Lee-Wick Fields out of Gravity

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Outline

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Lee-Wick QED

The Lagrangian:

$$\mathcal{L}_{LWQED} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{4}\tilde{F}_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{1}{2}M^2\tilde{A}_\mu\tilde{A}^\mu + \bar{\psi}(i\partial\!\!\!/ - eA\!\!\!/ - e\tilde{A}\!\!\!/ - m)\psi + \mathcal{L}(\tilde{\psi}). \quad (1)$$

- LW gauge field:

- A finite theory of QED: The mass, charge and field renormalizations are all finite.

T. D. Lee and G. C. Wick

Nucl. Phys. B **9**, 209 (1969); Phys. Rev. D **2**, 1033 (1970).

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- LW gauge field:
  - A different sign in the kinematic term (propagator).
  - Has mass M.
  - As a regulator in the Pauli-Villars regularization.
- A finite theory of QED: The mass, charge and field renormalizations are all finite.

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Lee-Wick SM

Grinstein etal. extend the Lee-Wick mechanism to the SM:

- Introduce a higher derivative operator for every field: $\frac{1}{2M^2}\partial_\mu F^{\mu\nu}\partial^\rho F_{\rho\nu}$, $i\frac{1}{M^2}\bar{\psi}\not{\partial}\not{\partial}\not{\partial}\psi$ and $-\frac{1}{2M^2}(\partial^2\varphi)^2$.
- Result in a LW partner for every SM particle.
- LW particles are heavy enough: EW data $\sim 1\,TeV$.
- LW particles cancel the quadratic divergences make the Higgs mass stable.

B. Grinstein, D. O'Connell, M.B. Wise

Phys. Rev. D **77**, 025012 (2008) arXiv:0704.1845[hep-ph]

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A way to solve the hierarchy problem!

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Procedure

- One-loop gravitational corrections to the two-point Green's functions in BFM.
- New higher derivative operators are generated from the corrections.
- Add these operators to the Lagrangian to get a one-loop renormalizable theory.
- The revised theory contains Lee-Wick particles.

Feng Wu and Ming Zhong, Phys. Lett. B **659**, 694 (2008) arXiv:0705.3287[hep-ph]

Maxwell-Einstein Theory

The action of the Maxwell-Einstein theory has the form:

$$S = -\int d^4x\sqrt{-g}\left(\frac{1}{\kappa^2}R + \frac{1}{4}g^{\mu\lambda}g^{\nu\rho}F_{\mu\nu}F_{\lambda\rho}\right). \tag{2}$$

- $\kappa \equiv \sqrt{16\pi G} \sim \frac{1}{M_{pl}}$.
- At low energy scale, $g_{\mu\nu}(x) = \eta_{\mu\nu} + \kappa h_{\mu\nu}(x)$.
- The theory is nonrenormalizable in QFT.

Background Field Method

The basic idea of the BFM:

- Expand the field to the background field and quantum fluctuation: $A_\mu(x) = \bar{A}_\mu(x) + a_\mu(x)$.
- Background field gauge is chosen to break the gauge invariance in a_μ, but keep the invariance in $\bar{A}_\mu$.
- Integrating out the quantum field.
- A gauge field theory is quantized without losing explicit gauge invariance.
- The Green's function and the divergent counterterms take a gauge invariant form.

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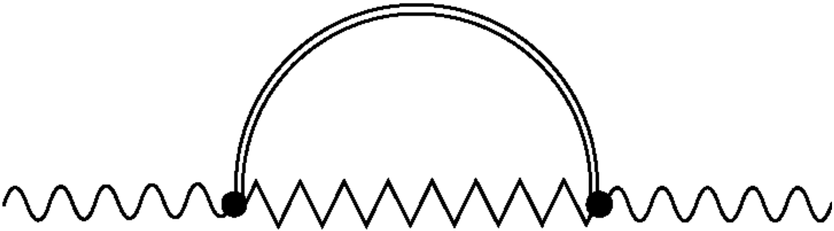
BFM makes the discussion unambiguous.

Corrections to Selfenergy

In the dimensional regularization scheme:
the tadpole diagram vanishes;
the rainbow diagram has non-trivial contribution.



