The Standard Model from the cosmological constant: gauge group uniqueness and the graviton edge-mode fraction

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Abstract

In a companion paper we showed that the logarithmic correction to entanglement entropy, applied at the cosmological horizon via the Cai–Kim first law, gives $\Lambda_{\rm SM}/\Lambda_{\rm obs} = 0.97$ with the graviton contribution left as a bracketing range [0.97, 1.07]. Here we close that bracket. The graviton's entanglement entropy trace anomaly ($\delta_{\rm EE} = -61/45$, Benedetti–Casini) differs from its effective-action anomaly ($\delta_{\rm EA} = -212/45$, Christensen–Duff) because 71% of the graviton anomaly is carried by diffeomorphism edge modes that do not contribute to the Clausius relation at the cosmological horizon. If one accepts this interpretation, the physical entanglement fraction $f_{\rm g} = \delta_{\rm EE}/\delta_{\rm EA} = 61/212$ is fixed by established QFT results, giving $\Lambda/\Lambda_{\rm obs} = 0.9999$ (0.01σ) with no free parameters beyond the foundational assumptions of the framework ($\Lambda_{\rm bare} = 0$, Jacobson thermodynamic gravity). Within the class of $\mathrm{SU}(N_c) \times \mathrm{SU}(N_w) \times \mathrm{U}(1)$ theories with anomaly-cancelling fermion content ($N_{\rm gen} = 1 \ldots 6$, 144 theories scanned), the continuous solutions $N_c = 3.005$, $N_w = 1.995$, $N_{\rm gen} = 2.997$ uniquely select the Standard Model gauge group and three generations. Within the same framework, supersymmetry is excluded, Majorana neutrinos are favoured, and no additional vector bosons are allowed. The framework makes ten falsifiable predictions, six of which are currently consistent with observation; the most serious tension is with DESI BAO data, which disfavours $w = -1$ at 3–4σ.

1 Introduction

The cosmological constant problem—the 10^{120}-fold discrepancy between the naïve quantum field theory estimate of vacuum energy and its observed value—has resisted resolution for decades [1, 2]. In a companion paper [3], we argued that, within the Jacobson thermodynamic framework [12] and under the assumption $\Lambda_{\rm bare} = 0$, the cosmological constant arises from the logarithmic correction to entanglement entropy across the de Sitter horizon.

The central result of Ref. [3] is the self-consistency condition

$$R \equiv \frac{|\delta_{\rm total}|}{6\,\alpha_{\rm total}} = \Omega_\Lambda\,, \tag{1}$$

where δ_{total} is the UV-finite trace anomaly coefficient summed over all fields, α_{total} is the area-law coefficient, and $\Omega_\Lambda \simeq 0.685$ is the dark energy fraction. Using heat kernel counting for all Standard Model species and a lattice measurement $\alpha_s = 0.02351 \pm 0.00012$ [3], the Standard Model alone gives $\Lambda_{\text{SM}}/\Lambda_{\text{obs}} = 0.970$—within 3% of observation. Including the linearised graviton with $\delta_{\text{grav}} = -61/45$ (Benedetti–Casini [4]) and $\alpha_{\text{grav}} = 2\alpha_s$ yields 1.07, so the observed value is bracketed: $0.97 < 1.0 < 1.07$.

Ref. [3] identified the graviton's entanglement fraction f_g as the single remaining open question. This paper resolves it, and in doing so uncovers a far richer structure.

Three advances.

1. **The graviton edge-mode fraction is determined by a physical argument, not fitted.** We argue that the trace anomaly relevant for the Clausius relation at the cosmological horizon is the *entanglement entropy* anomaly δ_{EE}, not the *effective action* anomaly δ_{EA}. For matter fields these coincide, but for the graviton $\delta_{\text{EE}} = -61/45$ [4] while $\delta_{\text{EA}} = -212/45$ [5]; the difference is carried by diffeomorphism edge modes. *If* this identification is correct, the ratio $f_g = \delta_{\text{EE}}/\delta_{\text{EA}} = 61/212 = 0.2877$ is fixed, giving $\Lambda/\Lambda_{\text{obs}} = 0.9999$ (0.01σ). We stress that the individual computations of δ_{EE} and δ_{EA} are established results; what is novel and unproven is the *interpretation* of their ratio as the graviton's contribution to horizon entropy. This interpretation depends on the physical status of graviton edge modes at observer-dependent horizons, which is an active area of research (see Section 2 for a detailed discussion).

2. **The gauge-fermion sector alone predicts Ω_Λ.** The pure gauge-plus-fermion content of the Standard Model (12 vectors + 45 Weyl fermions, no Higgs, no graviton) gives $R = 0.6851$, matching Ω_Λ to 0.06%. The number of generations, solved as a continuous variable, is $N_{\text{gen}} = 3.003$—essentially an exact integer.

3. **The Standard Model is uniquely selected.** Scanning 144 gauge theories $\text{SU}(N_c) \times \text{SU}(N_w) \times \text{U}(1)$ with $N_{\text{gen}} = 1 \ldots 6$, the continuous solutions of $R = \Omega_\Lambda$ give $N_c = 3.005$, $N_w = 1.995$, $N_{\text{gen}} = 2.997$. All three round uniquely to the Standard Model values $(3, 2, 3)$. Grand unified theories are excluded: SU(5) overshoots by 41%, SO(10) by 85%, E_6 by 89%.

The paper is organised as follows. Section 2 derives $f_g = 61/212$ from the edge-mode decomposition of the graviton trace anomaly. Section 3 presents the gauge-fermion miracle. Section 4 scans the landscape of gauge theories. Section 5 discusses GUT exclusion and cosmological stability. Section 6 derives BSM exclusion bounds. Section 7 gives the error budget and corrected statistical significance. Section 8 audits the derivation chain. Section 9 lists all predictions and falsification tests. Section 10 concludes.

2 Graviton edge modes and the entanglement fraction

2.1 Entanglement entropy vs. effective action for matter fields

The entanglement entropy of a quantum field across a smooth surface Σ in 3+1 dimensions takes the universal form

$$S_{\text{EE}} \;=\; \alpha\, A + \delta\, \ln\!\big(A/\epsilon^2\big) + \mathcal{O}(1)\,, \tag{2}$$

where A is the area of Σ, ϵ is a UV cutoff, α is a non-universal area-law coefficient, and δ is the UV-finite logarithmic coefficient determined by the type-A trace anomaly [10, 11].

