GAUGE CURVI-SYMMETRY AND ULTRAVIOLET NATURALNESS

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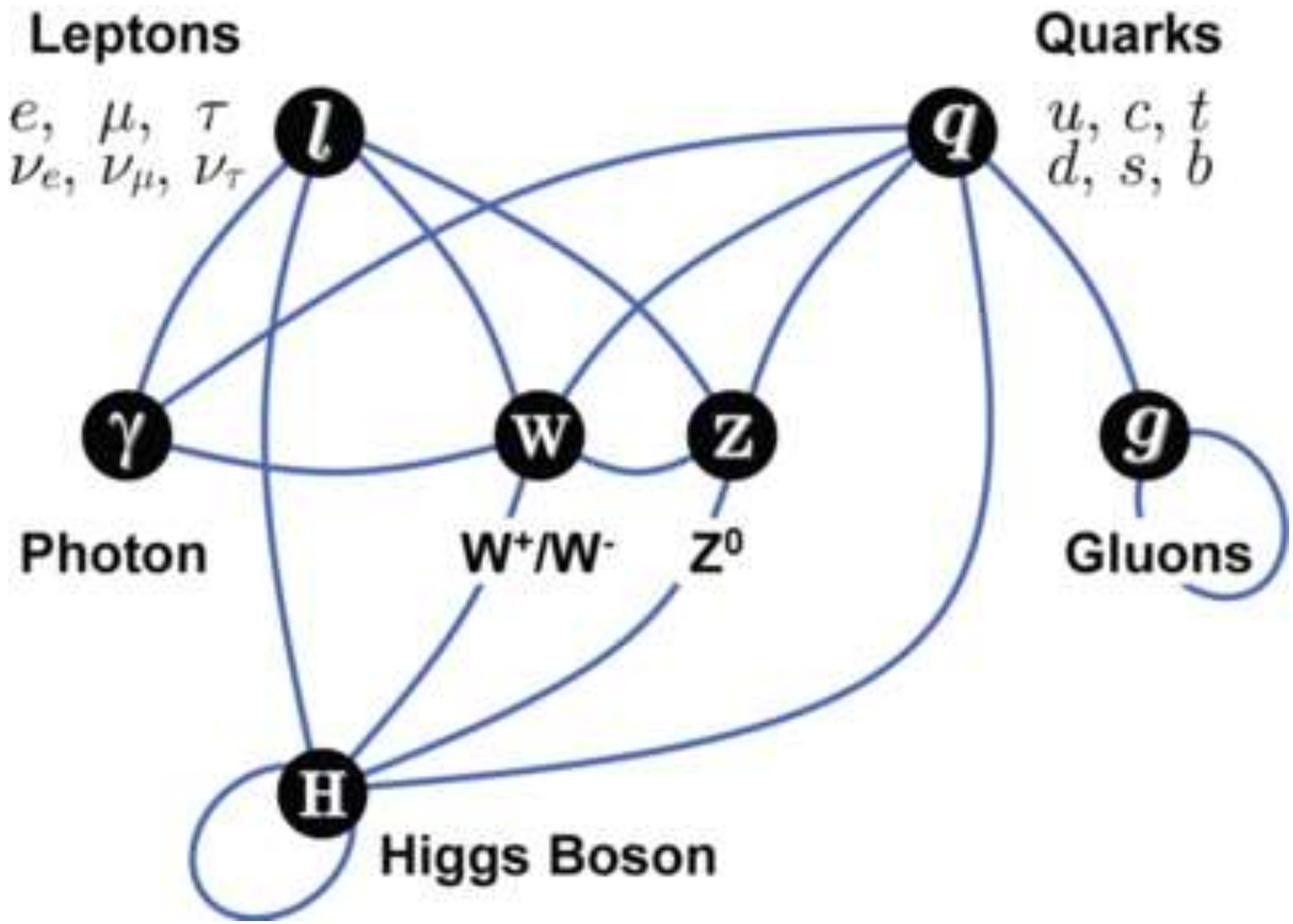
based on talk at the EASTERN MEDITERRANEAN UNIVERSITY - June, 29, 2016

ELEMENTARY PARTICLES

The SM is experimentally complete; all of its building-blocks have been observed. The last observation is the Higgs boson, H.

