Higgsless ElectroWeak Symmetry Breaking

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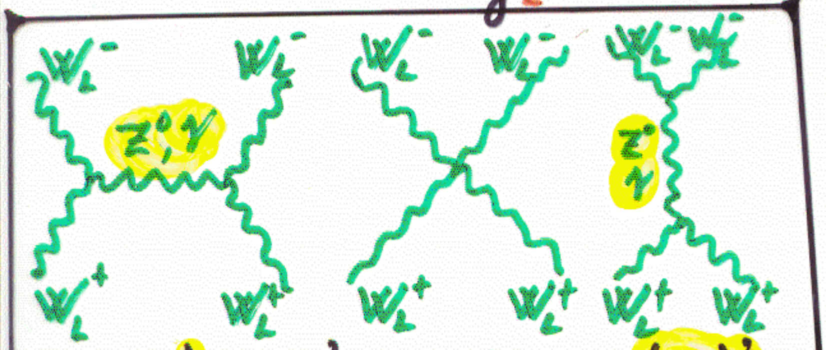
Why do we need a Higgs?

1) To give mass to W & Z:

Spontaneously Broken Gauge Theory

UV consistent theory [Cornwall et al '73] ['t Hooft] [Veltman '72] Renormalizable theory



$$\mathcal{A} = \frac{g^2}{M_W^2}(s-t) \propto g^2\left(\frac{E}{M_W}\right)^2 \qquad \mathcal{A} \propto -g^2\left(\frac{E}{M_W}\right)^2$$

Finite Amplitude $\mathcal{A} \propto g^2\left(\frac{M_H}{M_W}\right)^2$ ($\Rightarrow m_H < 1$ TeV)

2. To give mass to Quarks & Leptons

Chiral Theory: t_L & t_R have different couplings to W, Z

$$m\, t_L t_R \longleftarrow m \frac{H}{v} t_L t_R$$

$SU(2)_L \times U(1)_Y$ ✗ $\qquad$ $SU(2)_L \times U(1)_Y$ ✓

Higgs = a so useful particle ... yet unseen. A life without it?

Standard Scenari of EWSB

Weakly Coupled:

- (MS)SM
- **little Higgs** i.e. Higgs as a pseudo Goldstone boson

Strongly Coupled:

- (extended, walking, top color assisted) **technicolor**

Since the blooming of extradimensions, two new approaches.

- Higgs = component of gauge field in extradimension
- Symmetry breaking by boundary conditions a.k.a. **Higgsless**

$$m^2 = E^2 - \vec{p}_3^{\,2} - \vec{p}_\perp^{\,2}$$ no need for a mass from a Higgs!

Symmetry Breaking From Boundary Conditions

Sym. Breaking Different BC's for Different Gauge Directions

$SU(2) \searrow U(1)$

BCs

0 ——— πR

$$\Box_4 A_\mu^a - \partial_\perp^2 A_\mu^a = 0$$

At 0: $A_\mu^{1,2}\big|_0 = 0$, $\partial_\perp A_\mu^3\big|_0 = 0$

At πR: $\partial_\perp A_\mu^{1,2,3} = 0$

$m_{\gamma^{(0)}} = 0$

$m_{\gamma^{(k)}} = \frac{k}{R}$

$m_{W^{(k)}} = \frac{2k+1}{2R}$

$$A_\mu^1(x,y) = \sum_{k=0}^{\infty} \frac{1}{\sqrt{\pi R}} \sin\frac{(2k+1)y}{2R} \left(W_\mu^{+(k)}(x) + W_\mu^{-(k)}(x) \right)$$

$$A_\mu^2(x,y) = \sum_{k=0}^{\infty} \frac{i}{\sqrt{\pi R}} \sin\frac{(2k+1)y}{2R} \left(W_\mu^{+(k)}(x) - W_\mu^{-(k)}(x) \right)$$

$$A_\mu^3(x,y) = \sum_{k=0}^{\infty} \sqrt{\frac{2}{2^{\delta_{k,0}}\pi R}} \cos\frac{ky}{R}\, \gamma_\mu^{(k)}(x)$$

What are the most general BC's ?

What is the nature of the Breaking ?

Can we get a realistic EWSB model ?

Here: γ: $m = 0$; W: $m = \frac{1}{2R}$; $Z \equiv \gamma^{(1)}$: $m = 2\, m_W$

BC's for 5D Scalar Theory

$$S = \int d^4x \int_0^{\pi R} dy \; \underbrace{\left(\frac{1}{2} \partial_M \phi \partial^M \phi - V(\phi) \right)}_{\text{integration by part}} + \int_{y=0,\pi R} d^4x \; \frac{1}{2} M^2_{0,\pi R} \phi^2$$

Boundary Term

$$\delta S = \int_{y=0,\pi R} d^4x \; \delta\phi \left(\partial_y \phi + M^2_{0,\pi R} \phi \right) + \text{Bulk Part}$$

BC's

$$\delta\phi \left(\partial_y \phi + M^2_{0,\pi R} \phi \right) = 0$$

Bulk Eq. of motion

$$\Box_5 \phi = -V'(\phi)$$

Consistent BC's :

(i) Dirichlet $\quad \phi_{0,\pi R} = cst.$

(ii) Mixed BC's $\quad \partial_y \phi = -M^2 \phi \quad \xrightarrow{M \to \infty}$ Dirichlet, $\xrightarrow{M \to 0}$ Neumann

(iii) Non trivial cancellation among various boundary terms

BC's for 5D Gauge Theory

$$S = \int d^4x \int_0^{\pi R} dy \left(-\frac{1}{4} F^a_{MN} F^{aMN} - \underbrace{\frac{1}{2\xi}\left(\partial_\mu A^{a\mu} - \xi\, \partial_5 A^a_5\right)^2}_{\text{Gauge Fixing Terms}} \right)$$

$$\delta S = \int_{y=0,\pi R} d^4x \left(\frac{1}{2} F^a_{\nu 5}\, \delta A^{a\nu} + \left(\partial_\sigma A^{a\sigma} + \xi\, \partial_5 A^a_5\right) \delta A^a_5 \right) + \text{Bulk Part}$$

Consistent BC's:

(i) $A^a_\mu = 0 \quad , \quad A^a_5 = \text{cst.}$

(ii) $A^a_\mu = 0 \quad , \quad \partial_5 A^a_5 = 0$

(iii) $\partial_5 A^a_\mu = 0 \quad , \quad A^a_5 = \text{cst.}$

(iv) non trivial cancellation among various boundary terms.

Gauge Symmetry Breaking — different BC's for different gauge directions

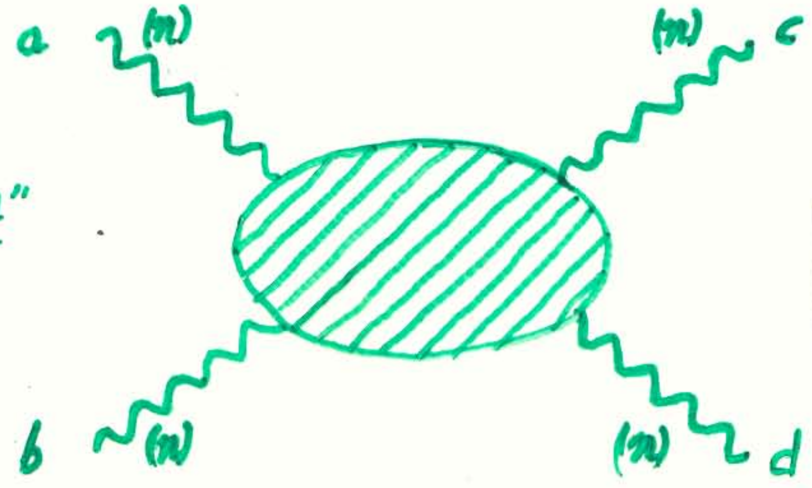
(No automorphism restriction; No Parity restriction)

No Explicit Symmetry Breaking Terms

¿ Soft Breaking ?

