

Dark Sector at Low Energy $e^+ e^-$ Experiments

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Based on: M. Reece and LTW, arXiv:0904.1743

More information and simulation tools at:

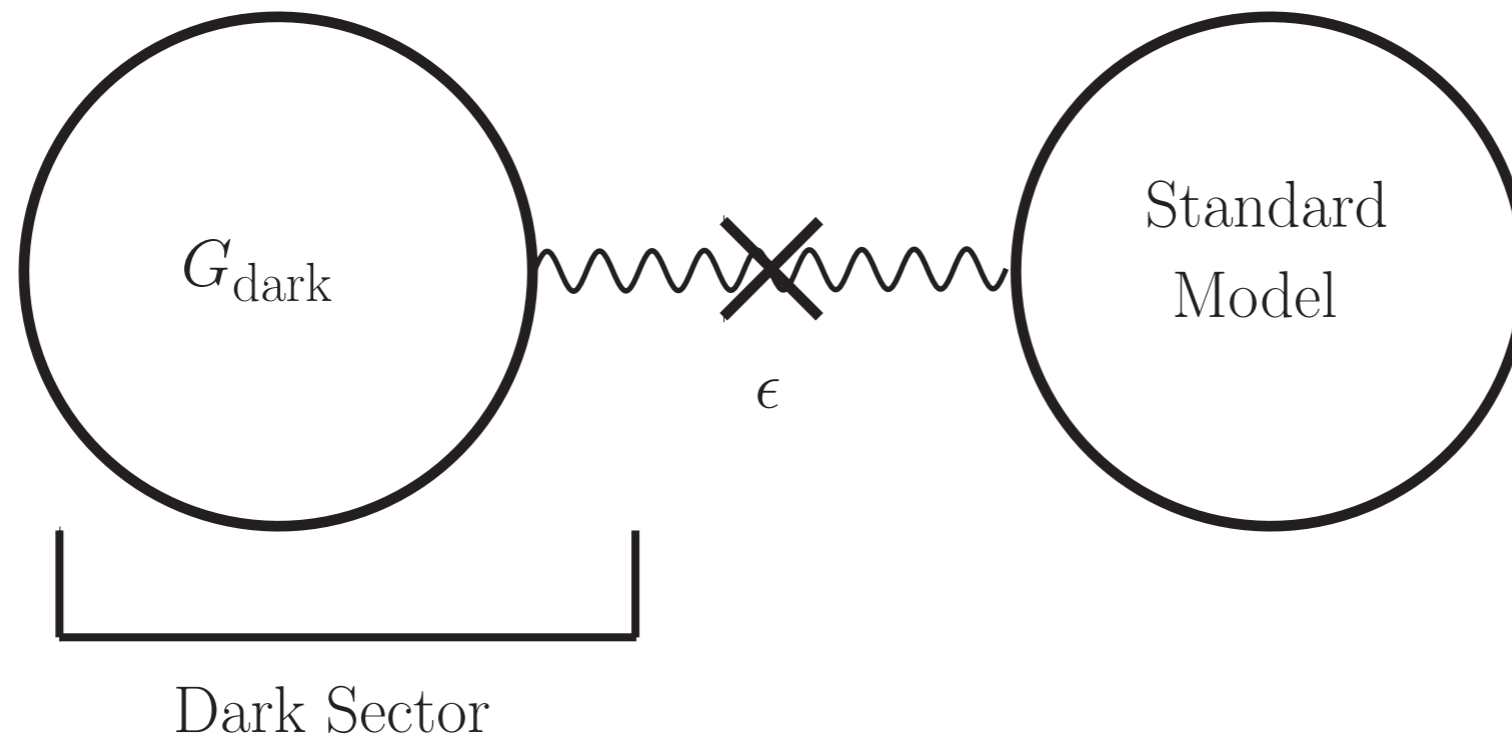
<http://phy-hal.physics.harvard.edu/LeptonJets/LE.html>

Charm 2010, Institute of High Energy Physics, Beijing

Outline

- Introduction to GeV dark sector.
 - Review of basic structure.
- Survey of search channels.
 - Focusing on low energy e^+e^- experiments.
- Conclusion.

Basic dark sector



- Dark sector and the SM sector is connected via some small coupling, “portal”.

Motivation of Light Dark Sector

- Dark Matter in the universe.
 - Cold, dark, and gravitationally coupled.
- Perhaps dark matter has self-interactions too.
 - Force carrier is an example of dark sector.
- Motivations from astrophysical observations.
 - Fermi, Pamela, ... $M_{\text{dark}} \sim \text{GeV}$

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May or may not be the right motivation.

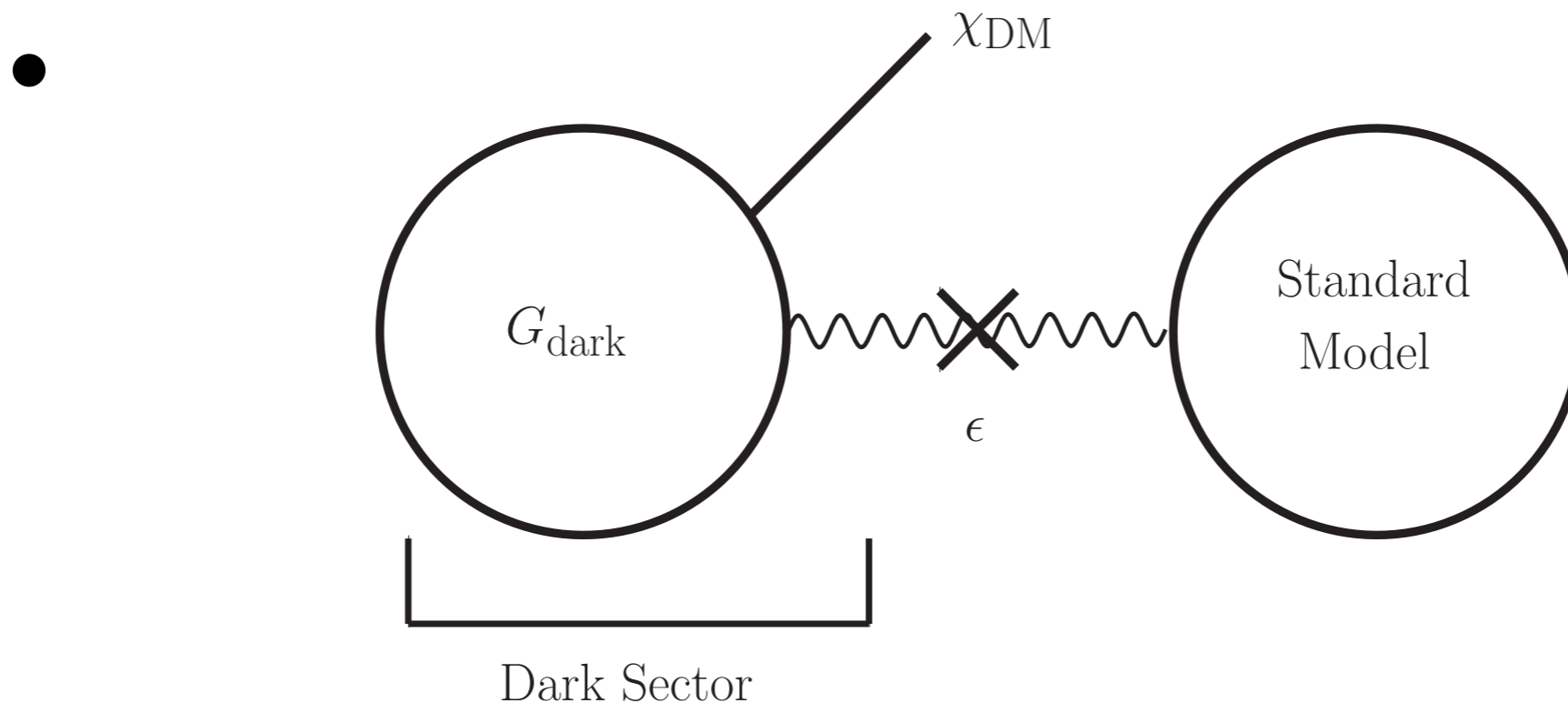
But this class of dark sector can be generic and interesting on its own.

A GeV dark sector.

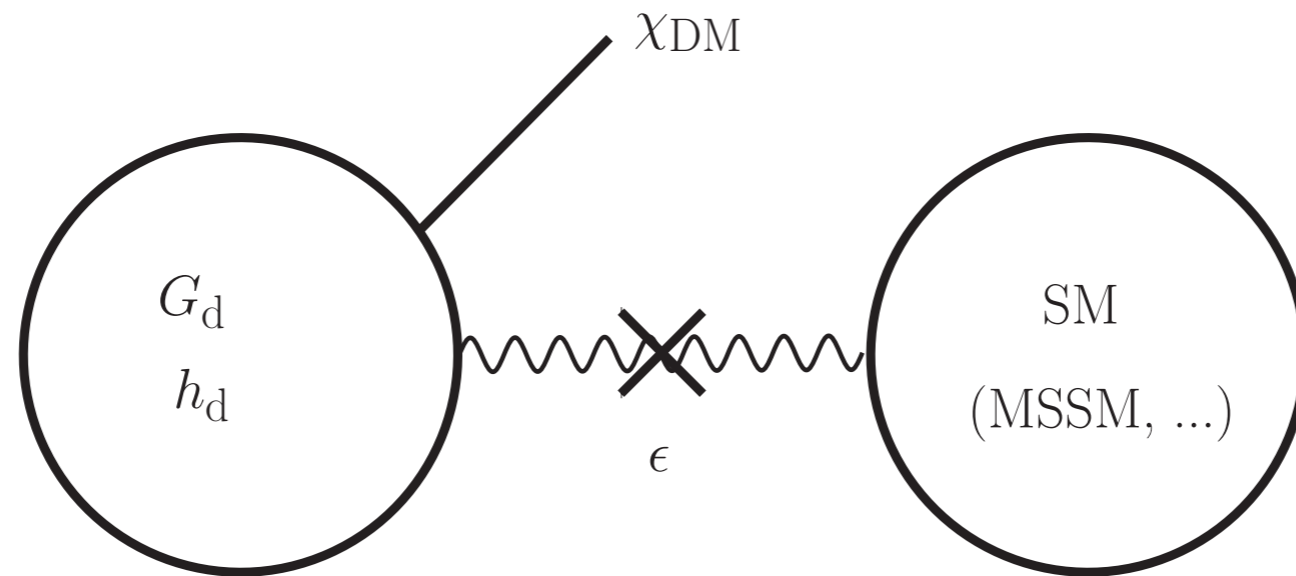
- Dark matter self-interaction, mediated by

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

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



Basic dark sector model ingredients:

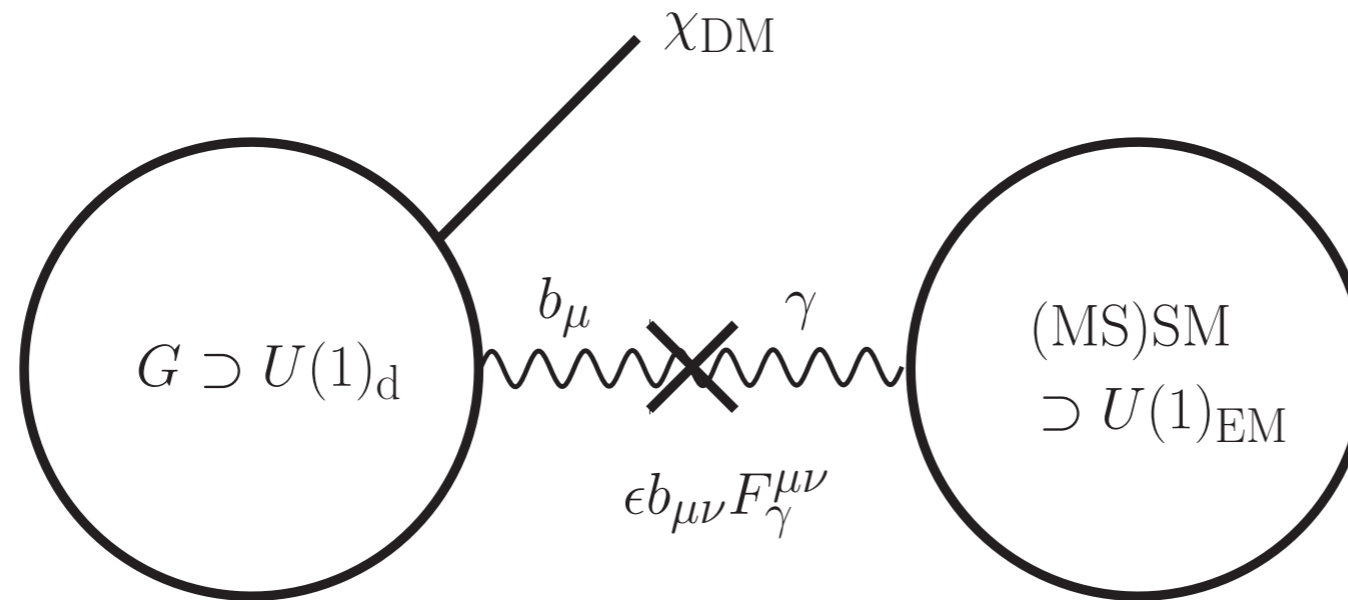


- Model choices:
 - Dark matter identity.
 - Self-interaction G_d : gauge interaction...
 - GeV scale, dark higgs h_d : $v_d = \langle h_d \rangle \sim \text{GeV}$
 - Supersymmetric scenarios: natural generation of the GeV Scale.

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, L. T. Wang, 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: $G_d = U(1)_d$
- Natural connection to the SM: kinetic mixing

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

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

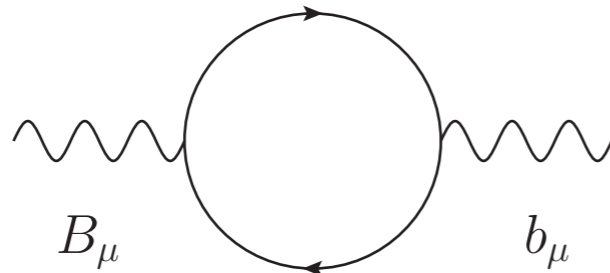
For a very simple and predictive construction:

C. Cheung, J. Ruderman, L. T. Wang 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.


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

- 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:

- Dark sector couples very weakly to the SM particles.
- Most model independent search requires high luminosity.
- Advantage of low energy searches at meson factories.

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 LTV, 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.

Dark sector couplings to the SM

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

$$A_\mu \rightarrow A_\mu + \epsilon \cos\theta_W b_\mu$$

$$b_\mu \rightarrow b_\mu - \epsilon \sin\theta_W Z_\mu$$

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

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

The “dark photon”, sometimes also called

γ' , U-boson, V_μ , or a_μ .

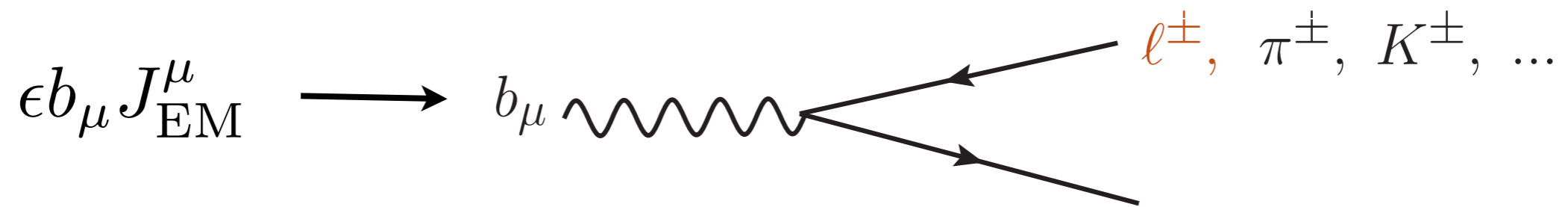
$$\text{Notation: } A' = \gamma' = b_\mu = V = a_\mu = U$$

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:

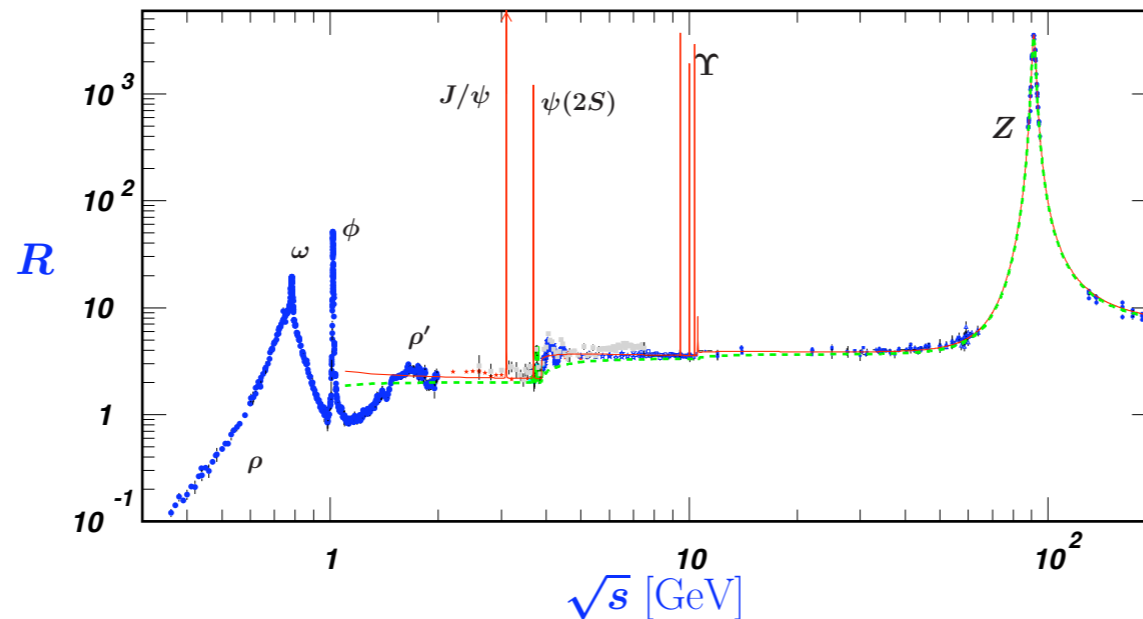
- Dark photon is the only connection, “portal”, to the Standard Model.
- Dark photon decay to SM is always the last stage of dark sector process, giving rise directly to observable signals.



