HIGGSLESS ELECTROWEAK SYMMETRY BREAKING

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WITH

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INTRODUCTION

- THE MOST IMPORTANT QUESTION FACING PARTICLE PHYSICS IS :

"WHAT BREAKS ELECTROWEAK SYMMETRY ?"

WE KNOW :

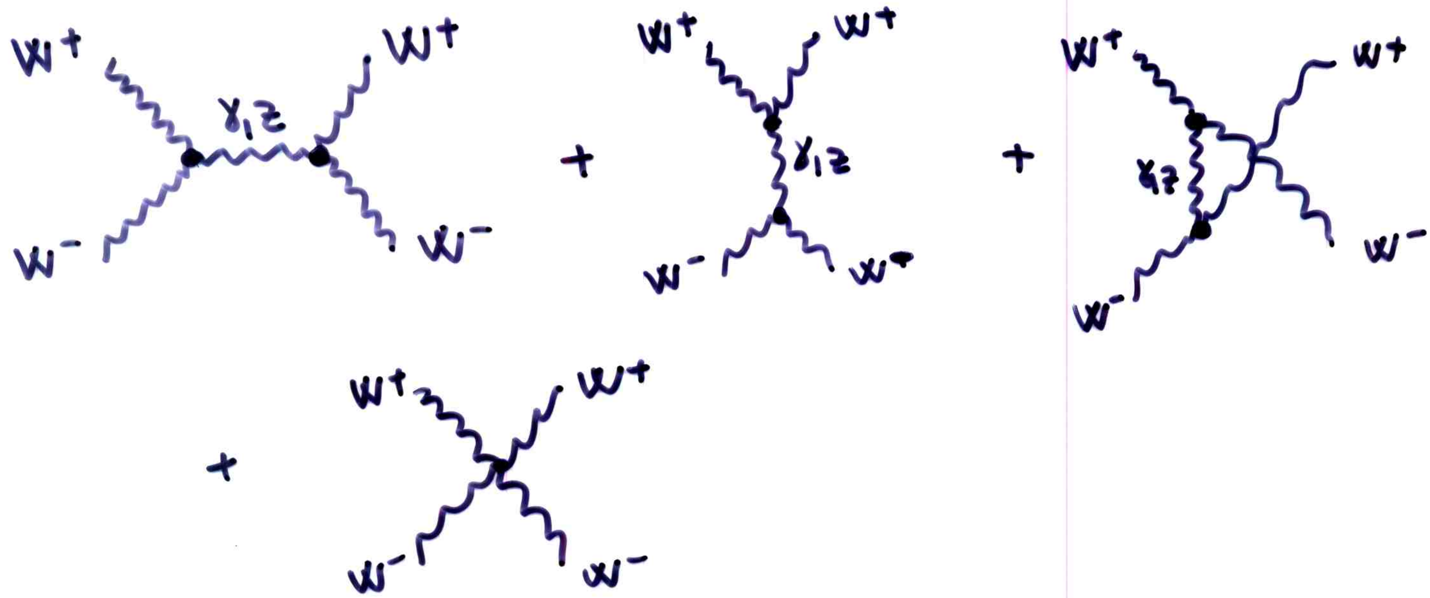
- W, Z MASSIVE GAUGE BOSONS
- THERE HAS TO BE NEW PHYSICS COMPLETING THE THEORY OF MASSIVE GAUGE BOSONS AT

$$E \sim \frac{4\pi M_W}{g} \sim 1\text{-}2\,\text{TeV}$$

THIS IS THE RANGE TO BE PROBED BY LHC.

HOW DO WE KNOW?

SCATTERING OF MASSIVE GB'S:



AMPLITUDE GROWS WITH ENERGY

$$\mathcal{A} = A^{(4)} \frac{E^4}{M_W^4} + A^{(2)} \frac{E^{(2)}}{M_W^2} + \text{FINITE} + \mathcal{O}\left(\frac{M_W^2}{E^2}\right)$$

IF LAGRANGIAN OF THE FORM

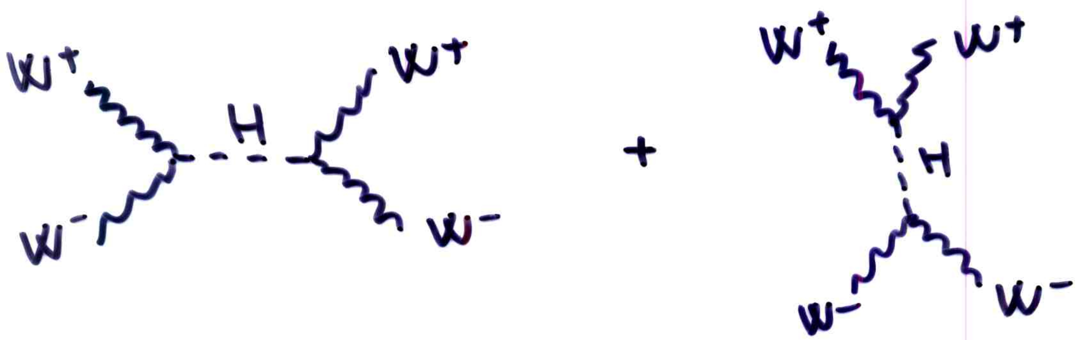
$$\mathcal{L} = -\tfrac{1}{4}\left(F^a_{\mu\nu}\right)^2 + M_W^2 W^+_\mu W^{\mu -} + \frac{M_Z^2}{2} Z_\mu Z^\mu$$

$A^{(4)} = 0$, $A^{(2)} \sim \frac{g^2}{16\pi^2}$, $\mathcal{A} \sim 1$ AT $E \sim \frac{4\pi M_W}{g}$

USUAL WAY OUT :

(CORNWALL, LEVIN, TIKTOPOULOS '73)

THERE HAS TO BE A HIGGS WHICH UNITARIZES THE AMPLITUDE



TOGETHER WITH PREVIOUS DIAGRAMS $A^{(2)} = 0$, NO GROWING AMPLITUDE LEFT.

THEOREM: THE ONLY WAY TO UNITARIZE AMPLITUDE IS BY A SCALAR HIGGS

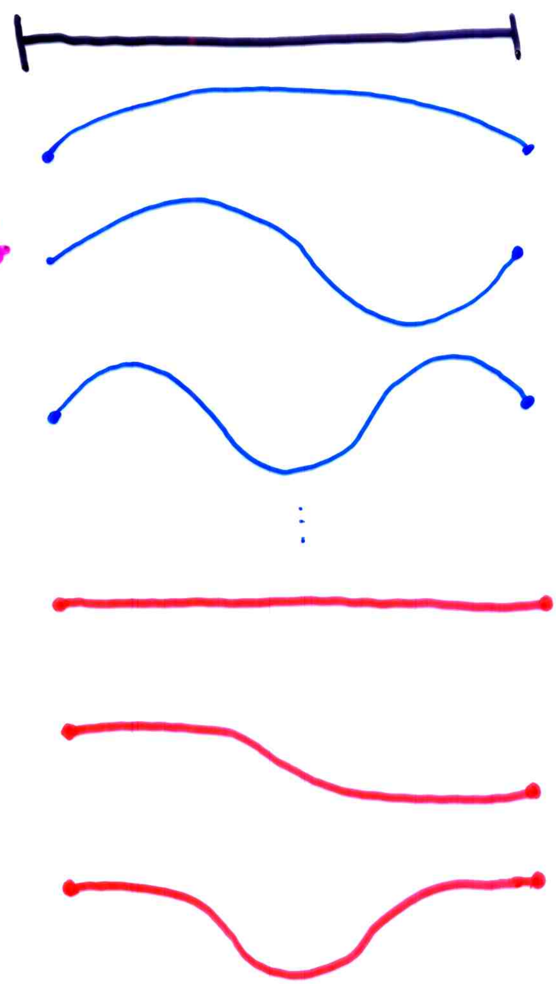
POSSIBILITIES:
- SM HIGGS (BUT UNSTABLE)
- SUSY HIGGS
- STRONG DYNAMICS – NO PERT. UNITARITY OK.

BUT: IMAGINE AN EXTRA DIMENSION

A 5D PARTICLE WILL APPEAR AS A TOWER OF KK MODES IN 4D. THE PROPERTIES OF TOWER ARE DETERMINED BY

BOUNDARY CONDITIONS

LIKE MODES OF VIBRATING STRING...



DIRICHLET-DIRICHLET

$$M_n^2 = \frac{n^2}{R^2}$$

$n = 1, 2, \ldots$

NEUMANN-NEUMANN

$$M_n^2 = \frac{n^2}{R^2}$$

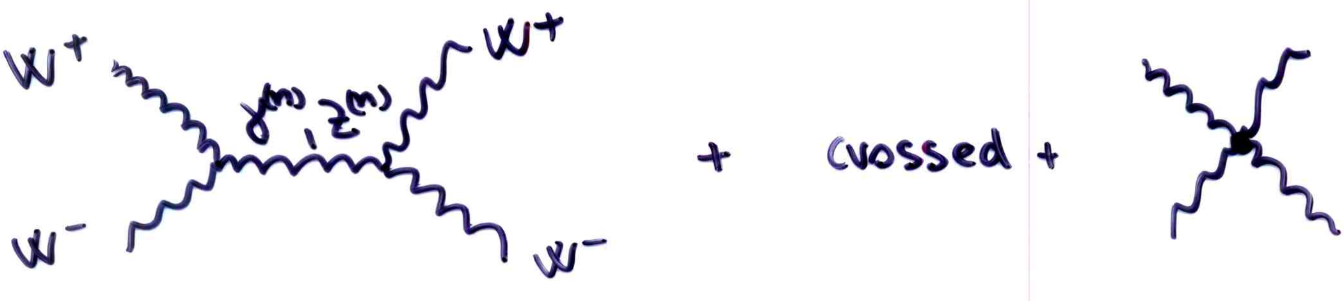
$n = 0, 1, \ldots$

CAN BREAK GAUGE SYMMETRIES BY BOUNDARY CONDITIONS

(80's STRING THEORY, ORBIFOLD GUT'S HALL, NOMURA, BARBIERI, HALL, NOMURA, ...)

