Prospective Study

on

Muon Colliders

Strong Electroweak Symmetry Breaking at Muon Colliders

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Summary

- Introduction
- Description of the Resonances
- s-channel Processes
- Fusion Processes
- Drell-Yan Processes
- Conclusions

Introduction

- No SM of SEWS. General features: Strong Interactions at the TeV scale, implying resonances with masses $\approx 1\ TeV$.

- Theoretical analysis difficult and model dependent. Best way: use phenomenological lagrangians for spontaneous broken symmetries.

- Physics at NLC and μC very similar for heavy resonances. At μC greater energy and possibility of looking for narrow resonances. A μC with $\sqrt{s} \approx 2 \div 4\ TeV$ would allow to explore the spectrum of the resonances of the SEWS models.

- How to look for these resonances?

1 - $\ell^+\ell^- \to f\bar{f}$ (s-channel processes)

For most of the models scalar and vector resonances, for $M_R > 2m_W$, have as main decay mode $R \to W^+W^-$. Since

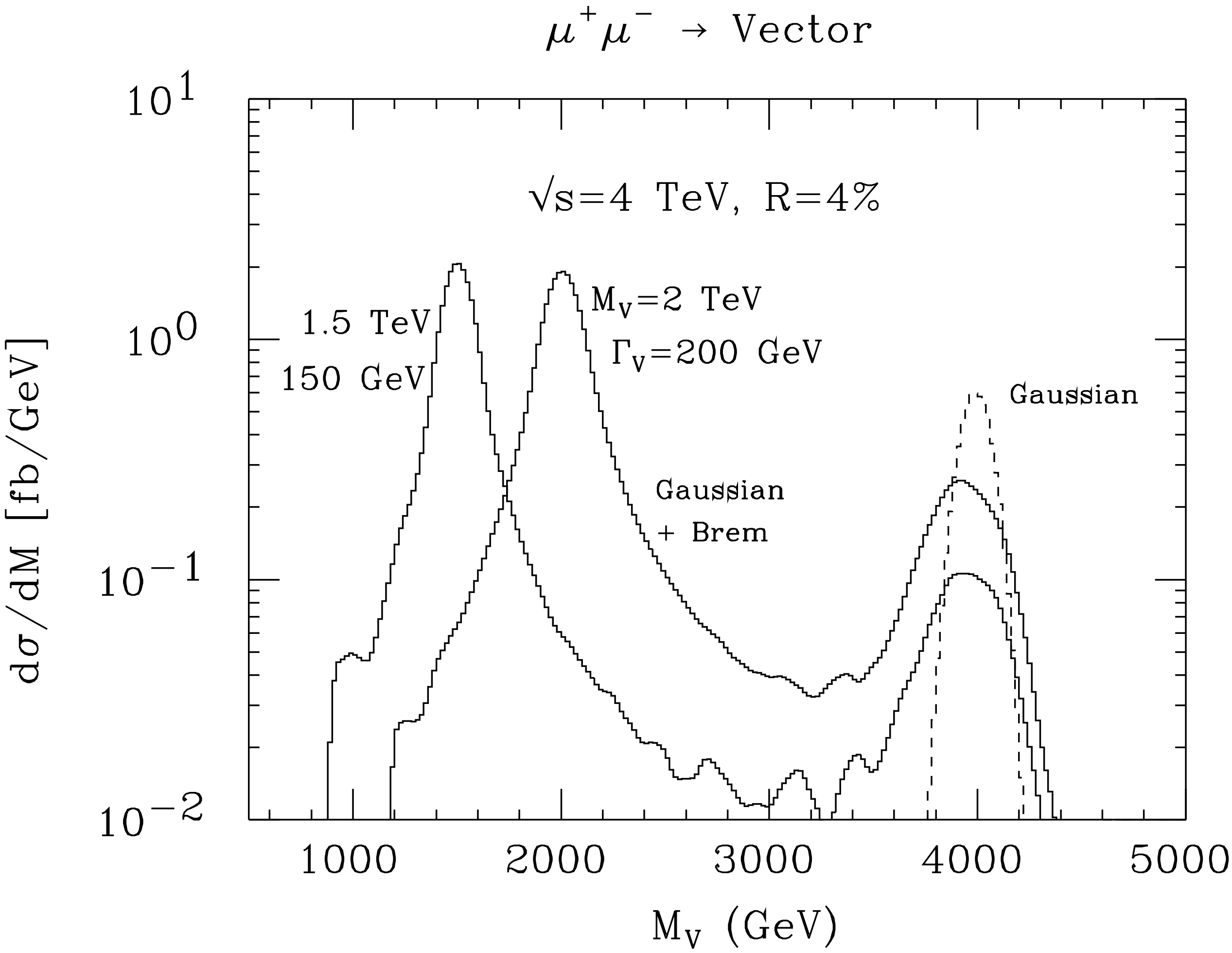
$$\sigma_{peak} \propto BR(R \to \ell^+\ell^-)BR(R \to \bar{f}f)$$

for increasing M_R the possibility of detection is decreasing (examples are Higgs-like resonances or chirally coupled vectors, see BESS model). But, for vector resonances, there are also models (degenerate BESS) where

$$\Gamma(V \to \bar{f}f) \approx \Gamma(V \to W^+W^-)$$

Necessity to know in advance the approximate mass of the resonance to be able to build up an optimized final storage ring. To localize approximately the resonance one needs previous machines or the use of the bremsstrahlung tail of a higher energy lepton collider.

Detection of a heavy vector resonance through the bremsstrahlung tail at the μC with $\sqrt{s} = 4\ TeV$, for $M_V = 1.5\ TeV$ and $M_V = 2\ TeV$, assuming a $BR(V \to \mu^+\mu^-) = 3\%$ (Barger et al. hep-ph/9604334)

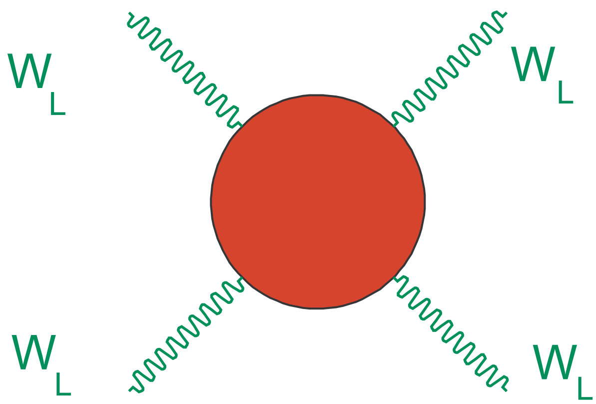


2 - $\ell^+\ell^- \to \nu\bar{\nu}WW$ (fusion processes)

Whenever the dominant decay mode is

$$R \to WW$$

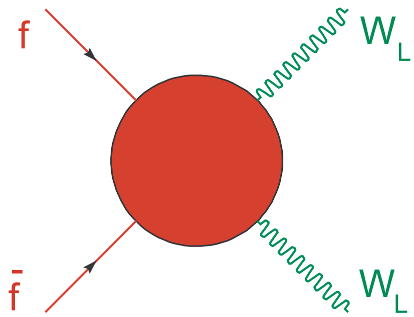
a convenient way to look for the resonance is through the fusion process



This allows to study various spin and isospin channels (analogue of $\pi\pi \to \pi\pi$)

3 - $\ell^+\ell^- \to WW$ (Drell-Yan processes)

This process is related to fusion through final state re-scattering ($Im\, F_\pi \propto A_{\pi\pi\to\pi\pi}$), but only the channel $I = J = 1$ is accessible.



In the case of hadron colliders ($\ell \to q$) this competes with the fusion, but at lepton colliders they can be discriminated. Since for vector resonances the $BR(V \to f\bar{f})$ does not decrease as fast as for the scalars, this channel takes advantage from the very efficient use of the CM energy. It has been studied at hadron colliders, but for lepton colliders only indirect bounds have been studied. The production of vector resonances in this channel will deserve a more careful study.