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

Dark Photon decay branching ratios:

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



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

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

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

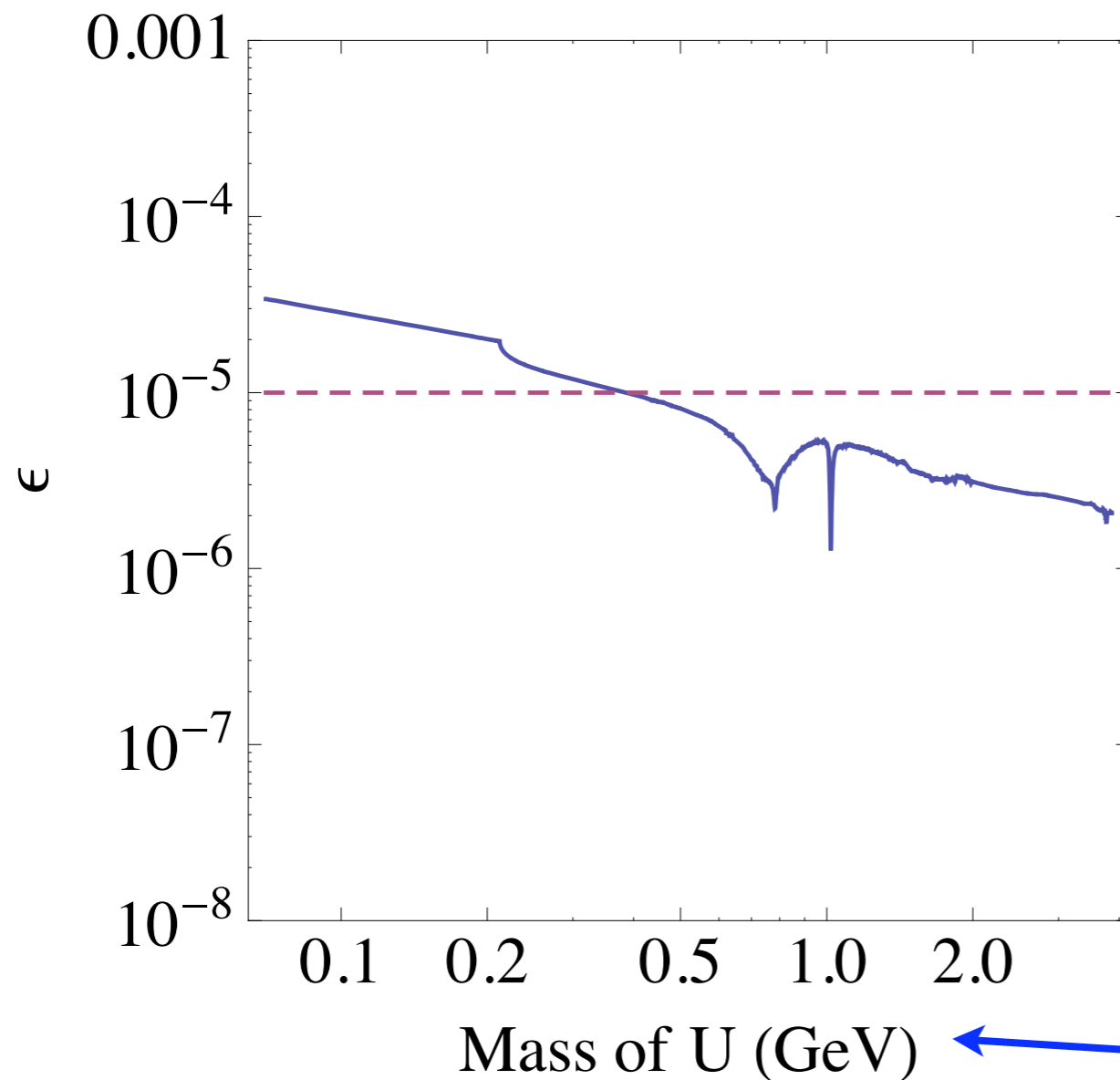
I will focus mainly on leptons here.

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



$$c\tau \sim \alpha \epsilon^2 m_{b_\mu}$$

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

Mass of U (GeV) $\leftarrow m_U = m_{b_\mu}$, dark photon mass

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 $BR \sim \epsilon^2 \times BR(\rightarrow \text{photon})$.

Reach in meson decays, rough estimates:

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

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

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

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

Reaches in some channels:

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

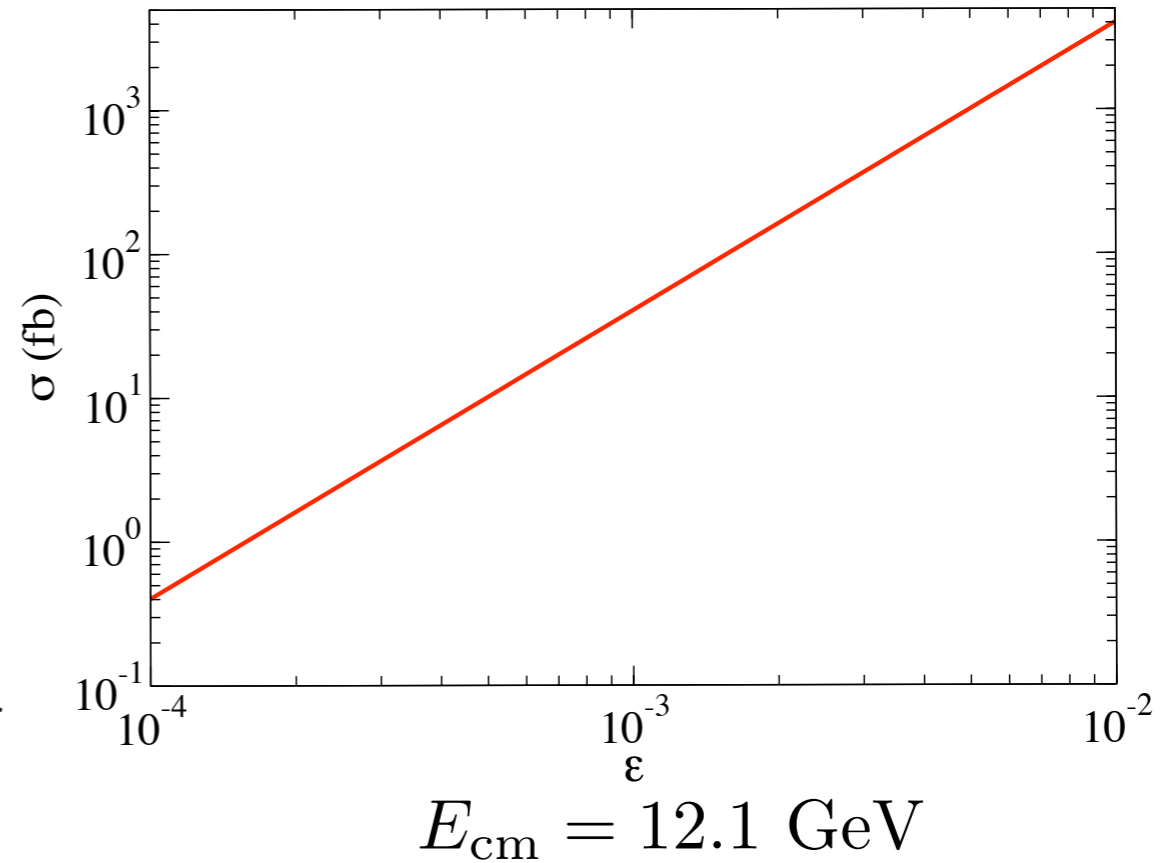
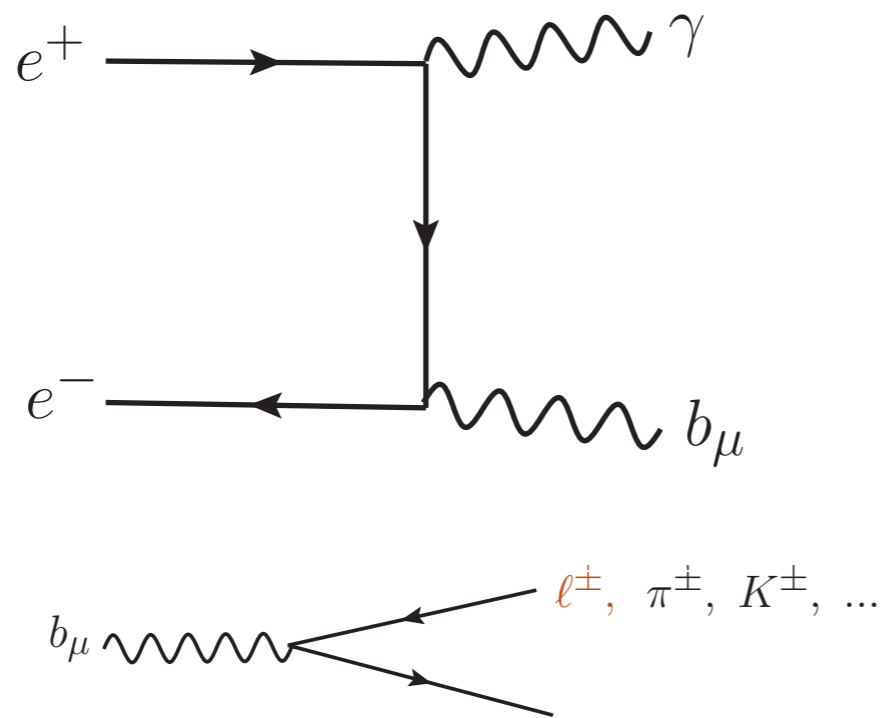
- In addition:

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

Searches of direct production of the dark photon

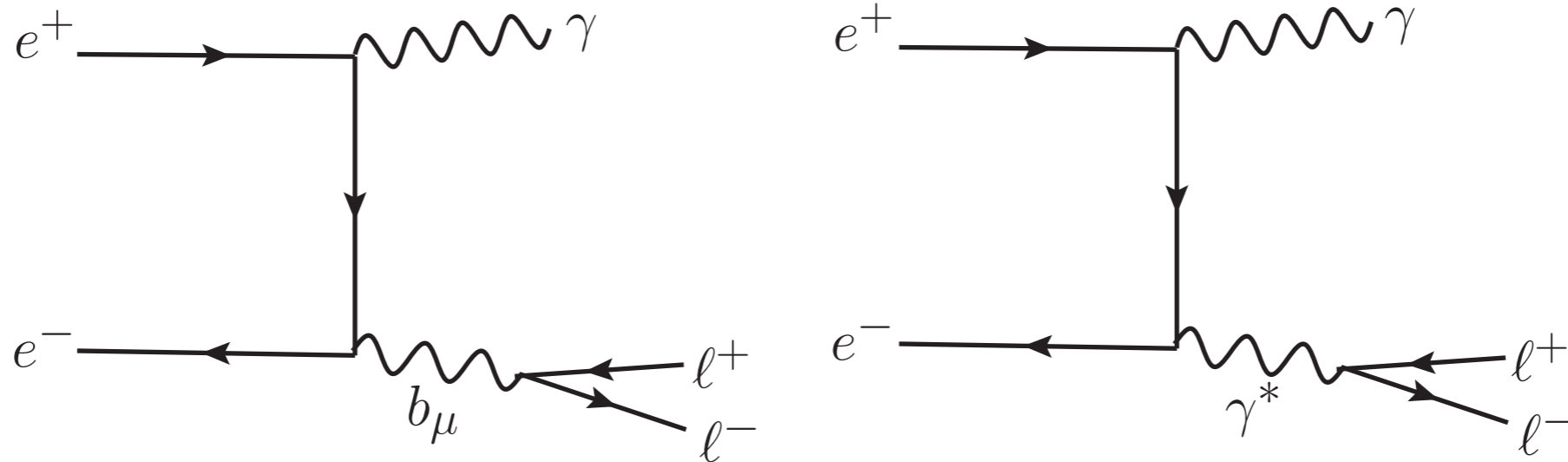
Production: associated with photon

$$e^+ e^- \rightarrow \gamma b_\mu$$



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

Signal vs background estimates:



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

\mathcal{L} : integrated luminosity; δm : resolution

$\sigma_0 = \text{rate}(e^+ e^- \rightarrow \gamma\gamma) \sim 1 \times 10^4 \text{ pb}$

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

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

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

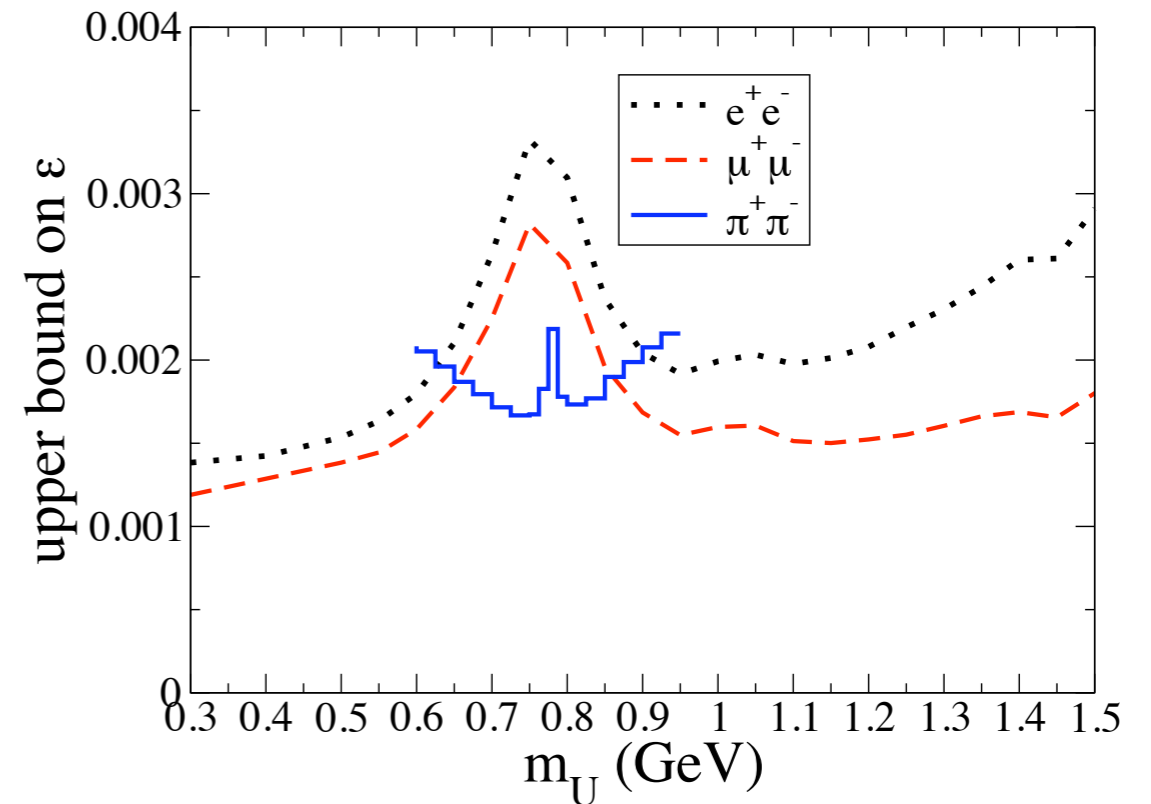
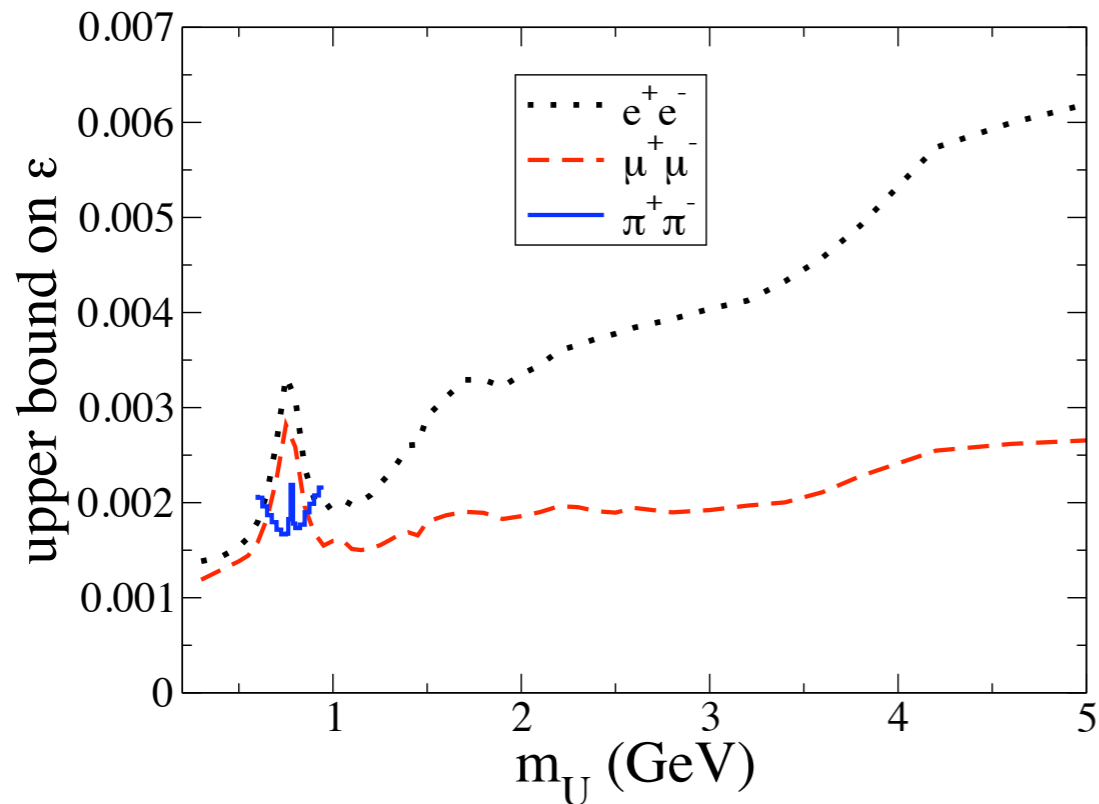
Earlier lepton colliders:

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 μ^\pm for larger m_b due to Bhabha scattering.

In our paper, we used crude approximation:

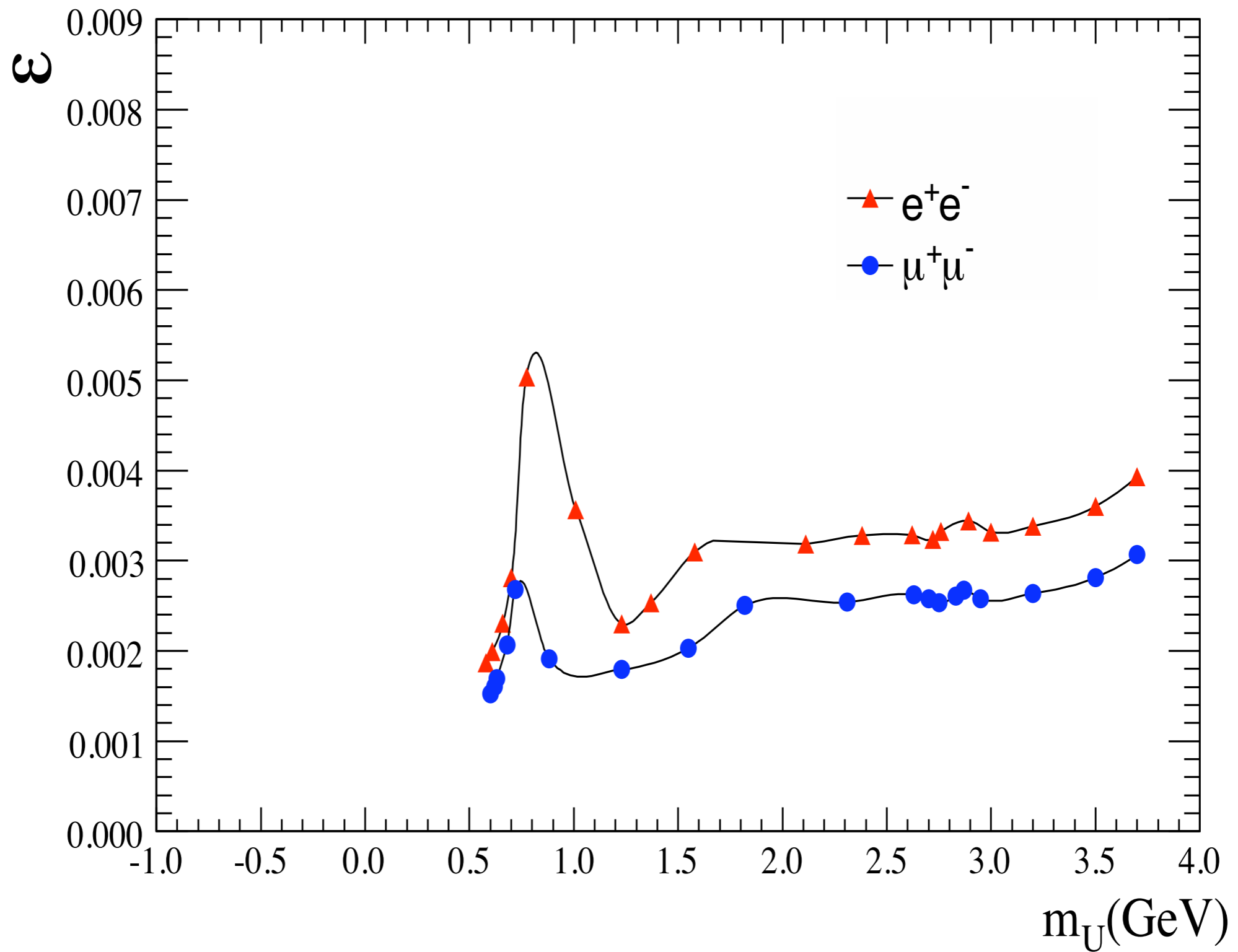
$$\mathcal{L} \simeq 500 \text{ fb}^{-1}$$

$$E_\gamma > 20 \text{ MeV}, \quad -0.890 < \cos \theta_\gamma < 0.775$$

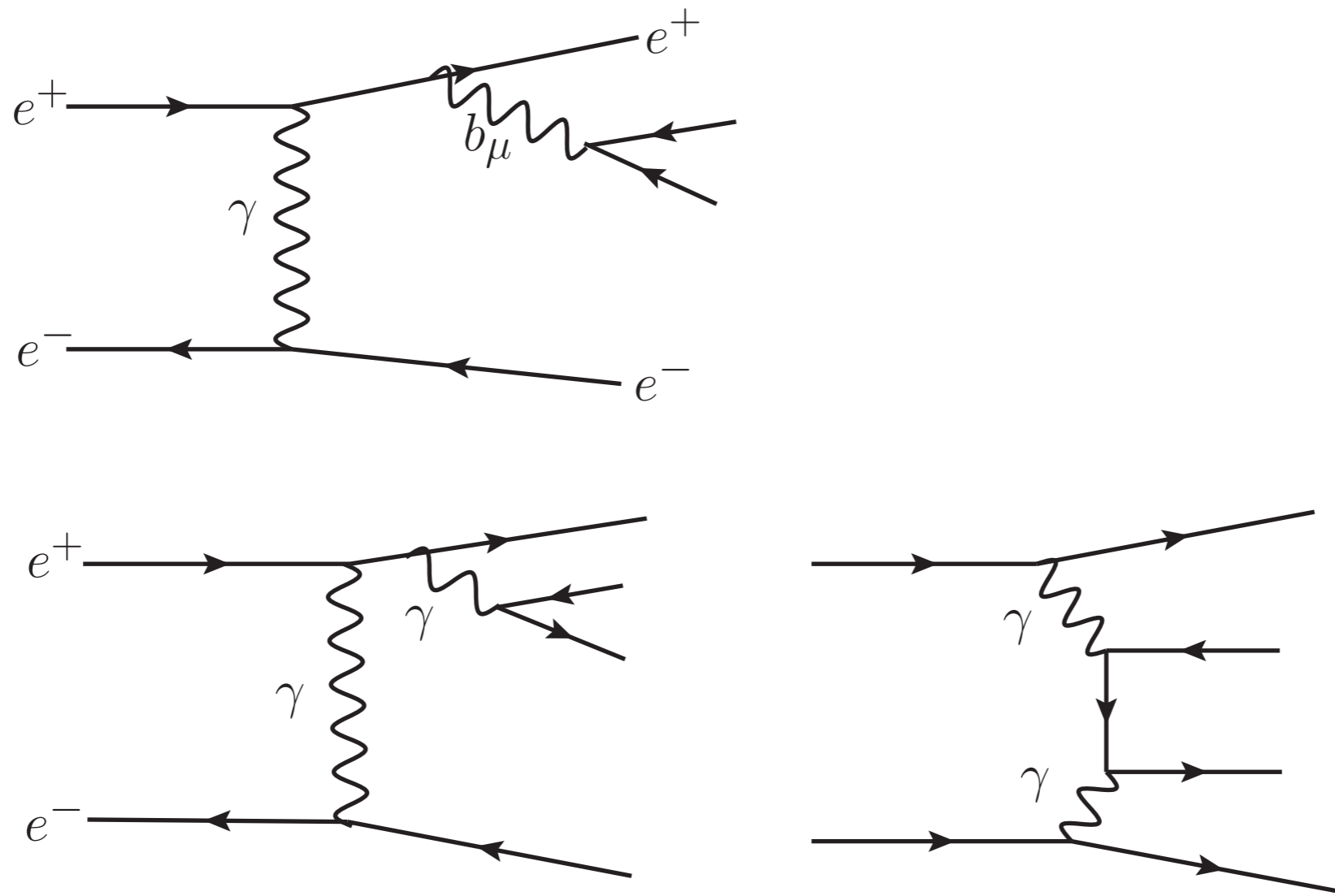
$$p_T^\ell > 60 \text{ MeV}, \quad -0.956 < \cos \theta_\ell < 0.865$$

