Precision study of the minimal $B - L$ model using the 'SUSY toolbox'

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FS, T. Ohl, W. Porod, C. Speckner (arXiv:1109.5147)
B. O'Leary, W. Porod, FS (arXiv:1112.4600)
L. Basso, M. Krauss, B. O'Leary, W. Porod, FS (in prep.)

3rd LC Forum Metting

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Introduction

- Models with a low scale gauged $B-L$ symmetry

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

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  - Might explain origin of R-parity and its possible spontaneous breaking
  - Can be a result of an $E_8 \times E_8$ heterotic string theory
  - Could explain neutrino data

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  become popular recently
    - Might explain origin of R-parity and its possible spontaneous breaking
    - Can be a result of an $E_8 \times E_8$ heterotic string theory
    - Could explain neutrino data
- They provide a rich phenomenology
    - Z' gauge boson at TeV scale
    - Extended Higgs sector
    - Extended Neutralino sector
    - Extended neutrino and sneutrino sector

The Model

Particle content

SF	Spin 0	Spin $\frac{1}{2}$	Generations	$(U(1)_Y \otimes SU(2)_L \otimes SU(3)_C \otimes U(1)_{B-L})$
$\hat{Q}$	$\tilde{Q}$	Q	3	$(\frac{1}{6}, \mathbf{2}, \mathbf{3}, \frac{1}{6})$
$\hat{D}$	$\tilde{d}^c$	d^c	3	$(\frac{1}{3}, \mathbf{1}, \overline{\mathbf{3}}, -\frac{1}{6})$
$\hat{U}$	$\tilde{u}^c$	u^c	3	$(-\frac{2}{3}, \mathbf{1}, \overline{\mathbf{3}}, -\frac{1}{6})$
$\hat{L}$	$\tilde{L}$	L	3	$(-\frac{1}{2}, \mathbf{2}, \mathbf{1}, -\frac{1}{2})$
$\hat{E}$	$\tilde{e}^c$	e^c	3	$(1, \mathbf{1}, \mathbf{1}, \frac{1}{2})$
$\hat{\nu}$	$\tilde{\nu}^c$	ν^c	3	$(0, \mathbf{1}, \mathbf{1}, \frac{1}{2})$
$\hat{H}_d$	H_d	$\tilde{H}_d$	1	$(-\frac{1}{2}, \mathbf{2}, \mathbf{1}, 0)$
$\hat{H}_u$	H_u	$\tilde{H}_u$	1	$(\frac{1}{2}, \mathbf{2}, \mathbf{1}, 0)$
$\hat{\eta}$	η	$\tilde{\eta}$	1	$(0, \mathbf{1}, \mathbf{1}, -1)$
$\hat{\bar{\eta}}$	$\bar{\eta}$	$\tilde{\bar{\eta}}$	1	$(0, \mathbf{1}, \mathbf{1}, 1)$

The superpotential is given by

$$W = Y_u^{ij}\, \hat{U}_i\, \hat{Q}_j\, \hat{H}_u\, - Y_d^{ij}\, \hat{D}_i\, \hat{Q}_j\, \hat{H}_d\, - Y_e^{ij}\, \hat{E}_i\, \hat{L}_j\, \hat{H}_d + \mu\, \hat{H}_u\, \hat{H}_d$$
$$+ Y_\nu^{ij}\, \hat{L}_i\, \hat{H}_u\, \hat{\nu}_j\, - \mu'\, \hat{\eta}\, \hat{\bar{\eta}} + Y_x^{ij}\, \hat{\nu}_i\, \hat{\eta}\, \hat{\nu}_j$$

Kinetic mixing

$F^Y_{\mu\nu} F^{B-L,\mu\nu}$ is gauge invariant and both abelian gauge groups mix. We can express this by off-diagonal gauge coupings:

$$D_\mu = \partial_\mu - i(Q^Y, Q^{B-L}) \begin{pmatrix} g_{YY} & g_{YB} \\ g_{BY} & g_{BB} \end{pmatrix} \begin{pmatrix} A^Y_\mu \\ A^B_\mu \end{pmatrix}$$

