# Hidden Photons in Beam Dump Experiments

## and in connection with Dark Matter

Sarah Andreas
DESY

April 26th, 2013

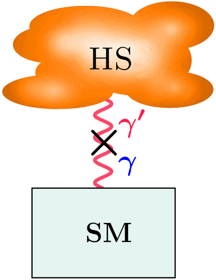
Intensity Frontier Workshop

based on: 1209.6083 and 1109.2869

with M. Goodsell, C. Niebuhr, A. Ringwald

# Outline

# Hidden Sector with Hidden Photon



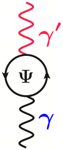

- Hidden Sectors in many BSM scenarios

  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 $\chi$



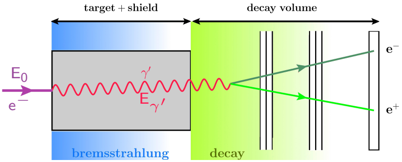

[Holdom '86; Galison, Manohar '84]

- 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 $m_{\gamma'} \sim \text{GeV}$

# Production




- $\gamma'$ emitted from $e^-$-beam

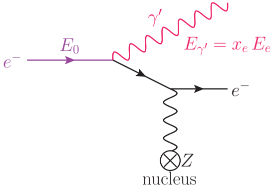
  in process similar to ordinary Bremsstrahlung

- production cross section

  Weizäcker-Williams approximation [Kim, Tsai '73; Tsai '74; Tsai '86; Bjorken, Essig, Schuster, Toro '09]

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

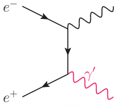
$$\frac{d\sigma_{\gamma'}}{dx_e} \overset{m_e \to 0}{\simeq} \frac{4\,\alpha^3\,\chi^2}{m^2_{\gamma'}}\,\Phi(Z)\,\sqrt{1-\frac{m^2_{\gamma'}}{E_e^2}}\left(1+\frac{x_e^2}{3(1-x_e)}\right)$$



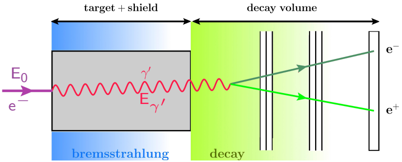

$$\sigma \;\propto\; \alpha^3 Z^2 \frac{\chi^2}{m^2_{\gamma'}} \;\simeq\; \mathcal{O}(10\text{ pb})$$

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

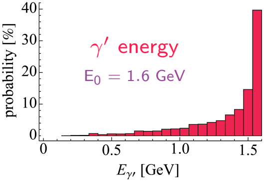
$\sigma \propto \frac{\alpha^2\chi^2}{E^2} \sim \mathcal{O}(10\text{ fb})$



# Decay



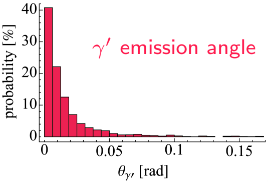

- $\gamma'$ can penetrate the dump
  - carrying most of beam energy
  - emitted in forward direction




- decay into SM particles

$$\Gamma_{\gamma' \to \ell^+ \ell^-} \simeq \frac{\alpha \chi^2}{3} m_{\gamma'}$$

- exponential decay with a decay length

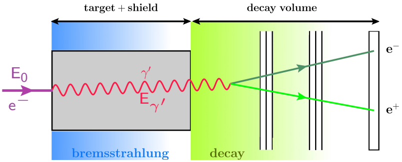



$$l_{\gamma'} = \gamma \beta c \tau_{\gamma'} \sim \frac{E_{\gamma'}}{\alpha \chi^2 m_{\gamma'}^2}$$

$$\sim 10\text{cm} \; \frac{E_{\gamma'}}{1\text{GeV}} \left(\frac{10^{-4}}{\chi}\right)^2 \left(\frac{10\text{MeV}}{m_{\gamma'}}\right)^2$$

$$\sim \mathcal{O}(\text{mm} - \text{km})$$

# Detection

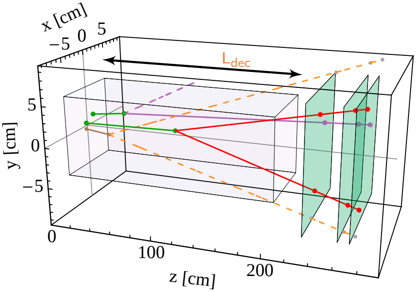



- decay must take place within decay volume to be observable
- detect decay products, mostly $e^+e^-$
  no SM background (if shield long enough)
- number of expected events from $\gamma'$ produced in bremsstrahlung detected via decay products:

$$N_{\text{events}} \sim N_e \; n_{\text{sh}} \int dE_{\gamma'} \int dE_e \int dl \;\; I_e(E_0, E_e, l) \; \frac{d\sigma_{\gamma'}}{dE_{\gamma'}} \; e^{-L_{\text{sh}}/l_{\gamma'}} \left(1 - e^{-L_{\text{dec}}/l_{\gamma'}}\right) \text{BR}_{e^+e^-}$$

energy distribution $I_e(E_0, E_e, l)$ 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

  $\longrightarrow$ angles, track, energies

$\Rightarrow$ experimental acceptance

[Monte Carlo by Rouven Essig, Philip Schuster, Natalia Toro]

# Shape & Experimental Limitations

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

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

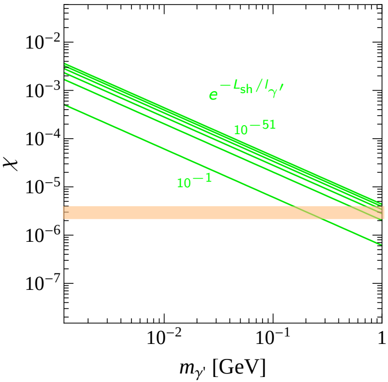
$$N_{events} \propto N_e \, e^{-L_{sh}/l_{\gamma'}}$$
$$l_{\gamma'} \propto E_{\gamma'}/\chi^2 \, m^2_{\gamma'}$$

## enough decays within decay volume

number of events for small $\chi$:

$$N_{events} \propto N_e \, \sigma \left(e^{-L_{sh}/l_{\gamma'}} - e^{-L_{tot}/l_{\gamma'}}\right)$$
$$\propto N_e \, \sigma \, \frac{L_{dec}}{l_{\gamma'}} \quad \text{for} \quad l_{\gamma'} \gg L_{sh,dec}$$
$$\propto N_e \, \frac{\chi^2}{m^2_{\gamma'}} \, \chi^2 m^2_{\gamma'} \, L_{dec} \quad \propto N_e \, \chi^4 L_{dec}$$

$\Rightarrow$ independent of $m_{\gamma'}$



# Shape & Experimental Limitations

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

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

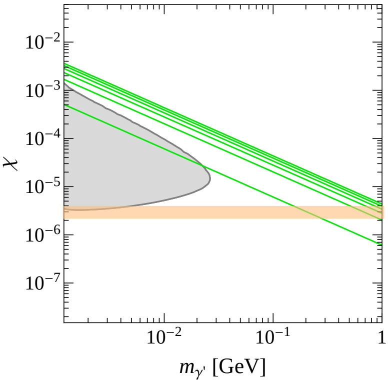
$$N_{events} \propto N_e \; e^{-L_{sh}/l_{\gamma'}}$$
$$l_{\gamma'} \propto E_{\gamma'}/\chi^2 \; m^2_{\gamma'}$$

### enough decays within decay volume

number of events for small $\chi$:

$$N_{events} \propto N_e \; \sigma \left( e^{-L_{sh}/l_{\gamma'}} - e^{-L_{tot}/l_{\gamma'}} \right)$$
$$\propto N_e \; \sigma \; \frac{L_{dec}}{l_{\gamma'}} \qquad \text{for} \quad l_{\gamma'} \gg L_{sh,dec}$$
$$\propto N_e \; \frac{\chi^2}{m^2_{\gamma'}} \; \chi^2 m^2_{\gamma'} \; L_{dec} \qquad \propto N_e \; \chi^4 L_{dec}$$

$\Rightarrow$ 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 $l_{\gamma'} \ll L_{sh}$:

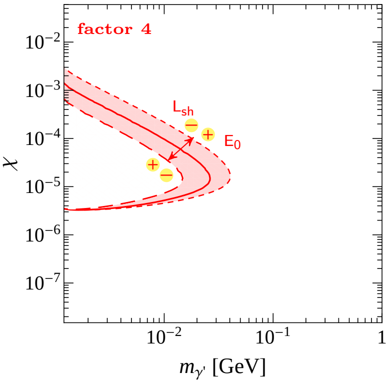
$$N_{events} \propto N_e \, e^{-L_{sh}/l_{\gamma'}}$$
$$l_{\gamma'} \propto E_{\gamma'}/\chi^2 \, m^2_{\gamma'}$$

