Drell-Yan production at the LHC in deconstructed Higgsless models

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Outline of the talk

based on papers by: Accomando, Casalbuoni, DC, Dolce, Dominici, Fedeli, Gatto

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

Problems of the Higgs sector

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

$$\frac{1}{\lambda(M)} = \frac{1}{\lambda(m_H)} - \frac{3}{4\pi^2}\log\frac{M^2}{m_H^2} \qquad M_{Lp} = m_H e^{4\pi^2 v^2/3m_H^2}$$

- 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:

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

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

If we keep the cutoff ~ 1 TeV, λ is large, m_H is O(TeV). The theory is non perturbative

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

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

Symmetry Breaking without the Higgs

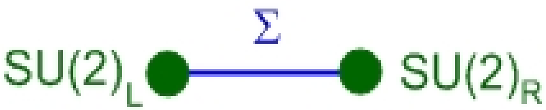
- A strongly interacting theory can only rely on an **effective description.** For the SB sector use a general σ model formulation

- For $SU(2)_L x SU(2)_R / SU(2)_V$ 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**

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



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

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

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

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

The unitarity properties improve (as it is known from QCD)

To be consistent with the non-linear realization use the tool of hidden gauge symmetries (Bando,Kugo, et al 1985):

- Introduce a non- dynamical gauge symmetry and 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 vector resonances as 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

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 $SU(2)_L x SU(2)_R/SU(2)$ with an additional local group G_1=SU(2)

New vector resonances as the gauge fields of G_1

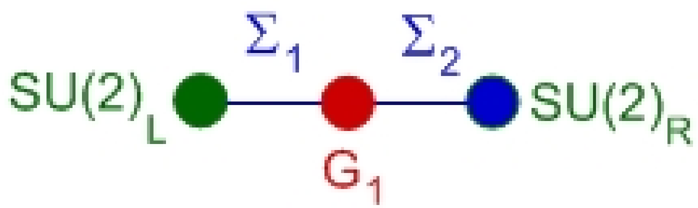
$$\boxed{L = f_1^2 \mathrm{Tr}\left[D_\mu \Sigma_1^\dagger D^\mu \Sigma_1 \right] + f_2^2 \mathrm{Tr}\left[D_\mu \Sigma_2^\dagger D^\mu \Sigma_2 \right] - \frac{1}{2} \mathrm{Tr}\left[F_{\mu\nu}(V) F^{\mu\nu}(V) \right]}$$

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

This model describes 6 scalar fields and 3 gauge bosons.

After the breaking $SU(2)_L x SU(2)_R x SU(2)_{local} \rightarrow SU(2)$, 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

$$M_V^2 = (f_1^2 + f_2^2) g_1^2 \quad (g_1 = \text{gauge coupling of } V)$$



Linear Moose model

(Son,Stephanov; Foadi et al; Casalbuoni et al; Chivukula et al; Georgi; Hirn,Stern)

- **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. Important feacture: $SU(2)_{diag}$ is a custodial symmetry**
- **The BESS model can be recast in a 3-site model (K=1), and its generalization with vector and axial-vector resonances (Casalbuoni, DC, Dominici, Gatto, Feruglio, 1989) can be recast in a 4-site model (K=2) (see also Foadi,Frandsen,Ryttov,Sannino, 2007)**

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 compact fifth dimension → linear moose as an effective scheme for different theoretical context with extra spin-one particles

- The continuum limit is defined by

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

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

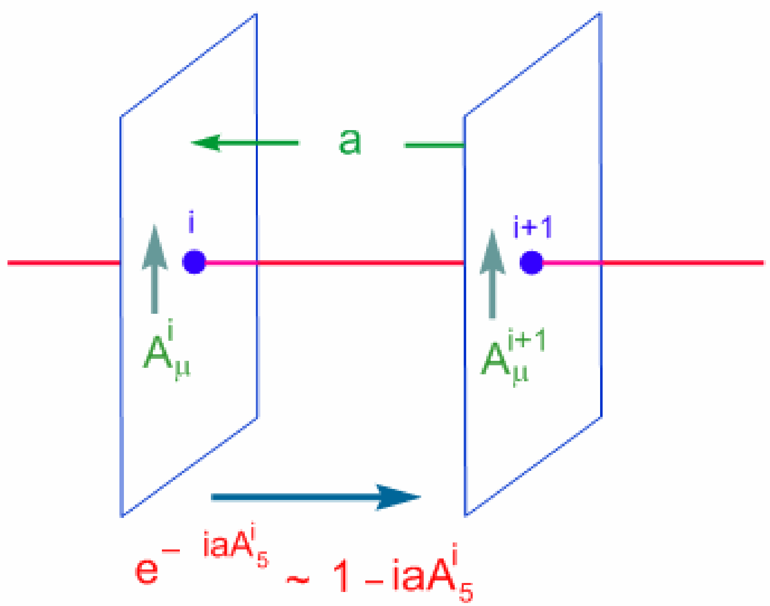
a = lattice spacing, R= compactification radius, g_5= bulk gauge coupling

- The link couplings f_i and the gauge couplings g_i can be simulated in the continuum by generally warped 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 Σ 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, 2001)

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

- Sintetically described by a moose diagram (Georgi, 1986, Arkani-Hamed, Cohen, Georgi, 2001)

Unitarity bounds for the Linear Moose

(Chivukula, He; 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 $s \gg M_W^2$ use the equivalence theorem and evaluate the amplitudes for the corresponding GB's $\Sigma_i = e^{i\vec{\pi}_i\cdot\vec{\tau}/2f_i}$ In the high-energy limit: $A_{\pi_i^+\pi_i^-\to\pi_i^+\pi_i^-} \to -\frac{u}{4f_i^2}$
- The unitarity limit is determined by the smallest link coupling

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

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

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

$$\Downarrow$$

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

Hardly compatible with electro-weak experimental constraints

Constraints from EWPT

- Oblique 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 loops see Dawson et al, Chivukula et al, Barbieri et al):

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

- Since $\boxed{0 \le y_i \le 1 \quad \Rightarrow \quad \varepsilon_3 \ge 0}$

- 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, $g_c\sim 10\sqrt{K}$ → strongly interacting gauge bosons → UNITARITY VIOLATION

Direct fermionic couplings

(Csaki et al, Foadi et al, Casalbuoni et al, Chivukula et al)

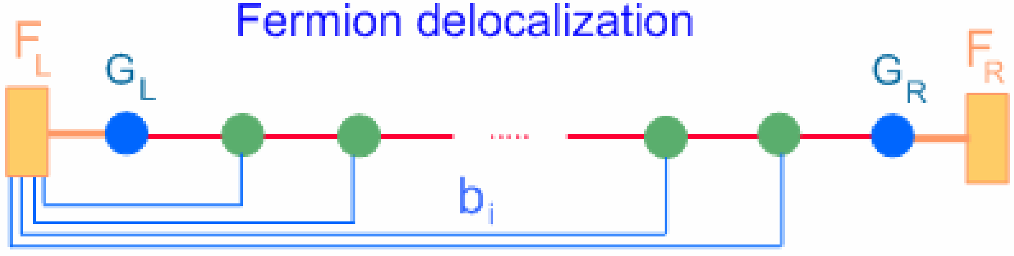
- Left- and right-handed fermions, $\psi_{L\,(R)}$ are coupled to the ends of the moose, but they can couple to any site by using a Wilson line

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

$$\Downarrow$$

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

Fermion delocalization



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

Extra contribution to ε_3

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

b_i from 5D bulk fermions with brane kinetic terms

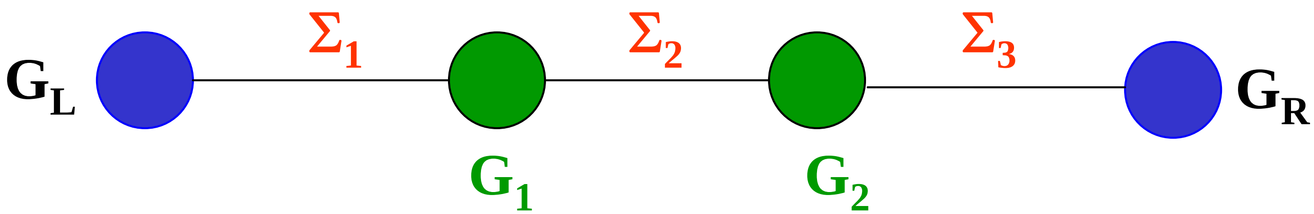
(Foadi,Gopalakrishna,Schmidt; Csaki,Hubitsz,Meade; Bechi,Casalbuoni, DC, Dominici)

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)

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

$$M_1 = f_1 g_1$$

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

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

New charged and neutral gauge bosons almost degenerate

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

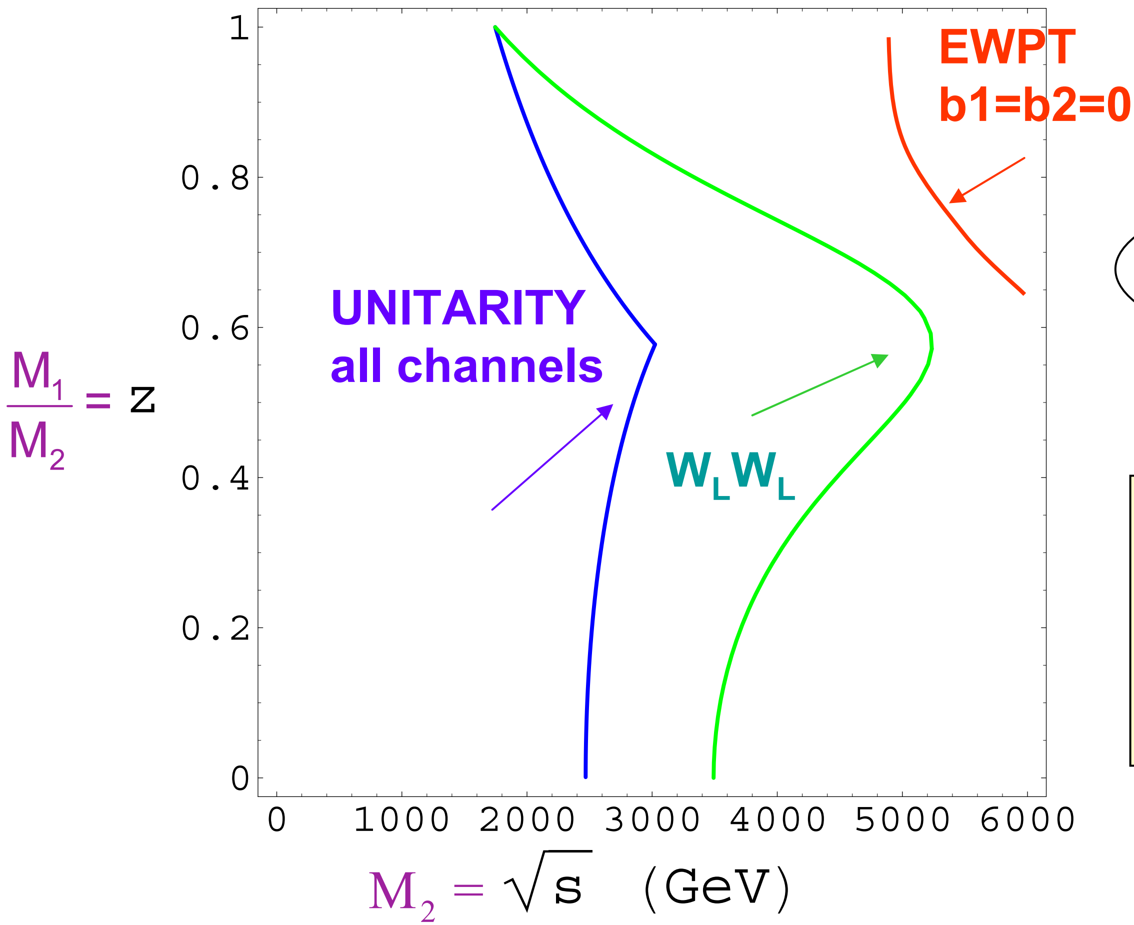
The Higgsless 4-site Linear Moose model

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: $b_{1,2} \neq 0$

The Higgsless 4-site Linear Moose model

EW precision tests

Calculations $O(e^2/g_1^2)$, exact in b_1, b_2

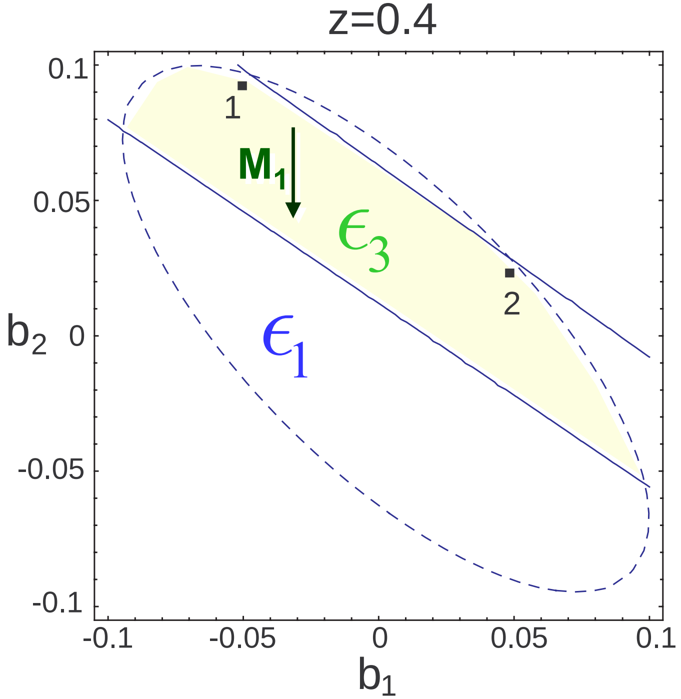
$$\varepsilon_{1,2} \approx O(b^2), \quad \varepsilon_3 \approx \left(\frac{g^2}{2g_1^2}(1-z^4) - \frac{b}{2} \right)$$