Description of the Resonances

Scalar Resonances

In order to be consistent with the electroweak symmetry breaking pattern

$$SU(2)_L \otimes SU(2)_R \to SU(2)$$

a scalar resonance must be coupled to the W bosons very much like as a Higgs. In TC models this would be a **techni-sigma**. For $M > 2m_W$, as expected, the main decay mode is given by $S \to W^+W^-$ with

$$\Gamma_S = \frac{3h^2M^3}{32\pi v^2}$$

with $h = 1$ for the Higgs case. Best way of detection is through fusion.

Pseudo Nambu-Goldstone Bosons

Most of the models give rise to PNGB's. The only two candidates for the s-channel production are the two neutral P^0 and $P^{0'}$. P^0 is expected to be rather light ($\approx\leq 200\ GeV$, see Dominici's talk in Step 2), whereas $P^{0'}$ is expected to decouple from the charged leptons. P^0 and $P^{0'}$ decouple from W^+W^-. We have not considered here the possibility of associated production of colored and charged PNGB's (see for instance, R.C. et al. Z. Phys. **C65** (1995) 327)

Vector Resonances

Consistency with symmetry breaking pattern fixes the couplings of a vector resonance. In the BESS model the parameters are denoted by

$$(M_V, g'', b)$$

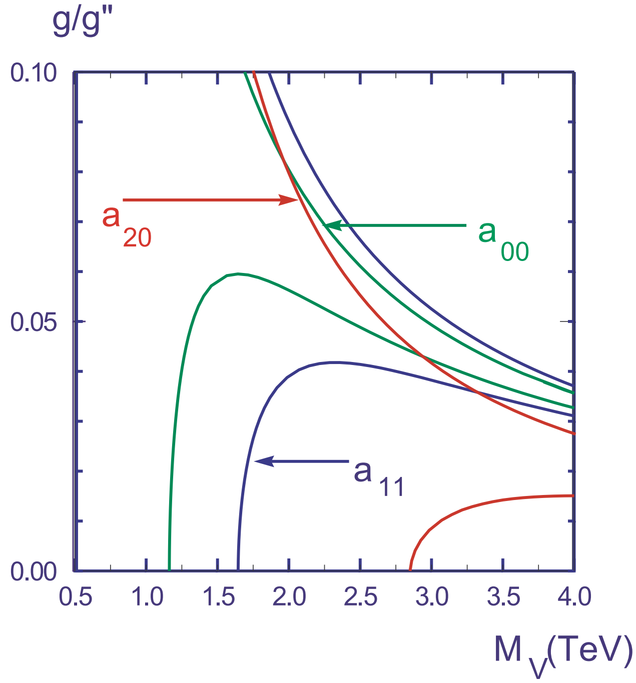
Mass, gauge coupling and direct coupling to the fermions respectively. They are constrained by unitarity and experimental bounds (LEP, SLD, Tevatron and Low energy), see figs.

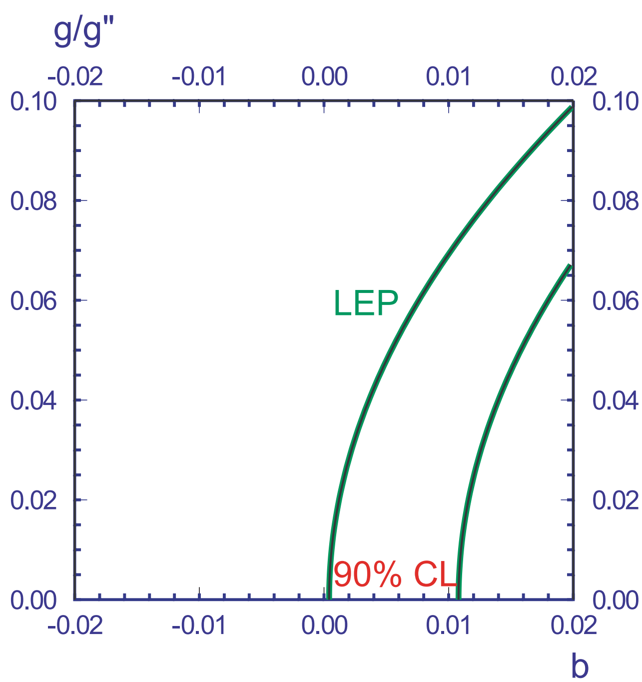
It is important to compare the decay rates

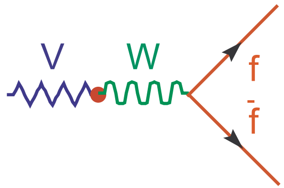
$$V \to \bar{f}f, \quad V \to WW$$

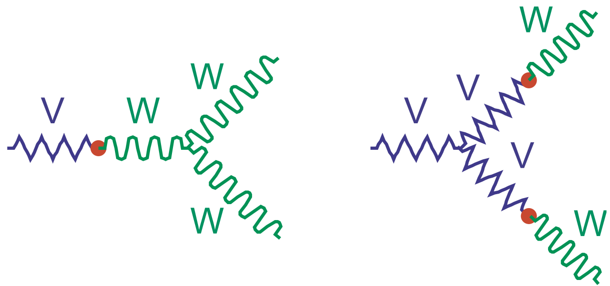
The relevant diagrams (as an example we take $b = 0$) are

Unitarity and experimental bounds in BESS









$$\Gamma(\bar{f}f) \approx \theta_f^2 \frac{M_V}{m_W} \Gamma_{W \to \bar{f}f} \approx M_V \theta_f^2 m_W^2 G_F$$

$$\Gamma(WW) \approx \theta_W^2 M_V g^2 \underbrace{\left(\frac{M_V}{m_W}\right)^4}_{W_L W_L} \approx M_V \theta_W^2 \frac{M_V^4}{m_W^2} G_F$$

$$\frac{\Gamma(\bar{f}f)}{\Gamma(WW)} \approx \left(\frac{m_W}{M_V}\right)^4 \left(\frac{\theta_f}{\theta_W}\right)^2$$

