A decoupling model for Electroweak Symmetry Breaking

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(R. Casalbuoni, P. Chiappetta, A. Deandrea, S. De Curtis, D. Dominici, F. Feruglio, R. Gatto, M.G.)

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Outline

- Motivations
- A decoupling model with vector and axial vector resonances
- The linear realization
- Comparison with present data
- Phenomenology at Tevatron Run2
- LHC
- Summary

Motivations for decoupling models

- SM survived LEP1 tests at the level of per mille
- This precision gives a beautiful test of radiative corrections within the SM

$$\Downarrow$$

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

New physics effects are naturally small if decoupling holds:

$$\mathcal{L}_{NP}(\Lambda_{NP}) \to \mathcal{L}_{SM} \text{ as } \Lambda_{NP} \to \infty$$

All the corrections at LEP1 would be of order M_Z^2/Λ_{NP}^2

This is the case for MSSM for very massive sparticles

For models with Dynamical Symmetry Breaking (DSB) as ordinary TC this does not happen since

$$\Lambda_{NP} \sim v$$

and M_Z^2/Λ_{NP}^2 is not suppressed

$\Rightarrow$ there are large positive corrections to ϵ_3

A natural question is:

Do examples of DSB models with decoupling exist ?

We will look at this problem from the point of view of an effective lagrangian representing the low energy limit of an unknown underlying dynamical theory

This effective lagrangian describes the possible resonances produced by the strong interaction responsible for EWSB

The ϵ_i parameters encode possible deviations from the SM

If $SU(2)$ custodial is an exact global symmetry we get

$\epsilon_1,\ \epsilon_2 \to 0$

but $\epsilon_3 \neq 0$ because it contains a singlet part

(eventually electroweak corrections make all $\epsilon_i \neq 0$)

For ϵ_3 a dispersive representation exists:

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

M.E. Peskin, T. Takeuchi (1990)

where

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

Typically

$$\mathrm{Im}\Pi_{VV} \sim \mathrm{Im}\Pi_{AA} \sim \left(\frac{1}{\Lambda_{NP}^2}\right)^0$$

To send $\epsilon_3 \to 0$ we need a further symmetry to let

$$\mathrm{Im}\Pi_{VV} - \mathrm{Im}\Pi_{AA} \sim \mathcal{O}\left(\frac{1}{\Lambda_{NP}^2}\right)$$

Assume vector dominance

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

$$\Downarrow$$

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

- In TC models (scaled up QCD) from Weinberg sum rules

  $$g_V = g_A \quad M_A^2 = 2M_V^2$$

  Using KSFR we get:

  $$\epsilon_3 = \frac{3}{2}\frac{M_W^2}{M_V^2}$$

  and it is not suppressed since $M_V^2 \sim v^2$

- In a model with only vector resonances (BESS model)

  $$g_A = 0 \qquad \epsilon_3 = \left(\frac{g}{g''}\right)$$

$$\Downarrow$$

A possible solution is:

$$g_A = g_V \quad M_A = M_V \Rightarrow \epsilon_3 = 0$$

That is vector and axial vector resonances degenerate in masses and couplings

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

Casalbuoni, De Curtis, Dominici, Gatto (1989)

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

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

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

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 go to give mass to W and Z when part of G is promoted to local EW gauge symmetry

9 GB can be described by 3 fields L,M,R with the following transformations under G'

$$L \to g_L L h_L \quad R \to g_R R h_R \quad M \to h_R^\dagger M h_L$$

where

$$g_L \in (SU(2)_L)_{global} \quad g_R \in (SU(2)_R)_{global}$$

$$h_L \in (SU(2)_L)_{local} \quad h_R \in (SU(2)_R)_{local}$$

Introduce $P : L \overset{P}{\longleftrightarrow} R \quad M \overset{P}{\longleftrightarrow} M^\dagger$

Define

$$D_\mu L = \partial_\mu L - L\mathbf{L}_\mu \qquad D_\mu R = \partial_\mu R - R\mathbf{R}_\mu$$

$$D_\mu M = \partial_\mu M - M\mathbf{L}_\mu + \mathbf{R}_\mu M$$

and the vectors

$$V_0^\mu = L^\dagger D_\mu L \quad V_1^\mu = M^\dagger D_\mu M \quad V_2^\mu = M^\dagger (R^\dagger D_\mu R) M$$

$$V_i^\mu \to h_L^\dagger V_i^\mu h_L$$

The invariants under $G' \otimes P$ with at most two derivatives are

$$I_1 = Tr[(V_0 - V_1 - V_2)^2] \quad I_2 = Tr[(V_0 + V_2)^2]$$

$$I_3 = Tr[(V_0 - V_2)^2] \quad I_4 = Tr[V_1^2]$$

The most general lagrangian invariant under $G' \otimes P$ is

$$\mathcal{L} = -\frac{v^2}{4}\Big[a_1 I_1 + a_2 I_2 + a_3 I_3 + a_4 I_4\Big]$$

Add kinetic terms for $\mathbf{L}_\mu$, $\mathbf{R}_\mu$

$$\mathcal{L}_{kin} = \frac{1}{g''^2} Tr[F_{\mu\nu}(\mathbf{L})]^2 + \frac{1}{g''^2} Tr[F_{\mu\nu}(\mathbf{R})]^2$$

In the general case

$$M_V^2 = \frac{v^2}{4} a_2 g''^2 \qquad M_A^2 = \frac{v^2}{4}(a_3 + a_4) g''^2$$

Only recently it was realized that in the degenerate case, corresponding to the choice $a_4 = 0 \quad a_2 = a_3$ the global symmetry is increased:

$$SU(2) \otimes SU(2) \to [SU(2) \otimes SU(2)]^3$$

So this special case is protected by an additional custodial symmetry

The linear realization

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 cutoff at the TeV scale

Let us consider the $u \to \infty$ limit

- 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 standard model 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 $u, \lambda \to \infty$ and at tree level we get back the non linear model

