Strong Constraints on Sub-GeV Dark Matter and Other Light States From E137

Ze'ev Surujon

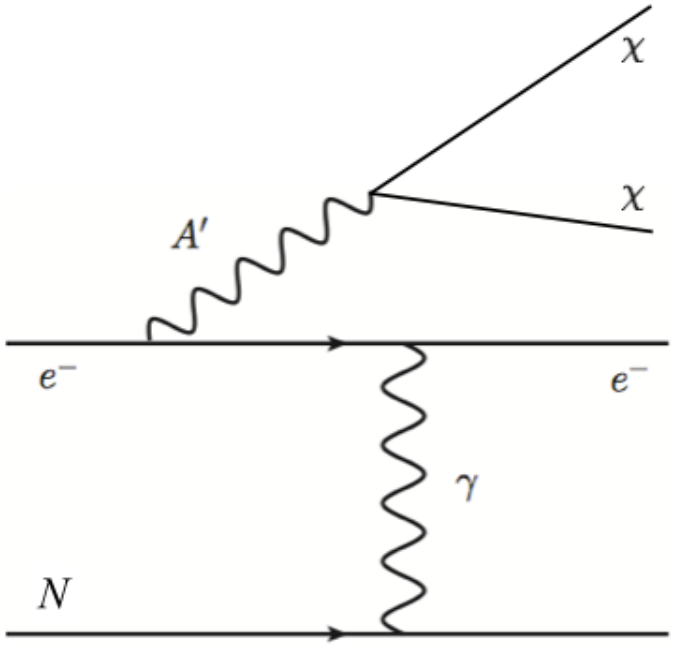
Stony Brook University

May 1, 2014

arXiv:1405.xxxx with Brian Batell and Rouven Essig

In a Nutshell:

- DM can be charged under a hidden U(1) $\Longrightarrow$ dark photon A'
- Dark photon (A') can mix with the SM photon
- Efficiently probed by fixed target experiments: E137



Outline

- Intro (1): Kinetic Mixing
- Intro (2): Fixed Target Experiments
- Results
- Future Directions

Motivation

may be complicated

"Portals": $H^\dagger H\, \mathcal{O}^{(d=2)}$ $\quad F^{\mu\nu}\, \mathcal{O}^{(d=2)}_{\mu\nu}$ $\quad \bar{L}^\alpha H\, \mathcal{O}^{(d=3/2)}_\alpha$

$$\boxed{F^{\mu\nu}\, F'_{\mu\nu}}$$

- Could explain $(g-2)_\mu$ discrepancy ($\sim 3\,\sigma+$)

Kinetic Mixing: Basics

$$\mathcal{L} \supset \frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu}$$

- Always invariant
- Renormalizable (Dimension-4)
  - can be sizable even if generated at very high scale
  - should be written down

Now the charge can be non-integer (irrational...) (Holdom, 1986)

Kinetic Mixing: Basics

Two U(1) gauge fields A_μ, A'_μ with kinetic mixing:

$$\mathcal{L} \supset -\frac{1}{4}F_{\mu\nu}^2 - \frac{1}{4}F_{\mu\nu}'^2 - \frac{\epsilon}{2}F^{\mu\nu}F'_{\mu\nu}$$

(possibly higgsed)

1. Move to canonical basis (rotate + rescale = non-orthogonal)
2. Rotate to mass basis (orthogonal)

If $m_A = 0$ and $m_{A'} > 0$:

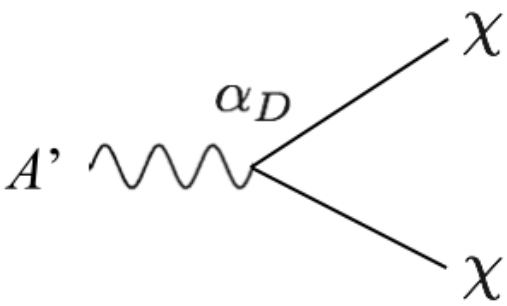
$$A_\mu \to A_\mu - \frac{\epsilon}{1-\epsilon^2}A'_\mu \qquad A'_\mu \to \frac{1}{1-\epsilon^2}A'_\mu$$

$$\implies \quad \mathcal{L} \supset j^\mu(A_\mu + \epsilon A'_\mu) + j'^\mu A'_\mu + \mathcal{O}(\epsilon^2)$$

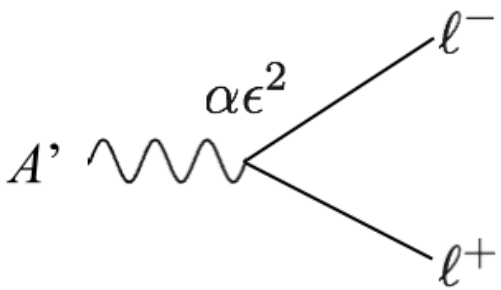
Kinetic Mixing: SM+A'

$$\mathcal{L} = (A^\mu \; Z^\mu \; A^{\mu'}) \begin{pmatrix} 1 & 0 & 0 \\ -c_w t_\epsilon s_\xi & s_w t_\epsilon s_\xi + c_\xi & s_\xi / c_\epsilon \\ -c_w t_\epsilon c_\xi & s_w t_\epsilon c_\xi - s_\xi & c_\xi / c_\epsilon \end{pmatrix} \begin{pmatrix} e J^\mu_{\rm EM} \\ g / c_w J^\mu_Z \\ g_D J^\mu_{A'} \end{pmatrix}$$