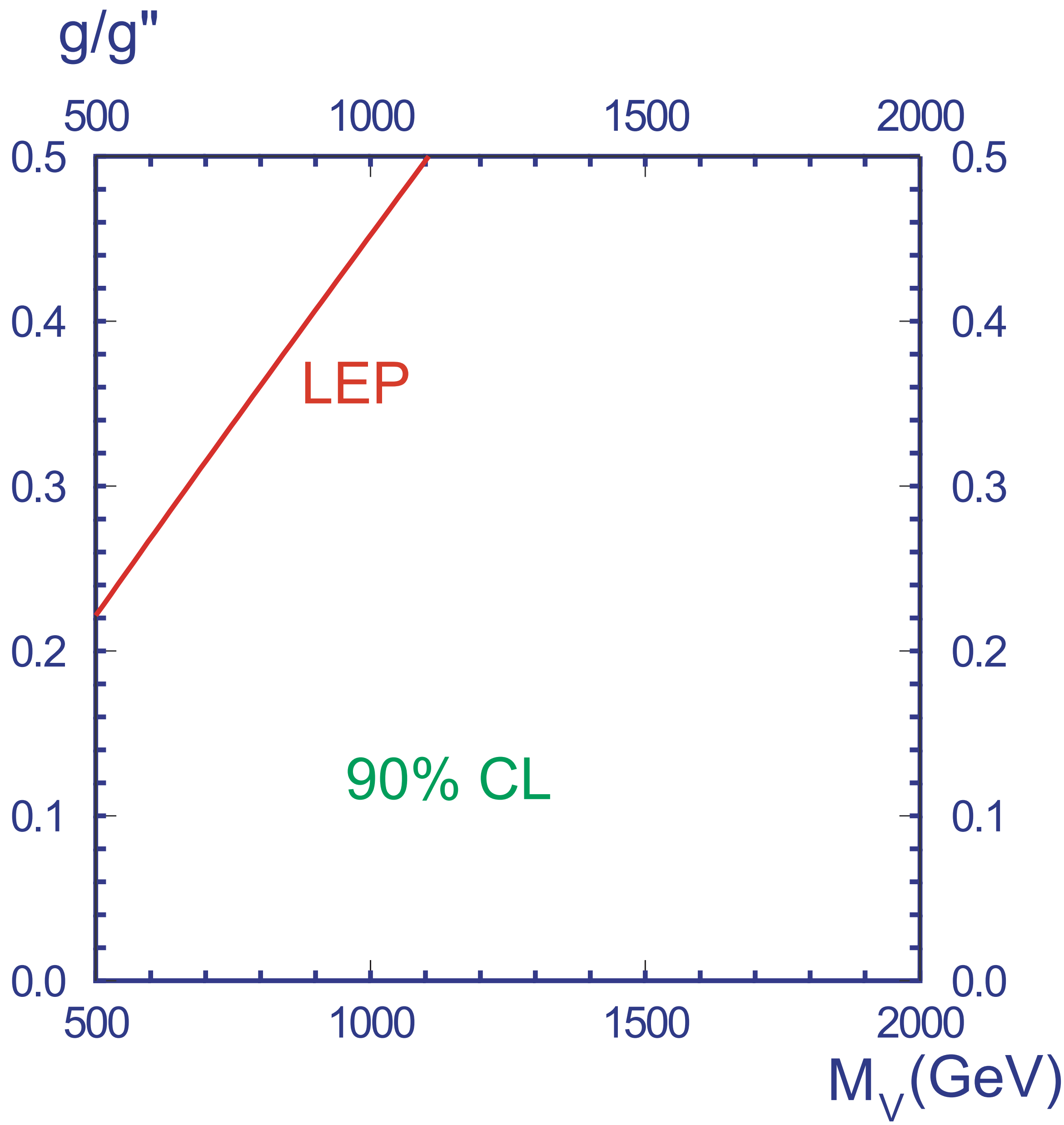
In most of the models $\theta_f \approx \theta_W \to \Gamma(\bar{f}f) \ll \Gamma(WW)$. But in degenerate BESS model, the decoupling implies $\theta_W \approx \theta_f (m_W/M_V)^2 \to \Gamma(\bar{f}f) \approx \Gamma(WW)$.

s-channel processes

- Not possible for heavy scalars or generic heavy vectors (at LHC the visibility limit is about $M_V \approx$ 500 GeV for $q\bar{q} \to \ell^+\ell^-$, (see R.C. et al. Phys. Lett. **253B** (1991) 275)). Possible for specific vector resonances as in the degenerate BESS model (R.C. et al. Phys. Rev. **D53** (1996) 5201 and Phys. Rev. **D56** (1997) 2812) where the fermionic channels are better than the WW. The model describes two degenerate isovector vector resonances $(\vec{L}, \vec{R})$ characterized by two parameters

$$(M_V, g'')$$

the mass and the gauge coupling. The main virtue of the model is the **decoupling** property implying loose bounds from precision experiments (see fig.)


g/g"
500
1000
1500
2000
0.5
0.4
0.3
0.2
0.1
0.0
LEP
90% CL
M_V(GeV)

The total widths for the neutral vectors in the degenerate BESS model are

$$\Gamma_{L_3} \approx 0.068 \left(\frac{g}{g''}\right)^2 M_V, \quad \Gamma_{R_3} \approx 0.01 \left(\frac{g}{g''}\right)^2 M_V$$