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

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

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

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

Anomalous gauge boson couplings

The elimination of the $\mathbf{L}_\mu$ and $\mathbf{R}_\mu$ fields using their equations of motion give rise to anomalous gauge boson couplings

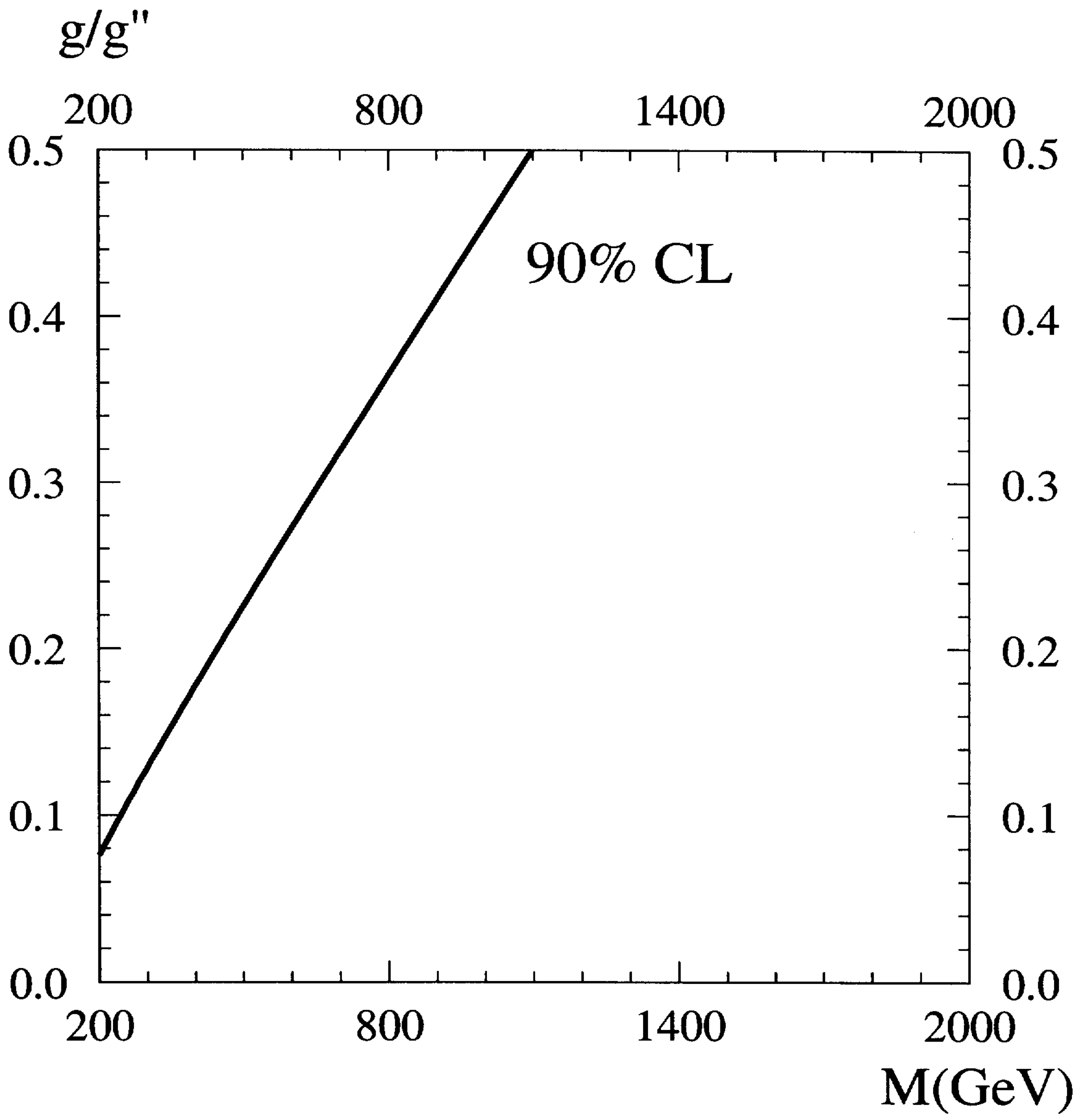
The process relevant to study trilinear couplings is $e^+e^- \to W^+W^-$ so we can assume $\partial \cdot W = 0$ (W on shell) and $\partial \cdot Z = \partial \cdot A = 0$ (since they are coupled to light fermions)

We get:

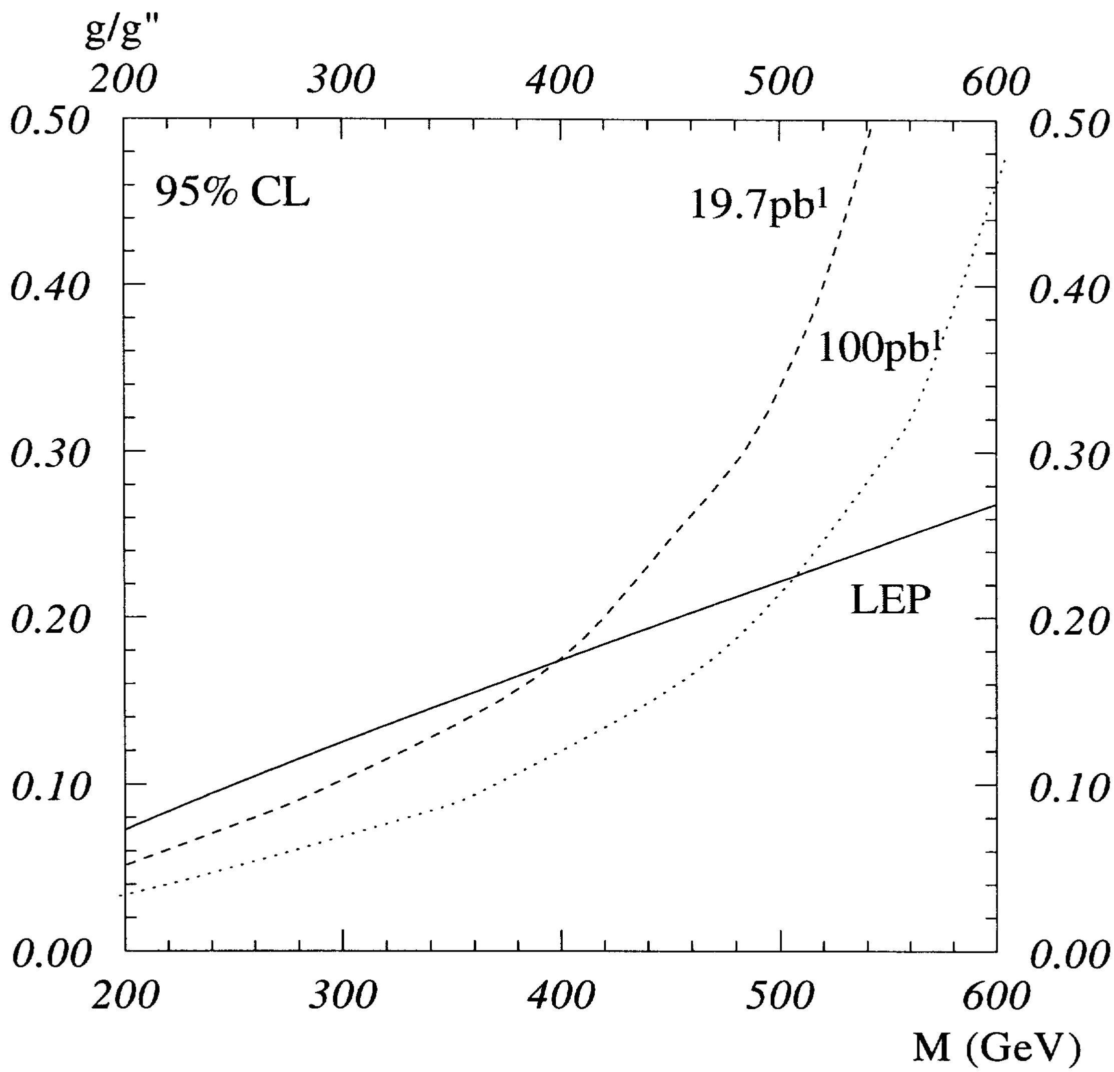
$$\mathcal{L}_{eff}^{kin(3)} = ie\text{ctg}\theta\Big(1 + \frac{z_z}{2c_{2\theta}}\frac{M_Z^2}{M^2} - \frac{z_w}{2}\frac{\Box_+ + M_W^2}{M^2} - \frac{z_w}{2}\frac{\Box_- + M_W^2}{M^2}$$
$$- \frac{z_z}{2}\frac{\Box_Z + M_Z^2}{M^2}\Big)\Big(Z^{\mu\nu}W_\mu^- W_\nu^+ + Z^\nu(W_{\mu\nu}^- W^{\mu+} - W_{\mu\nu}^+ W^{\mu-})\Big)$$
$$+ ie(1 - \frac{z_w}{2}\frac{\Box_+ + M_W^2}{M^2} - \frac{z_w}{2}\frac{\Box_- + M_W^2}{M^2} + (\frac{z_\gamma}{2} - z_w)\frac{\Box_A}{M^2})$$
$$\Big(A^{\mu\nu}W_\mu^- W_\nu^+ + A^\nu(W_{\mu\nu}^- W^{\mu+} - W_{\mu\nu}^+ W^{\mu-})\Big)$$

The tensor structure is the same as in the SM but we get non trivial form factors