- *EM charges of SM do not get shifted*
- *Dark current does* **not** *acquire EM charge*
- *SM acquires dark charge* $\propto \epsilon$



$(m_{A'} > 2m_\chi)$



$(m_{A'} > 2m_\chi$ *or* $\alpha_D < \alpha\epsilon^2)$

Collider vs Fixed Target

Collider vs Fixed Target

	Sym. Collider	Fixed Target
$E_{\rm CM}$	$E_1 + E_2$	$\sqrt{(E+E_T)^2 - \mathbf{p}^2} \sim \sqrt{2E\Lambda_{\rm QCD}} \sim 3.5$ GeV *
Lumi.	1000 $\rm fb^{-1}$	$N_{\rm EOT} \times \frac{\rho \times \ell \times N_{\rm Av.}}{A} \sim 10^{44}\,{\rm cm}^{-2} \sim 10^5\,{\rm fb}^{-1}$ *

* E137

Hadron Colliders at ***Fixed Target Mode*****:**

$E_{\rm CM}(e^-$ fixed target$) \approx 65$ GeV $\sqrt{\frac{2E_1}{14{\rm TeV}}}$

Collider vs Fixed Target

	Sym. Collider	Fixed Target
$E_{\rm CM}$	$E_1 + E_2$	$\sqrt{(E+E_T)^2 - \mathbf{p}^2} \sim \sqrt{2E\Lambda_{\rm QCD}} \sim 3.5$ GeV *
Lumi.	1000 $\rm fb^{-1}$	$N_{\rm EOT} \times \frac{\rho \times \ell \times N_{\rm Av.}}{A} \sim 10^{44}\,{\rm cm}^{-2} \sim 10^5\,{\rm fb}^{-1}$ *

* E137

Hadron Colliders at ***Fixed Target Mode*****:**

$E_{\rm CM}(e^-$ fixed target$) \approx 65$ GeV $\sqrt{\frac{2E_1}{14{\rm TeV}}}$

- 14 TeV *LHC* $\Rightarrow$ 65 GeV (??)
- 30 TeV *FHC* $\Rightarrow$ 95 GeV (Single Z)
- 50 TeV *SFHC* $\Rightarrow$ 126 GeV (Single Higgs)
- 100 TeV *CHC* $\Rightarrow$ 173 GeV (Single top)

Sample Fixed Target Experiments

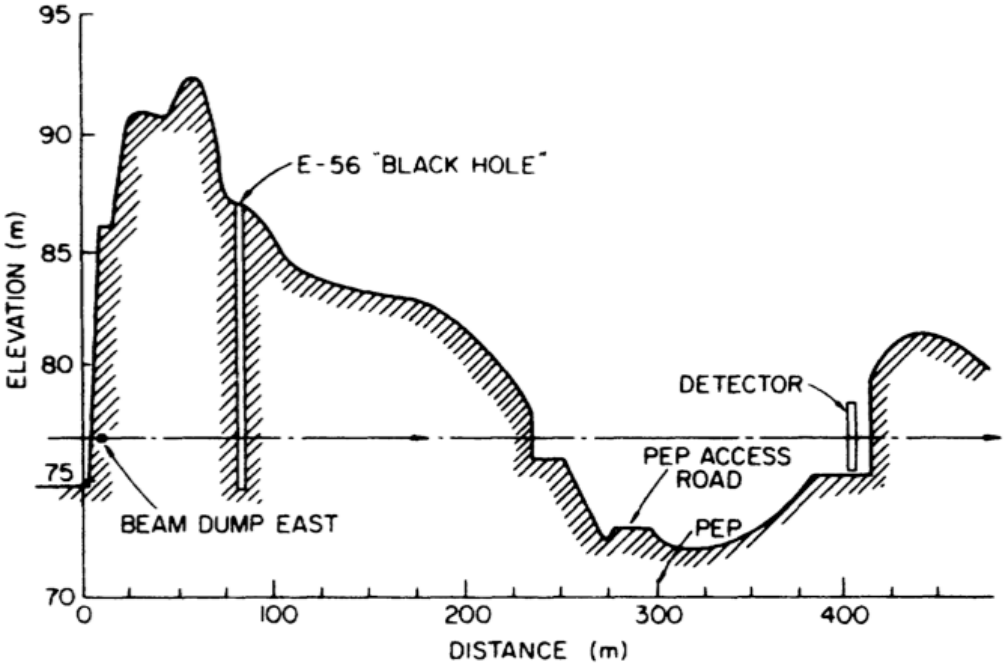
Proton Beam (Talks by McKeen, Dharmapalan, Frugiuele, Yu&Jackson, Soper,...)
$p^+ N \to X\pi, \pi \to \gamma A'$, $A' \to \chi\chi$ (Batell, Pospelov, Ritz '09 ; DeNiverville, McKeen '11, ...)

