Constraining Supersymmetric Hidden Sectors

arXiv: 1305.xxxx

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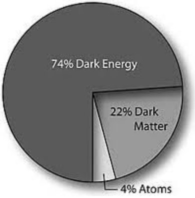
Outline

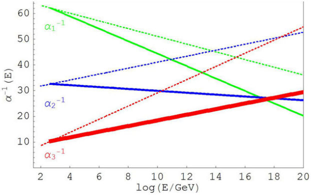
Supersymmetry Is Out There

Standard SUSY Motivations

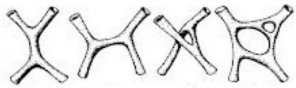
Hierarchy Problem



Gauge Unification



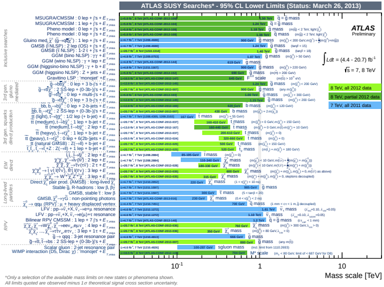
Dark Matter

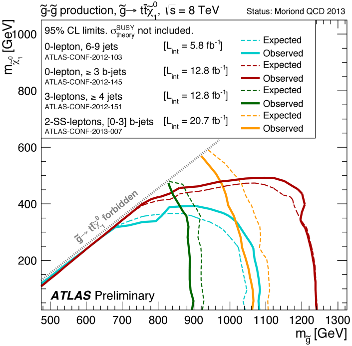


String Theory

SUSY in 2013

Wait a Minute!





ATLAS Experiment © 2013 CERN

Relevant Possible Implications

- Maybe Supersymmetry isn't there?
- Visible Sector Sparticles all in the TeV Range
  - Maybe SUSY is just fine-tuned
  - Will return to this later
- Hiding Supersymmetry
  - *e.g. Stealth SUSY, Compressed Spectra, RPV*
  - Most common SUSY handle: $\not{E}_T$
  - Light sectors give superpartners R-partity-preserving decays
  - Complex light sectors offer many paths back to SM

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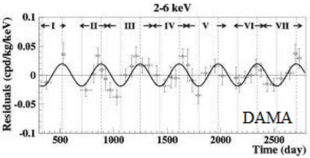
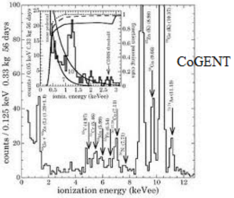
Light Hidden Sectors

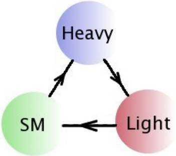
Some Alternative Motivations

Dark Matter Anomalies!





Asymmetric Dark Matter!

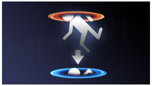


Hidden Valleys!

$$E_8 \supset E_7 \supset E_6 \supset SO(10) \supset SU(5)$$

Grand Unification!

Portals



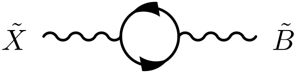
Hidden Sector $\Rightarrow$ Neutral under $\mathcal{G}_{SM}$

3 Renormalisable, Gauge Invariant Couplings to SM

$$\mathcal{L} \supset -\frac{1}{2}\epsilon B^{\mu\nu} X_{\mu\nu} \qquad \mathcal{L} \supset \kappa\,(H^\dagger H)\,(S^\dagger S) \qquad \mathcal{L} \supset \eta(L \cdot H)N$$

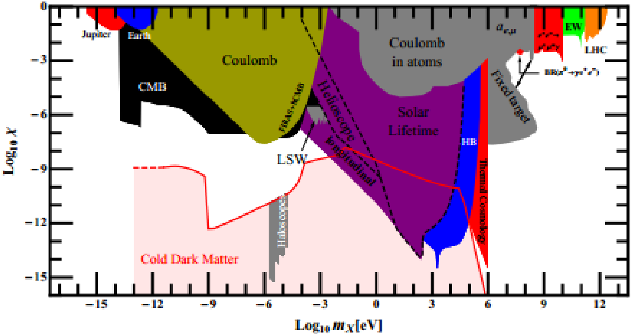
Vector portal — Higgs portal — Neutrino portal

