Spin-1 resonances from a 4-site Higgsless model

Stefania De Curtis
INFN and Dept. of Physics, Florence

- Motivations for Higgsless models: simplest example BESS model
- Linear moose: effective description for extra gauge bosons
- Unitarity bounds and EW constraints, direct couplings to fermions
- The 4-site model, new vector and axial-vector resonances
- Drell-Yan processes @ the LHC and @ a LC (very preliminary)

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

CLIC08 Workshop
CERN, 14-17 October 2008

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:

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 ~ 1 TeV, λ is large, m_H is O(TeV). The theory is non perturbative

1) $\lambda << 1 \Rightarrow$ new particles lighter than 1 TeV
2) $\lambda >> 1 \Rightarrow$ new particles around 1 TeV

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 of the type G/H

- 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

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

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

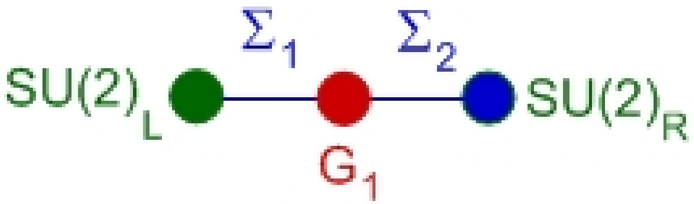
$$L = f_1^2 Tr\left[D_\mu \Sigma_1^\dagger D^\mu \Sigma_1 \right] + f_2^2 Tr\left[D_\mu \Sigma_2^\dagger D^\mu \Sigma_2 \right] - \frac{1}{2} Tr\left[F_{\mu\nu}(V) F^{\mu\nu}(V) \right]$$

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

This model describes 6 scalar fields and 3 gauge bosons.

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

$$M_V^2 = (f_1^2 + f_2^2) g_1^2$$ (g_1=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. $SU(2)_{diag}$ is a custodial symmetry. The BESS model can be recast in a 3-site model (K=1)**

- **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, ($A\mu^i$ = KK modes)**

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 behavior comes from the **scattering of longitudinal vector bosons.** For $s >> M_W^2$ these amplitudes can be evaluated using the **equivalence theorem.** Introduce the GB's, $\left(\Sigma_i = e^{i\vec{\pi}_i\cdot\vec{\tau}/2f_i}\right)$, 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 $f_i = f_c$:

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

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

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

$$\Downarrow$$

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

too big EW corrections

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):

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

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

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

Direct fermionic couplings

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

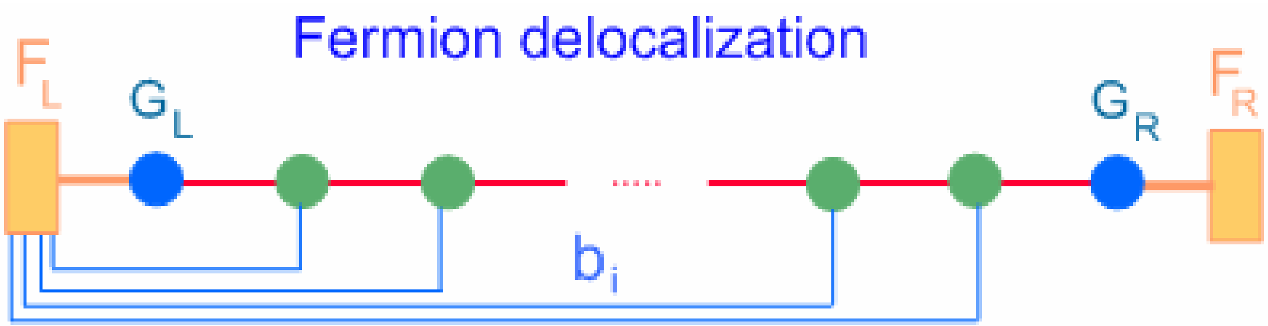
- **Left- and right-handed fermions, $\psi_{L\,(R)}$ are coupled to the ends of the moose, but they can couple to any site by using a Wilson line**

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

$$\Downarrow$$

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

no delocalization of the right-handed fermions.

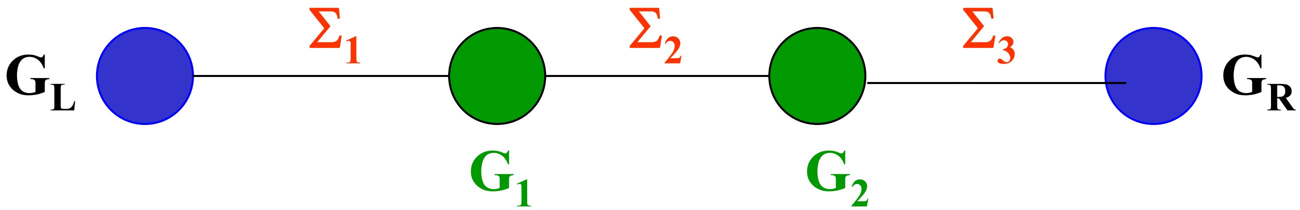


Small terms since they could contribute to right-handed currents constrained by the K_L-K_S mass difference

The Higgsless 4-site Linear Moose model

(Accomando, DC, Dominici,Fedeli)

- 2 extra gauge groups G_i=SU(2) with global symmetry $SU(2)_L \otimes SU(2)_R$ plus LR symmetry: $g_2=g_1$, $f_3=f_1$ (specific choice of BESS with vector and axial vector resonances);
- 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)

$$f_1, f_2 \rightarrow M_1, M_2$$

$$M_1 = f_1 g_1$$

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

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

charged and neutral extra gauge bosons almost degenerate

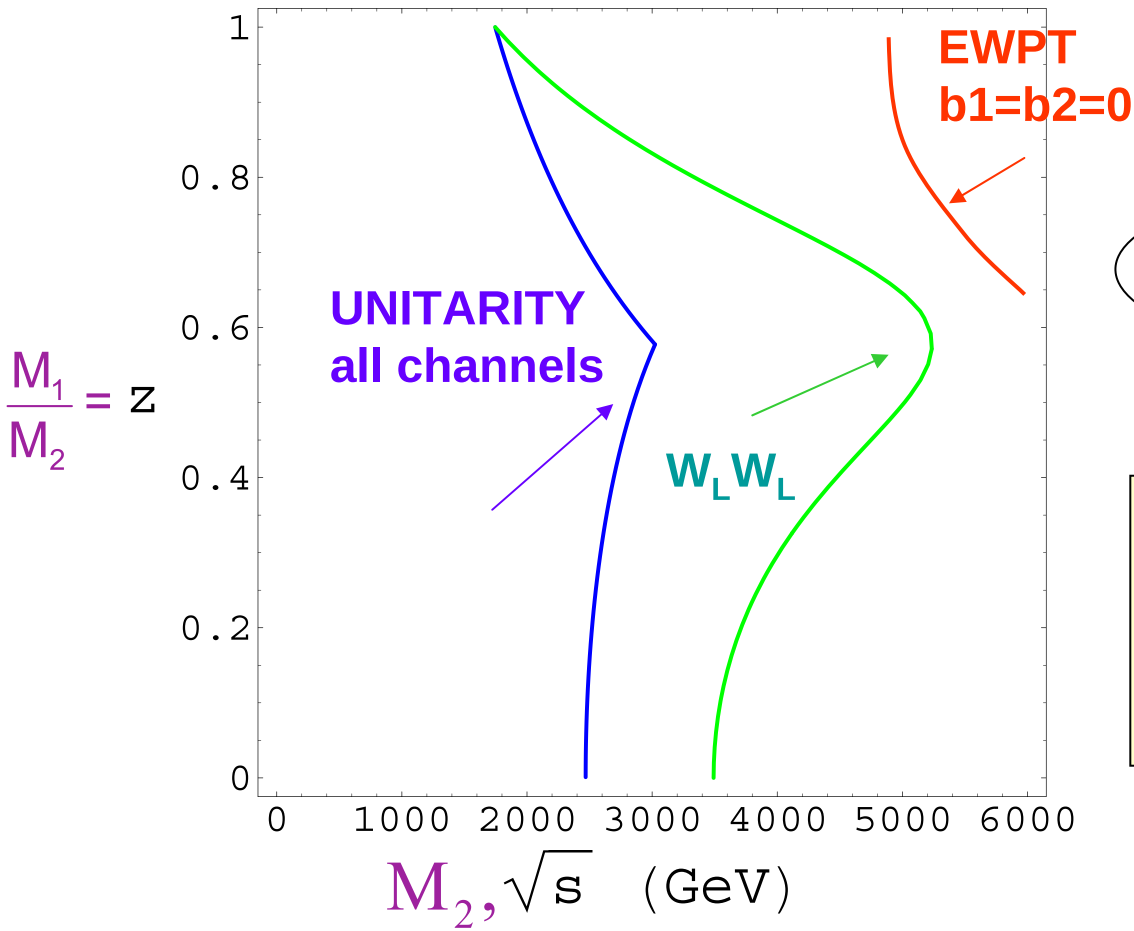
$$M_{1,2}^{c,n} \sim M_{1,2} + O\left(\frac{e^2}{g_1^2}\right)$$

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

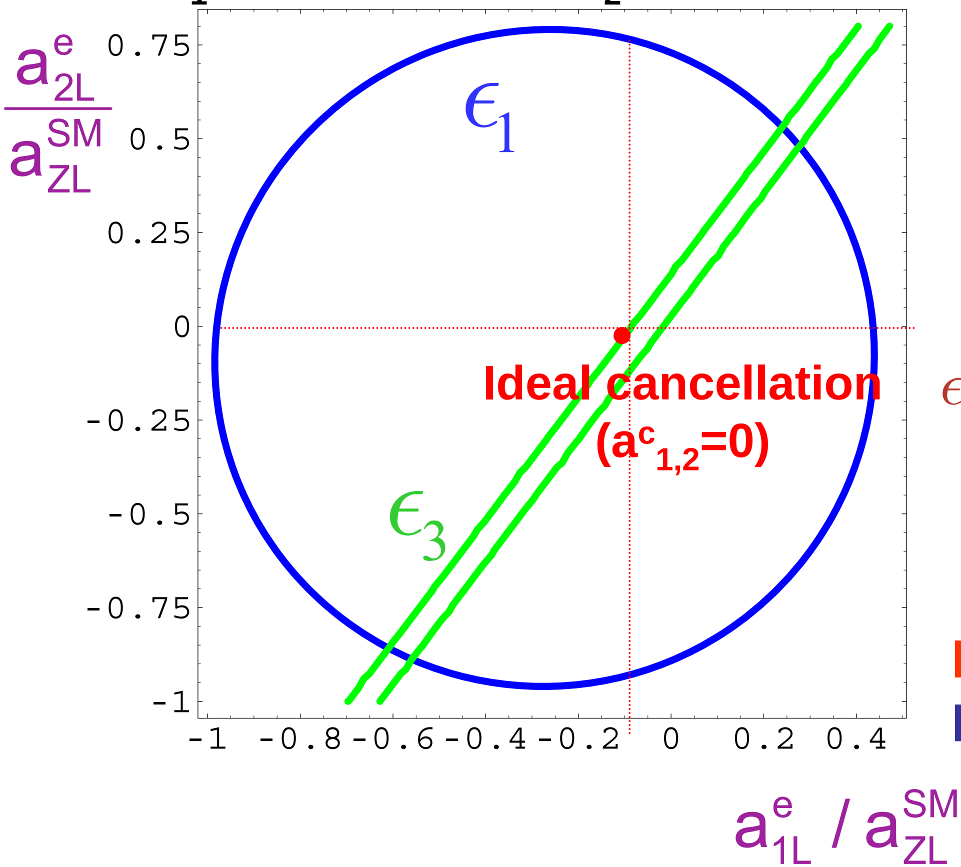
EW precision tests

Calculations $O(e^2/g_1^2)$, exact in 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 neutral couplings (and masses) from low energy precision measurements ε_i

