Probing a GeV Dark Sector at Colliders

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Based on:
M. Baumgart, C. Cheung, J. Ruderman, LTW, I. Yavin, arXiv:0901.0283
C. Cheung, J. Ruderman, LTW, I. Yavin, arXiv:0902.3246
Matt Reece and LTW, arXiv:0904.1743
C. Cheung, J. Ruderman, LTW, I. Yavin, arXiv:0909.0290
More information at: http://phy-hal.princeton.edu/LeptonJets/index.html (work in propress)

Outline

- Introduction to GeV dark sector
  - Motivation
  - Basic structure
- Survey of signatures and search channels.
- Conclusion.

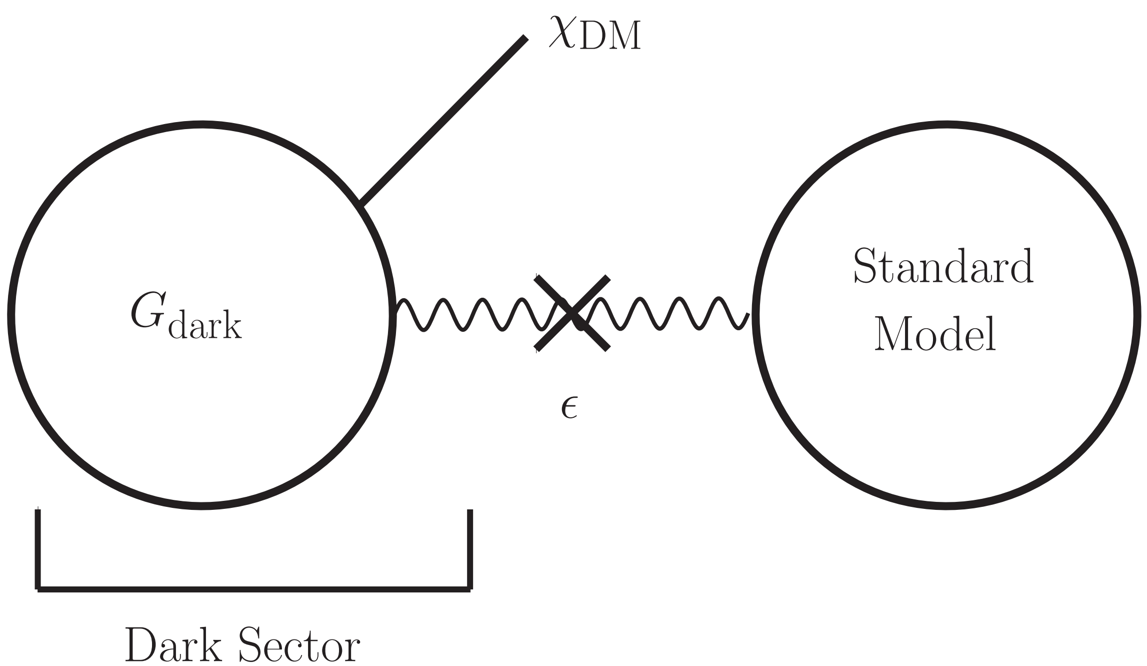
What is a GeV dark sector?

- Dark matter self-interaction, mediated by

$$b_{\mathrm{dark}} \subset \text{dark sector.}$$

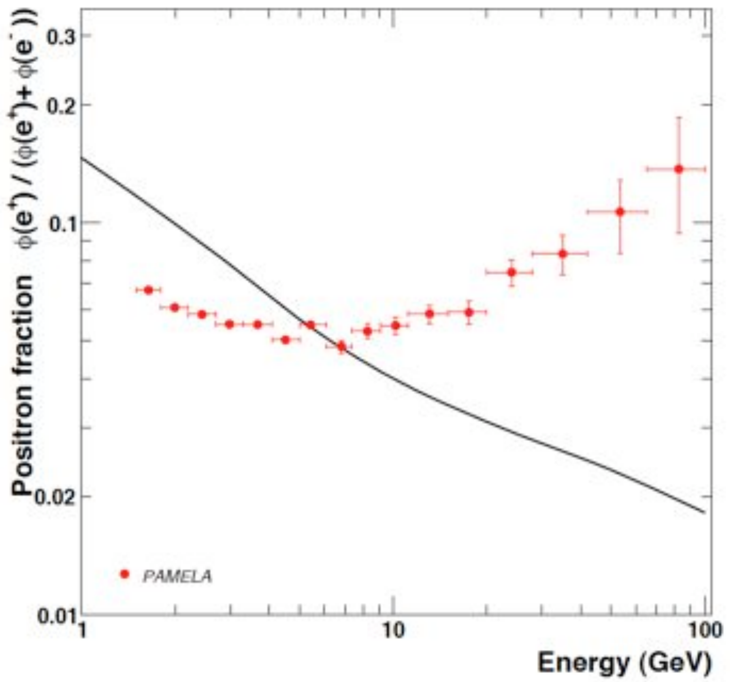
Many scenarios, for example: J. Feng and J Kumar, arXiv:0803.4196

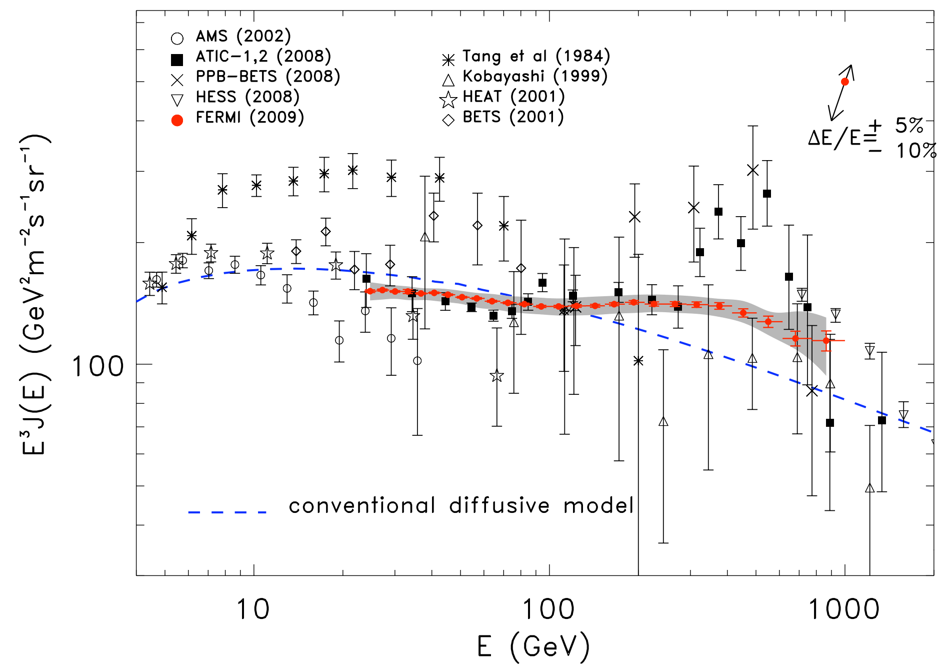
- In addition:
  - Range of dark force $m_{b_{\mathrm{dark}}} \sim 100s\ \mathrm{MeV} - \mathrm{GeV}$
  - Dark sector couples to SM with tiny couplings, parameterized by ϵ Typically: $\epsilon \leq 10^{-3}$



Motivation: dark matter annihilation

- Excesses in cosmic-ray electron and positron.





PAMELA: O. Adriani, et al., arXiv:0810.4995

Fermi-LAT: Abdo, et. al. arXiv:0905.0025

Also: ATIC, PPB-BETS, EGRET.

Astrophysics interpretation possible.
Here, we focus on the hypothesis of dark matter annihilation as source to the excess.
Leading to testable predictions.

DM interpretation of the excesses:

Arkani-Hamed, Finkbeiner, Slatyer, Weiner 0810.0713
Arkani-Hamed, Weiner 0810.0714
also see Pospelov, Ritz, Voloshin 0711.4866

- Correct thermal relic density fixes DM annihilation rate:

$$\Omega_{\rm DM} h^2 = 0.1 \times \left(\frac{< \sigma v >_{\rm freeze-out}}{3 \times 10^{-26}\ {\rm cm}^3\ {\rm s}^{-1}} \right)^{-1}$$

- Cosmic ray flux:

$$R_{e^+,\gamma,\bar{p}\ldots} \propto (n_{\rm DM}^{\rm halo2}) \times < \sigma v >_{\rm halo}$$

$$\text{Assume} \ \ < \sigma v >_{\rm halo} \simeq < \sigma v >_{\rm freeze-out} \ \rightarrow R_{e^+,\gamma,\bar{p}\ldots}$$

