Non-abelian Dark Sectors
and
Their Collider Signatures

Lian-Tao Wang
Princeton University
Outline

• Basic model ingredients. Neal Weiner’s talk.

• Some possible models
  – SUSY with kinetic mixing mediation
    For details: I. Yavin’s talk, later in this workshop

• Collider signals with lepton jets:
  Tevatron and LHC.
  – Non-SUSY: production w/ kin mixing.
  – SUSY: modified decay chains.

• Conclusions.
Recent experimental observations

- Evidences for 100s GeV – TeV WIMP
  - HEAT ’97 and ’04, AMS-01 ’07
  - PAMELA ’08, ATIC ’08
  - WMAP haze, Finkbeiner ’99.
  - EGRET ’05.

- Possible evidence for a much smaller mass scale(?)
  - INTEGRAL ’06, $m \approx 1$ MeV
  - DAMA/LIBRA 08, inelastic DM $\delta m \approx 100$ keV

Smith and Weiner, 2001 and 2005
• Many model considerations.
  – See the program of this workshop.
• We will focus a recent proposed scenario with a non-abelien sector at GeV scale.
• We will explore the models and the collider phenomenology of this scenario.
• We will not fit detailed parameters and spectrum to observations.
  – A non-abelian dark sector is interesting in its own right.
  – General features of phenomenology independent of details of parameter choices.
Basic model ingredient: dark sector

Dark sector: non-abelian gauge symmetry.
Gauge symmetry breaking at 1 GeV.
Dark Matter: non-trivial multiplets under $G_{\text{dark}}$. 
Basic mode ingredients: kinetic mixing

$\mathcal{L}_{\text{gauge}} = -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} b_{\mu\nu} b^{\mu\nu} + \frac{\epsilon}{2} B_{\mu\nu} b^{\mu\nu}$

$\epsilon = -\frac{g_Y g_y}{16\pi^2} \sum_i Q_i q_i \log \left( \frac{M_i^2}{\mu^2} \right)$  \hspace{1cm} \epsilon \sim 10^{-4} - 10^{-3}$

Kinetic mixing: dark $U(1)$ and SM hypercharge.

> A "window" into the dark sector.

Other variations possible. We will focus on this here.
eXciting DM (XDM) and inelastic DM (iDM)

Finkbeiner and Weiner, astro-ph/0702587

Need at least 3 states, and proper mass splittings between them.

Chang, Kribs, Tucker-Smith and Weiner arXiv:0807.2250
Mass splitting, MeV and 100 keV.

- From radiative correction.
  - Members of the dark matter multiplet are split from gauge boson loops after gauge symmetry breaking.
    \[ \Delta m \approx \alpha \Lambda_{\text{dark}} \]  
    Thomas and Wells, hep-ph/9804359
  - Right size for \( \Lambda_{\text{dark}} \approx \text{GeV} \)
  - Detail: choose coupling and charge to get the right splitting.

- From higher dimensional operator involving dark sector and dark matter fields, suppressed by \( \sim \text{TeV} \).
  \[ \delta m \sim \Lambda_{\text{dark}}^2 / M_X \sim \text{MeV} \]
  - For details: I. Yavin’s talk and our paper.
Dark sector symmetry breaking at GeV.

- Break all symmetries. No "charge" conservation.
- Must have the proper couplings between proper states..
We choose to study the minimal case:

- Dark gauge group: $SU(2)_{\text{dark}} \times U(1)_y$
- Dark matter: triplet under $SU(2)_{\text{dark}}$
- Additional symmetry:
  - custodial SU(2). Must break to have proper XDM couplings.
We considered several possible Higgs sectors.

- Need extended Higgs sector to break all the symmetries.
- Charge breaking
  - 1 Higgs doublet cannot work. 2HD with misalignment.
- Custodial SU(2) breaking.
  - Radiatively from $U(1)_y$
  - With triplets.
- Extension to SUSY requires more Higgses.
  - Must be complex.
  - Anomaly cancellation.
Fermion mass splitting

Ratio of XDM and iDM mass splittings, in a 2 doublet 1 triplet model.