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

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



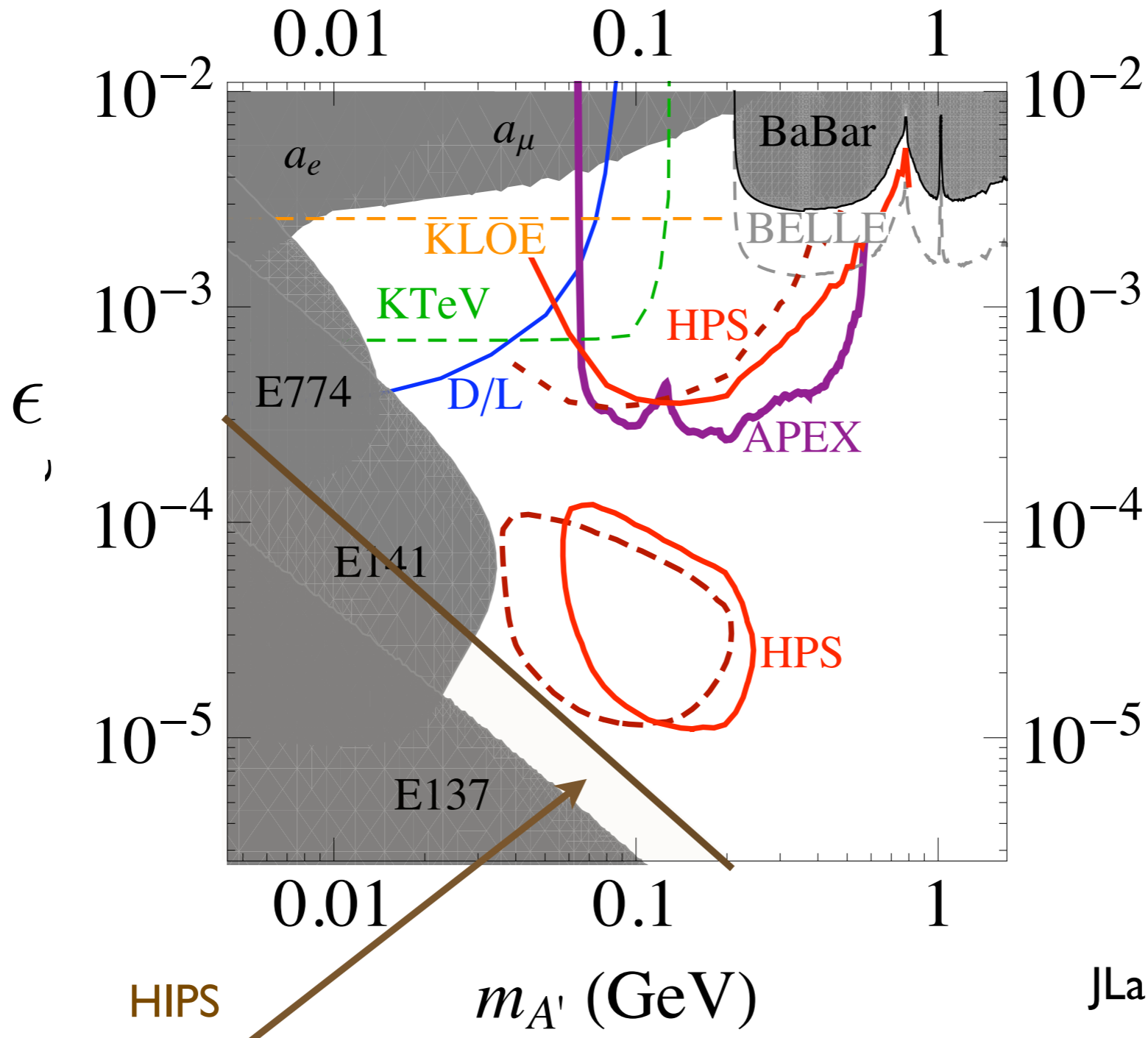
Production: final state radiation



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

M. Reece, LTW, arXiv:0904.1743.

Dark photon searches

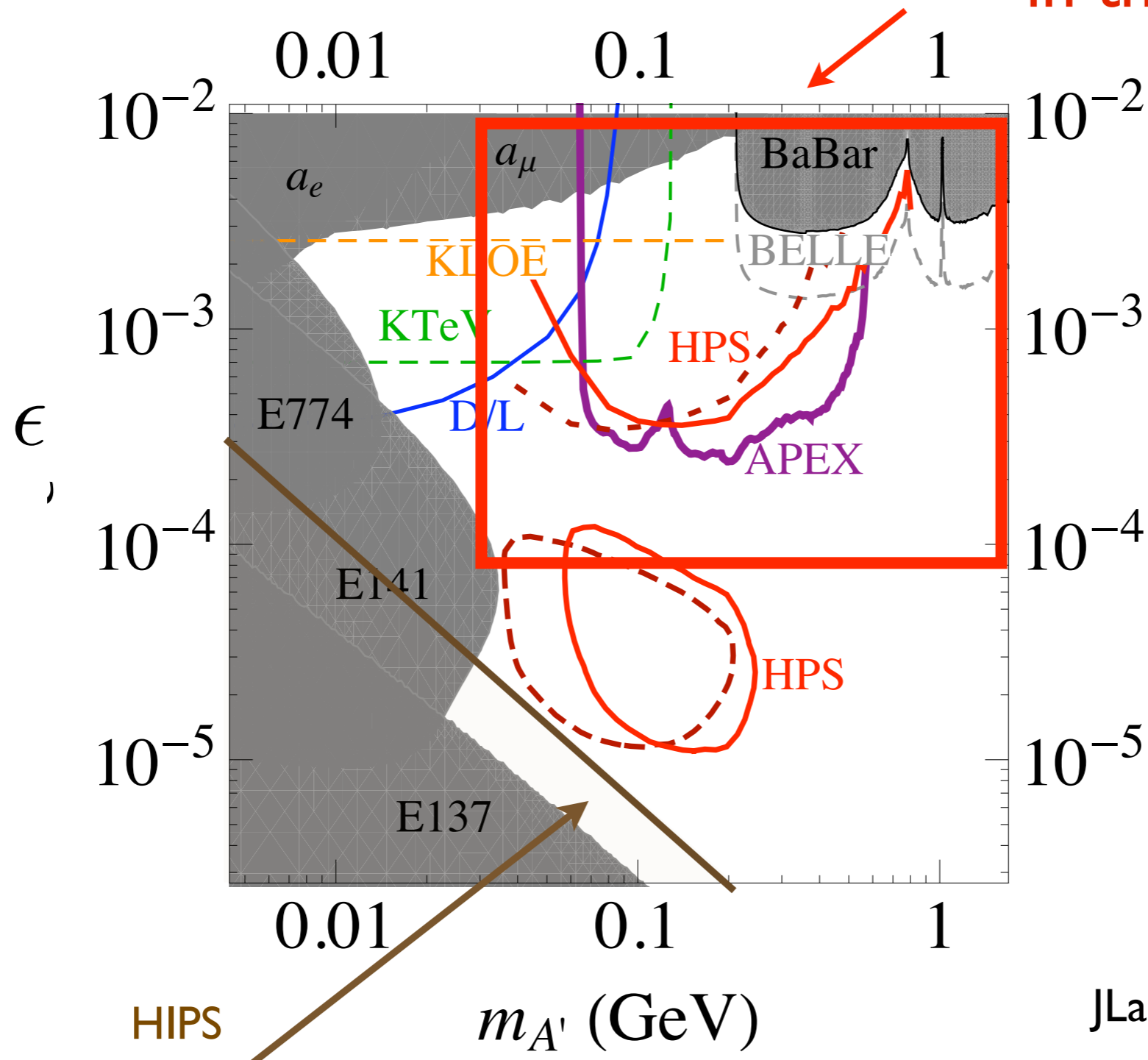


R. Essig.
JLab conference, 2010

Notation: $A' = \gamma' = b_\mu = V = a_\mu = U$

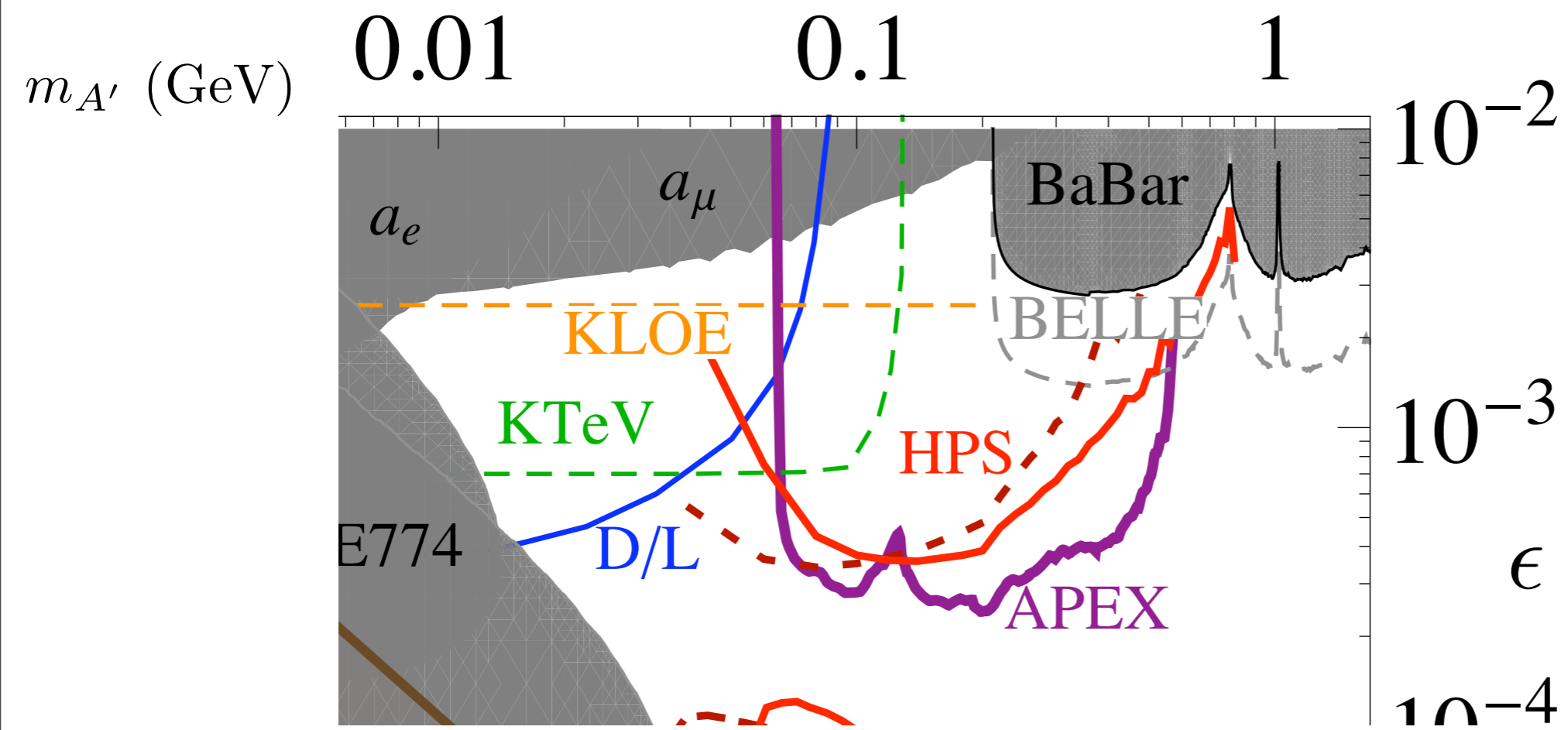
Dark photon searches

Scenario covered
in this talk

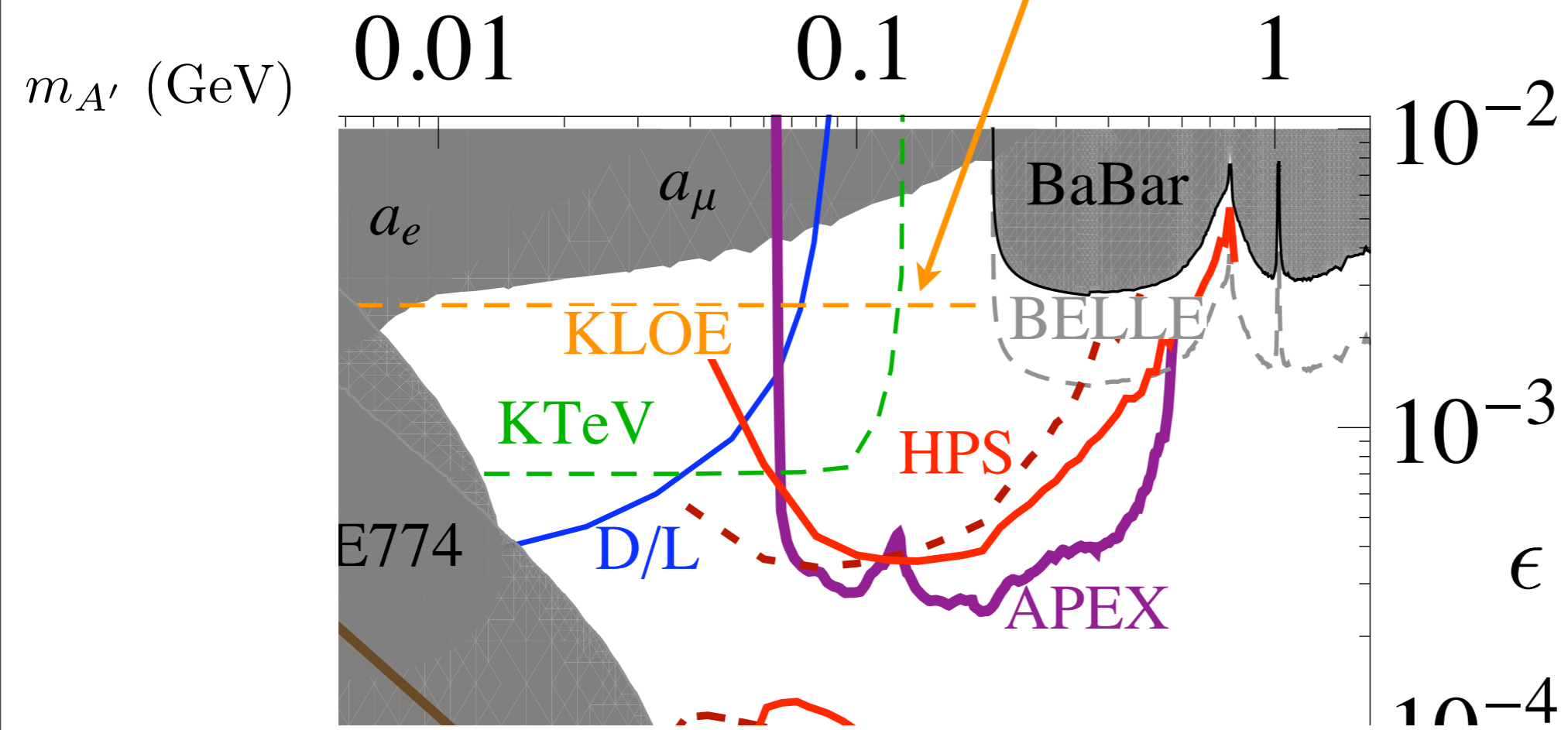


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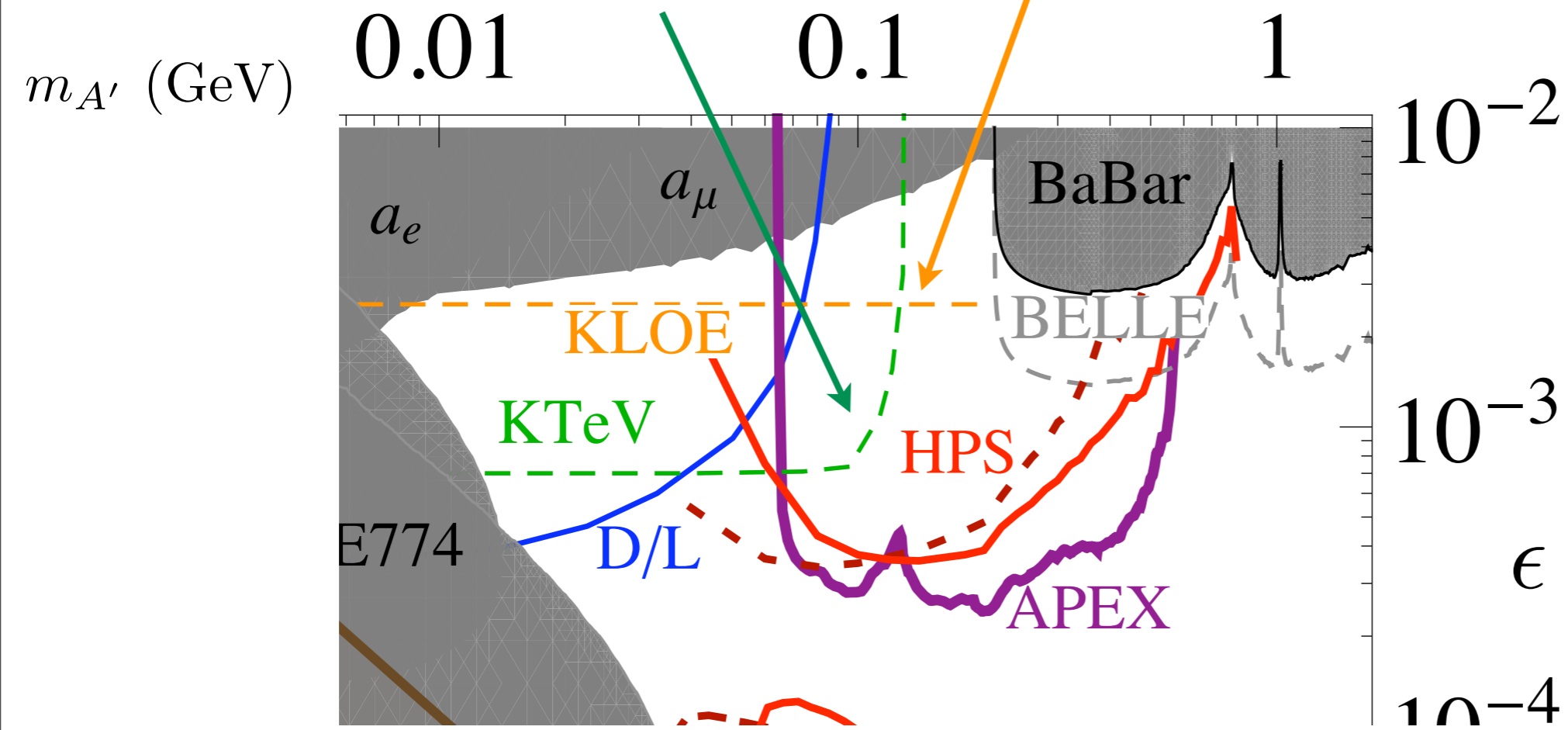


$\phi \rightarrow \eta A' \rightarrow \eta + l^+ l^-$, $\sim 10^{10} \phi$ KLOE (underway)



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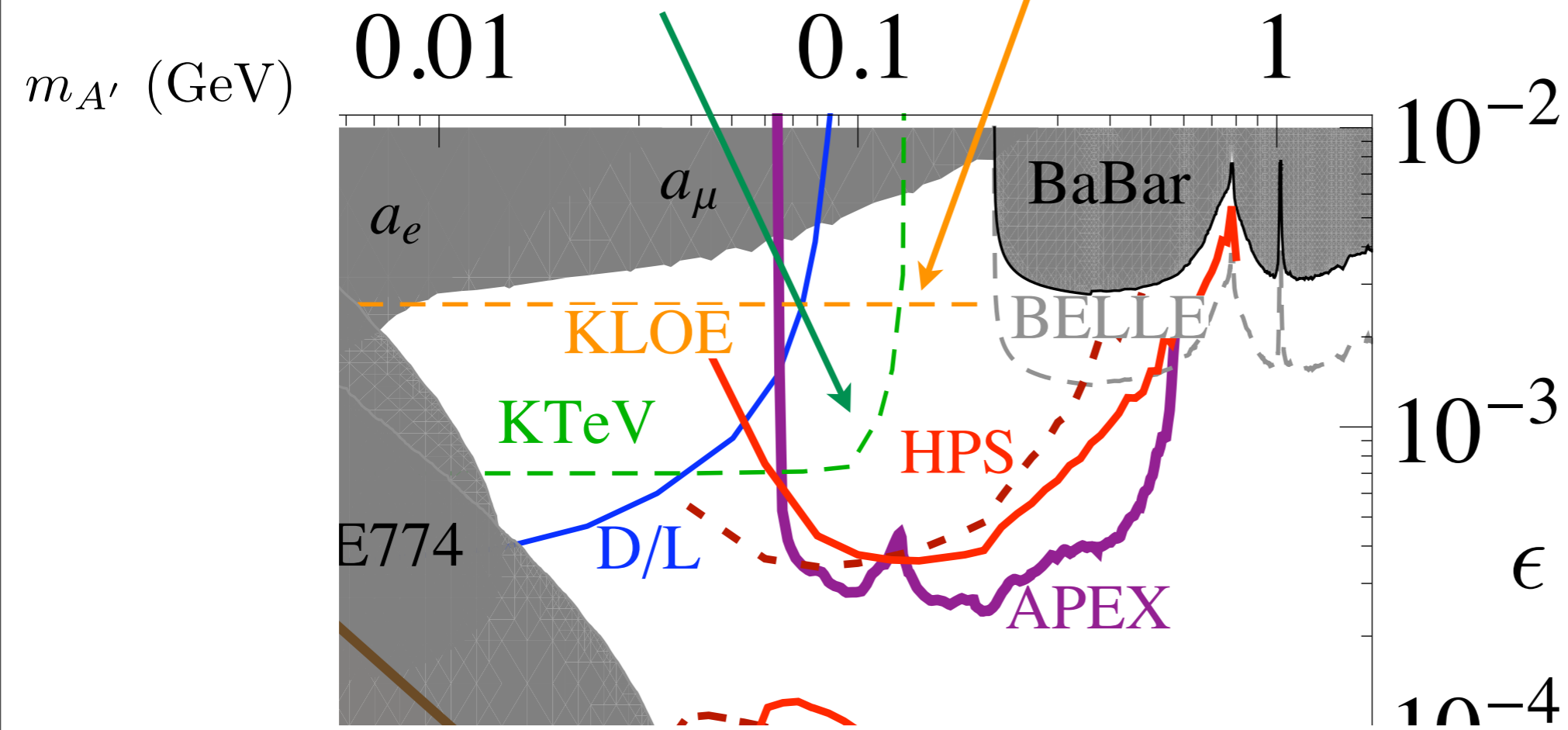
$\pi \rightarrow \gamma A' \rightarrow \gamma e^+ e^-, \sim 10^{10} \pi^0$ KTeV, estimate



