Status of sub-GeV Hidden Particle Searches

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Outline

1 Motivation for sub-GeV Hidden Sector
   - Bottom-Up
   - Top-Down

2 NMSSM CP-odd Higgs
   - Introduction
   - Constraints

3 Hidden U(1) gauge boson
   - Introduction
   - Constraints

4 Conclusions
Outline

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Bottom-Up Motivation

Dark Matter

Several astrophysical and terrestrial observations that might originate from Dark Matter

Indirect Detection

- Annihilation products in cosmic radiation
- Excess of $e^+$ (PAMELA) and $e^+ + e^-$ (FERMI)

*but:* no excess in anti-protons (PAMELA)

Direct Detection

- Scattering on nuclei
- Nuclear recoils observed (DAMA & CoGeNT)

*but:* no signal observed (CDMS & XENON)
DM Properties

**PAMELA & FERMI**
- larger annihilation cross section than needed for correct relic abundance:
  \[ \sigma v_{\text{ann}} \gg \sigma v_{\text{ann}} \Omega h^2 \]
- dominant annihilation into leptons (*leptophil*):
  \[ \chi \chi \rightarrow l^+ l^- \]
- high mass scale:
  \[ m \sim \mathcal{O}(\text{TeV}) \]

**DAMA & GoGeNT vs. CDMS & XENON**
- light DM candidate:
  \[ m \sim 5 - 10 \text{ GeV} \]
- inelastic heavy DM with excited states:
  \[ \Delta m \sim 100 \text{ keV} \]

⇒ difficult in usual WIMP models
Model Extension

Hidden Sector with light messenger particle

\[ \chi \rightarrow e^+ e^- \]
Motivation

Bottom-Up

Model Extension

Hidden Sector with light messenger particle

- Sommerfeld effect $\Rightarrow$ enhanced annihilation cross section
- kinematics $\Rightarrow$ decay into light leptons

\[ \chi \gamma' e^+ + e^- \]
Model Extension

Hidden Sector with light messenger particle

- Sommerfeld effect $\Rightarrow$ enhanced annihilation cross section
- kinematics $\Rightarrow$ decay into light leptons
- inelastic scattering on nuclei

Example

- Axion-like Particle
  - NMSSM CP-odd Higgs $^{[\text{Hooper & Tait 2009}]}$
- Hidden U(1) Photon
  - Hidden Sector $^{[\text{Arkani-Hamed et al. 2009}]}$
  - Asymmetric Mirror World $^{[\text{An et al. 2010}]}$
Top-Down Motivation

String compactifications

Hidden Sectors (HS)

appear naturally in various supersymmetric models descending from string theory

- mediators are weakly coupled to visible sector
- mediators can be light

\[
\begin{align*}
\text{Hidden Sector} & \quad \text{Messenger} \\
SU(3) \times SU(2) \times U(1) & \quad \text{Standard Model}
\end{align*}
\]
Motivation

Top-Down

String compactifications

- heterotic string can reproduce the NMSSM\cite{Lebedev & Ramos-Sanchez 2010} in a Peccei-Quinn limit
  - with a light Pseudo-Goldstone boson, an axion-like particle (ALP)

- breaking of larger groups down to the SM gauge group can yield hidden U(1) symmetries
  - may remain unbroken down to small energy scales
  - hidden Photon may be light
  - weak coupling to visible sector via kinetic mixing
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The $Z_3$-symmetric NMSSM

- MSSM with addition scalar field $S$ and $Z_3$-symmetry

$$W = \lambda S H_u H_d + \frac{1}{3} \kappa S^3$$

- limit $\kappa \rightarrow 0$: approximate Peccei-Quinn symmetry

- naturally light CP-odd Higgs $A^0$: $m_{A^0}^2 \simeq \kappa \cdot \mathcal{O}(\text{EW-scale})^2$

- from string theory $\kappa \gtrsim 10^{-6}$: $m_{A^0} \sim 100$ MeV
  $m_{A^0} < 2m_\mu$ not well studied

- coupling of $A^0$ to fermions $\propto C_{Aff}$

- avoid violation of perturbativity and/or finetuning

$$10^{-2} \lesssim C_{Aff} \lesssim 10^2$$
Constraints: Meson-decays

**invisible**

\[ X \rightarrow Y + A^0 \rightarrow Y + \text{inv.} \]

\[ A^0 \] sufficiently long lived to escape detector

\[ \Gamma_{X \rightarrow Y + A^0} / \Gamma_{\text{tot}} < B^{\exp} \]

**visible**

\[ X \rightarrow Y + A^0 \rightarrow Y + e^+ e^- \]

\[ A^0 \] decays within detector

\[ \text{BR}_{X \rightarrow Y + A^0} \ast \text{BR}_{A^0 \rightarrow e^+ e^-} < B^{\exp} \]

\[ K^+ \rightarrow \pi^+ + X \]

peak in \( \pi^+ \) momentum spectrum
Constraints: Pion-decay & Muon $g - 2$

$$\pi^0 \rightarrow e^+ e^-$$

in SM through loop diagrams

tree level channel through $A^0$

$$\Gamma_{\pi^0 \rightarrow e^+ e^-} / \Gamma_{\text{tot}} < B_{\text{exp}}$$

$a_\mu$

currently $a_\mu^{\text{exp}} > a_\mu^{\text{SM}}$

several NMSSM contributions

negative $A^0$ loop contribution

not worsen discrepancy beyond $5\sigma$

... and others

beam-dump and reactor experiments

light $A^0$ excluded!

