Degenerate BESS

at LHC

A decoupling model for Strong Electroweak Symmetry Breaking

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Outline

- Motivations
- A decoupling model with vector and axial vector resonances
- Bounds from present data
- Phenomenology at Tevatron Upgrade
- Signals and bounds from LHC
- Conclusions

Motivations for decoupling models

- SM survived LEP tests at the level of 0.1% (see the "pulls")
- This level of precision gives a beautiful test of radiative corrections within the SM (see fig. (M_{top}, M_W))

$$\Downarrow$$

New physics can only marginally affect the SM structure at low energy

New physics effects are naturally small if decoupling holds: $\mathcal{L}_{NP}(\Lambda_{NP}) \to \mathcal{L}_{SM}$ as $\Lambda_{NP} \to \infty$

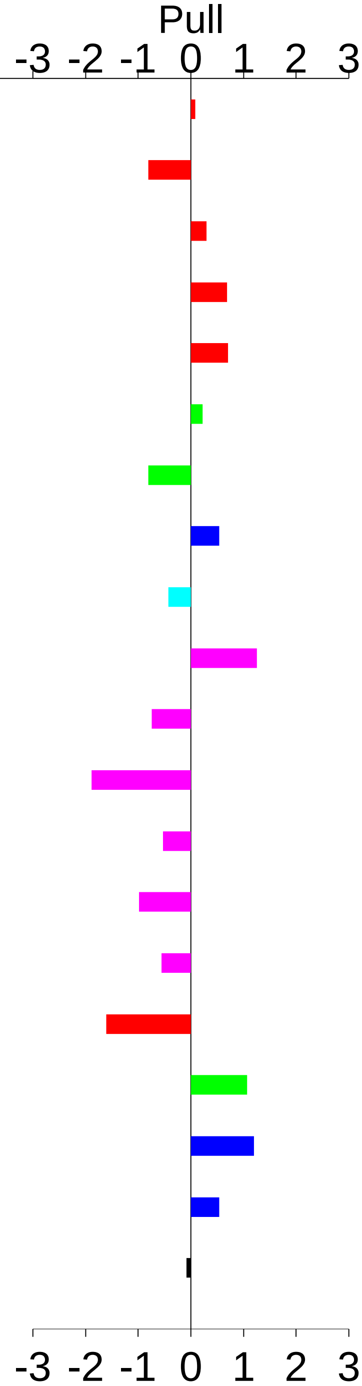
All the corrections at LEP would be of order M_Z^2/Λ_{NP}^2

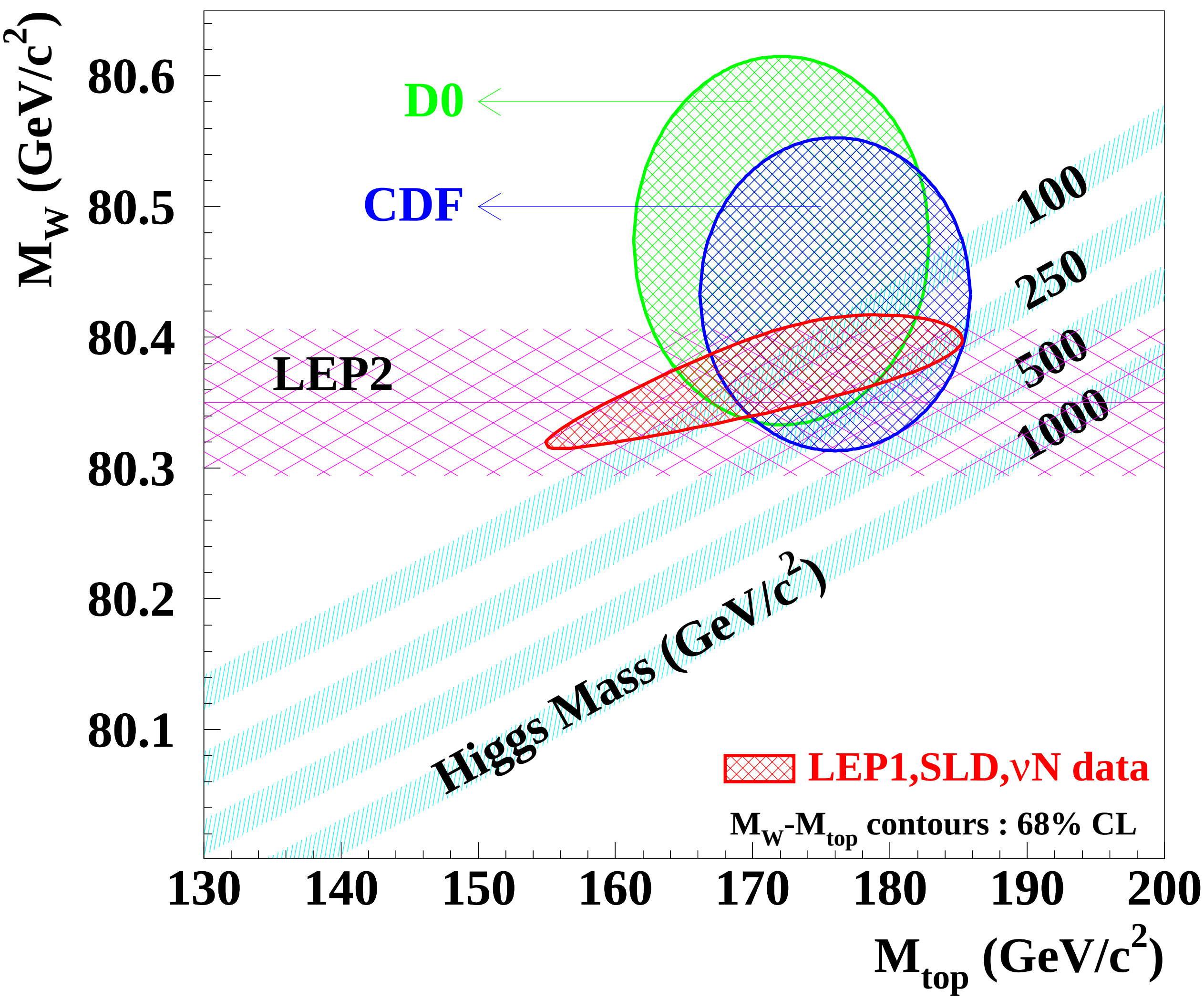
This is the case for MSSM for very massive sparticles or for extra-Z' models.

Do examples of Dynamical Symmetry Breaking models with decoupling exist ?

Moriond 1999

	Measurement	Pull
m_Z [GeV]	91.1867 ± 0.0021	.08
Γ_Z [GeV]	2.4939 ± 0.0024	-.81
σ^0_{hadr} [nb]	41.491 ± 0.058	.30
R_e	20.765 ± 0.026	.69
$A^{0,e}_{fb}$	0.01683 ± 0.00096	.71
A_e	0.1479 ± 0.0051	.23
A_τ	0.1431 ± 0.0045	-.81
$\sin^2\theta^{lept}_{eff}$	0.2321 ± 0.0010	.54
m_W [GeV]	80.350 ± 0.056	-.43
R_b	0.21680 ± 0.00073	1.26
R_c	0.1694 ± 0.0038	-.75
$A^{0,b}_{fb}$	0.0991 ± 0.0020	-1.88
$A^{0,c}_{fb}$	0.0712 ± 0.0043	-.53
A_b	0.908 ± 0.027	-.99
A_c	0.651 ± 0.030	-.56
$\sin^2\theta^{lept}_{eff}$	0.23109 ± 0.00029	-1.61
$\sin^2\theta_W$	0.2255 ± 0.0021	1.07
m_W [GeV]	80.448 ± 0.062	1.20
m_t [GeV]	174.3 ± 5.1	.54
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02804 ± 0.00065	-.08





M_{top} and M_W extracted from the fit to the SM compared with the experimental data from direct search

Models with Dynamical Symmetry Breaking (DSB)

No elementary Higgs

General features:

- Strong Interactions at the TeV scale, composite fields play the role of the Higgs and NEW resonances with masses $\approx 1\ TeV$ (TC prototype)
- Theoretical analysis difficult and model dependent Best way: use phenomenological lagrangians for spontaneously broken symmetries

Our knowledge:

- Need at least 3 Goldstone Bosons from $G \to H$ (to generate M_W, M_Z)
- Experimentally the ρ parameter is very close to one $\to$ the unbroken H group contains the custodial $SU(2)_{L+R}$

The effective chiral lagrangians provide a phenomenological description of the Goldstone Boson dynamics (dictated by the symmetry and by the EW scale)

The new resonances produced by the strong interaction responsible for EWSB are easily introduced in the formalism of the non-linear realization of broken symmetries (Callan, Coleman, Wess, Zumino (1969))

BESS model

Breaking Electroweak Symmetry Strongly

Casalbuoni,D.C.,Dominici,Gatto (1985)

Effective Lagrangian parametrization which describes the symmetry breaking sector as a non-linear σ-model

Main idea theories describing the spontaneous symmetry breaking of $G \to H$ possess a hidden gauge symmetry group H_{loc} isomorphic to H (Balachandran et al. (1979))

Strategy give a linear formulation of the theory by enlarging the symmetry group to $G \otimes H_{loc}$ and describe the new vector resonances V as gauge fields of H_{loc}

Very important $\longrightarrow$ V bosons acquire mass through the same dynamical Higgs mechanism which gives mass to W and Z

General properties of the V resonances after gauging $SU(2)_L \times U(1)_Y$:

- mixing with $W, Z, \gamma \to$ strong bounds from experiments (LEP/SLC/Tevatron)
- strong coupling to $W_L W_L \to$ strong bounds from unitarity
- non-decoupling in the low-energy limit ($M_V \to \infty$)