- Vector portal advantages: photon massless, easily observable
- Possible Origin of Such a Term:



$$\sim \frac{g_x g_Y}{(4\pi)^2} \log\left(\frac{\Lambda^2}{\mu^2}\right) \sim 10^{-4}\text{–}10^{-2}$$

Extant Limits



Jaeckel, 1303.1821

- Many different exclusion limits exist
- GeV-scale masses relatively unconstrained

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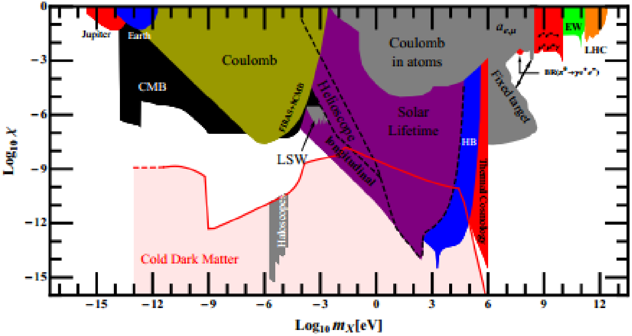

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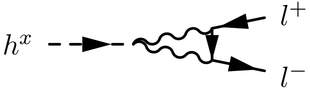
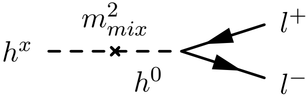
- GeV-scale masses relatively unconstrained

Loopholes and Links

- Normal assumption: X_μ decays to Visible Sector
  - (Schuster *et al*, 0910.1602 rare exception)
- What if Hidden Sector non-minimal?
  - X_μ decays to Hidden Sector possible
  - Massive vector $\Rightarrow$ hidden Higgs
- Hidden SUSY Higgs qualitatively different
  - SUSY kinetic mixing induces D-term mixing
  - Higgs mass mixing $\Rightarrow$ New decay path
  - Different ϵ-dependence (ϵ^2 vs ϵ^4)





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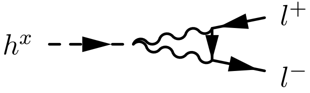

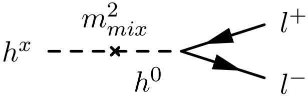

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Hidden Vector

- Obviously, we include a new $U(1)$ Gauge Boson X_μ
    - Gauge coupling g_x
- We define the kinetic mixing

$$\mathcal{L}_K \supset -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{2}\epsilon\, B^{\mu\nu}X_{\mu\nu} - \frac{1}{4}X^{\mu\nu}X_{\mu\nu}$$

- Vector mass: Stückelberg?

$$\mathcal{L}_X \supset \frac{1}{2}\left(m_X X_\mu - \partial_\mu \phi\right)^2$$

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- Vector mass: Higgsed

$$\mathcal{L}_X \supset \sum_i |D_\mu H_i|^2$$

. . . since we want a non-trivial hidden sector

Hidden Higgses

How Many?

We consider 2HDM:

- In SUSY context, Higgs accompanied by chiral Higgsino
- Minimal anomaly-free content:

Field	$U(1)_x$
H	$+1$
H'	-1

Problems with minimality?

- Small non-generic feature: $m_{h_1^x} < m_x$ (as in MSSM)
- But generically only lightest scalar long-lived
  - Constraints dominated by one decay width
  - Extra structure just $\mathcal{O}(1)$ change to mixing matrices

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The Minimal Model

- Seven hidden sector particles
  - X_μ, A^x, $h^x_{1,2}$, $\chi^x_{1,2,3}$
- Seven new parameters (over MSSM)
  - SUSY-preserving g_x, ϵ, μ' $(W = \mu' H H')$
  - SUSY-breaking m_{A^x}, m_x, M_{χ^x}, $\tan\zeta$
  - If $\not{CP}$ allowed, μ' can be complex
- What of $\not{SUSY}$?
  - If $\not{SUSY}$ → MSSM → HS,
    $M_{HS} \sim \epsilon M_{MSSM} \sim 10^{-3}$ (TeV) ∼ GeV
  - Problems – gravitino, μ' – but surmountable
- Bottom-up approach:
  - Fix benchmark slopes by low energy phenomenology