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

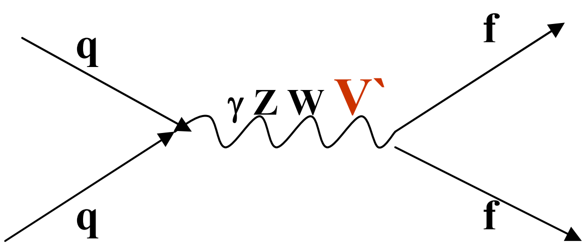
$$\epsilon_3 \sim \sqrt{2}\left(\frac{a^{(e)}_{1L}}{g_1} - z^2 \frac{a^{(e)}_{2L}}{g_1}\right) - \frac{e^2}{g_1^2}\frac{(1+z^4)}{\cos^2\theta_W}$$

ε_3 bounds favour $a_2 > a_1$

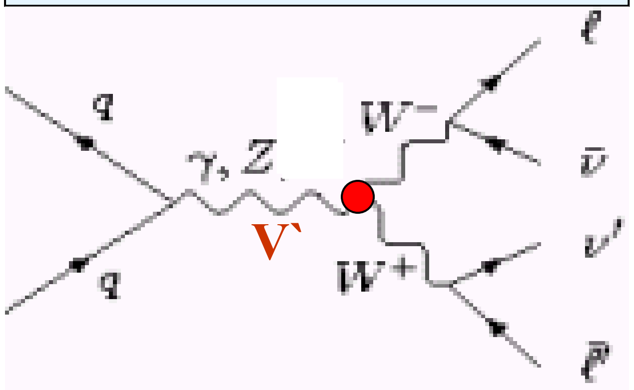
Ideal cancellation $a^c_2 = a^c_1 = 0$, $\varepsilon_3 = 0$)
BUT not fully fermiophobic

New spin-1 resonances @ the LHC

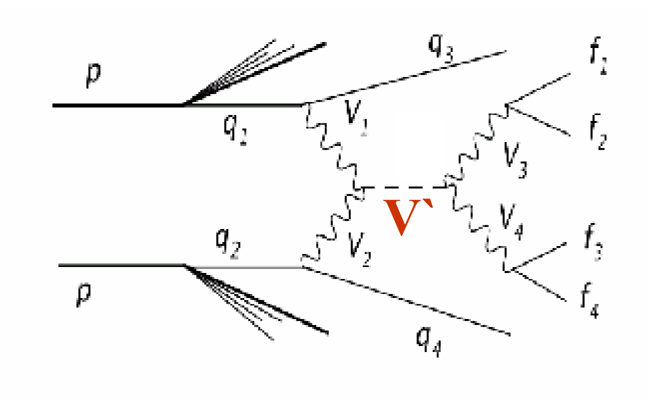
Drell-Yan



Di-boson production



Vector boson scattering



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

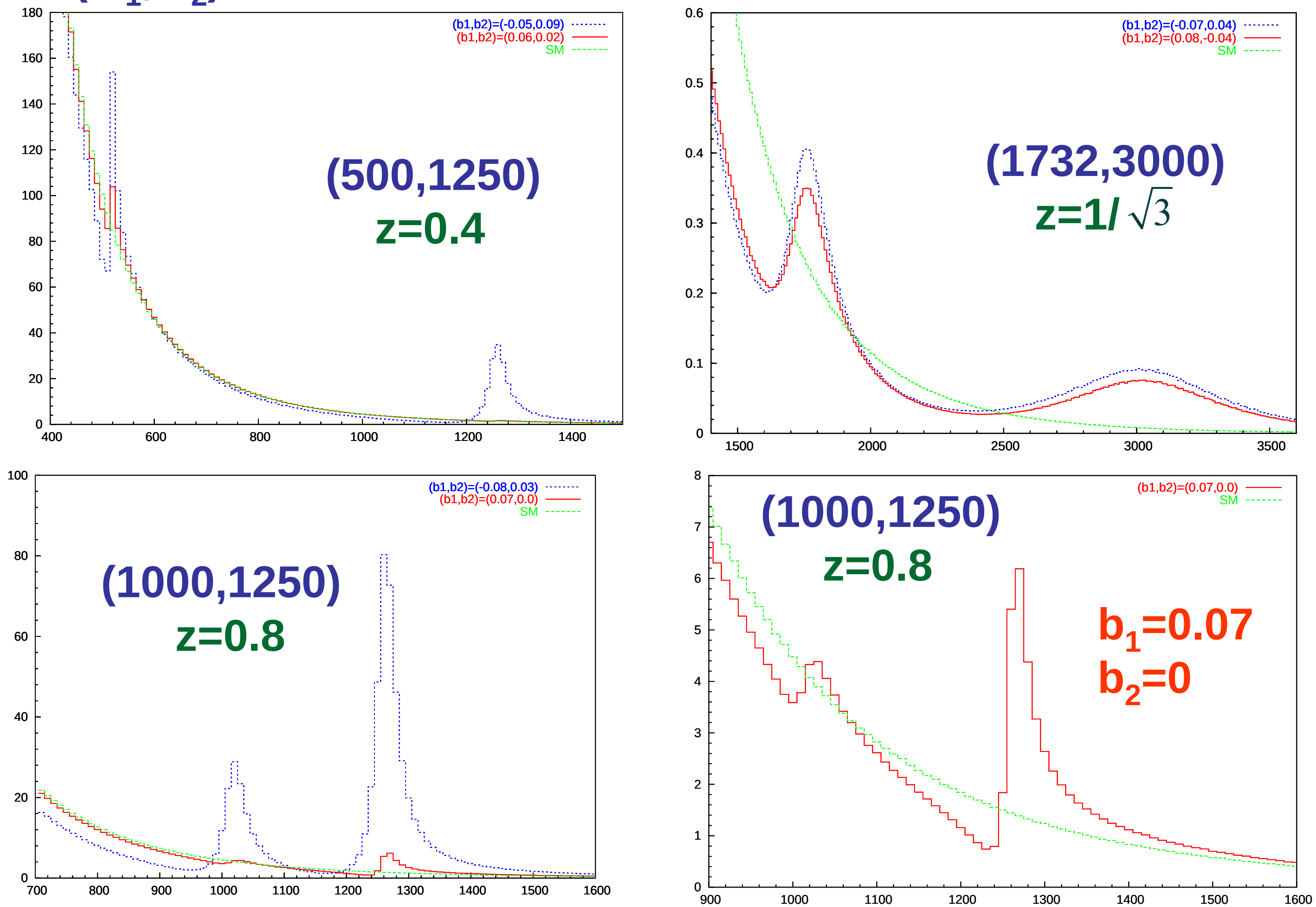
Here consider charged and neutral Drell-Yan leptonic channels

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

Use a MCEG dedicated to Drell-Yan processes at the LHC at the LO and interfaced with PYTHIA (Accomando)