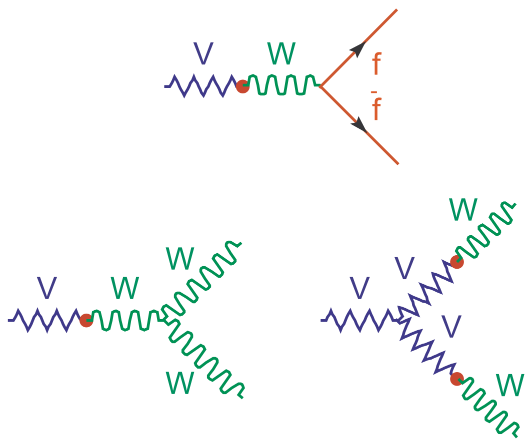
Consider for example:

$$G = SU(2)_L \otimes SU(2)_R \qquad H_{loc} = SU(2)_{L+R}$$

Triplet of vector resonances: $V^\pm,\ V^0$

Parameters: $\boxed{M_V,\ g'',\ b}$

Decay rates $\Gamma(V \to \bar{f}f)$ and $\Gamma(V \to W_L W_L)$ for $b = 0$:



$$\Gamma(\bar{f}f) \approx M_V \underbrace{\left(\frac{g}{g''}\right)^2}_{\text{mixing}} g^2_{W\bar{f}f} \approx \left(\frac{g}{g''}\right)^2 \frac{M_V}{M_W} \Gamma_{W\to\bar{f}f} \approx M_V M_W^4 \left(\frac{G_F}{g''}\right)^2$$

$$\Gamma(W_L W_L) \approx M_V \underbrace{\left(\frac{g}{g''}\right)^2}_{\text{mixing}} g^2 \underbrace{\left(\frac{M_V}{M_W}\right)^4}_{W_L W_L} \approx M_V^5 \left(\frac{G_F}{g''}\right)^2$$

$$\frac{\Gamma(\bar{f}f)}{\Gamma(W_L W_L)} \approx \left(\frac{M_W}{M_V}\right)^4 \ll 1$$

Clear signature at future colliders in the $W_L W_L$ processes

Unitarity bounds in BESS (V resonances)

The strong interaction of the GB sector propagates to the longitudinal components of the SM gauge bosons (Equivalence Theorem)

$$M(W_L W_L \to Z_L Z_L) =$$

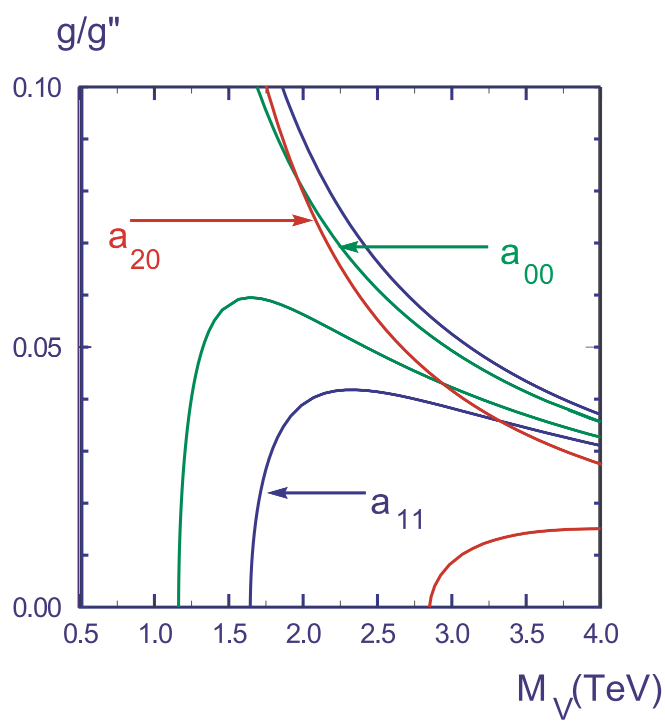
$$= \left(1 - \frac{3}{4}\alpha\right)\frac{s}{v^2} - \frac{1}{4}\frac{M_V^2}{v^2}\alpha\left(\frac{s-u}{t - M_V^2 + iM_V\Gamma_V} + (t \leftrightarrow u)\right)$$

here $\alpha = 4M_V^2/(g''^2 v^2)$ and $v = 246\ GeV$

Partial wave unitarity limits from WW scattering

Project the components with definite isospin into the lower partial waves

Require $|a_{IJ}| \leq 1$ up to a scale Λ such that $\Lambda/M_V \leq 1.5$



The intersection of the allowed regions gives a general upper bound $M_V \sim 2.5\ TeV$

The case $\alpha = 2$ corresponds to QCD-scaled TC

From this analysis $M_{\rho_T} \leq 2\ TeV$

Experimental bounds in BESS (V resonances)

Virtual effects of the V resonances in the low-energy limit ($M_V \to \infty$) can be encoded in the ϵ parameters.

From the $SU(2)_{\text{cust}}$ symmetry $\boxed{\epsilon_1,\ \epsilon_2 \to 0}$ but $\boxed{\epsilon_3 \neq 0}$ because it contains a singlet part. For ex. TC theories give a large and positive contribution to ϵ_3.

In BESS with only vector resonances

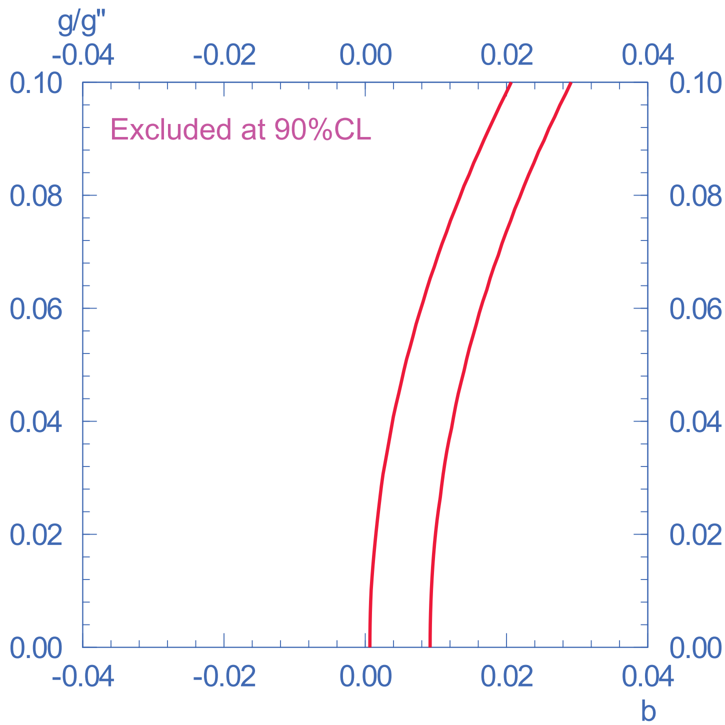
$$\epsilon_3 = \left[\left(\frac{g}{g"}\right)^2 - \frac{b}{2}\right]$$

The experimental value, by fitting all the high-energy data from LEP/SLC/Tevatron (Altarelli (1999)), is

$$\epsilon_3^{exp} = (4.19 \pm 1.00) \times 10^{-3}$$

To compare with the BESS predictions we must add the SM radiative corrections $\epsilon_3^{rad} = 6.65 \times 10^{-3}$

$$(m_t = 175.6\ GeV,\ m_H = \Lambda = 1\ TeV)$$



a FINE TUNING among ($M_V, g", b$) is necessary!

Is it possible to avoid the stringent bounds from LEP?

Dispersive representation for ϵ_3:

$$\epsilon_3 = -\frac{g^2}{4\pi}\int_0^\infty \frac{ds}{s^2}\Big[\mathrm{Im}\Pi_{VV} - \mathrm{Im}\Pi_{AA}\Big]$$

Peskin, Takeuchi (1990)

where $\Pi_{VV(AA)} = \langle J_{V(A)} J_{V(A)} \rangle$

Assume vector meson dominance:

$$\mathrm{Im}\Pi_{VV(AA)}(s) = -\pi g^2_{V(A)}\delta(s - M^2_{V(A)})$$

$g_{V(A)}$ is the coupling of $V(A)$ to $J_{V(A)}$

$$\epsilon_3 = \frac{g^2}{4}\Big[\frac{g_V^2}{M_V^4} - \frac{g_A^2}{M_A^4}\Big]$$

In QCD-scaled TC models, using Weinberg sum rules $g_V = g_A$, $M_A^2 = 2M_V^2$ and KSFR $g_V^2 = 2v^2 M_V^2$, we get $\epsilon_3 \simeq 0.0008 N_{TC} N_d$ which is ruled out by the experiments.

$\Downarrow$

A possibility for $\epsilon_3 \to 0$ is $g_A = g_V$ $M_A = M_V$ that is vector and axial-vector resonances degenerate in mass and couplings.
Meaningful ONLY if a further symmetry protects the degeneracy.

A model with vector and axial-vector resonances was formulated ten years ago

Casalbuoni,D.C.,Dominici,Feruglio,Gatto (1989)

The symmetry group is $G' = G \otimes H'_{local} \to H_D$ where

$G = SU(2)_L \otimes SU(2)_R$ $\qquad$ $H_D = SU(2)_V$

$H'_{local} = SU(2)_L \otimes SU(2)_R$ with gauge fields $\mathbf{L}_\mu, \mathbf{R}_\mu$ (triplets)

SSB of $G' \to H_D$ gives $3 \times 4 - 3 = 9$ GB

- 6 are absorbed by $\mathbf{L}_\mu, \mathbf{R}_\mu$ which get mass
- 3 give mass to W and Z when part of G is promoted to local EW gauge symmetry

Taking the same gauge coupling constant g'' for $\mathbf{L}_\mu, \mathbf{R}_\mu$, we end with two more parameters

$$\boxed{M_V,\ M_A,\ g'',z}$$

with the vector and axial-vector resonances defined as $\mathbf{V}_\mu = (\mathbf{L}_\mu + \mathbf{R}_\mu)/2$, $\mathbf{A}_\mu = (\mathbf{R}_\mu - \mathbf{L}_\mu)/2$ and $z = g_V/g_A$.

In the following we will take $b = 0$.