$$\frac{\Gamma_{R_3}}{\Gamma_{L_3}} \approx 15\%$$

The mass splitting between the two resonances is

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

The BR's are parameters independent and sizeable

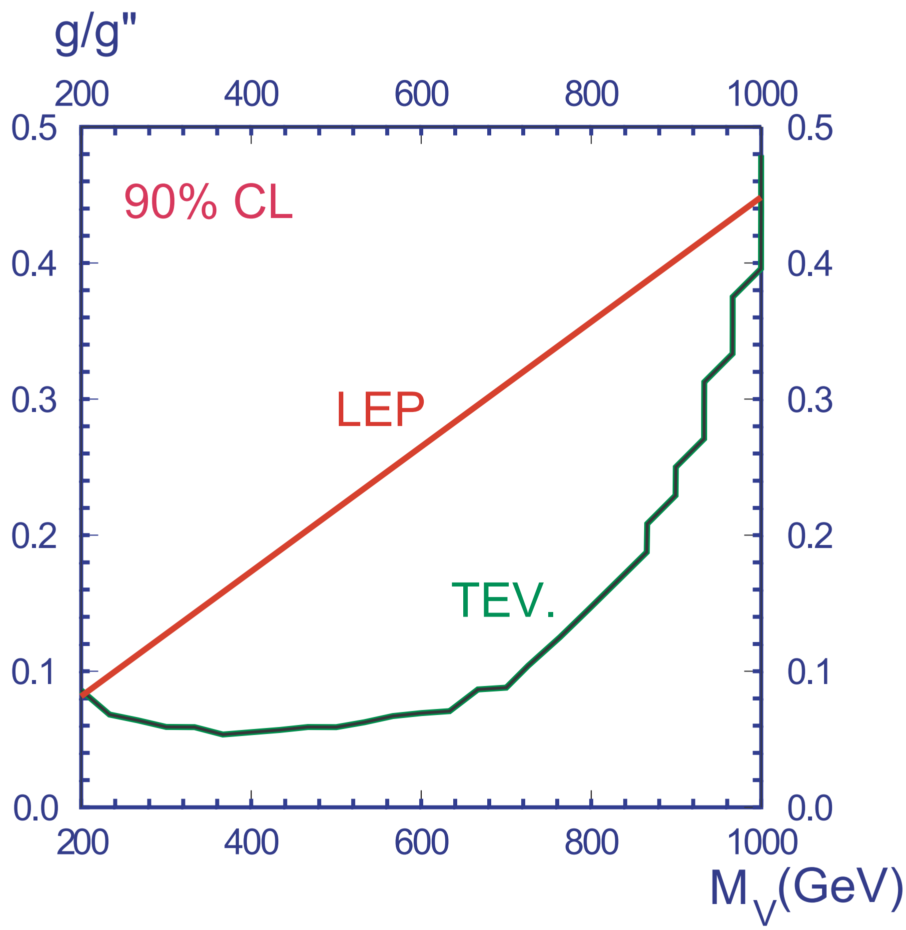
$$BR(L_3 \to \mu^+\mu^-) = 4\%$$

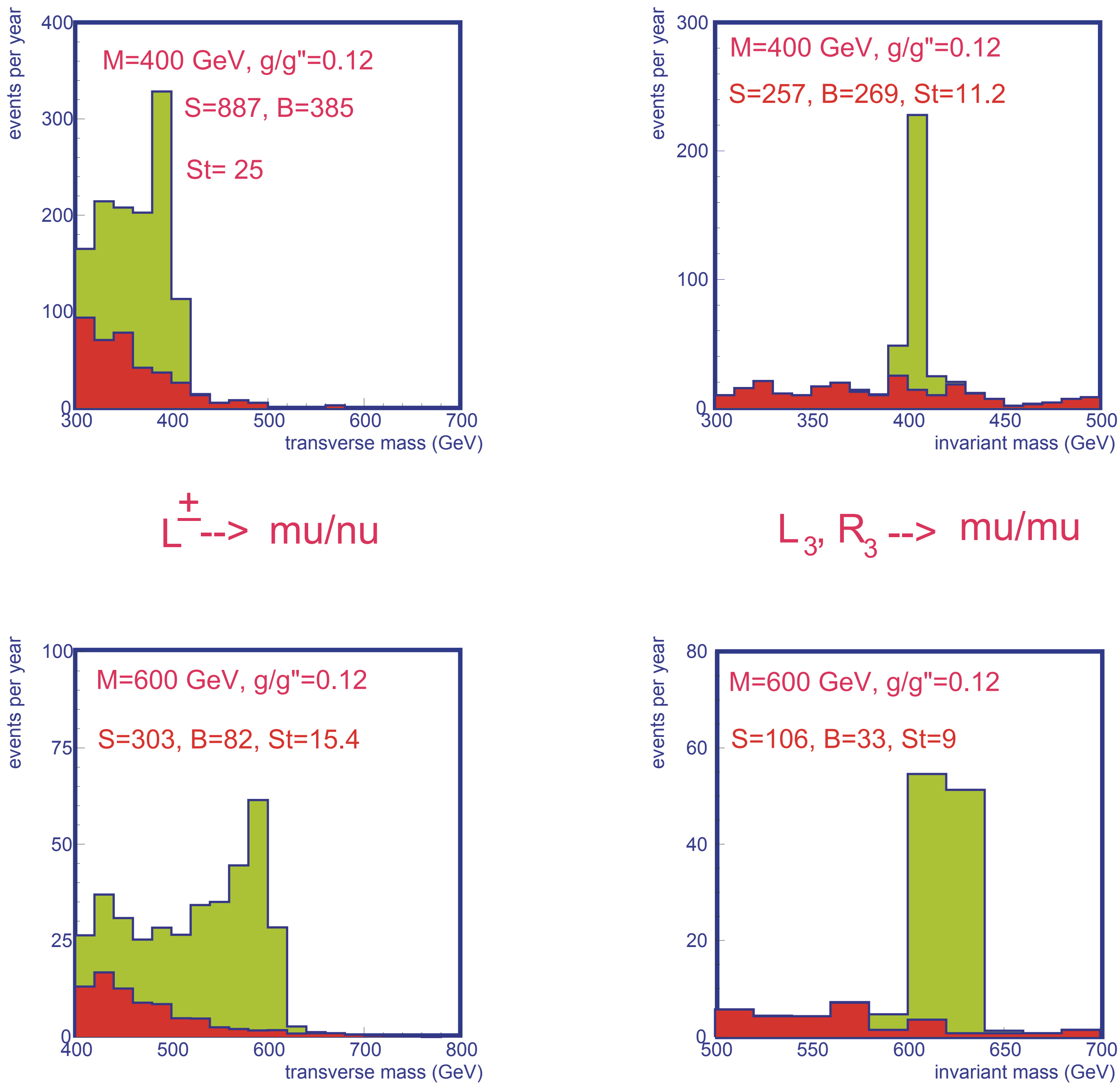
$$BR(R_3 \to \mu^+\mu^-) = 12\%$$

Discovery of L_3 and R_3 would be easy in the s-channel.

Hadron colliders and NLC

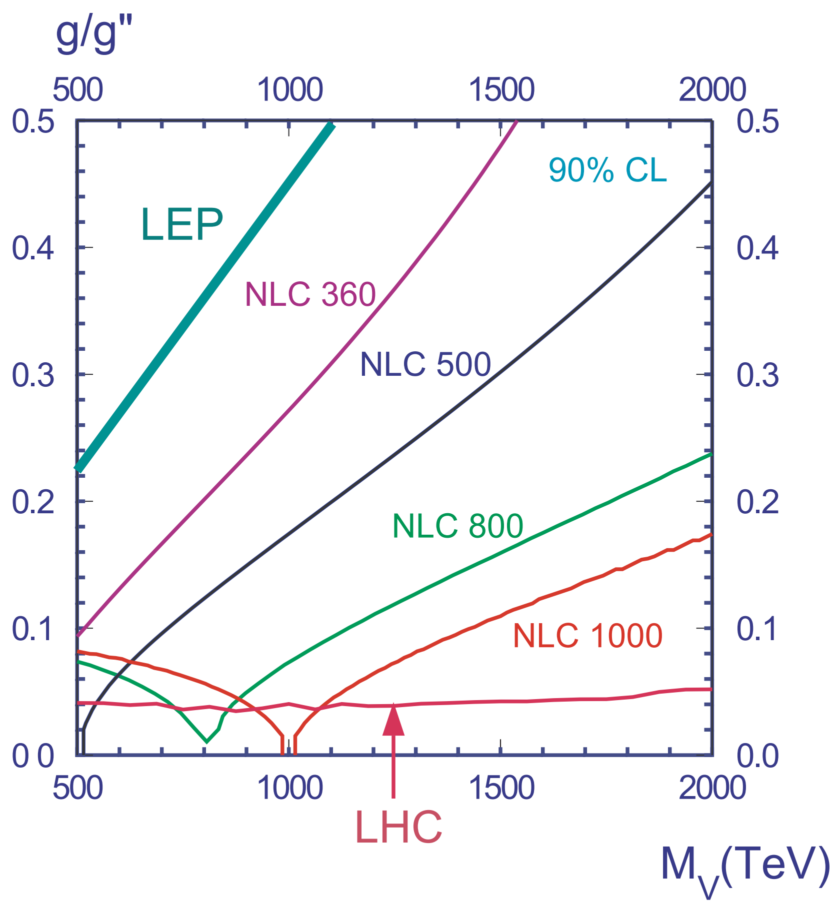
At **Tevatron Upgrade** with $\sqrt{s} = 2\ TeV$, L $=$ 10 fb^{-1} an improvement on the precision data is obtained up to about 1 TeV (R.C. et al. Phys. Rev. **D56** (1997) 2812)

