HIDDEN GAUGE SYMMETRY: A NEW POSSIBILITY AT COLLIDERS

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OUTLINE

A. INTRODUCTION

: MOTIVATION
: NEW PROPOSAL

B. THEORETICAL DIFFICULTIES

: HOW TO CIRCUMVENT
$\Rightarrow$ IDEA OF HIDDEN GAUGE SYM

: POSSIBLE MODELS

C. TWO CONCRETE MODEL

$\underline{SU(5)} \times SU'(3) \times SU'(2) \times U'(1)$

$\underline{SU(3)} \times SU(3)_c \times SU(2)' \times U'(1)$

D. PHENOMENOLOGICAL IMPLICATIONS (LHC & ILC)

E. CONCLUSIONS

A. INTRODUCTION

$$SM = SU(3)_C \times SU(2)_L \times U(1)_Y$$

: IN EXCELLENT AGREEMENT WITH EXPT. BELOW THE TeV SCALE

: BUT PROBABLY AN EFFECTIVE THEORY

$\Rightarrow$ MANY POSSIBILITIES FOR A FUNDAMENTAL THEORY BEYOND TeV SCALE

: GRAND UNIFICATION

: SUPERSYMMETRIES

: EXTRA DIMENSIONS

: STRINGS

⋮

: DISCOVERIES HIGHLY ANTICIPATED AT LHC

MOST LIKELY CANDIDATES

: HIGGS BOSONS

: SUPERSYMMETRY

: EXTRA Z BOSON

MORE EXOTIC POSSIBILITIES

: KALUZA-KLEIN EXCITATIONS

: BLACK HOLES

: STRING EXCITATIONS

⋮

NEW PROPOSAL :

: OBSERVATION OF TeV SCALE MASSIVE VECTOR BOSONS BELONGING TO NON-ADJOINT REPRESENTATIONS OF SM.

EXAMPLES :

UNDER $SU(3)_C \times SU(2)_L \times U(1)_Y$

: $(1, 2, Q_1) + (1, 2, -Q_1)$

: $(3, 1, Q_2) + (\bar{3}, 1, -Q_2)$

: $(3, 2, Q_3) + (\bar{3}, 2, -Q_3)$

: $(3, \bar{3}, Q_4) + (\bar{3}, 3, -Q_4)$

: $(6, 1, Q_5) + (\bar{6}, 1, -Q_5)$

: $(6, 2, Q_6) + (\bar{6}, 2, -Q_6)$

⋮

$\Rightarrow$ NEW WINDOW FOR OUR UNDERSTANDING OF THE FUNDAMENTAL THEORY

B. THEORETICAL DIFFICULTIES

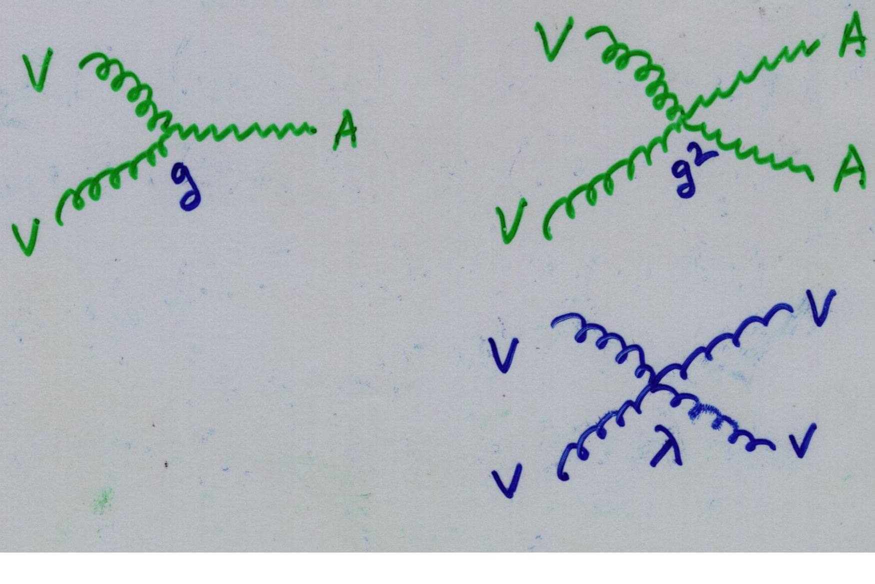
: SUCH MASSIVE VECTOR BOSONS, V_μ^α ARE <u>NOT</u> GAUGE BOSONS OF SM

