Probing the Z' sector of the minimal $B-L$ model at future Linear Colliders in the $e^+e^- \to \mu^+\mu^-$ process

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Lorenzo Basso, A. Belyaev, S. Moretti, C. Shepherd-Themistocleous: arXiv:0909.3113

Lorenzo Basso, A. Belyaev, S. Moretti, GMP: arXiv:0903.4777

Outline

1) The $B - L$ model
   - Motivations
   - Particle content

2) Phenomenology (at the LCs)
   - Discovery potentials
   - Z' properties: width and decays
   - Z' analysis
   - Indirect searches

3) Conclusions and outlook

A triply minimal extension

- **Motivations**
  - ν_R naturally included
  - interesting phenomenology
  - part of a bigger picture (GUT, baryogenesis)

- **Gauge sector**

$$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$$

- **Fermion sector**

One extra fermion per generation: ν_R

(Required by anomaly cancellation)

- **Scalar sector**

One extra SM-singlet scalar: χ

($U(1)_{B-L}$ symmetry breaking)

The model: triply-minimal extension

A $U(1)$ extension of the SM

$$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$$

New states:

- A scalar (χ, SM-singlet)
  $V = \cdots + \lambda_1 (H^\dagger H)^2 + \lambda_2 \mid \chi \mid^4 + \lambda_3 H^\dagger H \mid \chi \mid^2$
- 3 RH neutrinos: $\nu_R \xrightarrow{\text{see-saw}} \nu_h$ ($\mathcal{O}(100)$ GeV) (anomaly cancellation)
  $\mathscr{L}_Y = \cdots - y^\nu \overline{l_L} \nu_R \widetilde{H} - y^M \overline{(\nu_R)^c} \nu_R \chi + \text{H.c.}$

In certain regions of the parameter space, they both can be *long-lived* particles

ψ	$SU(3)_C$	$SU(2)_L$	Y	$B-L$
q_L	3	2	$\frac{1}{6}$	$\frac{1}{3}$
u_R	3	1	$\frac{2}{3}$	$\frac{1}{3}$
d_R	3	1	$-\frac{1}{3}$	$\frac{1}{3}$
l_L	1	2	$-\frac{1}{2}$	-1
e_R	1	1	-1	-1
ν_R	1	1	0	-1

ψ	$SU(3)_C$	$SU(2)_L$	Y	$B-L$
H	1	2	$\frac{1}{2}$	0
χ	1	1	0	2

Interactions and spectrum

Covariant derivative (in a suitable basis):

$$D_\mu \Psi_i = \partial_\mu \Psi_i + i \left[g_1 Y_i B_\mu + (Y_i \widetilde{g} + (B-L)_i g_1') B'_\mu \right] \Psi_i$$

$Z - Z'$ mixing:

$$\begin{pmatrix} B^\mu \\ {W_3}^\mu \\ B'^\mu \end{pmatrix} = \left(\begin{array}{cc|c} \cos\vartheta_w & -\sin\vartheta_w \cos\vartheta' & \sin\vartheta_w \sin\vartheta' \\ \sin\vartheta_w & \cos\vartheta_w \cos\vartheta' & -\cos\vartheta_w \sin\vartheta' \\ \hline 0 & \sin\vartheta' & \cos\vartheta' \end{array}\right) \begin{pmatrix} A^\mu \\ Z^\mu \\ Z'^\mu_{B-L} \end{pmatrix}$$

$$\widetilde{g} = 0 \longrightarrow \vartheta' = 0$$

No $Z - Z'$ mixing in the pure $B - L$ model

Aim of our work

$B - L$ symmetry breaking at the TeV scale

$\Downarrow$

Its phenomenology can be observed at TeV machines!

$e^+e^- \to \mu^+\mu^-$ channel at LCs: representative process to study new signatures from the Z'_{B-L} sector.

LC environment for two main reasons:

- if a Z' will be found at LHC, the underlying model will be probably hard to identify, whilst LC is more suitable to identify the model;
- if LHC will *not* find it, LCs prove to be more powerful in either discovering or being sensitive to the Z' presence.

Analysis details

We performed our analysis with the help of the CalcHEP package ($B-L$ implemented via LanHEP). Interface to $PYTHIA$ and $HERWIG$ avaliable.

ISR and Beamstrahlung: parameterisation specified in ILC Reference Design Report (arXiv:0712.1950).

We have assumed standard acceptance cuts on muons:

$$\begin{aligned} \text{LHC}: \quad p_T &> 10\ \text{GeV}, \quad |\eta| < 2.5, \\ \text{LC}: \quad E &> 10\ \text{GeV}, \quad |\cos\theta| < 0.95. \end{aligned}$$

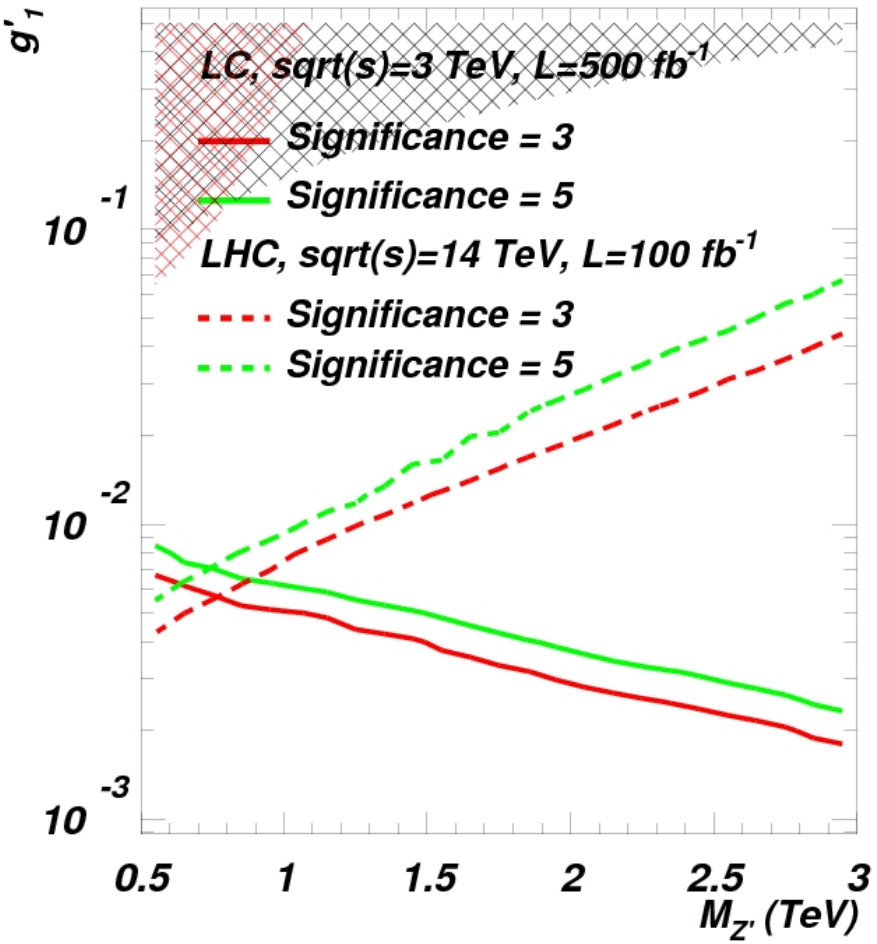
and a cut on $M_{\mu\mu}$:

$$\text{LHC}: \quad |M_{\mu\mu} - M_{Z'}| < \max\left(3\Gamma_{Z'},\ \left(0.03\sqrt{\frac{M_{Z'}}{\text{GeV}}} + 0.005\frac{M_{Z'}}{\text{GeV}}\right)\text{GeV}\right),$$

$$\text{LC}: \quad |M_{\mu\mu} - M_{Z'}| < \max\left(3\Gamma_{Z'},\ 0.15\sqrt{\frac{M_{Z'}}{\text{GeV}}}\text{GeV}\right).$$

