Symmergent Gravity and Curvature Completion

Durmuş Demir

İZMİR INSTITUTE OF TECHNOLOGY

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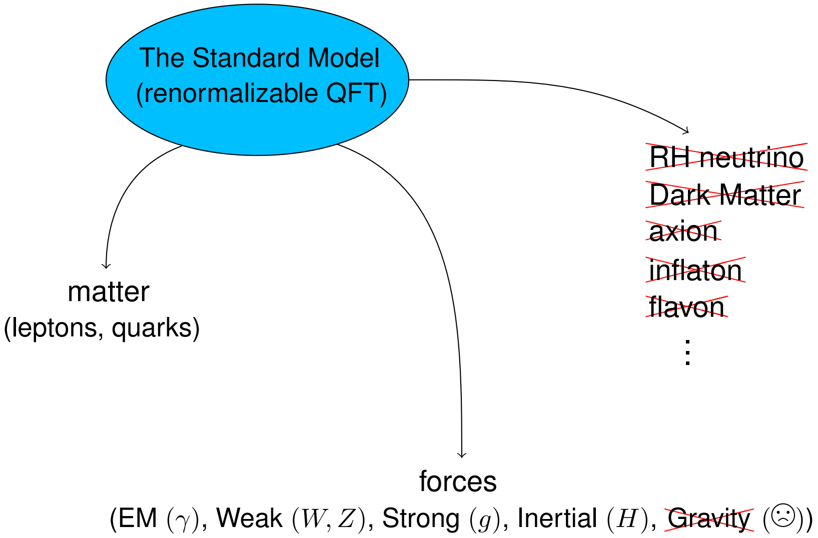
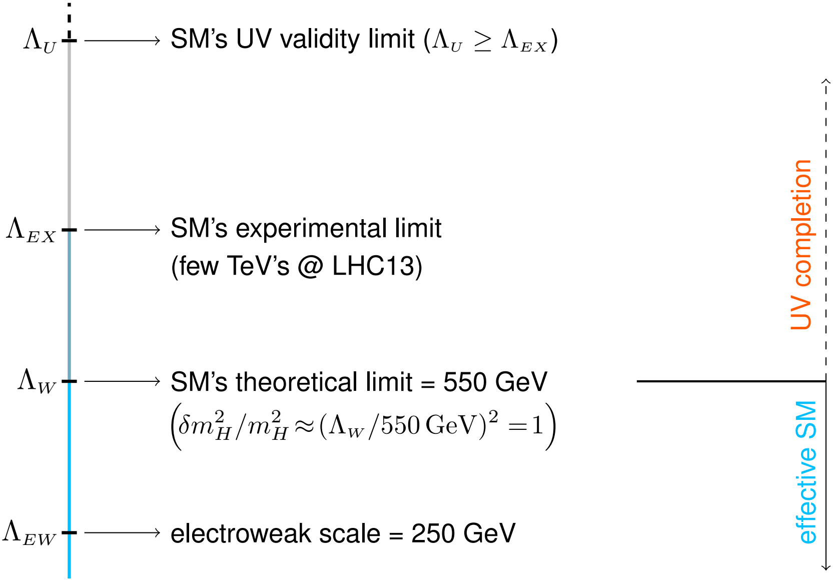
The Model

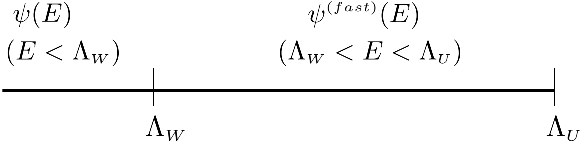

The Standard Model
(renormalizable QFT)
~~RH neutrino~~
~~Dark Matter~~
~~axion~~
~~inflaton~~
~~flavon~~
⋮
matter
(leptons, quarks)
forces
(EM (γ), Weak (W, Z), Strong (g), Inertial (H), ~~Gravity~~ (☹))

SM's UV Overextension



Effective SM

$\{\text{leptons}, \text{quarks}, H, V_\mu\}$



flat metric $\eta_{\mu\nu}$

$$e^{iS_{eff}(\eta,\psi)} = \int_{[\Lambda_W]}^{[\Lambda_U]} \mathcal{D}\psi^{(fast)} e^{iS\left(\eta,\psi,\psi^{(fast)}\right)}$$