Higher Derivative Operator

The result of the diagram is

$$\Pi^{\mu\nu}(p^2) = \frac{i\kappa^2}{24\pi^2}\frac{1}{\epsilon}p^2(p^2\eta^{\mu\nu} - p^\mu p^\nu) + [finite \ \ part]. \qquad (3)$$

- FT: $ip^2(p_\mu p_\nu - p^2\eta_{\mu\nu}) \rightleftarrows \partial^2 A^\mu \partial^2 A^\nu \eta_{\mu\nu} - \partial^2 A^\mu \partial_\mu \partial_\nu A^\nu$
  $= -\partial_\mu F^{\mu\nu} \partial^\rho F_{\rho\nu}$

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- One-loop gravitational corrections induce a higher derivative term for the gauge field.

The Revised Theory

In the framework of effective field theory:

- Without renormalizability as an axiom, the higher derivative term should be added in $\mathcal{L}$ at the beginning.

The revised theory

$$\mathcal{L} = \sqrt{-g}\left(-\frac{1}{\kappa^2}R - \frac{1}{4}g^{\mu\lambda}g^{\nu\rho}F_{\mu\nu}F_{\lambda\rho} + \frac{a_1}{{M_{pl}}^2}\mathcal{D}_\mu F^{\mu\nu}\mathcal{D}^\rho F_{\rho\nu} + \cdots\right) \quad (4)$$

The quadratic terms of the gauge field

$$-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{a_1}{{M_{pl}}^2}\partial_\mu F^{\mu\nu}\partial^\rho F_{\rho\nu} \quad (5)$$

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- The coefficient a_1 can be renormalized by introducing counterterm to cancel the divergence.
- The revised theory is one-loop renormalizable.

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The Propagator

The propagator for the photon:

$$\frac{-i}{p^2 - \frac{a_1}{{M_{pl}}^2}p^4 + i\epsilon}[\eta_{\mu\nu} - \frac{p_\mu p_\nu}{p^2} + \xi(1 - a_1\frac{p^2}{{M_{pl}}^2})\frac{p_\mu p_\nu}{p^2}]$$

$$= (\frac{-i}{p^2} - \frac{-i}{p^2 - \frac{{M_{pl}}^2}{a_1}})[\eta_{\mu\nu} - \frac{p_\mu p_\nu}{p^2} + \xi(1 - a_1\frac{p^2}{{M_{pl}}^2})\frac{p_\mu p_\nu}{p^2}] \quad (6)$$

- Two poles: $p^2 = 0 \Rightarrow$ massless photon
  $p^2 = \frac{M_{pl}^2}{a_1} \Rightarrow$ Lee-Wick particle.
- Lee-Wick particle has mass of order $M_{pl} \sim 10^{19} GeV$.
- At low energy scale, photon is dominant. Lee-Wick field serves as a regulator like Pauli-Villars regularization

Outline

Large Extra Dimension Model

- There are n extra spatial dimensions with radius R.
- $M_{\mathcal{EW}}$ is the only fundamental short distance scale.
- The Planck scale $M_{pl(4+n)}$ is taken to be $M_{\mathcal{EW}}$.
- The effective 4-d M_{pl} is defined as: $M_{pl} \sim M_{pl(4+n)} R^n$.

N. Arkani-Hamed, S. Dimopoulos and G. Dvali, Phys. Lett. B **429**, 263 (1998)

A Gauge-Matter-Gravity System

Gravity in (4+n)-d bulk, gauge and matter in 4-d spacetime. The action of the theory has the form

$$S = -\int d^4x d^n y (\mathcal{L}_{HE} + \mathcal{L}_M + \mathcal{L}_D + \mathcal{L}_{KG}). \tag{7}$$

$$\begin{aligned}
\mathcal{L}_{HE} &= \frac{1}{\hat{\kappa}^2}\sqrt{(-1)^{3+n}|\hat{g}^{(4+n)}|}\hat{R}, \\
\mathcal{L}_M &= \frac{1}{4}\sqrt{-|\hat{g}^{(4)}|}\hat{g}^{\mu\lambda}\hat{g}^{\nu\rho}F_{\mu\nu}F_{\lambda\rho}\delta^{(n)}(y), \\
\mathcal{L}_D &= -\sqrt{-|\hat{g}^{(4)}|}\bar{\psi}[i\hat{e}^{\mu}_{\alpha}\gamma^{\alpha}(D_\mu + \frac{1}{2}\hat{\omega}_{\mu ab}\sigma^{ab})]\psi\delta^{(n)}(y), \\
\mathcal{L}_{KG} &= -\frac{1}{2}\sqrt{-|\hat{g}^{(4)}|}(\hat{g}^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi - m_s^2\varphi^2)\delta^{(n)}(y),
\end{aligned} \tag{8}$$

with $\hat{\kappa}^2 \equiv 16\pi\hat{G}_N \sim \frac{1}{M^{2+n}_{pl(4+n)}}$.