The gauge symmetry is broken by

$$\langle H^0_d \rangle = v_d,\ \langle H^0_u \rangle = v_u,\ \langle \bar{\eta} \rangle = v_{\bar{\eta}},\ \langle \eta \rangle = v_\eta$$

with $\tan\beta = \frac{v_u}{v_d}$ and $\tan\beta' = \frac{v_\eta}{v_{\bar{\eta}}}$

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Because of kinetic mixing the MSSM and $B-L$ sectors mix already at tree-level:

$\rightarrow$ 3 neutral vector bosons, 7 neutralinos,
4 scalars, 2 pseudo scalars

SUSY Toolbox

FS,Ohl,Porod,Speckner,1109.5147

The SUSY toolbox is a collection of scripts to create an environment including

- SARAH [FS,0806.0538],[FS,0909.2863],[FS,1002.0840]
- SPheno [Porod,hep-ph/0301101],[Porod,FS,1104.1573]
- WHIZARD [Kilian,Ohl,Reuter,0708.4233],[Moretti,Ohl,Reuter,0102195]
- HiggsBounds [Bechtle,Brein,Heinemeyer,Weiglein,Williams,1102.1898]
- CalcHep [Pukhov et. al,hep-ph/9908288
- MicrOmegas [Belanger,Boudjema,Pukhov,Semenov,hep-ph/0405253]
- SSP

and to implement new models into the other tools based on the implementation in SARAH

http://projects.hepforge.org/sarah/Toolbox.html

Step 1: Implementation in SARAH

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- Tadpole equations
- Mass matrices
- Vertices
- Two-loop RGEs (including kinetic mixing)
- Expressions for one-loop corrections to masses ($\overline{\text{DR}}$-scheme)

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- Gives a first, analytical understanding of the model
- Derived information can be used to implement that model in other tools

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Features of SPhenoBLSSM

- Precise mass calculation using 2-Loop RGEs and full 1-Loop corrections
- MSSM 2-Loop corrections ($O(Y^4, \alpha_S Y^2)$) can be linked.
- Calculation of low-energy observables like $\mu \to e\gamma$ and $\mu \to 3e$
- Calculation of decay widths and branching ratios
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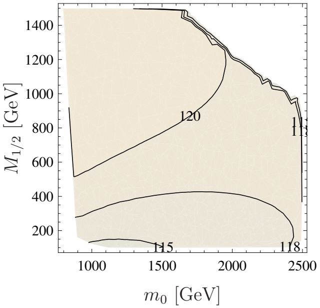
We are using CMSSM-like boundary conditions

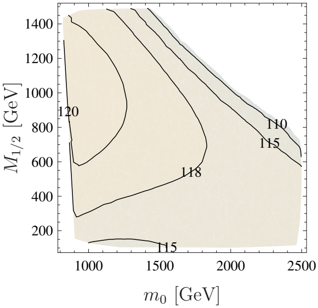
Free parameters

m_0, $M_{1/2}$, A_0, $\tan\beta$, $\tan\beta'$, sign(μ), sign(μ'), $M_{Z'}$, Y_x and Y_ν

Importance of kinetic mixing



no kinetic mixing

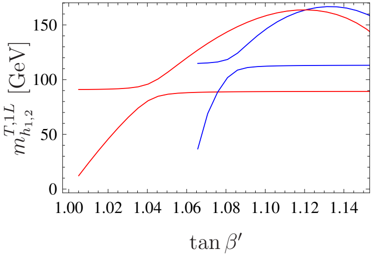


with kinetic mixing

Kinetic mixing

- Can change Higgs and neutralino masses by several per-cent
- Has also a sizable impact on other masses due to RGE running

Step 3: Checking Higgs constraints using HiggsBounds



Mixing in Higgs sector

- Especially for light bi-doublets the mixing in the Higgs sector can increase the MSSM-like Higgs mass sizable