Effective SM

$$S_{eff}\left(\eta, \psi, \frac{\Lambda_W}{\Lambda_U}, \Lambda_U^2 - \Lambda_W^2\right) = S_{tree}\left(\eta, \psi\right)$$

$$+ \delta S_{log}\left(\eta, \psi, \Lambda_W^2 \log \frac{\Lambda_W}{\Lambda_U}\right)$$

$$+ \delta S_{pow}\left(\eta, H, V_\mu, \frac{\Lambda_W}{\Lambda_U}, \Lambda_U^2 - \Lambda_W^2\right)$$

UV-Hypersensitive Pieces

$$\delta S_{pow} = \delta S_O + \delta S_H + \delta S_V$$

$$c_V = c_V\left(\frac{\Lambda_W}{\Lambda_U}\right)$$

$$\int d^4x\sqrt{-\eta}\, c_V\left(\Lambda_U^2 - \Lambda_W^2\right)\mathrm{Tr}\Big[V_\mu V^\mu\Big]$$

$$-\int d^4x\sqrt{-\eta}\, c_H\left(\Lambda_U^2 - \Lambda_W^2\right)H^\dagger H$$

$$-\int d^4x\sqrt{-\eta}\,\left\{c_O\left(\Lambda_U^2 - \Lambda_W^2\right)^2 + \left(2c_O\Lambda_W^2 + c_m m_H^2\right)\left(\Lambda_U^2 - \Lambda_W^2\right)\right\}$$

UV-Induced Problems

$$\delta S_{pow} = \delta S_O + \delta S_H + \delta S_V$$

cosmological constant problem in curved ST

explicit breaking of Color & EM & Weak

big hierarchy problem

Poincare breaking
(switch to curved geometry?)

How Not To Go To Curved Geometry

$$S_{eff}\left(\eta, \psi, \frac{\Lambda_W}{\Lambda_U}, \Lambda_U^2 - \Lambda_W^2\right)$$

$$\downarrow \quad \eta_{\mu\nu} \hookrightarrow g_{\mu\nu}$$

$$S_{eff}\left(g, \psi, \frac{\Lambda_W}{\Lambda_U}, \Lambda_U^2 - \Lambda_W^2\right)$$

$\downarrow$ add curvature by hand

$$S_{eff}\left(g, \psi, \frac{\Lambda_W}{\Lambda_U}, \Lambda_U^2 - \Lambda_W^2\right) - \int d^4x\sqrt{-g}\left\{M'^2 R(g) + a' R(g)^2 + \cdots\right\}$$

incalculable, arbitrary terms
since all loops are used up

A Gauge Route To Curvature

$$\delta S_V = \delta S_V + I_V(\eta) - I_V(\eta)$$

$$\int d^4x \sqrt{-\eta}\frac{c_V}{2}\text{Tr}\Big[V_{\mu\nu}V^{\mu\nu}\Big]$$

$$\int d^4x \sqrt{-\eta}\frac{c_V}{2}\text{Tr}\Big[V_{\mu\nu}V^{\mu\nu}\Big]$$

$$\int d^4x \sqrt{-\eta}(\Lambda_U^2 - \Lambda_W^2)c_V\text{Tr}\Big[V_{\mu}V^{\mu}\Big]$$

A Gauge Route To Curvature

$$= \int d^4x \sqrt{-\eta} (\Lambda_U^2 - \Lambda_W^2) c_V \, \mathrm{Tr}\Big[V_\mu V^\mu\Big]$$

$$+ \int d^4x \sqrt{-\eta} c_V \, \mathrm{Tr}\Big[V^\mu\Big(-D^2 \eta_{\mu\nu} + D_\mu D_\nu + V_{\mu\nu}\Big)V^\nu\Big]$$

$$+ \int d^4x \sqrt{-\eta} c_V \, \mathrm{Tr}\Big[\partial_\nu (V_\mu V^{\mu\nu})\Big] \qquad D = \partial - V$$

$$- I_V(\eta)$$

A Gauge Route To Curvature

$$\xrightarrow[\text{EEP}]{\eta_{\mu\nu}\hookrightarrow g_{\mu\nu}} \int d^4x\sqrt{-g}\left(\Lambda_U^2 - \Lambda_W^2\right)c_V\,\text{Tr}\left[V_\mu V^\mu\right]$$

