Theory and Phenomenology of Dark Vector Bosons

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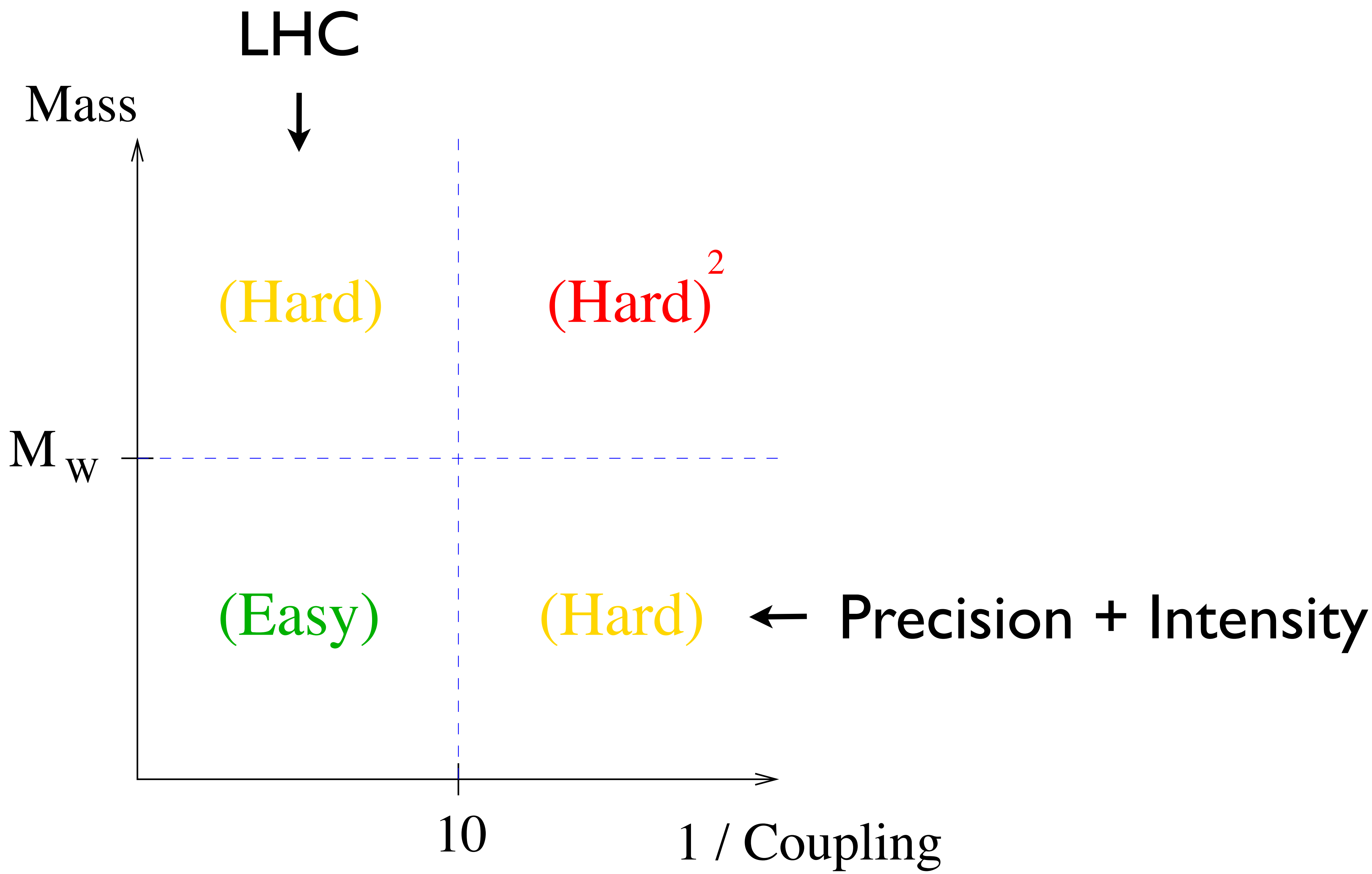
BNL Dark Interactions Workshop

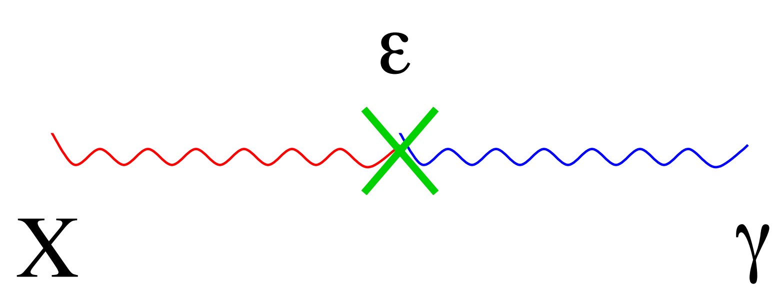
Searching for New Phenomena



Portals to Dark (Hidden) Physics

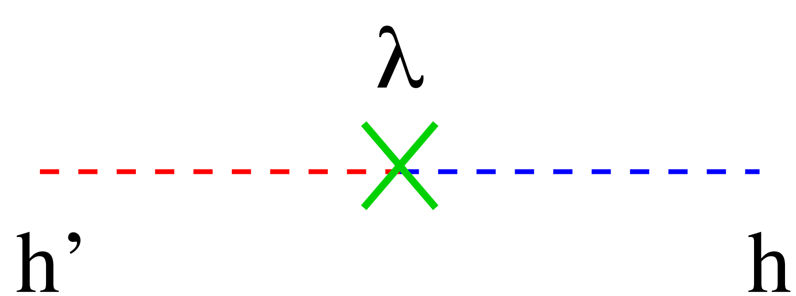
- Two nice* ways for new hidden physics to couple:
  - Vector Portal:
    (X = "hidden photon")

$$\epsilon X_{\mu\nu} F^{\mu\nu}$$



  - Higgs Portal:
    (H' = "hidden Higgs")

$$\lambda |H'|^2 |H|^2$$



* nice = renormalizable, no singlets

Dark Vectors

- Focus on the vector portal.
- Assumptions:
  - new $U(1)_x$ gauge invariance
  - unbroken or broken at $m_x << m_z$
  - no direct coupling to Standard Model matter
  - main connector is gauge kinetic mixing = vector portal

- Dark = Hidden
  May or may not be connected to dark matter.

Vector Portal Couplings

- $SU(2)_L \times U(1)_Y \times U(1)_x$ gauge invariance:

$$\mathcal{L} \supset -\frac{1}{4}(X_{\mu\nu})^2 - \frac{1}{4}(B_{\mu\nu})^2 - \frac{1}{4}(W^a_{\mu\nu})^2 - \frac{\epsilon}{2c_W} B_{\mu\nu} X^{\mu\nu}$$

$$\to (\ldots) - \frac{\epsilon}{2} X_{\mu\nu} \left(F^{\mu\nu} - t_W Z^{\mu\nu}\right)$$

- Here:

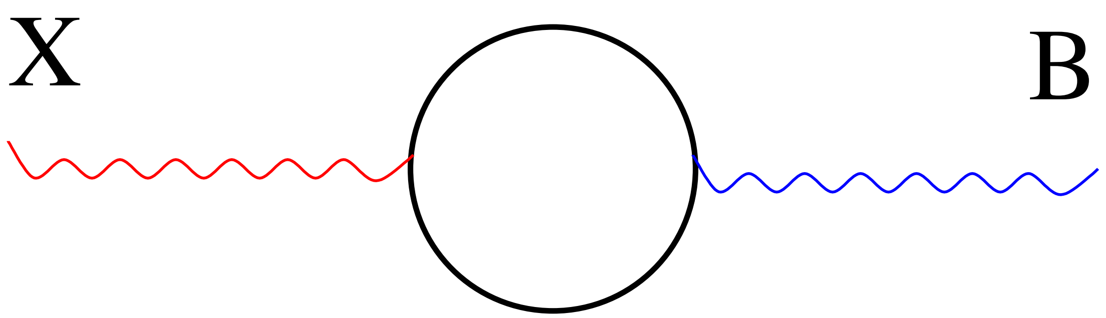
$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ photon

$Z_{\mu\nu} = \partial_\mu Z_\nu - \partial_\nu Z_\mu$ Z boson

$X_{\mu\nu} = \partial_\mu X_\nu - \partial_\nu X_\mu$ dark vector

Vector Portal Parameter: ϵ

- Can arise from loops of heavy matter M that is charged under both U(1)x and U(1)Y: [Holdom 1986]



$$\epsilon \sim \frac{g_x g_Y}{(4\pi)^2} \ln\left(\frac{M}{\mu}\right) \sim 10^{-2} - 10^{-4}$$

- Can be further suppressed for many reasons.

Vector Portal Parameter: ϵ

- What are the physical effects of this mixing?

$$\mathcal{L} \supset -\frac{\epsilon}{2} X_{\mu\nu} \left(F^{\mu\nu} - t_W Z^{\mu\nu} \right)$$

- Two Cases:

1. Massive X vector: Dark Photon

   1$'$. Massive X vector with extra mass mixing: Dark Z

2. Massless X vector: Paraphoton

Case 1: Massive Dark Photon

- If $U(1)_x$ is spontaneously broken:

$$\mathcal{L} \supset -\frac{\epsilon}{2} X_{\mu\nu} \left(F^{\mu\nu} - t_W Z^{\mu\nu} \right) + \frac{1}{2} m_x^2 (X^\mu)^2 + \frac{1}{2} m_Z^2 (Z^\mu)^2$$

- Kinetic mixing can be removed by the change of variables

$$\begin{cases} A^\mu & \rightarrow & A^\mu - \epsilon X^\mu \\ Z^\mu & \rightarrow & Z^\mu \\ X^\mu & \rightarrow & X^\mu + \epsilon\, t_W Z^\mu \end{cases}$$

Case 1: Induced Mass Mixing

- Great, but this induces residual mass mixing:

$$\mathcal{M}^2 = m_Z^2 \begin{pmatrix} \eta & \epsilon\, t_W \eta \\ \epsilon\, t_W \eta & 1 \end{pmatrix} \quad \text{with} \quad \eta = m_x^2/m_Z^2$$

- Rotating this away in addition, we have in total

$$\begin{cases} A^\mu & \to \quad A^\mu - \epsilon X^\mu \\ Z^\mu & \to \quad Z^\mu - \epsilon\, t_W \left(\frac{\eta}{1-\eta}\right) X^\mu \\ X^\mu & \to \quad X^\mu + \epsilon\, t_W \left(\frac{1}{1-\eta}\right) Z^\mu \end{cases}$$

Case I: Couplings to Matter

- These take the form:

$$-\mathcal{L} \supset eA_\mu j^\mu_{em} + g_Z Z_\mu j^\mu_Z + g_x X_\mu j^\mu_x$$

where

$$\begin{cases} j^\mu_{em} & = & (-1)\bar{e}\gamma^\mu e + \ldots \\ j^\mu_Z & = & \frac{1}{2}\bar{\nu}_L\gamma^\mu\nu_L + \ldots \\ j^\mu_x & = & \bar{\psi}\gamma^\mu\psi + \ldots \end{cases}$$

- Here, ψ is a SM-neutral dark fermion.

Case 1: Couplings to Matter

- Putting in the shifted vectors,

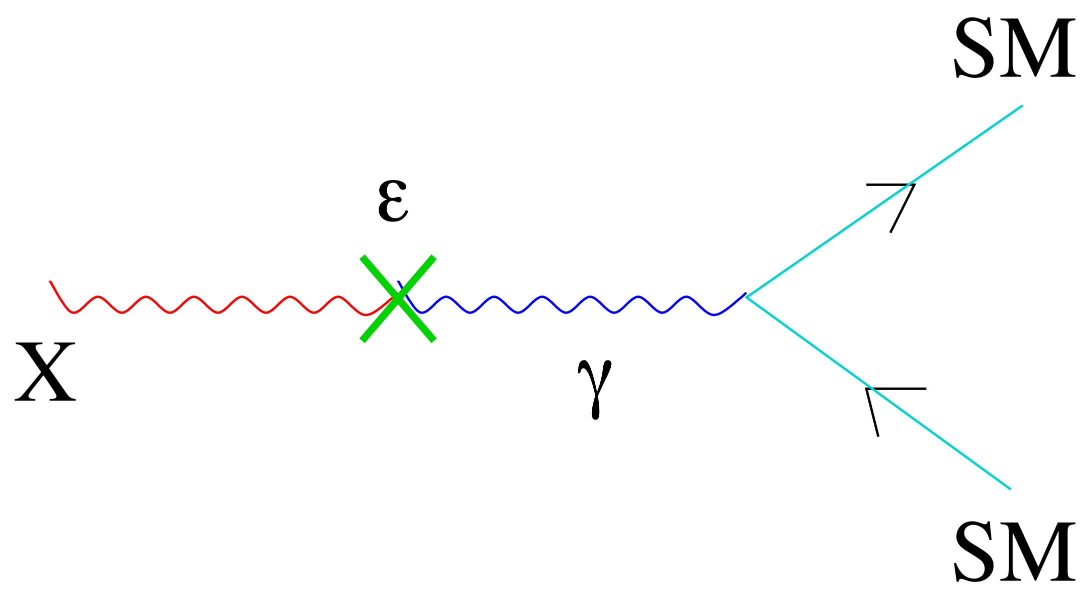
$$
\begin{aligned}
-\mathcal{L} \quad \supset \quad & e j^\mu_{em} A_\mu \\
& + \left[g_x j^\mu_x - \epsilon e j^\mu_{em} - \epsilon t_W \left(\frac{\eta}{1-\eta} \right) g_Z j^\mu_Z \right] X_\mu \\
& + \left[g_Z j^\mu_Z + \epsilon t_W \left(\frac{1}{1-\eta} \right) g_x j^\mu_x \right] Z_\mu
\end{aligned}
$$

- The hidden vector now couples to SM matter! ϵ controls the strength of the interaction.

Case 1: Couplings to Matter

- Key interaction:

$$-\mathcal{L} \supset -\epsilon e j^{\mu}_{em} X_{\mu}$$

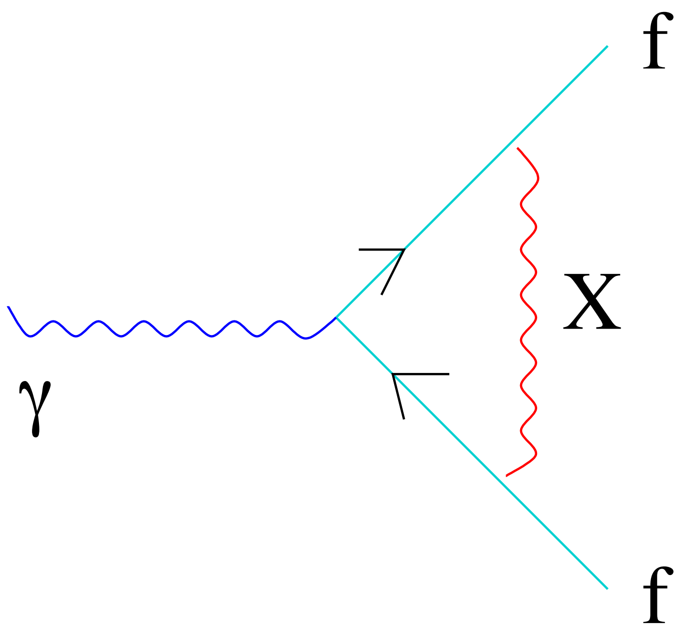


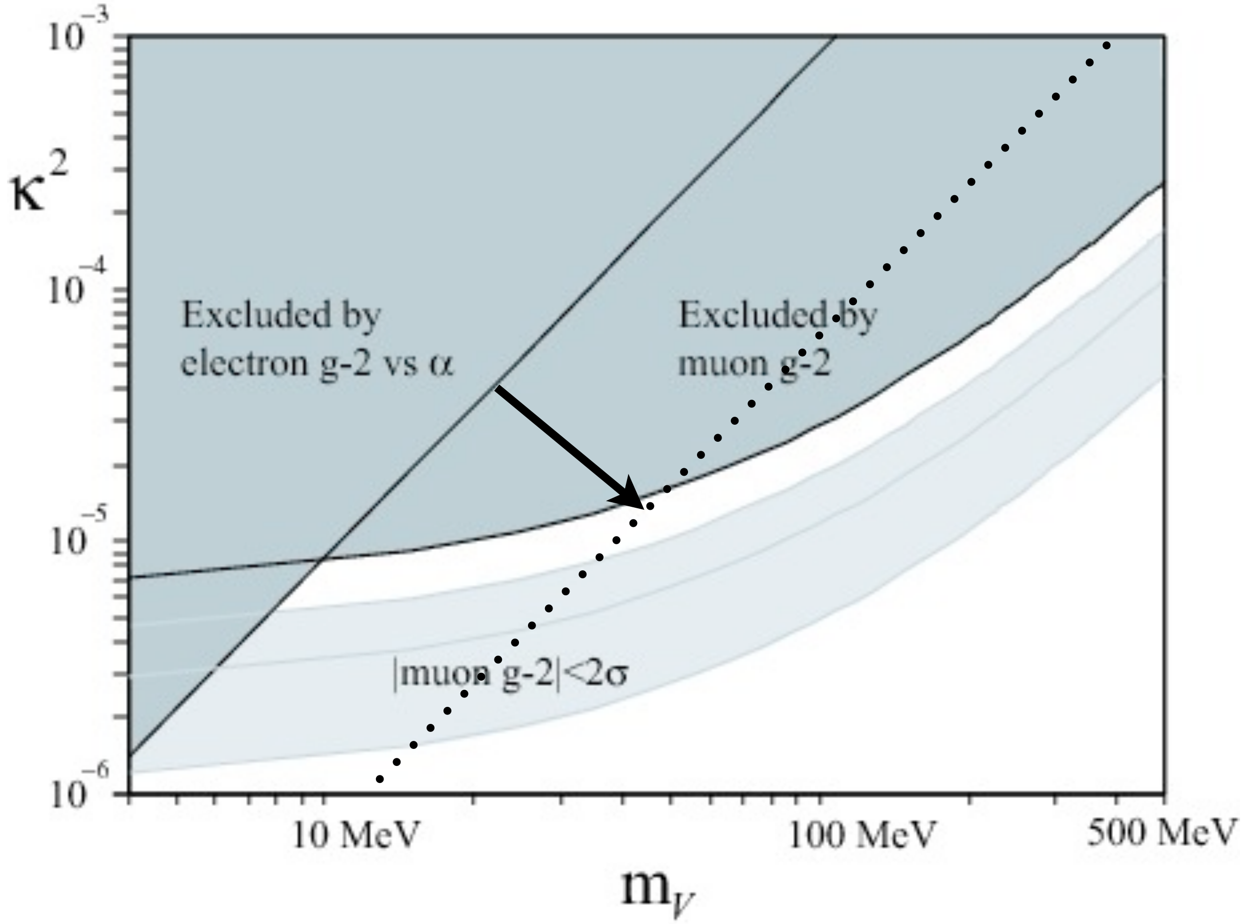
- Note: dark particles do not couple to the photon!