Degenerate BESS model

Casalbuoni,Deandrea,D.C.,Dominici,
Feruglio,Gatto,Grazzini (1995)

Choose the parameters in the BESS model Lagrangian in such a way that

$$M_V = M_A \qquad z = 1$$

the symmetry swells to

$$[SU(2)_L \otimes SU(2)_R]^2_{\text{global}} \otimes [SU(2)_L \otimes SU(2)_R]_{\text{local}}$$

So this special case is protected by an additional custodial symmetry $SU(2)_{\text{cust}} \to SU(2)_{\text{cust}} \otimes [SU(2)_L \otimes SU(2)_R]$

Features of the model

- After EW gauging $M_L = M_R = M$ (apart from EW corrections)

- DECOUPLING
  In the limit $M \to \infty$ one recovers the SM Lagrangian (for $M_H \to \infty$)

- $\mathbf{L}_\mu, \mathbf{R}_\mu$ are NOT coupled to $w^\pm, z$ (the GB eaten up by $W^\pm, Z$), in QCD dictionary $g_{\rho\pi\pi} = g_{\rho A\pi} = 0 \to$
  the $\mathbf{L}_\mu, \mathbf{R}_\mu$ decays in $W_L W_L$ are suppressed
  Unlike other schemes of SEWSB, the $W_L W_L$ final state is not enhanced

- No additional contribution to $W_L W_L$ scattering amplitude: same unitarity bounds as in the SM (for $M_H \to \infty$)

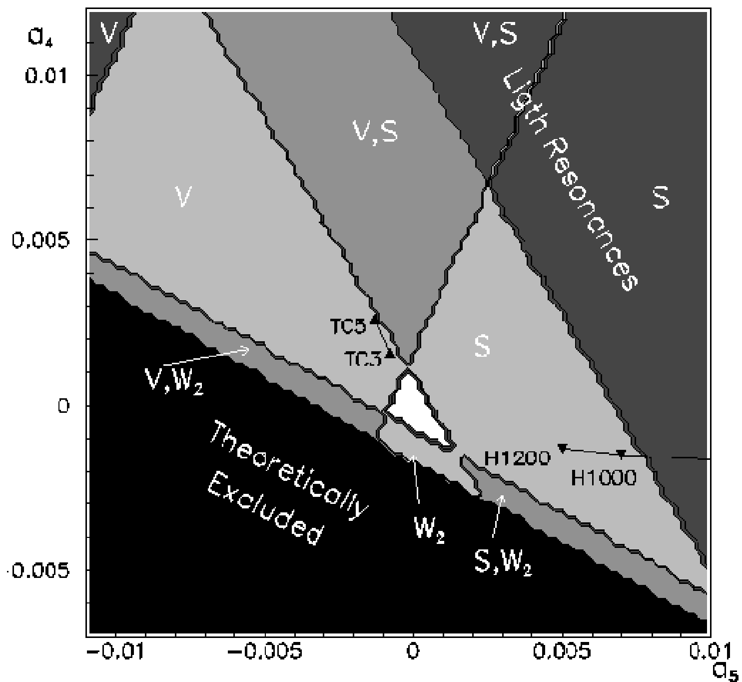
Comparison with the EChL approach

Effective EW chiral Lagrangians provide a low-energy description of the WW interaction in the strong regime.

To go beyond the low-energy theorems $\longrightarrow$ need some unitarization prescription. For ex.

$$\mathcal{L}^{(4)} = \alpha_4(\text{tr}(D_\mu U D^\nu U^\dagger))^2 + \alpha_5(\text{tr}(D_\mu U D^\mu U^\dagger))^2 + \cdots$$

where $U = \exp(i\pi_a\tau_a/2)$. After unitarization, the resonance spectrum of the strong SB sector is shown in fig.
(Dobado, Herrero, Peláez, Ruiz Morales (1999))



In BESS, eliminating the $\mathbf{V}$ and $\mathbf{A}$ fields we get

$$\alpha_4 = -\alpha_5 = -\frac{1}{4g''^2}(1 - z^2)^2$$

BESS lies on a half-line.
D-BESS ($z = 1$) corresponds to $\alpha_4 = \alpha_5 = 0$.

Features of the D-BESS model

- fermionic couplings of $\mathbf{L}_\mu$,$\mathbf{R}_\mu$ through mixing $\sim (g/g")$ with $W^\pm, Z, \gamma \to$ very good signatures at future colliders in the di-lepton channel

- from decoupling: $\Gamma(f\bar{f}) \sim \Gamma(WW) \sim M M_W^4 (G_F/g")^2$
$\to$ Very NARROW resonances
ex. $M \sim 1\ TeV$, $\Gamma \sim 1\ GeV$

- anomalous gauge couplings go to SM values for $M \to \infty$ (decoupling). Ex. $\delta_Z \sim (g/g")^2 (M_Z/M)^2$

- Very loose bounds from the experimental data
$\epsilon_i \to 0$ for M $\to \infty$
Calculation to the next-to-leading order:

$$\epsilon_1 = -\frac{c_\theta^4 + s_\theta^4}{c_\theta^2} X \qquad \epsilon_2 = -c_\theta^2 X \qquad \epsilon_3 = -X$$

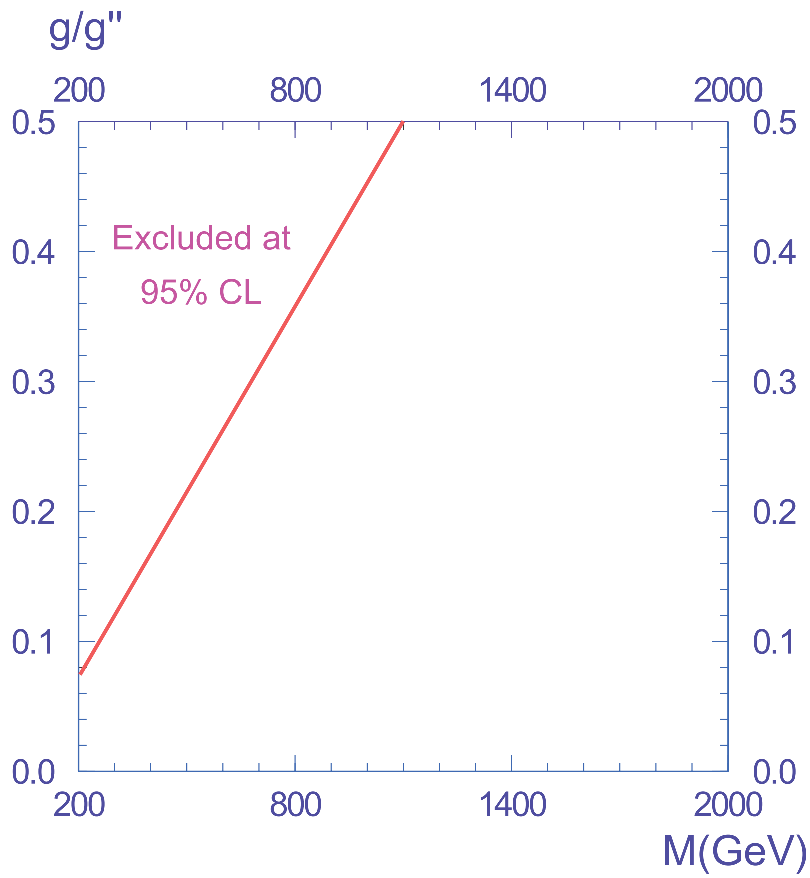
$$X = 2\ (g/g")^2 (M_Z/M)^2$$

double suppression factor

- BESS is non-renormalizable, radiative corrections must be defined by a cut-off Λ
In the non-linear σ-models the one-loop contributions go like $\log \Lambda$ (screening theorem Appelquist, Bernard (1980))
To compare to the experimental data consider for BESS the same radiative corrections of the SM with $m_H = \Lambda = 1\ TeV$ (neglect new physics loop corrections)

Bounds from the ϵ-parameters fit

(LEP/SLC/Tevatron)



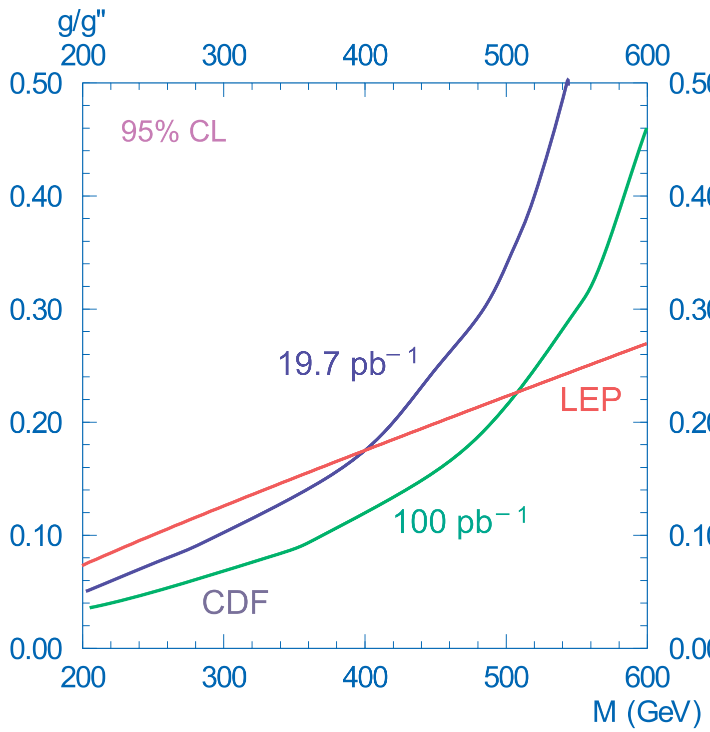
Experimental values from all High-Energy data fit
(Altarelli (1999))

$$\epsilon_1 = (3.92 \pm 1.14) \times 10^{-3}$$
$$\epsilon_2 = (-9.27 \pm 1.49) \times 10^{-3}$$
$$\epsilon_3 = (4.19 \pm 1.00) \times 10^{-3}$$

SM radiative corrections (Altarelli, Barbieri, Caravaglios (1998))
$\epsilon_1^{\text{rad}} = 3.79 \times 10^{-3}$, $\epsilon_2^{\text{rad}} = -6.67 \times 10^{-3}$, $\epsilon_3^{\text{rad}} = 6.65 \times 10^{-3}$
$(m_t = 175.6\ GeV,\ m_H = \Lambda = 1\ TeV)$

Bounds from CDF

Lower bound on M at fixed g/g'' by comparing the upper limit from CDF on $\sigma \cdot B(p\bar{p} \to W' \to e\nu_e)$ for $\sqrt{s} = 1.8\ TeV$, $L = 19.7\ pb^{-1}$ (Abe et al. PRL 74 (1995)) with the prediction of the D-BESS model $\sigma \cdot B(p\bar{p} \to L^{\pm} \to e\nu_e)$



Also shown:
–Extrapolation to $L = 100\ fb^{-1}$: $(\sigma \cdot B)_{\text{limit}} \sim$ scales with $1/\sqrt{L}$ when BKGD is present
–LEP bounds from the ϵ-parameters fit

Available also a similar D0 analysis (PRL 76 (1996)) for $L = 74\ pb^{-1}$ in $\sim$ agreement with our extrapolation.
Recently, a new CDF analysis for $L = 107\ pb^{-1}$ data sample in $\mu\nu_\mu$ channel, gives comparable bounds.

