SUGRA Grand Unification, LHC and Dark Matter

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Unification

The aim of particle physics is to achieve a unified theory of all interactions, i.e., of electroweak and strong interactions and of gravity.

- Possible candidates: string theory, $\cdots$
- A strong point of string theory is that it is a finite theory , so a valid model of quantum gravity. But string theory may not necessarily be unique. For example N=8 supergravity may also be finite. No solid proof yet but lot of recent progress.
- Compactification to D=4 may lead to 10^{1000} possibilities leading to a landscape of string vacua. Our world may be one of these possibilities. Only a proof by explicit construction can establish that our word belongs in the set of 10^{1000}.

A more modest approach:

- The field point of limit of strings is supergravity. Thus below the compactification scale it is valid to use the field point limit.
- Grand unification provides a framework for the unification of the electroweak and strong interactions,
- Thus a valid procedure is to use

  supergravity + grand unification = supergravity grand unification (SUGRA GUT) (Chamseddine, Arnowitt, PN -1982).

- SUGRA GUT resolves two problems of ordinary globally supersymmetric grand unification
  - Gravity mediated breaking leads to soft terms which break supersymmetry in a desirable way.
  - The potential of SUGRA GUT is not positive definite so one can fine tune the vacuum energy to be very small.
- Thus a pragmatic approach is to first establish if a SUGRA GUT is a valid picture of Nature for energies up to 10^{16} GeV. If we are able to do that, then it will provides a strong support for an underlying quantum theory of gravity such as strings.

Contents

Contents

- SUSY/SUGRA GUTs: Specifically $SO(10)$
- The little hierarchy problem: TeV size scalars are natural on the Hyperbolic Branch (HB).
- A Higgs mass of 125 can arise naturally on HB.
- Cosmic coincidence, asymmetric dark matter (AsyDM)[1] and SUGRA
- Conclusions

[1] The proposed AsyDM does not oscillate and is not washed out after it is generated.

$SO(10)$ grand unification

Gauge symmetry based on $SO(10)$ provides a framework for unifying the $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge groups and for unifying quarks and leptons in a single 16–plet spinor representation. Additionally, the 16–plet also contains a right–handed singlet state, which is needed to give mass to the neutrino via the seesaw mechanism.

- However, SUSY $SO(10)$ models, as usually constructed, have two drawbacks, both related to the symmetry breaking sector.
- First: Two different mass scales are involved in breaking of the GUT symmetry, one to reduce the rank and the other to reduce the symmetry all the way to $SU(3)_C \times SU(2)_L \times U(1)_Y$. Thus typically three types of Higgs fields are needed [2], e.g., $16 + \overline{16}$ or $126 + \overline{126}$ for rank reduction, and a 45, 54 or 210 for breaking the symmetry down to the standard model symmetry, and a 10 plet for electroweak symmetry breaking .
- Second: GUT models typically have the Doublet-Triplet problem.

[2] Review: PN, P. Fileviez Perez, Phys. Rept. **441**, 191 (2007).

Single Scale GUT Breaking

- Multiple step breaking requires additional assumptions relating VEVS of different breakings to explain gauge coupling unification of electroweak and strong interactions. A single step breaking does not require such an assumption.
- A single step breaking can be achieved with $144 + \overline{144}$.
  Babu, I. Gogoladze, PN, and Syed, Phys. Rev. D **72**, 095011 (2005); Phys. Rev. D **74**, 075004 (2006); PN, and Syed, JHEP **0602**, 022 (2006)

  The reason for this is easily understood by looking at the decomposition of 144 plet of $SO(10)$ under $SU(5) \times U(1)$.

  $$\overline{144} = \bar{5}(3) + 5(7) + 10(-1) + 15(7) + 24(-5) + 40(-1) + \overline{45}(3)$$

  Now the 24 plet carries a $U(1)$ quantum number and thus a VEV formation of it will reduce the rank of the group as well as break $SU(5)$.

- Additionally one can obtain a pair of light Higgs doublets needed for electroweak symmetry breaking from the same irreducible $144 + \overline{144}$ Higgs multiplet.

$$SO(10) \quad \underset{< 144 + \overline{144} >}{\rightarrow\rightarrow\rightarrow} \quad SU(3)_C \times U(1)_{em} \tag{1}$$

The Doublet- Triple Problem of GUTs

- Second, GUT theories typically have the doublet-triplet problem, i.e., one must do an extreme fine–tuning at the level of one part in 10^{14} to get the Higgs doublets of MSSM light, while color–triplets remain superheavy.

Some possible solutions to the doublet -triplet problem include

- Missing VEV: SO(10) breaks in the B-L direction.
- Flipped $SU(5) \times U(1)$
- Missing partner mechanism
- Orbifold GUTs

The missing partner mechanism and the orbifold GUTs are rather compelling in that some doublets are forced to be massless. We will discuss how it works in $SU(5)$ and then discuss how one can extend to $SO(10)$.

Missing partner mechanism in SU(5) Models

- In SU(5) to obtain Higgs doublets which are naturally light one uses an array of light and heavy Higgs multiplets[3]

$$\begin{aligned} \text{Heavy}: &\quad 50, \overline{50}, 75 \\ \text{Light}: &\quad 5, \bar{5} \end{aligned}$$

  i.e,, mass terms for $75, 50, \overline{50}$ and no mass terms for $5 + \bar{5}$.
- 75 plets breaks the GUT symmetry to $SU(3) \times SU(2) \times U(1)$.
- The key element is that $50 + \overline{50}$ have no doublet pairs (D) and only triplet/anti-triplet pairs (T)

$$\begin{aligned} 50 + \overline{50} &\quad 0D + 1T \\ 5 + \bar{5} &\quad 1D + 1T \end{aligned}$$

- The Higgs triplets/anti-triplets of $50 + \overline{50}$ mix with the Higgs triplets/anti-triplets of $5 + \bar{5}$ to become heavy. This is accomplished via the superpotential

$$W_0(75) + M 50.\overline{50} + \lambda_1 50.75.\bar{5} + \lambda_2 \overline{50}.75.5$$

  The doublets in $5 + \bar{5}$ have nothing to pair up with and remain light.