For a single field species, the trace anomaly coefficient entering the entanglement entropy is

$$\delta_{\rm EE} \;=\; -4\,a\,, \tag{3}$$

where a is the Euler (type-A) central charge. The same coefficient appears in the one-loop effective action on a curved background:

$$\delta_{\rm EA} \;=\; -4\,a_{\rm EA}\,. \tag{4}$$

For scalar, Weyl fermion, and vector fields, *these two quantities coincide*:

$$\delta_{\rm EE} = \delta_{\rm EA} \qquad \text{(scalars, Weyl fermions, vectors)}\,. \tag{5}$$

This equality is non-trivial. It holds because these fields have no gauge-redundant boundary degrees of freedom at the entangling surface: the decomposition of the Hilbert space into interior and exterior factors is clean. For Maxwell theory, Donnelly and Wall [6] showed that edge modes (boundary charges from gauge invariance) contribute to the entanglement entropy, but they enter only through the non-universal area term α, not through the UV-finite δ. Casini and Huerta [8] confirmed that the universal logarithmic coefficient $\delta_{\rm EE}$ for vector fields equals the effective-action value $\delta_{\rm EA}$.

2.2 The graviton anomaly: $\delta_{\rm EE}$ versus $\delta_{\rm EA}$

For the linearised graviton (symmetric traceless tensor field), the situation changes fundamentally. Diffeomorphism invariance introduces edge modes at the entangling surface—boundary gravitons that arise from the gauge redundancy of the metric perturbation at Σ.

The effective-action trace anomaly for the graviton was computed by Christensen and Duff [5]:

$$\delta_{\rm EA}^{\rm (grav)} = -\frac{212}{45} \approx -4.711\,. \tag{6}$$

The *entanglement entropy* trace anomaly was computed by Benedetti and Casini [4]:

$$\delta_{\rm EE}^{\rm (grav)} = -\frac{61}{45} \approx -1.356\,. \tag{7}$$

The difference,

$$\delta_{\rm edge}^{\rm (grav)} = \delta_{\rm EA}^{\rm (grav)} - \delta_{\rm EE}^{\rm (grav)} = -\frac{151}{45} \approx -3.356\,, \tag{8}$$

is carried entirely by diffeomorphism edge modes. These are gauge-redundant boundary degrees of freedom at the entangling surface, analogous to the boundary charges in Maxwell theory but now associated with the larger gauge group of diffeomorphisms [7, 9].

In percentage terms, edge modes carry 71.2% of the graviton's total effective-action anomaly:

$$\frac{|\delta_{\rm edge}|}{|\delta_{\rm EA}|} = \frac{151}{212} = 0.712\,. \tag{9}$$

2.3 Physical argument: why edge modes do not enter the Clausius relation

In Jacobson's thermodynamic derivation of Einstein's equations [12], gravity emerges from the Clausius relation $\delta Q = T\,dS$ applied to local Rindler horizons. The entropy S in this relation is the *entanglement entropy* between the observable and unobservable regions.

At the cosmological horizon—which is observer-dependent (every observer has their own)—the entropy that enters the Cai–Kim first law [13] is likewise the entanglement entropy S_{EE}. Edge modes at this boundary are diffeomorphism gauge artefacts: they depend on where the observer draws the horizon and have no observer-independent physical content. They do not represent genuine quantum correlations between the interior and exterior.

This yields a clean selection rule:

- **Matter fields** (scalars, fermions, vectors): $\delta = \delta_{\mathrm{EE}} = \delta_{\mathrm{EA}}$. No edge modes affect the type-A anomaly. The entanglement fraction is $f = 1$.
- **Graviton**: $\delta = \delta_{\mathrm{EE}} \neq \delta_{\mathrm{EA}}$. Edge modes contribute to δ_{EA} but not to δ_{EE}. The entanglement fraction is $f_{\mathrm{g}} = \delta_{\mathrm{EE}}/\delta_{\mathrm{EA}} = 61/212$.

We emphasise that the individual values of δ_{EE} and δ_{EA} are established results in the published literature [4, 5]. What is *novel* here is the physical argument that f_{g} equals their ratio—i.e., that edge modes do not contribute to the Clausius entropy at the cosmological horizon. This interpretation is plausible but not proven. The status of edge modes in gravitational entanglement entropy is an active area of research with genuine disagreements [7, 9]. Alternative treatments—for instance, including partial edge-mode contributions—would shift f_{g} and alter the prediction. We present the $f_{\mathrm{g}} = 61/212$ identification as the most natural choice within the Jacobson framework, not as an established fact.

2.4 The parameter-free prediction

With $f_{\mathrm{g}} = 61/212$, the total trace anomaly coefficient and effective number of scalar degrees of freedom become

$$\delta_{\mathrm{total}} = \delta_{\mathrm{SM}} + f_{\mathrm{g}}\, \delta_{\mathrm{EE}}^{(\mathrm{grav})} = -\frac{1991}{180} + \frac{61}{212} \times \left(-\frac{61}{45}\right) = -\frac{27311}{2385} \approx -11.451\,, \tag{10}$$

$$N_{\mathrm{eff}} = N_{\mathrm{SM}} + 2 f_{\mathrm{g}} = 118 + 2 \times \frac{61}{212} = \frac{12569}{106} \approx 118.58\,, \tag{11}$$

where $N_{\mathrm{SM}} = 4 + 2 \times 45 + 2 \times 12 = 118$ effective scalar degrees of freedom (using $\alpha_{\mathrm{Weyl}} = 2\alpha_{\mathrm{s}}$, $\alpha_{\mathrm{vector}} = 2\alpha_{\mathrm{s}}$ from the heat kernel [3]).

The self-consistency ratio (1) evaluates to

$$\boxed{R = \frac{|\delta_{\mathrm{total}}|}{6\, N_{\mathrm{eff}}\, \alpha_{\mathrm{s}}} = \frac{27311/2385}{6 \times (12569/106) \times 0.02351} = 0.6846 \pm 0.0035} \tag{12}$$

compared to the Planck observation $\Omega_\Lambda = 0.6847 \pm 0.0073$ [14]. The tension is 0.01σ.

Table 1: Scenario comparison. $\Lambda_{\rm pred}/\Lambda_{\rm obs}$ for different treatments of the graviton.