$\phi \rightarrow \eta A' \rightarrow \eta + l^+ l^-, \sim 10^{10} \phi$ KLOE (underway)

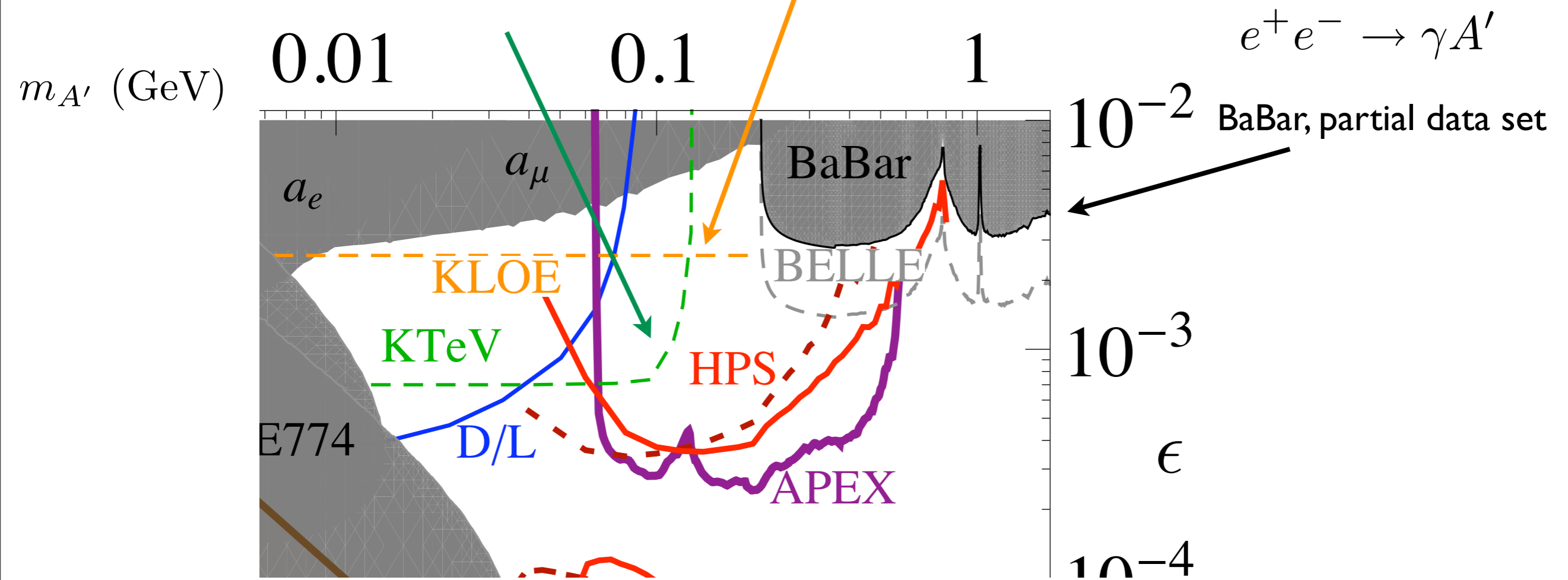
$\pi \rightarrow \gamma A' \rightarrow \gamma e^+ e^-, \sim 10^{10} \pi^0$ KTeV, estimate

$e^+ e^- \rightarrow \gamma A'$



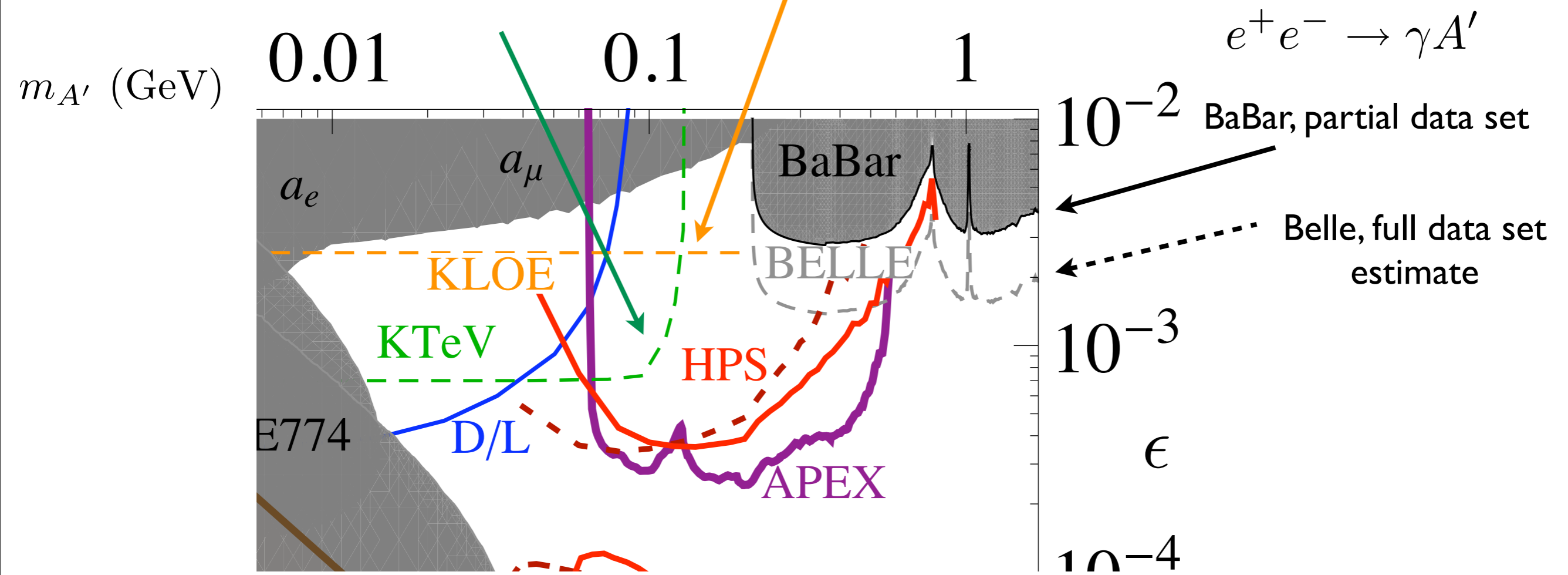
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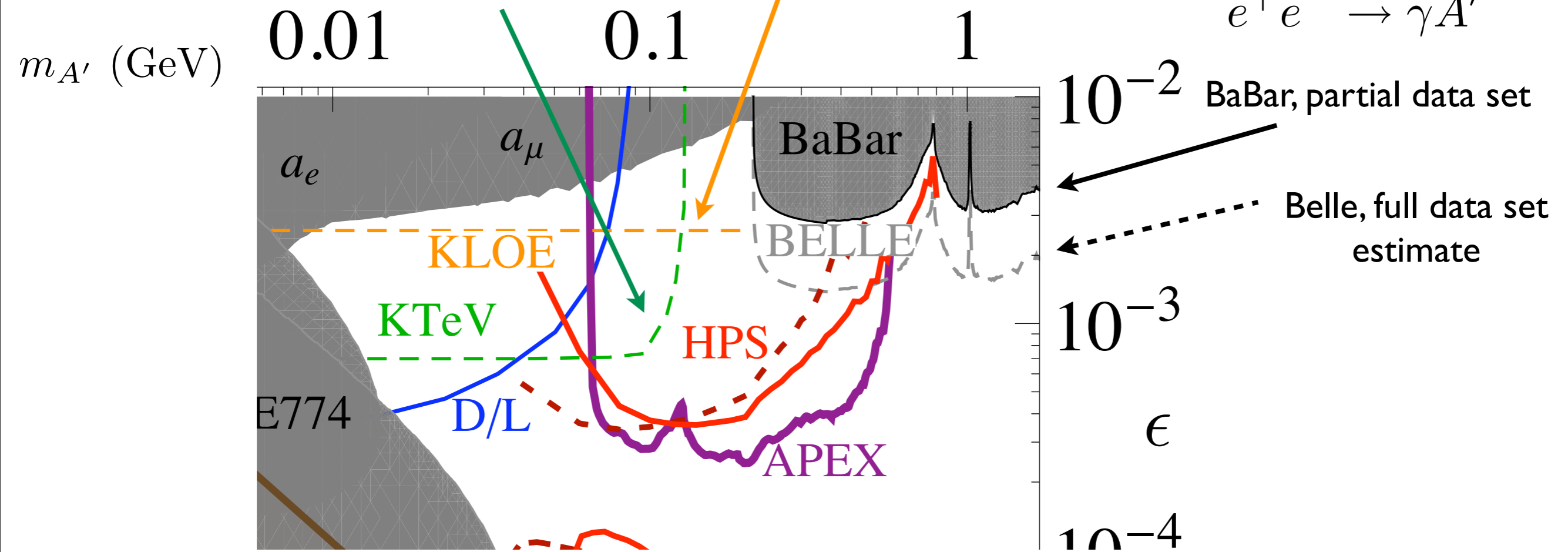
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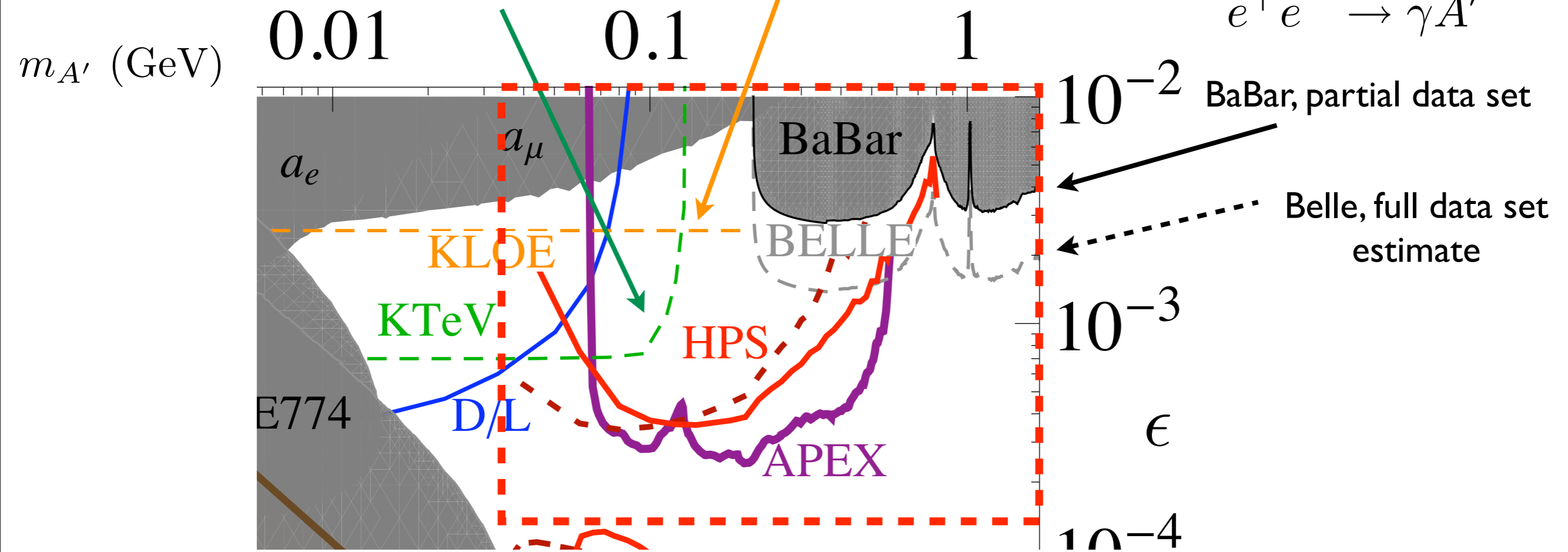


D/L, HPS, APEX, proposed fixed target experiments

$\phi \rightarrow \eta A' \rightarrow \eta + l^+ l^-, \sim 10^{10} \phi$ KLOE (underway)

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D/L, HPS, APEX, proposed fixed target experiments

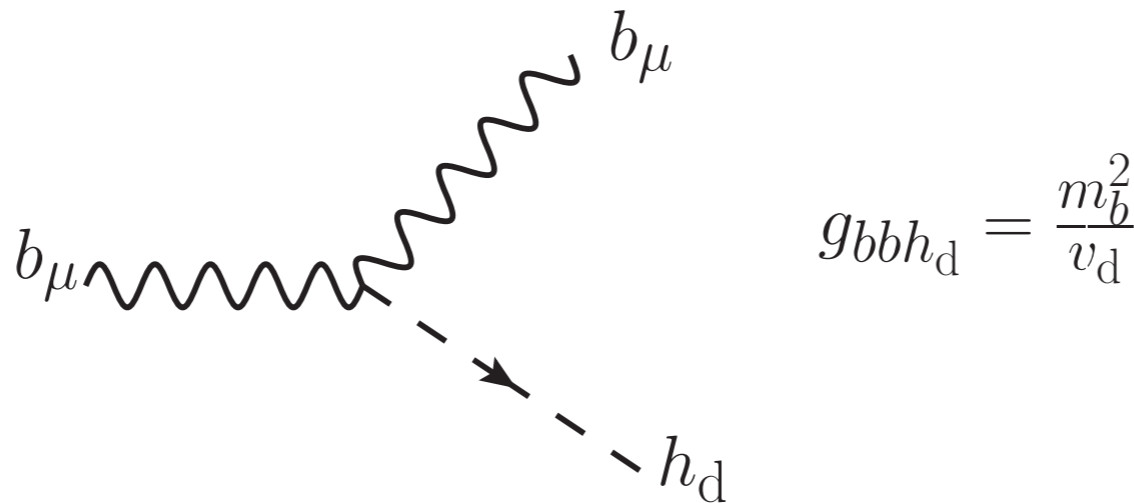
Dark Sector self-coupling

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

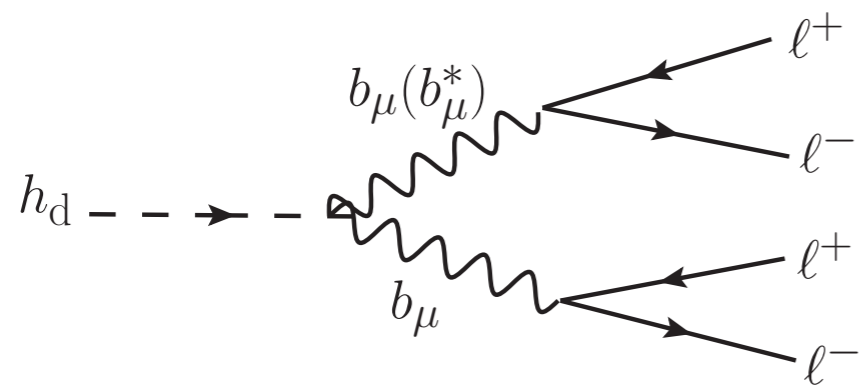
$$\mathcal{L} \supset |Dh_d|^2; \quad D_\mu h_d = (i\partial_\mu + g_d b_\mu)h_d$$

$$v_d \equiv \langle h_d \rangle \simeq \text{GeV}$$

- Dark photon - dark Higgs coupling



Decay of dark higgs



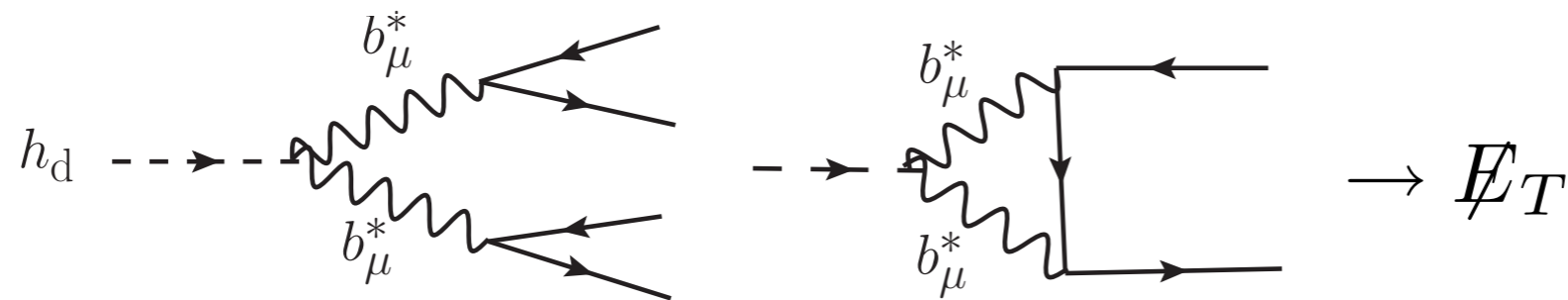
$m_{h_d} > m_b \rightarrow 4\ell$ final state

