Exploring a Novel Dark Hypercharge Symmetry

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Hemant Kumar Prajapati

(In collaboration with Dr. Rahul Srivastava)

IISER, Bhopal

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Introduction

The Standard Model (SM) has proven to be an extremely successful theory as it effectively accounts for the fundamental forces between particles up to the energy scales examined in recent research.
However, there are sufficient reasons to believe that The SM is not the final theory and it is just an effective theory in the low energy regime.

- Evidence for the existence of Dark Matter.
- Matter–antimatter asymmetry.
- Experimental evidense of Neutrino oscillation.
- Hierarchy problem.
- Muon's anomalous magnetic dipole moment.
- Strong CP problem.

New gauged symmetries beyond the SM (BSM) are motivated by these desire to explain observations that go beyond the SM.

- The simplest and highly motivated one is an extra $U(1)_X$ gauge symmetry. New $U(1)$ symmetry is highly inspired by Grand unified theories (GUT).
- Some symmetries higly explored in literatures are $B - L$, $L_\mu - L_\tau$, $B - 3L_\mu$, $B - 3L_\tau$, etc. [arXiv: 2202.11002]

Gauge Anomalies

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- An anomaly is a symmetry of the classical theory which does not survive to the quantum theory.
- Gauge symmetry plays a crucial role in establishing unitarity and renormalizability in gauge theories. An anomaly in the gauge symmetry would have severe consequences, leading to what is termed a gauge anomaly.

$$
\begin{aligned}
[SU(3)_C]^2 U(1)_Y &= \sum_q Y_{q_L} - \sum_q Y_{q_R} \\
[SU(2)_L]^2 U(1)_Y &= \sum_l Y_{l_L} + 3 \sum_q Y_{q_L} \\
[U(1)_Y]^3 &= \sum_{l,q} (Y_{l_L}^3 + 3 Y_{q_L}^3) - \sum_{l,q} (Y_{l_R}^3 + 3 Y_{q_R}^3) \\
[G]^2 U(1)_Y &= \sum_{l,q} (Y_{l_L} + 3 Y_{q_L}) - \sum_{l,q} (Y_{l_R} + 3 Y_{q_R})
\end{aligned}
\tag{1}
$$

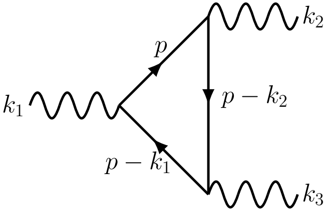

Figure: A triangle diagram.

The uniqueness of SM Hypercharge.

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- Hypercharges of all the SM fermions adds up in way to cancel these anomalies. However, these anomaly cancellation conditions solely does not fix the SM hypercharge uniquely.

Let us first consider only one generation of SM fermions:

- $Y_L = Y_Q = Y_{e_R} = Y_{u_R} + Y_{d_R} = 0.$
- The second solution is the standard SM chiral hypercharge assignment.

Q	u_R	d_R	L	e_R	Φ
$\frac{-Y}{3}$	$\frac{-4Y}{3}$	$\frac{2Y}{3}$	Y	$2Y$	$-Y$

- One more solution can be found by interchanging the hypercharges of u_R and d_R i.e. $Y_{u_R} = \frac{2Y}{3}$ and $Y_{d_R} = \frac{-4Y}{3}$.

Only standard solutions leads to correct electric charges of all fermions

- Another way to fix hypercharges uniquely : Mass generation mechanism.

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$$-\mathscr{L}_Y = Y_e \overline{L} \varphi e_R + Y_u \overline{Q} \tilde{\varphi} u_R + Y_d \overline{Q} \varphi d_R + \text{h.c.}\,. \tag{2}$$

- $$Y_{u_\mathrm{R}} = Y_Q + Y_L - Y_{e_\mathrm{R}}, \text{ and } Y_{d_\mathrm{R}} = Y_Q - Y_L + Y_{e_\mathrm{R}}\,. \tag{3}$$