Z' Discovery potentials in di-muons

Significance contour levels plotted against g'_1 and $M_{Z'}$



← **Tevatron** and **LEP** bounds

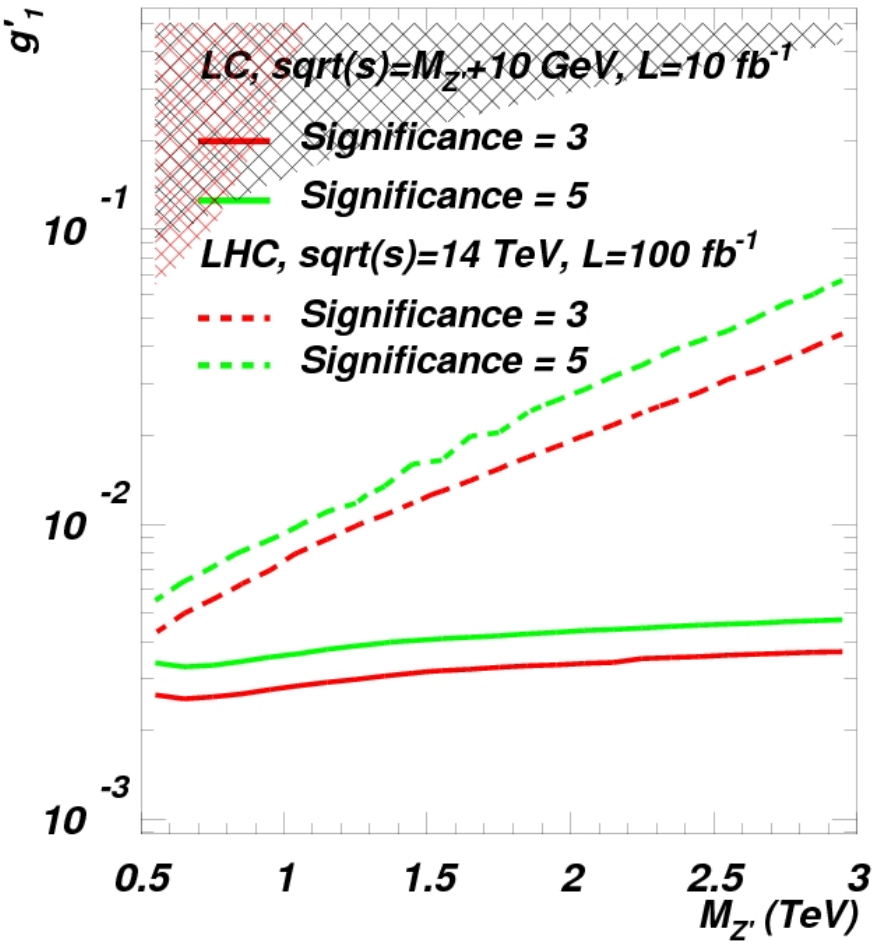
← LHC: $L = 100\ \mathrm{fb}^{-1}$ ($\sqrt{s_{pp}} = 14$ TeV)

and

← LC: $L = 500\ \mathrm{fb}^{-1}$, $\sqrt{s_{e^+e^-}} = 3$ TeV

Z' Discovery potentials in di-muons

Significance contour levels plotted against g'_1 and $M_{Z'}$



← **Tevatron** and **LEP** bounds

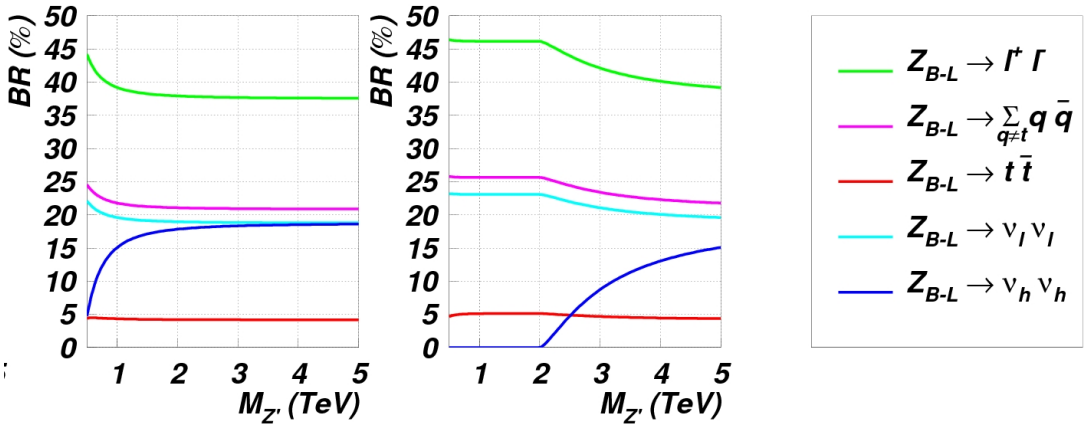
← LHC: $L = 100\ \text{fb}^{-1}$ ($\sqrt{s_{pp}} = 14$ TeV)

and

← LC: $L = 10\ \text{fb}^{-1}$, $\sqrt{s_{e^+e^-}} = M_{Z'} + 10$ GeV

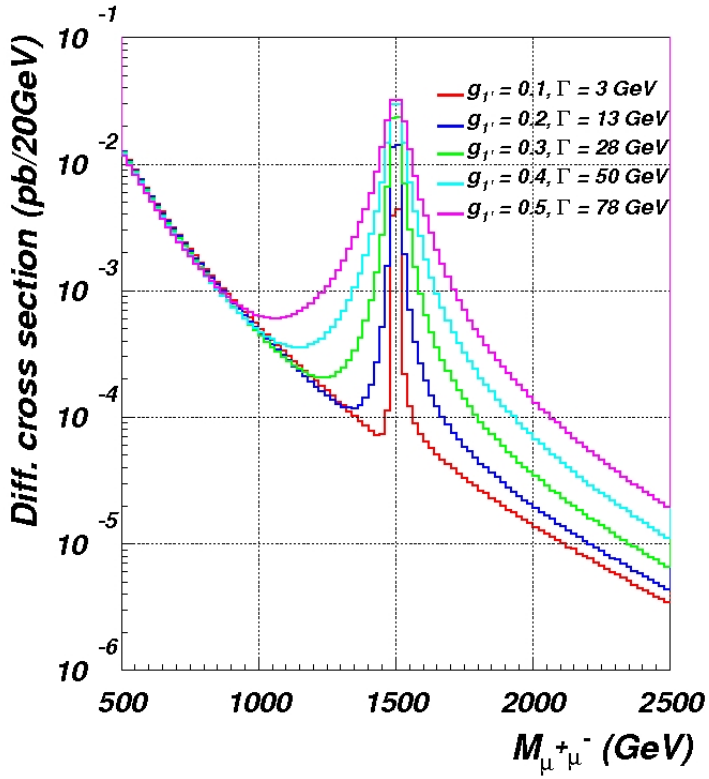
Z' phenomenology

$m_{\nu h} = 250$ GeV 1 TeV



$$\sum_k BR\left(Z'_{B-L} \to l_k \overline{l_k}\right) \sim \frac{3}{4} \qquad \sum_k BR\left(Z'_{B-L} \to q_k \overline{q_k}\right) \sim \frac{1}{4}$$