3 Grinstein (1982); Masiero, Nanopoulos, Tamvakis, Yanagida (1982)

Summary of $SO(10)$ Missing Partner Models

Babu, Gogoladze, PN, Syed: Phys. Rev. D 85, 075002 (2012) arXiv:1112.5387 [hep-ph])

Model	Heavy Fields	Light Fields	Pairs of D and T in Heavy Fields	Pairs of D and T in Light Fields	Residual Set of Light Modes
(i)	$126 + \overline{126} + 210$	$2 \times 10 + 120$	(2D+3T)+(D+T)	(2D+2T)+(2D+2T)	1D
(ii)	$126 + \overline{126} + 45$	$10 + 120$	(2D+3T)	(D+T)+(2D+2T)	1D
(iii)	$126 + \overline{126}$	$10 + 120$	(2D+3T)	(D+T)+(2D+2T)	1D
(iv)	$560 + \overline{560}$	$1 \times 320 + 2 \times 10$	4D+5T	(3D+3T)+ (2D+2T)	1D

The $560 + \overline{560}$ model has the dual feature that it breaks the $SO(10)$ GUT symmetry at one scale and at the same time, it has no doublet-triplet problem.

The case with heavy sector $126 + \overline{126}$ and light sector $10 + 120$ was discussed earlier by Babu, Gogoladze, Tavartkiladze, Phys. Lett. B **650**, 49 (2007).

Connecting High Scales to Low Energy Physics

- In order to make contact with low energy physics one needs to break supersymmetry. This is achieved in Supergravity Grand Unification
  Chamseddine, Arnowitt, PN 1982
- A broad class of models fall under this rubric. These include mSUGRA (CMSSM), and SUGRA models with non-universalities in the Higgs sector and in the gaugino sector.
- mSUGRA has the parameter space

$$m_0, m_{1/2}, A_0, \tan\beta, \mathrm{sign}(\mu).$$

- For non-universal SUGRA models there are additional parameters

$$m_{1/2} \to \tilde{m}_1, \tilde{m}_2, \tilde{m}_3 \quad \mathrm{non-universal\ gauginos}$$

$$m_0 \to m_{H_1}, m_{H_2} \quad \mathrm{non-universal\ Higgs\ sector}$$

Natural TeV Size Scalars

The Little Hierarchy: Keeping μ small while m_0 is large.

Chan, Chattopadhyay, PN: Phys.Rev.D58:096004,1998

Akula, Liu, PN, Peim, PLB 709, 192 (2012)

$$\mu^2 + \frac{1}{2}M_Z^2 = m_0^2 C_1 + A_0^2 C_2 + m_{\frac{1}{2}}^2 C_3 + m_{\frac{1}{2}} A_0 C_4 + \Delta\mu_{loop}^2$$

Ellipsoidal Branch (EB): $C_i > 0$ (all i)

Hyperbolic Branch (HB): ' In certain regions of the parameter space C_1 can turn negative. This converts the REWSB equation from a ellipsoidal surface to a hyperbolic surface

HB contains three regions

- **HB/FP: Focal Point:** $C_1 = 0$, and thus m_0 can get large for fixed μ.
- **HB/FC: Focal Curve:** $C_1 < 0$ and two soft parameters can get large for fixed μ.

$$(\bar{A}_0\sqrt{C_2})^2 - (\sqrt{|C_1|}m_0)^2 = \pm|\mu_1|^2 \Rightarrow \frac{\bar{A}_0}{m_0} \to \pm\sqrt{\frac{|C_1|}{C_2}},\ \bar{A}_0 \equiv A_0 + \frac{C_4}{2C_2}m_{1/2}.$$

- **HB/FS: Focal Surface:** $C_1 < 0$ and all three soft parameters $m_0, m_{1/2}, A_0$ can get large for fixed μ.

Intersection of Ellipsoidal and Hyperbolic Branches: $C_1 = 0$

The solution to the coupled one loop equations of the scalar masses of $m^2_{H_2}$, $m^2_{\tilde{U}}$ and $m^2_{\tilde{Q}}$ can be written in the form $m_i^2 = (m_i^2)_p + \delta m_i^2$ with $(m_i^2)_p$ being the particular solution and the δm_i^2 obey the homogeneous equation

$$\frac{d}{dt}\begin{bmatrix} \delta m^2_{H_2} \\ \delta m^2_U \\ \delta m^2_Q \end{bmatrix} = -Y_t \begin{bmatrix} 3 & 3 & 3 \\ 2 & 2 & 2 \\ 1 & 1 & 1 \end{bmatrix}\begin{bmatrix} \delta m^2_{H_2} \\ \delta m^2_U \\ \delta m^2_Q \end{bmatrix},$$

where $Y_t = h_t^2/(16\pi^2)$, and h_t is the Yukawa coupling at scale Q. The solution to the above with the universal boundary conditions at the GUT scale is given by

$$\begin{bmatrix} \delta m^2_{H_2} \\ \delta m^2_U \\ \delta m^2_Q \end{bmatrix} = \frac{m_0^2}{2}\begin{bmatrix} 3D_0(t) - 1 \\ 2D_0(t) \\ D_0(t) + 1 \end{bmatrix}, D_0(t) \equiv \exp[-6\int_0^t Y_t(t')dt'],$$

one finds that Thus

$$\delta m^2_{H_2} = m_0^2(3D_0 - 1)/2.$$

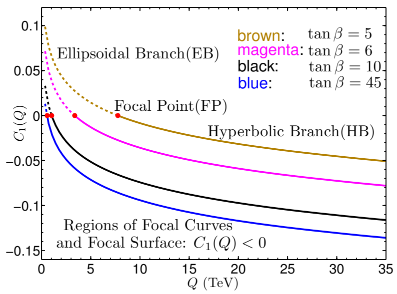
C_1 is related to $\delta m^2_{H_2}$ as (Akula, Liu, PN, Peim, PLB 709, 192 (2012))

$$C_1 \to -\frac{1}{m_0^2}\delta m^2_{H_2}, \quad (\tan\beta >> 1)$$

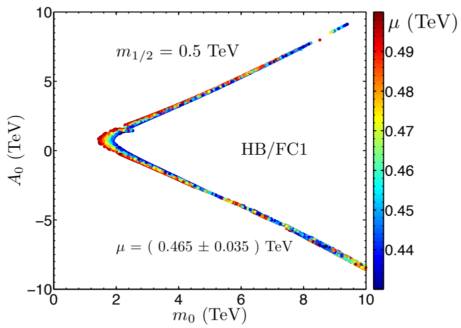
The correction $\delta m^2_{H_2}$ becomes independent of m_0 when $D_0 = 1/3$, which corresponds to the so called Focus Point region (Feng, Matchev, Moroi, 2000), which also implies that C_1 vanishes for $\tan\beta \gg 1$. Thus FP is just a point on HB which marks the transition between EB and HB.