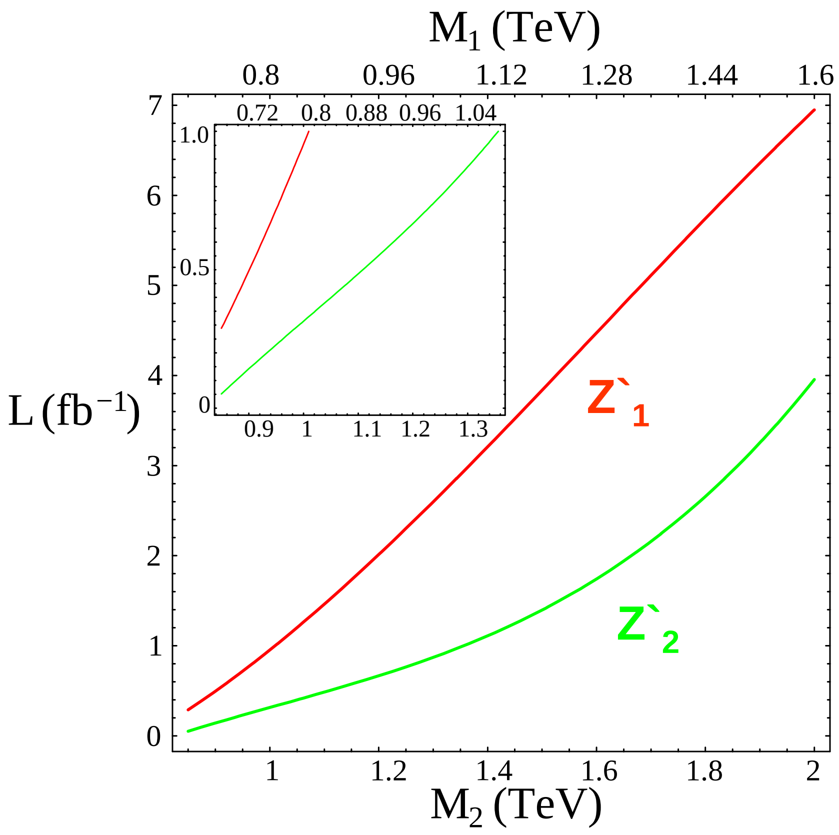
DY-production of Z'_1, Z'_2

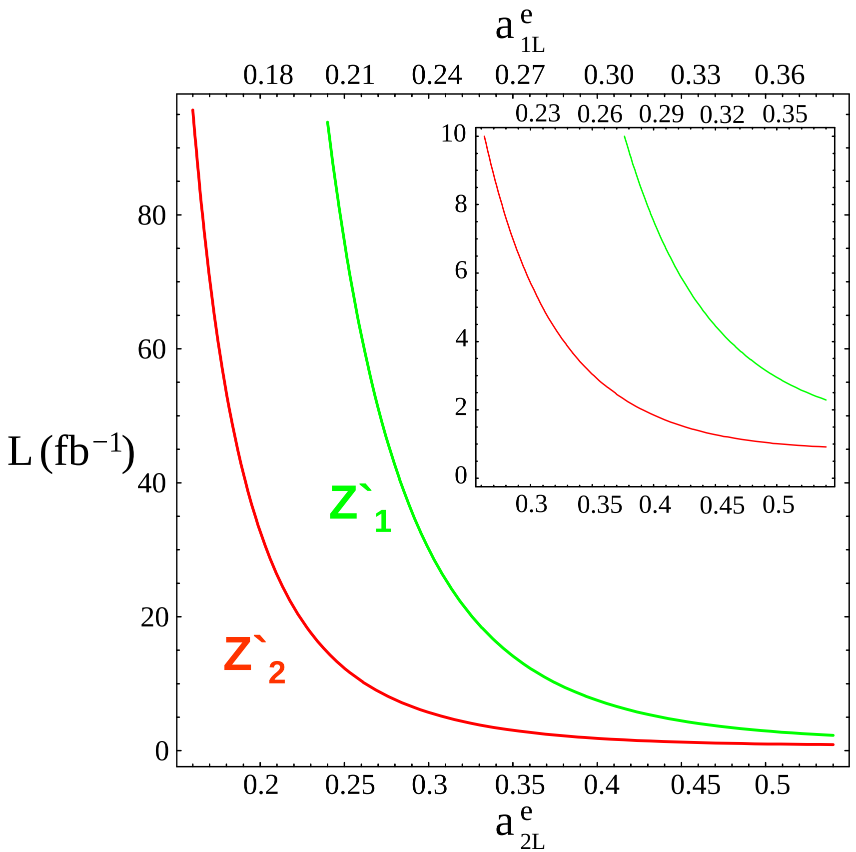
(M_1,M_2) GeV



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

Discovery @ LHC in the early stage low-luminosity run



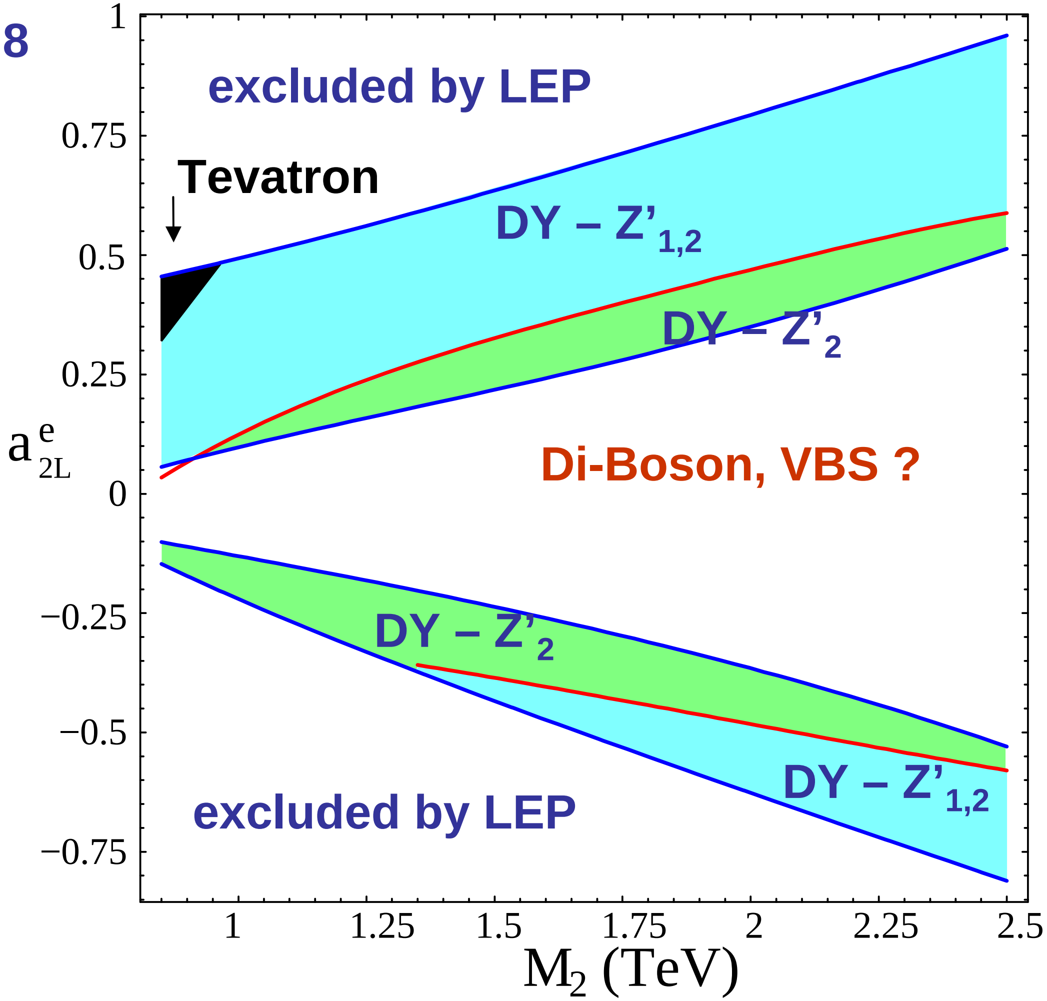


Luminosity needed for a 5σ-discovery for the maximum coupling allowed by EWPT (z=0.8)

Luminosity needed for a 5σ-discovery versus the electron-boson left handed coupling (z=0.8, M_1=1TeV, M_2=1.25TeV)

Discovery @ LHC
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 leptonic channels for L=4fb^{-1}

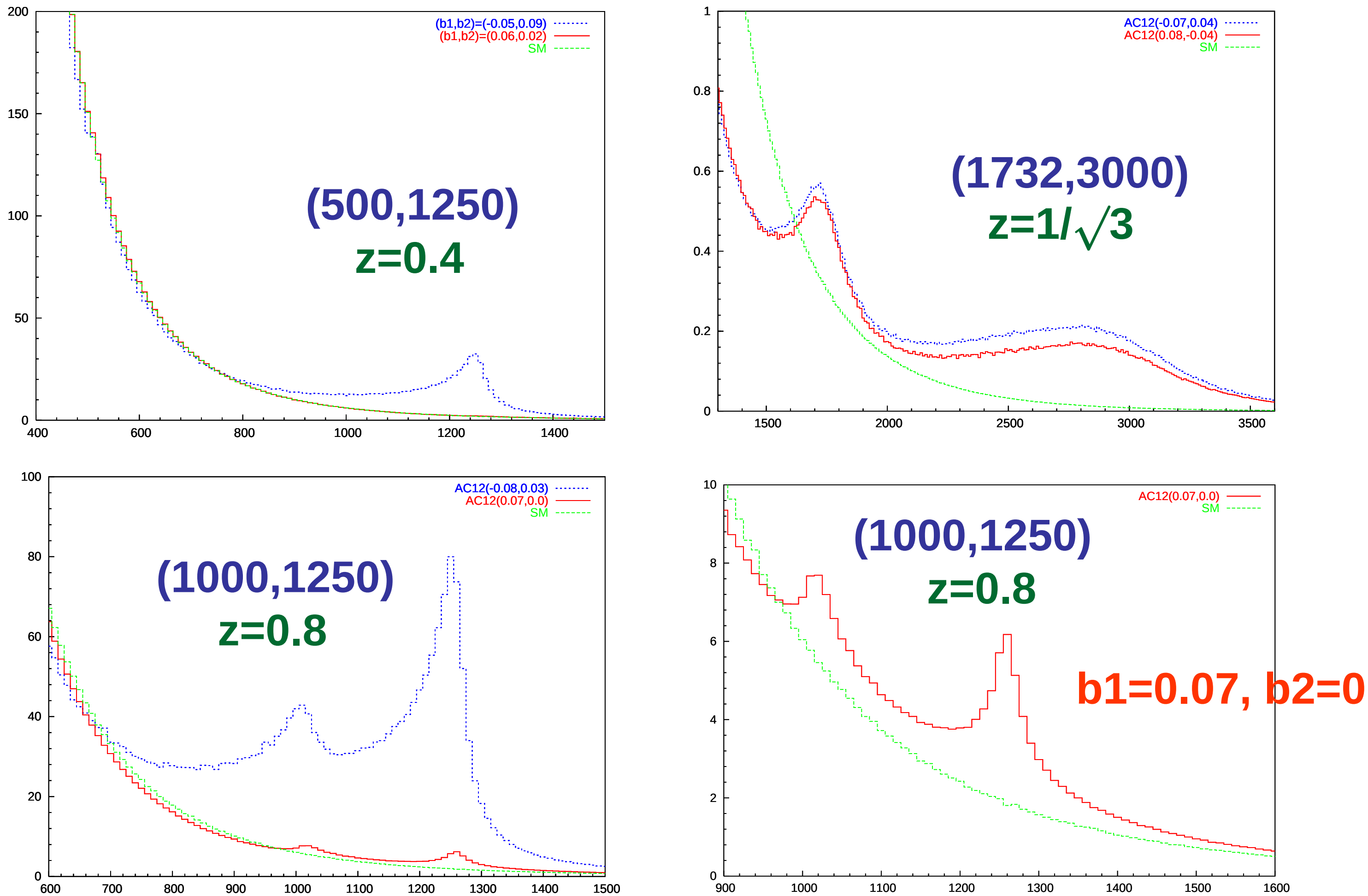
$$p\bar{p} \to l^+ l^- \quad (l = e, \mu)$$

Bounds from LEP2 not effective

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

W'_1, W'_2 production

	$M_{1,2}$(GeV)	$b_{1,2}$	M_t^{cut}(GeV)	$N_{\rm evt}^{\rm sig}(W_{1,2}^{\pm})$	$N_{\rm evt}^{\rm tot}(W_{1,2}^{\pm})$	σ
1	500,1250	-0.05,0.09	800	641	910	21.2
3	1732,3000	-0.07,0.04	1500	38	45	5.7
5	1000,1250	-0.08,0.03	700	1715	2323	35.6

# 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 $\rm fb^{-1}$

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

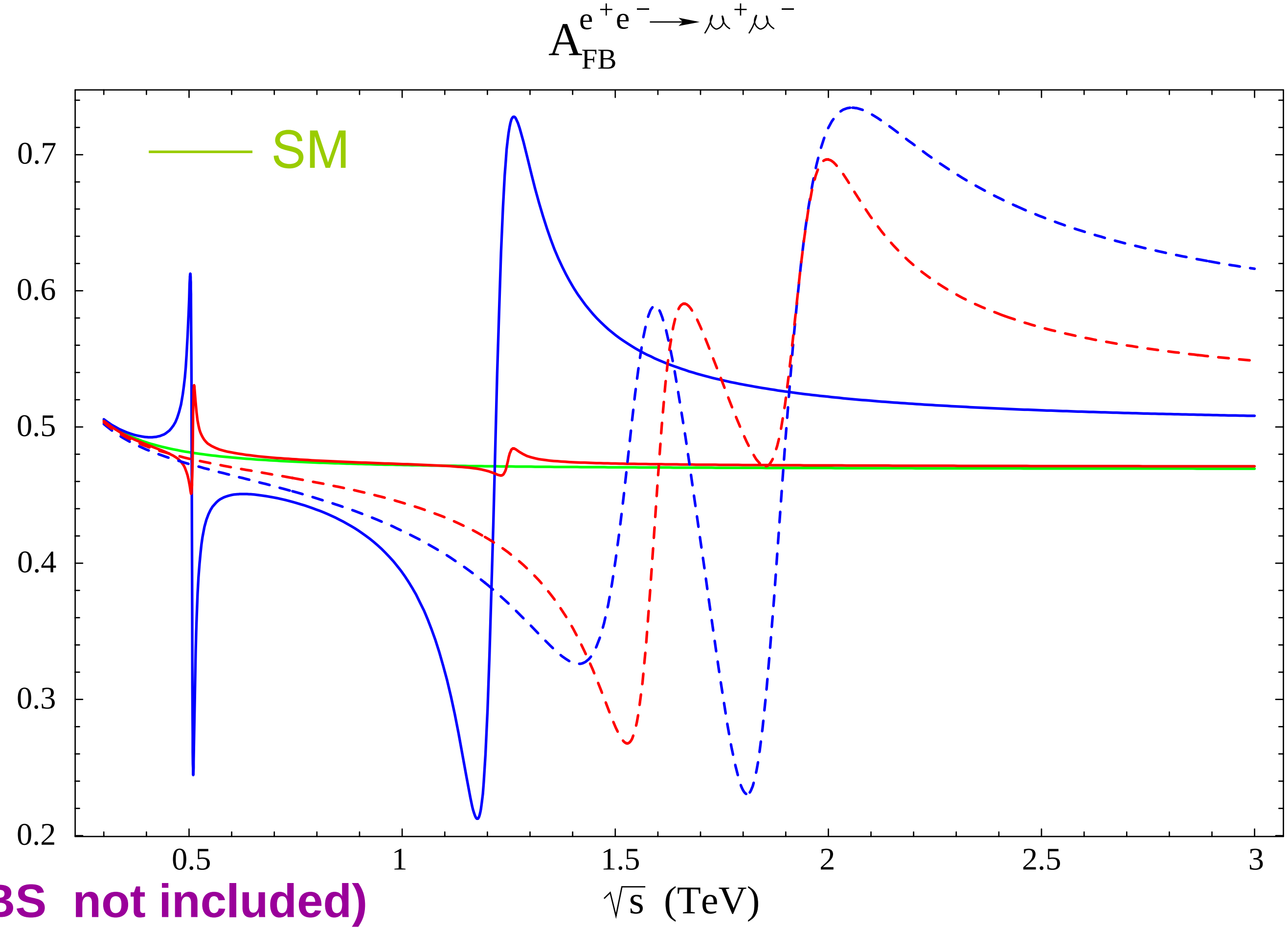
Neutral and charged channel are complementary