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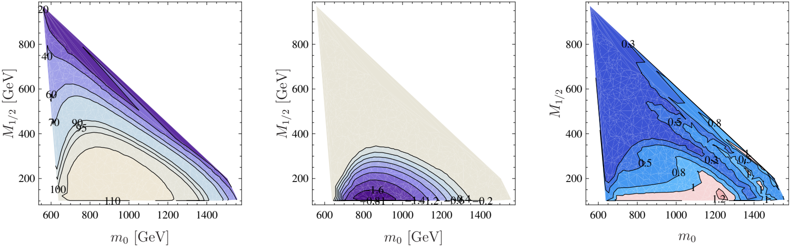
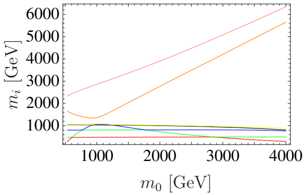


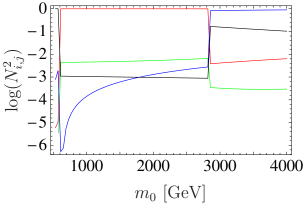
Mixing in Higgs sector

- Especially for light bi-doublets the mixing in the Higgs sector can increase the MSSM-like Higgs mass sizable
- The light mass eigenstates have some doublet fraction what rules out regions of parameter space

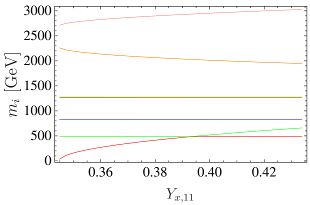
Dark matter - new candidates?

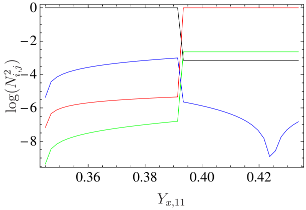
$M_{1/2} = 1000$, $\tan\beta = 10$, $A_0 = 2500$, $\tan\beta' = 1.2$, $M_{Z'} = 2000$, $Y_x^{ii} = 0.42$





$m_0 = M_{1/2} = 1000$, $\tan\beta = 10$, $A_0 = -1000$, $\tan\beta' = 1.15$, $M_{Z'} = 2500$, $Y_x^{11} = Y_x^{22} = 0.44$





red: bino/wino, green: higgsino, blue: blino, black: bileptino

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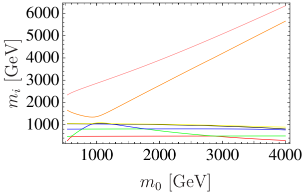

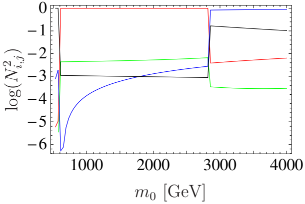

BLino LSP

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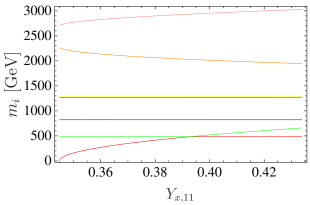

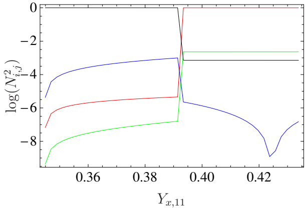

Bileptino LSP

red: bino/wino, green: higgsino, blue: blino, black: bileptino

Step 4: Implementation in MicrOmegas

Relic density calculation with MicrOmegas

The CalcHep model files created by SARAH can be used also for MicrOmegas to calculate the relic density. The parameters of SPheno are passed to MicrOmegas using the SLHA+ functionality.