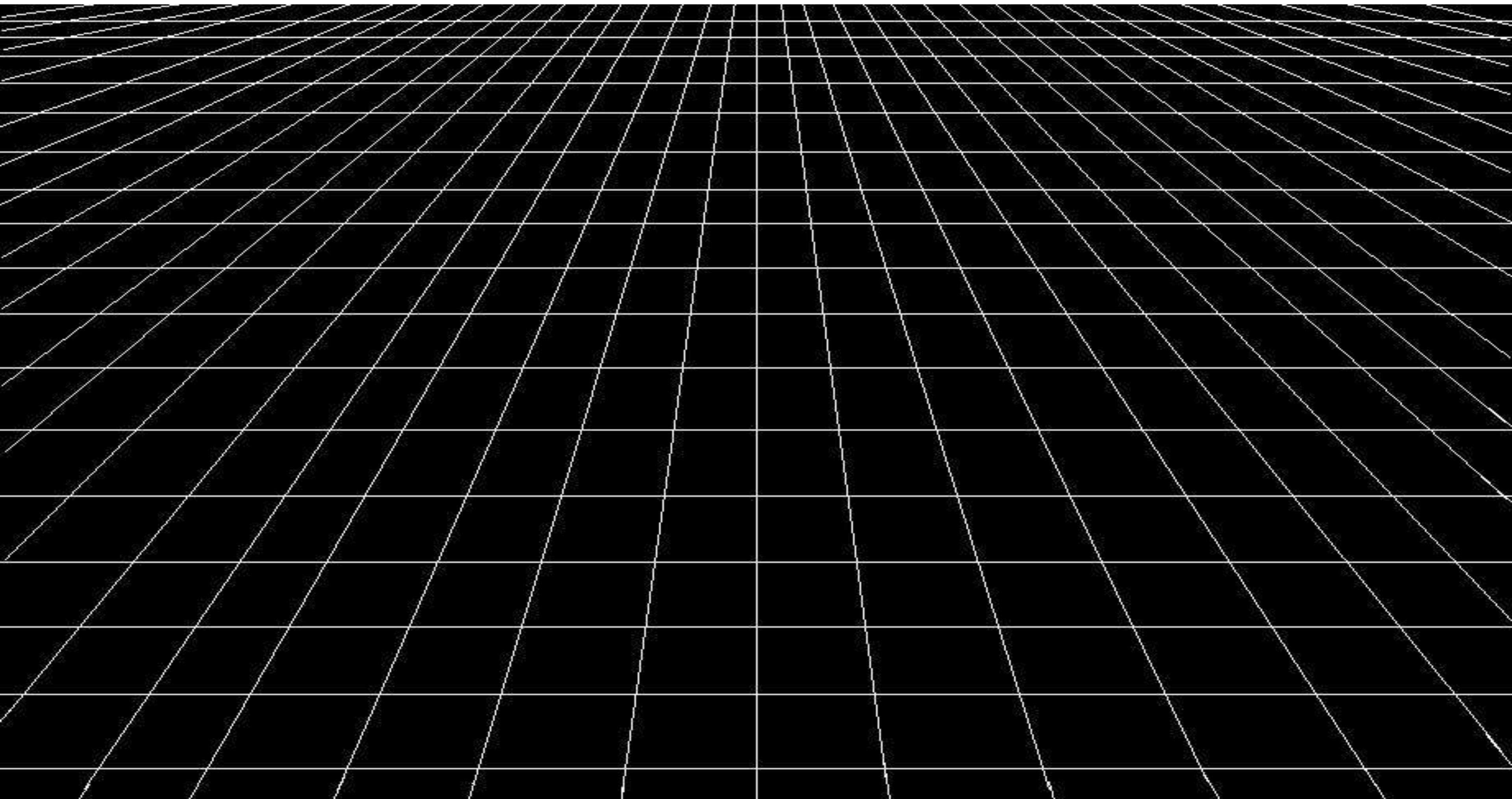
The SM is a quantum gauge field theory.

The SM encodes only ELECTRO-WEAK and STRONG forces.



The SM necessarily lives in flat spacetime.

This is because it does not encode <u>GRAVITY</u>.



In practice, gravity is incorporated into the SM by carrying the SM into curved spacetime. This seems normal and well-motivated. But:

- Classical gravity is INCONSISTENT:

$$\underbrace{G_{\mu\nu}}_{\text{classical}} \stackrel{?}{=} 8\pi G_N \underbrace{\widehat{T}_{\mu\nu}}_{\text{quantum}}$$

- Quantized gravity is NON-RENORMALIZABLE:

$$\int d^4x \sqrt{-g}\left\{ \underbrace{\frac{1}{16\pi G_N}}_{\text{Dim=-2}} R + \mathcal{L} \right\}$$

a consistent and renormalizable picture

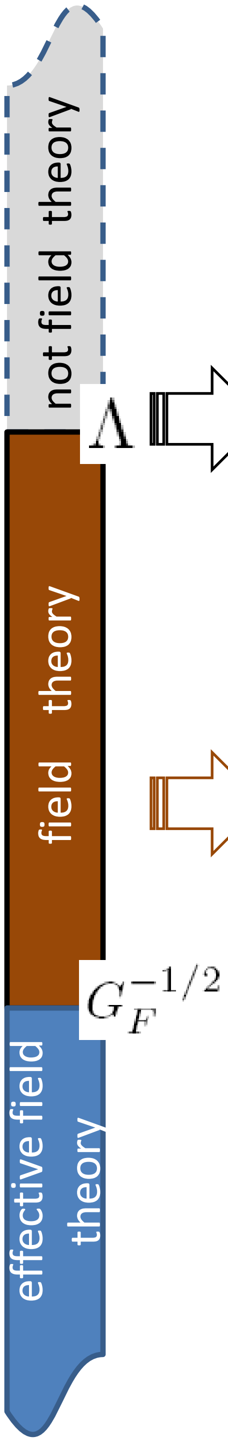
the SM effective action (“classical”)

the classical gravity

flat spacetime
SM effective action
(no gravity)

incorporate gravity
into the SM !

constructing the SM effective action



the UV validity border of the SM
(UV-limited SM)

a physical scale
(not a QFT scale; not a field mass)

gravity will leap out at this scale!

loop integrals are finite and physical
(they are not cutoff-regularized integrals hence they cannot be replaced with Dimensional or Pauli-Villars regularization integrals)

the SM effective action develops logarithmic, quadratic and quartic dependencies on Λ !

problem is to allay quartic and quadratic parts to stabilize the SM at the Fermi scale G_F !

resultant action will have effective SM at G_F plus classical gravity at Λ !