Case 1: Anomalous Magnetic Moments

- New contribution from dark photon:

[Pospelov 2008]



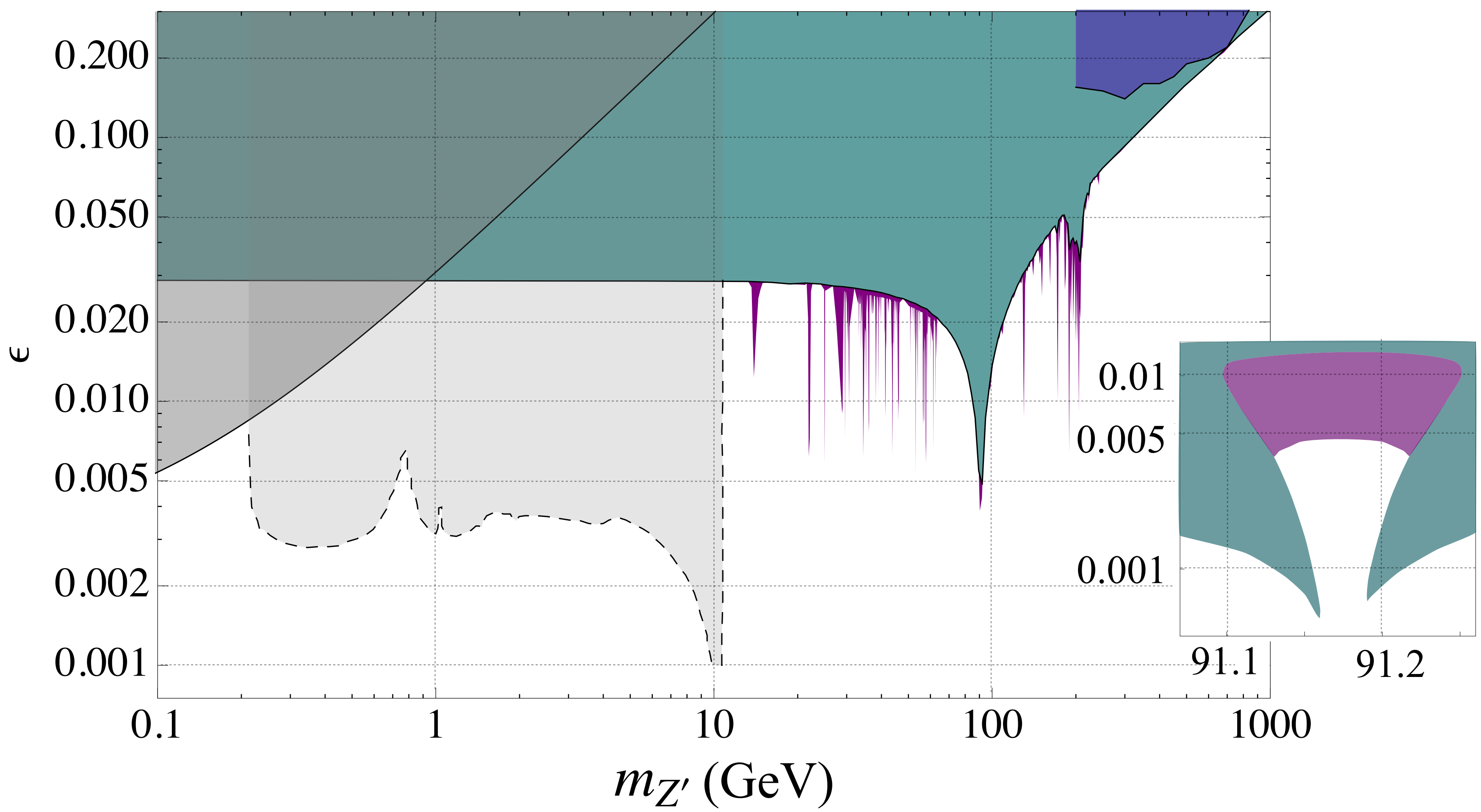


- Can account for the muon discrepancy:

$$a_\mu - a_\mu^{SM} = (287 \pm 80) \times 10^{-11}$$

Case 1: Precision Electroweak Constraints

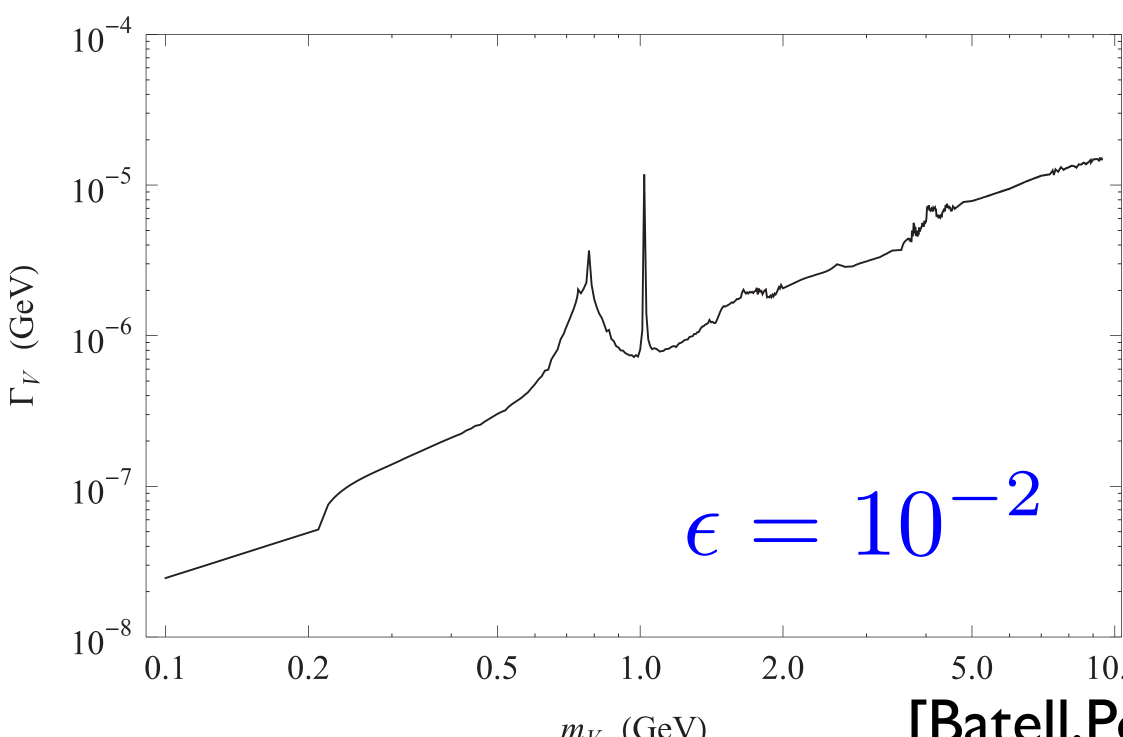
- Relatively weak due to a cancellation. Strongest effect is shifting the Z mass.

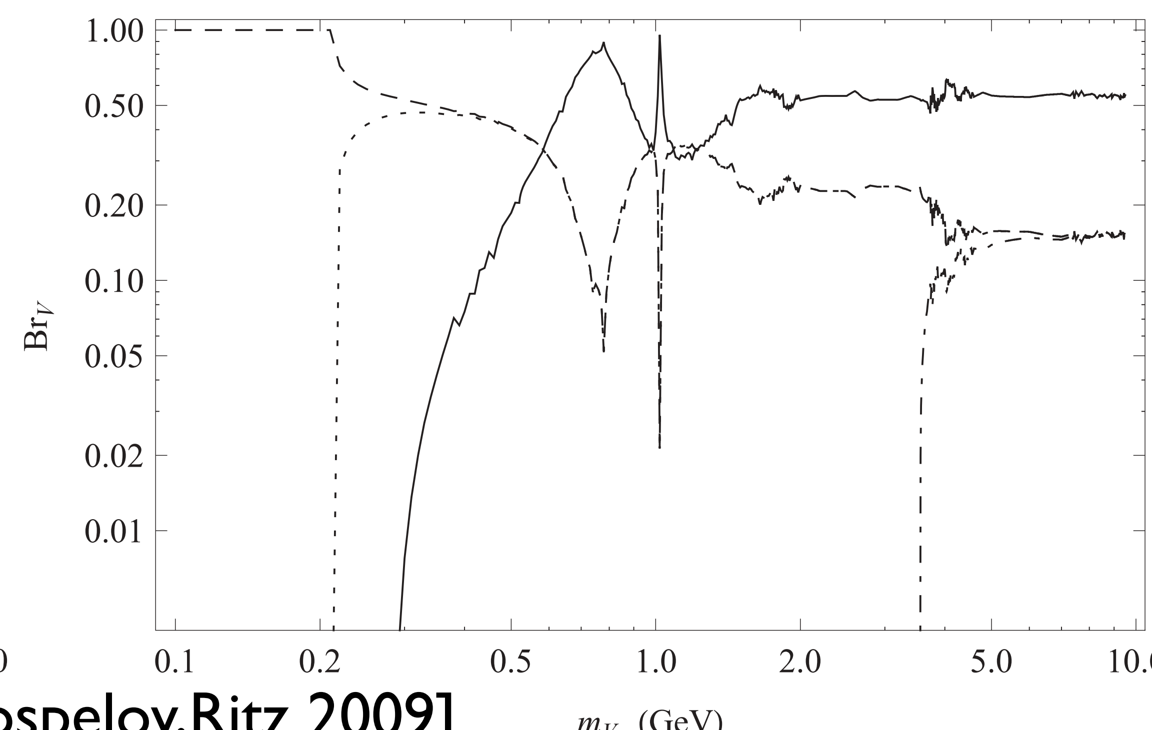


[Hook, Izaguirre, Wacker 2010]

Case 1: Dark Photon Decays

- Decays to other dark states tend to dominate.
  $e.g.\ \ X^\mu \to DM + DM$
- If no hidden decays are open, X^μ decays to SM states:
  - $m_x > 2m_e$: $X^\mu \to f\bar{f}$ decays follow electric charge



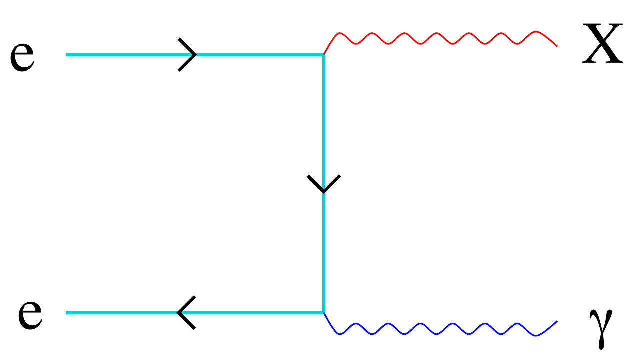


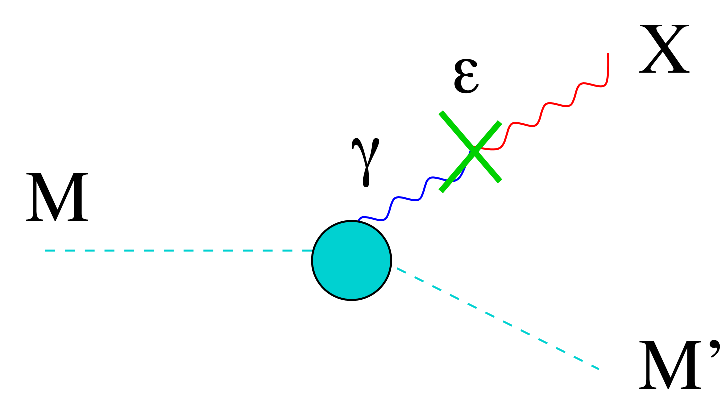
[Batell,Pospelov,Ritz 2009]

  - $m_x < 2m_e$: $X^\mu \to 3\gamma$, very slow (age of the Universe!)

Case 1: Flavor Factories

- Continuum production or meson decays:





- For $X^\mu \;\to\; SM + SM$:

[Bjorken, Essig, Schuster, Toro 2009]

  - Babar - resonance in $\Upsilon(ns) \to \gamma\mu^+\mu^-$ data.
  - KLOE - resonance in $\phi \to \eta\, e^+e^-$ data.

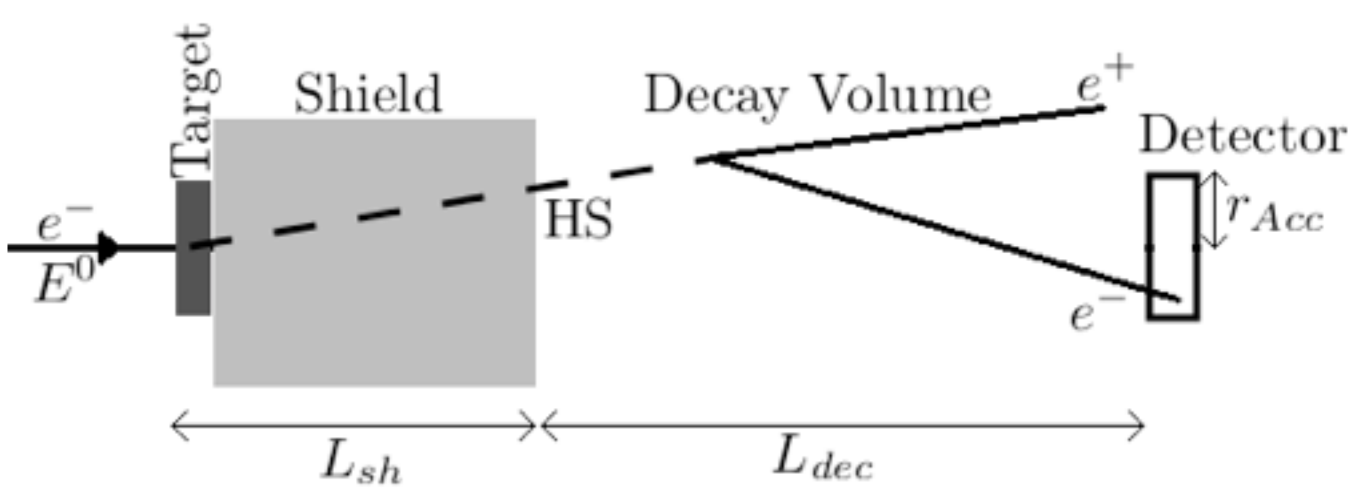
- For $X^\mu \;\to\; (invisible)$:

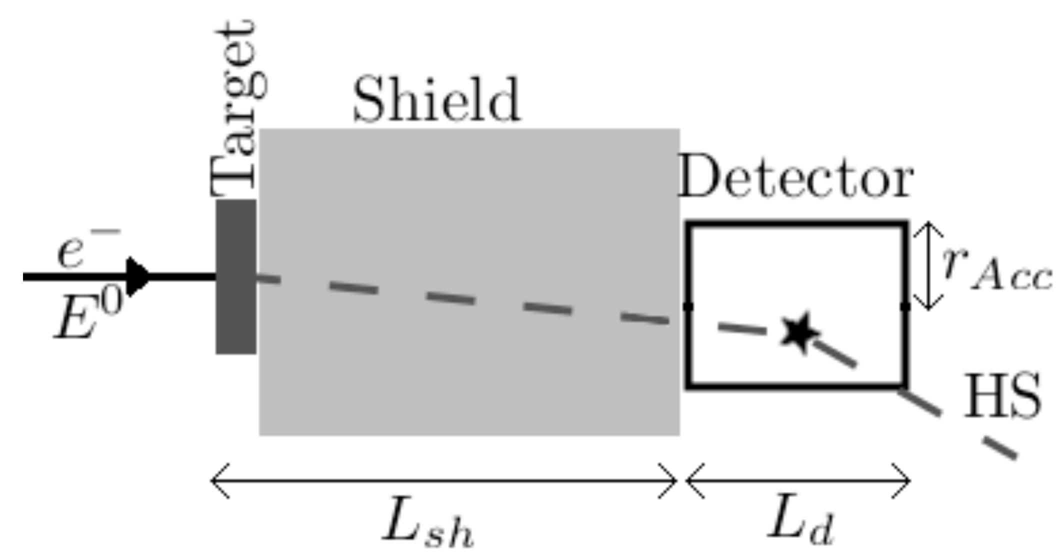
[Izaguirre *et al.* 2013; Essig *et al.* 2013]

  - BaBar - $\Upsilon(ns) \to \gamma + (invisible)$
  - BNL - $K^+ \to \pi^+ + (invisible)$

Case 1: Fixed-Target Experiments

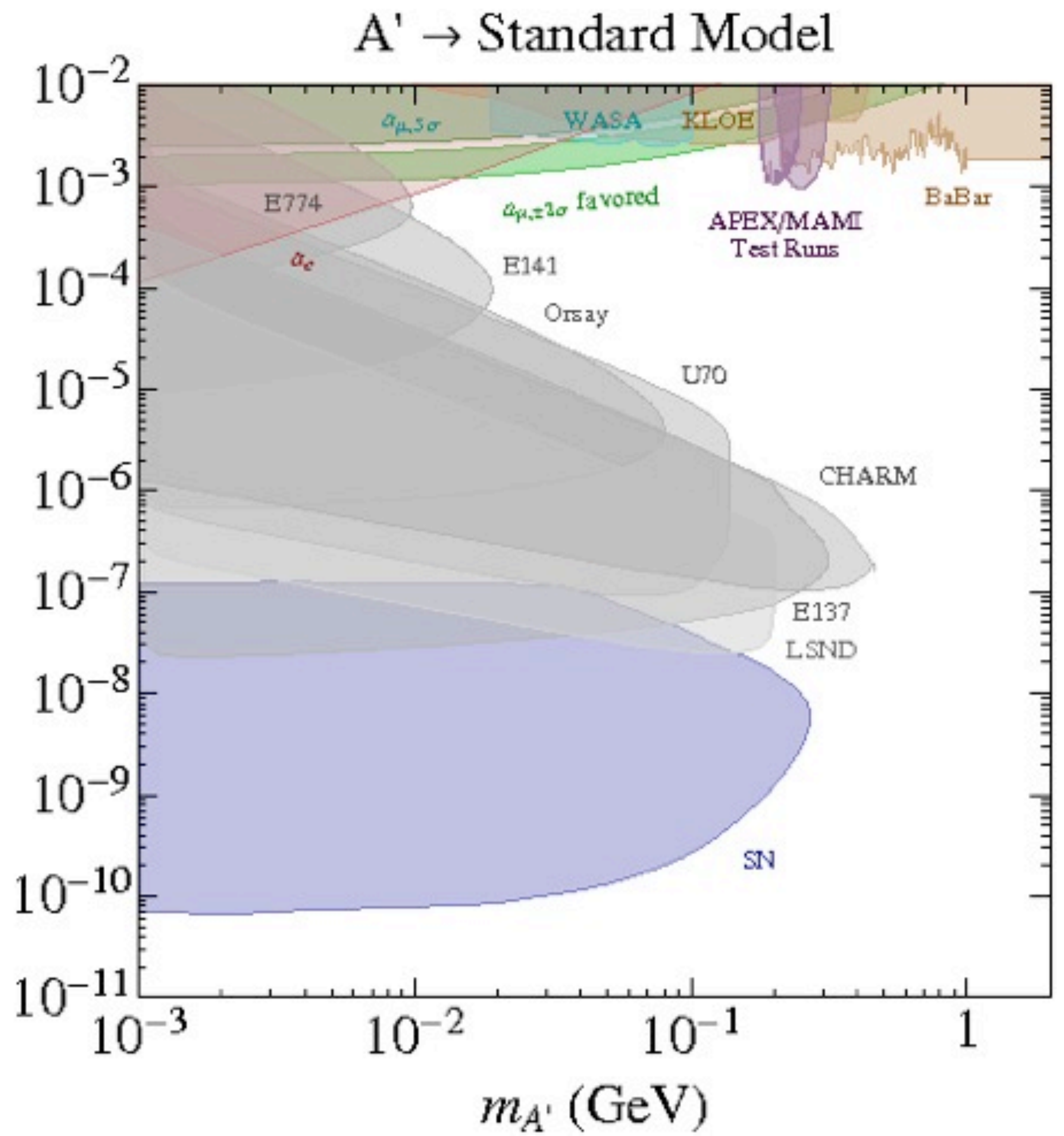
- Two signal mechanisms:
  1. visible decays in the detector
  2. quasi-elastic scattering of the dark state





Case 1: Experimental Limits

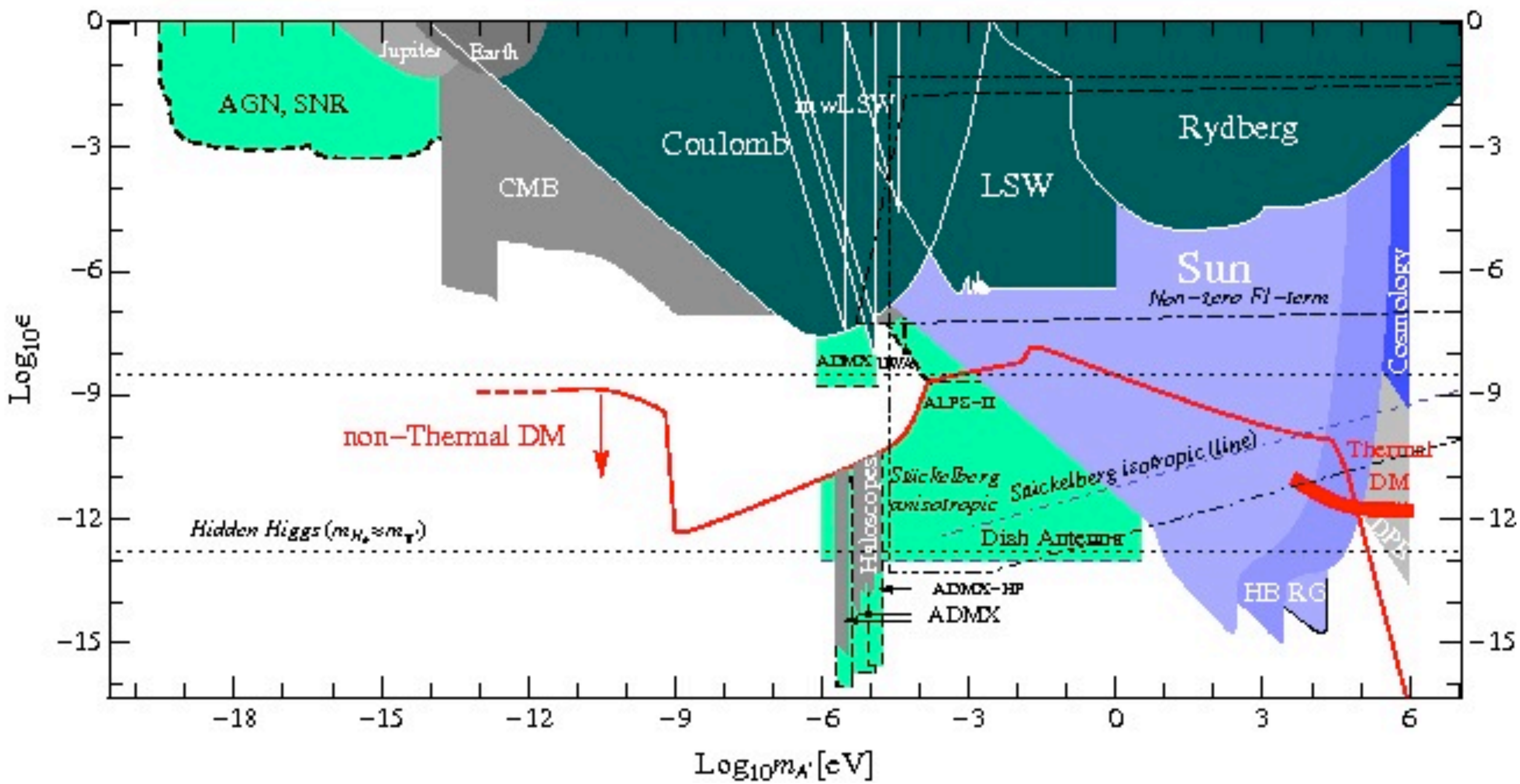
- If $X^\mu \;\to\; SM + SM$ dominates ($m_x > 2m_e$):