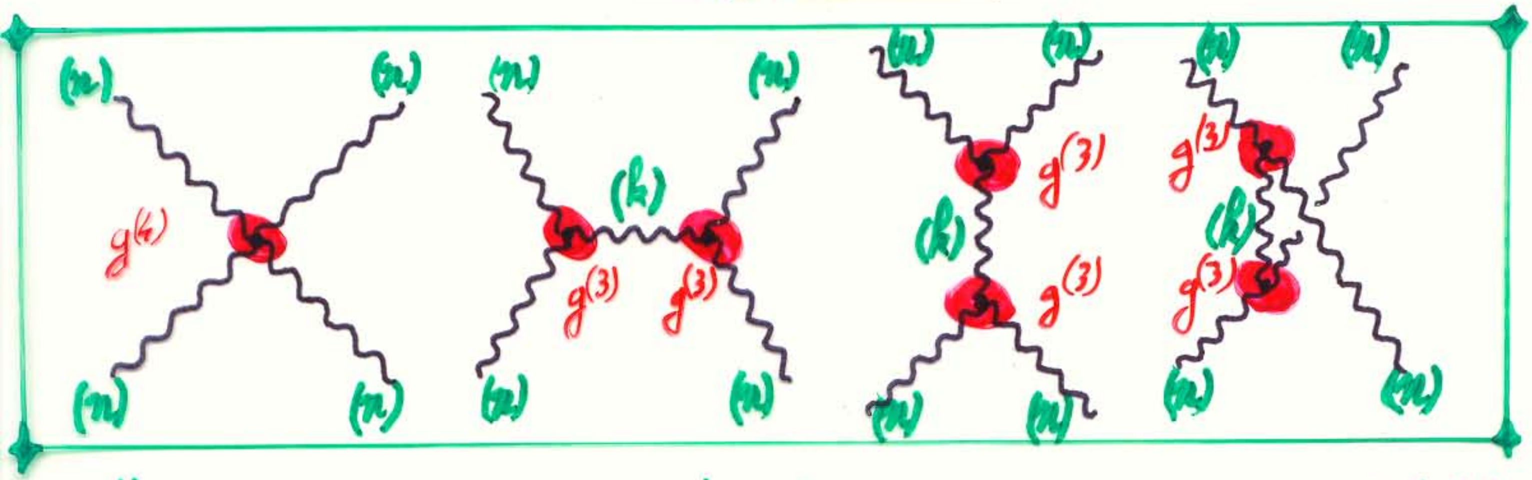
(Elastic) Scattering Amplitude

Same KK "in" and "out" ...



(longitudinal polarization $\varepsilon_\mu = \left(\frac{|\vec{p}|}{M}, \frac{E}{M}\frac{\vec{p}}{|\vec{p}|}\right)$)

$$\boxed{A = A^{(4)}\left(\frac{E}{M_n}\right)^4 + A^{(2)}\left(\frac{E}{M_n}\right)^2 + A^{(0)} + \ldots}$$



$$A^{(4)} = i\left(g^2_{nnnn} - \sum_k g^2_{nnk}\right)\left(f^{abe}f^{cde}(3+6c_\theta - c_\theta^2) + 2(3-c_\theta^2)f^{ace}f^{bde}\right)$$

$$A^{(2)} = i\left(4g^2_{nnnn} - 3\sum_k g^2_{nnk}\frac{M_k^2}{M_n^2}\right)\left(f^{ace}f^{bde} - \sin^2\frac{\theta}{2} f^{abe}f^{cde}\right)$$

K.K. Theory

$$\boxed{A^a_\mu = \sum_k f^a_{(n)}(y)\, \varepsilon_\mu\, e^{i p_n \cdot x}} \qquad (p_n^2 = M_n^2)$$

Wave functions:

Bulk Eq. : $f_n'' + M_n^2 f_n = 0$

BC's Eq. : $f_n' = V f_n \big|_{0,\pi R}$

$\Longrightarrow$ Spectrum & Wave functions

Effective couplings:

$g_{cubic} \longrightarrow g^{abc}_{mnp} = \int_0^{\pi R} dy\, f^a_m(y) f^b_n(y) f^c_p(y)\, g_5$

$g^2_{quartic} \longrightarrow g^{2\,abcd}_{mnpq} = \int_0^{\pi R} dy\, f^a_m f^b_n f^c_p f^d_q\, g_5^2$

(unless flat wavefunction, $g^2_{quartic} \neq g^2_{cubic}$)

deviations in the W, Z couplings

¿ observable @ NLC ?

Sum Rules

or unitarity without a Higgs!

E^4 terms

$$g^2_{nnnn} - \sum_k g^2_{nnk}$$

$$= g_5^2 \int_0^{\pi R} dy\, f_n^4(y) - g_5^2 \int_0^{\pi R} dy \int_0^{\pi R} dz\, f_n^2(y) f_n^2(z) \underbrace{\sum_k f_k(y) f_k(z)}_{\delta(y-z)}$$

$= 0$ [Csáki, C.G., Murayama, Pilo, Terning '03]

Completeness of KK modes since ∂_5^2 is selfadjoint

E^2 terms

$$4\, g^2_{nnnn} M_n^2 - 3 \sum_k g^2_{nnk} M_k^2$$

$$\sum_k M_k^2 \int_0^{\pi R} dy \int_0^{\pi R} dz\, f_n^2(y) f_n^2(z) f_k(y) f_k(z) \underbrace{=}_{\substack{\text{integration by part} \\ f_k'' = -M_k^2 f_k}} \frac{4}{3} M_n^2 \int_0^{\pi R} dy\, f_n^4(y)$$

up to boundary terms ...
$$-\frac{2}{3}\left[f_n^3 f_n'\right]_0^{\pi R} + 2 \sum_k \left[f_n f_n' f_k\right] \int_0^{\pi R} dy\, f_n^2 f_k - \sum_k \left[f_n^2 f_k'\right] \int_0^{\pi R} dy\, f_n^2(y) f_k(y)$$

that cancel for Dirichlet and Neumann BC's.

For mixed BC's: exchange of KK's doesn't unitarize $\mathcal{A}$

↳ needs for more degrees of freedom

(Higgs localized on the brane)

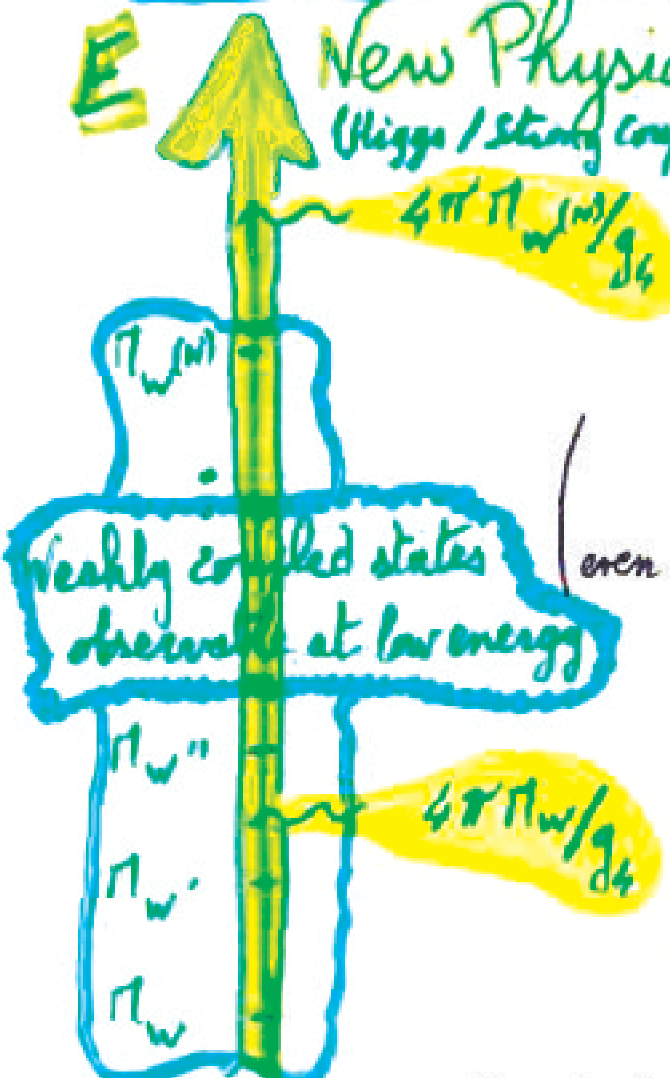
Spontaneous Breaking by BC's

A counter example to Cornwall et al. theorem?

No! E^2 cancellation requires an infinite # KK's

$$g^2_{nnnn} \overset{(E^4)}{=} \sum_k g^2_{nnk} \overset{(E^2)}{=} \sum_k g^2_{nnk} \frac{3 M_k^2}{4 M_n^2}$$

With a finite # KK's: (an effective theory of massive W, Z above M_W!)



True Cutoff (5D)

$$24\pi^3/g_5^2 = \frac{12\pi^2 M_W}{g_4^2}$$

(even in flat space, already a factor 10)

not directly set by the weak scale... (too high to be observed)

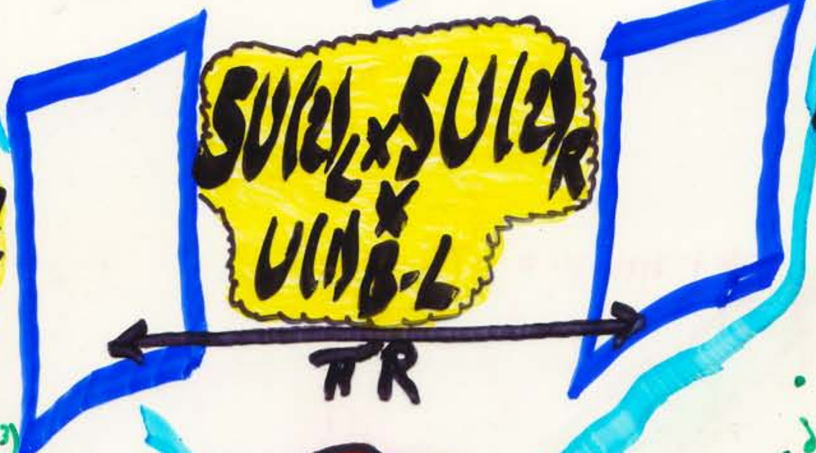
Naive Cutoff

Weak scale

No need for a scalar field at low energy anymore ...