We show proper couplings can also be obtained. Several examples are given in our paper.
Dark sector GeV scale generation

- Supersymmetry is probably most elegant way of GeV scale generation.

\[
\Lambda_{\text{dark}} \sim \text{GeV} \\
\begin{align*}
\bar{b}, \tilde{b}, \tilde{z}, \tilde{h}_1, \tilde{h}_2, \ldots \\
& b_{\mu}, z_{\mu}, w_{\mu}, h_1, h_2, \ldots
\end{align*}
\]
Supersymmetric dark sector models.

- ``Plank slop''.
  - High scale GMSB and gravity mediation for DS.
- GMSB, dark matter as messenger.
  - Could be consistent with unification if dark matter is $\mathbf{5} + \bar{\mathbf{5}}$
    
    These two options are in the original proposal.

- Kinetic mixing mediation. Our new proposal.
  - A little more detail here. (I. Yavin’s talk.)

We presented examples of both non-SUSY and SUSY models.
Kinetic mixing mediation.

\[ \mathcal{L}_{\text{gauge}} = \frac{1}{4} \int d^2 \theta \left( W_Y W_Y + W_y W_y - 2 \epsilon W_Y W_y + \text{h.c.} \right) \]

\[ V_{\text{gauge}} = \frac{1}{2} D_Y^2 + \frac{1}{2} D_y^2 - \epsilon D_Y D_y + g_Y D_Y \sum_i Q_i |H_i|^2 + g_y D_y \sum_i q_i |h_i|^2 \]

After integrating out the MSSM Higgs:

\[ V_{\text{gauge}} \supset \epsilon D_y \langle D_Y \rangle = \xi D_y \]
\[ \xi = \epsilon \langle D_Y \rangle = \epsilon \frac{g_Y}{2} \cos 2\beta v^2 \]

Effective FI term.
Kinetic mixing mediation

- Effective FI term, “mass” term for dark Higgses.

\[ \xi = \epsilon \langle D_Y \rangle = \epsilon \frac{g_Y}{2} \cos 2\beta v^2 \]

- The natural size of kinetic mixing.
  
  - If theory embedding in GUT, O(1) mixing forbidden.
  
  - Only induced after GUT breaking by loops.

\[ \epsilon \sim - \frac{g_Y g_\mu}{16\pi^2} \log \left( \frac{M_Y^2}{M^2} \right) \quad \epsilon \sim 10^{-3} - 10^{-4} \]

- Therefore, FI term \( \approx \sqrt{\epsilon} g_Y v_{EW} \approx \text{GeV} \)

  - generate the scale of the order of GeV.
  
  - This is the leading \( \propto \sqrt{\epsilon} \) contribution to DS from kin. Mixing.
Two directions in kinetic mixing mediation.

• Vanishing superpotential. SUSY preserving.
  – Light goldstones, higgsinos
• Superpotential determines the dynamics
  – SUSY breaking by D-term
  – Light gauginos
• Best model probably somewhere in between.
Colliders will play a crucial role in identifying the dark matter.

• "conventional" WIMP signal.
  – Couples to MSSM directly, no other interactions.
  – Missing energy.
• Signal of new dark interactions (dark sector).
  – Suppressed interaction with SM.
  – Rich pheno, "window" to the dark sector
Collider pheno of GeV non-abelian dark sector