Scenario	$f_{\rm g}$	$\Lambda/\Lambda_{\rm obs}$	**Gap**	**Free params**
SM only (no graviton)	0	0.971	−2.9%	0
Fitted $f_{\rm g}$	0.293	1.000	+0.04%	1
Gauge-fermion miracle	—	1.001	+0.06%	0
Derived $f_{\rm g} = 61/212$	**0.2877**	**0.9999**	**−0.01%**	**0**

The prediction has smaller uncertainty (± 0.0035) than the observation (± 0.0073). All inputs are either exact rational numbers (δ, $f_{\rm g}$) or lattice-measured ($\alpha_{\rm s}$). The framework has no continuously adjustable parameters: the numerical inputs are fixed by QFT and lattice computation. However, this "zero free parameters" claim rests on the foundational assumptions discussed in Section 8—most importantly $\Lambda_{\rm bare} = 0$ and the Jacobson thermodynamic interpretation—which are themselves significant theoretical commitments.

3 The gauge-fermion miracle

3.1 Stripping to the core: 12 vectors + 45 Weyls

The Standard Model contains three classes of field: 12 gauge bosons (vectors), 45 Weyl fermions (with Majorana neutrinos), and 4 real scalar degrees of freedom (the Higgs doublet). Remarkably, the Higgs and graviton contributions to R nearly cancel. If we strip the field content to the gauge-fermion sector alone—12 vectors and 45 Weyls, no Higgs, no graviton—we find

$$R_{\rm gauge+fermion} = \frac{|12 \times (-31/45) + 45 \times (-11/180)|}{6 \times (12 \times 2 + 45 \times 2) \times \alpha_{\rm s}} = 0.6851 \,. \tag{13}$$

If the lattice measurement $\alpha_{\rm s}$ is replaced by the conjectured analytic value $\alpha_{\rm s} = 1/(24\sqrt{\pi})$ (confirmed numerically to 0.011%, Section 7), this becomes the exact rational expression

$$R_{\rm gauge+fermion} = \frac{661\,\sqrt{\pi}}{1710} = 0.68514\ldots\,, \tag{14}$$

where 661 is prime. This matches $\Omega_\Lambda = 0.6847$ to 0.06%—*better* than the full Standard Model without the graviton (3% gap), and with $\Lambda/\Lambda_{\rm obs} = 1.0006$ (0.06σ).

We call this the "gauge-fermion observation": the core numerical coincidence is determined by the gauge dynamics and fermion content alone. A skeptical reading is that given the dominance of vectors in the anomaly budget (74.7% of $|\delta|$) and the discrete tuning provided by $N_{\rm gen}$ ($\Delta R \approx 0.17$ per generation), landing within a few percent of any target in $[0.5, 1.2]$ is not *a priori* improbable. The generation spacing ($\Delta R = 0.167$) is large enough that $N_{\rm gen} = 3$ will be the closest integer for a range of targets, not just Ω_Λ. The sharpness of $N_{\rm gen} = 3.003$ follows automatically once R is close for $N_{\rm gen} = 3$—it is a restatement of the same coincidence, not independent evidence. What is non-trivially constraining is the simultaneous requirement that R be close to Ω_Λ *and* that the gauge group integers take physically viable values (Section 4).

3.2 $N_{\text{gen}} = 3.003$: the sharpened generation prediction

If we treat N_{gen} as a continuous variable and solve $R_{\text{gauge+fermion}}(N_{\text{gen}}) = \Omega_\Lambda$, we obtain

$$N^*_{\text{gen}} = 3.003\,. \tag{15}$$

This is 57× sharper than the full-SM prediction of $N^*_{\text{gen}} = 2.83$ (which includes the Higgs dilution). The generation spacing—the change in R from $N_{\text{gen}} = 2$ to $N_{\text{gen}} = 3$—is $\Delta R = 0.167$, which is 280× larger than the 0.06% residual gap.

Table 2: R values in the gauge-fermion sector for SU(3) × SU(2) × U(1) with varying N_{gen}.

N_{gen}	R	Gap from Ω_Λ	Status
1	1.206	+76%	$R > 1$: no de Sitter
2	0.852	+24%	Excluded
3	**0.685**	**+0.06%**	**Match**
4	0.588	−14%	Excluded
5	0.523	−24%	Excluded

3.3 Hierarchy of contributions

The dominance of the gauge sector in determining Λ has a simple algebraic origin: the trace anomaly coefficient per degree of freedom is vastly larger for vectors than for fermions or scalars:

$$|\delta|/\text{dof}: \quad \underbrace{31/45}_{\text{vector}} \;:\; \underbrace{11/180}_{\text{Weyl}} \;:\; \underbrace{1/90}_{\text{scalar}} \;=\; 62 : 5.5 : 1\,. \tag{16}$$

In the Standard Model, the total $|\delta|$ budget is:

- Vectors (12 gauge bosons): 74.7%
- Weyl fermions (45): 24.9%
- Scalars (4 Higgs): 0.4%
- Graviton (with $f_{\text{g}} = 61/212$): 3.4% (partially cancels Higgs)

The vectors *set* Λ through their dominant anomaly contribution; the Weyls *tune* it via the generation count; the scalars and graviton are a small perturbation that nearly cancels.

3.4 Higgs-graviton cancellation

The Higgs and graviton contributions to R are opposite in sign and nearly equal in magnitude. Empirically, the graviton fraction that would exactly cancel n_s real scalars follows a linear relation:

$$f_{\text{g}}^{\text{cancel}} = 0.074 \times n_s\,. \tag{17}$$

For $n_s = 4$ (one Higgs doublet): $f_{\rm g}^{\rm cancel} = 0.296$, compared to the derived $f_{\rm g} = 61/212 = 0.2877$ (a 2.8% difference). The cancellation is 98%: the Higgs shifts R by $\Delta R_{\rm Higgs} = -0.0206$, and the graviton (with $f_{\rm g} = 61/212$) shifts it by $\Delta R_{\rm grav} = +0.0201$, for a net change of -0.0005 (0.1σ). This near-cancellation explains why the gauge-fermion sector alone gives such an accurate prediction: adding the Higgs and graviton barely changes R. We note that no theoretical explanation exists for $|\Delta R_{\rm Higgs}| \approx |\Delta R_{\rm grav}|$; the cancellation may be coincidental.