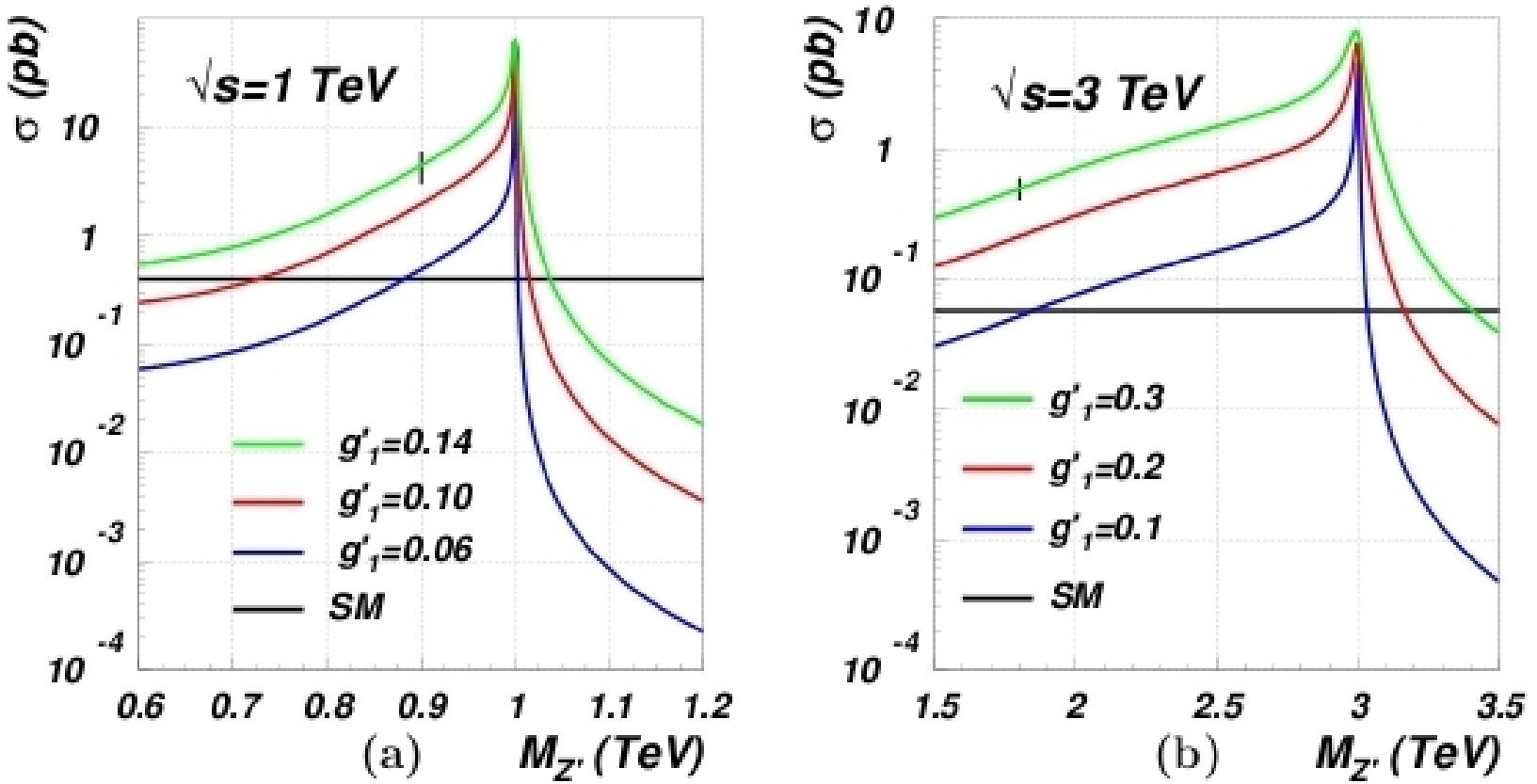
$p, p \to (\gamma, Z, Z') \to \mu^+ \mu^-$



- Dominantly coupled to *leptons*
- $Z' \to \nu_h \nu_h$ up to $\sim 20\%$

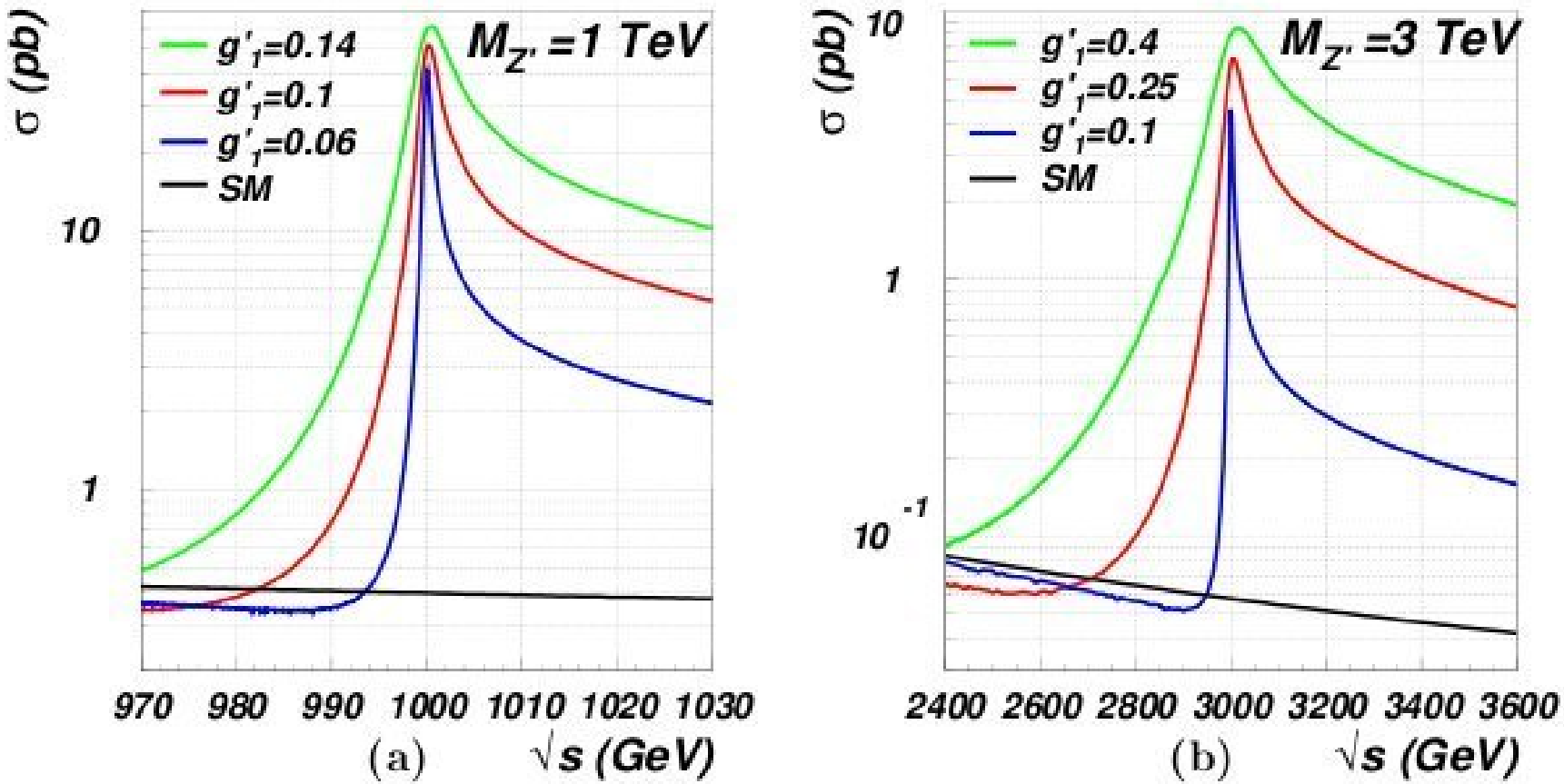
- $g'_1 < 0.5$ from RGE analysis
- Γ up to hundreds of GeV