[Bjorken, Essig, Schuster, Toro 2009; ...; Essig et al. 2013]

Case 1: Experimental Limits

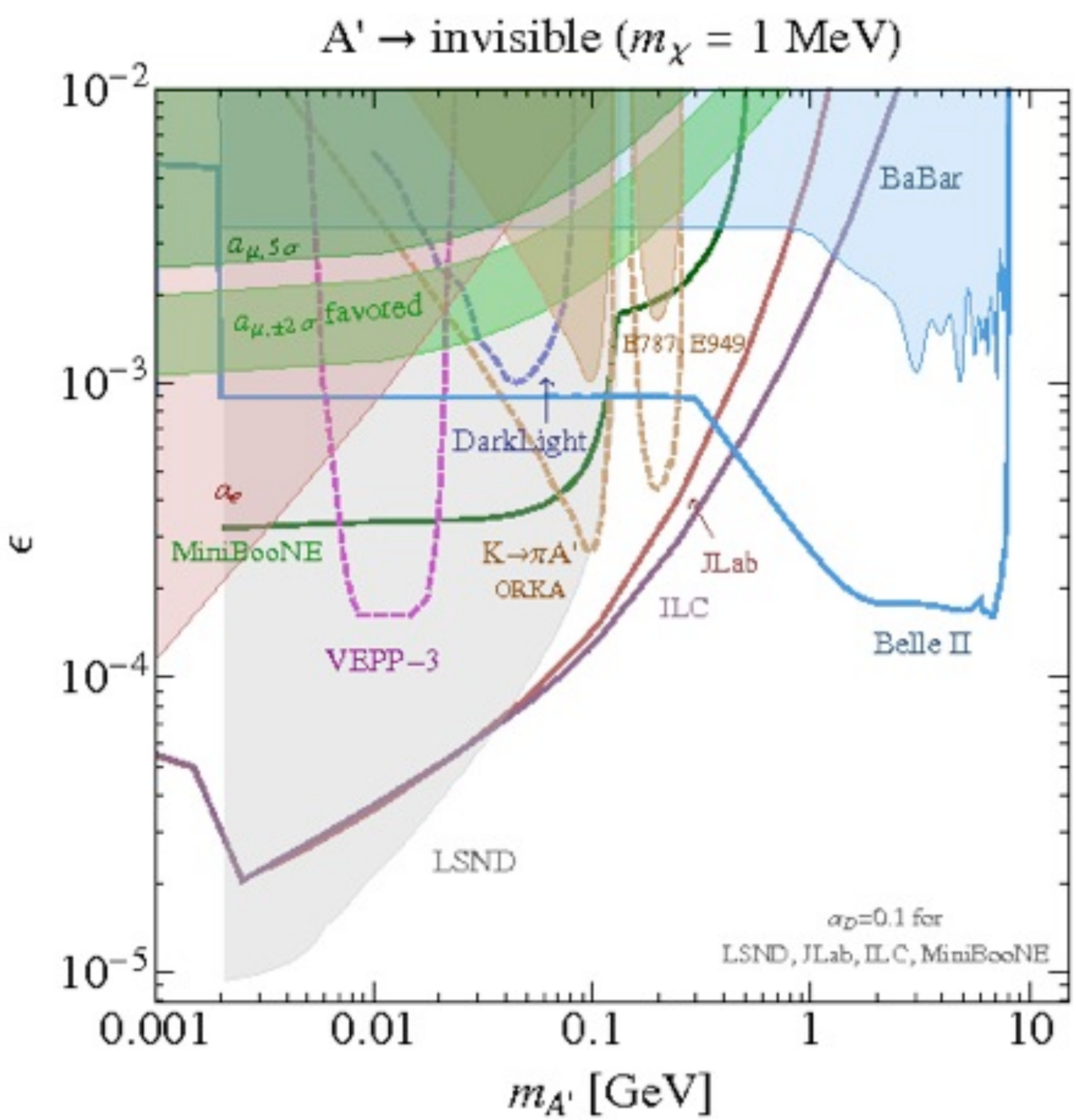
- If $X^\mu \rightarrow SM + SM$ dominates ($m_x < 2m_e$):



[Jaeckel, Ringwald 2010; Arias *et al.* 2012; An, Pospelov, Pradler 2013; Essig et al. 2013]

Case 1: Experimental Limits

- If $X^{\mu} \rightarrow (invisible)$ (e.g. dark matter) dominates:



[Batell, Pospelov, Ritz 2009; Izaguirre, Krnjaic, Schuster, Toro 2013; Essig et al. 2013]

A Slight Variation on Case I: Case I$'$

- Integrate out both vectors at low energies $|q^2| \ll m_x^2,\, m_Z^2$

$$-\mathcal{L}_{eff} \supset -\frac{\epsilon\, g_x\, e}{m_x^2} j_x^\mu\, j_{em\,\mu} - \frac{\epsilon\, t_W\, g_x g_Z}{m_x^2}\left(\frac{q^2}{m_Z^2}\right) j_x^\mu j_{Z\,\mu}$$

- The dark-Z cross term is very suppressed!
- This piece can be enhanced with extra mass mixing.

$\Rightarrow$ Case I$'$: the dark Z

Case I$'$: Extra Mass Mixing

[Davoudiasl, Lee, Marciano 2012]

- Mass matrix with general mixing:

$$\mathcal{M}^2 = m_Z^2 \begin{pmatrix} m_x^2/m_Z^2 & -\epsilon_Z \\ -\epsilon_Z & 1 \end{pmatrix} \quad \text{with} \quad \epsilon_Z = \left(\frac{m_x}{m_Z}\right)\delta$$

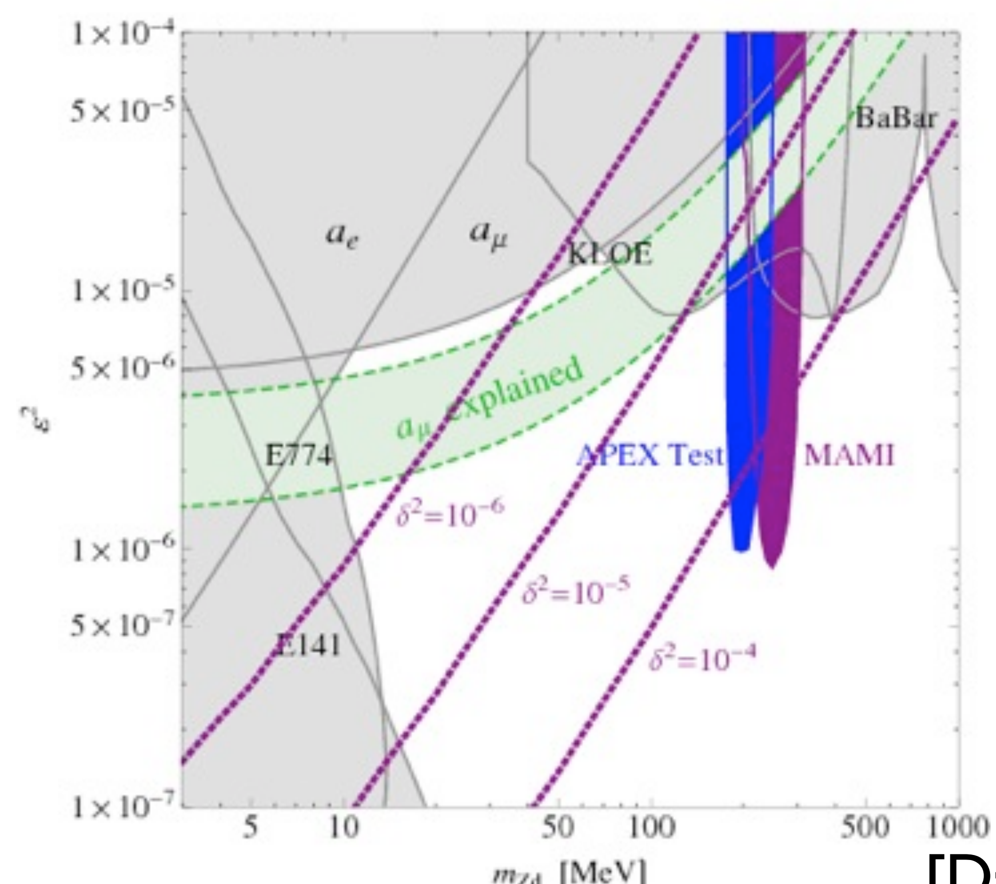
- At low energies:

$$-\mathcal{L}_{eff} \supset \delta \frac{g_x g_Z}{m_x m_Z} j_x^\mu j_{Z\,\mu} + (1+\delta^2)\frac{g_Z^2}{m_Z^2} j_Z^\mu j_{Z\,\mu}$$

Much less suppression!

Case I': Effects of the Mixing

- Coupling to the Z current modifies parity violation.
- Limits from APV, Moeller scattering constrain δ :



[Davoudiasl, Lee, Marciano 2012]

- Also, rare kaon decays, rare Higgs decays, ...

Case 2: Massless Dark Vector

- Start with massless X and A, massive Z vectors:

$$-\mathcal{L} \supset \frac{\epsilon}{2} X_{\mu\nu}\left(F^{\mu\nu} - t_W Z^{\mu\nu}\right) + eA_\mu j^\mu_{em} + g_Z Z_\mu j^\mu_Z + g_x X_\mu j^\mu_x$$

- Remove kinetic mixing with the change of variables

$$\begin{cases} A^\mu & \to & A^\mu \\ Z^\mu & \to & Z^\mu \\ X^\mu & \to & X^\mu - \epsilon A^\mu + \epsilon\, t_W Z^\mu \end{cases}$$

Case 2: Massless Dark Vector Couplings

- Putting in the shifted vectors,

$$\begin{aligned} -\mathcal{L} \quad &\supset \quad (e j^\mu_{em} - \epsilon\, g_x j^\mu_x)\, A_\mu \\ &+ \; (g_Z j^\mu_Z + \epsilon t_W\, g_x j^\mu_x)\, Z_\mu \\ &+ \; g_x j^\mu_x X_\mu \end{aligned}$$

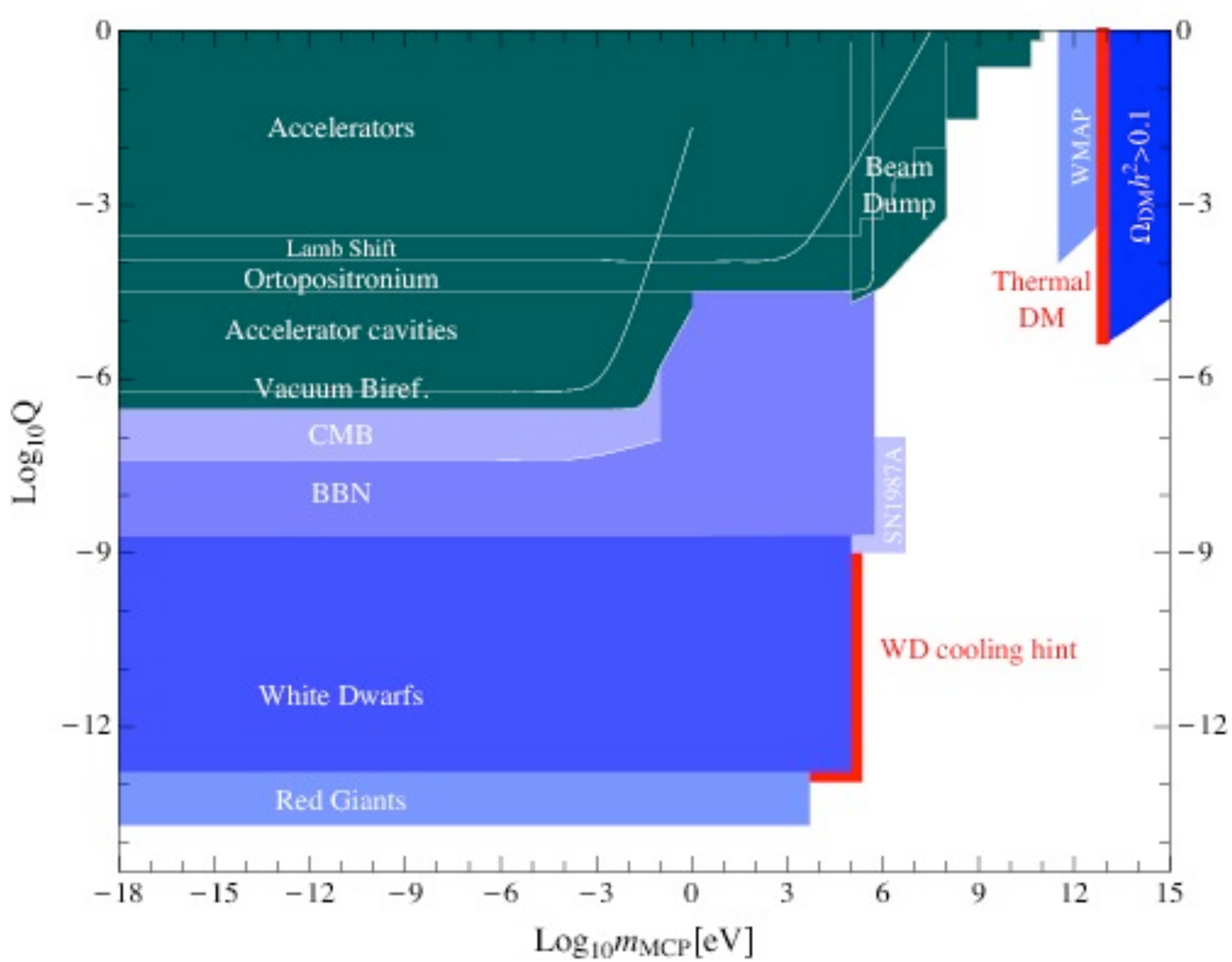
- Dark-sector matter acquires a millicharge:

$$Q_{eff} = -\epsilon \frac{g_x}{e}$$

- The dark photon does not couple to visible matter!

Case 2: Limits on Millicharged Particles

- Limits are quoted in the $m_{MCP} - Q_{eff}$ plane:



[Goodsell, Jaeckel, Redondo, Ringwald 2009]

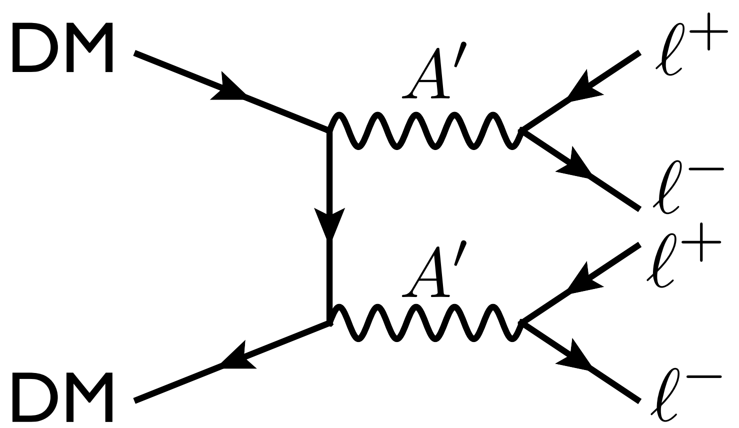
Dark Vector Friends

- The dark vector can be accompanied by other light states:
  - dark matter particles
  - dark Higgs bosons responsible for U(1)x breaking
  - new states associated with stabilizing the dark scale

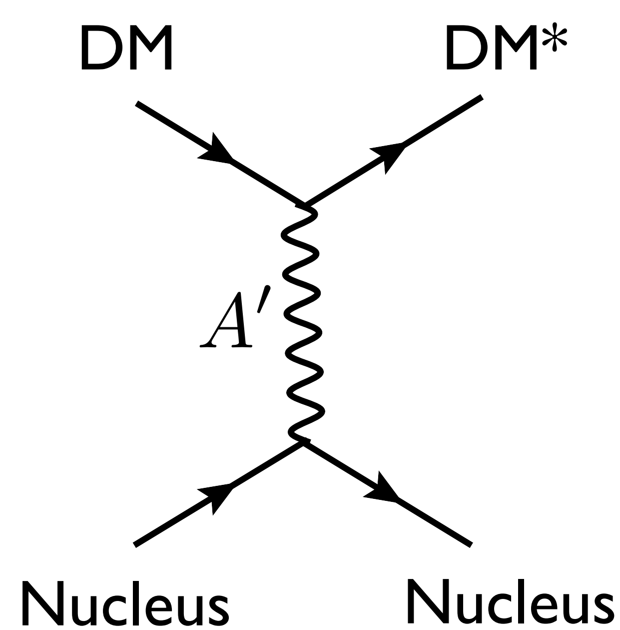
- These can produce new experimental signals.
- The dark vector could be a portal to a new dark sector!

Dark Vector Friends: Dark Matter

- Dark Matter may interact mainly with $U(1)_x$.
  [Pospelov, Ritz, Voloshin 2007; Arkani-Hamed, Finkbeiner, Slatyer, Weiner 2008, ...]
- DM Annihilation:



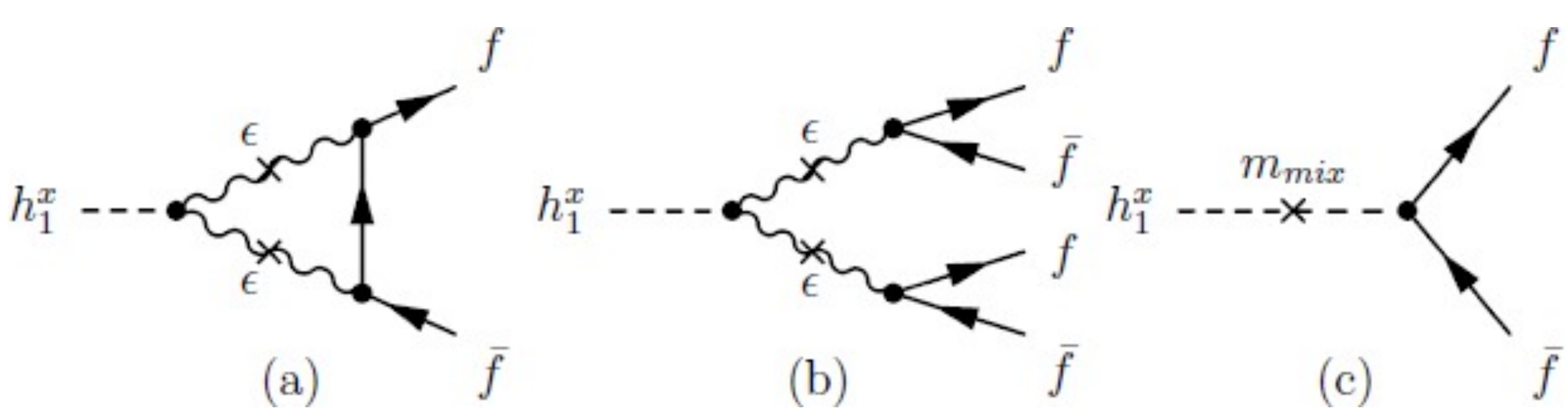
- Direct Detection Scattering:



Dark Vector Friends: Dark Higgs

- Dark $U(1)_x$ can be spontaneously broken by a dark Higgs.
- Signals depend on the relative mass:
  - $m_{h_x} < m_x/2$: dark Higgs decays to two dark vectors
    $\Rightarrow$ multi-lepton signals at B-factories [Batell, Pospelov, Ritz 2009]
  - $m_{h_x} > m_x$: dark Higgs decays via loop or Higgs portal
    $\Rightarrow$ highly displaced decays at fixed-targets

[Schuster, Toro, Yavin 2010; Chan, Low, DM, Spray 2011]



Dark Vector Friends: Dark Supersymmetry

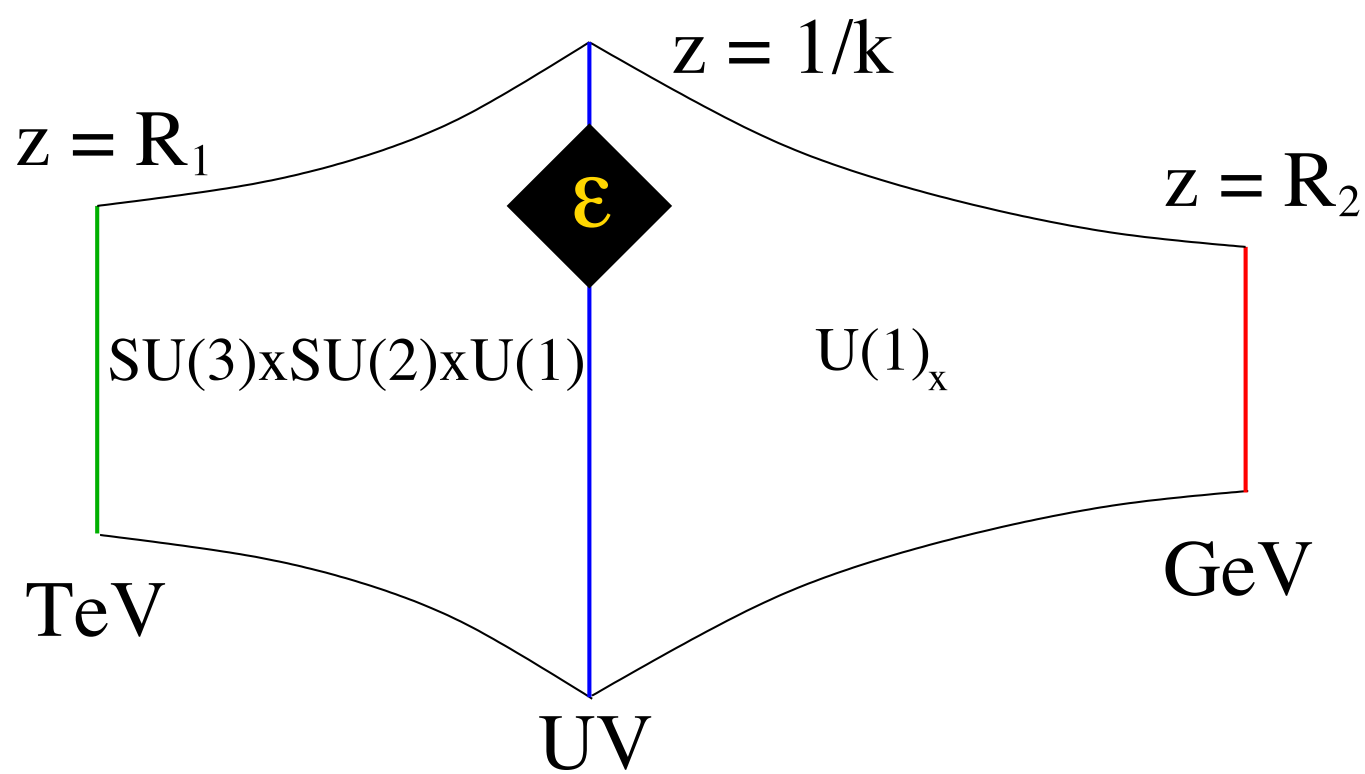
- Why is the dark vector mass so small?
- Supersymmetry! $m_x \sim \sqrt{\epsilon}\, m_z, \;\; \epsilon\, m_{MSSM}$

  [Arkani-Hamed+Weiner 2008; Cheung *et al.* 2009; DM, Poland, Zurek 2009; ...]