- Crucial gateway: kinetic mixing
  - Lepton jets
- Non-abelian:
  - More interesting lepton jets
- Supersymmetry:
  - Change the end of decay chain.
Kinetic mixing: couplings.  B. Holdom, 1986

\[ L_{\text{gauge mix}} = -\frac{1}{4} W_{3\mu \nu} W_{3\mu \nu} - \frac{1}{4} B_{\mu \nu} B^{\mu \nu} - \frac{1}{4} b_{\mu \nu} b^{\mu \nu} + \frac{e}{2} B_{\mu \nu} b^{\mu \nu} \]

\[ = -\frac{1}{4} Z_{\mu \nu} Z^{\mu \nu} - \frac{1}{4} F_{\mu \nu} F^{\mu \nu} - \frac{1}{4} b_{\mu \nu} b^{\mu \nu} + \frac{e}{2} (\cos \theta_W F_{\mu \nu} - \sin \theta_W Z_{\mu \nu}) b^{\mu \nu} \]

\[ A_\mu J^\mu_{\text{em}} + Z_\mu J^\mu_Z + b_\mu J^\mu_b + w_\mu J^\mu_w \]

Eliminating kin. Mixing by \[ A_\mu \rightarrow A_\mu + \epsilon \cos \theta_W b_\mu \]

\[ \epsilon b_\mu \left( \cos \theta_W J^\mu_{\text{em}} + \mathcal{O}(m_b^2/m_Z^2) J^\mu_Z \right) \]

SM charged particle charged under dark \( U(1)_y \). Dark sector neutral under SM \( U(1)_{\text{EM}} \).
Dark sector decay cascades

- Lightest dark sector states eventually decay into SM charged particles, leptons.
- Non-abelian: more leptons
  - 2, 4, 6, 8 leptons

\begin{align*}
\gamma' & \rightarrow \ell^+ \ell^- \\
\gamma' & \rightarrow \ell^+ \ell^-
\end{align*}

- With typical dark states $p_T \sim O(10^3) \text{ GeV}$, lepton collimated $\delta \theta \sim m_{\gamma'}/p_T < 0.1$. Lepton jets!

Deccay life time

- 2-body cascade

\[ c \tau_{2-\text{body}} \sim \frac{1}{\alpha \epsilon^2 m_{\gamma'}} = 2.7 \times 10^{-6} \text{ cm} \left( \frac{\text{GeV}}{m_{\gamma'}} \right) \left( \frac{10^{-3}}{\epsilon} \right)^2 \]

- Prompt in general.
- Decay could produce displaced vertex with smaller coupling and somewhat large boost.

- 3 body decay if 2 body is kinematically forbidden.
  - Displaced vertices from different resonances in the cascade.
Missing energy

- 3-body with more phase space suppression.

- If lightest particle is scalar.

\[ e^{-}\gamma\gamma' \quad \text{or} \quad e^{-}\gamma\gamma' \]

\[ c\tau \sim \mathcal{O}(\text{km}) \text{ for } m_{h'} \lesssim \text{GeV}. \]

- Important feature: missing energy is often collimated with the lepton jets.
Prompt-photon-like production

- Effective coupling

\[ \epsilon b_\mu \left( \cos \theta_W J_{em}^\mu + \mathcal{O}(m_b^2/m_Z^2) J_Z^\mu \right) \]

\[ \epsilon_{\text{eff}} = \epsilon e \cos \theta_W f_b \]
Rates

Cuts: $p_T > 10 \text{ GeV}, |\eta|_{\text{lepton jet}} < 2.4$
Triggering

- Consider muon only, no isolation on trigger.
- At least a couple of them have hard $p_T$. 

4-lepton LJ  
8-lepton LJ
Rates with triggering on muon

For example, estimating using CMS numbers.

2 muons with $p_T > 3 \text{ GeV}$ in $|\eta| < 2.4$

1 muon with $p_T > 7 \text{ GeV}$ and $|\eta| < 2.4$

CMS technical design report.
Identifying leptons within lepton jets

- Small opening angle

\[ \Delta \theta \approx \frac{\text{GeV}}{P_T} < 10^{-1} \Rightarrow 10^{-2} \]

- Should fly apart when reaching muon system.
  - For example: 20 GeV muons with 5 GeV difference. About 10 cm apart when reaching muon system at CMS.
  - Opposite sign muons even further away. 40 GeV tracks 0.5m apart.