ILC and CLiC, Z' resonance vs SM background



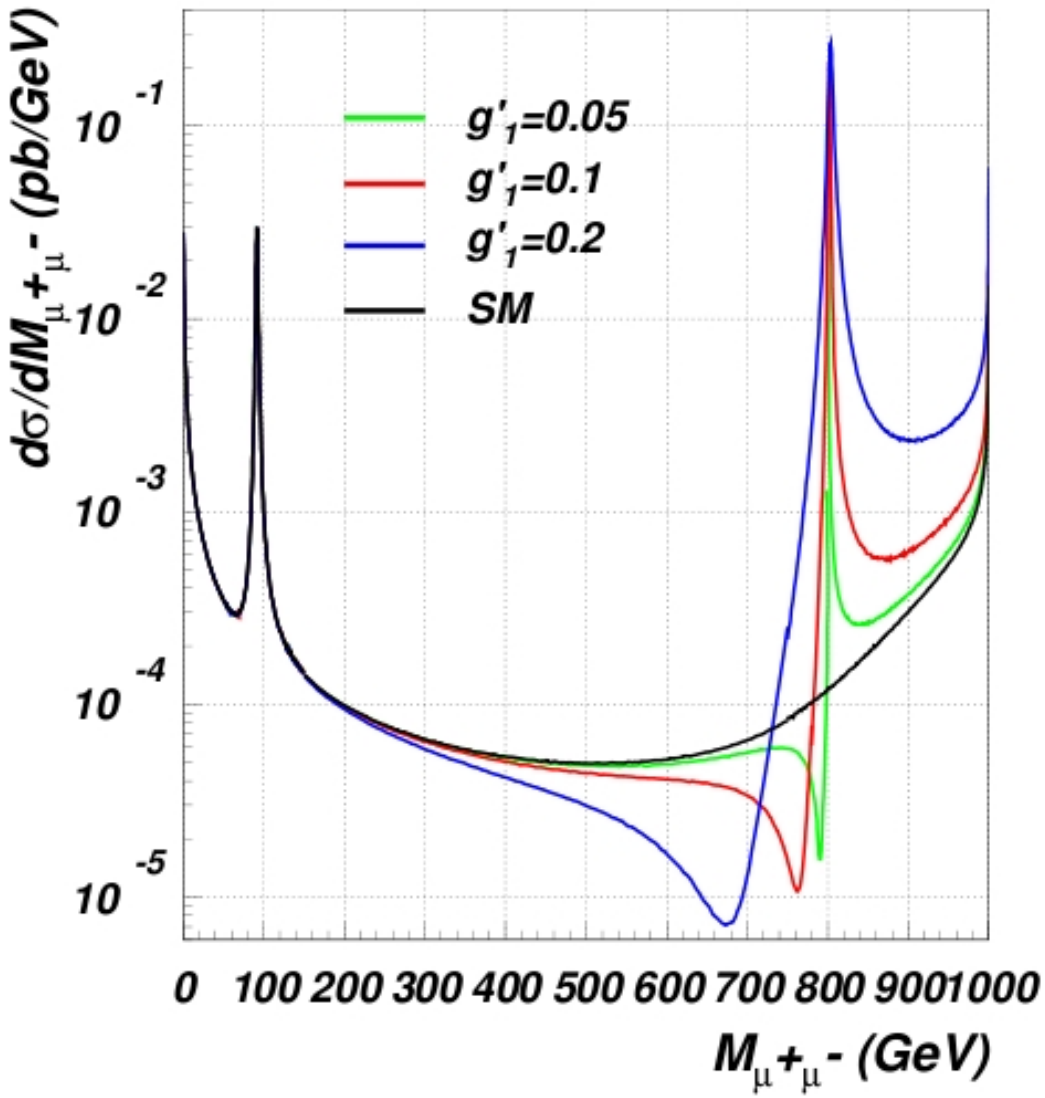
Cross section for the process $e^+e^- \to X \to \mu^+\mu^-$ for the signal ($X = Z'$) and the SM background ($X = \gamma, Z$, independent from $M_{Z'}$) plotted against $M_{Z'}$ at (a) a LC with $\sqrt{s_{e^+e^-}} = 1$ TeV and (b) a LC with $\sqrt{s_{e^+e^-}} = 3$ TeV. (The black vertical bar refers to the mass and coupling combinations excluded by experimental data, to the left of it.)

ILC and CLiC, Z' line shape (resonance)



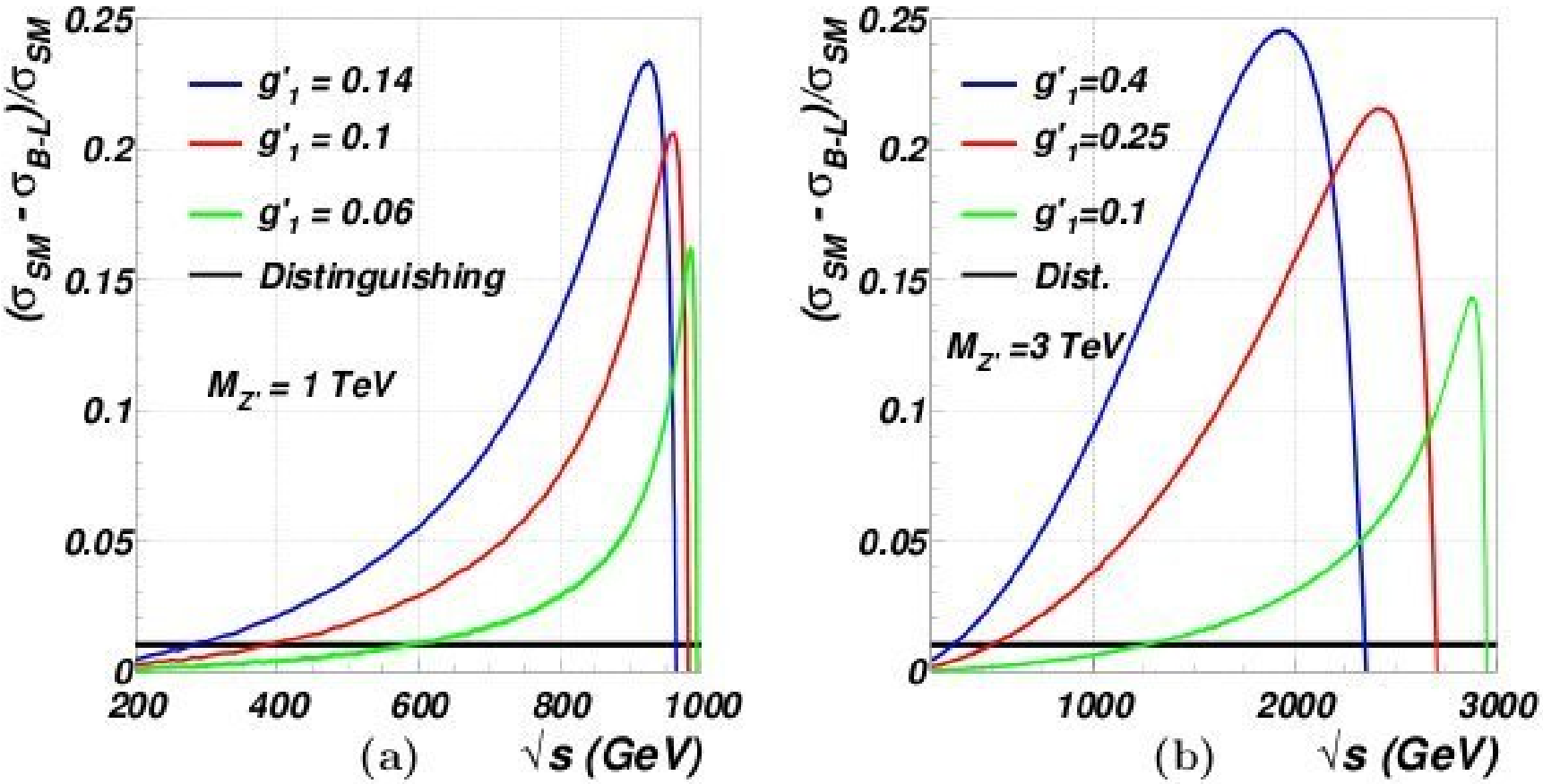
Cross section for the process $e^+e^- \to X \to \mu^+\mu^-$ cross section for the signal $(X = \gamma, Z, Z')$ and the SM background $(X = \gamma, Z)$ plotted against $\sqrt{s_{e^+e^-}}$ (notice here the GeV scale) at a LC, for (a) fixed $M_{Z'} = 1$ TeV and (b) fixed $M_{Z'} = 3$ TeV.

LC, Z' full line shape (INTERFERENCE EFFECTS!)



