Light Hidden Sectors at Fixed-Target Experiments

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Outline

1. Introduction and Motivation
2. Theory: Model and Benchmarks
3. Fixed Target Limits
4. Conclusions
Introduction and Motivation
Hidden Sectors

- Heavy stuff harder to probe!
  Increase $m \Rightarrow$ See only larger $g$

- $g \sim O(1)$ implies NP is TeV-scale!
- e.g. NP has gauge couplings
  $g \ll O(1)$ lets NP be light!

- Hidden sector gauge-neutral
Heavy stuff harder to probe! Increase $m \Rightarrow$ See only larger $g$

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$g \sim O(1)$ implies NP is TeV-scale
  e.g. NP has gauge couplings

$g \ll O(1)$ lets NP be light
  Hidden sector gauge-neutral
Thinking of New Light Stuff

- **μ Anomalous Magnetic Moment**
  \[
  \delta a_\mu \sim \frac{g_{NP}^2}{16\pi^2} \frac{m_\mu^2}{M_{NP}^2}
  \]
  \[
  \frac{g_{NP}}{10^{-3}} \sim \frac{M_{NP}}{\text{GeV}}
  \]

- **Hidden Valleys**

- **Dark Matter Anomalies**

- **Asymmetric Dark Matter**
Portals

- Three renormalisable couplings between SM and gauge-neutral operators

\[ -\frac{1}{2} \varepsilon B^{\mu\nu} X_{\mu\nu} \]

\[ -\frac{1}{2} \lambda (H^\dagger H)(\Phi^\dagger \Phi) \]

\[ y \bar{L} H N \]

- **Vector Portal: \( \gamma \)**
  - Photon Massless
  - \( X \) Couples \( \propto \varepsilon e Q \)

- **Higgs Portal**
  - LHC Only
  - Easy(?) to produce

- **Neutrino Portal**
  - Neutrino Light
  - \( N \) Hard to detect
Portals

- Three renormalisable couplings between SM and gauge-neutral operators

- **Vector Portal: γ**
  - Massless
  - Couples $\propto \varepsilon e Q$
  - One-Loop generated $\rightarrow \varepsilon \sim 10^{-3}$

- **Higgs Portal**
  - LHC Only
  - Easy(?) to produce

- **Neutrino Portal**
  - Near-massless
  - Hard to produce
Many previous studies and limits!

GeV-scale relatively unconstrained
Assumptions!

- Existing (GeV-scale) searches assume either: [1311.0029]
  - $X \rightarrow l^+ l^-$
    - Beam dump limits at small $\varepsilon$ and $m$
    - Motivated as minimal model
  - $X \rightarrow$ invisible
    - Weaker limits from neutrino expts
    - Motivated from dark matter
General Hidden Sectors

- Multiple possible vector decays:
  - Direct Decay to Visible Sector
  - Invisible Decay
  - Decay to SM via Hidden Scalars
  - Decay to SM via Hidden Fermions

Schuster et al, [0910.1602]
Can we construct a model with all these decay modes?
The Model
A Minimal Supersymmetric Hidden Sector

- We don’t need to build a model: already had one! [1112.2705]
- **Supersymmetric**: has both hidden scalars and fermions
- If add R-parity, lightest fermion is stable
- Minimal model with $U(1)_X$ gauge symmetry:
  - Vector field $X^\mu$ plus gaugino $\tilde{X}$
  - Two Higgses $H, H'$ plus Higgsinos $\tilde{H}, \tilde{H'}$
  - Minimal anomaly-free content
A Minimal Supersymmetric Hidden Sector

- We don’t need to build a model: already had one!
- **Supersymmetric**: has both hidden scalars and fermions
- If add R-parity, lightest fermion is stable
- Minimal model after breaking \( U(1)_x \):
  - Massive vector field \( Z^x \)
  - Two real scalars \( h^{x}_{1,2} \) and one pseudoscalar \( A^x \)
  - Three Majorana fermions \( \chi^{x}_{1,2,3} \)
Model as Benchmark

- Model is:
  - Minimal;
  - Has all four simple decay modes;
  - Has more complex decay chains
- Can be studied on own merits
- OR as framework to examine general hidden sectors
Four Benchmark Slopes

- Slices of parameter space: fixed ratios of mass parameters

A: \( m_{Z^x} < m_{A^x}, \mu', M_x \)

B: \( M_x < m_{Z^x} < m_{A^x}, \mu' \)

C: \( m_{A^x} < m_{Z^x} < \mu', M_x \)