- More detailed simulation certainly necessary, isolation(?).

- Identifying multiple muons (>2) suppresses most physics backgrounds, heavy flavor, \( J/\psi \), etc.
Kinetic mixing: $Z$ decay

$$L_{\text{gauge mix}} = -\frac{1}{4} W_{3\mu} W_{3}^{\mu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} b_{\mu\nu} b^{\mu\nu} + \frac{\epsilon}{2} B_{\mu\nu} b^{\mu\nu}$$

$$= -\frac{1}{4} Z_{\mu\nu} Z^{\mu\nu} - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{4} b_{\mu\nu} b^{\mu\nu} + \frac{\epsilon}{2} (\cos \theta_W F_{\mu\nu} - \sin \theta_W Z_{\mu\nu}) b^{\mu\nu}$$

$$b_\mu \rightarrow b_\mu - \epsilon \sin \theta_W Z_\mu$$

$$\epsilon Z_\mu \left( -\sin \theta_W J^\mu_b + \mathcal{O}(m^2_b/m^2_Z) J^\mu_w \right)$$

$$b_\mu \rightarrow \bar{\nu} \nu \quad \text{Suppressed by} \quad \left( \frac{m_b}{M_Z} \right)^2$$
Production.

- Useful rate

\[
\text{BR}(Z^0 \rightarrow d_i \bar{d}_i) = \frac{e d_i}{\Gamma_Z} \frac{e^2 g_s^2 y_i^2}{48\pi} \sin^2 \theta_W M_{Z^0},
\]

- Hard lepton jets. Reconstruct Z.

Cut imposed
\[|\eta|_{\text{lepton jet}} < 2.4\]
Dark sector spin measurement.

- Decaying into dark fermion or dark boson

- Need high statistics.
**SUSY cascades: couplings**

- Gaugino kinetic mixing

\[
\mathcal{L}_{\text{gaugino mix}} = -2i\epsilon\lambda_b^\dagger\tilde{\sigma}^\mu\partial_\mu\lambda_{\tilde{B}} + \text{h.c.}
\]

shift it by \(\lambda_{\tilde{b}} \rightarrow \lambda_{\tilde{b}} + \epsilon\lambda_{\tilde{B}}\)

\[
\mathcal{L}_{\text{coupling}} = \epsilon \left( \lambda_{\tilde{B}}\tilde{J}_b + \mathcal{O}(M_b/M_{\tilde{B}})\lambda_{\tilde{b}}\tilde{J}_B \right)
\]

\[
\tilde{J}_b = g_Y \sum_i q_i \tilde{h}_i^\dagger h_i
\]

\[
\tilde{J}_B = g_Y \sum_i Q_i \tilde{H}_i^\dagger H_i
\]

- MSSM Bino to dark sector, coupling order \(\epsilon\).
- MSSM sfermion to dark gaugino couplings are suppressed by an additional factor of \(\mathcal{O}(M_b/M_{\tilde{B}})\).
Supersymmetric cascades: MSSM to DS

- Decay cascades. MSSM → Dark Sector
  - Neutralino LSP, prompt.
    \[ \tau_{\text{LSP} \rightarrow h + \tilde{h}} \sim \left( \alpha_y^{\text{dark}} f_B^2 \epsilon^2 M_{\text{LSP}} \right)^{-1} \]
    \[ = 7 \times 10^{-19} \text{ s} \left( \frac{100 \text{ GeV}}{M_{\text{LSP}}} \right)^2 \left( \frac{0.01}{\alpha_y^{\text{dark}}} \right) \left( \frac{1.0}{f_B} \right)^2 \left( \frac{10^{-3}}{\epsilon} \right)^2 \]
  - Sfermion LSP.
    - 3 body off-shell MSSM gaugino.
      \[ \tau_{f \rightarrow 3\text{-body}} \sim \left[ \alpha_y^{\text{dark}} g_Y^2 \epsilon_f f_B^2 \frac{m_f}{16\pi^2} P(m_f/M) \right]^{-1} \]
      \[ = 8.3 \times 10^{-16} \text{ s} \left( \frac{100 \text{ GeV}}{m_f} \right) \left( \frac{0.01}{\alpha_y^{\text{dark}}} \right) \left( \frac{1.0}{f_B} \right)^2 \left( \frac{10^{-3}}{\epsilon} \right)^2 \frac{1}{P(m_f/M)} \]
    - 2 body.
      \[ \tau_{f \rightarrow f + h} \sim \left[ \alpha_Y^2 m_f \left( \frac{M_b}{M_B} \right)^2 \right]^{-1} \]
      \[ = 6.6 \times 10^{-15} \text{ s} \left( \frac{100 \text{ GeV}}{m_f} \right) \left( \frac{10^{-3}}{\epsilon} \right)^2 \left( \frac{1 \text{ GeV}}{M_b} \right)^2 \left( \frac{M_B}{100 \text{ GeV}} \right) \]