All six extra gauge bosons could be investigated at the LHC start-up with L ~ 1 fb^{-1}

4-site at 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

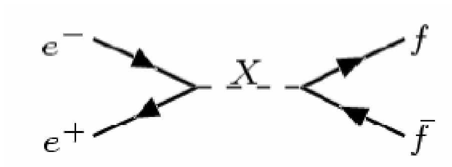


(ISR & BS not included)

4-site at 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}	
	1 ab^{-1} ILC - 1TeV (rescaled from CLIC)	1 ab^{-1} CLIC – 3TeV
$\sigma_{\mu^+\mu^-}$	$\pm 0.6\%$	± 0.010
$\sigma_{b\bar{b}}$	$\pm 0.7\%$	± 0.012
$\sigma_{t\bar{t}}$	$\pm 0.8\%$	± 0.014
$A_{FB}^{\mu\mu}$	$\pm 1\%$	± 0.018
A_{FB}^{bb}	$\pm 3\%$	± 0.055
A_{FB}^{tt}	$\pm 2\%$	± 0.040

CLIC – 3TeV

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

rescaled from CLIC 1 ab^{-1} ILC - 1TeV

4-site at a 1TeV-LC

$$\frac{\delta O}{O} = \frac{(O^{\text{4-site}} - O^{\text{SM}})}{O^{\text{SM}}}$$

$\sqrt{s} = 1$ TeV **ISR & BS not included**

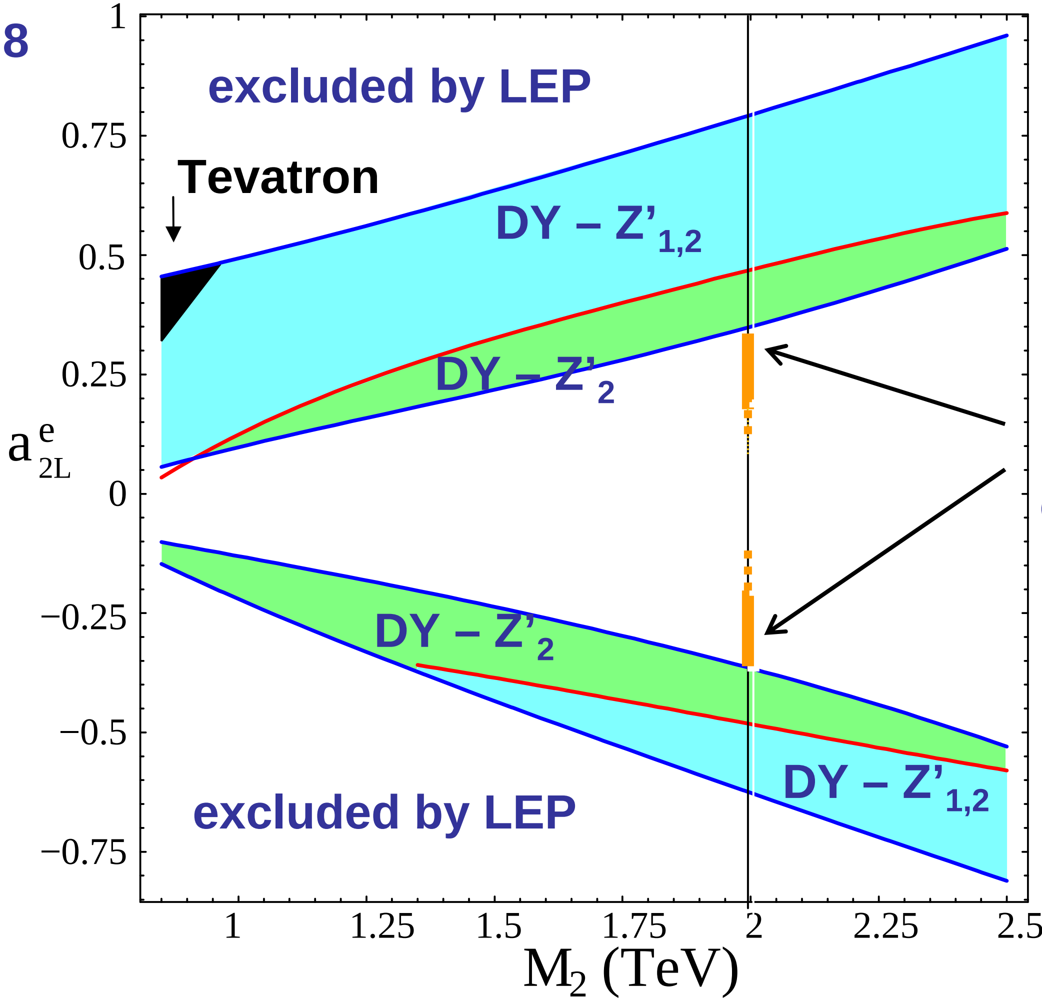
M_1=1.6 TeV
M_2=2 TeV

	$\delta\sigma / \sigma(\mu^+\mu^-)$	$\delta\sigma / \sigma(b\bar{b})$	$\delta A_{FB}^{\mu} / A_{FB}^{\mu}$	$\delta A_{FB}^{b} / A_{FB}^{b}$
$a_{2L} = 0.3$	-0.036	-0.079	-0.016	-0.014
$a_{2L} = 0.2$	-0.018	-0.035	-0.007	-0.006
$a_{2L} = 0.1$	-0.006	-0.008	-0.001	-0.0005
$a_{2L} = -0.1$	-0.006	-0.009	-0.001	-0.003
$a_{2L} = -0.2$	-0.013	-0.032	-0.010	-0.003
$a_{2L} = -0.3$	-0.020	-0.075	-0.020	-0.011

Compare with: $\delta\sigma / \sigma_{exp}(\mu^+\mu^-) \simeq 0.6\%, \quad \delta\sigma / \sigma_{exp}(b\bar{b}) \simeq 0.7\%$

$\delta A_{FB}^{\mu} / A_{FB}^{\mu} \simeq 1\%, \quad \delta A_{FB}^{b} / A_{FB}^{b} \simeq 3\%$ for 1 ab^{-1} rescaled from CLIC (conservative) very preliminary

Z=0.8

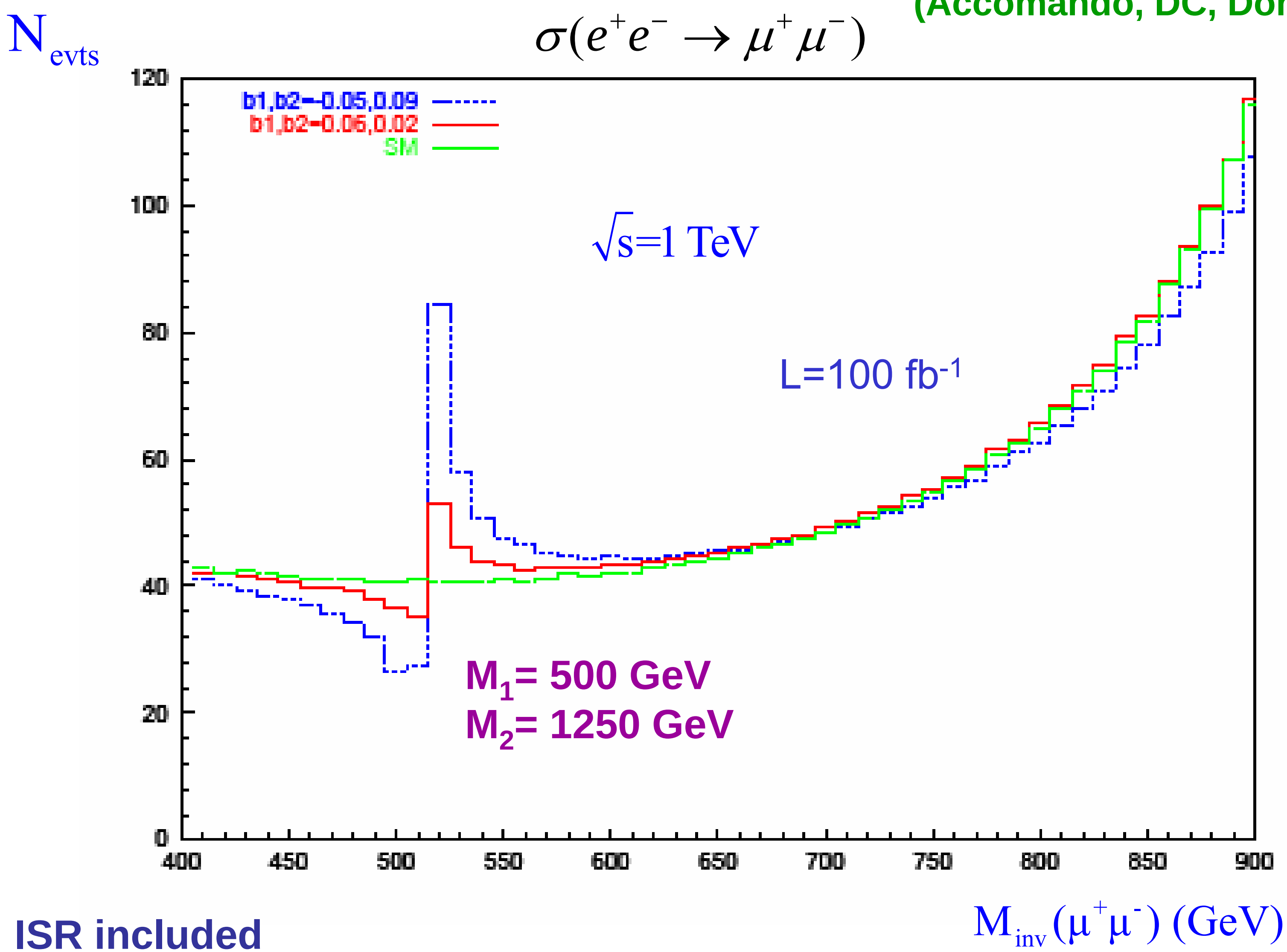


Excluded by 1TeV-LC precision measurements of cross-sections and A_{FB}

Work to do: include ISR & BS, combine the observables, cover the entire region, include polarization, ….

4-site at a LC (preliminary)

(Accomando, DC, Dominici,Fedeli)



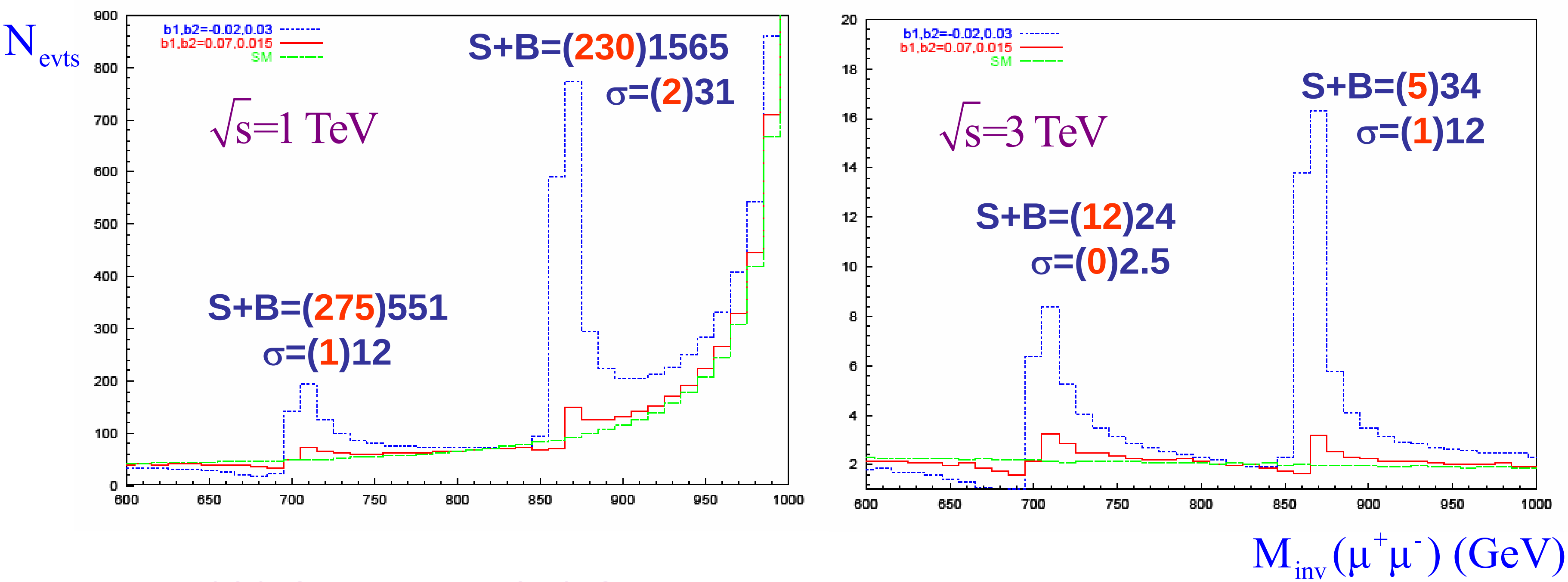
ISR included
BS not included

1TeV-LC or CLIC ?