Toy Model of EWSB

$SU(2)_R \times U(1)_{B-L} \to U(1)_Y$



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

- $\partial_5 B_\mu = -\frac{1}{4} g'\, v^2 (g' B_\mu - g A_\mu^{R3})$
- $\partial_5 A_\mu^{R3} = \frac{1}{4} g\, v^2 (g' B_\mu - g A_\mu^{R3})$
- $\partial_5 A_\mu^{R\pm} = -\frac{1}{4} g^2 v^2 A_\mu^{R\pm}$

$U(1)_{E.M.}$

- $A_\mu^L = A_\mu^R$
- $\partial_5 A_\mu^L = -\partial_5 A_\mu^R$

Example of non-trivial cancellation among various boundary terms

Spectrum

W

$$m \tan 2m\pi R = \frac{1}{4} g_5^2 v^2$$

$$m \simeq \frac{2k+1}{4R} + \mathcal{O}(1/R^2 v)$$

BRANE Higgs Decoupling

Z

$$m \tan m\pi R = \frac{g_5^2 + 2 g_5'^2}{8} v^2 - \frac{g_5^2 v^2}{8} \tan^2 m\pi R$$

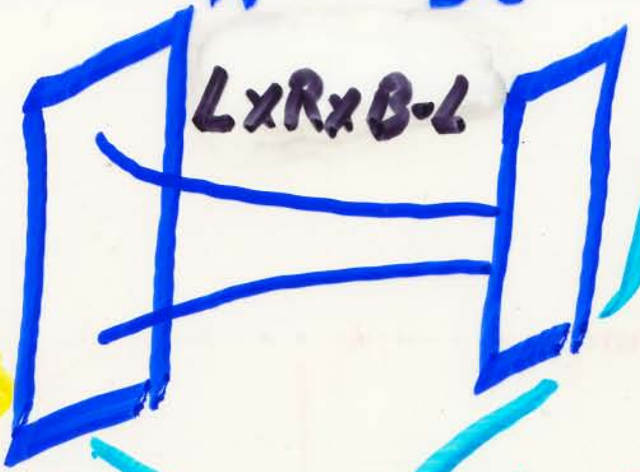
$$m = \frac{k}{R} \pm \frac{1}{\pi R} \arctan \sqrt{\frac{2 g_5'^2 + g_5^2}{g_5^2}} + \mathcal{O}(1/R^2 v)$$

Coupling to matter @ $y=0$

Usual couplings to $\gamma, W^\pm, Z$ BUT $\rho = \frac{M_W^2}{M_Z^2 \cos^2\theta_W} \sim 1.10$

... and too light W', Z' .... [Csáki, Grojean, Murayama, Pilo, Terning '03]

$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ in AdS_5



M_{Pl}

$SU(2)_R \times U(1)_{B-L} \to U(1)_Y$

$$A_R^{1,2} = 0$$
$$(g' B - g A_R^3) = 0$$
$$\partial_\perp (g B + g' A_R^3) = 0$$

TeV

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

$$A_L^a = A_R^a$$
$$\partial_\perp A_L^a = -\partial_\perp A_R^a$$

KK $\to$

$$A_\mu(x,z) = \sum_z z\left(a_k J_1(mz) + b_k Y_1(mz)\right) \tilde{A}_\mu^{(k)}(x)$$

W

$$(R_0 - R_0')(R_1 - R_1') + (R_1' - R_0)(R_0' - R_1) = 0$$

$$R_i; R_i' = \frac{Y_i(mz)}{J_i(mz)}\Big|_{M_{Pl}, TeV}$$

$$m_W^2 = \left(R_{TeV}^2 \ln \frac{R_{TeV}}{R_{M_{Pl}}}\right)^{-1}$$

Z

$$g^2\left((R_0 - R_0')(R_1 - R_1') + (R_1' - R_0)(R_0' - R_1)\right) = 2 g'^2 (R_0 - R_1')(R_0' - R_1)$$

$$m_Z^2 = \frac{g^2 + 2g'^2}{g^2 + g'^2}\left(R_{TeV}^2 \ln \frac{R_{TeV}}{R_{M_{Pl}}}\right)^{-1}$$

Solution of Little Hierarchy Pb. !

KK's : ($SU(2)_R$ multiplet)

... because of TeV localization ...

$m_W^{(2)} \sim m_Z^{(2)} \sim m_\gamma^{(2)} \sim 1.2$ TeV

$m_W^{(3)} \sim m_Z^{(3)} \sim 1.9$ TeV

[Csáki, C.G., Pilo, Terning '03
Agashe, Delgado, May, Sundrum '03]

AdS $\rightsquigarrow$ CFT dual: Walking Technicolor!

EW Effective Lagrangian

Gauge Sector :

$$-\frac{1}{2} W^-_{\mu\nu} W^{+\mu\nu} + M_W W^+_\mu W^{-\mu} - \frac{1}{4} Z_{\mu\nu} Z^{\mu\nu} + \frac{1}{2} M_Z Z_\mu Z^\mu - \frac{1}{4} V_{\mu\nu} V^{\mu\nu}$$

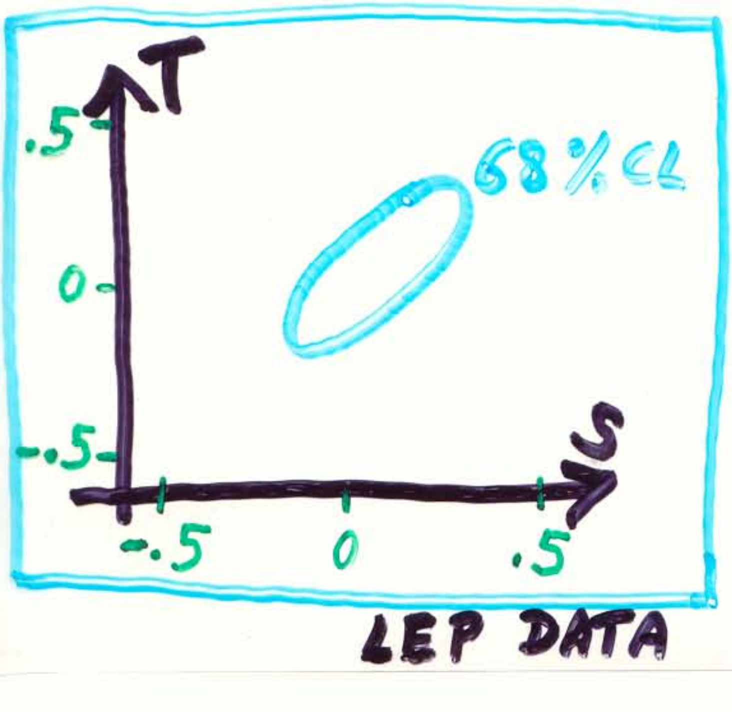
Gauge Fermion Interactions :

$$\left(-i g W^\mp_\mu T^\pm - i g' \sin\theta_W \left(T_{3L} - \tan\theta_W \frac{Y}{2}\right) Z_\mu - i e V_\mu \right) \psi$$

Tree Level + Quadratic order

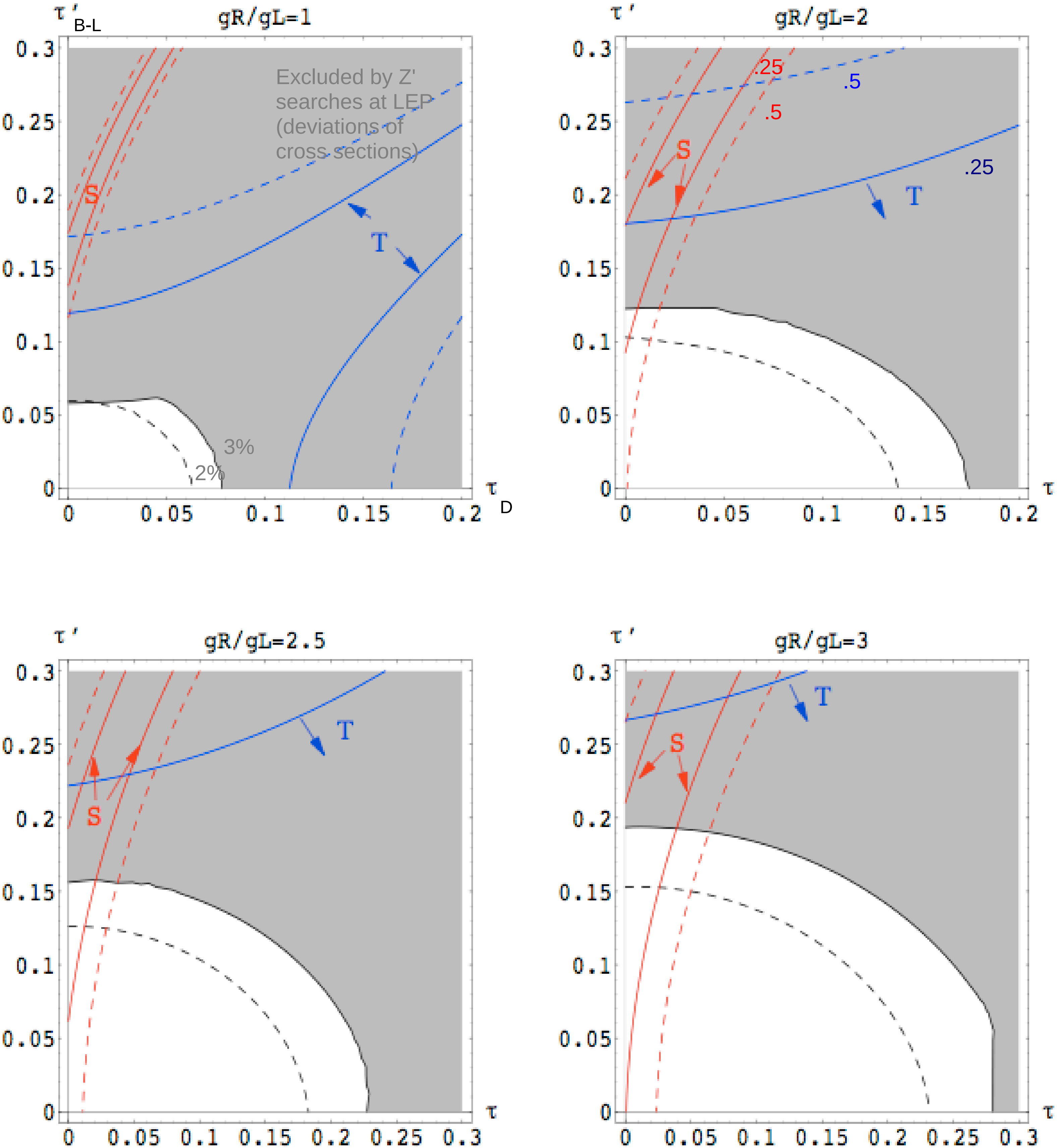
6 parameters : $\begin{cases} g_{SU(2)_L} \quad g'_{U(1)_Y} \quad v \ (M_Z) \\ S,\ T,\ U \end{cases}$