3 body and 2-body channels can be comparable.
Decay cascades in the dark sector

• Typically
  
  – Lepton jets

• Dark LSP (LDSP) decays to gravitino

\[
\tau_{\tilde{b} \rightarrow \gamma \tilde{G}} \sim \left[ \frac{e^2 M_{\tilde{b}}^5}{16\pi F^2} \right]^{-1} = 3.3 \times 10^3 \, s \left( \frac{10^{-3}}{\epsilon} \right)^2 \left( \frac{1 \text{ GeV}}{M_{\tilde{b}}} \right)^5 \left( \frac{\sqrt{F}}{100 \text{ TeV}} \right)^4
\]

• Outside detector. No photon like normal GMSB.
SUSY MSSM + dark sector decays

• Lepton jets at the end of the MSSM SUSY decay chain.
  – (much) More observable.
• Missing energy.
  – Massless and collimated with the lepton jets.
Greatly enhanced observability of EW-ino production

• Electroweak-ino production in MSSM
  – Crucial for discovery and measurement
  – However, hard to observe
    • LSP production, trigger on additional radiation?
    • Large SM background with similar final states: WW, WZ, …

• MSSM + dark sector

  Additional lepton jets

  Easier to trigger on.

  Good for background suppression
Electroweak-ino production at the LHC

- Bino. LSP pair production. Up to 1 TeV.
- Wino/higgsino.
  LSP + degenerate chargino/neutralino
  Up to 2 TeV

\[ m_{\text{squark}} = 750 \text{ GeV} \]
\[ |\eta|_{\text{Lepton jet}} < 2.4 \]
Electroweak-ino production at the Tevatron

- Wino/higgsino.
  LSP + degenerate chargino/neutralino
  Up to 300 GeV
Mass measurements and event reconstruction.

• Measuring the MSSM LSP mass.

  - Edge: $M_{\chi_0}/\sqrt{2}$.
    - Inv. Mass of lepton jets in the same decay chain.

• Can even fully reconstruct the dynamics.

• More measurements: spin…. 
Conclusions

• A GeV non-abelian dark sector typically have an extended dark Higgs sector as well.
  – We have given a set of examples.

• Supersymmetric implementations can generate the GeV scale natural, GMSB, “Planck slop”.
  – We propose a new mechanism, D-term kinetic mixing.

• Non-abelian DS with kin. Mixing with SM gives rich phenomenology.
  – Lepton jets have more than 2 leptons in it.
  – Produce through prompt photon-like process and Z-rare decay.
  – Promising at the LHC, could be possible at Tevatron.
Conclusions

• Lepton jets significantly alters conventional SUSY collider signal.
  – Extended reach for electroweak-ino direct production.
  – Much better even reconstruction.

• Much more model building and phenomenology study have to be carried out to fully explore the possibilities.
Production of dark matter multiplet.

• Impossible to see if the full dark matter multiplet is color neutral.

• Possible in the some extensions
  – Example:

Vector quark.
Long-lived colored particle.