- A minimal SUSY dark vector theory gives:
  - 1 X^μ massive dark photon
  - 3 $\chi^x_{1,2,3}$ hidden fermion "neutralinos" (lightest stable)
  - 2 $h^x_{1,2}$ hidden scalar Higgs bosons
  - 1 a^x hidden pseudoscalar Higgs boson
- All these can have masses near m_x .

Dark Vector Friends: Dark Extra Dimension

- Why is the dark vector mass so small?
- A warped extra dimension (compositeness)! [McDonald, DM 2010]
- Setup:



- Dark photon Kaluza-Klein partners, $n = 1,\, 2,\, 3, \ldots$

$$m_n \sim n\, m_x/\sqrt{\ln(M_{\rm Pl}/m_x)}, \qquad \epsilon_n \sim \epsilon/\sqrt{n\,\ln(M_{\rm Pl}/m_x)}$$

Summary

- New physics can be light if it is hidden.
- Kinetic mixing ϵ connects a dark vector to our world.
- Dark vectors produce new signals in lower-energy and precision experiments.
- A dark vector may also connect us to a dark sector.

Warning!

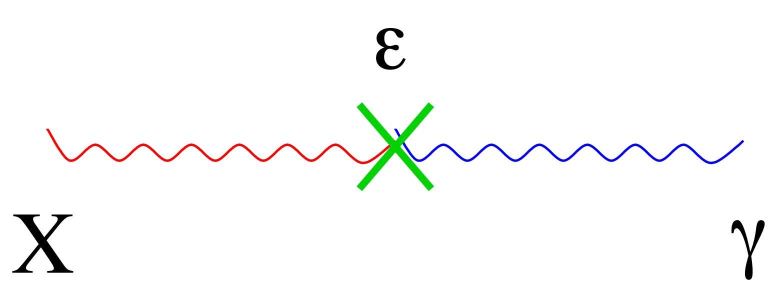
$$X = A' = A_d = \gamma' = Z_x = Z_d = Z_{hid} = Z' = V$$

$$\epsilon = \varepsilon = \kappa$$

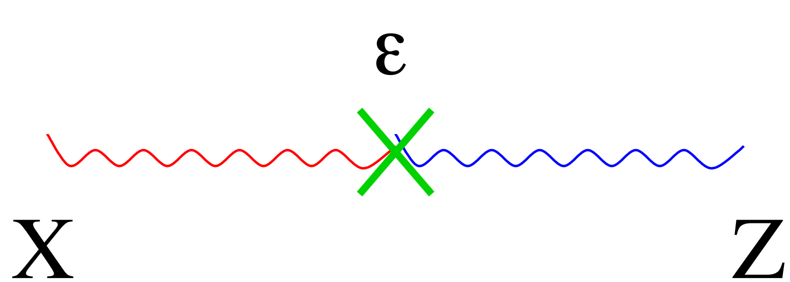
Extra Slides

A Trick for Low-Energy Estimates

- For $|q^2| \ll m_x^2,\, m_Z^2$, treat kinetic mixing as an interaction.



$$\sim \quad -\,\epsilon\, q^2$$

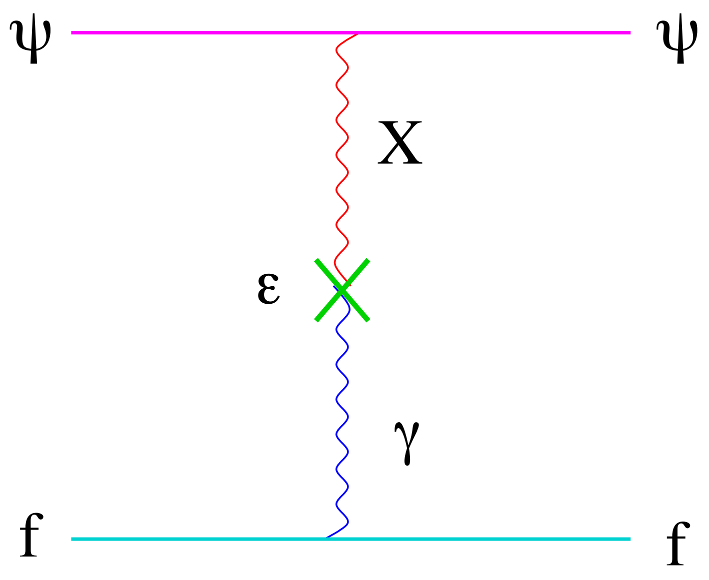


$$\sim \quad \epsilon\, t_W\, q^2$$

- Expand propagators in powers of $|q^2/m^2| \ll 1$.

Photon-Dark Interaction at Low Energy

- Using the trick, we get:



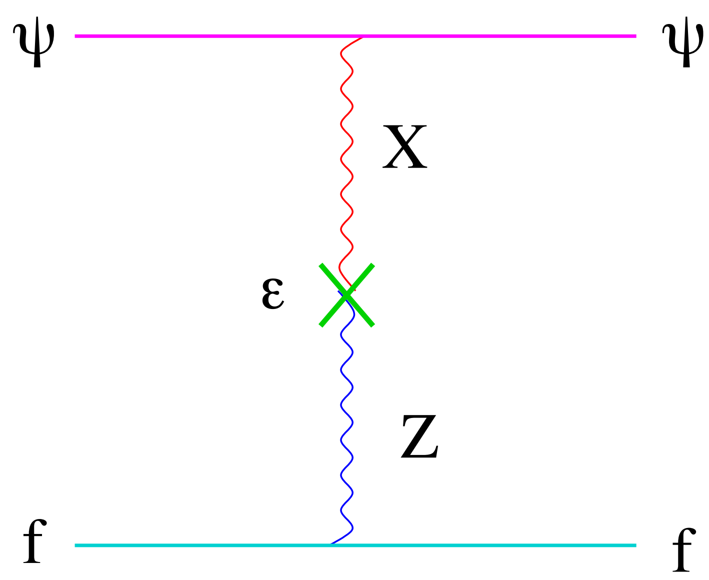
$$\sim \quad \frac{(eQ)}{q^2}\left(-\epsilon q^2\right)\frac{(g_x Q_x)}{q^2 - m_x^2}$$

$$\sim \quad \epsilon\,\frac{(eQ)(g_x Q_x)}{m_x^2}$$

- Non-singular as $q^2 \to 0$: hidden stuff gets no em charge.

Z-Dark Interaction at Low Energy

- Using the trick, we get:



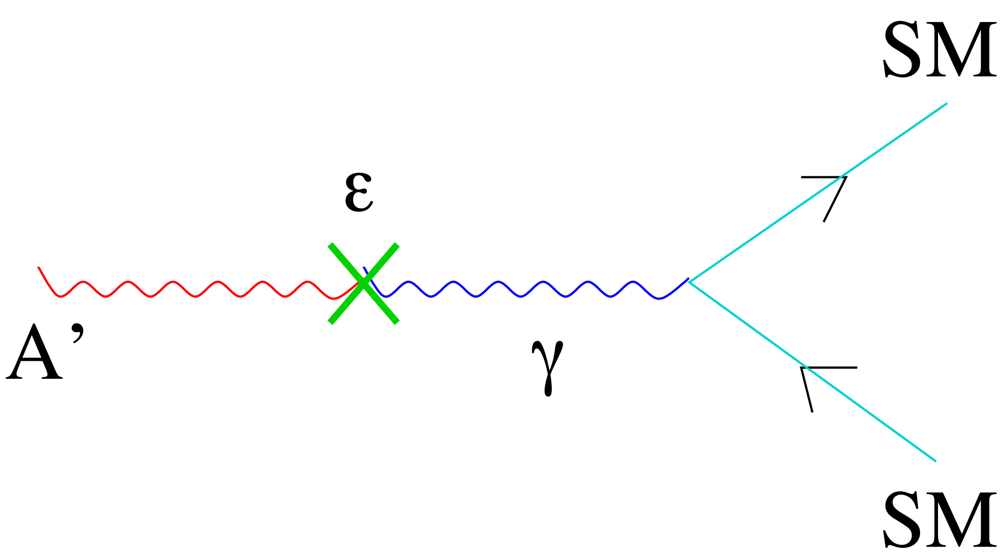
$$\sim \quad \frac{(g_Z Q_Z)}{q^2 - m_Z^2} \left(\epsilon t_W q^2\right) \frac{(g_x Q_x)}{q^2 - m_x^2}$$

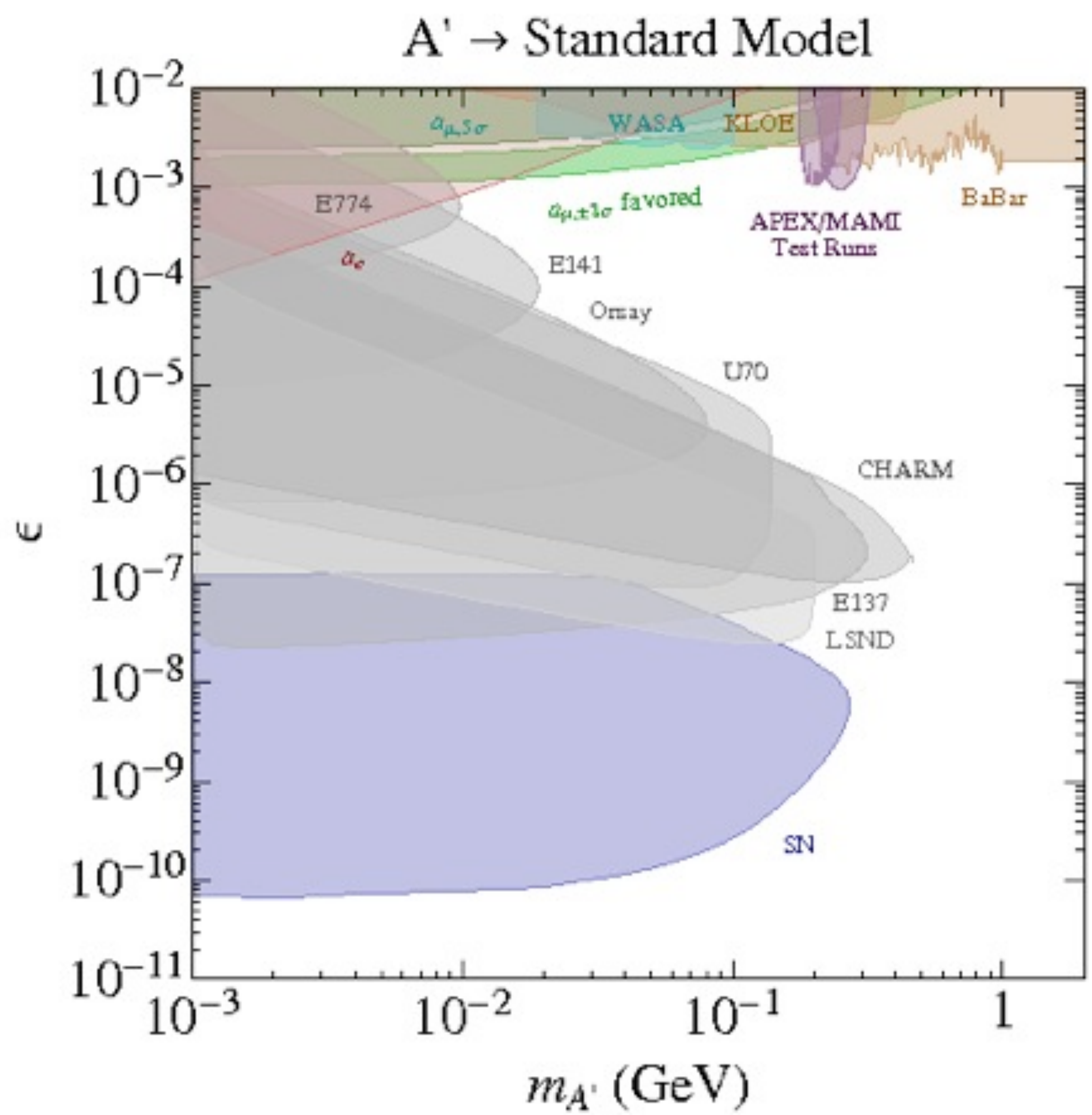
$$\sim \quad \epsilon \, \frac{(g_Z Q_Z)(g_x Q_x)}{m_x^2} \left(\frac{q^2}{m_Z^2}\right)$$

- Has additional suppression as $q^2 \to 0$.

Minimal Vector Portal

- Hidden photon A' with mass $m_{A'}$, A' → SM+SM:

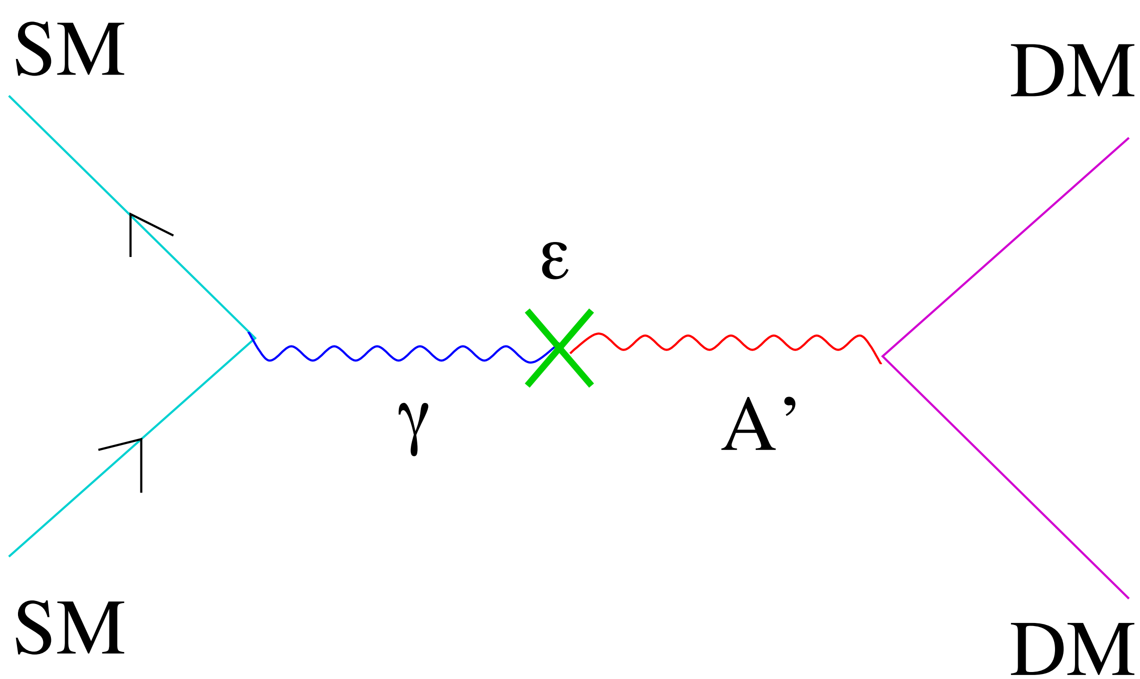


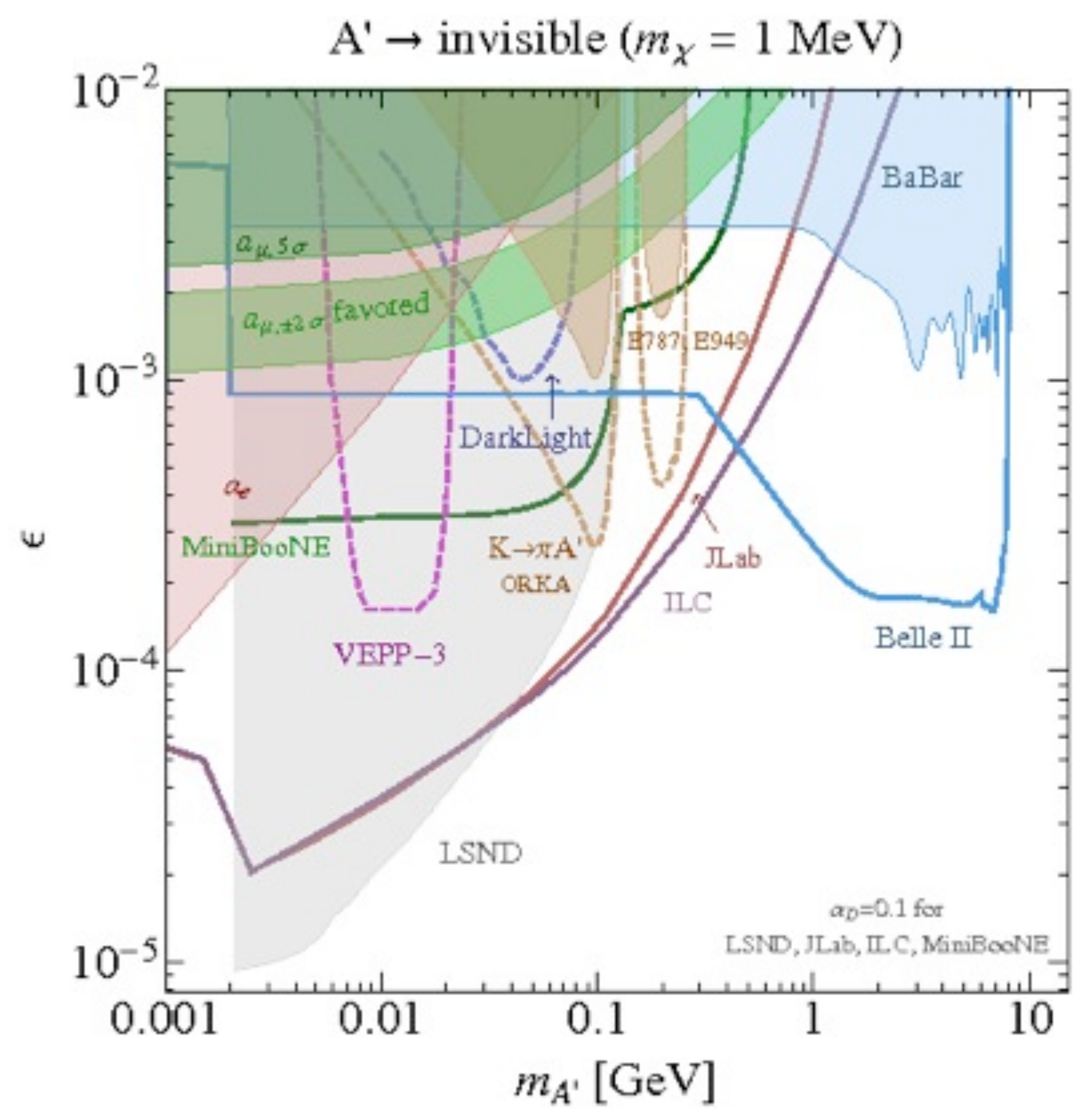


[Bjorken, Essig, Schuster, Toro 2009; ...; Essig et al. 2013]

Minimal Dark Vector Portal

- Hidden photon A' with mass $m_{A'}$, A' → DM+DM:

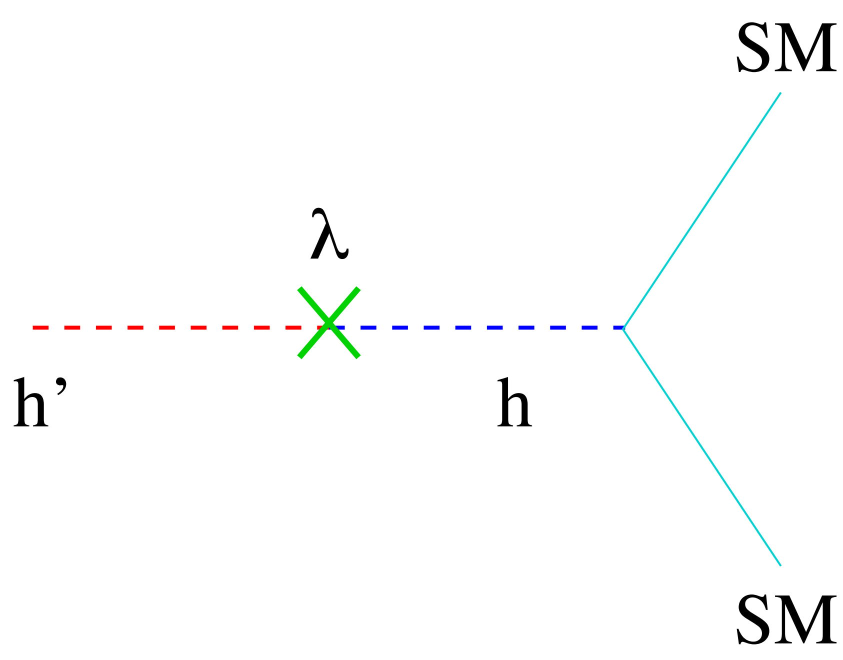




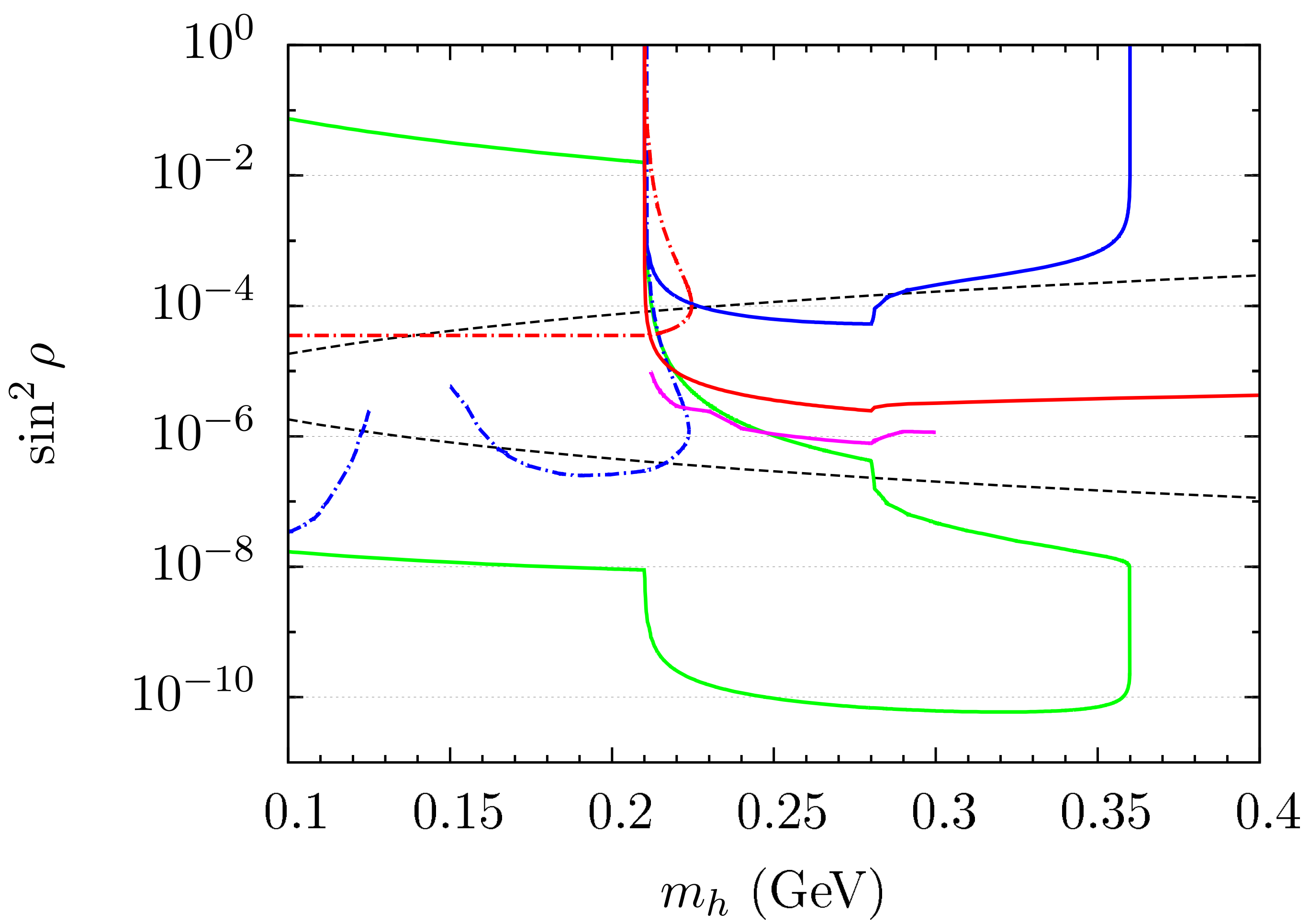
[Batell, Pospelov, Ritz 2009; ...; Essig et al. 2013]

Minimal Higgs Portal

- Hidden Higgs h' with mass $m_{h'}$, h' → SM+SM:



$$\sin^2\rho \simeq \lambda^2 \left(\frac{m_{h'}}{m_h}\right)^2$$



[...; Batell, Pospelov, Ritz 2009; Bezrukov+Gorbunov 2013; Clarke, Foot, Volkas 2013]

Beyond Minimal: a SUSY Hidden Vector

- Hidden sectors can be more complicated than minimal. These can produce new and interesting signatures.
- Why Supersymmetry (SUSY)?
  - Some people are quite fond of it.
  - Can explain why the hidden sector is so light.
  - Gives a concrete non-minimal vector portal theory.
  - Studying new theories can motivate new exp. searches.

SUSY Hidden Sector Setup

- Hidden U(1)' gauge symmetry kinetically mixes with $U(1)_Y$.
- Hidden Higgs fields spontaneously break the U(1)'.

$$\mathcal{L} \supset \int d^2\theta \left(\underbrace{\frac{\epsilon}{2c_w} B^\alpha X_\alpha}_{\text{vector portal}} + \underbrace{\mu' H H'}_{\text{hidden Higgs fields}} \right) + (h.c.)$$

- Physical states:
  - 1 A' massive hidden photon
  - 3 $\chi^x_{1,2,3}$ hidden fermion "neutralinos" (lightest is stable)
  - 2 $h^x_{1,2}$ hidden scalar Higgs bosons
  - 1 a^x hidden pseudoscalar Higgs boson

Experimental Signals of the Theory

- Depend mainly on how the hidden photon decays.
  This is determined mostly by the mass spectrum.

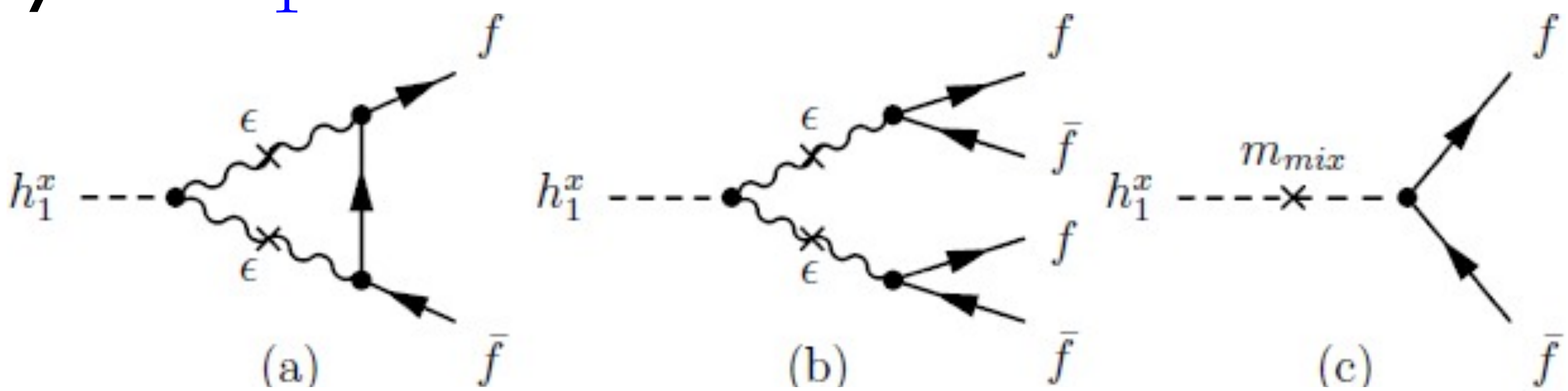
- Four main cases:

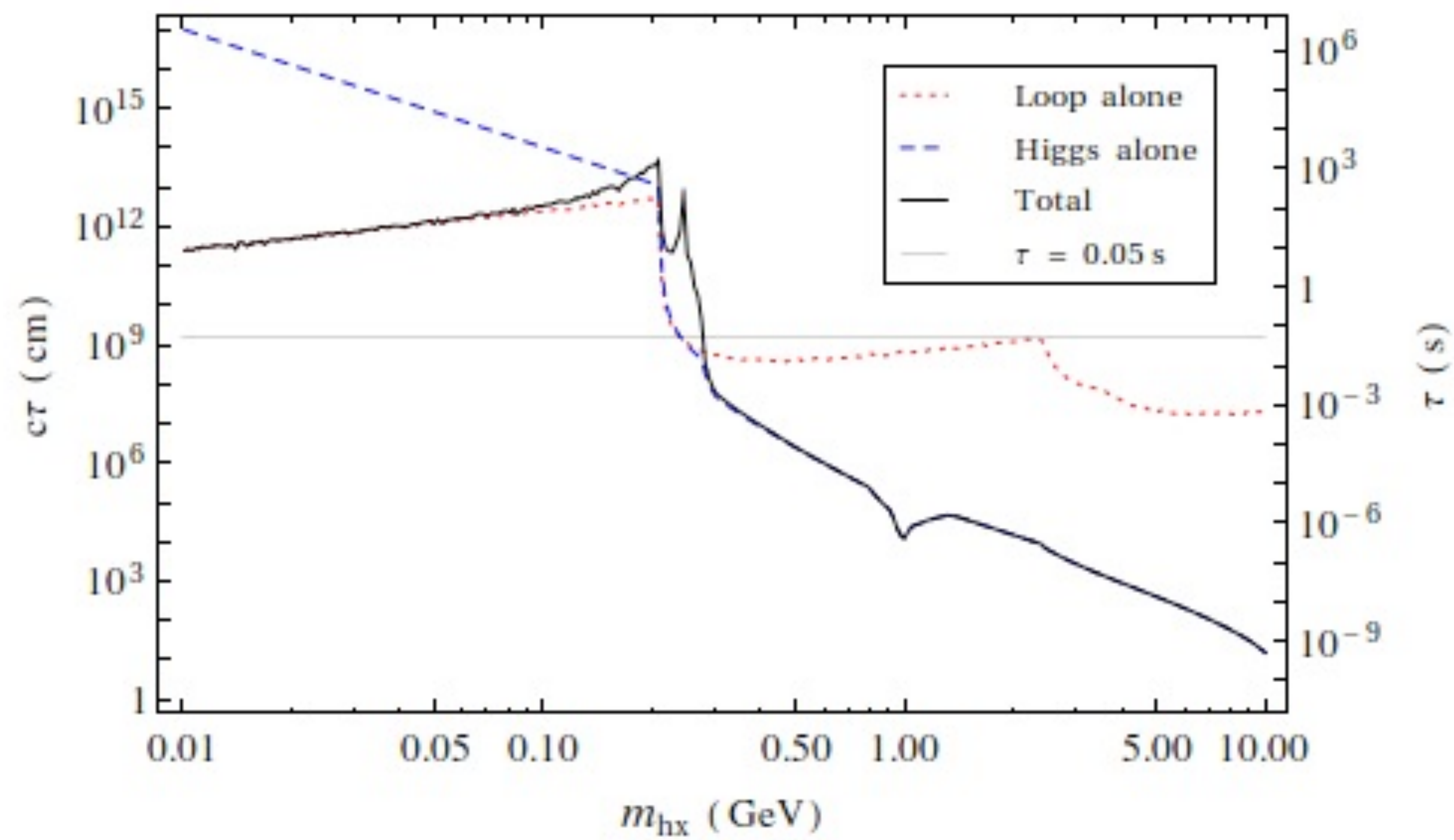
  - A: $A' \to SM + SM$, similar to minimal vector portal
  - B: $A' \to \chi_1^x + \chi_1^x$, similar to dark vector portal
  - C: $A' \to h_1^x + a^x$, not much attention [Schuster, Toro, Yavin 2009]
  - D: $A' \to \chi_1^x + \chi_2^x$, new!

- Focus on cases C and D. [DM, Spray 2014]

Case C: $A' \to h_1^x + a^x$

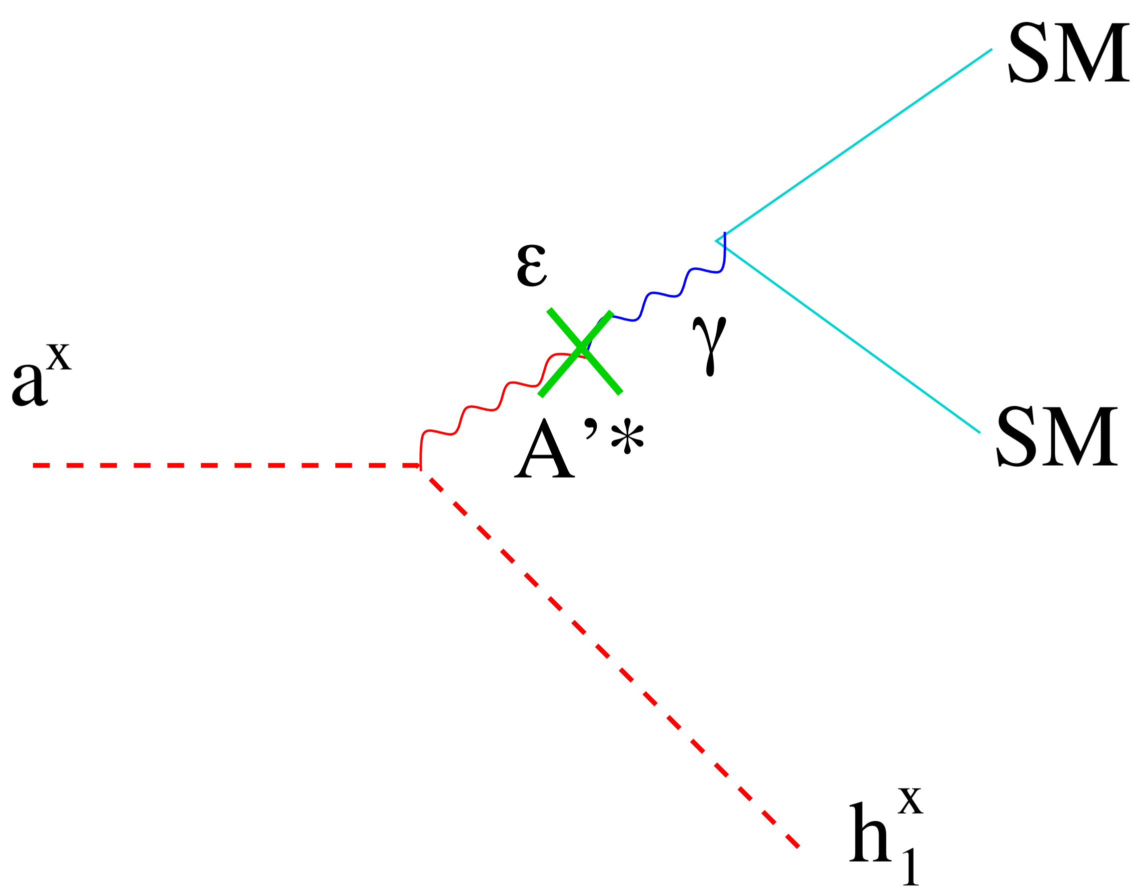
- Decays of h_1^x :





Case C: $A' \to h_1^x + a^x$

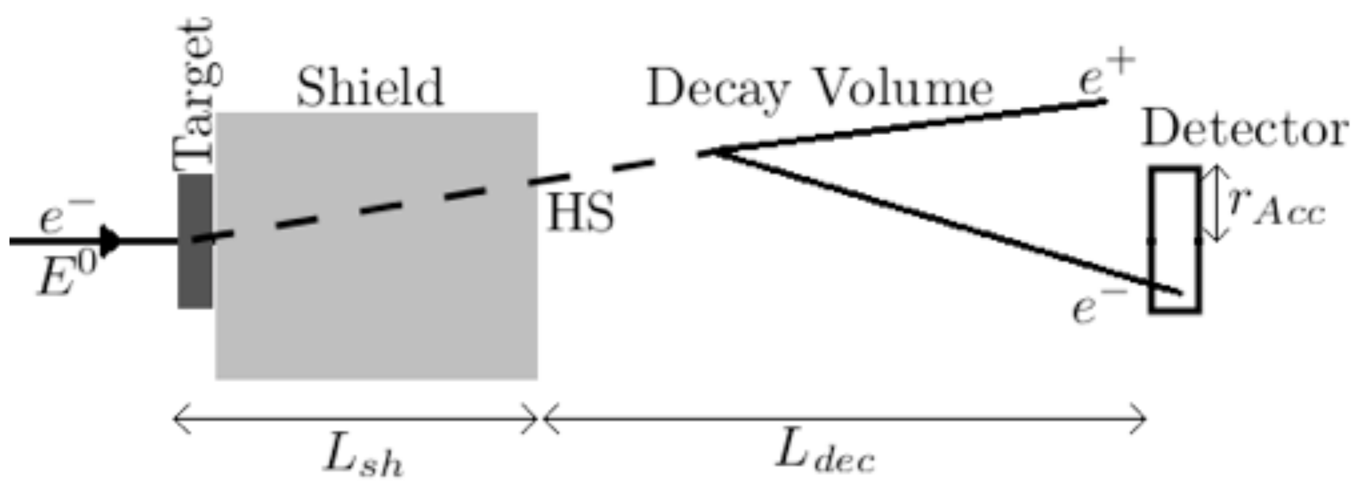
- Decays of a^x:

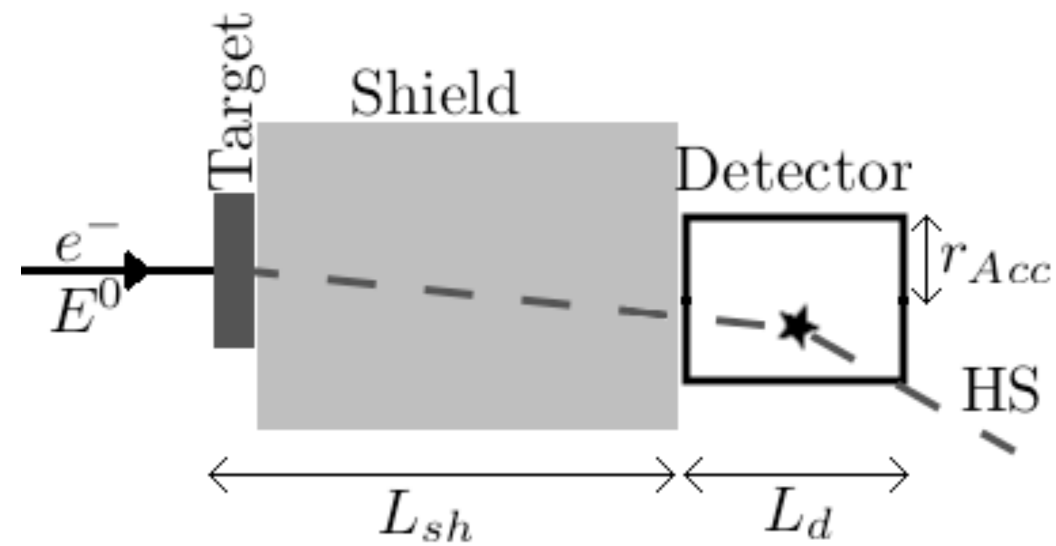


- Lifetime depends on relative a^x and A' masses.