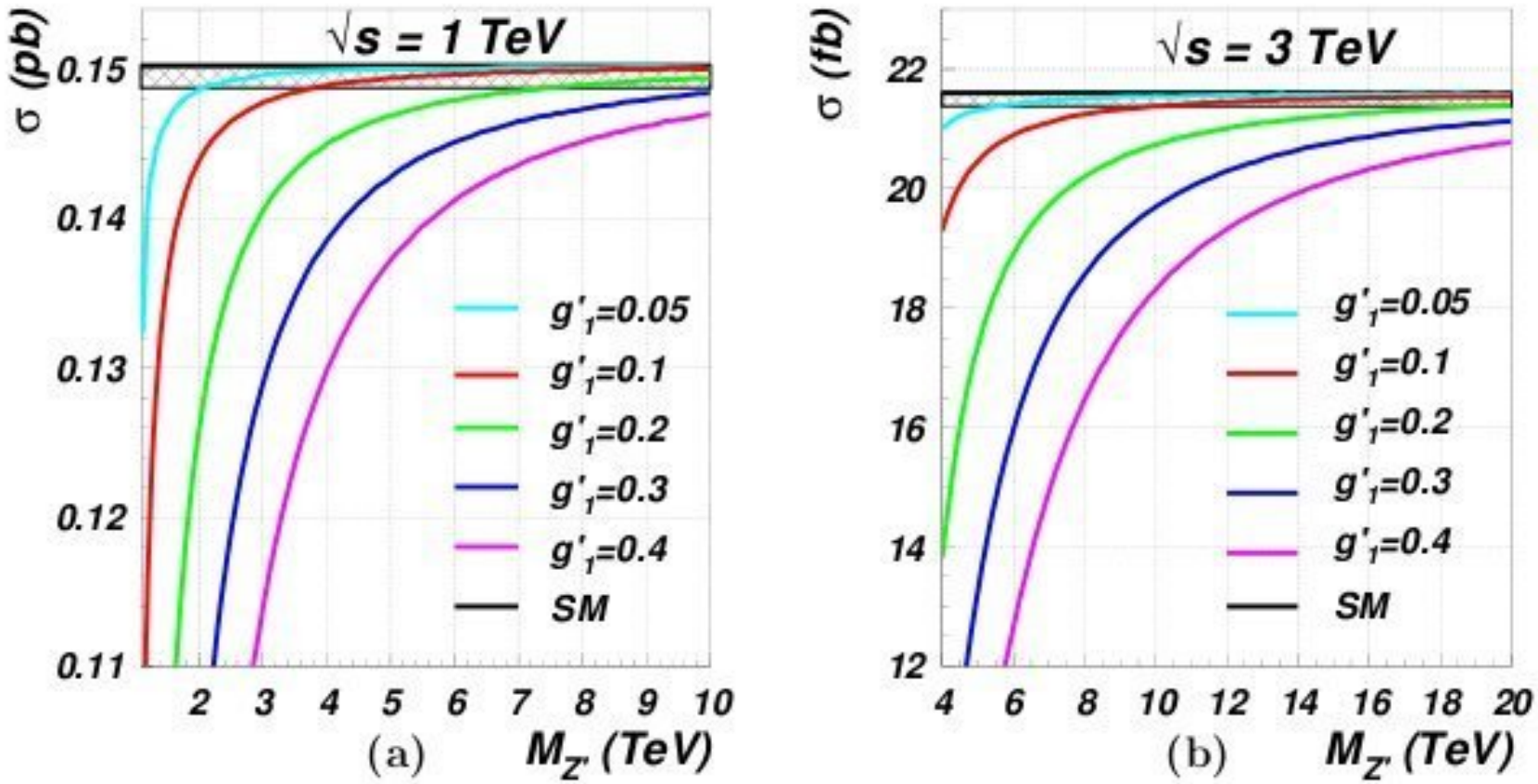
$\frac{d\sigma}{dM_{\mu\mu}}(e^+e^- \to \gamma, Z, Z' \to \mu^+\mu^-)$, for $\sqrt{s_{e^+e^-}} = 1$ TeV, $M_{Z'} = 800$ GeV and $g'_1 = 0.05,\ 0.1$ and 0.2. (Notice that the latter value is shown just for sake of illustration, although already excluded by ref. [22], see eq. 15).

ILC and CLiC, observable interference effects



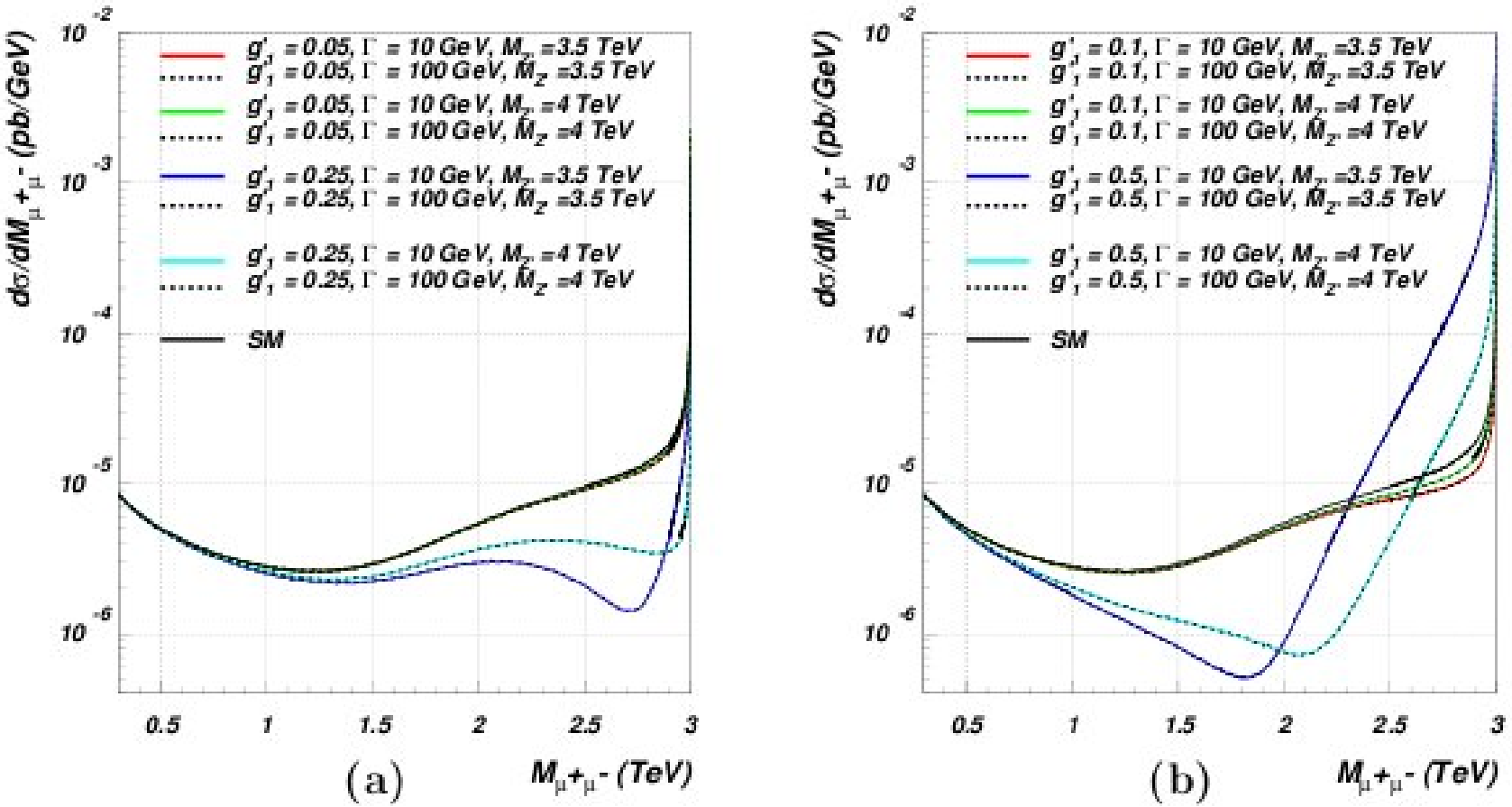
The relative difference for the cross section of the process $e^+e^- \to \mu^+\mu^-$ between the $B-L$ scenario and the SM plotted against $\sqrt{s_{e^+e^-}}$, for (a) $M_{Z'} = 1$ TeV and (b) $M_{Z'} = 3$ TeV. The horizontal line corresponds to a 1% deviation from the SM hypothesis.

ILC and CLiC, sensitivity to Z' interference effects



Cross section for the process $e^+e^- \to \gamma, Z, Z' \to \mu^+\mu^-$ plotted against $M_{Z'}$, for (a) $\sqrt{s_{e^+e^-}} = 1$ TeV and (b) $\sqrt{s_{e^+e^-}} = 3$ TeV. Notice that we have implemented here the cut $M_{\mu\mu} > 200$ GeV. The shading corresponds to a 1% deviation from the SM hypothesis.

ILC and CLiC, line shape and $\Gamma_{Z'}$



Cross section for the process $e^+e^- \to \mu^+\mu^-$ in the $B-L$ model plotted against $M_{\mu\mu}$, for several combinations of $M_{Z'}$ and g'_1, treating $\Gamma_{Z'}$ as an independent parameter. Here, $\sqrt{s_{e^+e^-}} = 3$ TeV.