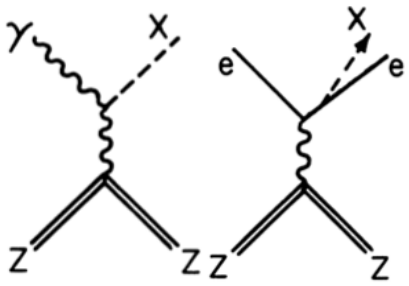
LSND (10^{23} p^+ @ 0.8 GeV),
MiniBooNE, MINOS, NOνA, LBNE, Project X, E613, E???, ...

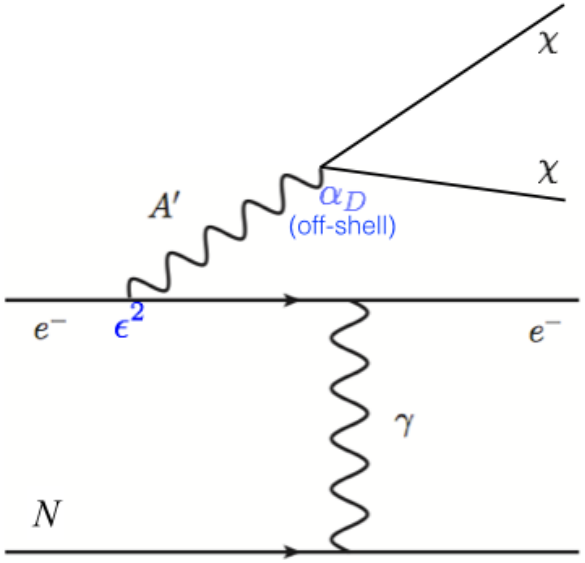
Electron Beam (Talks by Graham, Krnjaic...)

- E137 (10^{20} e^- @ 20 GeV), E???
- SLAC millicharge (10^{19} e^- @ 30 GeV)
- HPS, Darklight, APEX, ...

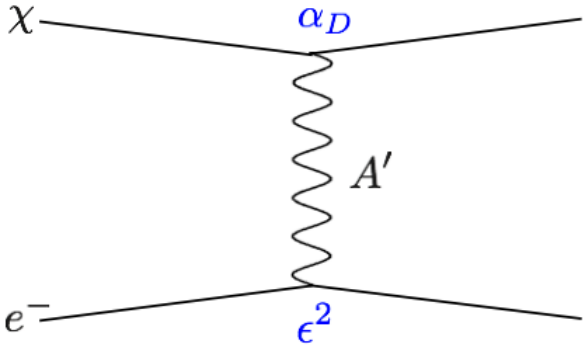
E137 @ SLAC (1982)





