Conformal Extensions of the Standard Model with Veltman Conditions

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Presenting…


A new working idea
On application of
scale-invariant
theories
to electroweak
physics

Coleman-Weinberg (CW) in Electroweak (EW) Theory

Has gained popularity with the recent Higgs-discovery; Why?

It naturally produces a *light* scalar compared to the new physics scale

Requires *conformality* at the classical level;

At some scale all dimensionfull couplings vanish

Spont. sym. breaking through quantum corrections

Does *not* solve the hierarchy-problem in *reality*

$$S = \int \mathrm{d}^4x \, \mathcal{L}_{\mathrm{Universe}} = \int^{\Lambda} d^4x \, \mathcal{L}_{\mathrm{SM}} + \int_{\Lambda} d^4x \, \mathcal{L}_{\mathrm{NP}}$$

Cutoff is physical, since SM is neither asympt. free nor safe

Fine-Tuning the Hierarchy Problem

Cutoff regularized scalar sector

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \phi_r)^2 - \frac{1}{2}m^2\phi_r^2 - \frac{\lambda}{4!}\phi_r^4 + \frac{\delta_Z}{2}(\partial_\mu \phi_r)^2 - \frac{\delta_m}{2}\phi_r^2 - \frac{\delta_\lambda}{4!}\phi_r^4$$

$$m^2 = m_0^2(1 + f_1(\lambda, g_i)\log\frac{\Lambda^2}{m_0^2}) - f_2(\lambda, g_i)\Lambda^2$$

Coleman-Weinberg Potential

$$m^2(\mu_0) \approx 0,\ \ \lambda(\mu_0) \approx 0 \qquad V(\phi_c) \approx V_1(\phi_c) = A_1\phi_c^4 + B_1\phi_c^4 \ln\frac{\phi_c^2}{\mu_0^2}\ ,$$

$$\ln\frac{\langle\phi_c^2\rangle}{\mu_0^2} = -\frac{1}{2} - \frac{A_1}{B_1}\ , \qquad m_{CW}^2 = \frac{\mathrm{d}^2V}{\mathrm{d}\phi^2}\Big|_{\langle\phi_c\rangle} = 8B_1\langle\phi_c^2\rangle$$

Without fine-tuning:

$$m_0^2 = 0, \qquad m_{CW}^2 = 8B_1\langle\phi_c^2\rangle - f_2(\lambda, g_i)\Lambda^2$$

Perturbative Natural Conformality

Coleman-Weinberg without fine-tuning;

Perturbative Natural Conformality (PNC)

$$m_0^2 = 0,$$

$$m_{CW}^2 = 8B_1\langle\phi_c^2\rangle - f_2(\lambda, g_i)\Lambda^2$$

Veltman meets Coleman-Weinberg;

Set $f_2 = 0$ at the *same* perturbative order as the CW-analysis

1. Classical Conformality and tree-level flatness

$$V_0(\phi_i) = \frac{\lambda_{ijkl}}{24}\phi_i\phi_j\phi_k\phi_l \qquad \lambda_{ijkl}(\mu_0)n_in_jn_kn_l \approx 0$$

