Higgsless Electroweak Symmetry Breaking

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S.M. Higgs Mechanism

Before EW SB

Gauge Bosons: $SU(2)_L \times U(1)_Y$

$3 + 1$

Higgs Doublet: $\begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$ 4 real scalars

After EW SB

$\langle H^0 \rangle = \frac{v}{\sqrt{2}} = 174$ GeV

massless γ

massive $W^\pm$ Z^0 3 eaten Goldstone

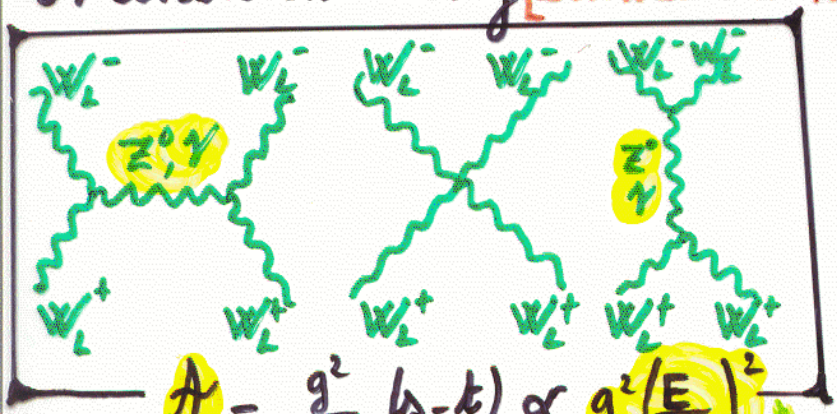
1 physical real scalar $H^0 = \frac{1}{\sqrt{2}}(v + h)$

Why do we need a Higgs?

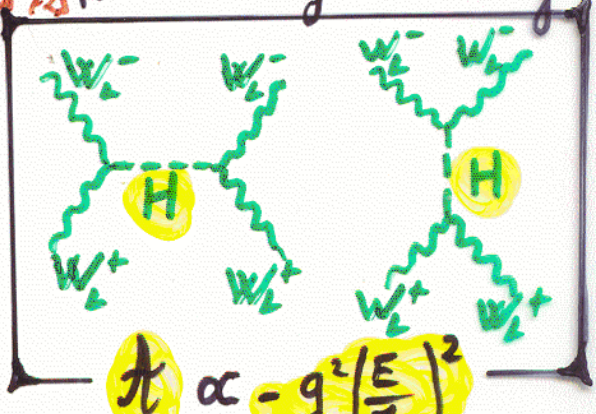
1. To give mass to W & Z:

Spontaneously Broken Gauge Theory

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



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



$$\mathcal{A} \propto -g^2\left(\frac{E}{m_W}\right)^2$$

Finite Amplitude

$$\mathcal{A} \propto g^2\left(\frac{m_H}{m_W}\right)^2 \quad (\Rightarrow m_H < 1\,\text{TeV})$$

2. To give mass to Quarks & Leptons

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

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

$SU(2)_L \times U(1)_Y$ ✗

$SU(2)_L \times U(1)_Y$ ✓

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

Why we don't like a Higgs

- fundamental scalar field.
- hierarchy / naturalness problem.
- triviality problem.
  (no continuum limit)
- not an explanation of EWSB.
- no experimental evidence.

But so far, no successful alternative...

Standard Scenari of EWSB

Weakly Coupled :

- (M S) SM
- Little Higgs ie. 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 !

How to Control Radiative Corrections

1 Spin Trick (analogous to BPS condition in SUSY)

Particle of spin s: $2s+1$ polarizations

... except if speed of light

... fewer polarizations

Spin 1: Gauge Invariance → no longitudinal polarization →

Spin 1/2: Chiral Symmetry → only one helicity →

$m = 0$

But S.M. Higgs is spin 0 ...

2 Goldstone Theorem:

Spontaneously Broken Symmetry → massless spin 0

But S.M. Higgs has non derivative couplings...

Symmetry Breaking From Boundary Conditions

Sym. Breaking

SU(2) → U(1)

Different BC's for Different Gauge Directions

BCs

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

$A_\mu^{1,2}|_0 = 0$

$\partial_\perp A_\mu^3|_0 = 0$

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

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

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

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

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

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

$$A_\mu^3(x,y) = \sum_{k=0}^{\infty} \sqrt{\frac{2}{2^{\delta_{k0}}\pi R}} \cos\frac{ky}{R}\, \gamma_\mu^{(k)}(x)$$

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

$$S = \int d^4x \int_0^{\pi R} dy \left(\frac{1}{2} \partial_\mu \phi \partial^\mu \phi - V(\phi) \right) + \int_{y=0,\pi R} d^4x \, \frac{1}{2} M^2_{0,\pi R} \phi^2$$

integration by part

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 $\quad \partial_y \phi = -M^2 \phi$

- $M \to \infty$ → Dirichlet
- $M \to 0$ → Neumann

(iii) Non trivial cancellation among various boundary terms

BC's for 5D Gauge Theory

$$S = \int d^4x \int_0^{\pi R} dy \left(-\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} - \frac{1}{2\xi} (\partial_\mu A^{a\mu} - \xi \partial_5 A_5^a)^2 \right)$$

Gauge Fixing Terms

$$\delta S = \int_{y=0,\pi R} d^4x \left(\frac{1}{2} F^a_{\nu 5} \delta A^{a\nu} + (\partial_\sigma A^{a\sigma} + \xi \partial_5 A_5^a) \delta A_5^a \right) + \text{Bulk Part}$$

Consistent BC's:

(i) $A^a_\mu = 0$, $A^a_5 = cst.$

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

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

(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 ?

Mixed BC's for Gauge Bosons

Explicit (localized) Breaking

$$S = \int d^4x \int_0^{\pi R} dy \left(-\frac{1}{4} F^a_{MN} F^{aMN} + G.F. \right) + \int_{y=0,\pi R} d^4x \; \frac{1}{2} m^{a^2} A^a_\mu A^{\mu b}$$

BC's in unitary gauge: ($\xi \to \infty$)

$$\partial_5 A^a_\mu = -m^{a^2} A^a_\mu \Big|_{0,\pi R}$$

Spontaneous (localized) Breaking

S = Bulk Action $+ \int d^4x \left(\frac{1}{2} D_\mu \Phi_i D^\mu \Phi_i - V(\Phi) \right)$

Boundary Higgs

$\Phi_i = \langle \Phi_i \rangle + \phi_i \qquad X^a_i = T^a_{ij} \langle \Phi_j \rangle$

G.F. $\quad -\frac{1}{2\xi} \left(\partial_\mu A^{\mu a} \Big|_{0,\pi R} - \xi g X^a_i \phi_i \right)^2$

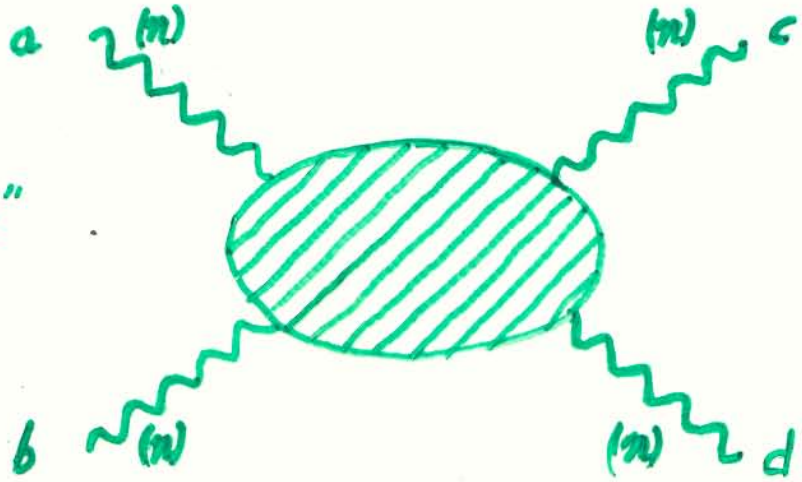
BC's:

$$\partial_5 A^a_\mu = g^2 X^a_i X^b_i A^b_\mu \Big|_{0,\pi R}$$

A Higgs on the Brane is very different than a Higgs in the Bulk (see later) !