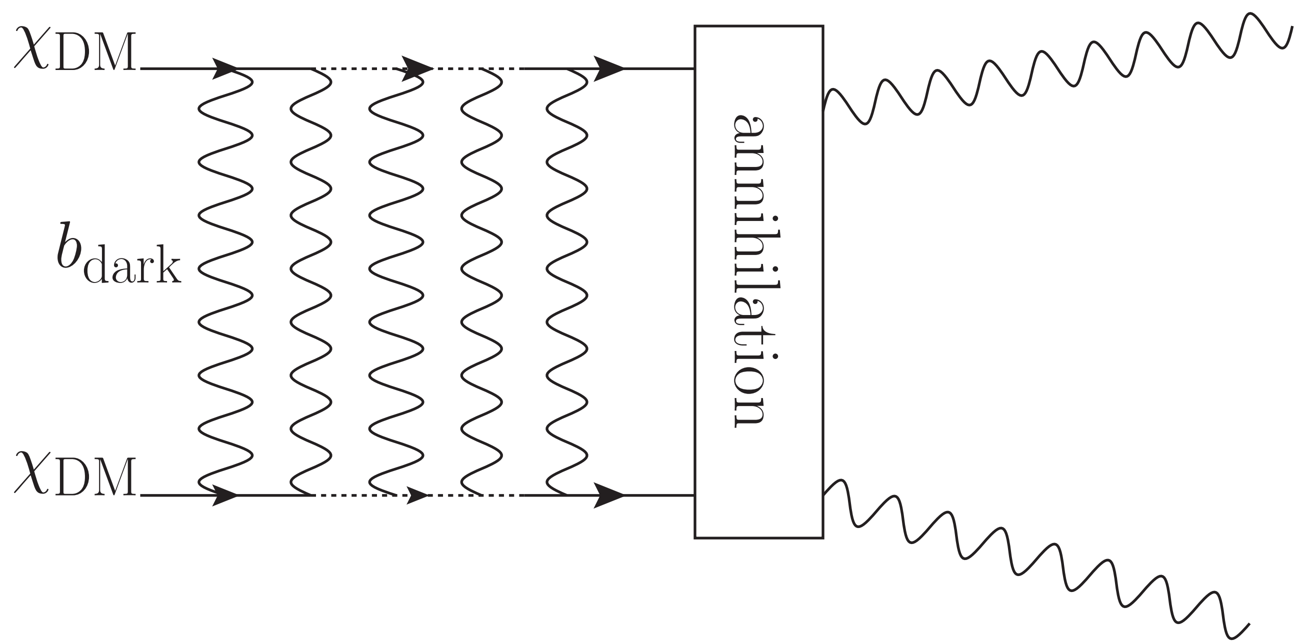
- Observed positron and electron excess needs an additional O(10s-100) enhancement.

  For example: P. Meade, M. Papucci, A. Strumia, T. Volansky, arXiv:0905.0480

- To preserve the success of relic density prediction, change late time physics.

  - Sommerfeld enhancement: $< \sigma v >_{\rm halo} \gg < \sigma v >_{\rm freeze-out}$

Sommerfeld enhancement



Earlier consideration:
J. Hisano, S. Matsumoto, M. Nojiri, and O. Saito, hep-ph/0412403
J. Hisano, S. Matsumoto, M. Nagai O. Saito, and M. Senami, hep-ph/0610249

Long range self-interaction of dark matter mediated by $b_{\rm dark}$

range$\sim m_b^{-1}$, coupling $\alpha_{\rm dark}$

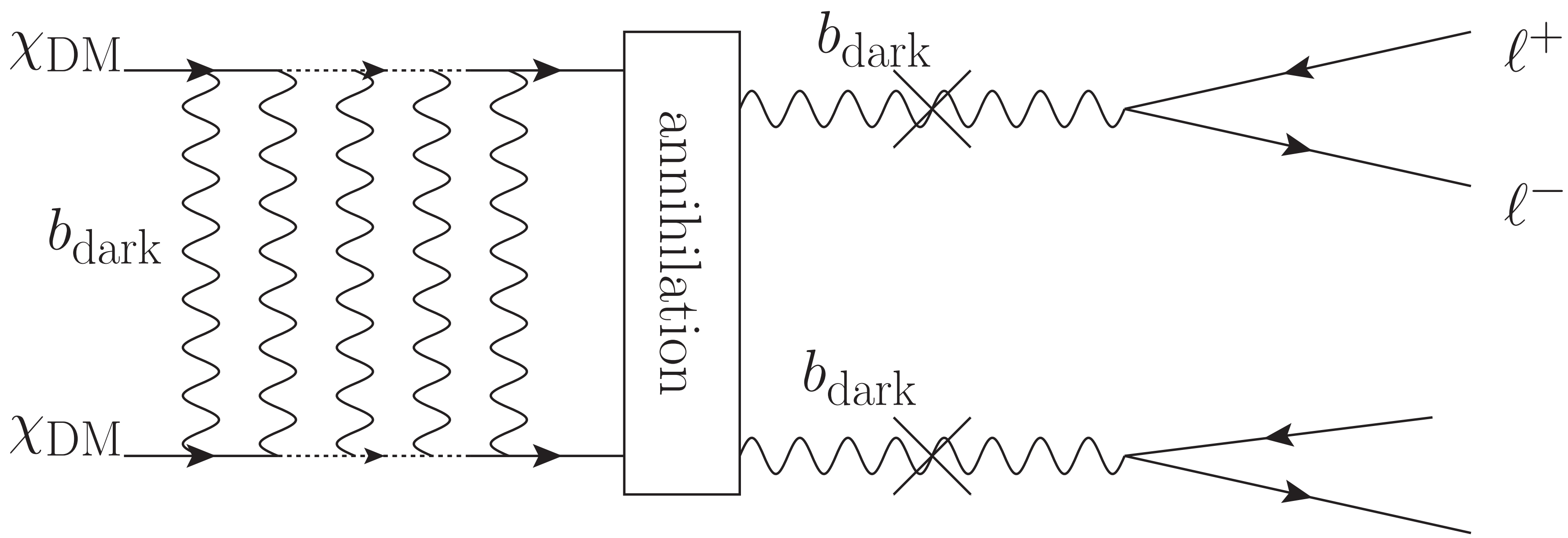
Enhancement sets in when $m_b \sim \alpha_{\rm dark} M_\chi$

Enhancement $\sim \alpha_{\rm dark}/v_{\rm halo}$, $v_{\rm halo} \sim 10^{-3}$.

Enhancement cuts off at $M_\chi \cdot v_{\rm halo} < m_b$.

$M_\chi \sim 10^2$ GeV, $\alpha_{\rm dark} \sim 0.1 - 0.01$, $\rightarrow m_b \sim$ GeV.

The observed signal at PAMELA/Fermi



- Dark matter annihilate into dark force carrier, which then decay to SM states, leading to observed excesses.
- Therefore, dark sector states must couple to the SM.
- The coupling has to be small to satisfy current constraints.

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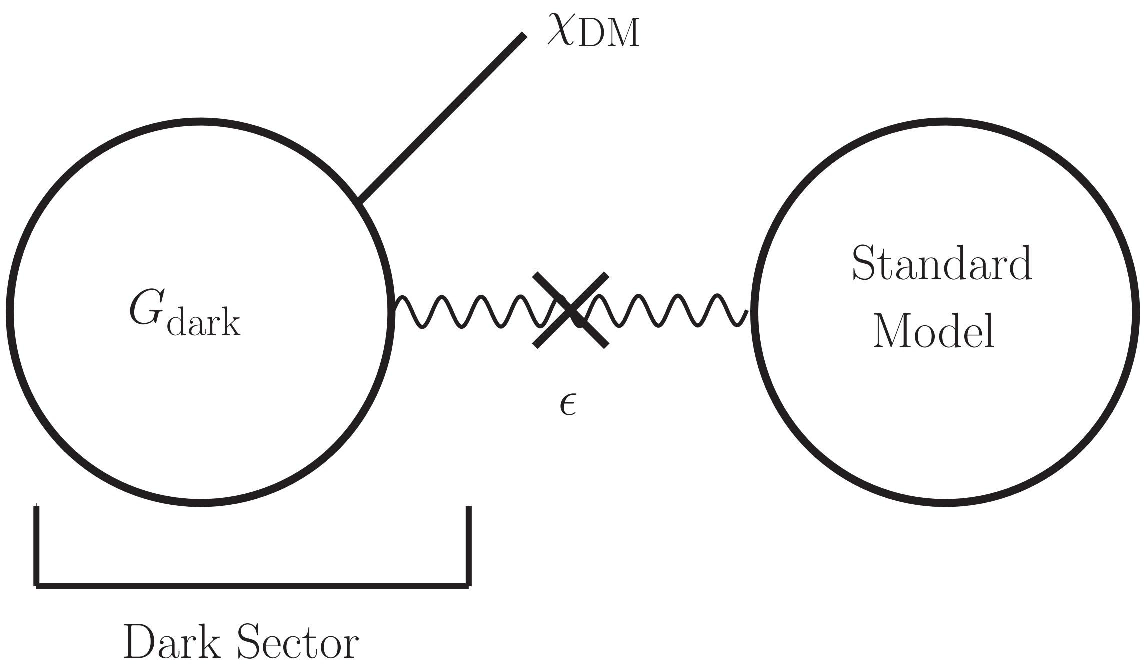
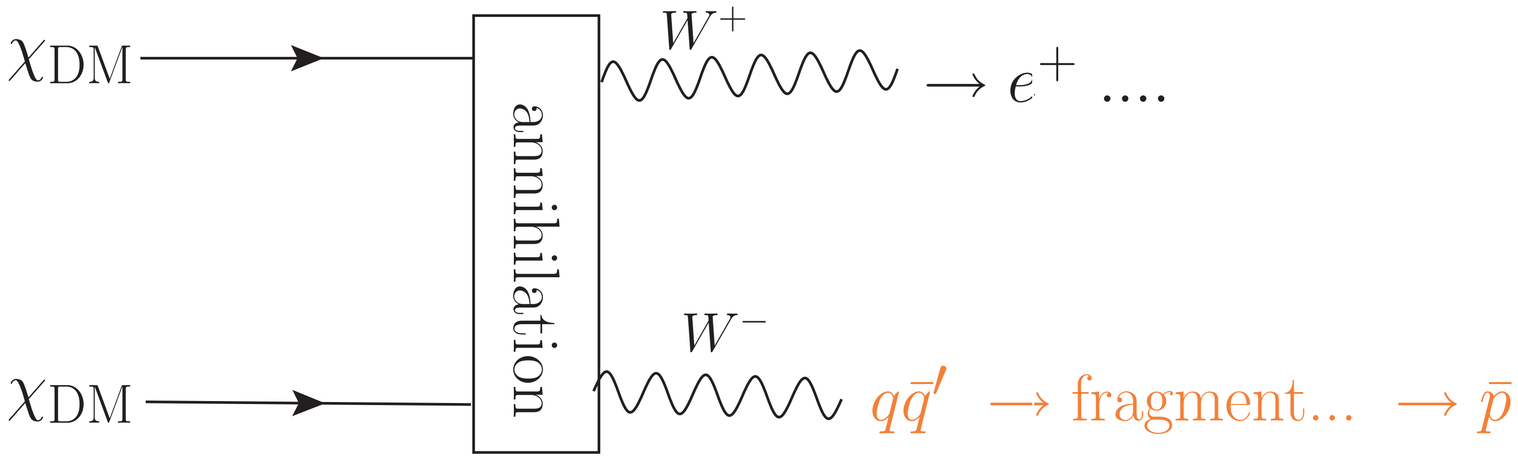
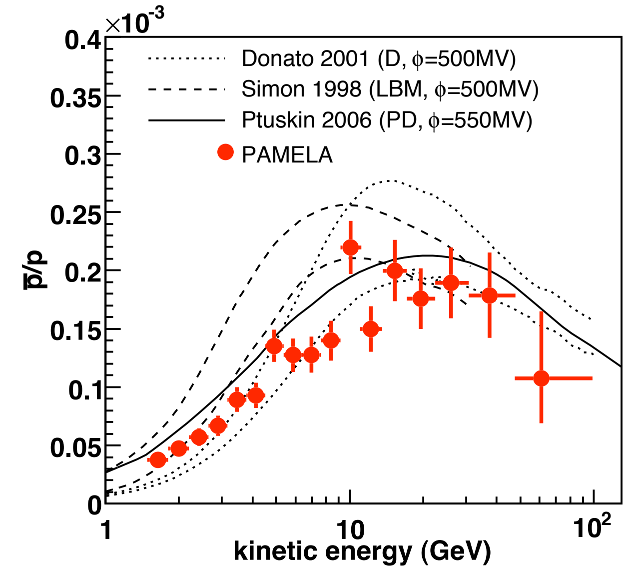