2. Quantum corrections retaining conformality

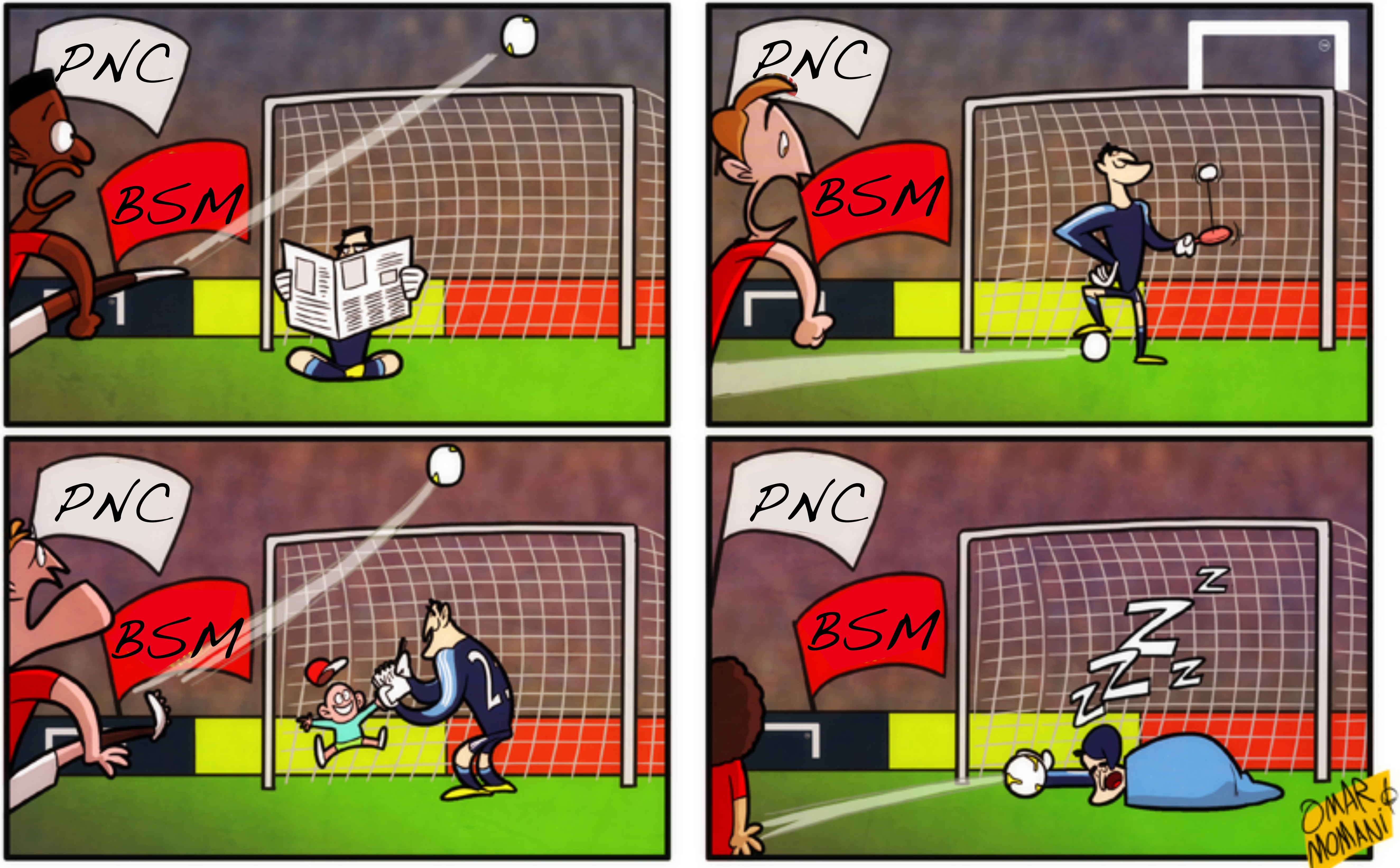
Delayed Naturalness

$$V_1(\phi_c) = \frac{1}{64\pi^2}Str\left[\Lambda^4\left(\ln\Lambda^2 - \frac{1}{2}\right) + 2M^2(\phi_c)\Lambda^2 + M^4(\phi_c)\left(\ln\frac{M^2(\phi_c)}{\Lambda^2} - \frac{1}{2}\right)\right] + c.t.$$

Cosm. const. — Quad. div. — (CW) phi-4 correction

$$\frac{1}{2}\frac{\partial^2 Str[M^2(\phi_i)]}{\partial\phi_i^2}\bigg|_{\mu_0} = 0 \qquad \text{(Veltman Condition)}$$

The PNC Shootout



PNC vs Standard Model (SM)

