Partial Gauge Invariant SM

Spontaneous Lorentz Violation (SLV)- Physical and Astrophysical Consequences

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Basic Motivation for SLV

To provide a dynamical approach
to QED, gravity and Yang-Mills theories
with photon, graviton and non-Abelian gauge fields
appearing as massless Nambu-Goldstone bosons

How to introduce Lorentz Violation

$$V = \lambda\left(A_\mu^2 - M^2 n_\mu^2\right)^2$$

M Lorentz violation scale

n_μ Lorentz violation direction In the space-time

$$SO(1,3) \rightarrow SO(3) \quad or \quad SO(1,2)$$

- Higgs Mode is very heavy, but conveniently we can exclude it in the non-linear sigma model limit

$$A_\mu^2 = M^2 n_\mu^2$$

- Goldstone mode

$$A_\mu = a_\mu + \frac{n_\mu}{n_\mu^2}(n^\nu A_\nu)$$

a_μ is pure goldstone mode $a_\mu n^\mu = 0$

How to observe SLV ?

- Via Higgs mode

It is extremely heavy and therefore unobservable in low energies

- Via Goldstone modes

Despite the fact that theory is non-linear and there are Lorentz violating interaction, physical Lorentz violation does not exist and SLV manifests itself only in axial gauge choice.

One can even postulate gauge invariance as a condition of non-existence of physical LV.

Physical Lorentz Violation

Partial gauge invariance

QED example:

$$L(A,\psi) \;=\; -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \overline{\psi}[i\gamma_\mu D^\mu - m_0]\psi + \frac{1}{\mathcal{M}} D'^{*}_{\mu}\overline{\psi}\cdot D'^{\mu}\psi$$

$$D^\mu \;\equiv\; \partial^\mu + ieA^\mu \qquad\qquad D'^\mu \equiv \partial^\mu + ie'A^\mu$$

$$p_\mu^2 \cong [m+2\delta(p_\mu n^\mu/n^2)]^2 \qquad\qquad \delta^2\mathcal{M} \le m_e$$

$$m = m_0 - \delta^2 n^2 \mathcal{M} \qquad \Longrightarrow \qquad |\delta| \le \overline{\delta} \equiv \sqrt{m_e/\mathcal{M}}$$

$$\delta \equiv (\Delta e)M/\mathcal{M} \qquad\qquad = 6.5\times 10^{-12}$$

Some immediate applications

- Effective masses

$$m_f^* \equiv \sqrt{p_\mu^2} \cong |m_f + 2\delta_f p_0|\,, \quad \delta_f = \delta_f \quad or \ \delta_f = \delta_f \cos\theta$$

- GZK cuttof revised $(p + \gamma \to \Delta \to \quad p + \gamma)$

$$E_p > \frac{m_\Delta^2 - m_p^2}{4[\omega - \delta(m_\Delta - m_p)]} = \frac{6.8}{\omega/\overline{\omega} - 8.1\delta/\overline{\delta}} \times 10^{20} eV$$

- Stable mesons $(m_\pi^* < m_\mu^*)$

$$E_\pi > \frac{1}{2}\frac{m_\pi - m_\mu}{\delta_\mu - \delta_\pi} \sim 10^{19} eV$$

- Partially gauge invariant term for SM

$$\mathcal{L}_{ENSM} = \mathcal{L}_{SM} + \frac{B_\mu B_\nu}{M_P^2}(\alpha_f T_f^{\mu\nu} + \alpha_g T_g^{\mu\nu} + \alpha_h T_h^{\mu\nu})$$

The “Gravity type” high dimension operator is suppressed by the Planck mass but being triggered by the hypercharge gauge field VEV may become significant at the high scale

→ The coupling constants for fermions, gauge and Higgs bosons being equal at the Planck scale becomes different when running to lower energies

Modified dispersion relations

- **Fermions**

In terms of shifted momentum

$$p'_\mu = p_\mu + \delta_f (n \bullet p) n_\mu \qquad \delta_f = \alpha_f (M^2 / M_P^2)$$

modified Dirac equation

$$(\gamma \bullet p' + m) u_\nu (p) = 0$$

gives $$p'^2_\mu = m^2$$

- **Vector bosons**

$$k^2 + 2\delta_g (n \cdot k)^2 = M_i^2 \ , \ \delta_g = \alpha_g (M^2/M_P^2) \ \ , \ i = \gamma, Z, W.$$

- **SM Higgs boson**

$$k^2 + 2\delta_h (n \cdot k)^2 = \mu_h^2 \ , \ \delta_h = \alpha_h (M^2/M_P^2)$$

• Some direct SLV consequences in SM

• **Weak boson stability**

$$W = \frac{g^2(1+g_v'^2)}{192\pi\cos^2\theta_w}\sqrt{M_{ef}^2}\ , \quad M_{ef}^2 \simeq M_z^2 - 2\delta_g(n_\nu k^\nu)^2 + 2\delta_f(n_\nu k^\nu)^2$$

• **Photon decay**

$$W = \frac{e^2}{12\pi}M_{ef} = \frac{e^2}{12\pi}\sqrt{2\delta}\,k_0\ , \quad \delta = (\delta_f - \delta_g) \ \text{ or } \ \delta = (\delta_f - \delta_g)\cos^2\varphi$$

• **Modified GZK cuttof** $(p+\gamma \to \Delta \to \ \ p+\gamma)$

$$E > \frac{m_\Delta^2 - m_p^2}{2\omega + \sqrt{4\omega^2 + 2(\delta_\Delta - \delta_p)(m_\Delta^2 - m_p^2)}}\ ,$$

$$(\delta_\Delta - \delta_p) \xrightarrow{space-like\ violation} (\delta_\Delta - \delta_p)\cos^2\theta$$

So, if $\delta_p - \delta_\Delta > \dfrac{2\omega^2}{m_\Delta^2 - m_p^2}$ cuttof does not exist or

depends on the orientation of the proton 3-momentum (space-like SLV)

Conclusion

- Photons (generally other gauge bosons) can well be treated as 4D space-time massless vector Goldstone bosons.

- Such emergent gauge invariance hides the physical Lorentz violation and disables some generic features of the Standard Model, which otherwise manifest themselves at high energies, if there appears non exact or partial gauge invariance. One may expect that quantum gravity could in general hinder the setting of arbitrary initial conditions at extra-small distances thus admitting superfluous restriction of vector fields. This eventually, through some high-order operators, would manifest itself in (partial) violation of gauge invariance.

- Phenomenologically, the physical SLV consequences might well be expected at energies $10^{18} - 10^{20}\ eV$ *(present* cosmic ray physics range). Lots of new effects in HE physics and astrophysics are predicted

Thanks for attention