## enough decays within decay volume

number of events for small $\chi$:

$$N_{events} \propto N_e \, \sigma \left(e^{-L_{sh}/l_{\gamma'}} - e^{-L_{tot}/l_{\gamma'}}\right)$$
$$\propto N_e \, \sigma \, \frac{L_{dec}}{l_{\gamma'}} \qquad \text{for} \quad l_{\gamma'} \gg L_{sh,dec}$$
$$\propto N_e \, \frac{\chi^2}{m^2_{\gamma'}} \, \chi^2 m^2_{\gamma'} \, L_{dec} \quad \propto N_e \, \chi^4 L_{dec}$$

$\Rightarrow$ 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 $l_{\gamma'} \ll L_{sh}$:

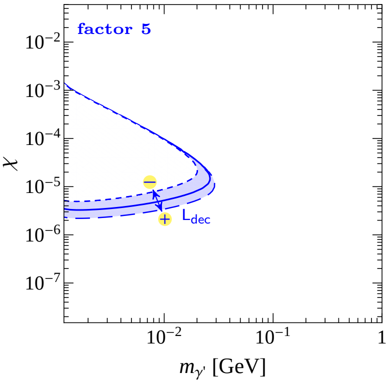
$$N_{events} \propto N_e\, e^{-L_{sh}/l_{\gamma'}}$$
$$l_{\gamma'} \propto E_{\gamma'}/\chi^2\, m^2_{\gamma'}$$

## enough decays within decay volume

number of events for small $\chi$:

$$N_{events} \propto N_e\, \sigma \left(e^{-L_{sh}/l_{\gamma'}} - e^{-L_{tot}/l_{\gamma'}}\right)$$
$$\propto N_e\, \sigma\, \frac{L_{dec}}{l_{\gamma'}} \qquad \text{for} \quad l_{\gamma'} \gg L_{sh,dec}$$
$$\propto N_e\, \frac{\chi^2}{m^2_{\gamma'}}\, \chi^2 m^2_{\gamma'}\, L_{dec} \quad \propto N_e\, \chi^4 L_{dec}$$

$\Rightarrow$ 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 $l_{\gamma'} \ll L_{sh}$:

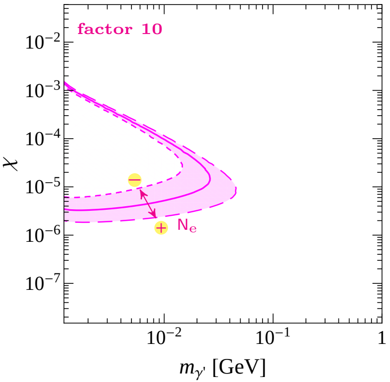
$$N_{events} \propto N_e \; e^{-L_{sh}/l_{\gamma'}}$$
$$l_{\gamma'} \propto E_{\gamma'}/\chi^2 \; m^2_{\gamma'}$$

## enough decays within decay volume

number of events for small $\chi$:

$$N_{events} \propto N_e \; \sigma \left(e^{-L_{sh}/l_{\gamma'}} - e^{-L_{tot}/l_{\gamma'}}\right)$$
$$\propto N_e \; \sigma \frac{L_{dec}}{l_{\gamma'}} \quad \text{for} \quad l_{\gamma'} \gg L_{sh,dec}$$
$$\propto N_e \frac{\chi^2}{m^2_{\gamma'}} \chi^2 m^2_{\gamma'} \; L_{dec} \quad \propto N_e \, \chi^4 L_{dec}$$

$\Rightarrow$ independent of $m_{\gamma'}$

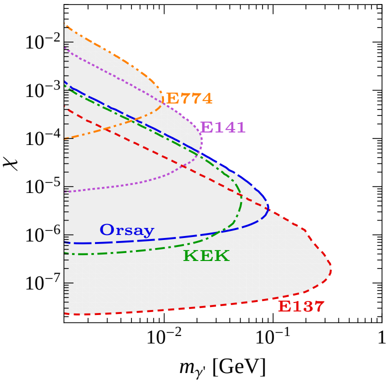



## experimental acceptance

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)**
  - 0.83 nC electrons at 275 GeV
  - shield: 30 cm tungsten
  - decay volume: 2 m [Bross *et al.* '91]