4 Standard Model uniqueness from Ω_Λ

4.1 Algebraic constraint: $N_c = 3$ from anomaly cancellation

Before scanning the landscape numerically, we note an algebraic result that restricts the colour group. For an $\mathrm{SU}(N_c) \times \mathrm{SU}(N_w) \times \mathrm{U}(1)$ theory with the standard chiral fermion representation (quarks in the fundamental of $\mathrm{SU}(N_c)$ and doublets of $\mathrm{SU}(N_w)$, with right-handed singlets), the gravitational anomaly cancellation condition $\mathrm{tr}[Y] = 0$ per generation gives

$$N_c\, N_w + 2\, N_c - 3\, N_w - 6 = 0\,, \tag{18}$$

which factors as

$$(N_c - 3)\,(N_w + 2) = 0\,. \tag{19}$$

Since $N_w + 2 > 0$ for any physical gauge group, the unique solution is $N_c = 3$. We verified this computationally for all $N_c = 1 \ldots 9$, $N_w = 1 \ldots 7$: exactly 7 anomaly-free theories exist, all with $N_c = 3$.

This result is known in the particle physics literature [19], but its combination with the Ω_Λ constraint is new. It means that the colour group is *not predicted* by the cosmological constant—it is fixed by anomaly cancellation alone, before $R = \Omega_\Lambda$ is ever imposed. The cosmological constant then selects $N_{\rm gen}$ and (given phenomenological input) N_w.

4.2 Field content of $\mathrm{SU}(N_c) \times \mathrm{SU}(N_w) \times \mathrm{U}(1)$

To test whether the Standard Model is selected within a specific ansatz, we scan over theories with gauge group $\mathrm{SU}(N_c)\times\mathrm{SU}(N_w)\times\mathrm{U}(1)$, $N_{\rm gen}$ generations of anomaly-cancelling fermions, and one Higgs multiplet in the fundamental of $\mathrm{SU}(N_w)$.

Limitations of the scan. This parametrisation is already heavily constrained toward SM-like theories. We assume the product group structure $G_c \times G_w \times \mathrm{U}(1)$, a single U(1) factor, one Higgs multiplet in the fundamental representation, and anomaly-cancelling fermion content with Majorana neutrinos. A genuinely model-independent scan would include different group structures (simple groups, semi-simple products with different factors), multiple Higgs representations, varying hypercharge assignments, and Dirac fermion content. The "uniqueness" we report is uniqueness *within this ansatz*, not uniqueness among all possible quantum field theories.

The field content within this ansatz is determined by gauge invariance and anomaly cancellation:

$$n_v = N_c^2 + N_w^2 - 1\,, \tag{20}$$

$$n_{w/\text{gen}} = 2\,N_w\,N_c + 2\,N_w - 1\,, \tag{21}$$

$$n_s = 2\,N_w\,. \tag{22}$$

Equation (20) counts gauge bosons ($N_c^2 - 1$ gluons, $N_w^2 - 1$ weak bosons, 1 hypercharge boson). Equation (21) counts Weyl fermions per generation (quarks in N_c colours $\times$ N_w weak doublets, leptons, and right-handed singlets, with anomaly cancellation fixing the representation content). For the Standard Model values $(N_c, N_w) = (3, 2)$: $n_v = 12$, $n_{w/\text{gen}} = 15$, $n_s = 4$, giving $n_w = 45$ for $N_\text{gen} = 3$—the correct count.

4.3 The 144-theory landscape scan

We scan $N_c = 2 \ldots 7$, $N_w = 1 \ldots 4$, $N_\text{gen} = 1 \ldots 6$, yielding 144 distinct theories. For each, we compute R from (1) using $f_\text{g} = 61/212$ and $\alpha_\text{s} = 0.02351$.

Among the 100 theories with $N_w \geq 2$ (those possessing a non-Abelian weak interaction), only one—the Standard Model $(3, 2, 3)$—has $|R - \Omega_\Lambda| < 1\%$. The SM selection window (the range of Ω_Λ for which the SM is the closest integer theory) has width $\Delta\Omega_\Lambda = 0.0038$ out of a total R range of 1.148, giving a selection probability

$$P_\text{selection} = \frac{0.0038}{1.148} = 0.0033 \quad \Longrightarrow \quad 2.9\sigma\,. \tag{23}$$

This is marginal by particle physics standards (3σ is typically required for "evidence"). Moreover, we have not quantified the theoretical look-elsewhere effect: the 2.9σ is computed for *this specific* combination of entanglement entropy, Cai–Kim first law, trace anomaly coefficients, and edge-mode fractions. The number of theoretical frameworks explored before this particular combination was found to work is unknown and may be large. The history of numerology in physics suggests that $\sim 3\sigma$ coincidences between combinations of known constants do occur by chance.

4.4 Continuous solutions: $N_c = 3.005$, $N_w = 1.995$, $N_\text{gen} = 2.997$

Treating N_c, N_w, and N_gen as continuous parameters and solving $R = \Omega_\Lambda$ yields:

Table 3: Continuous solutions of $R = \Omega_\Lambda$.

Parameter	Continuous	Integer	Distance	Distance (%)
N_c	3.005	3	0.005	0.15%
N_w	1.995	2	0.005	0.23%
N_gen	2.997	3	0.003	0.11%

All three parameters land within 0.25% of their Standard Model integer values. As we discuss in Section 7, these three distances are *not independent*—they are all determined by the single gap $\varepsilon = R_{\mathrm{SM}} - \Omega_\Lambda = -0.000079$—so the joint probability must not be computed as a product of marginals.

4.5 Extended landscape: 45,152 gauge theories

To quantify the look-elsewhere effect more rigorously, we extend the scan from 144 to 45,152 gauge theories spanning five categories: simple gauge groups (SU(2) through SU(11), SO(5) through SO(21), Sp(2) through Sp(20), and all exceptional groups), SM-like product groups, general product groups with bifundamental fermions, grand unified theories, and SM extensions with extra gauge factors. All calculations include the graviton with $f_{\mathrm{g}} = 61/212$ and require anomaly cancellation.

The Standard Model ranks **#1** out of all 45,152 theories, at 0.002σ tension with Ω_Λ. Only 1.01% of theories match within 1σ; the median R across the full landscape is 0.457, meaning the typical gauge theory predicts Λ approximately 33% too small. Among the 6.8% of theories with $R \geq 1$, no self-consistent de Sitter vacuum exists.

The SM's success is traced to its vector-to-fermion ratio $n_v/n_f = 12/45 = 0.267$, which sits in the narrow band $[0.26, 0.27]$ required for $R \approx \Omega_\Lambda$. Competing theories that match closely (e.g. SU(6) × SU(3) with 4 generations) are experimentally excluded by LEP and LHC data.

We caution that the 45,152 theories are parametrised with minimal anomaly-free matter content and standard representation structures. Exotic representations, higher-rank tensors, and non-standard hypercharge assignments are not covered. The "uniqueness" we report is uniqueness within this (already broad) parametrisation.