(Accomando, DC, Dominici, Fedeli)

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

L=100 fb^{-1}



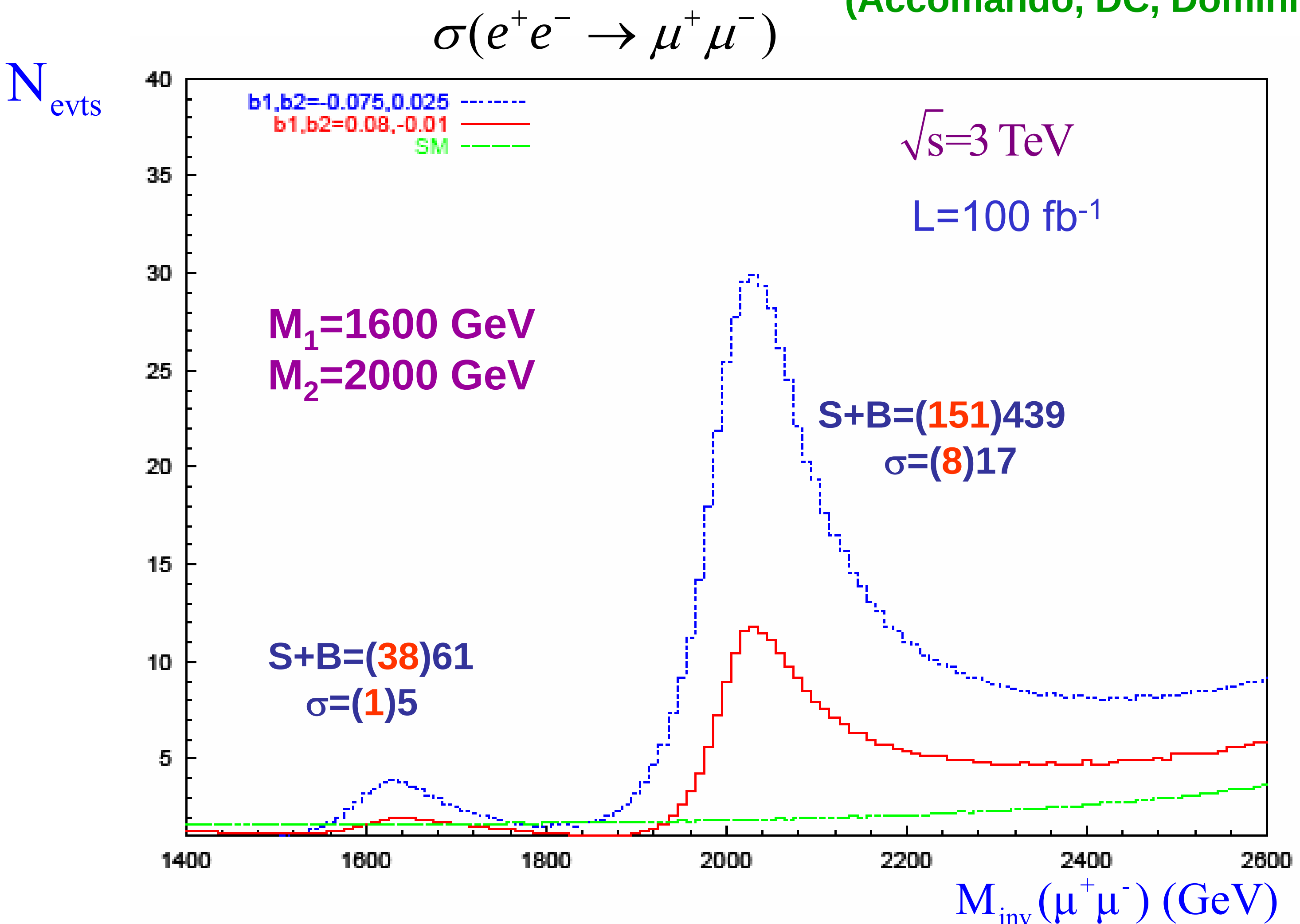
M_1=680 GeV M_2=850 GeV

S+B=#evts(M$\pm$2Γ)
σ=S/(S+B)

ISR included
BS not included

4-site at CLIC (preliminary)

(Accomando, DC, Dominici, Fedeli)



ISR included

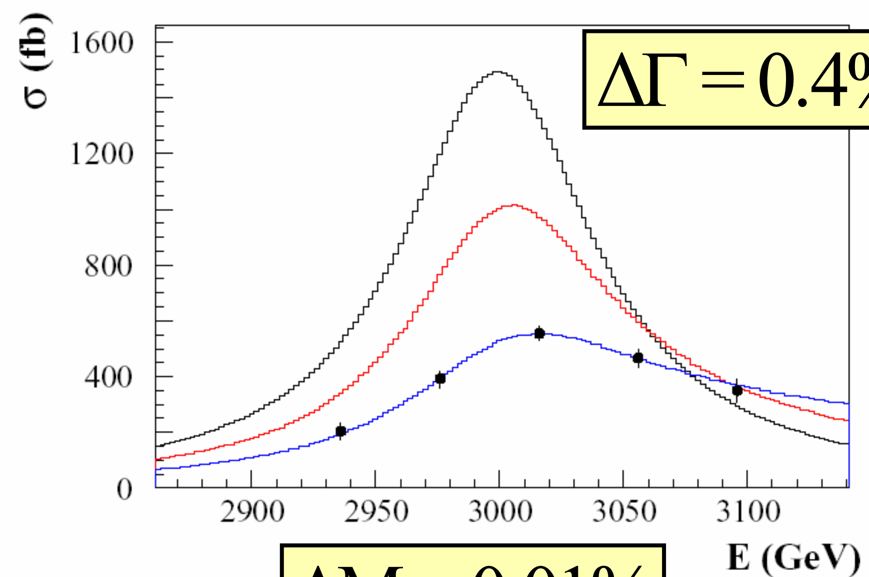
BS not included

S+B=#evts(M±Γ)

σ=S/(S+B)

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

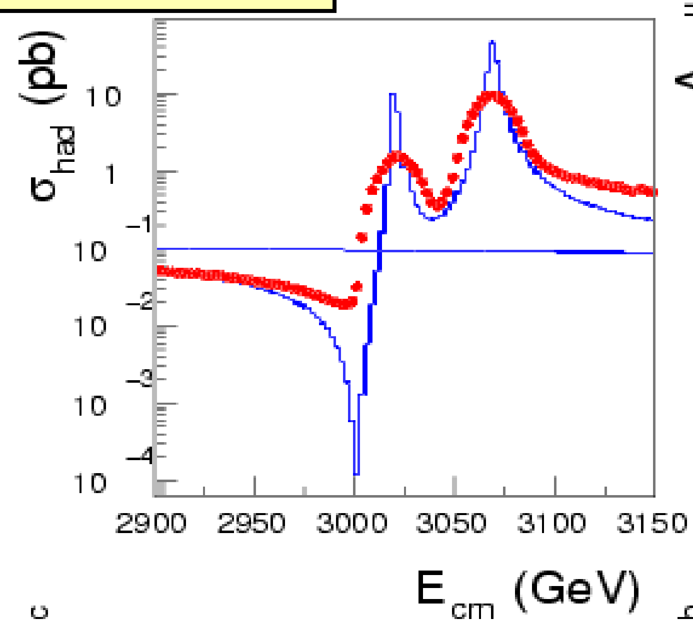
(Battaglia, DC, Dominici, 2002)

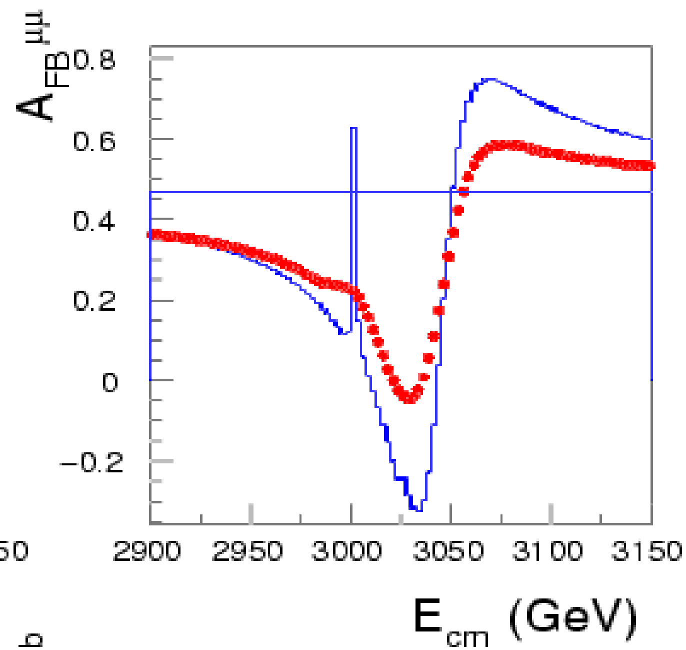


$\Delta\Gamma = 0.4\%$

$\Delta M = 0.01\%$

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





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 to energy scales higher than those probed at the LHC

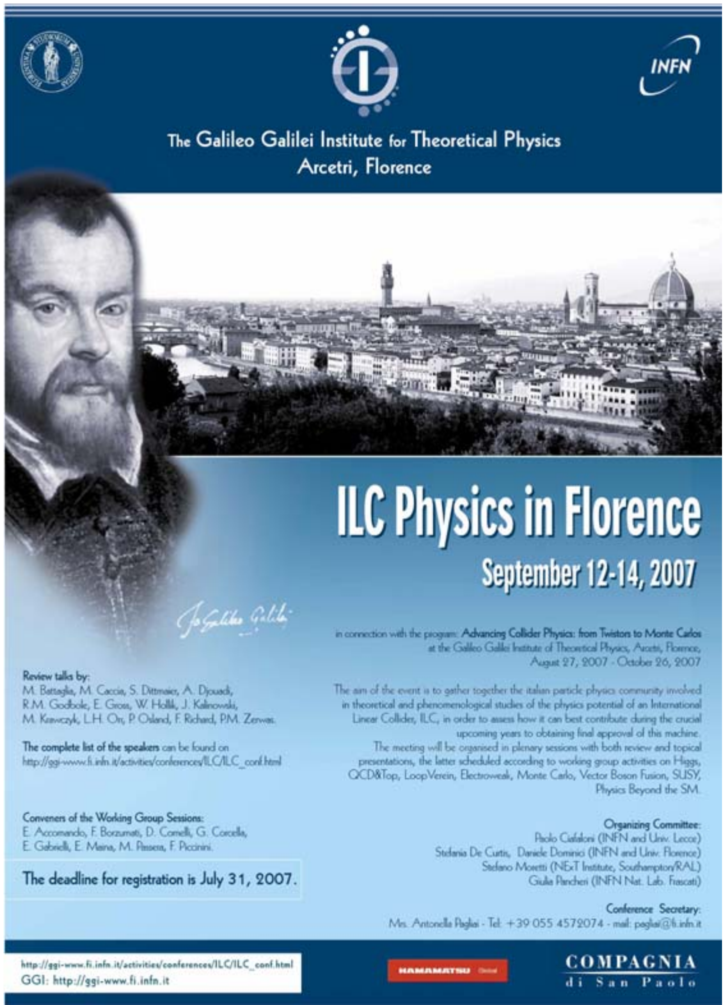
- Drell-Yan processes are a very good channel to discover these extra gauge bosons at the LHC. Di-boson production and VBS in progress (interesting because V_1~vector and V_2~ axial-vector)