The SM effective action ($\eta_{\mu\nu} = \mathrm{flat\ metric}$):

$$S(\eta) = S_{G_F}(\eta, \psi_{SM}, \log(G_F\Lambda^2)) + S^0_\Lambda(\eta) + S^1_\Lambda(\eta)$$

Tree-level SM action with
LOG quantum corrections

QUADRATIC quantum corrections
to gauge boson masses:

$$S^1_\Lambda(\eta) = \int d^4x \sqrt{\|\eta\|}\, c_V \Lambda^2 \eta_{\mu\nu} \mathrm{Tr}\{V^\mu V^\nu\}$$

QUADRATIC and QUARTIC
quantum corrections to
vacuum and Higgs sectors:

$$S^0_\Lambda(\eta) = \int d^4x \sqrt{\|\eta\|}\, \{a\Lambda^4 + a_m \Lambda^2 m_H^2 + b\Lambda^2 H^\dagger H\}$$

➢ "The Standard Model" confirmed by experiments refer to field configurations about the vacuum state of $S_{G_F}(\eta, \psi_{SM}, \log\left(G_F\Lambda^2\right))$. It is with respect to this vacuum state that, the quadratic and quartic UV corrections in $S^0_\Lambda(\eta)$ and $S^1_\Lambda(\eta)$ give unacceptably large UV contributions for $\Lambda \gtrsim 500\ \mathrm{GeV}$.

➢ Among them the most dangerous are those in the gauge sector. The reason is that explicit breaking of the gauge symmetries of the SM by $S^1_\Lambda(\eta)$ at the UV scale completely kills the model! It is thus necessary to deal with these symmetry-breaking terms first.

➢ The power-law divergences in $S^0_\Lambda(\eta)$, which give rise to the gauge hierarchy problem (Higgs naturalness problem) and the cosmological constant problem, must be dealt with within the framework which eradicates $S^1_\Lambda(\eta)$.

How to restore the gauge symmetries broken by $S^1_\Lambda(\eta)$?

Kibble (1979)

$$\int d^4x\sqrt{\|\eta\|}c_V\eta_{\mu\nu}\mathrm{Tr}\{D^\mu\Phi D^\nu\Phi\}\Big|_{\substack{\text{set:}\\ \Phi\models\Lambda e^{iS}}}$$

$$=\int d^4x\sqrt{\|\eta\|}c_V\Lambda^2\eta_{\mu\nu}\mathrm{Tr}\{(V^\mu-D^\mu S)(V^\nu-D^\nu S)\}\Big|_{\substack{\text{set:}\\ S\models 0}}$$

$$=\int d^4x\sqrt{\|\eta\|}c_V\Lambda^2\eta_{\mu\nu}\mathrm{Tr}\{V^\mu V^\nu\}$$

$$=S^1_\Lambda(\eta)\,!$$

Stueckelberg (1938)

This method necessitates a UV-scale scalar sector. The mass term can be construed as constant-field "cut-view" of a gauge-invariant theory. The Φ-setup (or S-setup) is gauge-invariant. It proves stable if Φ is "classical" but this is not possible insure at the UV scale.

How to restore the gauge symmetries broken by $S^1_\Lambda(\eta)$?

Consider, as an alternative approach, the trivial equality:

$$0 = -\int d^4x\sqrt{\|g\|}\frac{c_V}{2}\mathrm{Tr}\{g_{\mu\nu}g_{\alpha\beta}V^{\mu\alpha}V^{\nu\beta}\} + \underbrace{\int d^4x\sqrt{\|g\|}\frac{c_V}{2}\mathrm{Tr}\{g_{\mu\nu}g_{\alpha\beta}V^{\mu\alpha}V^{\nu\beta}\}}$$

$$\int d^4x\sqrt{\|g\|}c_V\,\mathrm{Tr}\{V^\mu(-\mathcal{D}^2g_{\mu\nu}+\mathcal{D}_\mu\mathcal{D}_\nu+V_{\mu\nu}+R_{\mu\nu})V^\nu\}+\int d^4x\,c_V\,\partial_\mu\,\mathrm{Tr}\left\{\sqrt{\|g\|}g^{\mu\nu}g^{\alpha\beta}V_\alpha V_{\nu\beta}\right\}$$

$$\mathcal{D} = \partial + \Gamma + V$$

$$R_{\mu\nu} = \partial_\alpha\Gamma^\alpha_{\mu\nu} - \partial_\nu\Gamma^\alpha_{\mu\alpha} + \Gamma^\alpha_{\beta\alpha}\Gamma^\beta_{\mu\nu} - \Gamma^\alpha_{\beta\nu}\Gamma^\beta_{\mu\alpha}$$

$$\begin{aligned}V_{\mu\nu} &= \mathcal{D}_\mu V_\nu - \mathcal{D}_\nu V_\mu \\ &= (\partial_\mu + V_\mu)\,V_\nu - (\partial_\nu + V_\nu)\,V_\mu \\ &= \partial_\mu V_\nu - \partial_\nu V_\mu + [V_\mu, V_\nu]\end{aligned}$$

Now, imagine fixing curvature and metric by first setting

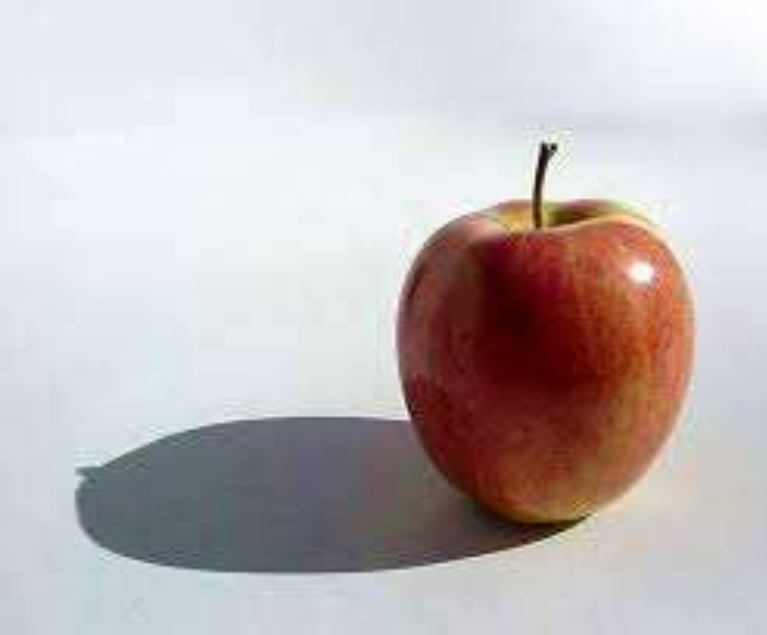
$$R_{\mu\nu}(g) \models \Lambda^2 g_{\mu\nu}$$