Conclusions

- Simple SM extension at TeV scale, RH-neutrinos
- motivated by high-scale physics
- pure $B - L$ model, no $Z - Z'$ mixing

$\surd$ We have shown the unique potential of future LCs in detecting Z' bosons produced resonantly via di-muon production within the minimal $B - L$.

$\surd$ We have also presented the indirect sensitivity of LCs to a Z' below its production threshold.

$\surd$ We have also shown that in either kinematic configuration (i.e, for LCs with centre-of-mass energy below or above the Z' mass), it may be possible to access both the mass and (leptonic) couplings of the Z'.

Work in progress

REMINDER: minimal $B - L$ model can be fully determined by a direct detection and a line shape analysis of the Z' resonance.

- Z'-physics with beam polarisation, asymmetries.
- Heavy neutrinos and Higgs bosons sectors.
- $B - L$ model at next to leading order.

Backup slides

Z' experimental limit

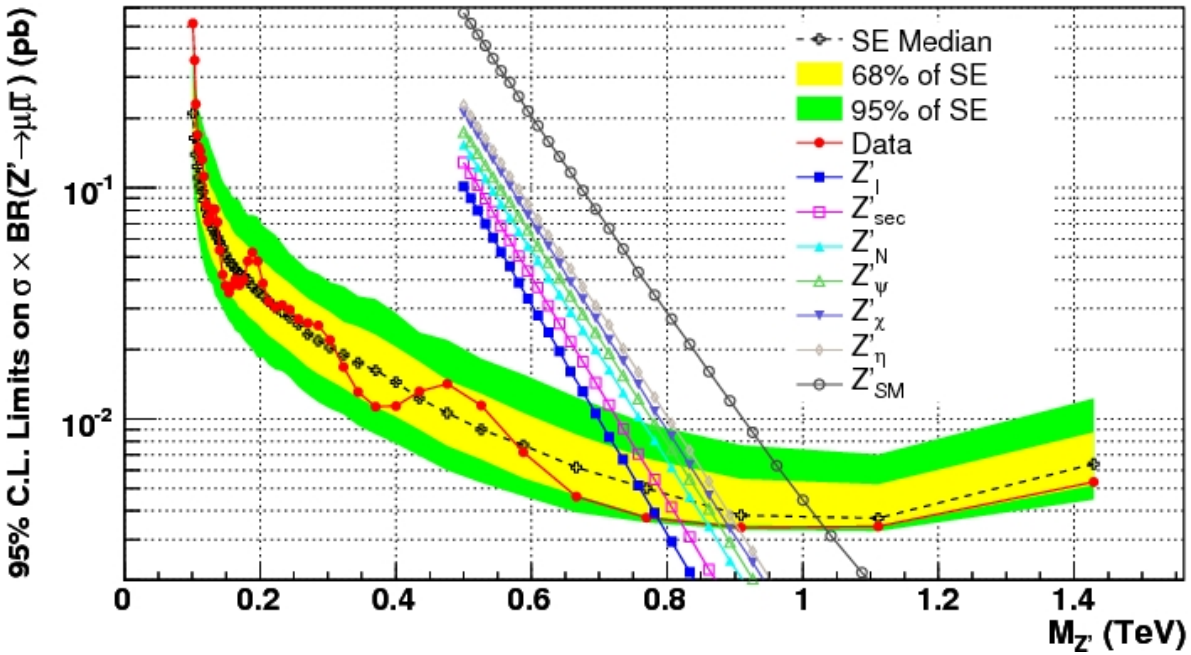
LEP bound:

G. Cacciapaglia *et all*, Phys. Rev. D **74** (2006) 033011

$$\frac{M_{Z'}}{g'_1} \geq 7 \text{ TeV}$$

Tevatron (Translating Z'_{SM} bound):

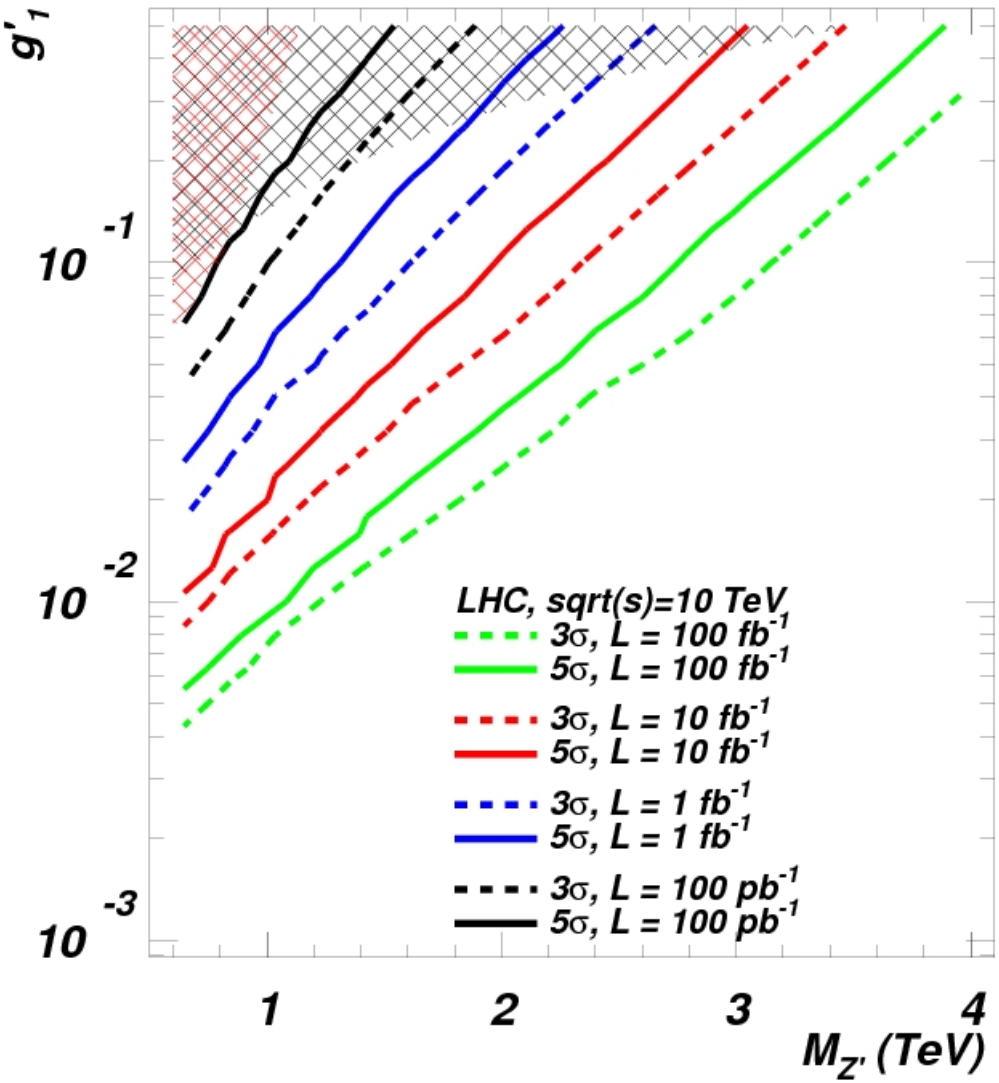
T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. Lett. **102**, 091805 (2009)