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

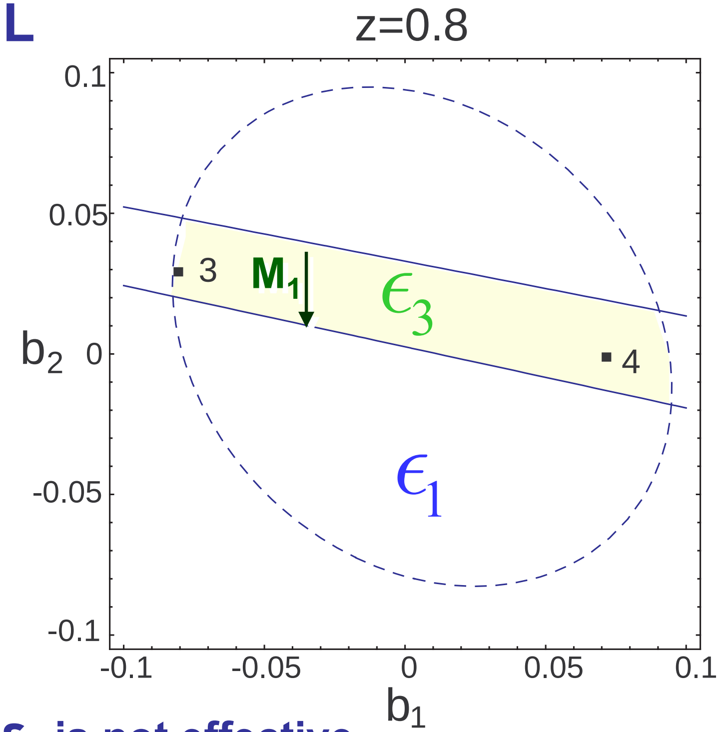
$M_2 = M_1/z$

95%CL

$500 < M_1 < 1000$ GeV



$700 < M_1 < 1600$ GeV



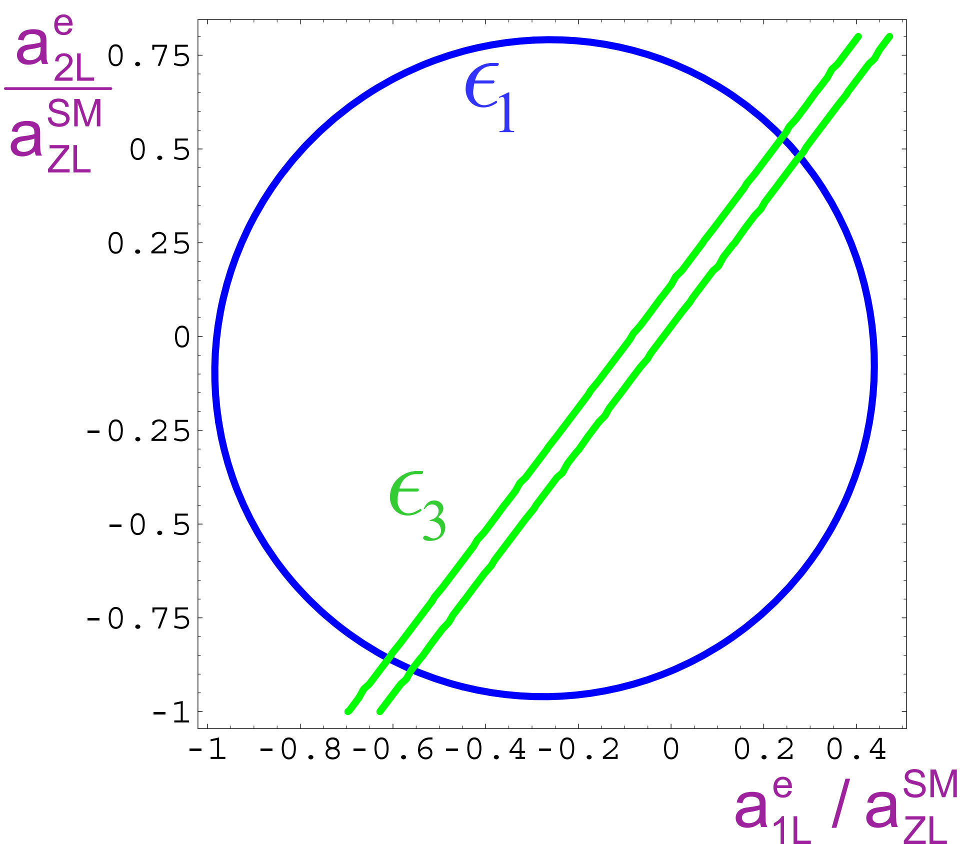
the bound from ε_2 is not effective

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 for fixed mass values

ϵ_3 bounds favour $a^e_{2L} > a^e_{1L}$

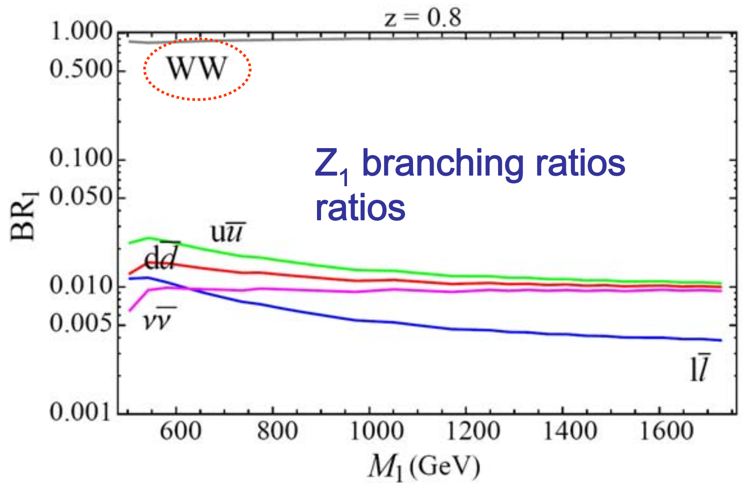
$$\boxed{-0.15 < a^L_{1,2}(Z_{1,2}\, ee) < 0.1}$$

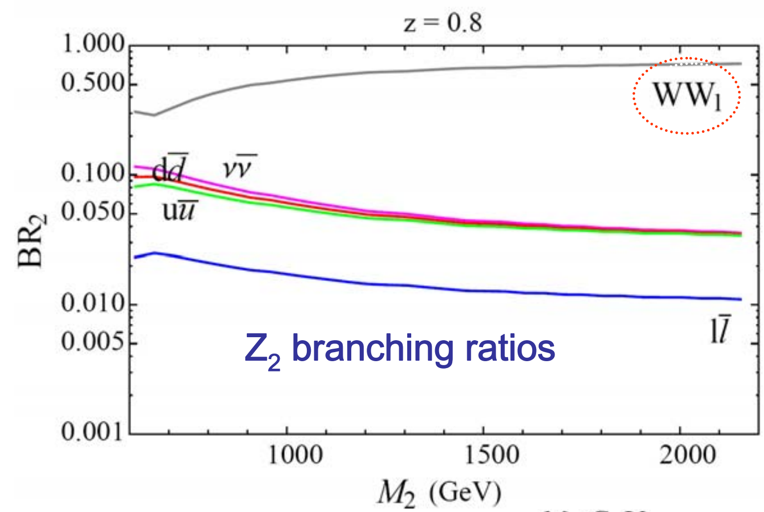
couplings are SM-size

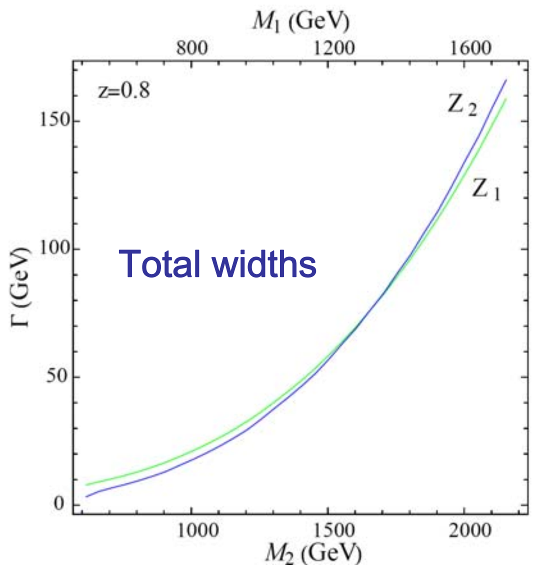
for larger $M_{1,2}$ the bounds from ε_1 are less stringent

Z_1, Z_2 properties

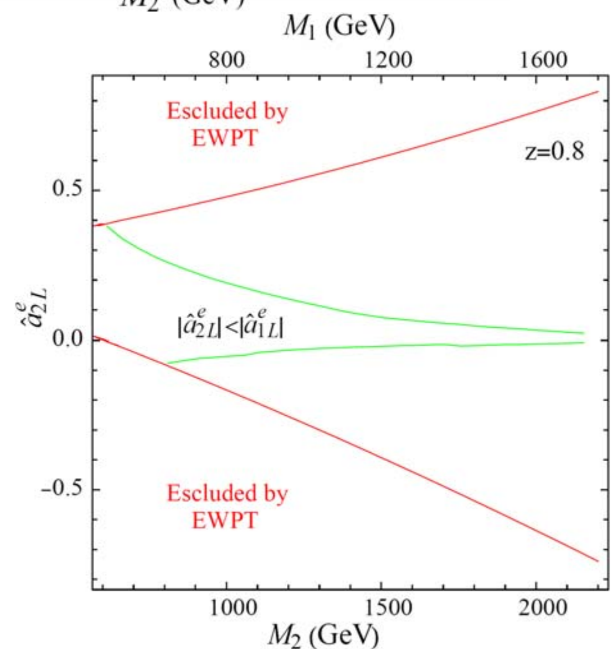
$z = M_1 / M_2$







in most part of the parameter space the Z_2 coupling to SM fermions is bigger than the Z_1 one

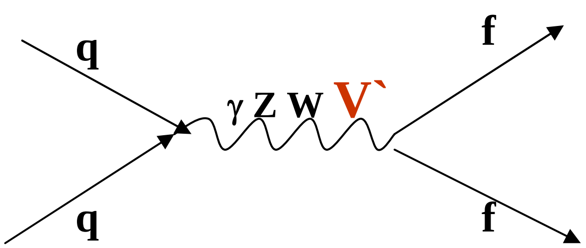


The BRs into fermions evaluated for the maximum coupling allowed by EWPT for each mass value

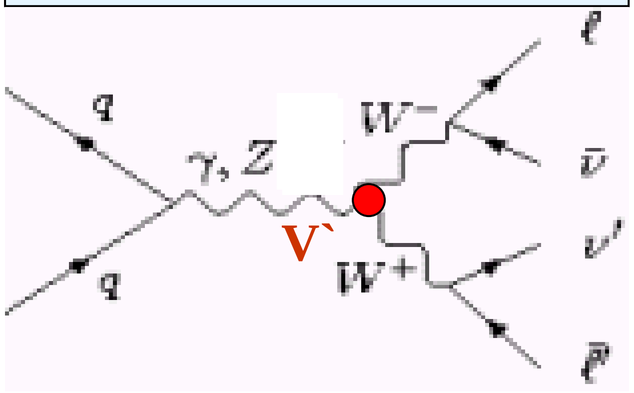
New spin-1 resonances @ the LHC

where do we get clues?

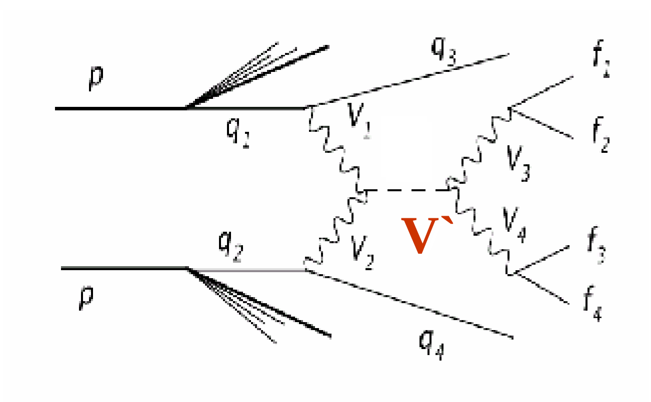
Drell-Yan



Di-boson production



Vector boson scattering



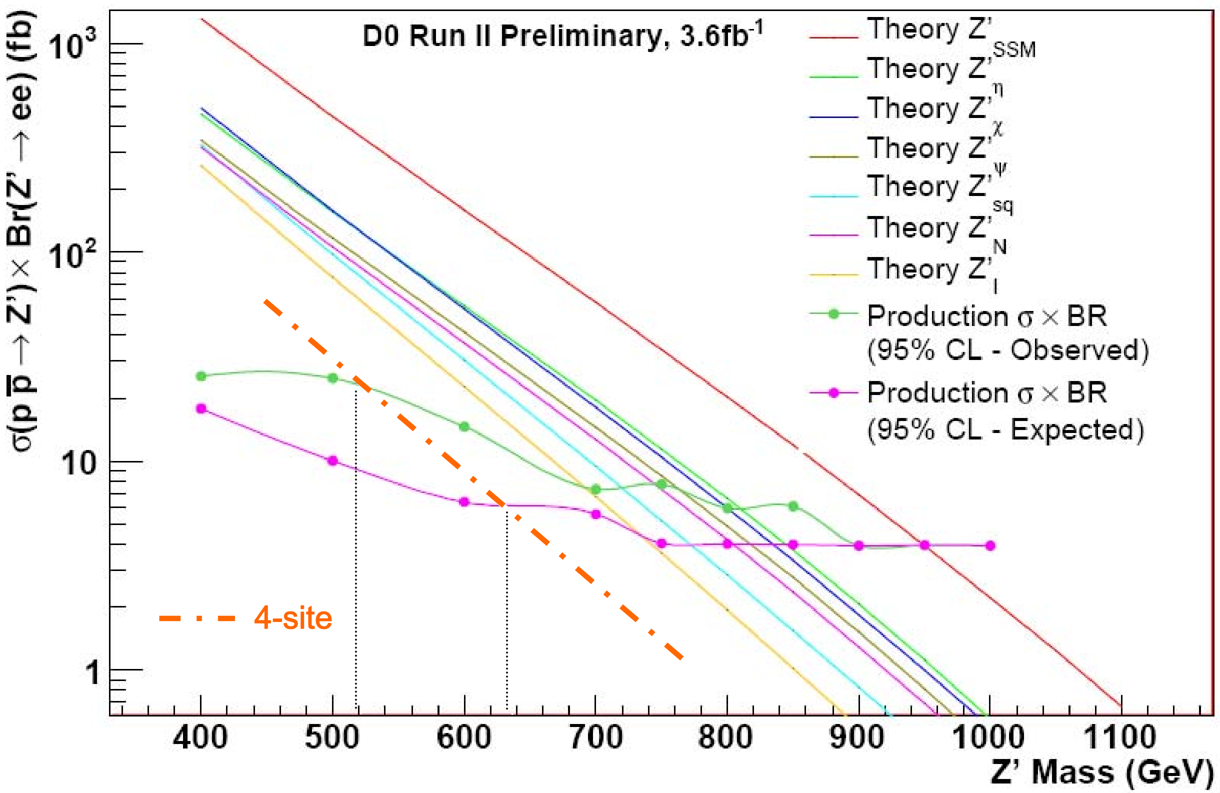
.... associated production, and ..... even more complicated processes where (extra) gauge bosons can be produced