Solves anti-proton flux “puzzle”

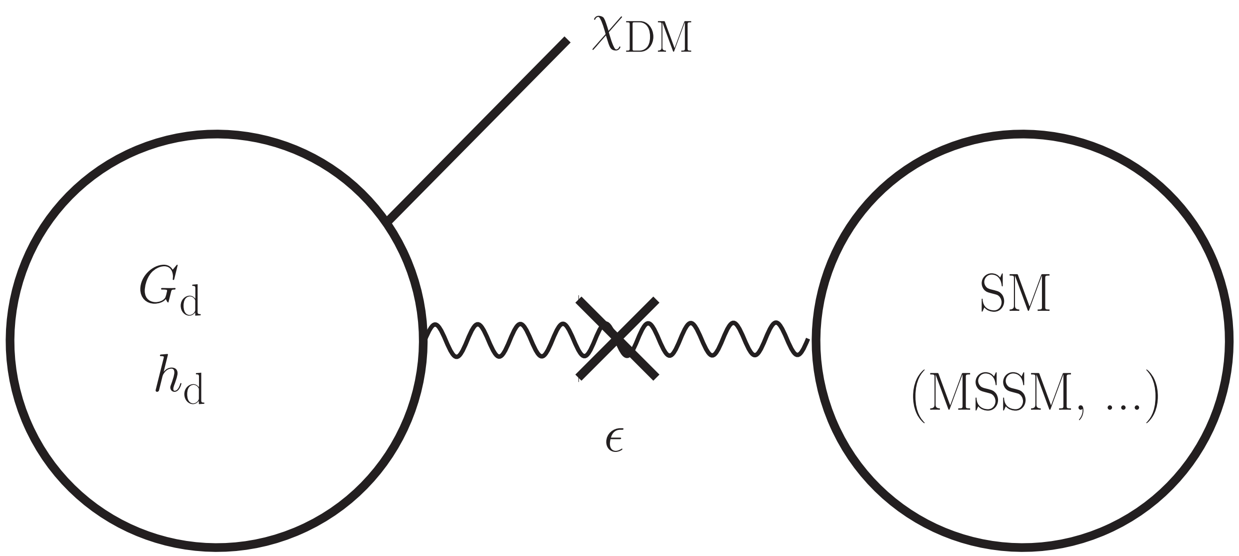




- Conventional WIMP annihilation also results in excess in anti-proton flux, not observed by PAMELA.

- Annihilation into GeV scale dark sector states and their subsequent decay will not generate anti-proton due to kinematical suppression.

Basic dark sector model ingredients:

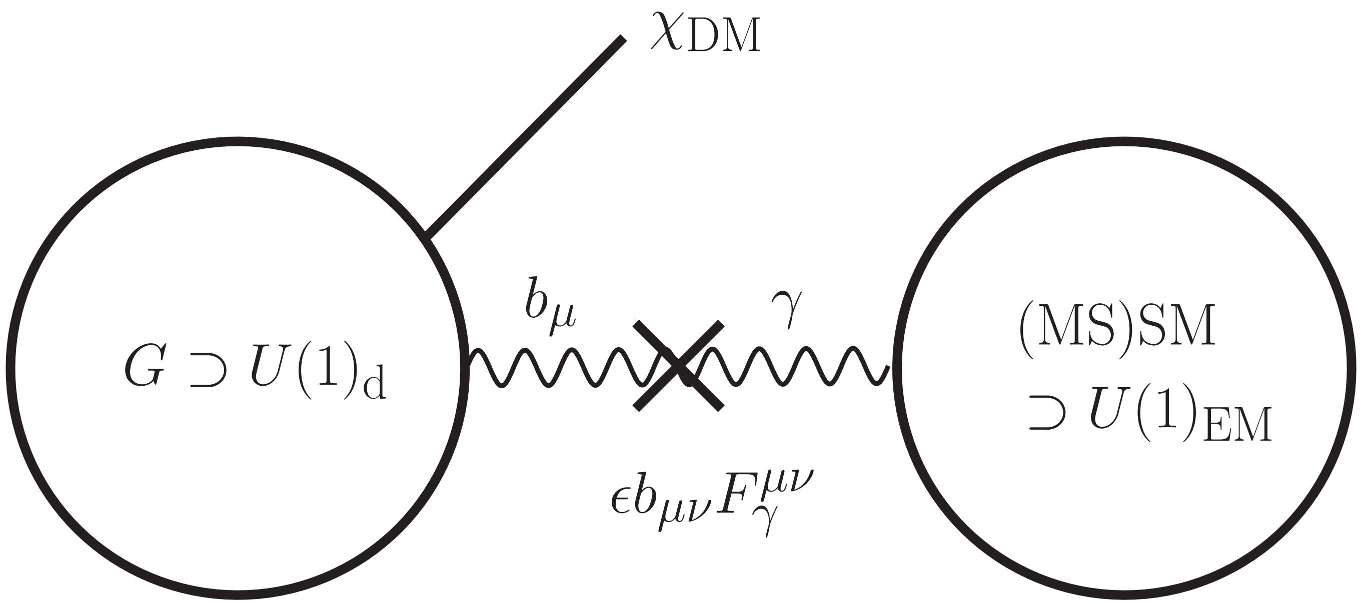


- Model choices:
  - Dark matter identity.
  - Self-interaction $G_{\rm d}$: gauge interaction...
  - GeV scale, dark higgs $h_{\rm d} : v_d = \langle h_d \rangle \sim \text{GeV}$
  - Supersymmetric scenarios: natural generation of the GeV Scale.

Various constructions:

- Earlier proposals:
  M. Pospelov, A. Ritz and M. Voloshin, arXiv:0711.4866
  N. Arkani-Hamed, D. Finkbeiner, T. Slatyer and N. Weiner, arXiv:0810.0713
- U(1) models:
  E. J. Chun and J. C. Park, arXiv:0812.0308
  C. Cheung, J. Ruderman, LTW, and I. Yavin, arXiv:0902.3246
  A. Katz and R. Sundrum, arXiv:0902.3271
  D. Morrissey, D. Poland and K. Zurek, arXiv:0904.2567
  J. Feng, M. Kaplinghat, H. Tu, H. B. Yu., arXiv:0905.3039
  M. Goodsell, J. Jaeckel, J. Redondo, and A. Ringwald, arXiv:0909.0515
- Non-abelian model, SUSY:
  M. Baumgart, C. Cheung, L.-T. Wang, J. Ruderman, I. Yavin, arXiv:0901.0283
- Scalar Portal:
  Y. Nomura and J. Thaler, arXiv:0810.5397
- Composite:
  D. Alves, S. Behbabani, P. Schuster, and J. Wacker, arXiv:0903.3945
- More...

Simplest choice: abelian dark sector



- Simplest self-interaction: $G_{\rm d} = U(1)_{\rm d}$
- Natural connection to the SM: kinetic mixing

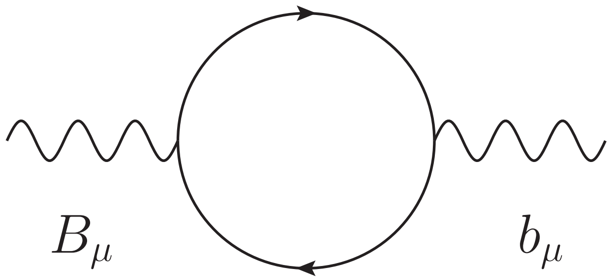
$$\mathcal{L}_{\rm kin.mix} = -\frac{\epsilon}{2} b_{\mu\nu} F_\gamma^{\mu\nu}$$

- Supersymmetry can be an elegant way of generating the GeV scale.