D: \( \mu' < m_{Z^x} < m_{A^x}, M_x \)
Pseudoscalar and Fermion Decays

- Signals: long-lived states
- Coupling suppression
  - (Case A)
- Stable fermion (all cases)
- Phase space suppression:
  - $A^x$ (Case C)
  - $\chi$ (Case D)
Hidden Higgs Decays

- Lightest scalar:
  - No HS bosonic decays
  - HS fermion decays (Case D)
- Decays to SM:
  - Four-body
    (irrelevant, Batell et al. [0903.0363])
  - Vector loop
  - Higgs mass mixing
- **Always** long-lived: Cases A—C
Fixed Target Limits
Fixed Target Experiments

- The other part of the title
- Examples of the **Intensity Frontier**:
  - High luminosity
    - Probe small coupling to SM
  - Low/Controlled backgrounds
    - Searches restricted to low mass
- One of the standard tools/proposals to limit Hidden Sectors
Electron Experiments

- $Z^x$ couples to EM current
- Production from $e$ is obvious!
- Recasting old experiments has placed important limits
- Proposed new searches
  - BUT miss Cases C, D
- Small angle quasi-elastic scattering dominates
Electron Experiments

- $Z^x$ couples to EM current
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Results

❖ **No** \( h^x \) limits in Case A or B

❖ Case C:
  ❖ Completely new \( h^x \) and \( A^x \) limits
  ❖ Exclude much of \( a_\mu \) region

❖ Case D:
  ❖ First limits on this decay type
  ❖ All from \( \chi^x_2 \) decays
Results

- No $h^x$ limits in Case A or B

- **Case C:**
  - Completely new $h^x$ and $A^x$ limits
  - **Exclude** much of $a_\mu$ region

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  - First limits on this decay type
  - All from $\chi^x_2$ decays
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❖ Case C:
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❖ Case D:
  ❖ First limits on this decay pattern
  ❖ All from $\chi^x_2$ decays
Proton Experiments

- Benefit from luminosity
- Easy to compute (for me!)
- One previous study:
  - $Z^x \rightarrow$ scalars $\rightarrow$ leptons
- No mass mixing
- Many prospective limits from neutrino expts
- Strong limits from $h^x$!
Proton Experiments

- Benefit from luminosity
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- One previous study:
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Proton Experiments

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High Mass: Partonic Production

Low Mass: Meson Decays

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Schuster et al, 0910, 1602
Limits from CHARM only new ones
Nearly exclude region that explains $a_{\mu}$!
Benchmark B

- Limits from CHARM + LSND fully exclude $a_\mu$-preferred region!
Benchmark C

- Upper/lower regions with/without $A^x$
- First limits in SUSY case
- Limits much expanded in non-SUSY case
- $a_\mu$-preferred region excluded!
- If CMB/BBN limits included, exclude $m_{Z^x} < 1$ GeV (except near $\mu$ threshold)
First limits on this case

CMB/BBN limits at $\varepsilon < 10^{-8}$

$a_\mu$-preferred region NOT excluded! ($h^x$ decays invisibly) But probed by JLab & INGRID
Conclusions

- Hidden Sectors coupling through kinetic mixing can have richer phenomenology than usually considered.
- Have discussed a simple model that illustrates this.
- Limits on $Z^x$ decaying to scalars/fermions with visible decays much expanded/completely new.
- Difficult to explain $a_\mu$ with hidden vector if it is higgsed, and the Higgs decays visibly.
Back-Up Slides
Parameter Space

- Model has seven parameters (over MSSM):
  - Supersymmetric:
    - Gauge coupling $g_x$
    - Kinetic Mixing $\epsilon$
      \[ \mathcal{L} \supset \frac{1}{2} \epsilon X^{\mu\nu} F_{\mu\nu} \]
    - Higgsino Mass $\mu'$
  - SUSY-breaking:
    - Vector mass $m_{Zx}$
    - Pseudoscalar mass $m_{Ax}$
    - Ratio of Higgs vevs $\tan \zeta$
    - Gaugino mass $M_x$

- Hidden Sector masses $\epsilon$-suppressed if only feel SUSY breaking through kinetic mixing.
Structure of Hidden Sector

- Hidden sector very similar to neutral sector of MSSM

\[ m_{Z^x} \leftrightarrow m_Z \quad m_{A^x} \leftrightarrow m_A \quad M_x \leftrightarrow M_B \quad \mu' \leftrightarrow \mu \quad \tan \zeta \leftrightarrow \tan \beta \]