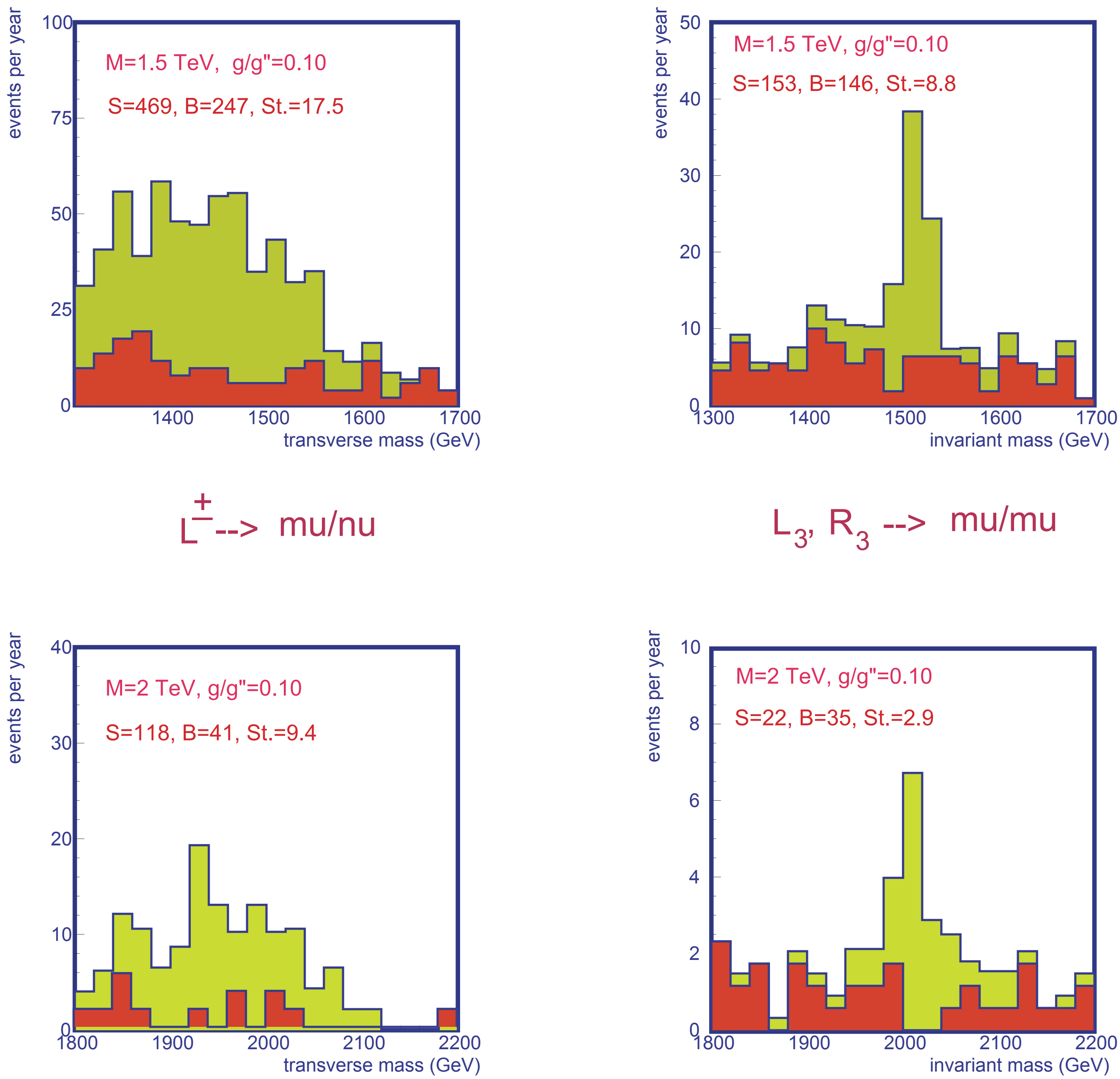




M=400 GeV, g/g"=0.12
S=887, B=385
St= 25
events per year
transverse mass (GeV)
M=400 GeV, g/g"=0.12
S=257, B=269, St=11.2
events per year
invariant mass (GeV)
L± --> mu/nu
L 3, R3 --> mu/mu
M=600 GeV, g/g"=0.12
S=303, B=82, St=15.4
events per year
transverse mass (GeV)
M=600 GeV, g/g"=0.12
S=106, B=33, St=9
events per year
invariant mass (GeV)

Studies have been done at NLC for the following choice of parameters $\sqrt{s}(GeV) = 360$, 500, 800, 1000, L =10, 20, 50 and 80 fb^{-1} (R.C. et al. ECFA-DESY Workshop 1996, hep-ph/9708287). NLC at 360 GeV improves bounds, and LHC with $\sqrt{s} = 14\ TeV$, L = 100 fb^{-1} almost closes the parameter space





events per year
M=1.5 TeV, g/g"=0.10
S=469, B=247, St.=17.5
transverse mass (GeV)
events per year
M=1.5 TeV, g/g"=0.10
S=153, B=146, St.=8.8
invariant mass (GeV)
L± --> mu/nu
L3, R3 --> mu/mu
events per year
M=2 TeV, g/g"=0.10
S=118, B=41, St.=9.4
transverse mass (GeV)
events per year
M=2 TeV, g/g"=0.10
S=22, B=35, St.=2.9
invariant mass (GeV)

Muon collider

Improvement with respect to NLC, since $(\vec{L}, \vec{R})$ are very narrow resonances and one can use the very small spread in energy. One has

$$\sigma_{\sqrt{s}} = 7\ MeV \left(\frac{R}{0.01\%}\right) \left(\frac{\sqrt{s}}{100\ GeV}\right)$$

R = beam energy resolution. A convenient choice of parameters for a muon collider of $\sqrt{s} \approx 3 \div 4\ TeV$ would be (J.K. Gunion, Gilman Panel talk (1997))

$$\mathcal{L} \approx 10^{35}\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}, \quad R \approx 0.14\%$$

The luminosity satisfies the approximate scaling law (for fixed number of muons)

$$\mathcal{L} \propto (\sqrt{s})^{11/7} R^{4/7}$$

showing that improving a factor of 2 in R implies a loss of 33% in luminosity. Sitting on a resonance one can sacrifice the luminosity to improve $\sigma_{\sqrt{s}}$. The typical value of R at NLC would be $\approx \geq 1\%$.

The production rate at the peak obtained by convoluting the Breit-Wigner with a Gaussian distribution of width $\sigma_{\sqrt{s}}$ is

$$\bar{\sigma} \approx \frac{3\pi\sqrt{2\pi}\Gamma(V \to \mu^+\mu^-)}{M_V^2 \sigma_{\sqrt{s}}} \left(1 + \frac{\pi}{8}\left[\frac{\Gamma_V}{\sigma_{\sqrt{s}}}\right]^2\right)^{-1/2}$$

In the limits

$$\sigma_{\sqrt{s}} \ll \Gamma_V, \quad \bar{\sigma} \to \sigma^{\text{peak}}$$

$$\sigma_{\sqrt{s}} \gg \Gamma_V, \quad \bar{\sigma} \to 0.6 \left(\frac{\Gamma_V}{\sigma_{\sqrt{s}}}\right) \sigma^{\text{peak}}$$

In our case

$$\sigma_{L_3}^{\text{peak}} \approx 6 \times 10^5 \left(\frac{1\ TeV}{M_V}\right)^2 \text{ fb}$$

$$\sigma_{R_3}^{\text{peak}} \approx 1.8 \times 10^6 \left(\frac{1\ TeV}{M_V}\right)^2 \text{ fb}$$

The main advantage of a muon collider over NLC would be the possibility of studying the shape of these resonances.

M_V	g/g''	ΔM	Γ_{L_3}	Γ_{R_3}	$\sigma_{\sqrt{s}}(NLC)$	$\sigma_{\sqrt{s}}(\mu C)$	R
TeV		GeV	GeV	GeV	GeV	GeV	%
0.5	0.2	14	1.4	0.2	3.5	0.21	0.06
1	0.4	112	11	1.6	7	0.70	0.1
2	0.8	900	87	13	14	1.4	0.1
2	0.1	14	1.4	0.2	14	0.82	0.06

- In the first 3 cases (close to the boundary of the allowed region) both NLC and μC can separate L_3 and R_3, but NLC will not be able to look at the line shape of both R_3 and L_3 (in this last case it could roughly do it for $M_V = 2\ TeV$)

- In the last case, far from the boundary, NLC would have difficulties even in separating the two resonances. In this case, even the μC would have hard life in exploring the line shape unless one is able to improve on R

Fusion processes

SEWS at LHC

- LHC has a good potential to probe the SEWS physics.
- Major difficulty is SM background
- Use only **Gold Plated Modes** (purely leptonic decays)
- Resonance parameters

$$\begin{array}{ll} M_S = 1\ TeV & \Gamma_S = 350\ GeV \\ M_V = 1\ TeV & \Gamma_V = 6\ GeV \\ M_V = 2.5\ TeV & \Gamma_V = 520\ GeV \end{array}$$

	Bkgd.	Scalar	Vec 1.0	Vec 2.5	LET − K
$ZZ(4\ell)$	0.7	4.6	1.4	1.3	1.4
$ZZ(2\ell 2\nu)$	1.8	17	4.7	4.4	4.5
W^+W^-	12	18	6.2	5.5	4.6
$W^\pm Z$	4.9	1.5	4.5	3.3	3.0
$W^\pm Z(DY)$	22		69		
$W^\pm W^\pm$	3.7	7.0	12	11	13

Parameters used:

$$\sqrt{s} = 14\ TeV, \quad \mathrm{L} = 100\ \mathrm{fb}^{-1}$$

DY refers to the Drell-Yan process. Cuts as in Bagger et al. Phys. Rev. **D52** (1985) 3878.

- Scalar resonances visible in the ZZ channel (specially in the $2\ell 2\nu$ mode) and in the W^+W^- one.

- Vector resonances visible in $W^\pm Z$ channel (mainly through DY up to $\approx 1.5\ TeV$. Discovery limit around $2\ TeV$ (R.C. et al. Phys. Lett. **249B** (1990) 130)

- The non-resonant model LET-K, defined as the unitarized $m_H \to \infty$ limit, gives event excess in the $Q = \pm 2$ channel.

