What Comes Beyond the Standard Models?
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Emergent Gauge Theories:

What Can We Learn From Spontaneous Lorentz Violation ?

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Abstract

It is well known that spontaneous Lorentz violation (SLV) may lead to an emergence of massless Nambu-Goldstone modes which are identified with photons and other gauge fields appearing in the Standard Model. We will review a present status of emergent gauge theories including non-Abelian gauge fields and tensor field gravity. A special line is related to supersymmetry playing an important role in the latest developments that is partially illustrated by the supersymmetric QED example. We argue that a generic trigger for massless gauge fields to dynamically emerge could be spontaneously broken supersymmetry rather than physically manifested Lorentz noninvariance. We consider supersymmetric QED model extended by an arbitrary polynomial potential of massive vector superfield that induces the spontaneous SUSY violation in the visible sector. As a consequence, massless photon appears as a companion of massless photino which emerges in fact as the Goldstone fermion state in the tree approximation. Remarkably, the photon masslessness appearing at the tree level is further protected against radiative corrections by the simultaneously generated special gauge invariance. Meanwhile, photino being mixed with another goldstino emerging from a spontaneous SUSY violation in the hidden sector largely turns into the light pseudo-goldstino. Such pseudo-goldstonic photino appears typically as the eV scale stable LSP or the electroweak scale long-lived NLSP, being in both cases accompanied by a very light gravitino, that could be considered as some observational signature in favor of emergent SUSY theories.

Basic motivation
for
Spontaneous Lorentz Violation:

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

started in	J.D. Bjorken, Ann. Phys. (N.Y.) 24 (1963) 174	QED
	P.R. Phillips, Phys. Rev. 146 (1966) 966	GR
	T. Eguchi, Phys. Rev. D 14 (1976) 2755	YM

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Some papers

1. J.L. Chkareuli, C.D. Froggatt, H.B. Nielsen*, LORENTZ INVARIANCE AND ORIGIN OF SYMMETRIES, Phys.Rev.Lett. 87:091601, 2001; ArXiv: hep-ph/0106036.*

2. J.L. Chkareuli, C.D. Froggatt, R.N. Mohapatra, H.B. Nielsen*, PHOTON AS A VECTOR GOLDSTONE BOSON: NONLINEAR SIGMA MODEL FOR QED, ArXiv: hep-th/0412225 (2004).*

3. A.T. Azatov, J.L. Chkareuli, *NONLINEAR QED AND PHYSICAL LORENTZ INVARIANCE, Phys. Rev. D73:065026 (2006); ArXiv: hep-th/0511178.*

4. J.L. Chkareuli, C.D. Froggatt, J.G. Jejelava, H.B. Nielsen*, CONSTRAINED GAUGE FIELDS FROM SPONTANEOUS LORENTZ VIOLATION, Nucl. Phys. B 796:211-223, 2008; ArXiv:0710.3479 [hep-th].*

5. J.L. Chkareuli, J.G. Jejelava, *SPONTANEOUS LORENTZ VIOLATION: NON-ABELIAN GAUGE FIELDS AS PSEUDO-GOLDSTONE VECTOR BOSONS, Phys. Lett. B659:754-760, 2008; ArXiv:0704.0553 [hep-th].*

6. J.L. Chkareuli, C.D. Froggatt, H.B. Nielsen, *DERIVING GAUGE SYMMETRY AND SPONTANEOUS LORENTZ VIOLATION, Nucl. Phys. B821:65-73,2009; ArXiv:hep-th/0610186.*

7. **J.L. Chkareuli, Archil Kobakhidze, Ray Volkas, *VECTOR FIELD DOMAIN WALLS, Phys. Rev. D80:065008, 2009; ArXiv:0901.0796 [hep-th].***

8. J.L. Chkareuli, C.D. Froggatt, H.B. Nielsen, *SPONTANEOUSLY GENERATED TENSOR FIELD GRAVITY, Nucl. Phys. B848: 498-522, 2011; ArXiv:1102.5440 [hep-th].*