g'_1	$M_{Z'}$ (GeV)
0.065	600
0.075	680
0.090	740
0.1	800
0.2	960
0.5	1140

Z' Discovery potentials in di-muons

Significance contour levels plotted against g'_1 and $M_{Z'}$

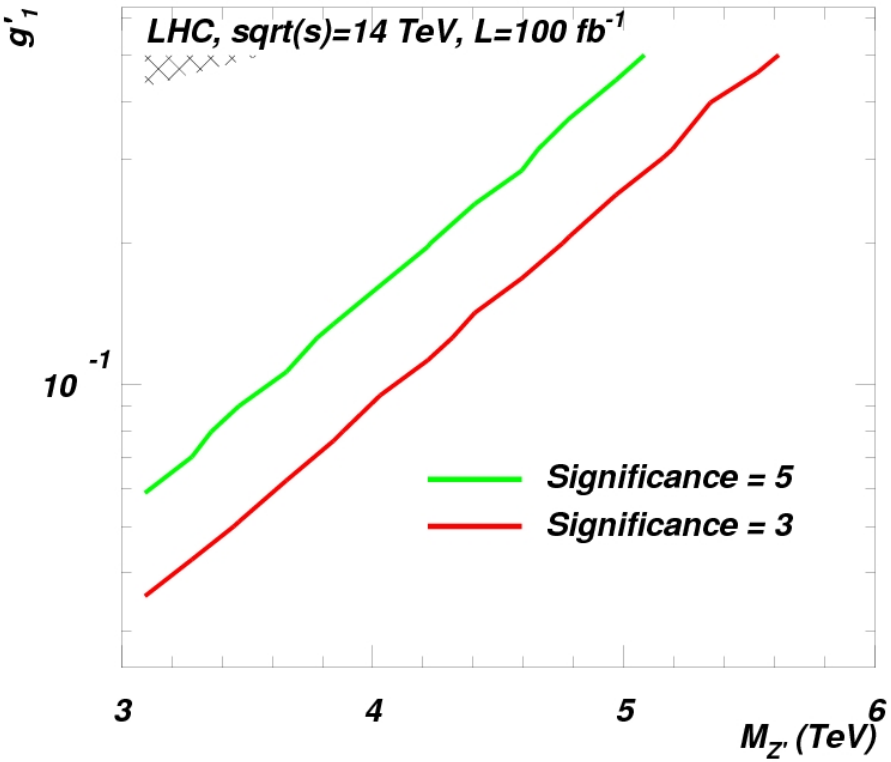


Preliminary

LHC: $\sqrt{s_{pp}} = 10$ TeV

Z' Discovery potentials in di-muons

Significance contour levels plotted against g'_1 and $M_{Z'}$



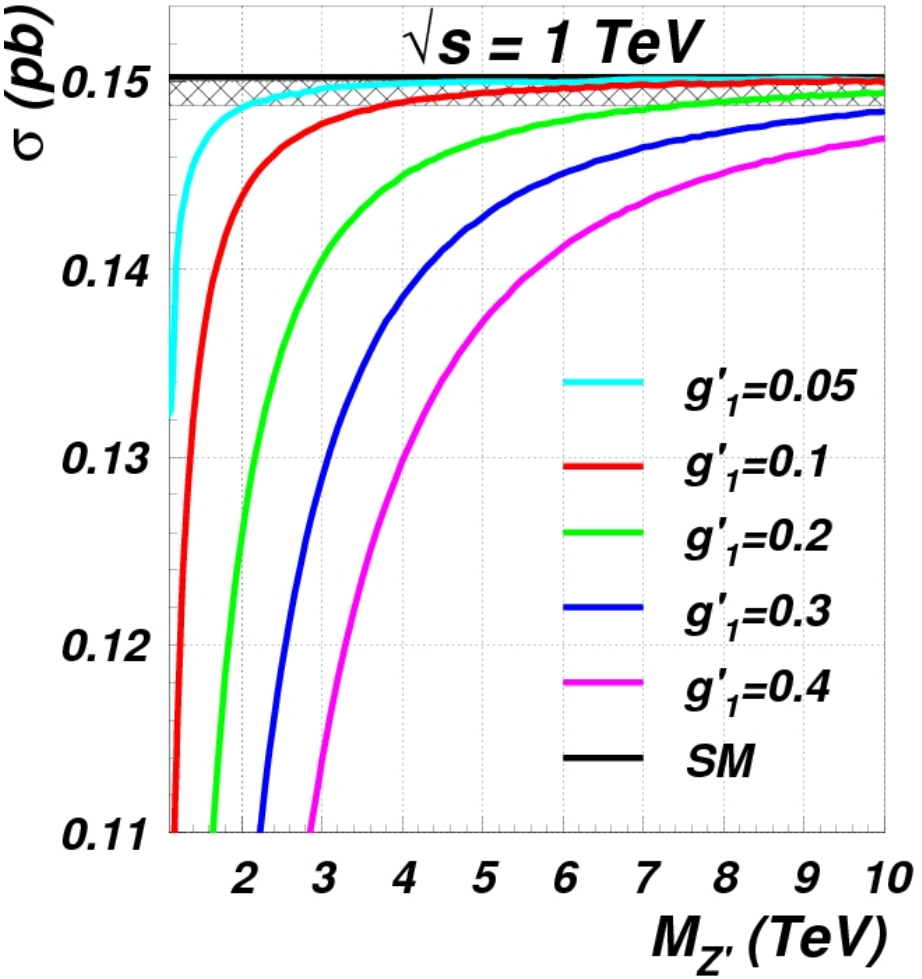
(b)

LHC: $L = 100\ \text{fb}^{-1}$ ($\sqrt{s_{pp}} = 14$ TeV)

$M_{Z'} \geq 3$ TeV

Z' Discovery potentials in di-muons

$\sigma(e^+e^- \to \gamma, Z, Z' \to \mu^+\mu^-)$ plotted against $M_{Z'}$, for $\sqrt{s_{e^+e^-}} = 1$ TeV ($M_{\mu\mu} > 200$ GeV)



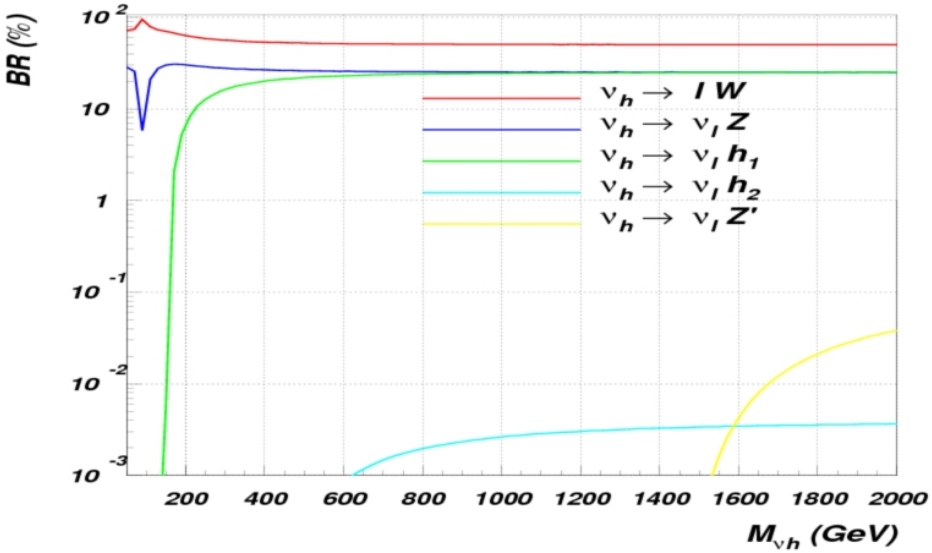
(c)

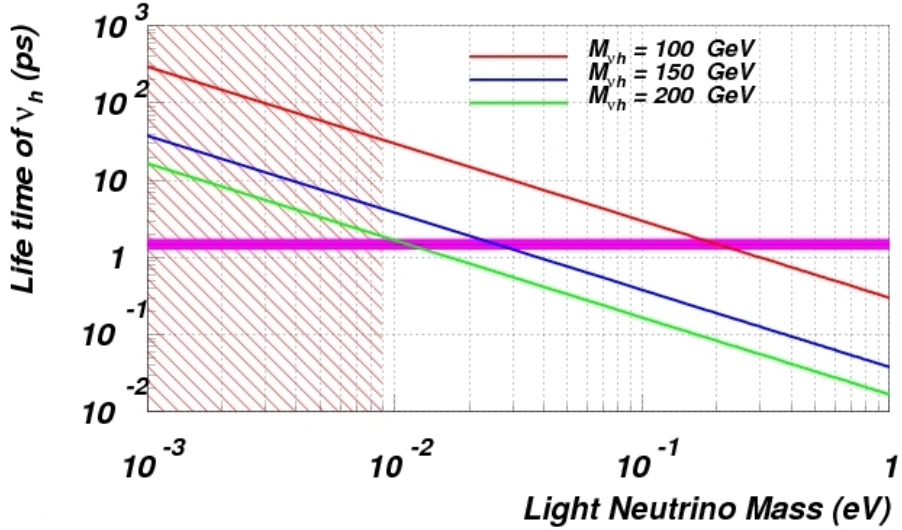
← 1% deviation from the SM hypothesis

g'_1	$M_{Z'}$ (TeV)	
	LHC 3σ observation	LC ($\sqrt{s} = 1$ TeV) 1% level
0.05	3.4	2.2
0.1	4.1	3.8
0.2	4.7	7.5