Channel	Scalar	Vec 1.0	Vec 2.5	LET – K
$ZZ(4\ell)$	2.5			
$ZZ(2\ell 2\nu)$	0.75	3.7	4.2	4.0
W^+W^-	1.5	8.5		
$W^\pm Z$		0.07		
$W^\pm W^\pm$	3.0	1.5	1.5	1.2

Same parameter as before. The table gives the number of years (if < 10) necessary for a 99% CL signal.

SEWS at NLC

In this case the decay mode considered is

$$WW \to 4 \text{ jets}$$

We follow the fusion analysis by Barger et al. Phys. Rev. **D52** (1995) 3815.

channels	Scalar $M_S = 1\ TeV$ $\Gamma = 350\ GeV$	Vector $M_V = 1\ TeV$ $\Gamma = 30\ GeV$	LET
$S(e^+e^- \to \bar{\nu}\nu W^+W^-)$	160	46	31
B(backgrounds)	170	4.5	170
$S/\sqrt{B}$	12	22	2.4
$S(e^+e^- \to \bar{\nu}\nu ZZ)$	130	36	45
B(backgrounds)	63	63	63
$S/\sqrt{B}$	17	4.5	5.7
$S(e^-e^- \to \nu\nu W^-W^-)$	35	36	42
B(backgrounds)	230	230	230
$S/\sqrt{B}$	2.3	2.4	2.8

Parameters are:

$$\sqrt{s} = 1.5\ TeV, \quad \mathsf{L} = 200\ \mathrm{fb}^{-1}$$

- 1 TeV scalar and vector easily detected in ZZ and W^+W^-

- The LET-K case detectable through ZZ

- W^+W^-/ZZ event ratio is a good probe for SEWS dynamics. A scalar enhances both W^+W^- and ZZ with a preference for the first case. A vector enhances mainly W^+W^-. The non-resonant case enhances ZZ

- Electron polarization would increase the signal ($\approx$ 2 times at fixed luminosity and for an e_L^- polarized beam) with small effects on the background

- The search for a vector should be better by looking at the DY process $e^+e^- \to W^+W^-$, but no detailed studies have been done so far (only indirect bounds have been evaluated)

SEWS at Muon Colliders

As for NLC the relevant decay mode is

$$WW \to 4 \text{ jets}$$

We follow the analysis of Barger et al. Phys. Rev. **D55** (1997) 142.

channels	Scalar $m_S = 1\ TeV$ $\Gamma_S = 0.5\ TeV$	Vector $M_V = 2\ TeV$ $\Gamma_V = 0.2\ TeV$	LET
$\mu^+\mu^- \to \bar{\nu}\nu W^+W^-$			
S(signal)	2400	180	370
B(backgrounds)	1200	25	1200
$S/\sqrt{B}$	68	36	11
$\mu^+\mu^- \to \bar{\nu}\nu ZZ$			
S(signal)	1030	360	400
B(backgrounds)	160	160	160
$S/\sqrt{B}$	81	28	32
$\mu^+\mu^+ \to \bar{\nu}\bar{\nu} W^+W^+$			
S(signal)	240	530	640
B(backgrounds)	1300	1300	1300
$S/\sqrt{B}$	7	15	18