9. J.L. Chkareuli, *EMERGENT GAUGE THEORIES AND SUPERSYMMETRY: A QED PRIMER, Phys. Lett. B 721 (2013) 146; ArXiv:1212.6939 [hep-th].*

10. J.L. Chkareuli, *GAUGE FIELDS AS GOLDSTONE BOSONS TRIGGERED BY SPONTANEOUSLY BROKEN SUPERSYMMETRY, JHEP (2013, in press); Arxiv: 1305.6898 [hep-th].*

I. Phenomenology (how might it work ?)

1. Spatial Parity

Weyl fermions $\Psi_{R,L} = \frac{1 \pm \gamma_5}{2} \Psi$ and neutrinos:

$$S_{R,L} = \frac{\overrightarrow{\sigma} \cdot \overrightarrow{p}}{|\overrightarrow{p}|} = \pm 1/2 \rightarrow \begin{pmatrix} ? \\ \nu_L \end{pmatrix}$$

PV :

$$\nu_L \rightarrow \nu_R \ (?)$$

Neutrino goes unseen in a mirror!

2. Relativistic invariance

$$E^2/c^2 - \overrightarrow{p}^2 = m^2c^2 \qquad or$$

$$p_\mu^2 = m^2 \qquad (c = 1)$$

LV dispersion relation:

$$p_\mu^2 = [m + \delta(n \cdot p)]^2$$

Present data: $\delta \leq 10^{-(10\div 11)}$

II. Motivation (why might it work ?)

1. 3D Space symmetry breaking case

Heisenberg ferromagnetism : $O(3) \rightarrow O(2)$

$J^{\pm}$- magnons

2. 4D Space-Time symmetry breaking:

$$SO(1,3) \rightarrow SO(3) \text{ or}$$
$$SO(1,3) \rightarrow SO(1,2)$$

Photons as 4D ST magnons (!)

3. Space-Time sigma-model

$$A_\mu^2 \equiv A_0^2 - A_i^2 = M^2 \quad\quad vs \quad \sigma^2 + \vec{\pi}^2 = f_\pi^2$$

Just as in the pion chiral dynamics one can deal with only Goldstone modes

Nambu, 1968; JC-Froggatt-Mohapatra-Nielsen, 2004

$$A_\mu = a_\mu + \frac{n_\mu}{n^2}(M^2 - n^2 a_\nu^2)^{\frac{1}{2}}, \ n_\mu a^\mu = 0$$

Does it mean that the SLV modes are really collected into physical photon or there are in general three separate massless Goldstone modes, two of which may mimic the transverse photon polarizations, while the third one must be appropriately suppressed?

III. Theoretical framework

1. The "Goldstone-gauging" theorem

JC-Froggat-Nielsen, 2006

$$L(\psi, A, ...) = L_? + \lambda(x)(A_\mu^2 - M^2)^2$$

For general relativistic Lagrangian

$$L_? \to L_{QED} \quad or \qquad L_{YM}$$

if one requires that vector fields NOT to be superfluously restricted (Caushy problem in classical theory, ETC problem in quantum case)

i. **Single-vector field case** with constraint $A_\mu^2 = M^2$

(no more constraints are allowed)

$$\partial_\mu\left(\frac{\partial L}{\partial A_\mu} - \partial_\nu\frac{\partial L}{\partial(\partial_\nu A_\mu)}\right) \equiv \left(\frac{\partial L}{\partial A_\mu} - \partial_\nu\frac{\partial L}{\partial(\partial_\nu A_\mu)}\right)(c)A_\mu + \\ + \left(\frac{\partial L}{\partial \psi} - \partial_\nu\frac{\partial L}{\partial(\partial_\nu \psi)}\right)(it)\psi + \\ + \overline{\psi}(-it)\left(\frac{\partial L}{\partial \overline{\psi}} - \partial_\nu\frac{\partial L}{\partial(\partial_\nu \overline{\psi})}\right).$$

$$\Downarrow$$

Invariance under transformations (the Noether's 2nd theorem)