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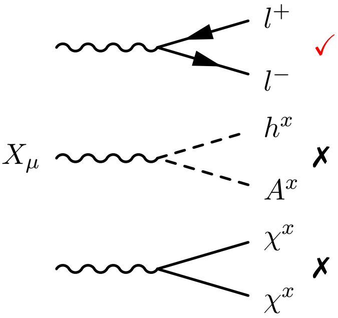
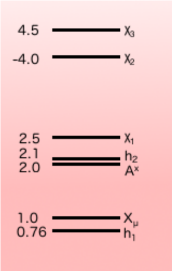
Benchmark I: Meet the New Boss

- Vector cannot decay to HS
- Limits mostly unchanged
- Some new results

Parameter	Value
$\tan\zeta$	3.0
g_x	0.3
m_{A^x}	2.0 m_x
M_{χ^x}	3.0 m_x
μ'	4.0 m_x

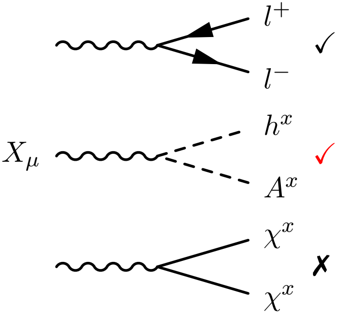


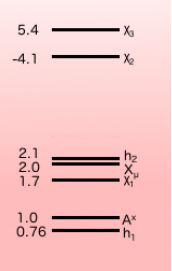


Benchmark II: Optimistic Case

- Vector decays to hidden scalars
- Best case:
  1. Resonant production
  2. Hidden scalars decay to SM

Parameter	Value
$\tan\zeta$	3.0
g_x	0.3
m_{A^x}	0.5 m_x
M_{χ^x}	3.0 m_x
μ'	4.0 m_x

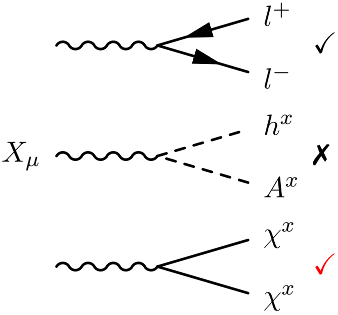


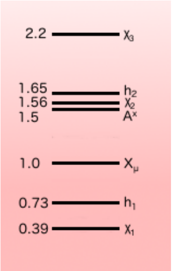


Benchmark III: Depressing Case

- Vector decays to hidden fermions
- Lightest fermion stable
- Only signals through off-shell scalar production

Parameter	Value
$\tan\zeta$	3.0
g_x	0.3
m_{A^x}	$1.5\ m_x$
M_{χ^x}	$1.0\ m_x$
μ'	$1.5\ m_x$





Origin of mass mixing

SUSY Gauge Kinetic Mixing:

$$\frac{1}{2}\epsilon\, B_{\mu\nu}X^{\mu\nu} \subset \int \mathrm{d}^2\theta\, X^{\alpha}B_{\alpha} + h.c. \supset \epsilon\, D_X D_B$$
$$\rightarrow \epsilon\, g_x\, g_Y \left(|H|^2 - |H'|^2\right)\left(|H_u|^2 - |H_d|^2\right)$$
$$\sim \epsilon\, s_W\, m_x\, m_Z\, h^0 h_a^x$$

Treat mixing as mass insertion:

- Doubly suppressed by ϵ and $\frac{m_x}{m_{h^0}}$
- Only relevant when competing interactions also suppressed

Define non-SUSY model as one with zero mass mixing

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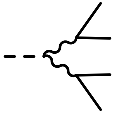
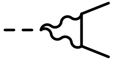
Competing Decays

