Degenerate BESS

at future colliders

A decoupling model for Strong Electroweak Symmetry Breaking

Stefania De Curtis

I.N.F.N. Firenze, Italy

CERN, CLIC meeting,
October 5-6, 2000

Outline

- Motivations
- A decoupling model with vector and axial-vector resonances
- Bounds from present data
- Signals and bounds from LHC
- Indirect effects at TESLA
- A multi-TeV e^+e^- collider for studying the properties of the resonances
- Conclusions

Motivations for decoupling models

- SM survived LEP tests at the level of 0.1%
- This level of 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: $\mathcal{L}_{NP}(\Lambda_{NP}) \to \mathcal{L}_{SM}$ 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 ?

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 ($M_V \to \infty$)

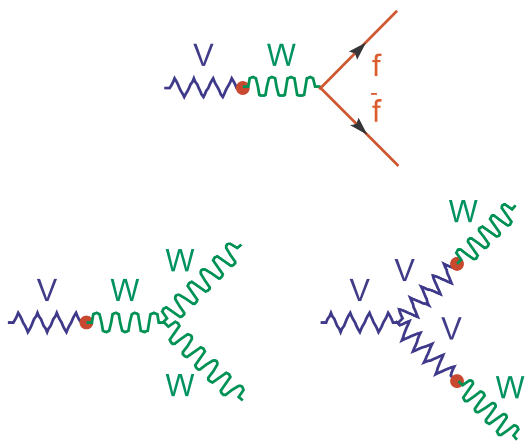
Consider for example:

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

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

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

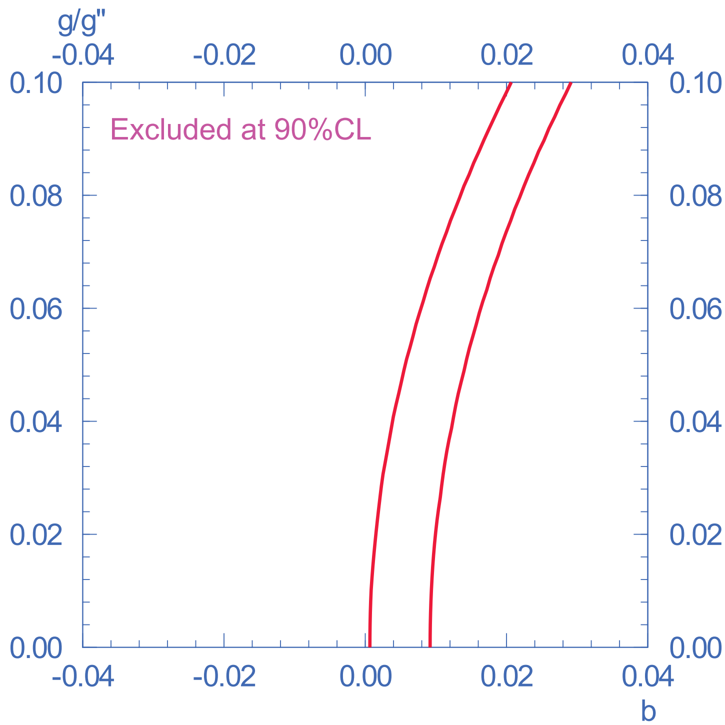
$$\epsilon_3 = \left[\left(\frac{g}{g''}\right)^2 - \frac{b}{2}\right]$$

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:

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

Peskin, Takeuchi (1990)

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

Assume vector meson dominance:

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

$g_{V(A)}$ 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 $g_A = g_V \quad M_A = M_V$ 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 several 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)

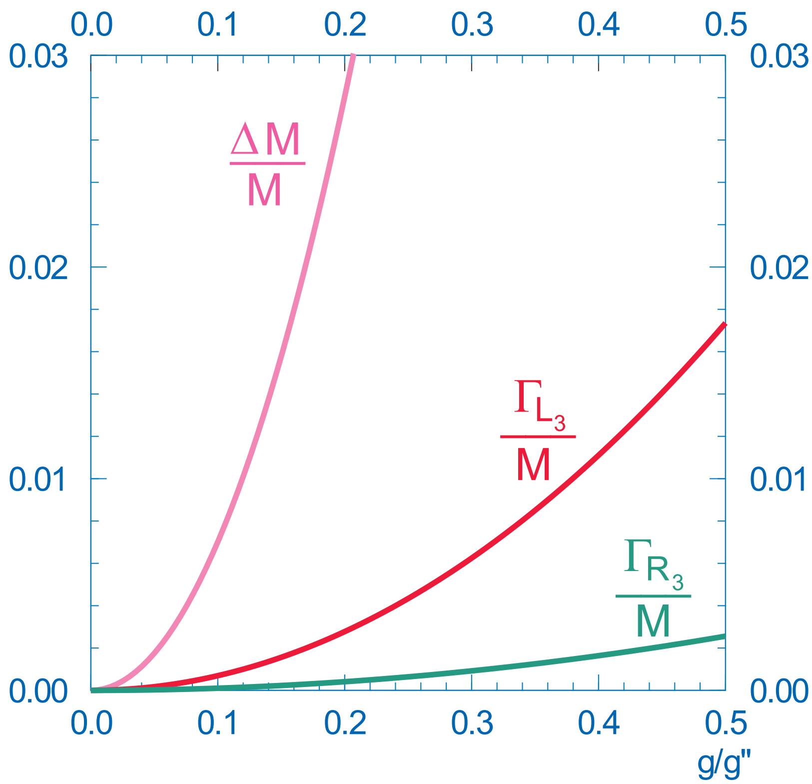
- DECOUPLING
  In the limit $M \to \infty$ one recovers the SM Lagrangian (for $M_H \to \infty$)

- $\mathbf{L}_\mu, \mathbf{R}_\mu$ 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

- 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.
  For ex. $Br(L_3(R_3) \to l^+l^-) \sim 4(12)\%$

- From decoupling: $\Gamma(f\bar{f}) \sim \Gamma(WW) \sim M M_W^4 (G_F/g'')^2$ $\to$ Very NARROW resonances. For ex. the total widths of the neutral resonances are (for $g/g'' \ll 1$):

$$\frac{\Gamma_{L_3}}{M} \sim 0.068 \left(\frac{g}{g''}\right)^2, \quad \frac{\Gamma_{R_3}}{M} \sim 0.01 \left(\frac{g}{g''}\right)^2, \quad \frac{\Gamma_{L_3}}{\Gamma_{R_3}} \sim 15\%$$



- The degeneracy between L_3 and R_3 is broken by weak corrections. The mass splitting is $(g/g'' \ll 1)$:

$$\frac{\Delta M}{M} \sim (1 - \tan^2\theta_W) \left(\frac{g}{g''}\right)^2 \sim 0.70 \left(\frac{g}{g''}\right)^2$$

Bounds from the ϵ-parameters fit

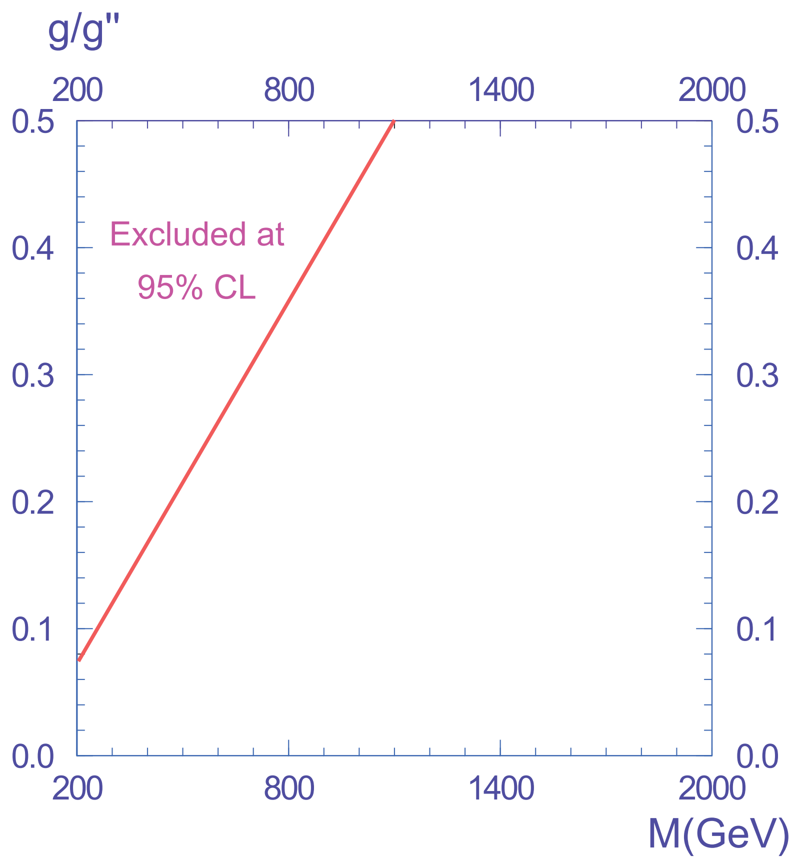
The D-BESS has very loose bounds from the existing experimental data: $\epsilon_i \to 0$ for $M \to \infty$
Calculation to the next-to-leading order:

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

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

double suppression factor

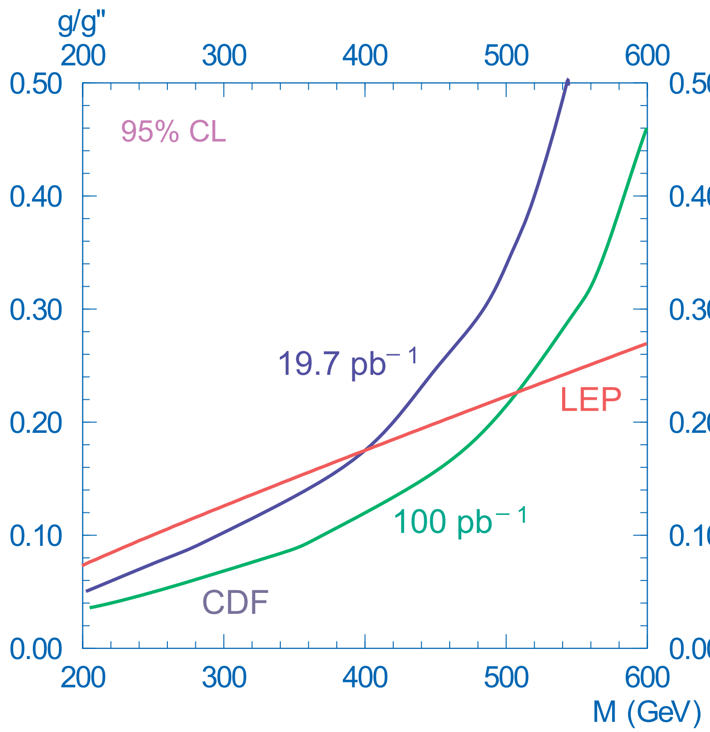
To compare to the experimental data consider for D-BESS the same radiative corrections of the SM with $m_H = \Lambda = 1\ TeV$ (neglect new physics loop corrections)



Experimental values from all High-Energy data fit:
$\epsilon_1 = (3.92 \pm 1.14) \times 10^{-3}$, $\epsilon_2 = (-9.27 \pm 1.49) \times 10^{-3}$,
$\epsilon_3 = (4.19 \pm 1.00) \times 10^{-3}$ (Altarelli (1999))

Bounds from CDF direct search of W'

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 lepton channel:

$$q\bar{q}' \rightarrow L^\pm, W^\pm \rightarrow (e\nu_e)\mu\nu_\mu$$
$$q\bar{q} \rightarrow L_3, R_3, Z, \gamma \rightarrow (e^+e^-)\mu^+\mu^-$$

In the charged channel only $L^\pm$ are relevant because $R^\pm$ are 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

Degenerate BESS at LHC

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

Casalbuoni,D.C.,Redi (2000)

Charged channel: $pp \to L^\pm, W^\pm \to e\nu_e(\mu\nu_\mu) + X$

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

Events simulated using PYTHIA MonteCarlo (6.136) and analyzed with CMSJET package which performs a simulation of the energy smearing of the CMS detector

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

BKGD Drell-Yan processes with SM gauge bosons exchange in the electron and muon channel (this is the relevant BKGD after isolation cuts on the outgoing leptons)

For each case we have selected cuts to maximize the statistical significance of the signal (cut on low p_T^l events, take m_T or $m_{l^+l^-}$ in a range containing the resonance)

The electron channel is experimentally much more convenient $\to$ the CMS detector has a better energy resolution (1%). The distributions are much more peaked around the resonances

The cleanest signature is in the neutral channel especially IF it is possible to disentangle the two resonances but the production rate is less favorable

Degenerate BESS at LHC

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

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

g/g''	M GeV	$\Gamma_{L^{\pm}}$ GeV	$\|p_T^e\|_c$ GeV	$\|m_T\|_c$ GeV	$\#B$	$\#S$	ss
0.10	1000	0.7	300	800	1468	2679	42
0.10	1500	1.0	500	1300	154	339	15
0.10	2000	1.4	700	1800	26	67	6.9

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

g/g''	M GeV	Γ_{L_3} GeV	Γ_{R_3} GeV	$\|p_T^e\|_c$ GeV	$\|m_{e^+e^-}\|_c$ GeV	$\#B$	$\#S$	ss
0.10	1000	0.7	0.10	300	800	590	375	12
0.20	1000	2.8	0.40	300	800	590	1342	31
0.10	1500	1.0	0.15	500	1300	58	46	4.5
0.20	1500	4.0	0.6	500	1300	58	189	12
0.10	2000	1.4	0.20	700	1800	9	9	2.1
0.20	2000	5.6	0.8	700	1800	9	43	6.0

Here $ss = S/\sqrt{S+B}$

DISCOVERY LIMIT $M \leq 2\ TeV$ for $g/g'' = 0.1$

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 GeV	$\Gamma_{L^{\pm}}$ GeV	$\lvert p_T^{\mu}\rvert_c$ GeV	$\lvert m_T\rvert_c$ GeV	$\#B$	$\#S$	ss
0.10	1000	0.7	300	800	1529	2876	43
0.10	1500	1.0	500	1300	166	422	17
0.10	2000	1.4	700	1800	31	92	8.3

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

g/g''	M GeV	Γ_{L_3} GeV	Γ_{R_3} GeV	$\lvert p_T^{\mu}\rvert_c$ GeV	$\lvert m_{\mu^+\mu^-}\rvert_c$ GeV	$\#B$	$\#S$	ss
0.10	1000	0.7	0.10	300	800	680	411	12
0.20	1000	2.8	0.40	300	800	680	1520	32
0.10	1500	1.0	0.15	500	1300	71	69	5.8
0.20	1500	4.0	0.6	500	1300	71	247	14
0.10	2000	1.4	0.20	700	1800	12	12	3.0
0.20	2000	5.6	0.8	700	1800	12	52	6.5