Degenerate BESS at hadron colliders

Future hadron colliders will be able either to discover the new resonances or to constrain the physical region still available.

We have studied the signatures of the D-BESS resonances at the Tevatron Upgrade and at the LHC with the following configurations:

- $\sqrt{s} = 2\ TeV$ and $\mathcal{L} = 10^{33} cm^{-2} sec^{-1}$ for the so-called TEV-33 option
- $\sqrt{s} = 14\ TeV$ and $\mathcal{L} = 10^{34} cm^{-2} sec^{-1}$ for the LHC

Production of $L^\pm, L^3, R^3$ through quark annihilation and decay in the muon channel:

$$q\bar{q}' \to L^\pm, W^\pm \to \mu\nu_\mu$$
$$q\bar{q} \to L_3, R_3, Z, \gamma \to \mu^+\mu^-$$

In the charged channel only $L^\pm$ is relevant because $R^\pm$ is completely decoupled (couplings to fermions are only through the mixing to SM gauge bosons)

Fusion process is negligible in D-BESS, the resonances are not strongly coupled to WW

Manifestation of a strong EW sector at hadron colliders

Casalbuoni, Dominici, Chiappetta, Deandrea, D.C., Gatto (1997)

Events simulated using PYTHIA MonteCarlo

Rough simulation of the detector assuming a smearing of the energy and an error in the 3-momentum determination of the muons

Tevatron Upgrade $\frac{\Delta E}{\sqrt{E}} = 10\%$ $\frac{\Delta p}{p} = 3 \div 5\%$

LHC $\frac{\Delta E}{\sqrt{E}} = 10\%$ $\frac{\Delta p}{p} = 3 \div 9\%$

Observables: transverse mass (charged channel) and invariant mass (neutral channel) distributions for several choices of D-BESS parameters (g'', M) taken inside the allowed region

The signal events compared with the BKGD from SM di-lepton production in the muon channel

For each case we have selected cuts to maximize the statistical significance of the signal

The cleanest signature is in the neutral channel but the production rate is less favorable

Degenerate BESS at Tevatron Upgrade

$\sqrt{s} = 2\ TeV \qquad \mathcal{L} = 10^{33} cm^{-2} sec^{-1} \qquad L = 10\ fb^{-1}$

Charged channel: $p\bar{p} \to L^{\pm}, W^{\pm} \to \mu\nu_\mu + X$

g/g''	M GeV	$\Gamma_{L^{\pm}}$ GeV	$\|p_T^\mu\|_c$ GeV	$\|m_T\|_c$ GeV	$\#B$	$\#S$	ss
0.12	400	0.4	150	300	385	887	24.9
0.20	600	1.7	200	400	82	303	15.4
0.40	1000	11.1	300	800	0	16	4.0

Neutral channel: $p\bar{p} \to L_3, R_3, Z, \gamma \to \mu^+\mu^- + X$

g/g''	M GeV	Γ_{L_3} GeV	Γ_{R_3} GeV	$\|p_T^\mu\|_c$ GeV	$\|m_{\mu^+\mu^-}\|_c$ GeV	$\#B$	$\#S$	ss
0.12	400	0.4	0.06	150	300	269	257	11.2
0.20	600	1.7	0.03	200	500	33	106	9.0
0.40	1000	11.1	1.64	300	800	1	3	1.5

For all the cases in the charged channel we have also applied a cut $|p_T^{miss}|_c = |p_T^\mu|_c$. Here $ss = S/\sqrt{S+B}$

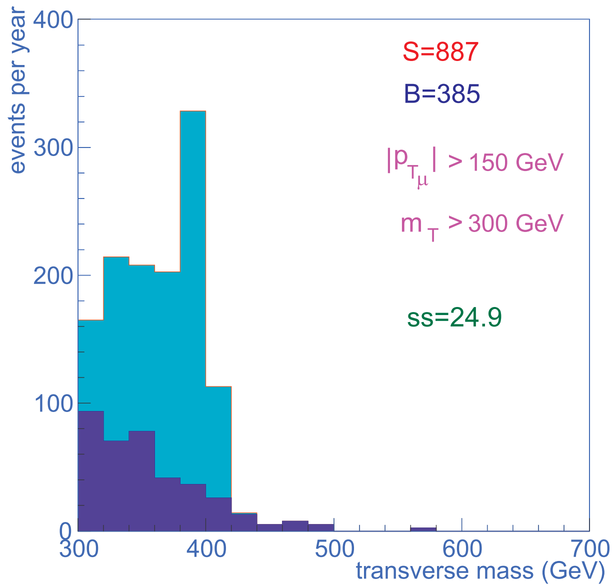
The number of signal events decreases for increasing M

DISCOVERY LIMIT $\sim 1\ TeV$

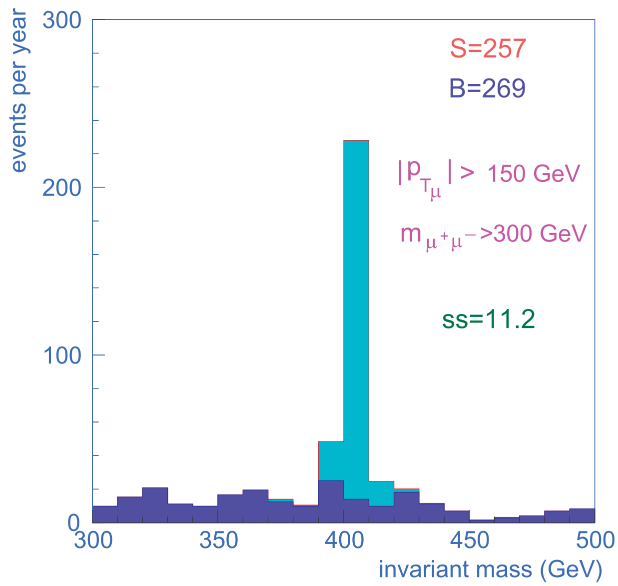
Degenerate BESS at Tevatron Upgrade

$\sqrt{s} = 2\ TeV \qquad \mathcal{L} = 10^{33} cm^{-2} s^{-1}$

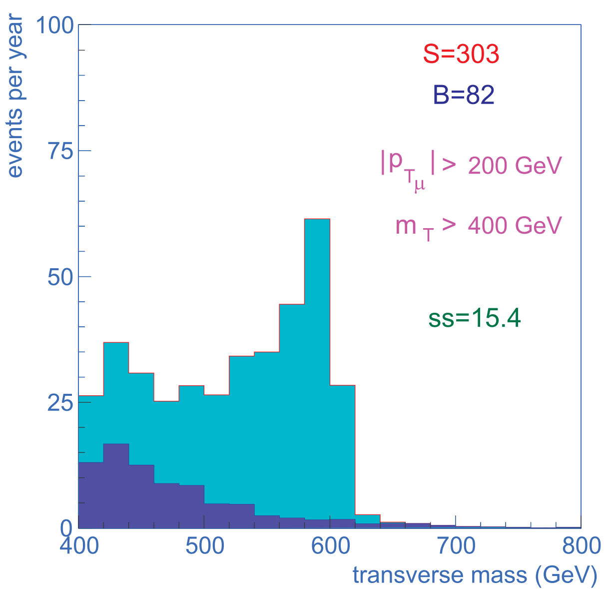
$p\bar{p} \to L^{\pm}, W^{\pm} \to \mu\nu_{\mu}$ $\qquad$ $p\bar{p} \to L_3, R_3, Z, \gamma \to \mu^+\mu^-$