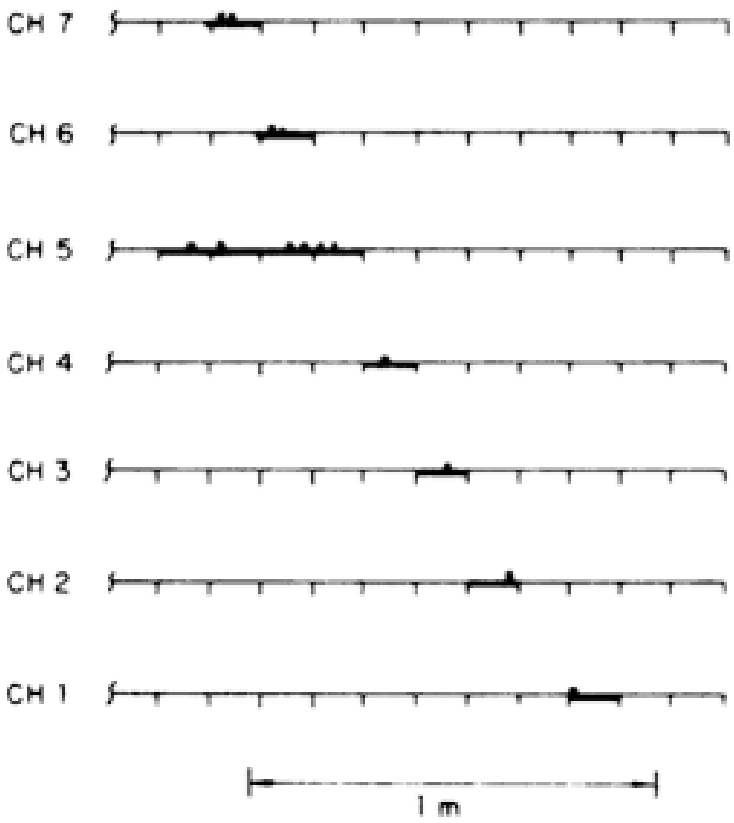


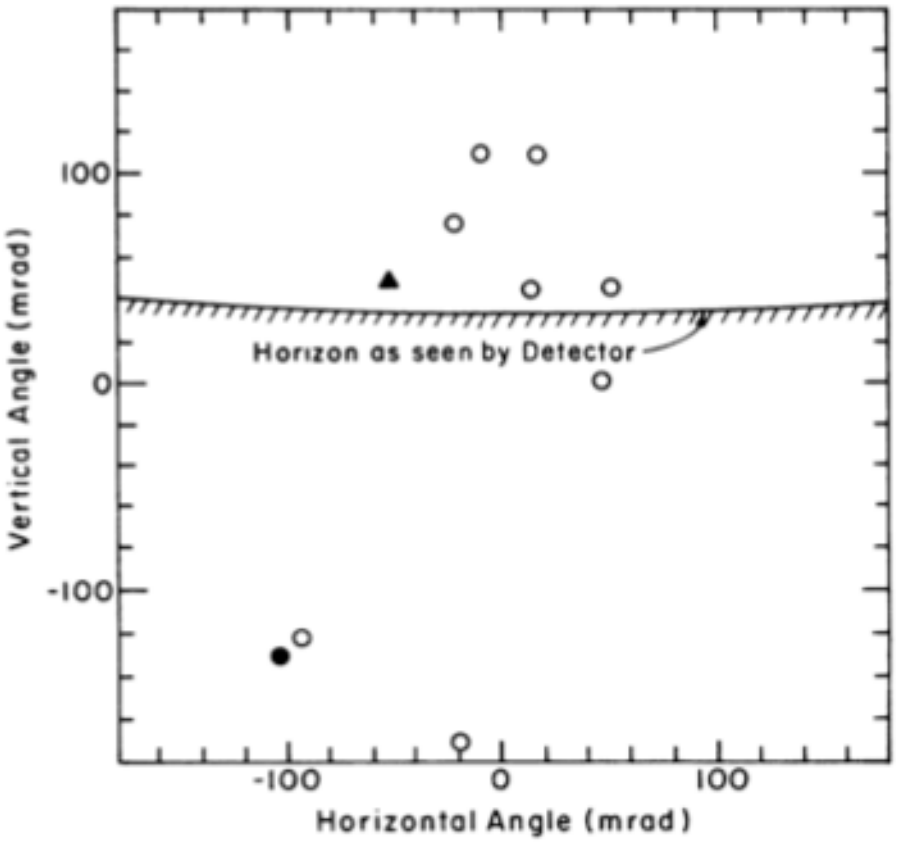
production $\sim \epsilon^2(\alpha_D)$



detection $\sim \epsilon^2 \alpha_D$

E137 @ SLAC (1982)





E137: Calculation

- Production Rate:

$$N_{\chi\chi} = N_e \times \sigma(e^- N \to e^- N \chi\chi) \times n_N^{\text{target}} \times \ell_{\text{eff}}^{\text{target}}$$

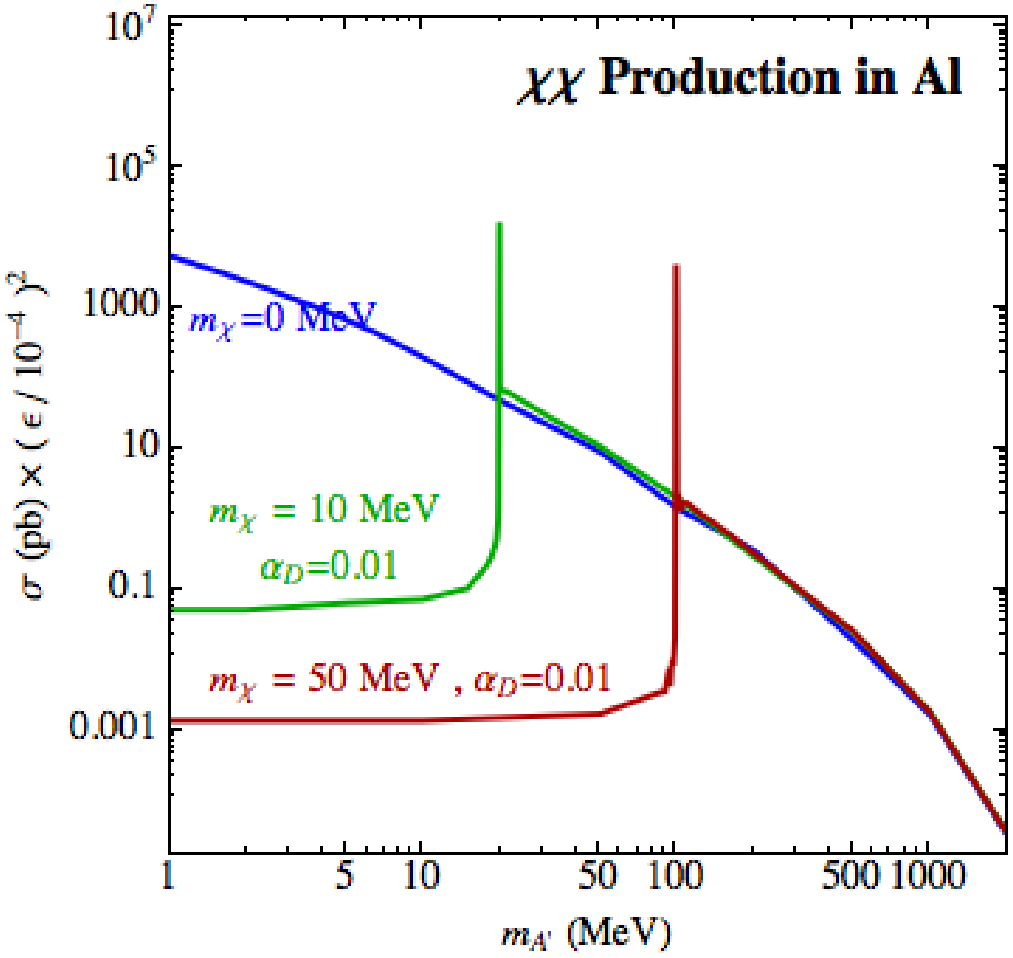
- Detection Probability: $P_{\text{det}} = \sigma_{\chi e^-} \times n_e^{\text{det}} \times \ell^{\text{det}}$