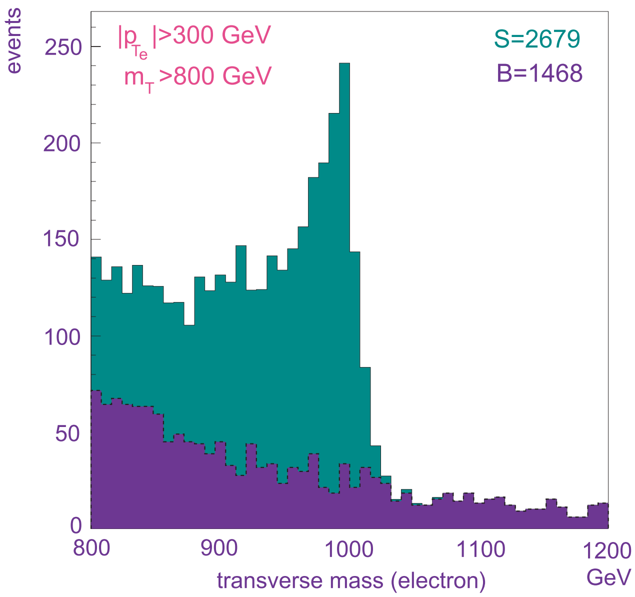
Here $ss = S/\sqrt{S+B}$

Signals of D-BESS at LHC

$\sqrt{s} = 14\ TeV \qquad L = 100\ fb^{-1}$

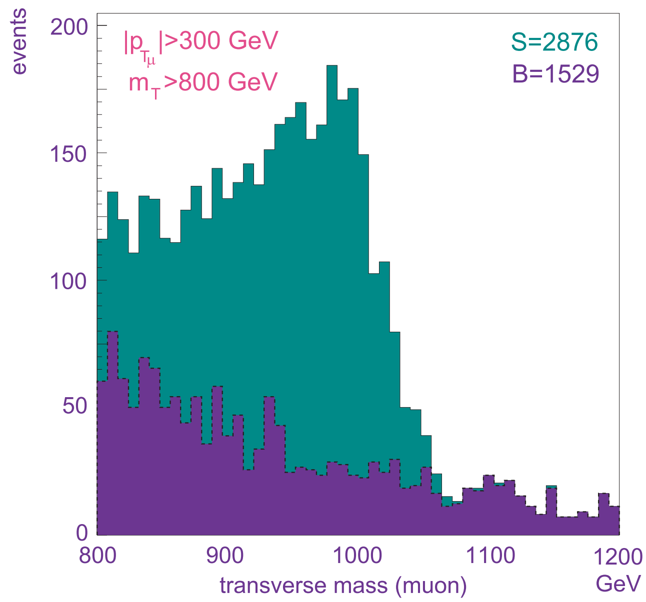
CHARGED CHANNEL

$pp \to L^{\pm}, W^{\pm} \to e\nu_e$



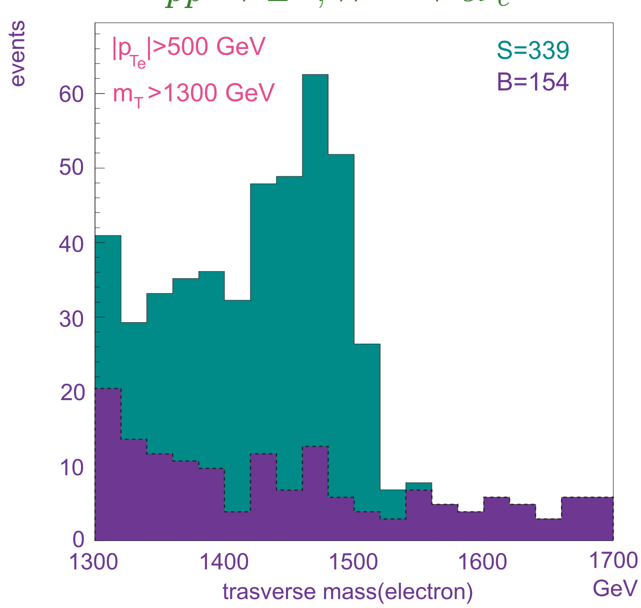
$M = 1000\ GeV \quad g/g'' = 0.1$

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



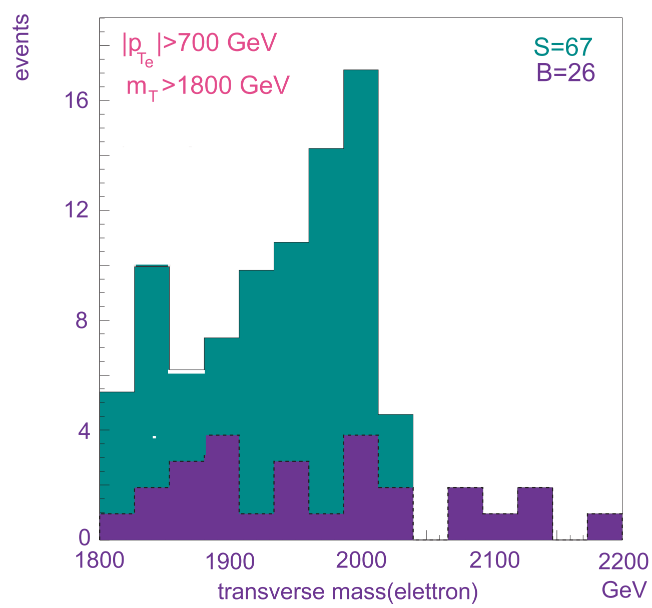
$M = 1000\ GeV \quad g/g'' = 0.1$

$pp \to L^{\pm}, W^{\pm} \to e\nu_e$



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

$pp \to L^{\pm}, W^{\pm} \to e\nu_e$



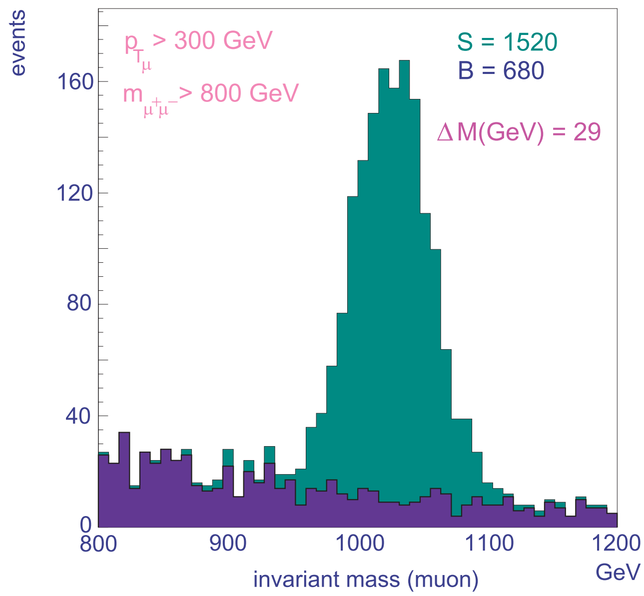
$M = 2000\ GeV \quad g/g'' = 0.1$

Signals of D-BESS at LHC

$\sqrt{s} = 14\ TeV \qquad L = 100\ fb^{-1}$

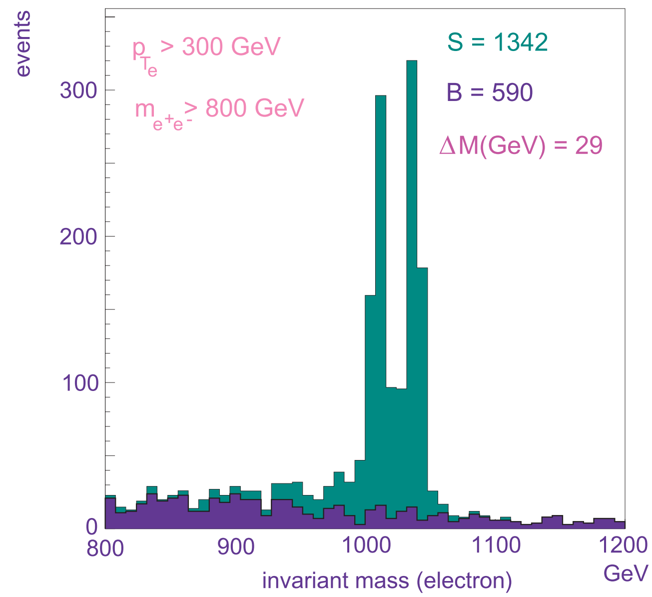
NEUTRAL CHANNEL

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



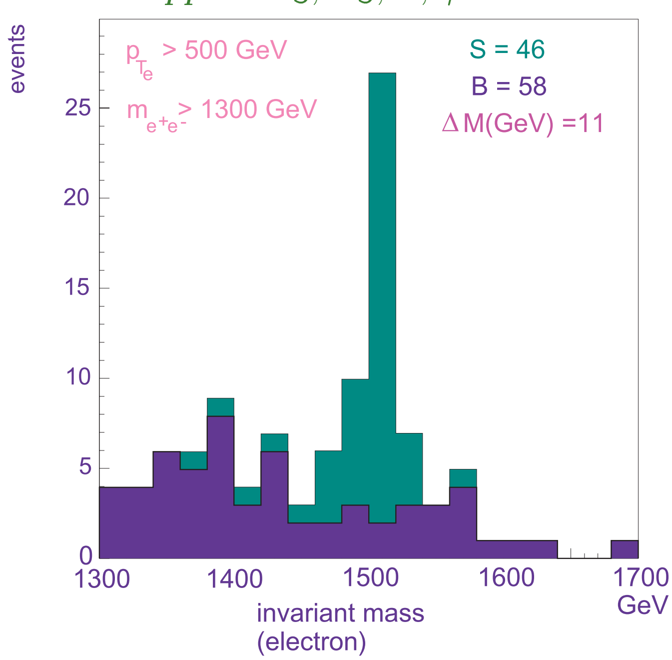
$M = 1000\ GeV \quad g/g'' = 0.2$

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



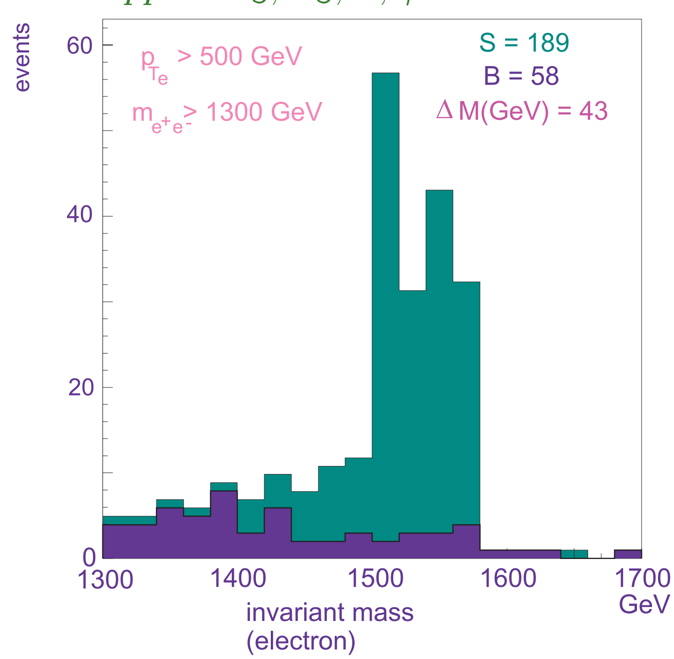