UV completion of mixed BC's

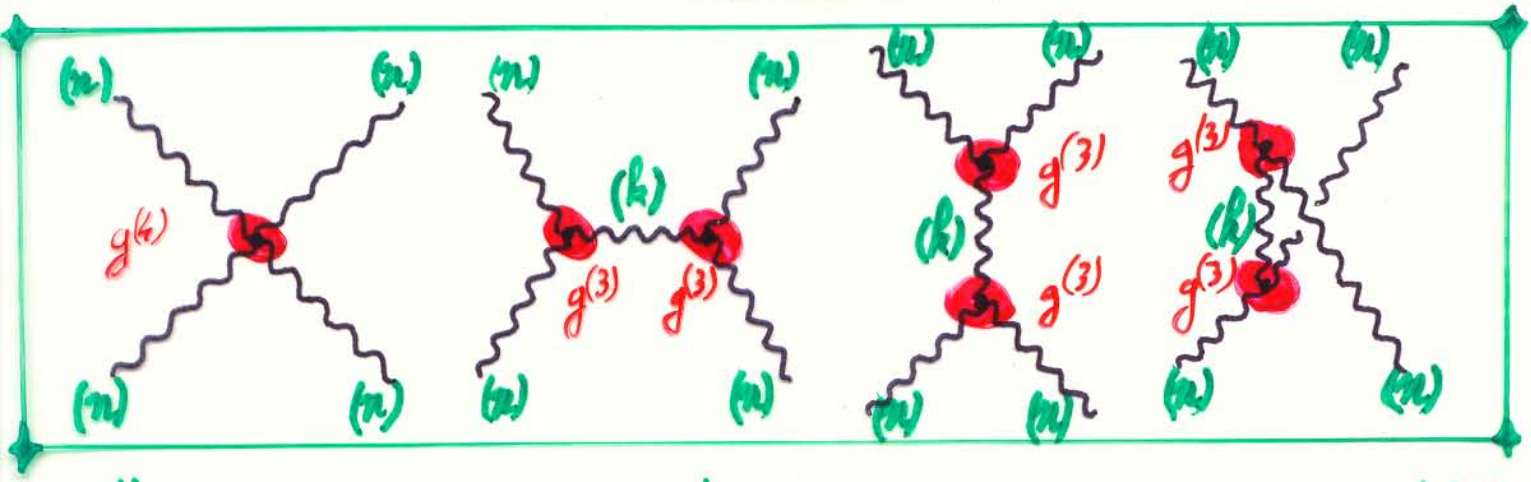
(Elastic) Scattering Amplitude



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

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

$$A = A^{(4)}\left(\frac{E}{m_n}\right)^4 + A^{(2)}\left(\frac{E}{m_n}\right)^2 + A^{(0)} + \dots$$



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

$$A^{(2)} = i\left(4g^2_{nnnn} - 3\sum_k g^2_{nnk}\frac{m_k^2}{m_n^2}\right)\left(f^{acebde} - \sin^2\frac{\theta}{2}f^{abe}f^{cde}\right)$$

K.K. Theory

$$A_\mu^a = \sum_k f_{(n)}^a(y)\, \varepsilon_\mu\, e^{i p_n \cdot x} \qquad (p_n^2 = m_n^2)$$

Wave functions:

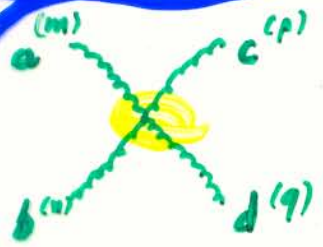
Bulk Eq. : $f_n'' + m_n^2 f_n = 0$

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

$\Rightarrow$ Spectrum & Wavefunctions

Effective couplings:

$$g_{cubic} \rightarrow g_{mnp}^{abc} = \int_0^{\pi R} dy\, f_m^a(y) f_n^b(y) f_p^c(y)\, g_5$$



$$g^2_{quartic} \rightarrow g^{2\,abcd}_{mnpq} = \int_0^{\pi R} dy\, f_m^a f_n^b f_p^c f_q^d\, g_5^2$$

(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.c., Murayama, Pilo, Terning '03]

Completeness of KK modes since ∂_5^2 is selfadjoint

E^2 terms

$$4 g^2_{nnnn} \Gamma_n^2 - 3 \sum_k g^2_{nnk} \Gamma_k^2$$

$$\sum_k \Gamma_k^2 \int_0^{\pi R} dy \int_0^{\pi R} dz\, f_n^2(y) f_n^2(z) f_k(y) f_k(z) = \frac{4}{3} \Gamma_n^2 \int_0^{\pi R} dy\, f_n^4(y)$$

integration by part: $f_k'' = -\Gamma_k^2 f_k$

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 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

$$g^2_{nnnn} \overset{(E^4)}{=} \sum_k g^2_{nnk} \overset{(E^4)}{=} \sum_k g^2_{nnk} \frac{3\pi k^2}{4\pi n^2}$$

(an effective theory of massive W, Z above π_w!)

With a finite # KK's:

E

New Physics (Higgs / Strong coupling)

$4\pi\pi_{w(n)}/g_4$

$\pi_{w(n)}$

Weakly coupled states observable at low energy

π_w''

$4\pi\pi_w/g_4$

π_w'

π_w

True Cutoff (5D)

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

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

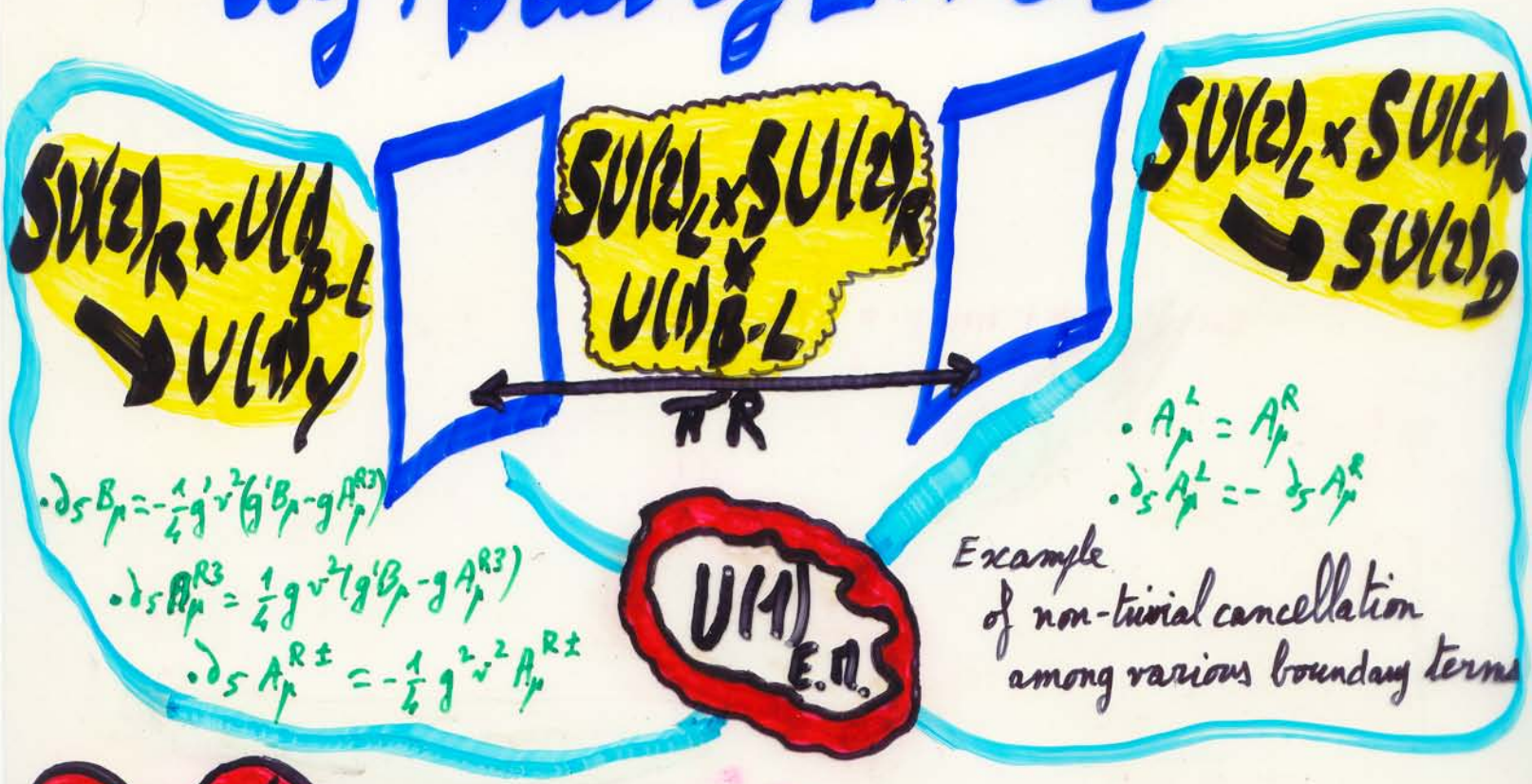
(even in flat space, already a factor 10)