Case C: Electron-Fixed-Target Signals

- Signal Sources:



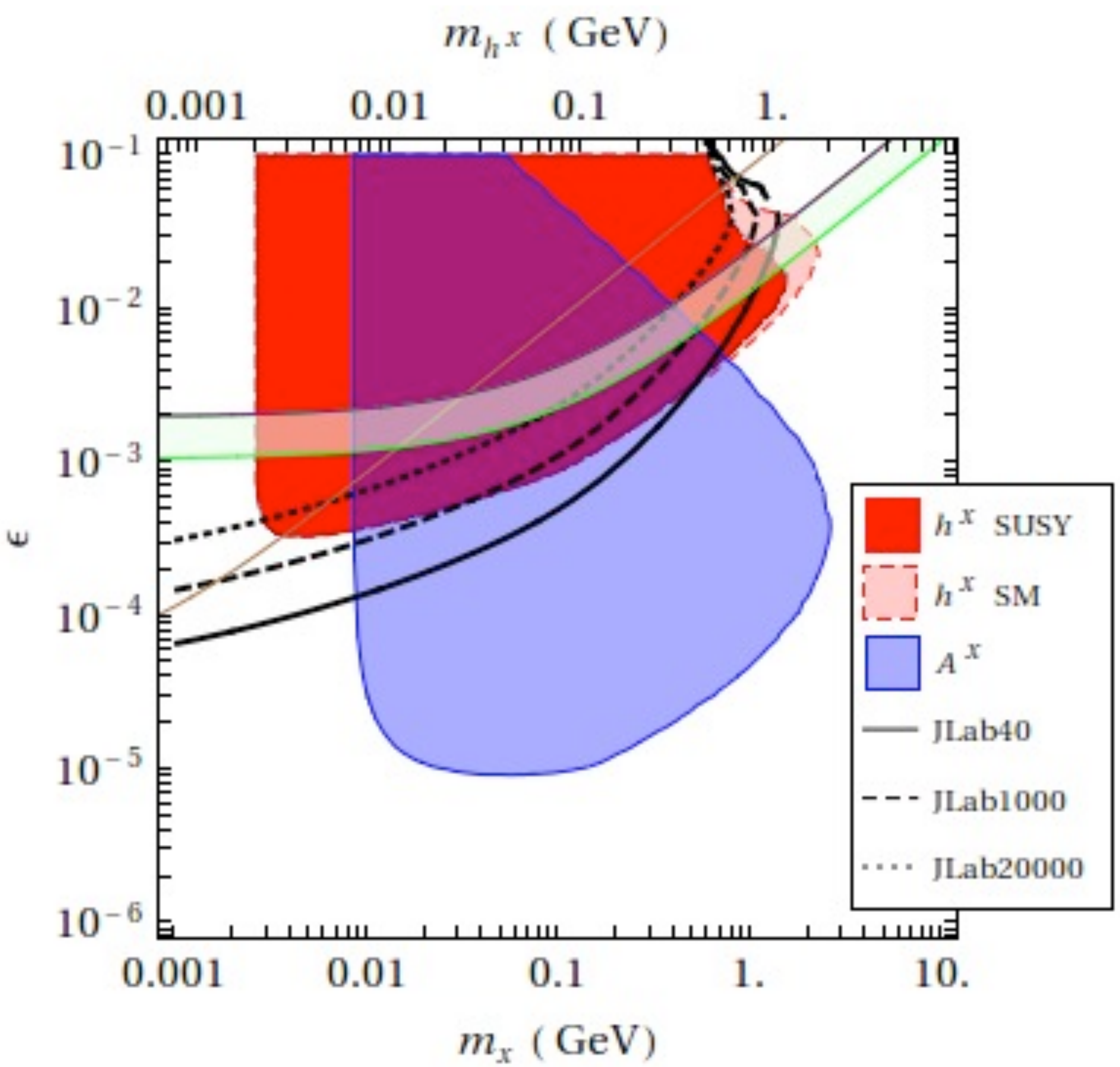


- A' is produced relatively efficiently, mostly along the beam.
- Two sources of signals:

1. decay products of h_1^x or a^x are seen in the detector.
2. h_1^x or a^x scatters quasi-elastically in the detector.

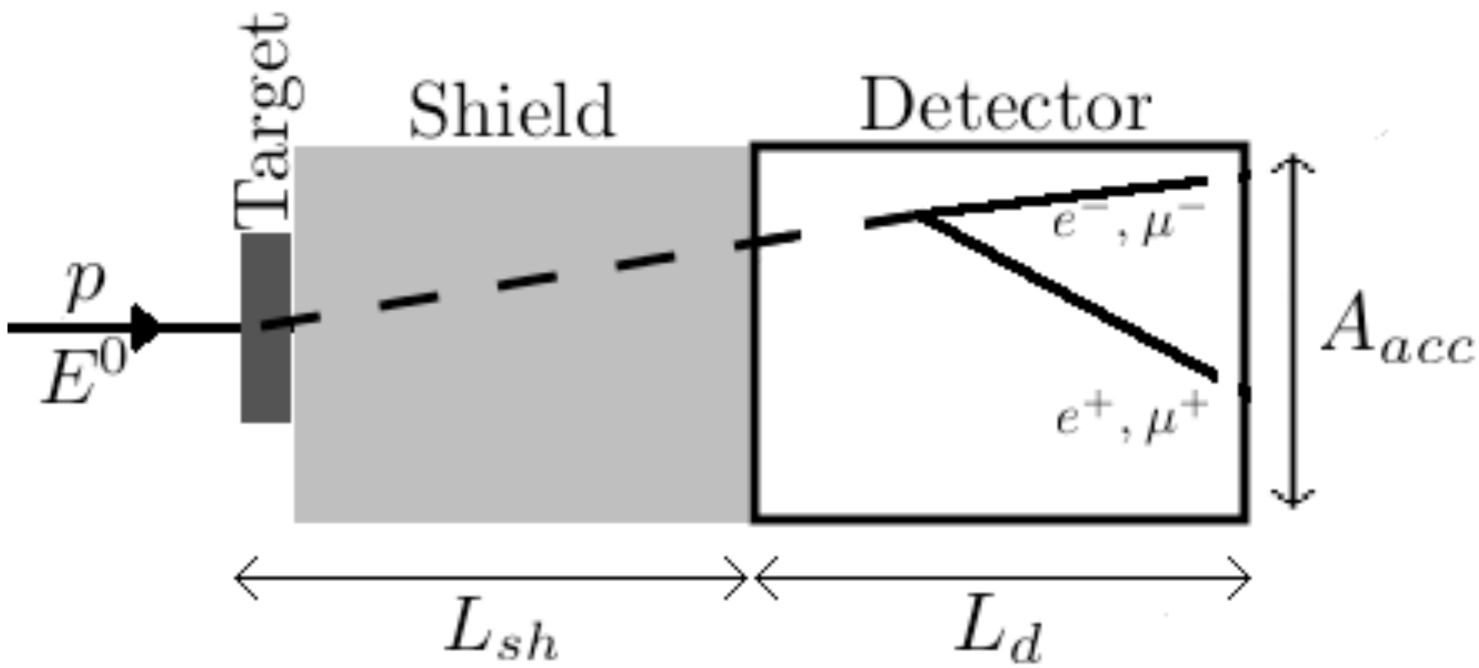
Case C: Electron Fixed Target Limits

- Set all parameters as fixed ratios of $m_{A'}$, $\alpha' = \alpha$.
- Best limits come from E137.



Case C: Hadronic Fixed Target Signals

- Signal Sources:

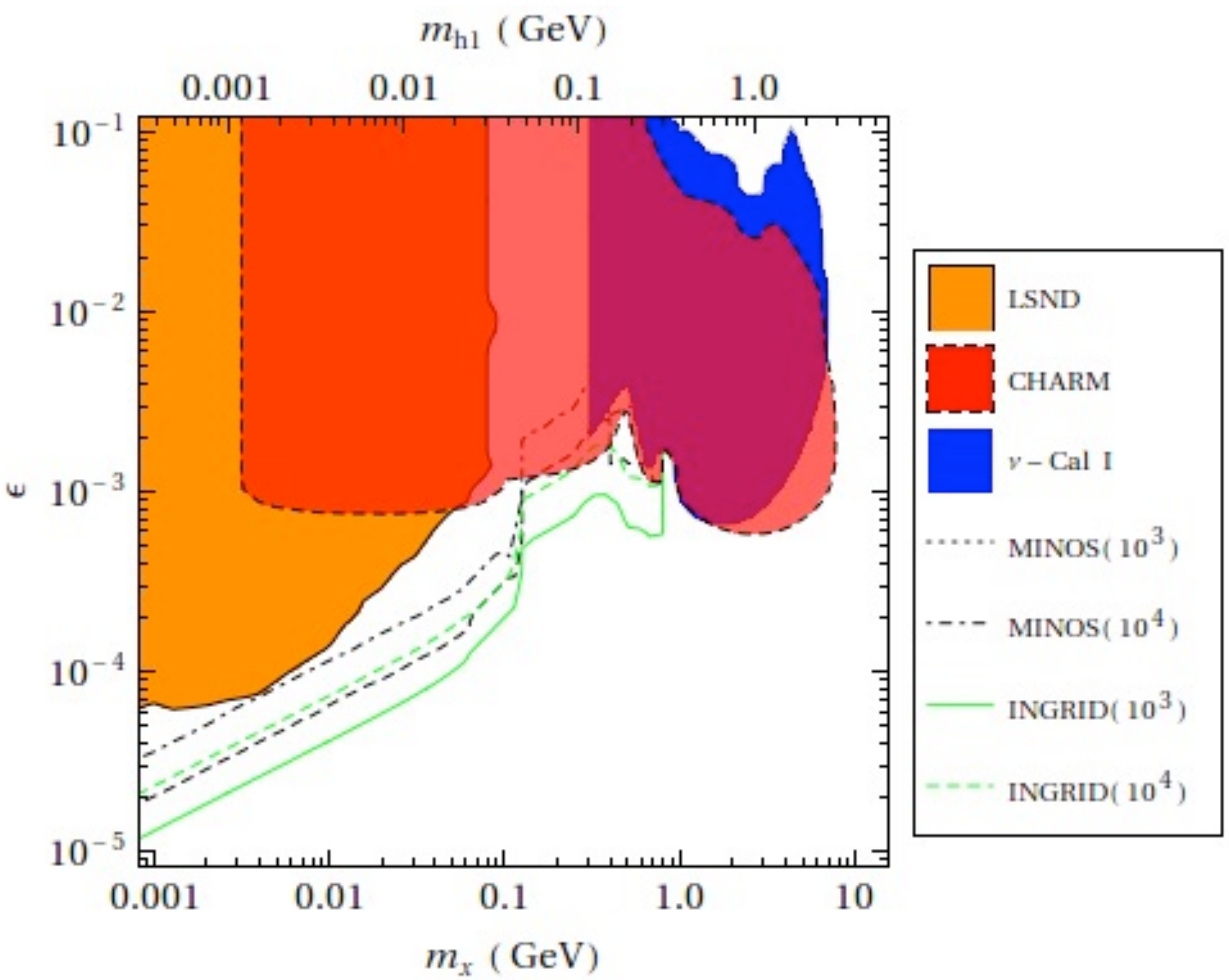


- A' production from parton collisions or meson decay.
- Two sources of signals:

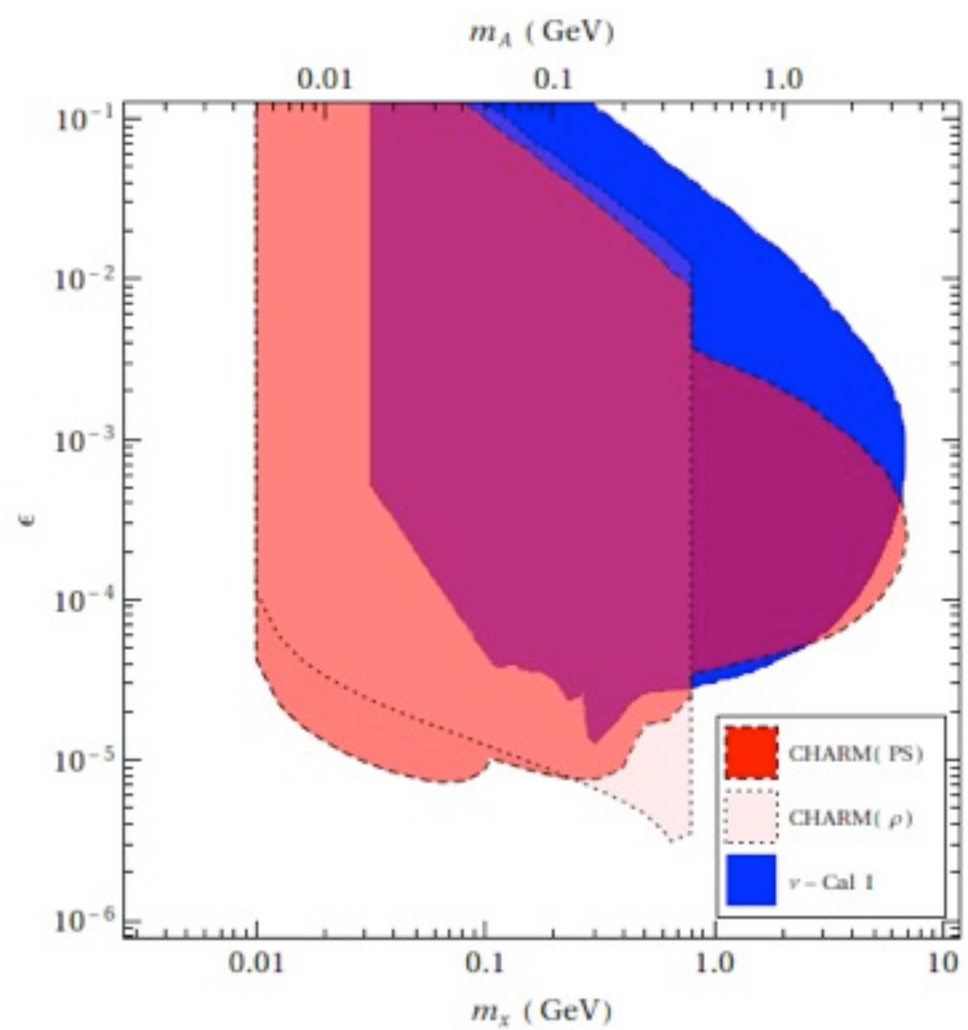
1. decay products of h_1^x or a^x are seen in the detector.
2. h_1^x or a^x scatters quasi-elastically in the detector.

Case C: Hadronic Fixed Target Limits

- Set all parameters as fixed ratios of $m_{A'}$, $\alpha' = \alpha$.
- Best limits come from CHARM, LSND, and ν-Cal I.



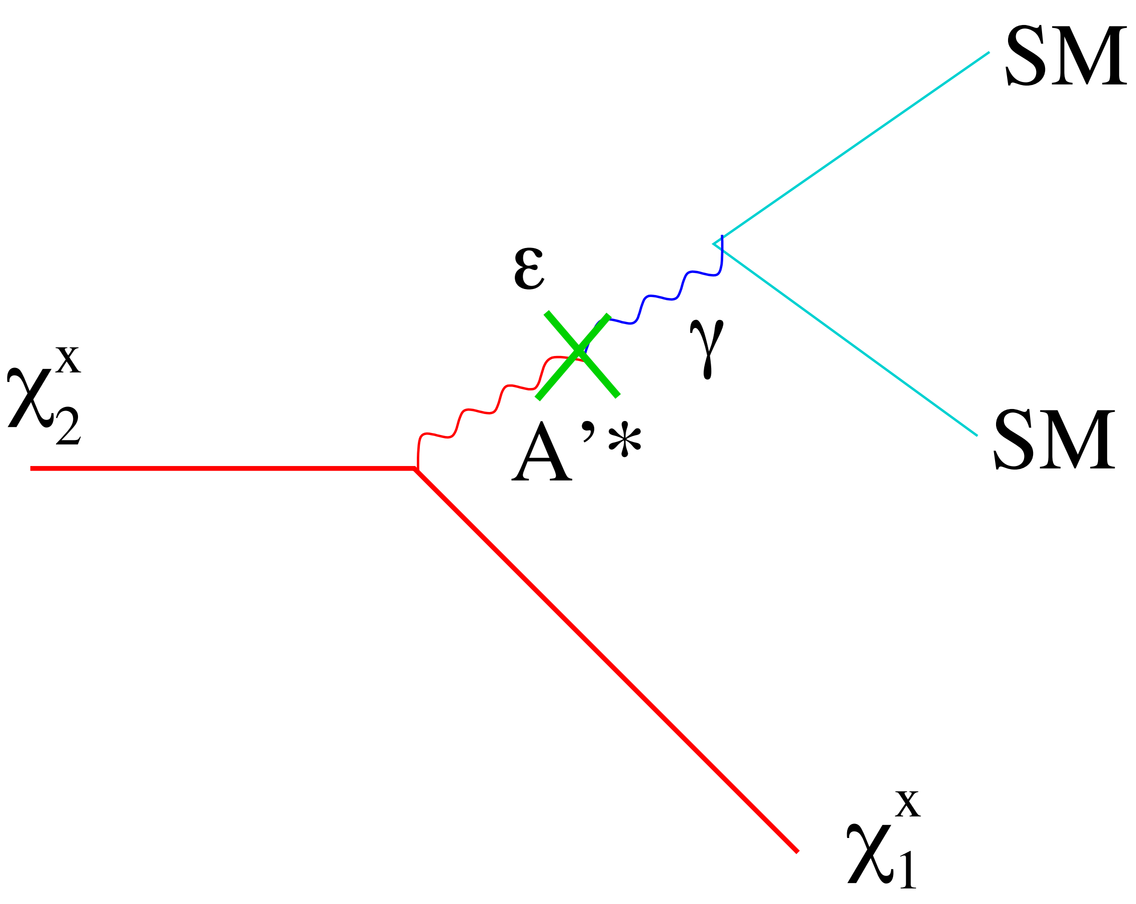
$h_1^x + invisible$



a^x

Case D: $A' \to \chi_1^x + \chi_2^x$

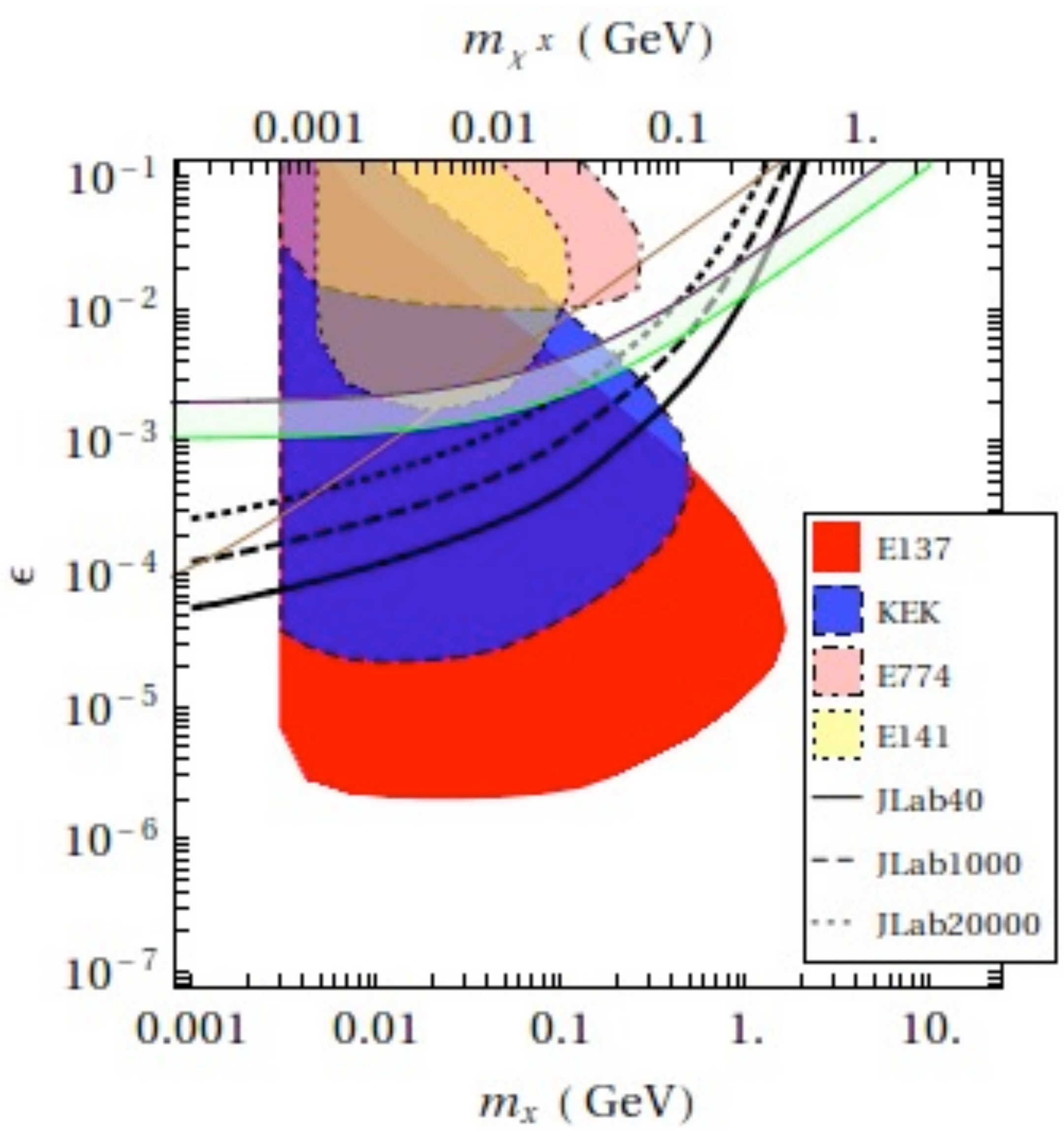
- Decays of χ_2^x:



- Lifetime depends on relative χ_2^x and A' masses.