For a very simple and predictive construction:
C. Cheung, J. Ruderman, LTW and I. Yavin, arXiv:0902.3246
See also: D. E. Morrissey, D. Poland and K. M. Zurek, arXiv:0904.2567

Kinetic mixing:

- Expected to be there!
  - Kinetic mixing between dark photon and SM hypercharge gauge boson B_μ is generically present in extensions of the Standard Model.



$$\epsilon = \frac{g_d g_Y}{16\pi^2} \Sigma_i Q_d^i Q_Y^i \log\left(\frac{M_i^2}{\mu^2}\right)$$

- Expected to be small (consistent with constraints).

$$\epsilon \sim \frac{g_d g_Y}{16\pi^2} \log\left(\frac{M}{M'}\right) \sim 10^{-3} - 10^{-4}$$

Searching for the GeV dark sector:

- Motivated by evidence of dark matter from astrophysical observations.
- Laboratory experiment in controlled environment will provide the definitive tests.
- In addition to searching for 100 GeV - TeV DM particle at high energy colliders, there is good motivation for looking for the GeV sector.
- Dark sector couples very weakly to the SM particles, typically only to EW states.

Dark sector couplings to the SM

$$\begin{aligned}\mathcal{L}_{\text{gauge}} &\supset -\frac{1}{4}W_{3\mu\nu}W_3^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}b_{\mu\nu}b^{\mu\nu} + \frac{\epsilon}{2}B_{\mu\nu}b^{\mu\nu} \\ &= -\frac{1}{4}Z_{\mu\nu}Z^{\mu\nu} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}b_{\mu\nu}b^{\mu\nu} \\ &+ \frac{\epsilon}{2}\left(\cos\theta_W F_{\mu\nu} - \sin\theta_W Z_{\mu\nu}\right) b^{\mu\nu}\end{aligned}$$

$$\begin{aligned}A_\mu &\to A_\mu + \epsilon\cos\theta_W b_\mu \\ b_\mu &\to b_\mu - \epsilon\sin\theta_W Z_\mu\end{aligned}$$

$$\to V \supset \boxed{\epsilon\cos\theta_W b_\mu J^\mu_{\text{EM}}} - \epsilon\sin\theta_W Z_\mu J^\mu_{\text{dark}}$$

Couples just like the Standard Model photon, but with a suppressed coupling.

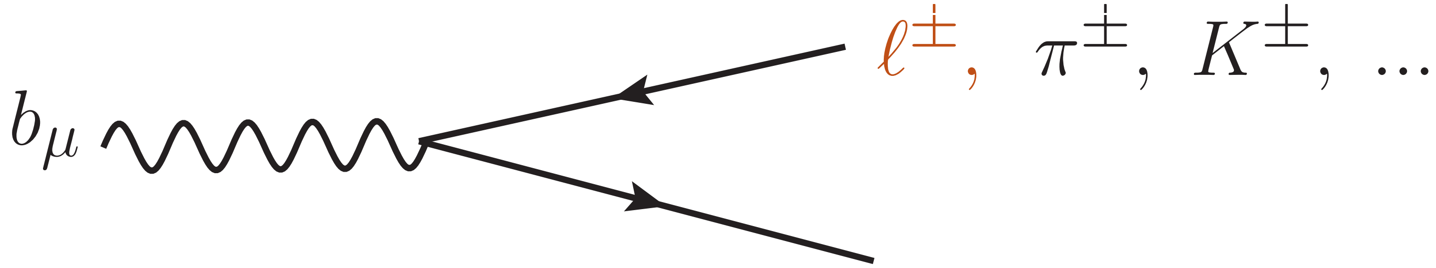
The "dark photon", sometimes also called

$$\gamma',\ \text{U-boson},\ V_\mu,\ \text{or}\ a_\mu.$$

Decay of dark photon:

- Dark photon is the only connection, "portal", to the Standard Model.

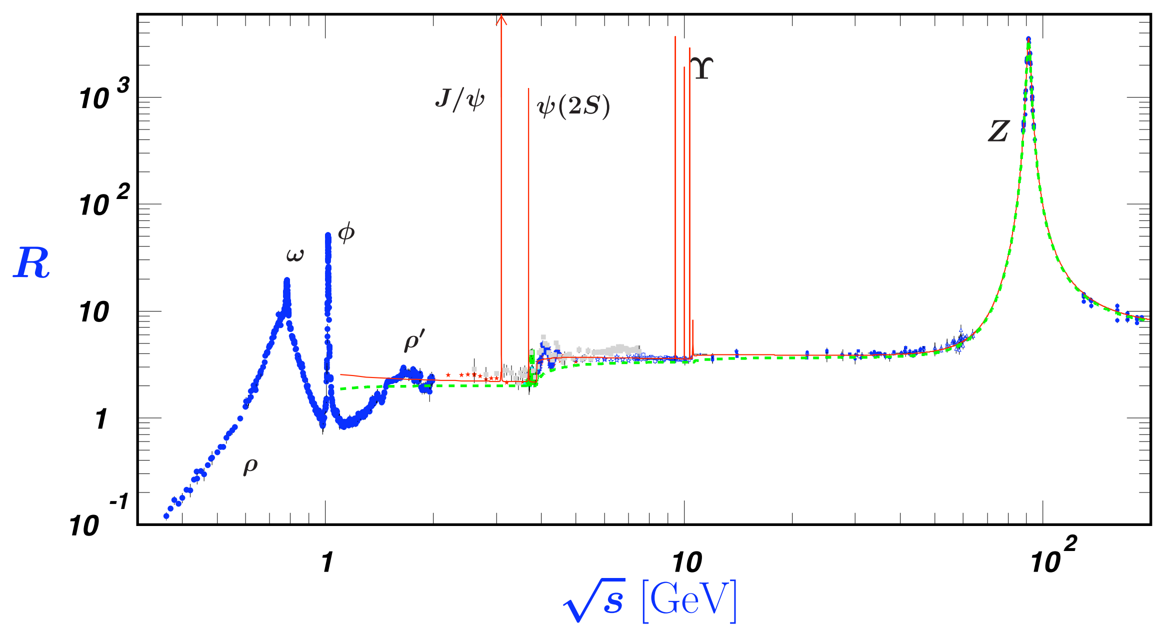
- Dark photon decay to SM is always the last stage of dark sector process, giving rise directly to observable signals.



- $m_{b_\mu} \sim 100\mathrm{s\ MeV} - \mathrm{GeV}$, form factors are important in determining decay branching ratios.

Dark Photon decay branching ratios:

- Decay form factor has been measured, known as R.



$$R(s) = \frac{\sigma(e^+e^- \to \text{hadrons},\ s)}{\sigma(e^+e^- \to \mu^+\mu^-,\ s)} = \frac{BR(b_\mu \to \text{hadrons})}{BR(b_\mu \to \mu^+\mu^-(\text{or } e^+e^-))} \quad (m_b = s)$$

$$\sim \frac{BR(b_\mu \to \pi^+\pi^-)}{BR(b_\mu \to \mu^+\mu^-(\text{or } e^+e^-))}, \text{ for } m_b \leq \text{GeV}$$

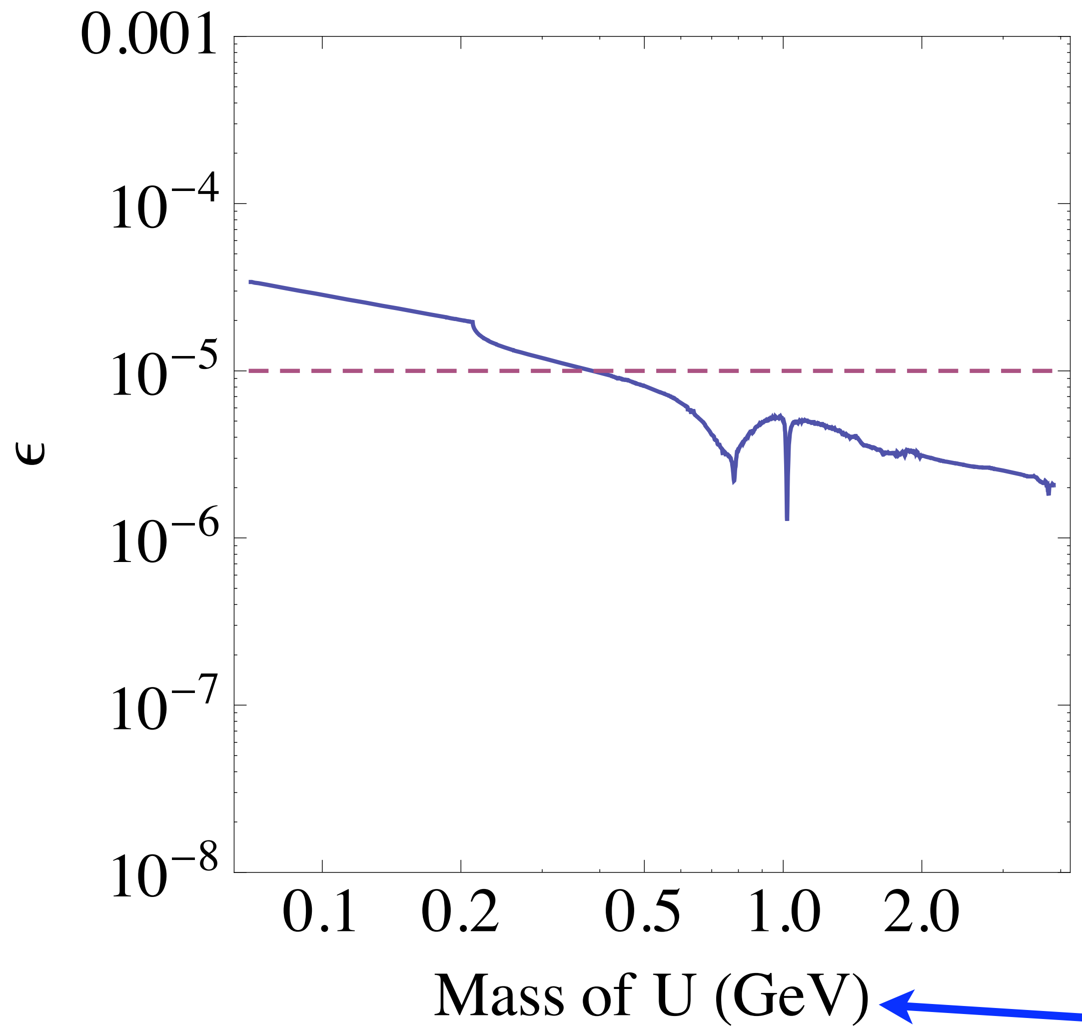
For example: $\pi^+\pi^- : \mu^+\mu^- : e^+e^- \simeq 1 : 1 : 1$ for $m_b \simeq 600$ MeV.