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu}^{\alpha} F^{\mu\nu\alpha} - m^2 V_\mu^\alpha V^{\mu\alpha} + \lambda (V_\mu^\alpha V^{\mu\alpha})^2$$

$$F_{\mu\nu}^{\alpha} \equiv \partial_\mu V_\nu^\alpha - \partial_\nu V_\mu^\alpha - g (T_a A_\mu^a)_{\alpha\beta} V_\nu^\beta$$

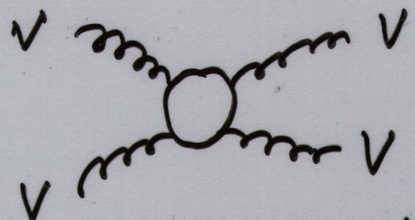
gauge bosons

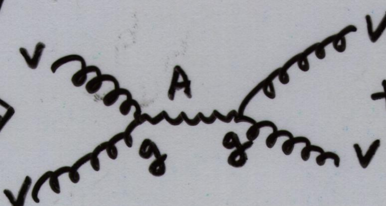
:COUPLINGS

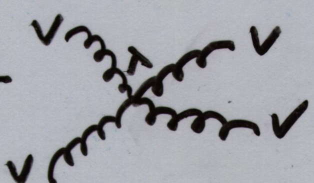


: PROBLEM WITH UNITARITY AND RENORMALIZABILITY

CONSIDER $VV \to VV$ SCATTERING



$\Rightarrow$  + t-CHANNEL + u-CHANNEL

+ 

$$\Rightarrow (\ )E^4 + (\ )E^2 + (\ )E^0$$

$\neq 0$ $\quad \neq 0$

: COEFFICIENT OF E^4 and E^2 TERM DO NOT CANCEL

(NO HIGGS CONTRIBUTION FROM GAUGE INTERACTIONS)

& CONTACT INTERACTION NOT RELATED TO GAUGE COUPLING.

$\Rightarrow$ THEORY NOT UNITARY

: NOT RENORMALIZABLE

Q: HOW DO WE CONSTRUCT AN UNITARY AND RENORMALIZABLE THEORY INVOLVING THESE MASSIVE VECTOR BOSONS?

$\Rrightarrow$ LEADS TO THE IDEA OF HIDDEN GAUGE SYMMETRY

: THESE MASSIVE BOSONS BELONG TO THE ADJOINT REPRESENTATION OF HIDDEN GAUGE SYMMETRY

+ GAUGE SYM BROKEN SPONTANEOUSLY VIA HIGGS AT TeV SCALE

$\Rrightarrow$ LEADS TO A CLASS OF MODELS

$$\mathcal{G} \equiv \underset{\substack{\Uparrow \\ \text{HIDDEN SYM}}}{G} \times \underbrace{SU(3)'_c \times SU(2)'_L \times U(1)'_Y}_{\text{SYMMETRY}}$$

: SM FERMIONS & HIGGS BOSONS ARE <u>SINGLETS</u> UNDER G

$$\mathcal{G} \equiv G \times SU'(3)_c \times SU'(2)_L \times U'(1)_Y$$

$$\Downarrow \text{SPONTANEOUSLY BROKEN AT THE TeV SCALE}$$

$$SM = SU(3)_c \times SU(2)_L \times U(1)_Y$$

: SOME OF THE MASSIVE GAUGE BOSONS FROM THE $\mathcal{G}$ BREAKING DO NOT BELONG TO THE ADJOINT REP OF SM

: THEY ARE GAUGE BOSONS AND GET MASSES FROM SPONT. SYM BREAKING

$\Rightarrow$ THEORY IS UNITARY AND RENORMALIZABLE

: WHAT ARE THE POSSIBLE CHOICES FOR THE HIDDEN SYM G?