to erase curvature from the action, and then taking

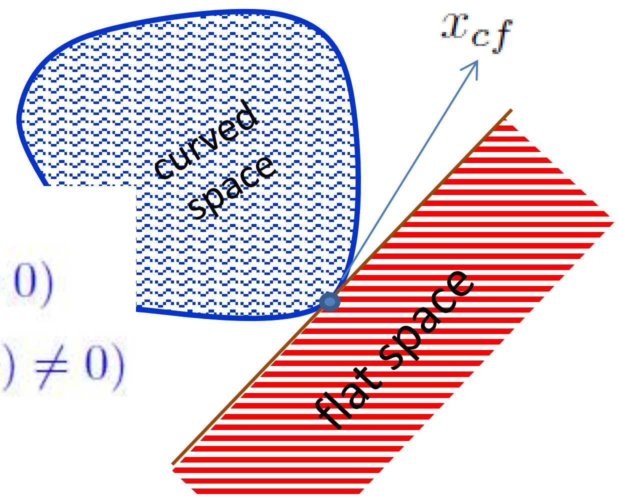
$$g_{\mu\nu} \models \eta_{\mu\nu}$$

as the background value for the metric.

These are again "cut-view" enforcements on curvature and metric. They are not the solutions of dynamical equations.



“cut-view” as “junction condition” at the curved/flat contact point x_{cf} :



at the curved side:

$\mathrm{metric}(x_{cf}) = \eta_{\mu\nu}$ $(\because \Gamma^{\lambda}_{\alpha\beta}(x_{cf}) = 0)$

$\mathrm{curvature}(x_{cf}) \neq 0$ $(\because \partial_\mu \Gamma^{\lambda}_{\alpha\beta}(x_{cf}) \neq 0)$

at the flat side:

$\mathrm{metric}(x_{cf}) = \eta_{\mu\nu}$ ($\therefore$ metric everywhere)

$\mathrm{curvature}(x_{cf}) = 0$ ($\therefore$ curvature everywhere)

Proposition:

$\mathrm{curvature}(x_{cf}) \doteq$ “UV inertia” in flat space $\equiv \Lambda^2 \eta_{\mu\nu}$

… and thus, the SM effective action at the contact x_{cf} is the curved spacetime effective action in the RNC continued into flat direction!

“cut-view” generates UV gauge masses from “nothing” in curved space:

$$0 \models -\int d^4x\sqrt{\|\eta\|}\frac{c_V}{2}\mathrm{Tr}\left\{\eta_{\mu\nu}\eta_{\alpha\beta}V^{\mu\alpha}V^{\nu\beta}\right\}+\int d^4x c_V \partial_\mu \underline{\mathrm{Tr}\left\{\sqrt{\|\eta\|}\eta^{\mu\nu}\eta^{\alpha\beta}V_\alpha V_{\nu\beta}\right\}}$$

$$+\int d^4x\sqrt{\|\eta\|}c_V \mathrm{Tr}\{\underline{V^\mu(-D^2\eta_{\mu\nu}+D_\mu D_\nu+V_{\mu\nu}}+\Lambda^2\eta_{\mu\nu})V^\nu\}$$

$$=-\int d^4x\sqrt{\|\eta\|}\frac{c_V}{2}\underline{\mathrm{Tr}\left\{\eta_{\mu\nu}\eta_{\alpha\beta}V^{\mu\alpha}V^{\nu\beta}\right\}}+\int d^4x\sqrt{\|\eta\|}\frac{c_V}{2}\underline{\underline{\mathrm{Tr}\left\{\eta_{\mu\nu}\eta_{\alpha\beta}V^{\mu\alpha}V^{\nu\beta}\right\}}}$$

$$+\int d^4x\sqrt{\|\eta\|}c_V \Lambda^2\eta_{\mu\nu}\mathrm{Tr}\{V^\mu V^\nu\}$$

$$=\int d^4x\sqrt{\|\eta\|}c_V \Lambda^2\eta_{\mu\nu}\mathrm{Tr}\{V^\mu V^\nu\} + \underline{0}$$

$$=S^1_\Lambda(\eta)!$$

“cut-view” holds as a general reduction method ($\psi = \psi_{SM}$ for the SM):

$$S\left[(\partial + \Gamma + V)\,\psi, \psi, g_{\mu\nu}, R_{\mu\nu}\right]$$

$$\Big\downarrow \; R_{\mu\nu}(g) \models \Lambda^2 g_{\mu\nu}$$

$$S\left[(\partial + \Gamma + V)\,\psi, \psi, g_{\mu\nu}, \Lambda^2\right]$$

$$\Big\downarrow \; g_{\mu\nu} \models \eta_{\mu\nu}$$

$$S\left[(\partial + V)\,\psi, \psi, \eta_{\mu\nu}, \Lambda^2\right]$$

all this means that:

$$\underbrace{S^1_\Lambda(\eta)}_{\text{flat}} \xrightarrow{(\eta_{\mu\nu}\to g_{\mu\nu}) \text{ and } (\Lambda^2 g_{\mu\nu}\to R_{\mu\nu})} \underbrace{0}_{\text{curved}}$$

curvature eradicates $S^1_\Lambda(\eta)$!

gauge symmetries are restored at the UV!

the SM is carried into curved spacetime!

