CP Violation from the Phase-Lag Mechanism

Complex Yukawa couplings, the Jarlskog invariant, and the concurrence of baryogenesis and CP violation

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Derivation record D3 — extracted from STF from First Principles V7.9, Appendix R. Companion to the framework backbone, First Principles V8.1 (The Two-Clock Theory).

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Provenance and status

This paper is the derivation record for the framework's CP-violation mechanism, extracted unchanged from *STF from First Principles* V7.9 Appendix R. It is published standalone because it is the connective tissue between the Standard Model constants derivation (baryogenesis) and the flavour-sector papers, and belongs to neither.

Untouched by the August 2026 two-clock revision: no dependence on the flyby, the curvature norm, the ghost-freedom proof, or the activation threshold's normalization. Its status is *derived within the compactification sector, conditional on the CICY #7447/$\mathbb{Z}_{10}$ choice and on the moduli-mass formula*.

The resonance-window argument depends on the Weil–Petersson computation published as its companion derivation paper.

Notation note. Throughout Appendices R and S, **Θ** denotes the Weil-Petersson scalar curvature of the complex-structure moduli space (defined precisely in R.5 and S.2). This is distinct from the expansion scalar Θ = ∇_μu^μ_φ used in Appendix C.6.3, which is a kinematic quantity of the scalar-field congruence (equal to 3H on an FLRW background). The two symbols refer to different objects in different physical contexts; no equation in this appendix or Appendix S involves the expansion scalar.

This appendix derives the origin of CP violation in the STF framework. The mechanism is a direct extension of the baryogenesis result in Appendix K.8: the same oscillating scalar field φ_S that sources the baryon asymmetry also drives a phase lag in the five complex-structure moduli z_α (Appendix Q), freezing a CP-odd component into the Yukawa coupling matrix. The two effects are concurrent — one resonant epoch, two Standard Model outputs.

R.1 Connection to K.8 Baryogenesis

Appendix K.8 derives the baryon asymmetry via a phase lag mechanism:

$$\chi_R(\omega) = \frac{1}{\omega_0^2 - \omega^2 - i\Gamma_R\omega}, \qquad \delta_R(\omega) = arctan\left(\frac{\Gamma_R\,\omega}{\omega_0^2 - \omega^2}\right)$$

At resonance $\omega \to \omega_0$, the phase lag δ_R → π/2, giving η_b = (π/2)(α/10)³ = 6.10×10⁻¹⁰ (99.74% of observed 6.12×10⁻¹⁰).

K.11 identifies the quantities that minimal STF does not address: quark mass hierarchies, CKM mixing, and CP violation, all requiring the complex-structure moduli z_α. Appendix Q establishes that exactly 5 such moduli survive the Z_{10} quotient. Appendix R derives the CP violation mechanism from those 5 moduli using the same phase lag structure as K.8.

R.2 Kähler Potential and Coupling Structure

The full Kähler potential of the CICY #7447/Z_{10} compactification is:

$$K = -3\ln\left(T+\bar{T}\right) - \ln\left[\int_X \Omega(z)\wedge\bar{\Omega}\left(\bar{z}\right)\right] = -6\sigma - 3\ln 2 - K_{\rm cs}\left(z,\bar{z}\right), \qquad \mathrm{Re}\,T \equiv e^{2\sigma}$$

Notation. Here σ is the logarithmic breathing coordinate, defined by Re T = e^{2σ}, so that −3 ln(T+T̄) = −6σ − 3 ln 2; it is distinct from the linear modulus Re T itself. Earlier versions of this appendix wrote −6σ without the constant and without stating this definition, which read as −3 ln(2σ) — the two coordinates share a symbol only through this relation.

where T = σ + iθ is the volume modulus (Re T = σ, with e^{6σ} = Vol(X)) and K_cs is the Weil-Petersson Kähler potential on complex structure moduli space.

The GVW superpotential is:

$$W = \int_X G_3 \wedge \Omega(z) = n^a \Pi_a(z)$$

where n^a are integer flux quanta and $\Pi_a(z)$ are periods of the holomorphic 3-form $\Omega(z)$.

The F-term scalar potential contains the cross-derivative:

$$\frac{\partial^2 V}{\partial\,(\mathrm{Re}\,T)\,\partial z_\alpha} \neq 0$$

because W depends on both $\sigma = \mathrm{Re}\,T$ (through e^K) and z_α (through the periods $\Pi_a(z)$). This coupling is a direct consequence of the Kähler potential — no additional assumption is made.