$M = 1000\ GeV \quad g/g'' = 0.2$

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



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

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

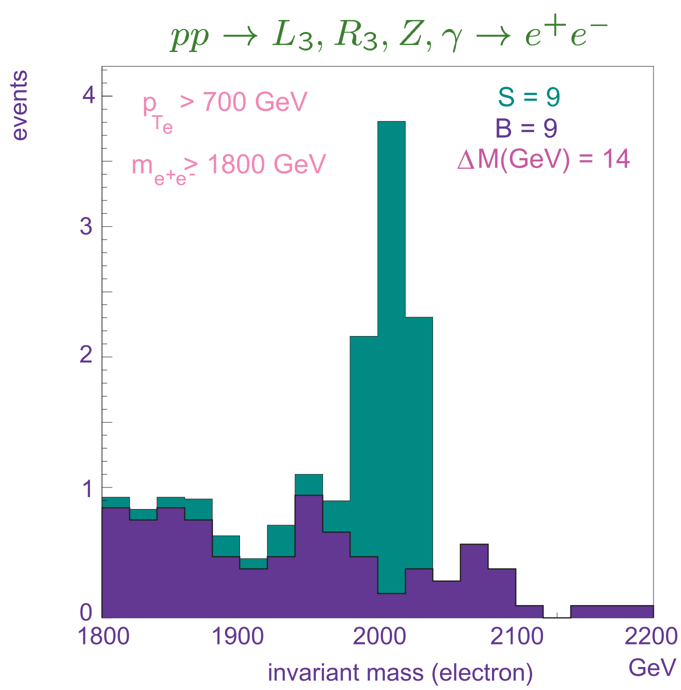


$M = 1500\ GeV \quad g/g'' = 0.2$

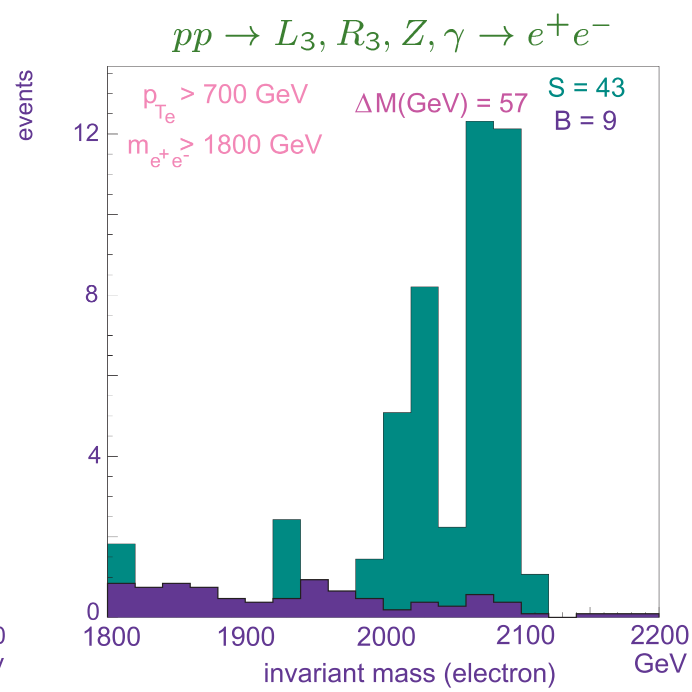
Signals of D-BESS at LHC

$\sqrt{s} = 14\ TeV \qquad L = 100\ fb^{-1}$

NEUTRAL CHANNEL



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



$M = 2000\ GeV \quad g/g'' = 0.2$

The possibility to disentangle the double peak depends strongly on g/g'' and smoothly on the mass (as long as a good statistical significance is achieved)

By comparing $R = 1\%$ with $\Delta M/M \sim (1 - \tan^2\theta_W)(g/g'')^2$ we find a threshold value $\boxed{g/g'' > 0.15 \text{ for } M \leq 2\ TeV}$

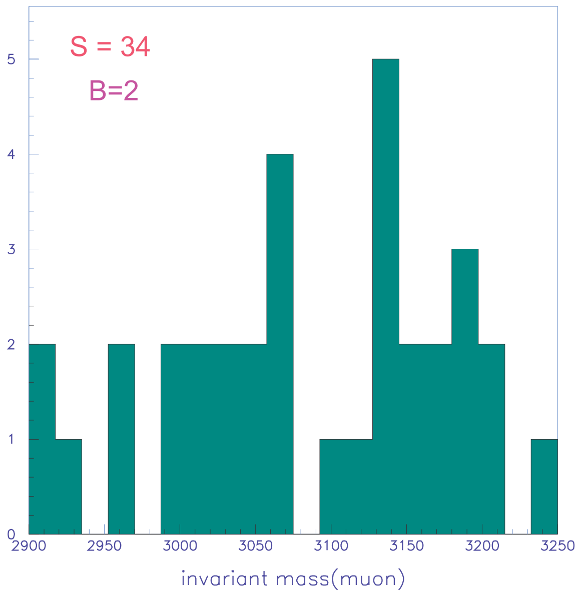
What about higher masses?

Signals of D-BESS at LHC (5 years with high luminosity)

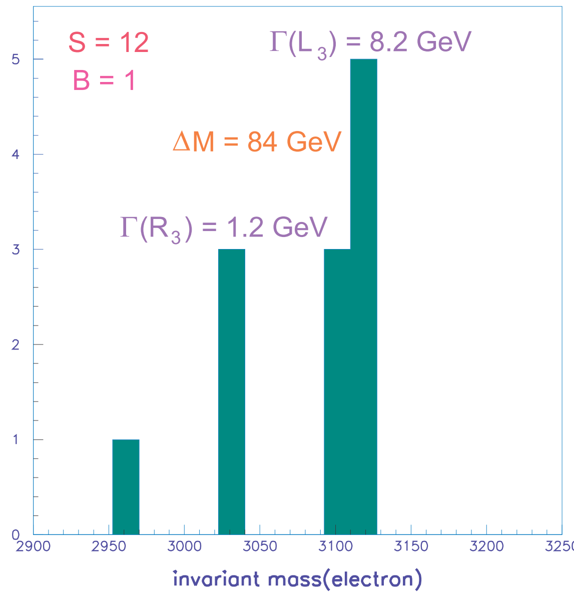
$\sqrt{s} = 14\ TeV \qquad L = 500\ fb^{-1}$

