Searching for the Light Dark Gauge boson in Low Energy Experiments

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Based on: M. Reece and LTW, arXiv:0904.1743
More information and simulation tools at:
http://phy-hal.princeton.edu/LeptonJets/LE.html (work in propress)

Outline

- Introduction to GeV dark sector.
  - Review of basic structure.
- Survey of search channels.
  - Focusing on low energy high luminosity experiments.
  - Estimates of constraints and reaches.
  - More detailed studies in talks in the rest of this workshop.
- Conclusion.

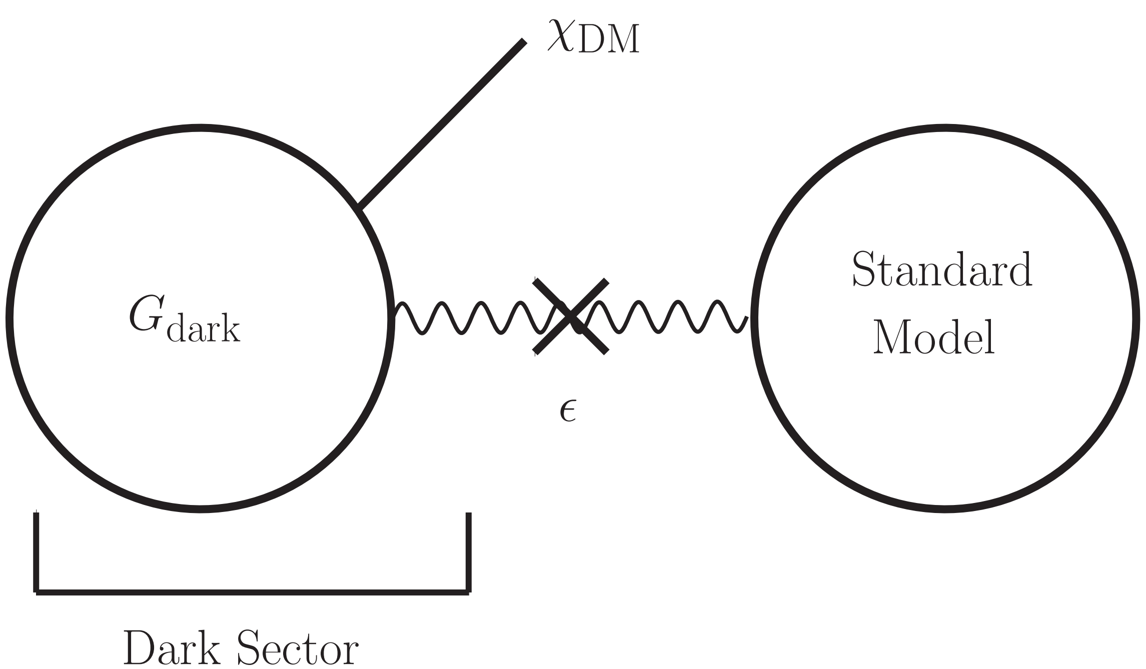
What is a GeV dark sector?

- Dark matter self-interaction, mediated by

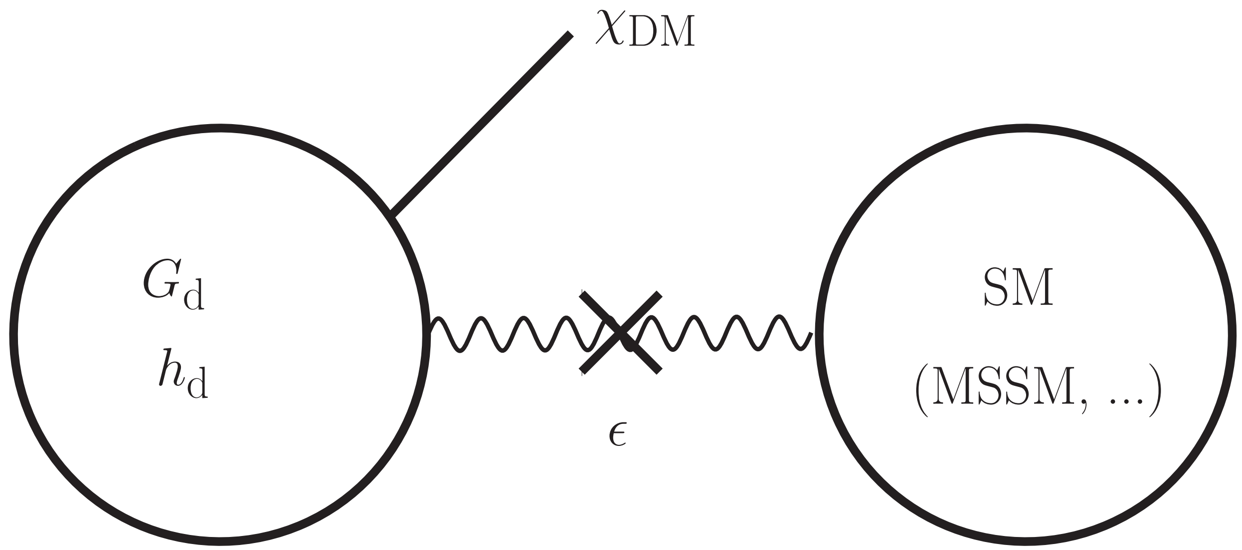
$$b_{\rm dark} \subset \text{dark sector.}$$

- Range of dark force $m_{b_{\rm dark}} \sim 100s \text{ MeV} - \text{GeV}$

- Dark sector couples to SM with tiny couplings, parameterized by ϵ Typically: $\epsilon \leq 10^{-3}$



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

  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:

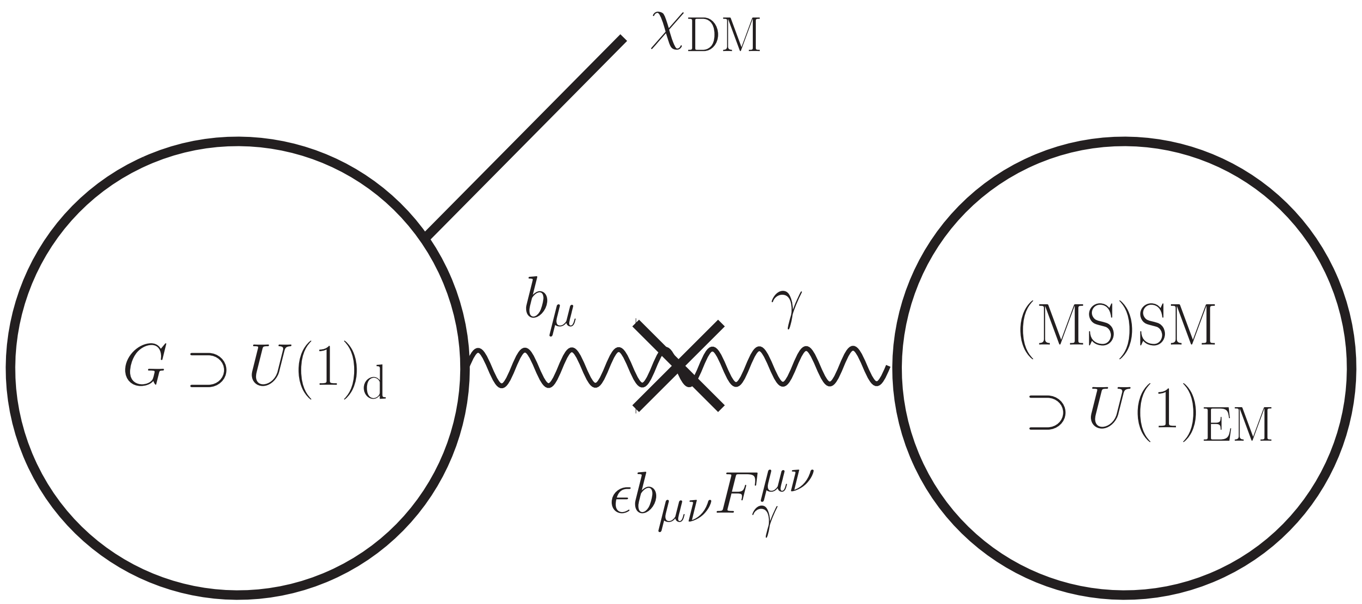
  Y. Nomura and J. Thaler, arXiv:0810.5397

- 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

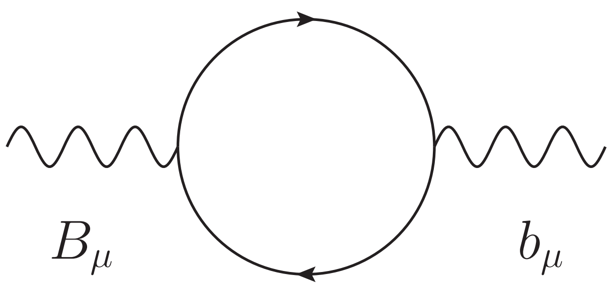
$$\mathcal{L}_{\rm kin.mix} = -\frac{\epsilon}{2} b_{\mu\nu} F_\gamma^{\mu\nu}$$

- 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.
    - Most model independent search requires high luminosity.
    - Unique advantage of low energy searches at meson factories, fix target experiments.