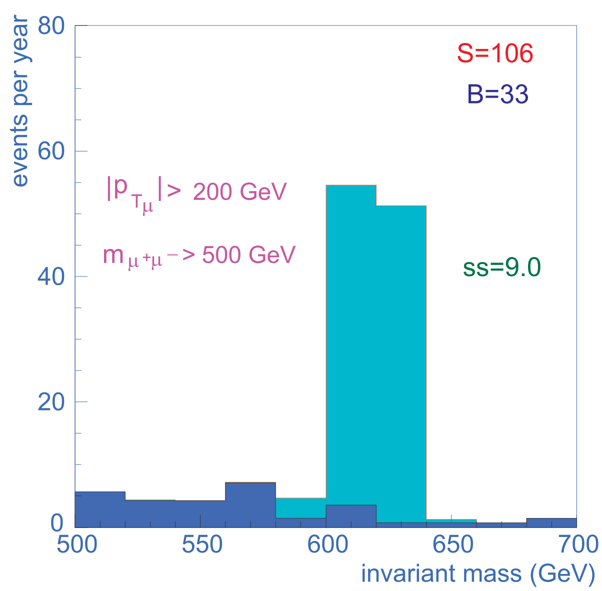
$M = 400\ GeV \quad g/g'' = 0.12$



$M = 400\ GeV \quad g/g'' = 0.12$



$M = 600\ GeV \quad g/g'' = 0.2$



$M = 600\ GeV \quad g/g'' = 0.2$

Bounds from TEV-33

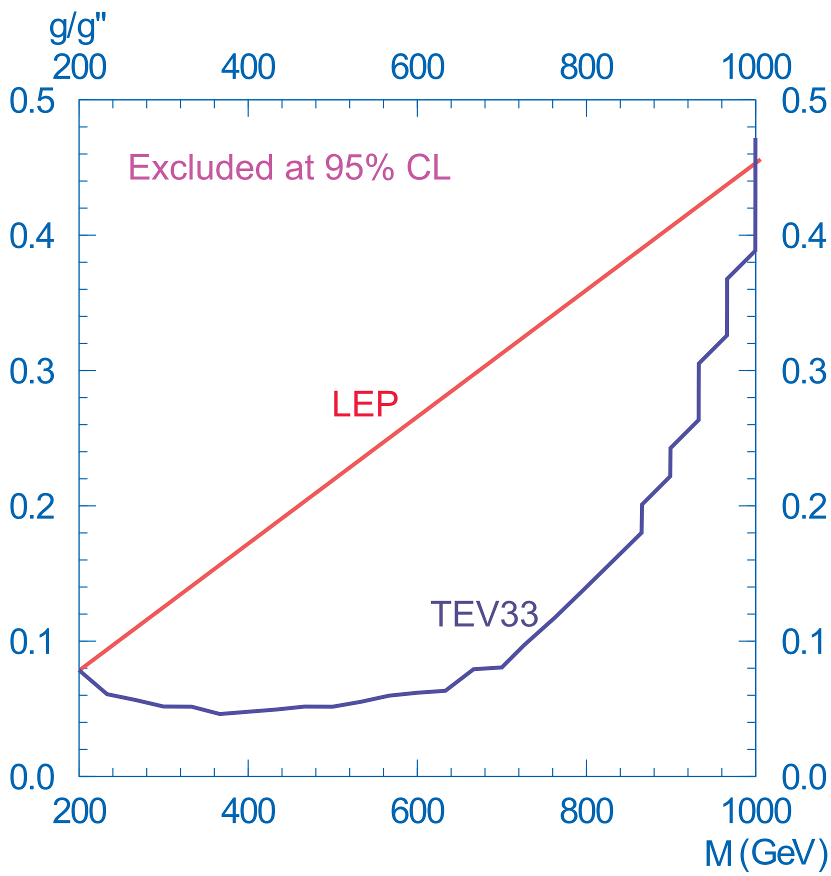
$\sqrt{s} = 2\ TeV \qquad L = 10\ fb^{-1}$

Consider the total-cross section

$$\sigma(p\bar{p} \to L^{\pm}, W^{\pm} \to \mu\nu_{\mu} + X)$$

and compare with the SM BKGD. A minimum of 10 events per year is required to claim the signal

IF NO DEVIATIONS are seen within the statistical error and a systematic 5% on the cross-section, we get the 95% CL bounds in figure



from a grid of 25×25 cross-section points in the parameter space of the model. Applied cut $|p_{T\mu}| > M/2 - 50 GeV$

Up to 1 TeV the bounds from TEV-33 option are much more stringent with respect to the LEP/SLC/Tevatron ones.

Degenerate BESS at LHC

$\sqrt{s} = 14\ TeV \qquad \mathcal{L} = 10^{34} cm^{-2} sec^{-1} \qquad L = 100\ fb^{-1}$

Charged channel: $pp \to L^{\pm}, W^{\pm} \to \mu\nu_{\mu} + X$

g/g"	M	$\Gamma_{L^{\pm}}$	$\lvert p_T^{\mu}\rvert_c$	$\lvert m_T\rvert_c$	$\#B$	$\#S$	ss
	GeV	GeV	GeV	GeV			
0.075	500	0.2	150	400	26300	20780	95.8
0.15	500	0.8	150	400	26300	85477	255.0
0.10	1000	0.7	300	800	2050	3130	43.5
0.10	1500	1.0	500	1300	247	469	17.5
0.10	2000	1.4	700	1800	41	118	9.4

Neutral channel: $pp \to L_3, R_3, Z, \gamma \to \mu^+\mu^- + X$

g/g"	M	Γ_{L_3}	Γ_{R_3}	$\lvert p_T^{\mu}\rvert_c$	$\lvert m_{\mu^+\mu^-}\rvert_c$	$\#B$	$\#S$	ss
	GeV	GeV	GeV	GeV	GeV			
0.075	500	0.2	0.03	150	400	16781	4300	29.6
0.15	500	0.8	0.11	150	400	16781	17480	94.4
0.10	1000	0.7	0.10	300	800	1145	605	14.5
0.10	1500	1.0	0.15	500	1300	146	153	8.8
0.10	2000	1.4	0.20	700	1800	35	22	2.9

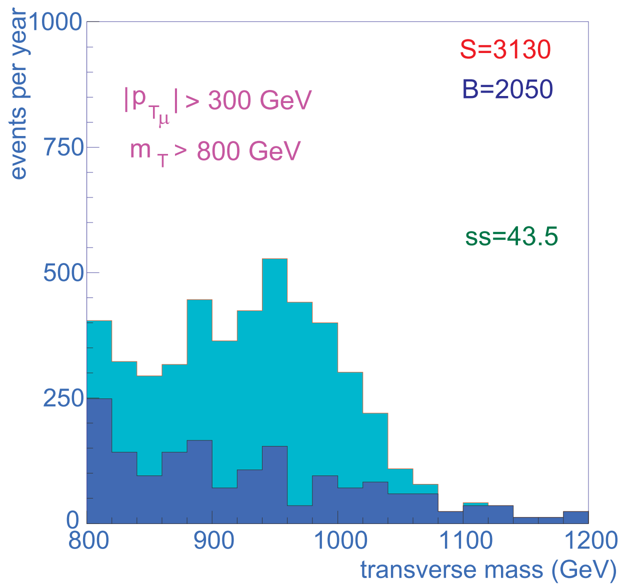
For all the cases in the charged channel we have also applied a cut $\lvert p_T^{miss}\rvert_c = \lvert p_T^{\mu}\rvert_c$. Here $ss = S/\sqrt{S+B}$.

DISCOVERY LIMIT $\sim 2\ TeV$

Signals of D-BESS at LHC

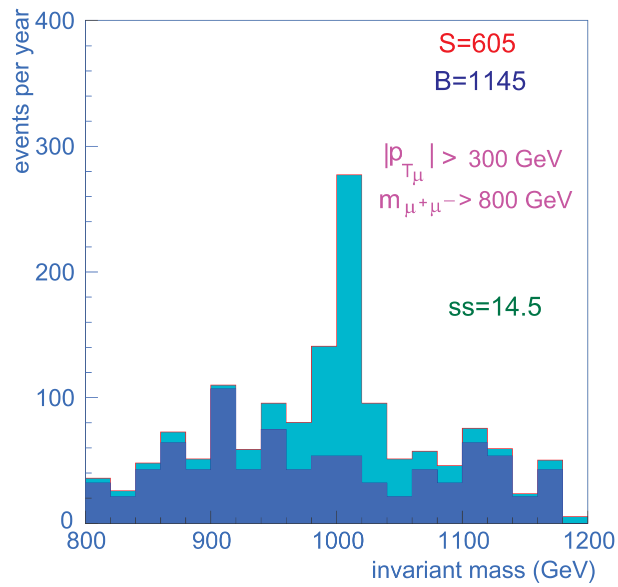
$$\sqrt{s} = 14\ TeV \qquad \mathcal{L} = 10^{34} cm^{-2} s^{-1}$$

$pp \to L^{\pm}, W^{\pm} \to \mu \nu_{\mu}$

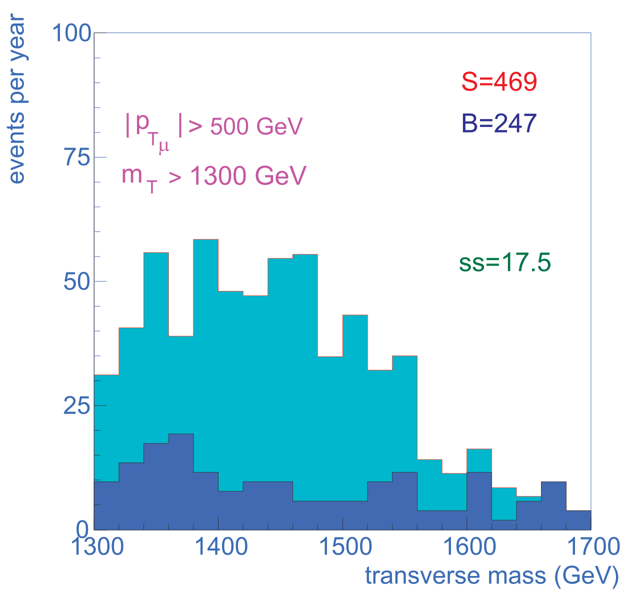


$M = 1000\ GeV \quad g/g'' = 0.1$

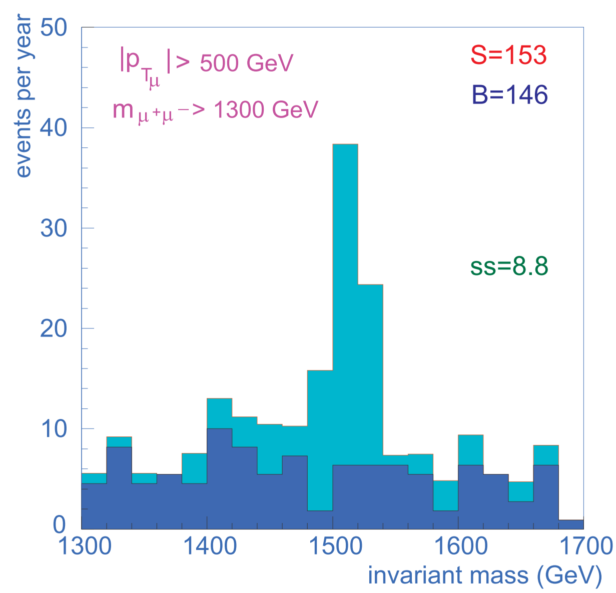
$pp \to L_3, R_3, Z, \gamma \to \mu^+ \mu^-$



