Hidden Photons
in Beam Dump Experiments
and in connection with Dark Matter

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based on: 1209.6083 and 1109.2869
with M. Goodsell, C. Niebuhr, A. Ringwald
Outline

1 Introduction

2 Electron Beam Dump Experiments
   Production in Bremsstrahlung
   Decay & Detection
   Beam Dump Limits

3 Hidden Dark Matter
   Toy Model
   Supersymmetric Model

4 Conclusions & Outlook
Hidden Sector with Hidden Photon

- **Hidden Sectors** in many BSM scenarios
e.g. string theory, supersymmetry

- simplest scenario: HS with extra U(1)
  - breaking of large gauge groups yield hidden U(1)s
e.g. heterotic or type II strings, supersymmetric models
  - hidden photon $\gamma'$ with kinetic mixing $\chi$

- most general Lagrangian
  \[ \mathcal{L} \supset -\frac{1}{4} X_{\mu\nu} X^{\mu\nu} + \frac{\chi}{2} X_{\mu\nu} F^{\mu\nu} + \frac{1}{2} m_{\gamma'}^2 X_{\mu} X^\mu \]
  - $\chi$ generated at loop level: $\chi \sim 10^{-3} - 10^{-4}$
  - hidden photon mass $m_{\gamma'} \sim \text{GeV}$

[Holdom '86; Galison, Manohar '84]
Production

- $\gamma'$ emitted from $e^-$-beam
  in process similar to ordinary Bremsstrahlung

- **production cross section**

Weizäcker-Williams approximation

(replace target particle $N$ by flux of effective photons $\Phi(Z)$)

$$
\frac{d\sigma_{\gamma'}}{dx_e} \approx 0 \overset{m_e \to 0}{\sim} \frac{4 \alpha^3 \chi^2}{m^2_{\gamma'}} \Phi(Z) \sqrt{1 - \frac{m^2_{\gamma'}}{E^2_{\gamma}}} \left(1 + \frac{x^2_e}{3(1 - x_e)}\right)
$$

$$
\sigma \propto \alpha^3 Z^2 \frac{\chi^2}{m^2_{\gamma'}} \approx \mathcal{O}(10 \text{ pb})
$$

compared to $e^+e^-$ collider case:

$$
\sigma \propto \frac{\alpha^2 \chi^2}{E^2} \sim \mathcal{O}(10 \text{ fb})
$$
Decay

- $\gamma'$ can penetrate the dump
  - carrying most of beam energy
  - emitted in forward direction

- decay into SM particles
  $$\Gamma_{\gamma' \to \ell^+ \ell^-} \approx \frac{\alpha \chi^2}{3} m_{\gamma'}$$

- exponential decay with a decay length
  $$l_{\gamma'} = \gamma' \beta c \tau_{\gamma'} \approx \frac{E_{\gamma'}}{\alpha \chi^2 m^2_{\gamma'}}$$
  $$\approx 10\text{cm} \frac{E_{\gamma'}}{1\text{GeV}} \left(\frac{10^{-4}}{\chi}\right)^2 \left(\frac{10\text{MeV}}{m_{\gamma'}}\right)^2$$
  $$\approx \mathcal{O}(\text{mm} - \text{km})$$
Detection

- decay must take place within decay volume to be observable
- detect decay products, mostly $e^+e^-$
  no SM background (if shield long enough)
- number of expected events from $\gamma'$ produced in bremsstrahlung detected via decay products:

$$N_{\text{events}} \sim N_e n_{\text{sh}} \int dE_{\gamma'} \int dE_e \int dl \ L(e_0, E_e, l) \frac{d\sigma_{\gamma'}}{dE_{\gamma'}} e^{-L_{\text{sh}}/l_{\gamma'}} \left(1 - e^{-L_{\text{dec}}/l_{\gamma'}}\right) \text{BR}_{e^+e^-}$$

energy distribution $L(e_0, E_e, l)$ of electrons in dump has to be taken into account
Events in Experiment

- **not all** events can be detected
  - geometry of set-up
  - finite detector size
  - possibly energy cuts

- compare with events from Monte Carlo simulations with MadGraph
  - four-momentum of produced $\gamma'$
  - four-momenta of decay leptons
    - angles, track, energies

$\Rightarrow$ experimental acceptance
Shape & Experimental Limitations

$\gamma'$ has to penetrate $\mathcal{O}(10 \text{ cm})$ dump

number of events for $l_{\gamma'} \ll L_{sh}$:

$$N_{\text{events}} \propto N_e e^{-L_{sh}/l_{\gamma'}}$$

$$l_{\gamma'} \propto E_{\gamma'}/\chi^2 m_{\gamma'}^2$$

enough decays within decay volume

number of events for small $\chi$:

$$N_{\text{events}} \propto N_e \sigma \left( e^{-L_{sh}/l_{\gamma'}} - e^{-L_{tot}/l_{\gamma'}} \right)$$

$$\propto N_e \sigma \frac{L_{\text{dec}}}{l_{\gamma'}} \quad \text{for} \quad l_{\gamma'} \gg L_{sh,\text{dec}}$$

$$\propto N_e \frac{\chi^2}{m_{\gamma'}^2} \chi^2 m_{\gamma'}^2, L_{\text{dec}} \propto N_e \chi^4 L_{\text{dec}}$$

$\Rightarrow$ independent of $m_{\gamma'}$
**Shape & Experimental Limitations**

- **γ'** has to penetrate \( \mathcal{O}(10 \text{ cm}) \) dump

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  \]

- Enough decays within decay volume

  number of events for small \( \chi \):
  
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  \[\Rightarrow \text{ independent of } m_{\gamma'}\]

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- Experimental acceptance from Monte Carlo simulations with MadGraph

