The BESS model revisited as a deconstructed Higgsless Model

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- Motivations for Higgsless models
- Example of breaking the EW symmetry without the Higgs (BESS)
- Linear moose: effective description for extra gauge bosons
- EWPT and Unitarity bounds reconciled by direct couplings to fermions
- The 4-site model, new vector and axial-vector resonances
- Drell-Yan processes @ the LHC and @ a LC (preliminary)

based on papers by: Casalbuoni, DC,Dolce, Dominici, Gatto
recent paper: Accomando, DC, Dominici, Fedeli, arXiv:0807.5051

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Problems of the Higgs sector

The evolution of the Higgs self-coupling (neglecting gauge fields and fermion contributions) shows up a **Landau pole**

$$\frac{1}{\lambda(M)} = \frac{1}{\lambda(m_H)} - \frac{3}{4\pi^2}\log\frac{M^2}{m_H^2}$$

$$M_{Lp} = m_H e^{4\pi^2 v^2/3m_H^2}$$

- or M_{Lp} pushed to infinity, but then λ goes to 0, triviality!
- or there is a physical cutoff at a scale $M < M_{Lp}$.

If the cutoff is big ($M \sim M_{Planck}$, or M_{GUT}), λ is small. The theory is perturbative, but the Higgs mass acquires big radiative corrections:

naturalness problem - to avoid it the quadratic divergence should cancel (SUSY)

$$\delta m_H^2 = \frac{\lambda}{8\pi^2} M^2$$

If we keep the cutoff of order of TeV, λ is large, m_H is O(TeV)
The theory is **non perturbative**

$$\boxed{\begin{array}{l} 1)\quad \lambda \ll 1 \Rightarrow \text{new particles lighter than 1 TeV} \\ 2)\quad \lambda \gg 1 \Rightarrow \text{new particles around 1 TeV} \end{array}}$$

In the following: **NEW STRONG PHYSICS at the TeV SCALE and NO HIGGS**

Symmetry Breaking without the Higgs

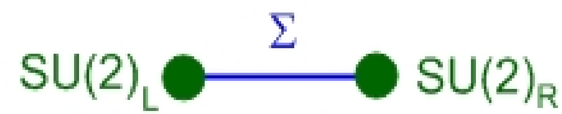
- A strongly interacting theory can only rely on an **effective description.** The SB sector is described at low energies by a general σ model of the type G/H

- For $SU(2)_L xSU(2)_R/SU(2)_V$ the σ model can be obtained as the formal limit M_H to infinity of the SM and is described in terms of a field Σ in SU(2)

$$\Sigma \to g_L \Sigma g_R^\dagger, \quad g_L \in SU(2)_L, \quad g_R \in SU(2)_R$$

- The strong dynamics is completely characterized by the transformation properties of the field Σ summarized in the **moose diagram**

$$L = \frac{v^2}{4}\left(\partial_\mu \Sigma \partial^\mu \Sigma^\dagger\right), \quad \Sigma = e^{i\vec{\pi}\cdot\vec{\tau}/v}, \langle\vec{\pi}\rangle = 0$$



- The breaking is produced by $\langle\Sigma\rangle = 1$

- Introduce covariant derivatives to **gauge the $SU(2)_L xU(1)_Y$**

$$D_\mu \Sigma = \partial_\mu \Sigma + igW_\mu \Sigma - ig'\Sigma Y_\mu$$

The interactions with W and Y are to be considered as **perturbations with respect to the strong dynamics** described by the σ model

- Due to **unitarity violation**, the validity of this description is up to

$$|a_0| = \frac{1}{16\pi}\frac{s}{v^2} \le 1 \;\Rightarrow\; E \le 4\sqrt{\pi}v \approx 1.7\ \text{TeV}$$

Enlarging the σ model

Enlarge the non-linear σ model by introducing **vector resonances.** One bonus is that unitarity properties improve (as it is known from QCD). To be consistent with the non-linear realization one uses the tool of **hidden gauge symmetries** (Bando,Kugo, et al 1985):

- Introduce a non-dynamical gauge symmetry together with a set of new scalar fields.
- The scalar fields can be eliminated by using the local symmetry and the theory is equivalent to the non linear σ–model.
- Promoting the local symmetry to be dynamical allows to introduce in a simple way vector resonances which are the gauge fields of the new gauge interaction.
- The new vector resonances are massive due to the breaking of the local symmetry implied by the non-linear realization.

To describe a non- linear theory breaking G to H, we do the following:

- **Introduce a mapping g(x) from the space-time to the group G:**

$$g(x) \in G$$

- **Contruct a lagrangian invariant under**

$$g(x) \to g'(x) = g_0 g(x) h(x), \; g_0 \in G, \; h(x) \in H, \; H \subset G$$

$$L(g, \partial_\mu g) = L(g', \partial_\mu g')$$

- **L depends only on the fields defined on the coset G/H. In fact, locally**

$$g(x) = \xi(x) h(x), \quad \xi \in G/H, \quad h \in H$$

and using the invariance of L:

$$L(g, \partial_\mu g) = L(\xi, \partial_\mu \xi), \quad g(x) \to g(x) h^{-1}(x)$$

The theory formulated in G with the (non-dynamical) local symmetry H is equivalent to the non-linear model formulated over G/H

The BESS model

The simplest enlargement of the non-linear model is the BESS (Breaking Electroweak Symmetry Strongly) model (Casalbuoni, DC, Dominici ,Gatto, 1985) based on $SU(2)_L xSU(2)_R/SU(2)$ with an additional local group G_1=SU(2)

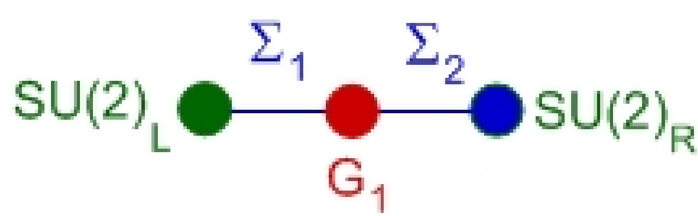
New vector resonances as the gauge fields of G_1

$$L = f_1^2 Tr\left[D_\mu \Sigma_1^\dagger D^\mu \Sigma_1\right] + f_2^2 Tr\left[D_\mu \Sigma_2^\dagger D^\mu \Sigma_2\right] - \frac{1}{2} Tr\left[F_{\mu\nu}(V) F^{\mu\nu}(V)\right]$$

$$(D_\mu \Sigma_1 = \partial_\mu \Sigma_1 + i g_1 \Sigma_1 V_\mu, \quad D_\mu \Sigma_2 = \partial_\mu \Sigma_2 - i g_1 V_\mu \Sigma_2)$$

This model describes 6 scalar fields and 3 gauge bosons.
After the breaking $SU(2)_L xSU(2)_R xSU(2)_{local} \rightarrow$ SU(2) , we get 3 Goldstone bosons (necessary to give mass to W and Z after gauging the EW group) and 3 massive vector bosons with mass

$$M_V^2=(f_1^2+f_2^2)g_1^2$$ **(g_1=gauge coupling of V)**



3-site model

Notice that in L we have inserted only terms corresponding to the two links. There is another invariant coupling of the type

$$\mathrm{Tr}\left[(\Sigma_1^\dagger D_\mu \Sigma_1)(\Sigma_2 D^\mu \Sigma_2^\dagger)\right]$$

which was considered in the original **BESS model** (1985).

In fact, the most general Lagrangian, symmetric under $G_{global} \otimes H_{local}$

$$G_{global} = SU(2)_L \otimes SU(2)_R \quad \text{and} \quad H_{local} = SU(2)_V$$

and under parity transformation, with at most two derivatives, can be constructed as the combination of two invariant terms:

$$f_1 = f_2$$

$$\omega_\mu^{\parallel} = \frac{1}{2}(L^\dagger \partial_\mu L + R^\dagger \partial_\mu R)$$

$$\omega_\mu^{\perp} = \frac{1}{2}(L^\dagger \partial_\mu L - R^\dagger \partial_\mu R)$$

$$(L = \Sigma_1, R = \Sigma_2)$$

Assuming the gauge bosons of the hidden symmetry become dynamical:

$$\mathcal{L}_{\text{BESS}} = -v^2\left[\mathrm{tr}(\omega_\mu^{\perp})^2 + \alpha\, \mathrm{tr}(\omega_\mu^{\parallel} - \mathbf{V}_\mu)^2\right] + \frac{2}{g''^2}\mathrm{tr}[F^{\mu\nu}(\mathbf{V})F_{\mu\nu}(\mathbf{V})]$$

The 3-site model corresponds to $\alpha = 1$, $g'' = 2g_1$

Linear Moose Model: Breaking the EW symmetry without Higgs Fields

- **Generalize the moose construction: many copies of the gauge group G intertwined by link variables Σ**

- **Simplest example: G_i = SU(2). Each Σ_i describes 3 scalar fields.**

- **The model has two global symmetries related to the beginning and to the end of the moose, $G_L = SU(2)_L$ and $G_R = SU(2)_R$ which can be gauged to the standard $SU(2)_L x U(1)_Y$**

- **Particle content: 3 massive gauge bosons, W and Z, the massless photon and 3K massive vectors. $SU(2)_{diag}$ is a custodial symmetry**

- **The BESS model can be recast in a 3-site model (K=1), and its V-A generalization (Casalbuoni, DC, Dominici, Gatto, Feruglio, 1989) can be recast in a 4-site model (K=2) (see also Foadi,Frandsen,Ryttov,Sannino, 2007)**

The transformation properties of the fields are

$$\Sigma_1 \to L\Sigma_1 U_1^\dagger,$$
$$\Sigma_i \to U_{i-1}\Sigma_i U_i^\dagger\ , \qquad i = 2, \cdots, K,$$
$$\Sigma_{K+1} \to U_K \Sigma_{K+1} R^\dagger,$$

$$U_i \in G_i \equiv SU(2)_i \qquad A_\mu^i = A_\mu^{ia}\tau^a/2, \quad g_i, \quad i = 1, 2, \cdots, K,$$
$$L \in G_L \equiv SU(2)_L \qquad \tilde{W}_\mu = \tilde{W}_\mu^a \tau^a/2, \quad \tilde{g},$$
$$R \in G_R \equiv SU(2)_R \supset U(1)_Y \qquad \tilde{Y}_\mu = \tilde{\mathcal{Y}}_\mu \tau^3/2, \quad \tilde{g}'$$

$$\boxed{\mathcal{L} = \sum_{i=1}^{K+1} f_i^2 \mathrm{Tr}[D_\mu \Sigma_i^\dagger D^\mu \Sigma_i] - \frac{1}{2}\sum_{i=1}^{K} \mathrm{Tr}[(F_{\mu\nu}^i)^2] - \frac{1}{2}\mathrm{Tr}[(F_{\mu\nu}(\tilde{W}))^2] - \frac{1}{2}\mathrm{Tr}[(F_{\mu\nu}(\tilde{Y}))^2]}$$

Covariant derivatives

$$D_\mu \Sigma_1 = \partial_\mu \Sigma_1 - i\tilde{g}\tilde{W}_\mu \Sigma_1 + i\Sigma_1 g_1 A_\mu^1,$$
$$D_\mu \Sigma_i = \partial_\mu \Sigma_i - i g_{i-1} A_\mu^{i-1}\Sigma_i + i\Sigma_i g_i A_\mu^i, \qquad i = 2, \cdots, K,$$
$$D_\mu \Sigma_{K+1} = \partial_\mu \Sigma_{K+1} - i g_K A_\mu^K \Sigma_{K+1} + i\tilde{g}'\Sigma_{K+1}\tilde{Y}_\mu$$

$$\mathcal{L}_{\text{mass}} = \frac{1}{2}\sum_{i,j=0}^{K+1}(M_2)_{ij}A^i_\mu A^{\mu j}$$

with $A^0_\mu = \tilde{W}^\mu$, $A^{K+1}_\mu = \tilde{Y}^\mu$, and

$$(M_2)_{ij} = g_i^2(f_i^2 + f_{i+1}^2)\delta_{i,j} - g_i g_{i+1} f_{i+1}^2 \delta_{i,j-1} - g_j g_{j+1} f_{j+1}^2 \delta_{i,j+1}$$

where $g_0 = \tilde{g}$, $g_{K+1} = \tilde{g}'$, $f_0 = f_{K+2} = 0$

$$\mathbf{M}_2 = \begin{bmatrix} \tilde{g}^2 f_1^2 & -\tilde{g} g_1 f_1^2 & & & & \\ -\tilde{g} g_1 f_1^2 & g_1^2(f_1^2+f_2^2) & -g_1 g_2 f_2^2 & & & \\ & -g_1 g_2 f_2^2 & g_2^2(f_2^2+f_3^2) & & & \\ & & & \ddots & & \\ & & & & g_K^2(f_K^2+f_{K+1}^2) & -\tilde{g}' g_K f_{K+1}^2 \\ & & & & -\tilde{g}' g_K f_{K+1}^2 & \tilde{g}'^2 f_{K+1}^2 \end{bmatrix}$$

Besides the massless photon, the lowest eigenvalues (at the leading order in $O((\tilde{g}/g_i)^2)$) are: $\tilde{M}_W^2 = v^2/(4\tilde{g}^2)$, $\quad \tilde{M}_Z^2 = \tilde{M}_W^2/\tilde{c}_\theta^2$, where we have identified $\tan\tilde{\theta} = \tilde{g}/\tilde{g}'$ and

$$\frac{4}{v^2} \equiv \frac{1}{f^2} = \sum_{i=1}^{K+1}\frac{1}{f_i{}^2} \qquad v = \text{EW scale} = 246\ \text{GeV}$$

+ a tower of K states with mass scale set by $g_i f_i$

The continuum limit

- The moose picture for large values of K can be interpreted as the discretization of a continuum gauge theory in 5D along a fifth dimension. The continuum limit is defined by

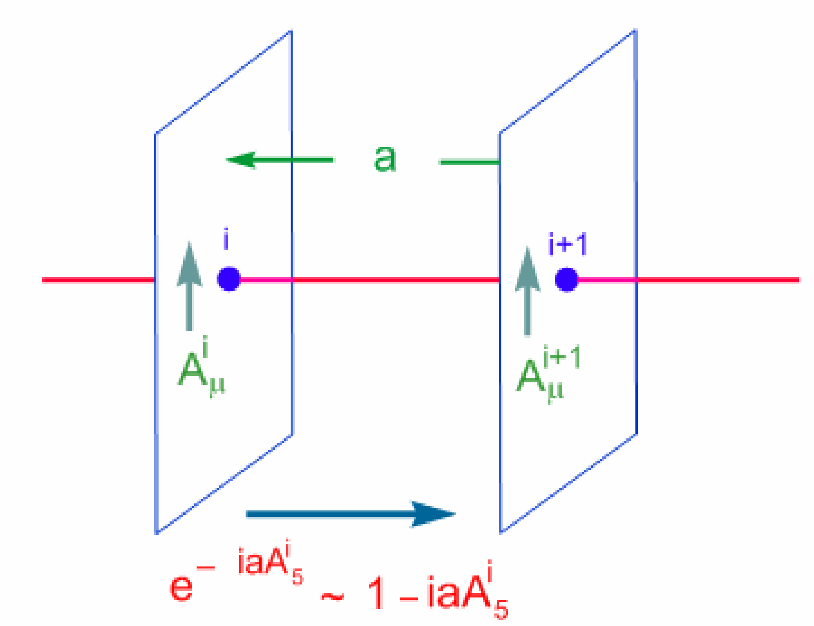
$$K \to \infty, \quad a \to 0, \quad Ka \to \pi R$$

$$\lim_{a\to 0} a g_i^2 = g_5^2, \quad \lim_{a\to 0} a f_i^2 = f^2(z)$$

a = lattice spacing, R= compactification radius, g_5= bulk gauge coupling

- The link couplings f_i and the gauge couplings g_i can be simulated in the continuum by non-flat 5-dim metrics.
- Flat metric corresponds to equal f's and g's
- In the continuum limit, the structure of the moose has an interpretation in terms of a **geometrical Higgs mechanism** in a pure 5D gauge theory.

- A gauge field is a connection: a way of relating the phases of the fields at nearby points. After discretizing the 5th dim the field A_5 is naturally substituted by a **link variable** realizing the parallel transport between two lattice sites (A_μ^i = KK modes)



$$\Sigma_i \approx 1 - iaA^i{}_5 \approx e^{-iaA^i{}_5}$$

$$\Sigma\Sigma^\dagger = 1$$

$$D_\mu \Sigma_i = -iaF^{i-1}_{\mu 5}$$

$$F^i_{\mu 5} = \partial_\mu A^i_5 - \partial_5 A^i_\mu - i[A^i_\mu, A^i_5]$$

- The action for the deconstructed gauge theory is (Hill, Pokorski, Wang; Arkani-Hamed, Cohen, Georgi, 2001)

$$S = \int d^4x \frac{a}{g_5^2}\left(-\frac{1}{2}\sum_i \mathrm{Tr}\left[F^i_{\mu\nu}F^{\mu\nu i}\right] + \frac{1}{a^2}\mathrm{Tr}\left[(D_\mu\Sigma_i)(D_\mu\Sigma_i)^\dagger\right]\right), \quad A^i_\mu = \mathrm{KK\ modes}$$

- Sintetically described by a moose diagram (Georgi, 1986)

Can the linear moose considered so far, be derived by discretizing a SU(2) gauge theory in 5D compactified on an interval?

To describe the moose structure including the breaking, one needs kinetic terms on the branes plus BC's. In the case of a conformally flat metrics along the fifth direction, the complete action for a SU(2)-moose would be

$$S = -\frac{1}{4}\int d^4x \int_0^{\pi R} dz\, e^{-A(z)} \frac{1}{g_5^2(z)}\left[(F^a_{\mu\nu})^2 - 2(F^a_{\mu 5})^2\right] +$$

$$-\frac{1}{4}\int d^4x \int_0^{\pi R} dz\, e^{-A(z)} \left[\frac{1}{\tilde{g}^2}(F^a_{\mu\nu})^2 \delta(z) + \frac{1}{\tilde{g}'^2}(F^3_{\mu\nu})^2 \delta(z-\pi R)\right]$$

$$\text{BC's}: \quad A^{1,2}_\mu \Big|_{z=\pi R} = 0, \quad \partial_z A^a_\mu \Big|_{z=0} = 0$$

- **Introducing the link variables** $\Sigma_i = e^{-iaA^i_5}$, $\quad$ **i = 1, ... , K + 1**

$$S_{moose} = \int d^4x \left(-\sum_{i=1}^{K} \frac{1}{2g_i^2} \mathrm{Tr}\left[F^i_{\mu\nu} F^{\mu\nu i}\right] + \sum_{i=1}^{K+1} f_i^2 \mathrm{Tr}\left[(D_\mu \Sigma_i)(D_\mu \Sigma_i)^\dagger\right] \right)$$

$$a e^{-A_i} / g_{5i}^2 = 1/g_i^2, \quad e^{-A_i}/(a g_{5i}^2) = f_i^2$$

$$A^1_\mu = W_\mu{}^a \tau_a / 2, \quad A^{K+1}_\mu = Y^\mu \tau_3 / 2$$

FLAT METRIC:

$$f_i = f_c, \quad g_i = g_c, \quad e^{-A_i} = 1, \quad g_{5i}^2 = a g_c^2$$

BUT ALSO….. The linear moose with K=2 and parity invariance is a particular vector axial-vector resonance model

(for ex. Casalbuoni, DC, Dominici, Gatto, Feruglio, 1989)

The symmetry group is $[SU(2)_L \otimes SU(2)_R]_{global} \otimes [SU(2)_L \otimes SU(2)_R]_{local}$
broken to the diagonal subgroup $SU(2)_D$

The 9 GBs can be described by 3 independent 2x2 matrices, L,M,R transforming according to: $\mathbf{L} \in (\frac{1}{2}, 0, \frac{1}{2}, 0);\ \mathbf{M} \in (0, 0\frac{1}{2}, \frac{1}{2});\ \mathbf{R} \in (0, \frac{1}{2}, 0, \frac{1}{2})$

The most general invariant Lagrangian, up to second order derivatives is

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

where

$$\begin{aligned} I_1 &= tr[(V_0 - V_1 - V_2)^2] \\ I_2 &= tr[(V_0 + V_2)^2] \\ I_3 &= tr[(V_0 - V_2)^2] \\ I_4 &= tr[V_1^2] \end{aligned}$$

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

$$\begin{aligned} D_\mu L &= \partial_\mu L - L\mathbf{L}_\mu \\ D_\mu R &= \partial_\mu R - R\mathbf{R}_\mu \\ D_\mu M &= \partial_\mu M - M\mathbf{L}_\mu + \mathbf{R}_\mu M \end{aligned}$$

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

gauge fields of the local group

Correspondence with the K=2 linear moose or 4-site model	$\mathbf{A}^\mu{}_1 = (\mathbf{L}^\mu + \mathbf{R}^\mu)/2, \quad \mathbf{A}^\mu{}_2 = (\mathbf{R}^\mu - \mathbf{L}^\mu)/2$ $a_1 = 0, a_2 = a_3 = 2f_1^2/v^2, a_4 = 4f_2^2/v^2, g'' = g_1\sqrt{2}$

see also the *composite* model by Barbieri, Isidori, Rychkov, Trincherini, 2008

Unitarity bounds for the Linear Moose

(Chivukula, He; Papucci; Muck, Nilse, Pilaftis, Ruckl; Csaki, Grojean, Murayama, Pilo, Terning)

- Spin-one resonances generally delay the perturbative unitarity bound

- The worst high-energy behaviour comes from the scattering of longitudinal vector bosons. For s >> M^2_W the amplitude can be evaluated using the Equivalence Theorem (Cornwall, Levin, Tiktopoulos, 1974; Vayonakis, 1976; Lee,Quigg,Thacker, 1977):

- Introduce the GB's $\Sigma_i = e^{i f \vec{\pi}\cdot\vec{\tau}/2 f_i^2}$ and evaluate the effective lagrangian for the pions and the heavy vectors. The 4-pion amplitude is

$$A_{\pi^+\pi^-\to\pi^+\pi^-} = -\frac{f^4}{4}\sum_{i=1}^{K+1}\frac{u}{f_i^6} + \frac{f^4}{4}\sum_{i,j=1}^{K} L_{ij}\left((u-t)(s-M_2)^{-1}_{ij} + (u-s)(t-M_2)^{-1}_{ij}\right)$$

$$L_{ij} = g_i g_j (1/f_i^2 + 1/f_{i+1}^2)(1/f_j^2 + 1/f_{j+1}^2)$$

- In the high-energy limit

$$A_{\pi^+\pi^-\to\pi^+\pi^-} = -\frac{f^4}{4}\sum_{i=1}^{K+1}\frac{1}{f_i^6}u$$

The unitarity limit is determined by the smallest link coupling.