- The “cut-view” prescription should hold for the entire SM.

- How to then construct the “curved spacetime SM” whose constant-curvature UV cut-view yields the flat spacetime SM effective action?

- It may seem that the curved spacetime SM cannot be determined uniquely. It actually is unique because:

  - The “curved spacetime SM” cannot involve any coupling not found in the flat spacetime SM effective action. The reason is that no quantum fluctuations are left to induce any extra coupling. Any new coupling is incalculable.

  - Curvature can lead to gravity with the Newton’s constant generated by the UV scale Λ -- the highest mass scale in the setup.

The SM effective action in curved spacetime (*a la* Sakharov, 1967):

$$S(R) = S_{G_F}\left(g, \psi_{SM}, \log\left(G_F \Lambda^2\right)\right) + \int d^4x \sqrt{\|g\|}\left(\underbrace{\frac{1}{4}\left(a\Lambda^2 + a_m m_H^2\right)}\, R(g) + \frac{1}{4} b R(g) H^\dagger H\right)$$

the Einstein-Hilbert term

(no power-law UV contributions to the cosmological constant !)

Higgs-curvature coupling

(no quadratic UV contributions to the Higgs boson mass !)

the SM Higgs sector is naturalized

(gauge hierarchy problem disappears!)

Alas! There is a problem:

$$a = \frac{1}{64\pi^2}\left(n_b - n_f\right) = \frac{1}{64\pi^2}(28 - 90) = -\frac{62}{64\pi^2} < 0$$

negative gravitational constant ! (anti-gravity)

- The SM spectrum alone lead to “repulsive” gravity!

- There must exist therefore some New Physics (NP) beyond the SM for gravity to be “attractive”.

- The NP does not need to interact with the SM for gravity to attract. It can exist as a secluded dark sector or can interact with the SM fully or partially.

The NP augments the SM particle spectrum with new particles above its fundamental scale of $G_{NP} \lesssim G_F$.

$$S_{SM+NP}(R) = \int d^4x \sqrt{\|g\|} \left(\frac{R(g)}{16\pi G_N} + \cdots \right)$$

$$4\pi G_N \cong \frac{1}{(a + a^{NP})\,\Lambda^2}$$

Gravity attracts if:

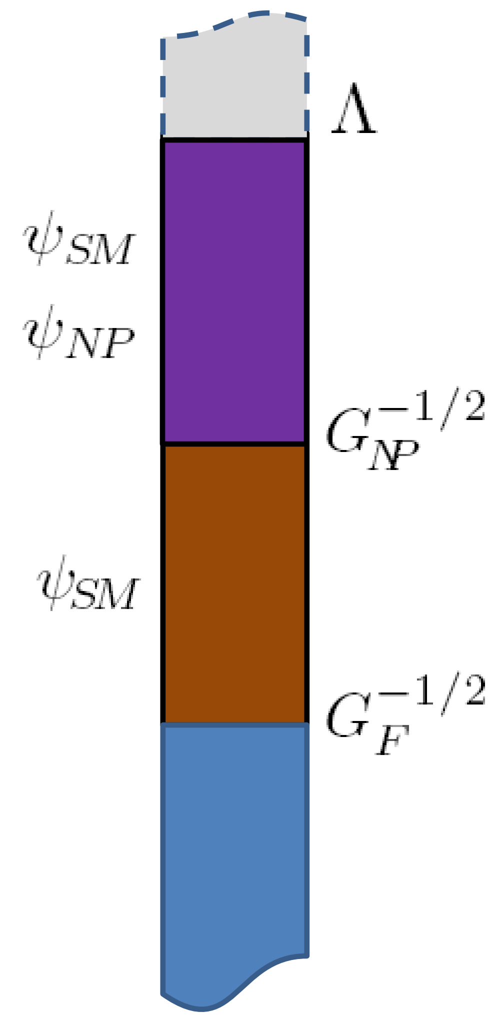
$$n_b^{NP} - n_f^{NP} \geq 63$$

$$\Lambda < (8\pi G_N)^{-1/2}$$

provided that

$$n_b^{NP} - n_f^{NP} > 128\pi^2 + 62 \approx 1325$$

NP is crowded !



If NP does not interact with the SM ...

The total effective action in curved spacetime takes the form

$$S_{SM+NP}(R) = S_{G_F}(g, \psi_{SM}, \log(G_F\Lambda^2)) + S_{G_{NP}}(g, \psi_{NP}, \log(G_{NP}\Lambda^2))$$
$$+ \int d^4x \sqrt{\|g\|}\left(\frac{R(g)}{16\pi G_N} + \zeta_H R(g) H^\dagger H + \zeta_S R(g) S^\dagger S\right)$$