SM without mass term is classically conformal

$$V_0^{SM} = \lambda \left(H^\dagger H\right)^2 - \frac{1}{2}\left(g^2 W_\mu^+ W^{-\mu} + \frac{g^2 + g'^2}{2} Z_\mu Z^\mu\right) H^\dagger H + y_t(\bar{t}_L, 0)\left(i\sigma^2 H^*\right) t_R + \text{h.c.} + \; c.t.$$

$$H = \frac{1}{\sqrt{2}}(\pi_2 + i\pi_1, v + h - i\pi_3)$$

Breaking EW spont. *and* the delaying naturalness scale yields

CW:

$$\lambda(\mu_0) \approx 0$$

Veltman:

$$\frac{1}{2}\frac{\partial^2 Str[M^2(h)]}{\partial h^2}\bigg|_{\mu_0} = 6\lambda(\mu_0) + \frac{9}{4}g^2(\mu_0) + \frac{3}{4}g'^2(\mu_0) - 6y_t^2(\mu_0) = 0$$

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$$\Longrightarrow \quad m_t \approx 73 \text{ GeV}$$

$$\Longrightarrow \quad m_h \approx 5 \text{ GeV}$$

Doesn’t work… as we already knew

PNC vs SM + Singlet Scalar

Simplest extension of the SM potential

$$V_0 = V_0^{SM} + \lambda_{HS} H^\dagger H S^2 + \frac{\lambda_S}{4} S^4 + c.t.$$

Stability: $\lambda \geq 0\,, \quad \lambda_S \geq 0\,, \quad \text{and if } \lambda_{HS} < 0: \quad \lambda \lambda_S \geq \lambda_{HS}^2$

2 x Veltman:

$$\frac{1}{2}\frac{\partial^2 Str[M^2(S)]}{\partial S^2}\bigg|_{\mu_0} = 3\lambda_S(\mu_0) + 4\lambda_{HS}(\mu_0) = 0$$

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Considering the moduli, $\langle H \rangle \neq 0$, $\langle S \rangle \neq 0$

CW:

$$\sqrt{\lambda(\mu_0)\lambda_S(\mu_0)} + \lambda_{HS}(\mu_0) = 0$$

$$\phi = \sqrt{\frac{4}{7}}h + \sqrt{\frac{3}{7}}s\ , \quad \Phi = \sqrt{\frac{4}{7}}s - \sqrt{\frac{3}{7}}h$$

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$$\phi = \sqrt{\frac{4}{7}}h + \sqrt{\frac{3}{7}}s\,, \quad \Phi = \sqrt{\frac{4}{7}}s - \sqrt{\frac{3}{7}}h$$

$$\Longrightarrow \quad m_\phi \approx 95 \text{ GeV}\,, \quad m_\Phi \approx 541 \text{ GeV}$$

?

PNC vs SM + Singlet Scalar + Singlet Fermion

Singlet fermions (sterile neutrinos and/or dark matter)

$$V_0 = V_0^{SM} + \lambda_{HS} H^\dagger H S^2 + \frac{\lambda_S}{4} S^4 + y_\chi S(\chi\chi + \bar{\chi}\bar{\chi}) + c.t.$$

2 x Veltman: $$\frac{1}{2}\frac{\partial^2 Str[M^2(S)]}{\partial S^2}\bigg|_{\mu_0} = 3\lambda_S(\mu_0) + 4\lambda_{HS}(\mu_0) - 8y_\chi^2 = 0$$

$$\frac{1}{2}\frac{\partial^2 Str[M^2(h)]}{\partial h^2}\bigg|_{\mu_0} = 6\lambda(\mu_0) + \frac{9}{4}g^2(\mu_0) + \frac{3}{4}g'^2(\mu_0) - 6y_t^2(\mu_0) + \lambda_{HS}(\mu_0) = 0$$

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Considering the SM moduli, *$\langle H\rangle \neq 0$, $\langle S\rangle = 0$,*

CW:

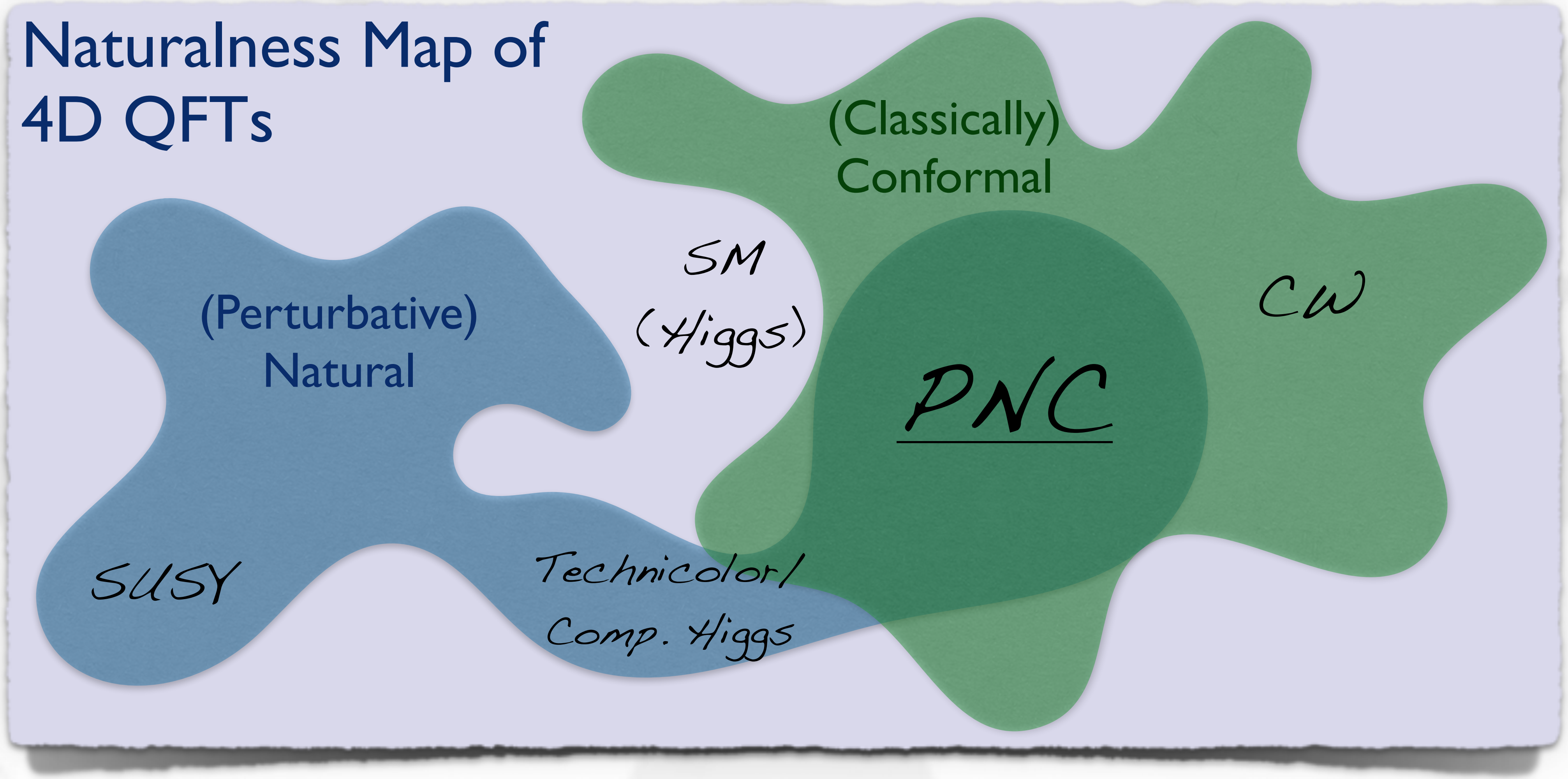
$$\lambda(\mu_0) \approx 0$$

$$m_h^2 = \frac{3}{8\pi^2}\Big[\frac{1}{16}\Big(3g^4 + 2g^2g'^2 + g'^4\Big) - y_t^4 + \frac{\lambda_{HS}^2}{3}\Big]v^2 \qquad \Longrightarrow \qquad m_h \approx 126\ \mathrm{GeV}\,,$$

$$m_S^2 = \lambda_{HS} v^2 \qquad \Longrightarrow \qquad m_S \approx 541\ \mathrm{GeV}\,.$$

Testable at the LHC - A natural CW scenario

Conclusions



Naturalness scale could *accidentally* be orders of mag. higher

Requires new physics at LHC

Simplest realization predicts a dark sector

Highly constrained!

Thank you !