$$\frac{d\sigma_{\chi e}}{dE_e} = 4\pi\epsilon^2\alpha\,\alpha_D \frac{2m_e E^2 - (2m_e E - m_e E_e + m_\chi^2 + 2m_e^2)(E_e - m_e)}{(E^2 - m_\chi^2)(m_{A'}^2 + 2m_e E_e - 2m_e^2)^2}$$

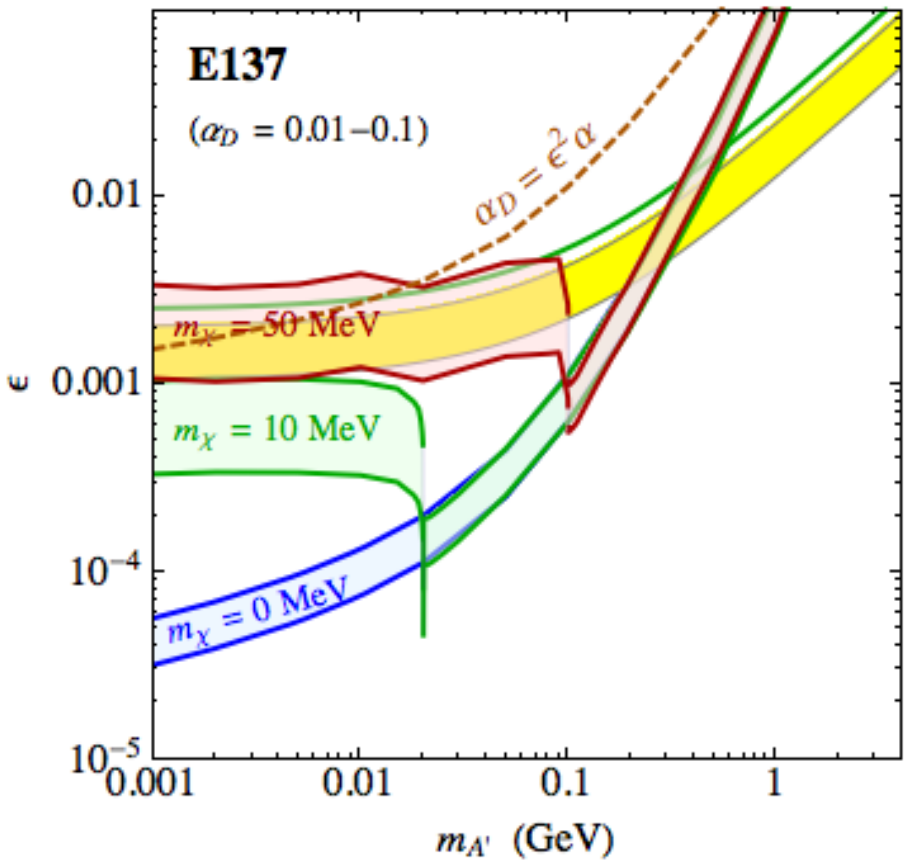
- Event Rate @ Detector: $N_{\text{det}} = 2N_{\chi\chi} \times P_{\text{det}} \times$ efficiency