Naive Cutoff

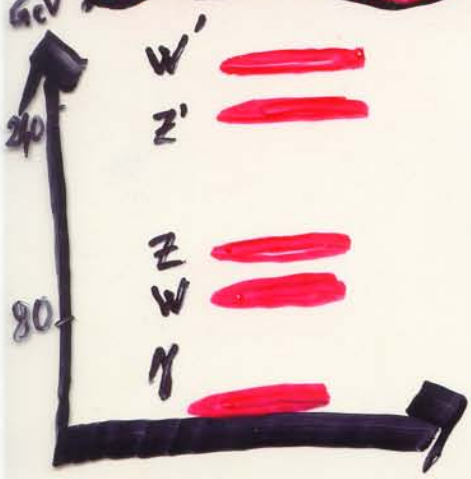
Weak scale

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

Toy Model of EWSB



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

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

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

Coupling to matter @ $y = 0$

Usual couplings to $\gamma, W^\pm, Z$ BUT

$$\rho = \frac{\Pi_W^2}{\Pi_Z^2 \cos^2\theta_W} \sim 1.10$$

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

The Missing Piece: custodial SU(2)

[Weinberg '79, Susskind '79, Sikivie et al. '80]

Higgs Doublet

4 Real scalars $\begin{pmatrix} h^+ + i\tilde{h}^+ \\ h^0 + i\tilde{h}^0 \end{pmatrix}$

Higgs Potential

$$V = \lambda\left(\underbrace{h^{+2} + \tilde{h}^{+2} + h^{0\,2} + \tilde{h}^{0\,2}}_{|H|^2} - v^2\right)^2$$

$SO(4) \sim SU(2)_L \times SU(2)_R$ Global Sym.

as a consequence at tree level :

$$\rho = \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = 1$$

EWSB

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

Need an almost $SU(2)_R$ global symmetry at low energy to recover S.M. spectrum & couplings

Custodial symmetry in AdS: Agashe, Delgado, May, Sundrum '03
Csáki, Grojean, Pilo, Terning '04

AdS/CFT for Beginners

[RANDALL-SUNDRUM]

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

$$\Omega = \frac{R_{TeV}}{R_{M_{Pl}}} \sim 10^{16} \gg 1$$

[Maldacena '97
Arkani-Hamed, Porratti, Randall '01
Rattazzi, Zaffaroni '01]

AdS Picture:

Bulk Gauge Sym. G

$G \to H$ M_{Pl} Breaking

$H \to H_0$ TeV Breaking

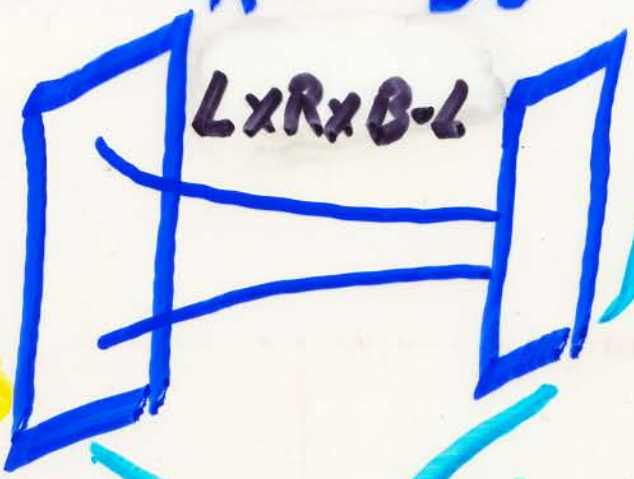
CFT Picture:

- 4D Gauge Sym. H
- 4D Global Sym. G/H

KK spectrum $\simeq$ G/H degenerate

- Spontaneous Breaking @ TeV: $H \to H_0$
- TeV Brane Matter = CFT composites
- M_{Pl} Brane Matter = CFT primordial fields.

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



Π_{Pl}

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

$A_R^{1,2} = 0$

$(g' B - g A_R^3) = 0$

$\partial_L (g B + g' A_R^3) = 0$

TeV

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

$A_L^a = A_R^a$

$\partial_L A_L^a = -\partial_L A_R^a$

KK →

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

W

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

$$R_i, R_i' = \frac{Y_i'(mz)}{J_i'(mz)} \; [\Pi_{Pl}, \Pi_{TeV}]$$

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

Z

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

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

Solution of Little Hierarchy Pb. !

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

... because of TeV localization ...

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

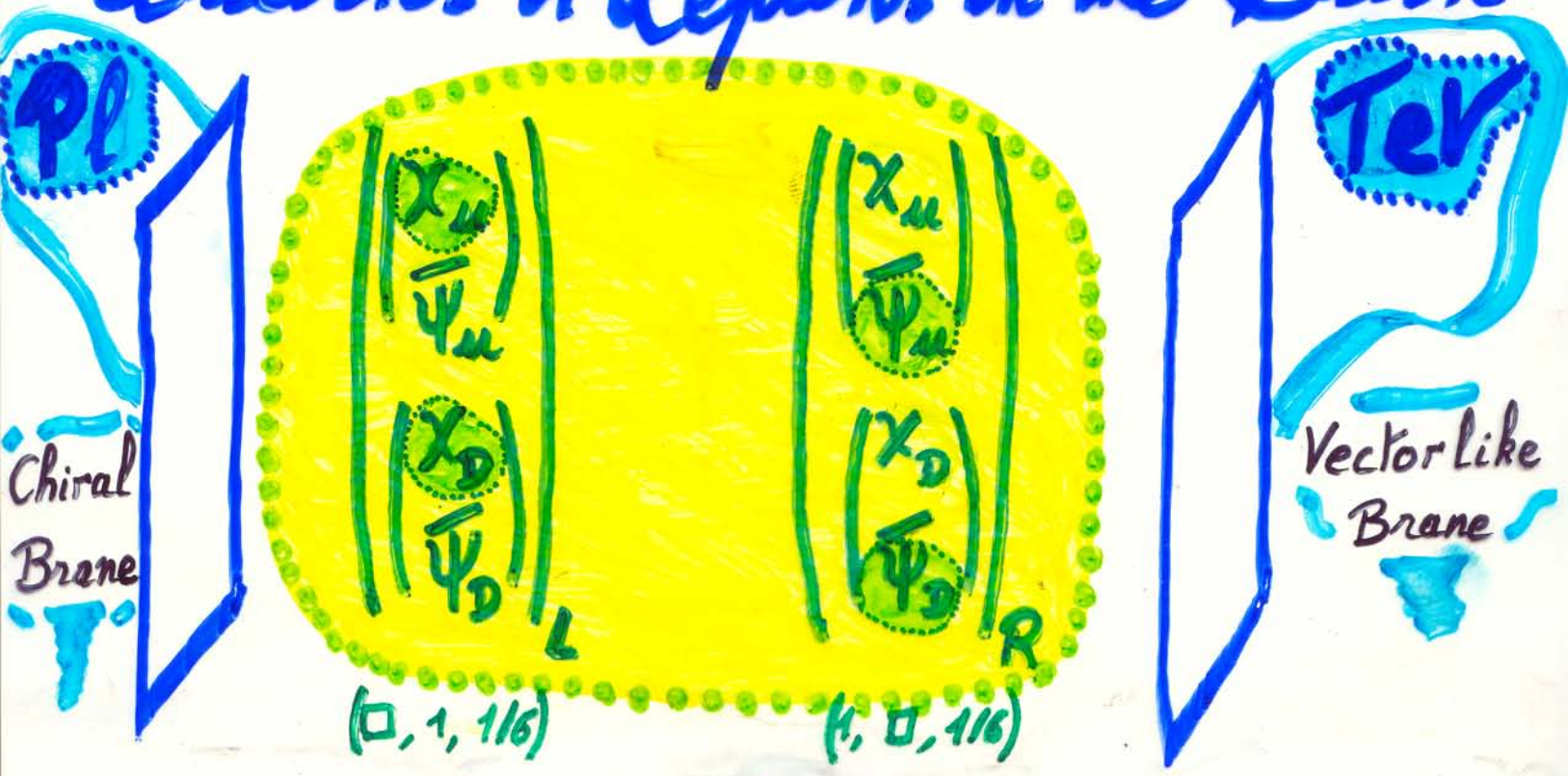
$m_W^{(3)} \sim m_Z^{(3)} \sim 1.9\,TeV$

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

AdS CFT dual:

→ Walking Technicolor !