$$\zeta_H = b/4$$

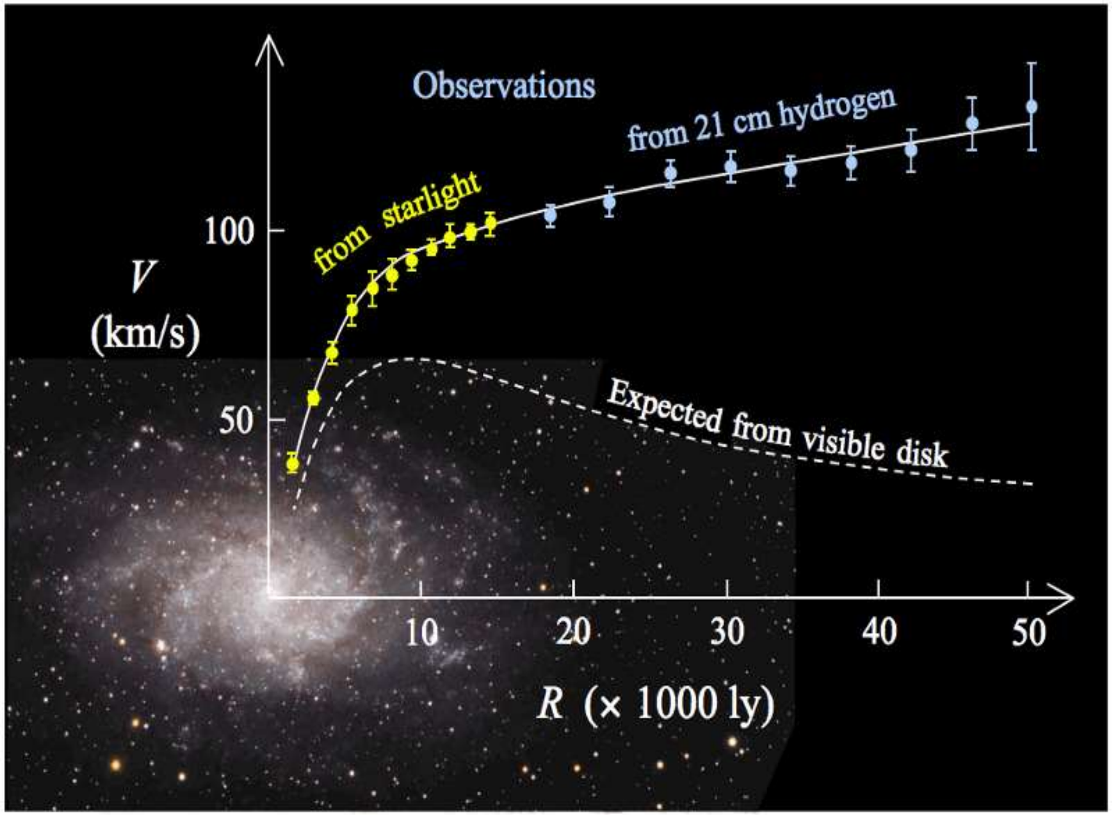
$$4\pi G_N = \frac{1}{(a + a^{NP})\Lambda^2 + a_m m_H^2 + a_m^{NP} m_S^2}$$

$$\zeta_S = b^{NP}/4$$

contribution of $S \in \psi_{NP}$

If NP does not interact with the SM ...

- It can naturally accommodate "non-interacting Dark Matter"
- This specific DM reveals itself via only its weight. The flat rotation curves of galaxies is the main signature.
- It evades direct detection (anyhow, those experiments have found nothing so far).



(Corbelli & Salucci, 2000)

If NP interacts with the SM …

- The Higgs boson mass receives then logarithmic corrections (from scalars , vector-like fermions in NP)

$$\delta m_h \sim G_{NP}^{-1/2} \log\left(G_{NP}\Lambda^2\right)$$

which destabilizes the Higgs sector unless the NP lies close to the SM scale: $G_{NP} \cong G_F$.

- This means that “detectable” new physics, if any, must be living close to the Fermi scale. It cannot be far! New stuff that can be discovered at the LHC, if ever, must weigh at the Fermi scale!

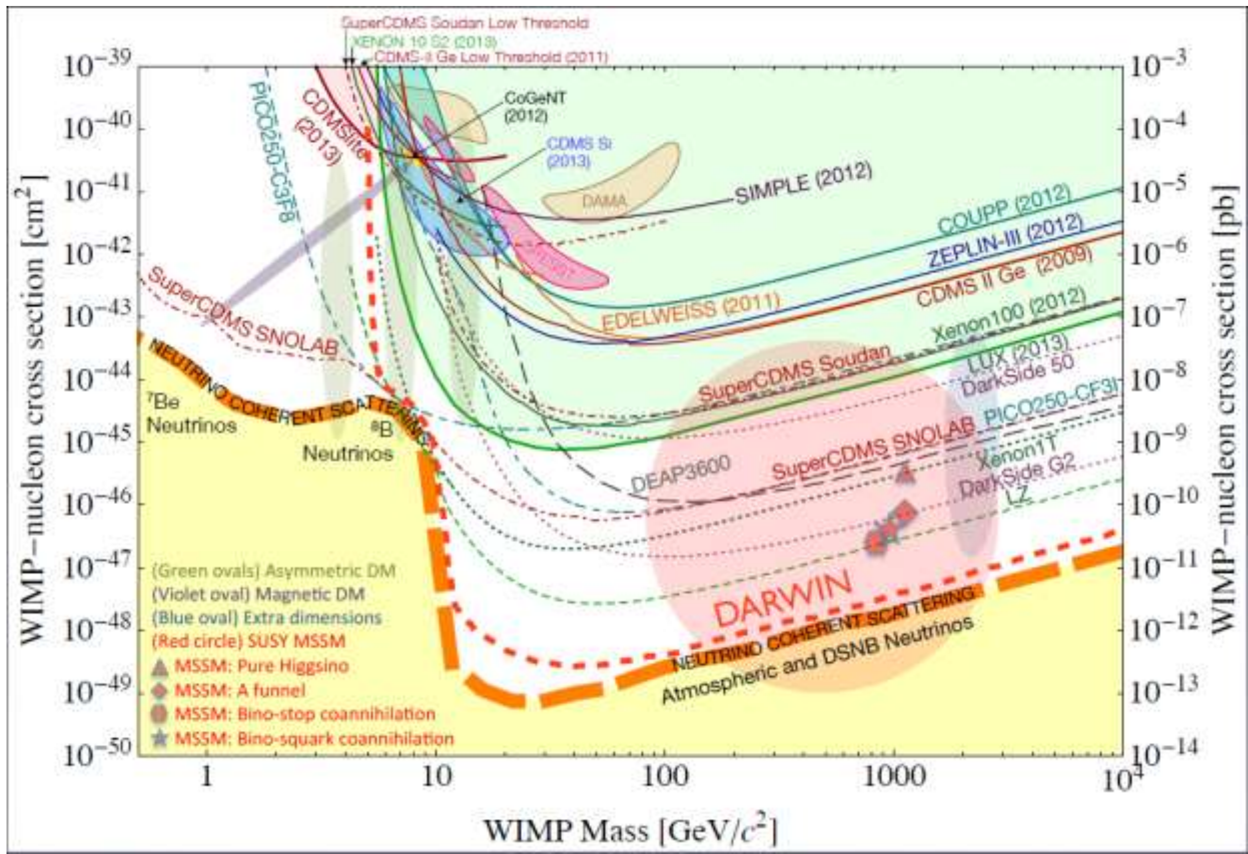
- Ultra high-energy colliders (*e.g.* the one at 100 TeV) are not therefore motivated from the naturalness point of view.