Regions of Focal Point, Focal Curves, and Focal Surfaces

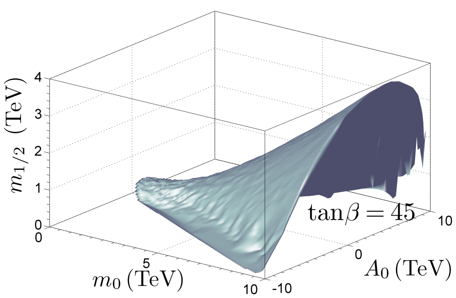
Akula, Liu, PN, Peim, PLB 709, 192 (2012)



EB, HB/FP, HB/FC



Focal Curve

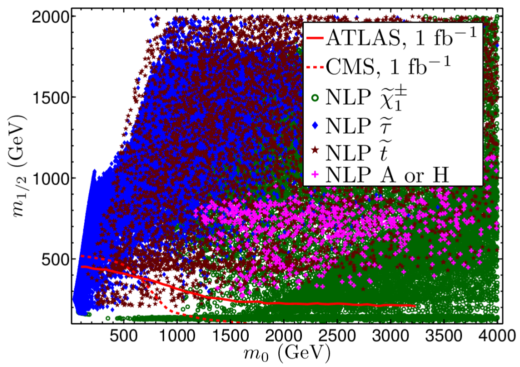


Focal Surface

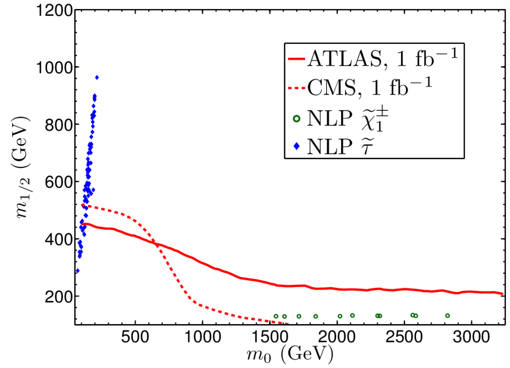
Decomposition of LHC Data into Focal Regions

Akula, Liu, PN, Peim, PLB 709, 192 (2012)

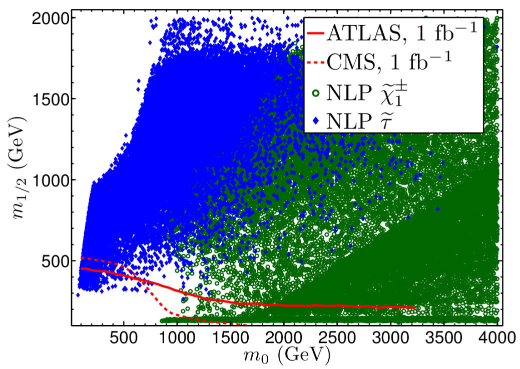
mSUGRA parameter space



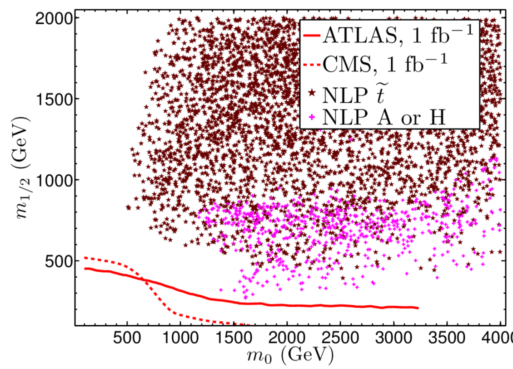
Focal point region



Focal surface (NLSP=$\tilde{\chi}^{\pm}$; $\tilde{\tau}$)

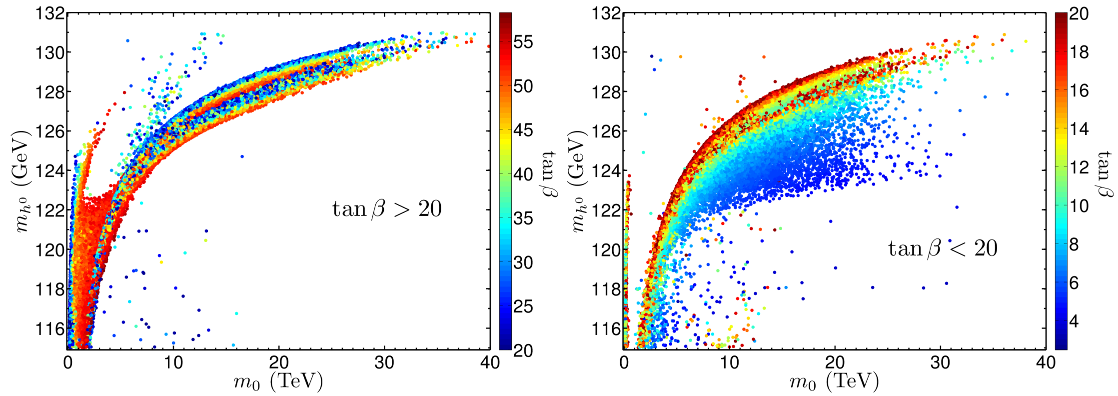


Focal surface (NLSP=$\tilde{t}$, A, H)



Higgs can be naturally size 125 GeV on the Hyperbolic Branch in SUGRA.

Akula, Altunkaynak, Feldman, PN, Peim, PRD 85 (2012) 075001, arXiv:1112.3645 [hep-ph].



Exhibition of the light Higgs mass [4] as a function of m_0 for $\tan\beta > 20$ (left panel) and $\tan\beta < 20$ (right panel). A 125 GeV Higgs requires a large A_0, i.e., $A_0 \sim \pm 2m_0$.

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[4] The dominant one loop contribution arises from the top/stop sector and is given by

$$\Delta m_h^2 \simeq \frac{3m_t^4}{2\pi^2 v^2} \ln \frac{M_S^2}{m_t^2} + \frac{3m_t^4}{2\pi^2 v^2} \left(\frac{X_t^2}{M_S^2} - \frac{X_t^4}{12 M_S^4} \right) ,$$

where $v = 246$ GeV, M_S is an average stop mass, and X_t is given by

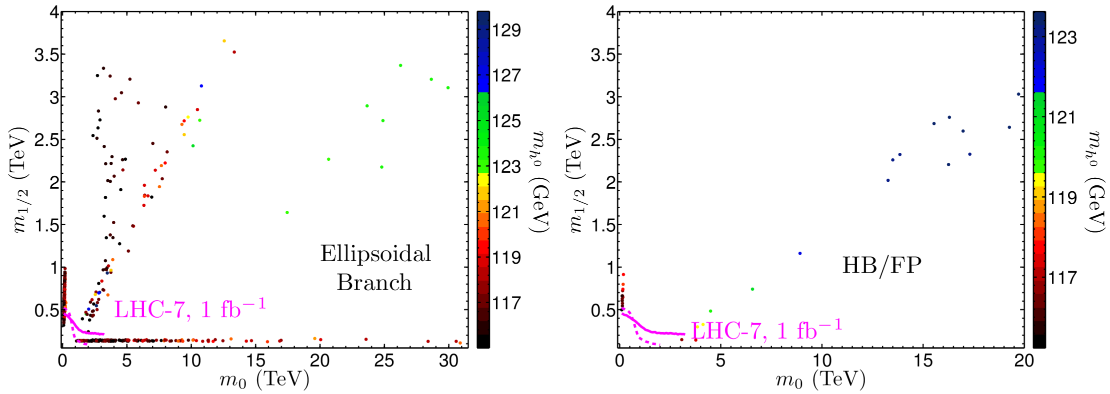
$$X_t \equiv A_t - \mu \cot\beta \ .$$

The loop correction is maximized when $X_t \sim \sqrt{6} M_S$.

