NATURALNESS NECESSITATES GRAVITY

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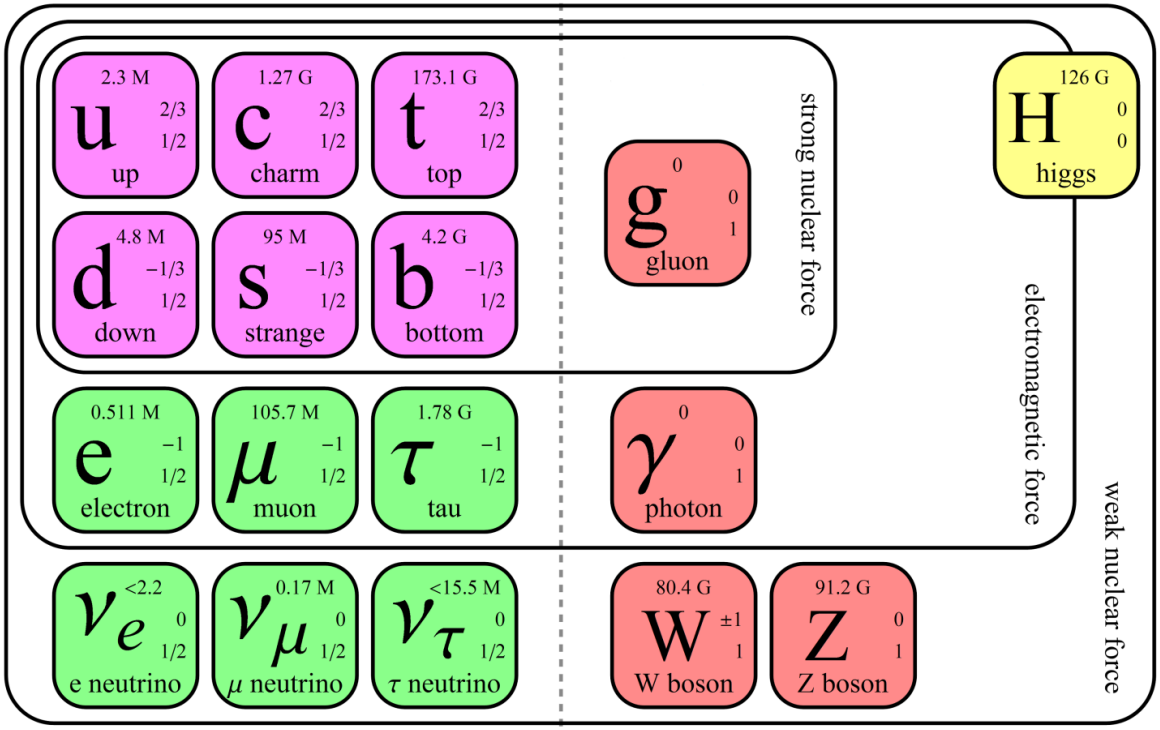
NEB-17 Recent Developments in Gravity
Sept. 19-22, 2016, Mykonos, GREECE

the Standard Model

fully confirmed by experiments



quantum field theory of the EM, Weak and Strong interactions. does **not** include **gravity**.