Three generations of SM fermions :

$$
\begin{aligned}
Y_{Q^i} &= -Y_{Q^j} = Y,\ \ Y_{Q^k} = 0; \quad i,j,k = 1,2,3\ \&\ i \neq j \neq k \\
Y_{u^l_\mathrm{R}} &= -Y_{u^m_\mathrm{R}} = Y',\ \ Y_{u^n_\mathrm{R}} = 0; \quad l,m,n = 1,2,3\ \&\ l \neq m \neq n \\
Y_{d^r_\mathrm{R}} &= -Y_{d^s_\mathrm{R}} = Y'',\ \ Y_{d^t_\mathrm{R}} = 0; \quad r,s,t = 1,2,3\ \&\ r \neq s \neq t \\
Y_{L^i} &= Y_{l^j} = 0; \quad i,j = 1,2,3\ \forall\, i,j.
\end{aligned}
$$

$$
\begin{aligned}
Y_{L^i} &= -Y_{L^j} = Y, Y_{L^k} = 0; \quad i,j,k = 1,2,3\ \&\ i \neq j \neq k \\
Y_{e^l_\mathrm{R}} &= -Y_{e^m_\mathrm{R}} = Y',\ \ Y_{e^n_\mathrm{R}} = 0; \quad l,m,n = 1,2,3\ \&\ l \neq m \neq n \\
Y_{Q^i} &= Y_{q^j} = 0; \quad i,j = 1,2,3\ \forall\, i,j.
\end{aligned}
$$

- Some solutions lead to correct mass generation (but not mixing) for the fermions. But no solution lead to correct electric charge.
- The standard SM hypercharge assignment remains unique even with three generations of SM

$U(1)_X$ anomaly cancellation

$$[SU(3)_C]^2[U(1)_X] = \sum_q X_{q_\mathrm{L}} - \sum_q X_{q_\mathrm{R}} \quad (4)$$

$$[SU(2)_\mathrm{L}]^2[U(1)_X] = \sum_l X_{l_\mathrm{L}} + 3\sum_q X_{q_\mathrm{L}} \quad (5)$$

$$[U(1)_Y]^2[U(1)_X] = \sum_{l,q}(Y^2_{l_\mathrm{L}} X_{l_\mathrm{L}} + 3Y^2_{q_\mathrm{L}} X_{q_\mathrm{L}}) - \sum_{l,q}(Y^2_{l_\mathrm{R}} X_{l_\mathrm{R}} + 3Y^2_{q_\mathrm{R}} X_{q_\mathrm{R}}) \quad (6)$$

$$[U(1)_Y][U(1)_X]^2 = \sum_{l,q}(Y_{l_\mathrm{L}} X^2_{l_\mathrm{L}} + 3Y_{q_\mathrm{L}} X^2_{q_\mathrm{L}}) - \sum_{l,q}(Y_{l_\mathrm{R}} X^2_{l_\mathrm{R}} + 3Y_{q_\mathrm{R}} X^2_{q_\mathrm{R}}) \quad (7)$$

$$[U(1)_X]^3 = \sum_{l,q}(X^3_{l_\mathrm{L}} + 3X^3_{q_\mathrm{L}}) - \sum_{l,q}(X^3_{l_\mathrm{R}} + 3X^3_{q_\mathrm{R}}) \quad (8)$$

$$[G]^2[U(1)_X] = \sum_{l,q}(X_{l_\mathrm{L}} + 3X_{q_\mathrm{L}}) - \sum_{l,q}(X_{l_\mathrm{R}} + 3X_{q_\mathrm{R}}) \quad (9)$$

- **Vector Solutions :** In the BSM scenarios, while gauging new $U(1)_X$ symmetries, vector charges are typically assigned to the SM particles. This is done to ensure the invariance of the Yukawa structure.
- $B-L$, $B-3L_\tau$, $L_\mu - L_\tau$ etc.
- **Chiral Solutions :** Chiral solutions are those in which SM fermions behave non-trivially under $U(1)_X$, meaning that SM fermions are chiral under this symmetry.
- In this study, we explored these chiral solutions. We will show that the induced gauge anomalies can be cancelled by adding right-handed fermions (RHFs).