By taking: $f_i = f_c \rightarrow A = -\frac{u}{(K+1)^2 v^2}$

$$\boxed{\Lambda_{moose} = (K+1)\Lambda_{HSM} \sim 1.7\ (K+1)\mathrm{TeV}}$$

- **By taking into account all the vector bosons and using the Equivalence Theorem, the amplitudes for the Goldstones are given by:**

$$\left(\Sigma_i = e^{i\vec{\pi}_i\cdot\vec{\tau}/2f_i}\right) \qquad A_{\pi_i^+\pi_i^-\to\pi_i^+\pi_i^-} \to -\frac{u}{4f_i^2}$$

- **The unitarity limit is determined by the smallest link coupling. By taking them all equal (see also Chivukula, He, 2002)**

Best unitarity limit

$$\mathbf{f_i = f_c \to A \to -\frac{u}{(K+1)v^2}}$$

$$\Lambda_{moose} = (K+1)^{1/2}\Lambda_{HSM} \sim 1.7\,(K+1)^{1/2}\,\mathrm{TeV}$$

$$M_V^{max} < \Lambda_{moose},\ \text{but roughly}:\ M_V^{max} \approx 2\sqrt{K+1}\,\frac{g_c}{g}M_W$$

$$\Downarrow$$

$$2\sqrt{K+1}\,\frac{g_c}{g}M_W < 1.7\sqrt{K+1}\,\mathrm{TeV} \Rightarrow \frac{g_c}{g} < 10$$

Hardly compatible with electro-weak experimental constraints

Constraints from EW data

- Assuming universality among different generations, the EW corrections are coded in 3 parameters ε_i, i=1,2,3 (Altarelli, Barbieri, 1991), or S,T,U (Peskin, Takeuchi, 1990).

- To the lowest order the new physics contribution to ε_1 and ε_2 vanishes due to the SU(2) custodial symmetry of the SB sector. At the same order ε_3 has a dispersive representation (for oblique corrections). Neglecting loop corrections (for loop see Dawson et al, Chivukula et al, Barbieri et al):

$$\varepsilon_3 = \frac{g^2}{4}\sum_{\mathbf{i}}\left(\frac{g_{iV}^2}{m_{\mathbf{i}}^4} - \frac{g_{iA}^2}{m_{\mathbf{i}}^4}\right) = g^2\sum_{i=1}^{K}\frac{(1-y_i)y_i}{g_i^2} \qquad \left(y_i = \sum_{j=1}^{i}\frac{f^2}{f_{\mathbf{j}}^2}, \quad \frac{1}{f^2} = \sum_{i=1}^{K+1}\frac{1}{f_i^2}\right)$$

- Since $\boxed{0 \leq y_i \leq 1 \quad \Rightarrow \quad \varepsilon_3 \geq 0}$

- Example: $f_i = f_c, \quad g_i = g_c \quad \Rightarrow \quad \varepsilon_3 = \frac{1}{6}\frac{g^2}{g_c^2}\frac{K(K+2)}{K+1}$

- $\epsilon_3^{exp} \sim 10^{-3}$, for K=1, g_c~(16 g)~10, for large K, g_c~10$\sqrt{K}$ $\longrightarrow$ strongly interacting gauge bosons, UNITARITY VIOLATION

in the continuum limit: $(Ka \Rightarrow \pi R, \quad a g_i^2 \Rightarrow g_5^2)$

$$\varepsilon_3 = \frac{1}{6}\frac{g^2}{g_c^2}\frac{K(K+2)}{K} \sim \frac{1}{6}\frac{g^2}{a g_c^2} aK \Rightarrow \frac{1}{6}\frac{g^2}{g_5^2}\pi R = \frac{1}{12}\frac{g^2}{g_4^2} \qquad \left(\frac{1}{g_5^2} = \frac{1}{2\pi R g_4^2}\right)$$

A 5D theory has a natural cutoff. According to NDA the loop factors grow with energy and perturbativity breaks down at $\Lambda_5 = \frac{24\pi^3}{g_5^2} = \frac{12\pi^2}{R g_4^2}$

By using $\frac{1}{R} > m_W = \frac{g\Lambda_{HSM}}{8\sqrt{\pi}}$ **we get:** $\Lambda_5 > \frac{3\pi}{2}\frac{g}{g_4^2}\sqrt{\pi}\Lambda_{HSM} \approx 10\frac{g}{g_4^2}\Lambda_{HSM}$

The 5D cutoff can be related to the lattice spacing: $a = \frac{1}{\Lambda_5} \Rightarrow K \sim \pi R \Lambda_5$

then, the unitarity cut-off will be: $\Lambda_{moose} \sim \sqrt{\pi R \Lambda_c}\,\Lambda_{HSM} = \frac{\sqrt{12\pi^3}}{g_4}\Lambda_{HSM} \approx \frac{20}{g_4}\Lambda_{HSM}$

The cutoff is the smaller between Λ_5 and Λ_{moose}

- **We could increase the cut-off of the theory within a perturbative context ($g_4 \sim g$), but this would be unacceptable for the EWPT. On the contrary, if we want to satisfy the EWPT bounds we need $g_4 \sim 10\ g$, making the cutoff of the order of Λ_{HSM}.**

- **Introducing fermions in the bulk one gets a negative contribution to ε_3 (Contino, Pomarol; Panico, Serone, Wulzer; Foadi, Schmidt). With the help of some fine-tuning one can satisfy both EWPT and unitarity bounds**

Direct fermionic couplings

(Casalbuoni, DC, Dolce, Dominici; Chivukula, Simmons, He, Kurachi)

- Left- and right-handed fermions, $\psi_{L\,(R)}$ are coupled to the ends of the moose, but they can couple to any site by using a Wilson line

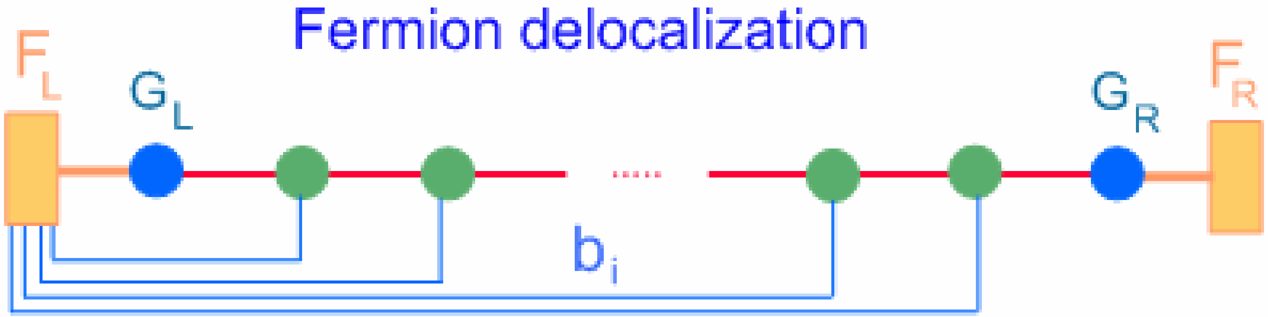
$$\chi_L^i = \Sigma_i^\dagger \Sigma_{i-1}^\dagger \cdots \Sigma_1^\dagger \psi_L, \qquad \chi_L^i \to U_i \chi_L^i$$

$$\Downarrow$$

$$b_i \bar{\chi}_L^i \gamma^\mu \left(\partial_\mu + i g_i V_\mu^i + \frac{i}{2} g'(B-L) Y_\mu \right) \chi_L^i$$

no delocalization of the right-handed fermions.

Small terms $O(10^{-3})$ since they could contribute to right-handed currents constrained by non-leptonic K- decays and $b \to s\gamma$ processes



In the unitary gauge ($\Sigma_i \equiv I$) and after a rescaling $\psi_L \to \frac{1}{\sqrt{1+\sum_i b_i}} \psi_L$:

$$\mathcal{L}^{tot}_{fermions} = \bar{\psi}_R i \gamma^\mu \left[\partial_\mu + i\tilde{g}' \frac{\tau^3}{2} \tilde{\mathcal{Y}}_\mu + \frac{i}{2} \tilde{g}' (B-L) \tilde{\mathcal{Y}}_\mu \right] \psi_R$$

$$+ \bar{\psi}_L i \gamma^\mu \left[\partial_\mu + \frac{1}{1+\sum_{i=1}^K b_i} \left(i\tilde{g}\tilde{W}_\mu + i \sum_{i=1}^K b_i g_i A^i_\mu \right) + \frac{i}{2} \tilde{g}' (B-L) \tilde{\mathcal{Y}}_\mu \right] \psi_L$$

correction to the SM gauge boson couplings

new couplings of the extra gauge bosons ~ $b_i\, g_i$

How can we get b_i from a 5D bulk?

(Foadi,Gopalakrishna,Schmidt; Csaki,Hubitsz,Meade; Bechi,Casalbuoni, DC, Dominici)

Consider fermions propagating in the warped 5D bulk with additional brane kinetic terms + BC's: $\psi_R|_0 = 0$, $\psi_L|_{\pi R} = 0$

$$S_{ferm.} = \int d^4x \int_0^{\pi R} dz \Big[e^{-4A(z)} [(\frac{i}{2}\bar{\psi}\Gamma^M D_M \psi + h.c.)] - e^{-A(z)} M \bar{\psi}$$

$$+ e^{-4A(0)} \frac{\delta(z)}{\hat{t}_L^2} i\bar{\psi}_L \gamma^\mu D_\mu \psi_L + \; e^{-4A(\pi R)} \delta(\pi R - z) i\bar{\psi}_R (\frac{1}{\hat{t}_R^2}) \gamma^\mu D_\mu \psi_R \Big]$$

where $D_M \psi = (\partial_M + iT^a A^a_M(z) + iY_L A^3_M(\pi R))\psi$ and $\hat{t}_{L,R}$ set the weight of the brane kinetic terms with respect to the bulk one.

• DISCRETIZE the fifth dimension $\longrightarrow$ the fermions on the j-site with $j = 0, .., K+1$, with a mass term $m_j = (aM_j + 1)/a$, $j = 1, .., K$, "hop" from one site to the near one due to ∂_z.

• Study the effects of ψ_i $(i = 1, .., K)$ in the low-energy limit that is neglect kinetic terms with respect to mass terms. DECOUPLE the heavy fermions with the solutions of their e.o.m. (consider only the quadratic interactions among fermions)

$$\alpha_j L_j - m_{j+1} L_{j+1} = 0, \qquad j = 0, .., K-1$$
$$\alpha_j R_{j+1} - m_j R_j = 0, \qquad j = 1, .., K$$

where $L_j = \psi_L^j$ e $R_j = \psi_R^j$ $(j = 1, .., K)$, L_0 and R_{K+1} are, up to mixing corrections, the left and right components of the SM fermions, and $\alpha_0 = \hat{t}_L/\sqrt{a}$, $\alpha_j = 1/a$ $(j = 1, .., K-1)$, $\alpha_K = \hat{t}_R/\sqrt{a}$, are the "hopping" strengths.

- **PLUG** the solutions in the gauge-fermion interaction, get direct SM fermion couplings to A_μ^i + SM fermion mass term (normalized fields):

$$S^b_{ferm} = \int d^4x \sum_{j=1}^{K} \frac{b_j^L}{1+\sum_{i=1}^K b_i^L} i\bar{L}_0 \gamma^\mu (\partial_\mu + i g_j T^a A_\mu^{aj} + i\tilde{g}' Y_L A_\mu^{K+1}) L_0$$
$$+ \sum_{j=1}^{K} \frac{b_j^R}{1+\sum_{i=1}^K b_i^R} \; i\bar{R}_{K+1} \gamma^\mu (\partial_\mu + i g_j T^3 A_\mu^{3j} + i\tilde{g}' Y_L A_\mu^{K+1}) R_{K+1}$$
$$+ \sum_{j=1}^{K} \frac{b_j^R}{1+\sum_{i=1}^K b_i^R} \frac{g_j}{\sqrt{2}} (\bar{R}_{K+1} \gamma^\mu A_\mu^{+j} R_{K+1} + h.c.) - m^f (\bar{L}_0^f R_{K+1}^f + h.c.)$$

with $b_j^L = (\frac{\alpha_0}{m_j} \prod_{i=1}^{j-1} \frac{\alpha_i}{m_i})^2 \geqslant 0$, $\quad b_j^R = (\frac{\alpha_K}{m_K} \prod_{i=j}^{K-1} \frac{\alpha_i}{m_i})^2 \geqslant 0$ $\quad (\alpha_K \ll \alpha_0)$

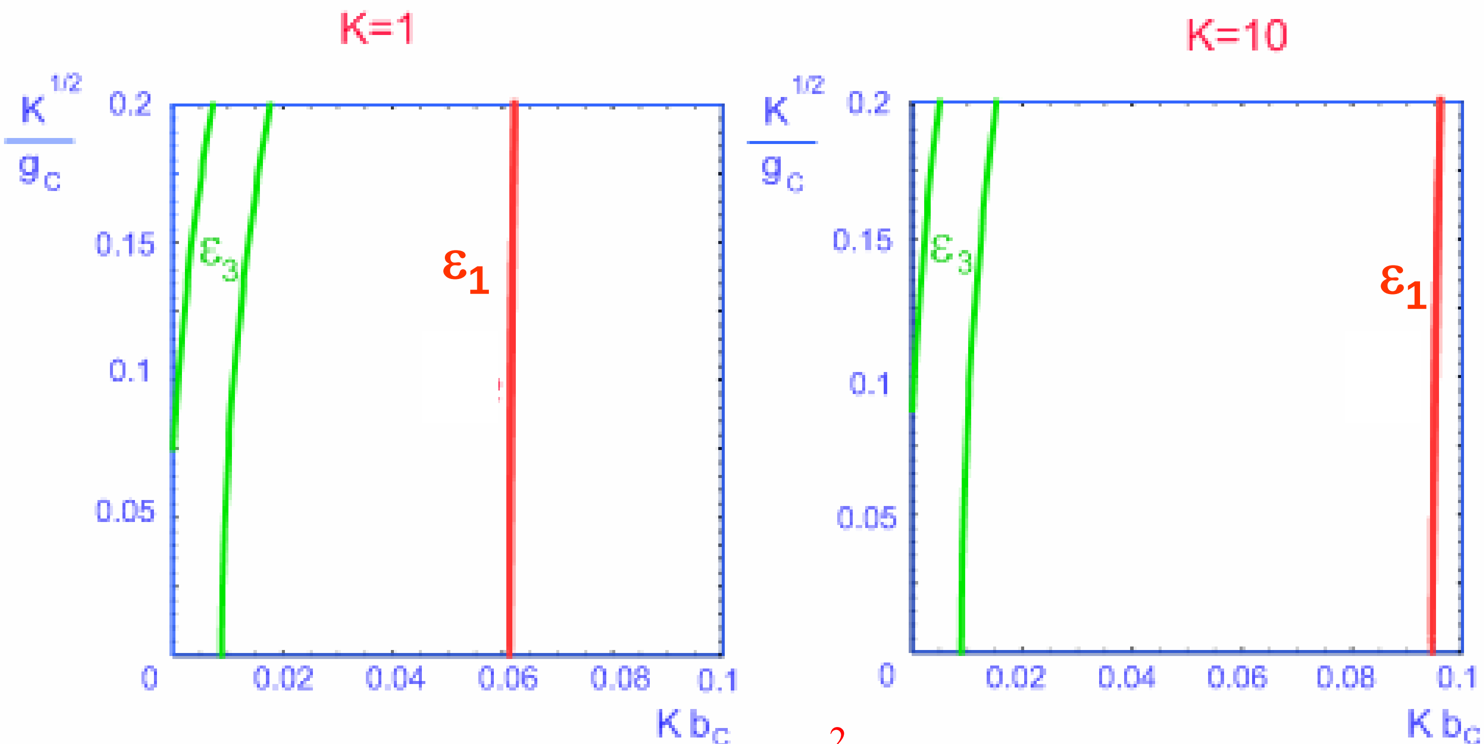
$$m^f = m_j \sqrt{\frac{b_j^L}{(1+\sum_{i=1}^K b_i^L)}} \sqrt{\frac{b_j^R}{(1+\sum_{i=1}^K b_i^R)}} \qquad \forall j = 1, .., K$$

$$\varepsilon_1 \approx O(b_i^2), \quad \varepsilon_2 \approx O(b_i^2), \quad \varepsilon_3 \approx \sum_{i=1}^{K} y_i \left(\frac{g^2}{g_i^2}(1-y_i) - b_i \right)$$

Possibility of agreement with EW data with fine-tuning:

- **Simplest case:** $f_i = f_c, \quad g_i = g_c, \quad b_i = b_c$

Neglecting:
$O(g^4/g_i^4)$,
$O(b_i g^2/g_i^2)$



(95% CL, with rad. corrs. as in the SM with 1 TeV Higgs)

Very loose bounds from ε_1 and ε_2

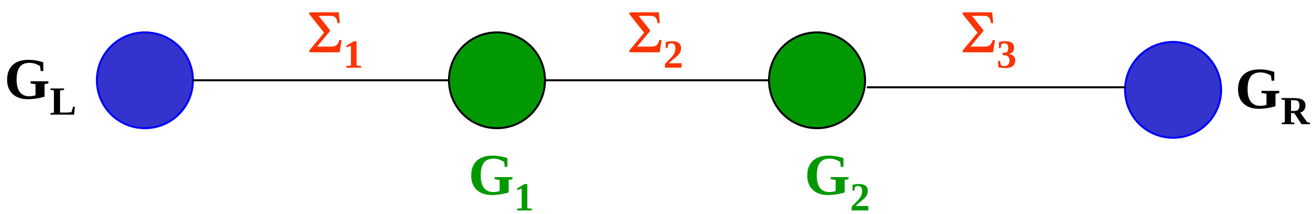
- **Ideal cancellation:** $b_i = \frac{g^2}{g_i^2}(1-y_i)$ **not preserved by loop corrs. (Dawson's talk)**

The Higgsless 4-site Linear Moose model

(Accomando, DC, Dominici, Fedeli, 2008)

• 2 gauge groups G_i=SU(2) with global symmetry $SU(2)_L \otimes SU(2)_R$ plus LR symmetry: $g_2=g_1$, $f_3=f_1$

• 6 extra gauge bosons $W`_{1,2}$ and $Z`_{1,2}$ (have definite parity when g=g`=0)



(K=2)

• 5 new parameters $\{f_1, f_2, b_1, b_2, g_1\}$ related to their masses and couplings to bosons and fermions (one is fixed to reproduce M_Z)

$$f_1, f_2 \to M_1, M_2$$

$$M_1 = f_1 g_1$$

$$M_2 = \frac{M_1}{z} > M_1$$

$$z = \frac{f_1}{\sqrt{f_1^2 + 2f_2^2}} < 1$$

charged and neutral gauge bosons almost degenerate

$$M_{1,2}^{c,n} \sim M_{1,2} + O\left(\frac{e^2}{g_1^2}\right)$$

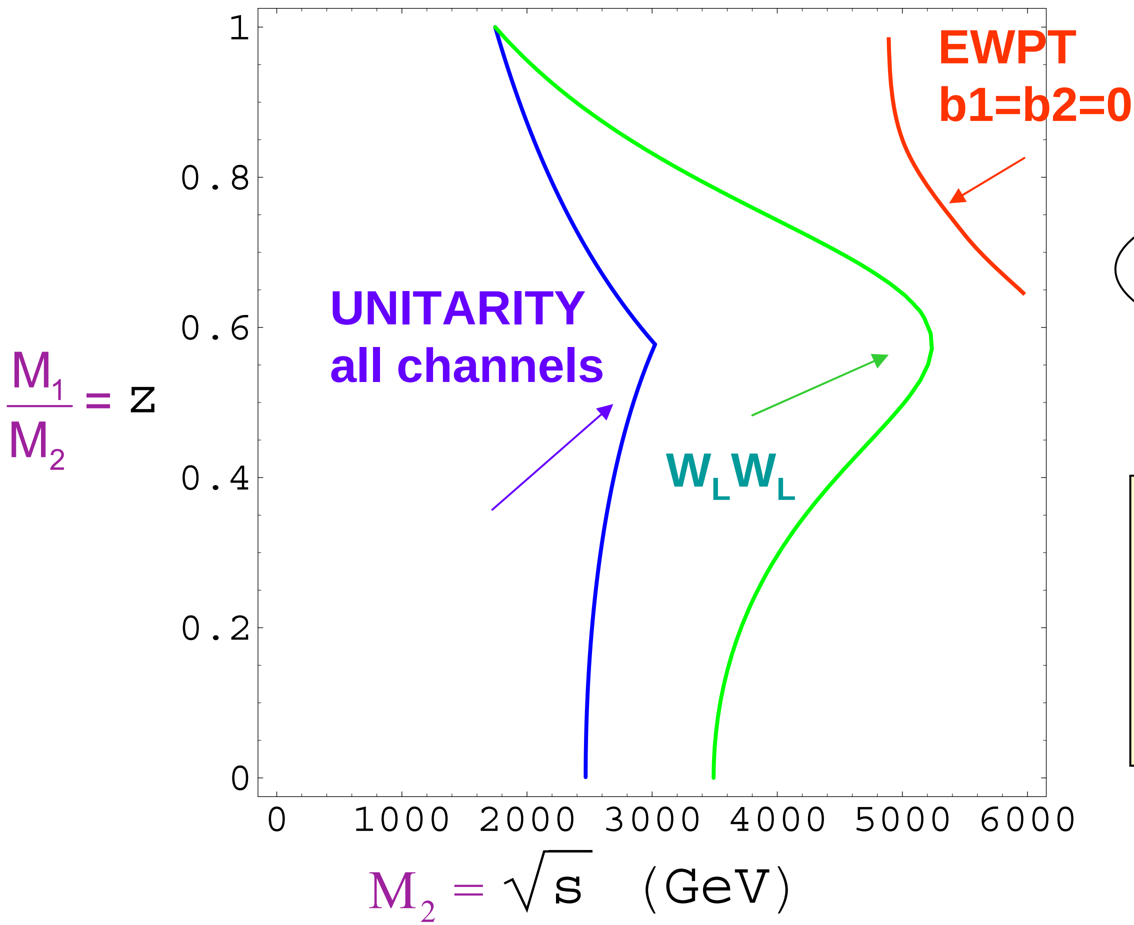
The Higgsless 4-site Linear Moose model

Unitarity and EW precision tests

$$\varepsilon_1 \approx 0 \quad \varepsilon_2 \approx 0, \quad \varepsilon_3 \approx \left(\frac{g^2}{2g_1^2}(1 - z^4) \right)$$

