Dark Matter and Gauge Coupling Unification in the Light of PAMELA and Fermi-LAT

Jiashu Lu
In cooperation with Chun Liu

ITP,CAS

Deceember 21, 2011

SKLTP

Motivation

- Gauge coupling unification
- Higgs identified as the fourth generation
- WIMP miracle
- Indirect DM detection

Gauge coupling unification

- Gauge coupling constants unify at 10^{16} GeV in MSSM.
- Extending MSSM by adding SU(5) multiplets preserves the unification.
- At 2-loop level of RGE running, after adding one vector-like 5-multiplet of SU(5) at 1 TeV, 10-multiplets can only be added at above 100 TeV or gauge couplings will run to Landau pole before unification.

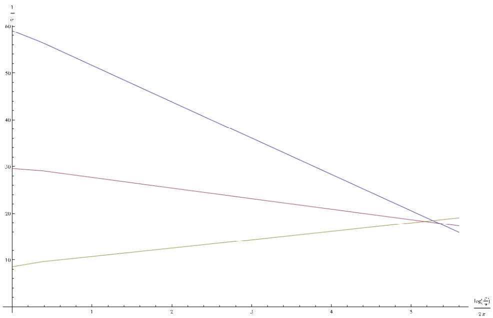

Figure: Add one 5-plet at 1 TeV.

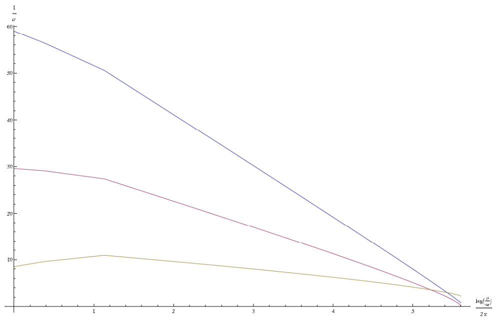

Figure: Add one 5-plet at 1 TeV and one 10-plet at 110 TeV.

Higgs identified as the fourth generation

- H_d has the same gauge quantum numbers as left hand leptons.
- Consider H_d and H_u as the 4th vectorlike generation and extend them to full representations of SU(5).
- As explained above, H_d and H_u can only be extended to $5 \oplus \bar{5}$ at TeV.
- R-Parity should be violated to allow H_d mixing with the first three generations.
- After the extension of Higgs, more particles needed for gauge coupling unification.

SKLTP

WIMP miracle

- Thermal dark matter relic density is
$$\Omega_{DM}h^2 = \frac{8.59\times 10^{-11}x_F}{(g_{*S}/\sqrt{g_*})\langle\sigma v\rangle}\ \mathrm{GeV}^{-2}.$$
- For a TeV scale DM with SM weak interaction, $\langle\sigma v\rangle \sim \frac{\pi\alpha_2^2}{\mathrm{TeV}^2}$, which gives $\Omega_{DM}h^2 \sim 0.1$.
- The simplest particle with SM weak interaction is a weak doublet.

Indirect DM detection

- Positron excess in cosmic rays has been observed by experiments like PAMELA, ATIC and Fermi-LAT.
- The excess can be explained by DM annihilation.
- In the WIMP situation, a new light-particle-mediated interaction is needed for a large boost factor. Dark matter annihilates into the light particle, which decay into leptons.
- If the interaction mediating particle is scalar particle, boost factor will be less than needed.
- If we choose the new interaction to be a gauge one, it can only be U(1).

Model

- Add a new vector-like particle with the same SM quantum number as H_u and H_d to MSSM. One of the neutral parts will become dark matter.
- H_u and H_d are expanded into $\mathbf{5} \oplus \bar{\mathbf{5}}$ of SU(5) to bring back unification.
- Assume baryon number symmetry instead of R-parity.
- New $U(1)_n$ gauge symmetry in dark sector.
- Small mixing between $U(1)_n$ and $U(1)_Y$.
- Other fields to spontaneously break $U(1)_n$.