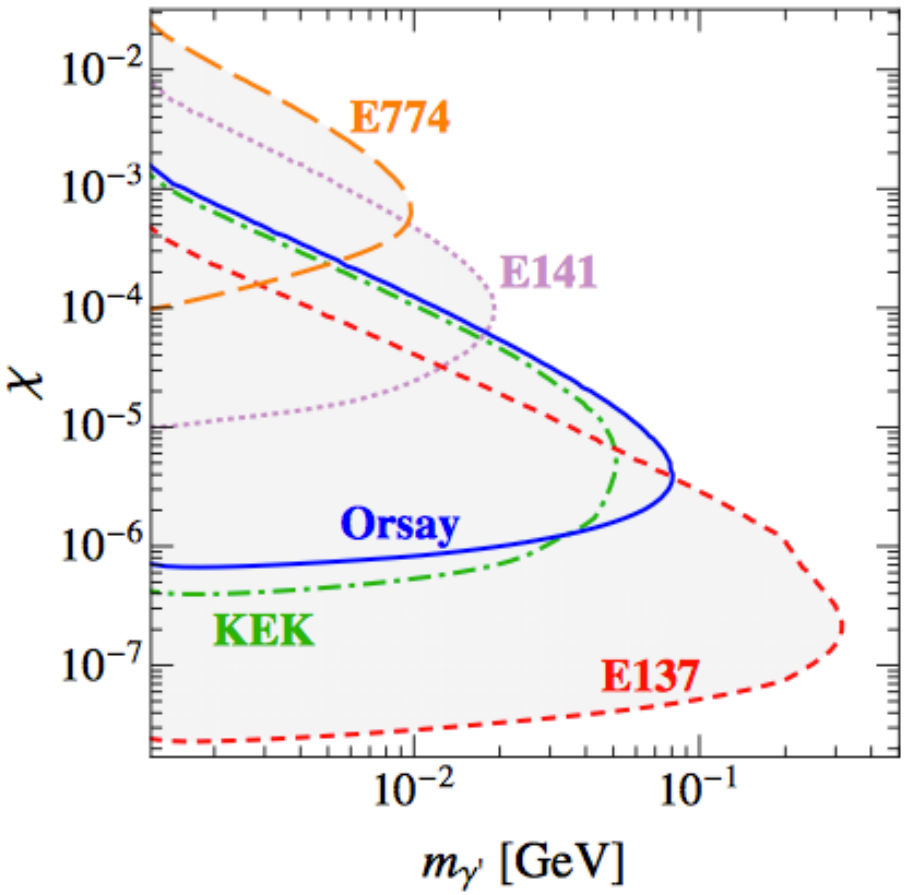
No Events Observed $\implies$ $3 > N_{\text{det}} \sim \varepsilon\epsilon^4\alpha_D^{(2)}$ @ 95% C.L.