$\delta A_\mu = \partial_\mu\omega + c\omega A_\mu \ (c = 0)$, $\delta\psi = it\omega\psi$

ii. **Vector field multiplet** A_μ^α (non-Abelian global symmetry G) with the SLV constraint A_μ^α

$$\mathrm{Tr}(\mathsf{A}_\mu A^\mu) = n^2 M^2, \quad \alpha = 1, 2, ..., D$$

Together with the SLV constraint there would be in general $D+1$ constraints (while only D constraints are allowed) for the vector field multiplet A_μ^α unless

$$\begin{aligned}
\partial_\mu \left(\frac{\partial \mathcal{L}}{\partial A_\mu^\alpha} - \partial_\nu \frac{\partial \mathcal{L}}{\partial(\partial_\nu A_\mu^\alpha)} \right) \equiv & \left(\frac{\partial \mathcal{L}}{\partial A_\mu^\beta} - \partial_\nu \frac{\partial \mathcal{L}}{\partial(\partial_\nu A_\mu^\beta)} \right) C_{\alpha\beta\gamma} A_\mu^\gamma + \\
& + \left(\frac{\partial \mathcal{L}}{\partial \psi} - \partial_\nu \frac{\partial \mathcal{L}}{\partial(\partial_\nu \psi)} \right) (iT_\alpha)\psi + \\
& + \overline{\psi}(-iT_\alpha) \left(\frac{\partial \mathcal{L}}{\partial \overline{\psi}} - \partial_\nu \frac{\partial \mathcal{L}}{\partial(\partial_\nu \overline{\psi})} \right).
\end{aligned}$$

$$\Downarrow$$

Invariance under transformations (the Noether's 2nd theorem)

$$\delta A_\mu^\alpha = \partial_\mu \omega^\alpha + C_{\alpha\beta\gamma}\omega^\beta A_\mu^\gamma, \quad \delta\psi \ = iT_\alpha \omega^\alpha \psi$$

iii. **Yang-Mills fields as pseudo-Goldstones**

Symmetry of YM Lagrangian

$\mathsf{L}(\mathsf{A}_\mu, \psi) \quad \Leftrightarrow \ SO(1,3) \times G$

Symmetry of constraint

$\mathrm{Tr}(\mathsf{A}_\mu A^\mu) = n^2 M^2 \Leftrightarrow \ SO(D, 3D)$

SLV $\ \mathsf{A}^\alpha_\mu(x) > \ = n^\alpha_\mu M$:

$SO(D,3D) \to SO(D-1,3D)/SO(D,3D-1)$

Spectrum: $4D-1$ massless Goldstone states

1 True GVB + (D-1) PGVBs + (D-1) scalars

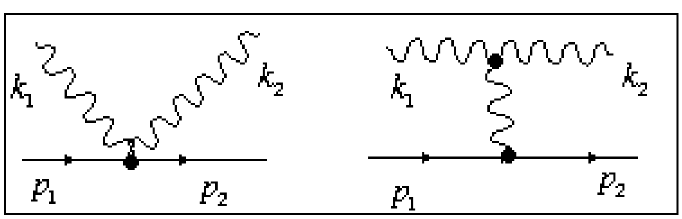
PGVBs remain strictly massless being protected by the simultaneously generated non-Abelian gauge invariance (just complete altogether the whole gauge field multiplet of the internal symmetry group G)