I will focus mainly on leptons here.
But, the hadronic final states can be interesting as well.

Life time of dark photon

- Prompt, except for tiny couplings, or very large boost.

Value of ϵ for which $c\tau$ = 1 mm



$$c\tau \sim \alpha \epsilon^2 m_{b_\mu}$$
$$= 3 \times 10^{-6} \text{cm} \left(\frac{\text{GeV}}{m_{b_\mu}}\right)\left(\frac{10^{-3}}{\epsilon}\right)$$

$m_U = m_{b_\mu}$, dark photon mass

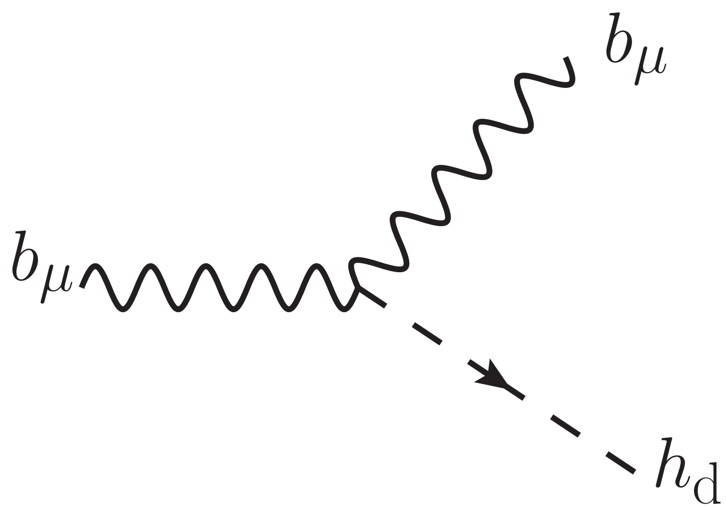
Dark Sector self-coupling

- Dark force has finite range.
  - Gauge symmetry spontaneously broken.

$$\mathcal{L} \supset |Dh_{\mathrm{d}}|^2; \; D_\mu h_{\mathrm{d}} = (i\partial_\mu + g_{\mathrm{d}} b_\mu) h_{\mathrm{d}}$$

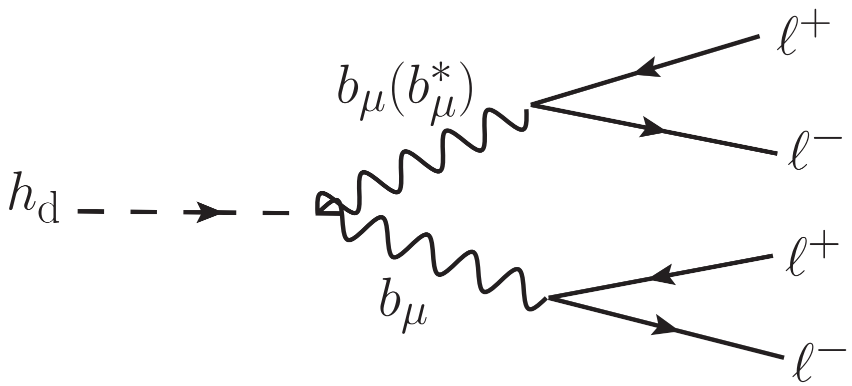
$$v_{\mathrm{d}} \equiv \langle h_{\mathrm{d}} \rangle \simeq \; \mathrm{GeV}$$

  - Dark photon - dark Higgs coupling



$$g_{bbh_{\mathrm{d}}} = \frac{m_b^2}{v_{\mathrm{d}}}$$

Decay of dark higgs



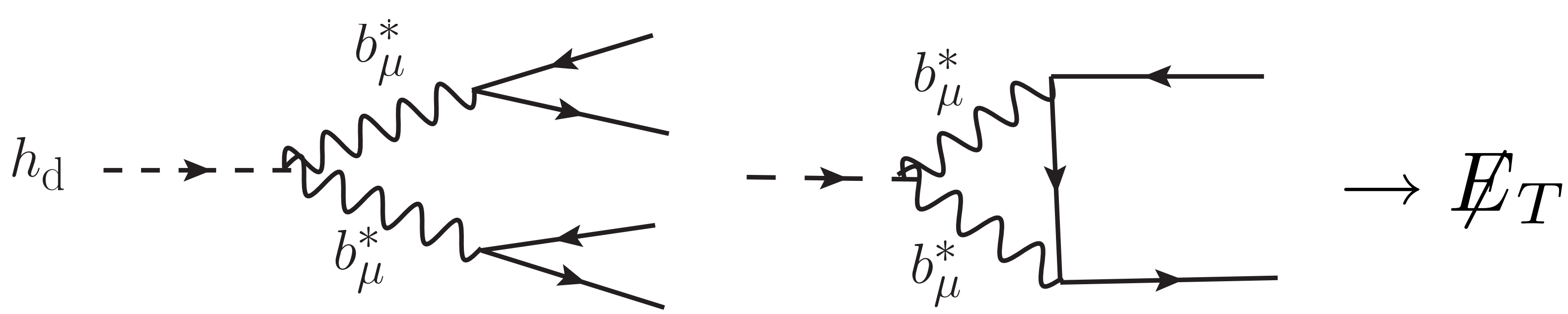
$m_{h_{\rm d}} > m_b \;\rightarrow\; 4\ell$ final state

Can have displaced vertex if $m_{h_{\rm d}} < 2m_b$

For example:

$\epsilon = 10^{-3},\; m_{h_d} = 1.2$ GeV$,\; m_b = 1$ GeV

$c\tau \simeq 10$ cm



For $m_{h_{\rm d}} < m_b$

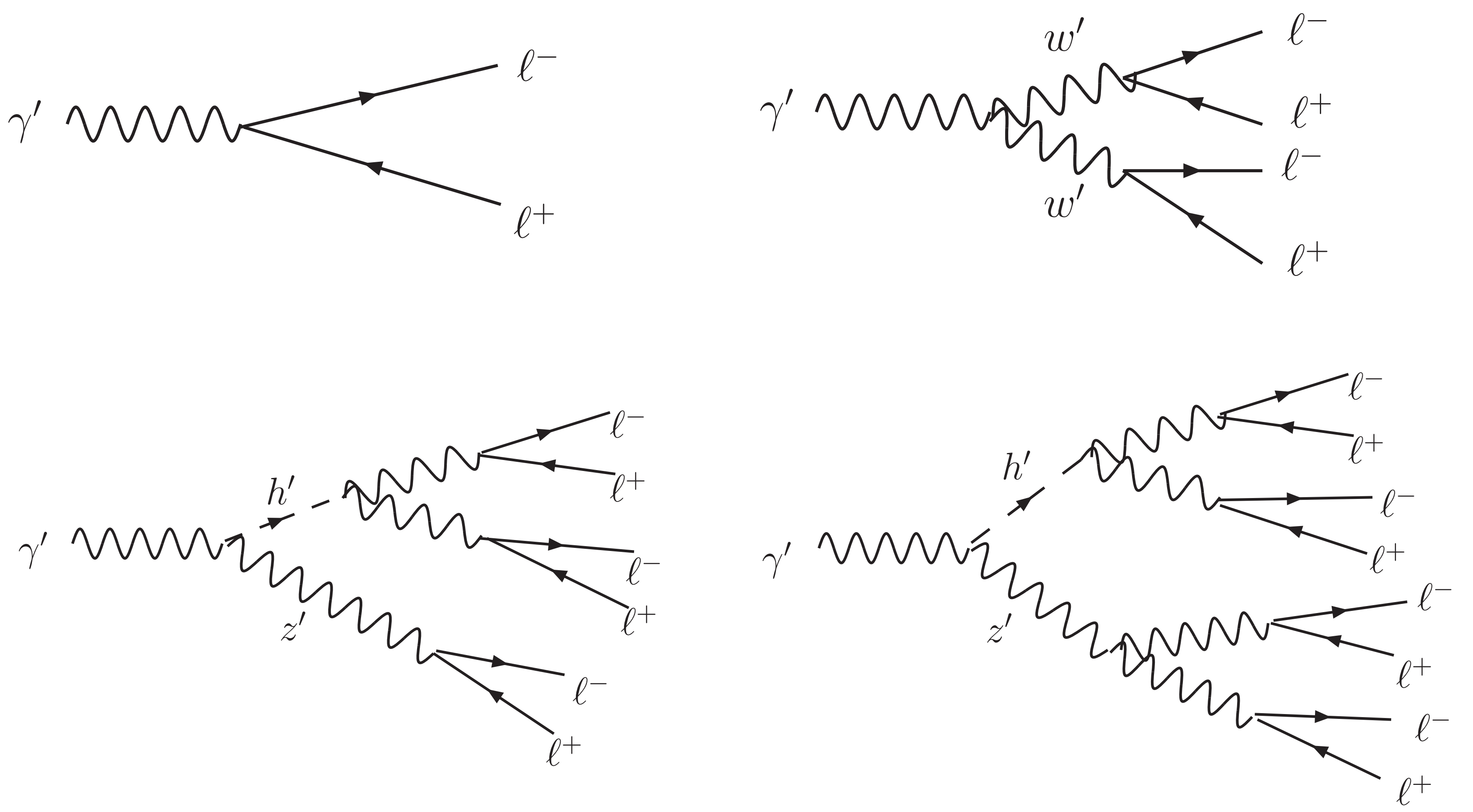
Very long lived: $c\tau \sim 1 - 100$ km