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

$c\tau \sim 10(\text{s})$ cm

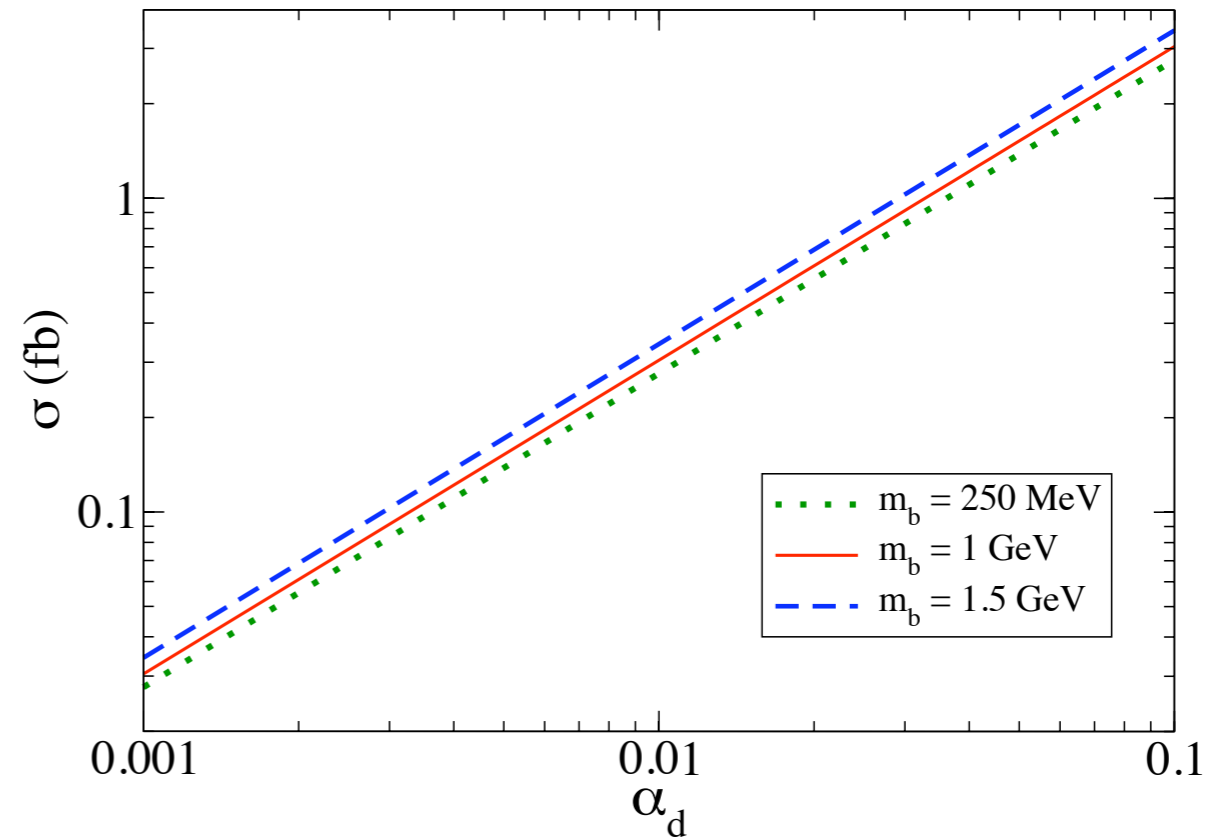
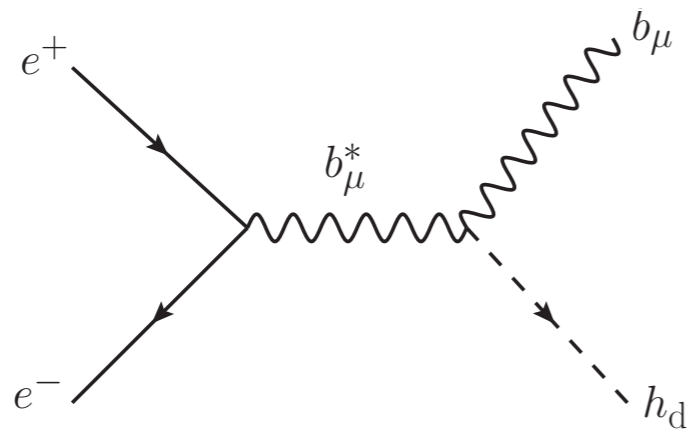


For $m_{h_d} < m_{b_\mu}$

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

Production: “Higgsstrahlung”

Production rate of $e^+e^- \rightarrow b_\mu + h_d$

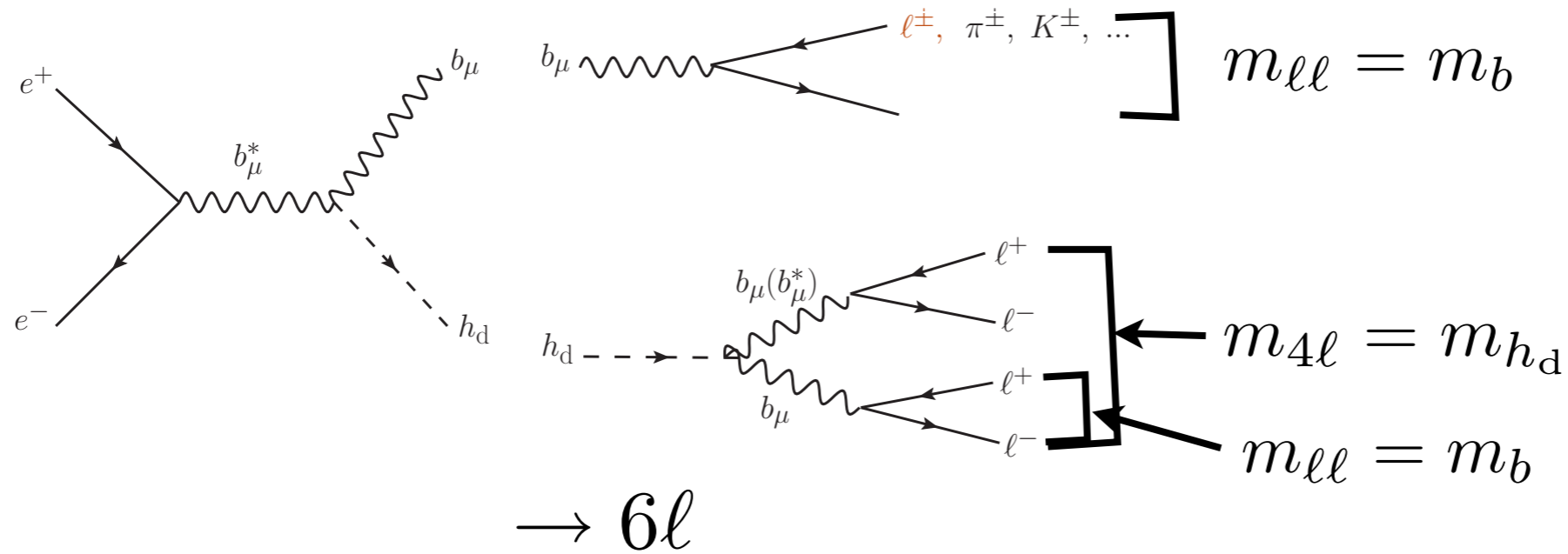


For detailed study:

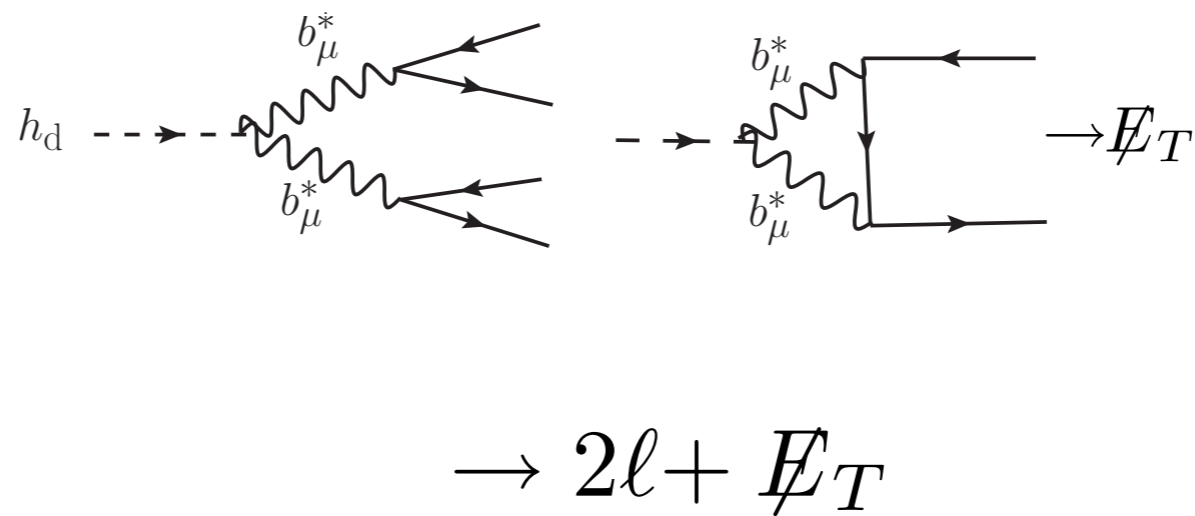
B. Batell, M. Pospelov, and A. Ritz, arXiv:0903.0363, and talk by B. Batell.

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

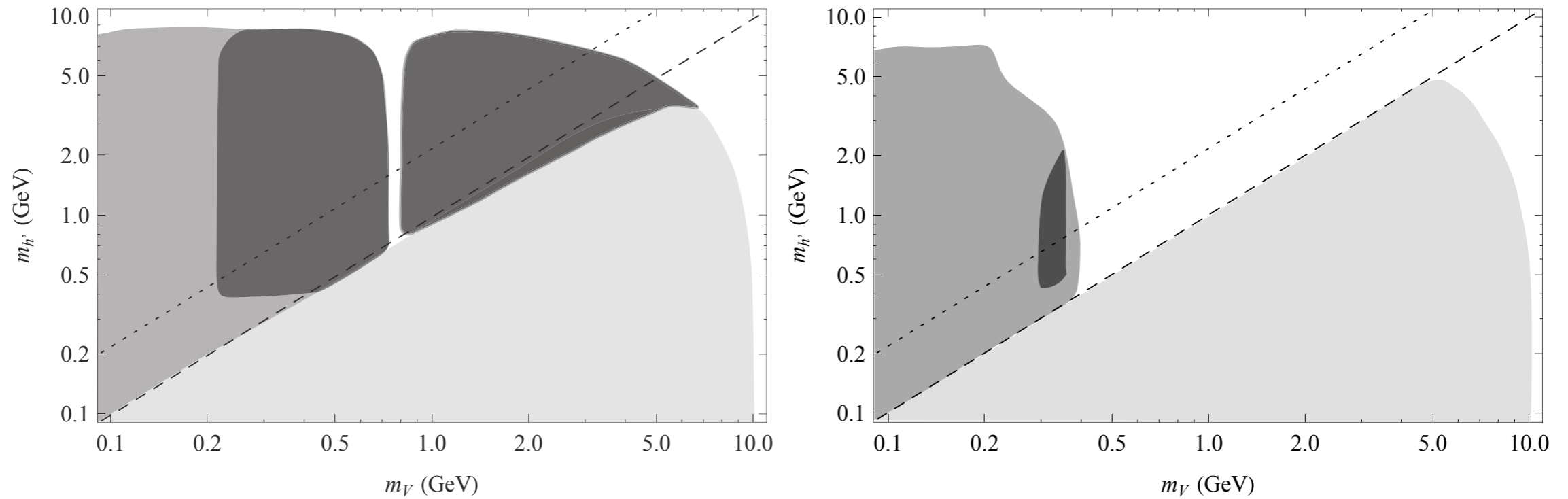
Signal of dark higgsstrahlung:



Or:



Reach estimate: B. Batell, M. Pospelov, and A. Ritz, arXiv:0903.0363.



light: $2\ell + \cancel{E}_T$; medium: $6e$; dark: 6μ

$m_V = m_{b_\mu}$

- Using 500 fb^{-1} .
- Contours for 10 signal events.

Decay in non-minimal models

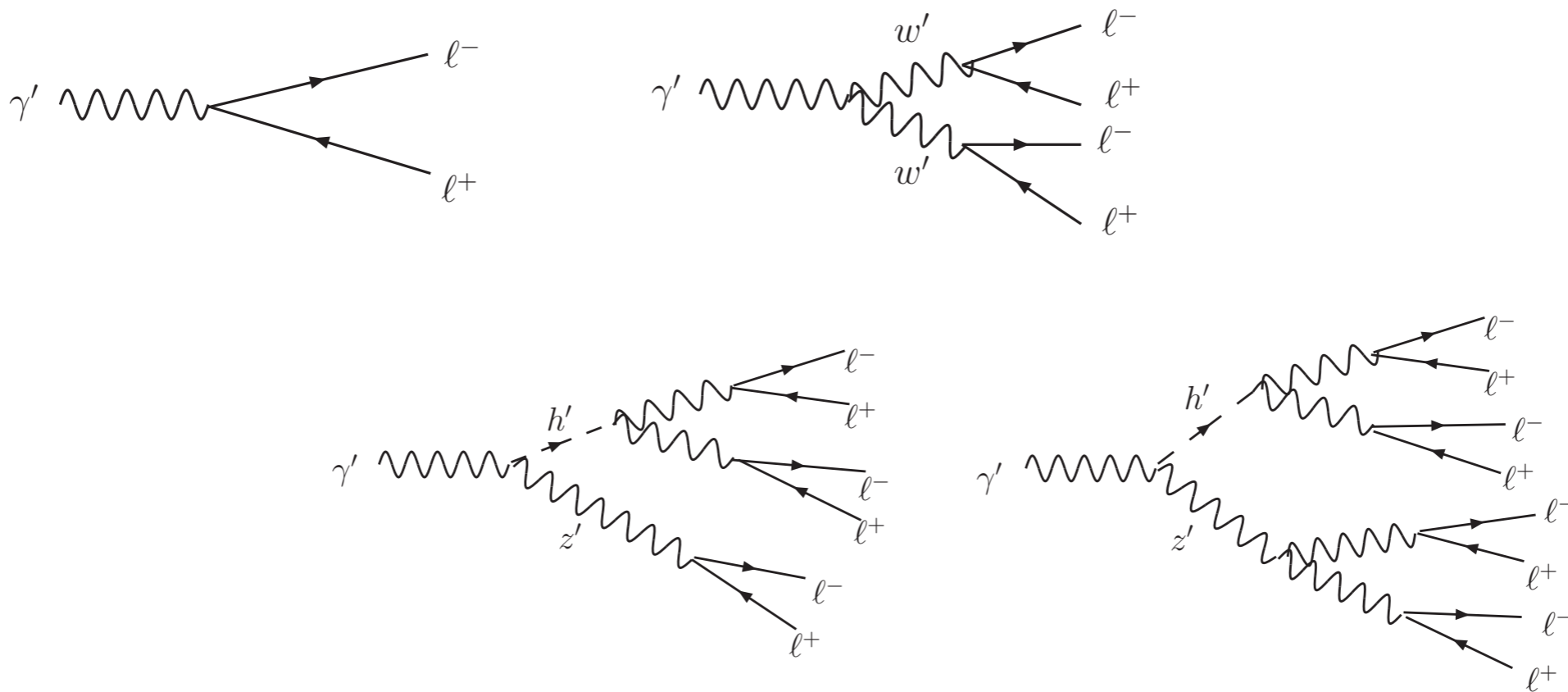
- Non-minimal models with non-Abelian dark-sector, multiple dark Higgses possible.