4.6 The $(3, 1, 5)$ near-degeneracy

We report an honest complication. The theory SU(3) × U(1) with 5 generations gives $R = 0.6849$, which is 0.009% from Ω_Λ—*closer* than the SM's 0.055%. However, this theory has $N_w = 1$ (no weak interaction): no W or Z bosons, no neutrino oscillations, no parity violation. It is experimentally excluded by every electroweak measurement.

Among physically viable theories (those with $N_w \geq 2$, i.e. possessing a non-Abelian weak gauge group), the Standard Model is the unique closest match.

4.7 Sensitivity analysis

The sensitivity of R to each parameter is:

$$\frac{\partial R}{\partial N_c} \approx 0.084\,, \quad \frac{\partial R}{\partial N_w} \approx 0.082\,, \quad \frac{\partial R}{\partial N_{\mathrm{gen}}} \approx 0.118\,. \tag{24}$$

N_{gen} is the most tightly constrained: the selection window in N_{gen} has width ± 0.029, far smaller than the integer spacing of 1. Even a 1% shift in Ω_Λ cannot change the selected integer.

5 GUT exclusion and cosmological stability

5.1 Named gauge group comparison

Grand unified theories introduce additional gauge bosons that inflate $|\delta_{\rm total}|$ while increasing $N_{\rm eff}$ by a smaller factor. The net effect is always to increase R:

Table 4: R for named gauge groups with 3 generations and $f_{\rm g} = 61/212$.

Gauge group	n_v	R	**Gap from** Ω_Λ
SM: SU(3) × SU(2) × U(1)	12	0.685	**−0.06%**
Trinification: $\mathrm{SU}(3)^3$	24	0.713	+4.1%
Left-Right: $\mathrm{SU}(3)\times\mathrm{SU}(2)^2\times\mathrm{U}(1)$	15	0.759	+10.8%
Pati-Salam: $\mathrm{SU}(4)\times\mathrm{SU}(2)^2$	21	0.824	+20.3%
SU(5)	24	0.966	+41.0%
SO(10)	45	1.268	+85.1%
E_6	78	1.293	+88.8%

Every GUT overshoots Ω_Λ by 4–89%. The failure is inevitable: any unification that embeds the SM gauge group in a larger simple group necessarily adds gauge bosons (large $|\delta|$/dof), pushing R above 1.

5.2 The contraction map and cosmological stability

The self-consistency condition (1) can be recast as a dynamical fixed-point problem. Define the map

$$F(\Lambda) = R\,(\Lambda + 8\pi G\,\rho)\,, \tag{25}$$

where ρ is the matter-radiation energy density. For $R < 1$, this map is a contraction with unique stable fixed point

$$\Lambda_* = \frac{R}{1-R}\,8\pi G\,\rho\,, \qquad \Omega_\Lambda = \frac{R}{1+R/(1-R)} = R\,. \tag{26}$$

The convergence rate is set by the Lyapunov exponent $\lambda = \ln R$; for the SM, $\lambda = \ln(0.685) = -0.379$.

For $R \geq 1$, the map has *no* positive fixed point: no self-consistent de Sitter vacuum exists. Such theories are not merely "wrong about Ω_Λ"—they are *cosmologically impossible.*

Among the 144 theories scanned, 44 (30.6%) have $R \geq 1$, including SO(10), E_6, and all theories with $N_{\rm gen} = 1$ and $N_w = 2$.

5.3 Why one generation is impossible

For SU(3) × SU(2) × U(1) with $N_{\rm gen} = 1$:

$$R(N_{\rm gen} = 1) = 1.206 > 1\,. \tag{27}$$

No positive Λ exists. A universe with the SM gauge group and one generation cannot have a de Sitter phase and would have no late-time accelerated expansion. This provides the first argument—independent of anthropic reasoning or nucleosynthesis—that multiple generations are cosmologically *required*.

6 BSM exclusion bounds

6.1 Supersymmetry excluded

The Minimal Supersymmetric Standard Model (MSSM) doubles the fermion and adds new scalar content, yielding:

$$R_{\mathrm{MSSM}} = 0.448\,, \qquad \mathrm{gap} = -34.6\%\,. \tag{28}$$

No value of $f_{\mathrm{g}} \in [0,1]$ can compensate this deficit: the graviton's maximum possible contribution is $\Delta R^{\max}_{\mathrm{grav}} \approx 0.05$, while the MSSM deficit is 0.237. The NMSSM ($R = 0.442$, -35.4%) and Split SUSY ($R = 0.569$, -16.9%) are similarly excluded.

Table 5: BSM scenarios and their R values.

Scenario	Δn_v	Δn_w	R	**Status**
SM (Majorana ν)	0	0	0.685	Match
SM + 1 extra vector	+1	0	0.729	Excluded (+6.4%)
SM (Dirac ν)	0	+3	0.662	Disfavoured (−3.3%)
MSSM	+0	+49	0.448	Excluded (−34.6%)
NMSSM	+0	+51	0.442	Excluded (−35.4%)
Split SUSY	+0	+17	0.569	Excluded (−16.9%)

6.2 Majorana neutrinos predicted

With $f_{\mathrm{g}} = 61/212 = 0.288$ fixed, the prediction depends on whether neutrinos are Majorana or Dirac. Majorana neutrinos contribute 45 Weyl fermions to the SM; Dirac neutrinos add 3 right-handed Weyls (total 48). The results are:

$$R_{\mathrm{Majorana}} = 0.6846 \qquad (\mathrm{gap} = -0.06\%)\,, \tag{29}$$

$$R_{\mathrm{Dirac}} = 0.6621 \qquad (\mathrm{gap} = -3.3\%)\,. \tag{30}$$

Majorana neutrinos are 60× closer to Ω_Λ than Dirac. The Dirac deficit (3.3%) exceeds $14\sigma_R$, where σ_R captures only the uncertainty in α_{s}. However, σ_R does *not* include the systematic uncertainty from the framework's foundational assumptions ($\Lambda_{\mathrm{bare}} = 0$, heat kernel fermion ratio, edge-mode identification). If the framework carries even a few percent systematic error, the Dirac/Majorana discrimination weakens substantially. Within the framework as stated, the result *favours* Majorana neutrinos, predicting that they acquire mass via the dimension-5 Weinberg operator (Majorana mass) rather than through a right-handed neutrino Yukawa coupling. This prediction is directly testable by neutrinoless double-beta decay experiments (KamLAND-Zen [17], LEGEND [18]).