Production cross-section



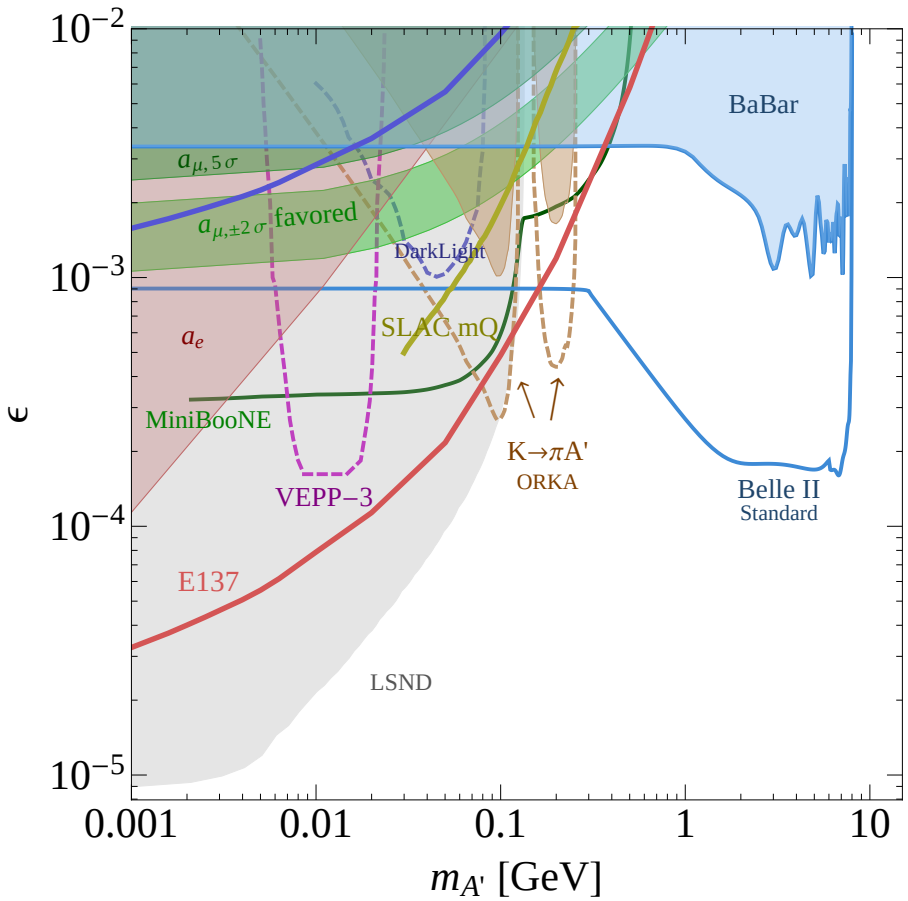
Results

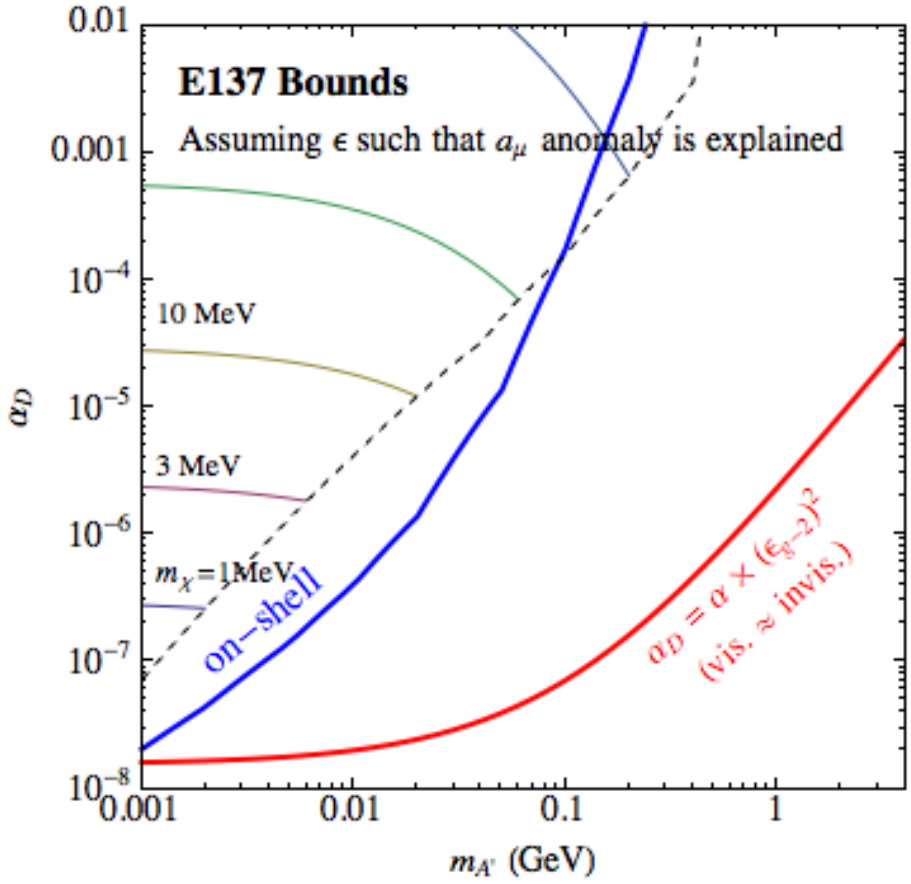




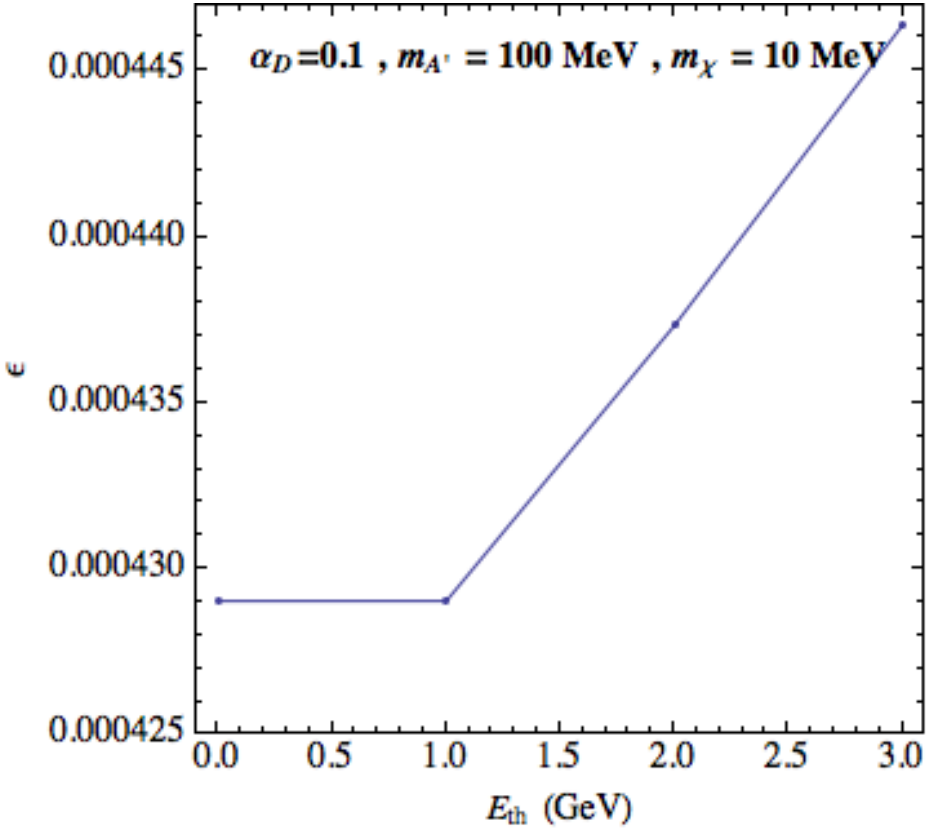
(Andreas, Niebuhr, Ringwald '12)

Results


BaBar
$a_{\mu,5\sigma}$
$a_{\mu,\pm2\sigma}$ favored
DarkLight
a_e
SLAC mQ
MiniBooNE
K→πA'
ORKA
VEPP−3
Belle II
Standard
E137
LSND
ϵ
$m_{A'}$ [GeV]