Decay in non-minimal models

- Non-minimal models with non-Abelian dark-sector, multiple dark Higgses possible.

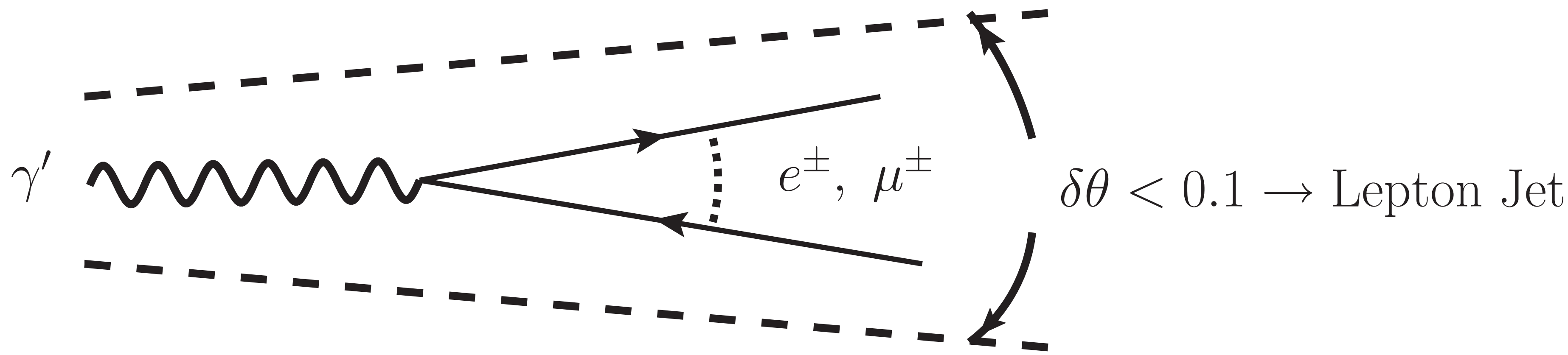
  M. Baumgart, C. Cheung, LTW, J.~Ruderman, I. Yavin, arXiv:0901.0283

- A cascade decay in the dark sector before decaying into SM states. Long decay chains, more leptons.



Lepton Jets

- Decay of the dark photon arising from a heavier particle (Z boson, MSSM LSP) leads to a highly collimated lepton pair.

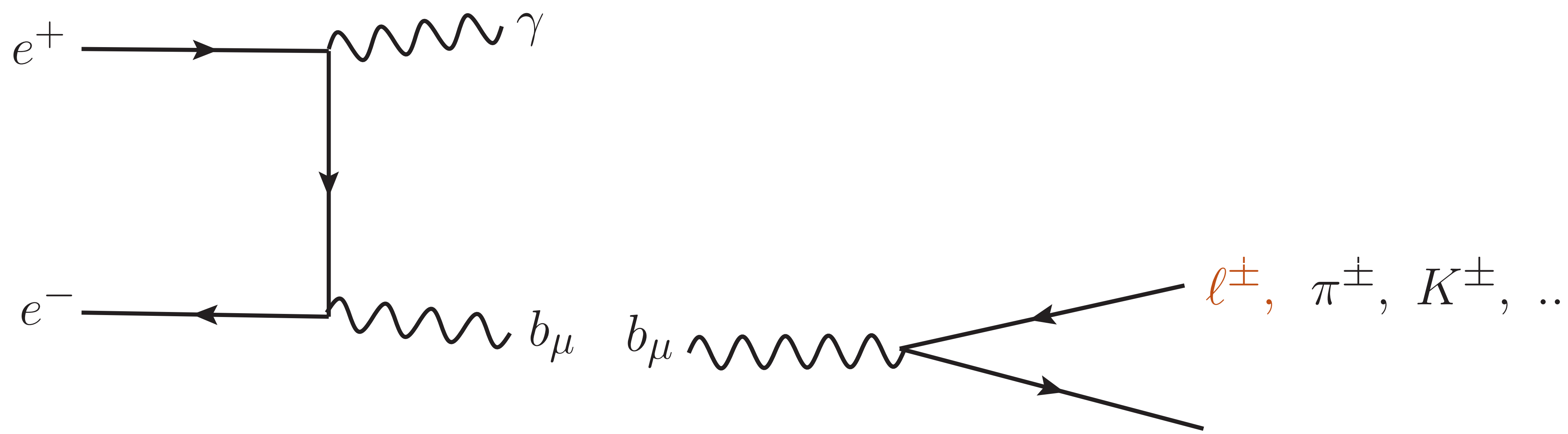


$$\begin{array}{c} \text{Typical } E_{\gamma'} > 10 \text{ GeV} \\ m_{\gamma'} \sim \text{ GeV} \end{array} \rightarrow \ \delta\theta \sim m_{\gamma'}/E_{\gamma'} < 0.1$$

- Arkani-Hamed, Weiner 0810.0714; Baumgart, Cheung, Ruderman, Wang, Yavin 0901.0283; Cheung, Ruderman, Wang, Yavin 0909.0290

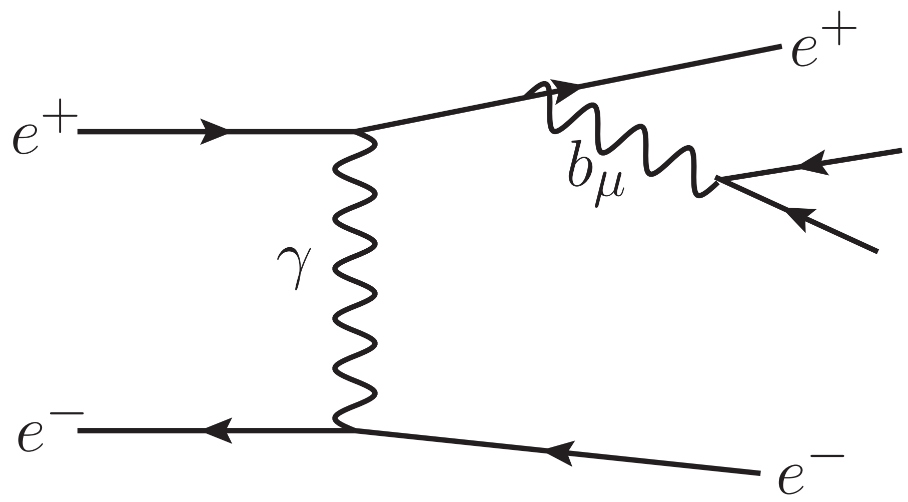
Production: just like producing photon

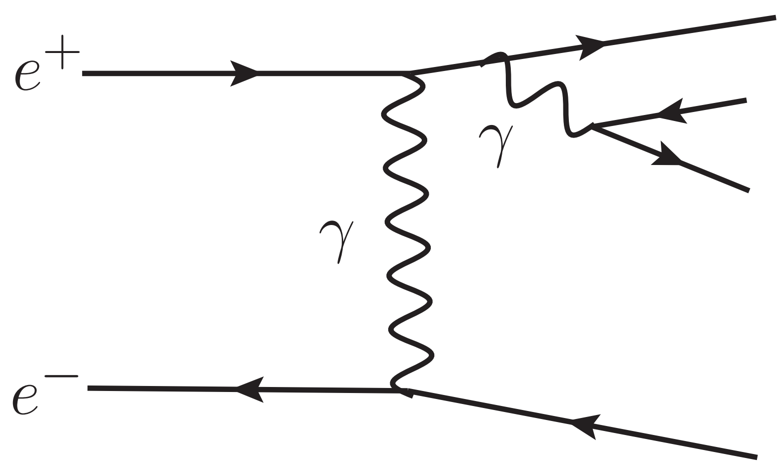
- Associated with a photon.