(measure the deviations to S.M.)



LEP DATA

SM tested experimentally at 0.1 %

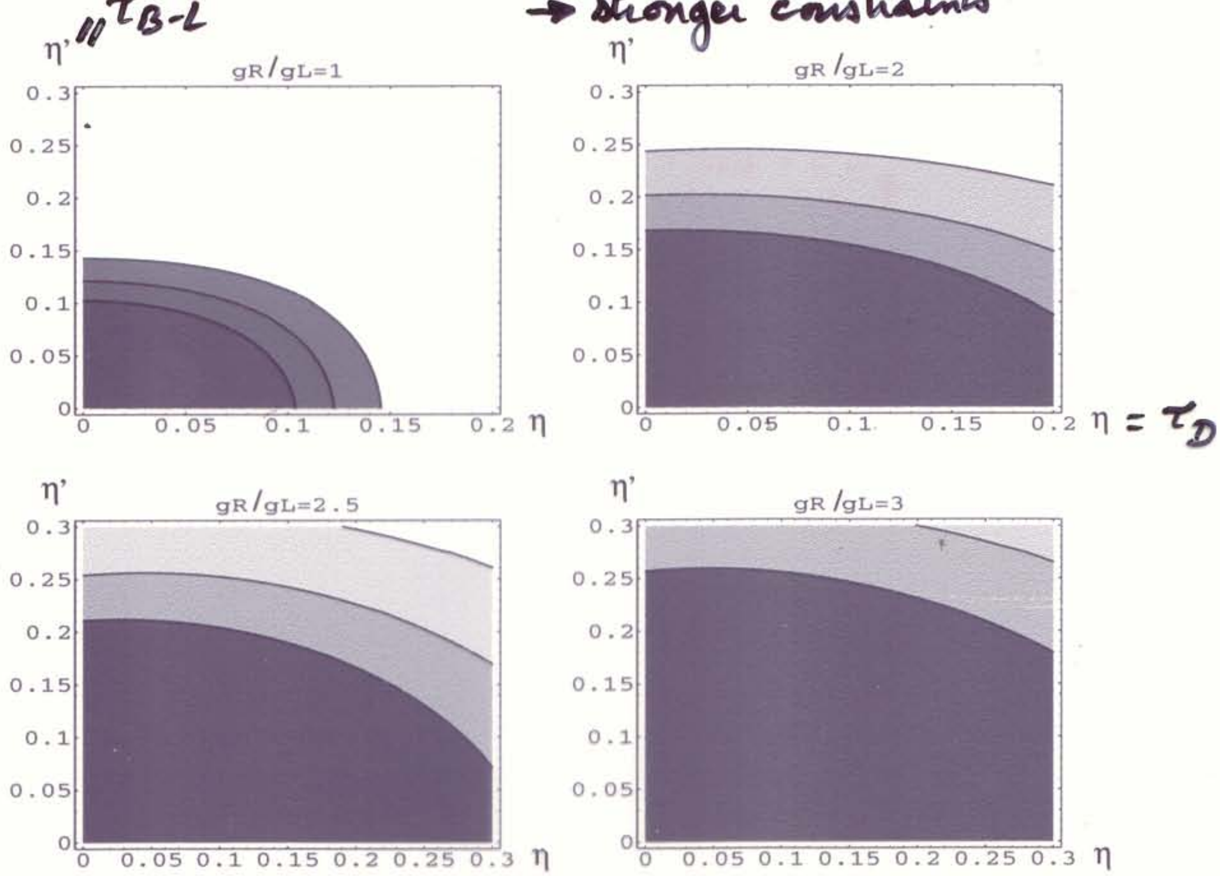


gR/gL=1
τ'B-L
τD
Excluded by Z' searches at LEP (deviations of cross sections)
S
T
3%
2%
gR/gL=2
τ'
τ
.25
.5
.5
.25
S
T
gR/gL=2.5
τ'
τ
S
T
gR/gL=3
τ'
τ
S
T

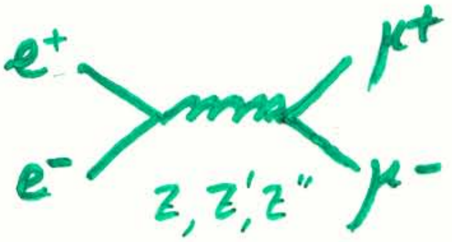
LEP constraints on Z'

(fit of $SU(2)_D$ & $U(1)_{B-L}$ TeV R.t.)

. τ_{B-L} & τ_D decrease $\Gamma_{Z'}$ ...
→ stronger constraints



Contours: 5%, 7%, 10%



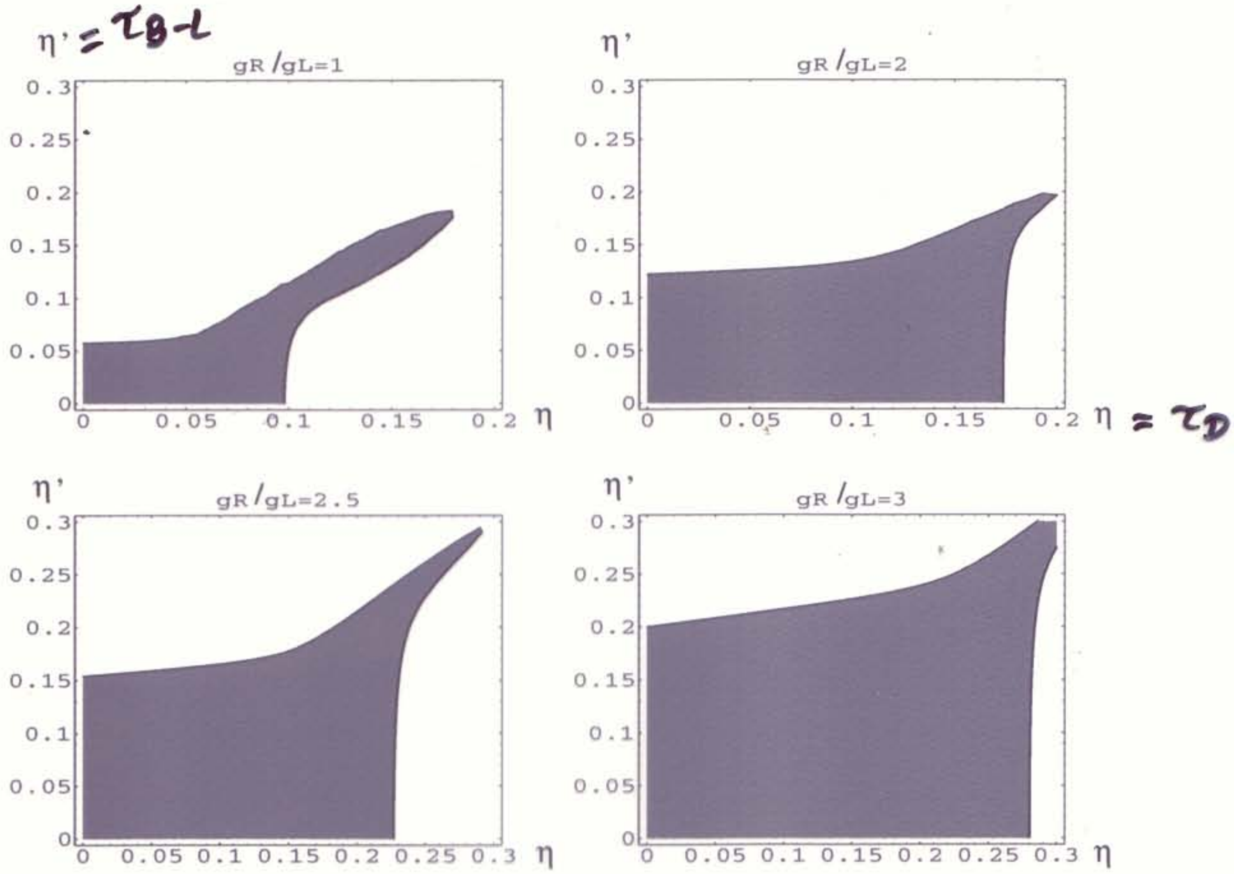
light Z'

↳ $\delta\sigma(e^+e^- \to \mu^+\mu^-)$

search for deviation for the cross section of $e^+e^- \to \mu^+\mu^-$ due to the light Z' from the S.M. prediction @ 200 GeV.