2. Nonlinear Goldstone-type theories

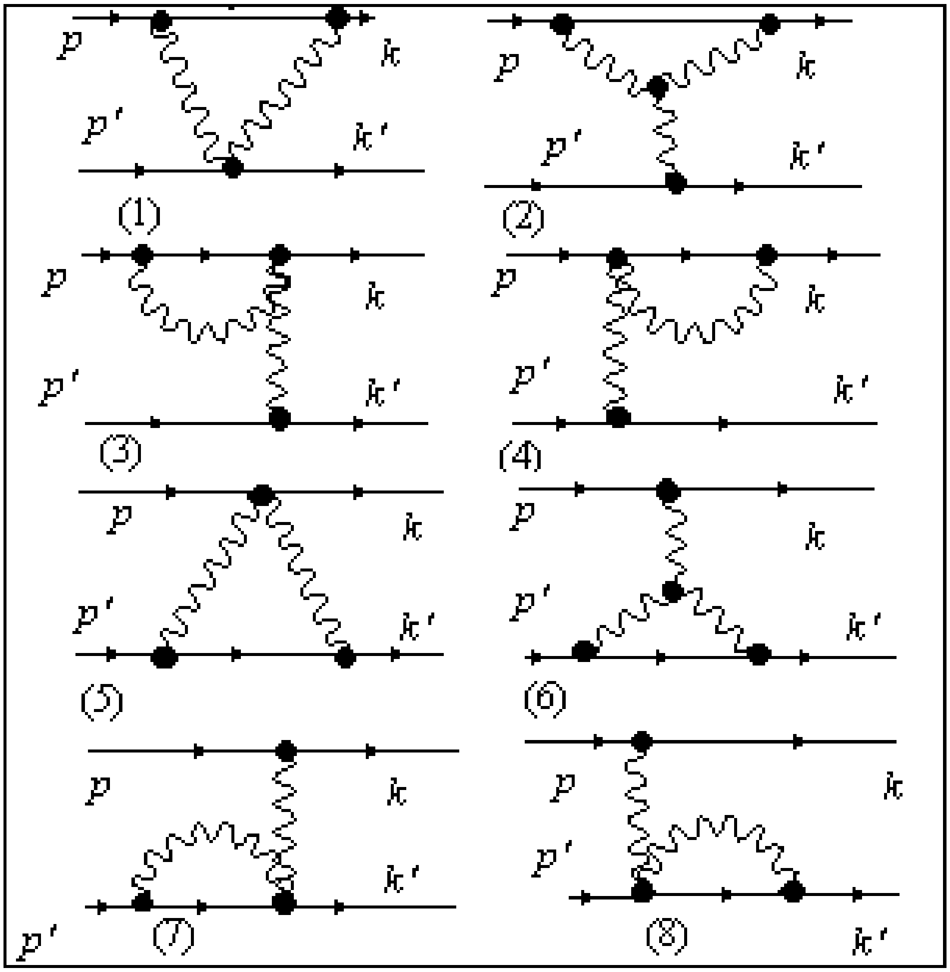
$$\mathsf{L}(\mathsf{a}_\mu, \psi) = L_{QED} - \frac{1}{2}\delta(n\cdot a)^2 -$$

$$- \ \frac{1}{2} f_{\mu\nu}^{(a)} (n^\mu \partial^\nu - n^\nu \partial^\mu) \frac{n^2 a^2}{2M} +$$
$$+ \ \ e\overline{\psi}(\gamma \cdot n)\psi \frac{n^2 a^2}{2M} + \cdots$$

For the starting gauge invariant theory the SLV constraint $A_\mu^2 = M^2$ appears as the gauge-fixing condition no leading to the physical Lorentz violation:



The SLV contribution to the Compton effect in the tree approximation (in the order of O($\frac{e}{M}$)) Nambu, 1968



The SLV contribution to the $e - e'$ scattering in the one-loop approximation (in the order of O($\frac{e^3}{M}$))
JC-A.Azatov-J.Jejelava-Z.Kepuladze, 2005

IV. Looking for physical Lorentz non-invariance - 5 steps

(1) While the photon seems to have a true Goldstonic nature, the physical Lorentz violation is still preserved due to internal gauge symmetry involved.

(2) Actually, gauge invariance in the Goldstonic QED appears in essence as a necessary condition for the starting vector field *A* not to be superfluously restricted in degrees of freedom, apart from the SLV constraint

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

due to which the true vacuum in the theory is chosen.

(3) For any extra restriction(s) imposed on the vector field it would be impossible to set the required initial conditions in the appropriate Cauchy problem and, in quantum theory, to choose self-consistent equal-time commutation relations.

(4) One may expect, however, that quantum gravity could in general hinder the setting of arbitrary initial conditions at extra-small distances thus admitting superfluous restriction of the starting vector field *A*.