Studies of low energy searches

- Earlier studies of light weakly coupled vector (U-boson).

  N. Borodatchenkova, D. Choudhury, and M. Drees, hep-ph/0510147
  P. Fayet et. al., hep-ph/0403226, hep-ph/0410260, hep-ph/0607094, hep-ph/0702176, arXiv:0812.3980
  S.-h. Zhu, hep-ph/0701001.

- Recent studies of search of dark sector states.

  M. Pospelov and A. Ritz, arXiv:0810.1502
  B. Batell, M. Pospelov, and A. Ritz, arXiv:0903.0363.
  R. Essig, P. Schuster, and N. Toro, arXiv:0903.3941.
  M. Reece and LTW, arXiv:0904.1743.
  P.-f. Yin, J. Liu, and S.-h. Zhu, arXiv:0904.4644.
  J.D. Bjorken, R. Essig, P. Schuster, and N. Toro, arXiv:0906.0580
  B. Batell, M. Pospelov, and A. Ritz, arXiv:0906.5614
  M. Freytsis, G. Ovanesyan, and J. Thaler, arXiv:0909.2862

  BABAR, arXiv:0908.2821.
  Talks by experimental groups at this workshop.

Dark sector couplings to the SM

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

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

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

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

The "dark photon", sometimes also called

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

Several low energy probes

- Precision QED measurements
  - $g_\mu - 2$.   M. Pospelov, arXiv:0811.1030
    Strongest constraint: $\epsilon^2 \leq 2 \times 10^{-5} (m_{b_\mu}/100 \text{ MeV})^2$
  - Others such as: $g_e - 2$, muonic hydrogen, ...
    Not competitive.

- $e\nu$ scattering.
  Requires coupling to neutrino, suppressed further by $m_{b_\mu}^2/m_Z^2$.
  $\epsilon^2 e^2/m_Z^2 < G_F \rightarrow \epsilon < 1$

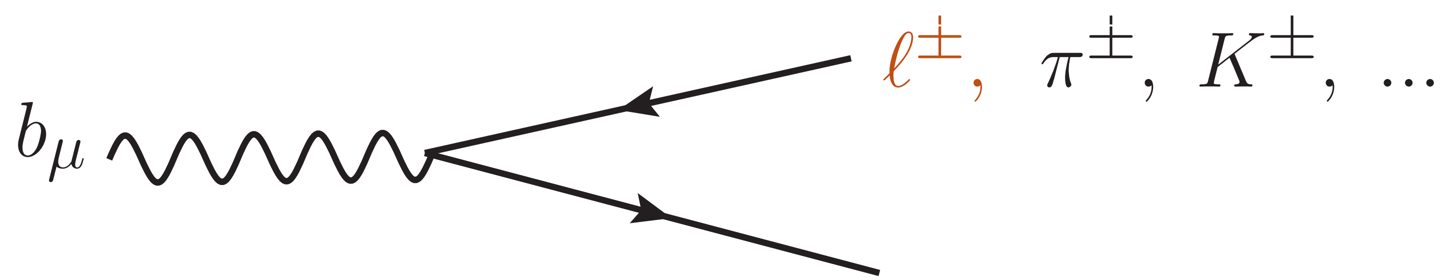
- Atomic parity.

  Constrains the product of vector and axial coupling.
  Same suppression factor. About $\epsilon < 10^{-1}$

Decay of dark photon:

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

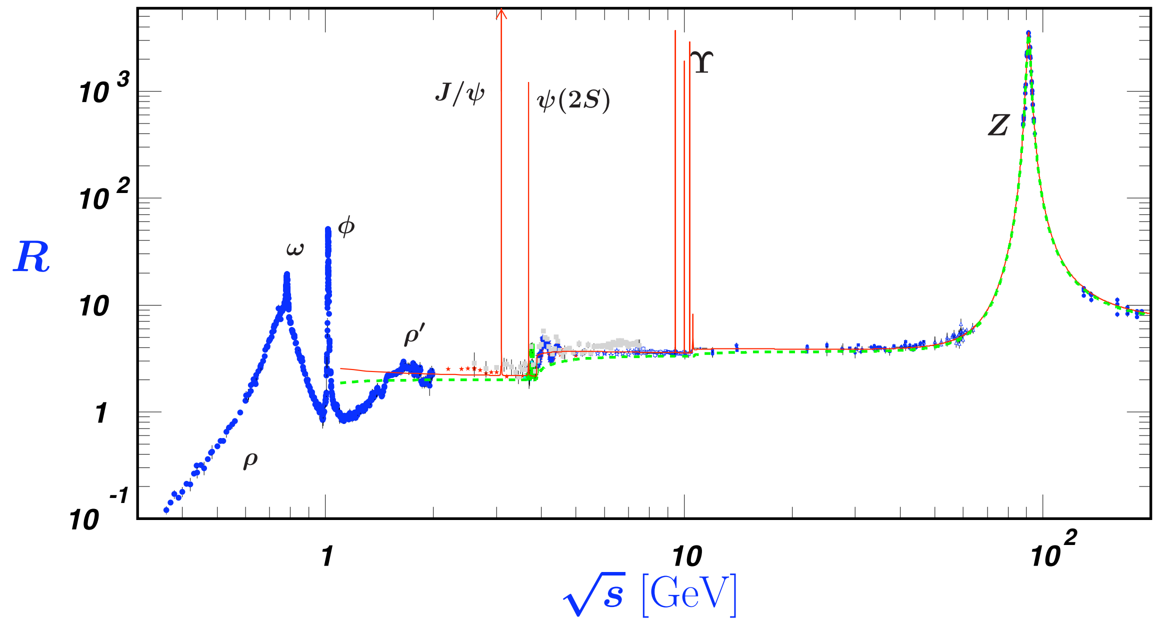
- Dark photon decay to SM is always the last stage of dark sector process, giving rise directly to observable signals.



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

Dark Photon decay branching ratios:

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



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

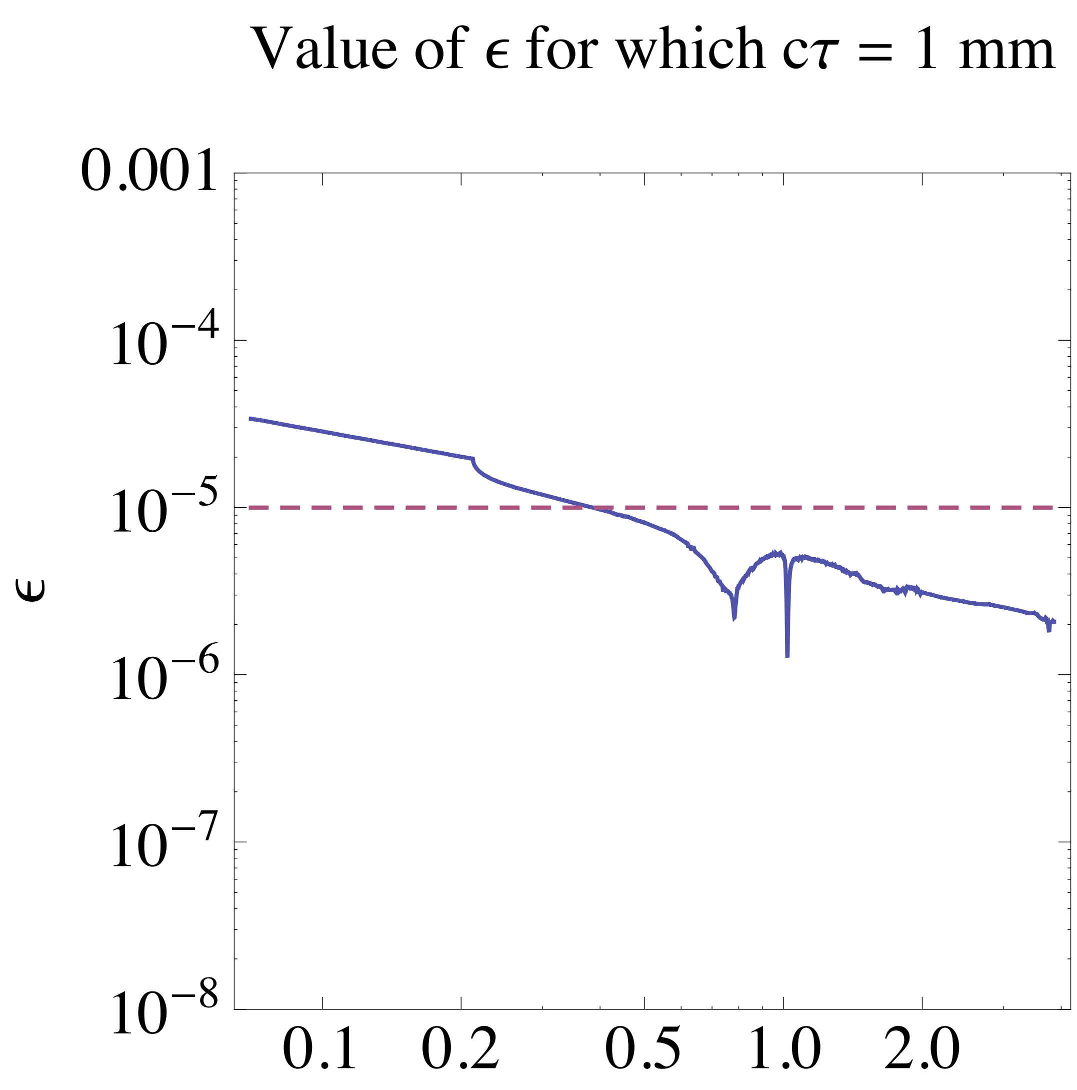
$$\sim \frac{BR(b_\mu \to \pi^+\pi^-)}{BR(b_\mu \to \mu^+\mu^-(\text{or } e^+e^-))},\ \text{for } m_b \leq \text{GeV}$$

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.