For the 4-site model DY processes can be a good discovery channel

Let's start with the TEVATRON

Exclusion at the Tevatron 3.6fb^{-1}

(D0 Note 5923-CONF)



Upper limit on the observed and expected cross section at 95% CL with superimposed the SSM Z', E6 Z', and 4-site models

D0 counting strategy: Asymmetric mass window: $M_{Z'} > M_{Z'} - 3R$ with R=mass resolution= 3.4% $M_{Z'}$

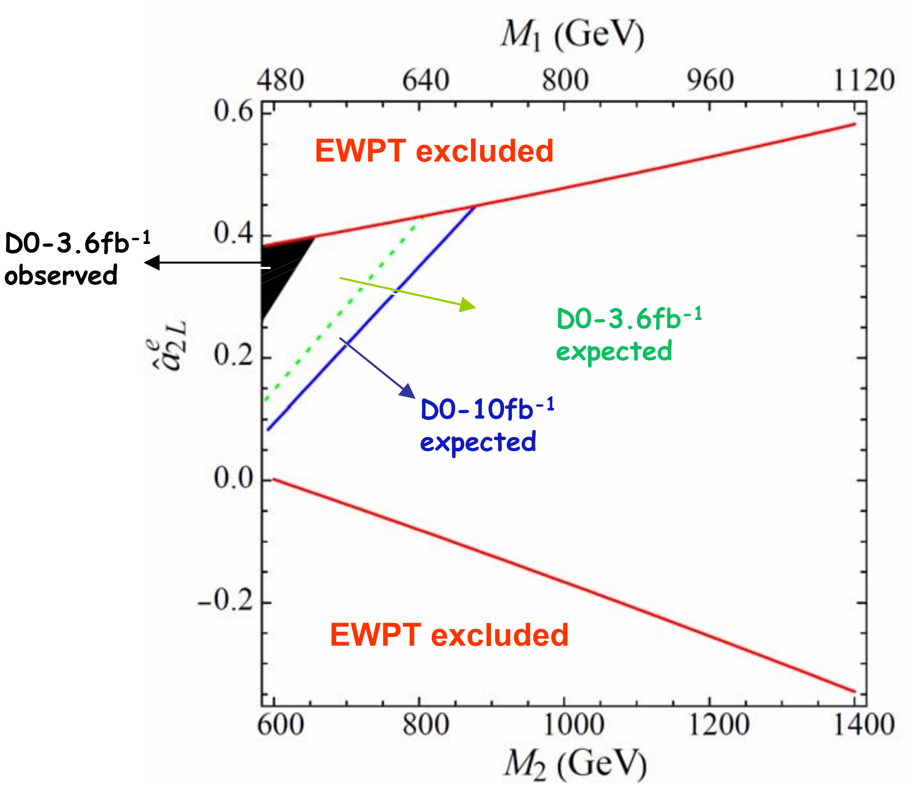
4-site model with z=0.8 - $Z'=Z_1$ (integration over the mass window contains both Z_1 and Z_2)

- for each Z_1 Mass take the maximum allowed electron coupling

95% Z_1,Z_2 mass limit from D0 observed data ~ 500,650 GeV (expected ~ 650,800 GeV)

DY-processes with Z_1, Z_2 exchange at theTevatron

Exclusion

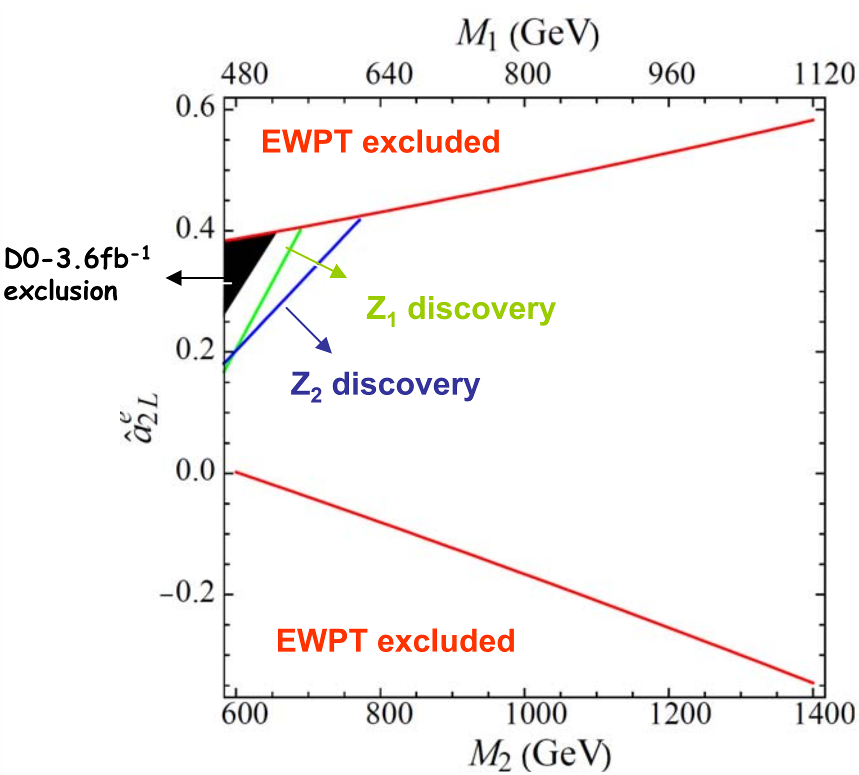


95% Exclusion with D0 counting strategy

M_2 limit from D0-3.6fb^{-1} observed data ~ 650 GeV

from D0-10fb-^{1} expected data ~ 900 GeV

Discovery



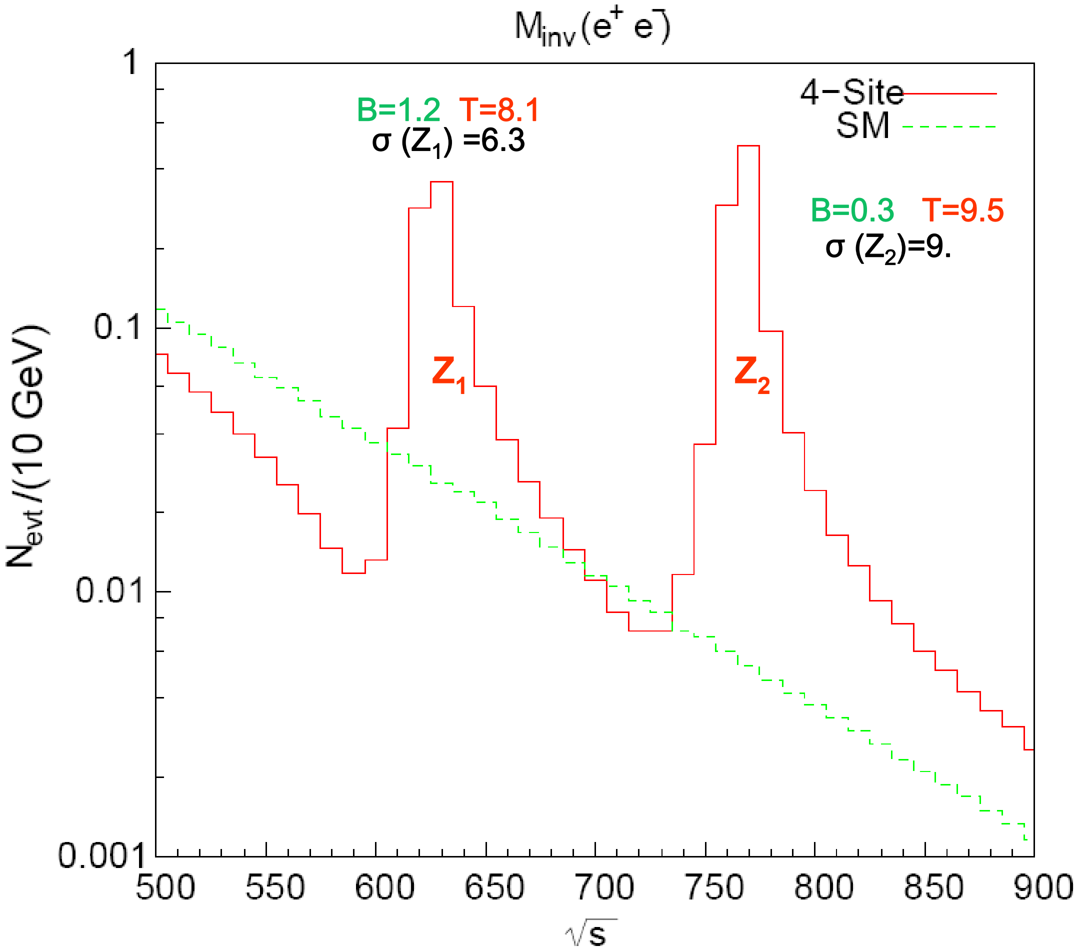
5σ-discovery with 10 fb^{-1} by requiring $\frac{S}{\sqrt{B}} > 5$

and min of 5 evts under the peak within M+/-R

R=mass resolution= 3 - 4% $M_{1,2}$

D-Y processes $p\bar{p} \to \gamma, Z, Z_1, Z_2 \to e^+e^-$ at the Tevatron L=10 fb^{-1}

M_1, M_2=600,750 GeV z=0.8



M^n_1, M^n_2 = 620,761 GeV

Γ_1, Γ_2 = 11.7,8.2 GeV

B= # background evts

T= # total evts

σ = (T-B) / √B

 # evts within M ±R

R =resolution=3.4% M

here R > Γ / 2

Signal acceptance 20%

DY-processes with $Z_{1,2}$ and $W^{\pm}_{1,2}$ exchange at the LHC

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 → *ll* with *l*=e,μ**
- **pp → $l\nu$ 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:

$M_{inv}(ll) > 150$ GeV for pp → *ll*

$P_t(l)>150$ GeV for pp → $l\nu$

no realistic detector simulation is included

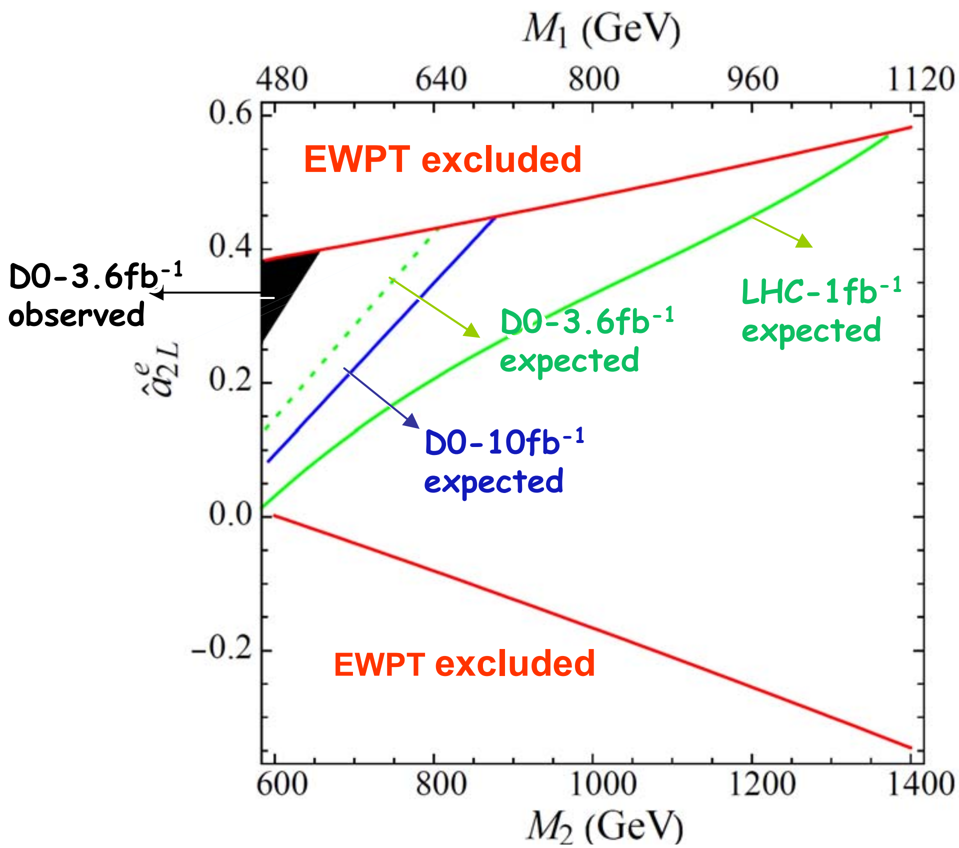
90% efficiency

LHC configurations :

$$\sqrt{s} = 7\,\mathrm{TeV}, \quad \mathrm{L} = 1\,\mathrm{fb}^{-1}$$

$$\sqrt{s} = 14\,\mathrm{TeV}, \quad \mathrm{L} = 10\,\mathrm{fb}^{-1}$$

Exclusion at the LHC ($\sqrt{s} = 7$ TeV, $L = 1\,\text{fb}^{-1}$)