Bounds from LEP1

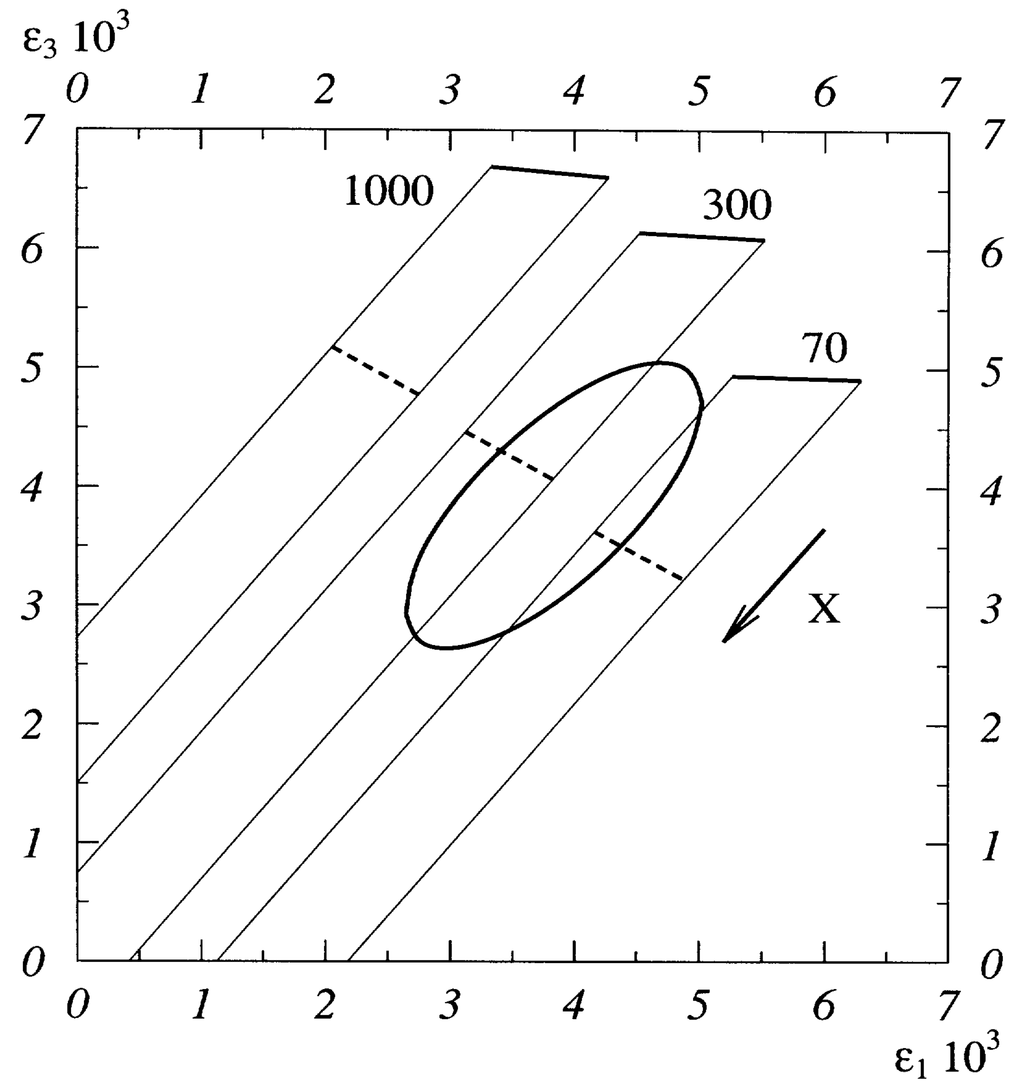


Bounds from CDF



Obtained using CDF limit on W' cross section compared with the prediction of the model at fixed g/g''

Predictions in the plane (ϵ_1, ϵ_3)



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

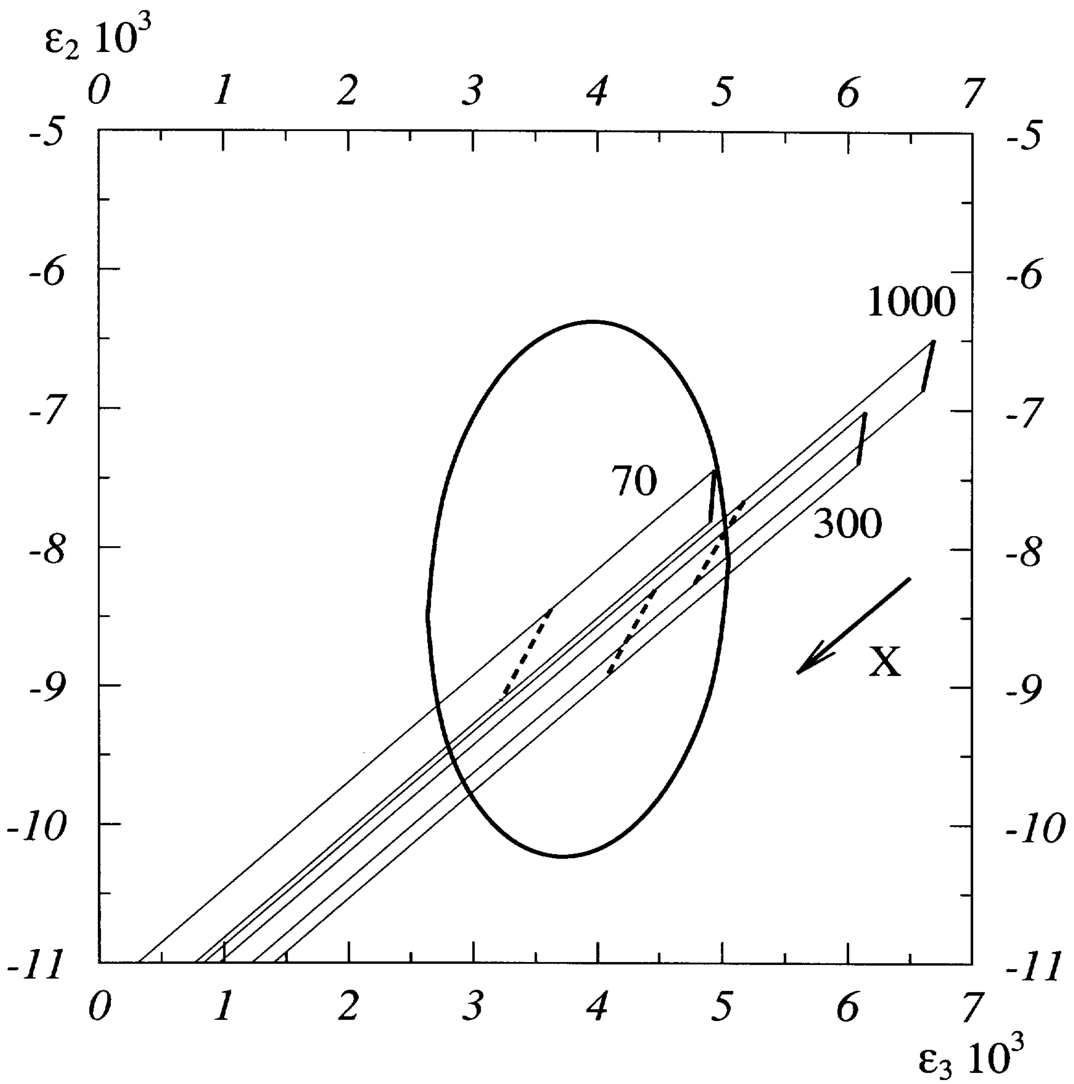
$170.1 < m_{top}(GeV) < 181.1$

$\epsilon_1 = (3.85 \pm 1.20)10^{-3}$

$\epsilon_2 = (-8.3 \pm 1.9)10^{-3}$

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

Predictions in the plane (ϵ_2, ϵ_3)