Background Field Expansion

Expand the fields as sums of background fields and quantum fluctuations

$$\begin{aligned} \hat{g}_{\hat{\mu}\hat{\nu}}(x,y) &= \hat{\eta}_{\hat{\mu}\hat{\nu}} + \hat{\kappa}\hat{h}_{\hat{\mu}\hat{\nu}}(x,y), \quad A(x) = \mathcal{A}(x) + a(x), \\ \psi(x) &= \Psi(x) + \tilde{\psi}(x), \qquad \varphi(x) = \Phi(x) + \tilde{\varphi}(x). \end{aligned} \tag{9}$$

Einstein-Hilbert term:

$$\begin{aligned} -\frac{\sqrt{(-1)^{3+n}|\hat{g}(x,y)|}\hat{R}(x,y)}{\hat{\kappa}^2} &= -\frac{1}{4}(\partial^{\hat{\mu}}\hat{h}^{\hat{\nu}\hat{\rho}}\partial_{\hat{\mu}}\hat{h}_{\hat{\nu}\hat{\rho}} - \partial^{\hat{\mu}}\hat{h}\partial_{\hat{\mu}}\hat{h} \\ &\quad -2\partial_{\hat{\nu}}\hat{h}^{\hat{\nu}\hat{\mu}}\partial^{\hat{\rho}}\hat{h}_{\hat{\rho}\hat{\mu}} + 2\partial_{\hat{\nu}}\hat{h}^{\hat{\nu}\hat{\mu}}\partial_{\hat{\mu}}\hat{h}) + \mathcal{O}(\hat{\kappa}). \end{aligned} \tag{10}$$

Kaluza-Klein Mode Expansions

Parameterizing the field $\hat{h}_{\hat{\mu}\hat{\nu}}$ as

$$\hat{h}_{\hat{\mu}\hat{\nu}} = V_n^{-\frac{1}{2}} \begin{pmatrix} h_{\mu\nu} + \eta_{\mu\nu}\phi_{ii} & A_{\mu j} \\ A_{i\nu} & 2\phi_{ij} \end{pmatrix}, \qquad (11)$$

$V_n = R^n$: volume of the n-d compactified torus T^n.
Kaluza-Klein mode expansions:

$$h_{\mu\nu}(x,y) = \sum_{\vec{n}} h^{\vec{n}}_{\mu\nu}(x) exp(i\frac{2\pi\vec{n}\cdot\vec{y}}{R}), \qquad (12)$$

$$A_{\mu i}(x,y) = \sum_{\vec{n}} A^{\vec{n}}_{\mu i}(x) exp(i\frac{2\pi\vec{n}\cdot\vec{y}}{R}), \qquad (13)$$

$$\phi_{ij}(x,y) = \sum_{\vec{n}} \phi^{\vec{n}}_{ij}(x) exp(i\frac{2\pi\vec{n}\cdot\vec{y}}{R}), \qquad (14)$$

Lagrangian of the Gravity

Use a special de Donder gauge fixing term

$$-\frac{1}{2}(\partial_{\hat{\rho}}\hat{h}^{\hat{\rho}\hat{\mu}}\partial^{\hat{\sigma}}\hat{h}_{\hat{\sigma}\hat{\mu}} - \partial_{\hat{\rho}}\hat{h}^{\hat{\rho}\hat{\mu}}\partial_{\hat{\mu}}\hat{h} + \frac{1}{4}\partial_{\hat{\mu}}\hat{h}\partial^{\hat{\mu}}\hat{h}) \quad (15)$$