D-Y processes with Z_1 and Z_2 exchange
only electron channel

z=0.8

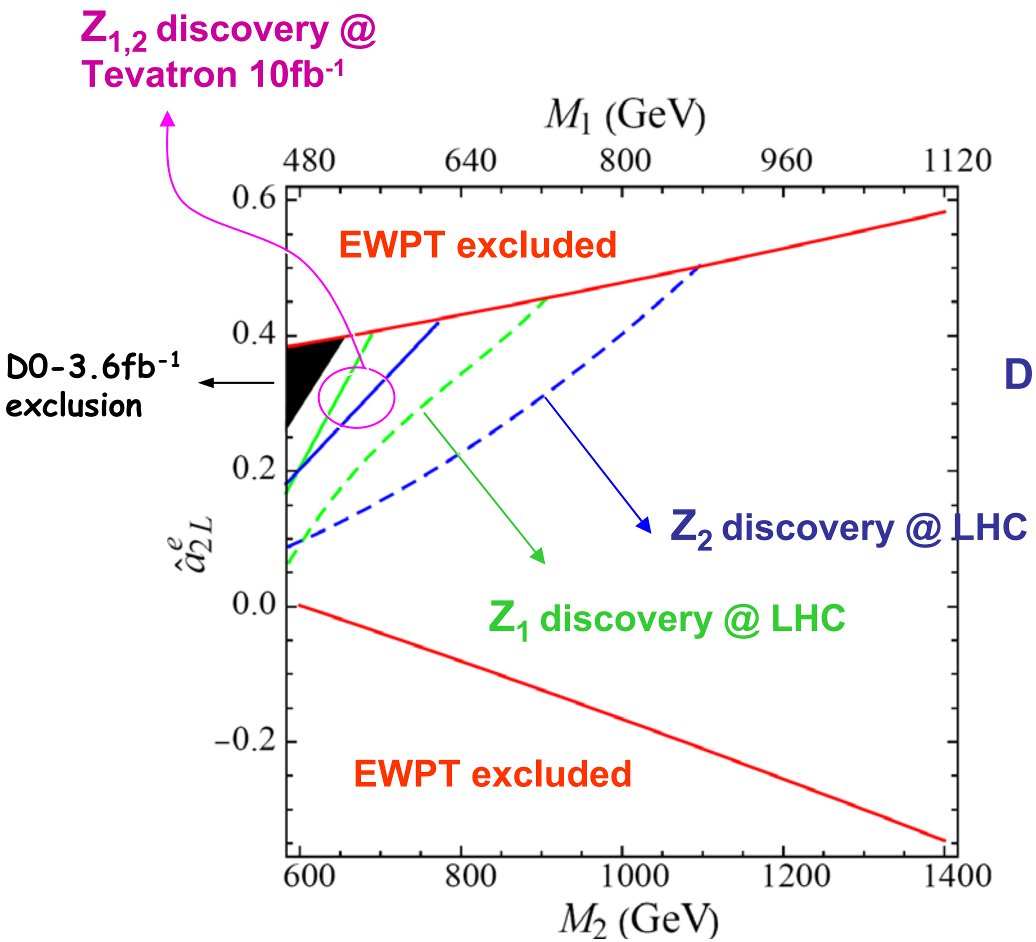
95% Exclusion with CMS counting strategy:

asymmetric mass window: $M_1 > M_1 - 3\,\Delta M_1$
$\Delta M = \max\,[\,R\,,\,\Gamma/2\,]$

R = mass resolution = 2% M at LHC

M_2 exclusion limit from LHC 1fb^{-1} expected data ~ 1400 GeV

Discovery at the LHC ($\sqrt{s} = 7\ \text{TeV},\quad L = 1\ \text{fb}^{-1}$)



Neutral channel: D-Y processes with Z_1 and Z_2 exchange (z=0.8)

only electron channel

Discovery with 1 fb^{-1} by requiring $\frac{S}{\sqrt{B}} > 5$

minimum of 5 evts under the peak within M +/- ΔM

ΔM = max [R , Γ / 2]

R = mass resolution = 2% M

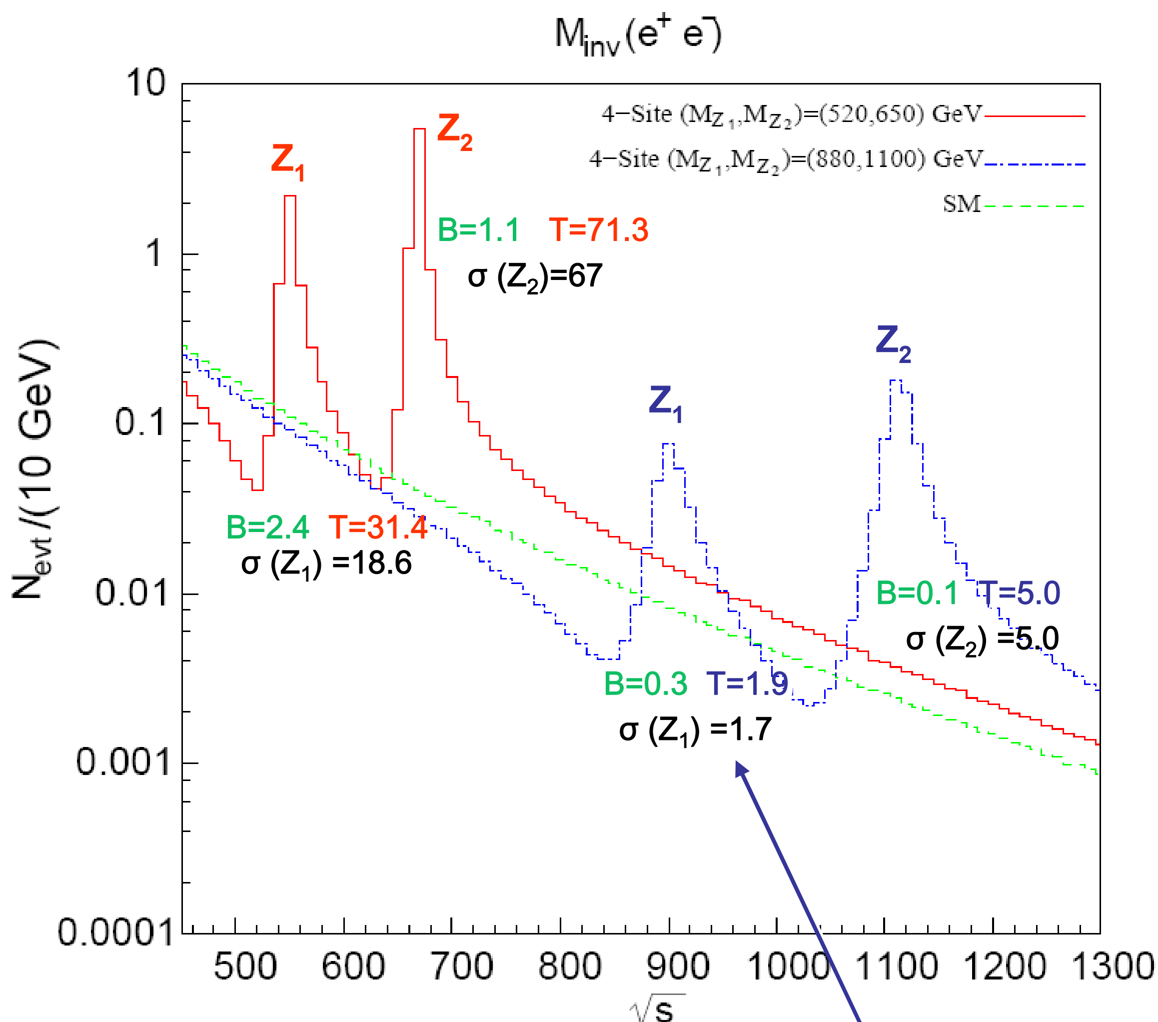
90% efficiency

5σ-(M_1,M_2) discovery limit from LHC 7TeV 1fb^{-1} expected data ~ (750, 1100) GeV

(z=0.8)

Drell-Yan process $pp \to \gamma, Z, Z_1, Z_2 \to e^+e^-$ at the LHC 7 TeV L=1 fb^{-1}

z=0.8



M^n_1, M^n_2 = 543,663 GeV
Γ_1, Γ_2 = 9.2,5.5 GeV

M^n_1, M^n_2 = 893,1107 GeV
Γ_1, Γ_2 = 21.3,17.9 GeV

B= # background evts

T= # total evts

σ = (T-B) / √B

 # evts within M± ΔM

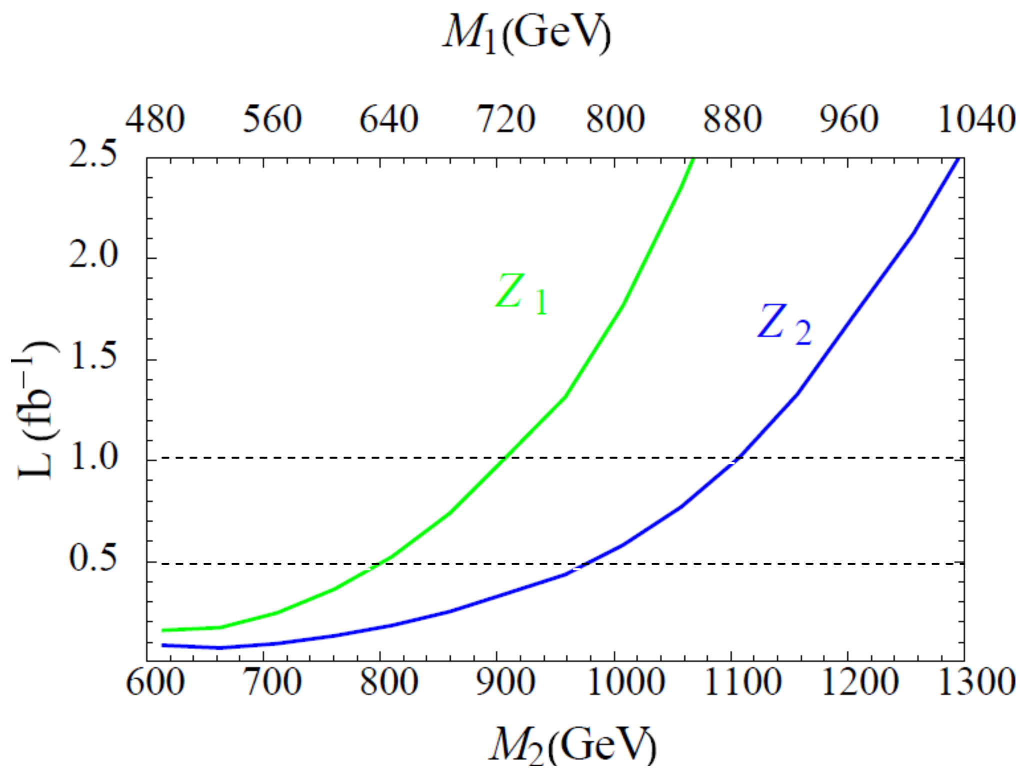
ΔM = max [R , Γ / 2]

R = mass resolution = 2% M

Efficiency 90%

need √s=14 TeV

Discovery @ LHC 7 TeV ($pp \to \gamma, Z, Z_1, Z_2 \to e^+e^-$)



z=0.8

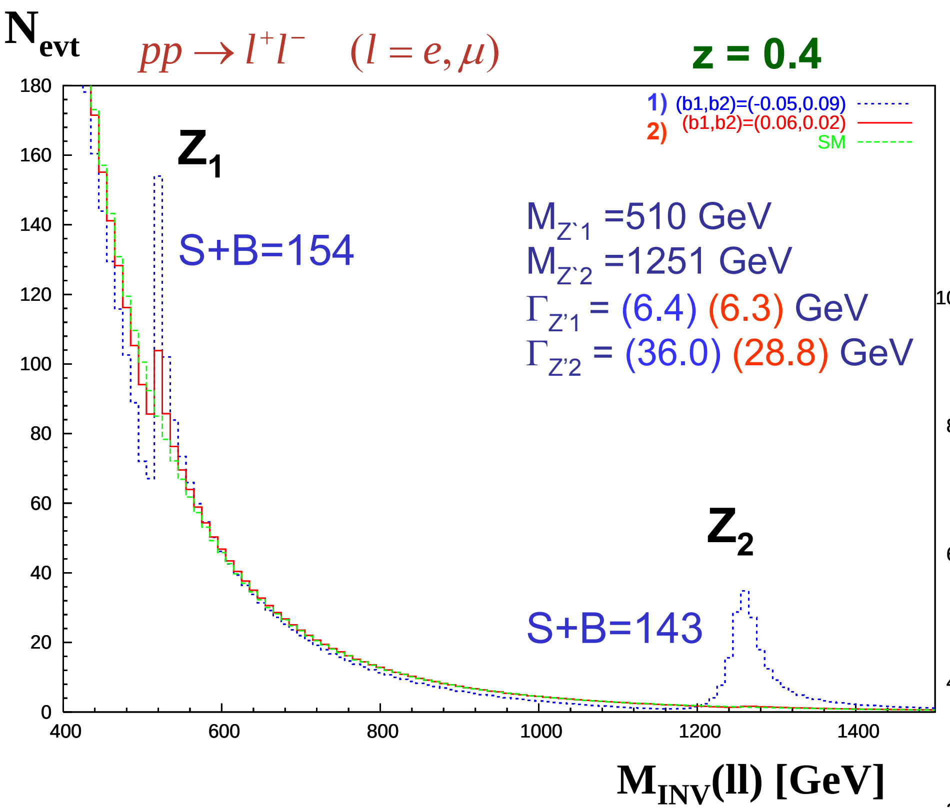
Luminosity needed for a 5σ-discovery for the maximum coupling allowed by EWPT