Quarks & Leptons in the Bulk



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

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

Beyond Model Building: Major Issues

1) Electroweak Precision Constraints

Oblique Corrections : S, T, U

Non Oblique Corrections : $Zb\bar{b}$

Constraints on light Z'

2) Fermion Mass

more precisely how to generate $Y_{top} \approx \mathcal{O}(1)$?

3) Strong Coupling Scale

What is the cutoff of the 5D effective theory ?

Notorious Pbs in technicolor ...

EW Effective Lagrangian

Gauge Sector:

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

Gauge Fermion Interactions:

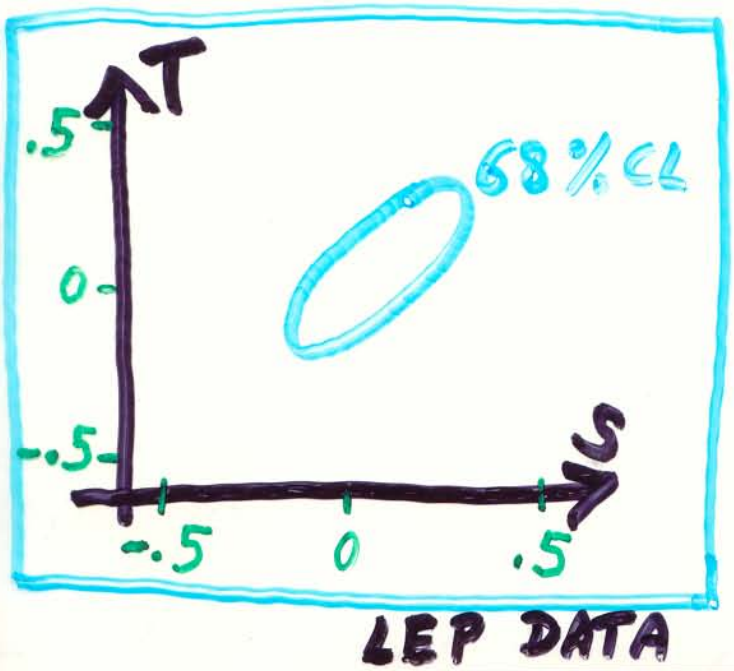
$$\left(-i g W^\mp_\mu T^\pm - i g' \sin\theta_W \left(T_{3L} - \tan\theta_W \frac{Y}{2} \right) Z_\mu - i e V_\mu \right) \psi$$

Tree Level + Quadratic order

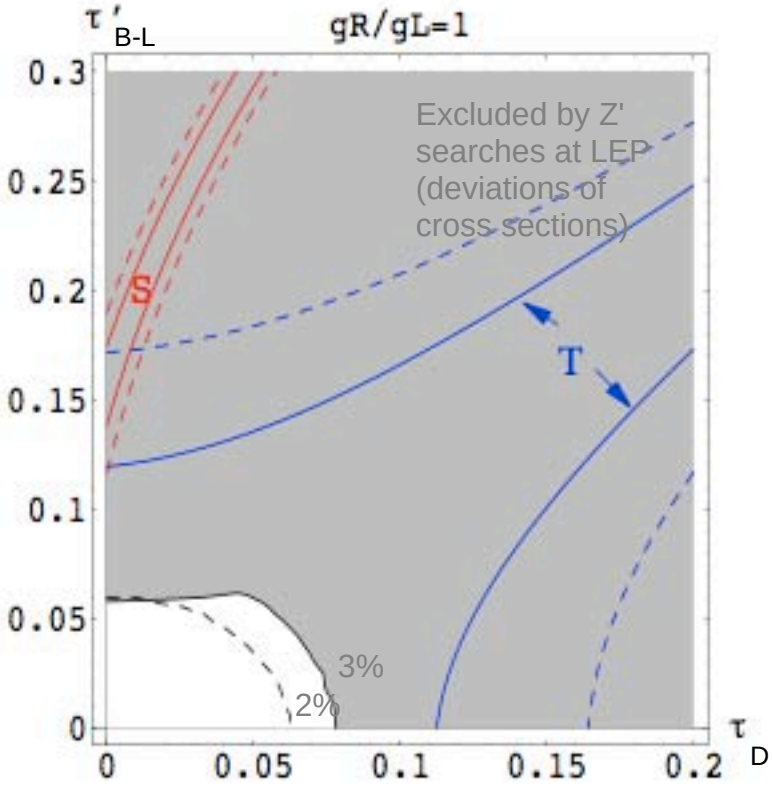
6 parameters: $\left\{ g_{SU(2)_L} \quad g'_{U(1)_Y} \quad v\ (m_Z) \right.$

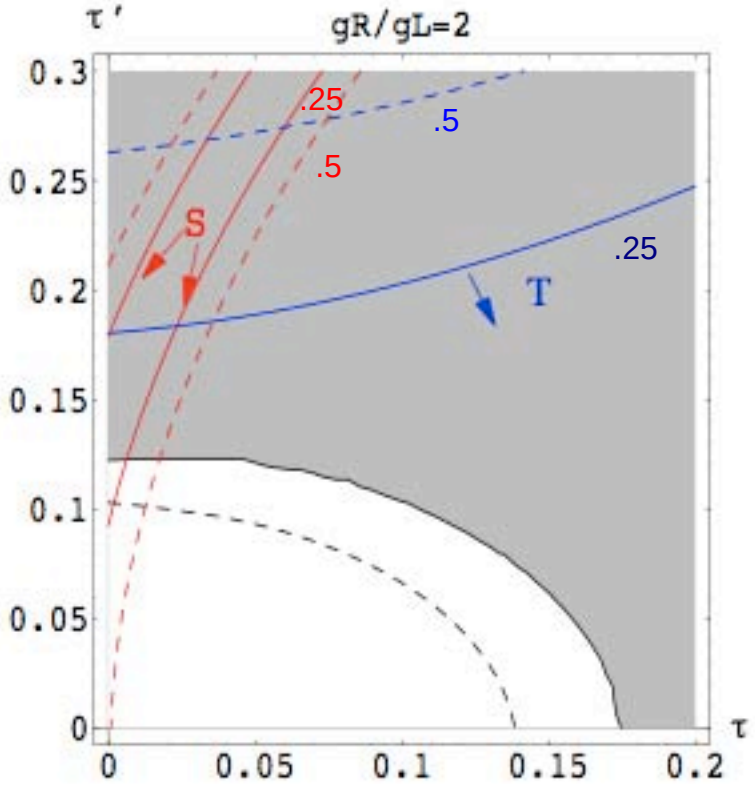
$\left. S \quad T \quad U \right.$

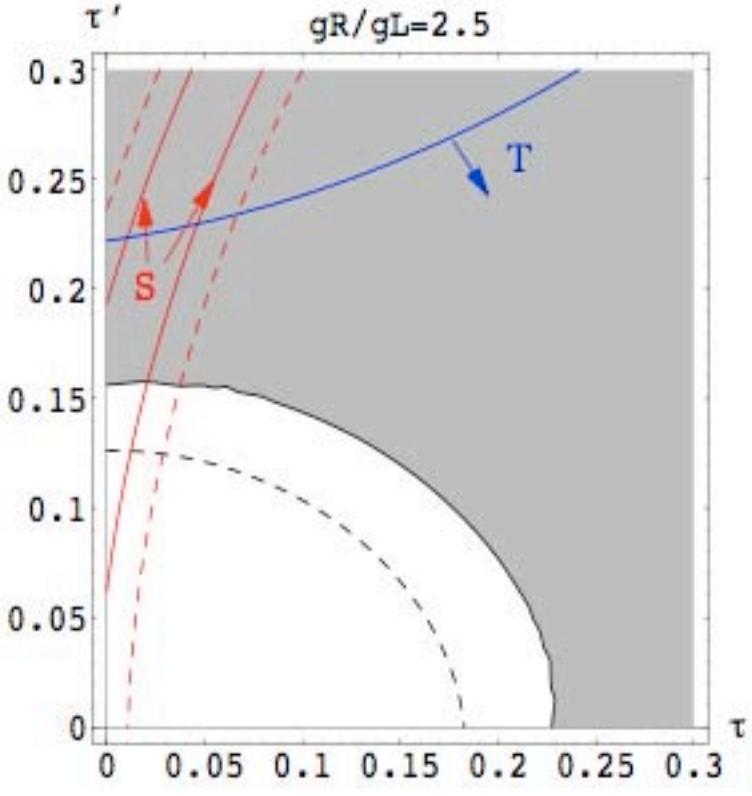
(measure the deviations to S.M.)