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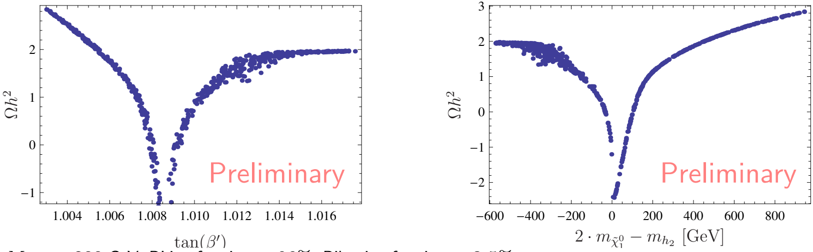
$m_0 \sim 2.8$ TeV, $M_{1/2} \sim 650$ GeV, $\tan\beta \sim 7$, $A_0 \sim -2.8$ TeV, $M_{Z'} \sim 3.2$ TeV, $Y_x^{ii} \sim 0.42$



$M_{\tilde{\chi}_1^0} \sim 280$ GeV, BLino fraction $\sim 96\%$, Bileptino fraction $\sim 3.5\%$

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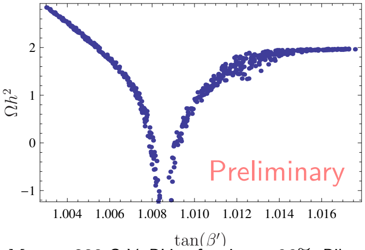

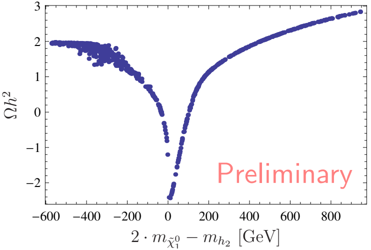

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$\rightarrow$ BLino dark matter possible because of Higgs resonance

Step 5: Implementation in WHIZARD

Model files for WHIZARD

SARAH can also write model files for WHIZARD.

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Results for ILC/LHC hopefully next time ...

Summary

- SUSY models with gauged $B-L$ symmetry lead interesting phenomenology:
  - Extended Higgs sector
  - New possibilites for dark matter
  - New particles at the TeV scale
- The SUSY toolbox provide a fast and easy approach for an exhaustive study of MSSM extension
  - Precise mass calculation (2-loop RGEs, 1-loop corrections)
  - Check of existing constraints: Higgs bounds and low-energy observables
  - Dark matter calculation and MC studies with powerful and well tested tools