O(e^2/g_1^2), b_1=b_2=0

Best unitarity limit for f_1=f_2 or z=1/$\sqrt{3}$



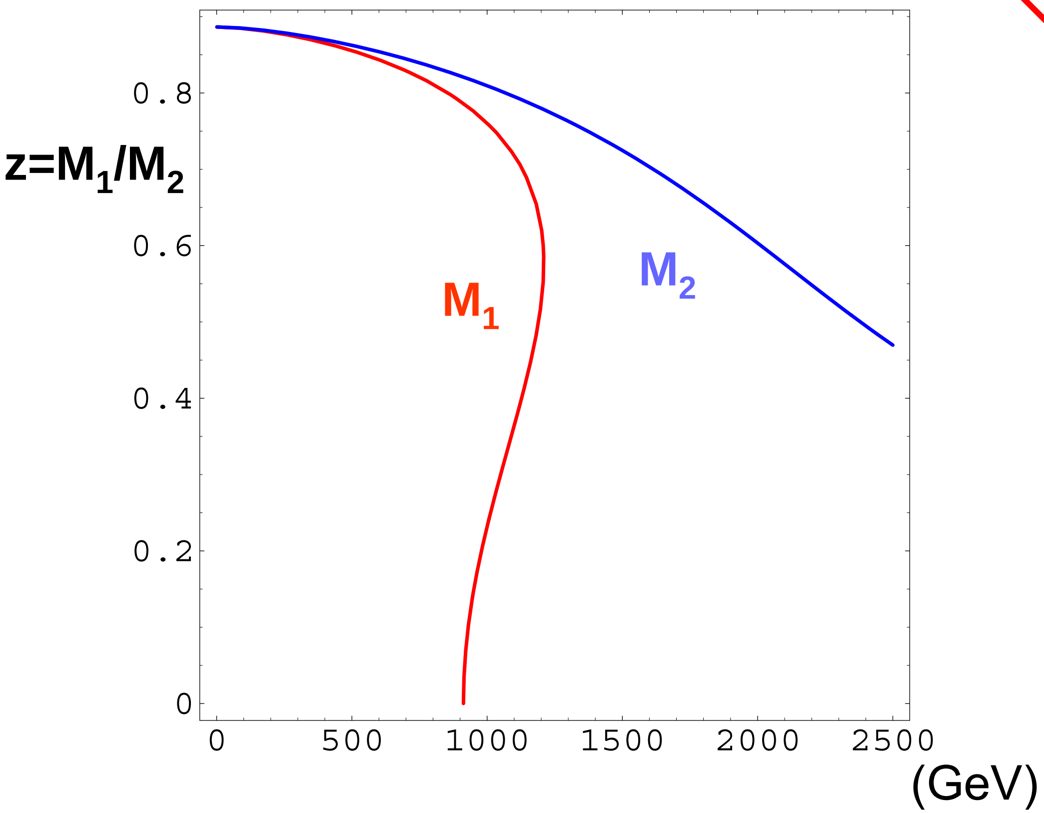
Unitarity and EWPT are hardly compatible !

A direct coupling of the new gauge bosons to ordinary matter must be included: $\mathbf{b_{1,2} \neq 0}$

Bounds from $W_L W_L$ elastic scattering amplitude

$$\mathcal{A}(s,t,u) = i\mathcal{A}(\pi^+\pi^- \to \pi^0\pi^0) = \frac{s}{v^2} - \frac{G_V^2}{v^4}\left[3s + M_V^2\left(\frac{s-u}{t-M_V^2} + \frac{s-t}{u-M_V^2}\right)\right] ,$$

$$G_V = \frac{v}{2}\sqrt{1-z^2}\,(1+z^2)$$



$M_1 = M_V$

$M_2 = M_1/z$

$|a_0^0| < 1$

$$\sqrt{s} = \Lambda = 2.5 \text{ TeV}$$

$$a_0^0 = \frac{M_V^2}{16\pi v^2}\left\{x\left(1 - \frac{3G_V^2}{v^2}\right) + \frac{2G_V^2}{v^2}\left[(2+x^{-1})\log(x+1) - 1\right]\right\} , \qquad x = \frac{s}{M_V^2} .$$

The Higgsless 4-site Linear Moose model

EW precision tests

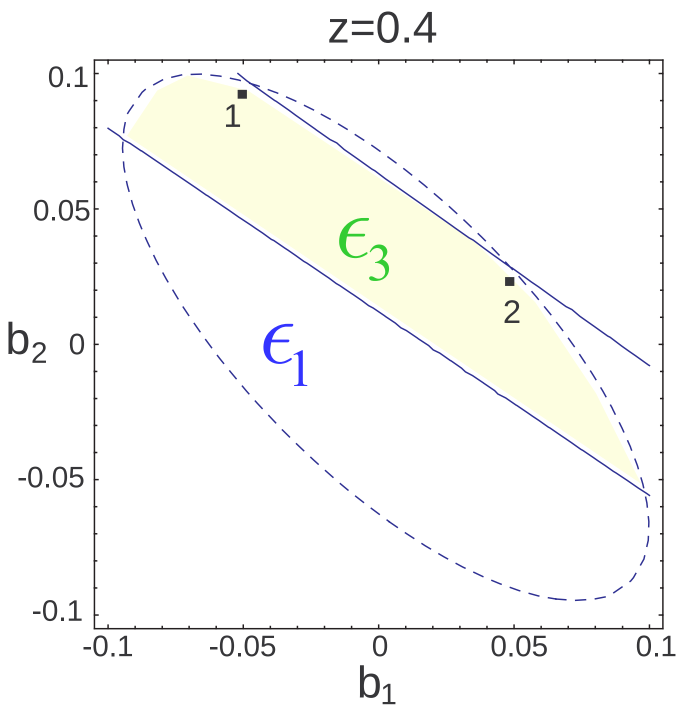
Calculations $O(e^2/g_1^2)$, exact in b1, b2

$$\varepsilon_{1,2} \approx O(b^2), \quad \varepsilon_3 \approx \left(\frac{g^2}{2g_1^2}(1-z^4) - \frac{b}{2} \right)$$

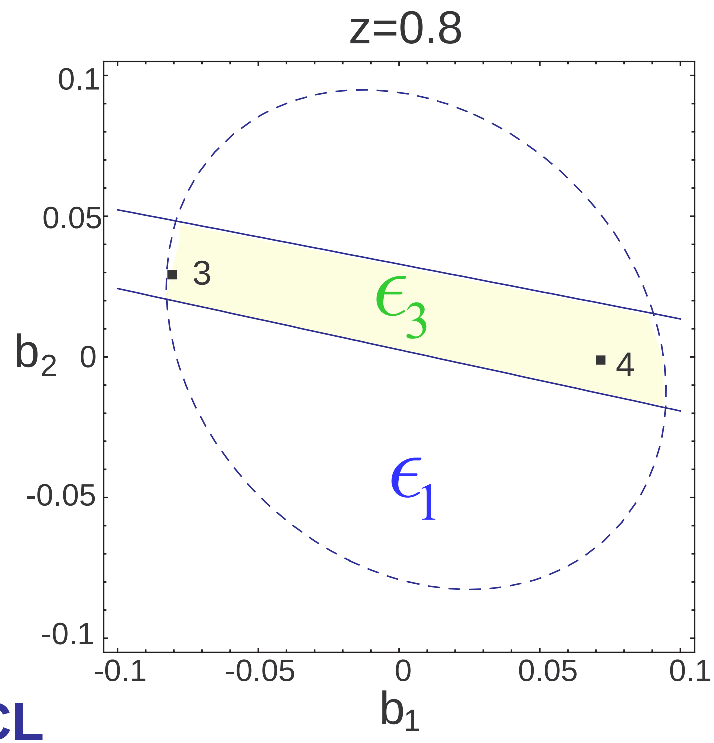
$$b = \frac{b_1 + b_2 - (b_1 - b_2)z^2}{1 + b_1 + b_2}$$

$M_2 = M_1/z$

$500 < M_1 < 1000$ GeV

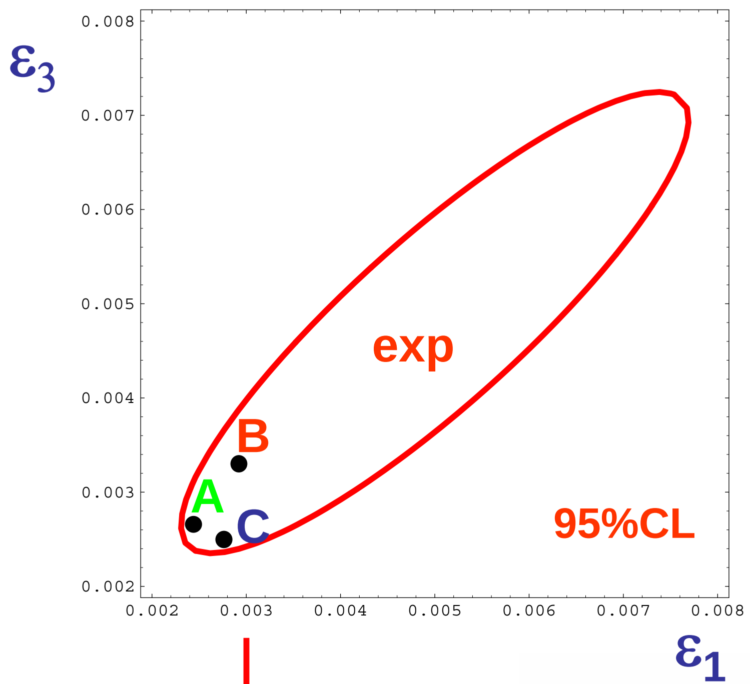


$700 < M_1 < 1600$ GeV

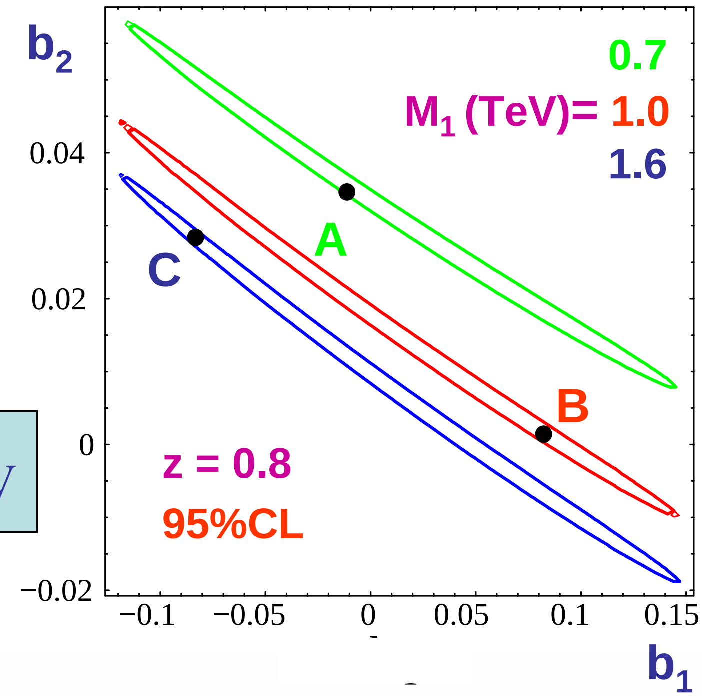


95%CL

Bounds from the EW precision observables



M_H=1TeV



$$\epsilon_1^{rad} = 3.4 \times 10^{-3}, \quad \epsilon_2^{rad} = -6.5 \times 10^{-3}, \quad \epsilon_3^{rad} = 6.7 \times 10^{-3}$$

(Barbieri, Pomarol, Rattazzi, Strumia (2004))

$$\begin{aligned} \varepsilon_1 &= +(5.0 \pm 1.1)\ 10^{-3} \\ \varepsilon_2 &= -(8.8 \pm 1.2)\ 10^{-3} \\ \varepsilon_3 &= +(4.8 \pm 1.0)\ 10^{-3} \end{aligned} \qquad \text{with correlation matrix} \qquad \rho = \begin{pmatrix} 1 & 0.66 & 0.88 \\ 0.66 & 1 & 0.46 \\ 0.88 & 0.46 & 1 \end{pmatrix}$$

No new physics one-loop contributions to ε_1 and ε_3 included

see Dawson and Isidori talks

Fine - tuning

The values of b_1 and b_2 allowed by precision electroweak data are narrowly constrained to a strip by ε_3

What level of fine- tuning is implied?

Assuming the standard definition of fine tuning (see for ex. Barbieri and Giudice, 1988)

$$\Delta = \left| \frac{a_i}{\epsilon_3} \frac{\partial \epsilon_3(a_i)}{\partial a_i} \right|, \qquad a_i = g_1, b_1, b_2$$

so that a percentage variation of any of the parameters a_i corresponds to a percentage variation of ε_3 which is Δ-times larger,

we get $\Delta \sim 10$ which amounts to tolerate in ε_3 cancellations among the parameters of, at most, one order of magnitude

The Higgsless 4-site Linear Moose model

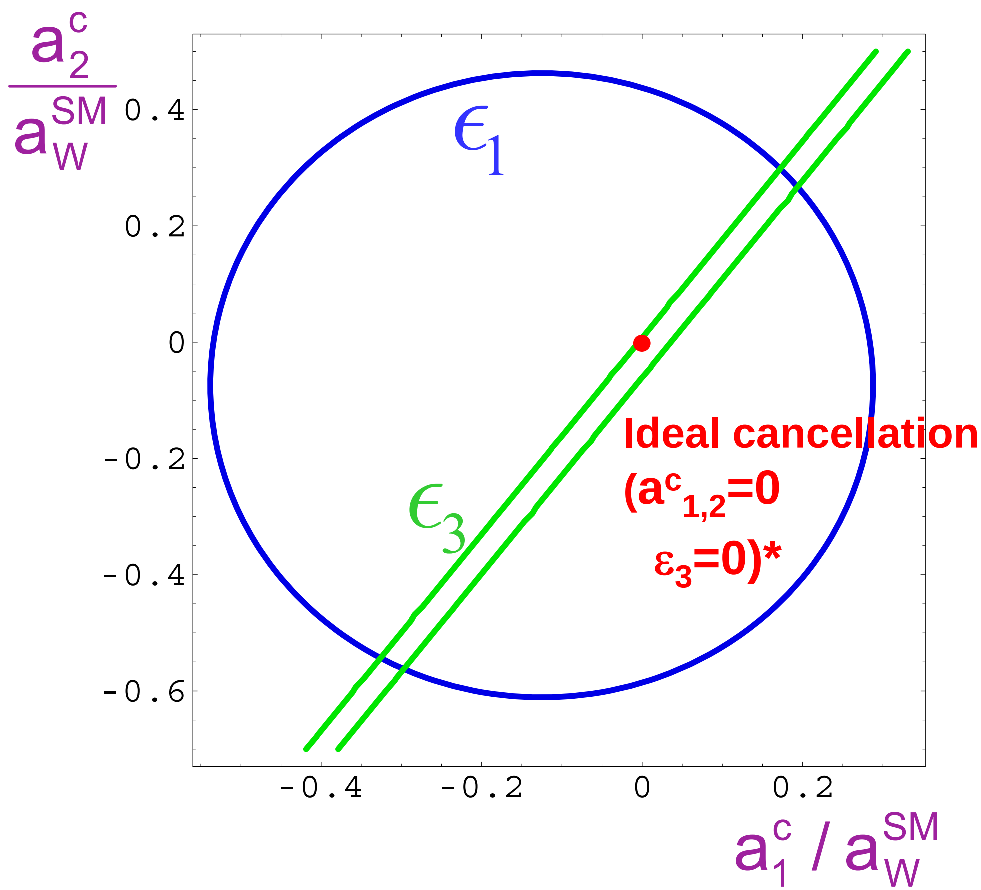
EW precision tests

Calculations $O(e^2/g_1^2)$, exact in b1, b2

$$\varepsilon_{1,2} \approx O(b^2), \quad \varepsilon_3 \approx \left(\frac{g^2}{2g_1^2}(1-z^4) - \frac{b}{2} \right)$$

$$b = \frac{b_1 + b_2 - (b_1 - b_2)z^2}{1 + b_1 + b_2}$$

M_1=1000 GeV and M_2=1300 GeV



Bounds on charged couplings (and masses) from low energy precision measurements ε_i

$$\varepsilon_3 \sim \frac{a_1^c}{g_1} - z^2 \frac{a_2^c}{g_1}$$

ε_3 bounds favour $a^c_2 > a^c_1$

$$\boxed{-0.1 < a^c_{1,2}(W`_{1,2}\, ff) < 0.25}$$

for larger $M_{1,2}$ the bounds from ε_1 are less stringent

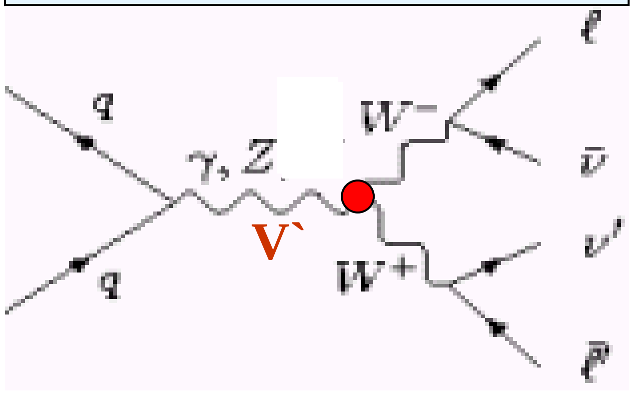
*** not preserved by loop corrections**
(Dawson, Jackson 2008)

New spin-1 resonances @ the LHC

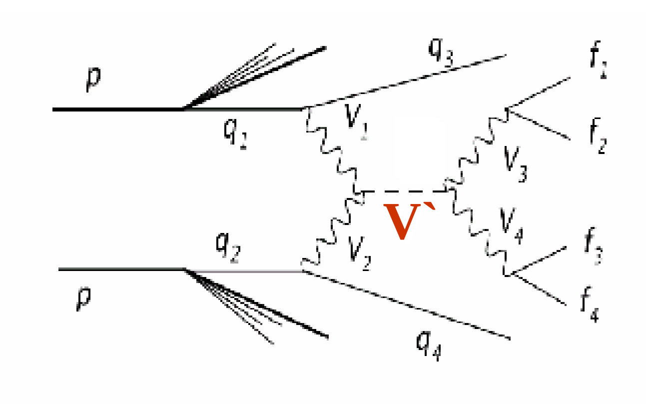
where do we get clues?