$$+\int d^4x\sqrt{-g}\,c_V\,\text{Tr}\left[V^\mu\left(-\,{}^g\mathcal{D}^2 g_{\mu\nu} + {}^g\mathcal{D}_\mu {}^g\mathcal{D}_\nu + V_{\mu\nu}\right)V^\nu\right]$$

$$+\int d^4x\sqrt{-g}\,c_V\,\text{Tr}\left[{}^g\nabla_\nu\left(V_\mu V^{\mu\nu}\right)\right]$$

$$-\,I_V(g)$$

$${}^g\mathcal{D} = {}^g\nabla - V \equiv \partial + {}^g\Gamma - V$$

$${}^g\Gamma^\lambda_{\mu\nu} = \frac{1}{2}g^{\lambda\iota}\left(\partial_\nu g_{\mu\iota} + \partial_\mu g_{\iota\nu} - \partial_\iota g_{\mu\nu}\right)$$

A Gauge Route To Curvature

$$= \int d^4x \sqrt{-g} c_V \, \text{Tr}\Big[V^\mu \Big(-{}^g\mathcal{D}^2 g_{\mu\nu} + {}^g\mathcal{D}_\mu {}^g\mathcal{D}_\nu + V_{\mu\nu} + \Big(\Lambda_U^2 - \Lambda_W^2\Big) g_{\mu\nu}\Big) V^\nu\Big]$$

$$+ \int d^4x \sqrt{-g} c_V \, \text{Tr}\Big[{}^g\nabla_\nu (V_\mu V^{\mu\nu})\Big]$$

$$- I_V(g)$$

if not to be put by hand, how can curvature arise ?

A Gauge Route To Curvature

$$= \int d^4x \sqrt{-g} c_V \, \text{Tr}\Big[V^\mu \Big(-{}^g\mathcal{D}^2 g_{\mu\nu} + {}^g\mathcal{D}_\mu {}^g\mathcal{D}_\nu + V_{\mu\nu} + \left(\Lambda_U^2 - \Lambda_W^2\right) g_{\mu\nu}\Big) V^\nu\Big]$$

$$+ \int d^4x \sqrt{-g} c_V \, \text{Tr}\Big[{}^g\nabla_\nu \left(V_\mu V^{\mu\nu}\right)\Big]$$

$$- I_V(g)$$

can this term be a door to curvature ?

can curvature lead to symmetry restoration ?

can curvature arise from an equivalence relation like $\eta_{\mu\nu} \hookrightarrow g_{\mu\nu}$?

A Gauge Route To Curvature

$$= \int d^4x \sqrt{-g} c_V \, \text{Tr}\Big[V^{\mu}\Big(-{}^{g}\mathcal{D}^2 g_{\mu\nu} + {}^{g}\mathcal{D}_{\mu}{}^{g}\mathcal{D}_{\nu} + V_{\mu\nu} + \left(\Lambda_U^2 - \Lambda_W^2\right) g_{\mu\nu}\Big)V^{\nu}\Big]$$

$$+ \int d^4x \sqrt{-g} c_V \, \text{Tr}\Big[{}^{g}\nabla_{\nu}\left(V_{\mu} V^{\mu\nu}\right)\Big]$$

$$- I_V(g)$$

an equivalence between UV-EW gap and curvature ?

$$(\Lambda_U^2 - \Lambda_W^2) g_{\mu\nu} \hookrightarrow R_{\mu\nu}(\Gamma)$$

affine connection $\Gamma^{\lambda}_{\mu\nu} \neq {}^{g}\Gamma^{\lambda}_{\mu\nu}$

affine curvature $R_{\mu\nu}(\Gamma) \neq R_{\mu\nu}({}^{g}\Gamma)$

A Gauge Route To Curvature

$$\xrightarrow[\text{GCEP}]{\left(\Lambda_U^2-\Lambda_W^2\right)g_{\mu\nu}\hookrightarrow R_{\mu\nu}(\Gamma)}$$