NEUTRAL CHANNEL $\boxed{M = 3\ TeV}$

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

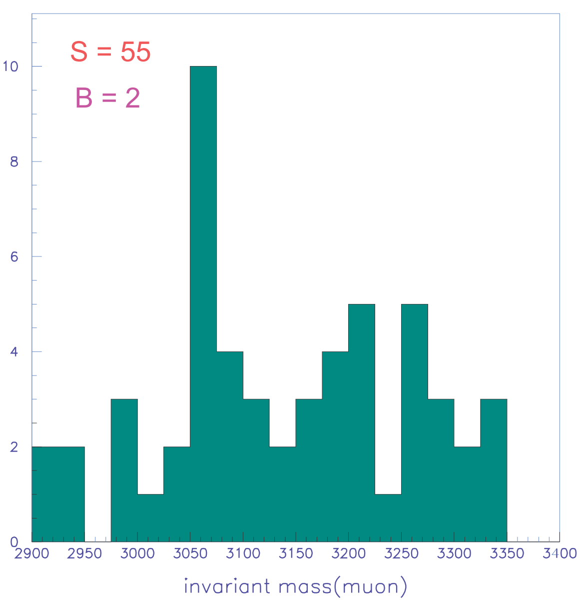


$pp \to L_3, R_3, Z, \gamma \to e^+e^-$

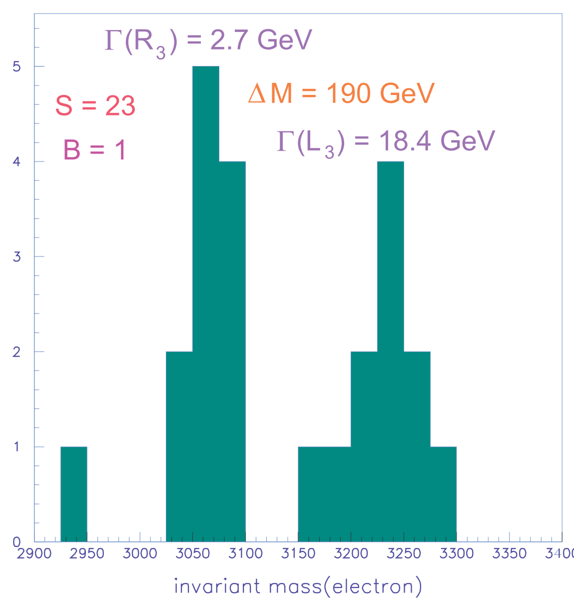


$g/g'' = 0.2, \qquad |p_T^l| > 700\ GeV, \qquad m_{l^+l^-} > 2900\ GeV$

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



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



$g/g'' = 0.3, \qquad |p_T^l| > 700\ GeV, \qquad m_{l^+l^-} > 2900\ GeV$

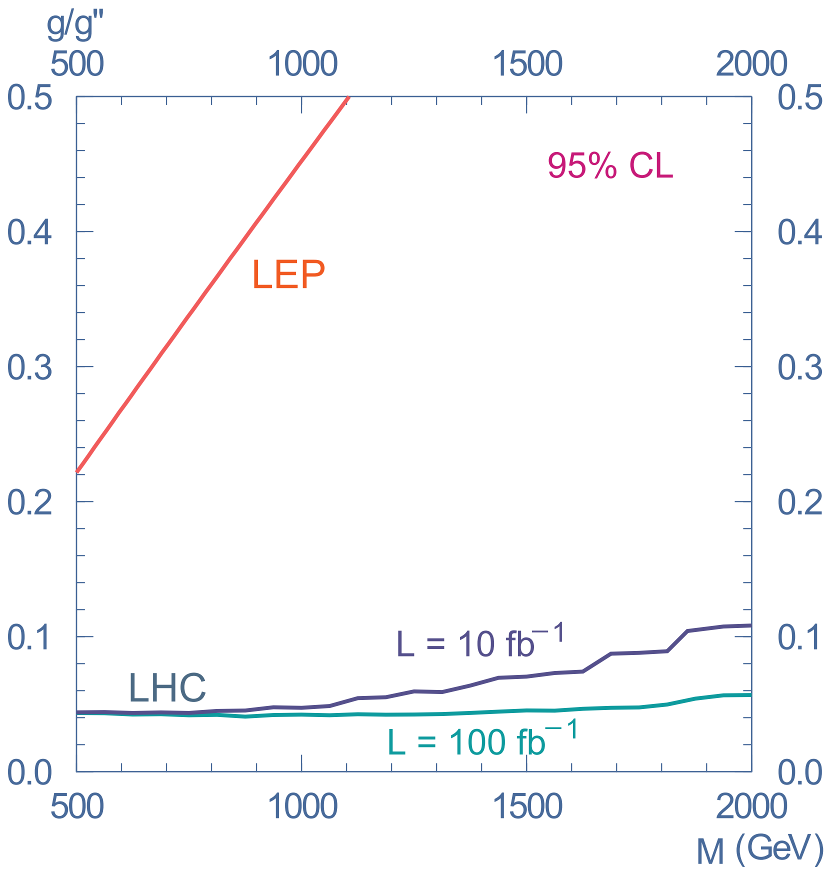
Bounds from LHC

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

Also shown are the bounds from LEP/SLC/Tevatron

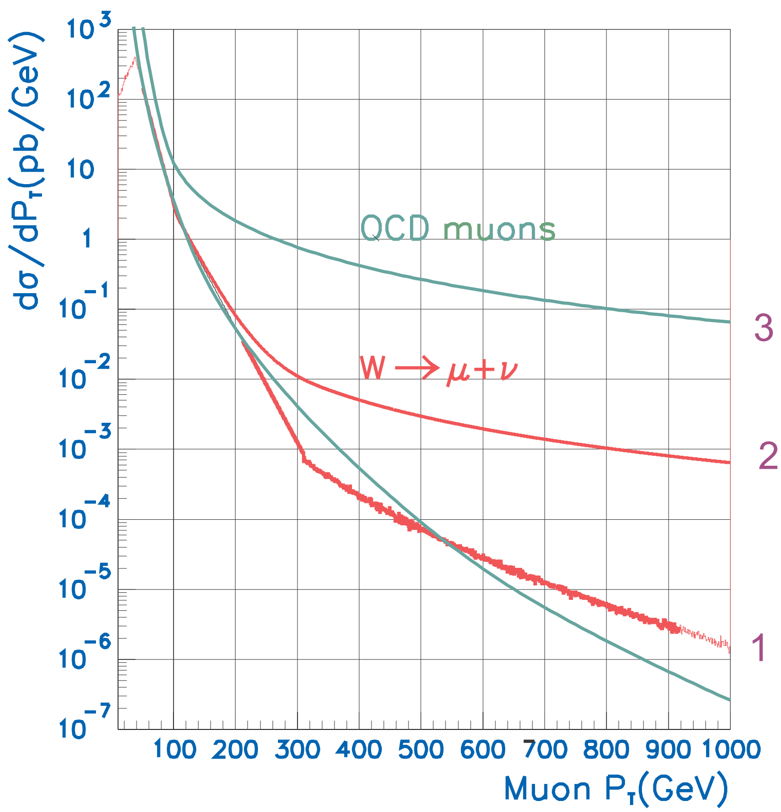
Muon reconstruction and BKGD suppression in CMS $pp \to L^{\pm}, W^{\pm} \to \mu\nu_{\mu} + X$

M.Spezziga thesis (2000)

Main BKGD's to $L^{\pm} \to \mu\nu_{\mu}$ are $W^{\pm} \to \mu\nu_{\mu}$ and QCD muons from $b\bar{b}$, $c\bar{c} \to \mu + X$

OPTIMISTIC SCENARIO good muon reconstruction for a wide p_T range; Gaussian smearing function $\to$ isolation cut can reduce the QCD BKGD to be three orders of magnitude lower than the irreducible $W^{\pm} \to \mu\nu_{\mu}$

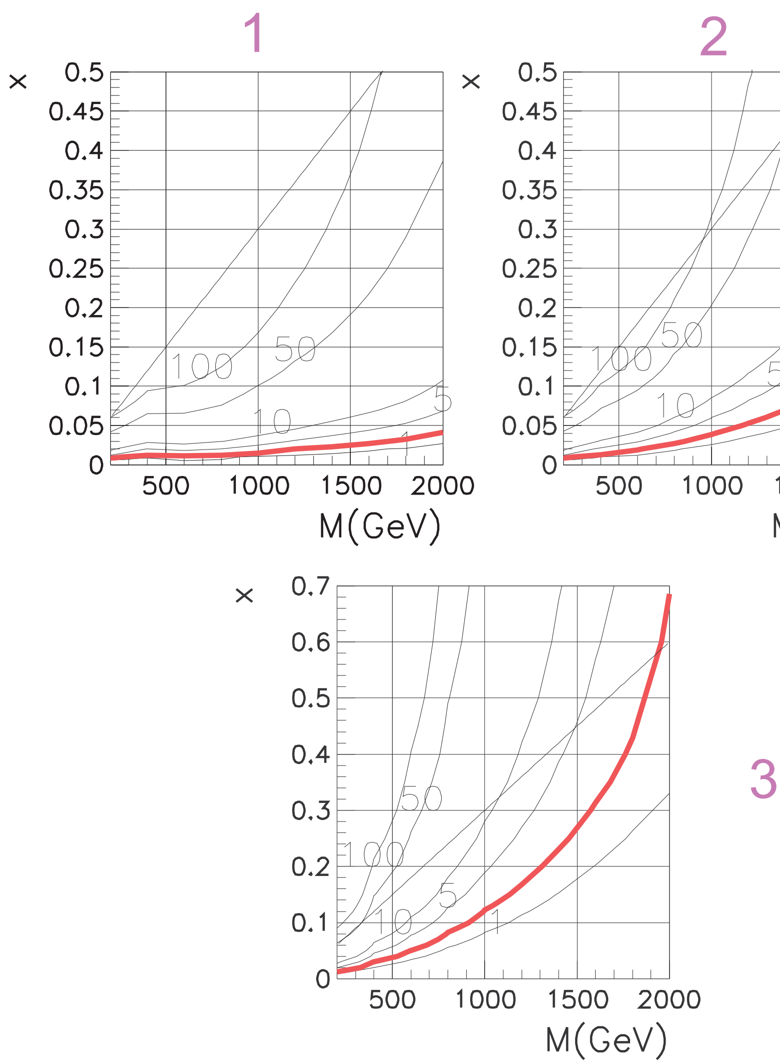
CONSERVATIVE SCENARIO the smearing function has larger tails in which the effect of badly reconstructed events is not negligible. The QCD BKGD rejection could be a problem



How do the limits on D-BESS change?

$\sqrt{s} = 14\ TeV \qquad L = 130\ fb^{-1}$

M.Spezziga thesis (2000)



Contour plots of $S/\sqrt{S+B}$. The red line corresponds to 90%CL ($S/\sqrt{S+B} = 2.15$)

1 - optimistic scenario → Gaussian smearing and QCD BKGD rejection

2 - conservative scenario → non Gaussian smearing and QCD BKGD rejection

3 - worst scenario → non Gaussian smearing and no QCD BKGD rejection

D-BESS at e^+e^- colliders

Casalbuoni,Deandrea,D.C.,Dominici,Gatto

In presence of new spin-one resonances the annihilation channel in $f\bar{f}$ and W^+W^- is much more efficient than the fusion channel.
In D-BESS, due to decoupling, L_3, R_3 are not strongly coupled to WW $\to$ the best channel for discovery is $f\bar{f}$

ASSUME a neutral resonance (hopefully two, nearly degenerate) with $M \leq 1\ TeV$ is seen at LHC $\to$ the first next generation of LC could measure widths and mass splitting depending on the beam energy spread (see later)

IF $M \geq 1\ TeV$ $\to$ wait for CLIC and study the indirect effects at TESLA in the cross-sections of

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

Analysis based on the following observables:

$$\sigma^\mu, \quad \sigma^h$$

$$A_{FB}^{e^+e^-\to\mu^+\mu^-}, \quad A_{FB}^{e^+e^-\to\bar{b}b}$$

$$A_{LR}^{e^+e^-\to\mu^+\mu^-}, \quad A_{LR}^{e^+e^-\to\bar{b}b}, \quad A_{LR}^{e^+e^-\to had}$$

We have assumed for σ^h (σ^μ) a total error of 2% (1.3%). For the other observable quantities we assumed only statistical errors.