Drell-Yan

Di-boson production



Vector boson scattering

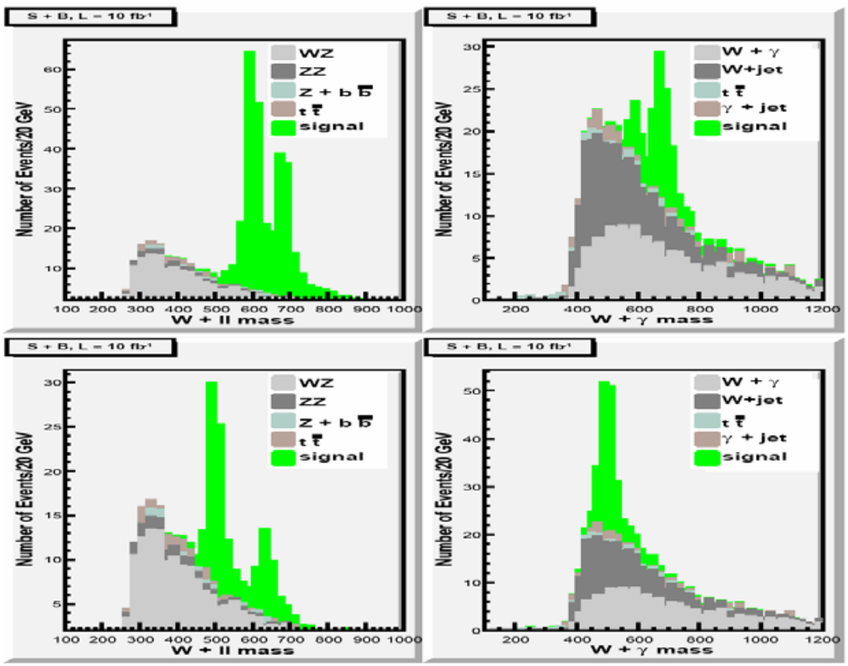


.... triple boson production, and ..... even more complicated processes where (extra) gauge bosons can be produced

Owing to the tension between unitarity and EW precision tests, the extra gauge-boson couplings to SM matter must be small

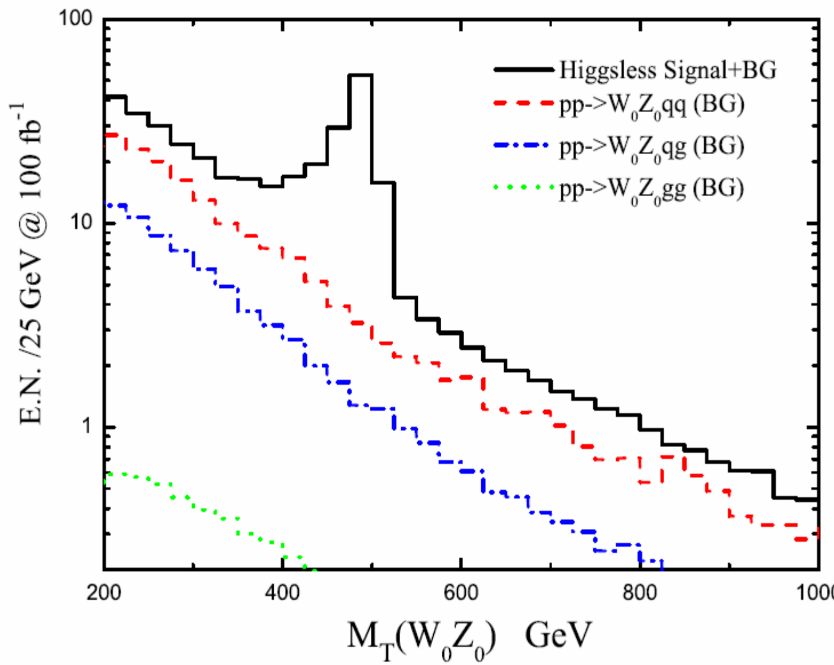
In literature main focus is on complex processes

(Hirn, Martin, Sanz `07)



WZ, Wγ di-boson production

(Belyaev,Chivukula, et al. `08)



Vector boson scattering

For the Higgsless 4-site Linear Moose Model DY processes can be as well a good discovery channel

Event Generator FAST_2f

(Accomando)

FAST_2f is an upgrade of PHASE [Accomando, Ballestrero, Maina], **a MCEG for multi-particle processes at the LHC. It is dedicated to Drell-Yan processes at the Leading-Order and interfaced with PYTHIA**

Processes

We consider charged and neutral Drell-Yan leptonic channels

- **pp $\rightarrow$ *ll* with *l*=e,μ**
- **pp $\rightarrow$ $l\nu$ with *l*=e,μ and $l\nu = l^-\nu + l^+\nu$**

CTEQ6L PDF

Kinematical cuts

Acceptance cuts:

$\eta(l)<2.5$, $P_t(l)>20$ GeV, $P_t^{miss} >20$ GeV

Selection cuts:

$M_{inv}(ll)$ >500 GeV for pp $\rightarrow$ *ll*

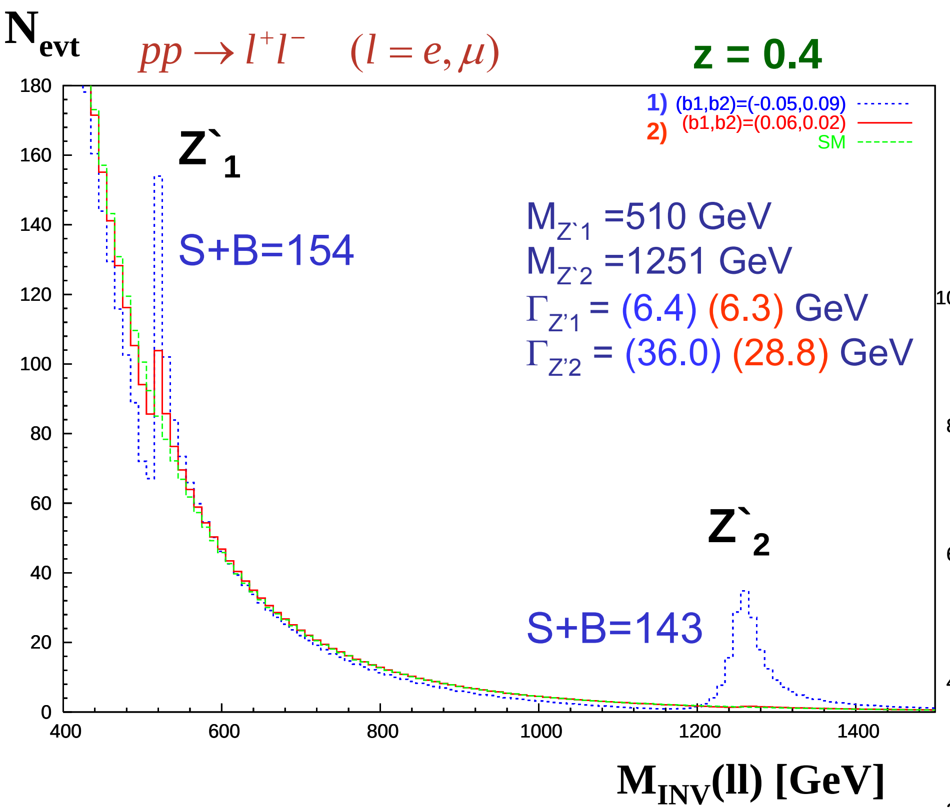
$P_t(l)>250$ GeV for pp $\rightarrow$ $l\nu$

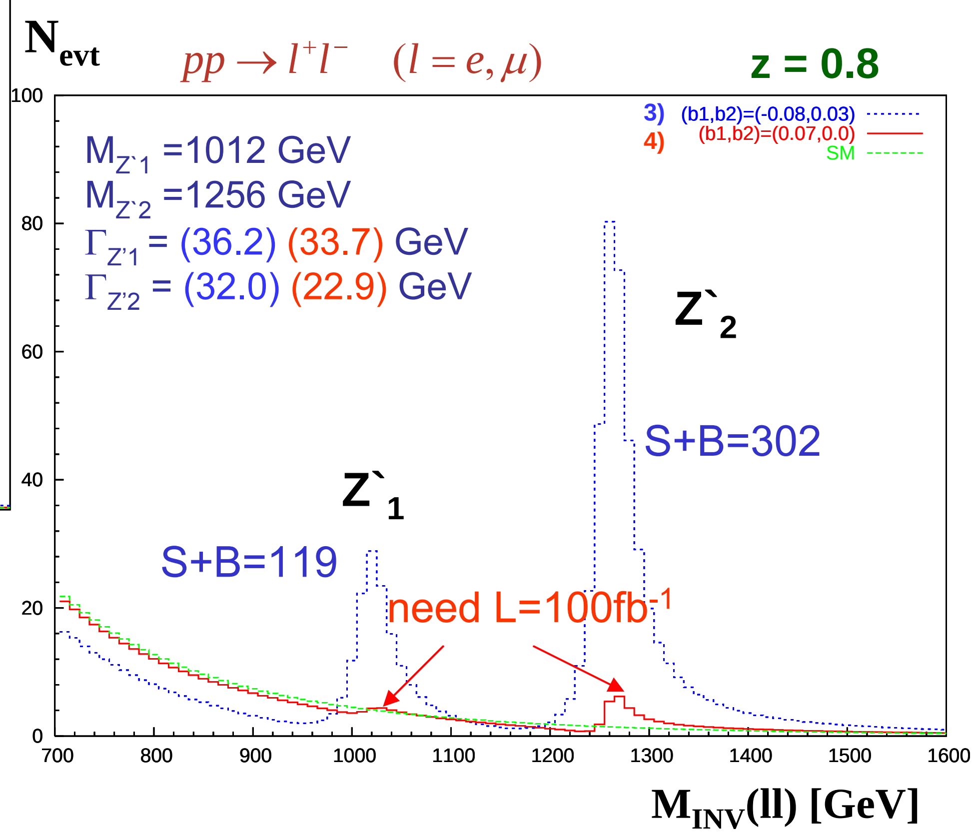
no detector simulation is included

Z'_1, Z'_2 Drell-Yan production @ the LHC

(Accomando, DC, Dominici, Fedeli)

$M_2 = M_1/z$

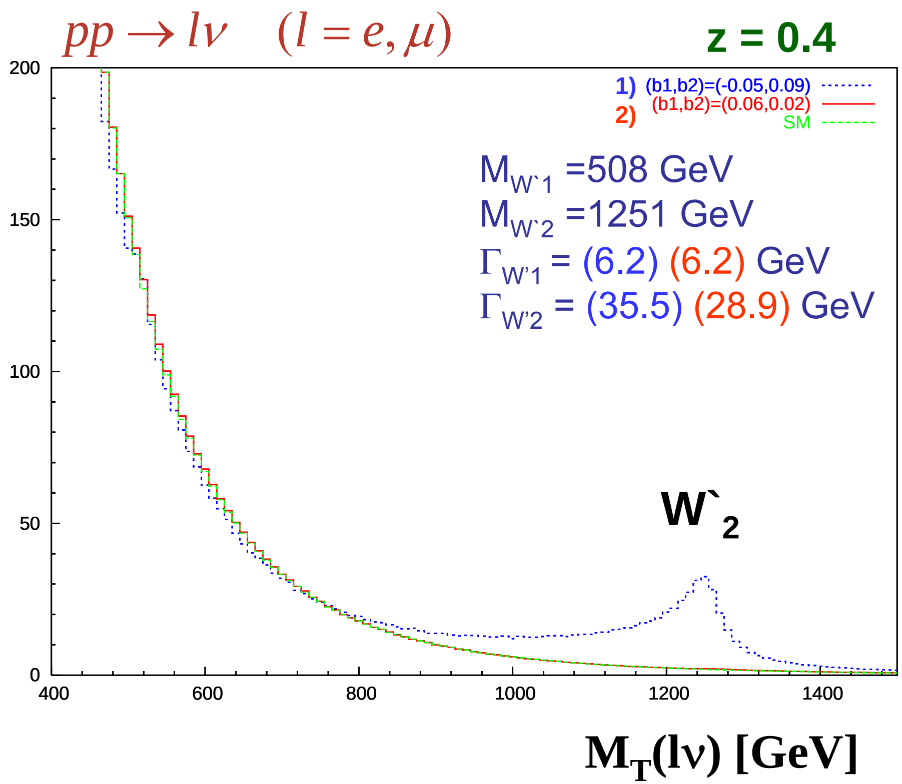




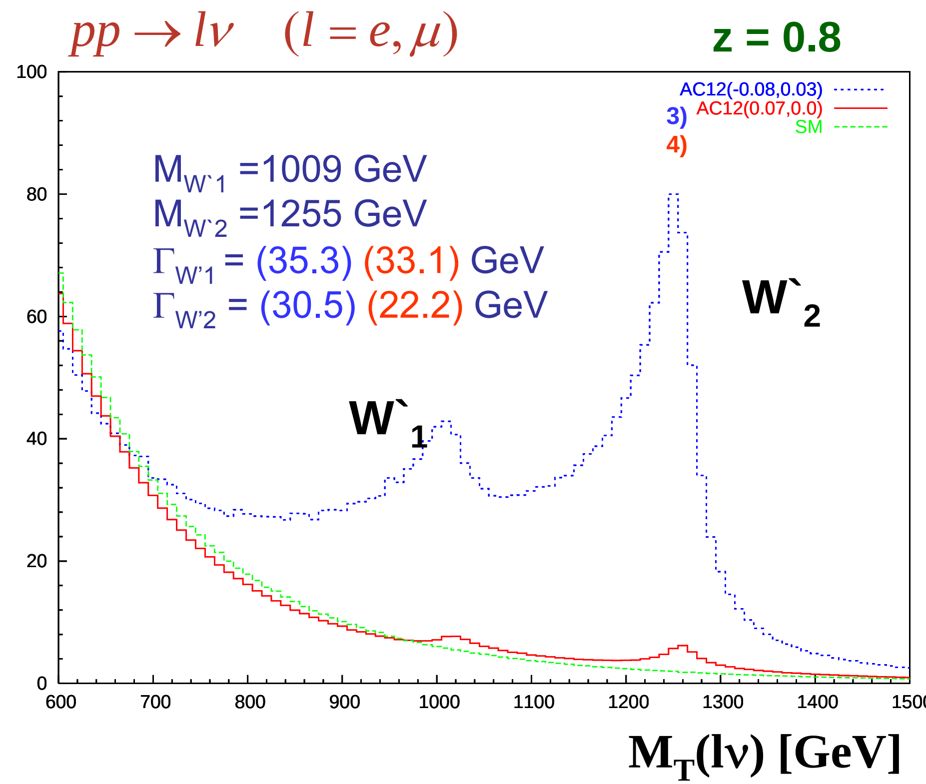
Total # of evts in a 10GeV-bin versus $M_{inv}(l^+l^-)$ for $L=10fb^{-1}$. Sum over e,μ

S+B=#evts($M \pm \Gamma$)

W'_1, W'_2 Drell-Yan production @ the LHC



$M_2 = M_1/z$



Z`$_i$ and W`$_i$ are nearly degenerate

Total # of evts in a 10GeV-bin versus $M_T(l\nu)$ for $L=10fb^{-1}$. Sum over e,μ

W'$_{1}$, W'$_{2}$ Drell-Yan production @ the LHC

	$M_{1,2}$(GeV)	$b_{1,2}$	M_t^{cut}(GeV)	$N_{\rm evt}^{\rm sig}(W_1)$	$N_{\rm evt}^{\rm tot}(W_1)$	$\sigma(W_1)$	$N_{\rm evt}^{\rm sig}(W_2)$	$N_{\rm evt}^{\rm tot}(W_2)$	$\sigma(W_2)$
1)	500,1250	-0.05,0.09	400	36	2435	0.7	776	2214	16.5
2)	500,1250	0.06,0.02	400	0	2609	0	1	1807	0
3)	1000,1250	-0.08,0.03	700	808	1230	23.0	1112	1189	32.3
4)	1000,1250	0.07,0.0	700	12	443	0.6	17	88	1.8

# of evts for the W\`$_{1,2}$ DY-production for $M_t(l\nu_l) > M_t^{cut}$

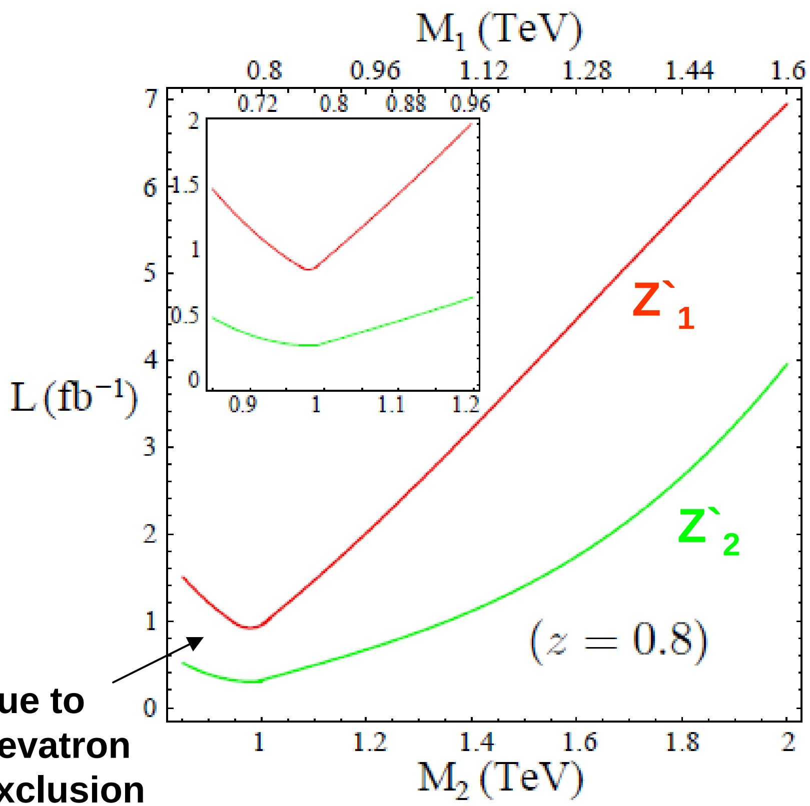
$\sigma = N_{\rm evt}^{\rm sig}/\sqrt{N_{\rm evt}^{\rm tot}}$ for an integrated luminosity L=10 fb^{-1}

The statistical significance for the W\`s production can be a factor 2 bigger than for the Z\`s but it is less clean.

Neutral and charged channel are complementary

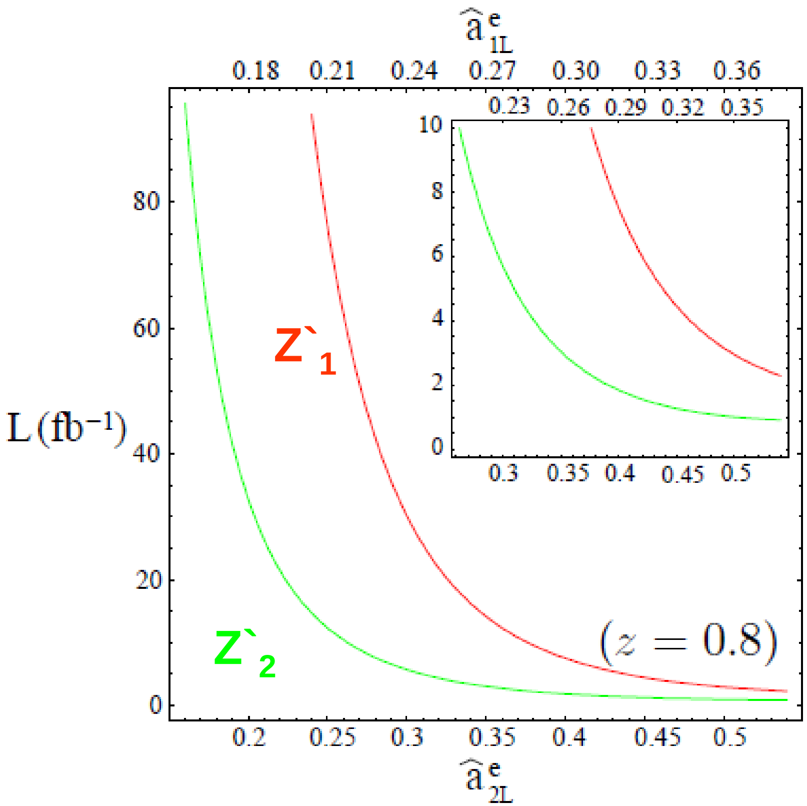
All six extra gauge bosons could be investigated at the LHC start-up with L ~ 1-2 fb^{-1} for $M_{1,2}$ < 1TeV

Discovery @ LHC in the early stage low-luminosity run



due to Tevatron exclusion region

Luminosity needed for a 5σ-discovery for the maximum coupling allowed by EWPT

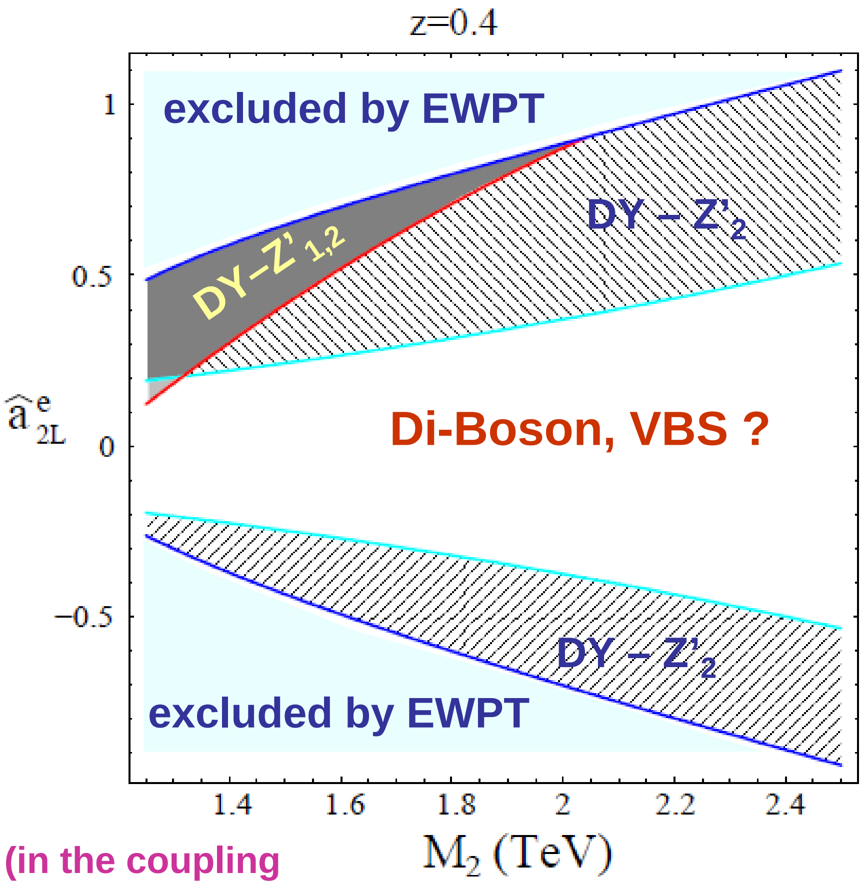


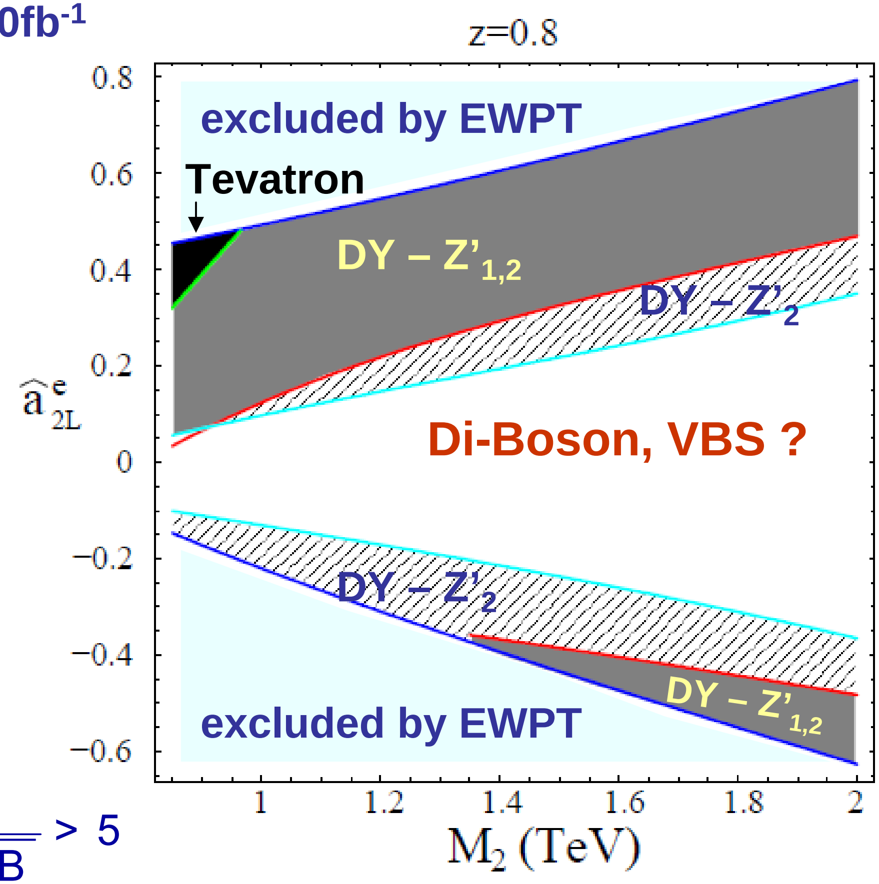
Luminosity needed for a 5σ-discovery versus the electron-boson left handed coupling (M_1=1TeV, M_2=1.25TeV)