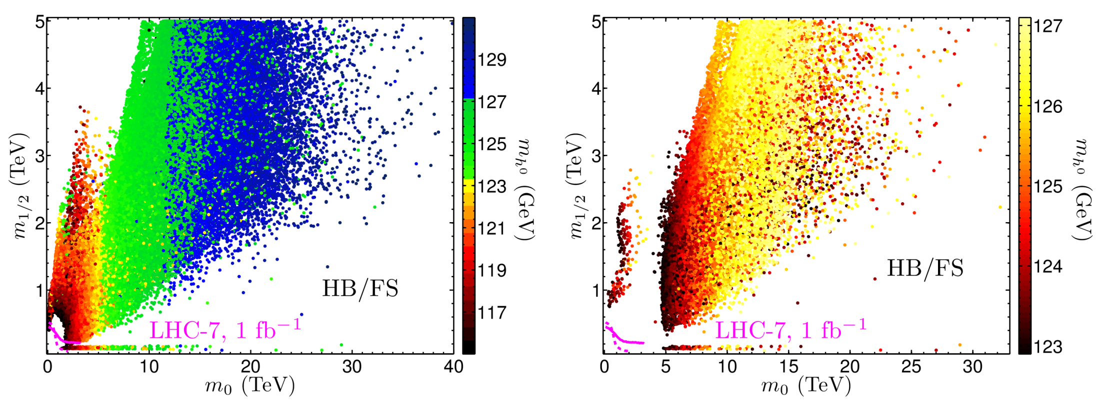
Implications for a relatively heavy Higgs for Focal Regions.

Akula, Altunkaynak, Feldman, PN, Peim - PRD 85 (2012) 075001, arXiv: 1112.3645

Ellipsoidal Branch (left panel); Focal Point (right panel)



Focal Surface: m_h= 115-130 GeV (left panel); m_h = 123 − 127 GeV (right panel)



Implications for a relatively heavy Higgs for Sparticle Spectra.

Akula, Altunkaynak, Feldman, PN, Peim -PRD 85 (2012) 075001, arXiv: 1112.3645

	$m_{h^0} > 115$	$m_{h^0} > 117$	$m_{h^0} > 119$	$m_{h^0} > 121$	$m_{h^0} > 123$	$m_{h^0} > 125$	$m_{h^0} > 127$
$m_{H^0} \sim m_{A^0}$	212	216	273	324	1272	1517	2730
$m_{H^\pm}$	230	234	288	337	1275	1520	2732
$m_{\tilde{\chi}_1^0}$	81	81	81	88	193	218	236
$m_{\tilde{\chi}_1^\pm} \sim m_{\tilde{\chi}_2^0}$	104	104	104	111	376	424	459
$m_{\tilde{g}}$	800	800	803	803	1133	1264	1373
$m_{\tilde{t}_1}$	156	197	228	230	231	246	260
$m_{\tilde{\tau}_1}$	142	161	201	232	321	576	1364
$m_{\tilde{q}}$	729	796	995	1126	1528	2235	2793
$m_{\tilde{l}}$	163	194	265	325	475	1631	2557
μ	107	107	107	120	1418	1863	2293

	$m_{h^0} > 115$	$m_{h^0} > 117$	$m_{h^0} > 119$	$m_{h^0} > 121$	$m_{h^0} > 123$	$m_{h^0} > 125$	$m_{h^0} > 127$
$m_{H^0} \sim m_{A^0}$	287	287	287	338	367	548	644
$m_{H^\pm}$	301	301	301	349	378	555	646
$m_{\tilde{\chi}_1^0}$	91	91	91	91	91	91	256
$m_{\tilde{\chi}_1^\pm} \sim m_{\tilde{\chi}_2^0}$	104	104	104	104	104	104	261
$m_{\tilde{g}}$	802	802	802	802	925	1006	1813
$m_{\tilde{t}_1}$	229	229	229	229	229	360	360
$m_{\tilde{\tau}_1}$	911	911	911	911	1186	1186	1186
$m_{\tilde{q}}$	4035	4035	4035	4035	4215	4493	4493
$m_{\tilde{l}}$	3998	3998	3998	4002	4085	4308	4308
μ	118	118	118	118	138	140	251

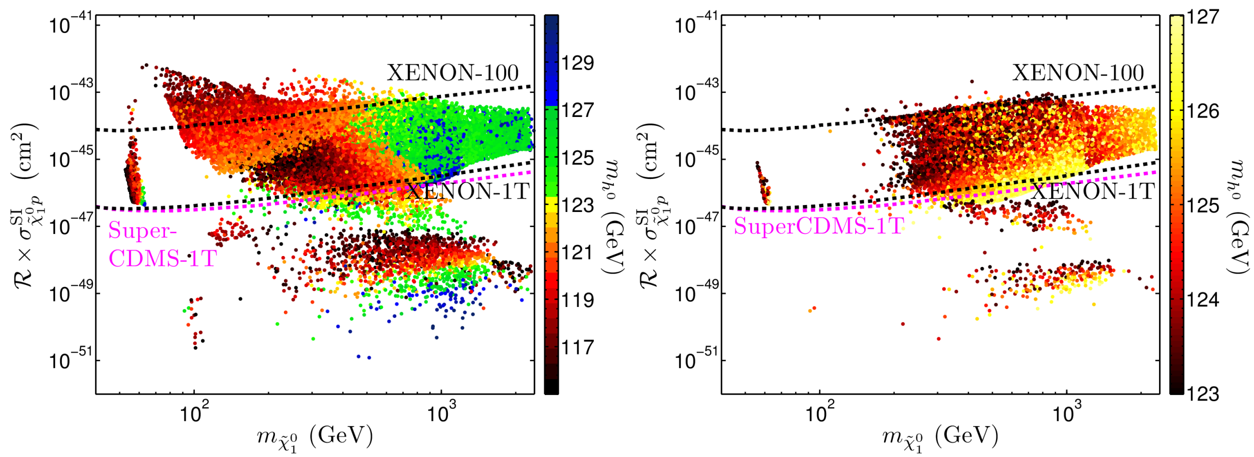
Benchmark	m_0	$m_{1/2}$	A_0/m_0	$\tan\beta$	m_{h^0}	$m_{\tilde{\chi}_1^0}$	$m_{\tilde{\chi}_1^\pm}$	$m_{\tilde{g}}$	$m_{\tilde{t}_1}$	$m_{\tilde{\tau}_1}$	$m_{\tilde{q}}$	$m_{\tilde{l}}$	μ
Light Stop	5108	764	2.549	33.29	125	321	621	1828	334	3604	5240	5108	3887
Light Gauginos, Low μ	3340	306	-0.395	29.521	121	91	115	832	1974	3070	3352	3335	125
Light Stau	248	548	-6.834	14	121	228	438	1254	569	232	1126	325	1072