$M = 1000\ GeV \quad g/g'' = 0.1$



$M = 1500\ GeV \quad g/g'' = 0.1$

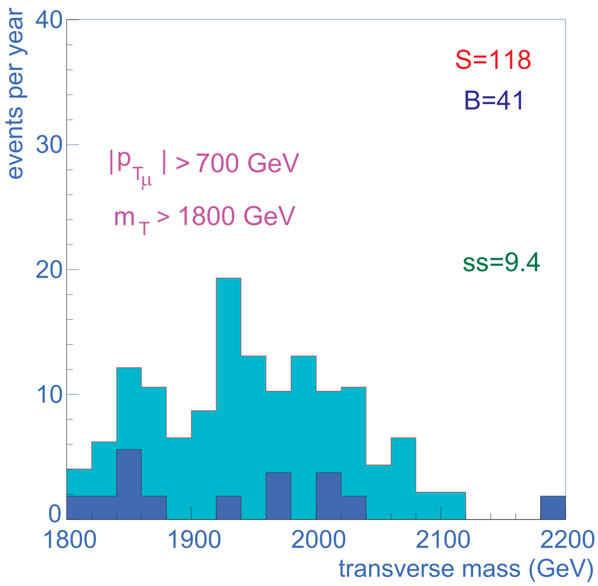


$M = 1500\ GeV \quad g/g'' = 0.1$

Signals of D-BESS at LHC

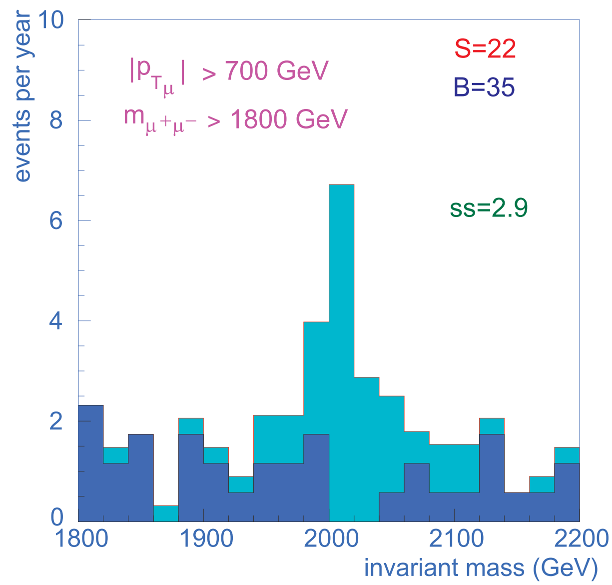
$$\sqrt{s} = 14\ TeV \qquad \mathcal{L} = 10^{34} cm^{-2} s^{-1}$$

$pp \to L^{\pm}, W^{\pm} \to \mu\nu_{\mu}$



$M = 2000\ GeV \quad g/g'' = 0.1$

$pp \to L_3, R_3, Z, \gamma \to \mu^+\mu^-$



$M = 2000\ GeV \quad g/g'' = 0.1$

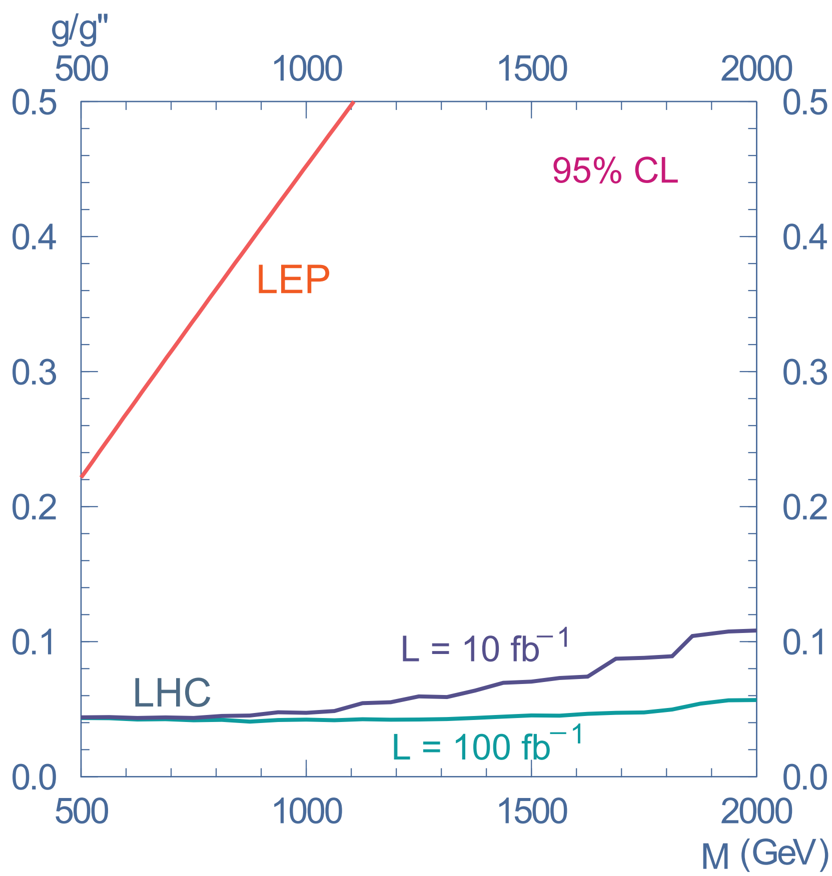
Bounds from LHC

Consider the total cross-section

$$\sigma(pp \to L^{\pm}, W^{\pm} \to \mu\nu_{\mu} + X)$$

and compare with the SM BKGD. A minimum of 10 events per year is required to claim the signal

IF NO DEVIATIONS are seen within the statistical error and a systematic 5% on the cross-section, we get the 95% CL bounds in figure



from a grid of 25 × 25 cross-section points in the parameter space of the model. Applied cut $|p_{T\mu}| > M/2 - 50GeV$

Also shown are the bounds from LEP/SLC/Tevatron

Conclusions

- In spite of the impressive agreement of the present data with the SM predictions, the origin of EW symmetry breaking remains unknown

- The success of the SM poses strong limitations on the possible forms of new physics

- Decoupling models are particularly appealing since they show little deviations from the SM structure

- Generally disfavoured are models with a nearby strong non perturbative regime like TC

- The Degenerate BESS model is an example of dynamical EWSB scenario with decoupling passing all the low energy precision tests

- The new spin 1 resonances predicted by the model will give quite visible signals at the Tevatron when the upgrading in luminosity is considered, with a discovery limit $M \sim 1\ TeV$

- The direct observation at LHC will be possible in a wide range of the parameter space of the model, in some cases with a spectacular number of events

A much more realistic analysis of the experimental set up is needed

D-BESS at e^+e^- colliders

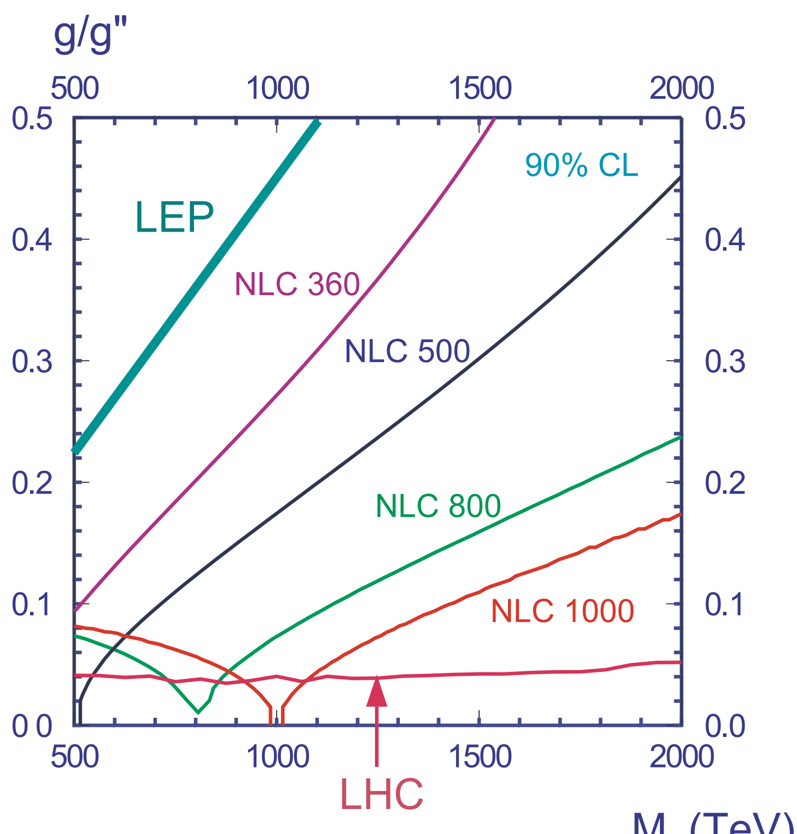
Casalbuoni,Deandrea,D.C.,Dominici,Gatto (1997)

Study of indirect effects:

$$e^+e^- \to L_3, R_3, Z, \gamma \to f^+f^-$$

We have analyzed cross-sections and asymmetries for the following NLC configurations: $\sqrt{s}(GeV) = 360, 500, 800, 1000$, $L(fb^{-1}) = 10, 20, 50, 80$

IF NO DEVIATIONS are seen within the statistical and systematic errors, a combined χ^2 analysis gives the 90% CL bounds in figure



NLC at 360 GeV improves the bounds from LEP and LHC almost closes the parameter space

Linear realization of D-BESS

Casalbuoni,D.C.,Dominici,Grazzini (1997)

The model has a linear realization with 3 Higgs doublets:

$$(h^+, h^0), \quad (\rho_L^+, \rho_L^0), \quad (\rho_R^+, \rho_R^0)$$

and two scales

$$\langle h^0 \rangle = v \quad \langle \rho_L^0 \rangle = \langle \rho_R^0 \rangle = u \quad \text{where} \quad v \ll u$$

h is the usual Higgs doublet whereas ρ_L and ρ_R give mass to L_μ and R_μ

The relation between the non-linear and the linear model is the same as the one between the non-linear and the linear σ-model

The non-linear model can be regularized assuming the linear model as the underlying theory and taking the Higgs mass as a cut-off at the TeV scale