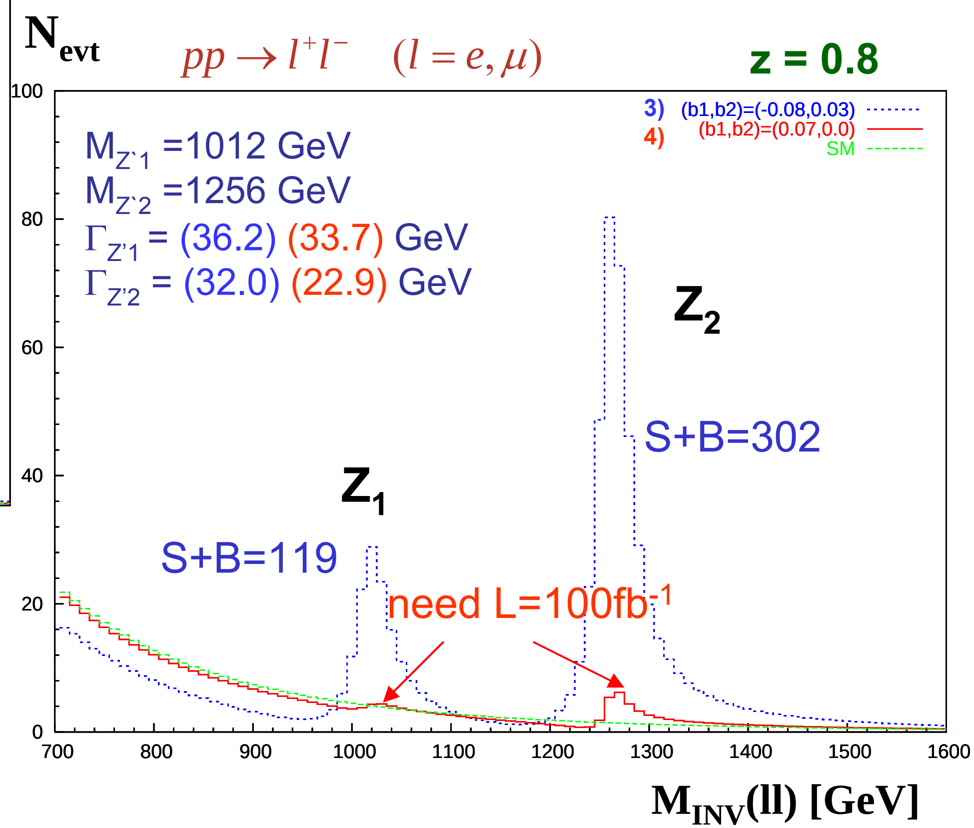
The low-edge of the spectrum detectable @ LHC 7TeV with L< 1 fb^{-1}
(500 pb^{-1} to discover a 800 GeV Z_1 and 1 TeV Z_2)

Z_1, Z_2 D-Y production @ the LHC 14TeV L=10 fb^{-1}

(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($M \pm \Gamma$)

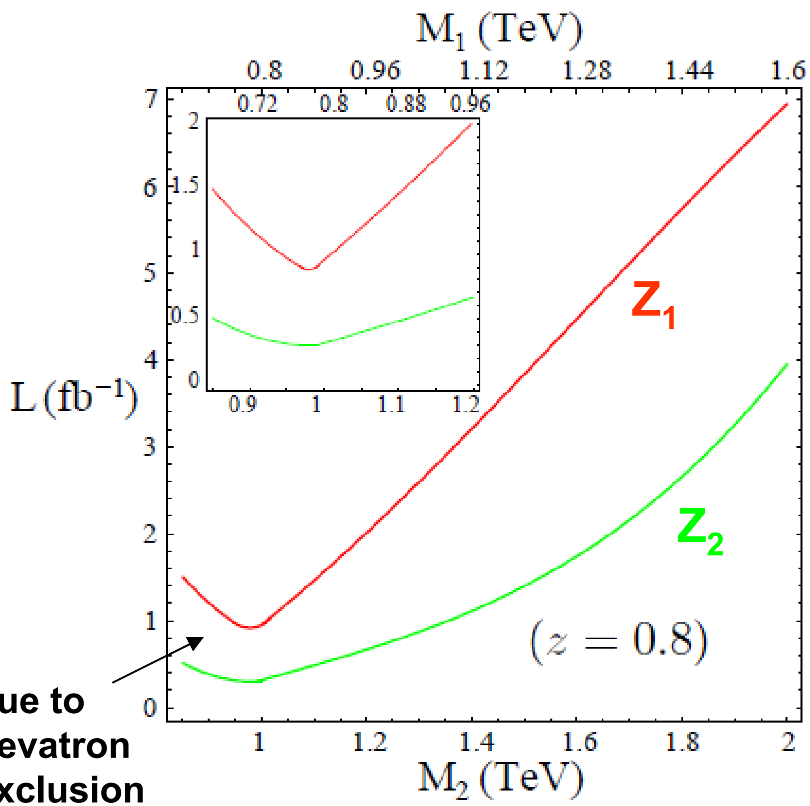
$Z_{1,}Z_2$ production @ the LHC 14TeV L=10 fb^{-1}

	$M_{1,2}$(GeV)	$b_{1,2}$	$N_{\rm evt}^{\rm sig}(Z_1)$	$N_{\rm evt}^{\rm tot}(Z_1)$	$\sigma(Z_1)$	$N_{\rm evt}^{\rm sig}(Z_2)$	$N_{\rm evt}^{\rm tot}(Z_2)$	$\sigma(Z_2)$
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

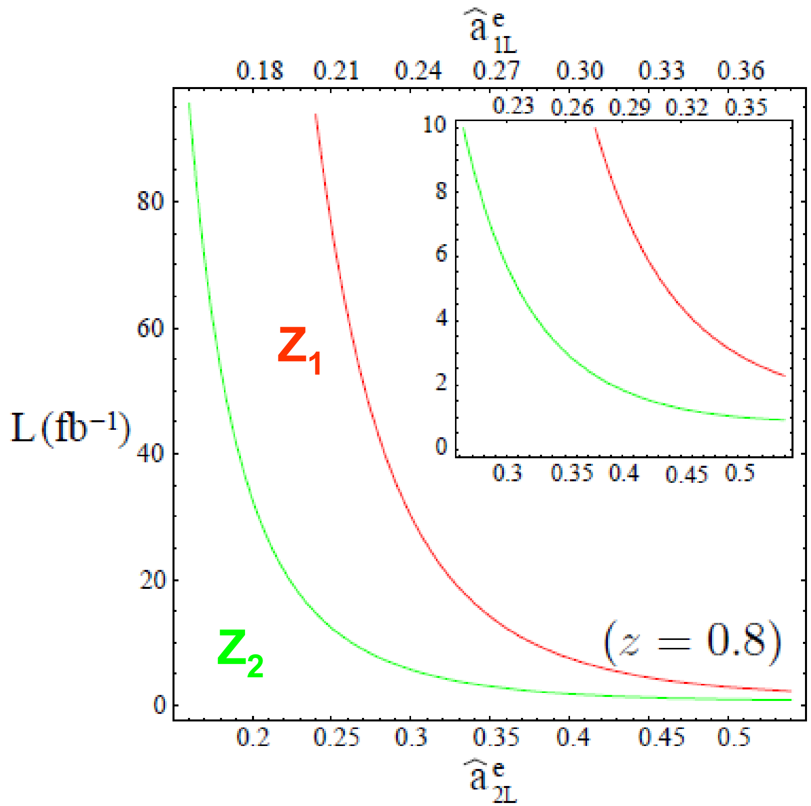
# of evts for the $Z_{1,2}$ DY production within $|M_{inv}(l^+l^-)-M_i| < \Gamma_i$

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

Discovery @ LHC 14TeV



due to Tevatron exclusion



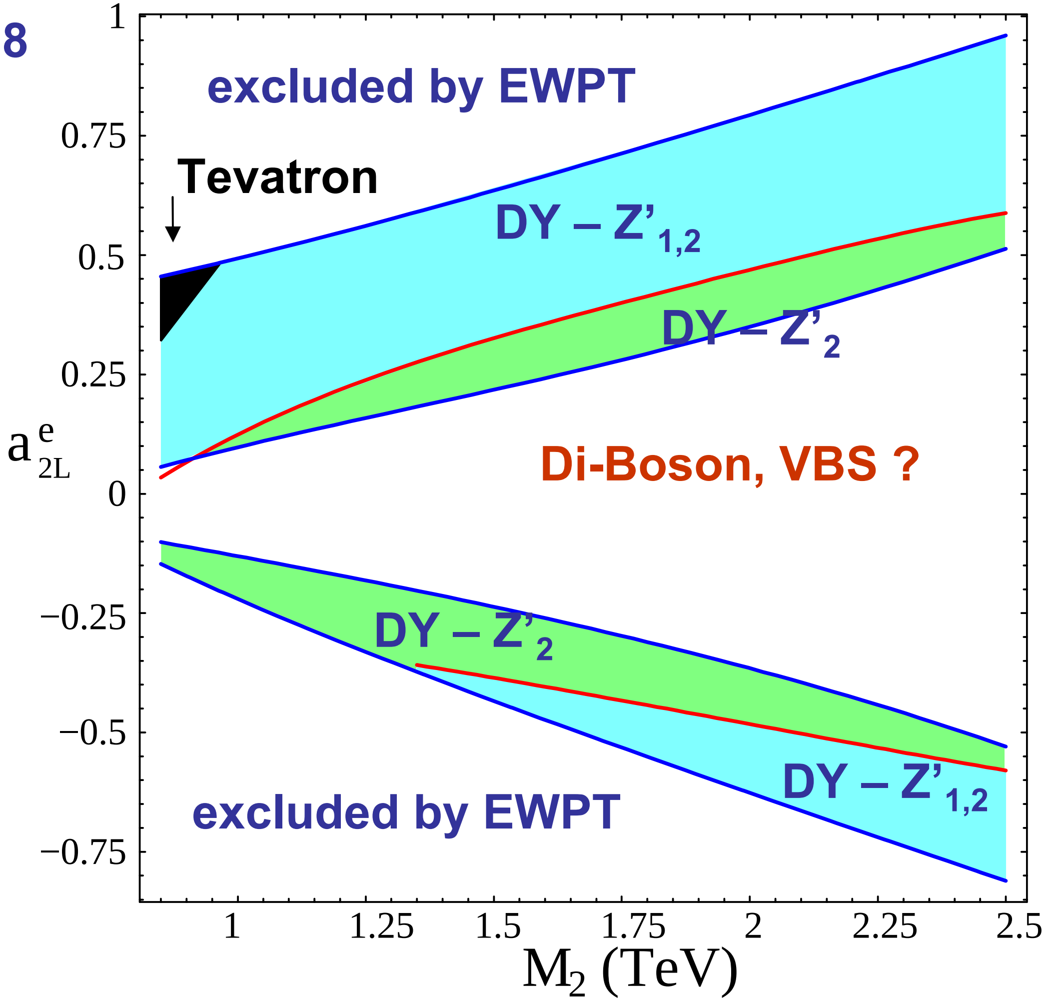
Luminosity needed for a 5σ-discovery for the maximum coupling allowed by EWPT

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

with L~10 fb^{-1} the full spectrum is detectable for maximum coupling

Discovery @ LHC 14TeV
DY-processes in the neutral channel, Z_1, Z_2 exchange

Z=0.8



L=100fb^{-1}
acceptance cuts:
$\eta(l)<2.5$, $Pt(l)>20$ GeV

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

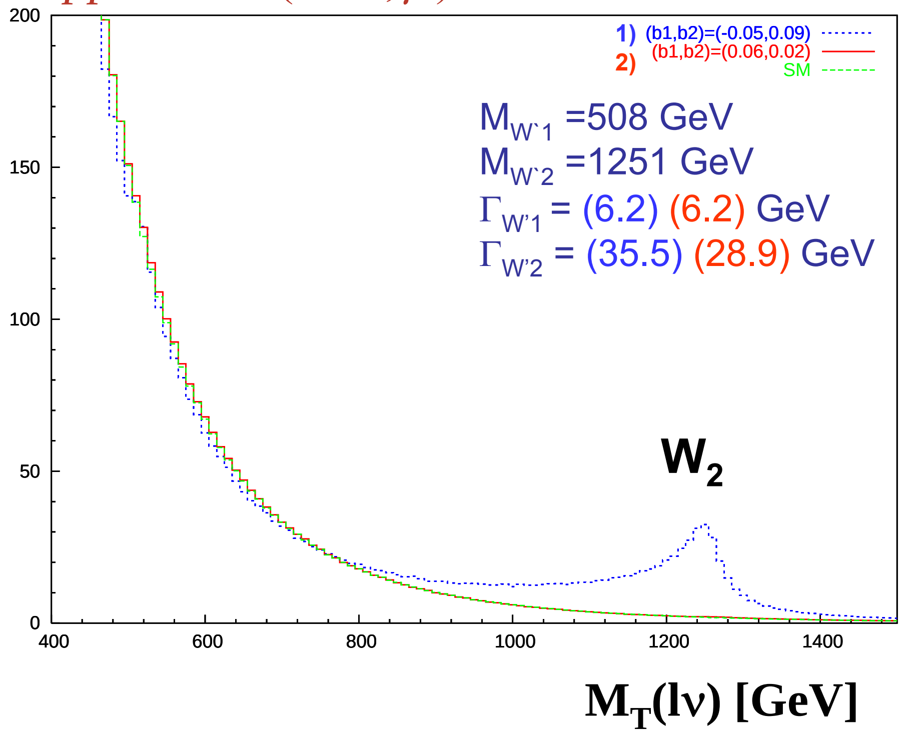
within $|M_{inv}(l+l-)-M_i| < \Gamma_i$ (i=1,2)

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

Tevatron: direct limit from neutral DY electron channels for L=3.6fb^{-1}

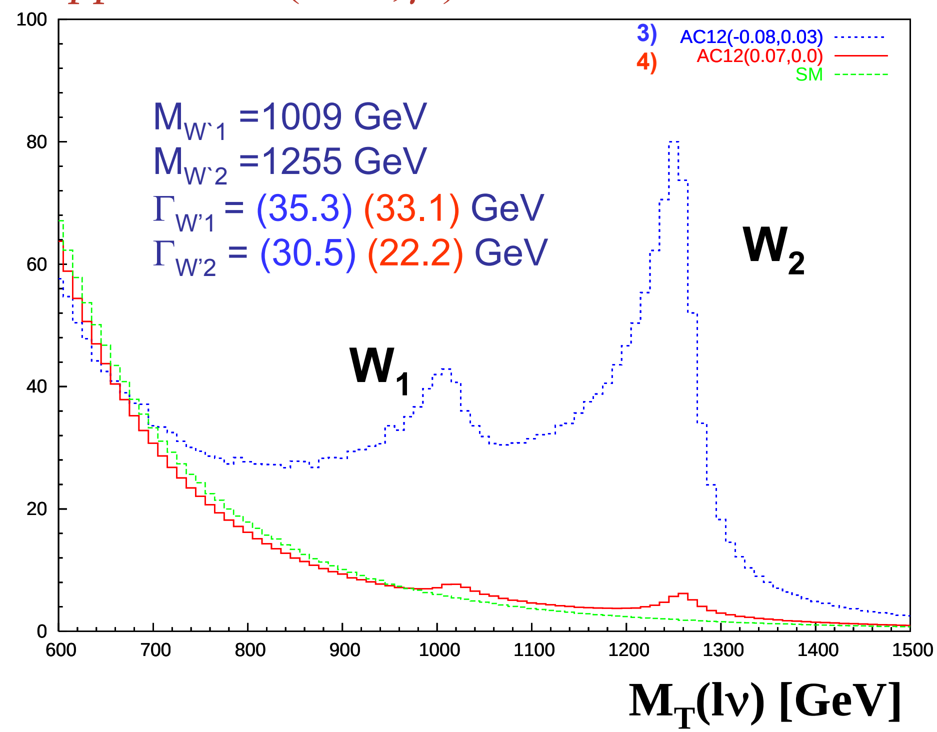
W_1, W_2 D-Y production @ the LHC 14TeV

$pp \rightarrow l\nu \quad (l = e, \mu)$ **z = 0.4**



$M_2 = M_1/z$

$pp \rightarrow l\nu \quad (l = e, \mu)$ **z = 0.8**



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

$W_{1,}W_2$ D-Y production @ the LHC 14TeV

	$M_{1,2}$(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

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 and **not excluded** by the EW precision measurements
- They describe new **spin-1 gauge bosons** which **delay the unitarity violation** to energy scales higher than those probed at the LHC
- **Drell-Yan processes** are a very good channel **to discover** these extra gauge bosons at the LHC already in the first stage with **7 TeV and L=1 fb^{-1}**
- A_{FB} for distinguishing among various models with Z`, peak height, line shape off the peak, ...