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

$$\epsilon_1 = (3.85 \pm 1.20)10^{-3}$$

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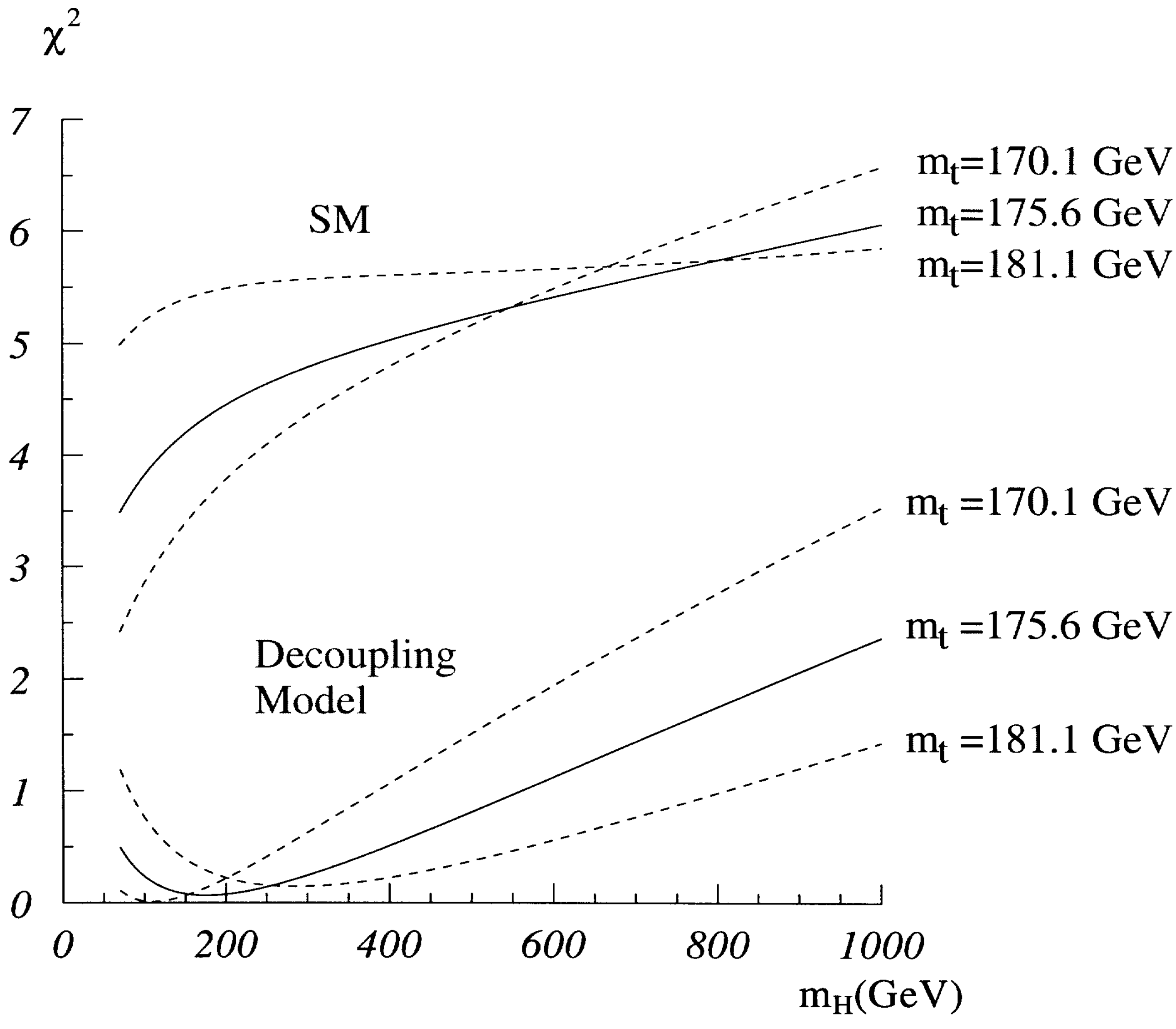


χ^2 as a function of m_H

Degenerate BESS at hadron colliders

We have studied the channels:

Tevatron upgrade	$p\bar{p} \to L^\pm, W^\pm \to l\nu_l$
	$p\bar{p} \to L_3, R_3, Z, \gamma \to \mu^+\mu^-$
LHC	$pp \to L^\pm, W^\pm \to l\nu_l$
	$pp \to L_3, R_3, Z, \gamma \to \mu^+\mu^-$

In the charged channel only $L_\pm$ is relevant because $R_\pm$ is completely decoupled

We have performed a rough simulation of the detector assuming

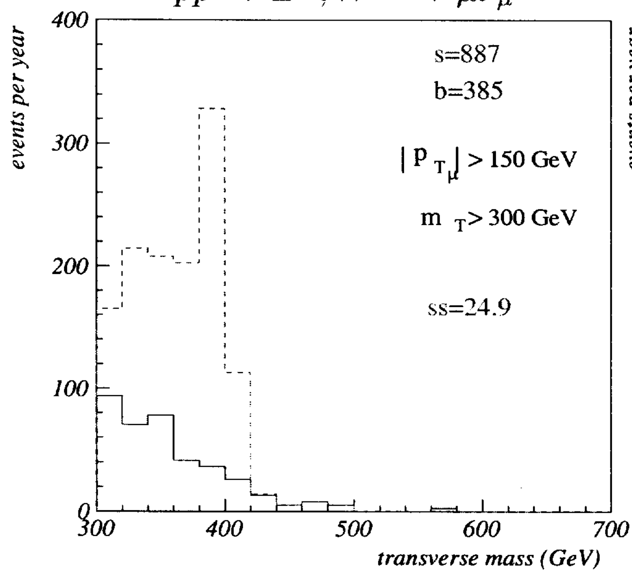
Tevatron Run2	$\dfrac{\Delta E}{\sqrt{E}} = 10\%$	$\dfrac{\Delta p}{p} = 3 - 5\%$
LHC	$\dfrac{\Delta E}{\sqrt{E}} = 10\%$	$\dfrac{\Delta p}{p} = 3 - 9\%$