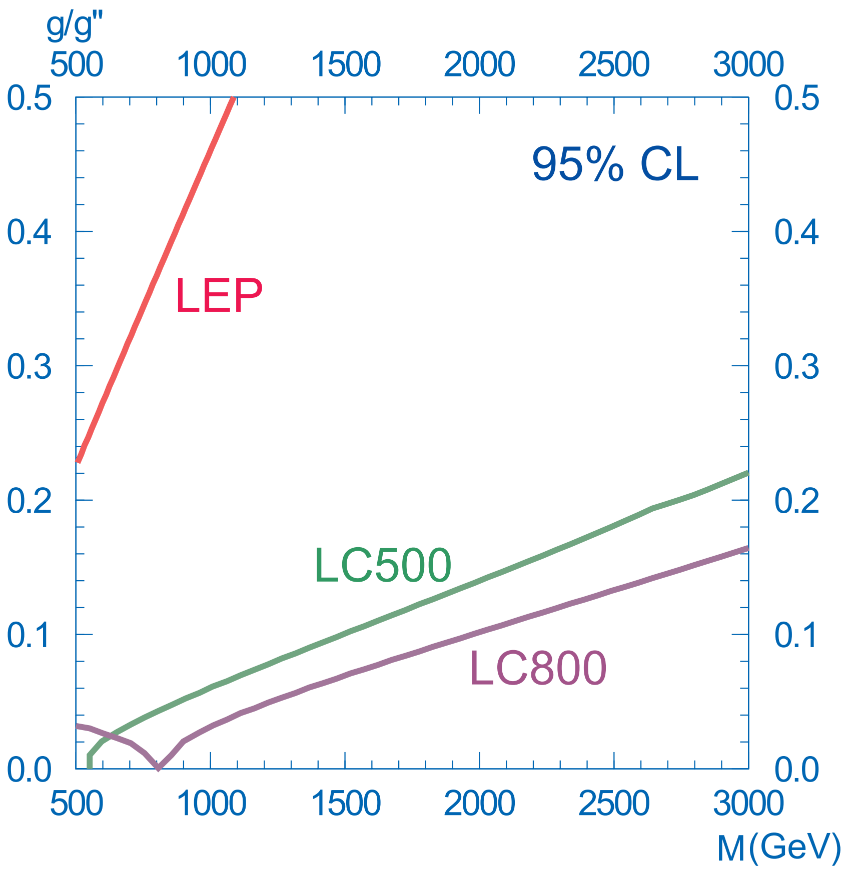
We have considered the following LC configurations:

LC500 : $\sqrt{s}(GeV) = 500$, $L(fb^{-1}) = 1000$

LC800 : $\sqrt{s}(GeV) = 800$, $L(fb^{-1}) = 1000$

with $P(e^{-}) = 80\%$

IF NO DEVIATIONS are seen within the statistical and systematic errors, a combined χ^2 analysis gives bounds the parameter space of D-BESS



Compare with the bounds from LHC (only studied for $M \leq 2\ TeV$):

optimistic scenario $\rightarrow$ LHC is superior for any g/g'', a LC with higher c.o.m. energy is needed to compete

conservative scenario$\rightarrow$ LHC and LC800 are comparable

worst scenario $\rightarrow$ LC500 is superior to LHC for any g/g''

Analysis of Narrow s-channel Resonances at Lepton Colliders

Casalbuoni, Deandrea, D.C., Dominici, Gatto, Gunion (1999)

If a resonance has been seen at LHC, especially if heavy, very little informations can be derived about its properties (also difficult to distinguish if it is a single one or two nearly degenerate) $\longrightarrow$ it can be studied at a high-energy lepton collider.

Main issues

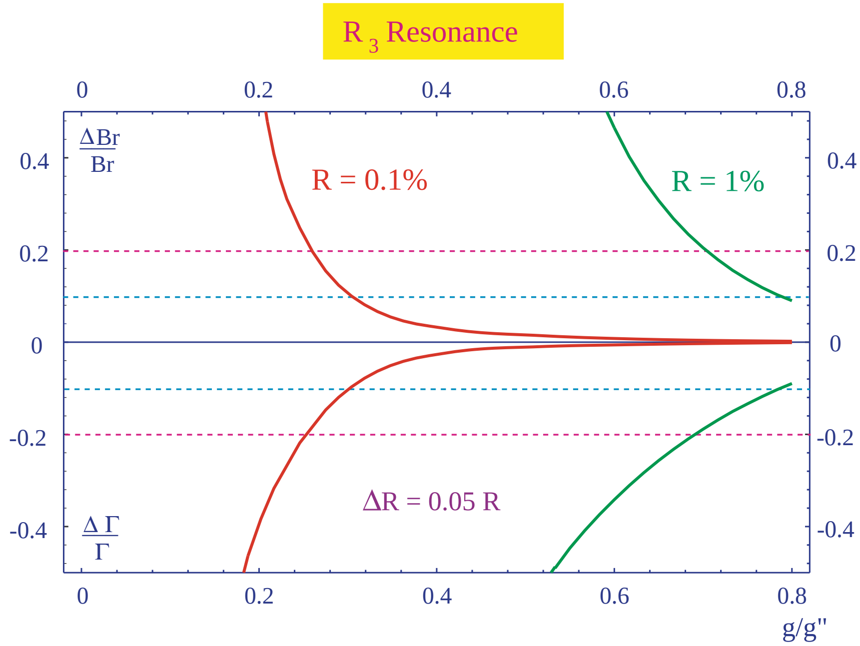
- the spread σ_E in the c.o.m. collision energy: intrinsic beam energy spread, ISR, beamstrahlung
- the uncertainty $\Delta\sigma_E/\sigma_E$ which may induce relatively large errors in the determination of the parameters of a resonance with $\Gamma \sim \sigma_E$

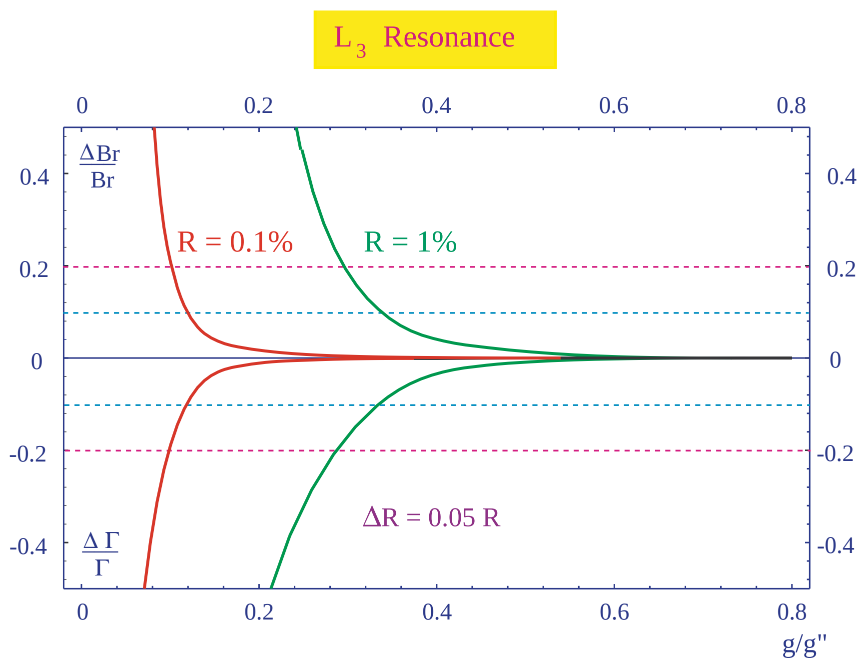
As a first step:
ASSUME to know exactly the beam energy
ASSUME a GAUSSIAN distribution energy peaked at the mass M of the resonance and characterized by

$$\sigma_M(GeV) \;=\; 0.007\; R(\%)\; M(GeV)$$

where R is the energy resolution of the collider
MAKE a convolution with a Breit-Wigner cross-section for the production of a vector resonance V
TAKE the narrow width limit
STUDY how an error on σ_M induces errors on Γ and $Br(V \to l^+l^-)$