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

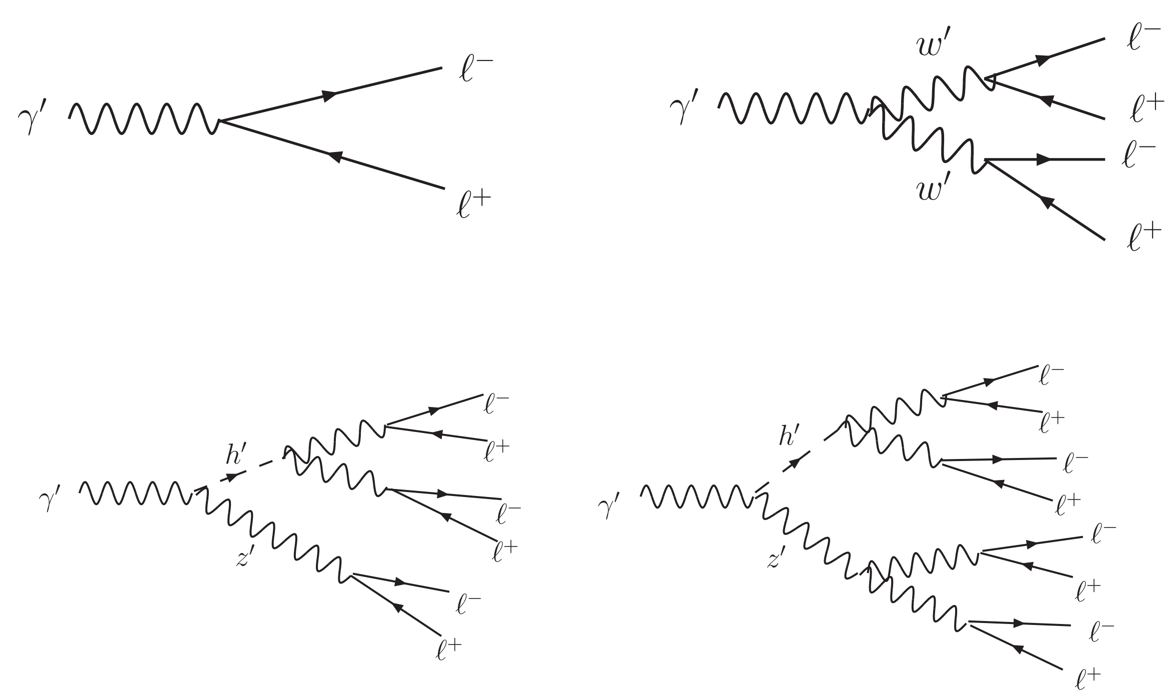
$m_{\mathrm{U}} = m_{b_\mu}$, dark photon mass

Decay in non-minimal models

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

  N. Arkani-Hamed, D. Finkbeiner, T. Slatyer and N. Weiner, arXiv:0810.0713
  M. Baumgart, C. Cheung, LTW, J.~Ruderman, I. Yavin, arXiv:0901.0283
  D. Alves, S. Behbabani, P. Schuster, and J. Wacker, arXiv:0903.3945

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



Meson decays

Large quantities of mesons, ρ, η, ϕ, Υ, J/ψ, etc., have been produced.

Many of them have decay channels into photons. As a result, they should also have rare decay into dark photon, with BR$\sim \epsilon^2 \times$BR($\rightarrow$ photon).

Reach in meson decays, rough estimates:

- Consider $X \to Y + b_\mu (b_\mu \to \ell^+ \ell^-)$.
  Background: $X \to Y + \gamma^* \to Y + \ell^+ \ell^-$
- Signal significance

$$\frac{\mathrm{S}}{\sqrt{\mathrm{B}}} \approx \sqrt{n_X} \frac{\epsilon^2 \times \mathrm{BR}(X \to Y + \gamma) \times \mathrm{BR}(b_\mu \to \ell^+ \ell^-)}{\sqrt{\mathrm{BR}(X \to Y + \gamma^* \to Y + \ell^+ \ell^-)}} \sqrt{\frac{m_{b_\mu}}{\delta m} \log \left(\frac{m_X - m_Y}{2 m_\ell} \right)}.$$

Reach $\propto n_X^{-1/4}$, and $\propto (\mathrm{BR}(X \to Y\gamma))^{1/2}$

- Typically: $\mathrm{BR}(X \to Y + \gamma^* \to Y + \ell^+ \ell^-) \sim 10^{-2} \times BR(X \to Y + \gamma)$
- Need $n_X \sim 10^9$ to reach $\epsilon < 10^{-3}$.

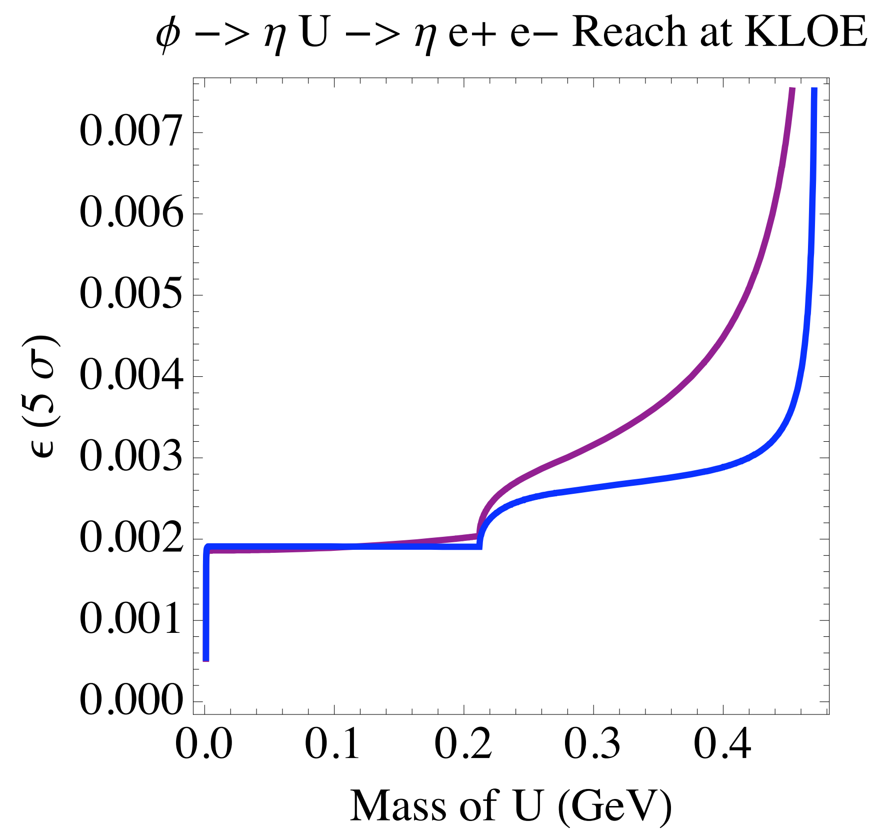
Reaches in some channels:

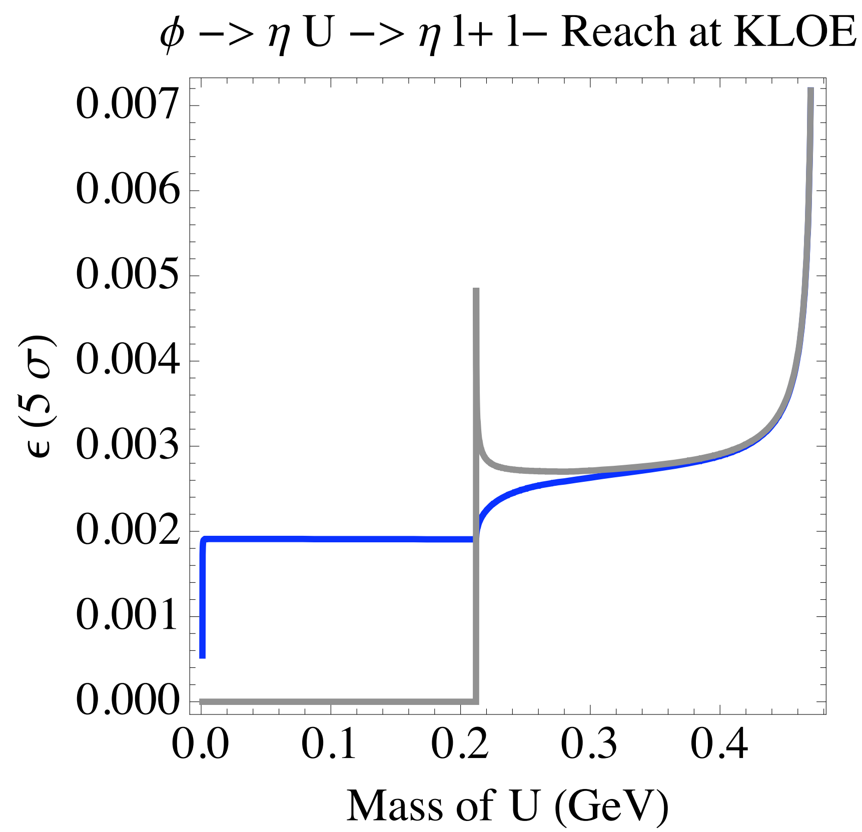
$X \to Y + b_\mu$	n_X	ΔM_{XY}	BR($X \to Y + \gamma$)	BR($X \to Y + \ell^+\ell^-$)	$\epsilon \leq$
$\eta \to \gamma b_\mu$	$n_\eta \sim 10^7$	547	$2 \times 39.8\%$	6×10^{-4}	2×10^{-3}
$\omega \to \pi^0 b_\mu$	$n_\omega \sim 10^7$	648	8.9%	7.7×10^{-4}	5×10^{-3}
$\phi \to \eta b_\mu$	$n_\phi \sim 10^{10}$	472	1.3%	1.15×10^{-4}	1×10^{-3}
$K_L^0 \to \gamma b_\mu$	$n_{K_L^0} \sim 10^{11}$	497	$2 \times (5.5 \times 10^{-4})$	9.5×10^{-6}	2×10^{-3}
$K^+ \to \pi^+ b_\mu$	$n_{K^+} \sim 10^{10}$	354	-	2.88×10^{-7}	7×10^{-3}
$K^+ \to \mu^+ \nu b_\mu$	$n_{K^+} \sim 10^{10}$	392	6.2×10^{-3}	7×10^{-8}	2×10^{-3}
$K^+ \to e^+ \nu b_\mu$	$n_{K^+} \sim 10^{10}$	496	1.5×10^{-5}	2.5×10^{-8}	7×10^{-3}

- In addition:
  - BR($J/\psi \to \gamma X$) $\sim 2\%$, BR($J/\psi \to \gamma e^+ e^-$) $\sim 0.8\%$. Interesting to look for $J/\psi \to b_\mu X$ and $J/\psi \to be^+e^-$. Currently, $n_{J/\psi} \sim 10^7$. BES-III can have 10^{10}.
  - $\Upsilon(1S) \to b_\mu \ell^+ \ell^-$ can be potentially interesting.
  - $\Upsilon(4S)$. $\Upsilon(4S) \to BB > 96\%$ and $B \to D^0/\bar{D}^0 + X \sim 62\%$. $D^0 \to \eta + X \sim 10\%$. Interesting source for η with $10^8 - 10^9$ $\Upsilon(4S)$.
  - $\pi^0 \to b_\mu \gamma$ could be useful for very light b_μ.

Estimate of potential reach at KLOE.

M. Reece and LTW, arXiv:0904.1743





Left: Reach with e^+e^- final state.

Purple: $F_{\phi\eta\gamma^*}(q^2) = 1$ Blue: $F_{\phi\eta\gamma^*}(q^2) = 1/(1 - 3.8\mathrm{GeV}^{-2}q^2)$.

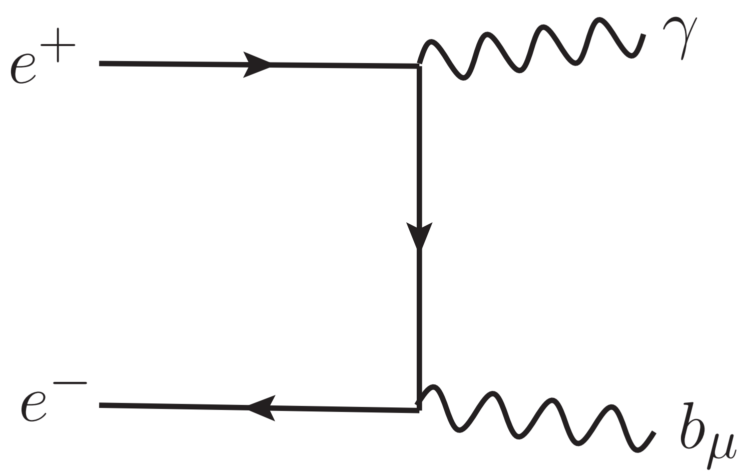
M. Achasov et. al. Phys. Lett. B**504**.

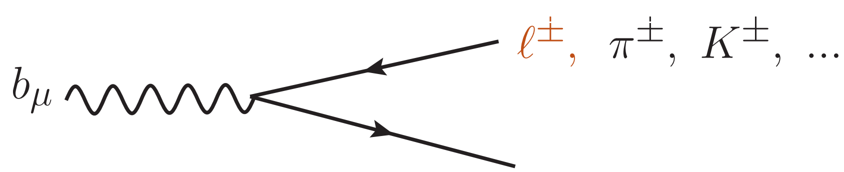
Right: including muon.

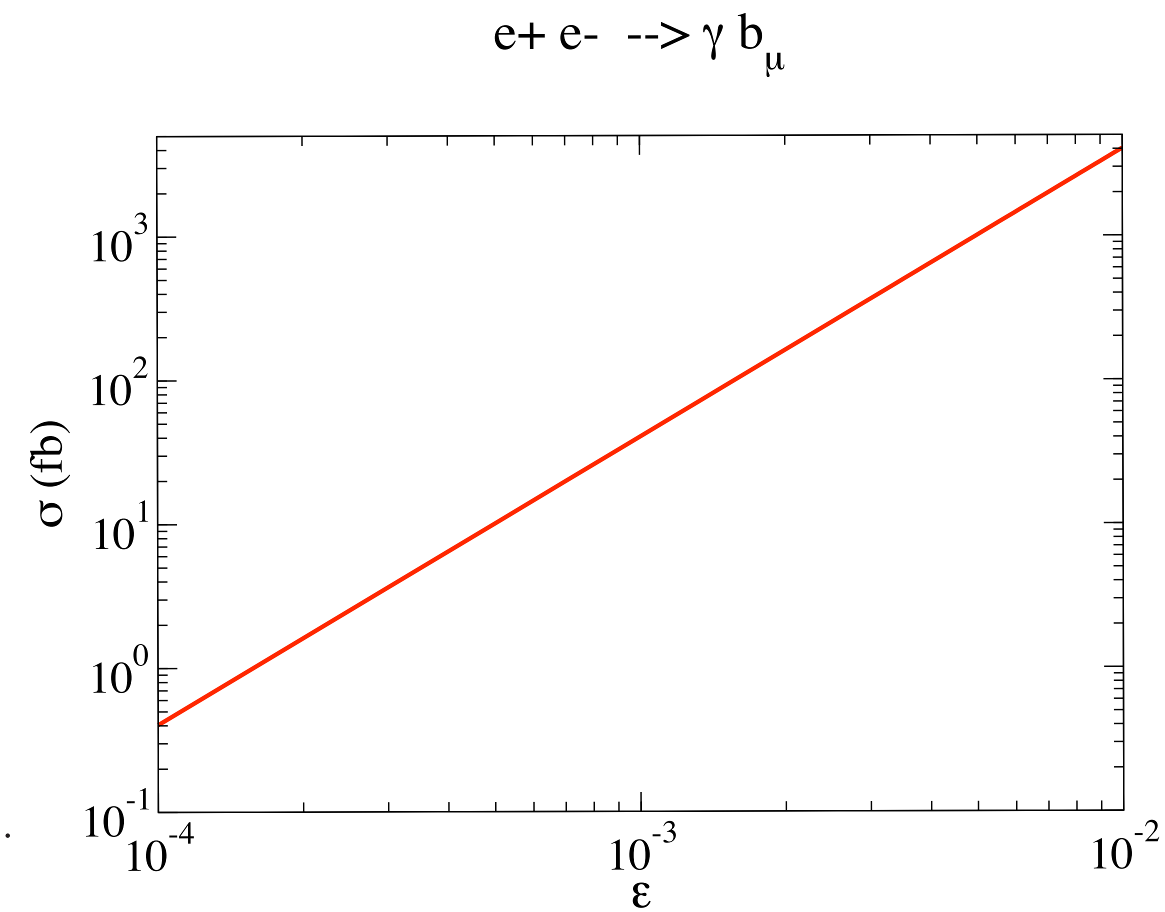
See also: F. Bossi, arXiv:0904.3815, and talk at this workshop