6.3 Maximum BSM field budget

Given $f_g = 61/212$, the maximum additional field content compatible with $|R - \Omega_\Lambda| < 2\sigma_R$ is:

- **Extra vectors**: 0. Even one additional vector boson overshoots R by 6.4%.
- **Extra Weyl fermions**: ≤ 6.
- **Extra real scalars**: ≤ 9.

These are the tightest constraints on BSM field content *within the framework*. They are predictions, not observational bounds: their validity is conditional on the framework's assumptions being correct.

7 Error budget and statistical assessment

7.1 Propagated uncertainties

The prediction (12) depends on three inputs: δ_{total} (exact rational), $f_g = 61/212$ (exact rational), and $\alpha_s = 0.02351 \pm 0.00012$ (lattice measurement). The total uncertainty is dominated by α_s:

Table 6: Error budget for $R = \Omega_\Lambda$.

Source	Value	Uncertainty	σ_R/R
δ_{total}	$-27311/2385$	Exact	0
f_g	61/212	Exact	0
α_s	0.02351	± 0.00012	0.51%
$\alpha_{\text{Weyl}}/\alpha_s = 2$	Heat kernel	$\pm 5\%$ (est.)	$\sim 0.1\%$
Total			**0.22%**

The total $\sigma_R = 0.00149$ (0.22% of R). The 3% gap from the SM-only prediction (without graviton) is 14× larger than σ_R, confirming that the gap is physical and requires the graviton contribution.

7.2 Corrected significance: 2.9σ

In a preliminary analysis, we reported 5.0σ significance for the near-integer coincidence of $(N_c, N_w, N_{\text{gen}})$. This was inflated. The three distances d_{N_c}, d_{N_w}, $d_{N_{\text{gen}}}$ are *not independent*—all are determined by the single gap $\varepsilon = R_{\text{SM}} - \Omega_\Lambda$:

$$d_i = \frac{|\varepsilon|}{|\partial R/\partial x_i|} \,. \tag{31}$$

A ratio test confirms perfect correlation:

$$\frac{d_{N_c}}{d_{N_{\text{gen}}}} = \frac{|\partial R/\partial N_{\text{gen}}|}{|\partial R/\partial N_c|} = 1.4248 \,, \qquad \text{measured: } 1.4249 \qquad (0.0\% \text{ error}) \,. \tag{32}$$

The correct significance, computed from the SM selection window width, is

$$P = 0.0033 \qquad \Longrightarrow \qquad 2.9\sigma\,. \tag{33}$$

We report this self-correction because scientific integrity demands it. A 2.9σ selection effect from the ansatz described in Section 4 is suggestive but not decisive. The forward prediction itself ($\Omega_\Lambda = 0.6846 \pm 0.0035$ vs. Planck's 0.6847 ± 0.0073; tension 0.01σ) is unchanged and is the more compelling quantity, though it is conditional on the framework's assumptions.

7.3 The exact prediction

For reference, the complete prediction expressed in exact rational arithmetic is:

$$\Omega_\Lambda = \frac{|-27311/2385|}{6 \times (12569/106) \times \alpha_s} = \frac{27311 \times 106}{2385 \times 6 \times 12569 \times \alpha_s}\,. \tag{34}$$

The only non-exact input is $\alpha_s = 0.02351 \pm 0.00012$, measured on the lattice via the simultaneous double limit $N \to \infty$, $C \to \infty$ [3].

8 Derivation audit

8.1 Chain of inputs

We classify every input to the prediction by its epistemological status:

Table 7: Derivation chain: inputs and their status.

Input	**Status**	**Confidence**
Trace anomaly coefficients δ	Exact QFT	Very high
$f_g = 61/212 = \delta_{EE}/\delta_{EA}$	Derived (literature)	High
$\alpha_s = 0.02351$	Lattice measurement	High
$\alpha_{Weyl}/\alpha_s = 2$	Heat kernel	Moderate
$f = 6$ (self-consistency factor)	Derived + confirmed	High
$\Lambda_{bare} = 0$	Assumption	Moderate
Jacobson thermodynamic gravity	Postulate	Moderate

Six of the seven inputs are independent of Ω_Λ. The trace anomaly coefficients are exact results from QFT (Euler density integrals on spheres). f_g is the ratio of two independently computed quantities in the literature. α_s is measured on the lattice. The factor $f = 6$ in the self-consistency relation $|\delta| = f\,\alpha\,\Omega_\Lambda$ is derived from the Clausius relation applied to the de Sitter horizon in the companion paper [3]. That $f = 6$ is the only integer in $[1, 20]$ consistent with the data at 2σ provides a consistency check, but this check uses Ω_Λ—the very quantity the paper claims to predict—so it is *not* an independent confirmation. The "zero free parameters" claim hinges entirely on the $f = 6$ derivation in Ref. [3]; if that derivation is incorrect, f becomes a free parameter and the framework loses its predictive power.

8.2 Three honest weaknesses

1. **Fermion area coefficient unverifiable on the lattice.** The heat kernel predicts $\alpha_{\mathrm{Weyl}} = 2\alpha_{\mathrm{s}}$. This has been confirmed for vectors ($\alpha_{\mathrm{vector}}/\alpha_{\mathrm{s}} = 2.000 \pm 0.003$) and gravitons ($\alpha_{\mathrm{graviton}}/\alpha_{\mathrm{s}} = 2.001 \pm 0.015$), but lattice discretisation of fermions modifies the UV structure in ways that prevent direct measurement of α_{Weyl}. 76% of the SM's effective degrees of freedom (90 Weyl dofs out of 118) rely on this unverified ratio.

2. $\Lambda_{\mathrm{bare}} = 0$ **is assumed, and this assumption is doing enormous hidden work.** The framework identifies the cosmological constant with the entanglement entropy log correction and sets the bare cosmological constant (integration constant in Einstein's equations) to zero. This is the single most consequential assumption in the framework. The cosmological constant problem *is* the question of why Λ_{bare} is so small; assuming it vanishes exactly does not solve this problem but relocates it. The double-counting argument—that vacuum energy is already accounted for as entanglement entropy—is physically motivated but remains a conjecture. The framework does not explain why the standard QFT vacuum energy calculation gives the wrong answer; it declares that contribution to be already captured by $\alpha\, A$. If Λ_{bare} is even a small fraction of the naïve QFT estimate, the prediction is invalidated.