Dark Hypercharge Symmetry

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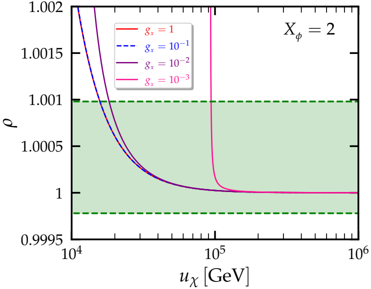
Scenarios	Q	u_R	d_R	L	e_R	f_1	f_2	f_3	φ
S_1	$-\frac{X_L}{3}$	$-\frac{4X_L}{3}+\kappa$	$\frac{2X_L}{3}-\kappa$	X_L	$2X_L-\kappa$	κ	κ	κ	$\kappa-X_L$
	$\frac{1}{s}$	$-(\kappa-\frac{4}{s})$	$\kappa-\frac{2}{s}$	$-\frac{3}{s}$	$\kappa-\frac{6}{s}$	5κ	-4κ	-4κ	$-(\kappa-\frac{3}{s})$
	$-\frac{X_L}{3}$	$\frac{-4X_L}{3}-\frac{s^2-1}{8}$	$\frac{2X_L}{3}+\frac{s^2-1}{8}$	X_L	$2X_L+\frac{s^2-1}{8}$	$\frac{1}{8}(-4s^2+3s+\frac{1}{s})$	$\frac{1}{8}(5s^2+3)$	$-\frac{1}{8}(4s^2+3s+\frac{1}{s})$	$-(X_L+\frac{s^2-1}{8})$
	$-\frac{X_L}{3}$	$\frac{-4X_L}{3}+\frac{s^2-1}{8}$	$\frac{2X_L}{3}-\frac{s^2-1}{8}$	X_L	$2X_L-\frac{s^2-1}{8}$	$\frac{1}{8}(3s^2+5)$	$-\frac{1}{8}(s^3+3s+4)$	$\frac{1}{8}(s^3+3s-4)$	$-X_L+\frac{s^2-1}{8}$
S_2	$\frac{-X_L}{3}$	$\frac{-4X_L}{3}$	$\frac{2X_L}{3}$	X_L	$2X_L$	0	k	$-k$	$-X_L$
	$\frac{-X_L}{3}$	$\frac{2X_L}{3}-X_{e_R}$	$\frac{-4X_L}{3}+X_{e_R}$	X_L	X_{e_R}	0	$2X_L-X_{e_R}$	$2X_L-X_{e_R}$	$X_L-X_{e_R}$
S_3	$\frac{-X_L}{3}$	$\frac{2X_L}{3}-X_{e_R}$	$\frac{-4X_L}{3}+X_{e_R}$	X_L	X_{e_R}	k	$-k$	$2X_L-X_{e_R}$	$X_L-X_{e_R}$

Charges of particles under $U(1)_X$ symmetry, satisfying gauge anomaly cancellation conditions and Higgs charge to write SM invariant Yukawas, considering three DFs ($m=3$).

$U(1)$	Q	u_R	d_R	L	e_R	f_1	f_2	f_3	φ	χ_0
$U(1)_Y$	$\frac{1}{3}$	$\frac{4}{3}$	$\frac{-2}{3}$	-1	-2	0	0	0	1	0
$U(1)_X$	$-\frac{1}{3}$	$\frac{5}{3}$	$-\frac{7}{3}$	1	-1	10	-18	17	2	-6

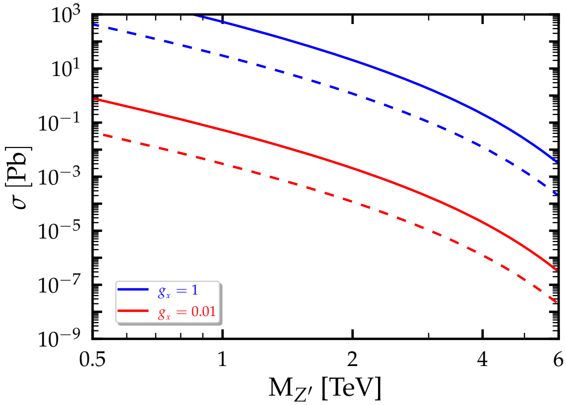
- $\rho = \frac{M_W^2}{M_Z^2 \cos^2\theta_W}$.
- $M_{Z'}[g_X, u_\chi] > M_Z[g_X, u_\chi]$