$$\int d^4x\sqrt{-g}c_V\,\text{Tr}\Big[V^{\mu}\Big(-{}^{g}\mathcal{D}^2 g_{\mu\nu}+{}^{g}\mathcal{D}_{\mu}{}^{g}\mathcal{D}_{\nu}+V_{\mu\nu}+R_{\mu\nu}(\Gamma)\Big)V^{\nu}\Big]$$

$$+\int d^4x\sqrt{-g}c_V\,\text{Tr}\Big[{}^{g}\nabla_{\nu}\left(V_{\mu}V^{\mu\nu}\right)\Big]$$

$$-\,I_V(g)$$

would combine to give $I_V(g)$
if it were $R_{\mu\nu}({}^{g}\Gamma)$ not $R_{\mu\nu}(\Gamma)$

A Gauge Route To Curvature

$$= I_V(g) - I_V(g) + \int d^4x \sqrt{-g}\, c_V \, \text{Tr}\Big[V^{\mu}\Big(R_{\mu\nu}(\Gamma) - R_{\mu\nu}({}^{g}\Gamma)\Big)V^{\nu}\Big]$$

possible if c_V is held unaffected while $(\Lambda_U^2 - \Lambda_W^2)g_{\mu\nu} \hookrightarrow R_{\mu\nu}(\Gamma)$

the EW/UV hierarchy $\frac{\Lambda_W}{\Lambda_U}$ is preserved

Effective SM Gets To Metric-Affine Geometry

$$S_{eff}\left(g, \psi, \frac{\Lambda_W}{\Lambda_U}, R(\Gamma)\right) = S_{tree}\left(g, {}^{g}\Gamma, \psi\right) + S_{log}\left(g, {}^{g}\Gamma, \psi, \Lambda_W^2 \log \frac{\Lambda_W}{\Lambda_U}\right)$$

$$+ \int d^4x \sqrt{-g}\, c_V\, \text{Tr}\left[V^{\mu}\left(R_{\mu\nu}(\Gamma) - R_{\mu\nu}({}^{g}\Gamma)\right)V^{\nu}\right]$$

$$- \int d^4x \sqrt{-g}\, \frac{c_H}{4} H^{\dagger} H g^{\mu\nu} R_{\mu\nu}(\Gamma)$$

big hierarchy problem is gone!

$$- \int d^4x \sqrt{-g} \left\{ \underbrace{\left(\frac{c_O}{2}\Lambda_W^2 + \frac{c_m}{4} m_H^2\right)}_{\frac{M_{Pl}^2}{2}} g^{\mu\nu} R_{\mu\nu}(\Gamma) + \frac{c_O}{16}\left(g^{\mu\nu} R_{\mu\nu}(\Gamma)\right)^2 \right\}$$

UV end of CCP is gone!

Gravitational Constant

$$(c_O)_{SM} = \frac{(n_b - n_f)}{64\pi^2} = \frac{-62}{64\pi^2}$$

unphysical !

what is physically needed is

$$c_O \simeq 10^{32} \Longrightarrow c_O \times \Lambda_W^2 \simeq M_{Pl}^2$$

but how? with what?

Physics Beyond The SM (BSM)

$$(c_O)_{SM} = \frac{(n_b - n_f)}{64\pi^2} = \frac{-62}{64\pi^2}$$

BSM

(H', V'_μ, f')

does not have to interact with the SM fields

must contain $n_b - n_f \simeq 10^{35}$ fields to yield $(c_O)_{BSM} \simeq 10^{32}$

must have masses $m' \lesssim \Lambda_W$

Effective (SM + BSM) Reconciles With MAG

$$S_{eff}\Big(g, \psi, \psi', R(\Gamma)\Big) \supset - \sum_{\phi = H, H'} \int d^4x \sqrt{-g}\frac{c_\phi}{4}\phi^\dagger \phi g^{\mu\nu} R_{\mu\nu}(\Gamma)$$

$$+ \sum_{\mathcal{V} = V, V'} \int d^4x \sqrt{-g} c_{\mathcal{V}} \text{Tr}\Big[\mathcal{V}^\mu \Big(R_{\mu\nu}(\Gamma) - R_{\mu\nu}({}^g\Gamma)\Big)\mathcal{V}^\nu\Big]$$