Measuring Γ and Br with a given error leads to an observability region in the parameter space.
For example in D-BESS, for a given σ_M (for $\sigma_M \ll \Delta M$ the analysis can be applied for R_3 and L_3 separately) and for a given $\Delta\sigma_M/\sigma_M$ we get:





Ex: $\Delta R/R = 5\%$, $R = 1\%$ for L_3: $\Delta\Gamma/\Gamma < 20\%$ for $g/g'' > 0.3$ (from LEP bound: $M > 700\ GeV$)

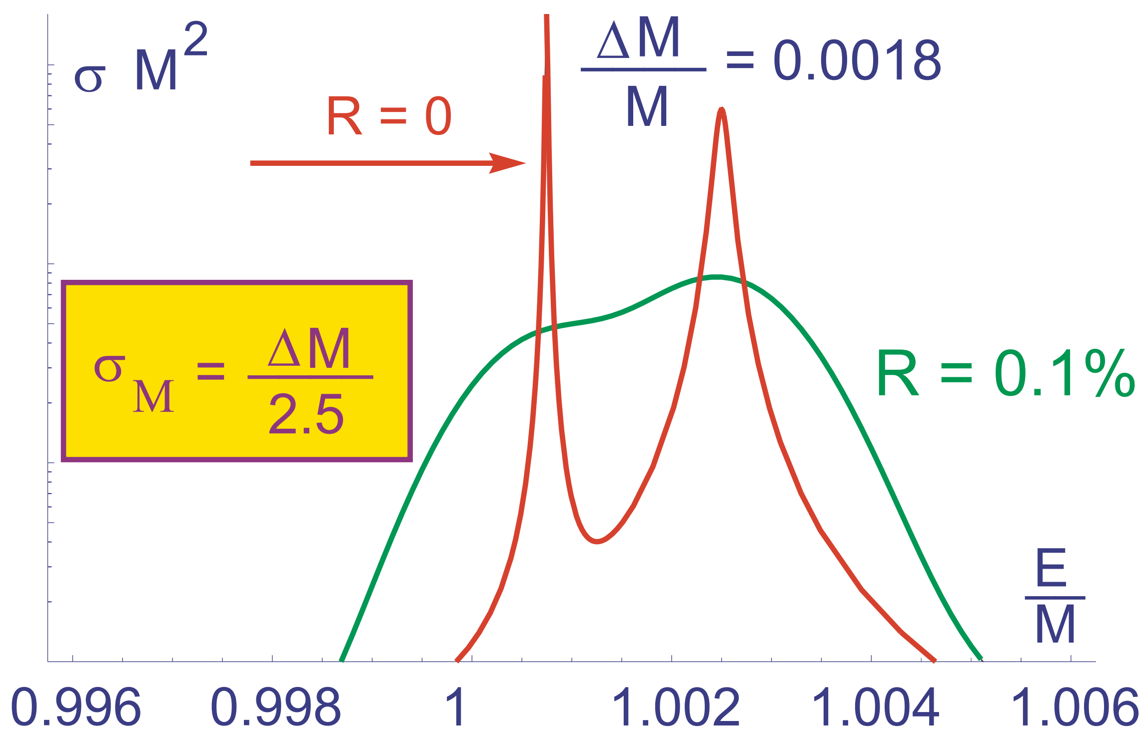
s-channel production of nearly degenerate resonances ($\sigma_M \approx \Delta M$)

To resolve two resonances one has to require that, from the convoluted cross section, one starts to detect the two peak structure .

In the narrow width limit ($\Gamma_1, \ \Gamma_2 \ll \Delta M, \ \sigma_M$) we get:

$$\sigma_M \le \frac{\Delta M}{2.5} \quad \text{or} \quad \frac{\Delta M}{M} \ge 0.0175 \ R(\%)$$

For example, in the D-BESS $\Gamma_{L_3}, \ \Gamma_{R_3} \ll \Delta M$ is verified. Take $g/g'' = 0.05$ (corresponding to $\Delta M/M = 0.0018$). The R_3, L_3 resonances can be resolved for $R \le 0.1\%$



Bounds on the D-BESS parameter space

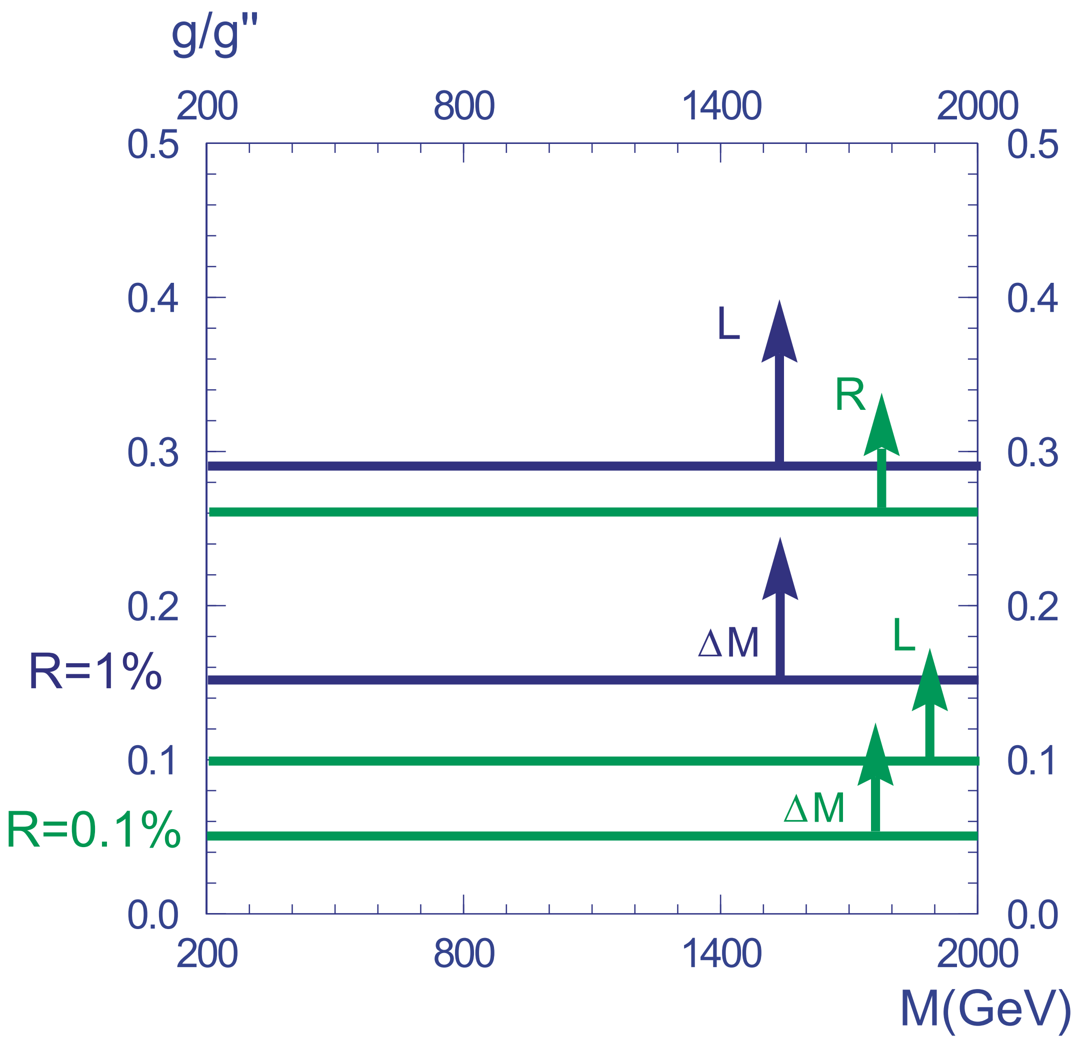
By requiring:

- $\Delta\Gamma_{L_3,R_3}/\Gamma_{L_3,R_3} \leq 20\%$

  (induced by $\Delta\sigma_M/\sigma_M = 5\%$)