The light sparticles accessible at LHC with Higgs at 125 GeV

Neutralino	$\tilde{\chi}_1^0$
Chargino	$\tilde{\chi}_1^{\pm}$
gluino	$\tilde{g}$
Stop	$\tilde{t}_1$
Stau	$\tilde{\tau}_1$
Higgses	$H^0, A^0, H^{\pm}$

Direct detection of dark matter in light of Higgs boson data.

Akula, Altunkaynak, Feldman, PN, Peim - PRD 85 (2012) 075001, arXiv: 1112.3645



- The left panel gives the full light Higgs boson mass range, i.e. 115 GeV to 131 GeV and the right panel only deals with the sensitive region between 123 GeV to 127 GeV.
- Higgs boson masses in the mass range 115-123 GeV allow neutralino masses to lie below 100 GeV. For a Higgs boson mass in the range 123 GeV and higher, most of the allowed parameter space indicates a neutralino mass above 100 GeV.
- Quite remarkably much of the parameter space for the Higgs boson mass in the range 123- 127 can be probed by current and the next generation direct detection experiments such a XENON-1T and SuperCDMS.

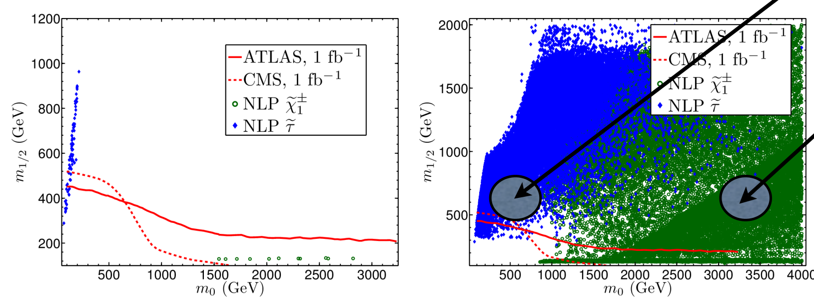
Enhancement of proton lifetime on a Focal Surface

$$\tau(p \to \bar{\nu} K^+) \propto (m_{\tilde{q}}^2 / m_{\chi^\pm})^2 (1/\tan\beta)^2$$

High m_0: $m_{\tilde{q}} = 3500$ GeV, $m_{\chi^\pm} = 600$ GeV
Low m_0: $m_{\tilde{q}} = 500$ GeV, $m_{\chi^\pm} = 600$ GeV

$$\tau(p \to \bar{\nu} K^+)_{\rm high} / \tau(p \to \bar{\nu} K^+)_{\rm low} \sim O(10^3).$$

Focal Point (HB/FP) Focal Surface (HB/FS)



SUSY here ? or here ?

LHC will decide.

Akula, Liu, PN, Peim, arXiv:1111.4589 [hep-ph]

Cosmic coincidence

One of the very interesting cosmic co-incidences is

$$\frac{\Omega_{DM}}{\Omega_B} = 4.99 \pm 0.20.$$

The above appears to indicate that the two are somehow related. One proposal is that dark matter is created by transfer of a net $B - L$ created in the early universe to the dark matter sector. This is the so called asymmetric dark matter (AsyDM)[5] .There are two main issues to address.

1. $B - L$ transfer.
2. Dissipation of thermal dark matter.

- Regarding the first item, a transfer of $B - L$ can occur via interactions of the type

$$\frac{1}{M_a^n} O_{DM} O_{asy}^{SM}$$

This interaction operates when

$$T_{int} > (M_a^{2n} M_{Pl}^{-1})^{\frac{1}{2n-1}}, \; M_{Pl} = 2.4 \times 10^{18} \text{ GeV}$$

- Regarding the second item, one needs to demonstrate in a quantitative fashion that the symmetric dark matter is efficiently annihilated.

[5] Nussinov; Kaplan, Luty, Zurek; Yanagida, Buckley, Profumo, $\cdots$; Review: Davoudiasl, Mohapatra (2012)

Generation of AsyDM

The early universe can be viewed as a weakly interacting plasma in which each particle carries a chemical potential μ_i. In such a plasma the particle-anti-particle asymmetries are given by

$$n_i - \bar{n}_i \simeq \frac{g_i \beta T^3}{6}(\mu_i(\mathrm{fermi}), 2\mu_i(\mathrm{bose})).$$

where g_i is the degrees of freedom, and $\beta = 1/T$. The chemical potentials are constrained by

- Sphaleron interactions
- Conservation of charge and hypercharge
- Yukawa and gauge interactions.

When the transfer interaction is in equilibrium, one can solve for the ratio Ω_{DM}/Ω_B

$$\frac{\Omega_{DM}}{\Omega_B} = \frac{X}{B}\frac{m_{DM}}{m_B} \simeq 5$$

where X is the dark matter number density and B is the baryon number density.

Variety of Models

Feng, PN, Peim arXiv:1204.5752 [hep-ph] (PRD to appear)

Model A	SM	$T_{\rm int} > T_{\rm EWPT}$
Model B		$T_{\rm EWPT} > T_{\rm int} > M_t$
Model C		$M_t > T_{\rm int} > M_W$
Model D	2HD	$T_{\rm int} > T_{\rm EWPT}$
Model E	MSSM	$T_{\rm int} > M_{\rm SUSY}$
Model F		$M_1 > T_{\rm int} > M_2 > T_{\rm EWPT}$

- Models A, B, C are anchored in the standard model, Model D in the two Higgs doublet model and Models E and F in MSSM.
- For each model there are various interactions that allow a transfer of the $B-L$ asymmetry from the standard model sector to the dark matter sector.