Di-boson production and VBS in progress

interesting because V_1=vector and V_2=axial vector (broken by weak ints)

Hard to compete with the Higgs boson but interesting mechanism with heavy spin-1 resonances

extra slides

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**

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

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

- **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:

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

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

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 metric along the fifth direction, the complete action for a SU(2)-moose would be

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

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

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

- **Introducing the link variables** $\Sigma_i = e^{-iaA_5^i}$, $i = 1, \ldots, K+1$

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

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

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

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

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 $M_1^2 = v^2 g_c^2$

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

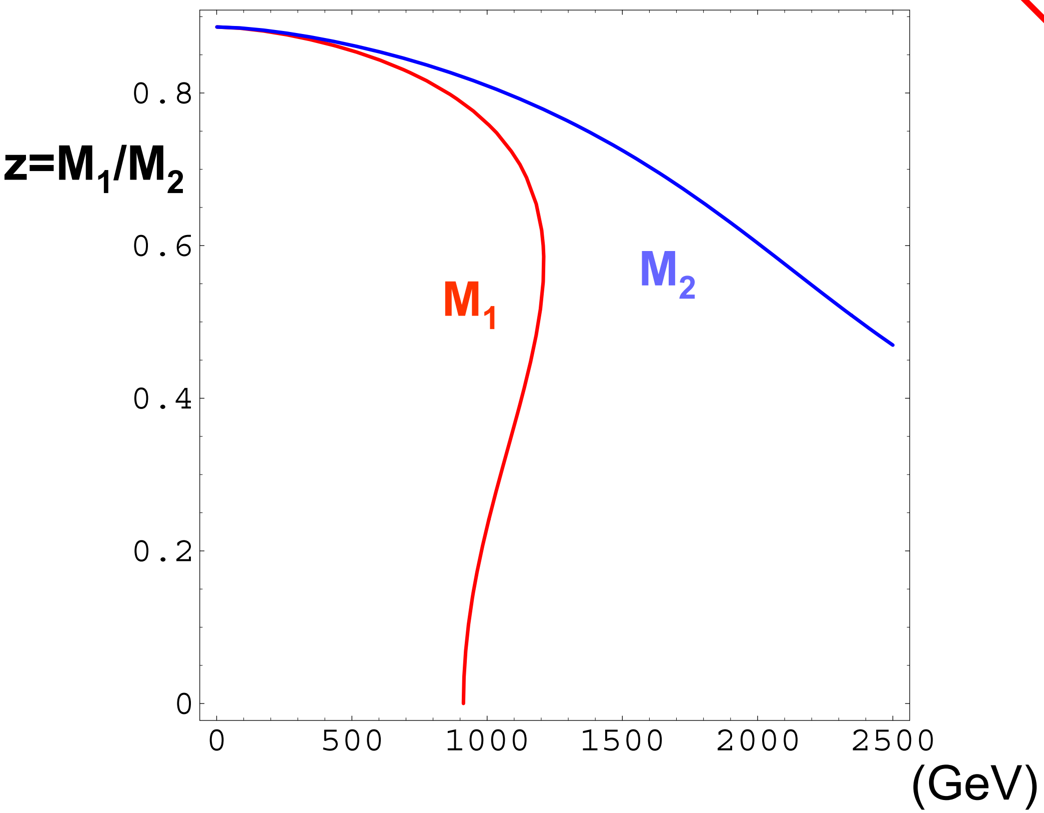
K=3 $M_1^2 \simeq 0.6 v^2 g_c^2, \quad M_2^2 = 2 v^2 g_c^2, \quad M_3^2 \simeq 3.4 v^2 g_c^2$

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, …..

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

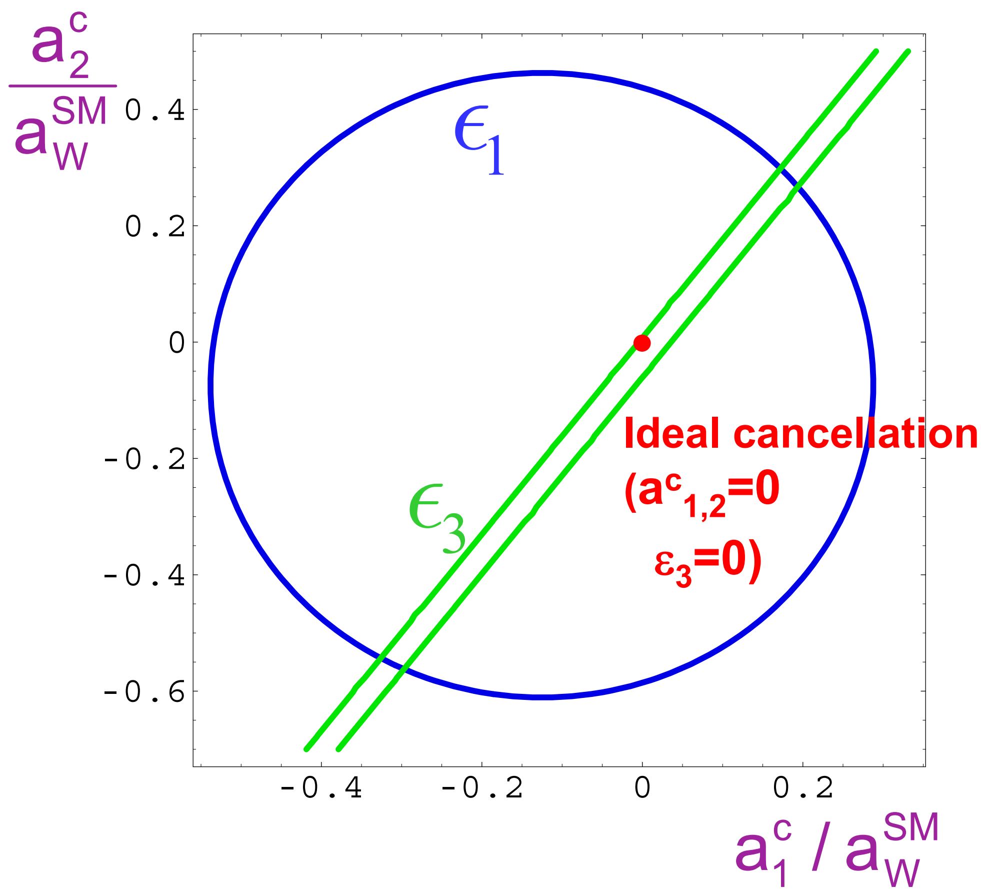
EW precision tests

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_1=1000 GeV and M_2=1300 GeV



Bounds on <u>charged couplings</u> (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

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?

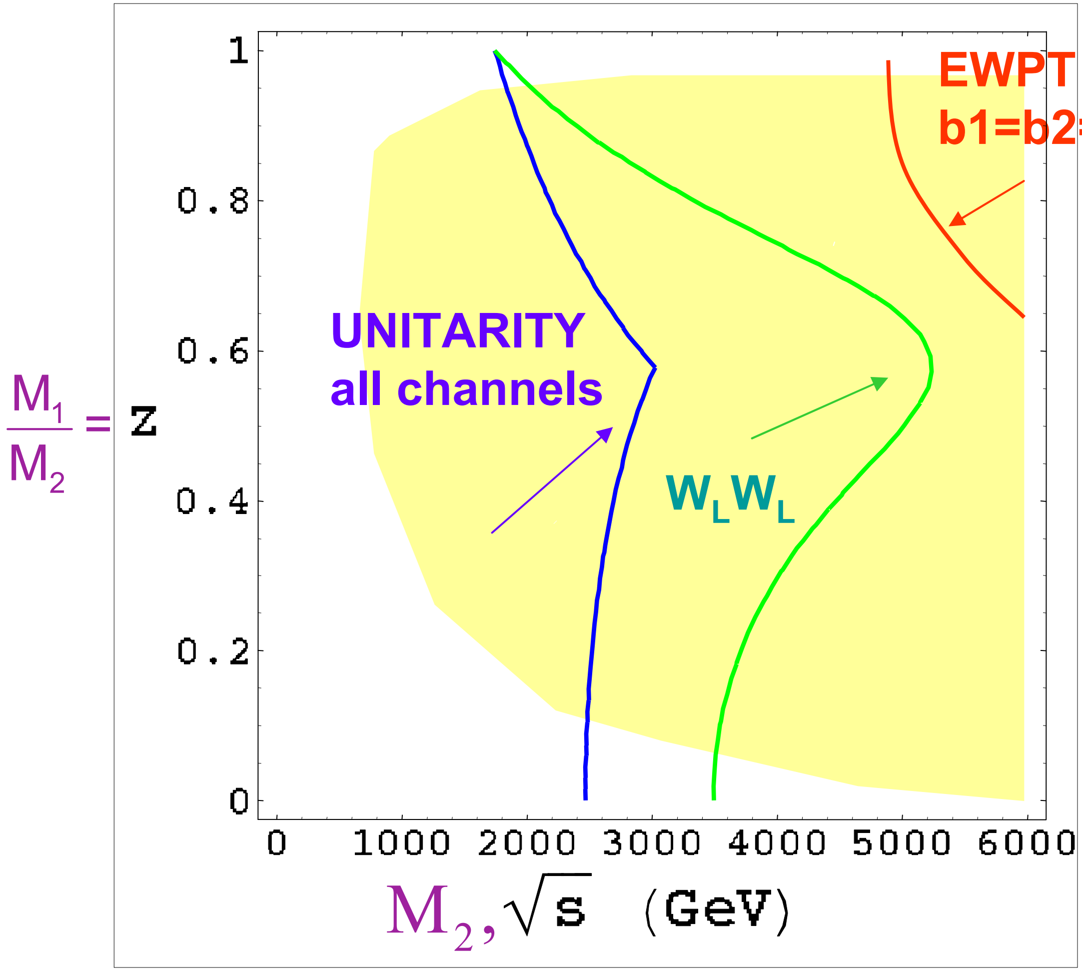
Assuming the standard definition of fine tuning (see for ex. Barbieri and Giudice, 1988)

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

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

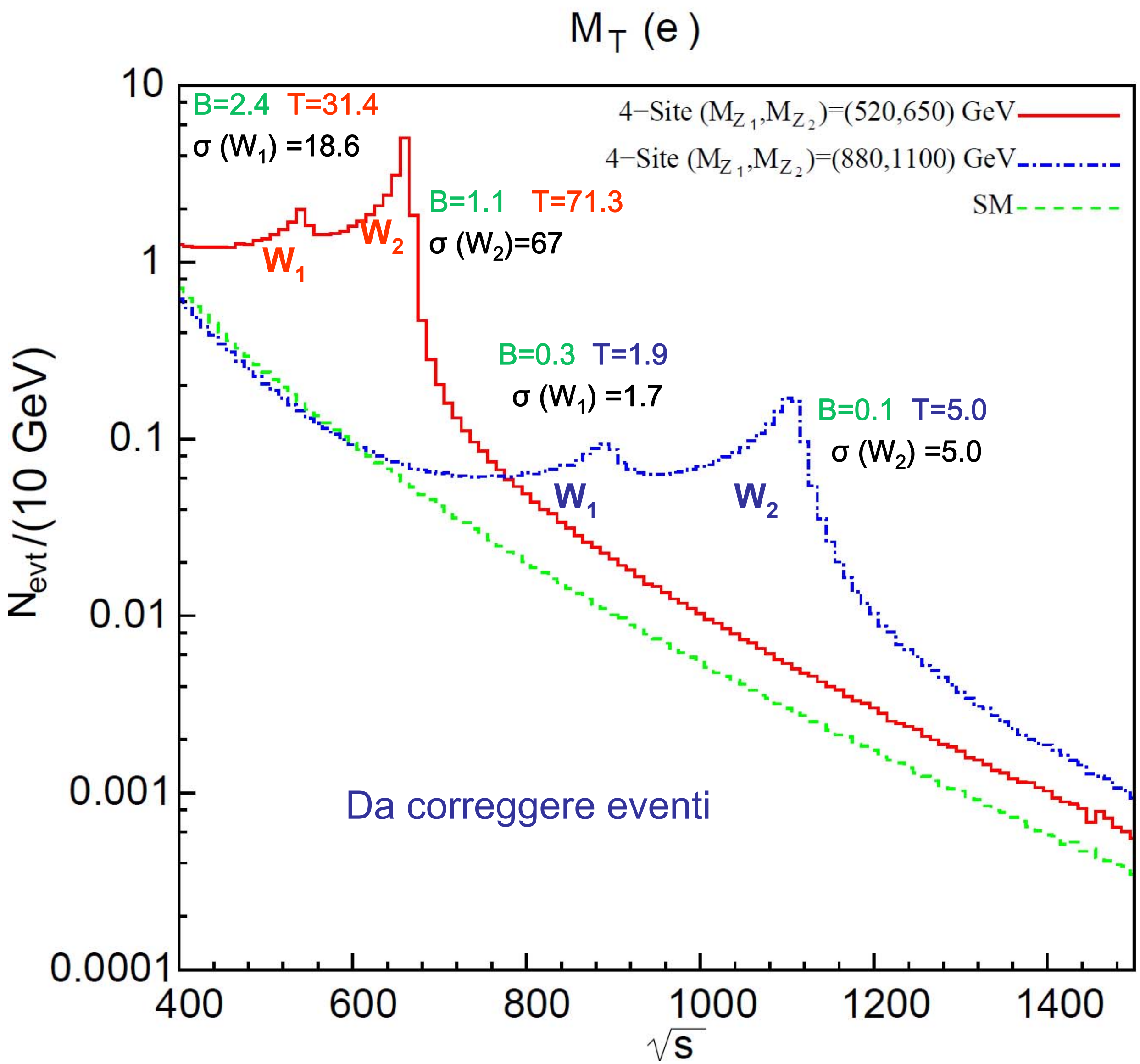


region of validity of the perturbative expansion

$(g/g_1)^4 < 0.005$

Drell-Yan process $pp \rightarrow W, W_1, W_2 \rightarrow e^+e^-$ at the LHC 7 TeV L=1 fb^{-1}