The events were simulated using PYTHIA montecarlo

Degenerate BESS at Tevatron upgrade

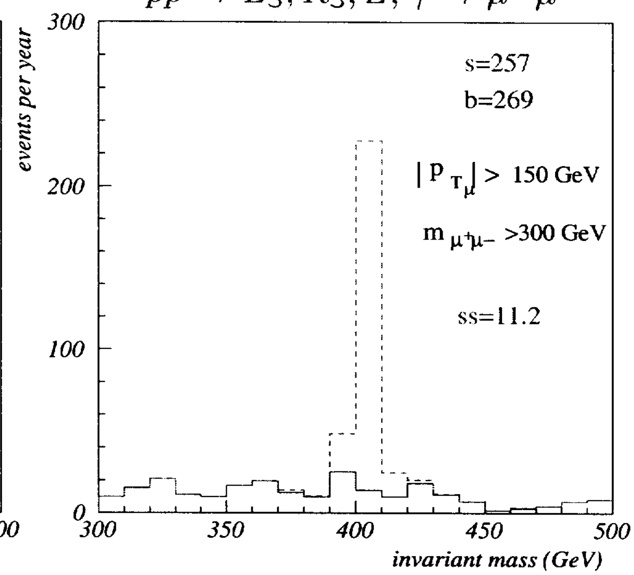
$$\sqrt{s} = 2\ TeV \qquad \mathcal{L} = 10^{33} cm^{-2} s^{-1}$$

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



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

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



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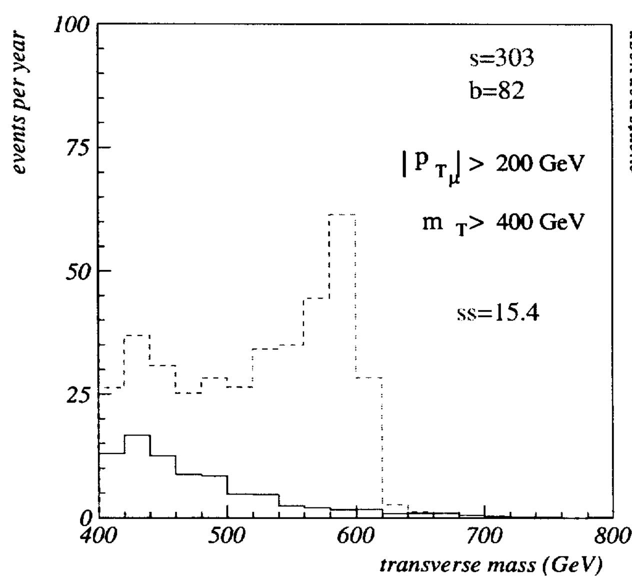
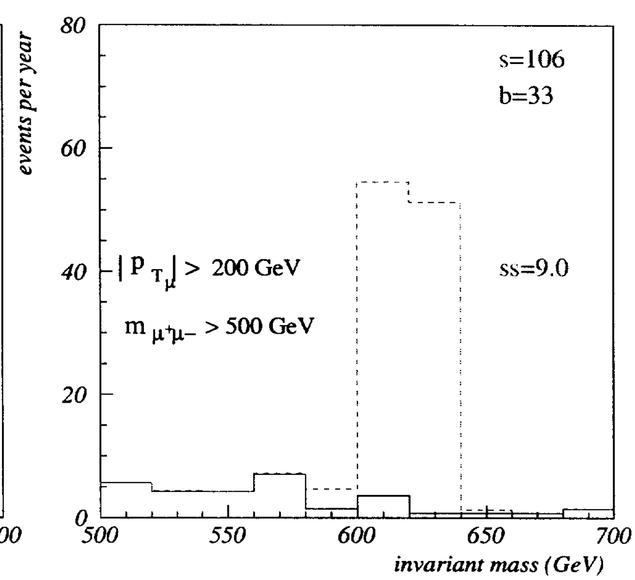