The Lagrangian of the gravity can then be written as a simple form

$$\begin{aligned}\mathcal{L}_{HE} = -& \frac{1}{4}\sum_{\vec{n}}(\partial^{\mu}h^{\vec{n},\nu\rho}\partial_{\mu}h^{-\vec{n}}_{\nu\rho} - \frac{1}{2}\partial^{\mu}h^{\vec{n}}\partial_{\mu}h^{-\vec{n}} + m^2_{\vec{n}}h^{\vec{n},\nu\rho}h^{-\vec{n}}_{\nu\rho} \\ & -\frac{1}{2}m^2_{\vec{n}}h^{\vec{n}}h^{-\vec{n}} + 2\partial^{\mu}A^{\vec{n},i\nu}\partial_{\mu}A^{-\vec{n}}_{i\nu} + 2m^2_{\vec{n}}A^{\vec{n},i\nu}A^{-\vec{n}}_{i\nu} \\ & +4\partial^{\mu}\phi^{\vec{n},ij}\partial_{\mu}\phi^{-\vec{n}}_{ij} + 2\partial^{\mu}\phi^{\vec{n}}\partial_{\mu}\phi^{-\vec{n}} + 4m^2_{\vec{n}}\phi^{\vec{n},ij}\phi^{-\vec{n}}_{ij} \\ & +2m^2_{\vec{n}}\phi^{\vec{n}}\phi^{-\vec{n}}) + \mathcal{O}(\kappa). \end{aligned} \quad (16)$$

PROPAGATORS

For gravitons:

$$\triangle^{h}_{\vec{n}\mu\nu,\vec{m}\rho\sigma}(k) = -i\frac{\delta_{\vec{n},-\vec{m}}(\eta_{\mu\rho}\eta_{\nu\sigma} + \eta_{\mu\sigma}\eta_{\nu\rho} - \eta_{\mu\nu}\eta_{\rho\sigma})}{k^2 + m^2_{\vec{n}} + i\epsilon} \quad (17)$$

$$\triangle^{A}_{\vec{n}i\mu,\vec{m}j\nu}(k) = -i\frac{\delta_{\vec{n},-\vec{m}}\delta_{ij}\eta_{\mu\nu}}{k^2 + m^2_{\vec{n}} + i\epsilon} \quad (18)$$

$$\triangle^{\phi}_{\vec{n}ij,\vec{m}kl}(k) = -i\frac{\delta_{\vec{n},-\vec{m}}[\frac{1}{4}(\delta_{ik}\delta_{jl} + \delta_{il}\delta_{jk}) - \frac{1}{4+2n}\delta_{ij}\delta_{kl}]}{k^2 + m^2_{\vec{n}} + i\epsilon}. \quad (19)$$

For photon:

$$\triangle^{a}_{\mu\nu}(k) = \frac{-i}{k^2 + i\epsilon}[\eta_{\mu\nu} - (1-\xi)\frac{k_\mu k_\nu}{k^2}]. \quad (20)$$

Interactions

Gravitons with photon $(h^{\vec{n}} a \bar{A})$:

$$\kappa \sum_{\vec{n}} [h^{\vec{n}}_{\mu\nu} \partial_\lambda \bar{A}_\rho \partial_\tau a_\sigma (\eta^{\lambda\tau}\eta^{\nu\sigma}\eta^{\mu\rho} + \eta^{\mu\lambda}\eta^{\rho\sigma}\eta^{\nu\tau} + \frac{1}{2}\eta^{\mu\nu}\eta^{\rho\tau}\eta^{\lambda\sigma} - \eta^{\lambda\sigma}\eta^{\mu\rho}\eta^{\nu\tau} - \eta^{\mu\lambda}\eta^{\rho\tau}\eta^{\nu\sigma} - \frac{1}{2}\eta^{\mu\nu}\eta^{\lambda\tau}\eta^{\rho\sigma})] \quad (21)$$