z=0.8



M^c_1, M^c_2 = 539,660 GeV

Γ_1, Γ_2 = 8.4,4.7 GeV

M^c_1, M^c_2 = 890,1105 GeV

Γ_1, Γ_2 = 25.8,21.9 GeV

B= # background evts

T= # total evts

$\sigma = (T-B) / \sqrt{B}$

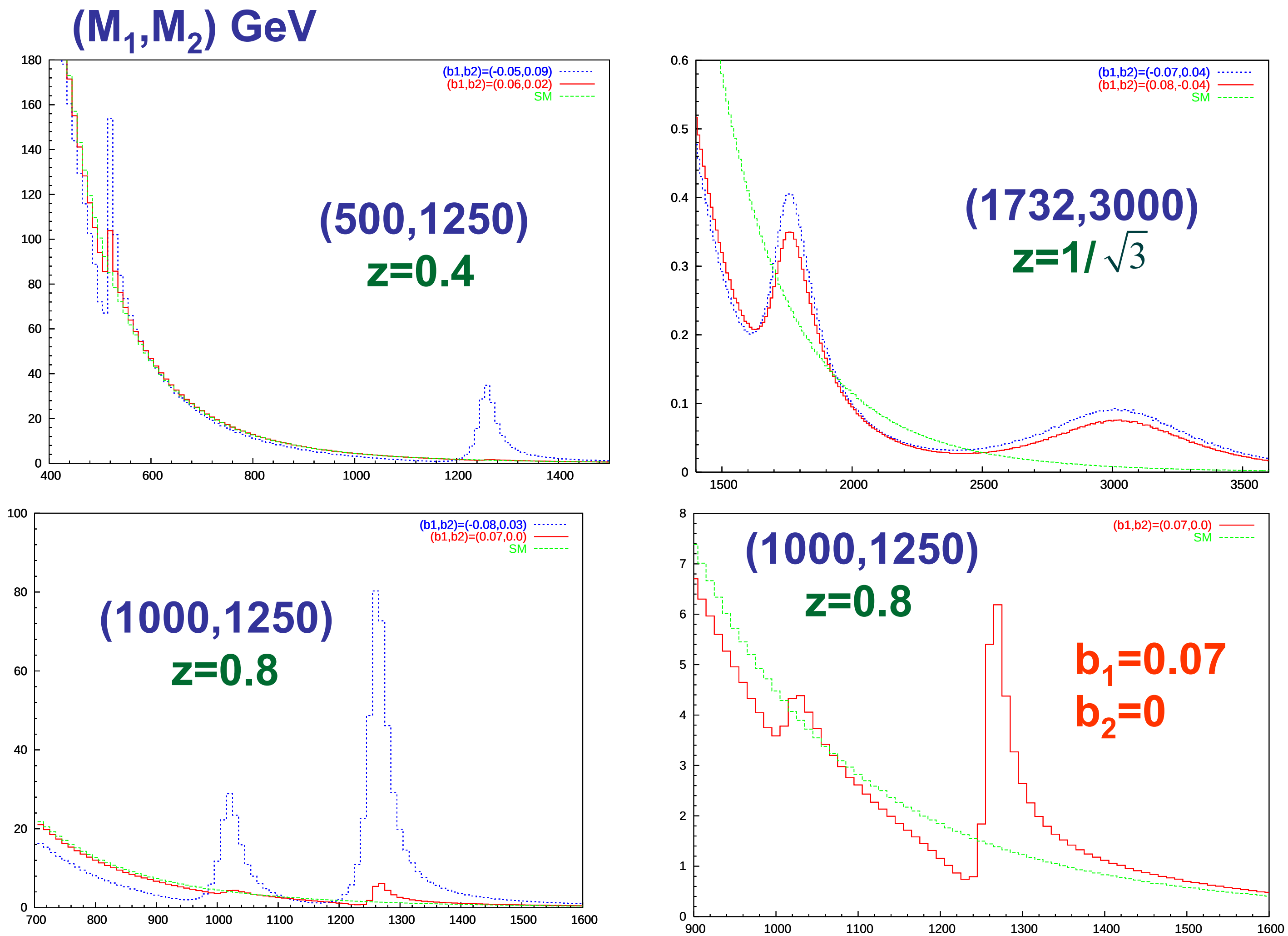
evts within $M \pm \Delta M$

$\Delta M = \max [R , \Gamma / 2]$

R = mass resolution = 2% M

Efficiency 90%

Z_1, Z_2 D-Y production @ the LHC 14TeV L=10 fb^{-1}

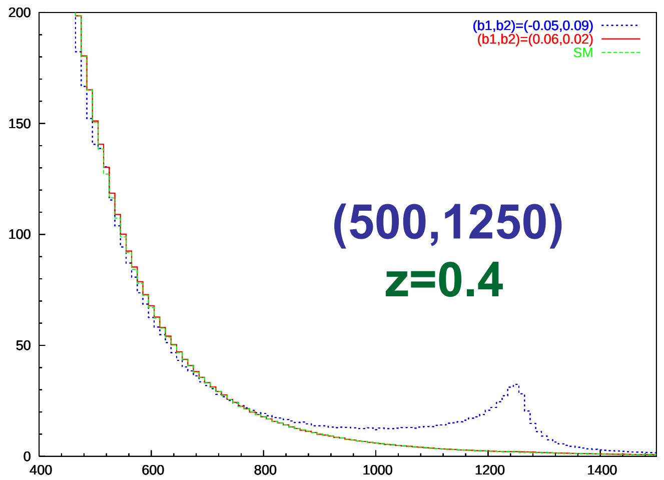


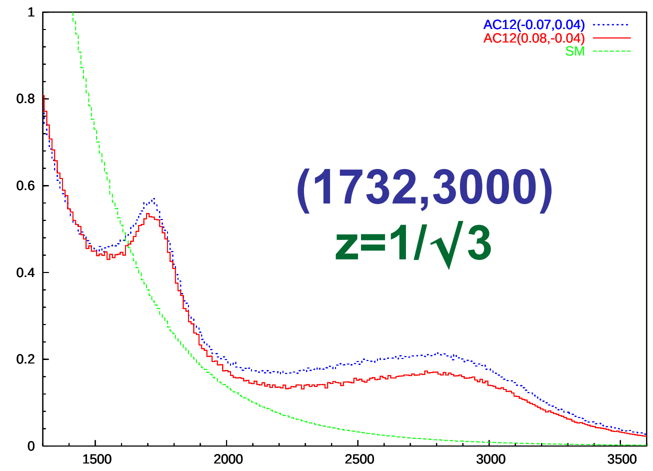
Total # of evts in a 10GeV-bin versus M_{inv}(l+l-) for L=10fb^{-1}. Sum over e,μ

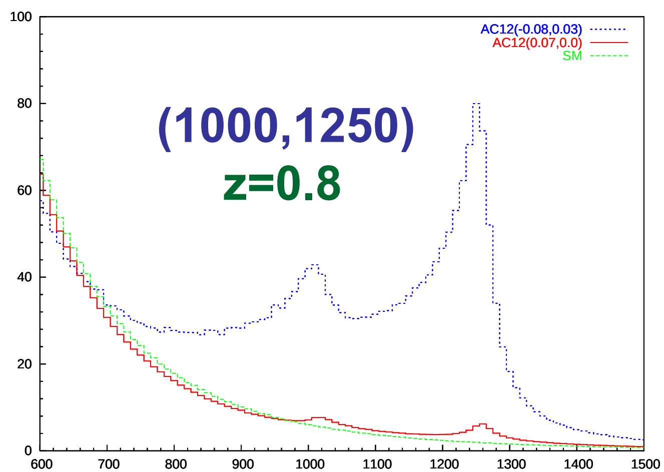
W'$_1$,W'$_2$ production

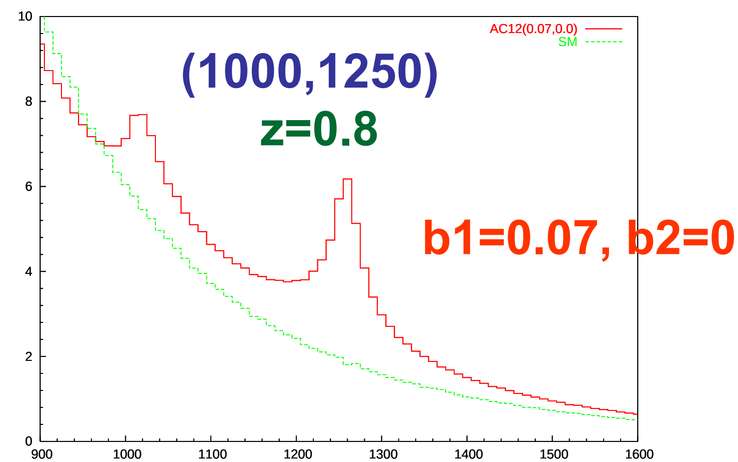
Z_i and W_i are nearly degenerate

(M_1,M_2) GeV









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

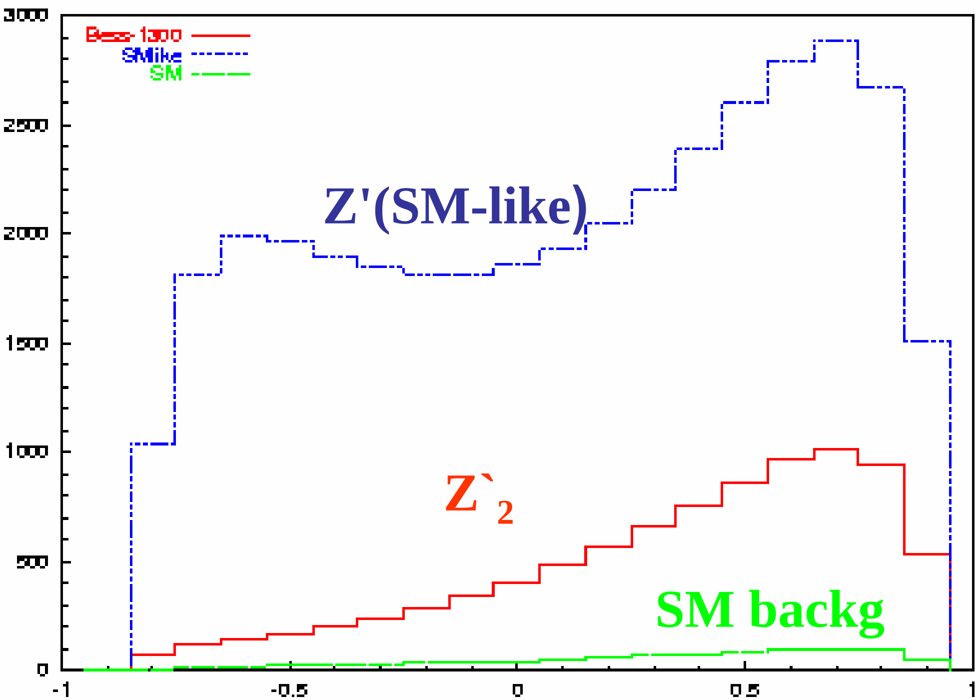
How to distinguish the various models?