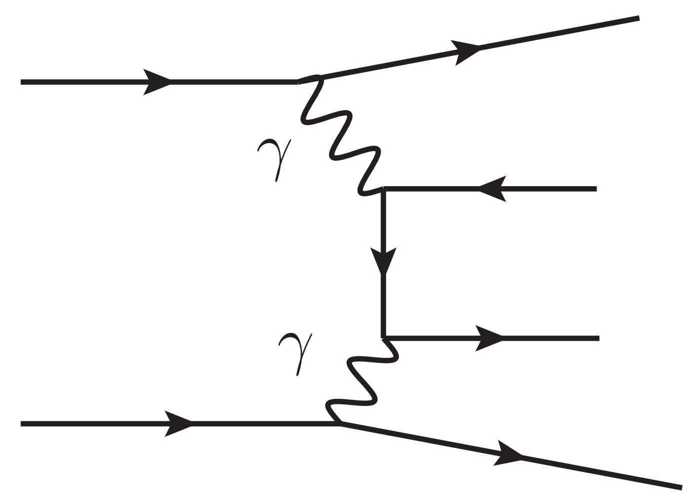


$$\text{Leptonic signal: } \gamma + \ell^+\ell^-, \; m_{\ell\ell} = m_{b_\mu}$$

Production: final state radiation

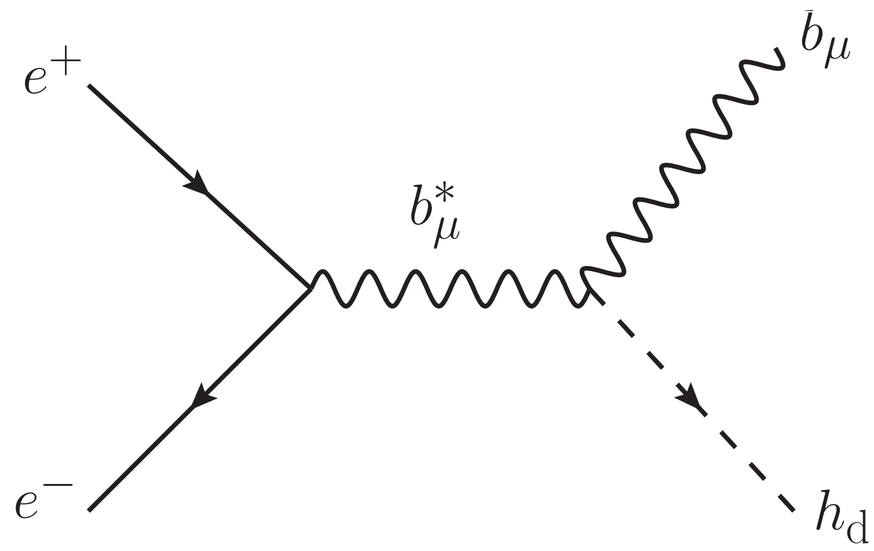






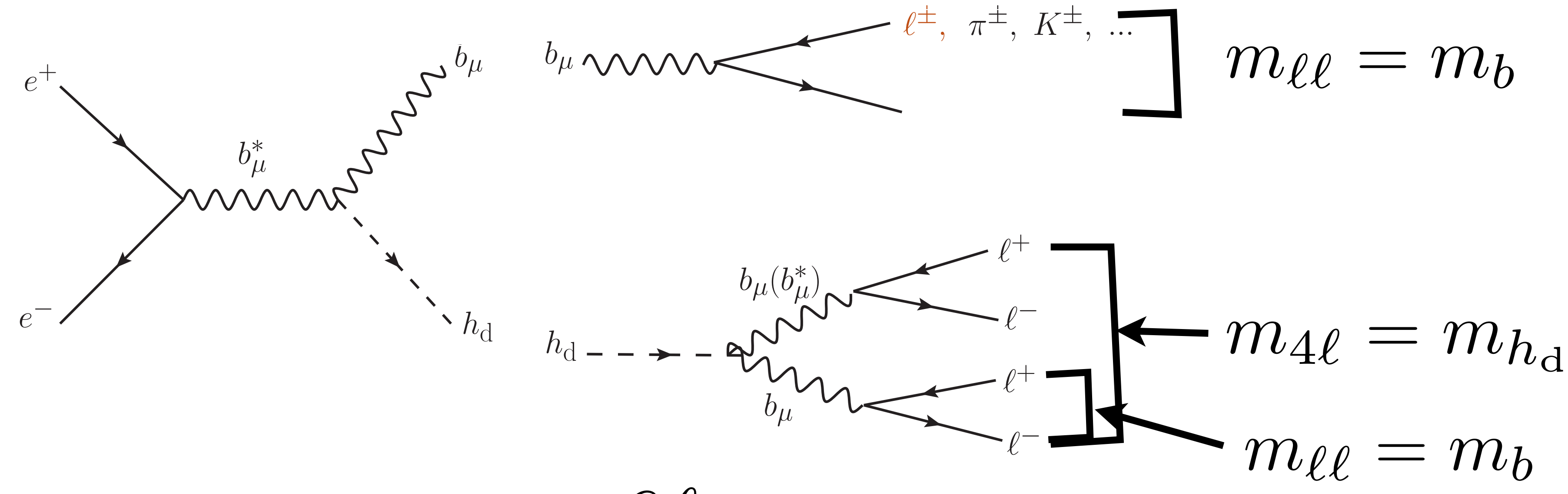
- Just like QED.
- Photon initial states are of course also possible.

Production: "Higgsstrahlung"



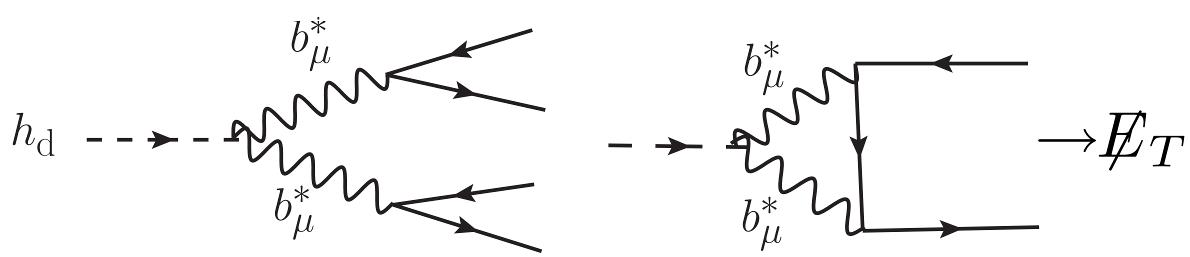
For detailed study:
B. Batell, M. Pospelov, and A, Ritz, arXiv:0903.0363, and talk by B. Batell.
R. Essig, P. Schuster, N. Toro, arXiv:0903.3941.

Signal of dark higgsstrahlung:



$\rightarrow 6\ell$

Or:

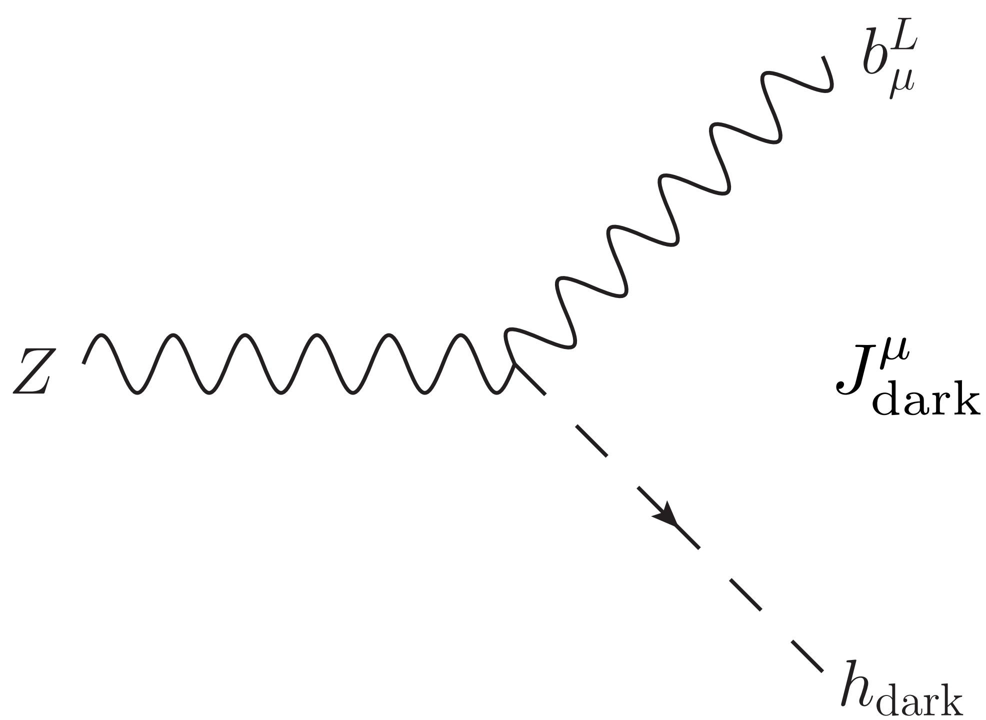


$\rightarrow 2\ell + \not{E}_T$

Rare Z decay

$$V \supset \epsilon \cos\theta_W b_\mu J^\mu_{\rm EM} - \boxed{\epsilon \sin\theta_W Z_\mu J^\mu_{\rm dark}}$$