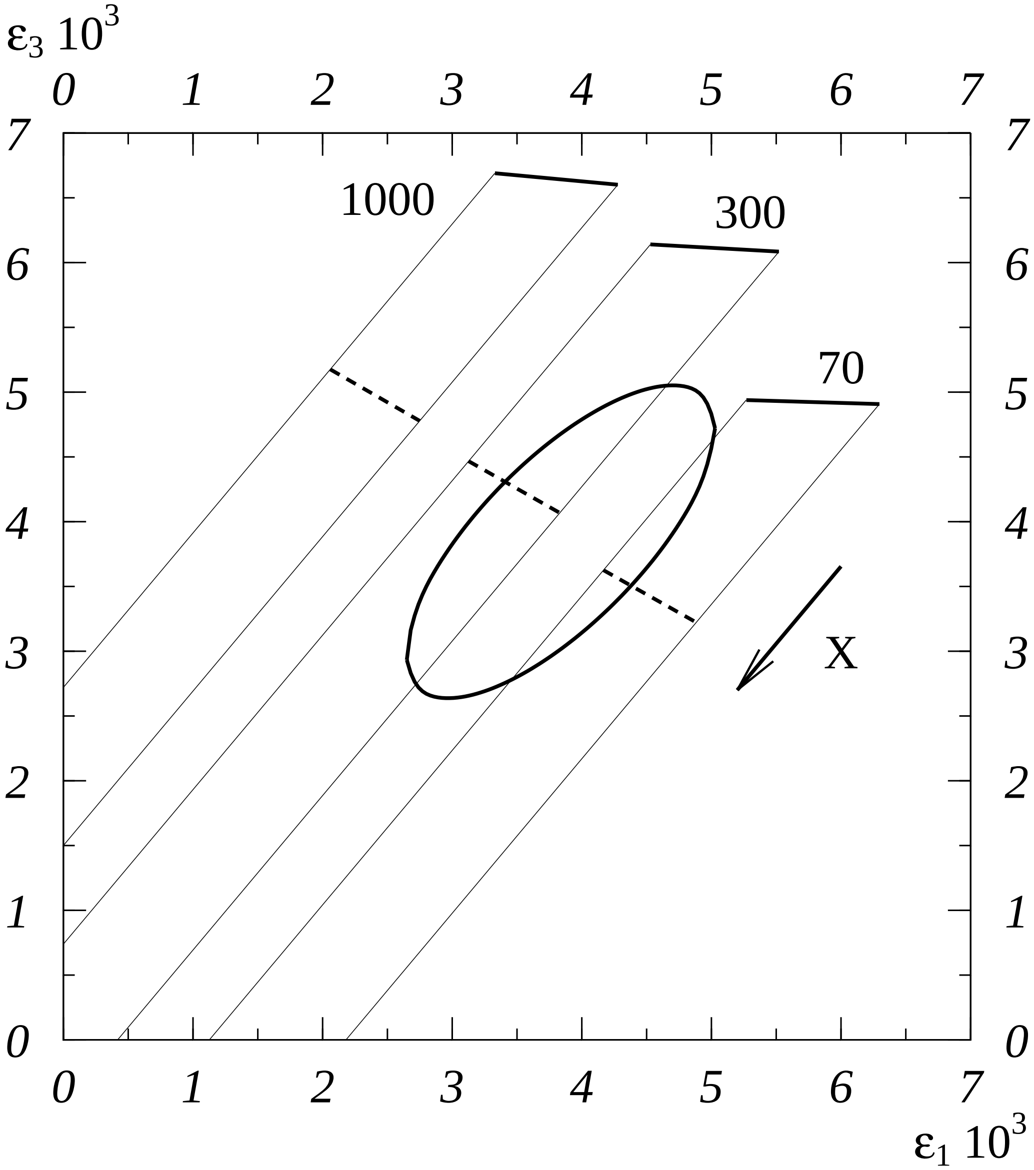
Let us consider the $u \to \infty$ limit (analogous to $M \to \infty$)

- In the limit in which $u \to \infty$ and the self coupling of the light Higgs λ is fixed the model decouples and we get back the SM with the usual Higgs

$$\lim_{u \to \infty} \mathcal{L}(h, \rho_L, \rho_R, L, R, \phi_{SM}) = \mathcal{L}(h, \phi_{SM})$$

- In the limit $u, \lambda \to \infty$ we get back the non-linear model (D-BESS)

Predictions in the plane (ϵ_1, ϵ_3)

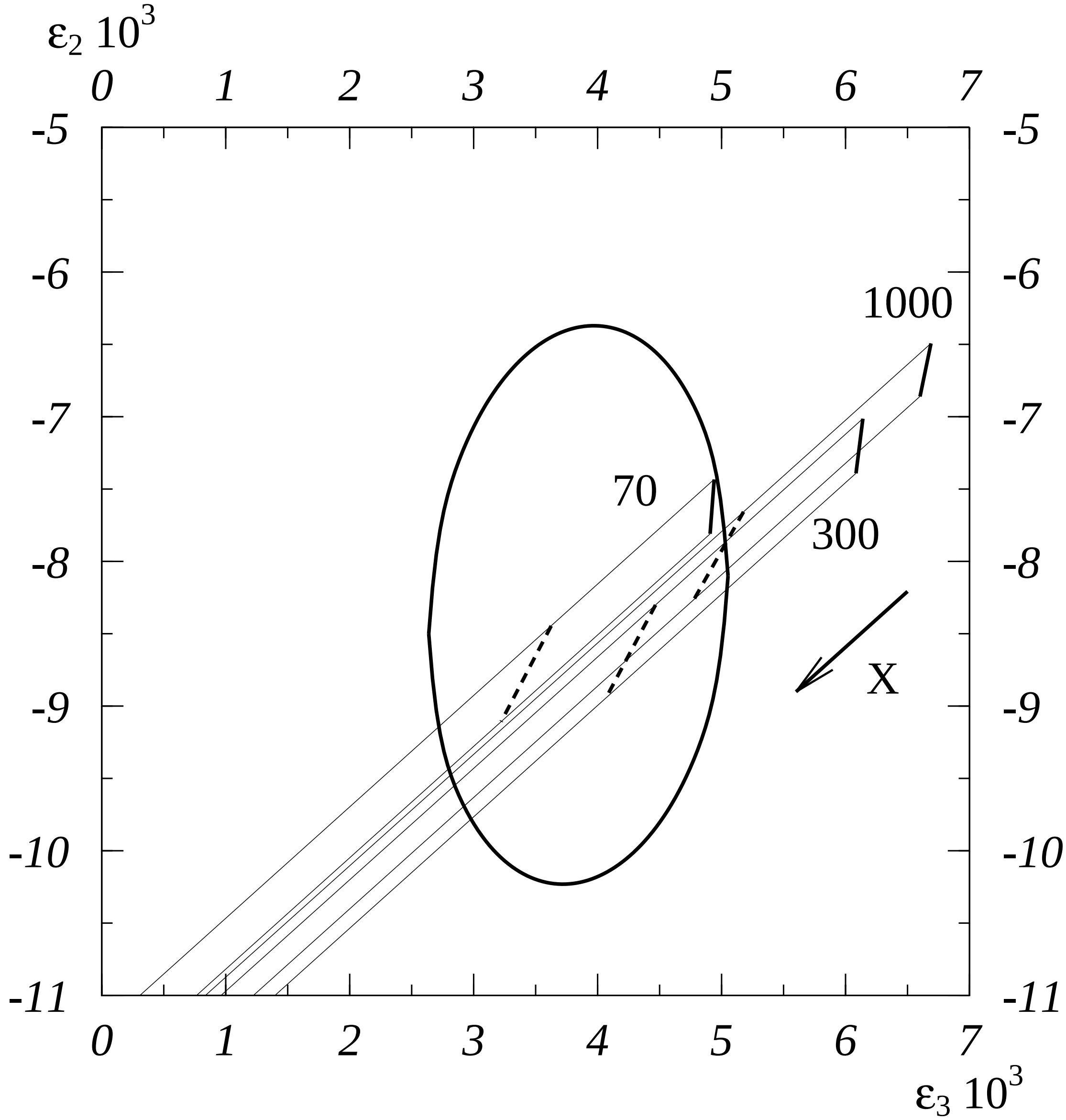


$$X = 2\frac{M_Z^2}{M^2}\left(\frac{g}{g''}\right)^2 \qquad 170.1 < m_{top}(GeV) < 181.1$$

$$\epsilon_1 = (3.85 \pm 1.20)10^{-3}, \qquad \epsilon_2 = (-8.3 \pm 1.9)10^{-3}$$