Searches at low energy high luminosity colliders

Production: associated with photon



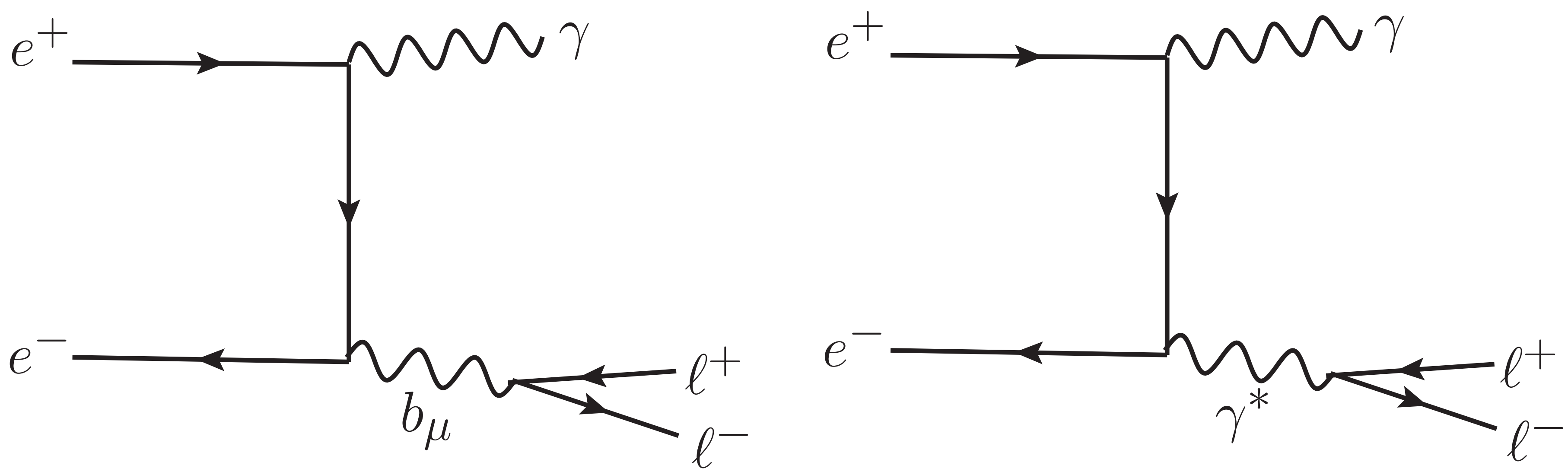




$E_{\rm cm} = 12.1 \text{ GeV}$

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

Signal vs background estimates:



$$\frac{\mathsf{S}}{\sqrt{\mathsf{B}}} \sim \sqrt{\sigma_0 \mathcal{L}} \frac{\epsilon^2}{\sqrt{\alpha/\pi}} \sqrt{\frac{m_{b_\mu}}{\delta m}} \times \ \mathsf{BR}(U \to \ell^+\ell^-).$$

$\mathcal{L}:$ integrated luminosity; $\delta m:$ resolution

$\sigma_0 =$ rate$(e^+e^- \to \gamma\gamma) \sim 1 \times 10^4$ pb

$\mathcal{L} \sim 100\text{s fb}^{-1}, \delta m \sim 1 - 10$ MeV,

rough estimate of reach: $\epsilon \sim 10^{-3}$

Luminosity crucial! Reach $\propto \mathcal{L}^{-1/4}$

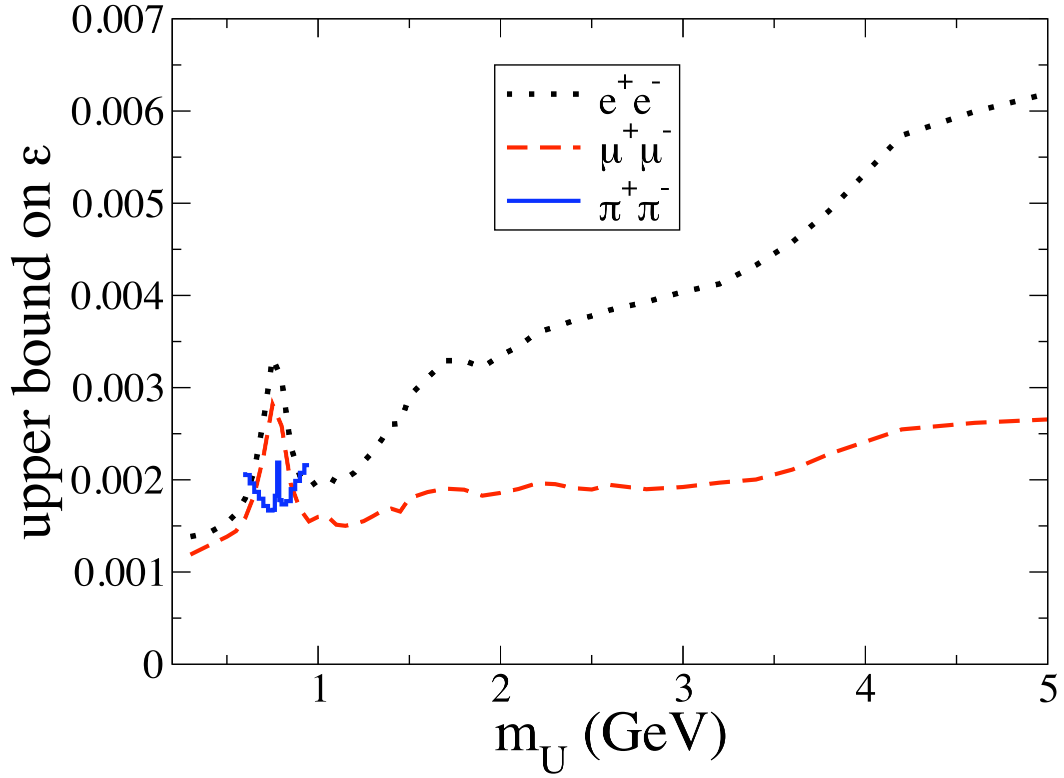
Earlier lepton colliders:

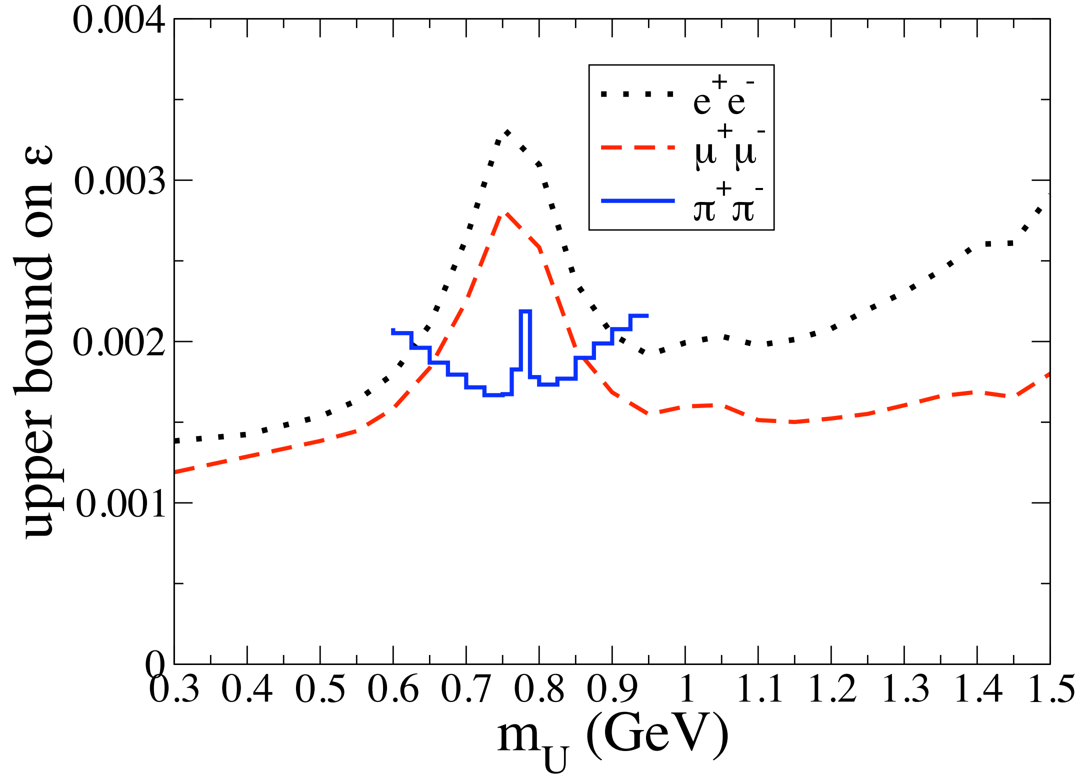
DCI, SPEAR, VEPP 4, DORIS, PEP, PETRA, TRISTAN

$\sim 10 - 100 \text{ pb}^{-1}\text{year}^{-1}$.

Reach estimate:

M. Reece, LTW, arXiv:0904.1743.





Pion mode used around ρ.

$e^\pm$ worse than $\mu^\pm$ for larger m_b due to Bhabha scattering.