Gravitons with fermion:

$$(h^{\vec{n}}\Psi\bar{\tilde{\psi}}) \quad \frac{\kappa}{2} \sum_{\vec{n}} \{\bar{\tilde{\psi}}[i\gamma^\mu (\partial_b h^{\vec{n}}_{a\mu} + \eta_{a\mu}\partial_b \phi^{\vec{n}})\sigma^{ab} - i(h^{\vec{n},\mu}_{\alpha} + \delta^\mu_\alpha \phi^{\vec{n}})\gamma^\alpha \partial_\mu + (h^{\vec{n}} + 4\phi^{\vec{n}}) i\gamma^\mu \partial_\mu]\Psi$$

$$(h^{\vec{n}}\bar{\Psi}\tilde{\psi}) \quad \bar{\Psi}[i\gamma^\mu (\partial_b h^{\vec{n}}_{a\mu} + \eta_{a\mu}\partial_b \phi^{\vec{n}})\sigma^{ab} - i(h^{\vec{n},\mu}_{\alpha} + \delta^\mu_\alpha \phi^{\vec{n}})\gamma^\alpha \partial_\mu + (h^{\vec{n}} + 4\phi^{\vec{n}}) i\gamma^\mu \partial_\mu]\tilde{\psi}\} \quad (22)$$

INTERACTIONS

Gravitons with scalar ($h^{\vec{n}}\Phi\tilde{\varphi}$):

$$-\frac{\kappa}{2}\sum_{\vec{n}} h^{\vec{n}}_{\mu\nu}[2\partial^{\mu}\tilde{\varphi}\partial^{\nu}\Phi - \eta^{\mu\nu}(\partial_{\lambda}\tilde{\varphi}\partial^{\lambda}\Phi - m_s^2\tilde{\varphi}\Phi)]$$
$$+\kappa\sum_{\vec{n}} \phi^{\vec{n}}(\partial_{\lambda}\tilde{\varphi}\partial^{\lambda}\Phi - 2m_s^2\tilde{\varphi}\Phi). \tag{23}$$

Rainbow Diagram for Gauge Field

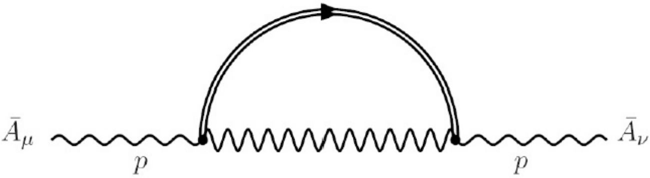

FIGURE: The diagram generating the higher derivative term of gauge field.

$$\Pi^R_{\mu\nu}(p^2) = i\frac{\kappa^2}{24\pi^2}\frac{1}{\epsilon}p^2(p^2\eta_{\mu\nu} - p_\mu p_\nu)\sum_{\vec{n}}\cdot 1$$
$$-i\frac{3\kappa^2}{8\pi^2}\frac{1}{\epsilon}(p^2\eta_{\mu\nu} - p_\mu p_\nu)\sum_{\vec{n}} m^2_{\vec{n}} + [finite\ \ part]$$

Summation Over K-K Towers

- Evaluate the loop integrals in DR scheme.
- The summation over the K-K states be written as an integration since they are near degenerate

$$\sum_{\vec{n}} f(m_{\vec{n}}) = \int_0^{\Lambda^2} dm_{\vec{n}}^2 \rho(m_{\vec{n}}) f(m_{\vec{n}}) = \int_0^{\Lambda^2} dm_{\vec{n}}^2 \frac{R^n m_{\vec{n}}^{n-2}}{(4\pi)^{n/2}\Gamma(n/2)} f(m_{\vec{n}}). \tag{24}$$

- Only valid below $M_{pl(4+n)}$: cutoff $\Lambda \sim M_{pl(4+n)}$.

Higher Derivative Operator

The final result is:

$$\Pi^R_{\mu\nu}(p^2) = i\frac{\hat{\kappa}^2}{24\pi^n}[\frac{2\Lambda^n}{(4\pi)^{n/2}\Gamma(n/2)n}]\frac{1}{\epsilon}p^2(p^2\eta_{\mu\nu} - p_\mu p_\nu) + \cdots . \quad (25)$$

- $p^2(p^2\eta_{\mu\nu} - p_\mu p_\nu) \Rightarrow \partial_\mu F^{\mu\nu}\partial^\rho F_{\rho\nu}$
- $\hat{\kappa}^2\Lambda^n \sim \frac{1}{M^2_{pl(4+n)}} \sim 1(TeV)^{-2}$
- Corrections due to large extra dimensional gravity induce

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- Corrections due to large extra dimensional gravity induce TeV scale higher derivative operator!