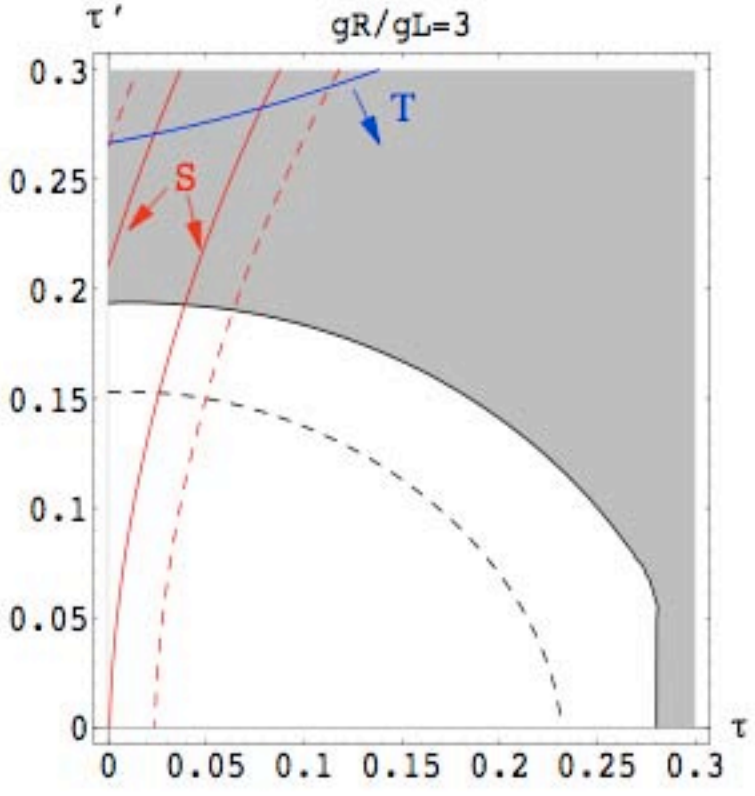


SM tested experimentally at 0.1 %


τ' B-L
gR/gL=1
Excluded by Z' searches at LEP (deviations of cross sections)
S
T
3%
2%
τ D
0.3
0.25
0.2
0.15
0.1
0.05
0
0 0.05 0.1 0.15 0.2


τ'
gR/gL=2
.25
.5
.5
.25
S
T
τ
0.3
0.25
0.2
0.15
0.1
0.05
0
0 0.05 0.1 0.15 0.2

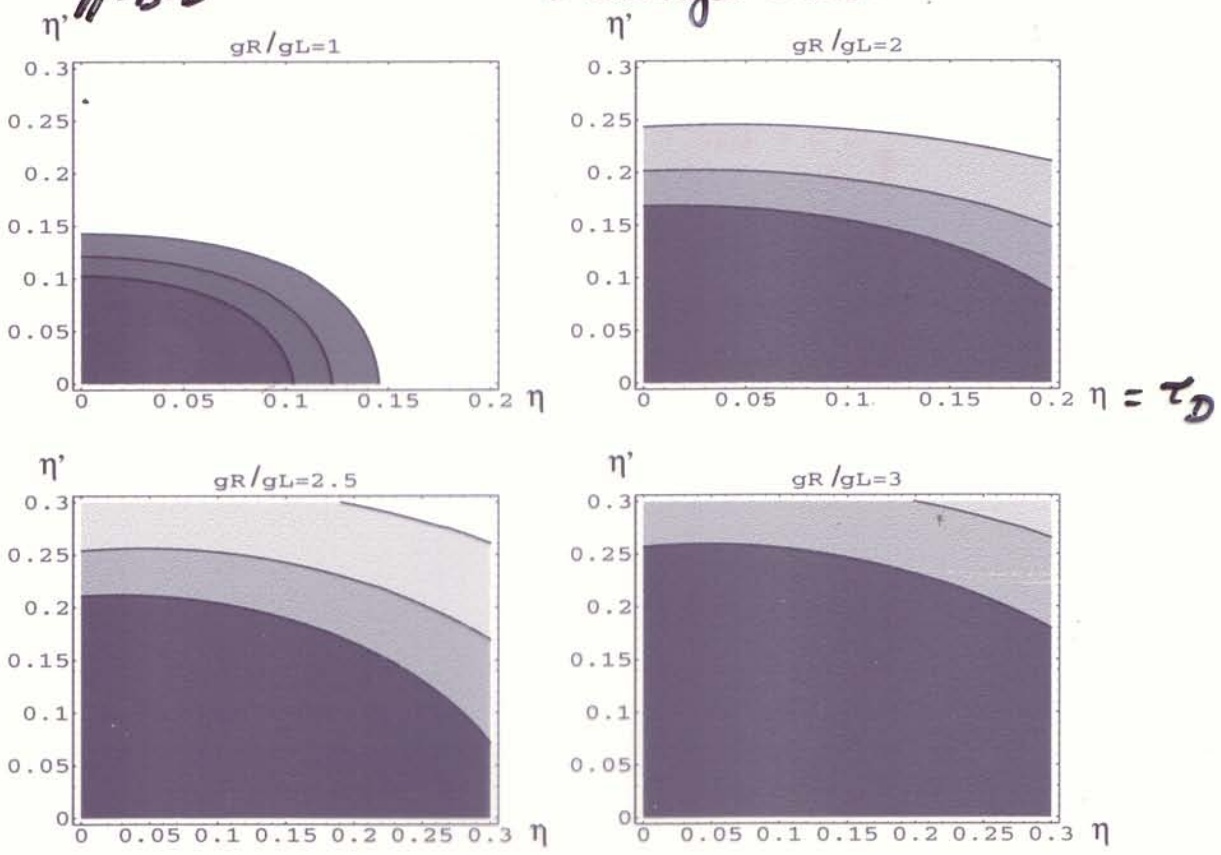

τ'
gR/gL=2.5
T
S
τ
0.3
0.25
0.2
0.15
0.1
0.05
0
0 0.05 0.1 0.15 0.2 0.25 0.3


τ'
gR/gL=3
T
S
τ
0.3
0.25
0.2
0.15
0.1
0.05
0
0 0.05 0.1 0.15 0.2 0.25 0.3

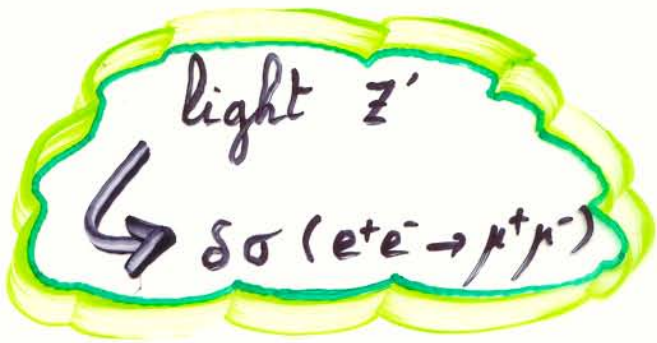
LEP constraints on Z'