$$\epsilon_3 = (3.85 \pm 1.21)10^{-3}$$

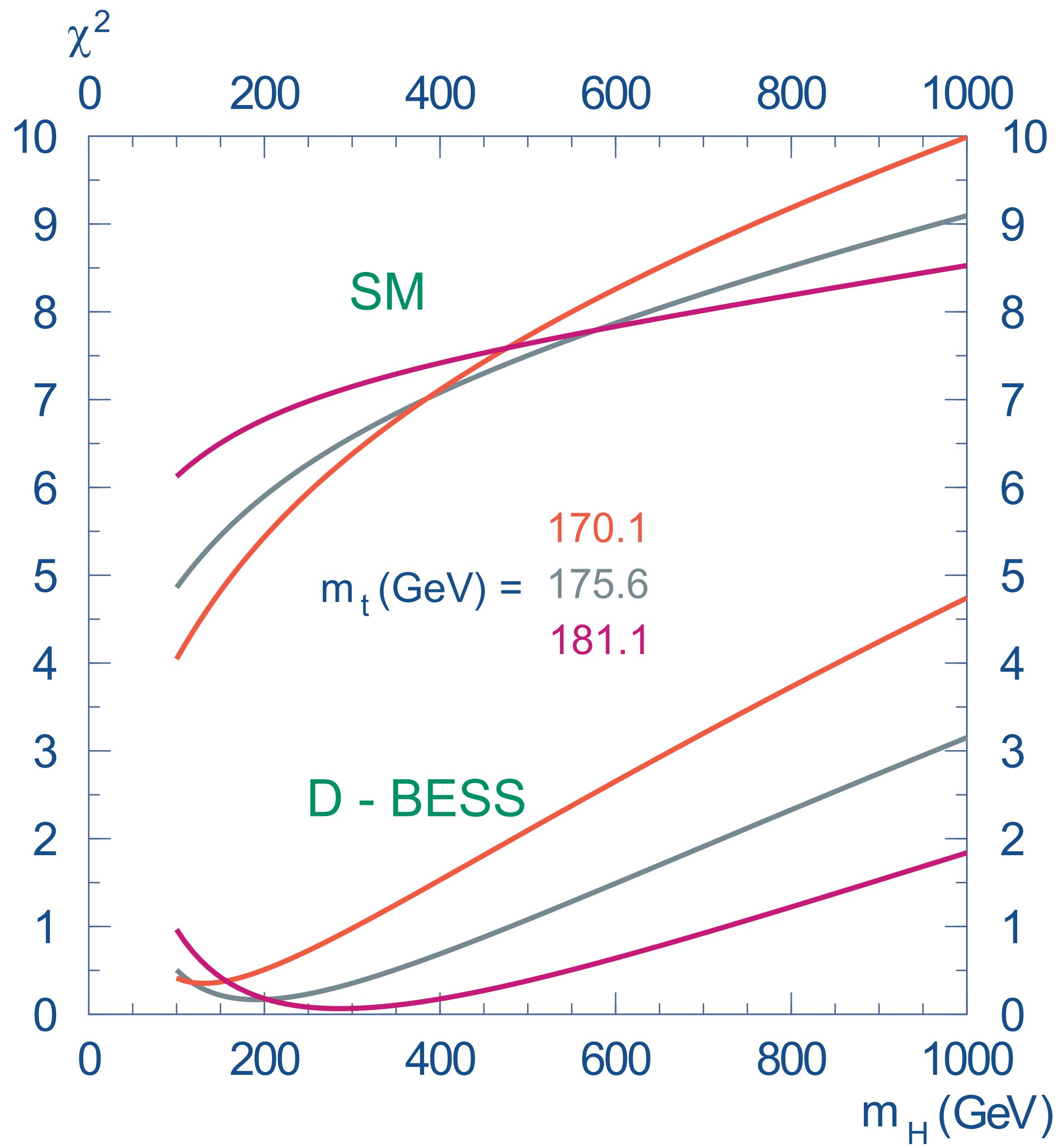
Predictions in the plane (ϵ_2, ϵ_3)



$X = 2\frac{M_Z^2}{M^2}\left(\frac{g}{g''}\right)^2$ $\qquad$ $170.1 < m_{top}(GeV) < 181.1$

$\epsilon_1 = (3.85 \pm 1.20)10^{-3}, \qquad \epsilon_2 = (-8.3 \pm 1.9)10^{-3}$

$\epsilon_3 = (3.85 \pm 1.21)10^{-3}$



χ^2 as a function of m_H for the SM
and for D-BESS with X taken at the best-fit value

A heavy Higgs may be compatible with the experimental data

Bounds from LEP1

The deviation from the SM can be parametrized as:

$$\frac{M_W^2}{M_Z^2} = c_\theta^2\left[1 - \frac{s_\theta^2}{c_{2\theta}}\Delta r_W\right]$$

$$\mathcal{L}_{neutral} = -\frac{e}{s_\theta c_\theta}\left(1 + \frac{\Delta\rho}{2}\right) Z_\mu \bar{\psi}[\gamma^\mu g_V + \gamma^\mu \gamma_5 g_A]\psi$$

$$g_V = \frac{T_L^3}{2} - s_{\tilde{\theta}}^2 Q \qquad\qquad g_A = -\frac{T_L^3}{2}$$

$$s_{\tilde{\theta}}^2 = (1 + \Delta k)s_\theta^2$$

In the large M limit the indirect effects of the new spin 1 resonances can be studied by eliminating the $\mathbf{L}_\mu$ and $\mathbf{R}_\mu$ fields using their equations of motion

We get

$$\Delta\rho = -\frac{c_\theta^4 + s_\theta^4}{c_\theta^2} X$$

$$\Delta r_W = -X$$

$$\Delta k = -2\frac{s_\theta^2 c_\theta^2}{c_{2\theta}} X$$

where

$$X = 2\frac{M_Z^2}{M^2}\left(\frac{g}{g''}\right)^2$$

In terms of the ϵ_i

$$\epsilon_1 = \Delta\rho = -\frac{c_\theta^4 + s_\theta^4}{c_\theta^2} X$$

$$\epsilon_2 = c_\theta^2 \Delta\rho + \frac{s_\theta^2}{c_{2\theta}} \Delta r_W - 2 s_\theta^2 \Delta k = -c_\theta^2 X$$

$$\epsilon_3 = c_\theta^2 \Delta\rho + c_{2\theta} \Delta k = -X$$

D-BESS Model

Approximate formulas in the limit $M \to \infty$ and $g'' \to \infty$

Mass eigenvalues

$$M^2_{R^\pm} \equiv M^2, \qquad M^2_{W^\pm} = \frac{v^2}{4} g^2, \qquad M^2_{L^\pm} = M^2(1 + 2x^2)$$

where $x = g/g''$, g is the usual $SU(2)$ gauge coupling constant and $v^2 = 1/(\sqrt{2} G_F)$.

In the neutral sector we have:

$$M^2_Z = \frac{M^2_W}{c^2_\theta}, \qquad M^2_{L_3} = M^2 \left(1 + 2x^2\right)$$

$$M^2_{R_3} = M^2 \left(1 + 2x^2 \tan^2\theta\right)$$

where $\tan\theta = s_\theta / c_\theta = g'/g$ and g' is the usual $U(1)_Y$ gauge coupling constant. Notice that for small x all the new vector resonances are degenerate in mass.

Charged fermionic Lagrangian

$$\mathcal{L}_{charged} = -\left(a_W W^-_\mu + a_L L^-_\mu\right) J^{(+)\mu}_L + H.c.$$

where (apart from higher order terms)

$$a_W = \frac{g}{\sqrt{2}}, \qquad a_L = -gx$$

and $J^{(+)\mu}_L = \bar{\psi}_L \gamma^\mu \tau^+ \psi_L$ with τ^+ the combination $(\tau_1 + i\tau_2)/2$. The $R^\pm$ are not coupled to the fermions.

Neutral fermionic Lagrangian

$$\begin{aligned}\mathcal{L}_{neutral} &= -\Big\{eJ^{\mu}_{em}\gamma_{\mu} + \Big[AJ^{(3)\mu}_{L} + BJ^{\mu}_{em}\Big]Z_{\mu} \\ &+ \Big[CJ^{(3)\mu}_{L} + DJ^{\mu}_{em}\Big]L_{3\mu} \\ &+ \Big[EJ^{(3)\mu}_{L} + FJ^{\mu}_{em}\Big]R_{3\mu}\Big\}\end{aligned}$$

where γ_{μ} is the photon field and again in the limit $M \to \infty$, $x \to 0$,

$$\begin{aligned}A &= \frac{g}{c_{\theta}} \qquad B = -\frac{g s^2_{\theta}}{c_{\theta}} \\ C &= -\sqrt{2}gx \qquad D = 0 \\ E &= \sqrt{2}g\frac{x}{c_{\theta}}\tan^2\theta \qquad F = -E\end{aligned}$$

and $J^{\mu}_{em} = Q\bar{\psi}\gamma^{\mu}\psi$, $J^{(3)\mu}_{L} = \bar{\psi}_L\gamma^{\mu}T^3_L\psi_L$ are the usual neutral currents.

Total fermionic widths

$$\begin{aligned}\Gamma^{fermion}_{L_3} &= \frac{2\sqrt{2}G_F M^2_W}{\pi} M_{L_3}\left(\frac{g}{g''}\right)^2 \\ \Gamma^{fermion}_{R_3} &= \frac{10\sqrt{2}G_F M^2_W}{3\pi}\frac{{s_{\theta}}^4}{{c_{\theta}}^4} M_{R_3}\left(\frac{g}{g''}\right)^2 \\ \Gamma^{fermion}_{L^{\pm}} &= \frac{2\sqrt{2}G_F M^2_W}{\pi} M_{L^{\pm}}\left(\frac{g}{g''}\right)^2\end{aligned}$$

for example:

$$\Gamma_{L_3\to\mu^+\mu^-} = 0.003\ M\left(\frac{g}{g''}\right)^2, \qquad \Gamma_{R_3\to\mu^+\mu^-} = 0.0012\ M\left(\frac{g}{g''}\right)^2$$

$$\Gamma_{L^\pm\to\mu\nu_\mu} = 0.005\ M\left(\frac{g}{g''}\right)^2$$

Widths into vector boson pairs

$$\begin{aligned}
\Gamma^{WW}_{L_3} &= \frac{\sqrt{2}G_F M_W^2}{24\pi} M_{L_3}\left(\frac{g}{g''}\right)^2 \\
\Gamma^{WW}_{R_3} &= \frac{\sqrt{2}G_F M_W^2}{24\pi}\frac{{s_\theta}^4}{{c_\theta}^4} M_{R_3}\left(\frac{g}{g''}\right)^2 \\
\Gamma^{WZ}_{L^\pm} &= \frac{\sqrt{2}G_F M_W^2}{24\pi} M_{L^\pm}\left(\frac{g}{g''}\right)^2
\end{aligned}$$

It may be useful to compare the widths of the new gauge bosons into vector boson pairs with those into fermions:

$$\begin{aligned}
\Gamma^{fermion}_{L_3} &= 48\ \Gamma^{WW}_{L_3} \\
\Gamma^{fermion}_{R_3} &= 80\ \Gamma^{WW}_{R_3} \\
\Gamma^{fermion}_{L^\pm} &= 48\ \Gamma^{WZ}_{L^\pm}
\end{aligned}$$

The total fermionic channel is dominant due to the multiplicity. Finally the total widths are

$$\Gamma_{L_3} = \Gamma_{l^\pm} = 0.068\ M\left(\frac{g}{g''}\right)^2, \qquad \Gamma_{R_3} = 0.01\ M\left(\frac{g}{g''}\right)^2$$