the SM continues to hold at high energies

ATLAS Exotics Searches* - 95% CL Exclusion

Status: August 2016

ATLAS Preliminary

$\int \mathcal{L}\, dt = (3.2 - 20.3)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 8, 13$ TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt [\mathrm{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	–	≥ 1 j	Yes	3.2	M_D 6.58 TeV	$n = 2$	1604.07773
	ADD non-resonant $\ell\ell$	2 e, μ	–	–	20.3	M_S 4.7 TeV	$n = 3$ HLZ	1407.2410
	ADD QBH $\to \ell q$	1 e, μ	1 j	–	20.3	M_{th} 5.2 TeV	$n = 6$	1311.2006
	ADD QBH	–	2 j	–	15.7	M_{th} 8.7 TeV	$n = 6$	ATLAS-CONF-2016-069
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 2 j	–	3.2	M_{th} 8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \ell\ell$	2 e, μ	–	–	20.3	G_{KK} mass 2.68 TeV	$k/\overline{M}_{Pl} = 0.1$	1405.4123
	RS1 $G_{KK} \to \gamma\gamma$	2 γ	–	–	3.2	G_{KK} mass 3.2 TeV	$k/\overline{M}_{Pl} = 0.1$	1606.03833
	Bulk RS $G_{KK} \to WW \to qq\ell\nu$	1 e, μ	1 J	Yes	13.2	G_{KK} mass 1.24 TeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2016-062
	Bulk RS $G_{KK} \to HH \to bbbb$	–	4 b	–	13.3	G_{KK} mass 360-860 GeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2016-049
	Bulk RS $g_{KK} \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	20.3	g_{KK} mass 2.2 TeV	BR = 0.925	1505.07018
	2UED / RPP	1 e, μ	≥ 2 b, ≥ 4 j	Yes	3.2	KK mass 1.46 TeV	Tier (1,1), BR($A^{(1,1)} \to tt$) = 1	ATLAS-CONF-2016-013
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	13.3	Z' mass 4.05 TeV		ATLAS-CONF-2016-045
	SSM $Z' \to \tau\tau$	2 τ	–	–	19.5	Z' mass 2.02 TeV		1502.07177
	Leptophobic $Z' \to bb$	–	2 b	–	3.2	Z' mass 1.5 TeV		1603.08791
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	13.3	W' mass 4.74 TeV		ATLAS-CONF-2016-061
	HVT $W' \to WZ \to qq\nu\nu$ model A	0 e, μ	1 J	Yes	13.2	W' mass 2.4 TeV	$g_V = 1$	ATLAS-CONF-2016-082
	HVT $W' \to WZ \to qqqq$ model B	–	2 J	–	15.5	W' mass 3.0 TeV	$g_V = 3$	ATLAS-CONF-2016-055
	HVT $V' \to WH/ZH$ model B	multi-channel			3.2	V' mass 2.31 TeV	$g_V = 3$	1607.05621
	LRSM $W'_R \to tb$	1 e, μ	2 b, 0-1 j	Yes	20.3	W' mass 1.92 TeV		1410.4103
	LRSM $W'_R \to tb$	0 e, μ	≥ 1 b, 1 J	–	20.3	W' mass 1.76 TeV		1408.0886
CI	CI $qqqq$	–	2 j	–	15.7	Λ 19.9 TeV	$\eta_{LL} = -1$	ATLAS-CONF-2016-069
	CI $\ell\ell qq$	2 e, μ	–	–	3.2	Λ 25.2 TeV	$\eta_{LL} = -1$	1607.03669
	CI $uutt$	2(SS)/≥3 e, μ	≥1 b, ≥1 j	Yes	20.3	Λ 4.9 TeV	$\lvert C_{RR}\rvert = 1$	1504.04605
DM	Axial-vector mediator (Dirac DM)	0 e, μ	≥ 1 j	Yes	3.2	m_A 1.0 TeV	g_q=0.25, g_χ=1.0, $m(\chi) < 250$ GeV	1604.07773
	Axial-vector mediator (Dirac DM)	0 e, μ, 1 γ	1 j	Yes	3.2	m_A 710 GeV	g_q=0.25, g_χ=1.0, $m(\chi) < 150$ GeV	1604.01306
	$ZZ\chi\chi$ EFT (Dirac DM)	0 e, μ	1 J, ≤ 1 j	Yes	3.2	M_* 550 GeV	$m(\chi) < 150$ GeV	ATLAS-CONF-2015-080
LQ	Scalar LQ 1st gen	2 e	≥ 2 j	–	3.2	LQ mass 1.1 TeV	$\beta = 1$	1605.06035
	Scalar LQ 2nd gen	2 μ	≥ 2 j	–	3.2	LQ mass 1.05 TeV	$\beta = 1$	1605.06035
	Scalar LQ 3rd gen	1 e, μ	≥1 b, ≥3 j	Yes	20.3	LQ mass 640 GeV	$\beta = 0$	1508.04735
Heavy quarks	VLQ $TT \to Ht + X$	1 e, μ	≥ 2 b, ≥ 3 j	Yes	20.3	T mass 855 GeV	T in (T,B) doublet	1505.04306
	VLQ $YY \to Wb + X$	1 e, μ	≥ 1 b, ≥ 3 j	Yes	20.3	Y mass 770 GeV	Y in (B,Y) doublet	1505.04306
	VLQ $BB \to Hb + X$	1 e, μ	≥ 2 b, ≥ 3 j	Yes	20.3	B mass 735 GeV	isospin singlet	1505.04306
	VLQ $BB \to Zb + X$	2/≥3 e, μ	≥2/≥1 b	–	20.3	B mass 755 GeV	B in (B,Y) doublet	1409.5500
	VLQ $QQ \to WqWq$	1 e, μ	≥ 4 j	Yes	20.3	Q mass 690 GeV		1509.04261
	VLQ $T_{5/3}T_{5/3} \to WtWt$	2(SS)/≥3 e, μ	≥1 b, ≥1 j	Yes	3.2	$T_{5/3}$ mass 990 GeV		ATLAS-CONF-2016-032
Excited fermions	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	3.2	q^* mass 4.4 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1512.05910
	Excited quark $q^* \to qg$	–	2 j	–	15.7	q^* mass 5.6 TeV	only u^* and d^*, $\Lambda = m(q^*)$	ATLAS-CONF-2016-069
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	8.8	b^* mass 2.3 TeV		ATLAS-CONF-2016-060
	Excited quark $b^* \to Wt$	1 or 2 e, μ	1 b, 2-0 j	Yes	20.3	b^* mass 1.5 TeV	$f_g = f_L = f_R = 1$	1510.02664
	Excited lepton ℓ^*	3 e, μ	–	–	20.3	ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e, μ, τ	–	–	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	LSTC $a_T \to W\gamma$	1 e, μ, 1 γ	–	Yes	20.3	a_T mass 960 GeV		1407.8150
	LRSM Majorana ν	2 e, μ	2 j	–	20.3	N^0 mass 2.0 TeV	$m(W_R) = 2.4$ TeV, no mixing	1506.06020
	Higgs triplet $H^{\pm\pm} \to ee$	2 e (SS)	–	–	13.9	$H^{\pm\pm}$ mass 570 GeV	DY production, BR($H_L^{\pm\pm} \to ee$)=1	ATLAS-CONF-2016-051
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	3 e, μ, τ	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, BR($H_L^{\pm\pm} \to \ell\tau$)=1	1411.2921
	Monotop (non-res prod)	1 e, μ	1 b	Yes	20.3	spin-1 invisible particle mass 657 GeV	$a_{non-res} = 0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	multi-charged particle mass 785 GeV	DY production, $\lvert q\rvert = 5e$	1504.04188
	Magnetic monopoles	–	–	–	7.0	monopole mass 1.34 TeV	DY production, $\lvert g\rvert = 1g_D$, spin 1/2	1509.08059