N. Arkani-Hamed, D. Finkbeiner, T. Slatyer and N. Weiner, arXiv:0810.0713

M. Baumgart, C. Cheung, L. T. Wang, J. Ruderman, I. Yavin, arXiv:0901.0283

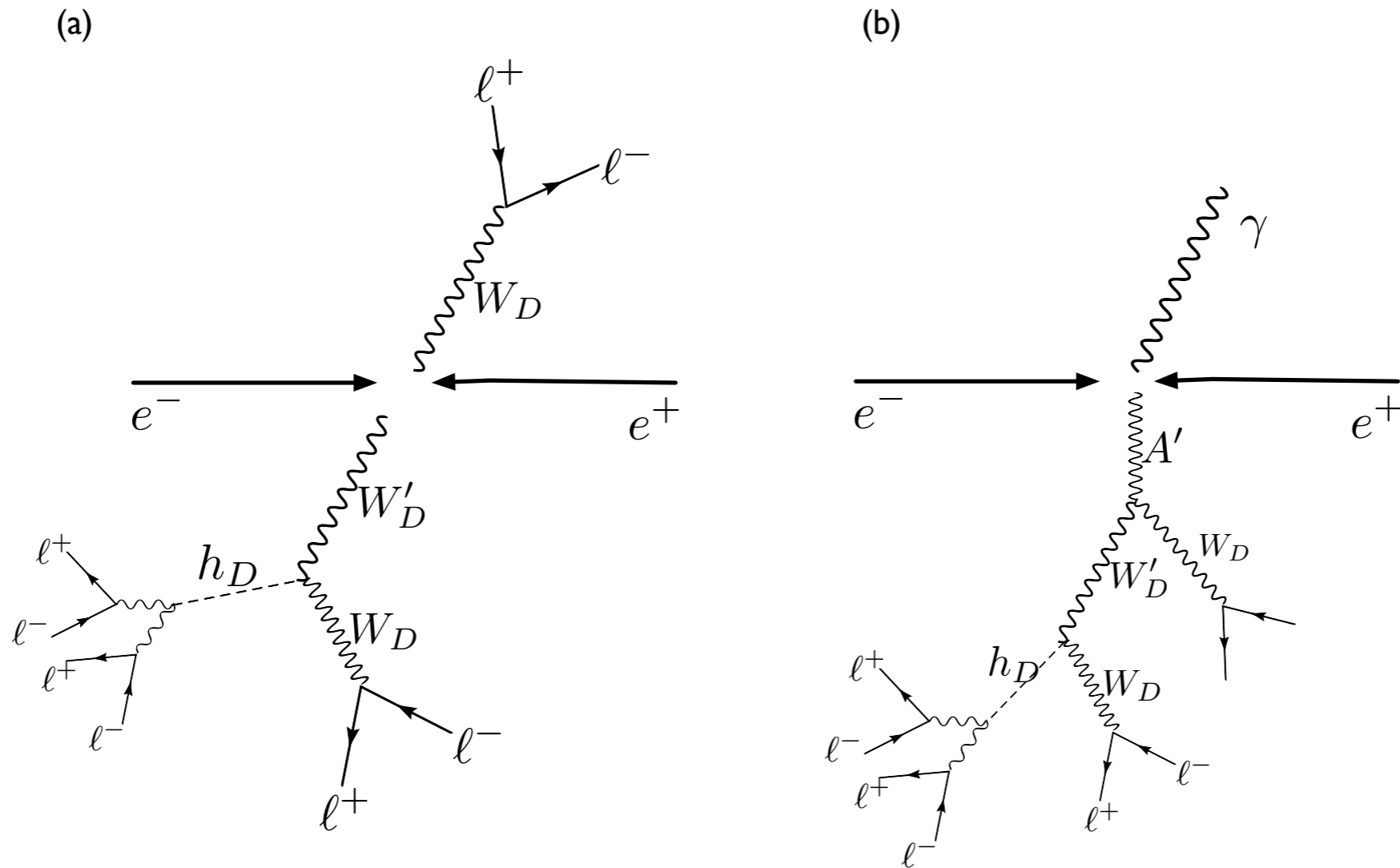
D. Alves, S. Behbabani, P. Schuster, and J. Wacker, arXiv:0903.3945

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



More possibilities in non-minimal models.

- Additional channels in non-minimal models.



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

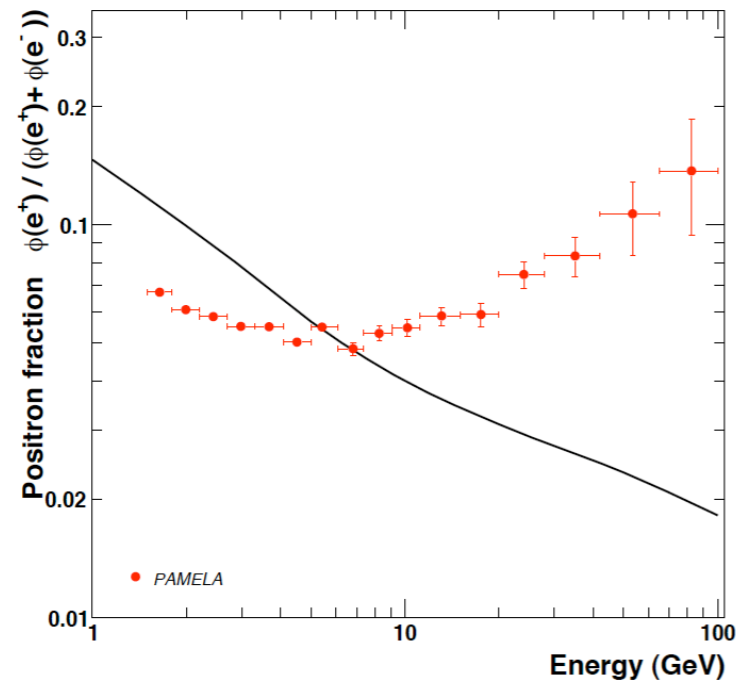
Conclusion:

- Weakly coupled light dark sector is a generic and interesting possibility of new physics beyond the Standard Model.
- Recent evidence in dark matter detection can be interpreted as suggesting such self-interaction is mediated by GeV dark sector states.
- Low energy e^+e^- 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.

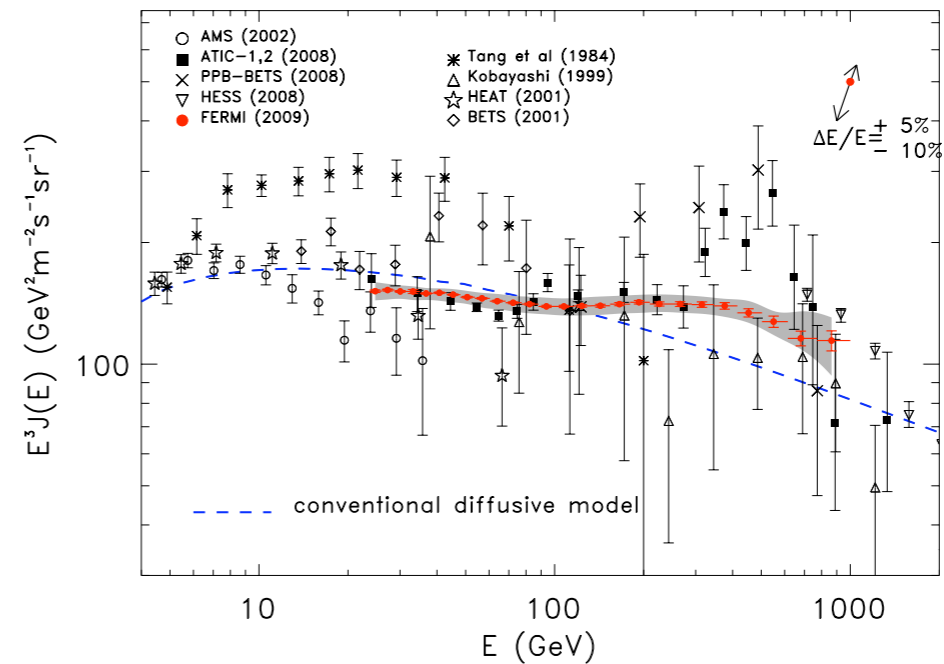
Backup Slides

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:

- Correct thermal relic density fixes DM annihilation rate:

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

- Cosmic ray flux:

$$R_{e^+, \gamma, \bar{p} \dots} \propto (n_{\text{DM}}^{\text{halo}})^2 \times \langle \sigma v \rangle_{\text{halo}}$$

$$\text{Assume } \langle \sigma v \rangle_{\text{halo}} \simeq \langle \sigma v \rangle_{\text{freeze-out}} \rightarrow R_{e^+, \gamma, \bar{p} \dots}$$

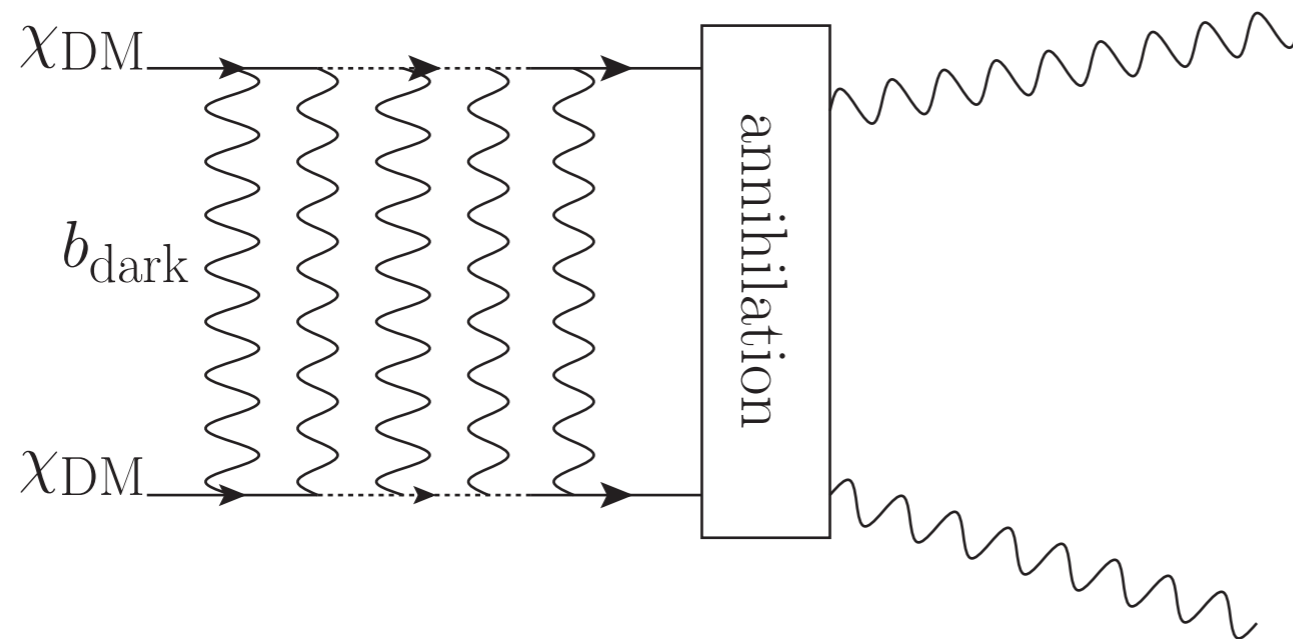
- Observed positron and electron excess needs an additional $\mathcal{O}(10\text{s}-100)$ enhancement.

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: $\langle \sigma v \rangle_{\text{halo}} \gg \langle \sigma v \rangle_{\text{freeze-out}}$

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_{dark}

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

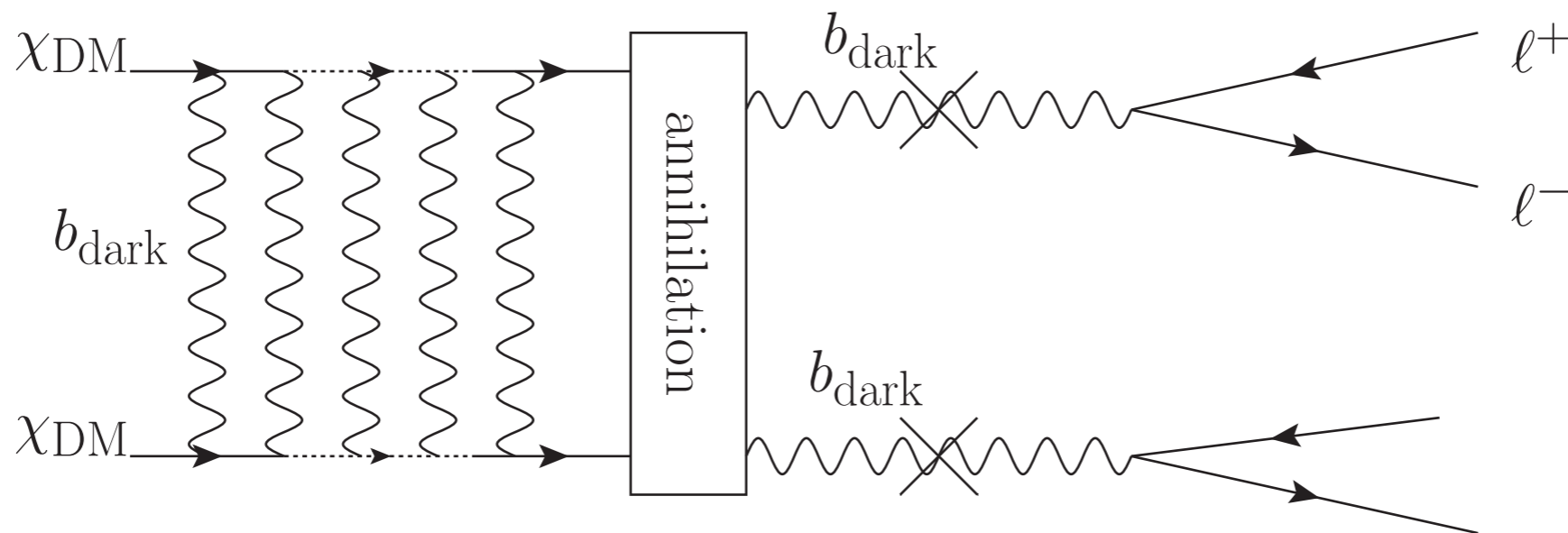
Enhancement sets in when $m_b \sim \alpha_{\text{dark}} M_\chi$

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

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

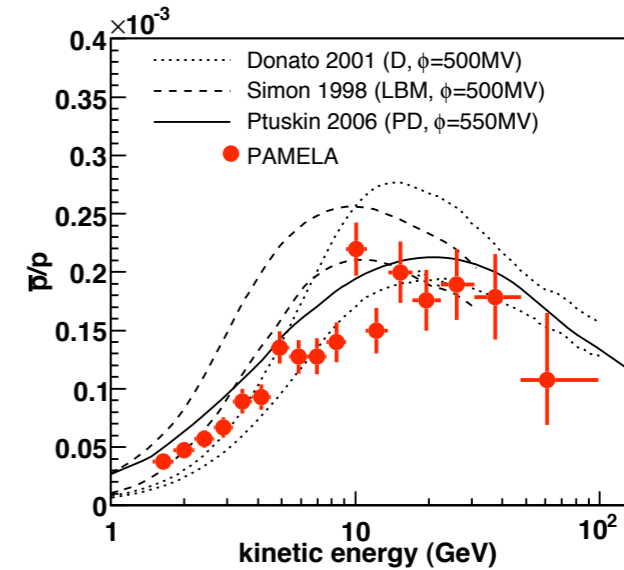
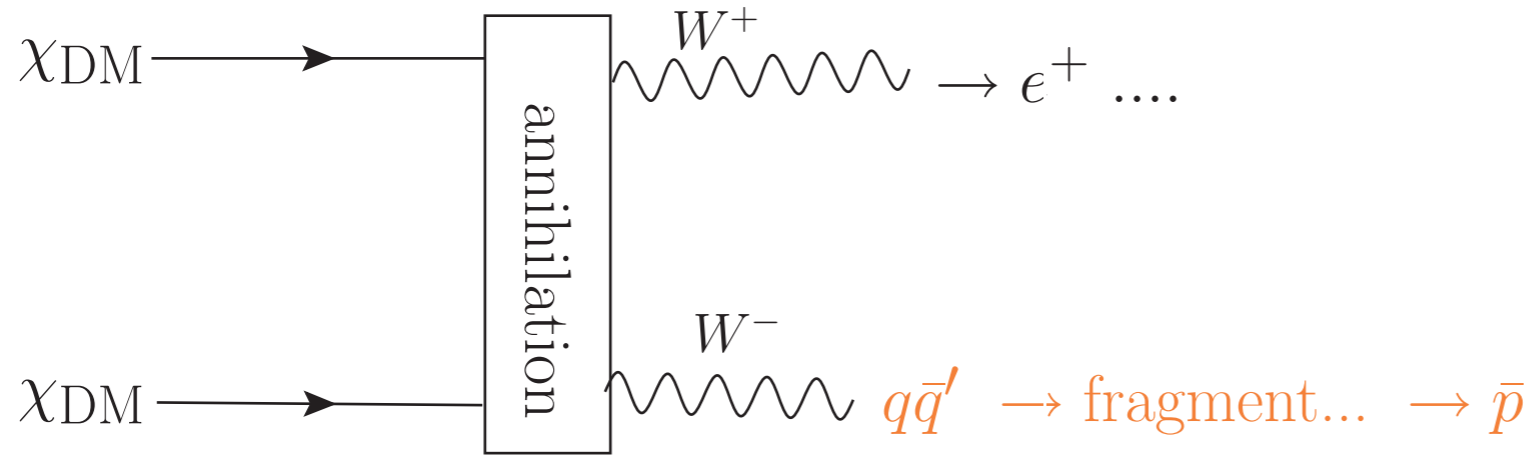
$M_\chi \sim 10^2$ GeV, $\alpha_{\text{dark}} \sim 0.1 - 0.01$, $\rightarrow m_b \sim$ GeV.