- Fermion sector: as MSSM neutralinos, without \( \tilde{W} \)

\[ \tilde{X} \leftrightarrow \tilde{B} \quad \tilde{H} \leftrightarrow \tilde{H}_u \quad \tilde{H}' \leftrightarrow \tilde{H}_d \]

- Scalar sector: as MSSM neutral Higgses

\[ H \leftrightarrow H_u^0 \quad H' \leftrightarrow H_d^0 \]

- At tree level, \( m_{h^x} < m_{Z^x} \)
Benchmark Slope A: $Z^x \rightarrow SM$

- Vector has no hidden decays
- Must decay to SM particles
- Generically true when
  \[ m_{Z^x} < m_{A^x}, \mu', M_x \]
- Can still produce HS through off-shell vector

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Benchmark Slope B: $Z^x \rightarrow \text{Inv}$

- Vector has one hidden decay:
  - To lightest (stable) fermion
  - Generically true when
    $$M_x < m_{Z^x} < m_{A^x}, \mu'$$
  - Can still get visible HS signals through off-shell vector

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Benchmark Slope C: \( Z^x \rightarrow \text{Scalars} \)

- Vector decays to hidden scalars
- Scalars must decay to SM!
- Generically true when

\[
m_{A^x} < m_{Z^x} < \mu', M_x
\]
Vector decays to HS fermions

\( \chi^x_2 \) must decay to SM!

\[ \text{BR}(Z^x \rightarrow \chi^x_2) = 94\% \]

Generically true when

\[ \mu' < m_{Z^x} < m_{A^x}, M_x \]
Non-Beam Dump Limits
Model-Independent Limits

- Electroweak Precision: $m_Z$
- Kinetic Mixing Modifies $Z$
  - $\varepsilon \approx 0.026$ [Hook et al, 1006.0973]
- Anomalous Magnetic Moments
- Intro QFT Calculation
- Limits from $a_e$ and $a_\mu$
- Possible explanation of $\delta a_\mu$
- Details: Pospelov, [0811.1030]
Meson Decays: Slopes A and B

- BaBar $\Upsilon (3s, 2s) \rightarrow \gamma a^0 \rightarrow \gamma \mu^+ \mu^-$
- KLOE $\varphi \rightarrow \eta Z^x \rightarrow \eta e^+ e^-$
- WASA $\pi^0 \rightarrow \gamma Z^x \rightarrow \gamma e^+ e^-$

- BaBar $\Upsilon (3s) \rightarrow \gamma a^0 \rightarrow \gamma + \text{inv}$
- E787, E949 $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

![Graphs showing results of meson decays.](image)
**Meson Search Topologies**

- **Search Topologies:**
  - Visible decays: Total energy = $E_{\text{Par}}$
  - Invisible decays: MET + tag
  - If $Z^x \rightarrow \text{Hidden Sector}$, instead have:
    - Tag + *lepton pair* + MET
    - Tag + $l^+l^-l^+l^-l^+l^-$
  - These searches not done; no limits
Meson Decays C: $Z^x \rightarrow$ Scalars

- Cosmology limits: CMB/BBN (late $h^x$ decays)
- Limits from BaBar $\Upsilon (3s) \rightarrow \gamma + Z^x \rightarrow \gamma + h^x + A^x \rightarrow \gamma + \text{inv}$
- Not shown: E787, E949 $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ limits for $\varepsilon \gtrsim 0.01$
Meson Decays D: $Z^x \rightarrow$ Fermions

- Cosmology limits from $\chi^{x_2}$ decays
- BaBar limits again from invisible search

\[ \Upsilon (3s) \rightarrow \gamma + Z^x \rightarrow \gamma + \chi^{x_1} + \chi^{x_{1,2}} \rightarrow \gamma + \text{inv} \]
Experimental Details

- Previous searches:
  - All somewhat relevant
  - Thresholds important

- Current/Future searches
  - Many impose cut: \( E(e^+) + E(e^-) = E_{\text{beam}} \)
  - Insensitive to \( h^x, A^x, \chi^x \) decays

- MAMI
- APEX
- HPS
- CERN SPS (Visible)
- DarkLight

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<th>Target</th>
<th>( E_0 )</th>
<th>( N_e )</th>
<th>( L_{ab} )</th>
<th>( L_{dec} )</th>
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Experiments

- Several past/current searches
- Visible: CHARM, MINOS, ν-Cal I, LSND
- Invisible (neutrino): MINOS, INGRID, LSND
- Inferior limits from NOMAD, PS-191, ND280, MiniBooNE
- Future limits from Project X, AFTER@LHC