The low-edge of the spectrum detectable with L~1-2 fb^{-1}

Discovery @ the LHC
DY-processes in the neutral channel, $Z`_1$, $Z`_2$ exchanges

$L=100fb^{-1}$





$$\frac{S}{\sqrt{S+B}} > 5$$

(in the coupling the electric charge –e is factorized)

within $|M_{inv}(l^+l^-)-M_i| < \Gamma_i$ (i=1,2)

acceptance cuts:
$\eta(l)<2.5$, $Pt(l)>20$ GeV

Tevatron: direct limit from neutral DY leptonic channels for $L=4fb^{-1}$ in $p\bar{p} \to l^+l^- \quad (l = e, \mu)$

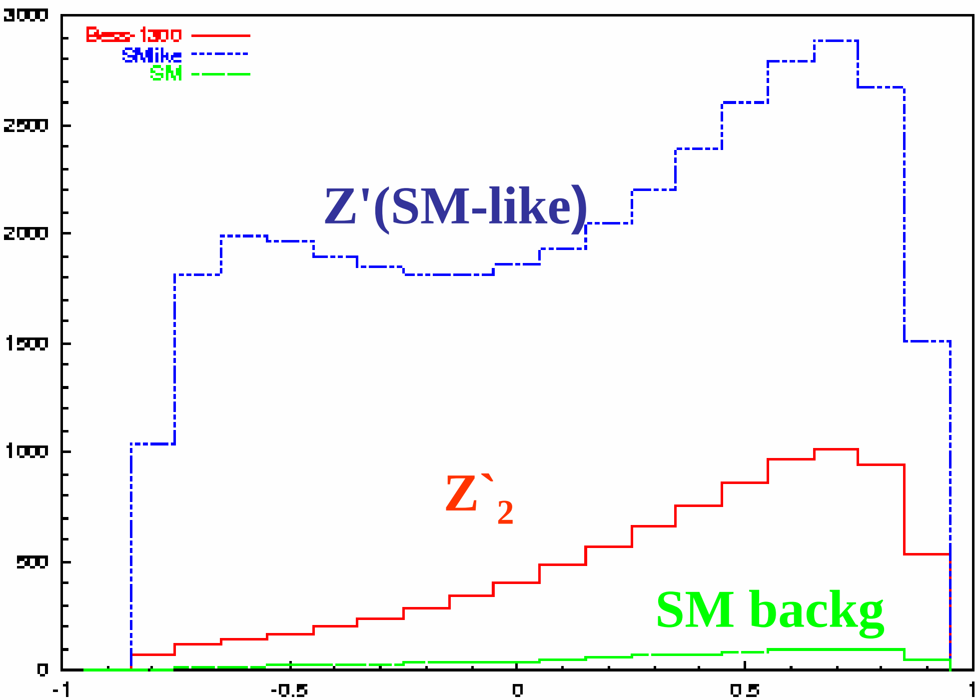
Bounds from LEP2 not effective

How to distinguish the various models? Forward-backward charge asymmetry A_{FB} in pp $\rightarrow l^+ l^-$

$$\frac{d\sigma}{d\cos\theta^*} \propto \frac{3}{8}(1+\cos^2\theta^*) + A^{\ell}_{FB}\cos\theta^*$$

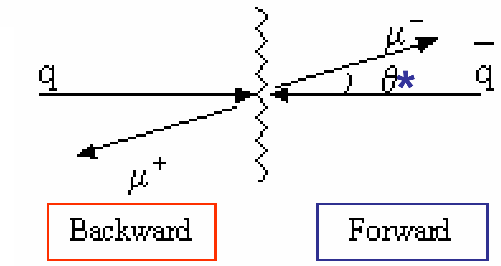
L=100 fb^{-1}

$d\sigma\ L/d\cos\theta^*(l^-)$ ($l=e,\mu$)



$\cos\theta^*(l^-)$

 # evts for Z$`_2$ ~ 1000



θ* is the angle of the l^- with the incoming quark in the dilepton frame (Collins-Soper)

Approximate the direction of the incoming quark with the boost direction of the leptonic system with respect to the beam axis (Dittmar, 1997)

$M_{Z`2}=M_{Z`(SM\text{-}like)}$=1.3 TeV

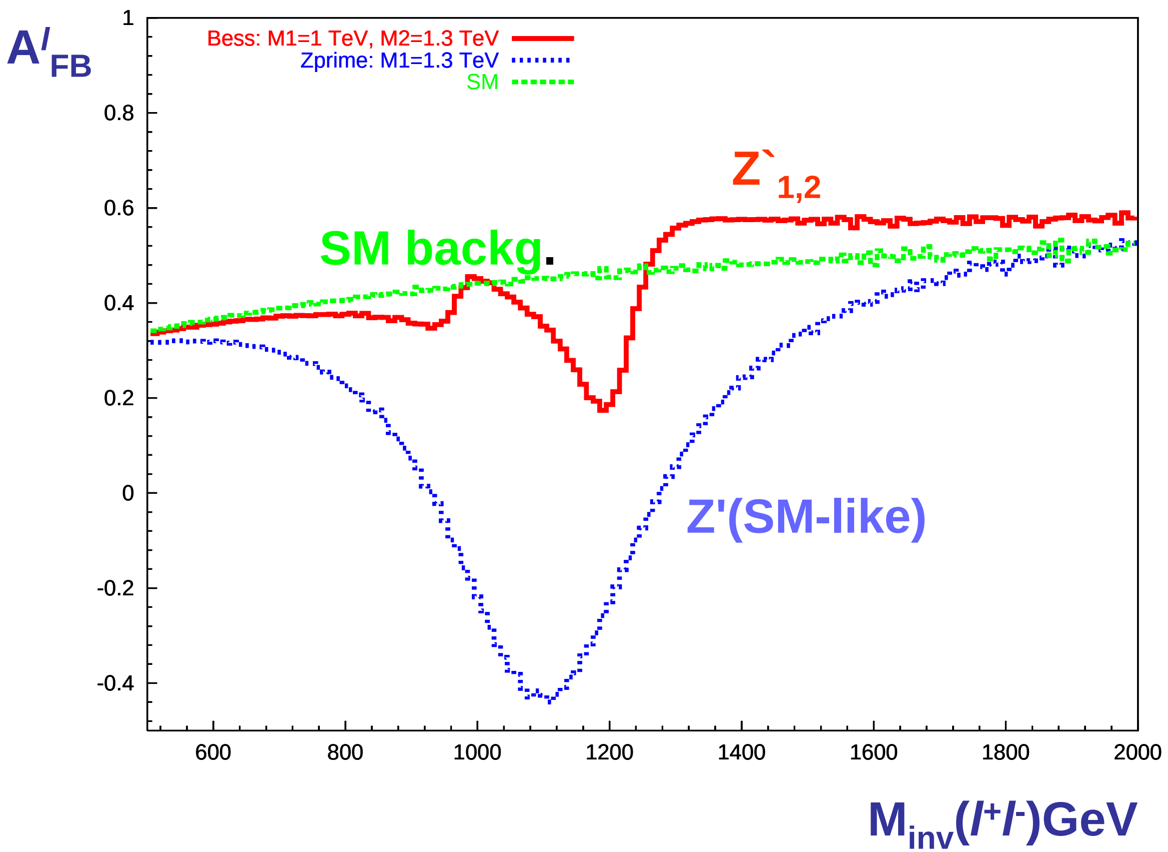
we select the events within

$|M_{inv}(l^+l^-)-M_{Z`}| < 3\Gamma_{Z`}$

Rapidity cut: $|y(l^+l^-)|>1$

Forward-backward asymmetry A_{FB} in pp$\rightarrow l^+l^-$

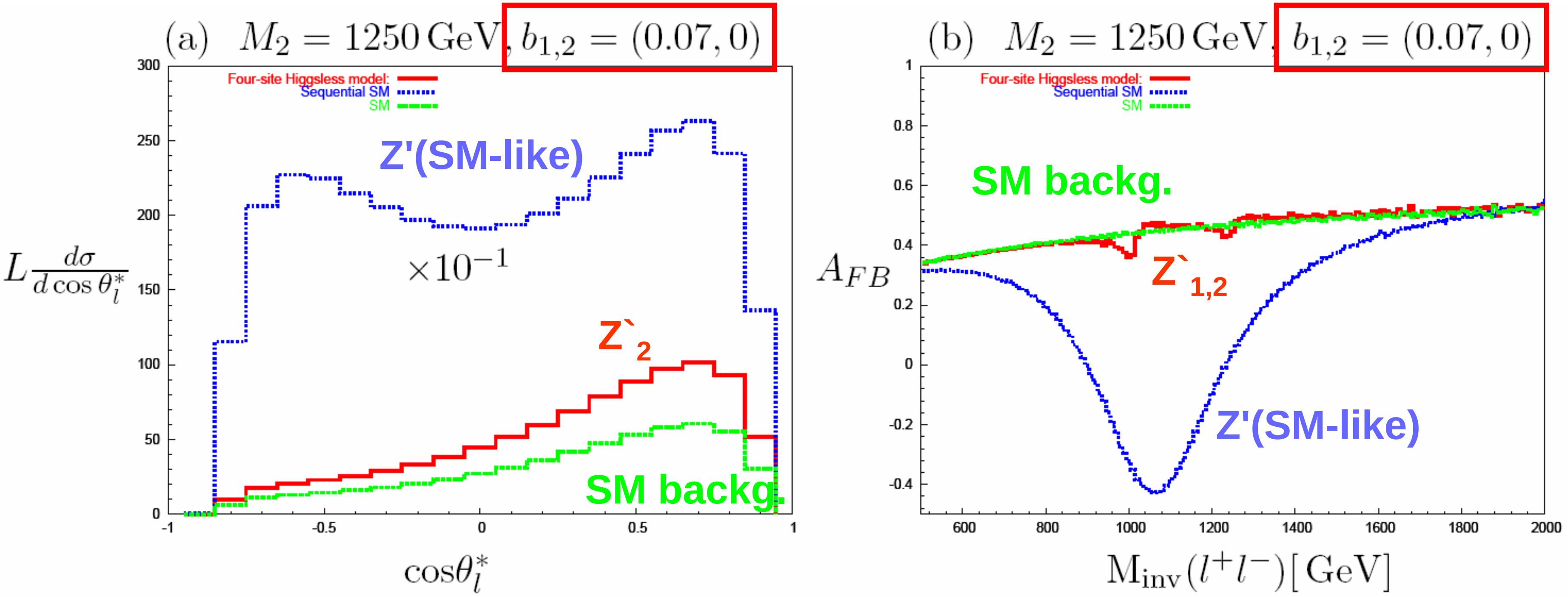
(Dittmar,Nicollerat,Djouadi 03; Petriello,Quackenbush 08)



$M_{Z`1}$ =1.0TeV
$M_{Z`2}$ =1.3TeV
$M_{Z`(SM\text{-}like)}$ =1.3TeV

$$A_{FB} = \left[\frac{d\sigma^F}{dM_{\rm inv}} - \frac{d\sigma^B}{dM_{\rm inv}}\right] / \left[\frac{d\sigma^F}{dM_{\rm inv}} + \frac{d\sigma^B}{dM_{\rm inv}}\right]$$

On- and off-resonance A_{FB} for a single resonance scenario

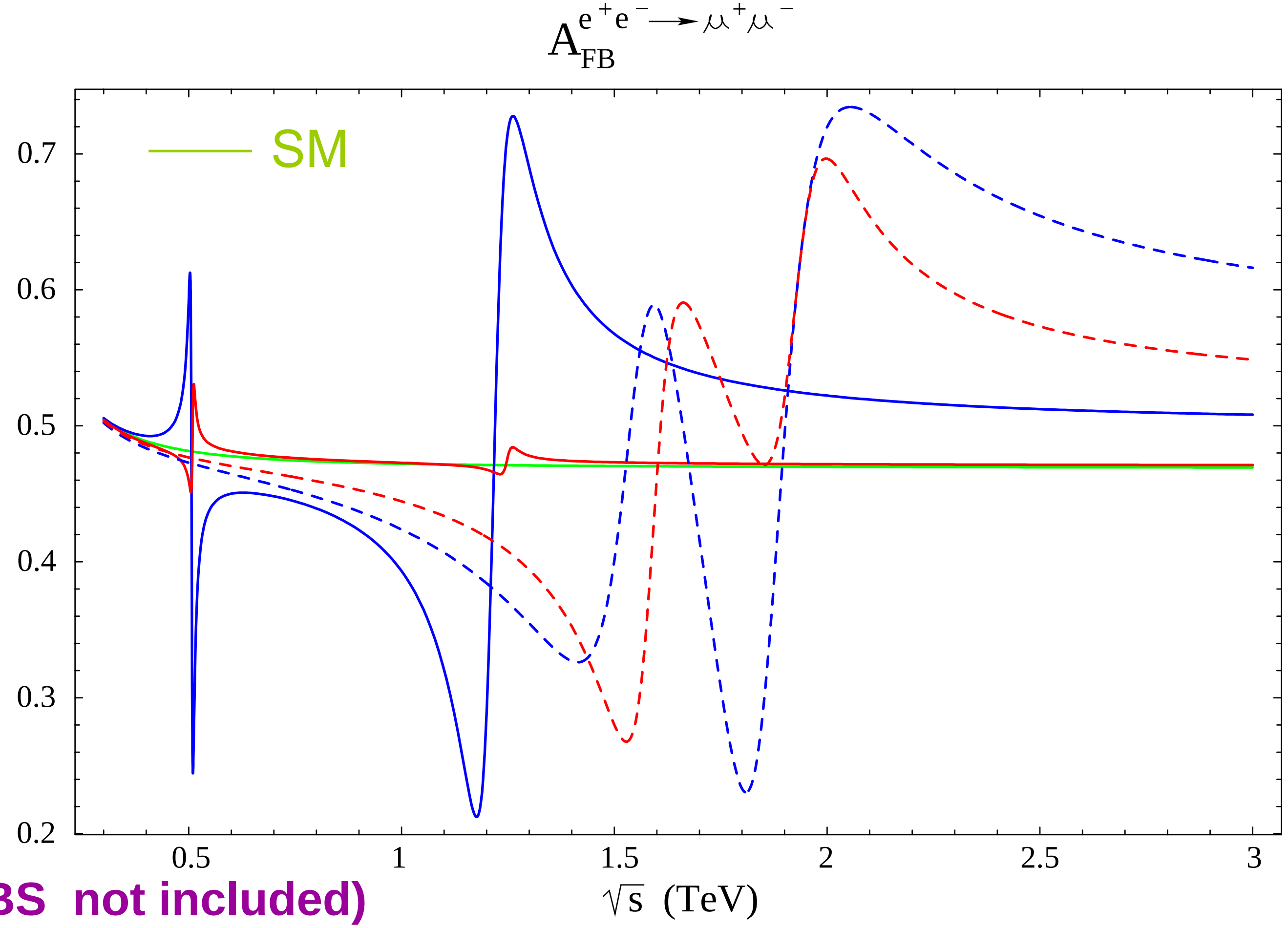


- The on-resonance A_{FB} is more pronounced in the 4-site model due to the difference between the left and the right-handed fermion-boson couplings
- The off-resonance A_{FB} could reveal the double-resonant structure not appreciable in the dilepton invariant mass distribution

4-site @ a LC (preliminary)

M_1= 500GeV, M_2=1250GeV — b_1=-0.05,b_2=0.09 — b_1= 0.06, b_2=0.02

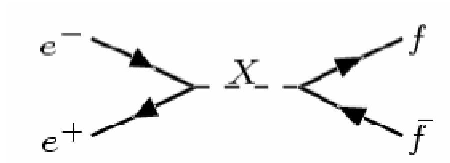
M_1=1600GeV,M_2=2000GeV - - - b_1=-0.07,b_2=0.02 - - - b_1= 0.08,b_2=-0.01



(ISR & BS not included)

4-site @ a Linear Collider
Indirect sensitivity

s-channel production:
$\sigma \propto 1/s$



$X = \gamma, Z, Z_1, Z_2$

Observable	Relative Stat. Accuracy $\delta\mathcal{O}/\mathcal{O}$ for 1 ab^{-1}	CLIC – 3TeV
$\sigma_{\mu^+\mu^-}$	$\pm0.6\%$	±0.010
$\sigma_{b\bar{b}}$	$\pm0.7\%$	±0.012
$\sigma_{t\bar{t}}$	$\pm0.8\%$	±0.014
$A_{FB}^{\mu\mu}$	$\pm1\%$	±0.018
A_{FB}^{bb}	$\pm3\%$	±0.055
A_{FB}^{tt}	$\pm2\%$	±0.040

Including the effect of $\gamma\gamma \to$ hadrons background
(Battaglia)