The observed signal at PAMELA/Fermi



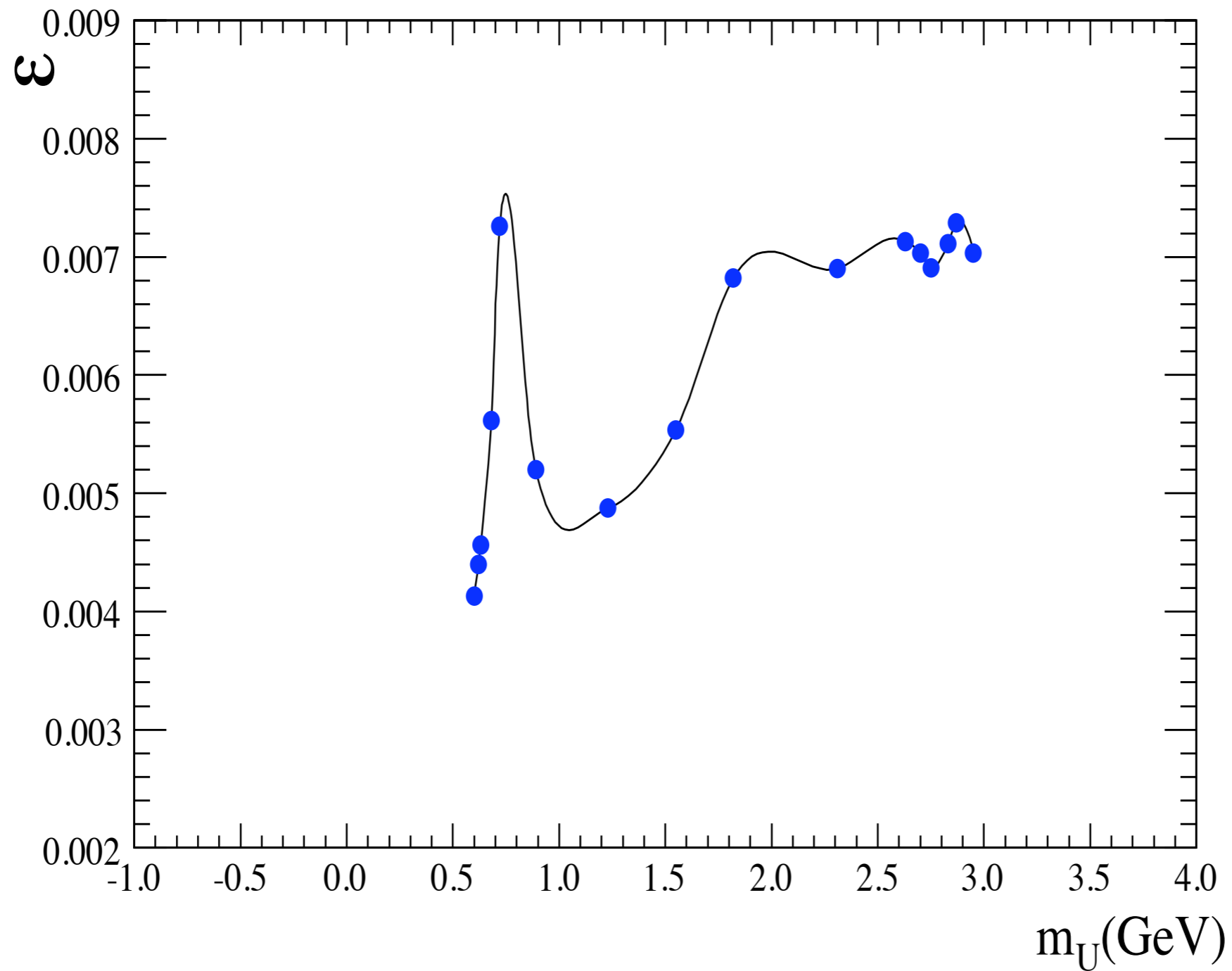
- Dark matter annihilate into dark force carrier, which then decay to SM states, leading to observed excesses.
- Therefore, dark sector states must couple to the SM.
- The coupling has to be small to satisfy current constraints.

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.

Search in J/ψ decay at BES III



Hai-Bo Li and Tao Luo, arXiv:0911.2067

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: $e^+e^- \rightarrow \gamma + b_\mu (\rightarrow \mu^+\mu^-)$ is enhanced by $R(m_\Upsilon) \times BR(\Upsilon \rightarrow \mu^+\mu^-) \sim 60$;

Similarly, $\frac{e^+e^- \rightarrow \Upsilon \rightarrow b_\mu h_d}{e^+e^- \rightarrow b_\mu^* \rightarrow b_\mu h_d} \sim 60$

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

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

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

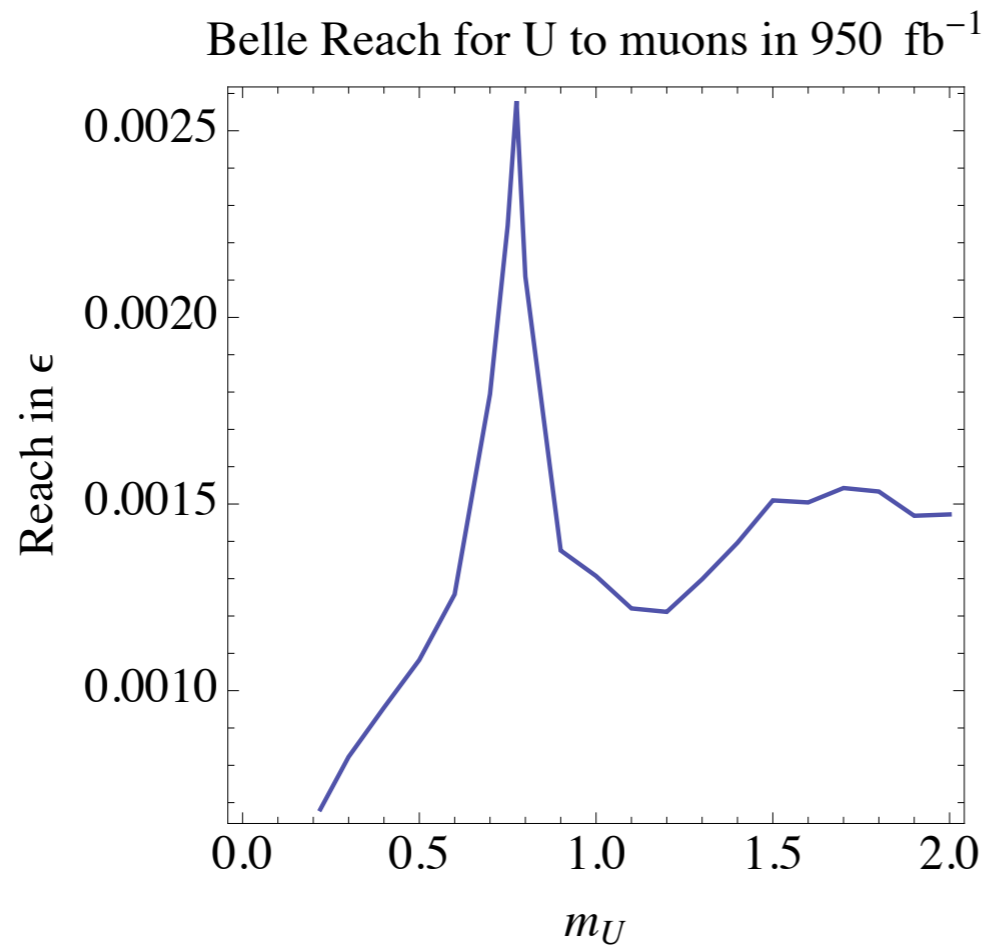
M. Baumgart, C. Cheung, J. Ruderman, LTW, I. Yavin, arXiv:0901.0283

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

D0, arXiv:0905.1478.

Both subjects will be covered in detail by dedicated talks.

Reach at Belle in $\mu^+ \mu^-$ channel

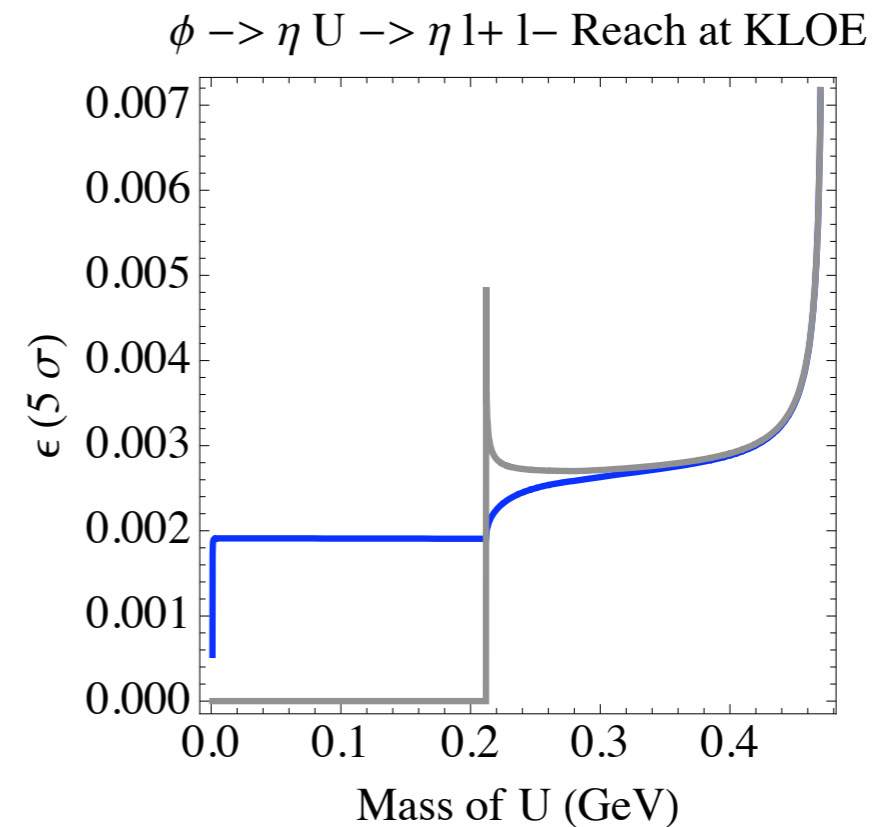
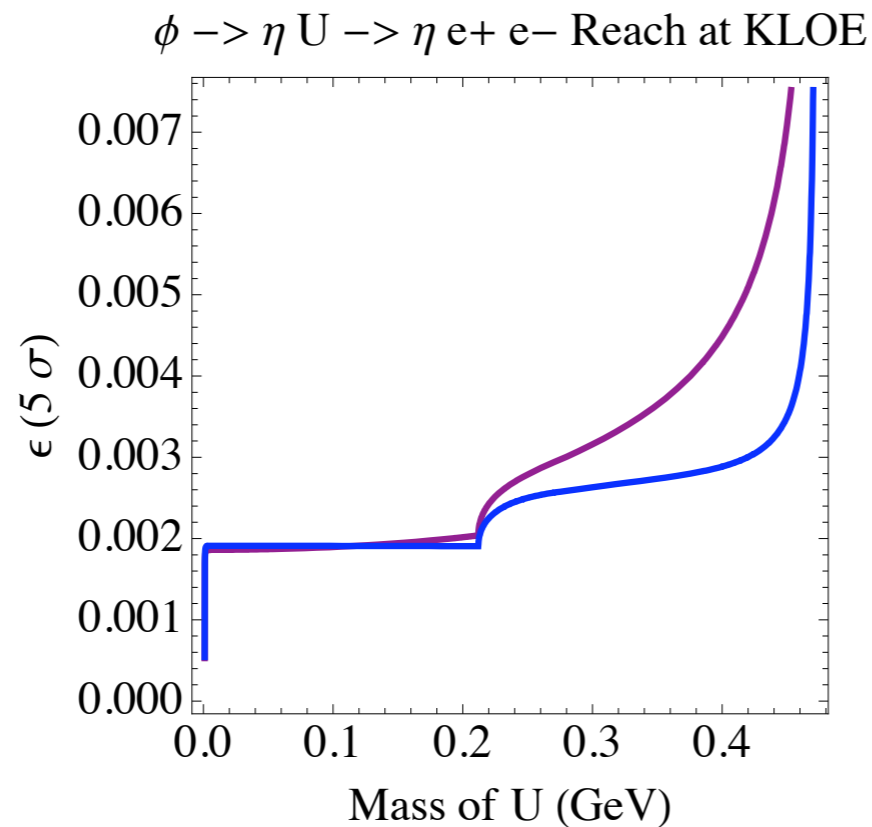


$$E_\gamma > 100 \text{ MeV}, 12.4^\circ < \theta_\gamma < 155^\circ$$

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

Estimate of potential reach at KLOE.

M. Reece and LTW, arXiv:0904.1743



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

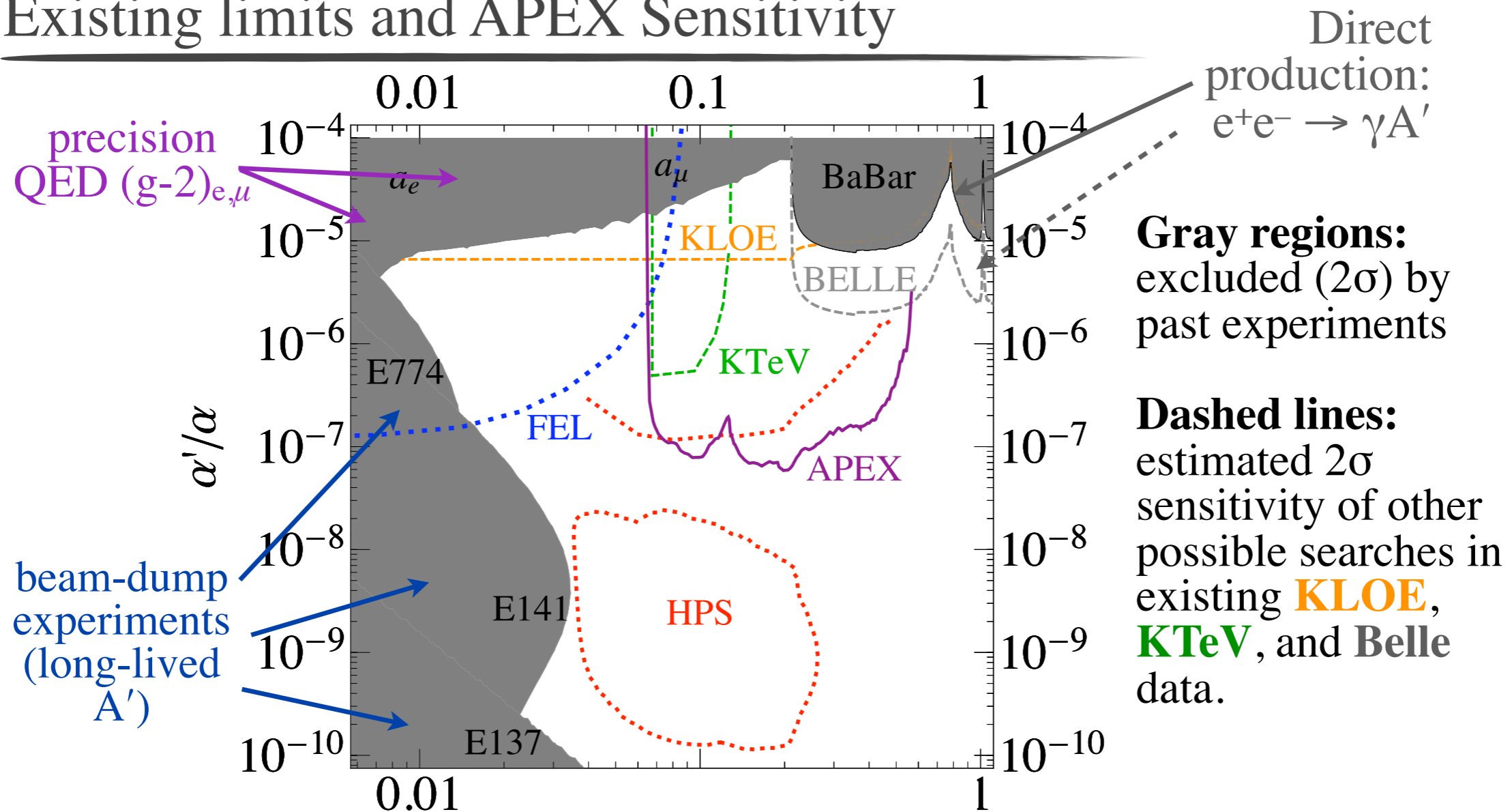
Purple: $F_{\phi\eta\gamma^*}(q^2) = 1$ Blue: $F_{\phi\eta\gamma^*}(q^2) = 1/(1 - 3.8\text{GeV}^{-2}q^2)$.

M. Achasov et. al. Phys. Lett. B504.

Right: including muon.

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

Existing limits and APEX Sensitivity



◆ $(g-2)_\mu$ ◆ dark matter motivation ◆ GUT region of α'/α

Wide open range of couplings to explore

Timely measurement, ready equipment
 Could be ready with 1-month notice

Related Searches:

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

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

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

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

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

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