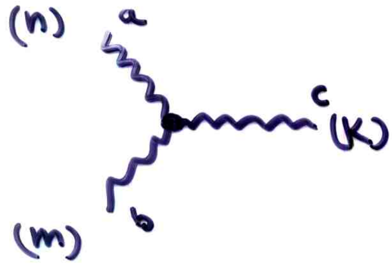
BUT HOW CAN I UNITARIZE WITHOUT A SCALAR?

IN EXTRA DIMENSIONS: WHOLE KK TOWER OF GAUGE FIELDS



NEED TO SUM UP CONTRIBUTIONS OF A WHOLE KK TOWER OF $\gamma^{(n)}, Z^{(n)}$ EXCHANGE ...

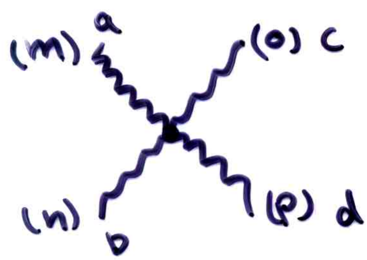
FEYNMAN RULES



$\sim \quad g^{abc}_{nmk}$

THIS EFFECTIVE CUBIC COUPLING IS DETERMINED BY OVERLAP OF 5D WAVE FUNCTIONS...

$$g^{abc}_{nmk} = g_5 \int dy \; f^a_n(y)\, f^b_m(y)\, f^c_k(y)$$



$\sim \quad g^{2\;abcd}_{mnop}$

$$g^{2\;abcd}_{mnop} = g_5^2 \int dy \; f^a_m(y)\, f^b_n(y)\, f^c_o(y)\, f^d_p(y)$$

RESULT OF SUMMING UP KK TOWER : $W_L^{(n)} W_L^{(n)} \to W_L^{(n)} W_L^{(n)}$

$$A^{(4)} \sim \left[g^2_{nnnn} - \sum_k g^2_{nnk} \right]$$

$$A^{(2)} \sim \left[g^2_{nnnn} M_n^2 - \tfrac{3}{4} \sum_k g^2_{nnk} M_k^2 \right]$$

IF THESE TWO <u>SUM RULES</u> SATISFIE

NO TERM GROWING WITH E $\rightarrow$

POSSIBILITY FOR <u>UNITARITY WITHOUT HIGG</u>

MORE ON THE SUM RULES

$$g_{nnnn}^2 = \sum_k g_{nnk}^2$$

SATISFIED IN ANY 5D GAUGE THEORY IRRESPECTIVE OF BC'S

$$g_{nnnn}^2 M_n^2 = \tfrac{3}{4} \sum_k g_{nnk}^2 M_k^2$$

SATISFIED, IF BOUNDARY CONDITIONS CAN BE DERIVED FROM GAUGE INVARIANT LAGRANGIAN...

IN ESSENCE, 5D GAUGE INVARIANCE GUARANTEES THAT SUM RULES OBEYED

SUM RULES IMPLY, THAT THE SM COUPLINGS OF W^+W^-Z, $W^+W^-\gamma$ (protected by U(1)$_{em}$) WOULD HAVE TO BE SLIGHTLY MODIFIED

OK, THESE COUPLINGS NOT VERY WELL KNOWN (~ 3-5% FOR CUBIC, NONE FOR QUARTIC) BUT COULD PERHAPS BE CHECKED AT NLC?

HOW DO WE GET AROUND THE OLD THEOREM?

- CONSIDER $W^{(0)}W^{(0)} \to W^{(0)}W^{(0)}$ (THE LIGHTEST KK MODE SCATTERING)

ONE NEEDS A SCALAR FOR THIS AS BY THEOREM, BUT IT CAN BE THE LONGI MODE OF ANOTHER, MORE MASSIVE GAUGE BOSON!

- $W^{(0)}W^{(0)} \to W^{(0)}W^{(0)}$ UNITARIZED, BUT NOW I HAVE ANOTHER, HEAVIER GB $W^{(1)}$.

$W^{(1)}W^{(1)} \to W^{(1)}W^{(1)}$ CAN BE UNITARIZED BY $W^{(2)}$ EXCHANGE, etc.

$$\left.\begin{array}{c} W^{(0)} \\ W^{(1)} \\ W^{(2)} \\ \vdots \end{array}\right\} \text{NEED A WHOLE KK TOWER TO HAVE A FULLY UNITARY THEORY.}$$

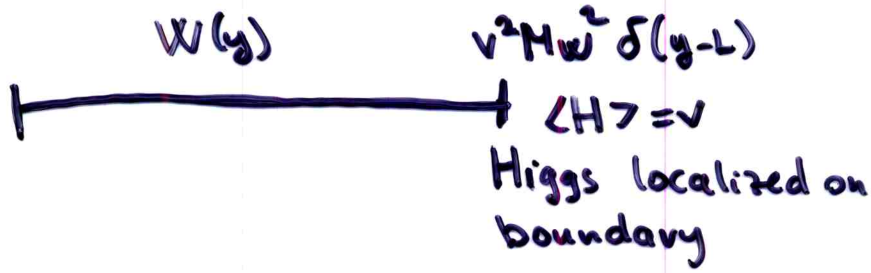
- IF I CUT THE TOWER AT ANY FINITE POINT (n), then $W^{(n)}W^{(n)}$ NOT UNITARY. BUT DON'T CARE ANYWAY ABOVE SCALE OF VALIDITY OF EFFECTIVE THEORY (Λ_5 ...)

THE MAIN RESULT TO BE USED FOR MODEL BUILDING:

DIRICHLET BC $W(0)=W(L)=0$ OK FOR UNITARITY.

NAIVELY DOES NOT FOLLOW FROM A GAUGE INVARIANT LAGRANGIAN, BUT

CAN GET IT FROM LIMIT $v \to \infty$



IN THIS LIMIT $v \to \infty$ WAVE FUNCTION PUSHED AWAY FROM BOUNDARY ($W(L) \to 0$ DIRICHLET BC) & HIGGS TOTALLY DECOUPLES & BECOMES VERY HEAVY.

HOW TO BUILD A MODEL THAT IS (CLOSE TO) REALISTIC?

- MAJOR ISSUE: HOW TO ENSURE

$$\frac{M_W^2}{M_Z^2} = \frac{g^2}{g^2+g'^2}$$

- LOOKS ALMOST IMPOSSIBLE, SINCE USUALLY FORM OF MASS

$$M^2 \sim \frac{n^2}{R^2} \qquad \frac{M_W}{M_Z} = 1, 2, \ldots$$

- IN SM, $\rho = 1$ RELATION ENSURED BY "CUSTODIAL SU(2)" SYMMETRY:

  HIGGS SECTOR HAS $SU(2)_L \times SU(2)_R$ GLOBAL SYMMETRY

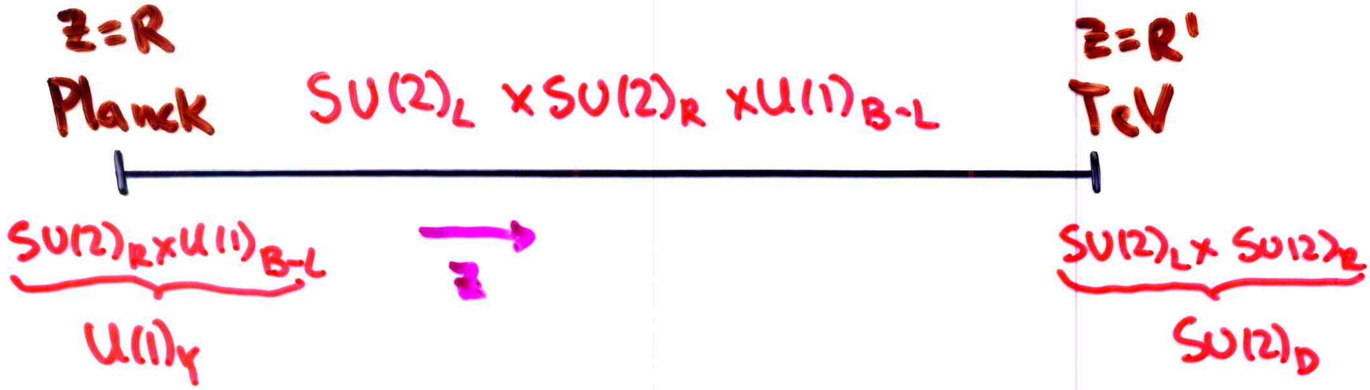
$$\underbrace{SU(2)_L \times SU(2)_R}_{SU(2)_D}$$

BREAKING PATTERN OF SM, WHERE $SU(2)_L \times U(1)_Y$ SUBGROUP GAUGED.

NEED ANALOG OF THIS SYMMETRY SOMEHOW IMPOSED ON THE HIGHER DIM. GAUGE THEORY!