$\sqrt{s}$ = 8 TeV $\sqrt{s}$ = 13 TeV

10^{-1} 1 10 **Mass scale [TeV]**

*Only a selection of the available mass limits on new states or phenomena is shown. Lower bounds are specified only when explicitly not excluded.

†Small-radius (large-radius) jets are denoted by the letter j (J).

incorporating gravity into the SM

carrying the SM into the **classical** curved spacetime is **inconsistent**

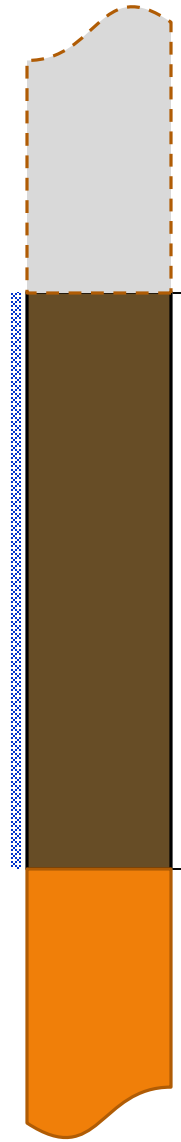
carrying the SM into **quantized** curved spacetime would be ideal but the latter is too **distant** to be of help

carrying the **effective** SM into **classical** curved spacetime seems to be a viable option

http://www.mysearch.org.uk/

"quantum trains" can't move on "classical spaces". only "barely-fluctuating (effective) trains" can.