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

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



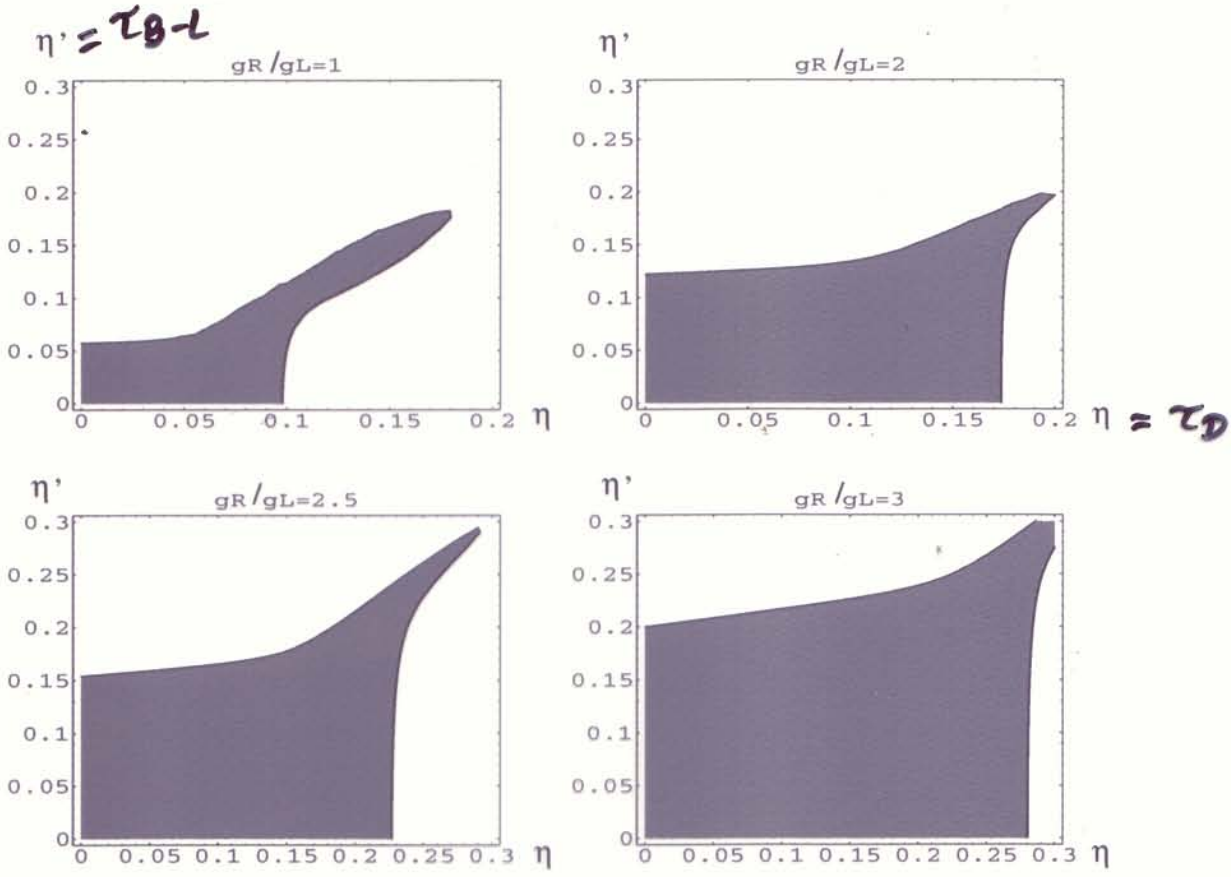
Contours: 5%, 7%, 10%



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.

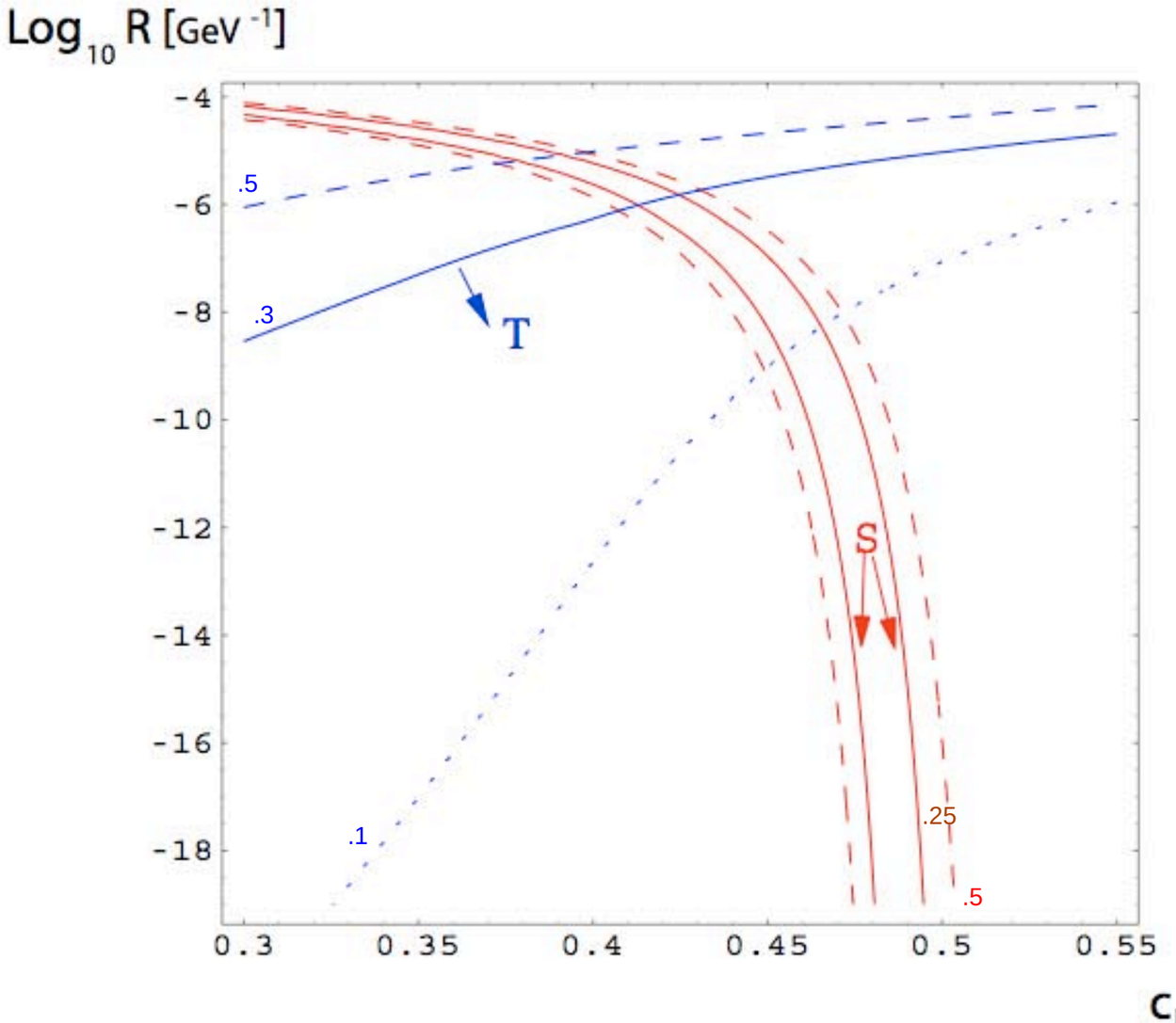
(deviation < 3-5%)

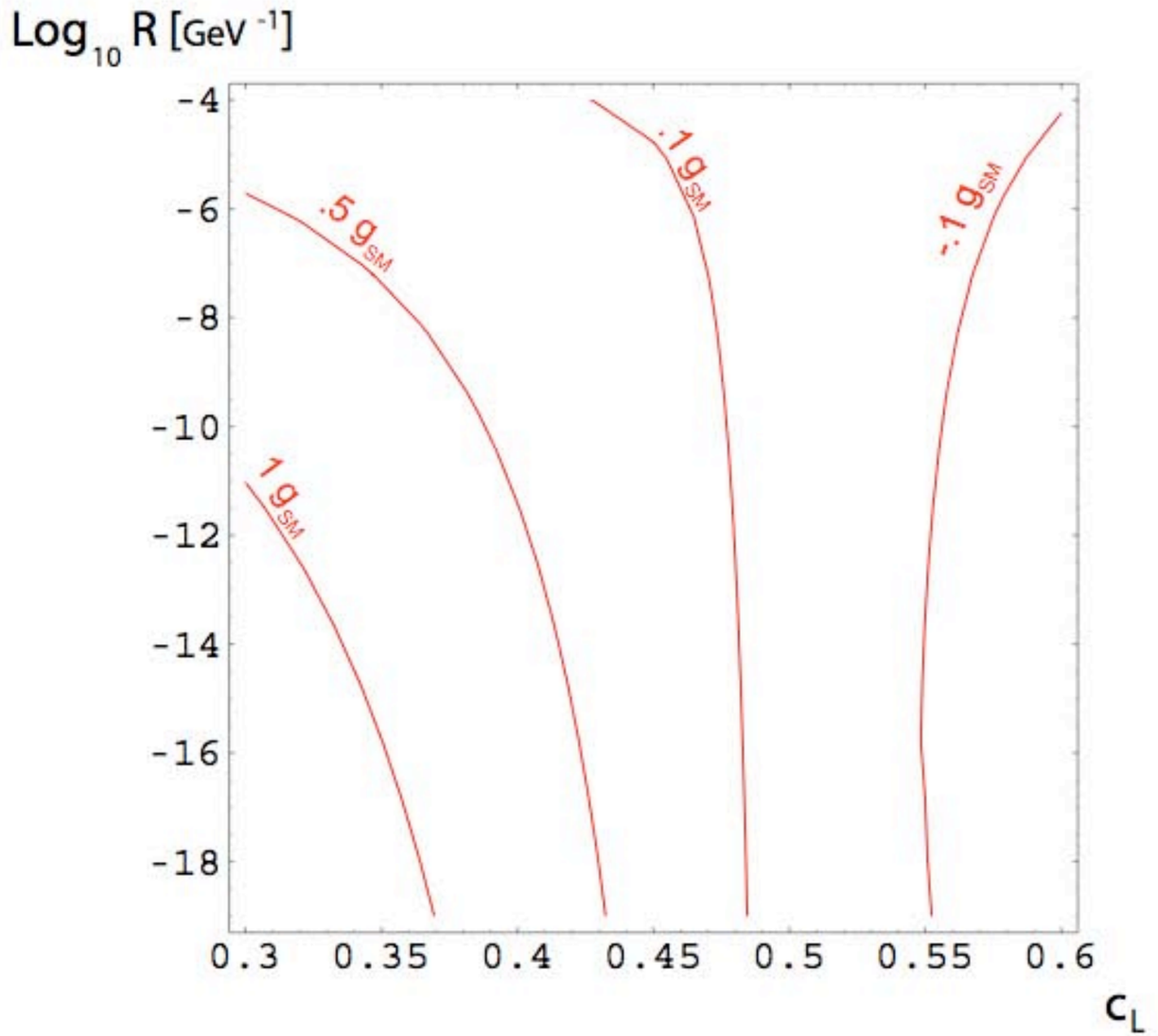
Tevatron Constraints on Z'
(Run I @ 110 pb^{-1})