$$\text{Rare Z decay: BR}(z \to \text{dark sector}) \sim 10^{-6}$$



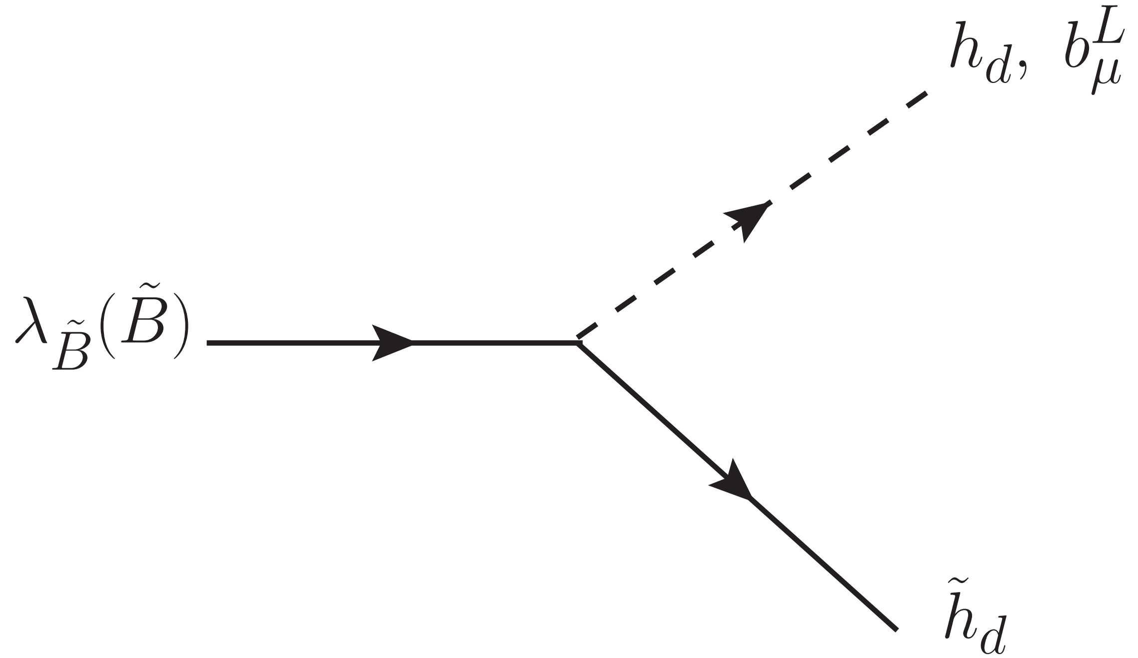
$$J^\mu_{\rm dark} \supset g_d \sum_i q_{h_i} (h^\dagger_{di} \partial^\mu h_{di} - h_{di} \partial^\mu h^\dagger_{di}) + \cdots$$

SUSY LSP decay

$$\mathcal{L}_{\rm gaugino} = -2i\epsilon\lambda_{\tilde{b}}\bar{\sigma}^{\mu}\partial_{\mu}\lambda_{\tilde{B}} + \text{h.c.}$$

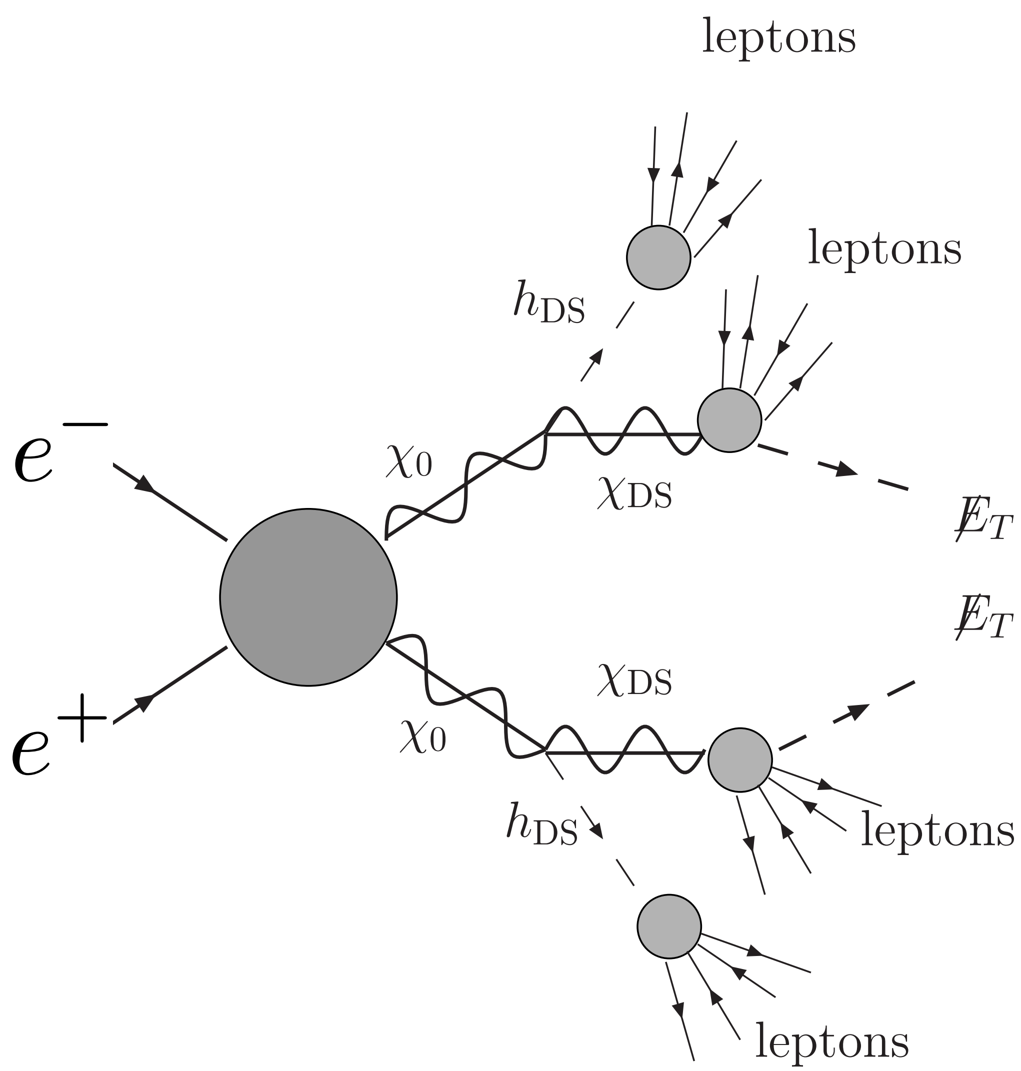
$$\lambda_{\tilde{b}} \to \lambda_{\tilde{b}} + \epsilon\lambda_{\tilde{B}} \;\; \to \mathcal{L} \supset \epsilon\lambda_{\tilde{B}}\tilde{J}_b$$

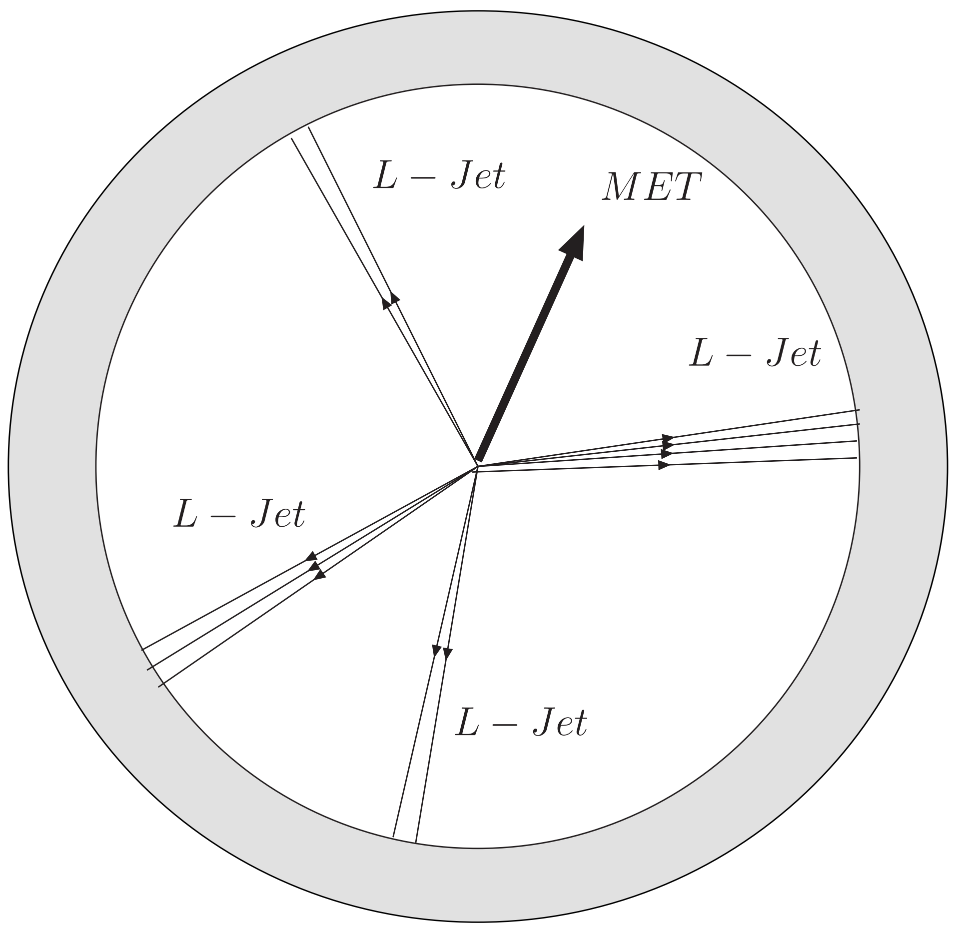
$$\tilde{J}_b = -i\sqrt{2}g_d \sum q_{h_i}\tilde{h}_{di}h_{di}$$



- SUSY LSP has to decay into dark sector states. The subsequent decay give lepton jets.

Topology of a SUSY Lepton Jet Event





- Baumgart, Cheung, Ruderman, LTW, and Yavin 0901.0283

Conclusion:

- Dark matter in the universe could have self-interactions.
- Recent evidence can be interpreted as suggesting such self-interaction is mediated by GeV dark sector states.
- Production of GeV dark sector results in distinct signals: multiple leptons....
- It is exciting to go into this un-explored territory.