A MODEL

5D GAUGE THEORY ON FINITE INTERVAL



INTRODUCE ADDITIONAL GAUGE SYMMETRY IN BULK, BUT BREAK IT TO USUAL SM GROUP ON ONE BOUNDARY. ON OTHER BOUNDARY BREAKING PATTERN LIKE IN SM.

- FLAT SPACE: STILL LARGE CORRECTIONS TO ρ PARAMETER
- INTRODUCE "WARPED BACKGROUND" ≡ NON-TRIVIAL METRIC BACKGROUND AdS_5 SPACE

$$ds^2 = \left(\frac{R}{z}\right)^2 \left(dx^\mu dx^\nu \eta_{\mu\nu} - dz^2\right)$$

AdS|CFT will guarantee presence of $SU(2)_R$ GLOBAL SYMMETRY → GOOD MASS RATIO

(ALTERNATIVE: ADD LARGE BRANE INDUCED KINETIC TERM ON $SU(2)_L \times U(1)_Y$ BRANE BARBIERI, POMAROL, RATTAZZI)

R: curvature of AdS $\sim \frac{1}{M_{Pl}}$ $z = R$ Planck br.

R': scale of EWSB $\sim \frac{1}{\text{TeV}}$ $z = R'$ TeV brane

$$\log \frac{R'}{R} \sim 30$$

RESULT :

$$M_W^2 = \frac{1}{R'^2 \log\left(\frac{R'}{R}\right)}$$

$$M_Z^2 = \frac{g_5^2 + 2\tilde{g}_5^2}{g_5^2 + \tilde{g}_5^2} \frac{1}{R'^2 \log\left(\frac{R'}{R}\right)}$$

$$\hookrightarrow = \frac{g^2 + g'^2}{g^2}$$

IN TERMS OF 4D COUPLINGS

EXCITED MODES $\sim \frac{1}{R'^2}$ (NO LOG SUPRESSION)

NATURALLY EXPLAIN, WHY $\frac{M_W}{M_{W'}} \sim \frac{1}{10}$

(LITTLE HIERARCHY DUE TO LOG SUP.)

KK MODES

$$M_2^W \sim M_2^Z \sim M_2^\gamma \sim 1.2\,\text{TeV}$$

- HEAVY ENOUGH TO EVADE DIRECT OBSERVATION AT TEVATRON
- LIGHT ENOUGH TO UNITARIZE SCATERING AMPLITUDES

$$M_3^W \sim M_3^Z \sim 1.9\,\text{TeV}$$

$$\vdots$$

- $M_K^W \sim M_K^Z$ ALWAYS DUE TO CUSTODIAL SU(2) GLOBAL SYMMETRY

- THESE MODES SHOULD BE OBSERVABLE AT LHC

- MODIFICATION OF GB COUPLINGS SHOULD BE MEASURABLE AT NLC

CFT INTERPRETATION

(FOR THEORISTS ONLY...)

BULK OF AdS_5 ⟷	A 4D CFT THEORY
GAUGE BOSONS IN BULK ⟷	CFT HAS A GLOBAL SYMMETRY
GAUGE SYM'S BROKEN ON PLANCK BRANE ⟷	JUST GLOBAL SYMMETRY
GAUGE SYM'S BROKEN ONLY ON TeV BRANE ⟷	SUBGROUP OF GLOBAL SYM. WEAKLY GAUGED
APPEARANCE OF TeV BRANE ⟷	CFT SPONTANEOUSLY BROKEN AT TeV SCALE
BC BREAKING OF $SU(2)_L \times SU(2)_R \to SU(2)_D$ ON TeV BRANE ⟷	CONFORMAL SYM. BREAKING ALSO TRIGGERS EWSB
2-2-1 WARPED HIGGSLESS MODEL ⟷	WALKING TECHNICOLOR THEORY

↑ CAN RELIABLY CALCULATE CERTAIN QUANTITIES HERE

MAJOR ISSUES (TECHNICOLOR?)

- **FERMION MASSES** IN SM HIGGS PROVIDES BOTH GAUGE BOSON & FERMION MASSES VIA YUKAWAS.
  USUALLY VERY HARD IN TECHNICOLOR

- **ELECTROWEAK PRECISION** & OTHER CONSTRAINTS

  OBLIQUE CORRECTIONS S, T, U :
  USUALLY VERY LARGE IN TECHNICOLOR

  NON-OBLIQUE : $Zb\bar{b}$ COUPLING

- **STRONG COUPLING SCALE**
  WHERE DOES THE THEORY BECOME STRONGLY COUPLED?

FERMION MASSES

- WHERE SHOULD WE PUT FERMIONS?

  TeV BRANE NOT CHIRAL → NOT LIKE SM

  Planck BRANE / CHIRAL: CANNOT GET MASS

  ↓

  NEED TO PUT FERMIONS <u>IN BULK</u>!

- FOR EXAMPLE LEPTONS:

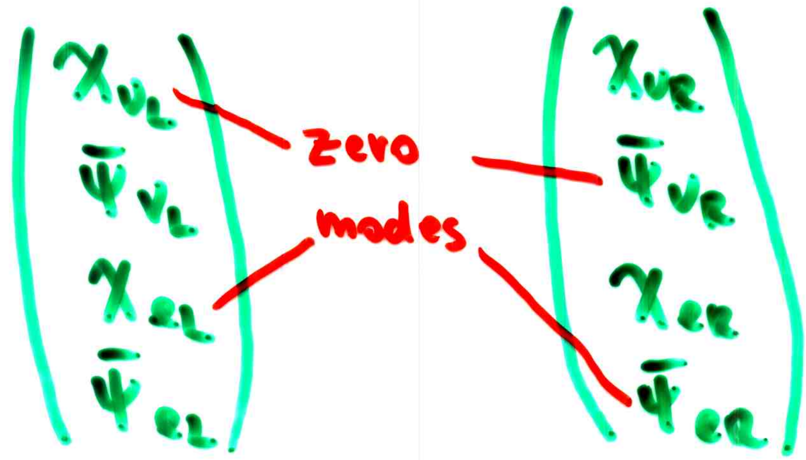
	$SU(2)_L$ ×	$SU(2)_R$ ×	$U(1)_{B-L}$
$\begin{pmatrix}\nu\\ e\end{pmatrix}_L$	2	1	$-1/2$
$\begin{pmatrix}\nu\\ e\end{pmatrix}_R$	1	2	$-1/2$

- 5D FERMIONS IN BULK → 4D DIRAC FERMIONS $\Psi = \begin{pmatrix}\chi_\alpha\\ \bar{\psi}^{\dot\alpha}\end{pmatrix}$

EVERY FERMION NEEDS TO BE DOUBLED...

- TO GET CHIRAL SPECTRUM : BOUNDARY CONDITIONS ψ DIRICHLET, χ NEUMANN } OR REVERSE

- FOR EXAMPLE



- ON TeV BRANE : THEORY NON-CHIRAL

$SU(2)_L \times SU(2)_R \rightarrow SU(2)_D$

CAN JUST ADD A DIRAC MASS FOR LEFT-RIGHT FERMIONS...

SINCE TeV BRANE HAS $SU(2)_D$ UNBROKEN $\rightarrow$ e, ν OR t, b EQUAL MASS, NEED TO SPLIT IT...

- ON PLANCK BRANE :

ADD MAJORANA MASS FOR ν_R ALLOWED

ADD MIXING FOR DOWN-TYPE QUARK WITH BRANE-LOCALIZED $SU(2)_R$ SINGLET...

- AN ANALOG OF THE SEE-SAW FORMULA:

$$m_{\nu_i} \sim \frac{m_{L_i}^2}{M_R}$$

← Majorana mass on Planck brane

- A SAMPLE SPECTRUM:

LOCALIZED ON TeV BRANE (→ 3rd GEN.)

Planck brane (→ 1st, 2nd, 3rd GEN.)

QUARKS

1st GEN.	2nd GEN.	3rd GEN.
$c_L = -c_R = 0.6$	$c_L = -c_R = 0.52$	$c_L = 0.4$, $c_R = -1/3$
$M_D = 50$ GeV	$M_D = 112$ GeV	$M_D = 900$ GeV
$(M/f)_u = 3.8$	$(M/f)_s = 50$	$(M/f)_b = 4\cdot 10^4$
$m_u \sim 3$ MeV	$m_c \sim 1.3$ GeV	$m_{top} \sim 175$ GeV
$m_d \sim 6$ MeV	$m_s \sim 110$ MeV	$m_b \sim 4.5$ GeV
$m_{KK} \sim 1.2$ TeV	$m_{KK} \sim 1.1$ TeV	$m_{KK} \sim 700$ GeV

LEPTONS

1st GEN.	2nd GEN.	3rd GEN.
$c_L = -c_R = 0.55$	$c_L = -c_R = 0.52$	$c_L = -c_R = 0.51$
$M_D = 100$ GeV	$M_D = 1$ TeV	$M_D = 2$ TeV
$(M/f)_e = 1500$	$(M/f)_\mu \sim 500$	$(M/f)_\tau \sim 100$
$M_R = 10^{16}$ GeV	$M_R \sim 10^{15}$ GeV	$M_R = 6\cdot 10^{14}$
$m_e \sim 500$ keV	$m_\mu \sim 100$ MeV	$m_\tau \sim 1.7$ GeV
$m_{\nu_e} \sim 10^{-8}$ eV	$m_{\nu_\mu} \sim 2\cdot 10^{-3}$ eV	$m_{\nu_\tau} \sim 3\cdot 10^{-2}$ eV