CONSIDER $G = SU(n)$

ADJOINT : $n^2 - 1$

EX: $SU(4) \longrightarrow SU(3)_c$

$$15 = 8 + 3 + \bar{3} + 1$$

NON-ADJOINT
WITH RESPECT
TO SM color

$SU(3) : \longrightarrow SU(2)_L$

$$8 = 3 + \underbrace{2 + 2 + 1}_{\text{non-adjoint with REPECT TO } SU(2)_L \text{ of SM}}$$

$SU(5) : \longrightarrow SU(3) \times SU(2) \times U(1)$

$$24 = (8,1) + (1,3) + (1,1)$$

$$+ \underbrace{(3,2) + (\bar{3},2)}_{\text{non-adjoint}}$$

$$\mathcal{G} = G \times SU'(3) \times SU'(2)_L \times U'(1)_Y$$

: MANY POSSIBLE CHOICES FOR G

$G = SU(3),\ SU(4),\ G_2,\ F(4),\ Sp(4),$
$SU(5),\ SO(10),\ \cdots\cdots$

: ALSO MORE GENERALLY

$$\mathcal{G} = \prod_i G_i \times SU'(3) \times SU'_L(2) \times U'_Y(1)$$

NOTE : OUR GAUGE BOSONS ARE DISTINCT FROM OTHER MODELS

$$\left\{ \begin{array}{l} \text{TOP COLOR} \Rightarrow SU(3)_{C1} \times SU(3)_{C2} \times SU(2)_L \times U(1)_Y \\ \text{TOP FLAVOR} \Rightarrow SU(3)_c \times SU(2)_1 \times SU(2)_2 \times U(1)_Y \end{array} \right.$$

: EXTRA GAUGE BOSONS BELONG TO ADJOINT REP OF SM

C. A SIMPLE MODEL : FORMALISM

$$\mathcal{G} = SU(5) \times SU'(3) \times SU'(2)_L \times U'(1)_Y$$

$$g_5 \qquad \underbrace{g_3' \qquad g_2' \qquad g_Y'}_{\tilde{A}_\mu}$$

$$\hat{A}_\mu \qquad a3 \qquad a2 \qquad a1$$

AND $\tilde{a}$

HIDDEN GAUGE SYM ¦ FOR $SU(5)/SU(3) \times SU(2) \times U(1)$

$$\mathcal{G} \xrightarrow[\text{TO}]{\text{BROKEN}} SM = SU(3)_c \times SU(2)_L \times U(1)_Y$$

USING FOUR BI-FUNDAMENTAL HIGGS

$$U_1 = (5, \bar{3}, 1, \tfrac{1}{3})$$

$$U_2 = (\bar{5}, 3, 1, -\tfrac{1}{3})$$

$$U_3 = (5, 1, \bar{2}, -\tfrac{1}{2})$$

$$U_4 = (\bar{5}, 1, 2, \tfrac{1}{2})$$

CHOOSE

$$\langle U_1 \rangle = \begin{pmatrix} v_1 & 0 & 0 \\ 0 & v_1 & 0 \\ 0 & 0 & v_1 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \quad \langle U_2 \rangle = \begin{pmatrix} v_2 & 0 & 0 \\ 0 & v_2 & 0 \\ 0 & 0 & v_2 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$\langle U_3 \rangle = \begin{pmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ v_3 & 0 \\ 0 & v_3 \end{pmatrix}, \quad \langle U_4 \rangle = \begin{pmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ v_4 & 0 \\ 0 & v_4 \end{pmatrix}$$

from SU(5)?

$\{v_i\} \longrightarrow$ in the TeV scale

$$\sum_{i=1}^{4} \left(D_\mu U_i\right)^\dagger \left(D^\mu U_i\right)$$

$SU(3) \times SU(2) \times U(1)$

$$\Rightarrow \frac{1}{2}\left(v_1^2+v_2^2\right)\left(g_5 \hat{A}_\mu^{a3} - g_3' \tilde{A}_\mu^{a3}\right)^2$$

$$+ \frac{1}{2}\left(v_3^2+v_4^2\right)\left(g_5 \hat{A}_\mu^{a2} - g_2' \tilde{A}_\mu^{a2}\right)^2$$

$$+ \left(\frac{v_1^2}{3} + \frac{v_2^2}{3} + \frac{v_3^2}{2} + \frac{v_4^2}{2}\right)\left(g_5^Y \hat{A}_\mu^{a1} - g_Y' {}^{a1}\right)^2$$