[Bjorken, Essig, Schuster, Toro '09]

[SA, Niebuhr, Ringwald]

# 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

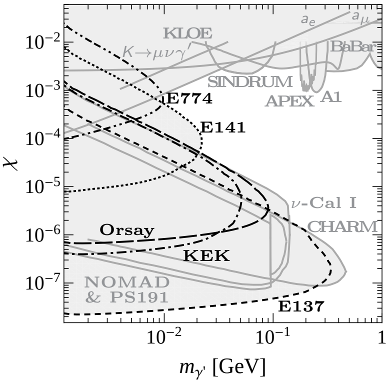
▶ SLAC E141 (1987) [Riordan *et al.* '87]

- 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

[SA, Niebuhr, Ringwald]




▶ Fermilab E774 (1991)

- 0.83 nC electrons at 275 GeV
- shield: 30 cm tungsten
- decay volume: 2 m

[Bross *et al.* '91]

[Bjorken, Essig, Schuster, Toro '09]

# Outline

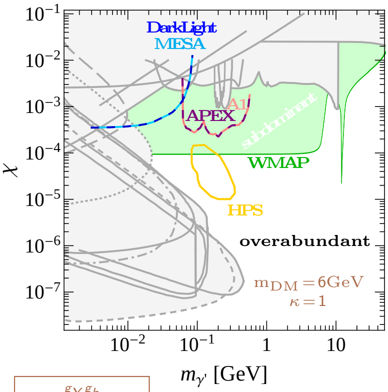
# Toy Model: Dirac fermion DM

Simplest hidden sector with DF & DM

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

Additional Dirac fermion $\psi$

- one extra mass parameter $m_\psi$

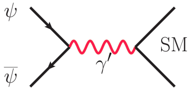


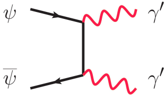

$$\chi = \frac{g_Y g_h}{16\pi^2} \times \kappa$$

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




[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]

[SA, Goodsell, Ringwald '11]

# Toy Model: Dirac fermion DM

Simplest hidden sector with DF & DM

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

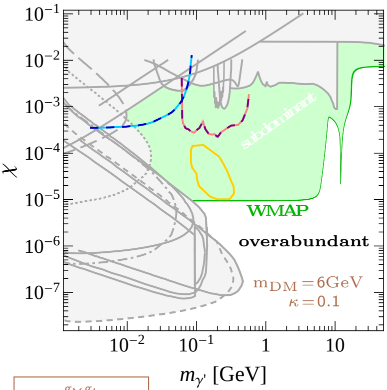
Additional Dirac fermion $\psi$

- one extra mass parameter $m_\psi$

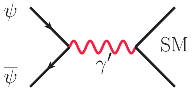
Relic abundance $\Omega h^2$

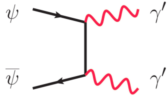
- annihilation of $\psi$ through and into $\gamma'$
- s-channel: resonance for $m_{\gamma'} = 2\ m_\psi$
- t-channel only when $m_{\gamma'} <\ m_\psi$

$\Rightarrow$ $\psi$ total DM or subdominant component




$$\chi = \frac{g_Y g_h}{16\pi^2} \times \kappa$$



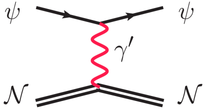

[Fayet '04; Pospelov, Ritz, Voloshin '08; Cheung, Ruderman, Wang, Yavin '09; Morrissey, Poland, Zurek '09; Dudas, Mambrini, Pokorski, Romagnoni '09; Chun, Park '10; Essig, Kaplan, Schuster, Toro '10; Mambrini '10; Cline, Frey '12; Hooper, Weiner, Xue '12]

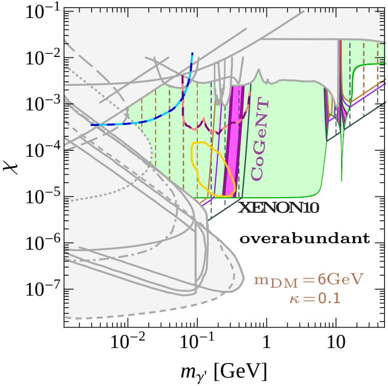
[SA, Goodsell, Ringwald '11]