ELECTROWEAK PRECISION

TECHNICOLOR: USUALLY EXPECT LARGE S-PARAMETER

HERE CALCULABLE IN TERMS OF PARAMETERS OF 5D THEORY

Planck | TeV

$-\frac{r}{4}(W_{\mu\nu}^{L})^2$, $-\frac{r'}{4}(Y_{\mu\nu})^2$ | $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ | $\frac{R'}{R}\left(-\frac{\tau}{4}(W_{\mu\nu}^{D})^2 - \frac{\tau'}{4}B_{\mu\nu}^2\right)$

g_{5L}, g_{5R}, $\tilde{g}_5$: BULK GAUGE COUPLINGS

BRANE INDUCED KIN. TERMS

R INSENSITIVE TO PRECISE VALUE $= 10^{-19}\frac{1}{GeV}$

R' SETS MASS SCALE

R' FIXED BY W MASS

2 COMBINATIONS OF $g_{5L}, g_{5R}, \tilde{g}_5$ FIXED BY g, g'

FREE PARAMETERS: (IN GAUGE SECTOR)

$\frac{g_{5R}}{g_{5L}}, \tau, \tau', r, r'$

APPROXIMATE EXPRESSION FOR OBLIQUE CORRECTIONS:

$$S \sim \frac{6\pi}{g^2 \log\frac{R'}{R}} \frac{2}{1+\frac{g_{5R}^2}{g_{5L}^2}} \frac{1}{1+\frac{r}{R\log\frac{R'}{R}}} \left(1+\frac{4\tau}{3R}\right) - \frac{8\pi}{g^2}\left(1-\frac{g'^2}{g^2}\right)\frac{\tau'^2}{(R\log R'/R)^2}$$

$$T \sim -\frac{2\pi}{g^2}\left(1-\left(\frac{g'}{g}\right)^4\right)\frac{\tau'^2}{(R\log R'/R)^2}$$

$$U \sim 0$$

- FOR $\frac{g_{5R}}{g_{5L}}=1$, $\tau=\tau'=r=r'=0$

  $S \sim 1.15$, $T=0$, $U=0$ EXCLUDED

- CAN REDUCE S BY
  - RAISING $\frac{g_{5R}}{g_{5L}}$ → WILL RAISE KK SCALE, MORE STRONGLY COUPLED
  - RAISE r (SIMILAR TO $\frac{g_{5R}}{g_{5L}}$)
  - RAISE τ' → LOWERS Z' MASS

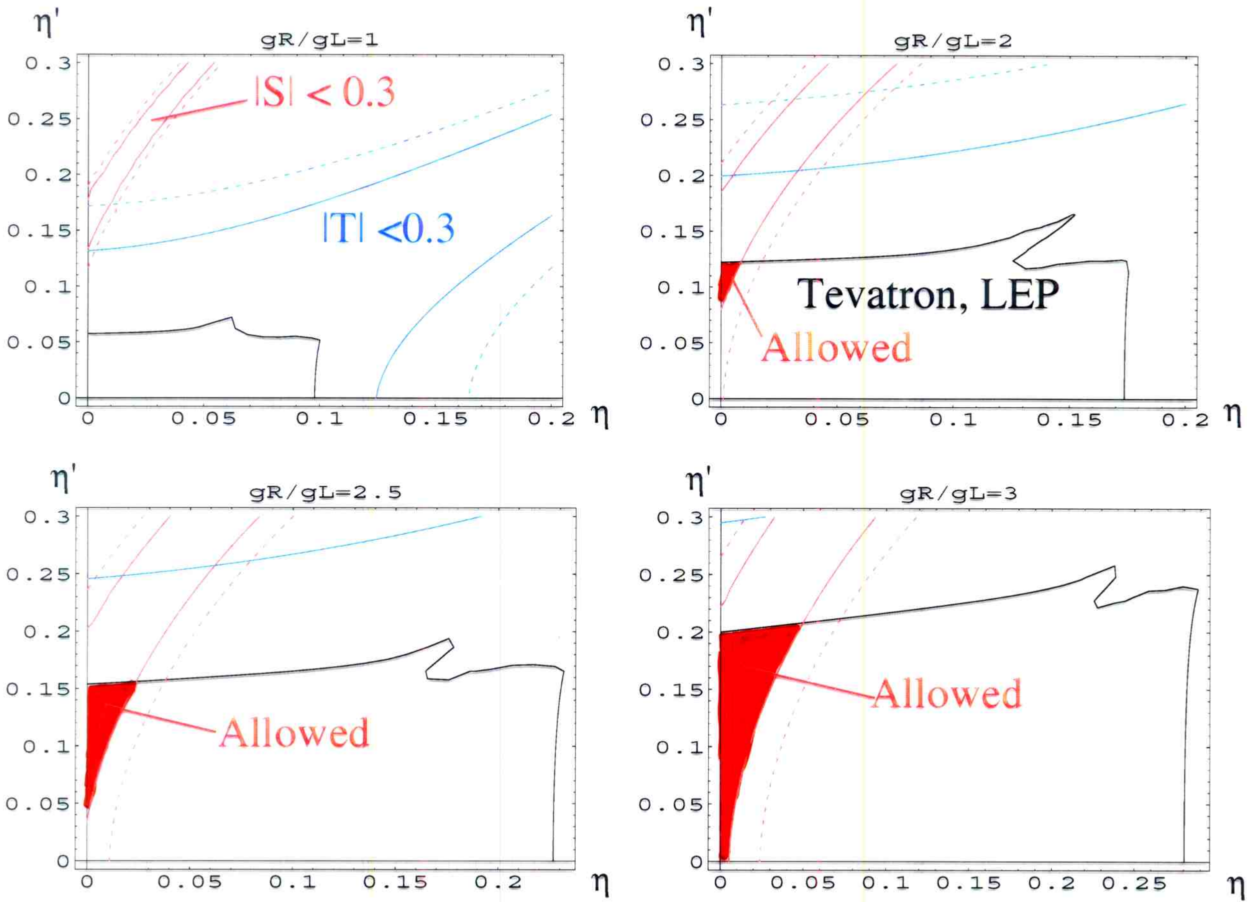
ADDITIONAL CONSTRAINTS

LEP 200 IF Z' TOO LIGHT, COULD CAUSE TOO LARGE EXCESS CROSS SECTION FOR $e^+e^- \to f\bar{f}$ AT $s \sim 200$ GeV

TEVATRON NON-OBSERVATION OF Z' AT RUN I BELOW ~600 GeV (RUN II: SOME EXCESS EVENTS, BOUNDS NOT VERY DIFFERENT)

→ SEE PLOTS FOR CONSTRAINTS INDIVIDUALLY, AND COMBINED PRECISION + LEP2 + TEVATRON

Bounds



$$\eta' = \tau'/(R \log R'/R)$$

CONCLUSIONS

- POSSIBLE TO BREAK EW SYMMETRY W/O HIGGS IN SPECTRUM VIA BC'S
- SCATTERING OF $W_L^+ W_L^-$ WILL BE UNITARIZED BY EXCHANGE OF MASSIVE GAUGE BOSONS (KK TOWER)
- SIGNATURE: WEAKLY COUPLED MASSIVE GAUGE BOSONS AROUND TeV SCALE (< 1.8 TeV) MODIFICATION OF CUBIC, QUARTIC COUPLINGS...
- POSSIBLE TO ALSO GENERATE FERMION MASSES BY BOUNDARY CONDITIONS
- CONSTRAINTS FROM ELECTROWEAK PRECISION OBSERVABLES, LEP2 EXCESS CROSS SECTION, DILEPTON TEVATRON SEARCH

Additional Slides

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⋮

5 PARALLEL SESSION TALKS: Y. NOMURA, G. CACCIAPAGLIA, H. DAVOUDIASL, M. KURACHI, G. SEIDL

- FIRST CONDITION

$$g_{nnnn}^2 = \sum g_{nnk}^2$$

$$\int_0^{\pi R} dy\, f_n^4(y) = \sum_k \int_0^{\pi R} dy \int_0^{\pi R} dz\, f_n^2(y)\, f_n^2(z) \underbrace{f_k(y) f_k(z)}_{\delta(y-z)}$$

AS LONG AS BULK LAGRANGIAN HERMITIAN WRT. BC, COMPLETENESS:

$$\sum_k f_k(y) f_k(z) = \delta(y-z)$$

<u>CONDITION SATISFIED ALWAYS</u>

- SECOND CONDITION

$$\sum_k M_k^2 g_{nnk}^2 = 4/3\, M_n^2\, g_{nnnn}^2$$ WE FIND

$$\sum_k M_k^2 \left(\int dy\, f_n(y) f_n(y)\right)^2 =$$

$$= 4/3\, M_n^2 \int dy\, f_n^4(y) - \frac{2}{3}\left[f_n^3 f_n'\right]$$

$$- \sum_k \left[f_n^2 f_k'\right] \int dy\, f_n^2(y) f_k(y) + 2 \sum_k \left[f_n f_n' f_k\right] \int dy\, f_n^2(y) f_k$$

FOR EXAMPLE

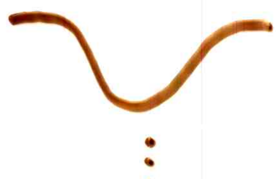
SU(2) GAUGE GROUP IN 5D

$W_1'=0$	$W_1=0$	SU(2)
$W_2'=0$	$W_2=0$	$\downarrow$
$W_3'=0$	$W_3'=0$	U(1)