$$+ \frac{g_5^2}{2}\left(v_1^2+v_2^2+v_3^2+v_4^2\right)\left(X_\mu \bar{X}^\mu + Y_\mu \bar{Y}^\mu\right)$$

$$SU(5) \times SU'_c(3) \times SU'_L(2) \times U'_Y(1)$$

$$\Big\Downarrow \text{ BREAKS TO}$$

$$SM = SU(3)_c \times SU_L(2) \times U_Y(1)$$

A^{ai}_μ : Massless gauge bosons

B^{ai}_μ : Massive " "

from SU(5)

$$\begin{pmatrix} A^{ai}_\mu \\ B^{ai}_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_i & \sin\theta_i \\ -\sin\theta_i & \cos\theta_i \end{pmatrix} \begin{pmatrix} \hat{A}^{ai}_\mu \\ \tilde{A}^{ai}_\mu \end{pmatrix}$$

from $SU'(3) \times SU'(2) \times U'(1)$

$i = 3, 2, 1$

$$\sin\theta_j = \frac{g_5}{\sqrt{g_5^2 + g_j'^2}} \quad , \quad j = 3, 2$$

$$\sin\theta_1 = \frac{g_5}{\sqrt{(g_5^Y)^2 + (g'_Y)^2}}$$

(X, Y) AND $(\bar{X}, \bar{Y})$ ARE THE OTHER

$\Uparrow$ $(3,2)$ $\qquad$ $\Uparrow$ $(\bar{3},2)$

MASSIVE GAUGE BOSONS IN TeV SCALE

SM GAUGE COUPLINGS, g_j:

$$\frac{1}{g_j^2} = \frac{1}{g_5^2} + \frac{1}{g_j'^2} \quad , \quad j = 3, 2$$

$$\frac{1}{g_Y^2} = \frac{1}{(g_5^Y)^2} + \frac{1}{g_Y'^2}$$

: THE THEORY IS UNITARY AND RENORMALIZABLE

D. PHENOMENOLOGICAL IMPLICATIONS

GAUGE BOSON SECTOR:

$$\mathcal{L}_{gauge} = \mathcal{L}_{gauge}^{(SU(5))} + \mathcal{L}_{gauge}\left(SU'(3) \times SU'_L(2) \times U'_Y(1)\right)$$

$$\Rightarrow \frac{1}{2} g_j \left[A^3 + 3AB^2 + 2\cot 2\theta \; B^3\right]$$

$$+ \frac{1}{4} g_j^2 \left[A^4 + 6A^2B^2 + 4(2\cot 2\theta) AB^3 + (\tan^2\theta + \cot^2\theta - 1) \; B^4\right]$$

+ INTERACTIONS OF X AND Y

$j = 2, 3$.

A: SM gauge bosons

B: Tev scale heavy gauge bosons

$\Rightarrow$ A SINGLE HEAVY BOSON, B DO NOT COUPLE TO TWO OR THREE A BOSONS.

THUS :

: B CAN ONLY BE PAIR PRODUCED (VIA gluon-gluon fusion or gluon exchanges for B_3 at LHC, or, via EW gauge boson fusion or B_2 exchanges at ILC.

: X & Y WILL COUPLE TO SM GAUGE BOSONS FROM THE SU(5) KINETIC TERM

$\Rightarrow$ CAN BE PAIR PRODUCED DOMINANTLY VIA GLUON FUSION OR GLUON EXCHANGES at the LHC, or, EW gauge boson fusion at the ILC.

FERMION SECTOR

: FERMIONS DO <u>NOT</u> COUPLE TO THE HIDDEN GAUGE SYMMETRY, $SU(5)$

: FERMIONS COUPLE TO $SU'(3) \times SU'_L(2) \times U'_Y(1)$ JUST AS IN SM, AND THUS TO A AND B VIA MIXING.