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

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

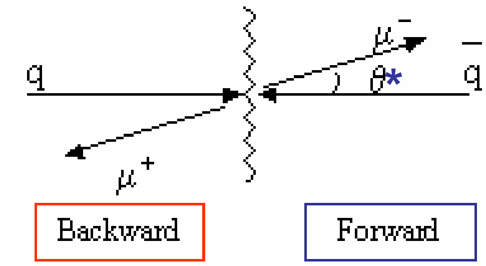
L=100 fb^{-1}

dσ L/dcosθ^*(l^-)   (l=e,μ)



cosθ^*(l^-)

 # evts for Z`$_2$ ~ 1000



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

We assume the direction on the z-axis of the dilepton system to give the direction of the incoming quark

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

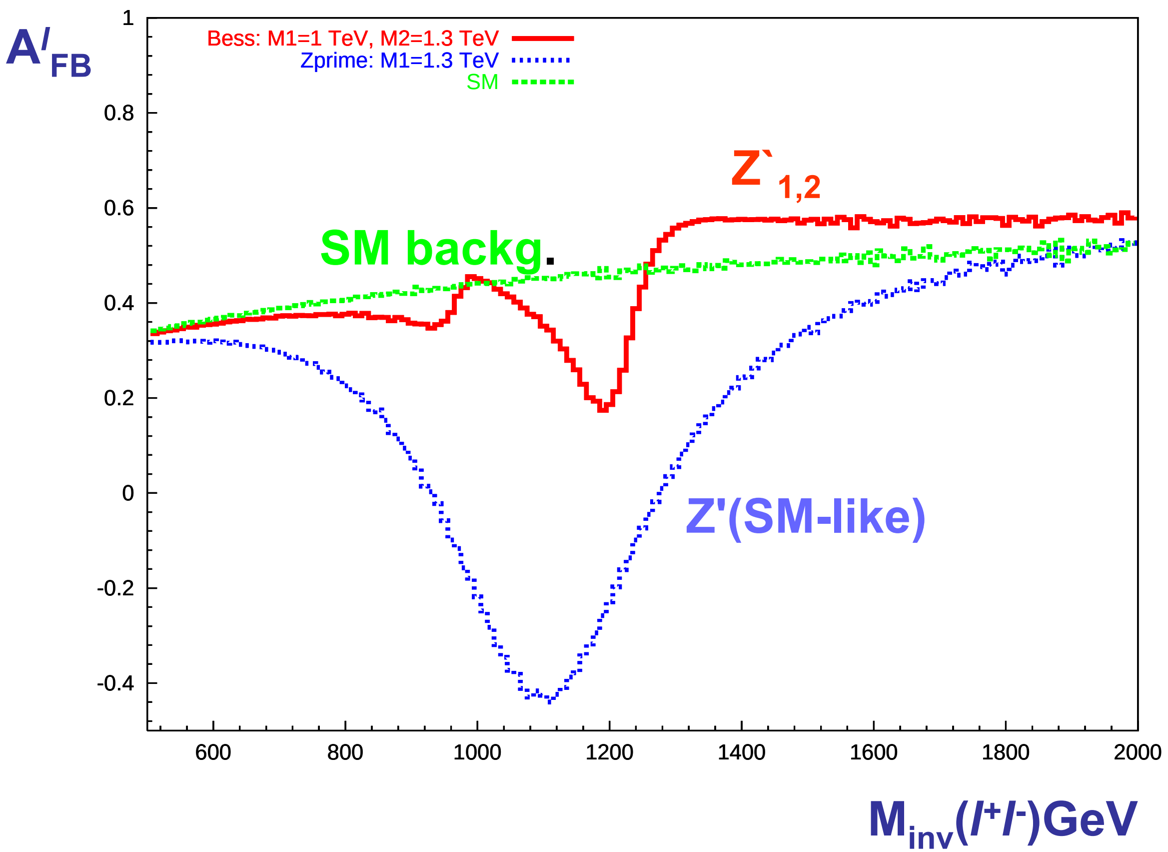
we select the events within

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

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

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

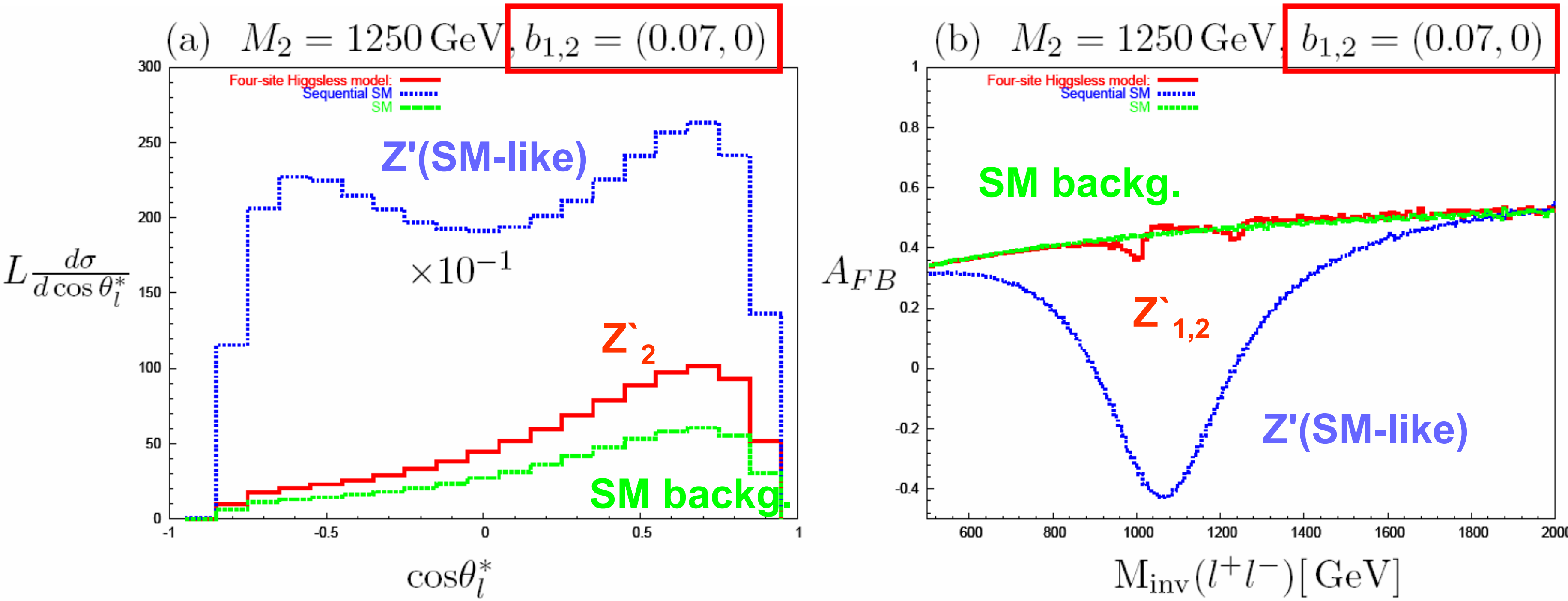
(Dittmar,Nicollerat,Djouadi 03; Petriello,Quackenbush 08)



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

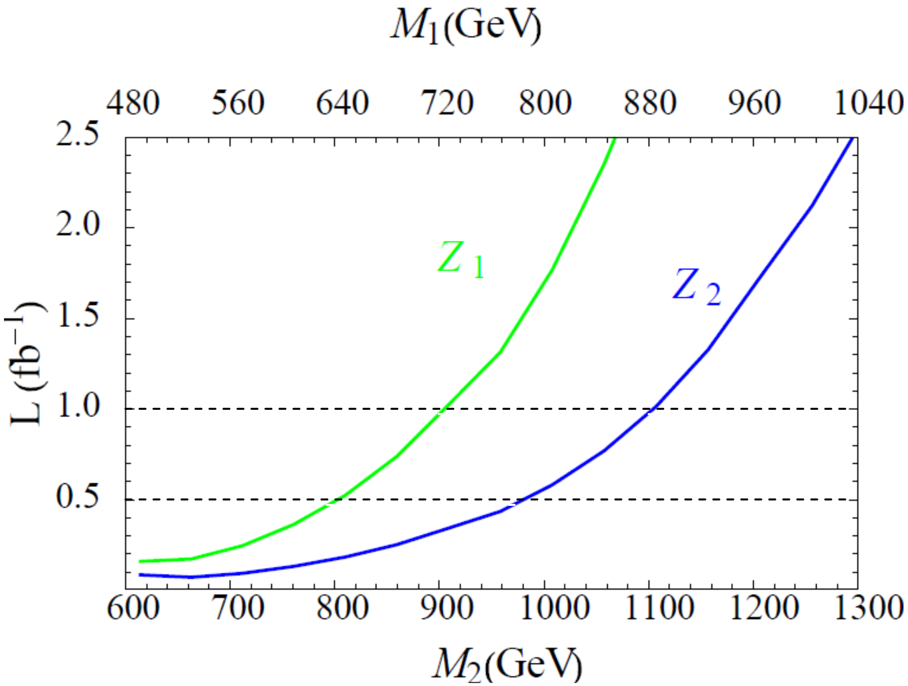
$$A_{FB} = \left[\frac{d\sigma^F}{dM_{\rm inv}} - \frac{d\sigma^B}{dM_{\rm inv}}\right] / \left[\frac{d\sigma^F}{dM_{\rm inv}} + \frac{d\sigma^B}{dM_{\rm inv}}\right]$$

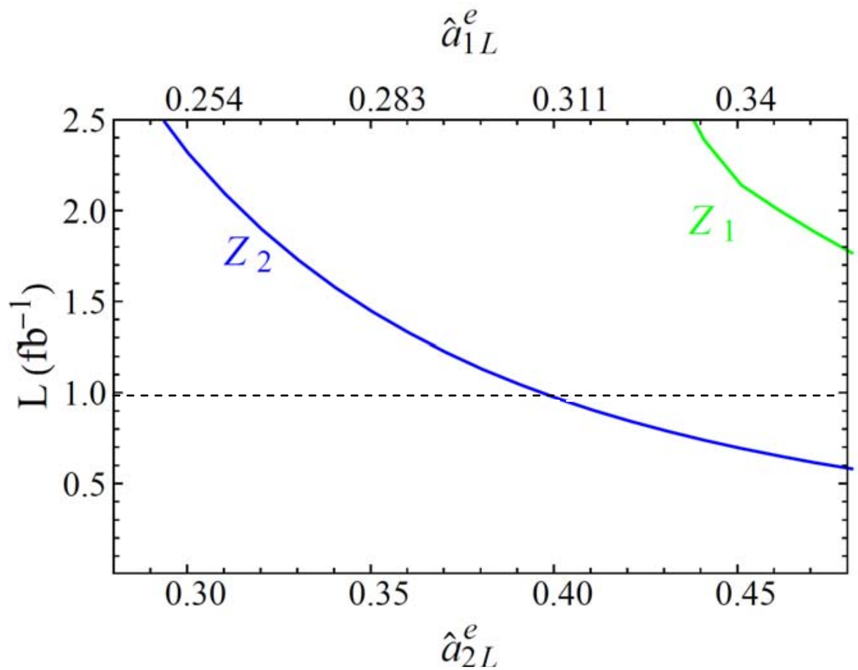
On- and off-resonance A_{FB} for a single resonance scenario



- 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

Discovery @ LHC 7 TeV





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=0.8TeV, M_2=1TeV)

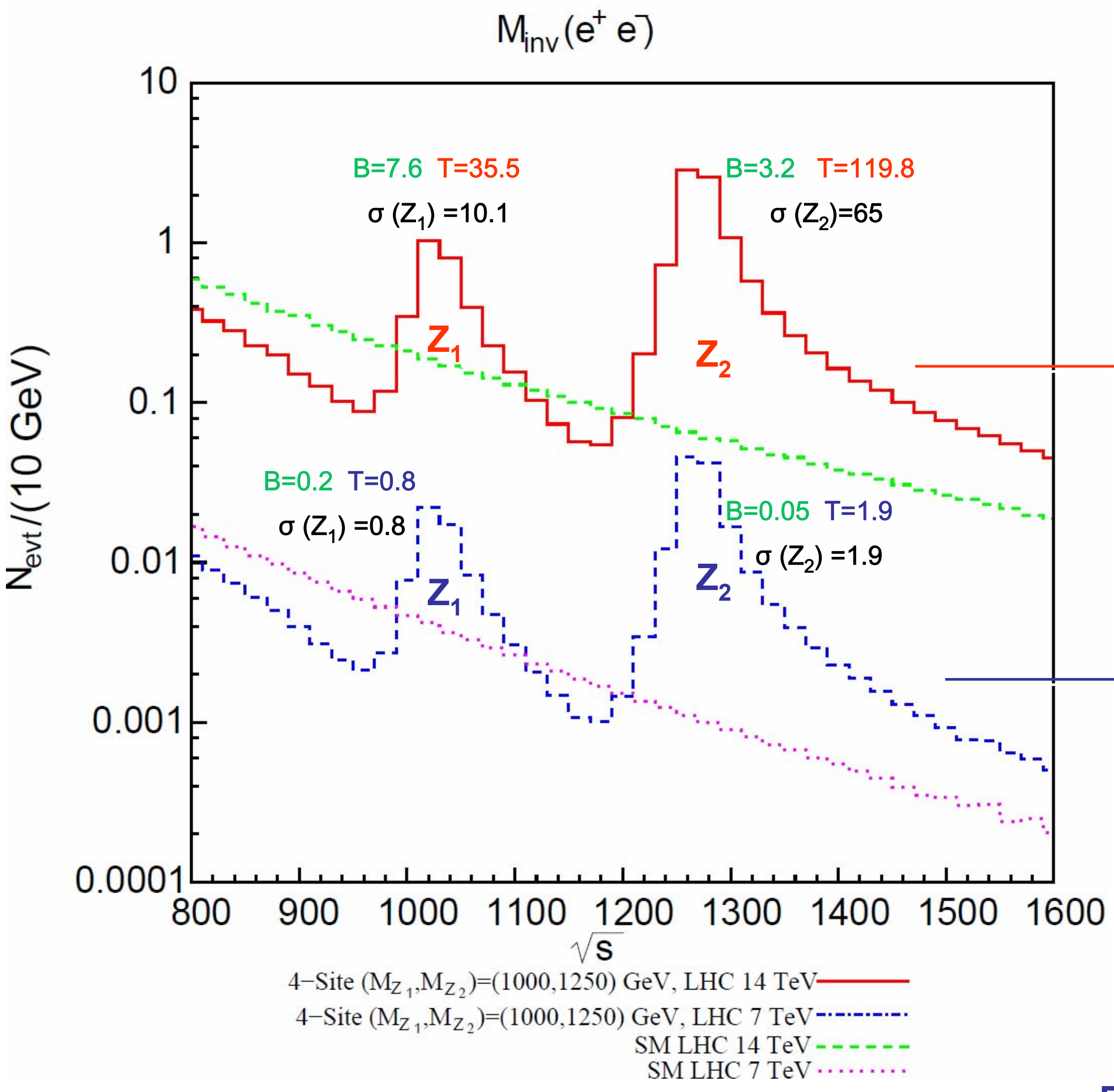
The low-edge of the spectrum detectable @ LHC 7TeV with L< 1 fb^{-1}

Drell-Yan process $pp \to \gamma, Z, Z_1, Z_2 \to e^+e^-$ at the LHC 7 TeV L=1 fb^{-1}

z=0.8

M^n_1, M^n_2 = 1012,1256 GeV

Γ_1, Γ_2 = 36,32 GeV



LHC 14 TeV L=10 fb^{-1}

LHC 7 TeV L=1 fb^{-1}

B= # background evts

T= # total evts

$\sigma = (T-B) / \sqrt{B}$

evts within M $\pm$ ΔM

ΔM = max [R , Γ / 2]

R = mass resolution = 2% M

Efficiency 90%

same distributions with linear scale