W_3 :

$M^2=0 \sim \gamma$

$M^2=\left(\frac{\pi}{R}\right)^2 \sim Z$



$M^2=\left(\frac{2\pi}{R}\right)^2 \sim Z'$

$W_{1,2}$

$M^2=\left(\frac{\pi}{2R}\right)^2 \sim W^{\pm}$

$M^2=\left(\frac{3\pi}{2R}\right)^2 \sim W^{\pm\prime}$

BUT $\frac{M_Z}{M_W}=2$

BC's EXACTLY AS BEFORE

$z=R'$ $\begin{cases} \partial_z (A_\mu^{+a}) = 0 \ ; \ A_\mu^{-a} = 0 \ ; \ \partial_z B = 0 \end{cases}$

TeV BRANE

$z=R$ $\begin{cases} \partial_z A_\mu^{La} = 0 \ ; \ A_\mu^{R\,1,2} = 0 \ ; \\ \partial_z (g_5 B_\mu + \tilde{g}_5 A_\mu^{R3}) = 0 \ ; \ \tilde{g}_5 B_\mu - g_5 A_\mu^{R3} = 0 \end{cases}$

PLANCK BRANE

WAVE FUNCTIONS NOW NOT sin, cos, BUT BESSEL FUNCTIONS

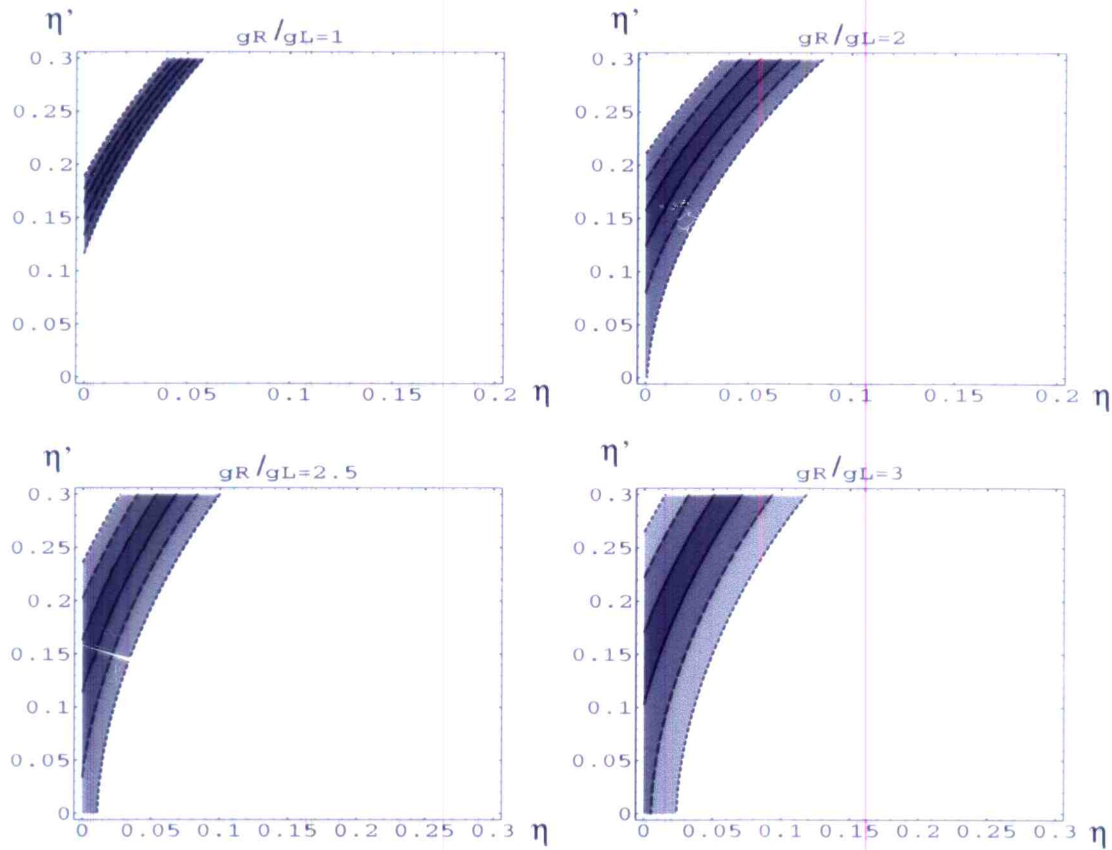
$$\left(\partial_z^2 - \frac{1}{z}\partial_z + q^2\right)\psi(z) = 0$$

$$\psi_k^{(A)}(z) = z\left[a_k^{(A)} J_1(q_k z) + b_k^{(A)} Y_1(q_k z)\right]$$

KK EXPANSION AS BEFORE

$$\begin{cases} B_\mu(x,z) = g_5 a_0 \gamma_\mu(x) + \sum_{k=1}^{\infty} \psi_k^{(B)}(z)\, Z_\mu^{(k)}(x) \\ A_\mu^{L,R3}(x,z) = \tilde{g}_5 a_0 \gamma_\mu(x) + \sum_{k=1}^{\infty} \psi_k^{(LR3)}(z)\, Z_\mu^{(k)}(x) \\ A_\mu^{LR\pm}(x,z) = \sum_{k=1}^{\infty} \psi_k^{(LR\pm)}(z)\, W_\mu^{(k)\pm}(x) \end{cases}$$

