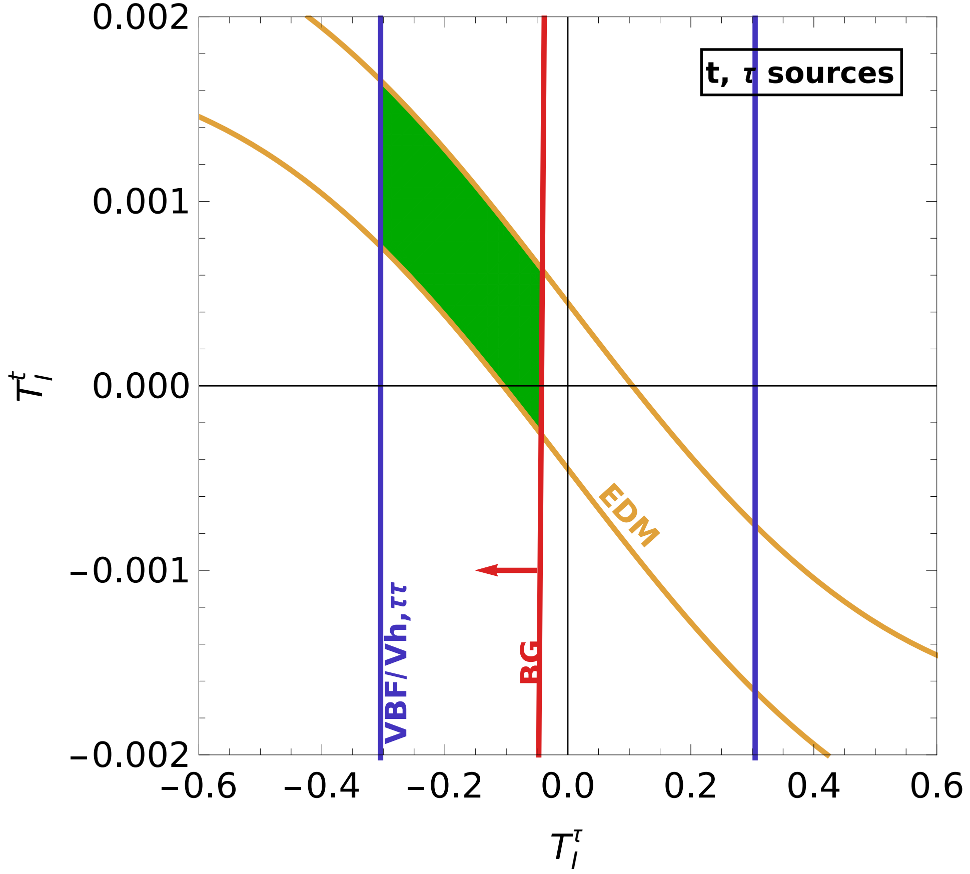


$$T_R^f = 0$$

Combined sources tau-t

$$\mu^{\tau\tau}_{\mathrm{ggF}} = 0.99 \pm 0.44$$
$$\mu^{\tau\tau}_{\mathrm{VBF}+Vh} = 1.09 \pm 0.26$$
$$\mu^{VV}_{\mathrm{ggF}+tth} = 1.08 \pm 0.08$$





$$T_R^f = 0$$

$$Y_B^{t+\tau,\mathrm{max}} = Y_B^{t+\tau}(T_I^\tau = -0.3,\, T_I^t = +0.0016) \simeq 6.4\, Y_B^{\mathrm{obs}}$$

SM-like solutions $Y_B = Y_B^{\rm obs}$ with $d_e \simeq 0$ and $\mu_l^F \simeq 1$

Choose

T_I^τ and T_I^b such that $d_e = 0$,

T_R^τ and T_R^b such that $\mu_b = \mu_\tau = 1$

$$Y_B^{b+\tau,\max}(d_e = 0, \mu_b = \mu_\tau = 1) = 10.25\, Y_B^{\rm obs}$$

Recap + Signature

With two flavours:

- We can produce the BAU without any deviation of μ_I^F

- No CPV signal from a single EDM, ……other additional EDMs??

- For BAU and EDMs additive contributions of different Yukawa couplings.

μ_I^F measurements at colliders is flavor specific.

CP violation in H->tau tau to determine T_I^τ by measuring angular distributions in Higgs boson decays to pairs of tau leptons.

Implication for EFT Scales

Upper bounds on $T_{I,R}$ from collider and EDMs.

$$\Lambda/\sqrt{X^f_{R,I}} \gtrsim \frac{v}{\sqrt{2}} \frac{1}{(y_f T_{R,I})^{1/2}} \sim \mathrm{few} - \mathcal{O}(10)\ \mathrm{TeV}$$

For Y_B^{obs}, T_I^τ in the range $0.01 - 0.1$

$$\Lambda/\sqrt{X_I^\tau} \lesssim 18\ \mathrm{TeV}\ (0.01/T_I^\tau)^{1/2}$$

Conclusions

- Baryon asymmetry can be produced with a tau CPV source.
- The CPV sources for the top and bottom cannot provide a large enough baryon asymmetry, due to EDM constraint.
- CPV source for the muon cannot provide large enough Y_B due to collider constraint h->mu mu.
- When multiple CPV sources (tau-t; tau-b) are present: cancellations to EDMs while enhancing $Y_B > Y_B^{\mathrm{obs}}$
- Smoking gun of this scenario is measuring CPV in Higgs boson decays to tau leptons.