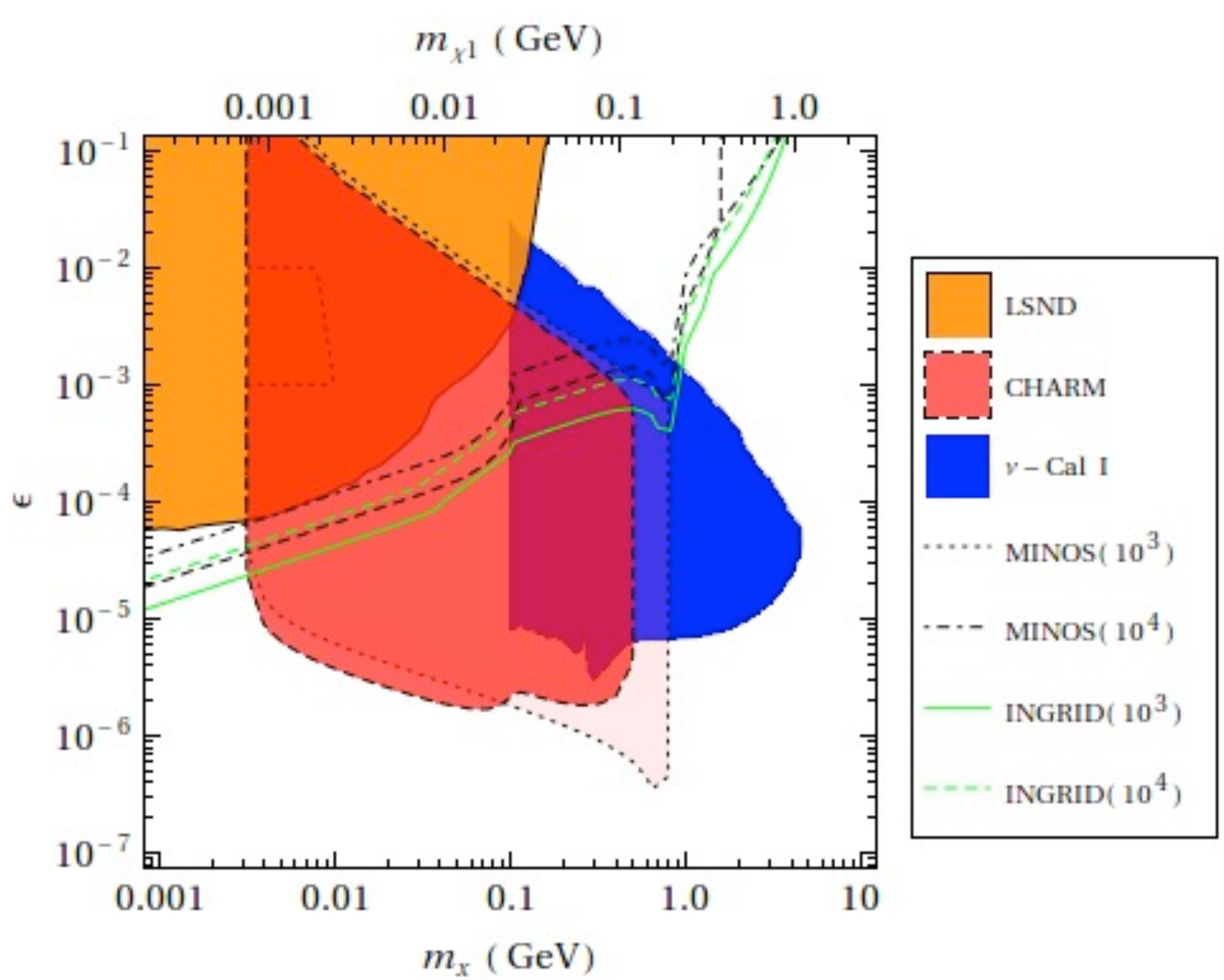
Case D: Electron Fixed Target Limits

- Set all parameters as fixed ratios of $m_{A'}$, $\alpha' = \alpha$.
- Best limits come E137 and others.



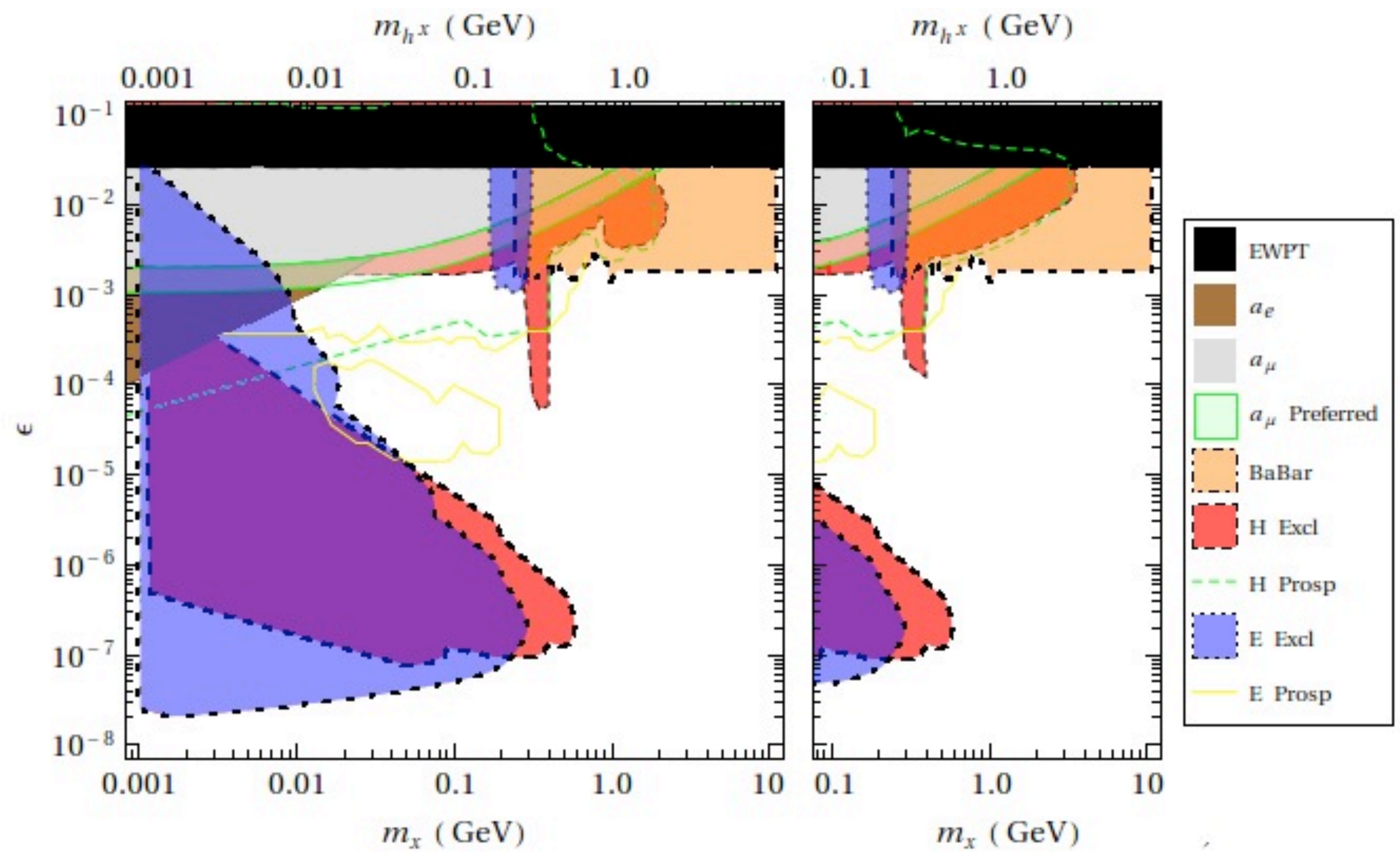
Case D: Hadronic Fixed Target Limits

- Set all parameters as fixed ratios of $m_{A'}$, $\alpha' = \alpha$.
- Best limits come from CHARM, LSND, and ν-Cal I.



One Last Comment

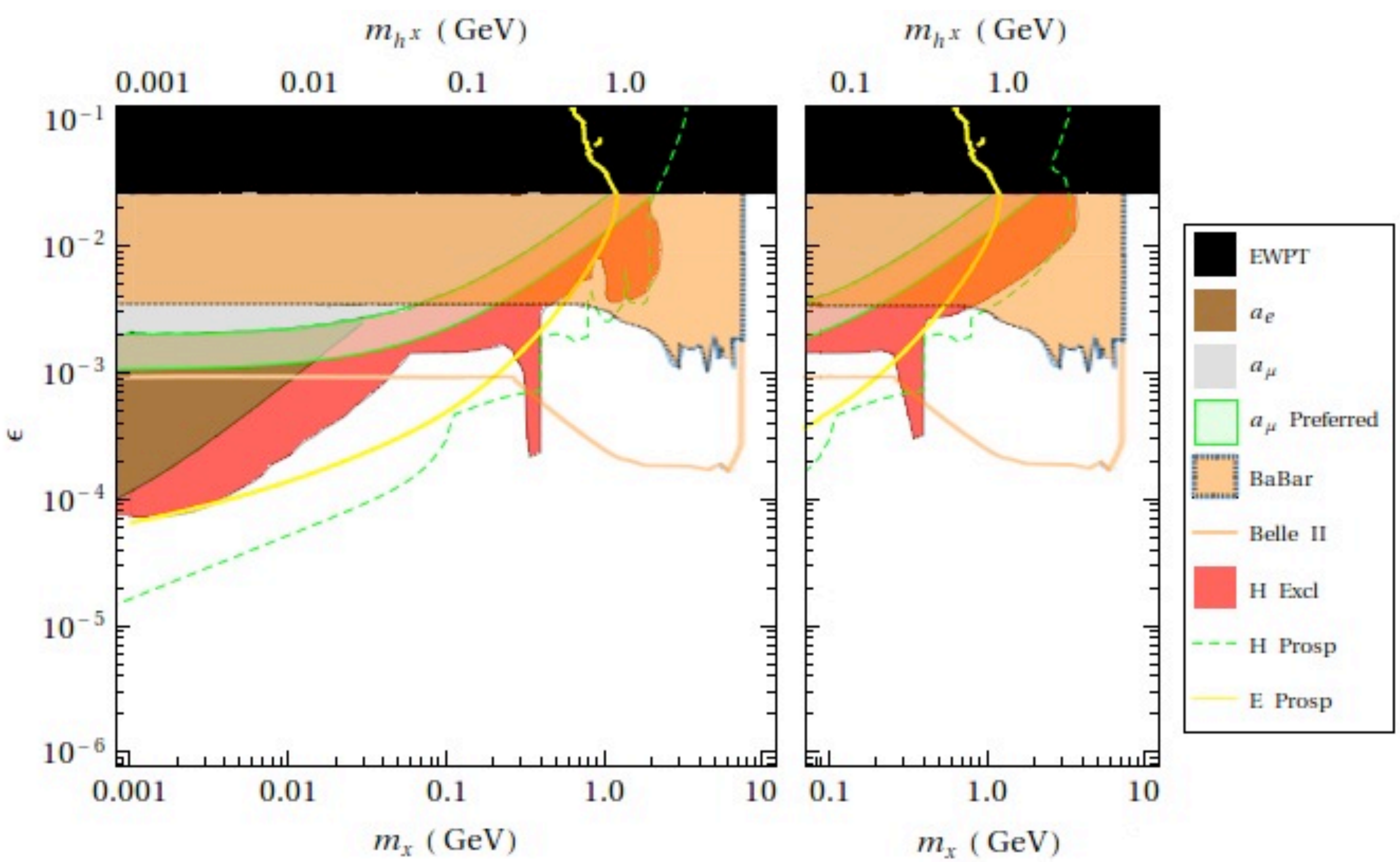
- Long-lived $h_1^x,\ a^x,\ \chi_2^x$, states can also contribute in Cases A and B via production by an off-shell vector.



Case A

One Last Comment

- Long-lived h_1^x, a^x, χ_2^x, states can also contribute in Cases A and B via production by an off-shell vector.



Case B

Electron Fixed-Target Experiments

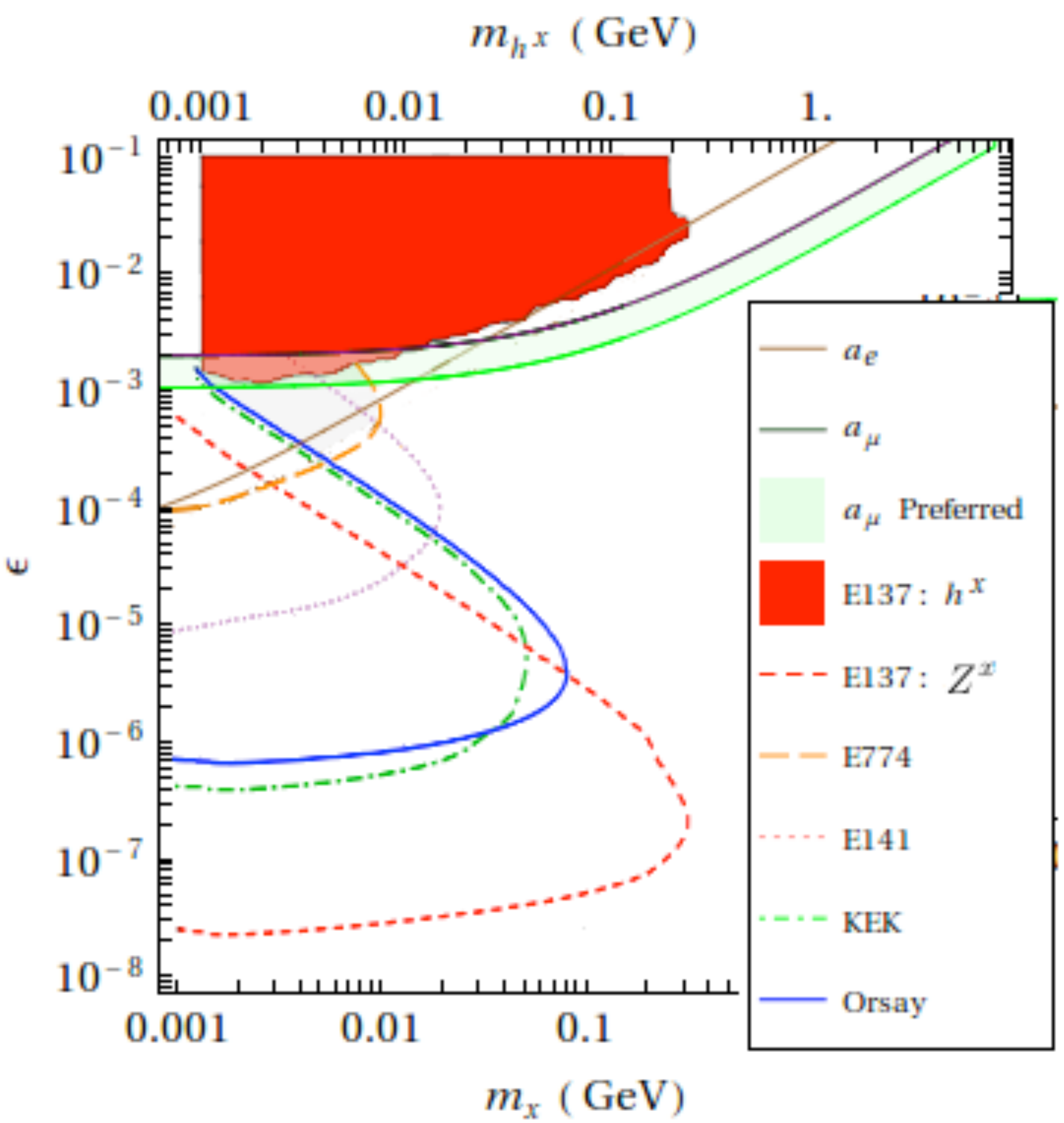
Expt	Target	E (GeV)	$\text{Log}_{10}N_e$	L_{sh}	L_{dec}
E137	Al	20	20	179	204
E141	W	9	15	0.12	35
E774	W	275	9	0.3	2
KEK	W	2.5	17	2.4	2.2
Orsay	W	1.6	16	1	2
JLab	Al	12	20	10	1

[Izaguirre, Krnjaic, Schuster, Toro 2013]

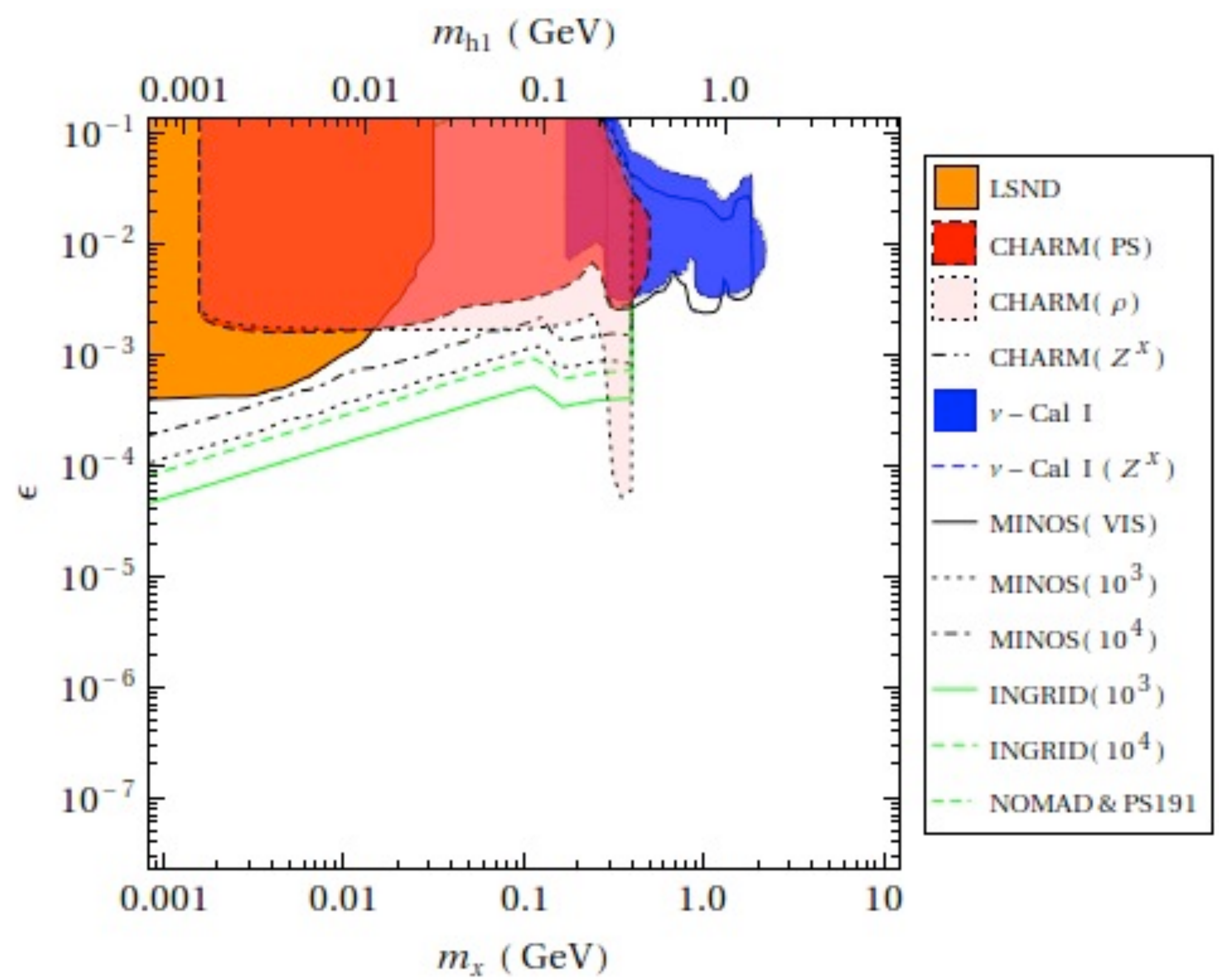
Hadronic Fixed-Target Experiments

Expt	Target	E (GeV)	$\mathrm{Log}_{10}N_p$	L_{sh}	L_{dec}
CHARM	Cu	400	18	480	35
MINOS	C	120	21	1040	1.3
ν-Cal I	Fe	70	18	64	23
INGRID	C	30	21	280	0.585
LSND	...	0.798	...	30	8.3