(deviation < 3-5%)

Tevatron Constraints on Z'
(Run I @ 110 pb^{-1})



Search for dilepton pairs with large transverse momentum.
(bound on production cross section × branching fraction)

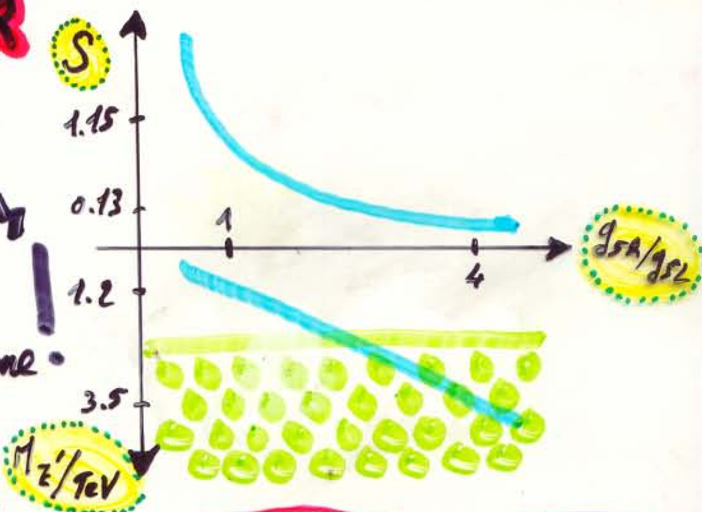
How to Suppress S

[Cacciapaglia, Csáki, C.G., Terning
HEP-PH/0401160]

Asymmetric $SU(2)_L \times SU(2)_R$

$$S = S_0 \cdot \frac{2}{1+(g_{5R}/g_{5L})^2}$$

EW Precision Test
vs.
Weakly Coupled Regime



Brane localized kinetic terms

$SU(2)_L$ $\cdot \; -\frac{1}{2}\tau_L W^{(L)+}_{\mu\nu} W^{-\mu\nu}_{(L)}$

$U(1)_Y$ $\cdot \; -\frac{1}{4}\tau_Y Y_{\mu\nu} Y^{\mu\nu}$

$\cdot \; -\frac{1}{2}\tau_D W^{(D)-}_{\mu\nu} W_D^{+\mu\nu}$ $SU(2)_D$

$\cdot \; -\frac{1}{4}\tau_{B-L} B_{\mu\nu} B^{\mu\nu}$ $U(1)_{B-L}$

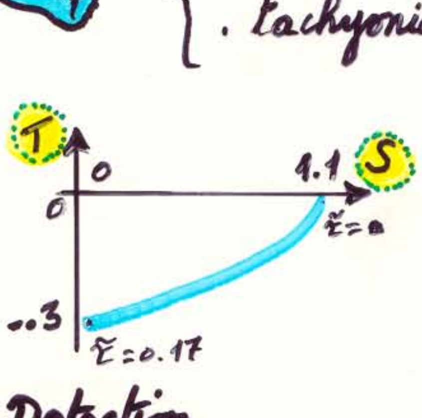
Pl TeV

$(\tilde{\tau}_i = \tau_i / R \log(R'/R))$

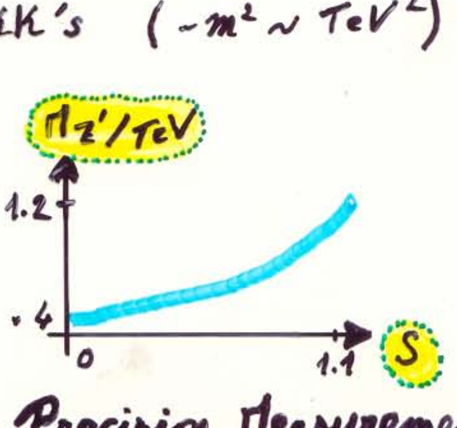
$$S = S_0 \cdot \frac{2}{1+(g_{5R}/g_{5L})^2} \cdot \frac{1}{1+\tilde{\tau}_L} + \frac{8\pi}{g_4^2} \cdot \frac{2}{1+(g_{5R}/g_{5L})^2} \cdot \frac{\tilde{\tau}_D}{1+\tilde{\tau}_L} - \frac{16\pi}{g_4^2} \cdot \frac{g_{5R}^2}{g_{5R}^2+g_{5B}^2} \cdot \frac{1}{1+\left(\frac{g_{5R}}{g_{5L}}\right)^2} \tilde{\tau}_{B-L}$$

$SU(2)_L$, $SU(2)_D$, $U(1)_Y$ { . loss of perturbative unitarity
. tachyonic KK's $(-m^2 \sim \mathrm{TeV}^2)$