The STF field φ_S is the canonically normalised volume modulus: $\varphi_S = \sqrt{24}\, M_{Pl} \cdot \sigma = \sqrt{24}\, M_{Pl} \cdot \mathrm{Re}\, T$ (Appendix L.3.2). Therefore $\partial/\partial\varphi_S = (\sqrt{24}\, M_{Pl})^{-1} \cdot \partial/\partial(\mathrm{Re}\, T)$, and the cross-derivative in terms of φ_S is:

$$\frac{\partial^2 V}{\partial \phi_S\,\partial z_\alpha} = \frac{1}{\sqrt{24}\,M_{\mathrm{Pl}}} \cdot \frac{\partial^2 V}{\partial\,(\mathrm{Re}\,T)\,\partial z_\alpha} \neq 0$$

The non-vanishing is preserved under this rescaling, and the prefactor $(\sqrt{24}\, M_{Pl})^{-1}$ is absorbed into the effective coupling coefficient on the right-hand side of the driven EOM (V6.0) in R.3. The 5 moduli z_α are sourced whenever φ_S oscillates.

R.3 Equation of Motion and Phase Lag Formula

The volume modulus φ_S oscillates at the reheating epoch with amplitude A and frequency $\omega = m_s$:

$$\delta\phi_S(t) = A\cos\left(m_s t\right)$$

The driven equation of motion for the complex structure modulus z_α, linearised around the vacuum z_0, is:

$$\boxed{\delta\ddot{z}_\alpha + 3H\,\delta\dot{z}_\alpha + m_z^2\,\delta z_\alpha = \left.\frac{\partial^2 V}{\partial\phi_S\,\partial z_\alpha}\right|_{z_0} \cdot A\cos\left(m_s t\right)}$$

The steady-state solution is:

$$\delta z_\alpha(t) = \left|\chi_z\left(m_s\right)\right| \cdot \left.\frac{\partial^2 V}{\partial\phi_S\,\partial z_\alpha}\right|_{z_0} \cdot A\cos\left(m_s t - \delta_z\right)$$

with susceptibility $\chi_z(\omega) = 1/(m_z^2 - \omega^2 - i\cdot 3H\cdot\omega)$ and **phase lag:**

$$\boxed{\delta_z\left(m_s\right) = arctan\left(\frac{3H\,m_s}{m_z^2 - m_s^2}\right)}$$

This is structurally identical to the K.8 formula with the replacement $\Gamma_R \to 3H$. The same physics — driven harmonic oscillator with damping — produces the same phase lag. At exact resonance m_z

= m_s:

$$\delta_z \to \frac{\pi}{2}$$

Phase lag verification (computed):

H/m_z	δ_z near resonance (ω = 0.9999 m_z)
0.1	89.96°
0.01	89.62°
0.001	86.19°
0.0001	56.31°

At exact resonance (ω = m_z): δ_z → 90° analytically for all H > 0.

R.4 Complex Yukawa Couplings and the Jarlskog Invariant

The holomorphic Yukawa coupling of quarks in the heterotic compactification is:

$$Y_{\text{ij}}\left(z_\alpha\right) = \int_X \Omega(z) \wedge A_i \wedge A_j$$

where A_i are bundle-valued (0,1)-forms representing the quark wavefunctions. Expanding around the vacuum z_0:

$$Y_{\text{ij}}(t) = Y_{\text{ij}}^{(0)} + \sum_{\alpha=1}^{5} \left.\frac{\partial Y_{\text{ij}}}{\partial z_\alpha}\right|_{z_0} \cdot |\delta z_\alpha| \cdot \cos\left(m_s t - \delta_z\right)$$

The sum runs over **exactly 5 terms** — a direct consequence of the character decomposition in Appendix Q.3. The 40 non-invariant moduli do not appear because they are projected out by the Z_{10} orbifold.

> **Note on Z_5 decoupling at the symmetric locus.** At the Z_{10}-symmetric locus z_2=…=z_5=0, and with the stabilising flux n*=(−247,−266,0,−3) lying in H³(X̃,ℤ)^{Z_{10}} (so the full background preserves Z_5), the cross-derivatives ∂²V/∂φ_S∂z_α vanish for α=2,…,5 by symmetry: φ_S is Z_5-invariant while z_α (α>1) transforms with phase ω^(α−1), making a linear coupling term φ_S z_α non-invariant and therefore forbidden. This decoupling is symmetry-exact — not a leading-order approximation — since the flux by construction lies in the Z_{10}-invariant sublattice and loop corrections cannot generate Z_5-violating terms when the symmetry is exact. At the physical vacuum φ_res≈0.420, only z_1 contributes to f; the contributions of z_2,…,z_5 vanish identically and would only reappear if the background broke Z_5, which it does not.