SKLTP

SM relevant particle content

- $$\begin{pmatrix} L \\ D^c \\ Q \\ U^c \\ E^c \end{pmatrix}_{1,2,3}, \underbrace{\begin{pmatrix} L \\ D^c \end{pmatrix}_4, \begin{pmatrix} H_u \\ D_H^c \end{pmatrix}}_{opposite\ SU(3)\ and\ U(1)}$$
- $\mathcal{W} = \mu_m L_m H_u + \mu_m^D D_m^c D_H^c + \lambda_{mni} L_m L_n E_i^c + \lambda'_{imn} Q_i L_m D_n^c + y_{ij} Q_i H_u U_j^c + \tilde{y}_{ij} E_i^c D_H^c U_j^c$

Redefinition of fields

- H_d field and the 4th down type quark can be redefined as $H_d \equiv \frac{\mu_m}{\mu} L_m$, $D_4^c \equiv \frac{\mu_m^D}{\mu^D} D_m^c$, where $\mu \equiv \sqrt{\sum_{m=1}^4 |\mu_m|^2}$, $\mu^D \equiv \sqrt{\sum_{m=1}^4 |\mu_m^D|^2}$
- The superpotential turns out to be $\mathcal{W} = \mu H_d H_u + \mu^D D_4^c D_H^c + y_{ij}^l L_i H_d E_j^c + y_{ij}^d Q_i H_d D_j^c + y_{ij} Q_i H_u U_j^c + \lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} Q_i L_j D_k^c + \lambda_{ij}^D Q_i L_j D_4^c + y_i^D Q_i H_d D_4^c + \tilde{y}_{ij} E_i^c D_H^c U_j^c$

SKLTP

Electroweak breaking

- Assuming universality of soft masses, SUSY soft breaking terms are
  $-\mathcal{L} \supset M^2 \tilde{L}_m^\dagger \tilde{L}_m + M_h^2 h_u^\dagger h_u + M_E^2 \tilde{E}_i^{c\dagger} \tilde{E}_i^c + M_Q^2 \tilde{Q}_i^\dagger \tilde{Q}_i + M_U^2 \tilde{U}_i^{c\dagger} \tilde{U}_i^c + M_D^2 \tilde{D}_m^{c\dagger} \tilde{D}_m^c + M_{DH}^2 \tilde{D}_H^{c*} \tilde{D}_H^c + (B\mu_m \tilde{L}_m h_u + B^D \mu_m^D \tilde{D}_m^c \tilde{D}_H^c + h.c.)$
- Universality is preserved after redefining H_d and D_4^c :
  $-\mathcal{L} \supset M^2 \tilde{L}_i^\dagger \tilde{L}_i + M^2 h_d^\dagger h_d + M_h^2 h_u^\dagger h_u + M_E^2 \tilde{E}_i^{c\dagger} \tilde{E}_i^c + M_Q^2 \tilde{Q}_i^\dagger \tilde{Q}_i + M_U^2 \tilde{U}_i^{c\dagger} \tilde{U}_i^c + M_D^2 \tilde{D}_m^{c\dagger} \tilde{D}_m^c + M_{DH}^2 \tilde{D}_H^{c*} \tilde{D}_H^c + (B\mu h_d h_u + B^D \mu^D \tilde{D}_4^c \tilde{D}_H^c + h.c.)$
- EWSB happens if
  $(M^2 + \mu^2)(M_h^2 + \mu^2) < |B\mu|^2$ and
  $\left(M_D^2 + \mu^{D2}\right)\left(M_{DH}^2 + \mu^{D2}\right) > |B^D \mu^D|^2$
- The first inequality can be realized like in MSSM. The second one is realized natually if $\mu < \mu^D$.

Dark sector particle content

- $\chi_1, \ \chi_2$: H$_u$-H$_d$-like, U$(1)_n$ charge ± 1
- $\phi_1, \ \phi_2$: SM singlets, U$(1)_n$ charge ± 2
- X: SM and U$(1)_n$ singlet
- $\mathcal{L}_{\rm dark} = (\chi_1^\dagger e^{g_2 V_2 + g_1 V_1 + g_1' V_1'} \chi_1 + \chi_2^\dagger e^{-g_2 V_2 - g_1 V_1 - g_1' V_1'} \chi_2 + \phi_1^\dagger e^{2 g_1' V_1'} \phi_1 + \phi_2^\dagger e^{-2 g_1' V_1'} \phi_2 + X^\dagger X)|_{\theta\theta\bar\theta\bar\theta} + (\mu' \chi_1 \chi_2|_{\theta\theta} + cX(\phi_1\phi_2 - \mu''^2)|_{\theta\theta} + h.c.)$
- Mixing between U$(1)_n$ and U$(1)_Y$: $\mathcal{L}_{\rm mixing} = \epsilon F_n^{\mu\nu} F_{Y\mu\nu}, \quad \epsilon \sim 10^{-3} - 10^{-4}$