the SM effective action



around the fundamental scale of gravity

the SM effective action at Λ_W

"classical" action with quantum-corrected couplings and masses

the SM effective action

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

"natural"

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

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

"unnatural"

all gauge symmetries are broken explicitly !

adding curvature as usual

$$S^1_\Lambda(\eta) \xrightarrow[\text{comma}\to\text{semicolon}]{\eta_{\mu\nu}\prec g_{\mu\nu}} \int d^4x\sqrt{\|g\|}c_V\Lambda^2 g_{\mu\nu}\mathrm{Tr}\{V^\mu V^\nu\}$$

$$\xrightarrow{\text{add curvature}} \int d^4x\sqrt{\|g\|}\Big[c_V\Lambda^2 g_{\mu\nu}\mathrm{Tr}\{V^\mu V^\nu\} + M^2R(g) + V + c_R R(g)^2 + \dots\Big]$$

the problem remains and diversifies !

incalculable unknown coefficients

adding curvature by gauge invariance

$$S^1_\Lambda(\eta) = S^1_\Lambda(\eta) - \int d^4x \sqrt{\|\eta\|}\frac{c_V}{2}\mathrm{Tr}\left\{\eta_{\mu\alpha}\eta_{\nu\beta}V^{\mu\nu}V^{\alpha\beta}\right\} + \int d^4x \sqrt{\|\eta\|}\frac{c_V}{2}\mathrm{Tr}\left\{\eta_{\mu\alpha}\eta_{\nu\beta}V^{\mu\nu}V^{\alpha\beta}\right\}$$

$$\overset{\text{by-parts}}{=\!=\!=} \quad -\int d^4x \sqrt{\|\eta\|}\frac{c_V}{2}\mathrm{Tr}\{\eta_{\mu\alpha}\eta_{\nu\beta}V^{\mu\nu}V^{\alpha\beta}\}$$

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

$$+ \quad \int d^4x \sqrt{\|\eta\|}c_V\mathrm{Tr}\{D_\mu\left(\eta_{\alpha\beta}V^\alpha V^{\beta\mu}\right)\}$$

$$\overset{\eta_{\mu\nu}\prec g_{\mu\nu}}{\underset{\text{comma}\to\text{semicolon}}{=\!=\!=}} \quad -\int d^4x \sqrt{\|g\|}\frac{c_V}{2}\mathrm{Tr}\{g_{\mu\alpha}g_{\nu\beta}V^{\mu\nu}V^{\alpha\beta}\}$$

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

$$+ \quad \int d^4x \sqrt{\|g\|}c_V\mathrm{Tr}\{\mathcal{D}_\mu\left(g_{\alpha\beta}V^\alpha V^{\beta\mu}\right)\}$$

$$\xrightarrow[\text{gauge invariance}]{\Lambda^2 g_{\mu\nu}\prec R_{\mu\nu}({}^g\Gamma)} \quad -\int d^4x \sqrt{\|g\|}\frac{c_V}{2}\mathrm{Tr}\{g_{\mu\alpha}g_{\nu\beta}V^{\mu\nu}V^{\alpha\beta}\}$$

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

$$+ \quad \int d^4x \sqrt{\|g\|}c_V\mathrm{Tr}\{\mathcal{D}_\mu\left(g_{\alpha\beta}V^\alpha V^{\beta\mu}\right)\}$$

$$\overset{\text{by-parts back}}{=\!=\!=} -\int d^4x \sqrt{\|g\|}\frac{c_V}{2}\mathrm{Tr}\{g_{\mu\alpha}g_{\nu\beta}V^{\mu\nu}V^{\alpha\beta}\} + \int d^4x \sqrt{\|g\|}\frac{c_V}{2}\mathrm{Tr}\{g_{\mu\alpha}g_{\nu\beta}V^{\mu\nu}V^{\alpha\beta}\}$$

$$= \quad 0$$

adding curvature by gauge invariance

What happened is this:

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

$S^1_\Lambda(\eta)$ is eradicated !

gauge symmetries are restored at the UV!

a way is revealed for carrying the SM into curved spacetime!

taking the SM into curved spacetime

the SM in curved spacetime must involve:

no extra couplings not found in $S(\eta, \Lambda)$ as no quantum loops are left to induce any new coupling

no curvature-free term as curved geometry must disappear as soon as quantum corrections are removed:

$$\tilde{S}^0_\Lambda(g, R)\Big|_{R=0} = S^0_\Lambda(\eta)\Big|_{\Lambda=0}$$

no new forces other than gravity as spacetime can attain required elasticity if Λ nears M_{Pl}

the SM in curved spacetime

the SM effective action in curved spacetime:

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

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!)

need to New Physics

There is a crucial problem:

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

the SM spectrum alone leads to "repulsive" gravity!

some NP is needed to make gravity "attractive"

the NP does not have to interact with the SM !

particle spectrum of the NP

$$\tilde{S}_{SM+NP}(g, R, \Lambda) = \int d^4x \sqrt{\|g\|} \left(\tfrac{1}{2} M_{Pl}^2 R + \cdots\right)$$

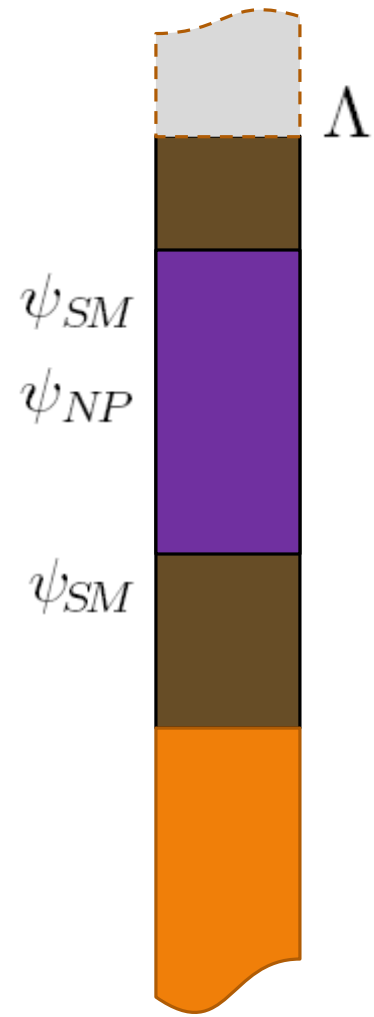
$$M_{Pl}^2 \cong \tfrac{1}{2}\left(a + a^{NP}\right)\Lambda^2$$

gravity attracts if:

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

$\Lambda < M_{Pl}$ provided that

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



log-naturalness constraints on the NP

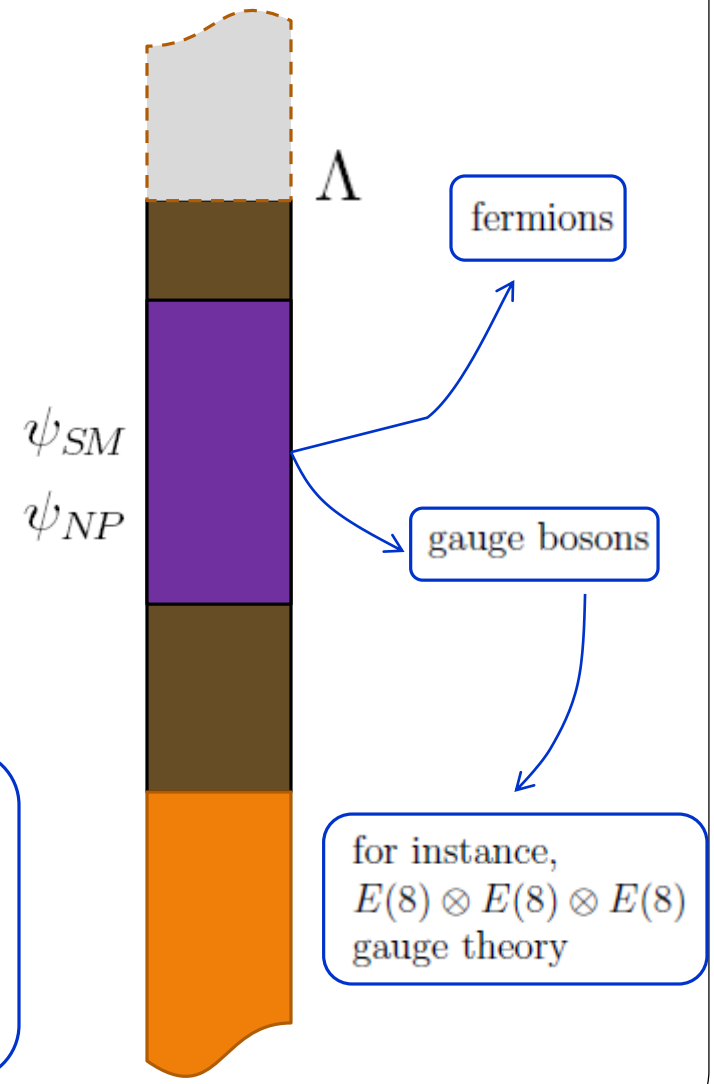
Scalars $S \in NP$ give rise to

$$\delta m_h^2 \propto m_S^2 \log \frac{\Lambda}{m_S}$$

which destabilize the SM unless $m_S \simeq \Lambda_W$!

But, the LHC didn't see any new particle!

- No scalars in the NP!
- No vector-like fermions in the NP!
- No singlet vectors in the NP!



natural setup

The eventual setup is both UV-natural and log-natural:

$$\tilde{S}_{SM+NP}(g, R, \Lambda) = S_{G_F}(g, \psi_{SM}, \log(G_F\Lambda^2))$$
$$+ S_{G_{NP}}(g, \psi_{NP}, \log(G_{NP}\Lambda^2))$$
$$+ \int d^4x \sqrt{\|g\|}\left(\tfrac{1}{2}M_{Pl}^2 R(g) + \zeta_H R(g) H^\dagger H\right)$$

possible to reinterpret within Dim. Reg. by making the identification

$$\log(G_F\Lambda^2) \equiv 2/\epsilon + \log G_F\mu^2$$

in momentum space of dimension $D = 4 - \epsilon$ and volume $\mu^{2\epsilon}\infty^{4-2\epsilon}$

$$\zeta_H = (b + b^{NP})/4$$

inflation

An SU(2) gauge field in the NP leads to successful inflation:

$$S_{G_{NP}}(g, \psi_{NP}, \log(G_{NP}\Lambda^2)) \ni$$

$$\int d^4x \sqrt{\|g\|}\Big(-\tfrac{1}{2}\mathrm{Tr}\left\{F_{\mu\nu}F^{\mu\nu}\right\} + \tfrac{1}{\Lambda^4}\left(\mathrm{Tr}\left\{F_{\mu\nu}\tilde{F}^{\mu\nu}\right\}\right)^2\Big)$$

$$\Lambda \approx 1.7 \times 10^{-3} M_{Pl}$$

a matter of $n_b^{NP} - n_f^{NP}$

Sheikh-Jabbari & Maleknejad, 2011

the Dark Matter

Singlet fermions in the NP form a distinctive source for cold Dark Matter:

$$S_{G_{NP}}(g, \psi_{NP}, \log(G_{NP}\Lambda^2)) \ni \int d^4x \sqrt{\|g\|}\left(\overline{\chi}\gamma^\mu \nabla_\mu \chi - m\overline{\chi}\chi\right)$$