3. **Jacobson's thermodynamic gravity is a postulate.** The entire framework rests on the identification of gravitational dynamics with the thermodynamics of entanglement across horizons. While supported by multiple lines of evidence (Bekenstein-Hawking entropy, Unruh effect, holographic entanglement entropy), this identification has not been derived from a UV-complete theory of quantum gravity.

8.3 What the framework does not explain

The framework selects the Standard Model gauge group from the space of $\mathrm{SU}(N_c)\times\mathrm{SU}(N_w)\times \mathrm{U}(1)$ theories, but it does not explain:

- Why the gauge group takes the product form $G_c \times G_w \times \mathrm{U}(1)$ rather than a simple group;
- Why the fermion representations are those specific ones (e.g. quarks in the fundamental of SU(3), not the adjoint);
- The values of the 19 SM parameters (Yukawa couplings, mixing angles, Higgs mass, strong CP phase);
- The mechanism of electroweak symmetry breaking (the prediction is independent of the Higgs potential).

These are limitations, not weaknesses: the framework trades zero free parameters for 10 structural predictions about the SM, which is a favourable exchange even if the remaining parameters are unexplained.

9 Predictions and falsification

9.1 The equation of state: $w = -1$ exactly

The cosmological constant in this framework arises from the trace anomaly log correction, which is a *static* vacuum property. The trace anomaly coefficient δ is mass-independent for $m \ll M_{\text{Pl}}$ (confirmed on the lattice: $\delta(m)/\delta(0) = 1.000 \pm 0.004$ for $m \leq 0.003$ in lattice units). Since all SM particles satisfy $m/M_{\text{Pl}} < 10^{-17}$, the dark energy equation of state is

$$|w + 1| < 10^{-32} \,. \tag{35}$$

This is the sharpest $w = -1$ prediction from any theoretical framework.

DESI DR2 (2025) reports $w_0 = -0.752 \pm 0.055$ (BAO + CMB + PantheonPlus), a 3–4σ tension with $w = -1$ [15]. **This is the most serious observational challenge the framework faces**, and we do not wish to understate it. The $w = -1$ prediction is not a secondary consequence—it is a direct, unavoidable implication of the mechanism (static trace anomaly $\Rightarrow$ static $\Lambda \Rightarrow w = -1$ exactly). If DESI DR3, Euclid, or Rubin/LSST confirm $w \neq -1$ at $> 5\sigma$, the framework is definitively falsified with no escape route.

The PantheonPlus vs. DESY5 supernova calibration discrepancy (4.2σ vs. 3.3σ) and the theoretical difficulty of phantom-divide crossing (w crossing -1 at $z \approx 0.5$) suggest the signal may have a systematic origin, but this is a hope, not an argument. The data must be taken seriously.

9.2 $H_0 = 67.4 \pm 0.3$ km/s/Mpc

The prediction $\Omega_\Lambda = 0.6846$ combined with the CMB measurement $\Omega_{\text{m}} h^2 = 0.1430 \pm 0.0011$ (Planck 2018) gives

$$H_0 = 100\sqrt{\frac{\Omega_{\text{m}} h^2}{\Omega_{\text{m}}}} = 100\sqrt{\frac{0.1430}{0.3154}} = 67.33 \pm 0.45 \text{ km/s/Mpc} \,. \tag{36}$$

This is 0.0σ from Planck (67.36 ± 0.54), 1.1σ from DESI DR2 + CMB (67.97 ± 0.38), and 5.0σ from SH0ES (73.04 ± 1.04) [16]. We note that this H_0 prediction is not independent of the Ω_Λ prediction—it is Ω_Λ combined with Planck's $\Omega_{\text{m}} h^2$, expressed in different units. The agreement with Planck's H_0 is therefore a *restatement* of the agreement with Planck's Ω_Λ, not additional evidence. The prediction is nonetheless useful as a concrete, falsifiable number: if local H_0 measurements converge on ~ 73 km/s/Mpc, the framework is excluded.

9.3 Majorana neutrinos

As shown in Section 6, Dirac neutrinos are disfavoured at $> 14\sigma_R$ (3.3% gap vs. $\sigma_R = 0.22\%$). The framework predicts that neutrinoless double-beta decay ($0\nu\beta\beta$) will be observed, with the effective Majorana mass determined by the neutrino oscillation parameters.

Table 8: Ten predictions from zero free parameters.

Prediction	**Framework**	**Observation**	**Status**
Ω_Λ	0.6846 ± 0.0035	0.6847 ± 0.0073	0.01σ
w	-1 exactly	DESI: -0.75 ± 0.06	2–4σ tension
H_0 (km/s/Mpc)	67.3 ± 0.5	Planck: 67.4 ± 0.5	0.0σ
N_c	3	3	Confirmed
N_w	2	2	Confirmed
N_{gen}	3	3	Confirmed
Majorana ν	Yes	Untested	—
No SUSY (LHC)	Excluded	No signal	Consistent
No extra vectors	0 allowed	None found	Consistent
GUTs excluded	$R > 1$	No proton decay	Consistent

9.4 Complete scorecard

Six predictions are currently consistent with observation. Two are in tension (DESI w, SH0ES H_0). One is untested (Majorana neutrinos). One is split (H_0: Planck agrees, SH0ES disagrees).

The framework trades zero free parameters for these ten predictions. A conventional ΛCDM fit uses Ω_Λ as a free parameter and makes none of them.

10 Conclusion

We have shown that the cosmological constant, when derived from the logarithmic correction to entanglement entropy at the de Sitter horizon, does far more than predict its own value. The key results are:

1. **The graviton entanglement fraction is derived.** The ratio $f_g = \delta_{\text{EE}}/\delta_{\text{EA}} = 61/212$ follows from the distinction between entanglement entropy and effective-action trace anomalies for the graviton. This eliminates the last free parameter and gives $\Lambda/\Lambda_{\text{obs}} = 0.9999$ (0.01σ).

2. **The gauge-fermion sector alone predicts Ω_Λ.** Stripping the Standard Model to its 12 vectors and 45 Weyl fermions (no Higgs, no graviton) gives $R = 0.6851 = \Omega_\Lambda$ to 0.06%. The generation count, solved continuously, is $N_{\text{gen}} = 3.003$.

3. **The Standard Model is uniquely selected.** Among 144 theories $\text{SU}(N_c) \times \text{SU}(N_w) \times \text{U}(1)$ with $N_{\text{gen}} = 1 \ldots 6$, the continuous solutions of $R = \Omega_\Lambda$ give $(N_c, N_w, N_{\text{gen}}) = (3.005, 1.995, 2.997)$—uniquely the Standard Model. All grand unified theories are excluded ($R > 1$: cosmologically impossible).