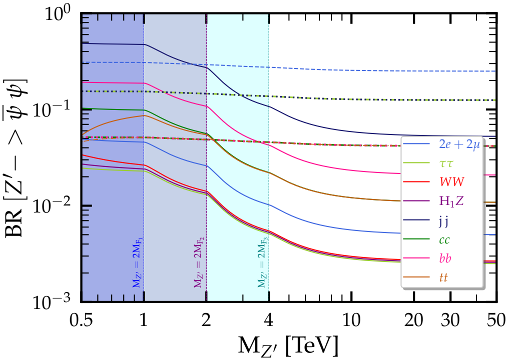
Production an decays of Z'

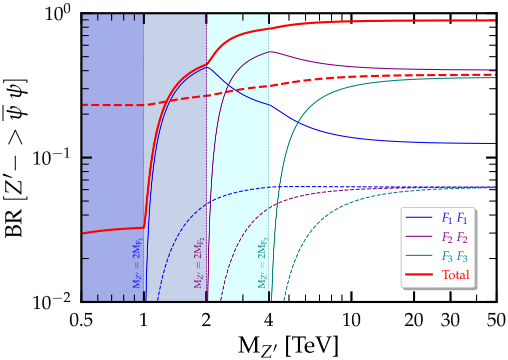
In hadronic colliders the most efficient process involving Z' production is Drell-Yan. At parton level it can be written as

$$q\,\bar{q} \longrightarrow Z'\,, \tag{10}$$



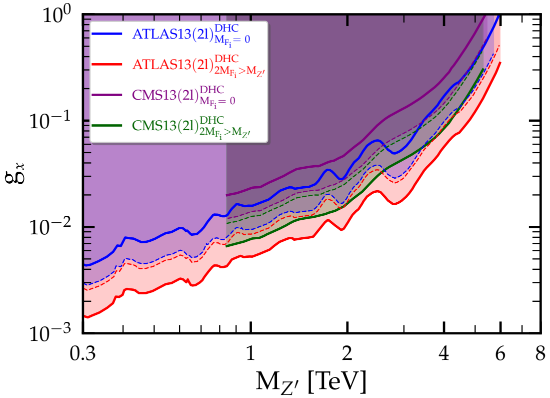
- In the DHC symmetry, the total branching fraction of invisible decay is approximately 90% when the branching fraction saturates. In contrast, in the $B-L$ symmetry, it is about 38%.
- in the fermionic decay modes, the dileptonic branching fraction, which is maximum in $B-L$ symmetry (25%), is minimum in DHC symmetry (0.5%).





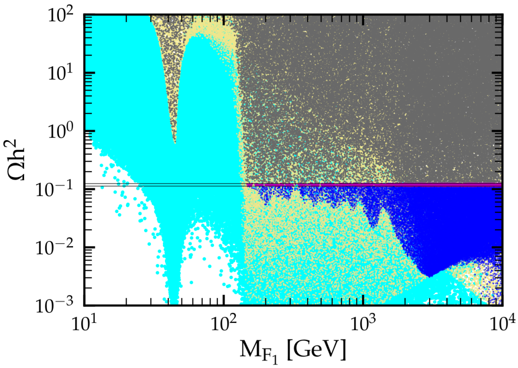
Collider Constraints

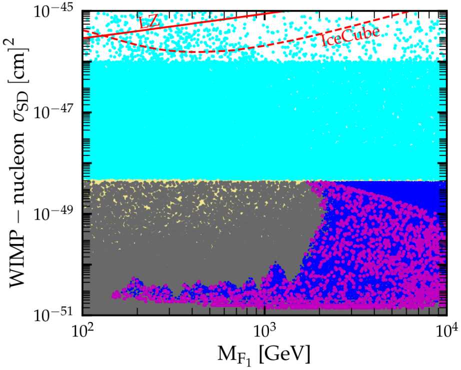
We used the ATLAS search for Z' in Dilepton resonance at pp collisions with ($\sqrt{s} = 13$) TeV and an integrated luminosity of 139 fb^{-1}, arXiv:1903.06248 [hep-ex]. Additionally, we incorporated results from CMS, arXiv:2103.02708 [hep-ex].