$B - L$ model file

```
(*------------------------------------------*)
(*  Particle Content*)
(*------------------------------------------*)

Gauge[[1]]={B,   U[1], hypercharge, g1,False};
Gauge[[2]]={WB,  SU[2], left,        g2,True};
Gauge[[3]]={G,   SU[3], color,       g3,False};
Gauge[[4]]={Bp,  U[1], BminusL,          g1p, False};


Fields[[1]] = {{uL,  dL},  3, q,   1/6, 2, 3, 1/6};
Fields[[2]] = {{vL,  eL},  3, l,  -1/2, 2, 1, -1/2};
Fields[[3]] = {{Hd0, Hdm}, 1, Hd, -1/2, 2, 1, 0};
Fields[[4]] = {{Hup, Hu0}, 1, Hu,  1/2, 2, 1, 0};

Fields[[5]] = {conj[dR], 3, d,  1/3, 1, -3, -1/6};
Fields[[6]] = {conj[uR], 3, u, -2/3, 1, -3, -1/6};
Fields[[7]] = {conj[eR], 3, e,    1, 1,  1, 1/2};
Fields[[8]] = {conj[vR], 3, vR,   0, 1,  1, 1/2};

Fields[[9]]  = {C10, 1, C1, 0, 1, 1, -1};
Fields[[10]] = {C20, 1, C2,  0, 1, 1, 1};

(*--------------------------------------------------------*)
(* Superpotential *)
(*--------------------------------------------------------*)

SuperPotential = { {{1, Yu},{u,q,Hu}}, {{-1,Yd},{d,q,Hd}},  {{-1,Ye},{e,l,Hd}},
                   {{1,\[Mu]},{Hu,Hd}}, {{1,Yv},{l,Hu,vR}}, {{-1,MuP},{C1,C2}},
                   {{1,Yn},{vR,C1,vR}}  };

(*  ---   Rotations ----                              *)

NameOfStates={GaugeES, EWSB};

DEFINITION[GaugeES][GaugeFixing]=
 { {Der[VWB],  -1/(2 RXi[W])},  {Der[VG],   -1/(2 RXi[G]) }};

(*--- Gauge Sector ---- *)

DEFINITION[EWSB][GaugeSector] =
{
  {{VB,VWB[3],VBp},{VP,VZ,VZp},ZZ},
  {{VWB[1],VWB[2]},{VWm,conj[VWm]},ZW},
  {{fWB[1],fWB[2],fWB[3]},{fWm,fWp,fW0},ZfW}
};
```

```
(*--- VEVs ---- *)

DEFINITION[EWSB][VEVs]=
{    {SHd0, {vd, 1/Sqrt[2]}, {sigmad, \[ImaginaryI]/Sqrt[2]},{phid,1/Sqrt[2]}},
     {SHu0, {vu, 1/Sqrt[2]}, {sigmau, \[ImaginaryI]/Sqrt[2]},{phiu,1/Sqrt[2]}},
{SC10, {x1, 1/Sqrt[2]}, {sigma1, \[ImaginaryI]/Sqrt[2]},{phi1, 1/Sqrt[2]}},
{SC20, {x2, 1/Sqrt[2]}, {sigma2, \[ImaginaryI]/Sqrt[2]},{phi2, 1/Sqrt[2]}}
};


(*--- Matter Sector ---- *)

DEFINITION[EWSB][MatterSector]=
{    {{SdL, SdR}, {Sd, ZD}},
     {{SuL, SuR}, {Su, ZU}},
     {{SeL, SeR}, {Se, ZE}},
     {{SvL, SvR}, {Sv, ZV}},
     {{phid, phiu,phi1, phi2}, {hh, ZH}},
     {{sigmad, sigmau,sigma1,sigma2}, {Ah, ZA}},
     {{SHdm,conj[SHup]},{Hpm,ZP}},
     {{fB, fW0, FHd0, FHu0,fBp,FC10,FC20}, {L0, ZN}},
     {{{fWm, FHdm}, {fWp, FHup}}, {{Lm,UM}, {Lp,UP}}},
     {{FvL,conj[FvR]},{Fvm,UV}},
     {{{FeL},{conj[FeR]}},{{FEL,ZEL},{FER,ZER}}},
     {{{FdL},{conj[FdR]}},{{FDL,ZDL},{FDR,ZDR}}},
     {{{FuL},{conj[FuR]}},{{FUL,ZUL},{FUR,ZUR}}}                   \
       };

(*--- Gauge Fixing ---- *)

DEFINITION[EWSB][GaugeFixing]=
  {     {Der[VP],                                           - 1/(2 RXi[P])},
        {Der[VWm]+\[ImaginaryI] Mass[VWm] RXi[W] Hpm[{1}],   - 1/(RXi[W])},
        {Der[VZ] - Mass[VZ] RXi[Z] Ah[{1}],                 - 1/(2 RXi[Z])},
        {Der[VZp] - Mass[VZp] RXi[Zp] Ah[{2}],              - 1/(2 RXi[Zp])},
        {Der[VG],                                           - 1/(2 RXi[G])}};


DEFINITION[EWSB][Phases]=
{    {fG, PhaseGlu}     };

DEFINITION[EWSB][DiracSpinors]={
 Fd ->{  FDL, conj[FDR]},  Fe ->{  FEL, conj[FER]},
 Fu ->{  FUL, conj[FUR]},  Fv ->{  Fvm, conj[Fvm]},
 Chi ->{ L0, conj[L0]}, Cha ->{ Lm, conj[Lp]},
 Glu ->{ fG, conj[fG]}  };
```