$U(1)_{B-L}$

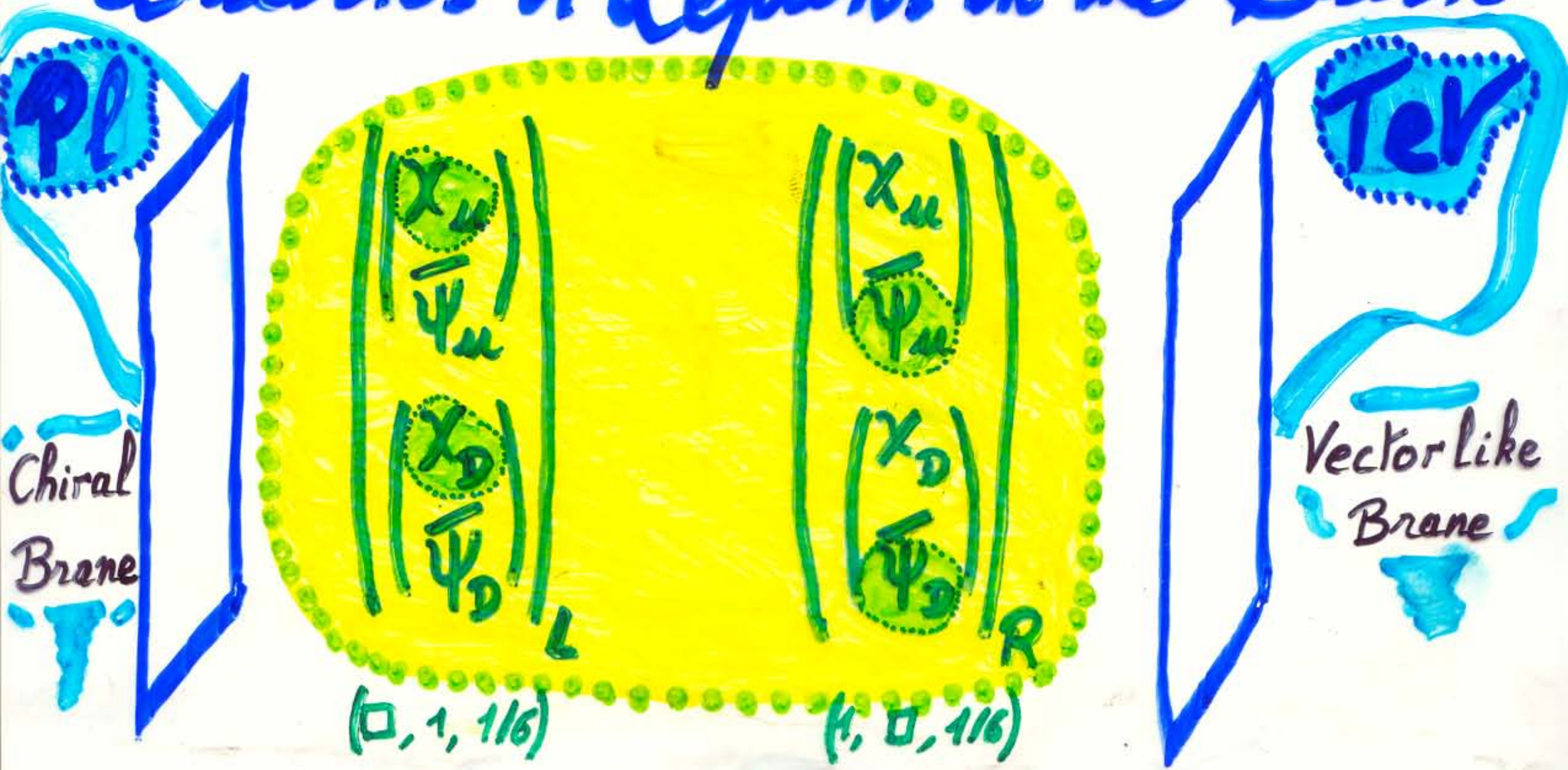


Direct Detection
OK



Precision Measurements
Non oblique corrections

Quarks & Leptons in the Bulk



	Bulk $L \times R \times B\text{-}L$	Pl $L \times Y$	TeV $D \times B\text{-}L$	4D Q
$\begin{pmatrix} \chi_u \\ \chi_D \end{pmatrix}_L$	$(\Box, 1, 1/6)$	$(\Box, 1/6)$	$(\Box, 1/6)$	$2/3$ $-1/3$
$\begin{pmatrix} \psi_u \\ \psi_D \end{pmatrix}_L$	$(\bar{\Box}, 1, -1/6)$	$(\bar{\Box}, -1/6)$	$(\bar{\Box}, -1/6)$	$-2/3$ $1/3$
$\begin{pmatrix} \chi_u \\ \chi_D \end{pmatrix}_R$	$(1, \Box, 1/6)$	$(1, 2/3)$ $(1, -1/3)$	$(\Box, 1/6)$	$2/3$ $-1/3$
$\begin{pmatrix} \psi_u \\ \psi_D \end{pmatrix}_R$	$(1, \bar{\Box}, -1/6)$	$(1, -2/3)$ $(1, 1/3)$	$(\bar{\Box}, -1/6)$	$-2/3$ $1/3$

$Q = Y + T_{3L}$ $\qquad$ $Y = B\text{-}L + T_{3R}$

Chiral & Massless 4D Fermion

(from a 5D vectorlike & massive fermion...)

$\begin{pmatrix}\chi\\ \psi\end{pmatrix}$ 5D Dirac

$$S = \int d^5x \left(\frac{R}{z}\right)^4 \left(-i\bar{\chi}\bar{\sigma}^\mu\partial_\mu\chi - i\psi\sigma^\mu\partial_\mu\bar{\psi} + \frac{1}{2}\left(\psi\overleftrightarrow{\partial_5}\chi - \bar{\chi}\overleftrightarrow{\partial_5}\bar{\psi}\right) + \frac{c}{z}\left(\psi\chi + \bar{\chi}\bar{\psi}\right)\right)$$

$$\longrightarrow \delta S_{B.} = \frac{1}{2}\int d^4x \left(\frac{R}{z}\right)^4 \left(\delta\chi\psi - \delta\psi\chi + h.c.\right)$$

Bulk Eqs of Motion & Boundary Conditions

$$\left.\begin{aligned} &\bullet\ -i\bar{\sigma}^\mu\partial_\mu\chi - \partial_5\bar{\psi} + \frac{c+2}{z}\bar{\psi} = 0 \\ &\bullet\ -i\sigma^\mu\partial_\mu\bar{\psi} + \partial_5\chi + \frac{c-2}{z}\chi = 0 \end{aligned}\right\}$$

the bulk eqs. of motion restrict the BCs.

$$\chi_1 = 0 \implies \partial_5\psi_1 = \frac{c+2}{z}\psi_1$$

no independent BCs for χ and ψ!

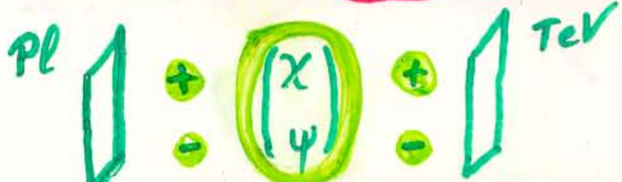
χ Dirichlet $\leftrightarrow$ ψ Neumann

ψ Dirichlet $\leftrightarrow$ χ Neumann

Chiral Spectrum

Zero Mode

$$\frac{c}{z}\left(\psi\chi + h.c\right)$$



$\longrightarrow$ 5D mass $\implies$ localization of the zero mode

$$\chi = \left(\frac{z}{R}\right)^{2-c}\frac{1}{R^c}\sqrt{\frac{(1-2c)}{R'^{1-2c} - R^{1-2c}}}$$

$$\psi = 0$$

$c > 1/2$ remains normalizable even if $R' \to \infty$ $\to$ Planck Brane localized

$c < 1/2$ remains normalizable even if $R \to 0$ $\to$ TeV Brane localized

Delocalized Fermion to Suppress S

gauge boson/fermion coupling = overlapp of wavefunctions

$$\left(T_{3L} + \underbrace{\frac{g_{5B} \int_R^{R'} dz \left(\frac{R}{z}\right)^4 f_{\chi_L}^2 f_{B-L}}{g_{5L} \int_R^{R'} dz \left(\frac{R}{z}\right)^4 f_{\chi_L}^2 f_{L3}}}_{-g'/g} Y \right) Z_\mu \chi_L$$

. gauge coupling matching
. W and Z normalizations depend on the fermion profile

$$f_{\chi_L}(z) = \frac{1}{R'} \sqrt{\frac{1-2c}{R'^{1-2c} - R^{1-2c}}} \left(\frac{z}{R}\right)^{2-c}$$