Frozen CP-odd component. At the epoch when φ_S oscillation ceases (H drops below m_z), the phase-lagged displacement δz_α freezes at its current value. The imaginary part of the Yukawa matrix is:

$$\boxed{Im\left(Y_{\mathrm{ij}}\right) = -\sum_{\alpha=1}^{5} \left.\frac{\partial Y_{\mathrm{ij}}}{\partial z_\alpha}\right|_{z_0} \cdot |\delta z_\alpha|_{\mathrm{frozen}} \cdot \sin\left(\delta_z\right)}$$

At resonance (δ_z = π/2, sin(δ_z) = 1):

$$Im\left(Y_{\mathrm{ij}}\right)|_{\mathrm{res}} = -\sum_{\alpha=1}^{5} \left.\frac{\partial Y_{\mathrm{ij}}}{\partial z_\alpha}\right|_{z_0} \cdot |\delta z_\alpha|_{\mathrm{max}}$$

Jarlskog invariant. From the Jarlskog construction J = Im(det[Y_u Y_u†, Y_d Y_d†]):

$$\boxed{J \propto \sin^2\left(\delta_z\right) \times f\left(\left.\frac{\partial Y}{\partial z}\right|_{z_0}, |\delta z|\right)}$$

where f encodes the geometric factor from the Yukawa derivatives and moduli displacements. At resonance:

$$J|_{\mathrm{res}} = f$$

Phase lag table — sin²(δ_z) vs ρ = m_z/m_s, evaluated at the freeze-out epoch H = m_z (computed):

(Each row gives the phase lag that freezes when the Hubble rate drops to H = m_z for that row's ρ. Substituting H = m_z and ω = m_s into (V6.1): δ_z = arctan(3m_z · m_s/(m_z² − m_s²)) = arctan(3ρ/(ρ² − 1)).)

ρ = m_z/m_s	δ_z	sin²(δ_z)	J/f
1.0 (resonance)	90.0°	1.0000	1.0000
1.5	74.5°	0.9284	0.9284
2.0	63.4°	0.8000	0.8000
3.0	48.4°	0.5586	0.5586
3.303 (boundary)	45.0°	0.5000	0.5000
5.0	32.0°	0.2809	0.2809
10.0	16.9°	0.0841	0.0841
540.6	0.318°	3.08×10^{-5}	3.08×10^{-5}
1.59×10^{10} (LVS)	~0°	3.56×10^{-20}	3.56×10^{-20}

R.5 Moduli Mass Formula and Derivation of the Resonance Window

Mass formula. The GVW F-term mass matrix for the z_α moduli at the critical point D_αW = 0 is:

$$M^{2}{}_{\alpha\bar{\beta}} = m_{3/2}^2 \times \Theta_{\alpha\bar{\beta}}$$

where Θ_{αβ̄} = g^{γδ̄}∂γ∂{δ̄}K_cs is the Weil-Petersson curvature tensor. At the Z_{10}-invariant locus z_α = z_0, the symmetry forces g_{αβ̄} = g·δ_{αβ̄} (all moduli are equivalent under the residual symmetry), giving:

$$\boxed{m_z = m_{3/2} \times \sqrt{\Theta}, \qquad \Theta \equiv g^{\alpha\bar{\alpha}}\partial_\alpha\partial_{\bar{\alpha}}K_{\text{cs}}|_{z_0}}$$

In the KKLT-type stabilization of Appendix O.4, the gravitino mass satisfies m_{3/2} ~ m_s: both are set by the same three-term flux superpotential, with m_{3/2} = e^{K/2}|W_0| and m_s² ∝ V''(σ_0)/M²_Pl, related via the same W_0 and volume at the KKLT minimum [33]. Therefore:

$$m_z = m_s \times \sqrt{\Theta}$$

Θ is pure geometry: it depends only on the period matrix of CICY #7447/Z_{10} at the Z_{10}-invariant locus, and is computable via the Picard-Fuchs system of Appendix S. The flux integers n^a cancel in the ratio m_z/m_s.

LVS is excluded. The Large Volume Scenario would give m_z/m_s ~ √Vol = e^{3σ_0} = 1.59×10¹⁰ (computed from σ_0 = 7.83 of Appendix O.4). At this mass ratio:

$$\sin^2(\delta_z)_{\text{LVS}} \approx \left(\frac{3m_s}{m_z}\right)^2 = \frac{9}{\text{Vol}} = 3.56 \times 10^{-20}$$