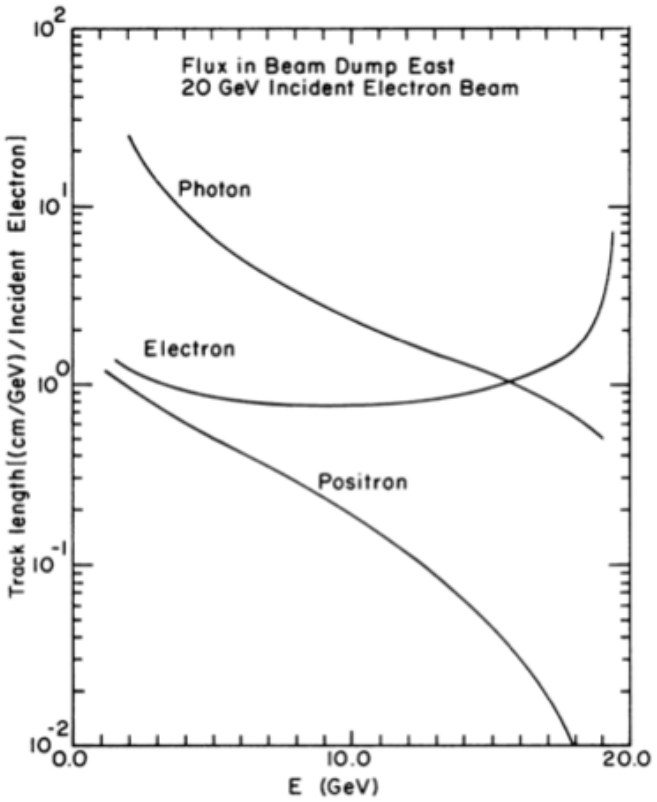

E137 Bounds
Assuming ϵ such that a_μ anomaly is explained
10 MeV
3 MeV
m_χ=1MeV
on−shell
$\alpha_D = \alpha \times (\epsilon_g-2)^2$
(vis. ≈ invis.)
α_D
$m_{A'}$ (GeV)

Effect of Energy Threshold



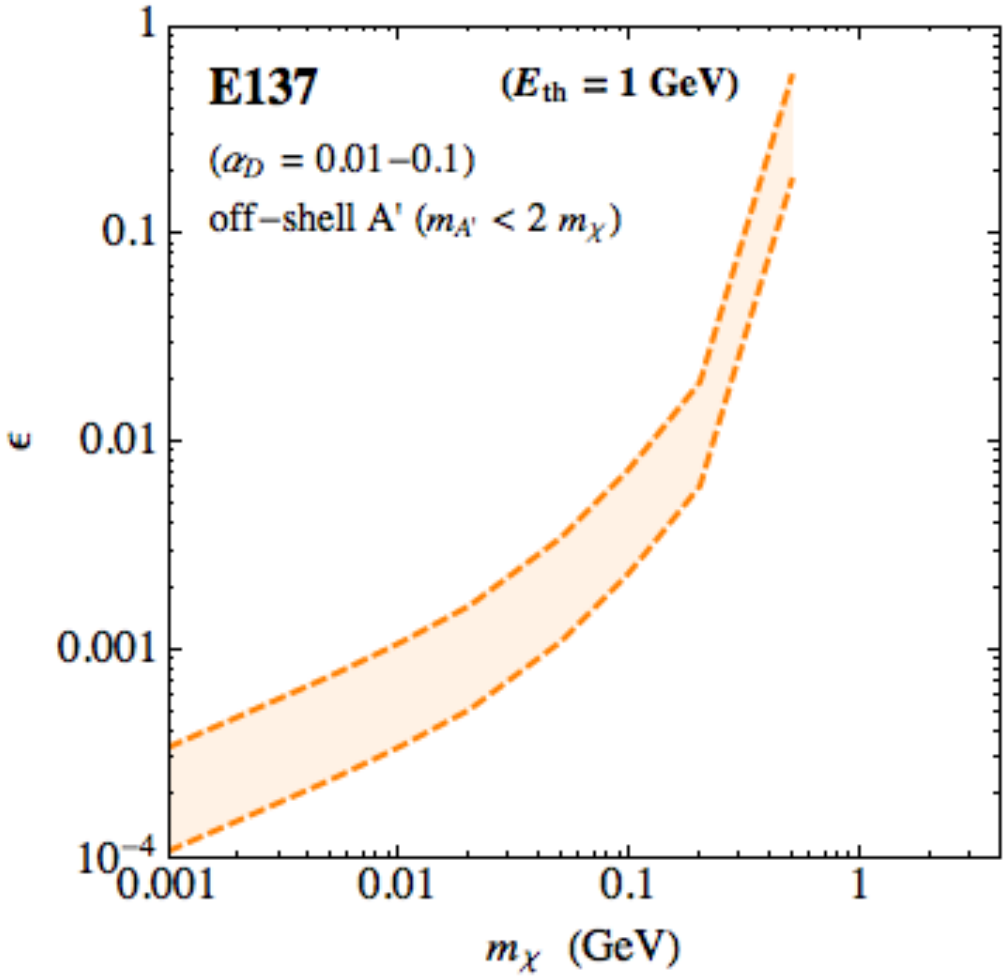
Future Directions

- Direct Production at Proton Beams



- Rescattered photons, positrons
- Avoiding B-factories? (not forever..) Split DM (Talk by Krnjaic)

HEAVY PHOTON
SEARCH
OM


E137
(E_{th} = 1 GeV)
(α_D = 0.01–0.1)
off–shell A' ($m_{A'}$ < 2 m_χ)
1
0.1
0.01
0.001
10^{-4}
ϵ
0.001
0.01
0.1
1
m_χ (GeV)