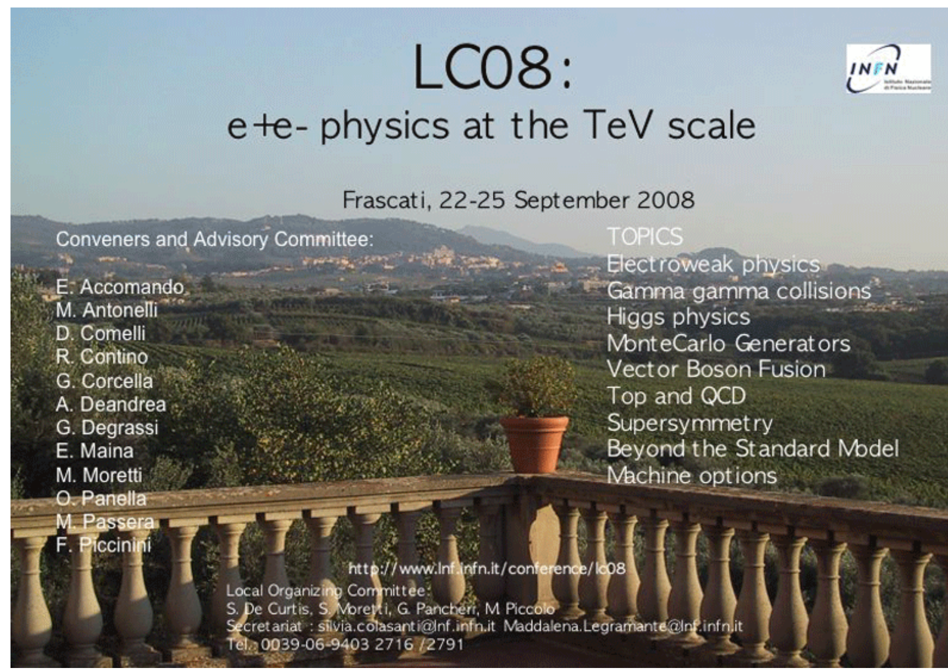
- 1TeV-LC has indirect sensitivity to the 4-site model and/or profile low-mass Z`s

- 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

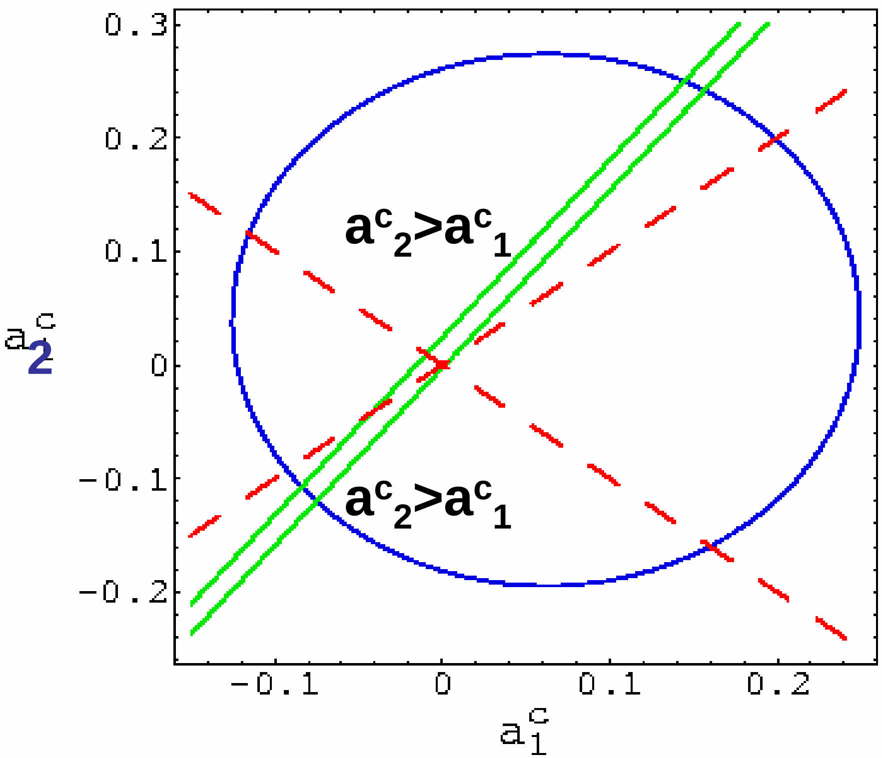




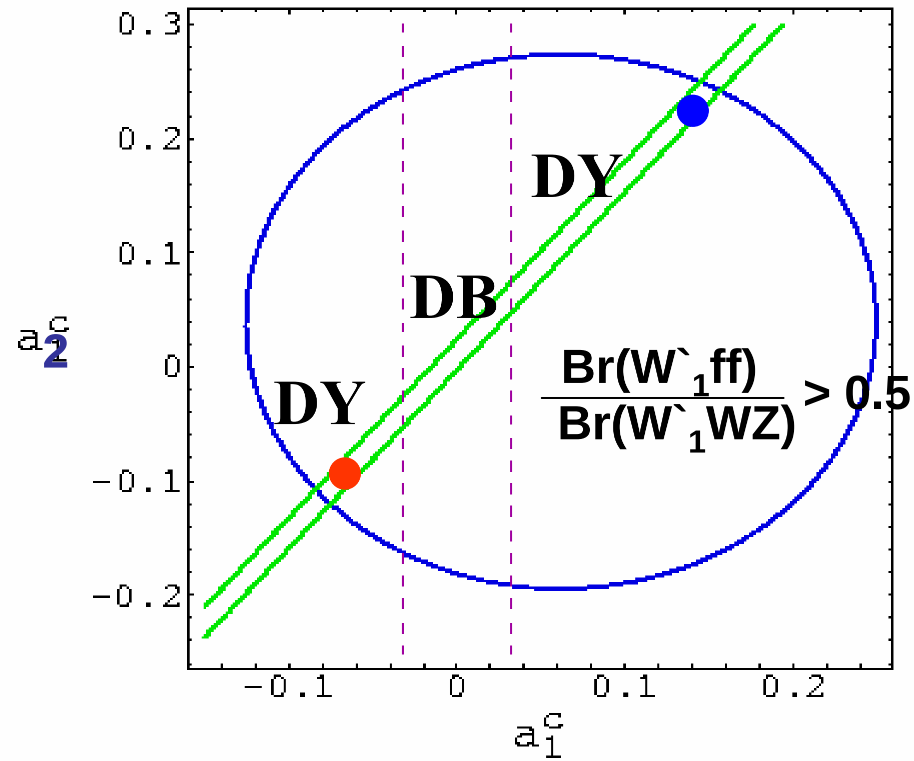
extra slides

The Higgsless 4-site Linear Moose model

Fermionic coupling features



Resonance hierarchy



Drell-Yan vs Di-Boson

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

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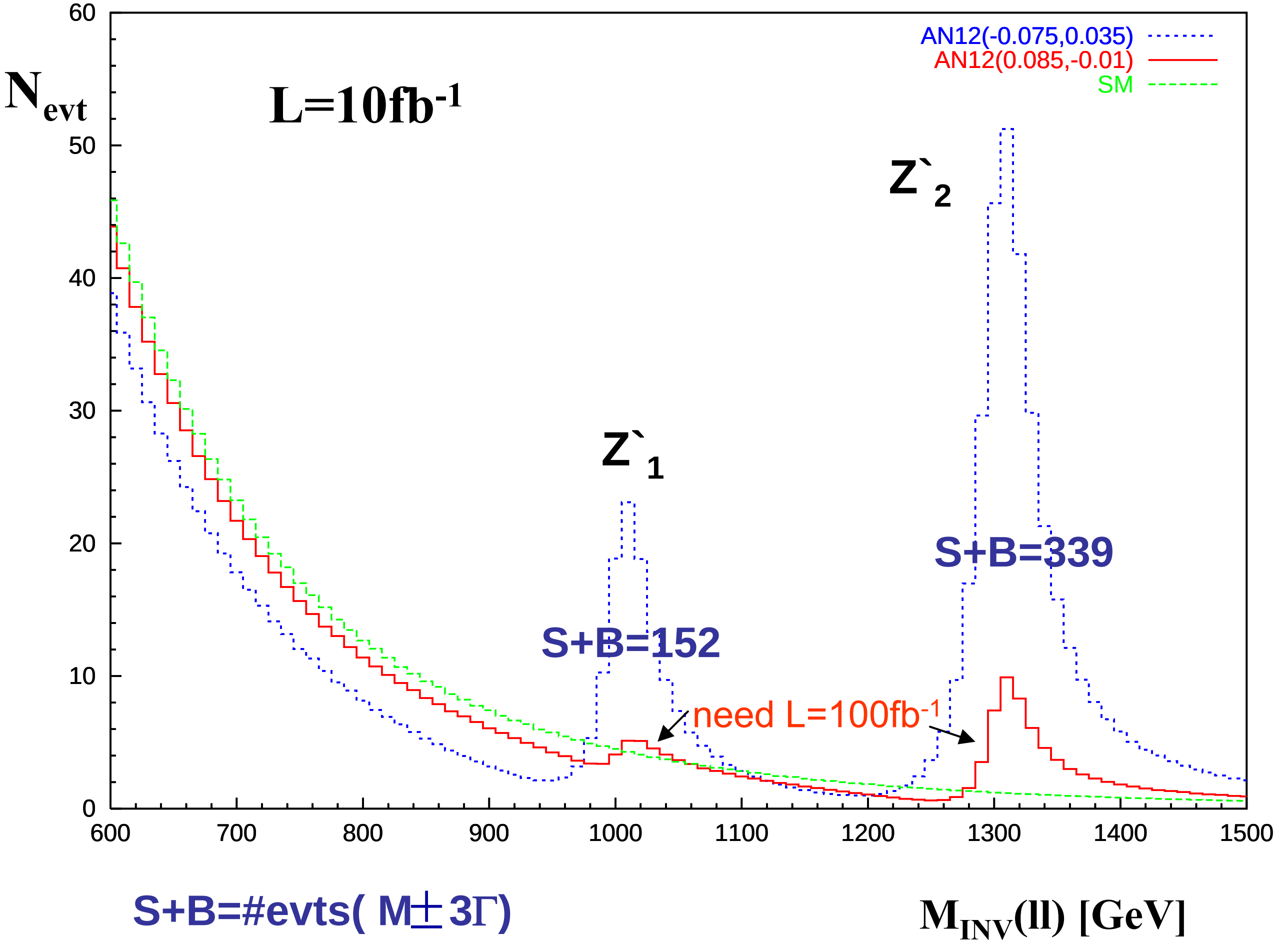
Drell-Yan processes