(5) This eventually, through some high-order operators, would manifest itself in violation of the gauge invariance (while masslessness of photon being guarantied by SLV).

1. QED with non-exact gauge invariance

$$L(\psi) = \overline{\psi}(i\gamma_\mu\partial^\mu - m_0)\psi + \frac{1}{\mathcal{M}}\partial_\mu\overline{\psi}\cdot\partial^\mu\psi$$

$$\Downarrow$$

$$\begin{aligned} L\,(A,\psi) &= -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \overline{\psi}[i\gamma_\mu D^\mu - m_0]\psi + \frac{1}{\mathcal{M}}D'^{*}_{\mu}\overline{\psi}\cdot D'^{\mu}\psi \\ D^\mu &\equiv \partial^\mu + ieA^\mu, \qquad\qquad D'^\mu \equiv \partial^\mu + ie'A^\mu \end{aligned}$$

$$\Downarrow$$

$$\begin{aligned} \mathcal{L}\,(a_\mu,\psi) &= L(A_\mu \to a_\mu + n_\mu(a^2/2M + \cdots),\psi) + \\ & -i\Delta e\frac{M}{\mathcal{M}}\frac{n_\mu}{n^2}\overline{\psi}\partial^\mu\psi + (\Delta e)^2 n^2\frac{M^2}{\mathcal{M}}\overline{\psi}\psi \end{aligned}$$

$$\Downarrow$$

$$p_\mu^2 \cong [m+2\delta(p_\mu n^\mu/n^2)]^2, \quad m = m_0-\delta^2 n^2\mathcal{M}, \quad \delta \equiv (\Delta e)M/\mathcal{M}$$

$$\Downarrow$$

$$\delta^2\mathcal{M} \leq m_e, \quad |\delta| \leq \overline{\delta} \equiv \sqrt{m_e/\mathcal{M}} = 6.5\times 10^{-12}$$

2. Some immediate applications

i. Effective masses

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

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

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

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

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

iv. Modified nucleon decays (stable neutrons)

$$E > \frac{m_n - m_p}{2(\delta_p - \delta_n)} = \frac{m_n - m_p}{2(\delta_u - \delta_d)} \sim 10^{18} eV$$

V. Alternative SUSY Scenario

1. Where SLV and Goldstonic QED may really come from?

2. Are Goldstonic QED and standard QED the same theory?

3. May massless photon simply be other massless particle companion?

4. What might offer SUSY?

Extending SUSY QED to

$$
\begin{aligned}
L &= L_{SQED} + \left(\sum_n a_n V^n\right)_D = \\
&= U\left(D + \frac{1}{2}\partial^2 C\right) + \\
&\quad + U'_C\left(\frac{1}{2}RR^* - \frac{1}{2}A_\mu^2 - \frac{i}{2}\chi\sigma\partial\overline{\chi} - \lambda\chi - \overline{\lambda}\overline{\chi}\right) + \\
&\quad + U''_C/2\left(\frac{i}{2}R\overline{\chi\chi} - \frac{i}{2}R^*\chi\chi - A_\mu\cdot\chi\sigma^\mu\overline{\chi}\right) + \\
&\quad + U'''_C/8\left(\chi\chi\overline{\chi\chi}\right)
\end{aligned}
$$

$$
U(C) \equiv \sum_n a_n\,\frac{n}{2}C^{n-1}(x) = -D, \qquad R \equiv M + iN
$$

SUSY is spontaneously broken vs Lorentz is unbroken

$$D \neq 0, \;\; D\prime(C) = U\prime(C) = 0$$

Photon (as the Goldstone photino companion) is massless at least in tree approximation.

Actually, much more, as follows from the auxiliary C, R, and χ field equation(s) of motion taken in the potential minimum $C = <C>$

$$A_\mu^2 = R^* R, \; \chi = 0$$

with freely chosen scalar R field as some constant (or even vanishing) field thus leading to the time-like (or light-like) SLV gauge choise in QED.