. $c \gg 1/2$ Pl localized

. $c \ll -1/2$ TeV localized

Pl fermion $\Longrightarrow$ positive contribution to S

TeV fermion $\Longrightarrow$ negative contribution to S

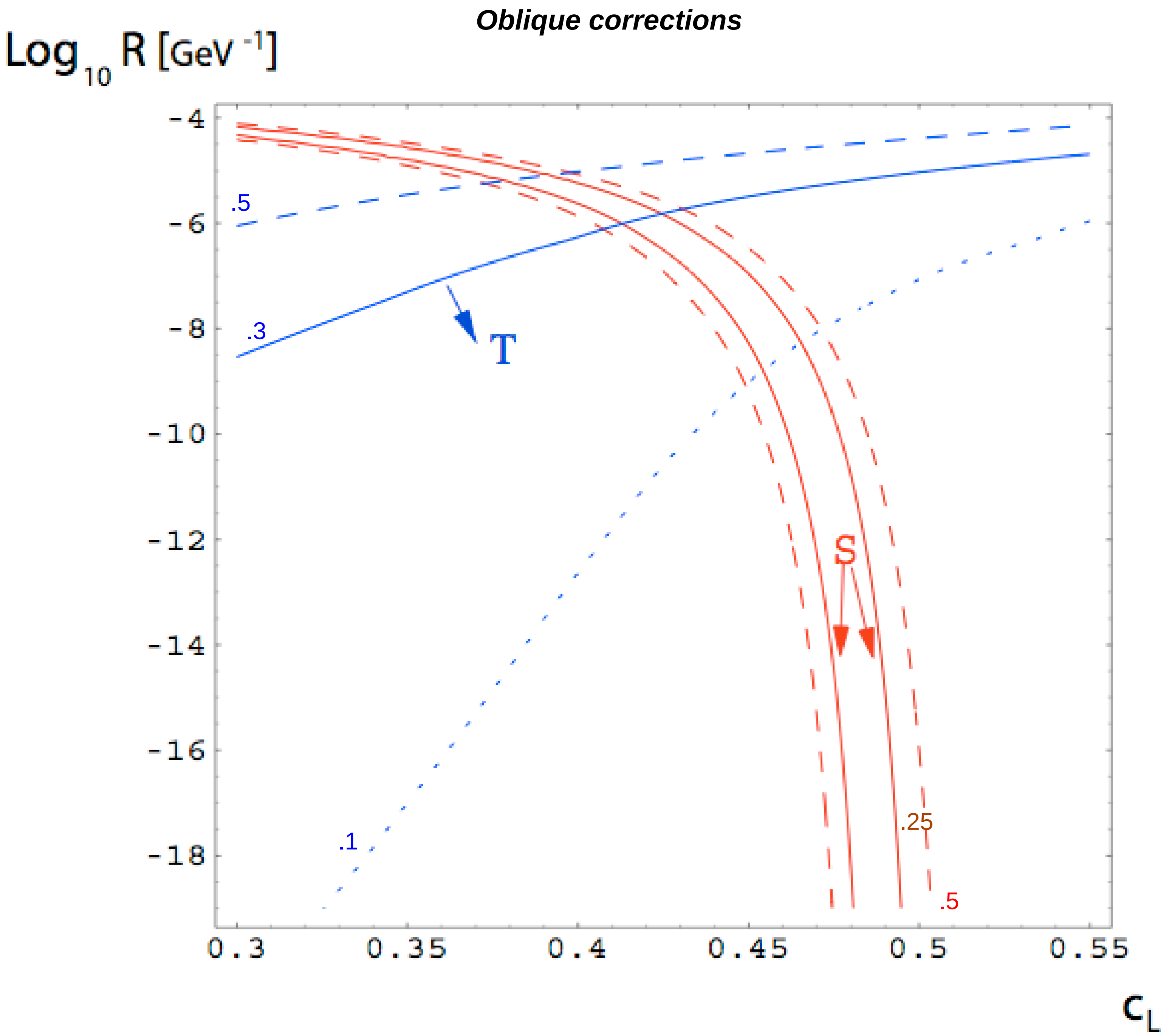
somewhere in middle

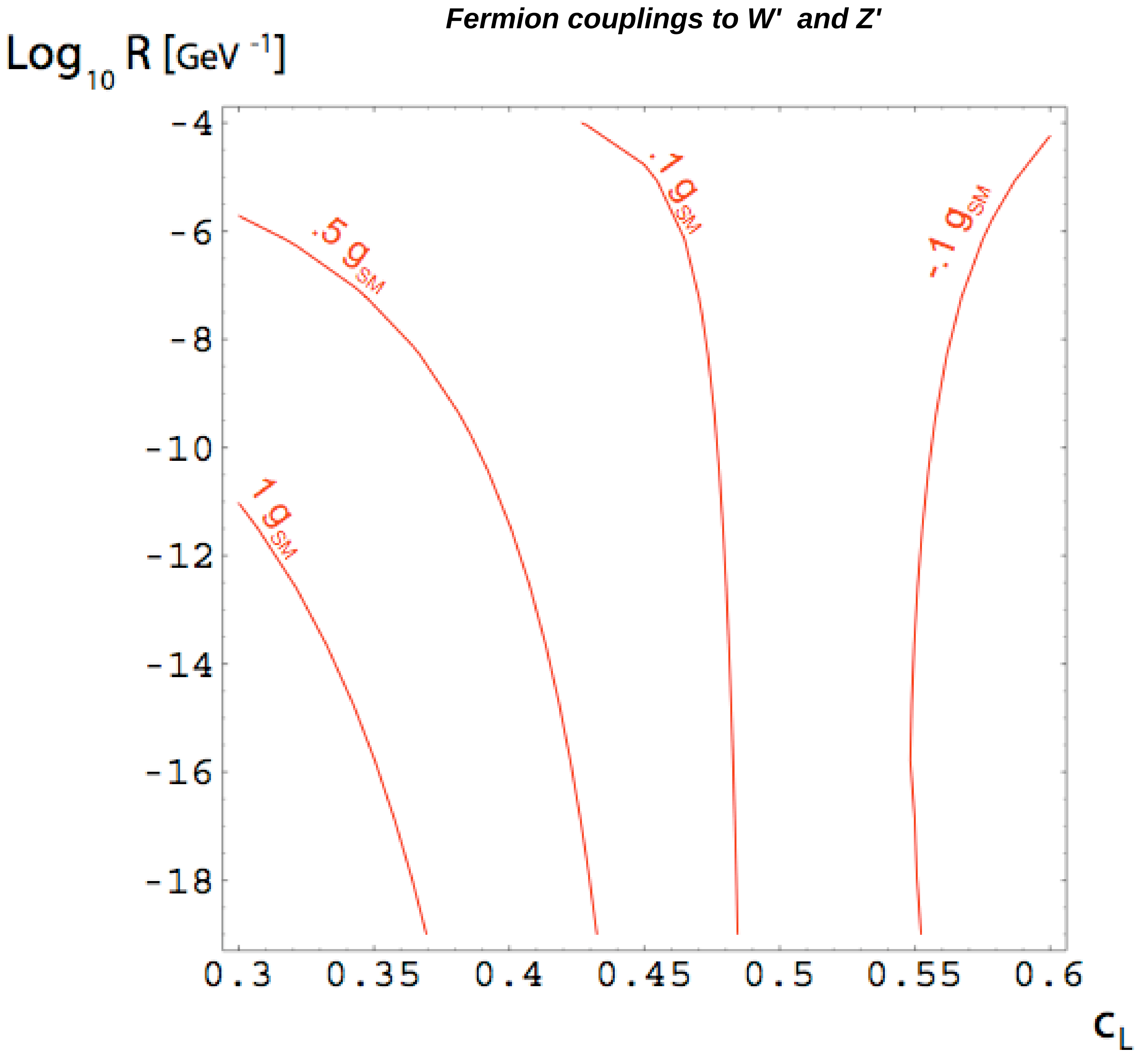
$S \sim 0$

Allow to suppress S without modifying Γ_Z.

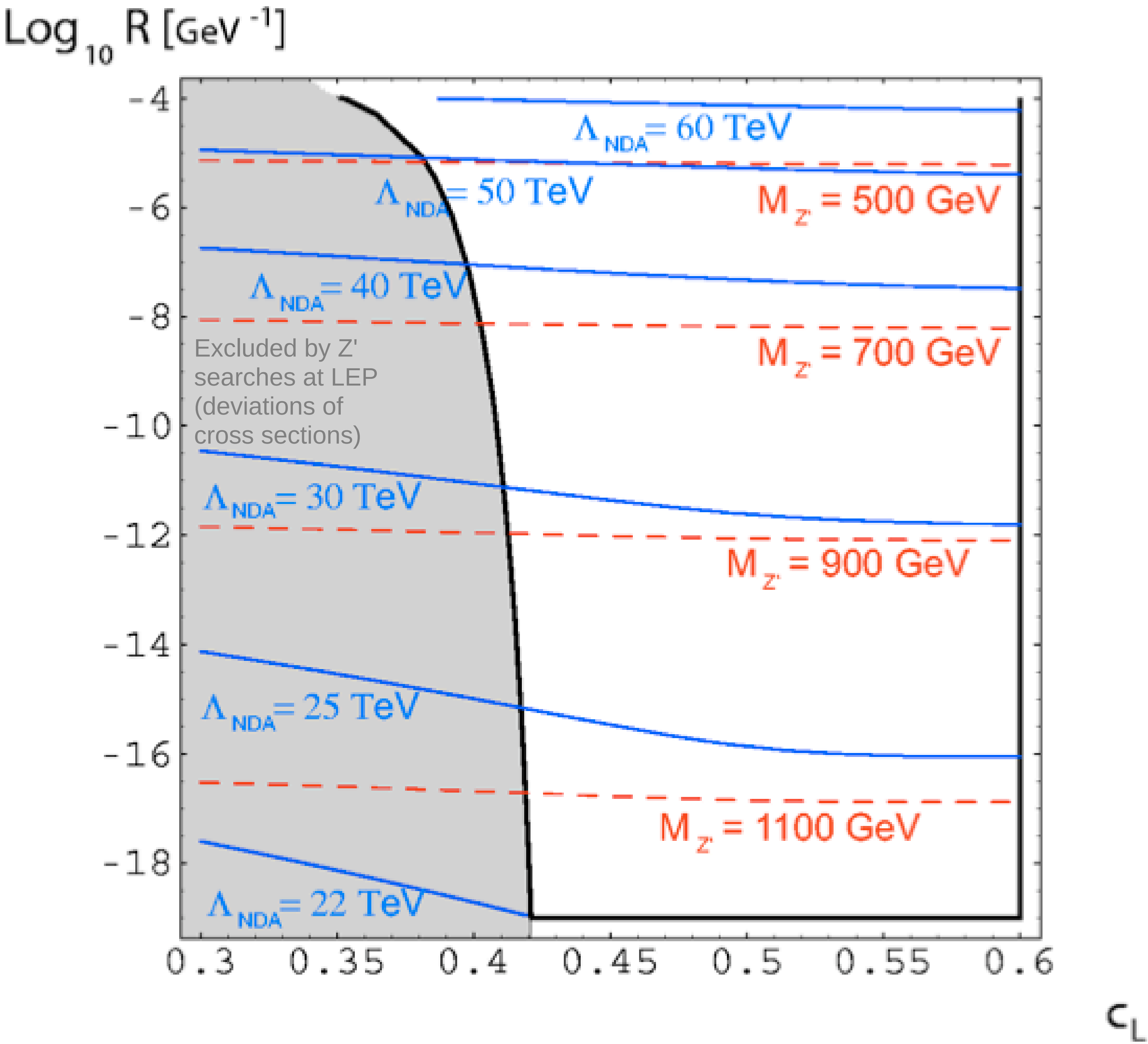
(no trouble with LEP nor Tevatron constraints)

EWPT with delocalized fermions





Strong coupling scale



Gauge Coupling Non Universality

fermion mass $\Longleftrightarrow$ wave fct profile in the bulk

coupling $\Longleftrightarrow$ wave fct overlapp

different masses $\Longrightarrow$ different couplings to W, Z

Non Universal Couplings

First two generations:

$$\frac{\delta g_{SM}}{g_{SM}} \sim O\left(\frac{m}{TeV}\right) \simeq 0.1\,\%$$ at most

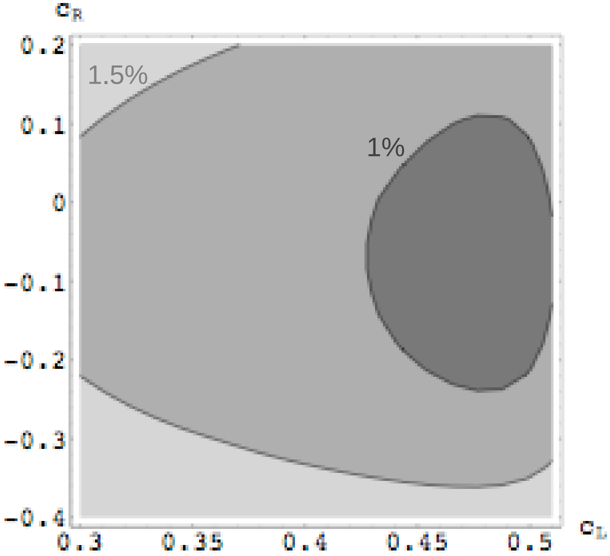
Third generation:

$m_t \simeq 178\,GeV$ important distortion of the profile

large $\delta g_{Zb_L\bar{b}_L}$ expected.