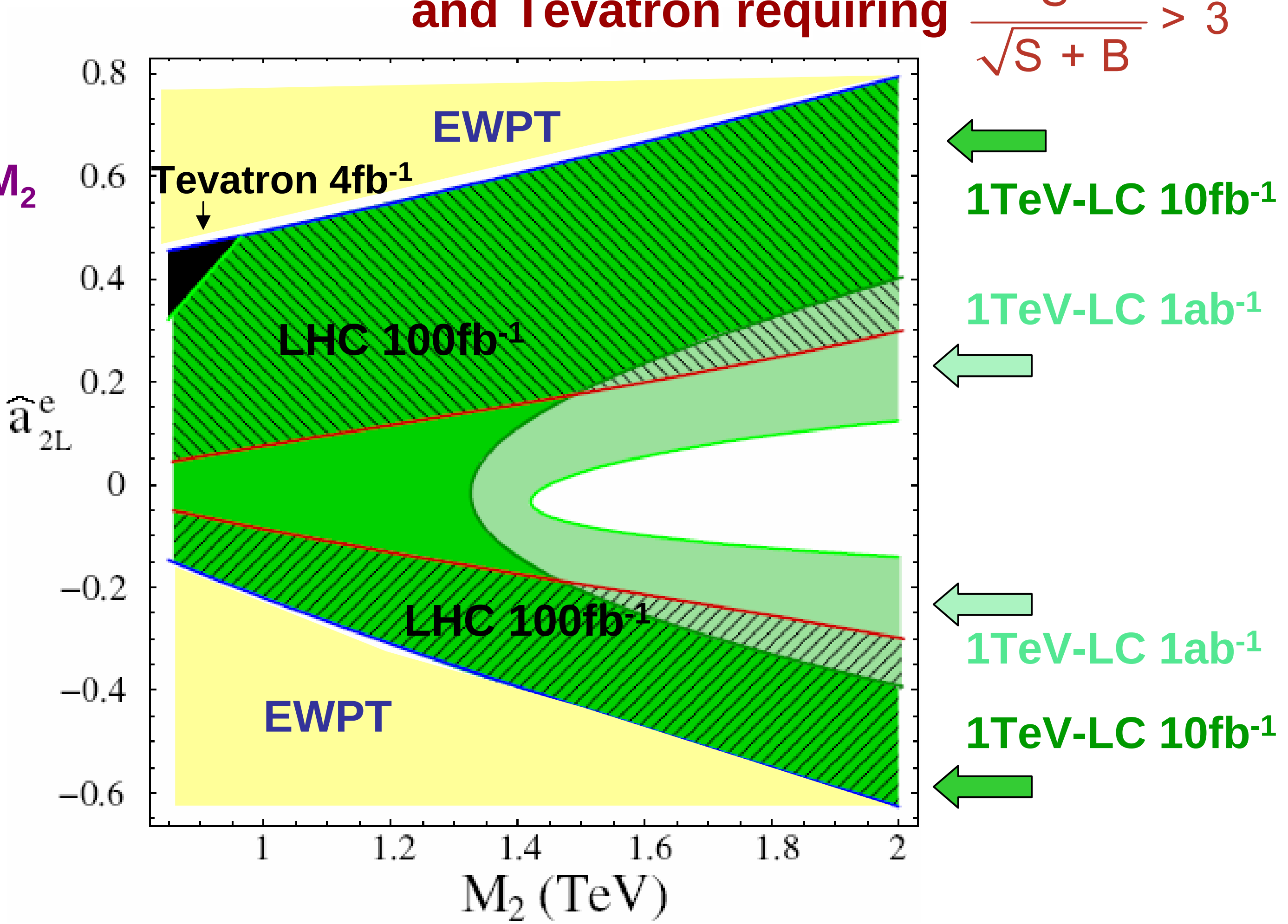
rescaled from CLIC

$1\,ab^{-1}$ **ILC - 1TeV**

4-site model 95%CL region excluded by 1TeV-LC measurements of $\sigma^{\mu^+\mu^-}, \sigma^{b\bar{b}}, A_{FB}^{\mu}, A_{FB}^{b}$ Also shown are the direct limits from LHC and Tevatron requiring $\frac{S}{\sqrt{S+B}} > 3$

z=0.8

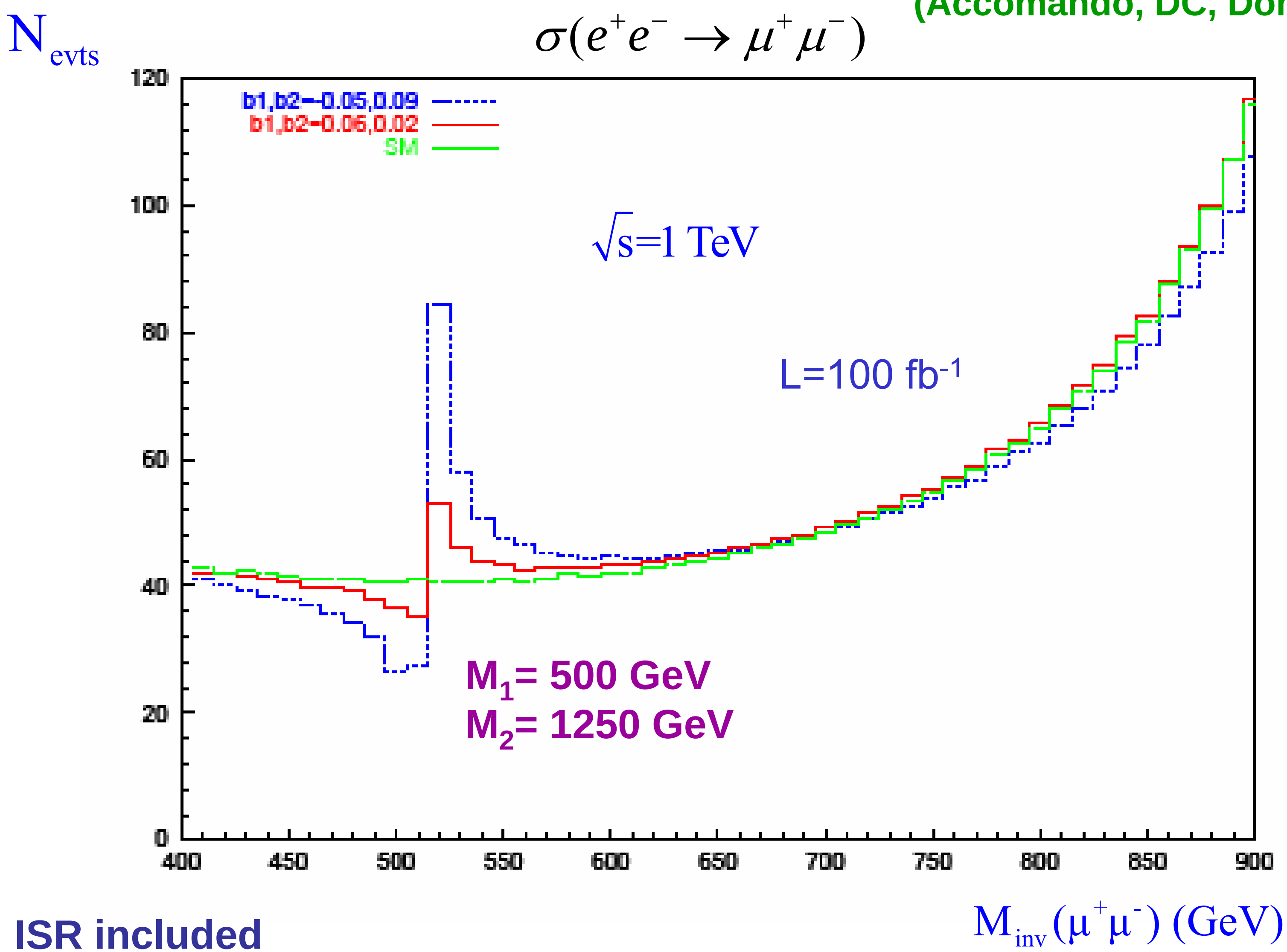
$M_1 = z\, M_2$



Work to do: include polarization and other EW observables, better evaluation of the errors here rescaled from CLIC, ….

4-site at a LC (preliminary)

(Accomando, DC, Dominici,Fedeli)



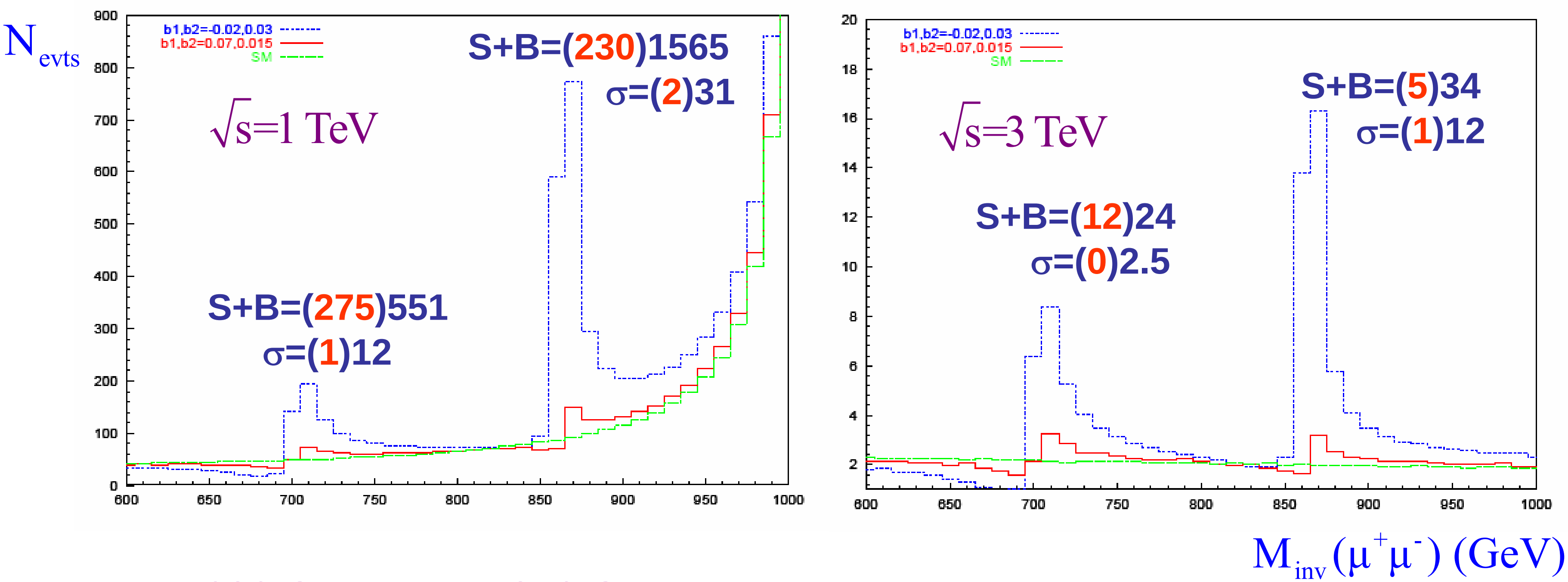
ISR included
BS not included

1TeV-LC or CLIC ?

(Accomando, DC, Dominici, Fedeli)

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

L=100 fb^{-1}



M$_1$=680 GeV **M$_2$=850 GeV**

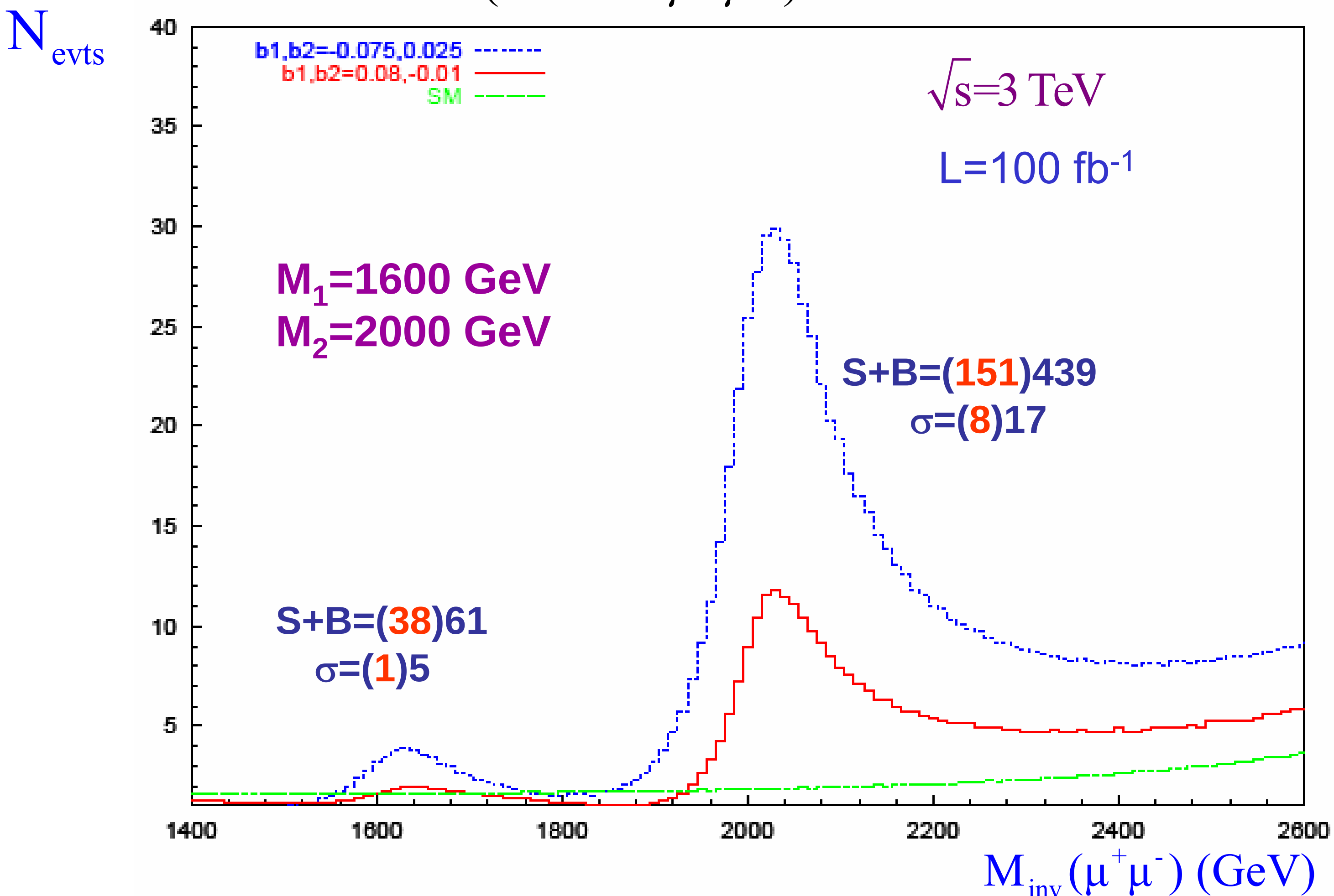
ISR included
BS not included

S+B=#evts(M$\pm$2Γ)
σ=S/(S+B)

4-site at CLIC (preliminary)

(Accomando, DC, Dominici, Fedeli)

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

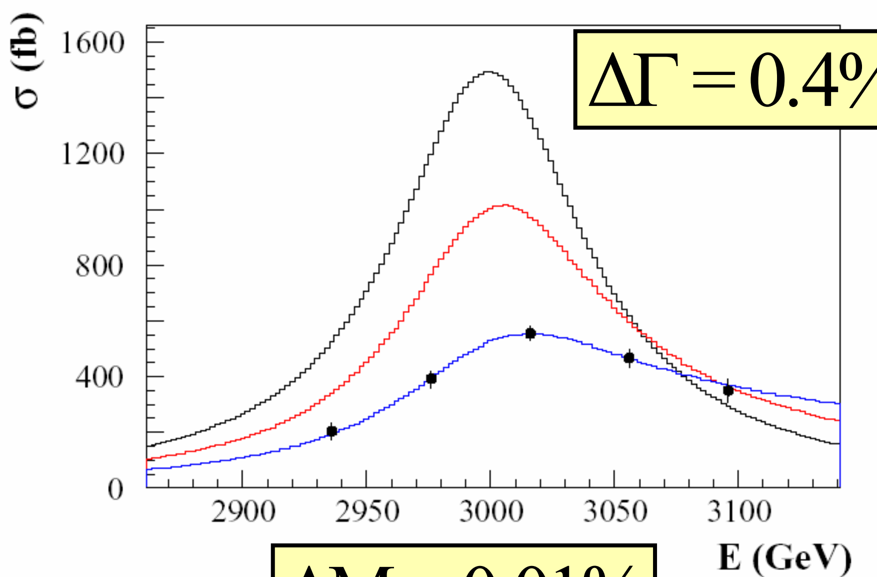


ISR included
BS not included

S+B=#evts(M$\pm$2Γ)
σ=S/(S+B)

CLIC smeared luminosity spectrum allows still for precision measurements: measure a Z’ and reveal a double resonant structure

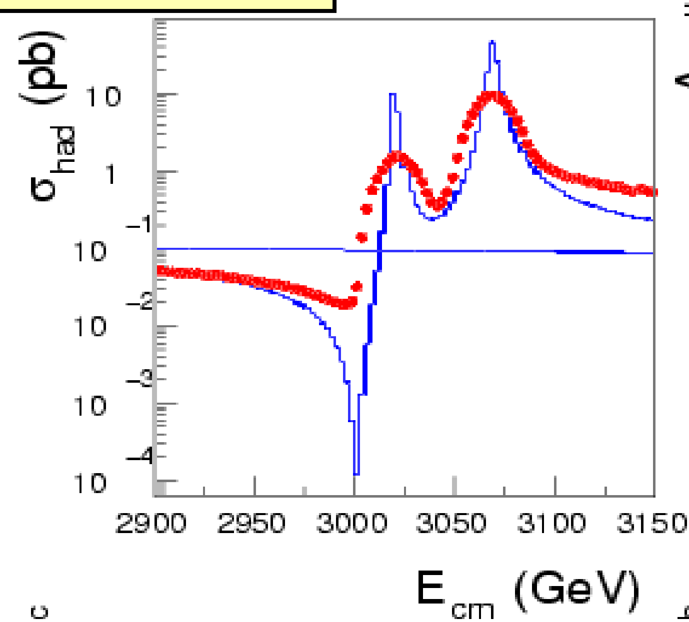
(Battaglia, DC, Dominici, 2002)

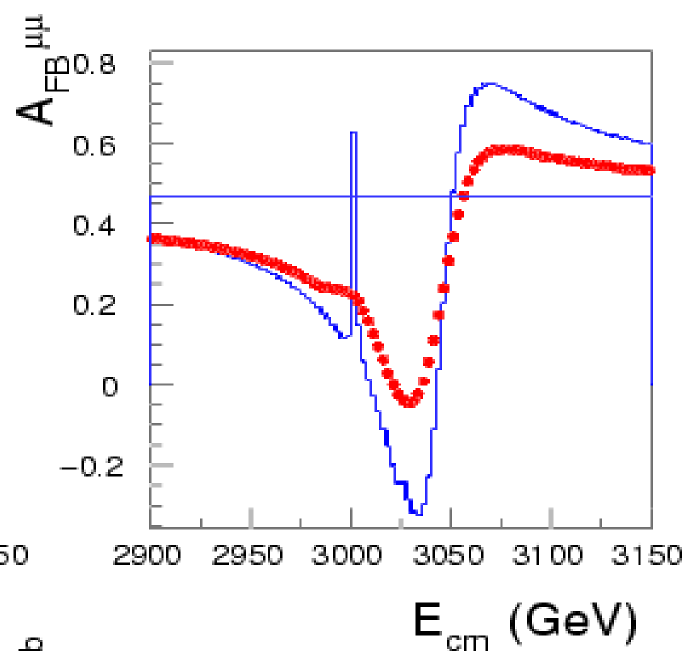


$\Delta\Gamma = 0.4\%$

$\Delta M = 0.01\%$

$M_1 - M_2 \sim 13\,\mathrm{GeV}$





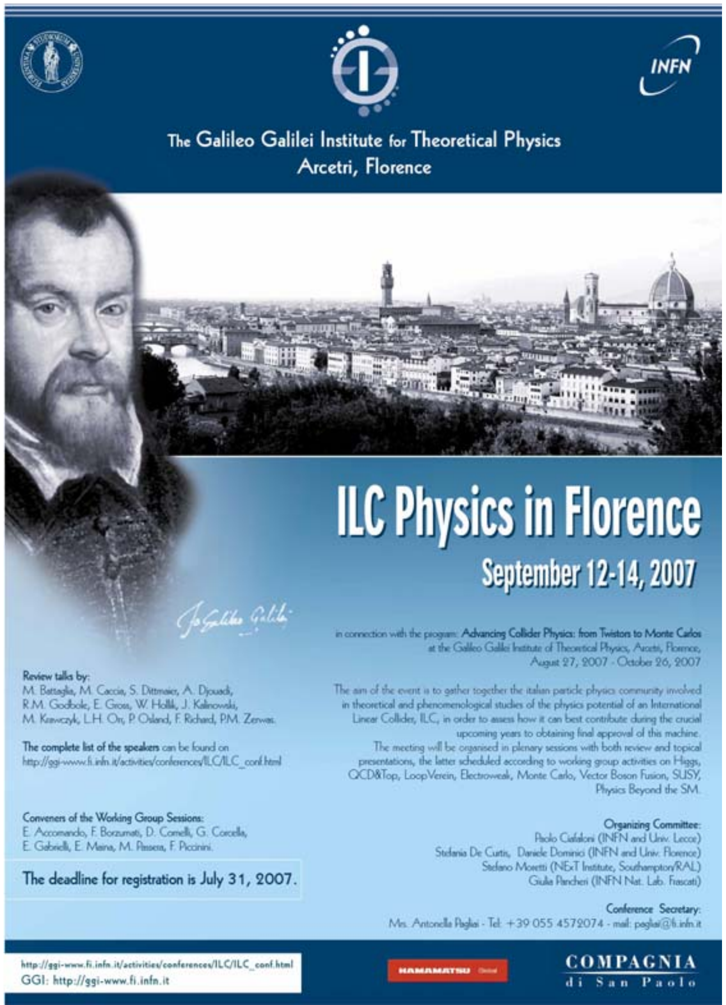
D-BESS model

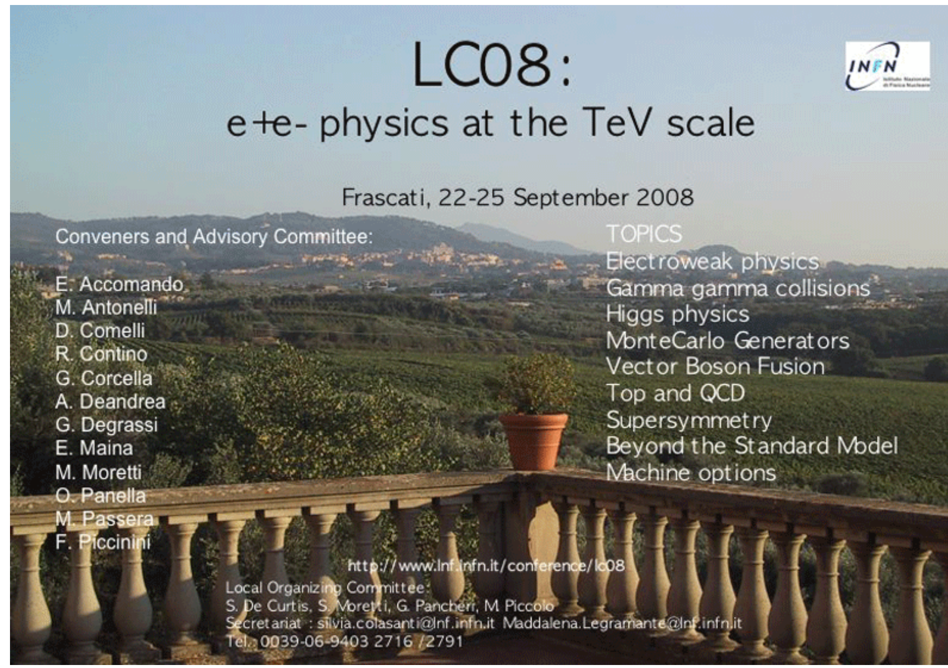
Conclusions

- Higher dimensional gauge theories naturally suggest the possibility of Higgsless theories
- Linear moose models provide an effective description of Higgsless theories. They are calculable, not excluded by the EW precision measurements and describe new spin-1 gauge bosons which delay the unitarity violation scale
- Drell-Yan processes are a very good channel to discover these extra gauge bosons at the LHC
- A_{FB} for distinguishing among various models with Z`
- 1TeV-LC has indirect sensitivity to the 4-site model and can profile low-mass Z`s. CLIC needed for heavy mass spin-1 resonances and for studying strong WW scattering with high statistics and precision