If NP interacts with the SM …

It can have a DM sector which may or may not interact with the SM.

- ➢ If DM does not interact with the SM it forms the non-interacting DM (in agreement with the flat galactic rotation curves)

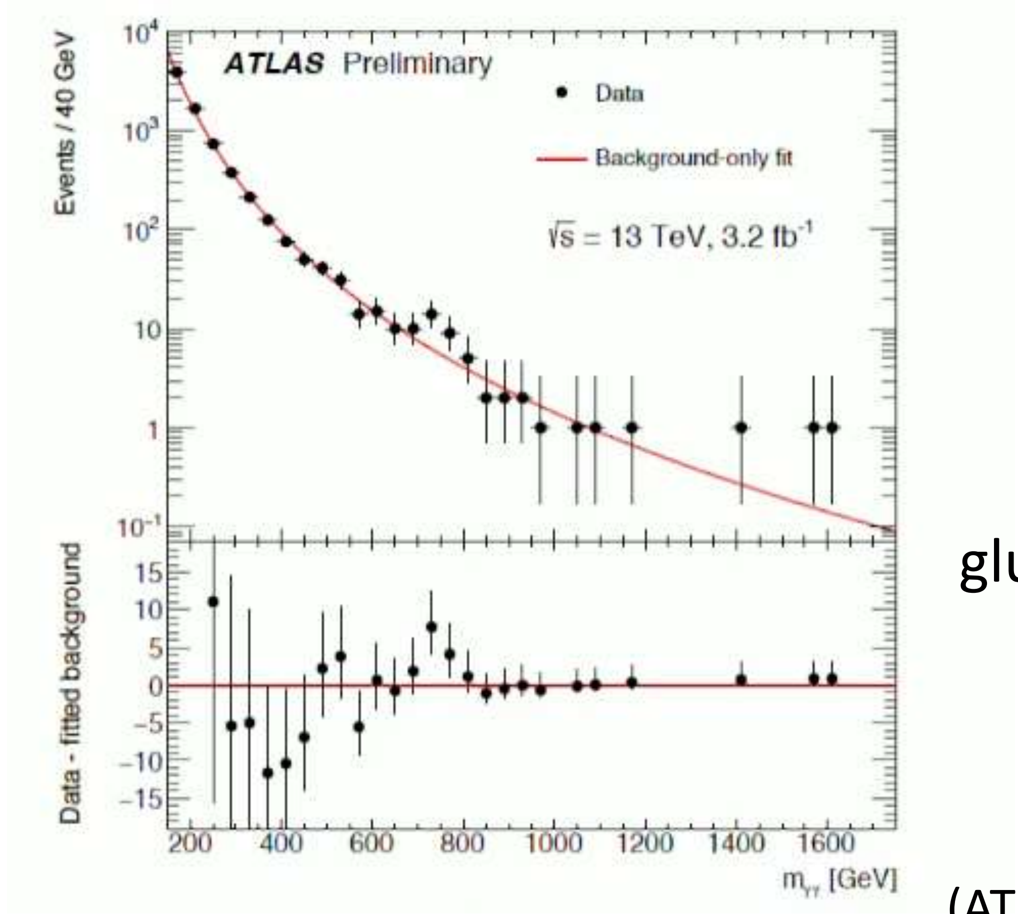
- ➢ If DM interacts with the SM, depending on the interaction strength, it can be observed via direct detection experiments.

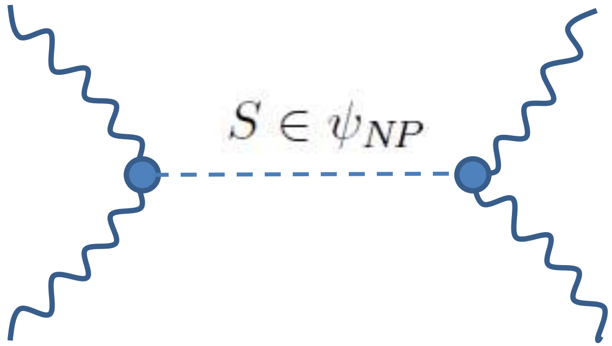


(Fiorillo, 2014)

If NP interacts with the SM …

It can generate observable signals at current or future colliders. The LHC diphoton excess around $m_S \simeq G_{NP}^{-1/2} \simeq 750\ \mathrm{GeV}$ if real, could be mediated by a scalar field $S \in \psi_{NP}$.





(ATLAS, 2015)

Irrespective of if the NP and the SM interact...