EXAMPLE: FOR A QUARK $Q_i\,(1, 3, 2, \frac{1}{3})$

$$-\mathcal{L} = \bar{Q}_i \gamma^\mu D_\mu Q_i$$

WITH

$$D_\mu \equiv \partial_\mu - i g_3' T^{a3} \tilde{A}_\mu^{a3} - i g_2' T^{a2} \tilde{A}_\mu^{a2} - \frac{i}{6} g_Y' \tilde{A}_\mu^{a1}$$

$$= \partial_\mu - i g_3 T^{a3} \left(A_\mu^{a3} + \cot\theta_3 \, B_\mu^{a3} \right)$$

$$- i g_2 T^{a2} \left(A_\mu^{a2} + \cot\theta_2 \, B_\mu^{a2} \right)$$

$$- i \frac{1}{6} g_Y \left(A_\mu^{a1} + \cot\theta_1 \, B_\mu^{a1} \right)$$

: FERMIONS DO <u>NOT</u> COUPLE TO X AND Y GAUGE BOSONS, SO <u>NO</u> PROTON DECAY.

: SINCE $U_i \rightarrow$ BIFUNDAMENTAL (5,3) OR (5,2)

$\Rightarrow$ NEED TWO U_i FIELDS TO COUPLE TO FERMIONS

$$\Rightarrow \frac{1}{\Lambda_{cutoff}} q q u_i u_i \; : \text{DIM } 5$$

$\Lambda_{cutoff} \nearrow M_{PL}$ $\Rightarrow$ NO OBSERVABLE PROTON DECAY

: THIS SIMPLE MODEL HAS <u>TWO</u> KINDS OF <u>TEV</u> SCALE MASSIVE GAUGE BOSONS

$B_\mu^{ai} \Rightarrow B_\mu^{a3}, B_\mu^{a2}, B_\mu^{a1}$: ALL ADJOINT REP OF SM

$(X, Y) \Rightarrow (3, 2), (\bar{3}, 2)$: NON-ADJOINT

$\Rightarrow$ LEADS TO MANY INTERESTING PHENOMENOLOGICAL IMPLICATIONS

i) $B_\mu^{a3} : (8, 1, 0)$

: $gg \rightarrow B\bar{B}$, $WW \rightarrow B\bar{B}$, $B \rightarrow q\bar{q}$, $\bar{B} \rightarrow q\bar{q}$

$\Rightarrow$ 4 JETS WITH HIGH P_T

$\Rightarrow$ 4 JETS WITH HIGH P_T SIGNAL WILL BE SIGNIFICANTLY ENHANCED OVER THE SM

ii) $B^{a2}, B^{a1} \Rightarrow$ HEAVY EW GAUGE BOSONS

: $$q\bar{q} \rightarrow B \rightarrow q\bar{q}$$
$$e^+e^- \rightarrow B \rightarrow \ell^+\ell^-$$

: CLEAN SIGNAL FOR HEAVY Z AND HEAVY PHOTON

iii) SIGNALS FOR B^{ai} $(i = 3, 2, 1)$ ARE DIFFERENT TOPCOLOR OR TOPFLAVOR MODELS; SINCE THESE B'S COUPLE UNIVERSALLY TO ALL FERMION FAMILIES.

iv) OFF SHELL EFFECTS IN LINEAR COLLIDER & CONTRIBUTION TO $g_\mu - 2$.

v) $\underbrace{X, Y}_{\text{NON-ADJOINT REP.}}$: CAN BE PRODUCED VIA gg (LHC) or WW (ILC)

$$gg \rightarrow X\bar{X},\ Y\bar{Y}$$
$$WW \rightarrow$$

: SINCE X, Y DO NOT COUPLE TO FERMIONS $\Rightarrow$ STABLE/METASTABLE

: HEAVY QUARK-LIKE OBJECTS PASSING THROUGH DETECTOR

$\Rightarrow$ CAN BE DETECTED BY THEIR IONIZATION.

C. ANOTHER SIMPLE MODEL

$$\mathcal{G} = \underset{g_3}{SU(3)} \times \underset{g_c}{SU(3)_c} \times \underset{g_2'}{SU(2)'} \times \underset{g_1'}{U(1)'}$$

: SM FERMIONS & EW HIGGS ARE SINGLETS UNDER $SU(3)$.