TeV Lee-Wick Gauge Field

- The modified Maxwell theory in the curved spacetime:

$$-\int d^4x d^n y[\sqrt{-|\hat{g}^{(4)}|}(\frac{1}{4}\hat{g}^{\mu\lambda}\hat{g}^{\nu\rho}F_{\mu\nu}F_{\lambda\rho} - \frac{a_1}{2M^2}\hat{g}^{\mu\rho}\hat{g}^{\nu\lambda}\hat{g}^{\sigma\tau}\mathcal{D}_\mu F_{\rho\sigma}\mathcal{D}_\nu F_{\lambda\tau})$$

- The Lagrangian for photon:

$$-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{a_1}{M^2_{pl(4+n)}}\partial_\mu F^{\mu\nu}\partial^\rho F_{\rho\nu}. \qquad (27)$$

- The propagator for the photon has two poles:

$$p^2 = 0 \Rightarrow \text{the massless photon}$$
$$p^2 = \frac{M^2_{pl(4+n)}}{a_1} \Rightarrow \text{Lee-Wick particle.}$$

Rainbow Diagrams for Fermion

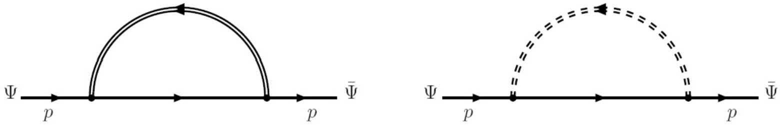

FIGURE: The diagrams generating the higher derivative term of fermion.

The final result is:

$$\Sigma^R(\not{p}) = -i\frac{\hat{\kappa}^2}{128\pi^2}\left[\frac{\Lambda^n}{(4\pi)^{n/2}\Gamma(n/2)n(n+2)}\right]\frac{1}{\epsilon}(n-16)p^2\not{p} + \cdots . \qquad (28)$$

TeV Lee-Wick Fermion

- $p^2 \not{p} \Rightarrow \bar{\Psi} \not{\partial}\not{\partial}\not{\partial} \Psi$
- The propagator for the fermion:

$$\frac{i}{\not{p} - \frac{a_2}{M^2_{pl(4+n)}} p^2 \not{p}} = \frac{-i}{\frac{a_2}{M^2_{pl(4+n)}} (p^2 - \frac{M^2_{pl(4+n)}}{a_2}) \not{p}}, \quad (29)$$

- It has two poles: $p^2 = 0 \Rightarrow$ massless fermion
$p^2 = \frac{M^2_{pl(4+n)}}{a_2} \Rightarrow$ Lee-Wick fermion.

Rainbow Diagram for Scalar

FIGURE: The diagrams generating the higher derivative term of scalar.

$$\Omega^R(p^2) = -i\frac{\hat{\kappa}^2}{16\pi^2}\frac{\Lambda^n}{(4\pi)^{n/2}\Gamma(n/2)}\frac{1}{\epsilon}\Big(\frac{1}{n+2}p^4 + \frac{n+16}{n(n+2)}m_s^2 p^2 - \frac{5n+8}{(n+2)^2}\Lambda^2 p^2 + \frac{8n-16}{n(n+2)}m_s^4\Big) + [\mathit{finite\ \ part}]. \quad (30)$$

TeV Lee-Wick Scalar

- $p^4 \Rightarrow (\partial^2\Phi)^2$
- The propagator for the scalar:

$$\frac{i}{p^2 - \frac{a_3}{M_{pl(4+n)}^2} p^4 - m_s^2}. \quad (31)$$

- For $\frac{M_{pl(4+n)}}{\sqrt{a_3}} \gg m_s$, it has poles at $p^2 \simeq m_s^2$ and at $p^2 \simeq M_{pl(4+n)}^2 / a_3$

Feng Wu and Ming Zhong, arXiv:0807.0132 [hep-ph].

Outline

SUMMARY

- Lee-Wick mechanism introduces massive particles to regulate the momentum integration.
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- Lee-Wick mechanism introduces massive particles to regulate the momentum integration.
- Lee-Wick SM: No quadratic divergences, stable Higgs mass.
- Planck scale Lee-Wick particles can be induced from 4-d gravity.
- TeV scale Lee-Wick particles can be induced from large extra dimensional gravity. (More Than Lee-Wick SM?)

Thank you !