$$- \int d^4x \sqrt{-g}\left\{\frac{M_{Pl}^2}{2} g^{\mu\nu} R_{\mu\nu}(\Gamma) + \frac{(c_O)_{tot}}{16}\Big(g^{\mu\nu} R_{\mu\nu}(\Gamma)\Big)^2\right\}$$

$$(c_O)_{SM} + (c_O)_{BSM} \simeq 10^{32}$$

Affine Connection

$$\nabla^{\Gamma}_{\lambda}\left(\sqrt{-g}Q_{\mu\nu}\right) = 0$$

$$\frac{M^2_{Pl}}{2} g_{\mu\nu} + \frac{c_\phi}{4}\phi^\dagger \phi g_{\mu\nu} - c_{\mathcal{V}} \mathrm{Tr}\left[\mathcal{V}_\mu \mathcal{V}_\nu\right] + \frac{(c_O)_{tot}}{8} R_{\mu\nu}(\Gamma)$$

curvature of $\Gamma^{\lambda}_{\mu\nu}$ appears!

Low-Curvature & High-Curvature Regimes

$$\nabla^{\Gamma}_{\lambda}\left(\sqrt{-g}Q_{\mu\nu}\right) = 0$$

$$\Gamma^{\lambda}_{\mu\nu} = {}^{g}\Gamma^{\lambda}_{\mu\nu} + \frac{1}{2}\left(Q^{-1}\right)^{\lambda\gamma}\left({}^{g}\nabla_{\mu}Q_{\nu\gamma} + {}^{g}\nabla_{\nu}Q_{\gamma\mu} - {}^{g}\nabla_{\gamma}Q_{\mu\nu}\right)$$

$${}^{g}\Gamma^{\lambda}_{\mu\nu} + \mathcal{O}\left(\frac{\Lambda_W^3}{M_{Pl}^2}\right)$$ if $|g^{\mu\nu}R_{\mu\nu}(\Gamma)| \ll \Lambda_W^2$ (low curvature)

$${}^{g}\Gamma^{\lambda}_{\mu\nu} + \,?$$ if $|g^{\mu\nu}R_{\mu\nu}(\Gamma)| \gg \Lambda_W^2$ (high curvature)

Low-Curvature MAG Is Nearly GR

$$\int d^4x \sqrt{-g}\frac{M_{Pl}^2}{2} g^{\mu\nu} R_{\mu\nu}(\Gamma) \rightsquigarrow \int d^4x \sqrt{-g}\frac{M_{Pl}^2}{2} g^{\mu\nu} R_{\mu\nu}({}^g\Gamma) + \mathcal{O}\left(\frac{\Lambda_W^6}{M_{Pl}^2}\right)$$

$$\int d^4x \sqrt{-g}\phi^\dagger \phi g^{\mu\nu} R_{\mu\nu}(\Gamma) \rightsquigarrow \int d^4x \sqrt{-g}\phi^\dagger \phi g^{\mu\nu} R_{\mu\nu}({}^g\Gamma) + \mathcal{O}\left(\frac{\Lambda_W^6}{M_{Pl}^2}\right)$$

$$\int d^4x \sqrt{-g}\,\mathrm{Tr}\left[\mathcal{V}^\mu \Big(R_{\mu\nu}(\Gamma) - R_{\mu\nu}({}^g\Gamma)\Big)\mathcal{V}^\nu\right] \rightsquigarrow 0 + \mathcal{O}\left(\frac{\Lambda_W^6}{M_{Pl}^2}\right)$$

Low-Curvature MAG Yields The “Usual”

$$S_{eff}\Big(g,\psi,\psi',R(\Gamma)\Big) \supset$$

$$-\int d^4x\sqrt{-g}\,\frac{M_{Pl}^2}{2}\,g^{\mu\nu}R_{\mu\nu}({}^{g}\Gamma)$$

$$-\sum_{\phi=H,H'}\int d^4x\sqrt{-g}\frac{c_\phi}{4}\phi^\dagger\phi g^{\mu\nu}R_{\mu\nu}({}^{g}\Gamma)$$

$$+\,\mathcal{O}\left(\frac{\Lambda_W^6}{M_{Pl}^2}\right)$$

→ explicit gauge breaking
is now Planck-suppressed
(Color & EM ✓)
(EW breaking is spontaneous ✓)