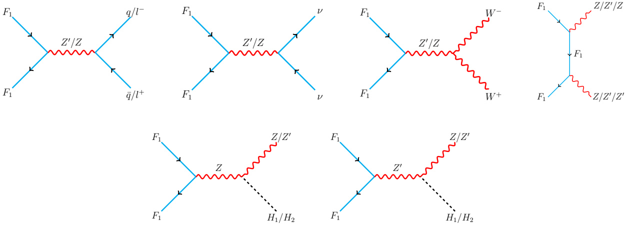
Dark Matter Constraints

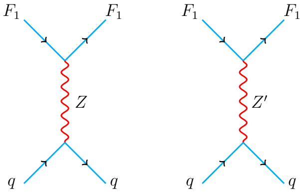
- $0.1126 \leq \Omega h^2 \leq 0.1246$.





Feynman diagrams contributing to DM annihilation and nucleon scattering:





Conclusions

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- Extensions of the SM with $U(1)$ gauge symmetries hold strong motivations. These new symmetries alter the SM's gauge anomaly conditions, placing constraints on charges of new fermions beyond the SM.
- We have examined such chiral solutions, providing a set of solutions for gauge anomaly cancellation using three new right-handed BSM fermions.
- Our presented solution involves new fermions with higher $U(1)x$ charges compared to SM fermions. These fermions serve as promising dark matter candidates, with their interactions through Z' being sufficient to fulfil dark matter properties. We confirm that our dark matter candidate, F_1, with a mass range $M_{F_1} \gtrsim 150$ GeV, satisfies all the DM relevant properties and current constraints.

Thank You

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SM Symmetries $\longrightarrow SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$

Lepton Doublet $L \rightarrow (1,2,-1)$	Quark Doublet $Q \rightarrow (3,2,1/3)$	Lepton Singlet $l_R \rightarrow (1,1,-2)$	Up quark $u_R \rightarrow (3,1,4/3)$	Down quark $d_R \rightarrow (3,1,-2/3)$
$\begin{bmatrix} \nu_e \\ e \end{bmatrix}_L$	$\begin{bmatrix} u \\ d \end{bmatrix}_L$	e_R	u_R	d_R
$\begin{bmatrix} \nu_\mu \\ \mu \end{bmatrix}_L$	$\begin{bmatrix} c \\ s \end{bmatrix}_L$	μ_R	c_R	s_R
$\begin{bmatrix} \nu_\tau \\ \tau \end{bmatrix}_L$	$\begin{bmatrix} t \\ b \end{bmatrix}_L$	τ_R	t_R	b_R

Table: SM Particle Content

Extras

Z' Mass

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The covariant derivative is defined as

$$D_\mu = \partial_\mu + ig_s T^a_g G^a_\mu + igT^a_w W^a_\mu + ig' \frac{Y}{2} B_\mu + ig_x XC_\mu \,. \tag{11}$$

After the breaking of both the electroweak symmetry and $U(1)_X$, the vev of these scalar fields can be represented as follows:

$$\langle\varphi\rangle = \frac{1}{\sqrt{2}} \begin{bmatrix} 0 \\ v \end{bmatrix}, \quad \langle\chi_i\rangle = \frac{v_i}{\sqrt{2}} \,. \tag{12}$$

The mass spectrum of the gauge bosons are generated by the expansion of the kinetic terms of the scalars, as given below

$$(D_\mu)^\dagger D^\mu + (D_\mu \chi_i)^\dagger D^\mu \chi_i \,, \tag{13}$$

here repeated indices are summed over. Replaycing the fields and covariant derivativs by the expression defined in Eq. (12) and Eq. (11), we can write the mass matrix of the gauge bosons in the basis (B^μ, W^μ_3, C^μ) as

$$\mathcal{M}^2_V = \frac{v^2}{4} \begin{pmatrix} g'^2 & -gg' & 2g' X_\varphi g_x \\ -gg' & g^2 & -2gX_\varphi g_x \\ 2g' X_\varphi g_x & -2gX_\varphi g_x & 4u^2 g_x^2 \end{pmatrix} , \tag{14}$$

where $u^2 = X_\varphi^2 + u_\chi^2/v^2$, and u_χ is defined as $u_\chi = \sqrt{\sum_i (X^2_{\chi_i} v_i^2)}$.