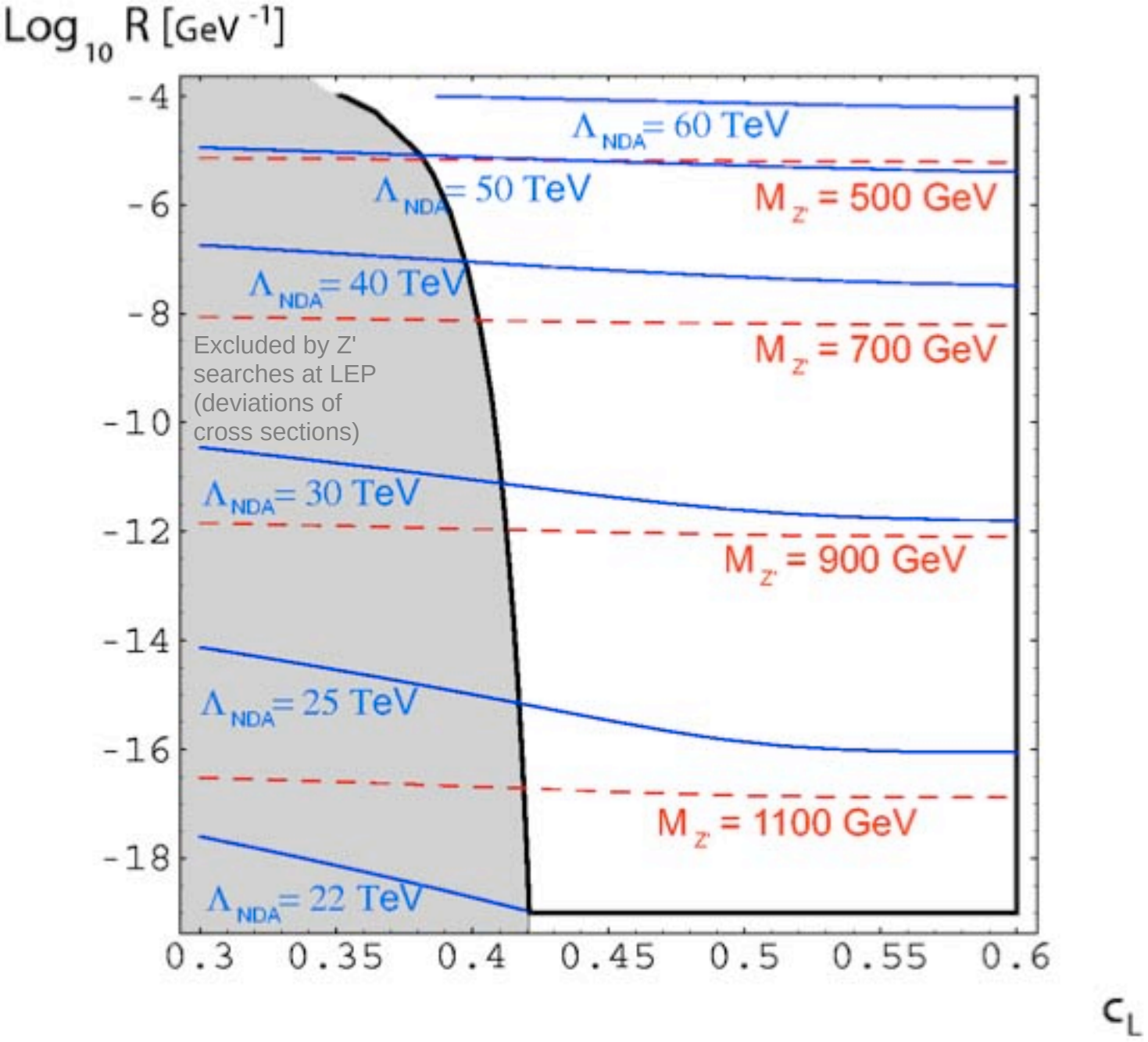
Search for dilepton pairs with large transverse momentum.
(bound on production cross section × branching fraction)

EWPT with delocalized fermions





Strong coupling scale



Gauge Coupling Non Universality

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

coupling $\leftrightarrow$ wave fct overlapp

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

Non Universal Couplings

First two generations:

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

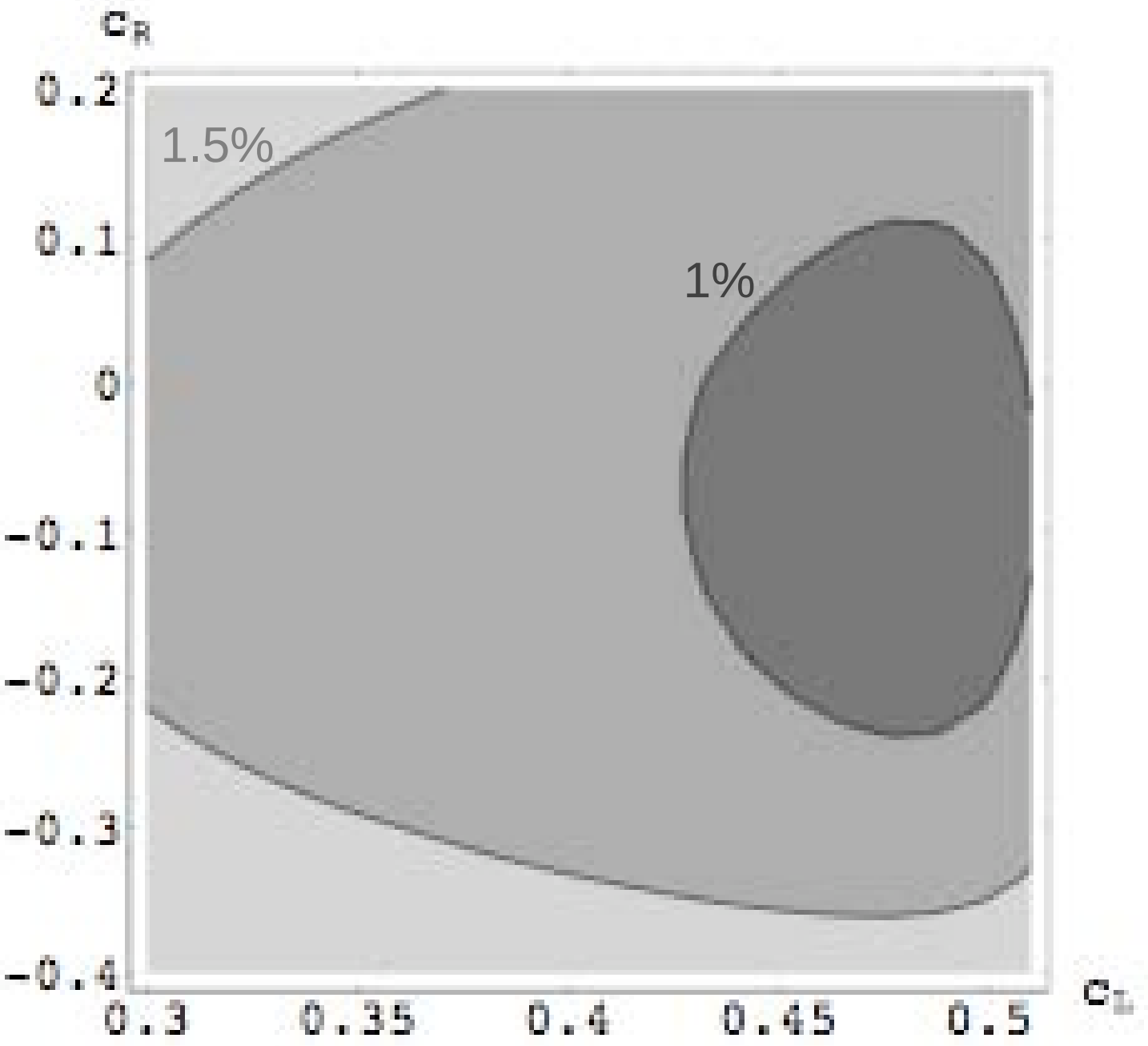
Third generation:

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

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

ZbLbL deviations

(gR/gL=5)



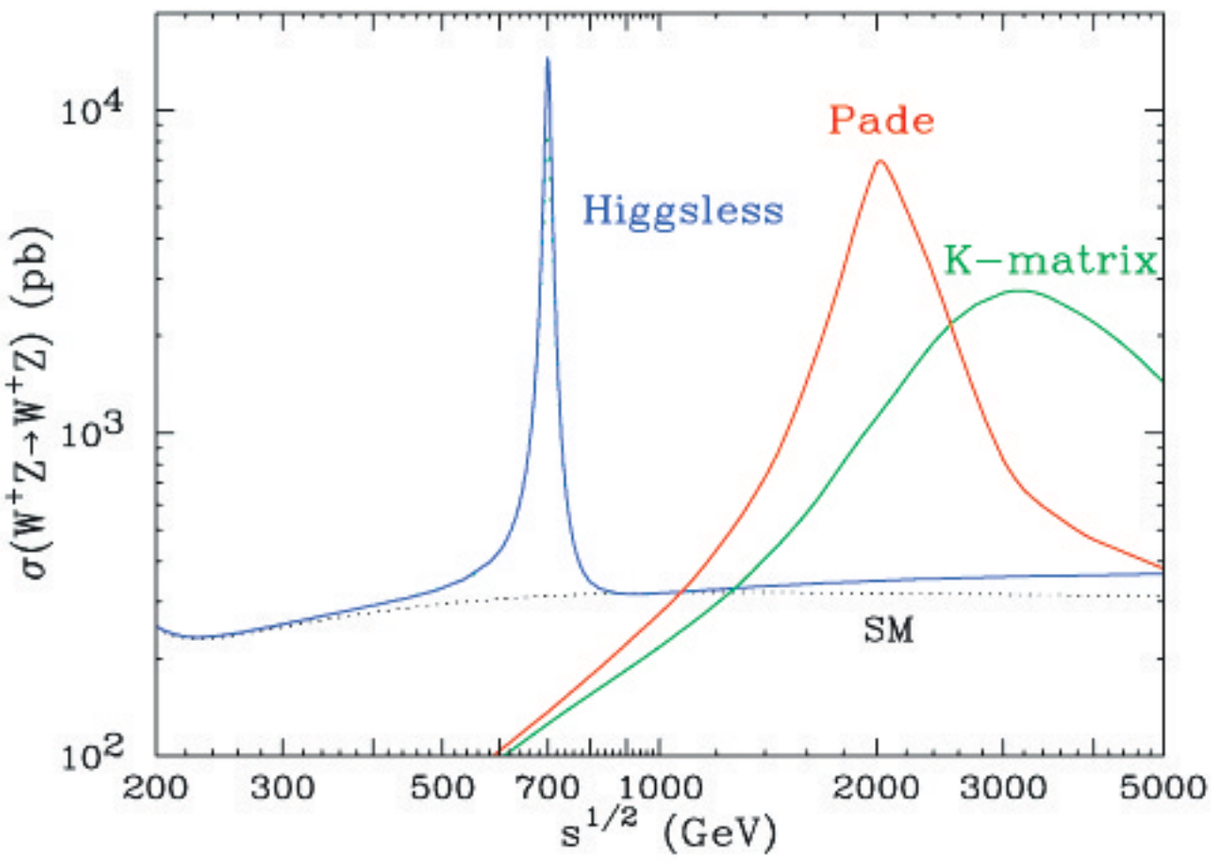
Collider Signals

[Birkedal, Matchev, Perelstein '04]

General Picture:

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

$$g_{WW'Z} \lesssim \frac{g_{WWZ}\,\Pi_Z^2}{\sqrt{3}\,\Pi_{W'}\cdot\Pi_W} \qquad \Gamma(W' \to WZ) \simeq \frac{\alpha\,\Pi_{W'}^3}{144\,\Delta_W^2\,\Pi_W^2}$$



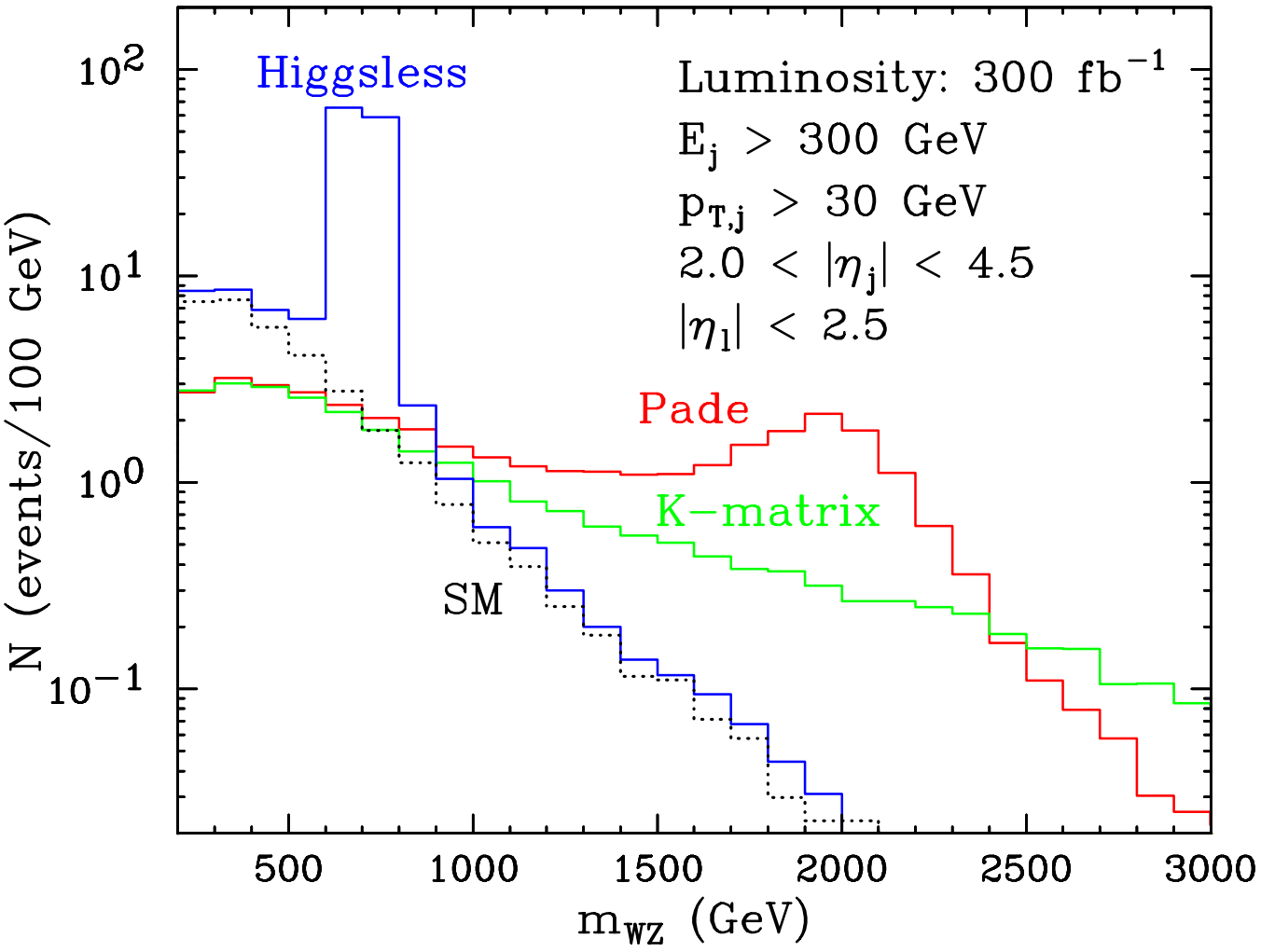
WZ elastic scattering cross sections in the SM (dotted), the Higgsless model (blue) and two technicolor-like models

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 ...