Strongly Interacting Dark Sectors at Fixed Target Experiments

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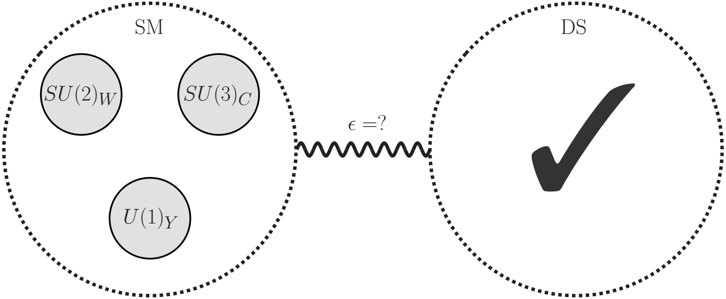
US Cosmic Visions, March 23, 2017

1704.xxxxx with Asher Berlin, Philip Schuster and Natalia Toro

with thanks to Takashi Maruyama

Dark Sectors

We know there is a Dark Sector



Does it couple to the the SM?

Dark Sectors

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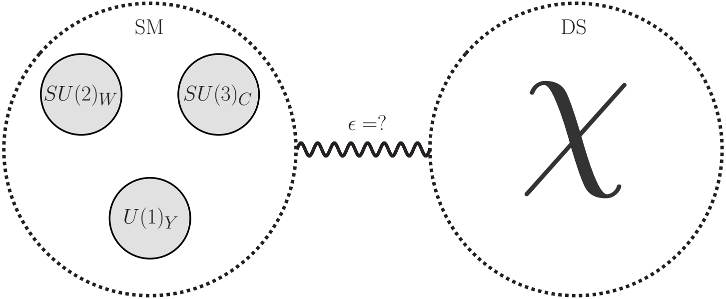

Does it couple to the the SM?

Dark Sectors

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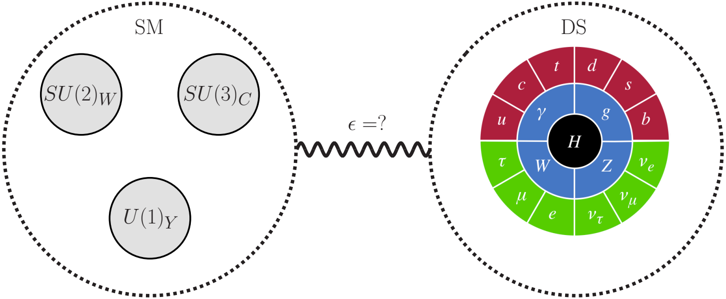


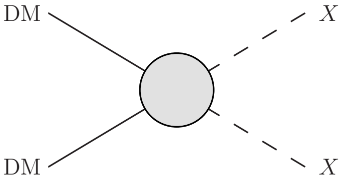
Does it couple to the the SM?

PC: Kyle Cranmer/Particle Fever

Dark Matter Depletion

Large initial density $n_{\rm dm} \sim T_{\rm RH}^3$ must be depleted

Annihilation ($2 \to 0$)

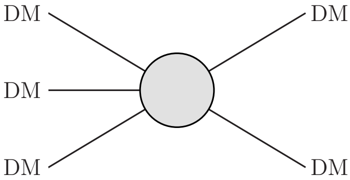


$X \in \mathrm{SM}$ or X talks to SM, otherwise new light d.o.f.

Dark Matter Depletion

Large initial density $n_{\rm dm} \sim T_{\rm RH}^3$ must be depleted

Cannibalization ($3 \to 2$, $n \to n - k$)



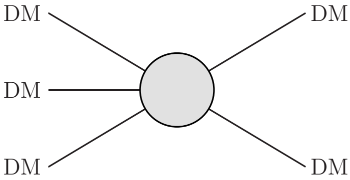
Carlson, Machacek and Hall (1992)

Kinetic equilibrium with SM required for viable cosmology

See Hochberg, Kuflik, Volansky and Wacker (2014) and talk by Maxim Perelstein!