- $\Delta M/M \geq 0.0175\ R(\%)$

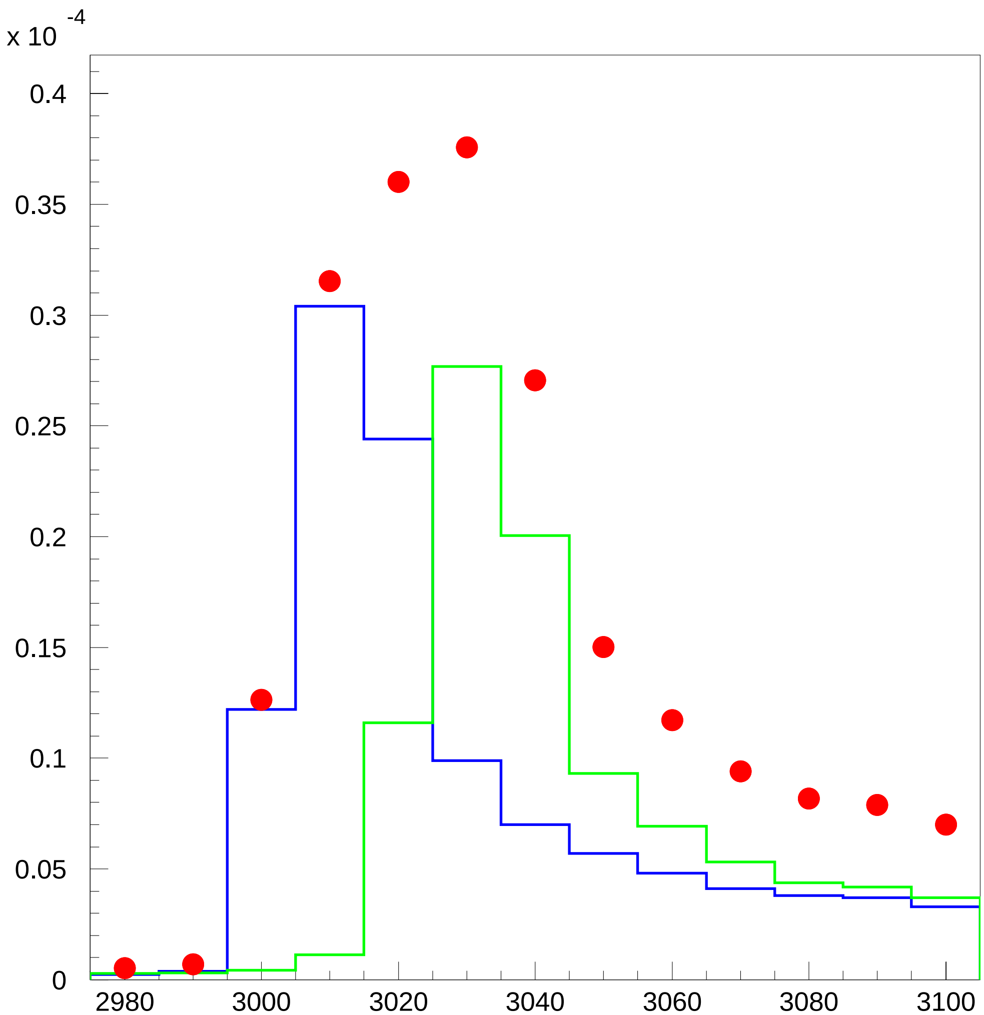
  (to detect the two peaks)



D-BESS at CLIC

Physics generator (PYTHIA 6) + CLIC Beam Energy Spectrum (ISR, Beam energy spread, beamstrahlung)

M.Battaglia

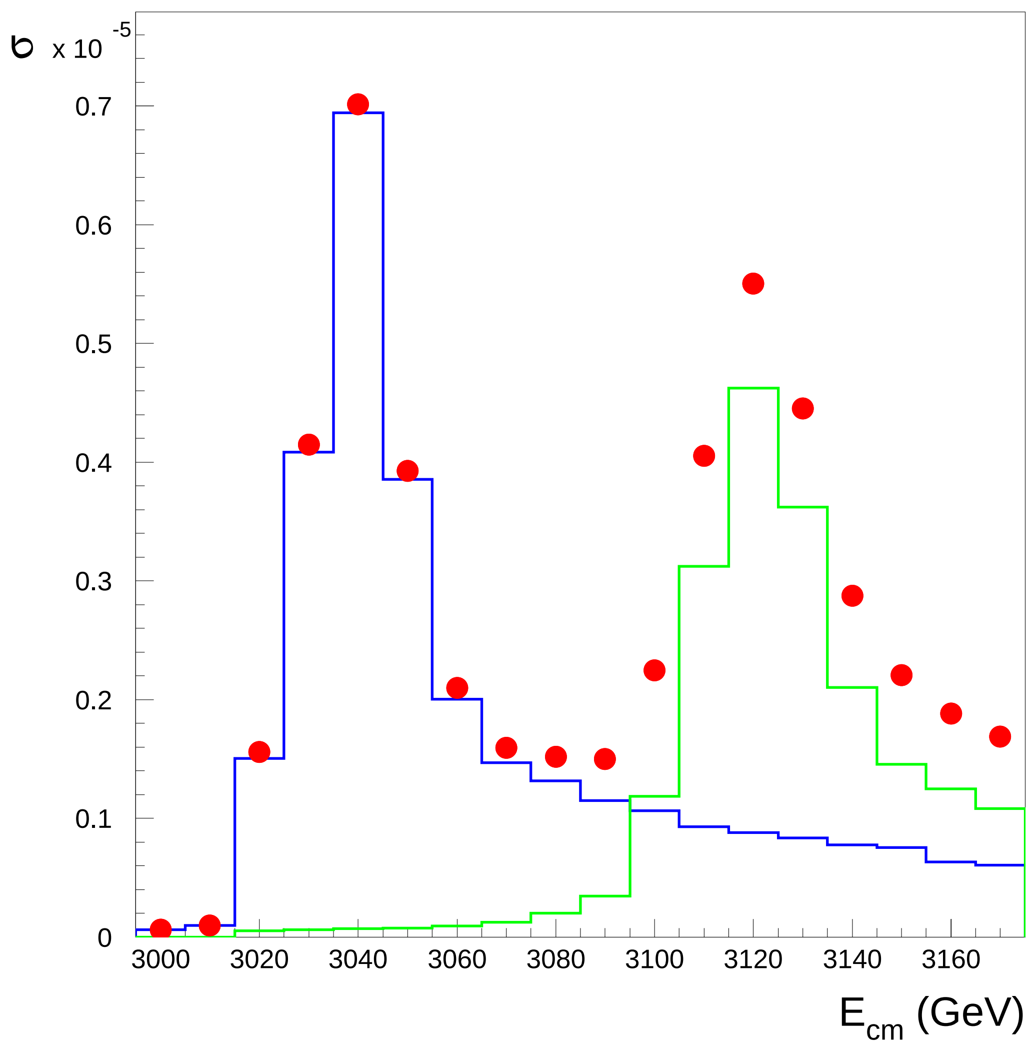


$M = 3\ TeV,\ g/g'' = 0.1,\ \Delta M = 21\ GeV$
$\Gamma_{R_3} = 300\ MeV,\ \Gamma_{L_3} = 2\ GeV$
$M_{R_3} = 3009\ GeV,\ M_{L_3} = 3030\ GeV$

D-BESS at CLIC

Physics generator (PYTHIA 6) + CLIC Beam Energy Spectrum (ISR, Beam energy spread, beamstrahlung)

M.Battaglia



$M = 3\ TeV,\ g/g'' = 0.2,\ \Delta M = 84\ GeV$

$\Gamma_{R_3} = 1.2\ GeV,\ \Gamma_{L_3} = 8.2\ GeV$

$M_{R_3} = 3035\ GeV,\ M_{L_3} = 3118\ GeV$

A heavy Z' or a degenerate pair L_3, R_3?

(additional informations)

T.Rizzo (1999)

A high energy lepton collider (like CLIC), sitting on the resonance peak, could distinguish a single resonance from a nearly degenerate pair by the line shape analysis or by factorization tests among EW observables

From the Z-pole studies at SLC and LEP $\rightarrow$ important tree-level factorization result $\boxed{A_{LR} A_{FB}^{pol}(f) = A_{FB}^f}$

It comes from $A_{FB}^{pol}(f) = 3/4\ A_f$, $A_{FB}^f = 3/4\ A_e A_f$, $A_{LR} = A_e$ with $A_f = 2 v_f a_f/(v_f^2 + a_f^2)$ and $v_f(a_f)$ the vector (axial-vector) coupling of the Z to fermions.

In general, these relations are no longer satisfied for two almost degenerate resonances (for ex. A_{LR} is flavor dependent). Define (Rizzo 1999)

$$T_2(f) = A_{LR}^f A_{FB}^{pol} / A_{FB}^f$$

For a single resonance $T_2 = 1$ at tree-level for any fermion channel

We have evaluated T_2 within the D-BESS model (in the small mixing limit the g/g'' dependence drops out)

$$\boxed{T_2(\mu) = 0.306, \quad T_2(b) = 0.127, \quad T_2(c) = 0.211}$$

The single resonance relations are numerically badly broken in the D-BESS model

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. The Degenerate BESS model is an example of dynamical EWSB scenario with decoupling

- D-BESS predicts new spin 1 resonances which could give well visible signals in the di-lepton channels at the LHC for $M \leq 2 \div 3\ TeV$

- The first next generation of linear e^+e^- colliders could put bounds on the parameter space of the model if the resonances are too heavy to be discovered

- If the mass of the resonances is in the multi-TeV range CLIC could to perform a detailed study of their properties, in particular, disentangle the two very narrow nearly degenerate neutral resonances, the distinctive feature of D-BESS