ZbLbL deviations

(gR/gL=5)



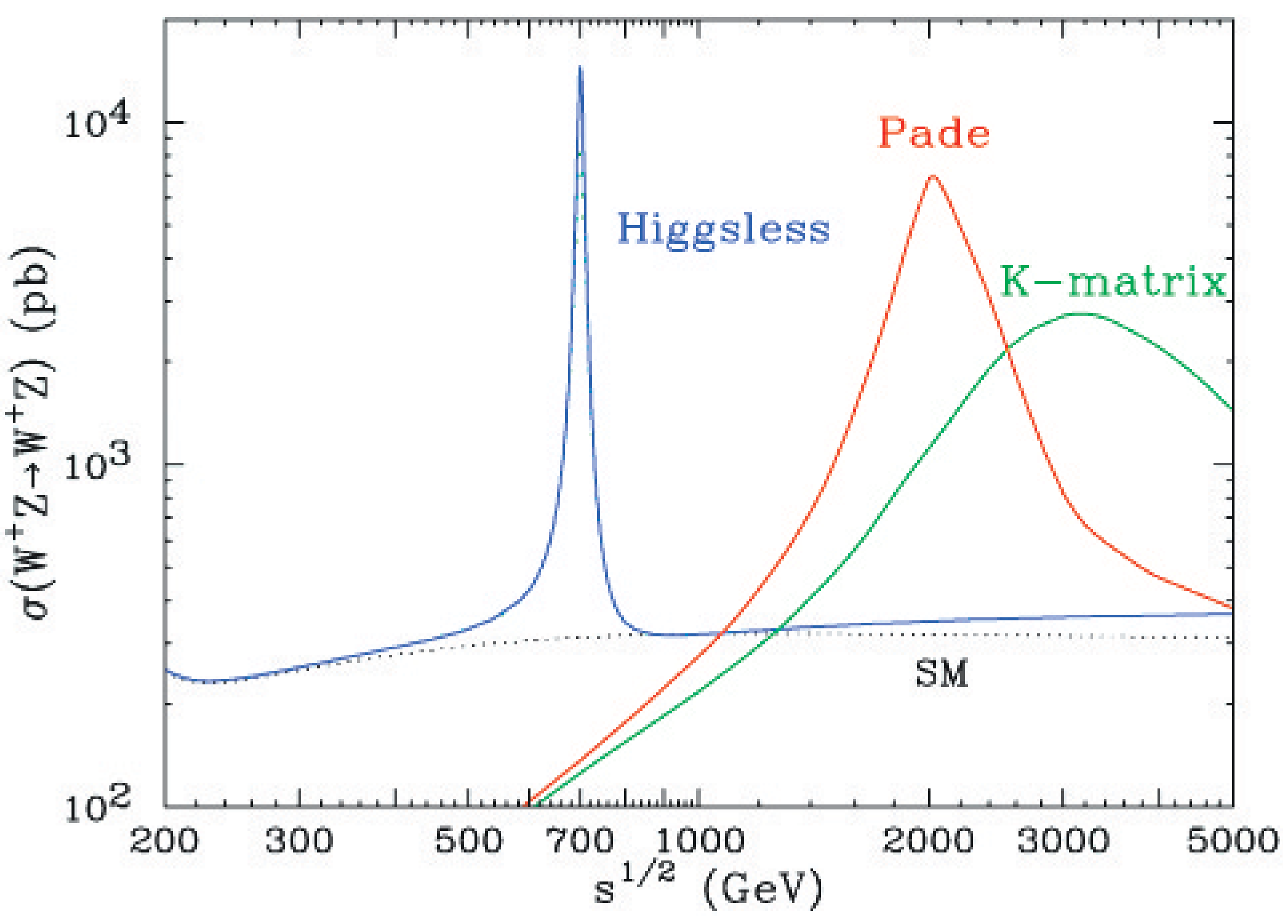
Collider Signals

[Birkedal, Matchev, Perelstein '04]

General Picture:

unitarity restored by vector resonances whose masses and couplings are constrained by the unitarity sum rules.

$$g_{WW'Z} \le \frac{g_{WWZ} M_Z^2}{\sqrt{3}\, M_{W'} M_W} \qquad \Gamma(W' \to WZ) \simeq \frac{\alpha\, M_{W'}^3}{144\, s_w^2\, M_W^2}$$



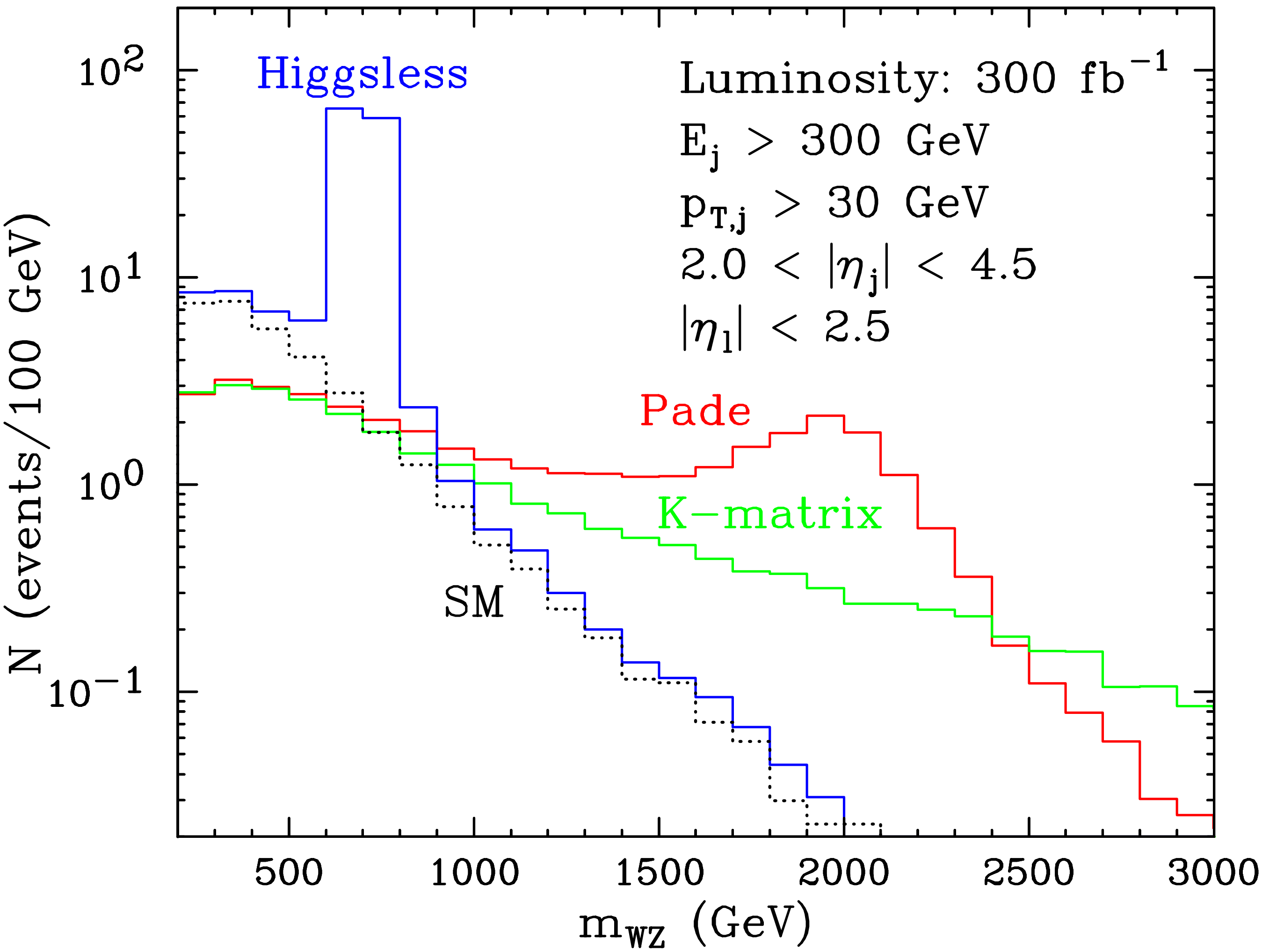
WZ elastic scattering cross sections in the SM (dotted), the Higgsless model (blue) and two technicolor-like models

Vector Boson Fusion

Birkedal, Matchev, Perelstein '04

(model independent since the couplings are constrained by unitarity sum rules)

10 fb-1 (one year of LHC) can find a W' up to Mw' < 550 GeV
60 fb-1 can find a W' up to Mw' < 1 TeV



Number of events per 100 GeV bin in the 2j + 3 l + nu channel at the LHC with an integrated luminosity of 300 fb-1

Conclusions

LHC will tell us how EW symmetry is broken!

We can see a Higgs.

But there is still room for interesting/exciting surprises ...