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\( \Rightarrow \) independent of \( m_{\gamma'} \)

Experimental acceptance from Monte Carlo simulations with MadGraph
Shape & Experimental Limitations

\[ \gamma' \] has to penetrate \( \mathcal{O}(10 \text{ cm}) \) dump

Number of events for \( I_{\gamma'} \ll L_{\text{sh}} \):

\[
N_{\text{events}} \propto N_e e^{-L_{\text{sh}}/I_{\gamma'}}
\]

\[ I_{\gamma'} \propto E_{\gamma'}/\chi^2 m^2_{\gamma'} \]

Enough decays within decay volume

Number of events for small \( \chi \):

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\[ \Rightarrow \text{independent of } m_{\gamma'} \]

Experimental acceptance from Monte Carlo simulations with MadGraph
Shape & Experimental Limitations

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number of events for \( l_{\gamma'} \ll L_{sh} \):

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eff

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experimental acceptance
from Monte Carlo simulations with MadGraph
Limits from Experiments

▶ KEK Japan (1986) [Konaka et al. ’86]
  - 27 mC electrons at 2.5 GeV
  - shield: 3.5 cm tungsten target, 2.4 m iron
  - decay volume: 2.2 m

▶ Orsay France (1989) [Davier, Nguyen Ngoc ’89]
  - 3.2 mC electrons at 1.6 GeV
  - shield: 65 cm tungsten target, 1 m lead
  - decay channel: 2 m inside concrete wall

▶ SLAC E141 (1987) [Riordan et al. ’87]
  - 0.32 mC electrons at 9 GeV
  - shield: 12 cm tungsten; decay volume: 35 m

▶ SLAC E137 (1988) [Bjorken et al. ’88]
  - 30 C electrons at 20 GeV
  - shield: alu, 179 m rock; decay volume: 204 m

▶ Fermilab E774 (1991) [Bross et al. ’91]**
  - 0.83 nC electrons at 275 GeV
  - shield: 30 cm tungsten
  - decay volume: 2 m

[SA, Niebuhr, Ringwald]
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3. Hidden Dark Matter
   - Toy Model
   - Supersymmetric Model

4. Conclusions & Outlook
Toy Model: Dirac fermion DM

Simplest hidden sector with DF & DM

Hidden Photon with mass $m_{\gamma'}$ and mixing $\chi$

Additional Dirac fermion $\psi$

- one extra mass parameter $m_{\psi}$

Relic abundance $\Omega h^2$

- annihilation of $\psi$ through and into $\gamma'$
- s-channel: resonance for $m_{\gamma'} = 2 m_{\psi}$
- t-channel only when $m_{\gamma'} < m_{\psi}$

$\Rightarrow \psi$ total DM or subdominant component

$\chi = \frac{g_Y g_H}{16 \pi^2} \times \kappa$
Toy Model: Dirac fermion DM

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$[\text{Fayet '04; Pospelov, Ritz, Voloshin '08; Cheung, Ruderman, Wang, Yavin '09; Morrissey, Poland, Zurek '09; Dudas, Mambrini, Pokorski, Romagnoni '09; Chun, Park '10; Essig, Kaplan, Schuster, Toro '10; Mambrini '10; Cline, Frey '12; Hooper, Weiner, Xue '12}]$

$[\text{SA, Goodsell, Ringwald '11}]$
Toy Model: Dirac fermion DM

Direct Detection

- elastic scattering on nuclei
- mediated by $\gamma'$
- spin-independent vector-like interaction

\[
\psi \rightarrow \gamma' \rightarrow \psi
\]

Comparison with experiments

- signal claims by DAMA, CoGeNT, CRESST, CDMS
- limits on $\sigma_{SI}$: XENON10 & 100, DAMIC

[SA, Goodsell, Ringwald '11]
Supersymmetric Dark Force models

- most simple anomaly-free HS:
  - three chiral superfields $S$, $H^+$, $H^-$ charged under $U(1)_h$
  - superpotential: $W \supset \lambda_S \, S H^+ H^-$
    (assume MSSM in visible sector)

- consider gravity mediation [Morrissey, Poland, Zurek '09]
  - gravitino is not the LSP
  - DM can consist of stable hidden sector particle
    is either Majorana or Dirac fermion

- hidden gauge symmetry breaking:
  - radiatively through running
  - induced by visible sector
Radiative breaking

- running of Yukawa coupling $\lambda_S$ induces breaking
  - choose masses & couplings at high scale
- Majorana fermion $\Psi_M$: total & subdominant DM
  - axial coupling generates SD scattering
  - minor SI scattering (Higgs Portal $\sim 10^{-46}\text{cm}^{-2}$)

$\Rightarrow$ SD in reach of experiments  SI beyond reach
Visible sector induced breaking

- via effective Fayet-Iliopoulos term
  - assume gravitino heavier than HS

- Majorana & Dirac fermion as DM
  - $\Psi_M$: mostly SD (like rad. breaking)
  - $\Psi_D$: mostly SI (like Toy-Model, but $m_\Psi < m_{\gamma'}$)

$0.1 \leq \kappa \leq 10$

$\Rightarrow$ SI probe $\Psi_D$  SD probe $\Psi_M$
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Conclusions & Outlook

- **electron beam dump experiments**
  - cover lower left corner of the parameter space
  - extending the limits
    - upwards requires short $L_{sh}$ and/or high $E_0$
    - downwards requires long $L_{dec}$ and/or large $N_e$
  - which electron beams are available in the future?
  - can they be used parasitically for new bounds?

- **dark matter in hidden sector**
  - viable models with large parameter space
  - SUSY models with gravity mediation also possible
  - what is the preferred parameter space?
  - constraints from indirect detection?