S.A., O. Lebedev, S. Ramos-Sánchez and A. Ringwald, *JHEP* 1008:003, 2010 [arXiv:1005.3978]
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Hidden Photon and Kinetic Mixing

- additional $U(1)_h$-symmetry in HS
  - ⇒ hidden photon $\gamma'$
- SM not charged under HS and vice versa

**dominant interaction:** kinetic mixing of $\gamma'$ and $\gamma$

- most general Lagrangian

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{4} X_{\mu\nu} X^{\mu\nu} + \frac{\chi}{2} X_{\mu\nu} F^{\mu\nu} + \frac{m_{\gamma'}^2}{2} X_{\mu} X^{\mu}$$

- $\chi \sim \frac{\alpha}{4\pi} \sim \mathcal{O}(10^{-4} - 10^{-3})$
  - generated by loops of heavy particles charged under both $U(1)$ groups
- $\gamma'$ couples and can decay to SM fermions through kinetic mixing
Constraints

Muon & Electron $g - 2$

1-loop contribution from $\gamma'$ [Pospelov 2009]

Past beam-dump experiments

$\gamma'$ emitted via bremsstrahlung from e-beam [Bjorken et al. 2009]

Search for decay $\gamma' \rightarrow e^+ e^-$

Sensitivity of future experiments

- JLab: APEX, HPS, DarkLight
- DESY: HIPS

S.A. and A. Ringwald, arXiv:1008.4519
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Summary

- HS well motivated: DM, SM extensions, string theory
- possibly light particles in HS with very weak couplings to SM
- constraints from various experiments

NMSSM: $A^0$ lighter than 210 MeV excluded
(or 10 000 times weaker couplings to fermion than SM Higgs)

Hidden $U(1)$: $\gamma'$ still possible

complementary searches at future fixed-target experiments
  - JLab: APEX, HPS, DarkLight
  - DESY: HIPS
Motivation

- Asymmetric Mirror DM with hidden photon [An et al. 2010]
- Hidden Sector with hidden photon [Bjorken et al. 2009]
Motivation

- **NMSSM and PAMELA** [Hooper & Tait 2009]
- $\chi^0\chi^0 \rightarrow A^0 h$ followed by $h \rightarrow A^0 A^0$ and $A^0 \rightarrow e^+ e^-$ (top) or $\mu^+ \mu^-$ (bottom)
- normalized to PAMELA, boost from Sommerfeld enhancement

![Graphs showing positron fraction results](image)
Constraints

- $2m_\mu < m_{A^0} < 3m_\pi$: $C_{Aff} < \mathcal{O}(10^{-2})$ from K- and B-decays
- $m_{A^0} \sim 3m_\pi - m_\gamma$: $C_{Aff} < \mathcal{O}(10^{-1} - 1)$ from $\Upsilon$-decays
- $m_{A^0} \gtrsim 12 \text{ GeV}$: $C_{Aff} < \mathcal{O}(10)$ from $e^+e^- \rightarrow b\bar{b}A^0 \rightarrow b\bar{b}b\bar{b}$
- $m_{A^0} < 2m_\mu$: not well studied

$$\Gamma_{tot} = \Gamma(A^0 \rightarrow \gamma\gamma) + \Gamma(A^0 \rightarrow e^+e^-)$$

- Meson-decays (visible & invisible)
- Pion-decay
- Muon $g - 2$
- Beam dump experiments
- Reactor experiments
Why NMSSM?

- **µ-problem:** Why is $\mu \ll M_{\text{GUT}}$?
  
  solution: replace mass term $\mu$ by coupling to scalar field $S$

  $$W = \lambda S H_u H_d + \frac{1}{3} \kappa S^3 \implies \mu = \lambda \langle S \rangle$$

  $Z_3$-symmetric NMSSM (no direct $\mu$-term)

  $\Rightarrow$ new particles: additional CP-odd Higgs $A^0$ (ALP)

- little hierarchy problem/fine-tuning:

  tree-level prediction $m_h \leq m_Z$ vs. LEP bound $m_h \geq 114$ GeV

  solution: additional decay $h \rightarrow 2A^0$ for light $A^0$ reduces LEP limit
The $Z_3$-symmetric NMSSM

- **Superpotential**: \( W = \lambda S H_1 H_2 + \frac{1}{3} \kappa S^3 \)

- **Soft terms**:
  \[
  V_{\text{soft}} = m_1^2 |H_1|^2 + m_2^2 |H_2|^2 + m_S^2 |S|^2 + \left( \lambda A_\lambda S H_1 H_2 + \frac{1}{3} \kappa A_\kappa S^3 + \text{h.c.} \right)
  \]

- \( \kappa \to 0 \): Lagrangian is invariant under the transformation
  \[
  H_{1,2} \to e^{i\alpha} H_{1,2}, \quad S \to e^{-2i\alpha} S
  \]

- Symmetry broken at EW-scale, resulting in the “axion”
  \[
  A^0 = \frac{1}{N} \left( \nu \sin 2\beta A^0_{\text{MSSM}} - 2 s S_l \right), \quad \text{with} \quad m_{A^0}^2 \simeq -3 \kappa A_\kappa s
  \]

- **Coupling of** \( A^0 \) **to fermions**:
  \[
  \Delta \mathcal{L} = -i \frac{g}{2m_W} C_{\text{Aff}} \left( m_d \bar{d} \gamma_5 d + \frac{1}{\tan^2 \beta} m_u \bar{u} \gamma_5 u + m_l \bar{l} \gamma_5 l \right) A^0
  \]
Beam-dump & Reactor Experiments

search for decay $A^0 \rightarrow e^+ e^-$

beam-dump experiments

ALP emitted via bremsstrahlung from $e^-$ or $p$-beam

reactor experiments

ALP emitted in place of photons from excited nuclear levels

S.A., O. Lebedev, S. Ramos-Sánchez und A. Ringwald,
JHEP 1008:003, 2010 [arXiv:1005.3978]