FULLY NUMERICAL SCAN OF S-PARAMETER



$\eta' = \frac{\tau'}{R \log R'/R}$; $\eta = \frac{\tau}{R \log \frac{R'}{R}}$

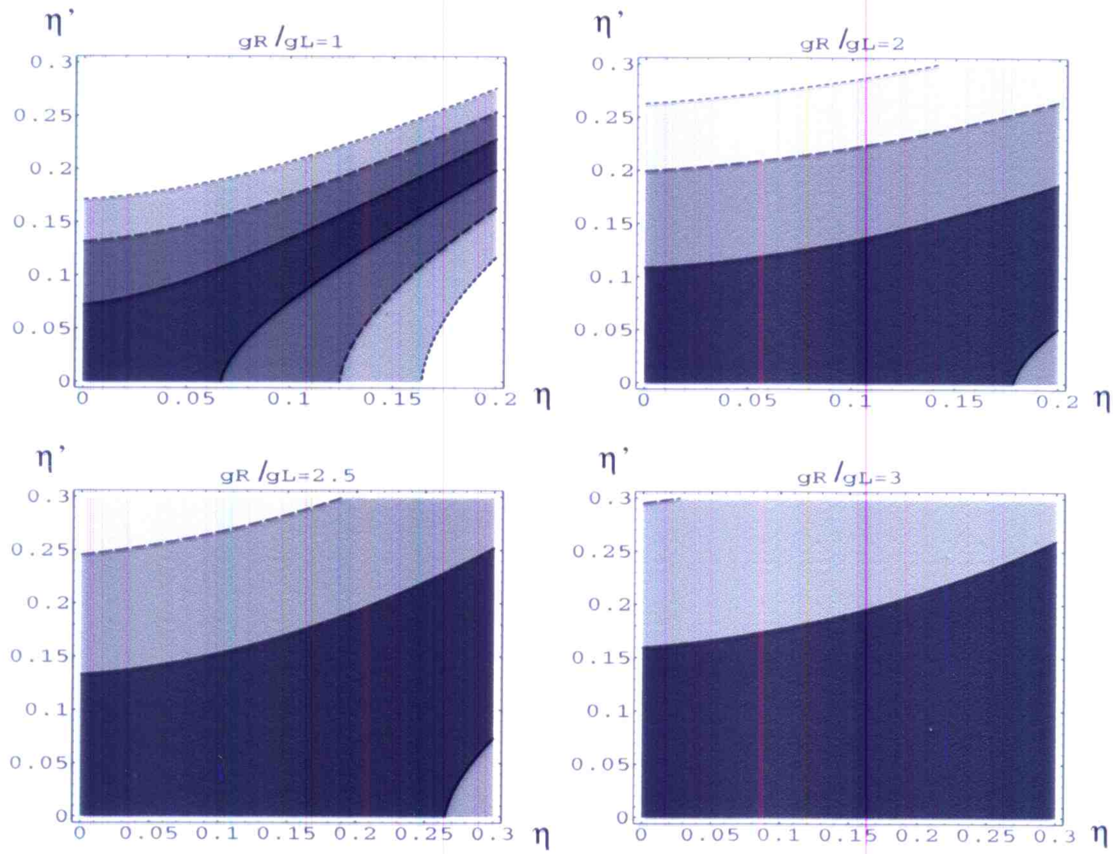
TeV induced Kinetic terms

DARKEST : $|S| < 0.1$

MIDDLE : $|S| < 0.3$ ← REASONABLE BOUND

LIGHT : $|S| < 0.5$

NUMERICAL SCAN OF T-PARAMETER



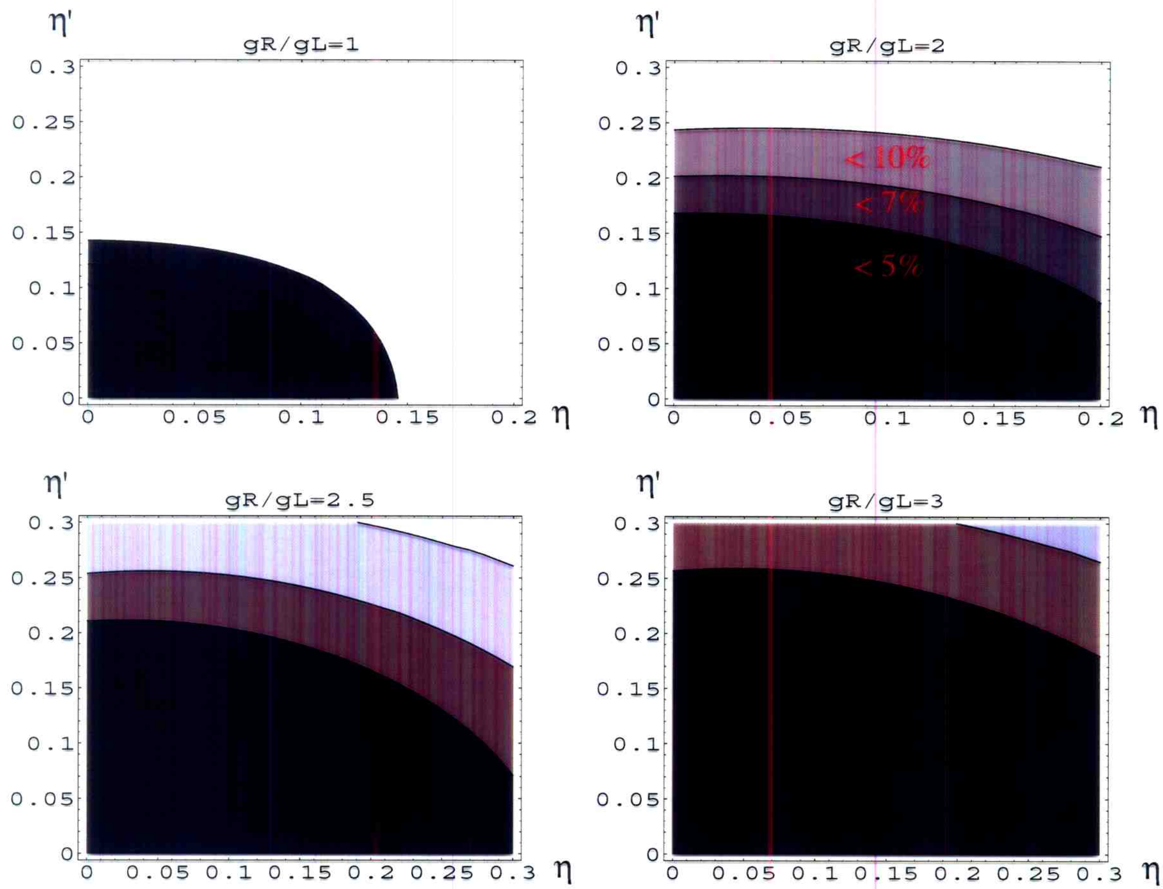
DARKEST |T| < 0.1

MIDDLE |T| < 0.3 ← USE THIS

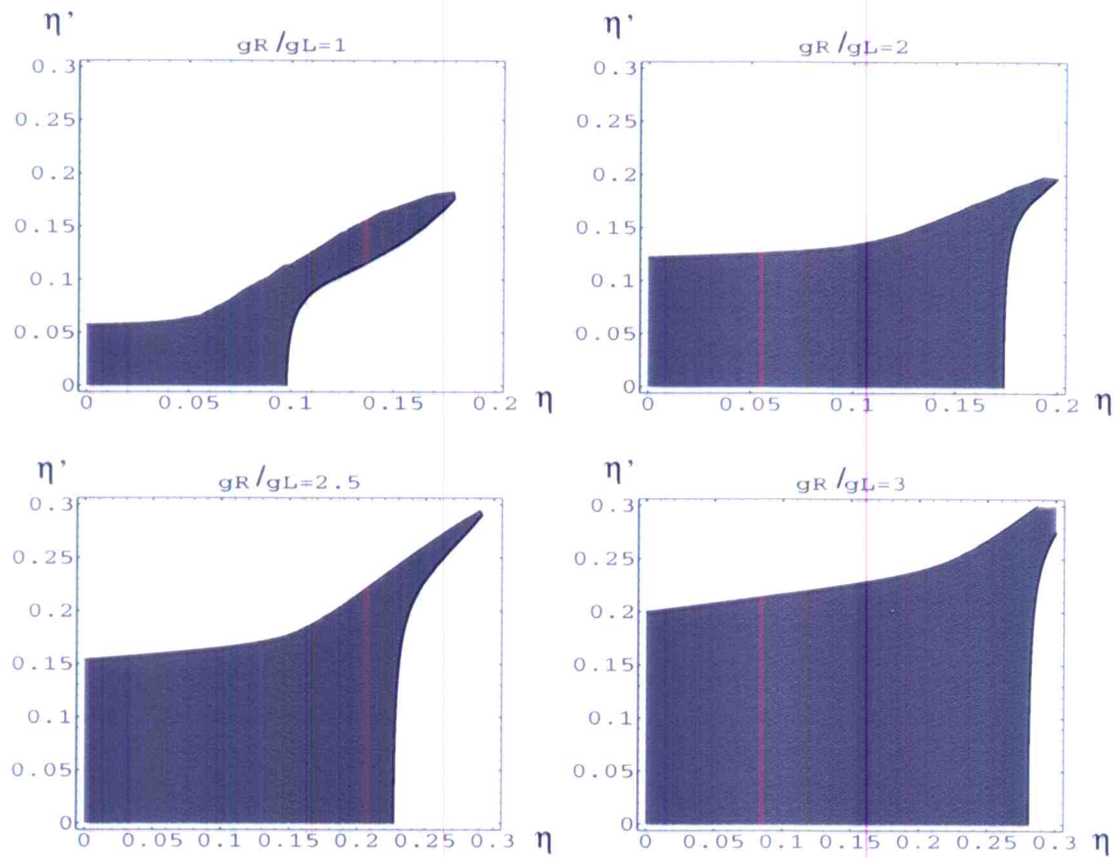
LIGHT |T| < 0.5

Z's at LEP 2

deviation of $\sigma(e^+e^- \to \mu^+\mu^-)$

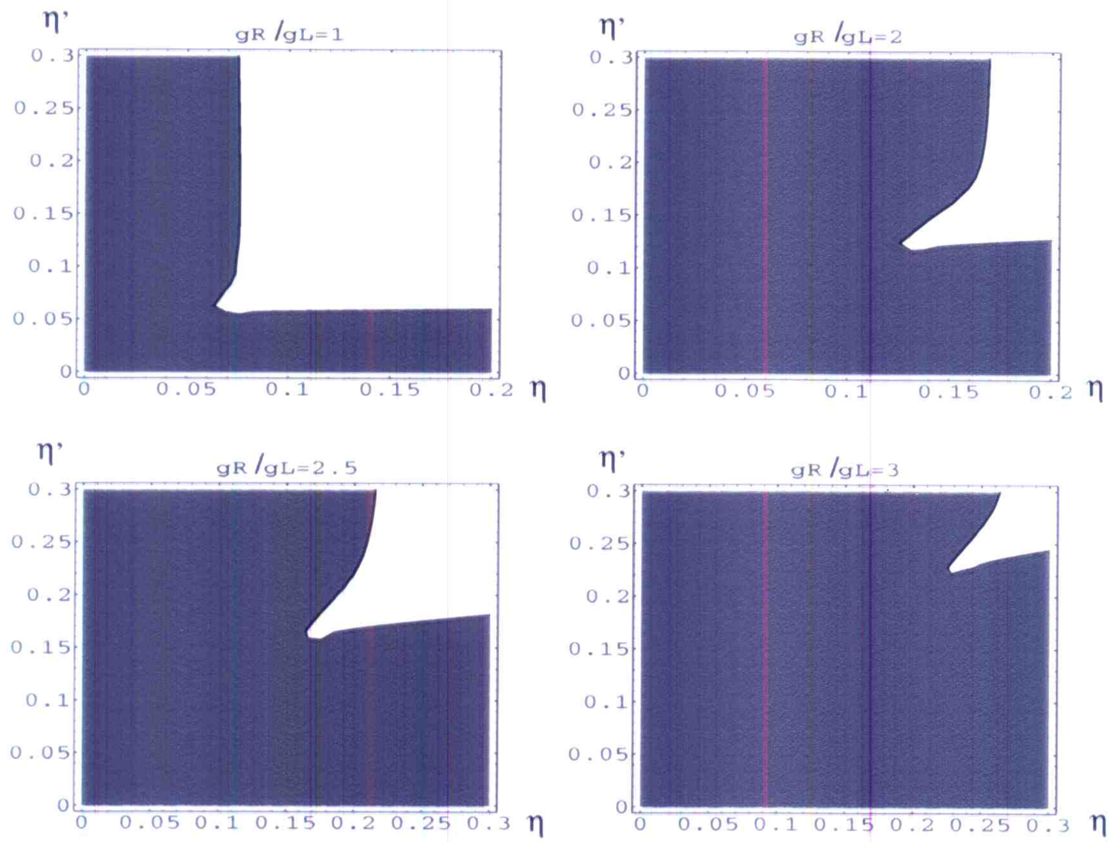


TEVATRON BOUND NON-OBSERVATION OF Z'



SHADED REGION ALLOWED

TEVATRON RUN I BOUND NON-OBSERVATION OF Z''