SKLTP

$U(1)_n$ breaking

- Soft terms of dark sector are $\mathcal{L}_{\text{dark,soft}} = -\frac{1}{2} m_1' \lambda^{1\prime} \lambda^{1\prime} + m^2_{\tilde{\chi}_1} \tilde{\chi}_1^* \tilde{\chi}_1 + m^2_{\tilde{\chi}_2} \tilde{\chi}_2^* \tilde{\chi}_2 + m^2_\phi (\phi_1^* \phi_1 + \phi_2^* \phi_2) + m_x^2 x^* x + (B' \mu') \tilde{\chi}_1 \tilde{\chi}_2 + h.c.)$
- $m_{\tilde{\chi}_{1,2}}$ and m_x are assumed to be large enough.
- $V_{\text{dark}} = 4 g_1'^2 (\langle \phi_1 \rangle^2 - \langle \phi_2 \rangle^2)^2 + c^2 |\langle \phi_1 \rangle \langle \phi_2 \rangle - \mu''^2|^2 + m_\phi^2 (\langle \phi_1 \rangle^2 + \langle \phi_2 \rangle^2)$
- $\langle \phi_1 \rangle = \langle \phi_2 \rangle = \langle \phi \rangle = (\mu''^2 - \frac{m_\phi^2}{c})^{1/2}$
- Fine tuning of parameters is needed here to get $\langle \phi \rangle \sim 1$ GeV
- The boson $\phi_{light} \approx \frac{\phi_1 + \phi_2}{\sqrt{2}}$ has mass $\sim$ GeV.
- The boson $\phi_{heavy} \approx \frac{\phi_1 - \phi_2}{\sqrt{2}}$ has mass $\sim$ m_ϕ .

SKLTP

Mass splitting of χ_1 and χ_2

- Originally χ_1 and χ_2 have Dirac mass term $-\mu'\chi_1\chi_2$, where $\mu' \sim 1$ TeV
- High dimensional operators can be involved:
$$\mathcal{L}^{\text{dim.5}} = \frac{a_1}{\Lambda}(\chi_1 H_u)(\chi_2 H_d)|_{\theta\theta} + \frac{a_2}{\Lambda}(\chi_1 H_d)(\chi_2 H_u)|_{\theta\theta} + h.c.$$
$$\mathcal{L}^{\text{dim.6}} = \frac{a_4}{\Lambda^2}\phi_2(\chi_1 H_u)(\chi_1 H_u)|_{\theta\theta} + \frac{a_5}{\Lambda^2}\phi_1(\chi_2 H_d)(\chi_2 H_d)|_{\theta\theta} + h.c.$$
- After EWSB breaking, charged and neutral parts are splitted by $\Delta M = (a_1 + a_2)\frac{v^2 \sin 2\beta}{4\Lambda}$
- After U(1)$_n$ breaking, two neutral particles are further splitted by $\Delta m = (\frac{v}{\Lambda})^2\langle\phi\rangle(a_4 \sin^2\beta + a_5 \cos^2\beta)$
- $\Lambda \sim 10 - 100$ TeV, $\Delta M \sim 0.1 - 1$ GeV, $\Delta m \sim 10 - 1000$ keV

SKLTP

Mass eigenstates and their couplings

- χ_1^- and χ_2^+ form a Dirac particle.
- $\chi_d' \approx (\chi_1^0 + \chi_2^0)/\sqrt{2}$
- $\chi_d \approx i(\chi_1^0 - \chi_2^0)/\sqrt{2}$
- $m_{\chi_d'} > m_{\chi_d}$
- The four components of χ_1 and χ_2 only have gauge interactions.
- χ_d couples to Z and dark photon through χ_d'.