“Symmergent Gravity”

“gravity is a symmetry-restoring, emergent phenomenon”

High-Curvature MAG Is Scale-Invariant

$$S_{eff}\Big(g, \psi, \psi', R(\Gamma)\Big) = -\int d^4x \sqrt{-g}\,\frac{(c_O)_{tot}}{16}\Big(g^{\mu\nu} R_{\mu\nu}(\Gamma)\Big)^2$$

$+$ subleading contributions from EH & matter

nearly scale-invariant and almost purely geometrical

Symmergent Gravity Results In Dim. Reg.

holding $\log\frac{\Lambda_W}{\Lambda_U}$ unaffected while $(\Lambda_U^2-\Lambda_W^2)g_{\mu\nu} \Longmapsto R_{\mu\nu}(g)$

$$\downarrow$$

$$\log\frac{\Lambda_W}{\Lambda_U} \rightsquigarrow -\frac{1}{\epsilon} - \log\frac{\mu}{\Lambda_W}$$

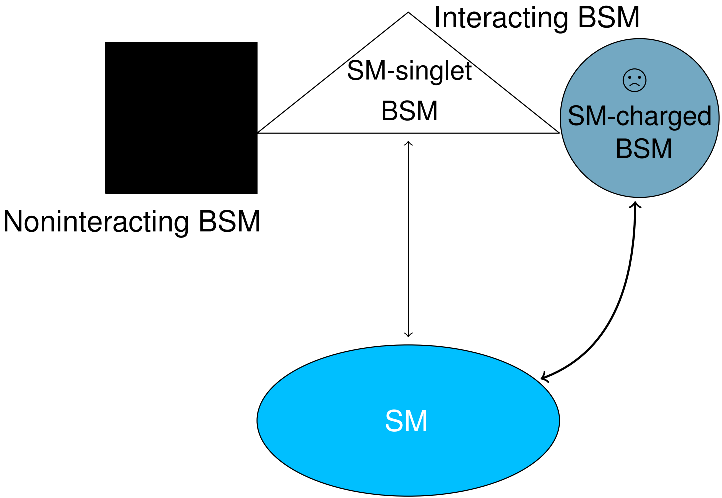
$$\downarrow$$

$$\delta S_{log}\left(\psi, \log\frac{\Lambda_W}{\Lambda_U}\right) \rightsquigarrow \text{Dim. Reg.}$$

$$\downarrow$$

the usual RGEs

BSM Comes In Two Types



NonInt-BSM Is Sweet Home For “Dark Stuff”

- It can span only SM-singlet non-Abelian gauge fields and fermions.
- It can be structured with large gauge groups.
- It may be governed by actions of the form:

$$S^{(ni)} = \int d^4x \sqrt{-g} \Big\{ -\frac{1}{2g_{V'}^2} \text{Tr}\left\{ V'_{\mu\nu} V'^{\mu\nu} \right\} + \overline{\chi}' \left(i\not{D} - m' \right) \chi' \Big\}$$

glueballs

hadrons

Dark Energy

$H_0(CMB)$ vs. $H_0(SS)$

pitch-Dark Matter

(interacts only gravitationaly)

(no way to see at direct searches)

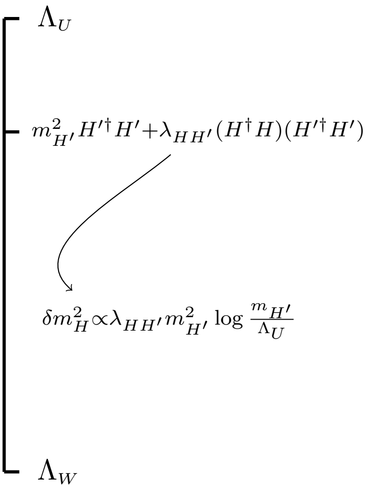
Inflaton?