$$m^2 = \frac{v^2}{8}(A_0 - \sqrt{B_0^2 + C_0^2}),\ M^2 = \frac{v^2}{8}(A_0 + \sqrt{B_0^2 + C_0^2}), \tag{15}$$

where $A_0 = g^2 + g'^2 + 4u^2 g_x^2,\ B_0 = 4X_\varphi g_x \sqrt{g^2 + g'^2},\ C_0 = 4u^2 g_x^2 - (g^2 + g'^2)$.
And the W boson mass is given as $M_W^2 = (gv)^2/4$.

Scalar Sector

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$$\mathcal{L}_s = (D^\mu \varphi)^\dagger (D_\mu \varphi) + (D^\mu \chi_0)^\dagger (D_\mu \chi_0) - \mathcal{V}(\varphi, \chi_0), \tag{16}$$

$$\mathcal{V}(\Phi, \chi_0) = m_{\chi_0}^2 (\chi_0^* \chi_0) + \frac{1}{2} \lambda_{\chi_0} (\chi_0^* \chi_0)^2 + m_\varphi^2 (\varphi^\dagger \varphi) + \frac{1}{2} \lambda_\varphi (\varphi^\dagger \varphi)^2 + \lambda_{\varphi\chi_0} (\chi_0^* \chi_0)(\varphi^\dagger \varphi). \tag{17}$$

$$\varphi = \frac{1}{\sqrt{2}} \begin{bmatrix} \sqrt{2} G^+ \\ v + R_\varphi + i I_\varphi \end{bmatrix}, \qquad \chi_0 = \frac{1}{\sqrt{2}} (v_0 + R_0 + i I_0). \tag{18}$$

First we solve the minimization equations for the mass parameters, m_{χ_0} and m_φ.

$$\begin{aligned} 2 m_\varphi^2 + v^2 \lambda_\varphi + v_0^2 \lambda_{\varphi\chi_0} &= 0 \,, \\ 2 m_{\chi_0}^2 + v^2 \lambda_{\varphi\chi_0} + v_0^2 \lambda_{\chi_0} &= 0. \end{aligned} \tag{19}$$

$G^\pm$ are the Goldstone boson corresponding to $W^\pm$. I_φ and I_0 will mix and give rise to the Goldstone bosons corresponding to the neutral gauge bosons Z and Z'. The mass matrix of CP-even Higgs scalars in the basis (R_1, R_2) reads as

$$\mathcal{M}_R^2 = \begin{pmatrix} A & C \\ C & B \end{pmatrix} = \begin{pmatrix} v^2 \lambda_\varphi & v v_0 \lambda_{\varphi\chi_0} \\ v v_0 \lambda_{\varphi\chi_0} & v_0^2 \lambda_{\chi_0} \end{pmatrix}. \tag{20}$$

The mass eigenvalues of light and heavy mass eigenstates as

$$M_{H_1}^2 = \frac{1}{2}\left[A + B - \sqrt{(A-B)^2 + 4C^2}\right], \tag{21}$$

$$M_{H_2}^2 = \frac{1}{2}\left[A + B + \sqrt{(A-B)^2 + 4C^2}\right]. \tag{22}$$

We follow the convention $M_{H_1} < M_{H_2}$ and have identified H_1 as the SM Higgs, with mass $M_{H_1} = 125$ GeV. The two mass eigenstates H_1, H_2 are related with the (R_1, R_2) fields through the following rotation matrix as

$$\begin{bmatrix} H_1 \\ H_2 \end{bmatrix} = \begin{bmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{bmatrix} \begin{bmatrix} R_\varphi \\ R_0 \end{bmatrix}, \text{ with } \tan 2\beta = \frac{2C}{B-A}. \tag{23}$$