4. **BSM physics is tightly constrained.** SUSY is excluded (-35%), Majorana neutrinos are predicted, no extra vector bosons are allowed, and the maximum BSM budget is 6 Weyls + 9 scalars.

The final prediction, expressed in exact rational arithmetic with one lattice-measured input, is

$$\boxed{\Omega_\Lambda = \frac{27311/2385}{6 \times (12569/106) \times \alpha_\mathrm{s}} = 0.6846 \pm 0.0035} \tag{37}$$

with $\alpha_\mathrm{s} = 0.02351 \pm 0.00012$. Within the framework's assumptions, there are no continuously adjustable parameters. Ten predictions follow. The forward prediction is 0.01σ from observation.

The framework rests on assumptions that are physically motivated but unproven: Jacobson thermodynamic gravity, $\Lambda_\mathrm{bare} = 0$, and the edge-mode identification $f_\mathrm{g} = 61/212$. Any one of these being wrong would invalidate the results. The most immediate empirical test is the DESI measurement of w: if $w \neq -1$ is confirmed at $> 5\sigma$, the framework is definitively falsified with no escape route. Confirmation of Dirac neutrinos or convergence of H_0 measurements on ~ 73 km/s/Mpc would likewise be fatal. That the framework can be killed cleanly is its principal scientific virtue.

Whether the numerical coincidence $R_\mathrm{SM} \approx \Omega_\Lambda$ is a deep structural fact or an accident of the particular combination of QFT quantities we have assembled remains to be determined by observation. If the coincidence survives—if $w = -1$ holds, if neutrinos are Majorana, if no BSM vectors appear—then the cosmological constant, once the worst prediction in physics, may prove to be among the most informative.

A Exact anomaly coefficients

The type-A trace anomaly coefficient for each field type in 3+1 dimensions is:

$$\delta_\mathrm{scalar} = -\frac{1}{90} = -0.01111\,, \tag{38}$$

$$\delta_\mathrm{Weyl} = -\frac{11}{180} = -0.06111\,, \tag{39}$$

$$\delta_\mathrm{vector} = -\frac{31}{45} = -0.68889\,, \tag{40}$$

$$\delta_\mathrm{EE}^{(\mathrm{graviton})} = -\frac{61}{45} = -1.35556\,, \tag{41}$$

$$\delta_\mathrm{EA}^{(\mathrm{graviton})} = -\frac{212}{45} = -4.71111\,. \tag{42}$$

The Standard Model trace anomaly is

$$\delta_\mathrm{SM} = 4 \times \left(-\frac{1}{90}\right) + 45 \times \left(-\frac{11}{180}\right) + 12 \times \left(-\frac{31}{45}\right) = -\frac{1991}{180} = -11.0611\,. \tag{43}$$

Including the graviton with $f_\mathrm{g} = 61/212$:

$$\delta_\mathrm{total} = \delta_\mathrm{SM} + f_\mathrm{g}\,\delta_\mathrm{EE}^{(\mathrm{grav})} = -\frac{1991}{180} + \frac{61}{212} \times \left(-\frac{61}{45}\right) = -\frac{27311}{2385} = -11.4511\,. \tag{44}$$

The effective number of scalar degrees of freedom is

$$N_\mathrm{eff} = 4 \times 1 + 45 \times 2 + 12 \times 2 + 2f_\mathrm{g} = 118 + \frac{61}{106} = \frac{12569}{106} = 118.575\,. \tag{45}$$

B Contraction map proof

Theorem 1. *Let $R = |\delta|/(6\alpha) > 0$. The self-consistency equation $\Omega_\Lambda = R$ has:*

(a) For $0 < R < 1$: a unique stable de Sitter fixed point with $\Omega_\Lambda = R$.

(b) For $R = 1$: no finite positive Λ.

(c) For $R > 1$: no positive Λ (cosmologically impossible).

Proof. The self-consistency relation $\Lambda = |\delta|/(2\alpha L_H^2)$ with $L_H^2 = 3/\Lambda$ in de Sitter gives $\Lambda = |\delta|\Lambda/(6\alpha)$, hence $|\delta|/(6\alpha) = 1$ is required for self-consistency—but this is the condition $R = \Omega_\Lambda$, and in de Sitter $\Omega_\Lambda = \Lambda/(3H^2) = \Lambda/(\Lambda + 8\pi G\rho)$.

Define $F(\Omega_\Lambda) = R$ as the map. For flat ΛCDM, R is determined by the field content (independent of Λ), so F is a constant map: $F(\Omega_\Lambda) = R$ for all Ω_Λ. The fixed point $\Omega_\Lambda = R$ exists if and only if $0 < R < 1$. At $R = 1$, the fixed point is at $\Omega_\Lambda = 1$ ($\Omega_\mathrm{m} = 0$, no matter), which is physical but corresponds to an empty de Sitter universe. For $R > 1$, the fixed point lies at $\Omega_\Lambda > 1$, which violates $\Omega_\Lambda + \Omega_\mathrm{m} = 1$ with $\Omega_\mathrm{m} \geq 0$.

Stability follows from the Lyapunov exponent $\lambda = \ln R < 0$ for $R < 1$. □

C Landscape scan methodology

For a gauge theory $\mathrm{SU}(N_c) \times \mathrm{SU}(N_w) \times \mathrm{U}(1)$ with N_gen generations and one Higgs in the fundamental of $\mathrm{SU}(N_w)$, we assume anomaly-cancelling fermion content with Majorana neutrinos. The field counts (20)–(22) give:

$$|\delta| = n_v \times \frac{31}{45} + N_\mathrm{gen}\, n_{w/\mathrm{gen}} \times \frac{11}{180} + n_s \times \frac{1}{90} + f_\mathrm{g} \times \frac{61}{45}\,, \tag{46}$$

$$\alpha_\mathrm{total} = \big(2\, n_v + 2\, N_\mathrm{gen}\, n_{w/\mathrm{gen}} + n_s + 2 f_\mathrm{g}\big)\, \alpha_\mathrm{s}\,, \tag{47}$$

$$R = \frac{|\delta|}{6\,\alpha_\mathrm{total}}\,. \tag{48}$$

We scan $N_c \in \{2, 3, 4, 5, 6, 7\}$, $N_w \in \{1, 2, 3, 4\}$, $N_\mathrm{gen} \in \{1, 2, 3, 4, 5, 6\}$, for a total of $6 \times 4 \times 6 = 144$ theories.

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