$\frac{1}{M^n} X^k \mathcal{O}^{\rm SM}_{\rm asy}$	Model	DM Mass	Model	DM Mass	Model	DM Mass	Model	DM Mass
$\frac{1}{M^3}\psi^3 LH$	A_1	11.11 GeV	B_1	15.60 GeV	C_1	15.52 GeV	D_1	11.86 GeV
$\frac{1}{M^4}\psi^2 (LH)^2$	A_2	5.55 GeV	B_2	7.80 GeV	C_2	7.76 GeV	D_2	5.93 GeV
$\frac{1}{M^3}\phi^2 (LH)^2$	A_3	2.78 GeV	B_3	3.90 GeV	C_3	3.88 GeV	D_3	2.96 GeV
$\frac{1}{M^5}\psi^3 LLe^c$	A_4	11.11 GeV	B_4	15.60 GeV	C_4	15.52 GeV	D_4	11.86 GeV
$\frac{1}{M^5}\psi^3 Lqd^c$	A_5	11.11 GeV	B_5	15.60 GeV	C_5	15.52 GeV	D_5	11.86 GeV
$\frac{1}{M^5}\psi^3 u^c d^c d^c$	A_6	11.11 GeV	B_6	15.60 GeV	C_6	15.52 GeV	D_6	11.86 GeV

AsyDM in a Stueckelberg Extension

Feng, PN, Peim arXiv:1204.5752 [hep-ph]

Relic density in AsyDM

$$\Omega_{\rm DM} = \Omega_{\rm DM}^{\rm asy} + \Omega_{\rm DM}^{\rm sym}\,, \quad \Omega_{\rm DM}^{\rm sym} << \Omega_{\rm DM}^{\rm asy}.$$

- Thus we need an efficient mechanism for the annihilation of dark matter that is produced thermally. We accomplish this via the exchange of a gauge field using the Stueckelberg formalism [6] where the gauge field couples to $L_\mu - L_\tau$.
- In the unitary gauge the massive vector boson field will be called Z' and its interaction with fermions is given by

$$L_{\rm int} = Q^\psi g_C \bar\psi \gamma^\mu \psi Z'_\mu + Q^f g_C \bar f \gamma^\mu f Z'_\mu\,, \ f = \mu, \tau.$$

where f runs over μ and τ families and $Q_C^\mu = -Q_C^\tau$.

- The LEP constraints on the $M_{Z'}$ mass are not valid since Z' does not couple with the first generation leptons. The strongest constraint comes from $g_\mu - 2$.

$$\Delta(g_\mu - 2) = (\frac{1}{2} g_C Q_C^\mu)^2 \frac{m_\mu^2}{6\pi^2 M_{Z'}^2}.$$

Imposing the constraints $\Delta a_\mu = \Delta(g_\mu - 2)/2 \leq 3 \times 10^{-9}$ one finds the restriction

$$M_{Z'}/(g_C Q_C^\mu) \geq 90 {\rm GeV}$$

The above constraint allows for a low lying Z' which couples only to muons and taus and allows for a rapid annihilation of symmetric dark matter via the Z' pole.

[6] Kors, PN (2004); Feldman, PN, Peim (2010).

Stueckelberg from couplings to a 2 -form

$$L_0 = -\frac{1}{12} H_{\mu\nu\rho} H^{\mu\nu\rho} - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{1}{4} m \epsilon^{\mu\nu\rho\sigma} F_{\mu\nu} B_{\rho\sigma}$$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu, \; H_{\mu\nu\rho} = \partial_\mu B_{\nu\rho} + \partial_\nu B_{\rho\mu} + \partial_\rho B_{\mu\nu}$$

Write L in an alternative form

$$L_1 = -\frac{1}{12} H_{\mu\nu\rho} H^{\mu\nu\rho} - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{m}{6} \epsilon^{\mu\nu\rho\sigma} (H_{\mu\nu\rho} A_\sigma + \sigma \partial_\mu H_{\nu\rho\sigma})$$

You can recover L_0 by integrating over σ which gives

$$d^* H = 0$$

and inserting back in L_1 gives L_0. Instead suppose we solve for H

$$H^{\mu\nu\rho} = -m \epsilon^{\mu\nu\rho\sigma} (A_\sigma + \partial_\sigma \sigma)$$

Insertion back in L_1 gives

$$L_2 = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{2} m^2 (A_\sigma + \partial_\sigma \sigma)^2$$

Boltzmann Equations with asymmetry

Feng, PN, Peim arXiv:1204.5752 [hep-ph]

To obtain relic densities at current temperatures for ψ and $\bar{\psi}$ one must solve the Boltzman equations in the presence of asymmetries. The Boltzmann equations obeyed by f_ψ and $f_{\bar{\psi}}$ take the form

$$\frac{df_\psi}{dx} = \alpha\langle\sigma v\rangle(f_\psi f_{\bar{\psi}} - f_\psi^{\rm eq} f_{\bar{\psi}}^{\rm eq})\,,$$

$$\frac{df_{\bar{\psi}}}{dx} = \alpha\langle\sigma v\rangle(f_\psi f_{\bar{\psi}} - f_\psi^{\rm eq} f_{\bar{\psi}}^{\rm eq})\,,$$

where $x = k_B T/m_\psi$ and $f_\psi = \frac{n_\psi}{hT^3}$, $\;f_{\bar{\psi}} = \frac{n_{\bar{\psi}}}{hT^3}$. One finds that

$$\gamma = f_\psi - f_{\bar{\psi}},$$

is a constant independent of temperature. The relic densities for ψ and $\bar{\psi}$ are then given by

$$\frac{\Omega_\psi h_0^2}{(\Omega_\psi h_0^2)_{\xi=0}} \simeq \frac{J(x_f)}{\left(\frac{1}{\xi} - \frac{1}{\xi} e^{-\xi J(x_f)}\right)} \quad \to 1 \quad (\text{as } \xi \to 0)$$

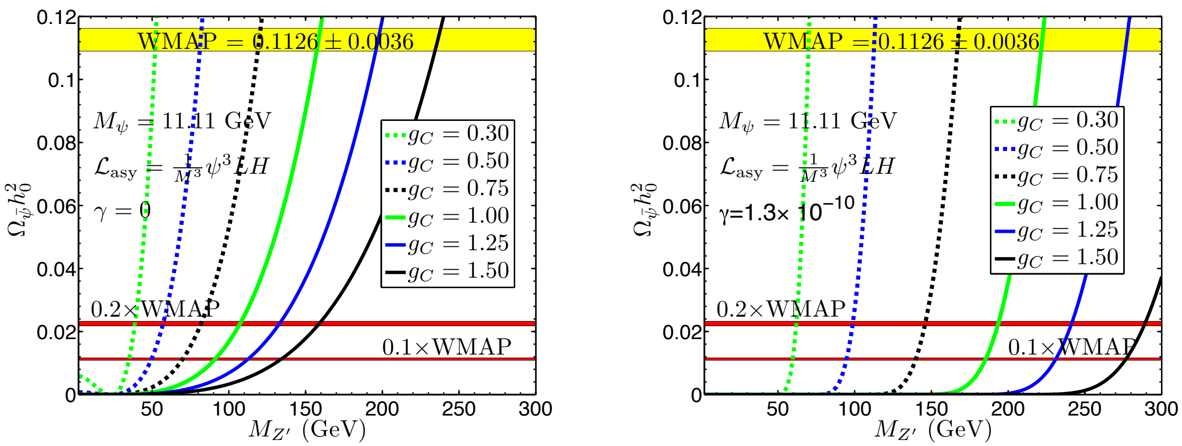
where $\xi = \gamma C$ where C is a numerical constant and $J(x_f) \equiv \int_{x_0}^{x_f} \langle\sigma v\rangle\, dx$, and

$$\frac{\Omega_{\bar{\psi}} h_0^2}{\Omega_\psi h_0^2} \simeq e^{-\xi J(x_f)} \quad \to 1 \quad (\text{as } \xi \to 0)$$