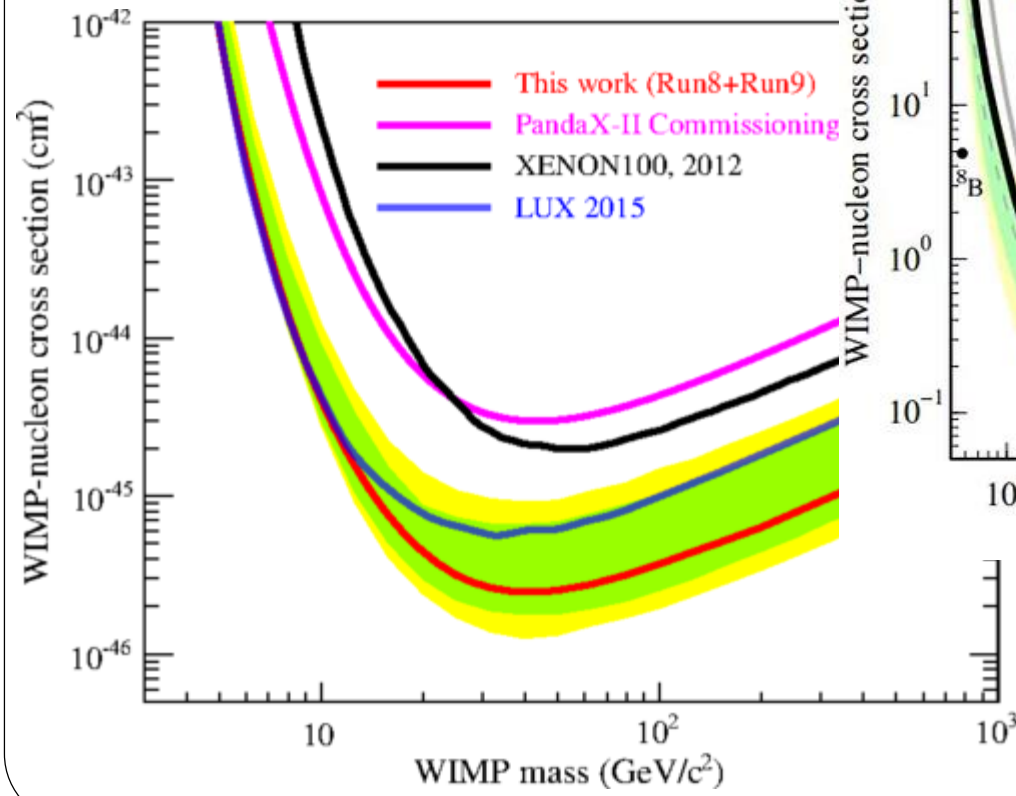
no way to interact with the SM !

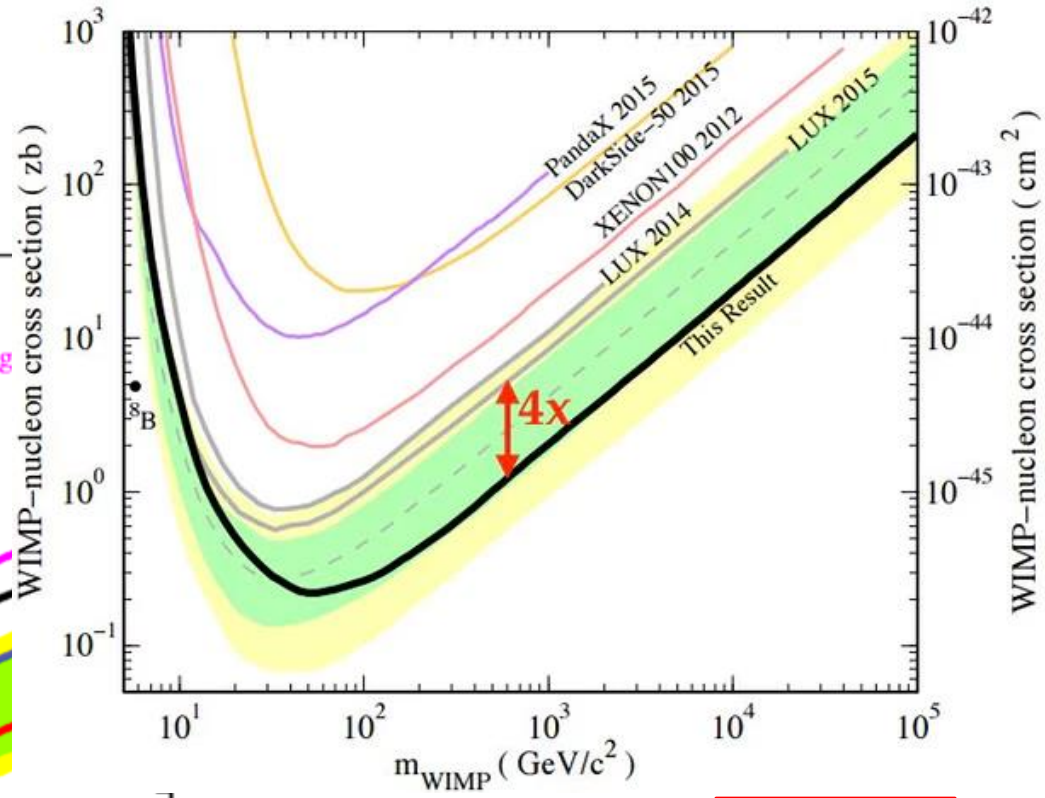
a non-interacting DM revealing itself only gravitationally?