Z`$_1$ and Z`$_2$ production in the neutral channel

$$pp \rightarrow l^+l^- \quad (l = e, \mu)$$



S+B=#evts(M$\pm$3Γ)

g_1= 3.7

(M_1,M_2)=(1000,1300)GeV

b_1 = (-0.075) (0.085)

b_2 = (0.035) (-0.01)

$M_{Z`1}$ =1010.2 GeV

$M_{Z`2}$ =1304.8 GeV

$\Gamma_{Z'1}$ = (37.6) (35.1) GeV

$\Gamma_{Z'2}$ = (44.6) (35.0) GeV

Z'_1, Z'_2 production

	$M_{1,2}$(GeV)	$b_{1,2}$	$N^{sig}_{evt}(Z_1)$	$N^{tot}_{evt}(Z_1)$	$\sigma(Z_1)$	$N^{sig}_{evt}(Z_2)$	$N^{tot}_{evt}(Z_2)$	$\sigma(Z_2)$
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 $|M_{inv}(l^+l^-)-M_i| < \Gamma_i$

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

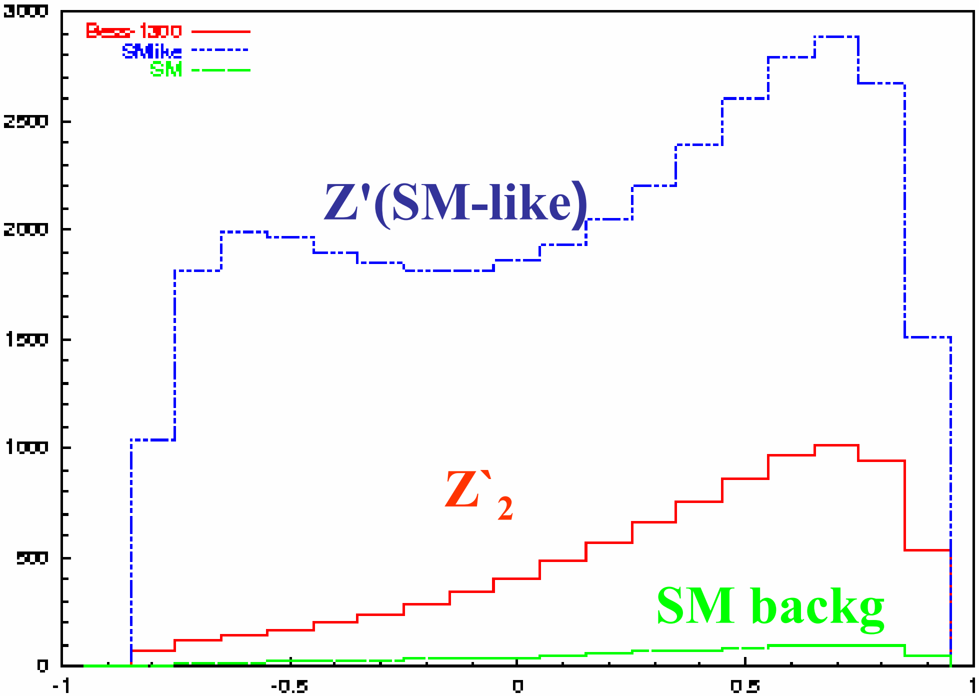
How to distinguish the various models?

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

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

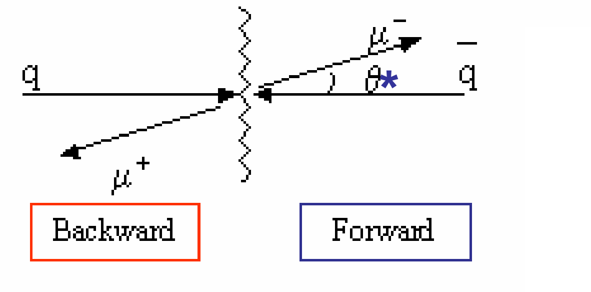
L=100 fb^{-1}

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



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

evts for Z`$_2$ ~ 1000



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

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

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

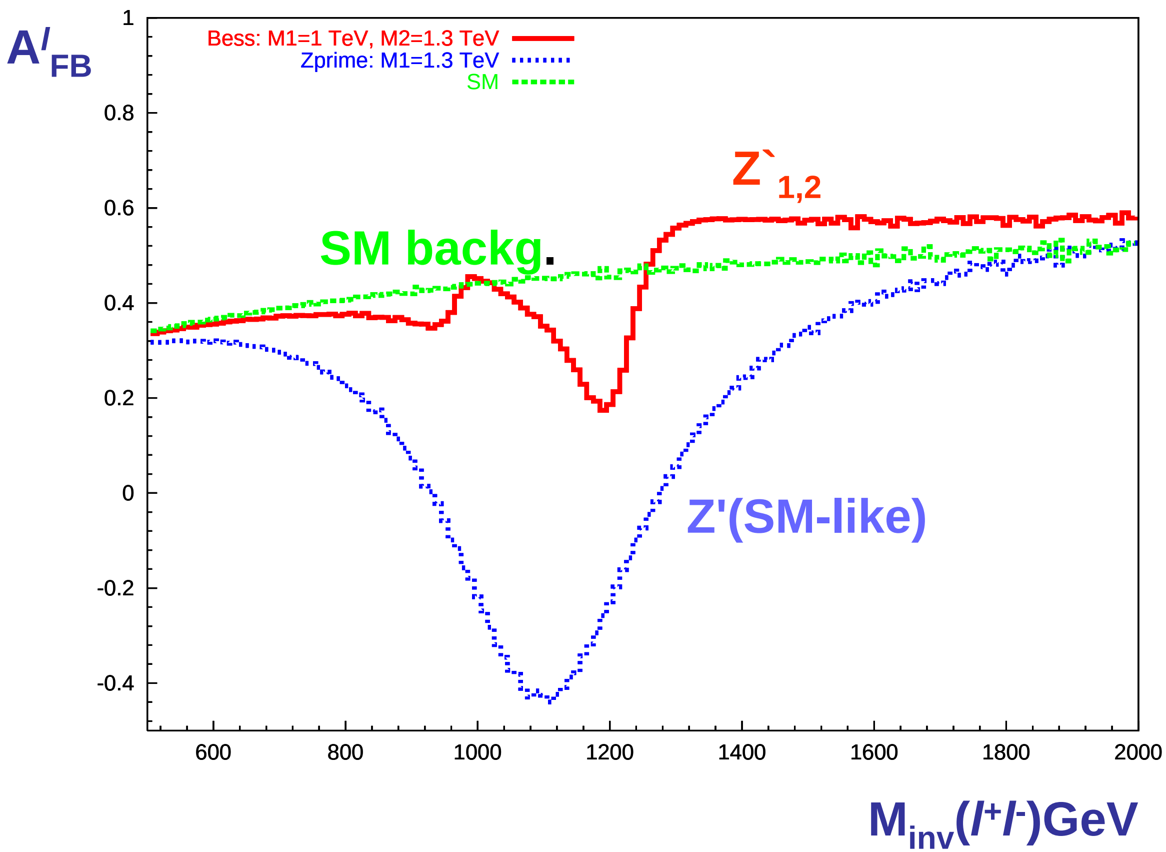
we select the events within

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

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

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

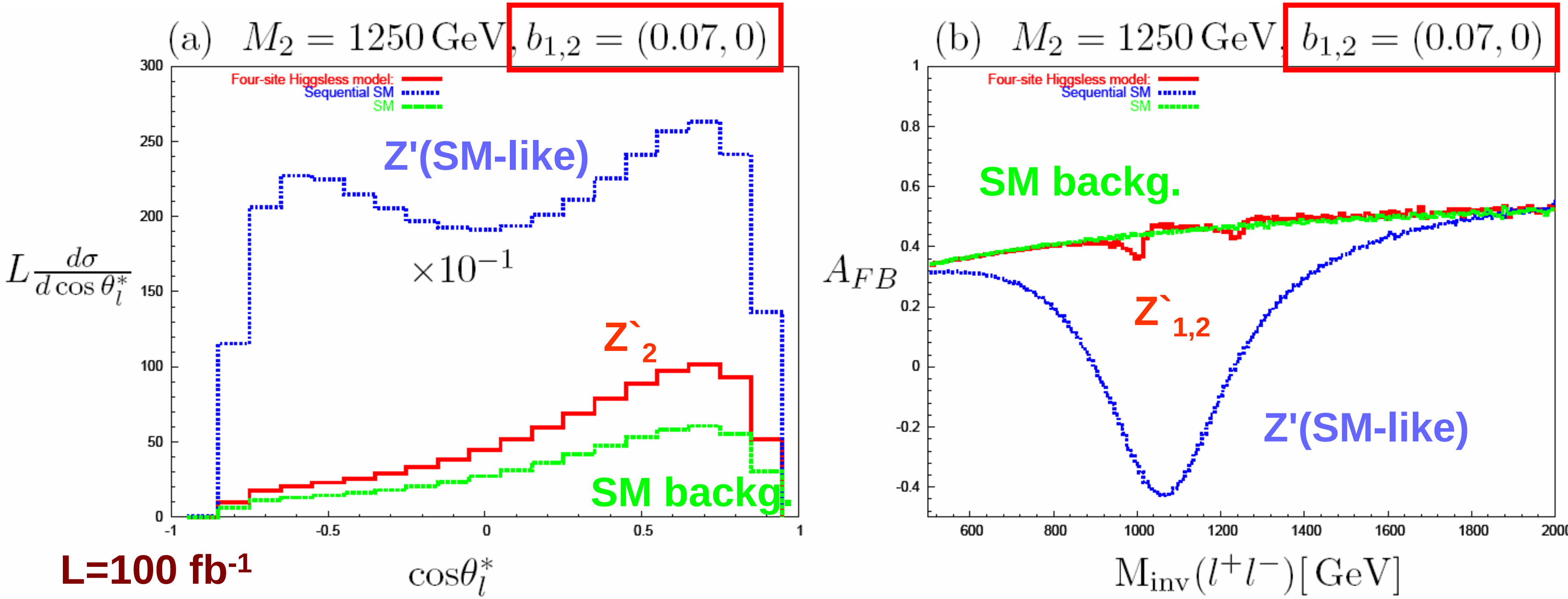
(Dittmar,Nicollerat,Djouadi 03; Petriello,Quackenbush 08)