We need to show that $\Omega_{\bar{\psi}} h_0^2 << (\Omega h_0^2)_{\rm WMAP}$ and that $\Omega_\psi h_0^2$ is the major component of WMAP value.

Annihilation of symmetric dark matter.

Feng, PN, Peim arXiv:1204.5752 [hep-ph]



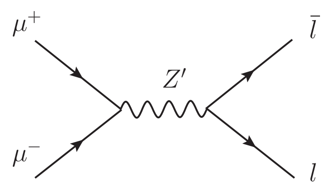
An exhibition of the thermal relic density of $\bar{\psi}$ as a function of mass of Z' for different couplings. Analysis shows that the symmetric dark matter can be efficiently annihilated. Also the effect of asymmetry on the relic density is seen to be large.

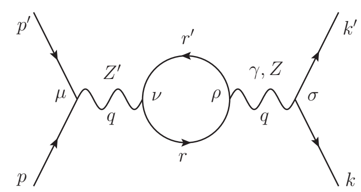
- Majorana masses for dark matter are not allowed by gauge invariance. Thus $\psi - \bar{\psi}$ oscillations are not allowed which could washout out the asymmetric dark matter.

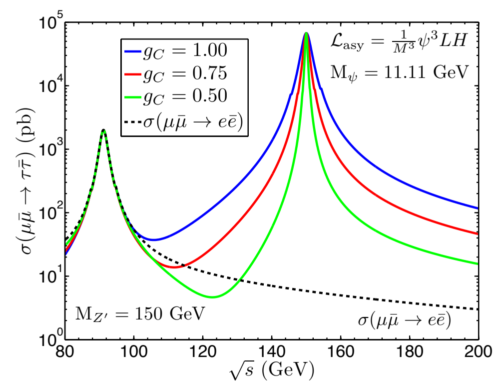
Signatures at a Muon Collider

Feng, PN, Peim arXiv:1204.5752 [hep-ph]

In a muon collider there would be final states with muons and taus and their neutrinos but no e^+e^- final states providing a smoking gun signature for the model. The analysis is done including one loop corrections arising from the first and second generation leptons in the loop.







Asymmetric dark matter (AsyDM) in SUSY.

Feng, PN, Peim arXiv:1204.5752 [hep-ph]

One can carry out a direct extension of AsyDM to the supersymmetric case. The basic interaction responsible for the asymmetry has the form

$$W_{\rm asy} = \frac{1}{M_a^n} O_{DM} O_{\rm asy}^{\rm mssm} \ .$$

- In general there are many possibilities for the operators $O_{\rm asy}^{\rm mssm}$ such as

$$LH_2, LLE^C, QLD^C, U^C D^C D^C$$

  or any products thereof. Obviously $O_{\rm DM}$ will carry the opposite quantum numbers to those of $O_{\rm asy}^{\rm mssm}$.

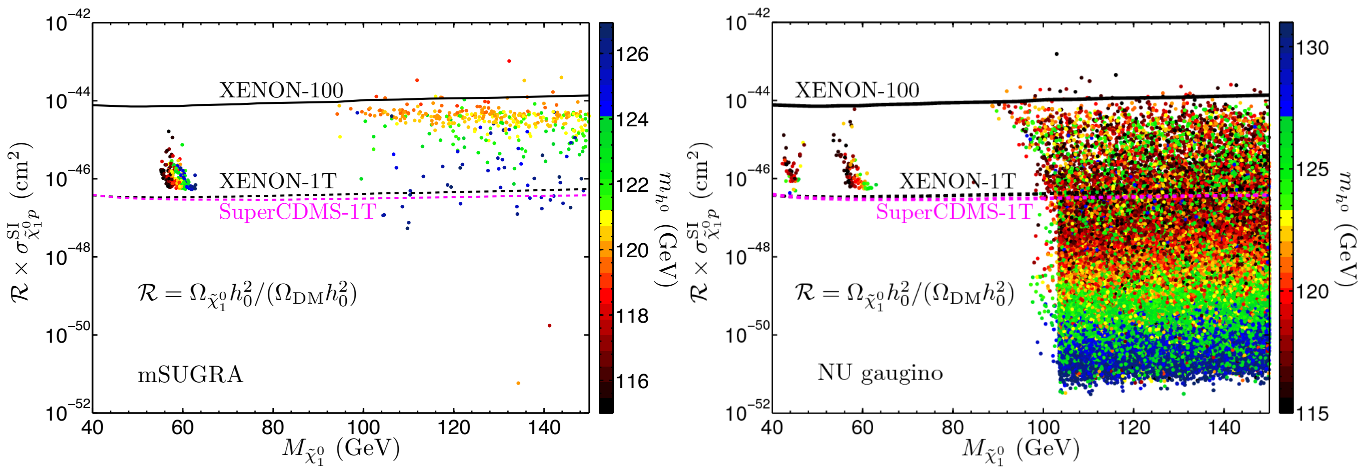
- In this case there two dark matter particles, i.e., ψ and $\tilde{\chi}^0$ and there the total relic density is

$$\Omega_{\rm DM} = \Omega_{\rm DM}^{\rm asy} + \Omega_{\rm DM}^{\rm sym} + \Omega_{\tilde{\chi}^0} \ ,$$

  where $\Omega_{\tilde{\chi}^0}$ is the relic density from the neutralino. One must show that the neutralino contribution is subdominant, i.e., it is no more than 10% of the WMAP value. An interesting question is if a subdominant neutralino is detectable. This appears to be the case.

Subdominant neutralino is detectable

Feng, PN, Peim arXiv:1204.5752 [hep-ph]



R Parity

- Within MSSM R parity is ad hoc.
- R parity as a global symmetry is not desirable since it can be broken by wormhole effects (G. Gilbert (1989)).