$$SU(3) \longrightarrow SU(2) \times U(1)$$

$$8 \longrightarrow 3 + \underbrace{2 + 2}_{\Uparrow} + 1$$

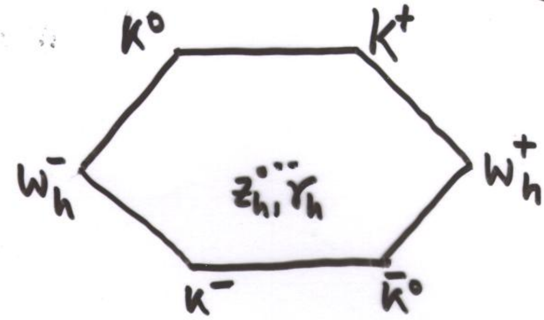
GAUGE BOSONS BELONGING TO THE <u>NON-ADJOINT</u> REP. OF SM

$$\mathcal{G} \xrightarrow[\substack{\Phi(3,1,\bar{2}) \\ \langle\Phi\rangle = V}]{\text{broken to}} SU(3)_c \times SU(2)_L \times U(1)_Y$$

$$\Big\downarrow \text{broken to } H(1,1,2),\ \langle H\rangle = v$$

$$SU(3)_c \times U(1)$$

SU(3):



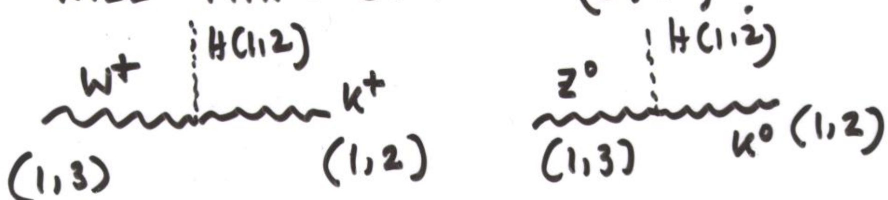
Gauge bosons:

$W^\pm, Z, \gamma$; $W_h^\pm, Z_h, \gamma$ $\Rightarrow$ BELONG TO THE ADJOINT REP. OF SM

$K^\pm, K^0, \bar{K}^0$ $\Rightarrow$ MASSIVE GAUGE BOSONS AT THE TEV SCALE BELONGING TO THE NON-ADJOINT REP. OF SM.

$$\begin{pmatrix} K^+ \\ K^0 \end{pmatrix}, \begin{pmatrix} \bar{K}^0 \\ K^- \end{pmatrix} \Rightarrow (\underset{SU(3)_c}{1}, \underset{SU(2)_L}{2})$$

: WHEN $SU(2)_L$ IS BROKEN, W^+ AND K^+ WILL MIX. SO ARE (Z, K^0)



$$\sin\theta \sim \left(\frac{m_W}{M}\right)^2$$

PHENOMENOLOGICAL IMPLICATIONS :

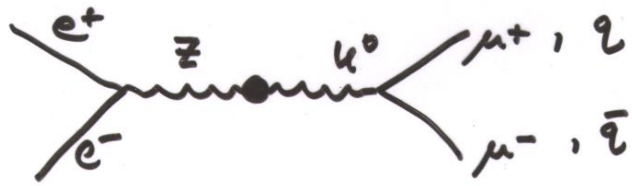
: NEW RESONANCES AT THE TeV SCALE

$k^{\pm}$, k^0, $\bar{k}^0$

: THESE ARE $SU(2)_L$ DOUBLETS

: CAN DECAY TO $\ell^+\ell^-$, $q\bar{q}$ VIA MIXING WITH EW GAUGE BOSONS

ILC:



: $k^{\pm} \rightarrow k^0 W^{\pm}$: Possibility of new signals.

To be studied:

: constraint on the ρ- parameter

: constraint from $g-2$ of muon, ...

CONCLUSIONS

PROPOSED A NEW POSSIBILITY AT LHC AND ILC:
OBSERVATION OF TEV SCALE MASSIVE VECTOR BOSONS BELONGING TO NON-ADJOINT REPRESENTATIOS OF SM

: PRESENTED A CLASS OF MODELS

$$\mathcal{G} = G \times SU'(3)_C \times SU'(2)_L \times U'(1)_Y$$

HIDDEN SYM

REALIZING THIS POSSIBILITY

: GAUGE SYMMETRY, G IS SPONTANEOUSLY BROKEN AT TEV SCALE TO SM

: THESE THEORIES ARE UNITARY AS WELL AS RENORMALIZABLE

: MANY NEW INTERESTING SIGNALS

: OBSERVATION OF SUCH GAUGE BOSONS WILL OPEN UP A NEW WINDOW FOR PHYSICS BEYOND THE SM.