# Toy Model: Dirac fermion DM

## Direct Detection

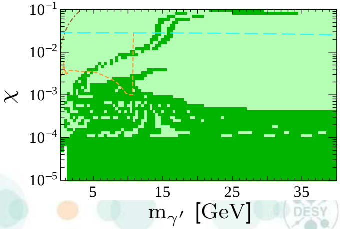
- elastic scattering on nuclei
- mediated by $\gamma'$
- spin-independent vector-like interaction




## 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 $\mathrm{U}(1)_h$
  - superpotential: $W \supset \lambda_S\, S H_+ H_-$

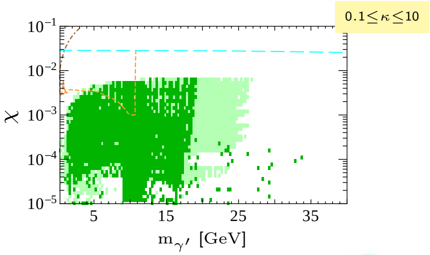
    (assume MSSM in visible sector)
- consider gravity mediation gauge med. in [Morrissey, Poland, Zurek '09]
  - gravitino is not the LSP
  - DM can consist of stable hidden sector particle

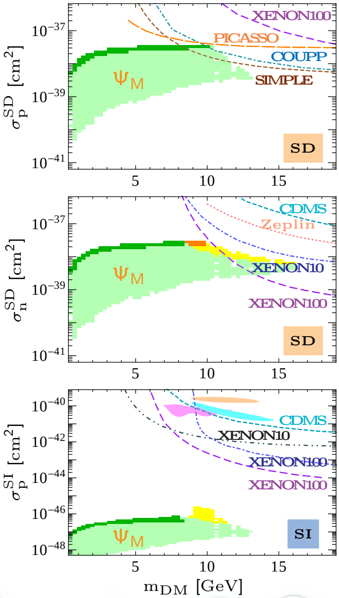
    is either Majorana or Dirac fermion
- hidden gauge symmetry breaking:
  - radiatively through running
  - induced by visible sector

[SA, Goodsell, Ringwald '11]

# 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 $\sim 10^{-46}\text{cm}^{-2}$)



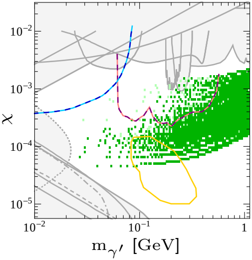



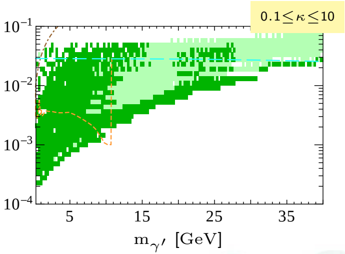

⇒ SD in reach of experiments | SI bejond reach

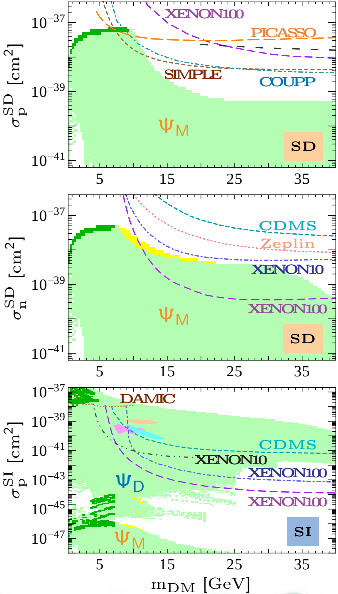
[SA, Goodsell, Ringwald '11]

# 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 $m_\Psi < m_{\gamma'}$)



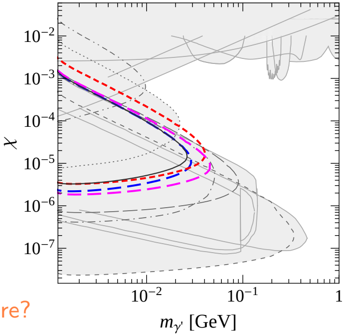




⇒ SI probe $\Psi_D$ SD probe $\Psi_M$

[SA, Goodsell, Ringwald '11]

# Outline

# 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?