In our paper, we used crude approximation:

$\mathcal{L} \simeq 500 \text{ fb}^{-1}$

$E_\gamma > 20 \text{ MeV}, \; -.890 < \cos\theta_\gamma < 0.775$

$p_T^\ell > 60 \text{ MeV}, \; -0.956 < \cos\theta_\ell < 0.865$

$$\delta m(e^+e^-) = \left(2.0 + 3.9\left(\frac{m_U}{1.0 \text{ GeV}}\right) + 0.25\left(\frac{m_U}{1.0 \text{ GeV}}\right)^2\right) \text{MeV}$$

$$\delta m(\mu^+\mu^-) = \left(1.8 + 4.1\left(\frac{m_U}{1.0 \text{ GeV}}\right) + 0.28\left(\frac{m_U}{1.0 \text{ GeV}}\right)^2\right) \text{MeV}$$

Related Searches:

- CLEO W. Love, et. al. [CLEO Collaboration], arXiv:0807.1427

$$\Upsilon(1S) \to A^0(\to \mu^+\mu^-) + \gamma,\ \ A^0:\ \text{pseudo-scalar}, 1.1\ \text{fb}^{-1}$$

Same final state as: $e^+e^- \to b_\mu(\to \mu^+\mu^-) + \gamma$

$$BR(\Upsilon(1S) \to A^0 + \gamma) \times BR(A^0 \to \mu^+\mu^-) < 2.3 \times 10^{-6}$$

$\to$ < 50 signal events $\to \epsilon \leq 7.5 \times 10^{-3}$.

Using 8 fb^{-1} $\Upsilon(4S)$ data could push $\epsilon \leq 4.5 \times 10^{-3}$

- A similar BaBar search, somewhat stronger bound.

B. Aubert [The BABAR Collaboration], arXiv:0902.2176
Talk by Hojeong Kim.

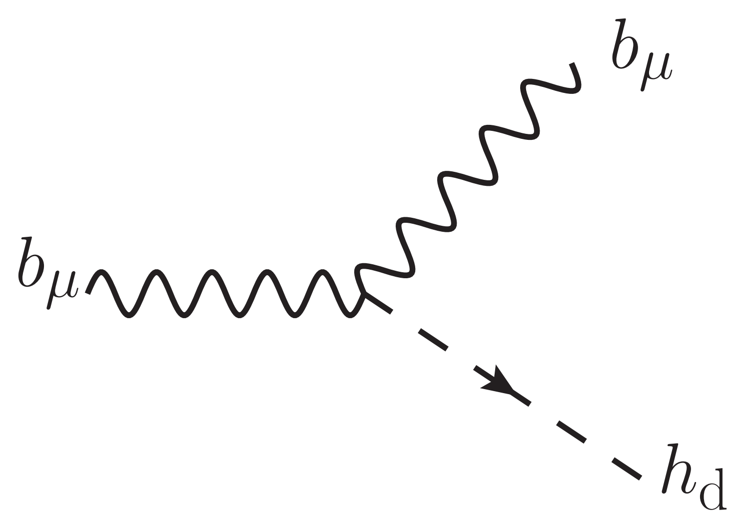
Dark Sector self-coupling

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

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

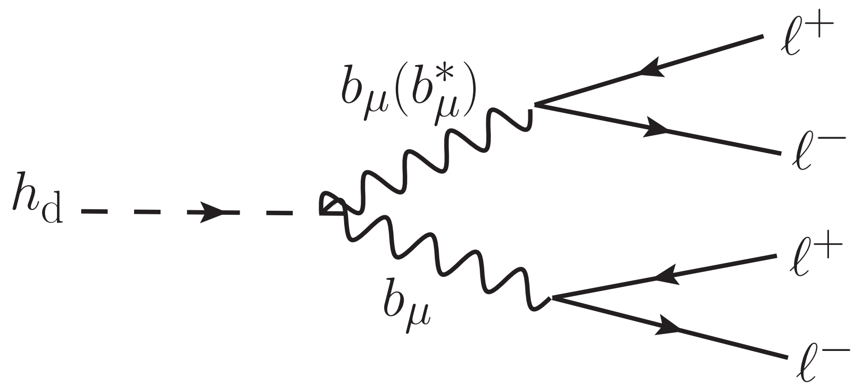
$$v_{\rm d} \equiv \langle h_{\rm d} \rangle \simeq \; \text{GeV}$$

  - Dark photon - dark Higgs coupling



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

Decay of dark higgs



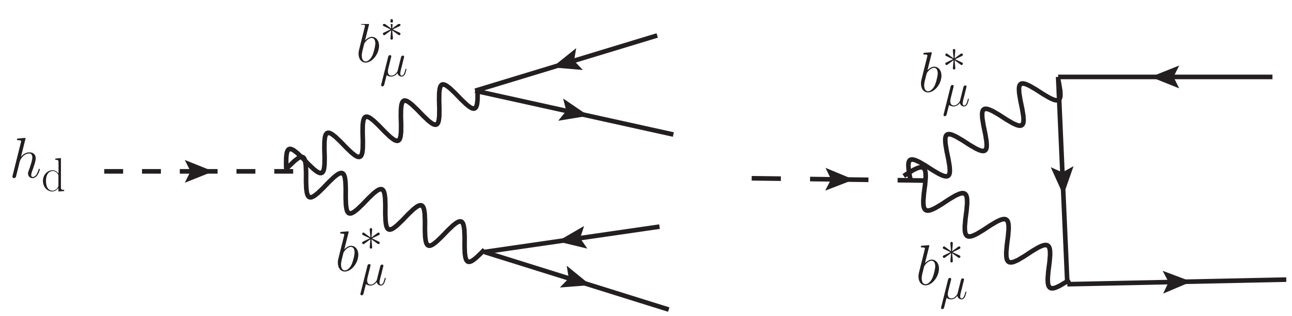
$m_{h_d} > m_b \;\rightarrow\; 4\ell$ final state

Can have displaced vertex if $m_{h_d} < 2m_b$

For example:

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

$c\tau \sim 10$(s) cm

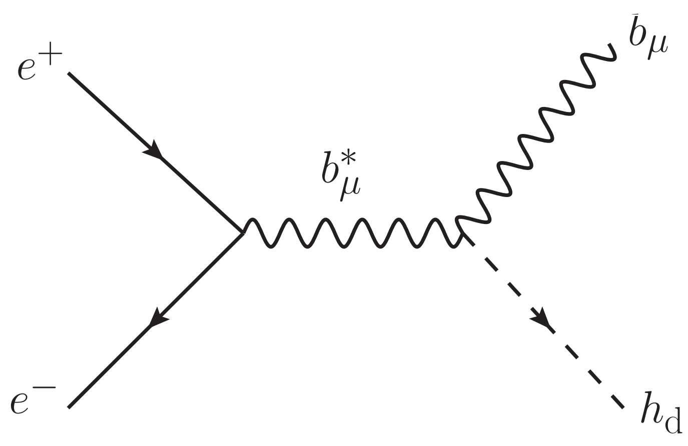


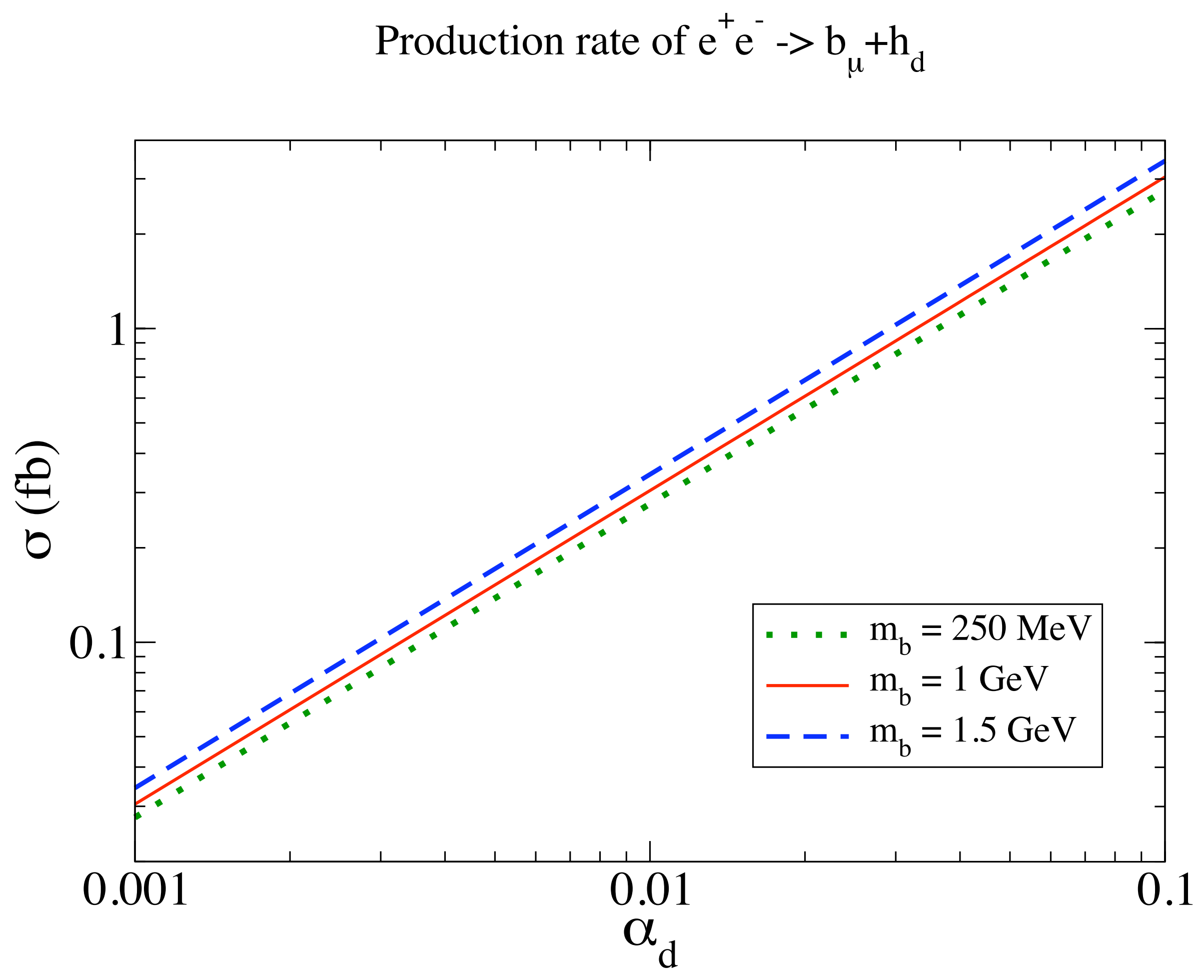
$\rightarrow \not{E}_T$

For $m_{h_d} < m_{b_\mu}$

Very long lived: $c\tau \sim$ 10s m $-\ 10^2$ km.

Production: "Higgsstrahlung"



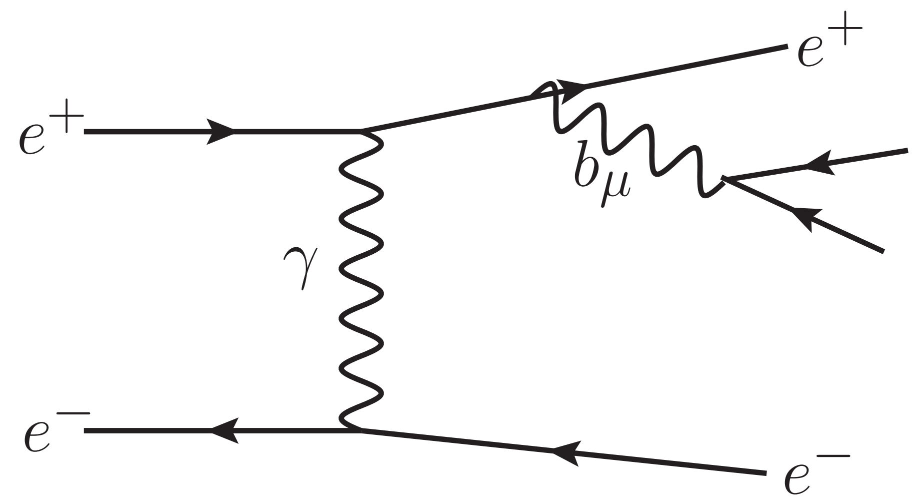


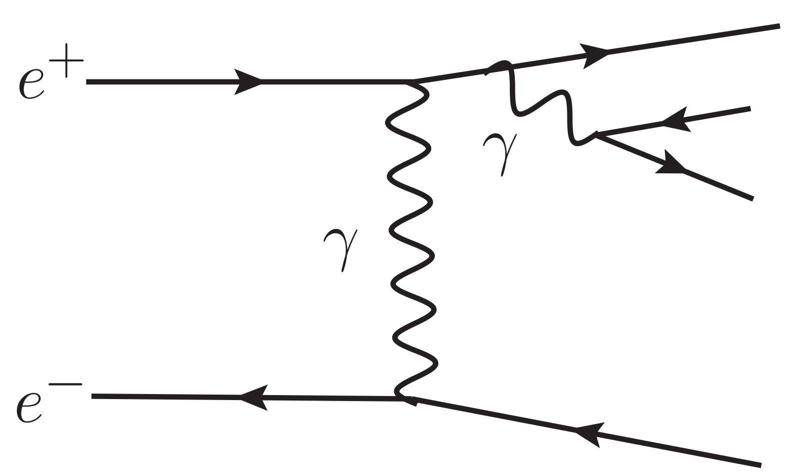
For detailed study:

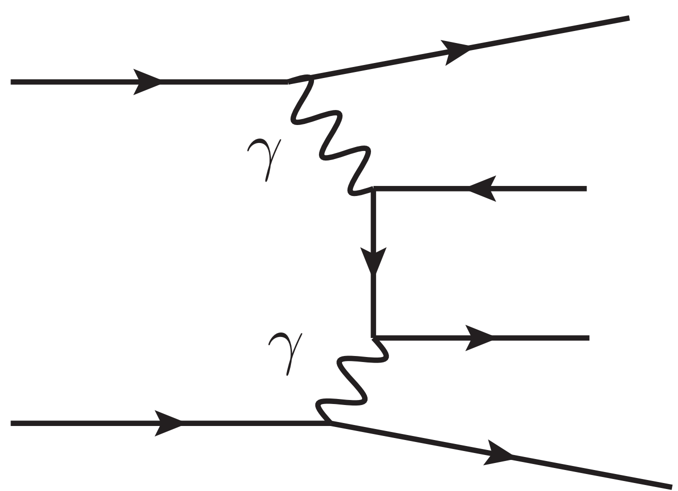
B. Batell, M. Pospelov, and A, Ritz, arXiv:0903.0363, and talk by B. Batell.

R. Essig, P. Schuster, N. Toro, arXiv:0903.3941.

Production: final state radiation





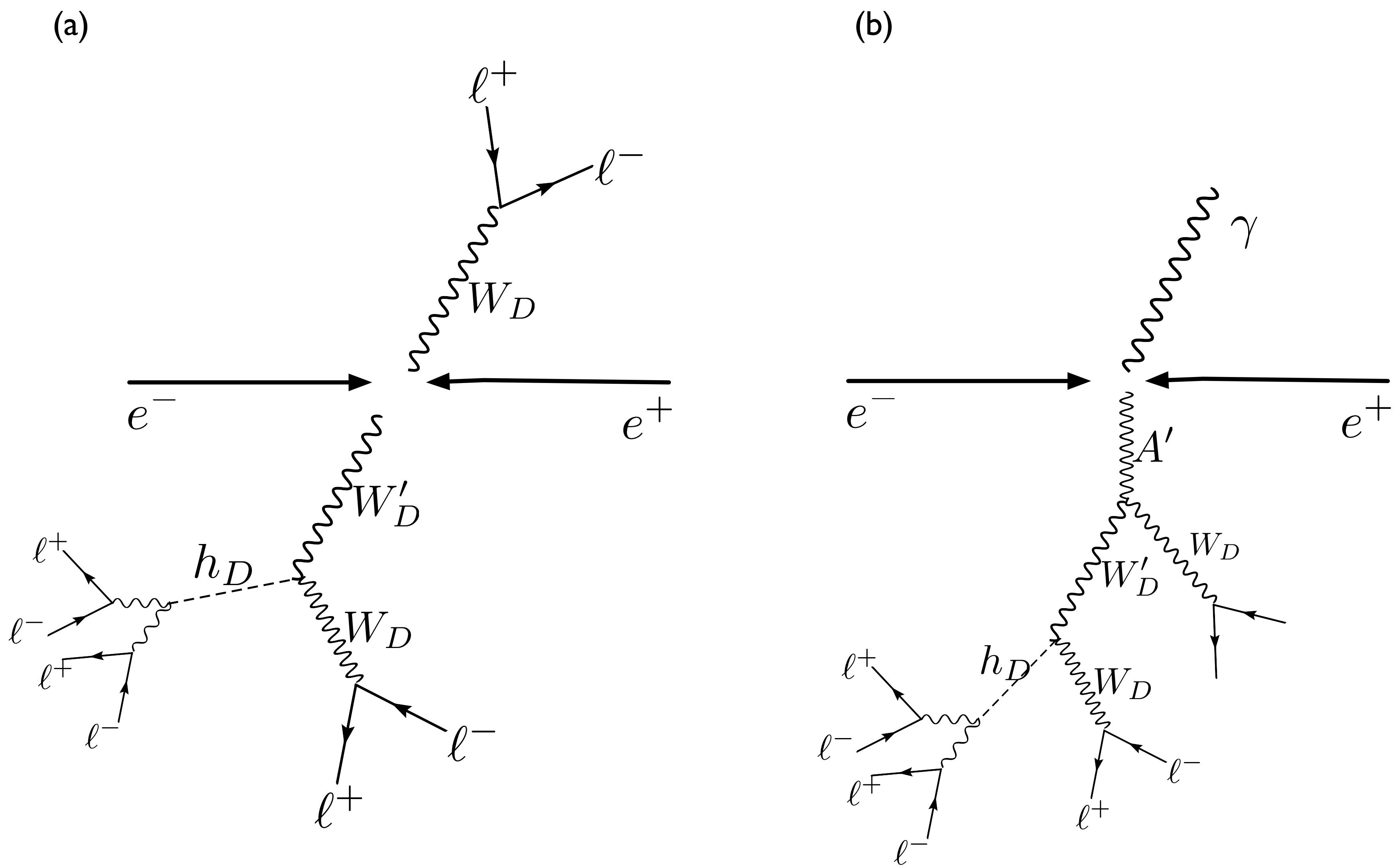


Reach a factor of several worse than $e^+e^- \to \gamma + b_\mu$

M. Reece, LTW, arXiv:0904.1743.

More possibilities.