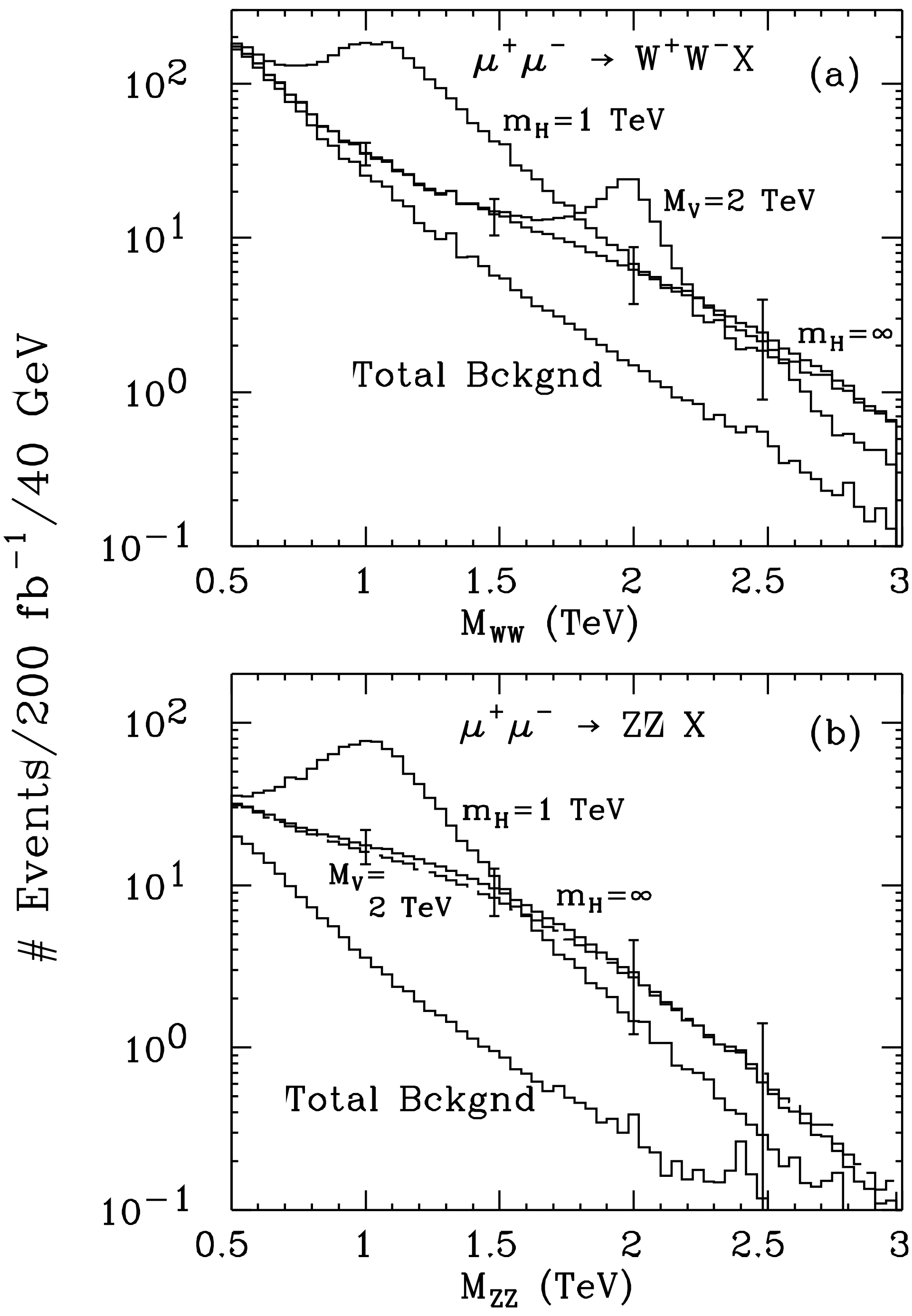
Parameters are

$$\sqrt{s} = 4\ TeV, \quad \mathrm{L} = 200\ \mathrm{fb}^{-1}$$

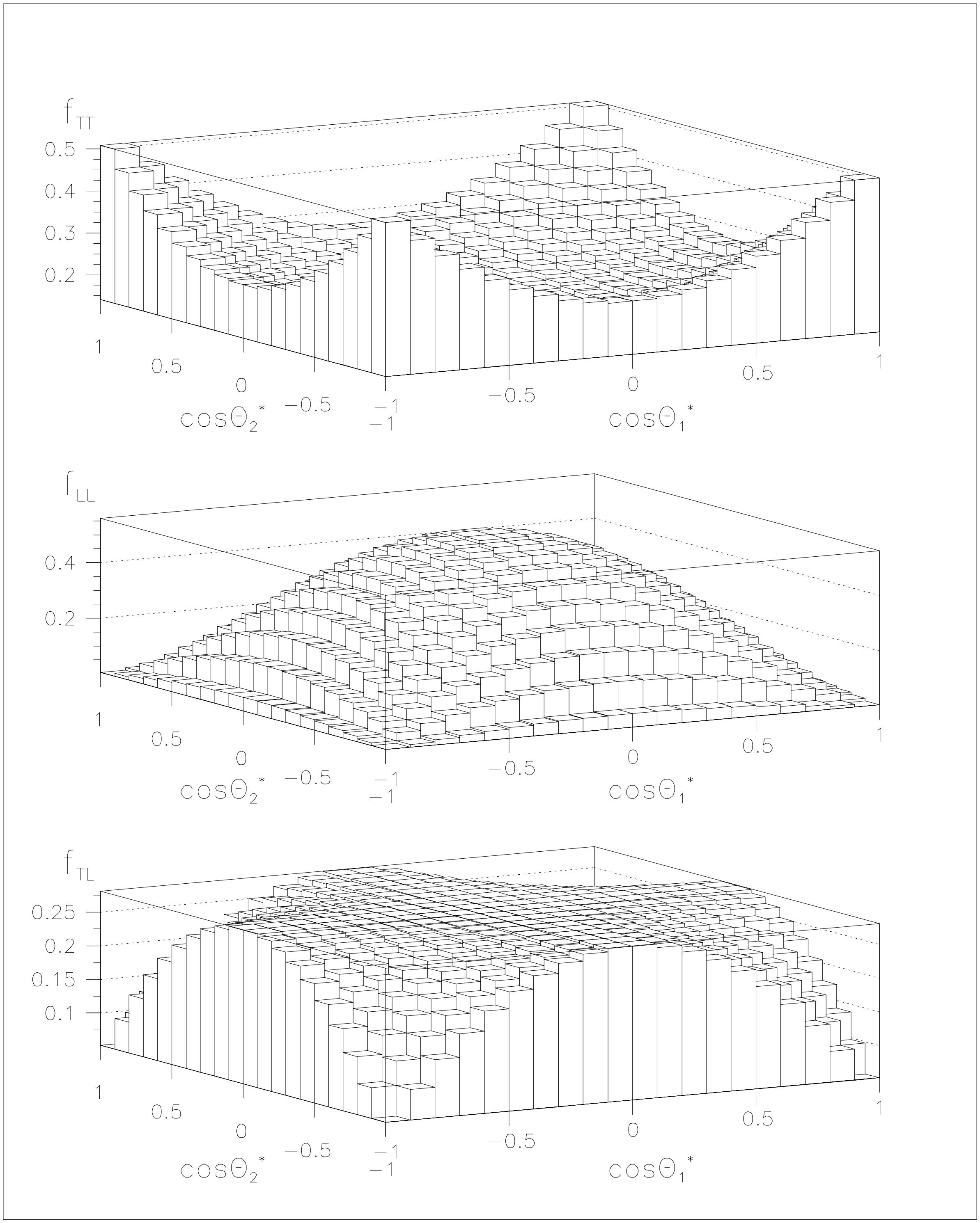
- Very high statistical significance in all channels

- As for NLC different models can be distinguished from one another as can be clearly seen in the $M(WW)$ distribution (see Fig.)

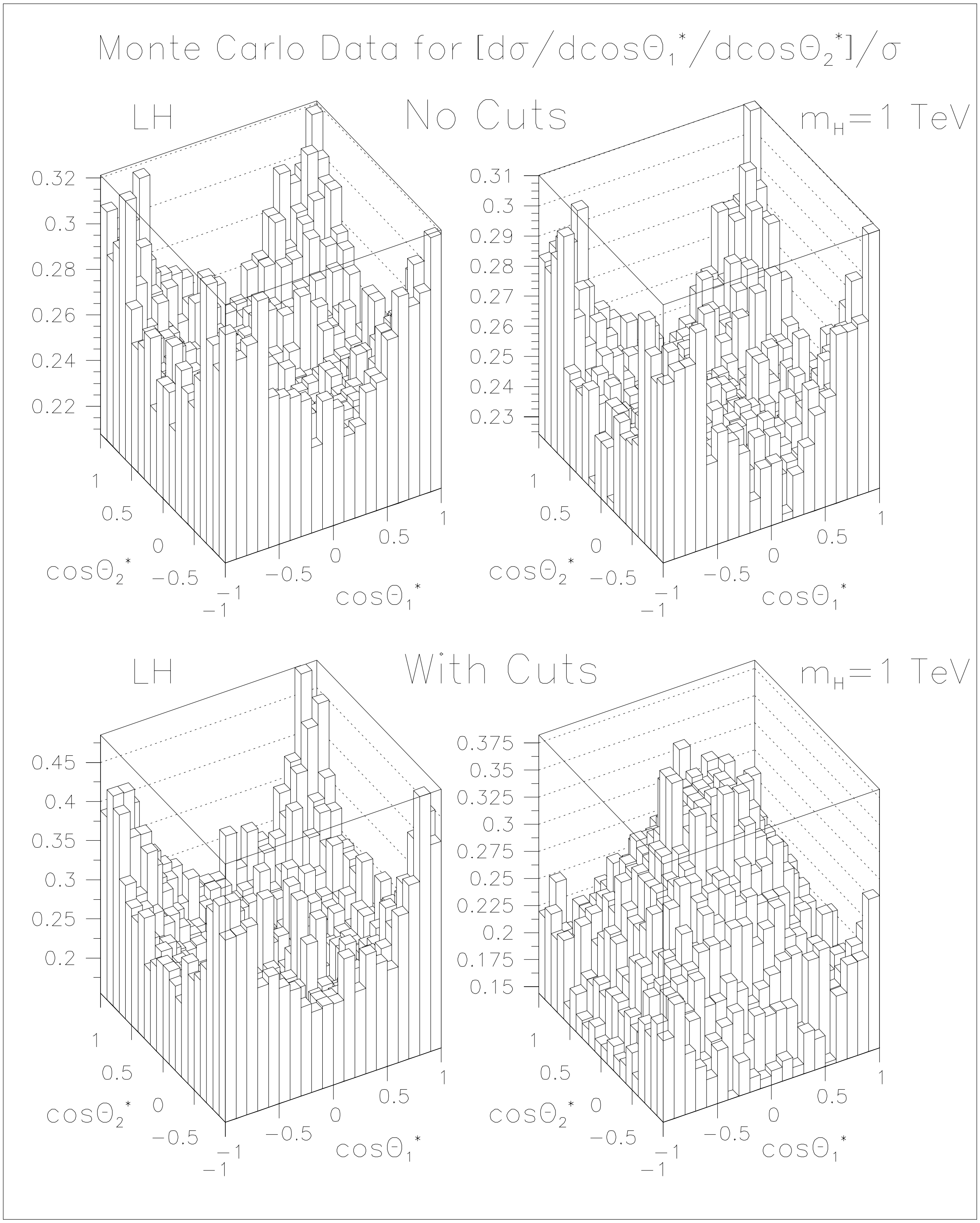
- Statistics is such to allow to isolate the polarization components TT, TL and LL of the cross-section, which would improve the possibility of discrimination among the various models.