Ph-ILC Working Group

Italian particle physics community involved in theoretical and phenomenological studies of the LC physics potential





Next Workshop
Perugia, September 2009

extra slides

The Higgsless 4-site Linear Moose model charged gauge boson spectrum

$$\boxed{\begin{aligned} M_W^2 &\approx \tilde{M}_W^2 \left(1 - \frac{\tilde{g}^2}{g_1^2} z_W\right) \\ M_{1,c}^2 &\approx M_1^2 \left(1 + \frac{\tilde{g}^2}{2g_1^2}\right) \\ M_{2,c}^2 &\approx M_2^2 \left(1 + \frac{\tilde{g}^2}{2g_1^2} z^4\right) \end{aligned}}$$

$$\tilde{M}_W^2 = \tilde{g}^2 \frac{f_1^2 f_2^2}{f_1^2 + 2f_2^2} \quad z_W = \frac{f_1^4 + 2f_1^2 f_2^2 + 2f_2^4}{(f_1^2 + 2f_2^2)^2} = \frac{1}{2}(1 + z^4)$$

$$M_1^2 = f_1^2 g_1^2 \quad M_2^2 = g_1^2 (f_1^2 + 2f_2^2) \quad z = \frac{M_1}{M_2} = \frac{f_1}{\sqrt{f_1^2 + 2f_2^2}}$$

neglecting terms $\mathcal{O}(\tilde{g}^4/g_1^4)$

The Higgsless 4-site Linear Moose model neutral gauge boson spectrum

$$M_\gamma^2 = 0$$

$$M_Z^2 = \tilde{M}_Z^2 \left(1 - \frac{\tilde{g}^2}{g_1^2} z_Z\right)$$

$$M_{1,n}^2 = M_1^2 \left(1 + \frac{\tilde{g}^2}{g_1^2} \frac{\sec^2\tilde{\theta}}{2}\right)$$

$$M_{2,n}^2 = M_2^2 \left(1 + \frac{\tilde{g}^2}{g_1^2} \frac{z^4 \sec^2\tilde{\theta}}{2}\right)$$

$$\tan\tilde{\theta} = \frac{\tilde{g}'}{\tilde{g}} \qquad \tilde{M}_Z^2 = \frac{\tilde{M}_W^2}{\cos^2\tilde{\theta}}, \qquad z_Z = \frac{1}{2}\frac{(z^4 + \cos^2 2\tilde{\theta})}{\cos^2\tilde{\theta}}$$

neglecting terms $\mathcal{O}(\tilde{g}^4/g_1^4)$

The Higgsless 4-site Linear Moose model fermionic couplings charged sector

$$\mathcal{L}_{CC} = \bar{\psi}_L \gamma^\mu T^- \psi_L \left(a_W W_\mu^+ + a_1^c W_{1\mu}^+ + a_2^c W_{2\mu}^+ \right) + h.c.$$

$$a_W = -\frac{\tilde{g}}{\sqrt{2}} \left(1 - \frac{b}{2}\right) \left(1 - \frac{\tilde{g}^2}{g_1^2} \frac{z_W}{2}\right)$$

$$a_1^c = -\frac{g_1}{2(1+b_+)} \left(b_+ - \frac{\tilde{g}^2}{g_1^2}\right)$$

$$a_2^c = -\frac{g_1}{2(1+b_+)} \left(b_- - \frac{\tilde{g}^2}{g_1^2} z^2\right)$$

$$z_W = \frac{1}{2}(1+z^4) \qquad b = \frac{b_+ - b_- z^2}{(1+b_+)} \qquad b_\pm = b_1 \pm b_2 \qquad z = \frac{f_1}{\sqrt{f_1^2 + 2 f_2^2}}$$

neglecting terms $\mathcal{O}(\tilde{g}^4/g_1^4)$ **and** $\mathcal{O}(b_i \tilde{g}^2/g_1^2)$

The Higgsless 4-site Linear Moose model fermionic couplings neutral sector

$$\mathcal{L}_{NC} = \bar{\psi}\gamma^{\mu}(-a_F \mathbf{Q} A_{\mu} + a_1^n Z_{1\mu} + a_2^n Z_{2\mu} + a_Z Z_{\mu})\psi$$

$$a_F = \tilde{g} s_{\tilde{\theta}} \left(1 - \frac{\tilde{g}^2}{g_1^2} z_{\gamma}\right) \equiv e$$

$$a_Z = -\frac{\tilde{g}}{c_{\tilde{\theta}}} \left(1 - \frac{b}{2}\right) \left(1 - \frac{\tilde{g}^2}{g_1^2} \frac{z_Z}{2}\right) \left[\mathbf{T^3} - \frac{s_{\tilde{\theta}}^2}{(1 - \frac{b}{2})} \left(1 - \frac{\tilde{g}^2 c_{\tilde{\theta}}}{g_1^2 s_{\tilde{\theta}}} z_{Z\gamma}\right) \mathbf{Q}\right]$$

$$a_1^n = -\frac{g_1}{\sqrt{2}(1 + b_+)} \left(b_+ - \frac{\tilde{g}^2}{g_1^2} \frac{c_{2\tilde{\theta}}}{c_{\tilde{\theta}}^2}\right) \mathbf{T^3} + \frac{\tilde{g}^2 \tan^2 \tilde{\theta}}{\sqrt{2} g_1} \mathbf{Q}$$

$$a_2^n = -\frac{g_1}{\sqrt{2}(1 + b_+)} \left(b_- - \frac{\tilde{g}^2}{g_1^2} \frac{z^2}{c_{\tilde{\theta}}^2}\right) \mathbf{T^3} - \frac{\tilde{g}^2 z^2 \tan^2 \tilde{\theta}}{\sqrt{2} g_1} \mathbf{Q}$$

with $$z_{\gamma} = s_{\tilde{\theta}}^2, \qquad z_Z = \frac{1}{2} \frac{(z^4 + c_{2\tilde{\theta}}^2)}{c_{\tilde{\theta}}^2}, \qquad z_{Z\gamma} = -\tan\tilde{\theta} c_{2\tilde{\theta}}$$

$$\mathbf{T^3} = \tau_L^3/2 \ (\tau_L^3 \psi_L = \pm \psi_L \text{ and } \tau_L^3 \psi_R = 0), \ \tan\tilde{\theta} = s_{\tilde{\theta}}/c_{\tilde{\theta}} = \tilde{g}'/\tilde{g}$$

Low-energy limit

The low-energy limit of the theory is obtained by eliminating the A_i $(i = 1, \cdots K)$ fields with the solution of the e.o.m. for $g_i >> \tilde{g}$ corresponding to heavy masses for A_i:

$$A_i^{\pm} = \frac{1}{g_i}(\tilde{g}\tilde{W}^{\pm} z_i), \quad A_i^3 = \frac{1}{g_i}(\tilde{g}'\tilde{\mathcal{Y}} y_i + \tilde{g}\tilde{W}^3 z_i)$$

with $z_i = \sum_{j=i+1}^{K+1} f^2/f_j^2$ and $y_i = 1 - z_i$. By substituting in $\mathcal{L}^{(2)}$:

$$\boxed{\mathcal{L}_{eff}^{(2)} = -\frac{1}{4}(1+z_\gamma)\tilde{A}_{\mu\nu}\tilde{A}^{\mu\nu} - \frac{1}{2}(1+z_W)\tilde{W}^+_{\mu\nu}\tilde{W}^{-\mu\nu} - \frac{1}{4}(1+z_Z)\tilde{Z}_{\mu\nu}\tilde{Z}^{\mu\nu} + \frac{1}{2} z_{Z\gamma}\tilde{A}_{\mu\nu}\tilde{Z}^{\mu\nu}}$$

$$z_\gamma = \tilde{s}_\theta^2 \sum_{i=1}^{K}\left(\frac{\tilde{g}}{g_i}\right)^2, \quad z_w = \sum_{i=1}^{K}\left(\frac{\tilde{g}}{g_i}\right)^2 (1-y_i)^2, \quad z_z = \frac{1}{\tilde{c}_\theta^2}\sum_{i=1}^{K}\left(\frac{\tilde{g}}{g_i}\right)^2\left(\tilde{c}_\theta^2 - y_i\right)^2$$

$$z_{z\gamma} = -\frac{\tilde{s}_\theta}{\tilde{c}_\theta}\sum_{i=1}^{K}\left(\frac{\tilde{g}}{g_i}\right)^2\left(\tilde{c}_\theta^2 - y_i\right), \quad M_Z^2 = \tilde{M}_Z^2(1 - z_z), \quad M_W^2 = \tilde{M}_W^2(1 - z_w)$$

From this, after a finite renormalization, one can evaluate the EW parameters ε_i.

Electroweak Corrections

(Burgess et al.; Anichini, Casalbuoni, DC)

EW precision tests put very stringent bounds on models of new physics. These limits, assuming universality among different generations, are coded in 3 parameters (using G_F, m_Z and α as input parameters)

$$\Delta r_W : \qquad \frac{m_W^2}{m_Z^2} = \left[\frac{1}{2} + \sqrt{\frac{1}{4} - \frac{\pi\alpha(m_Z)}{\sqrt{2} G_F m_Z^2 (1 - \Delta r_W)}} \right]^2$$

And from the modifications of the Z couplings to fermions:

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

$$g_V = \frac{1}{2}(T_3)_L - \bar{s}_\theta^2 Q_{em}, \quad g_A = -\frac{1}{2}(T_3)_L$$

$$\bar{s}_\theta^2 = s_\theta^2 (1 + \Delta k), \quad c_\theta^2 = \frac{1}{2} + \sqrt{\frac{1}{4} - \frac{\pi\alpha(m_Z)}{\sqrt{2} G_F m_Z^2}}$$

It is usual to introduce another set of parameters ε_i, i=1,2,3 (Altarelli, Barbieri, 1991), or S,T,U (Peskin, Takeuchi, 1990), much more convenient on the theoretical side

$$\boxed{\epsilon_1 = \Delta\rho, \quad \epsilon_2 = c_\theta^2\,\Delta\rho + \frac{s_\theta^2}{c_{2\theta}}\Delta r_W - 2 s_\theta^2\,\Delta k, \quad \epsilon_3 = c_\theta^2\,\Delta\rho + c_{2\theta}\,\Delta k}$$

At the lowest order in the EW corrections the parameters ε_1 and ε_2 vanish if the SB sector has a SU(2) custodial symmetry (as it is the case for the BESS model). At the same order, ε_3 has a convenient dispersive representation

$$\epsilon_3 = -\frac{g^2}{4\pi}\int_0^\infty \frac{ds}{s^2}\left[\mathrm{Im}\,\Pi_{VV}(s) - \mathrm{Im}\,\Pi_{AA}(s)\right], \quad \Pi_{VV(AA)} = \langle J_{V(A)} J_{V(A)}\rangle_0$$

Assuming vector dominance:

$$\mathrm{Im}\Pi_{VV(AA)}(s) = -\pi\, g_{V(A)}^2\,\delta\left(s - M_V^2\right), \quad \langle 0|J^\mu_{V(A)}|V(k)\rangle = g_{V(A)}\epsilon^\mu(k)$$

In the BESS model $g_{V(A)} = (f_1^2 \pm f_2^2) g_1$ leading to:

$$\epsilon_3 = \frac{g^2}{4}\frac{g_V^2}{M_V^4} = \left(\frac{g}{g_1}\right)^2 \frac{f_1^2 f_2^2}{(f_1^2+f_2^2)^2} \xrightarrow{f_1=f_2} \frac{1}{4}\left(\frac{g}{g_1}\right)^2 \xrightarrow{g_1=g''/2} \left(\frac{g}{g''}\right)^2$$

Top quark problem

(Foadi,Schmidt; Bechi,Casalbuoni,D.C., Dominici)

Allowing a microscopically broken Lorentz invariance

$$R_f = R/\mathtt{k} \ : \quad S^{bulk}_{top} = \frac{1}{\hat{g}_5^2}\int d^4x \int_0^{\pi R} dy \left\{ \bar{\Psi} i\gamma^\mu D_\mu \Psi + \frac{\mathtt{k}}{2}[\bar{\Psi}\gamma^5\partial_5\Psi - \partial_5\bar{\Psi}\gamma^5\Psi] - M\bar{\Psi}\Psi \right\}$$

$$\begin{aligned} S^{\Sigma}_{4TOP} &= \frac{1}{\hat{g}_5^2}\int d^4x \int_0^{\pi R} dy\sqrt{g}\delta(y)\left\{\left[\frac{\hat{g}_5^2}{\mathtt{t}_L^2}\bar{q}_L i \not{D}_4 q_L + \mathtt{k}\left(\bar{\psi}_R q_L + \bar{q}_L\psi_R - \frac{1}{2}\bar{\Psi}\Psi\right)\right]\right. \\ &+ \left.\delta(y-\pi R)\left[\frac{\hat{g}_5^2}{\mathtt{t}_R^2}\bar{q}_R i \not{D}_4 q_R + \mathtt{k}\left(\bar{q}_R\psi_L + \bar{\psi}_L q_R - \frac{1}{2}\bar{\Psi}\Psi\right)\right]\right\} \end{aligned}$$

$$\psi_L(p,0) \equiv \mathtt{t}_L q_L \ , \qquad \psi_R(p,\pi R) \equiv q_R \mathtt{t}_R \ .$$

Interaction unchanged; rescaled mass $m_f \sim \mathtt{k}\frac{\mathtt{t}_{R;f}\mathtt{t}_L}{\hat{g}_5^2}$.

Exp. Bound on the right-handed CC for the III generation
$\mathtt{k}^{CC}_R = \frac{1}{2}\sqrt{B_{R;t}B_{R;b}} \leq 4\times 10^{-3}$;
Unitarity $R^{-1} \sim 1$ TeV ; ϵ_3 global cancellation:

$$\frac{m_t}{m_b} = \frac{\mathtt{t}_{R;t}}{\mathtt{t}_{R;b}} \sim 40 \Rightarrow \mathtt{k} > 2 \ .$$

Mass spectrum (charged sector): $f_i = f_c$; $g_i = g_c$; $x = g/g_c$

$$M^2 = g_c^2 f_c^2 \begin{pmatrix} x^2 & -x & 0 & \dots & 0 & 0 \\ -x & 2 & -1 & \dots & 0 & 0 \\ 0 & -1 & 2 & \ddots & 0 & 0 \\ \vdots & \vdots & \ddots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & \dots & 2 & -1 \\ 0 & 0 & 0 & \dots & -1 & 2 \end{pmatrix}$$

To the leading order in x:

$$M_W^2 = \frac{g^2 f_c^2}{K+1} \longrightarrow f_c^2 = (K+1)\frac{v^2}{4}$$

$$M_n^2 = 4 g_c^2 f_c^2 \sin^2\left(\frac{\pi n}{2(K+1)}\right) \qquad \textbf{n=1,..,K}$$

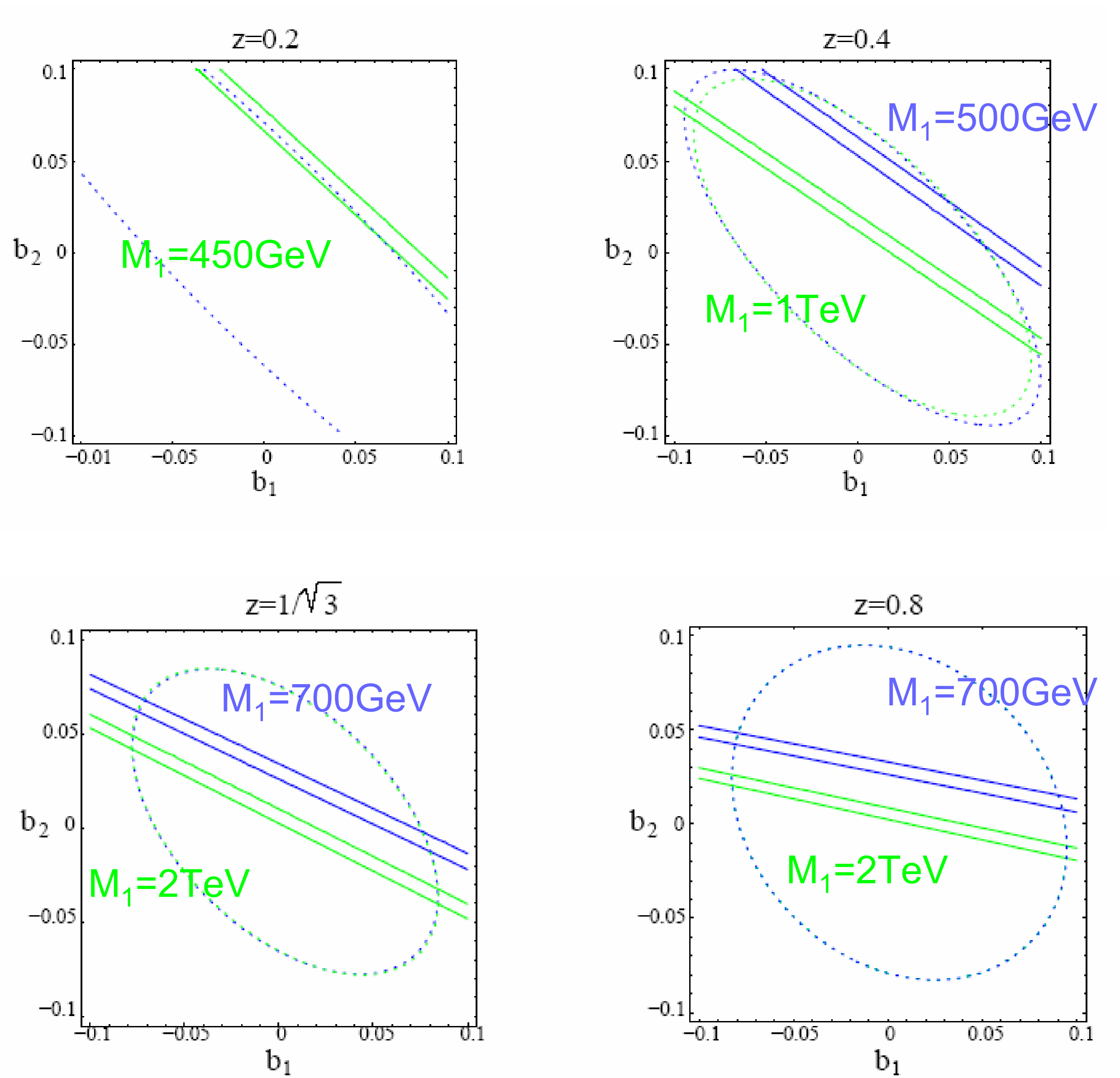
K=1 $\quad M_1^2 = v^2 g_c^2$

K=2 $\quad M_1^2 = \frac{3}{4} v^2 g_c^2, \quad M_2^2 = \frac{9}{4} v^2 g_c^2, \quad \left(z = \frac{1}{\sqrt{3}}\right)$

K=3 $\quad M_1^2 \simeq 0.6 v^2 g_c^2, \quad M_2^2 = 2 v^2 g_c^2, \quad M_3^2 \simeq 3.4 v^2 g_c^2$

Ex: $g_c \sim 2 \div 2.5$, M_1=500 GeV, M_2=900 GeV, M_3=1200 GeV, …..
$g_c \sim 4 \div 5$, M_1=1000 GeV, M_2=1800 GeV, M_3=2400 GeV, …..