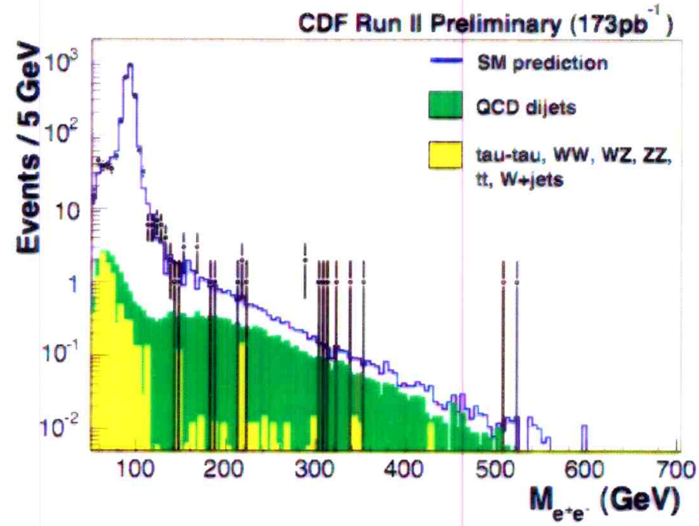


SHADED REGION ALLOWED

Tevatron Run II

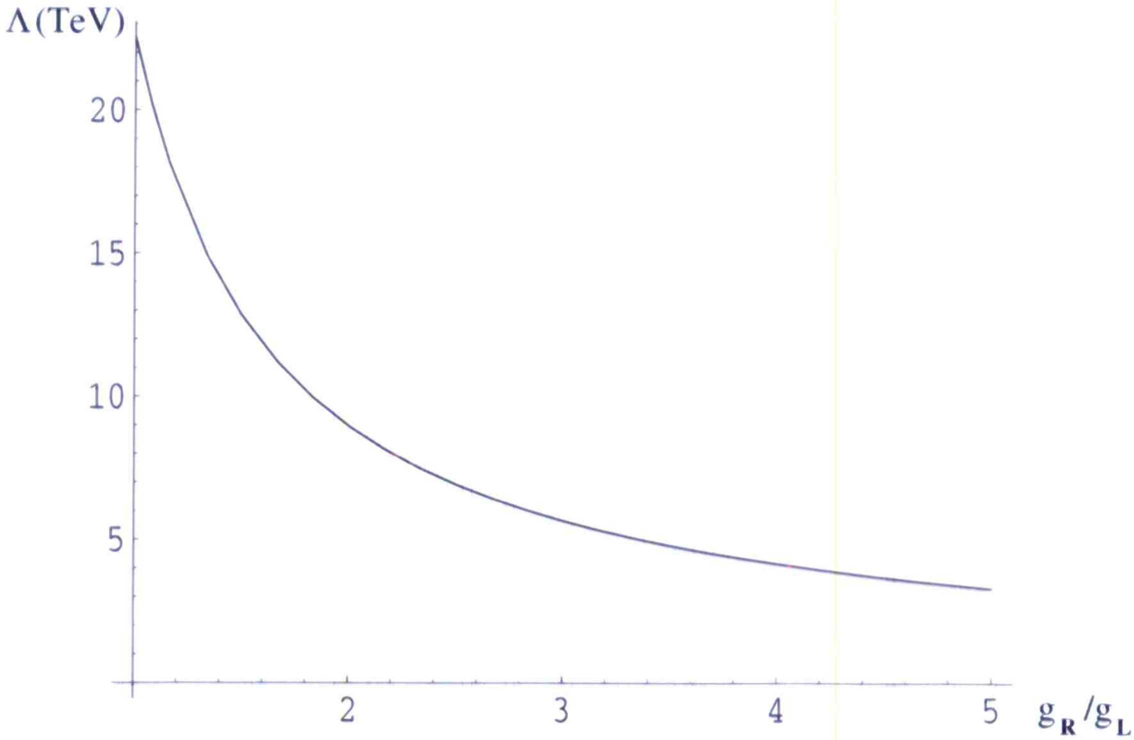
Mass>	NPred	Ndata
0	2414 " #$[illegible]&'$(	
)**[illegible]) ++%" ,-([illegible]) +.		
200	10.2 " &-&[illegible]) +	
&#*[illegible]#-*%") -&[illegible]) *		
'**[illegible]&-#%" *-([illegible]$		
'#*[illegible]) -+%" *-'% '		
+**[illegible]*-() %" *-* ([illegible]&		
+#*[illegible]*-' .%" *-* .[illegible]&		
#**[illegible]*-&) %" *-*+% &		
##*[illegible]*-) *%" *-*'[illegible]*		

Beyond t



J. Nachtman, talk given at the Aspen 2004 Winter Conference on Particle Physics

CUTOFF SCALE FROM NDA

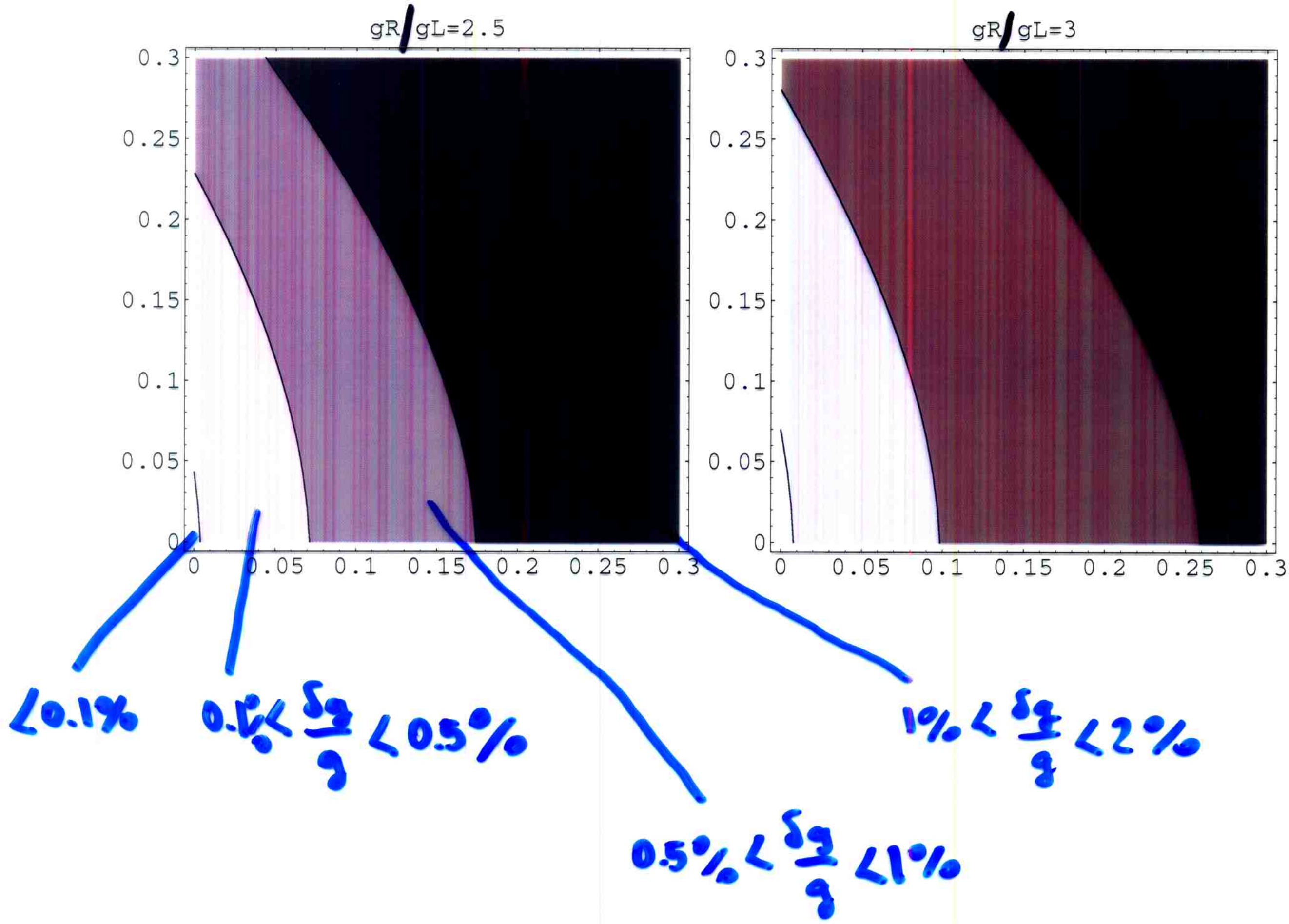


LOOP FACTOR $\frac{g_5^2}{24\pi^3} \cdot E$, WARP IT TO TeV SCALE

$$\Lambda_{NDA} = \frac{24\pi^3}{g_5^2} \frac{R}{R'}$$

FOR $\frac{g_{5R}}{g_{5L}} \sim 3$ $\Lambda \sim$ 5-6 TeV

Deviation of WWZ Coupling



Example Allowed Spectrum

$$\bar{\psi}\gamma^{\mu}\left[Z_{n\mu}(g_{Zn}T^3 + g_{Yn}Y/2) + W^+_{n\mu}g_{Wn}T^+\right]\psi$$

Table 1: for $g_{5R}/g_{5L} = 3$, $\tau = 0.043$, $\tau' = 0.20$.