- Additional channels in non-minimal models.



R. Essig, P. Schuster, N. Toro, arXiv:0903.3941
BABAR, arXiv:0908.2821

Enhancement on the resonance?

- Production rate could be enhanced if we are on a resonance. For example:

  In comparison with continuum production:

  on Υ resonance: $e^+e^- \to \gamma + b_\mu(\to \mu^+\mu^-)$ is enhance by $R(m_\Upsilon) \times BR(\Upsilon \to \mu^+\mu^-) \sim 60$;

  Similarly, $\dfrac{e^+e^- \to \Upsilon \to b_\mu h_\mathrm{d}}{e^+e^- \to b_\mu^* \to b_\mu h_\mathrm{d}} \sim 60$

- However, we cannot be precisely on the resonance, enhancement reduced by the spread of beam energy by a factor of

$$\frac{\Gamma_\Upsilon}{\delta E_\mathrm{beam}} \sim 10^{-2} - 10^{-3}$$

Other probes:

- New fixed target experiment, promising.

  M. Reece and LTW, arXiv:0904.1743.
  J.D. Bjorken, R. Essig, P. Schuster, and N. Toro, arXiv:0906.0580
  B. Batell, M. Pospelov, and A. Ritz, arXiv:0906.5614
  M. Freytsis, G. Ovanesyan, and J. Thaler, arXiv:0909.2862

- High energy colliders.

  - More optimal for massive EW states decaying into darksector.

  N. Arkani-Hamed and N. Weiner, arXiv:0810.0714
  M. Baumgart, C. Cheung, J. Ruderman, LTW, I. Yavin, arXiv:0901.0283
  C. Cheung, J. Ruderman, LTW, I. Yavin, arXiv:0901.0283

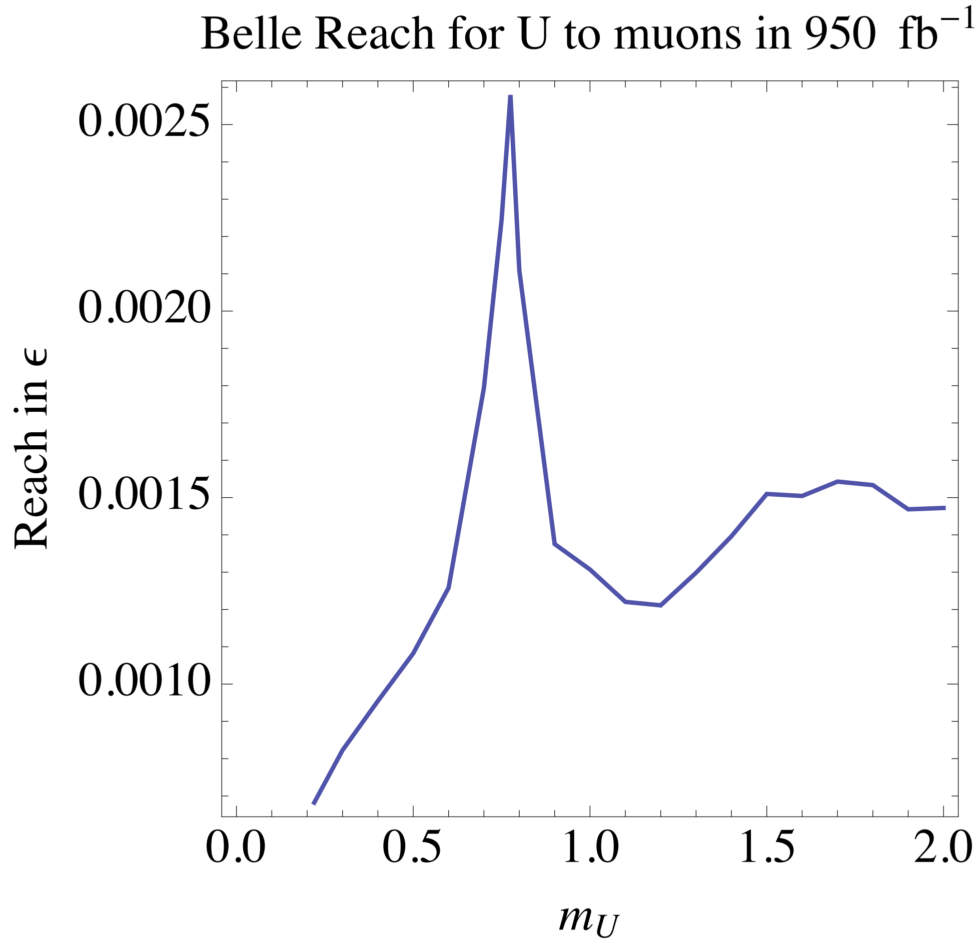
  D0, arXiv:0905.1478.

Both subjects will be covered in detail by dedicated talks.

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.
- Low energy experiments, with high luminosity, is the prime place to look for such states.
- Production of GeV dark sector results in distinct signals: multiple leptons....
- It is exciting to go into this un-explored territory.

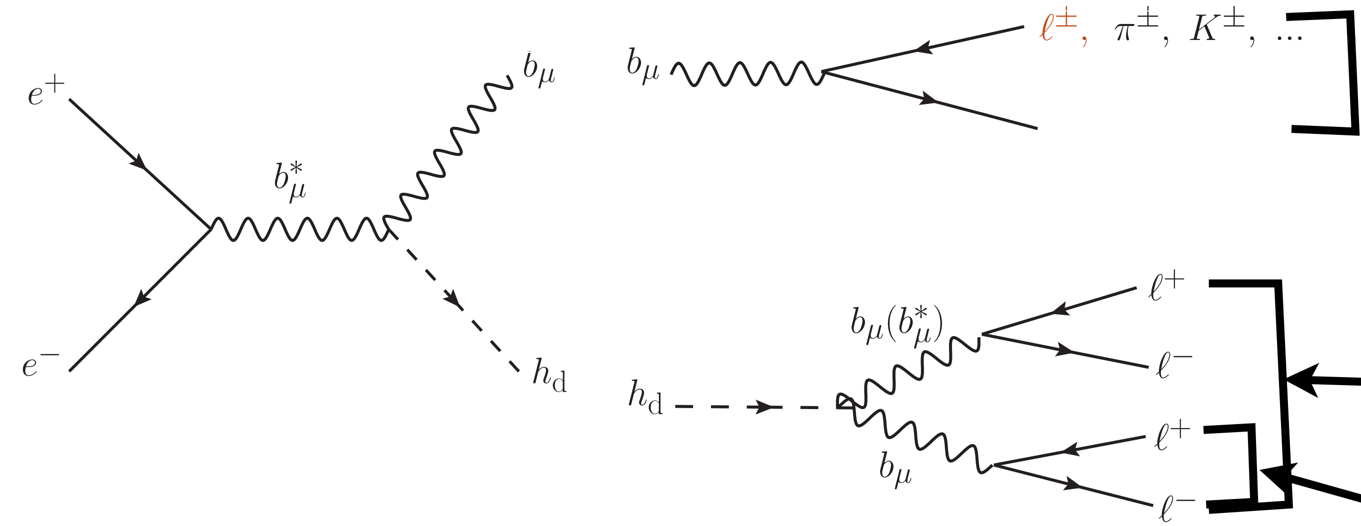
Reach at Belle in mu+ mu- channel



$$E_\gamma > 100\ \text{MeV},\ 12.4^\circ < \theta_\gamma < 155^\circ$$

$$p_T^\ell > 1\ \text{GeV},\ 17^\circ < \theta_\ell < 150^\circ$$

Signal of dark higgsstrahlung:



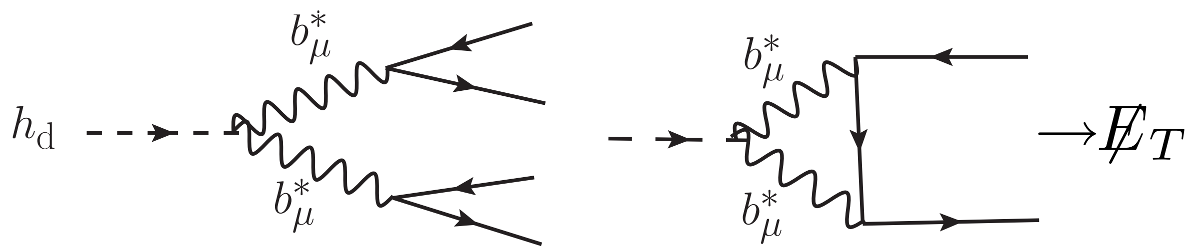
$m_{\ell\ell} = m_b$

$m_{4\ell} = m_{h_\mathrm{d}}$

$m_{\ell\ell} = m_b$

$\rightarrow 6\ell$

Or:



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