SKLTP

Remain Z_2 symmetry and dark matter

- After $U(1)_n$ breaking, a Z_2 symmetry remains, under which χ_1 and χ_2 are odd, other particles are even.
- χ_d is the lightest particle in χ_1 and χ_2, so it is dark matter.
- Dark matter couples to gauge bosons inelastically, which can limit or prevent tree level scattering with nuclei at low energy.

SKLTP

Coannihilation and relic density

- The four particles in χ_1 and χ_2 are near-degenerated, so coannihilation should be considered at freezing out time.
- $\frac{n^2}{2}\langle\sigma v\rangle_{total} = (\frac{n}{4})^2(\frac{1}{2}\sum_{i=1}^{4}\langle\sigma v\rangle_{ii} + \sum_{1\le i<j\le 4}\langle\sigma v\rangle_{ij})$
- Define $\sigma_0 = \frac{\pi\alpha_2^2}{\mu'^2}$ and $R = \frac{\alpha_1'}{\alpha_2}$, we have
  $\langle\sigma v\rangle_{\chi_d\chi_d} = \langle\sigma v\rangle_{\chi_d'\chi_d'} = (0.3365 + 0.6504R + 2R^2)\sigma_0$
  $\langle\sigma v\rangle_{\chi_-\chi_+} = (0.2125 + 0.1880R + 2R^2)\sigma_0$
  $\langle\sigma v\rangle_{\chi_d\chi_d'} = 0.007640$
  $\langle\sigma v\rangle_{\chi_d\chi_-} = \langle\sigma v\rangle_{\chi_d\chi_+} = \langle\sigma v\rangle_{\chi_d'\chi_-} = \langle\sigma v\rangle_{\chi_d'\chi_+} = (0.02432 + 0.5R)\sigma_0$.
- So $\langle\sigma v\rangle_{total} = (0.08174 + 0.3548R + 0.5R^2)\sigma_0$.
- For $\alpha_1' = \alpha_2$, relic density requires $\mu' = 1.2$ TeV.

SKLTP

Sommerfeld enhancemet factor

- $\langle\sigma v\rangle_{\chi_d\chi_d}/\langle\sigma v\rangle_{total}\sim 3$. Dark photons take up 78% of the annihilation results, the rest are W and Z bosons.
- The dark photon can always decay into e^+e^-, which hardens the e^+e^- spectrum. Lower the dark photon mass can further lower the needed boost factor.
- As a result, the needed boost factor will be $\sim$ 100. (As stated by D. P. Finkbeiner, L. Goodenough, T. R. Slatyer, M. Vogelsberger and N. Weiner, JCAP 1105 (2011), 002)
- Sommerfeld enhancemet factor can be estimated as S$=\frac{\pi\alpha_1'}{v}$. For $\alpha_1'=\alpha_2$, S $\sim$ 100.

Direct detection

- Xenon100 limits the DM-nucleon cross section to be less than 10^{-43} cm^2 for TeV DM.
- χ_d couples to W and Z bosons, so the cross section of it scattering with nucleons is natually large.
- The mass splitting of χ_d and χ'_d should be larger than the kinetic energy in the χ_d-Xe CM frame.
- For highest DM speed of 600 km/s, $\Delta m = 220$ keV is enough to prevent the tree level scattering.
- At 1-loop level, χ_d-nucleon cross section is about 10^{-47} cm^2.(J. Hisano, K. Ishiwata, N. Nagata and T. Takesako, JHEP 1107:005,2011)

Summary

- A pair of new H$_u$-H$_d$-like particles are added to MSSM at 1.2 TeV, in which the lightest neutral component is dark matter.
- Original H$_u$ and H$_d$ are extended into $\mathbf{5} \oplus \bar{\mathbf{5}}$ representation of SU(5) so that gauge coupling unification is preserved.
- A new U(1)$_n$ gauge symmetry is added in the dark sector. The "dark photon" gets $\sim$ GeV mass after U(1)$_n$ breaking.
- Annihilation of dark matter can get $\sim$ 100 Sommerfeld enhancement by exchanging the dark photon. The boost factor needed for explaining PAMELA and Fermi-LAT is also $\sim$ 100.
- DM-nuclei scattering at tree level are prevented by the big gap between χ_d and χ_d' to be in agree with Xenon100's negative result.

Thanks

Thanks