  This problem can be evaded if MSSM is embedded in a larger gauge symmetry so that R parity arises as a discrete remnant of a local gauge symmetry (Krauss, Wilczek (1989)).
- Since $R = (-1)^{2S+3(B-L)}$ the obvious extended symmetry is

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

  In this case the $U(1)_{B-L}$ gauge symmetry will forbid R parity violating interactions such as $u^c d^c d^c, L\bar{H}, QLd^c, LLe^c$.
- Of course $U(1)_{B-L}$ cannot be an unbroken gauge symmetry because it would have a massless gauge boson associated with it which will produce additional long range forces which are undesirable.

Breaking the $B-L$ gauge symmetry

- While R parity is guaranteed as long as an unbroken $B-L$ gauge symmetry exists, this is not necessarily the case when the $B-L$ gauge symmetry is spontaneously broken. In this case there are two possibilities
  1. 3(B-L)= even integer, R parity is preserved.
  2. 3(B-L)=odd integer, R parity is not preserved.
- Example: Consider an extension of MSSM with a $U(1)_{B-L}$ symmetry. Here for anomaly cancellation one needs three right handed neutrino fields ν^c. The extended superpotential in this case is

$$\mathcal{W} = \mathcal{W}_{\rm MSSM} \; + \; h_\nu \; L H_u \nu^c + h_{\nu^c} \nu^c \nu^c \Phi + \mu_\Phi \Phi \bar{\Phi}$$

  The $B-L$ quantum numbers of the new fields are $(\nu^c, \Phi, \bar{\Phi}) : (1, -2, 2)$.
- A VEV growth for $\tilde{\nu}^c$ will break R parity, but a VEV growth for Φ won't. However, the beta functions due to the coupling of the Φ and ν^c can turn the mass of $\tilde{\nu}^c$ tachyonic which leads to a VEV growth for $\tilde{\nu}^c$ and a violation of R parity.
  Aulakh and Mohapatra (1982); Masiero, Valle (1990), Khalil, Masiero (2008); Barger, Fileviez Perez, Spinnor (2009).

Stueckelberg Mass Growth and R Parity

Feldman, Fileviez Perez, PN, JHEP **1201**, 038 (2012)

- If one assumes that the $B-L$ gauge boson develops a mass via the Stueckelberg mechanism, and assumes charge conservation, i.e., $\langle\tilde{q}\rangle = 0,\ \langle\tilde{e}_L\rangle = 0 = \langle\tilde{e}^c\rangle$, then one also has $<\tilde{\nu}_L>= 0$ since the RG evolution of $M_{\tilde{e}_L}$ and of $M_{\tilde{\nu}_L}$ are very similar.
- Integration on residual Stueckelberg fields gives

$$V_{\tilde{\nu}^c} = M^2_{\tilde{\nu}^c}\tilde{\nu}^{c\dagger}\tilde{\nu}^c + \frac{g^2_{BL}M^2_\rho}{2(M^2_{BL}+M^2_\rho)}(\tilde{\nu}^{c\dagger}\tilde{\nu}^c)^2.$$

Now in RG analysis there are no beta functions to turn $M^2_{\tilde{\nu}^c}$ negative. Consequently the potential cannot support spontaneous breaking to generate a VEV of $\tilde{\nu}^c$ and

$$\langle\tilde{\nu}^c\rangle = 0$$

Thus with the Stueckelberg mechanism $B-L$ gauge boson gains a mass but R parity remains unbroken.

Conclusion

- A GUT group embedded in supergravity (SUGRA GUT) allows one to make contact between GUT physics and low energy physics.
- One of the predictions of SUGRA GUT is regarding the Higgs boson mass. It has been known for some time that the SUGRA GUT model predict the Higgs boson mass to be below around 130 GeV with m_0 in the several TeV region. The recent experimental data gives a hint of the Higgs boson mass of around 125 GeV. If this data is confirmed it would provide support for the Sugra GUT model.
- More LHC data expected in the coming months will provide further tests of SUGRA GUTs from the possible observation of sparticles. Here we expect some light third generation sfermion, a light chargino or a gluino. Thus LHC is an important laboratory for test of both SUSY and GUTS.
- Another front line issue is cosmic co-incidence and how it may interface with SUGRA GUT. We have explored a possible approach here within a two component dark matter picture. The asymmetric dark matter we propose does not oscillate and would not washout due to oscillations.

Extra Slides

A gauged $B - L$ model

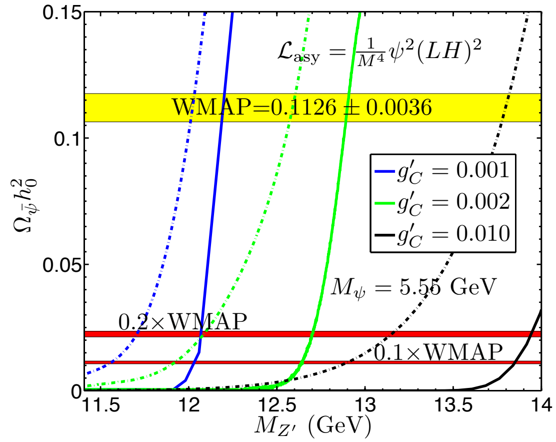
- Here we need right-handed neutrinos to gauge $B - L$. The dark matter mass in this case is 6.06 GeV.
- The $B - L$ transfer interaction

$$\mathcal{L}_{\rm asy} = \frac{1}{M^4}\psi^2 \left(LH\right)^2$$

  above the EWPT scale.
- There are more experimental constraints to consider which include collider (i.e., LEP, Tevatron, LHC) constraints as well as precision constraints (i.e., the measurements of the ρ parameter, the Υ width). Specifically the LEP constraint gives

$$M_{Z'}/g'_C \gtrsim 6 \ \ {\rm TeV}$$

  for heavy gauge bosons. A stricter bound within a specific framework is $M_{Z'} \geq 10$ TeV (JE Kim, S Shin, 2012). For lighter gauge bosons, as is needed in the AsyDM case , the UA2 cross section bound is more stringent. Our analysis here is consistent with these constraints.
- Now, as in the $L_\mu - L_\tau$ case, the thermal symmetric contribution to the relic density from AsyDM must still be consistent with WMAP, i.e. it must be depleted to below 10% of the WMAP-7 value.



A display of the thermal relic density of ψ as a function of $M_{Z'}$ for the model with a gauged $B - L$ for different couplings with $\gamma = 0$ (dashed line) and $\gamma = \gamma_0 = 1.3 \times 10^{-10}$ (solid line).

It is seen that resonant annihilation of thermal dark matter via the Z' pole allows the relic density of this component to be reduced to below 10% of the WMAP result for values of Z' around twice the mass of the dark particle.