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

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

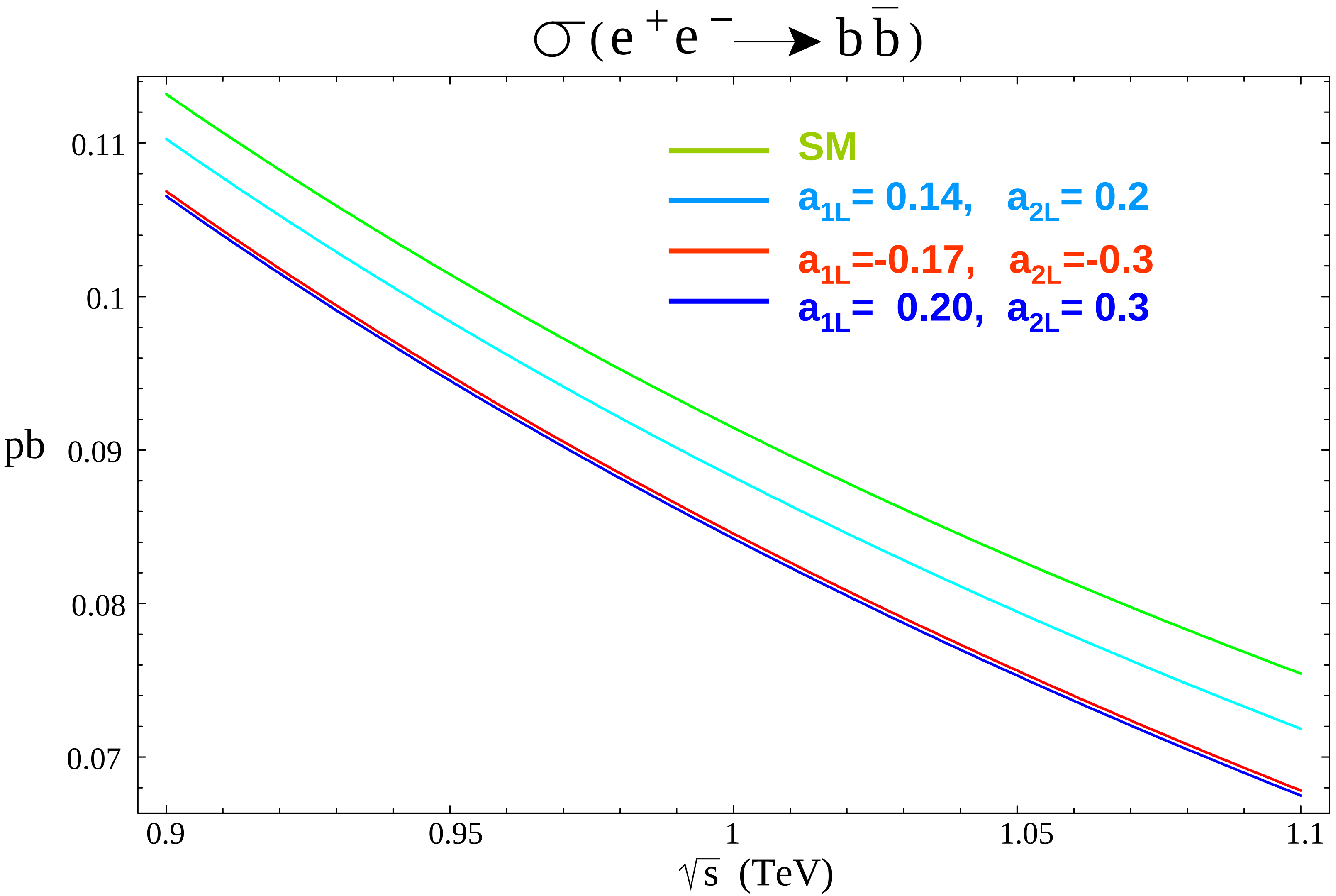
How to distinguish the various models?
Forward-backward asymmetry A_{FB} in pp $\longrightarrow l^+ l^-$



L=100 fb^{-1}

- 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 at a LC (preliminary)



M_1=1600 GeV M_2=2000 GeV (ISR not included)

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:

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

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

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

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, …..

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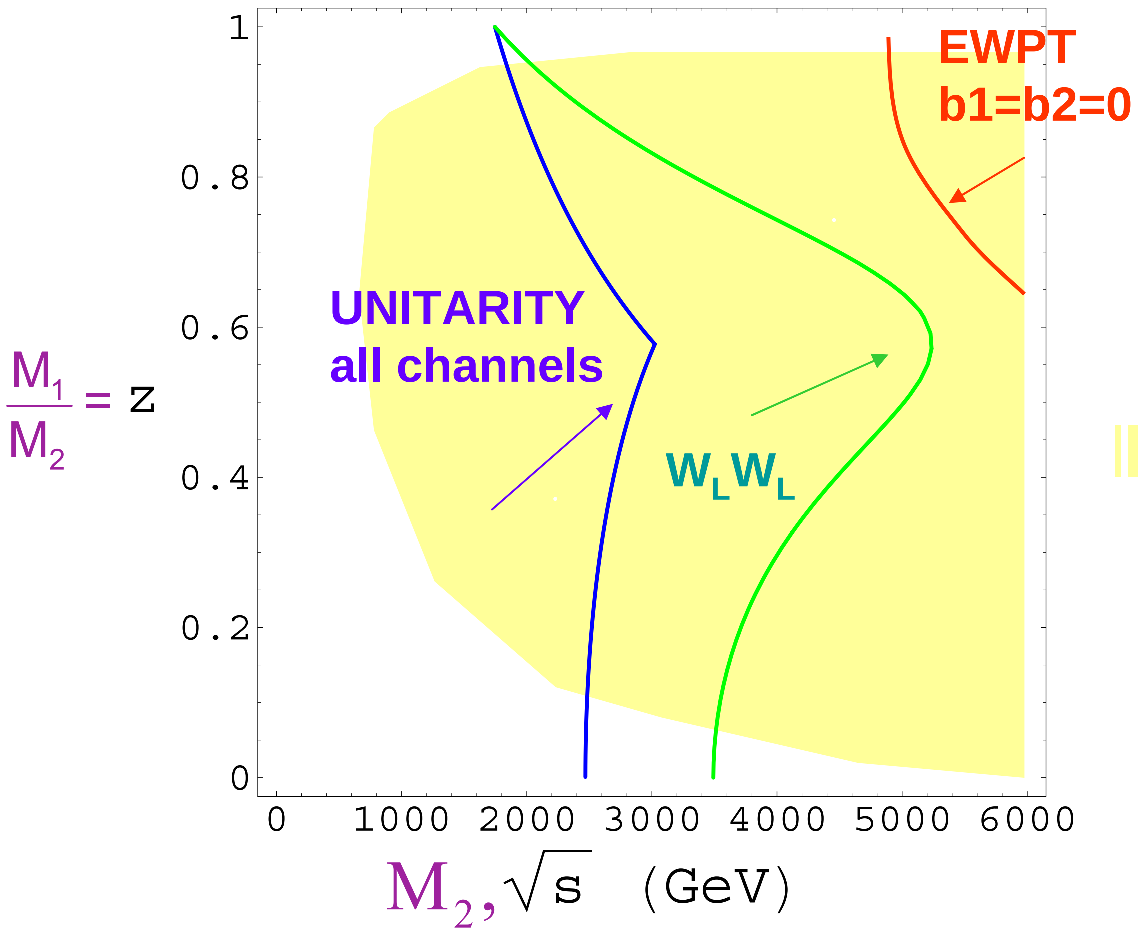


region of validity of the perturbative expansion

$(g/g_1)^4 < 0.005$

charged

	$M_{(1,2),c}$(GeV)	$\Gamma_{1,2}$(GeV)	a_1^c	a_2^c
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

	$M_{(1,2),n}$(GeV)	$\Gamma_{1,2}$(GeV)	a_{1L}^e	a_{1R}^e	a_{1L}^d	a_{1R}^d	a_{1L}^u	a_{1R}^u	a_{2L}^e	a_{2R}^e	a_{2L}^d	a_{2R}^d	a_{2L}^u	a_{2R}^u
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 (electric charge –e factorized)

Hadronic Final States

Processes

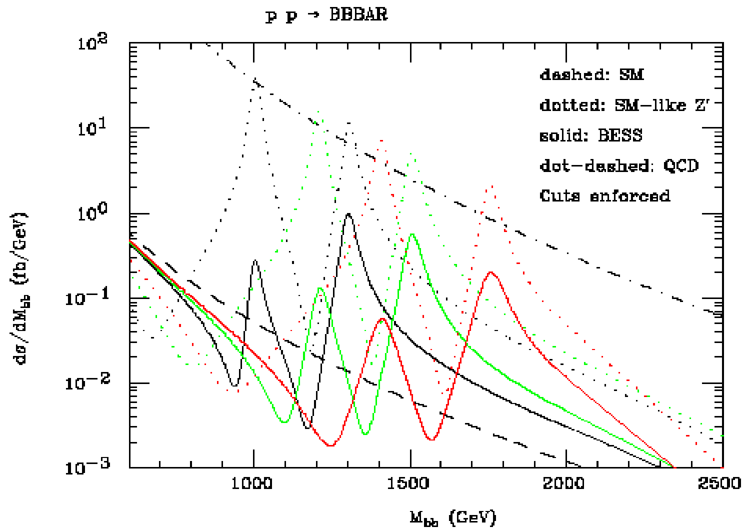
•pp → *qq* with *q=b,t*

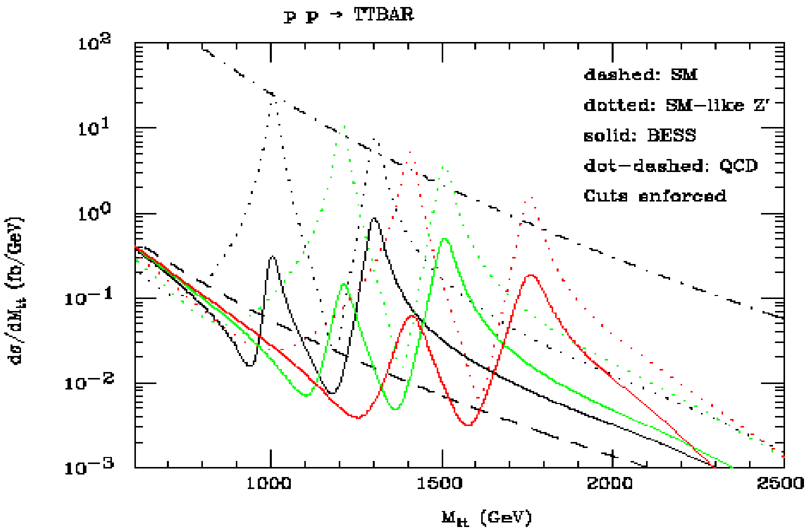
Can flavour tag b-jets and reconstruct top quarks

Kinematical cuts

Acceptance+Selection cuts:

$|\eta(q)|<2.5$, $P_t(q)>30$ GeV, $\sqrt{\hat{s}} > 500$ GeV





BESS resonance extraction tricky because of QCD background

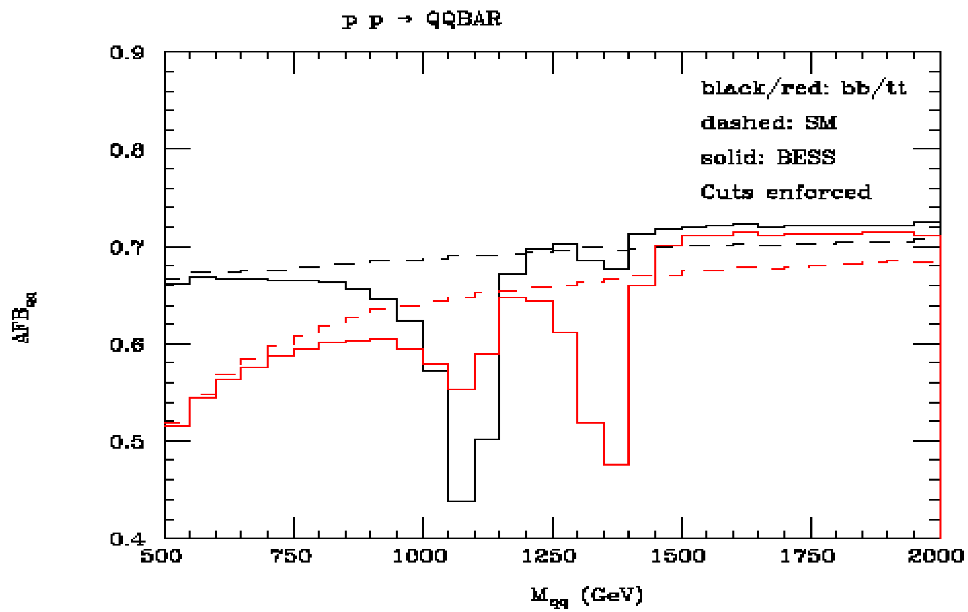
Forward-backward asymmetry A_{FB} in $pp \to q\bar{q}$

1. Can be defined by looking at leptonic q decay
2. LO QCD has no forward-backward asymmetry!

BESS:

$M_{Z`1}$=1210 GeV

$M_{Z`2}$=1505 GeV



Only NLO QCD can introduce $O(\alpha_s)$ effects
EW interferences are $O(\alpha_{EM})$ only