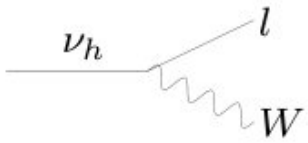
Table: maximum $M_{Z'}$ value accessible for selected g'_1 values

ν_h phenomenology





$$\tan 2\alpha_\nu = -2\sqrt{\frac{m_{\nu l}}{m_{\nu h}}}$$

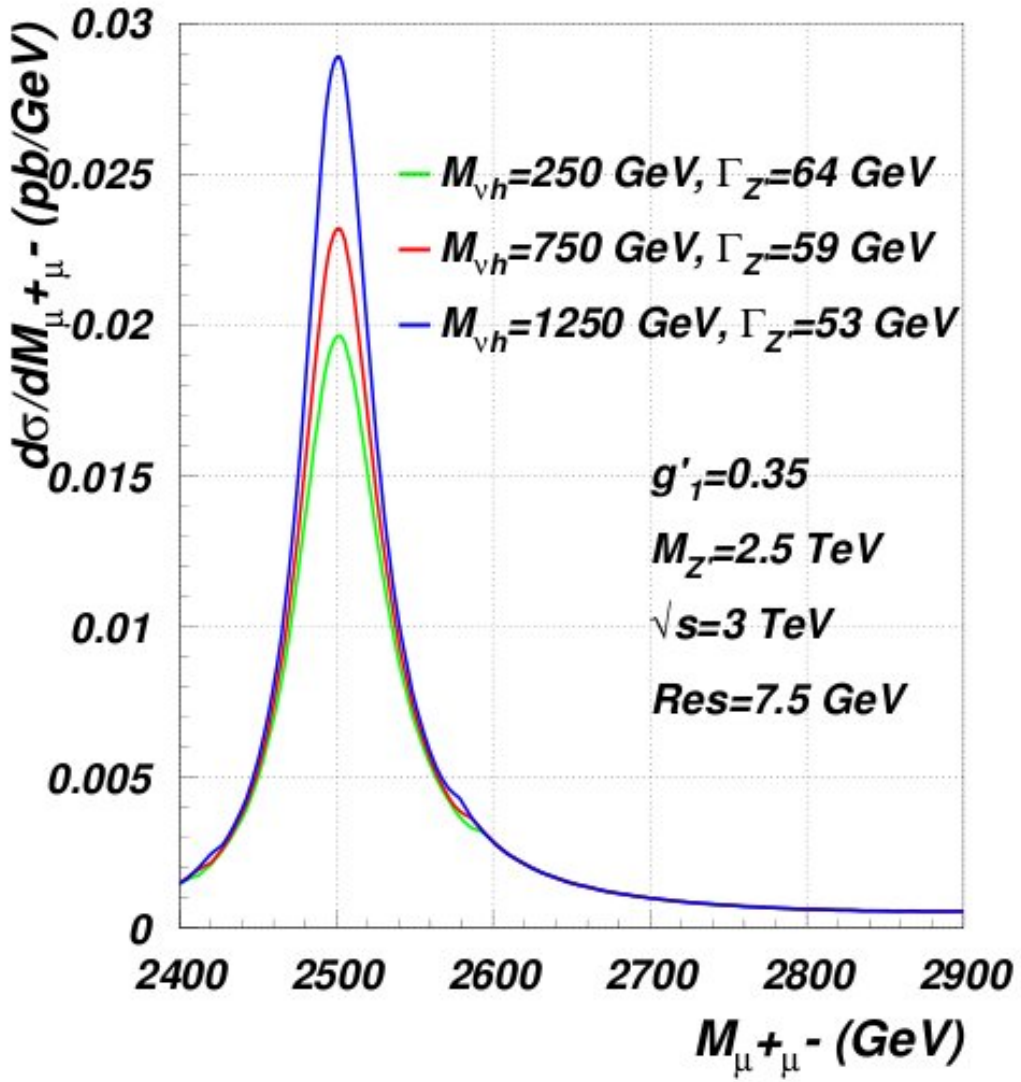


$$= \frac{\sqrt{2}e}{4\sin\vartheta_W}\sin\alpha_\nu$$

- $\Gamma = \Gamma(m_{\nu l}/m_{\nu h})$
- ν_h can be a long-lived particle
- DISPLACED VERTICES

χ can be decoupled from the SM: couples only to Z' and $\nu_{l,h}$: long-lived (under study)

LC, sensitivity to heavy neutrinos

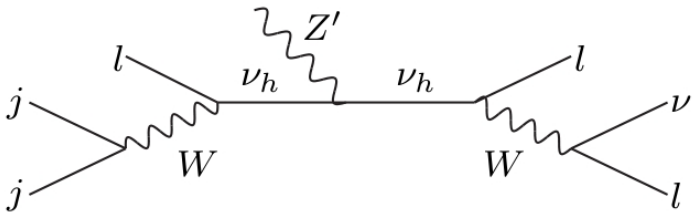


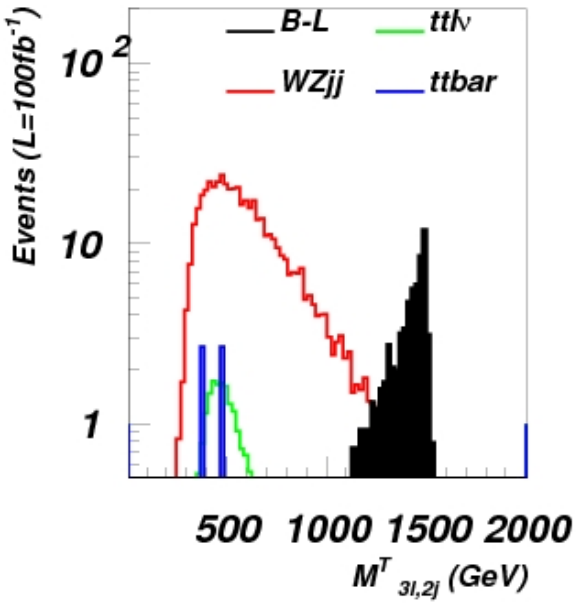
Z' line shape. Cross section for the process $e^+e^- \to \gamma, Z, Z' \to \mu^+\mu^-$ plotted against the di-muon invariant mass $M_{\mu\mu}$, for $M_{\nu h} = 250, 750, 1250$ GeV, $\sqrt{s_{e^+e^-}} = 3$ TeV, $M_{Z'} = 2.5$ TeV and $g'_1 = 0.35$.

ν_h @ LHC: $BR(Z' \to 3l + 2j + \not{P}_T\ (1\nu), l = e, \mu)$ up to 2.5%

$$m_T^2 = \left(\sqrt{M_{vis}^2 + P_{T,vis}^2} + \left|\not{P}_T\right|\right)^2 - \left(\vec{P}_{T\,vis} + \vec{\not{P}}_T\right)^2$$

V. Barger *at all,*
Phys. Rev. D **36** *(1987) 295*





$M_{Z'} = 1.5$ TeV, $g_1' = 0.2$: $\sigma(pp \to Z') = 0.3$ pb
$M_{\nu_h} = 200$ GeV, $\mathscr{L} = 100$ fb^{-1}, bin $= 20$ GeV

Backgrounds:

$WZjj$ associated production ($\sigma_{3l} = 246.7$ fb, $l = e, \mu, \tau$, w. cuts)

$t\bar{t}$ pair production ($\sigma_{2l} = 29.6$ pb, $l = e, \mu$) (3^{rd} lep. from b-quark)

$t\bar{t}l\nu$ associated production ($\sigma_{3l} = 8.6$ fb, $l = e, \mu, \tau$)

Cuts:

Kinematics, angular acceptance and isolation

W rec. from jets: $|M_{jj} - 80\ \text{GeV}| < 20$ GeV

Z' rec.: $\left|M_{3l,2j}^T - 1500\ \text{GeV}\right| < 250$ GeV