To achieve J = J_obs = 3.18×10⁻⁵ (PDG 2024), the geometric factor f would need to be f ~ 8.93×10¹⁴ — unphysically large. The factor f encodes holomorphic Yukawa derivatives ∂Y_ij/∂z_α and moduli displacements |δz_α|. The Yukawa couplings Y_ij = ∫_X Ω ∧ A_i ∧ A_j are integrals of a normalised holomorphic 3-form against bundle-valued (0,1)-forms over a compact CY3; in string units (where the manifold has volume O(1)), this gives Y_ij = O(1) and therefore ∂Y_ij/∂z_α = O(1) ([31]; [32]). The moduli displacement |δz_α| is bounded by the moduli space metric and is O(1) at resonance. Therefore f = O(1) is the natural expectation, and f ~ 10¹⁴ would require anomalously large period integrals with no geometric mechanism to produce them. **LVS is excluded as a mechanism for CP violation.** This is not an assumption: the Appendix O.4 potential is a three-term KKLT-type flux potential [33], and LVS requires additional α' corrections to K not present in that minimal action. The framework has already committed to KKLT.

Resonance window derivation. Requiring sin²(δ_z) ≥ 1/2 (>50% CP transfer efficiency, sufficient for J_obs with O(1) geometric factor f):

$$\arctan\left(\frac{3\rho}{\rho^2 - 1}\right) \geq 45^\circ, \quad \rho \equiv m_z/m_s$$

$$\Rightarrow \frac{3\rho}{\rho^2 - 1} \geq 1 \Rightarrow \rho^2 - 3\rho - 1 \leq 0 \Rightarrow \rho \leq \frac{3+\sqrt{13}}{2} = 3.303$$

$$\boxed{\Theta \in [1,\ 10.9]} \quad \Leftrightarrow \quad \rho = m_z/m_s \in [1,\ 3.30] \quad \Leftrightarrow \quad \sin^2(\delta_z) \geq 0.50$$

This is the **resonance window**: the range of WP curvature values for which the CP violation mechanism operates at ≥ 50% efficiency. Whether Θ(φ*) lands in this window is determined by the geometry of CICY #7447/Z_{10} — see Appendix S.

R.6 One-Epoch Structure: Baryogenesis and CP Violation Are Concurrent

V5.0 K.8 establishes that baryogenesis occurs at the epoch $H_{reh} \sim m_s$, when φ_S first enters resonance with the spacetime curvature oscillation. Appendix S shows that if $\Theta \sim O(1)$, then $m_z \sim m_s$, and the complex-structure moduli z_α also enter resonance at the same epoch.

The single epoch $H \sim m_s$ therefore produces both Standard Model outputs simultaneously:

Epoch $H \sim m_s$	Mechanism	Output
φ_S resonates with curvature R	K.8 baryogenesis phase lag δ_R	$\eta_b = (\pi/2)(\alpha/10)^3 = 6.10\times10^{-10}$
φ_S drives z_α oscillation	Appendix R phase lag δ_z	$\mathrm{Im}(Y_{ij}) \neq 0 \rightarrow J \propto \sin^2(\delta_z) \times f$

η_b / J ratio (computed):

$$\frac{\eta_b}{J_{\mathrm{obs}}} = \frac{6.10 \times 10^{-10}}{3.18 \times 10^{-5}} = 1.92 \times 10^{-5}$$

(Using the PDG 2024 value $J_{obs} = 3.18\times10^{-5}$. The ratio is $O(10^{-5})$ regardless of the ±5% uncertainty in J_{obs} between PDG editions.)

When f is computed from the Yukawa derivatives $\partial Y_{ij}/\partial z_\alpha$ via the period matrix (Route B, Appendix S), this ratio becomes a parameter-free prediction of the framework.

R.7 Falsifiable Predictions

The CP violation mechanism makes the following predictions, each independently testable:

Θ value	ρ = m_z/m_s	$\sin^2(\delta_z)$	Prediction
$\Theta \in [1, 10.9]$	1–3.30	≥ 0.50	$J = \sin^2(\delta_z(\Theta)) \times f \rightarrow$ full parameter-free prediction
$\Theta < 1$	< 1	overdamped	No frozen CP phase; $J \sim 0$ (mechanism fails)
$\Theta > 10.9$, $\Theta \ll \mathrm{Vol}$	3.30–$\sqrt{\mathrm{Vol}}$	< 0.50	$J \sim (3/\sqrt{\Theta})^2 \times f$, sub-resonant suppression
$\Theta = \mathrm{Vol}$ (LVS)	1.59×10^{10}	3.56×10^{-20}	$J \sim 10^{-24} \times f$, excluded by analysis above

Critical test: When $\Theta(\varphi^*)$ is computed via Route B (Appendix S), it immediately determines which row applies. If $\Theta \in [1, 10.9]$ is confirmed, the framework predicts $\sin^2(\delta_z)$ to four significant figures, and $J = \sin^2(\delta_z) \times f$ with f computed from the same period matrix. This is a fully predictive, parameter-free result.

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