$M = 600\ GeV \quad g/g'' = 0.2$



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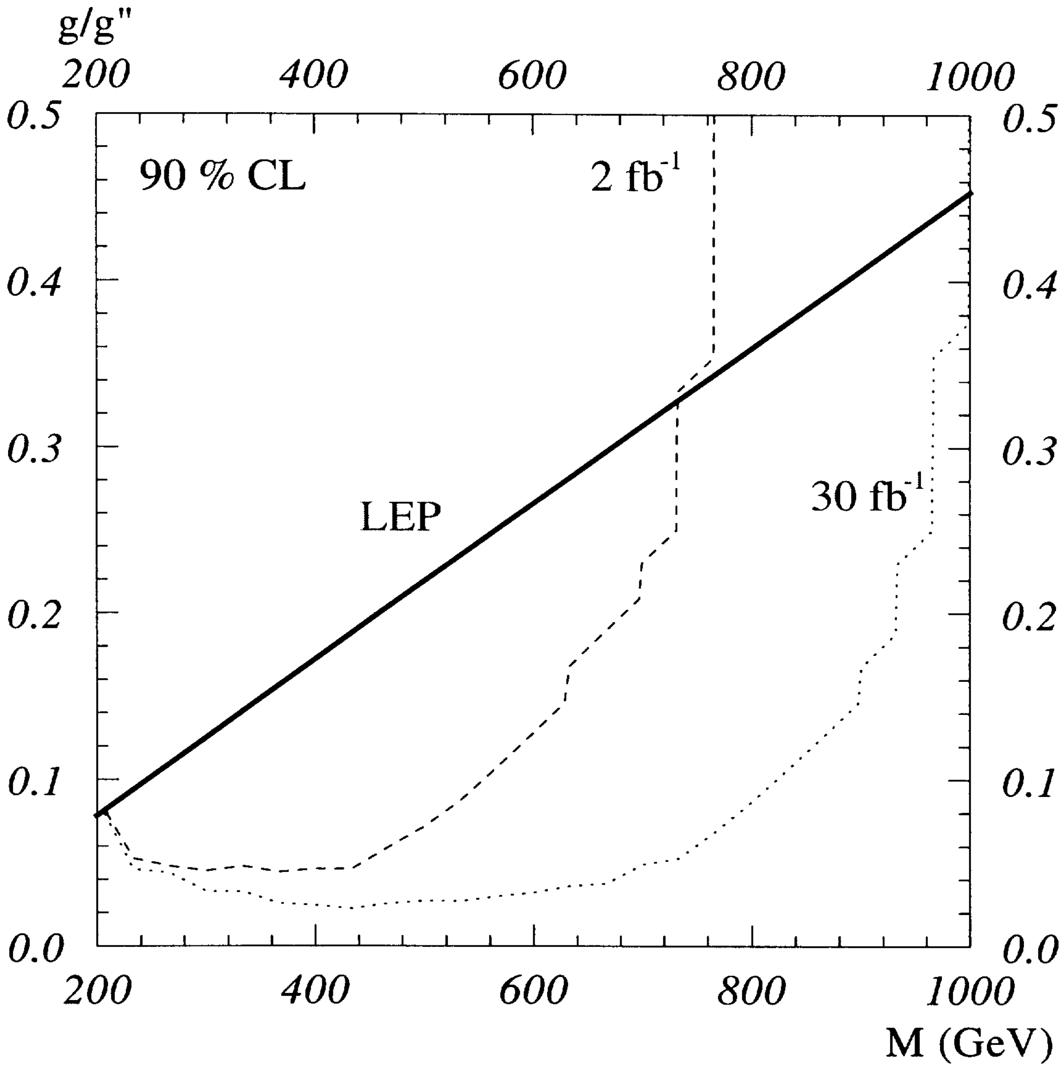
Bounds from Tevatron RUN2



Bounds obtained supposing no deviation is seen with respect to the SM in the total cross section $p\bar{p} \to \mu\nu_\mu$ from a grid of 25×25 points in the parameter space of the model

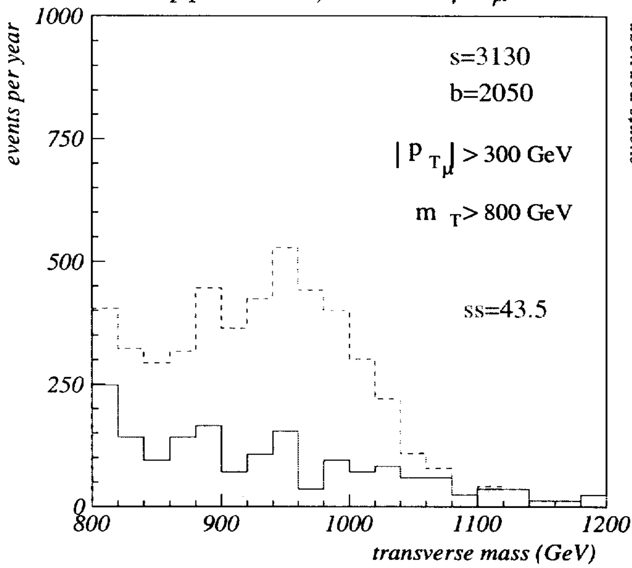
Applied cut $|p_{T\mu}| > M/2 - 50GeV$

The error assumed on σ_{tot} is 5% systematic plus statistical error

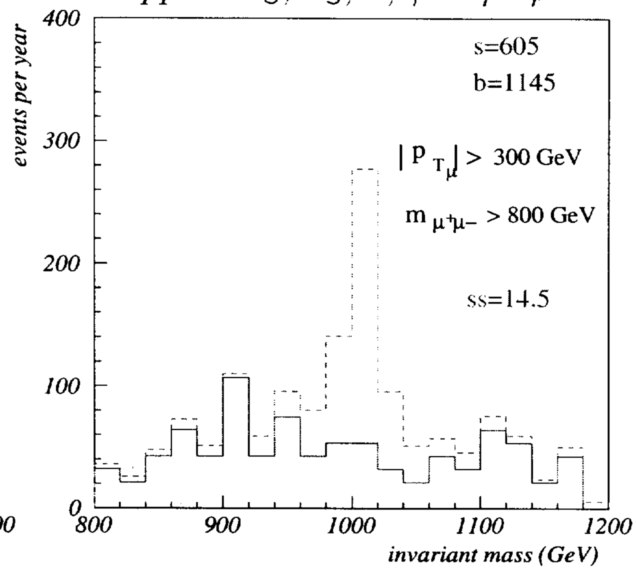
Degenerate BESS at LHC

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

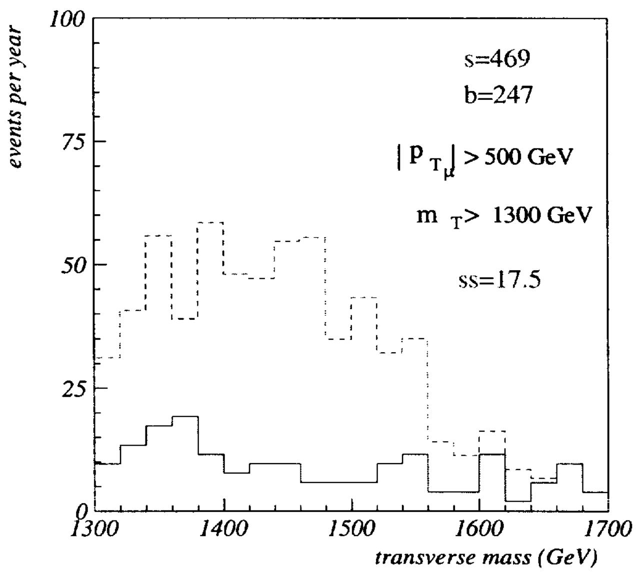
$pp \to L^{\pm}, W^{\pm} \to \mu\nu_{\mu}$ $\qquad$ $pp \to L_3, R_3, Z, \gamma \to \mu^{+}\mu^{-}$