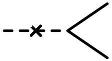
- Lightest scalar usually has no hidden sector decays
- Three relevant processes:



$$\sim \epsilon^4 \frac{m_{h^x}^2}{m_x^2}$$



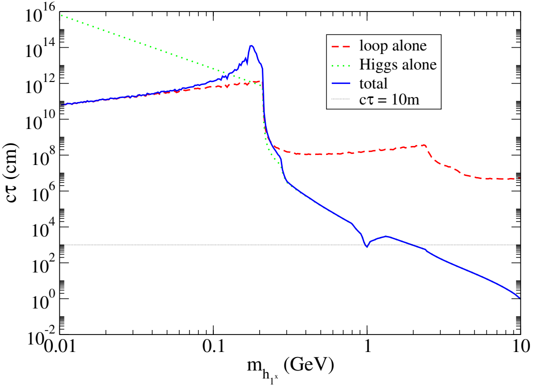
$$\sim \epsilon^4 \frac{m_l^2}{m_x^2}$$



$$\sim \epsilon^2 \frac{m_x^2 m_l^2}{m_h^4}$$

- For $m_{h^x} < m_x$, loop process dominates four-body decay [Batell *et al*, 0903.0363]
- Different channels dominate in different parameter regions

Effect of Mass Mixing



- $g_x = 0.3$
- $\epsilon = 10^{-3}$
- $m_x = 1.5 m_{h_1^x}$

- Transition at $\mu^+\mu^-$, $\pi\pi$ threshold
- Decay length significantly changed
- Near threshold, contributions destructively interfere

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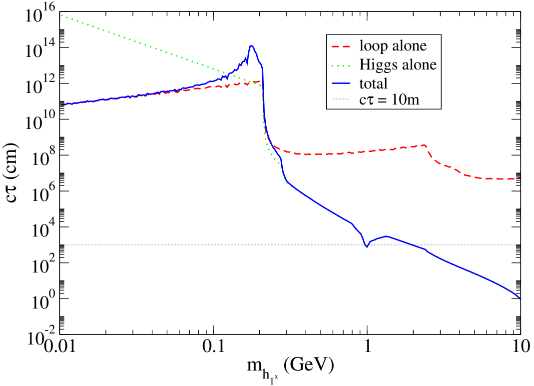

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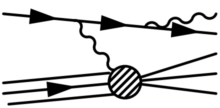
Electron Beam Dumps



- Electron interacts with atomic target:
  1. Electron cloud
  2. Nuclear electronic form factors
- Weizsäcker-Williams approximation:
  - Electron beam rest frame
  - Atomic target ⇒ Photon beam

Calculation well established:

Kim & Tsai, PRD 8 (3109) 1973, Bjorken *et. al.*, 0906.0580

$$\frac{d\sigma(a + P_i \to b + c + p_f)}{d(a \cdot b) d(b \cdot P_i)} \approx \frac{d\sigma(a + \gamma \to b + c)}{d(a \cdot b)} \times \frac{\alpha}{\pi} \frac{\chi}{c \cdot P_i}$$

- χ Effective photon flux, in terms of atomic form factors

Experiments

Several searches have presented results:

Experiment	Target	Energy (GeV)	N_{el}	L_{sh} (m)	L_{dec} (m)	$N_{95\%\text{up}}$
E137	Al	20	1.87×10^{20}	179	204	3
E141	W	9	2×10^{15}	0.12	35	3419
E774	W	275	5.2×10^{9}	0.3	2	18
KEK	W	2.5	1.69×10^{17}	2.4	2.2	3
Orsay	W	1.6	2×10^{16}	1	2	3

Andreas *et. al.*, 1209.6083

Our results dominated by E137

- Sufficiently high energy for GeV hidden sector
- Over 10^{10} more luminosity than E774

Experiments

Several searches have presented results:

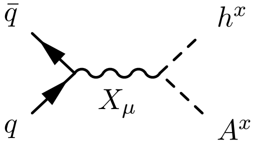
Experiment	Target	Energy (GeV)	N_{el}	L_{sh} (m)	L_{dec} (m)	$N_{95\%\text{up}}$
E137	Al	20	1.87×10^{20}	179	204	3
E141	W	9	2×10^{15}	0.12	35	3419
E774	W	275	5.2×10^{9}	0.3	2	18
KEK	W	2.5	1.69×10^{17}	2.4	2.2	3
Orsay	W	1.6	2×10^{16}	1	2	3