Events/200 fb⁻¹/40 GeV
μ⁺μ⁻ → W⁺W⁻X
(a)
m_H=1 TeV
M_V=2 TeV
m_H=∞
Total Bckgnd
M_WW (TeV)
μ⁺μ⁻ → ZZ X
(b)
m_H=1 TeV
M_V=
2 TeV
m_H=∞
Total Bckgnd
M_ZZ (TeV)



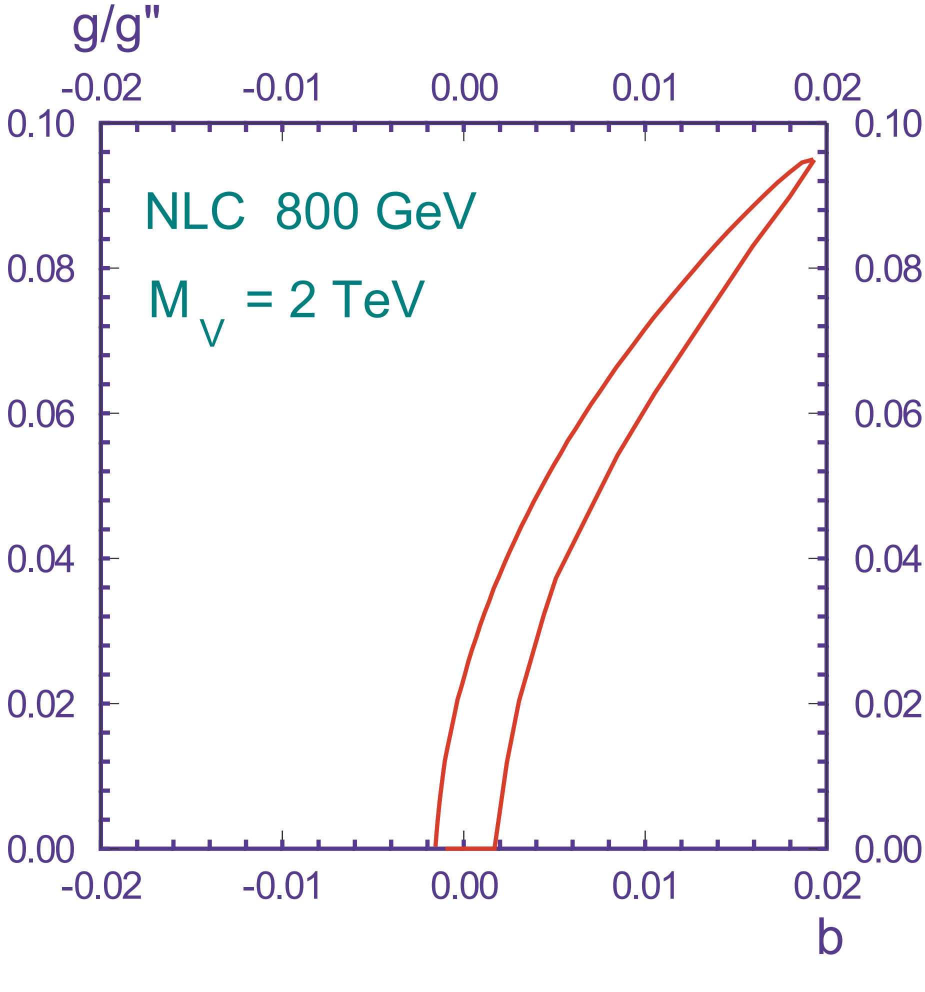
f_{TT}
0.5
0.4
0.3
0.2
1
0.5
0
−0.5
−1
−1
−0.5
0
0.5
1
$\cos\Theta_2^*$
$\cos\Theta_1^*$
f_{LL}
0.4
0.2
1
0.5
0
−0.5
−1
−1
−0.5
0
0.5
1
$\cos\Theta_2^*$
$\cos\Theta_1^*$
f_{TL}
0.25
0.2
0.15
0.1
1
0.5
0
−0.5
−1
−1
−0.5
0
0.5
1
$\cos\Theta_2^*$
$\cos\Theta_1^*$



Monte Carlo Data for [dσ/dcosΘ1*/dcosΘ2*]/σ
LH
No Cuts
mH=1 TeV
With Cuts
cosΘ2*
cosΘ1*

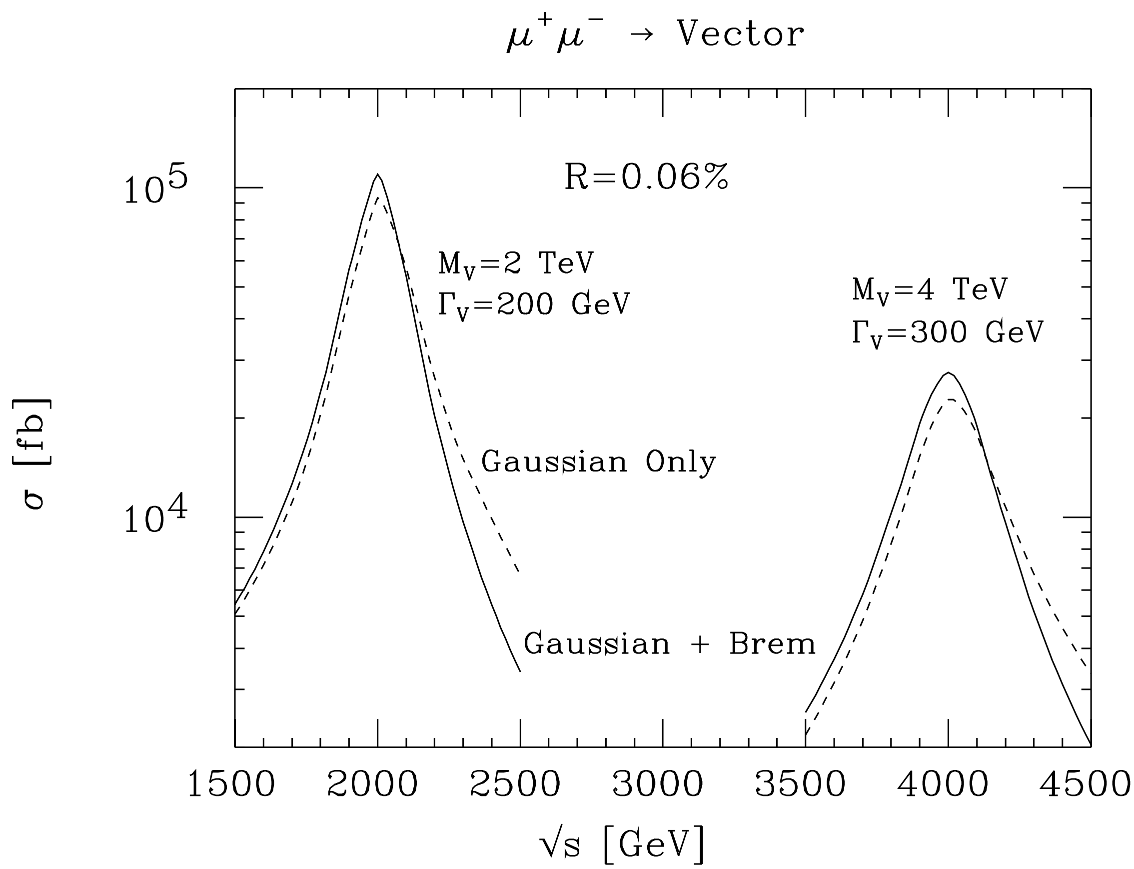
Drell-Yan processes

At LHC it goes with the fusion process. At NLC the parameter space practically closes at $\sqrt{s} = 1\ TeV$ (R.C. et al. ECFA-DESY Workshop 1996,hep-ph/9708287)



In the case of μC consider the reference case (Barger et al. hep-ph/9604334) with

$$BR(V \to \mu^+\mu^-) = 3\%$$



The typical BR's in BESS, both for $b = 0$ and $b \neq 0$ (within the allowed region), are much smaller and they scale with M_V^4 ($\Gamma_{\mu\mu} \propto M_V$, $\Gamma_V \propto M_V^5$). One finds

$M_V(TeV)$	BR	σ^{peak}(fb)
2	0.5×10^{-4}	170
4	0.3×10^{-5}	3

For an order of magnitude consider

$$\sigma(e^+e^- \to W^+W^-)_{SM} \approx 3 \times \left(\frac{1\ TeV}{\sqrt{s}}\right)^2 \text{ pb}$$

A 2 TeV resonance would be visible, but the case of 4 TeV will require a careful study.

Conclusions

- Analysis of heavy resonances with SEWS models for various decay modes

- Comparison among hadron and lepton colliders

- s-channel at μC promising for very narrow vector resonances

- Fusion channel at μC allows to study and compare scalar and vector resonances, including non resonant models of SEWS

- Drell-Yan channel requires further analysis