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



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



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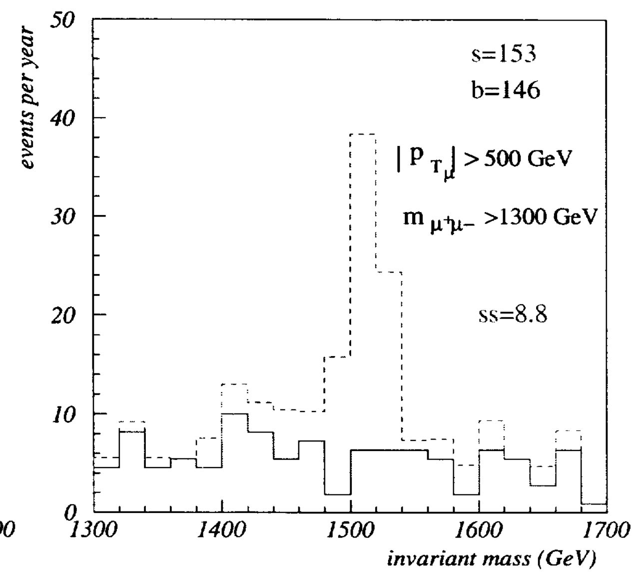

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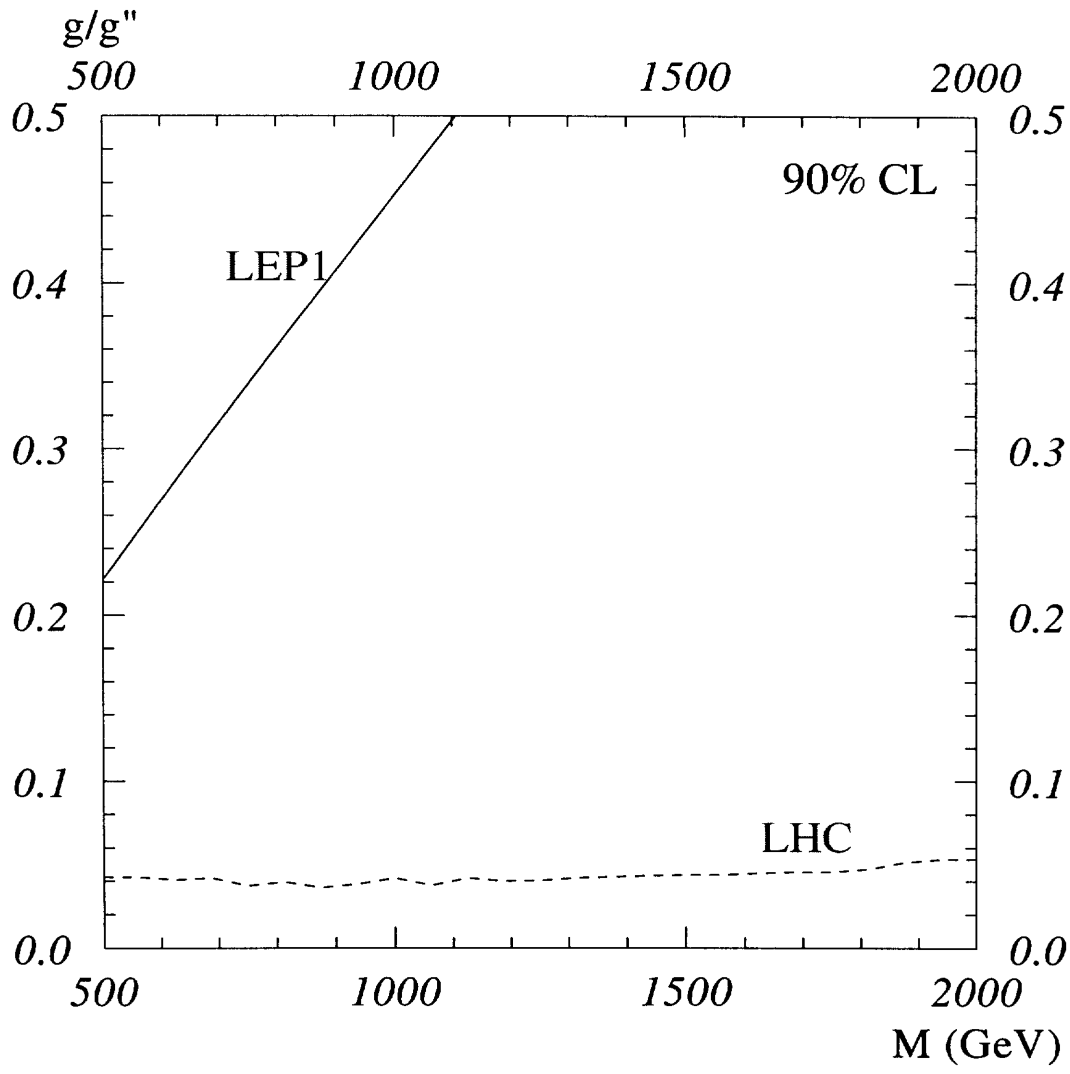
Bounds from LHC



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Summary

- Decoupling models are particularly appealing since they show little deviations from the standard model
- I have discussed an example of decoupling model inspired to an underlying DEWSB scenario
- Degenerate BESS not only has the decoupling property but the small deviations from the SM go in the direction which seems to be preferred by data
- The new spin 1 resonances predicted by the model will be easily detectable at Tevatron Run 2 and at LHC