Peebles & Vilenkin, 1999

the Dark Matter

Direct detection experiments constantly return negative results. The DM might indeed be non-interacting (ebony matter).





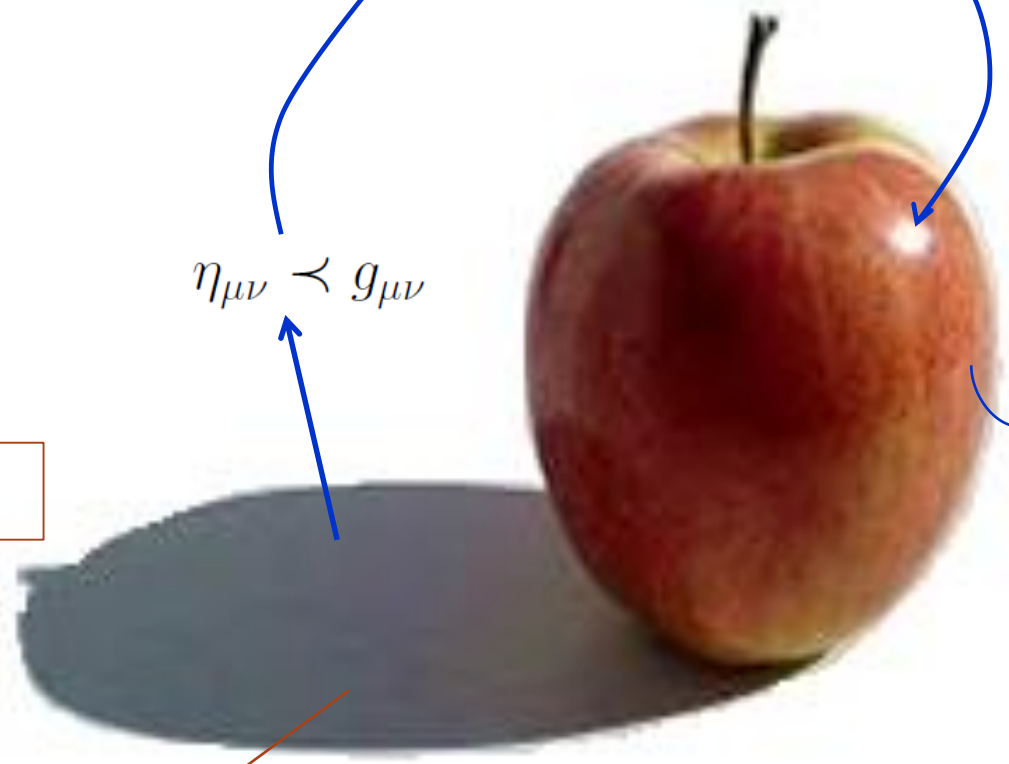
LUX, 2016

PANDAX, 2016

summary/conclusion

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

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



SM + NP

- ✓ natural
- ✓ exact gauge symmetry
- ✓ gravity
- ✓ dark matter
- ✓ inflaton
- ✓ ν-size CC
- ✓ new (½, 1) at colliders

SM

- unnatural
- broken gauge symmetry
- no gravity
- no dark matter

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)

Report number: IZTECH-HEP-04/2015

Cite as: **arXiv:1510.05570 [hep-ph]**

the 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]**

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Thank you ! Questions?