- The curved space theory cannot have arbitrary higher-curvature terms simply because the curved spacetime SM can have no couplings not found in the flat spacetime SM. In gravity sector, however, it is possible to interpret $\log\left(G_F \Lambda^2\right)$ as $\log\left(G_F R(g)\right)$ to obtain structures like $R(g) \log\left(R(g)\right)$.

- After ameliorating/eradicating power-law divergences by incorporating gravity, what remains is the logarithmically-divergent sector. That part, however, can be reinterpreted within Dimensional Regularization scheme via the association $\log(G_F \Lambda^2) \equiv 2/\epsilon + \log G_F \mu^2$ in a spacetime with dimensions $D = 4 - \epsilon$ and total volume $\mu^{2\epsilon} \infty^{4-2\epsilon}$. It is clear that ε parameter here is finite (as opposed to that in the true dimensional regularization in field theory).

Prescription

1) Let “SM+NP” be a (spontaneously broken) quantum gauge theory holding necessarily in flat spacetime, below a physical scale Λ.

2) Form the “SM+NP” Wilsonian effective action at the Fermi scale.

3) Interpret that effective action as constant-curvature UV cut-view of the corresponding curved spacetime effective action to eradicate the gauge boson UV masses.

4) Defuse, by the same token, quadratic and quartic UV contributions to the vacuum and Higgs sectors.

5) Relate Λ to the gravitational scale to induce gravity properly, generate the DM, and realize other possible effects through the NP.

Summary

1) SM + NP is valid up to the gravitational scale Λ.

2) NP must exist to enable gravity. It can also account for Dark Matter.

3) NP can be distributed over different scales.

4) NP doesn't have to interact with the SM. In this case, it can host the "noninteracting DM" – undetectable by the LHC and underground direct searches.

5) NP may interact with the SM to yield (interacting or noninteracting) DM and possible collider signals.

6) NP fields can couple to Higgs and destabilize its mass. Naturalness requires those NP fields to weigh near the Fermi scale. They, if any, should show up in LHC data.

Summary

logs → Dim. Reg.

Higgs is stabilized at the Fermi scale

$$\text{Action} = S_{G_F}(g, \psi_{SM}, \log(G_F \Lambda^2)) + \int d^4x \sqrt{\|g\|}\, \zeta_H R(g)\, H^\dagger H$$

$$+ \int d^4x \sqrt{\|g\|} \left(\frac{R(g)}{16\pi G_N} - V_{tot} \right)$$

CC is reduced

$V_{tot} \lesssim G_{NP}^{-2}$

$$+ S_{G_{NP}}(g, \psi_{NP}, \log(G_{NP} \Lambda^2)) + \int d^4x \sqrt{\|g\|}\, \zeta_S R(g)\, S^\dagger S$$

$$+ S^{int}_{G_F G_{NP}}$$

Dark Matter

(if exists)

new scalars are stabilized at NP scale

Higgs-NP interactions destabilize Higgs mass and hence $G_{NP} \simeq G_F$

new signals at the LHC

Conclusion

Ensuring gauge curvi-symmetry of the SM effective action leads to:

- incorporation of classical gravity (consistent with the effective SM),

- solution of the gauge hierarchy (Higgs naturalness) problem,

- suppression of the cosmological constant down to neutrino scale,

- prediction of new physics (hosting the DM (pitch-dark to visible) such that detectible matter weigh close to the Fermi scale)

This talk is based on:

Curvature-Restored Gauge Invariance and Ultraviolet Naturalness

Durmus Ali Demir

(Submitted on 2 May 2016)

It is shown that, $(a\Lambda^2 + b|H|^2)R$ in a spacetime of curvature R is a natural ultraviolet (UV) completion of $(a\Lambda^4 + b\Lambda^2|H|^2)$ in the flat-spacetime Standard Model (SM) with Higgs field H, UV scale Λ and loop factors a, b. This curvature completion rests on the fact that a Λ-mass gauge theory in flat spacetime turns, on the cut-view $R = 4\Lambda^2$, into a massless gauge theory in curved spacetime. It provides a symmetry reason for curved spacetime, wherein gravity and matter are both low-energy effective phenomena. Gravity arises correctly if new physics exists with at least 63 more bosons than fermions, with no need to interact with the SM and with dark matter as a natural harbinger. It can source various cosmological, astrophysical and collider phenomena depending on its spectrum and couplings to the SM.

Comments:	3 pp
Subjects:	**High Energy Physics - Phenomenology (hep-ph)**; Cosmology and Nongalactic Astrophysics (astro-ph.CO); General Relativity and Quantum Cosmology (gr-qc); High Energy Physics - Theory (hep-th)
Report number:	IZTECH-HEP-03/2016
Cite as:	arXiv:1605.00377 **[hep-ph]**

See also:

A Mechanism of Ultraviolet Naturalness

Durmus Ali Demir

(Submitted on 19 Oct 2015 (v1), last revised 3 May 2016 (this version, v2))

A naturalization mechanism is revealed by integrating-in spacetime curvature upon flat spacetime effective field theories with Planckian ultraviolet scales such that, quartic ultraviolet contributions to vacuum energy transmute into Einstein-Hilbert gravity and quadratic ultraviolet contributions to scalar masses turn into scalar curvature-scalar field nonminimal couplings. Extensions of the Standard Model (SM) having at least 63 more bosons than fermions enjoy this mechanism. They do not have to interact with the SM for the mechanism to work. They can form a secluded sector to source noninteracting dark matter observable via only its weight, or a weakly-coupled sector to source dark matter and various collider signals.

Comments: Improved discussions, clarified subtle points, added references; 3 pages

Subjects: **High Energy Physics - Phenomenology (hep-ph)**; General Relativity and Quantum Cosmology (gr-qc); High Energy Physics - Theory (hep-th)

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thank you !