Andreas *et. al.*, 1209.6083

Our results dominated by E137

- Sufficiently high energy for GeV hidden sector
- Over 10^{10} more luminosity than E774

Hadronic Beam Dumps



- Much simpler calculation
  (for collider phenomenologist!)
- Checked $\mathcal{O}(\alpha_S)$ corrections $\sim 10\%$
- Cross Section $\Rightarrow$ No. of events:
  Schuster *et. al.*, 0910.1602
- Use MadGraph for acceptances

Experiments:

Experiment	Energy (GeV)	N_{pot}	L (m)
CHARM	400	2.4×10^{18}	480
GARGAMELLE	400	3.5×10^{17}	950
CDHS	400	4.3×10^{17}	890
BEBC	400	3.5×10^{17}	820

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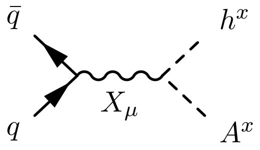

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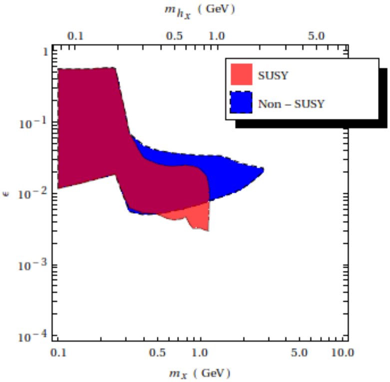

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- Electron beam dump searches too suppressed
- New limits from CHARM
- Unfortunately . . .

Note: Only $g-2$ constraints apply to Benchmarks II, III!

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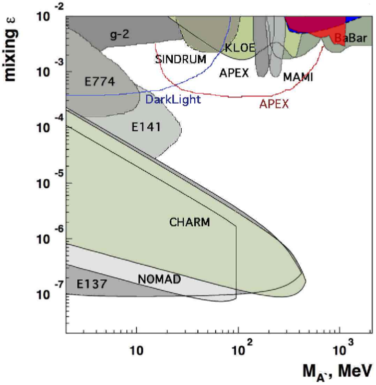

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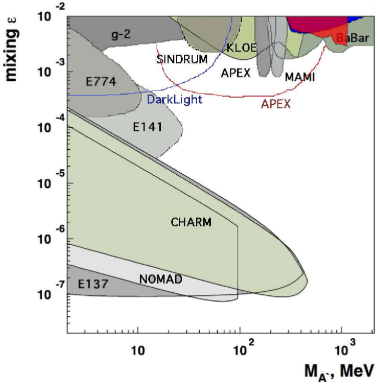

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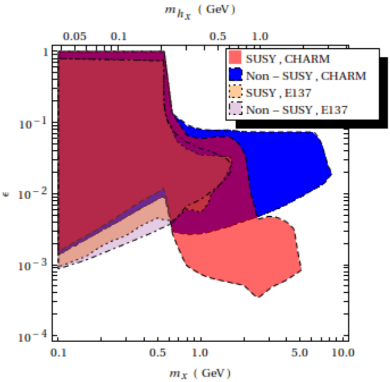
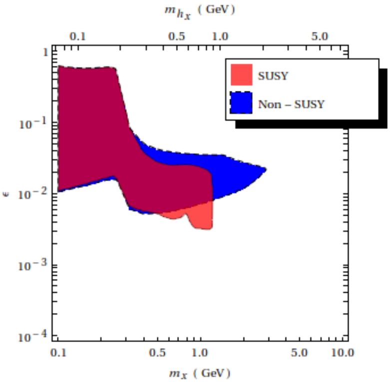
Benchmark II



- CHARM, E137 both relevant
- Mass mixing effect clear
- CHARM non-SUSY limits agree with previous work Schuster *et. al.*, 0910.1602

Benchmark III



- Similar to Benchmark I
  - Scalars produced through off-shell vector
- BUT other constraints no longer apply
- Not shown: DM constraints

Conclusions

- Supersymmetric kinetic mixing implies Higgs mass mixing
- SUSY hidden sectors then have new decay channels to SM
- Defined three benchmarks in Minimal Model
  to capture different low energy behaviour
- Found new exclusion limits from beam dump experiments