So, one automatically comes to Goldstonic QED when starting with an arbitrary polynomially extended SQED:

spontaneously broken SUSY
- rather than spontaneous Lorentz violation –
may provide masslessnes of the photon

5. Looking back

Physical SLV cannot be conceptually realized in the SUSY context:

- In contrast to an ordinary vector field theory where all kinds of polynomial terms $(A_\mu A^\mu)^n$ (n = 1, 2, ...) can be included into the Lagrangian, SUSY theories only admit the bilinear mass term $A_\mu A^\mu$ in the vector field potential energy constructed from vector superfields. Therefore, without stabilizing high-linear (at least quartic) vector field terms, the potential-based SLV never occurs in SUSY theories. Analogously, multi-fermi interactions $[(\bar{\psi}\gamma_\mu\psi)(\bar{\psi}\gamma^\mu\psi)]^n$ cannot appear for chiral superfields

- The both statements are simply the vulgar facts of SUSY mathematics: any power of vector or chiral superfields is only reflected in power of their scalar field components, while limiting the other field components to lowest possible (bilinear) powers

- As an immediate result, all physical SLV models considered so far (Bjorken's type multi-fermi composite models, Kostelecky's bumblebee models etc. and etc.) are ruled out in the SUSY framework

- So, SUSY unambiguously chooses the constraint-based "inactive" SLV case which, while producing gauge fields as the SLV Nambu-Goldstone modes, does not lead to physical Lorentz violation.

6. Emergent SSM: phenomenology

Physics of photino as pseudo-goldstino:

- Supertrace sum rule problem in the visible SUSY breaking sector

$$STrM^2 \equiv \sum_J (-1)^{2J}(2J+1)Tr(m_J^2) = 2TrQ\langle D\rangle$$

for all realistic cases requiring **TrQ = 0** to cancel the anomalies related to U(1)em this sum rule leads to some unacceptably light superpartners in a theory

- Usually, solution to this problem is related to a softly broken SUSY that in our case would be inaccessible. Indeed, inclusion of direct soft mass terms for superpartners in the model would mean that the visible SUSY is explicitly, rather than spontaneously, broken that would immediately invalidate the whole idea of the QED emergence nature

- Therefore, SUSY should break spontaneously in the visible sector. Such models (Kumar-Lykken, 2004) appear to include some relatively low-scale extra hypercharge U(1)' gauge symmetry which, when being properly assigned to quarks and leptons and their superpartners, allows to construct some phenomenologically viable supersymmetric SM extensions $STrM^2 = 2TrY'\langle D'\rangle$. In order to generate one-loop gaugino masses which are large enough to satisfy current experimental bounds the SUSY breaking scale is determined to be about 20 TeV

.

- **In general, these low scale models predict light gauginos and very heavy squarks and sleptons which may not be observable at LHC. The LSP is a stable very light (of eV scale) gravitino with a significant higgsino admixture, while the NLSP is mostly photino (or bino when extending to SM). These pseudo-Goldstonic photino are dominantly decaying into photon and gravitino with a lifetime 10^{-15} sec (for a typical mass value 100 GeV) that could make its mean decay length to reach up to a few microns under LHC energies.**

VI. Conclusions

I. Photons, gravitons and non-Abelian gauge fields can well be treated as 4D space-time massless vector and tensor Goldstone bosons. Gauge invariance in Goldstonic QED, GR and YM theories appears in essence as a necessary condition for vector and tensor fields not to be superfluously restricted in degrees of freedom once the SLV vacuum is chosen in the theory (Emergent Gauge Symmetry Conjecture).

II. Such emergent gauge invariance hides the physical Lorentz violation unless 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 and tensor fields. This eventually, through some high order operators, would manifest itself in (partial) violation of gauge invariance.

III. 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 may be predicted.

IV. One could gain a new insight into the spontaneously broken SUSY as an alternative source for a generic masslessness of gauge fields. In particular supersymmetric QED framework the massless photon emerges as a companion of the massless photino (being Goldstone fermion in the SUSY broken phase) and remains massless due to the simultaneously generated special gauge invariance just only restricted to the SLV nonlinear gauge $A^2 = M^2$.