Case A

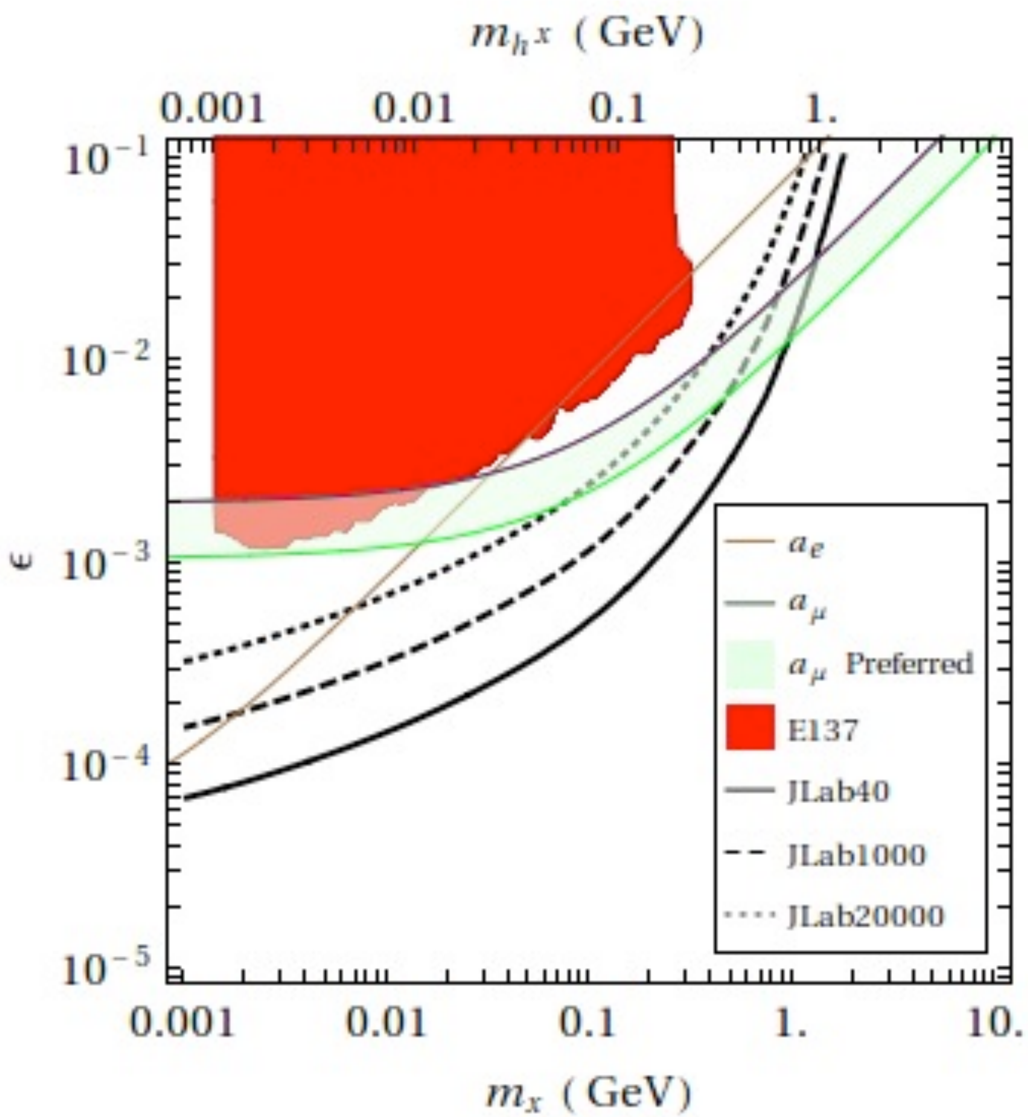


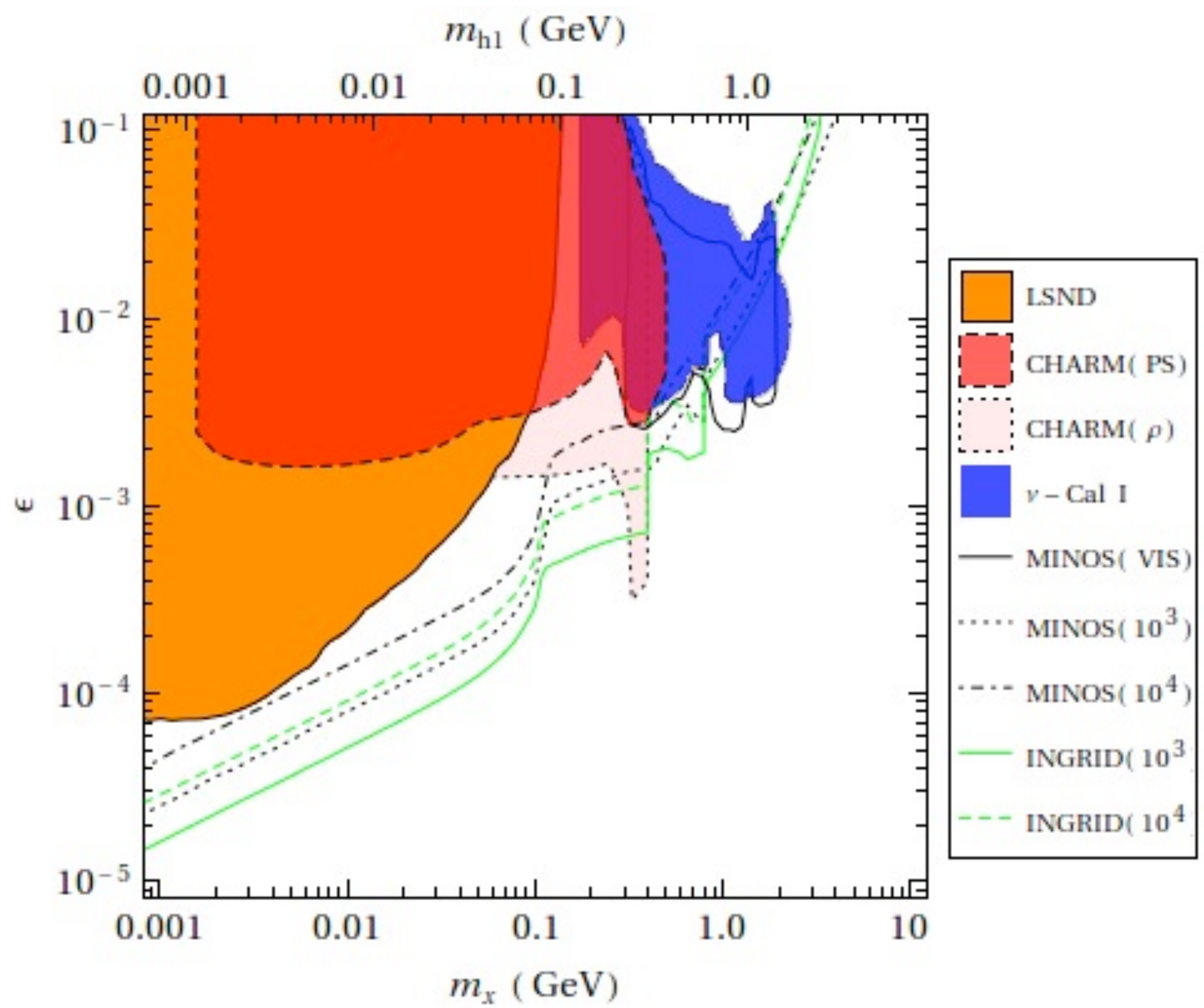
E Beam



H Beam

Case B

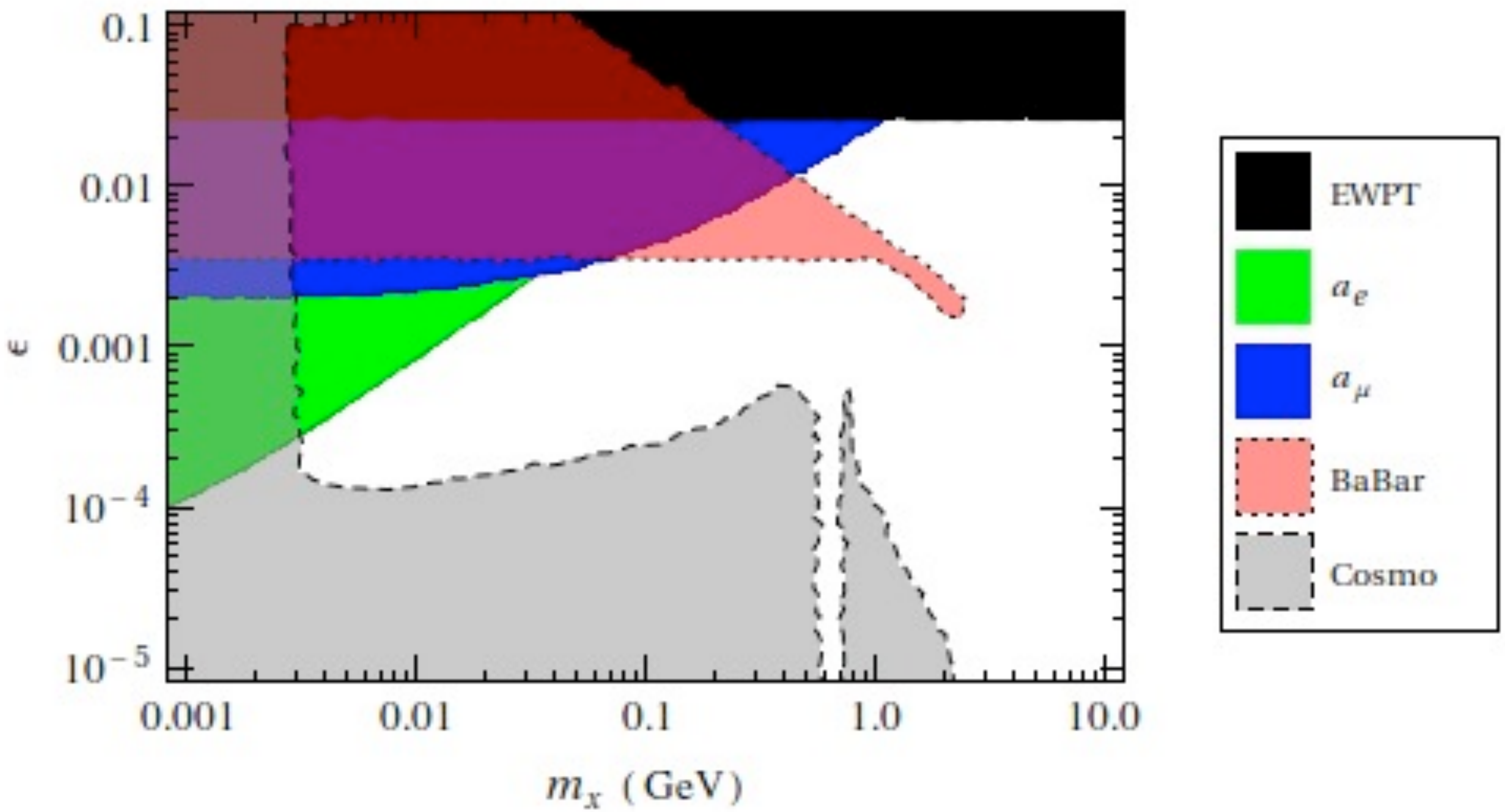




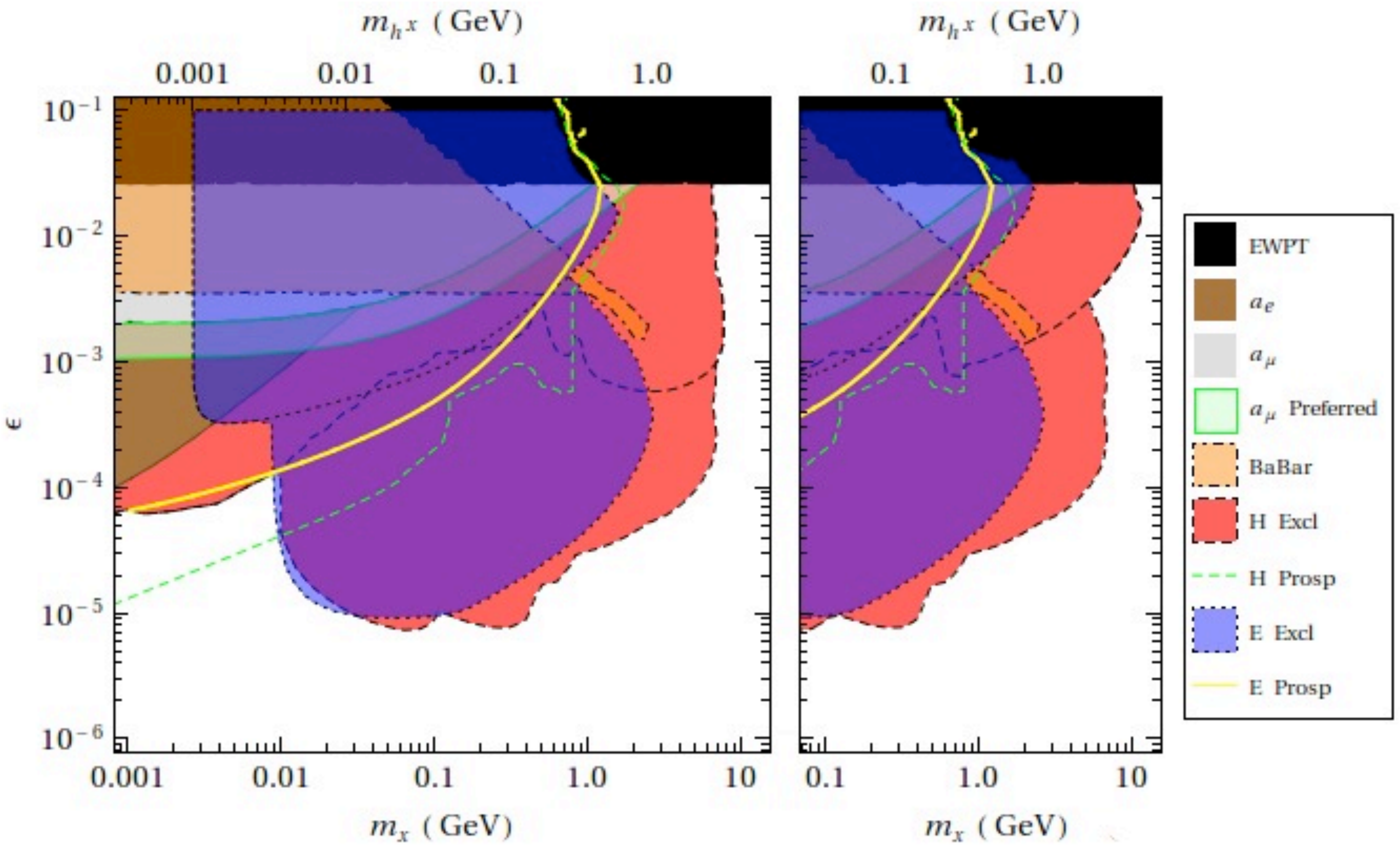
E Beam

H Beam

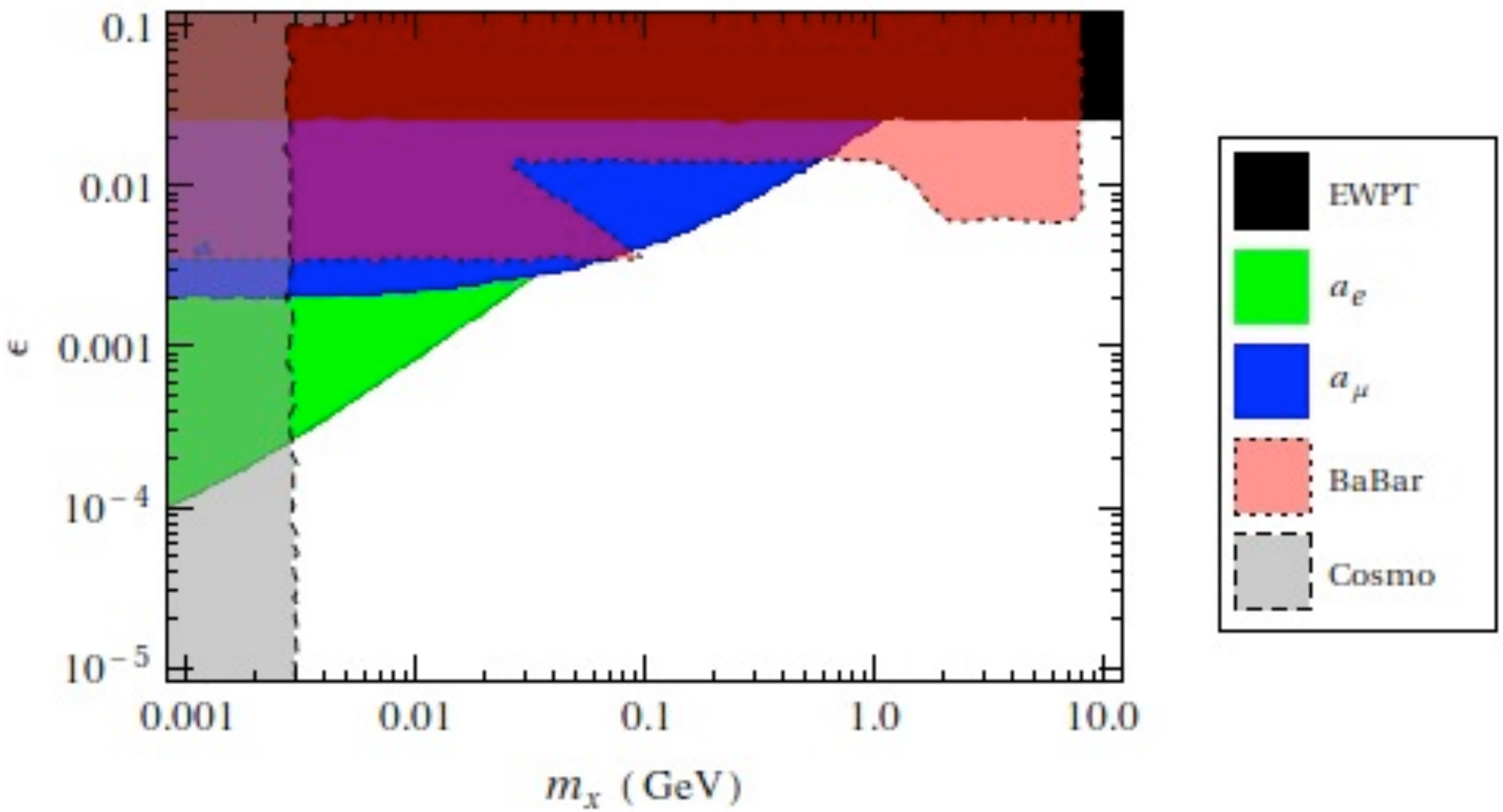
Case C - Precision and Meson Factories



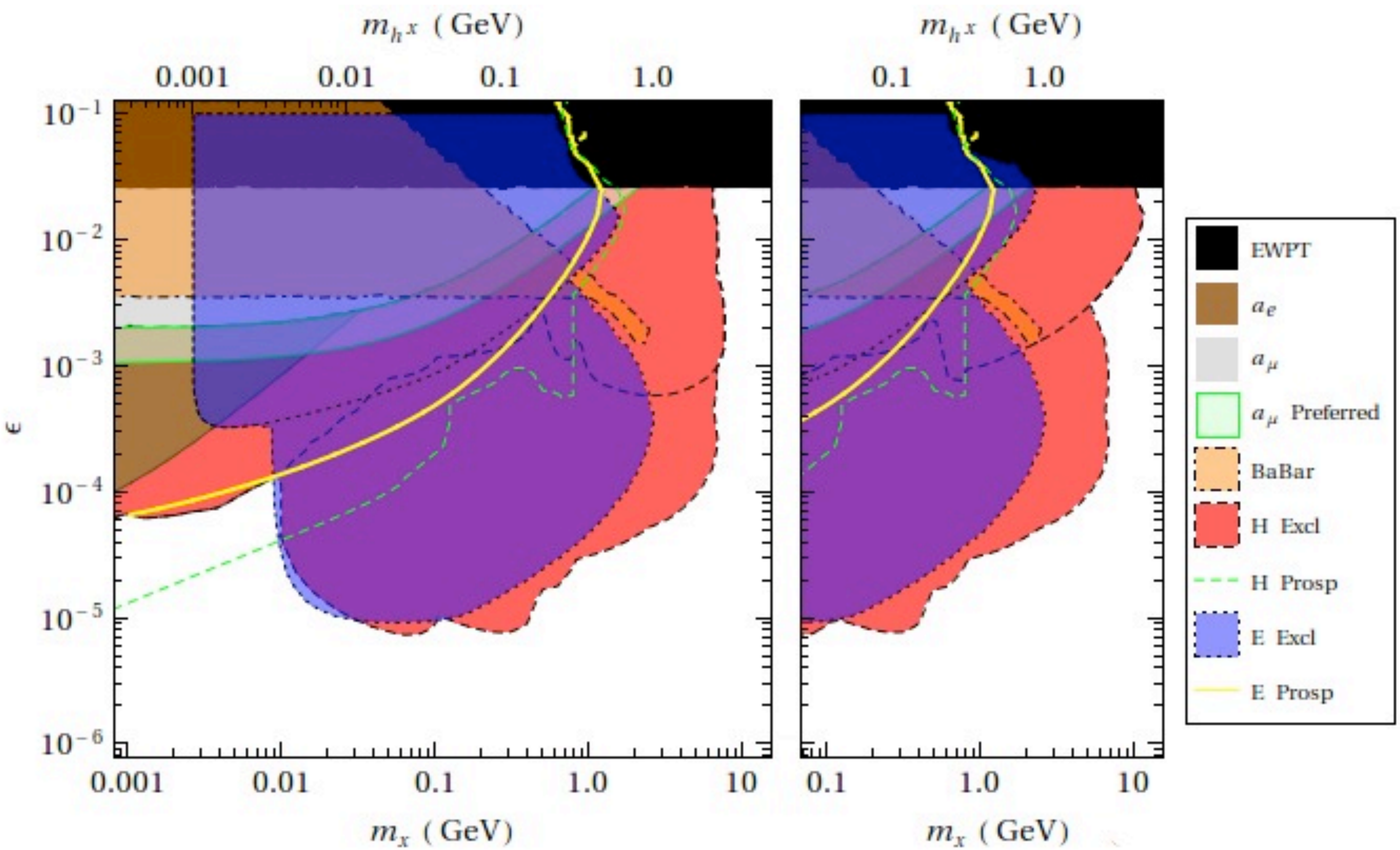
Case C - Summary



Case D - Precision and Meson Factories



Case D - Summary



Outline

- Very Brief Motivation
- Dark Vectors and Kinetic Mixing
- Case 1: Massive Dark Photon
- Case 1’: Massive Dark Z
- Case 2: Massless Dark Photon
- Dark Vector Friends
- Summary