	Mass (GeV)	g_{WWZ_n}	g_{Zn}	g_{Yn}
Z	91.19	0.57	0.57	-0.17
Z_1	621.23	0.003	0.0042	-0.17
Z_2	1183.5	0.013	0.16	0.006
Z_3	4230.0	-0.0055	0.026	-0.005
Z_4	4312.3	-0.0006	0.004	-0.06

	Mass (GeV)	g_{ZWW_n}	g_{Wn}
W_1	1183.3	0.015	0.16
W_2	4229.2	-0.006	0.026
W_3	4446.3	0.0014	0.096

NON-OBLIQUE CORRECTION: THE $Zb\bar{b}$ VERTEX

ISSUE: IN SIMPLEST MODEL FOR FERMION MASSES TOP QUARK ON TeV BRANE

- ON PLANCK-BRANE

$$m_{top}^2 \leq \frac{2}{R' \log \frac{R'}{R}}$$

FOR $\frac{g_{5R}}{g_{5L}} = 1$ $\quad R' \sim \frac{1}{500\,GeV}$ $\quad m_{top} \lesssim 120\,GeV$.

- IF ON TeV BRANE: b_L ALSO ON TeV BRANE. GAUGE BOSON WAVE FUNCTION VERY DIFFERENT ON TeV BRANE →

LARGE CORRECTION TO $g_{Zb_L\bar{b}_L}$ COUPLING

BUT FROM LEP $\delta g_{Zb\bar{b}}/g_{Zb\bar{b}} \lesssim 1\%$

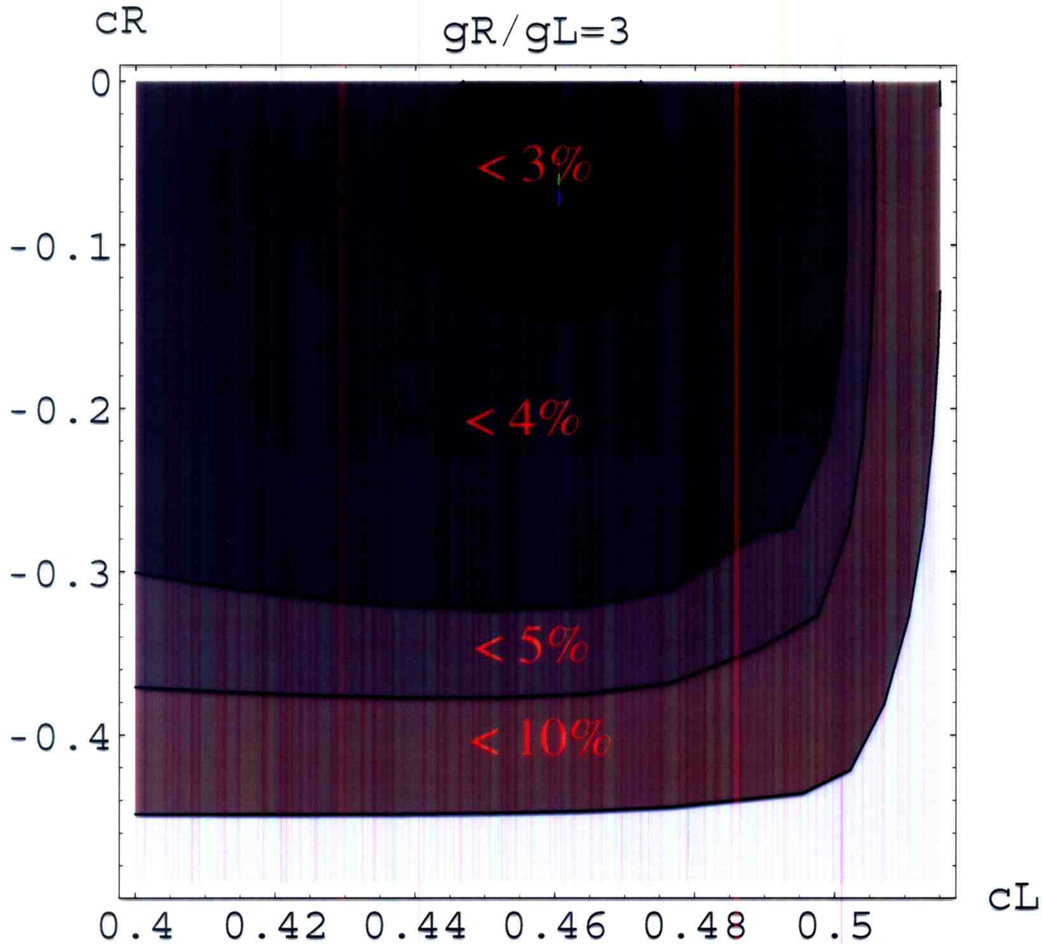
- ONLY WAY OUT: NEED TO RAISE R'.

THIS IS EXACTLY WHAT $\frac{g_{5R}}{g_{5L}} > 1$ DOES.

FOR $g_{5R}/g_{5L} \sim 3$ CAN GET $\delta g/g \sim 3\%$

~ 4-4.5 —"— $\delta g/g \lesssim 1\%$

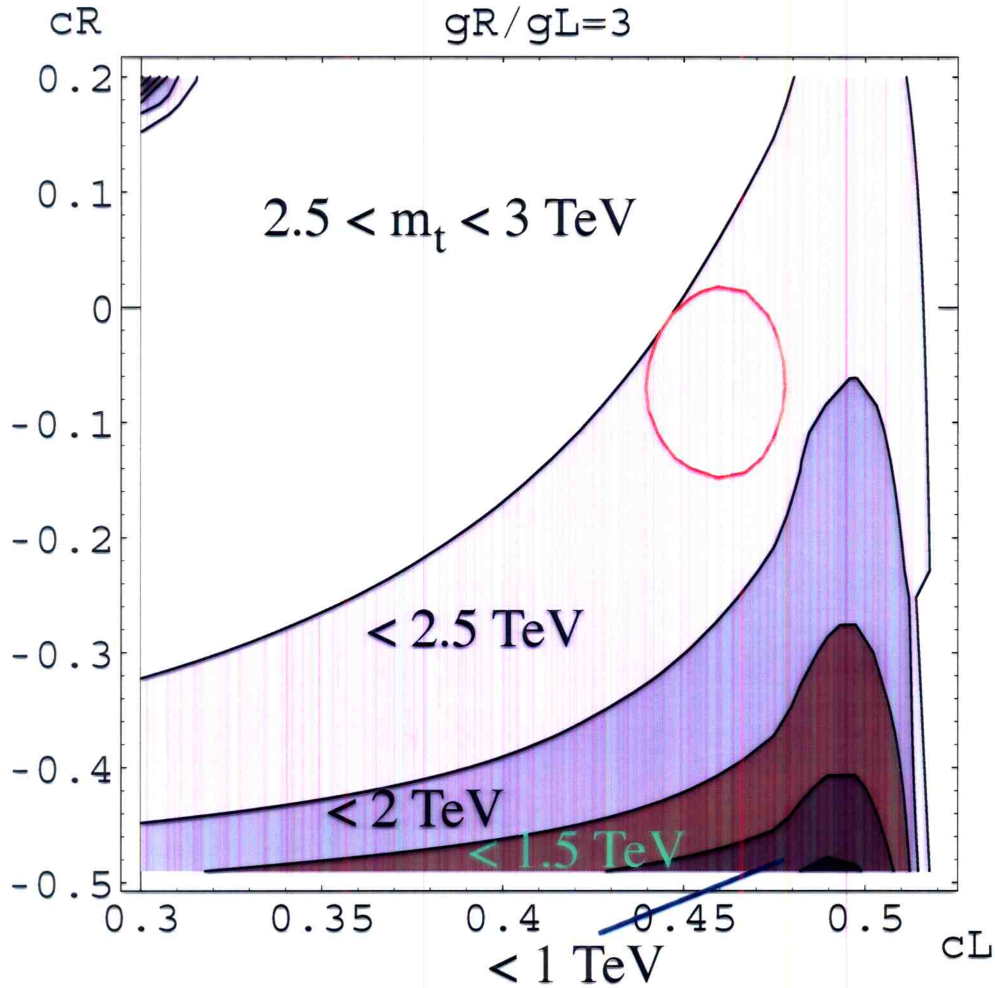
$Zb\bar{b}$ deviation



NEED TO GOTO $g_R/g_L \sim 4-4.5$ TO GET

<1%

top resonance



PARTIAL WAVE UNITARITY VS. STRONG COUPLING

- S-WAVE AMPLITUDE

$$a_0 = \frac{1}{32\pi} \int_0^{\pi} A \sin\theta \, d\theta$$

UNITARITY $\quad \mathrm{Re}\, a_0 < 1/2$

- BUT SOMETIMES KINEMATIC SINGULARITY
t-CHANNEL EXCHANGE

SMALL ANGLES

$$\sim E^2 \int d\theta \, \frac{\sin\theta}{t - M_{Z_n}^2} \sim E^2 \int d\theta \, \frac{\theta}{-2E^2\theta^2 - M_{Z_n}^2} = -\frac{1}{2}\log\left(E^2\theta^2 + M_{Z_n}^4\right)$$

- EVEN WHEN TERMS $\sim E^4, E^2$ CANCEL:
THERE CAN STILL BE $\log\left(\frac{E}{M_Z}\right)$ TERMS

$$a_0 \supset \frac{g^2_{WWZ_n}}{32\pi}\left(2 - \frac{M_{Z_n}^2}{M_W^2}\right)^2 \log\left(\frac{4E^2}{M_{Z_n}^2}\right)$$

THESE DON'T REFLECT STRONG COUPLING, BUT BREAKDOWN OF FORMULATION OF PERT. THEORY