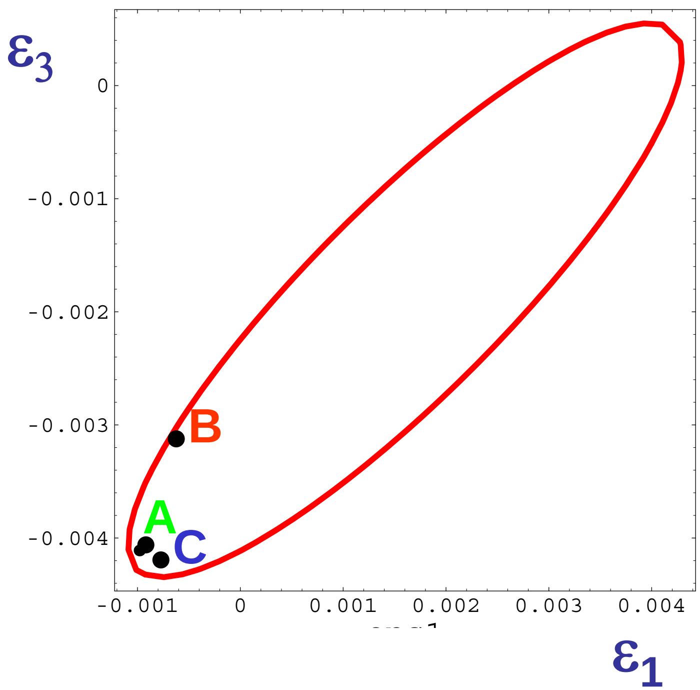
The Higgsless 4-site Linear Moose model

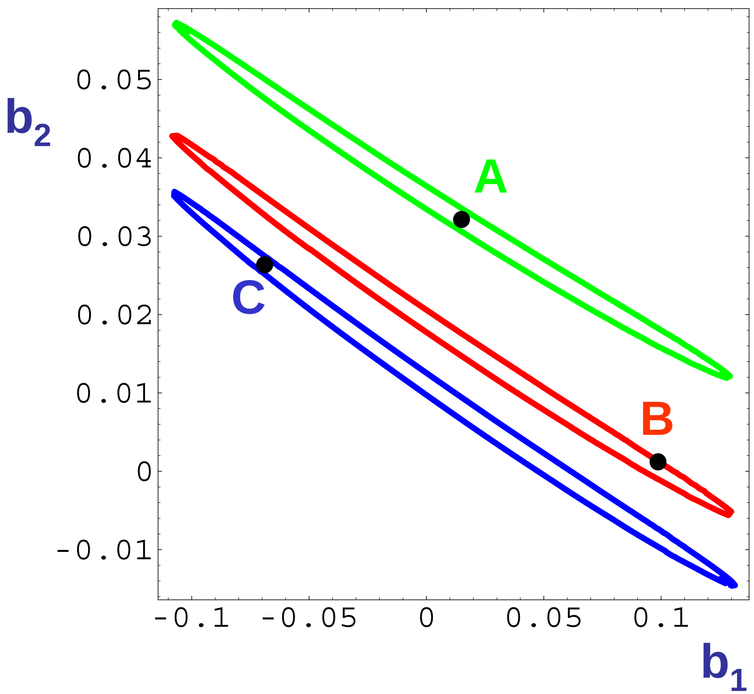


95% CL bounds on (b_1,b_2) from ε_1 (dash) and ε_3 (solid)

$M_2=M_1\,/\,z$

EW precision observables





z = 0.8

M_H=2 TeV

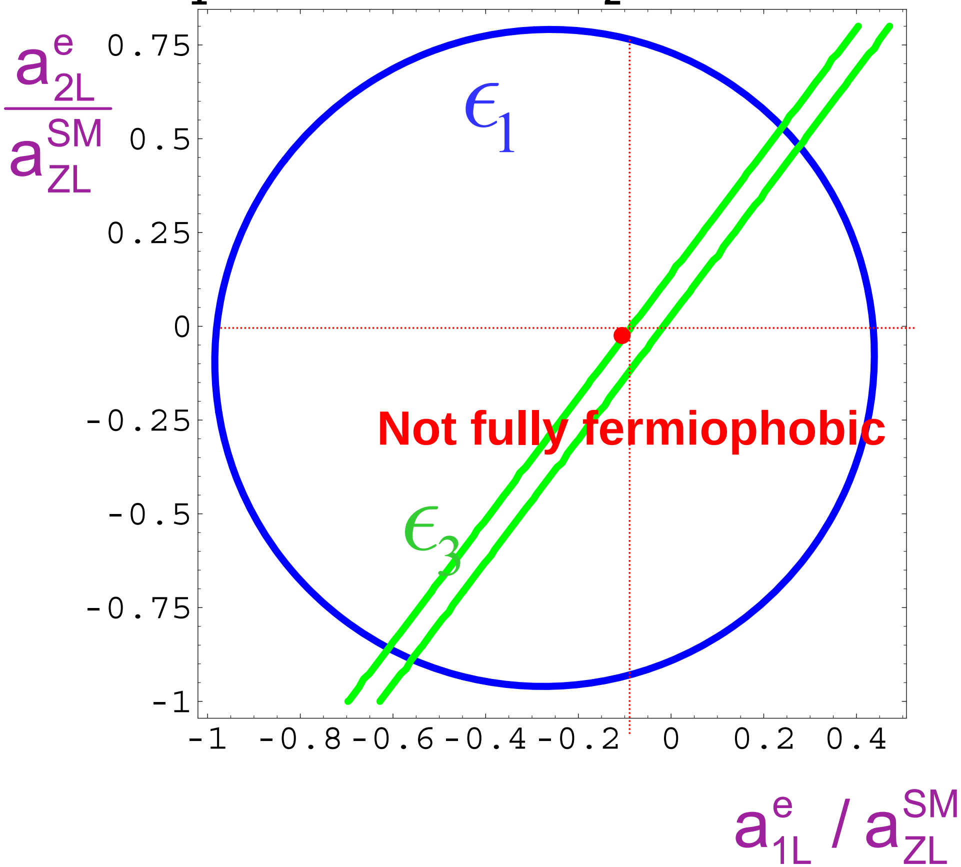
0.7
M_1 (TeV)= 1.0
1.6

The Higgsless 4-site Linear Moose model

EW precision tests

$$\epsilon_3 \sim \sqrt{2}\left(\frac{a^e_{1L}}{g_1} - z^2 \frac{a^e_{2L}}{g_1}\right) - \frac{e^2}{g_1^2}\frac{(1+z^4)}{\cos^2\theta_W}$$

M_1=1000 GeV and M_2=1300 GeV



Bounds on neutral couplings (and masses) from low energy precision measurements ε_i

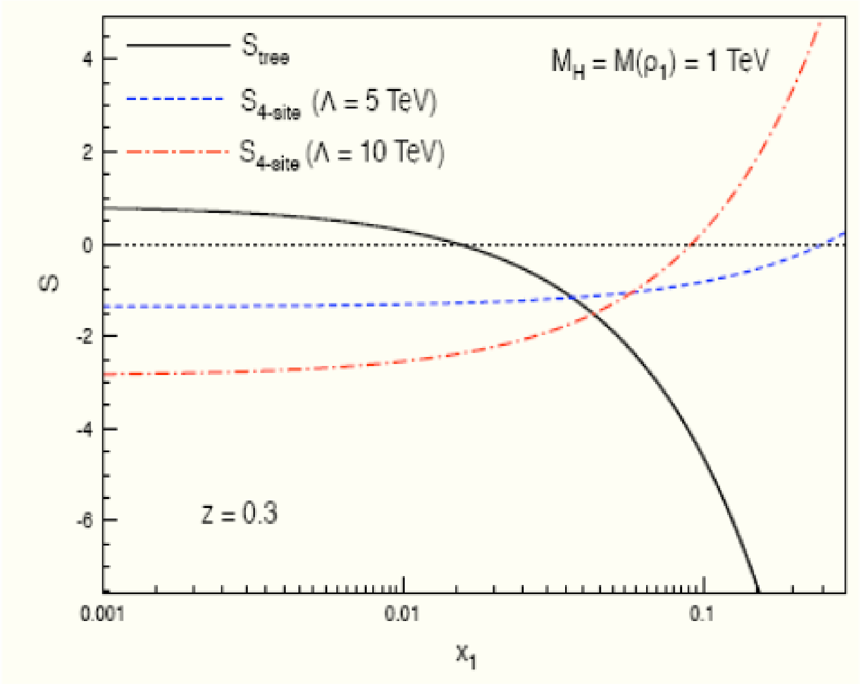
$-0.15 < a^e_{1L,2L}(Z`_{1,2}\ ee) < 0.1$

Ideal cancellation $a^c_2 = a^c_1 = 0$
BUT not fully fermiophobic

Dawson talk:

One-Site delocalization $L = -x_1 \overline{\psi} \gamma^\mu i (D_\mu \Sigma_1) \Sigma_1^{+} P_L \psi$ $x_1 = b_1$

One-Loop Results in 4-Site Model



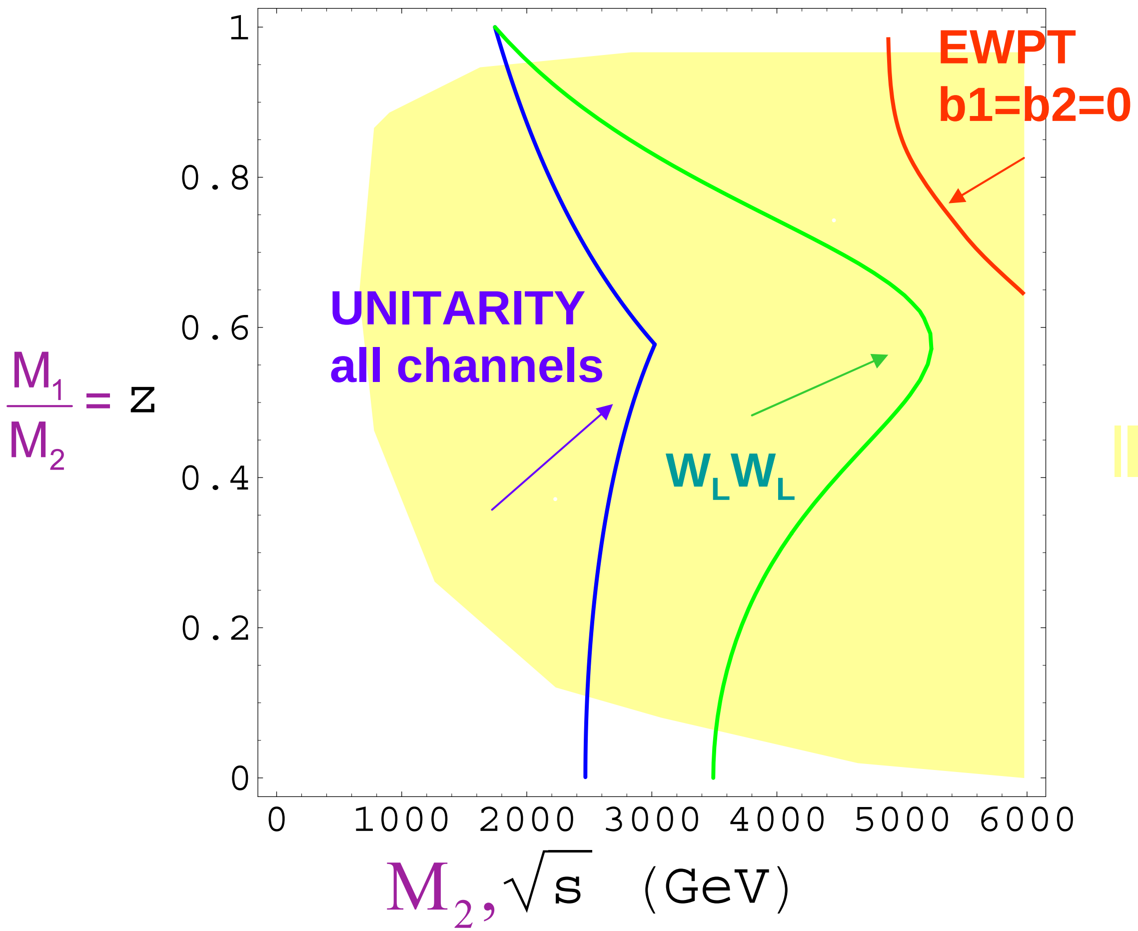
$$z = \frac{M_{\rho_1^\pm}}{M_{\rho_2^\pm}}$$

Large fine tuning needed at 1-loop

but also at tree level with fermions delocalized only to the first site.

Interesting to include b_2

The Higgsless 4-site Linear Moose model



region of validity of the perturbative expansion

$(g/g_1)^4 < 0.005$

	$M_{(1,2),c}$(GeV)	$\Gamma_{1,2}$(GeV)	a^c_1	a^c_2
1	508,1251	6.2,35.5	0.03	0.20
2	508,1251	6.2,28.9	-0.01	-0.03
3	1745,3001	183,746	0.15	0.47
4	1745,3001	183,734	-0.15	-0.44
5	1009,1255	35.3,30.5	0.14	0.24
6	1009,1255	33.1,22.2	-0.06	-0.09

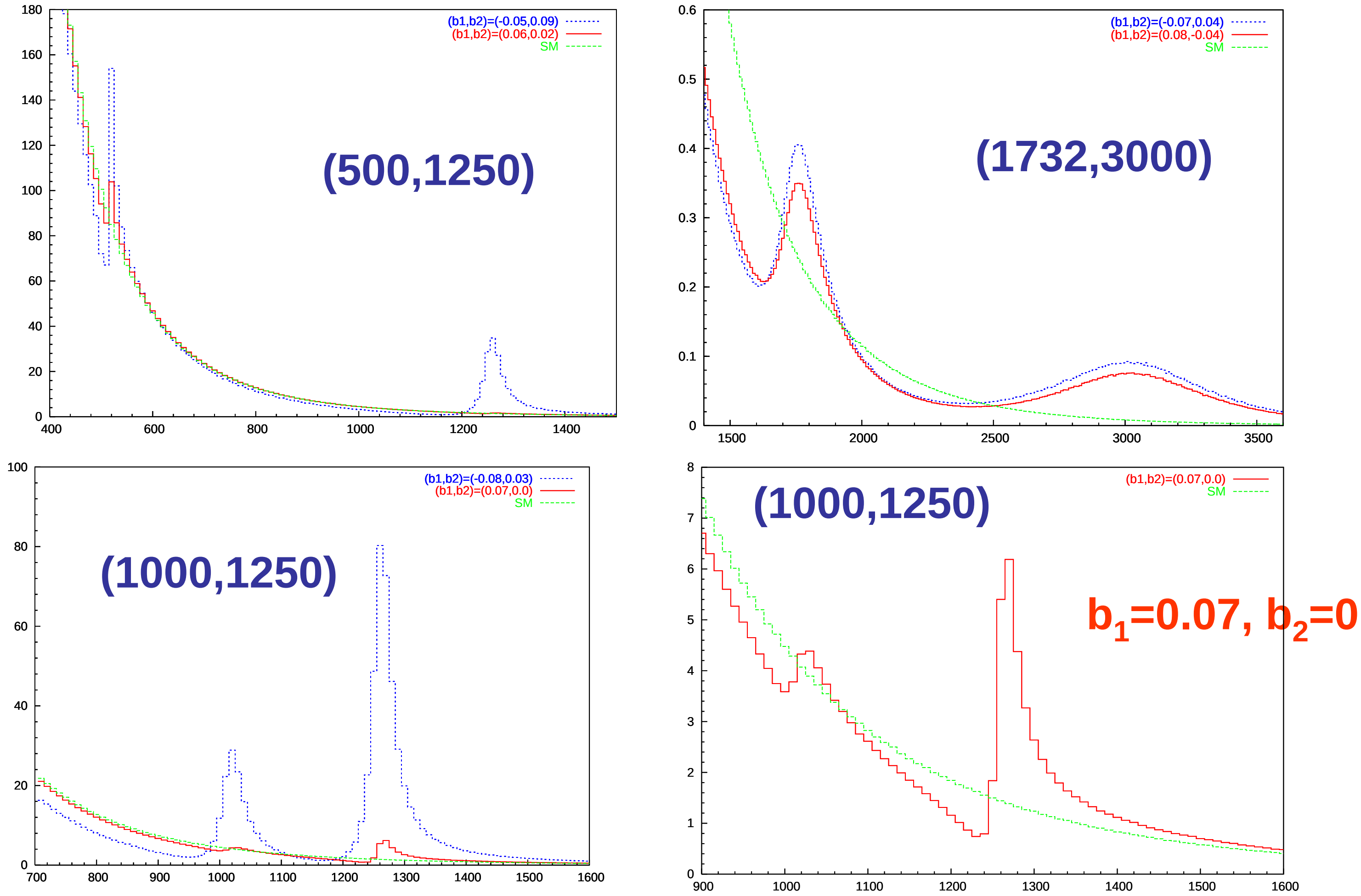
charged

	$M_{(1,2),n}$(GeV)	$\Gamma_{1,2}$(GeV)	a^e_{1L}	a^e_{1R}	a^d_{1L}	a^d_{1R}	a^u_{1L}	a^u_{1R}	a^e_{2L}	a^e_{2R}	a^d_{2L}	a^d_{2R}	a^u_{2L}	a^u_{2R}
1	510,1251	6.4,36.0	0.12	0.11	0.05	0.04	-0.09	-0.07	0.43	-0.02	0.46	-0.01	-0.44	0.01
2	510,1251	6.3,28.8	0.02	0.11	-0.05	0.04	0.01	-0.07	-0.08	-0.02	-0.07	-0.01	0.07	0.01
3	1736,3001	184,756	0.36	0.04	0.34	0.01	-0.35	-0.02	1.06	-0.01	1.07	0.0	-1.07	0.01
4	1736,3001	184,742	-0.32	0.04	-0.34	0.01	0.33	-0.02	-1.0	-0.01	-0.99	0.0	1.0	0.01
5	1012,1256	36.2,32.0	0.37	0.08	0.31	0.03	-0.34	-0.06	0.50	-0.05	0.54	-0.02	-0.52	0.04
6	1012,1256	33.7,22.9	-0.11	0.08	-0.16	0.03	0.14	-0.06	-0.24	-0.05	-0.20	-0.02	0.22	0.04

neutral

The Higgsless 4-site Linear Moose model, $Z`_{1,2}$ production

(M1,M2) GeV



Total # of evts in a 10GeV-bin versus M_{inv}(l+l-) for L=10fb^{-1}. Sum over e,μ

Z'_1, Z'_2 production

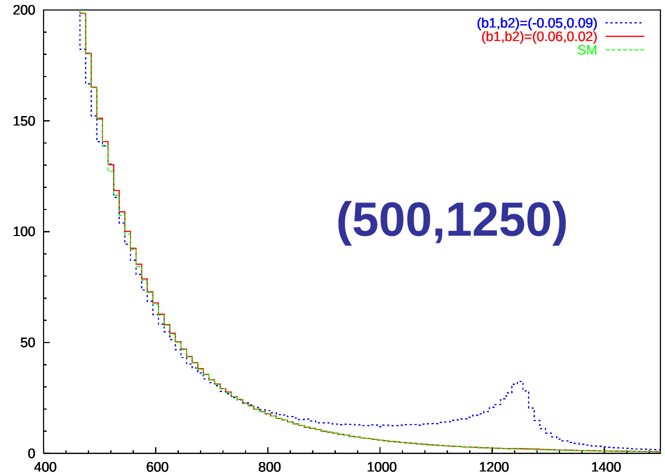
	$M_{1,2}$(GeV)	$b_{1,2}$	$N_{evt}^{sig}(Z_1)$	$N_{evt}^{tot}(Z_1)$	$\sigma(Z_1)$	$N_{evt}^{sig}(Z_2)$	$N_{evt}^{tot}(Z_2)$	$\sigma(Z_2)$
1	500,1250	-0.05,0.09	47	154	3.8	134	143	11.2
2	500,1250	0.06,0.02	11	123	1.0	0	9	0.0
3	1732,3000	-0.07,0.04	7	10	2.2	7	8	2.5
4	1732,3000	0.08,-0.04	5	9	1.7	6	6	2.4
5	1000,1250	-0.08,0.03	108	119	9.9	291	302	16.7
6	1000,1250	0.07,0.0	3	28	0.0	15	22	3.2

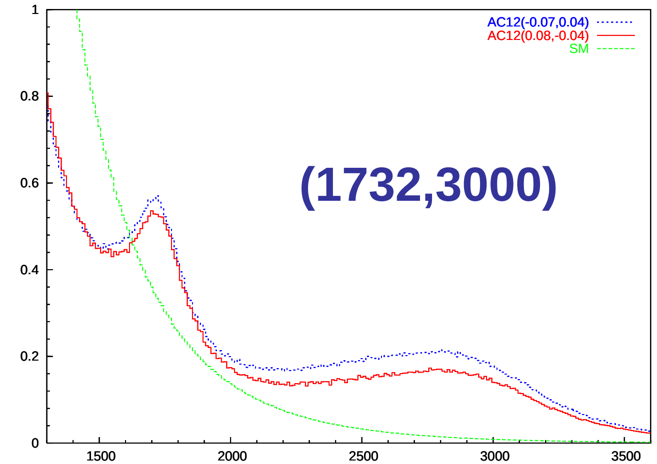
# of evts for the $Z`_{1,2}$ DY production within $|M_{inv}(l^+l^-)-M_i| < \Gamma_i$

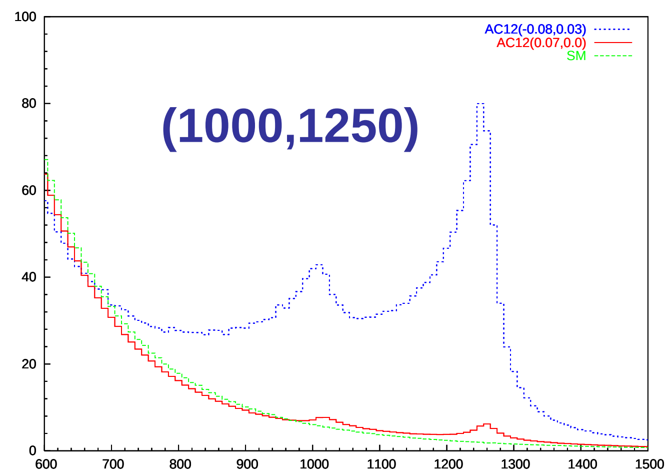
$\sigma = N_{evt}^{sig}/\sqrt{N_{evt}^{tot}}$ for an integrated luminosity L=10 fb^{-1}

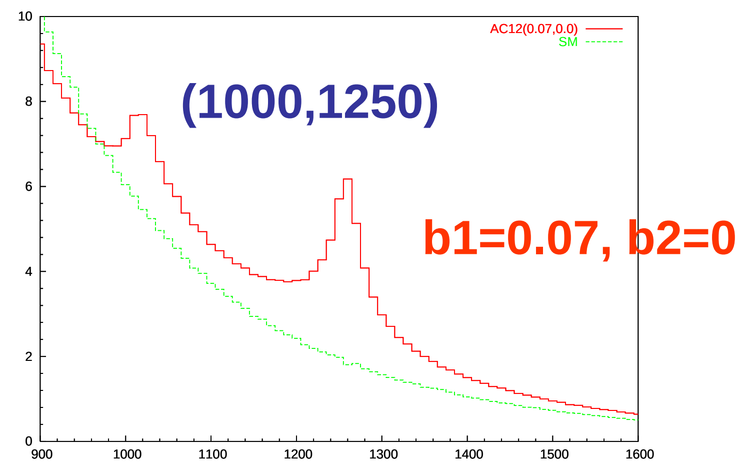
The Higgsless 4-site Linear Moose model, W`$_{1,2}$ production

(M1,M2) GeV









Total # of evts in a 10GeV-bin versus Mt(lν) for L=10fb-1. Sum over e,μ