SM-Singlet Int-BSM Must Couple Seesawly

- No evidence for interacting BSM at the LHC and DM searches.
- But, it is required at least for Flavor, Strong CP, Baryogenesis, Inflation, whose models can contain scalars H'.
- δm_H^2 can be suppressed only if

$$\lambda_{HH'} \lesssim \Lambda_W^2 / m_{H'}^2$$

- $\delta\lambda_{HH'} \propto \lambda_{HH'} \Longrightarrow \lambda_{HH'}$ is natural

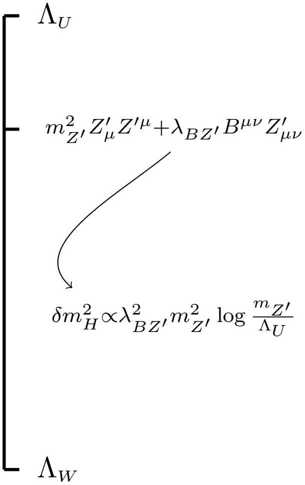


SM-Singlet Int-BSM Must Couple Seesawly

- Interacting BSM can contain a massive Z' gauge boson.
- It can mix with hypercharge gauge boson B kinetically.
- δm_H^2 can be suppressed only if

$$\lambda_{BZ'}^2 \lesssim \Lambda_W^2 / m_{Z'}^2$$

- $\delta\lambda_{BZ'} \propto \lambda_{BZ'} \Longrightarrow \lambda_{BZ'}$ is natural

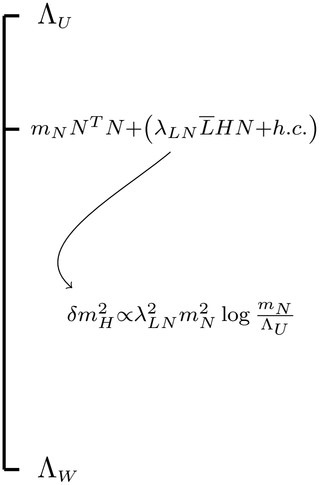


SM-Singlet Int-BSM Must Couple Seesawly

- Interacting BSM can contain a heavy right-handed neutrino N.
- It induces active neutrino masses
- δm_H^2 can be suppressed only if

$$\lambda_{LN}^2 \lesssim \Lambda_W^2 / m_N^2$$

- $m_N \lesssim 1000\,\mathrm{TeV}$



It Is OK Even If LHC Discovers Nothing New

Symmergent gravity necessitates “no new interacting particles”:

- ▶ No new particle needs be detected at the LHC and others.
- ▶ No new particle needs be detected in DM searches.
- ▶ “SM + Noninteracting BSM” can account for present data.

CCP Is “The” Problem

- The real challenge is to understand how CC can be reduced from $\frac{\Lambda_W^4}{M_{Pl}^2} \simeq m_\nu^2$ down to $\frac{m_\nu^4}{M_{Pl}^2} \simeq H_0^2$.

- Solution of the CCP can reveal the BSM since

  $$CC_{SM} + CC_{BSM} \cong H_0^2$$

  can necessitate strong correlations with the SM.

- The CCP may well be a door to sought new physics.
  (BSM, if noninteracting, can lie at ..., TeV’s, GeV’s, MeV’s, ... modulo the bounds from BBN and others)

MAG Has To Be Elucidated

- It seems highly involved but the affine connection Γ needs be solved.

- Black Holes, Hawking Radiation and similar phenomena need be restudied in metric-affine geometry by taking into account the scale invariance at high curvatures.

Summary

- Gravity emerges upon the effective SM in such a way that the gap between the UV and EW scales turns into affine curvature.

- A sub-EW BSM sector arises as an ultracrowded QFT for it to generate the gravitational constant from the EW scale.

- For sub-EW curvatures, the MAG with which effective SM + BSM reconciles reduces to GR and all gauge symmetries get restored.

- For sup-EW curvatures, a scale-invariant MAG dominates the all.

- The BSM does not have to interact with the SM and can contain fields of ebony DM, right-handed neutrinos, inflation and the like.

- SM + BSM comes out in Dimensional Regularization.

- CCP can be what reveals the physics of the BSM sector.
- BH, Hawking radiation and as such need be restudied in MAG.

Thank You For Your Attention

References:

- *Naturalizing Gravity of the Quantum Fields, and the Hierarchy Problem,* arXiv:1703.05733
- *Curvature-Restored Gauge Invariance and Ultraviolet Naturalness,* arXiv:1605.00377
- *A Mechanism of Ultraviolet Naturalness,* arXiv:1510.05570

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