Characteristic Scales

The reaction



freezes out when

$$n_{\rm dm}^2 \langle \sigma v^2 \rangle = H$$

Solving for $m_{\rm dm}$, we find for $\mathcal{O}(1)$ couplings

$$m_{\rm dm} \sim 0.1 \text{ GeV}$$

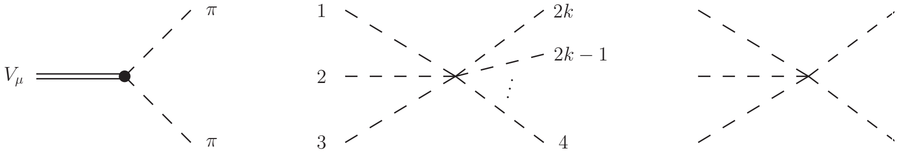
QCD-like Theories

Previous considerations realized in confining gauge theories.

$$G = SU(N_c) \times SU(N_f) \times SU(N_f)$$

Below confinement, this is a theory of mesons:

Pseudo-Nambu-Goldstones π **and** vector mesons V



Stable π make up the dark matter

Hochberg, Kuflik, Volansky and Wacker (2014), Hochberg, Kuflik and Murayama (2015)

Kinetic Equilibrium

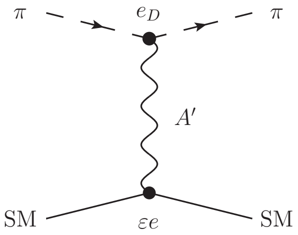
K.E. requires interactions active at low $T \Rightarrow U(1)_D$ dark photon a natural candidate

$$\mathscr{L} \supset -\frac{1}{2}\varepsilon F^{\mu\nu} F'_{\mu\nu}$$

A' couples to

- EM charges with strength εe
- $U(1)_D$ charges with strength e_D
- Neutral vector mesons via

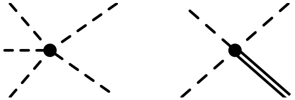
Kinetic equilibrium maintained by



Hochberg, Kuflik, Volansky and Wacker (2014), Hochberg, Kuflik and Murayama (2015)

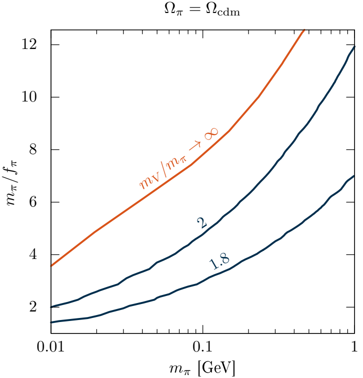
Dark Matter Production

Two processes determine abundance:



Rates depend on

1. m_π / f_π
2. m_V / m_π



Correct relic abundance requires $m_\pi / f_\pi \gtrsim$ few

Mass Spectrum

Vector mesons have masses close to the cutoff $m_V \sim 4\pi f_\pi$

$$\frac{m_V}{m_\pi} \sim \frac{1}{m_\pi/f_\pi}$$

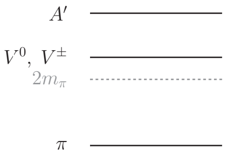
Harigaya and Nomura (2016), Georgi (1992)

Correct relic abundances $\Rightarrow m_\pi/f_\pi \gtrsim \text{ few } \Rightarrow m_V \lesssim 2m_\pi{}^*$

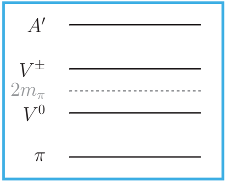
* up to quantum $U(1)_D$ corrections $\Rightarrow m_{V^\pm} > m_{V^0}$

If $m_V \lesssim 2m_\pi$, V decays to SM $\Rightarrow$ three types of mass spectra:

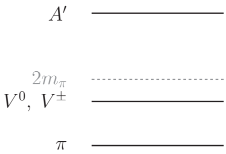
V **decay invisibly**



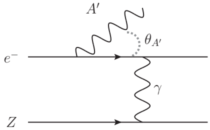
V^0 **vis.,** $V^\pm$ **inv.**



V **decay visibly**



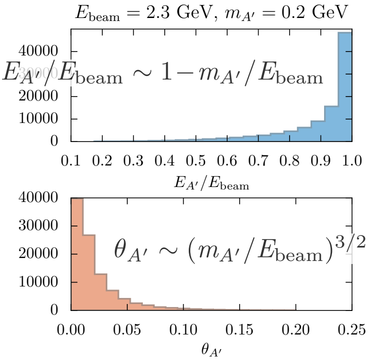
A' Production in a Fixed Target Collision



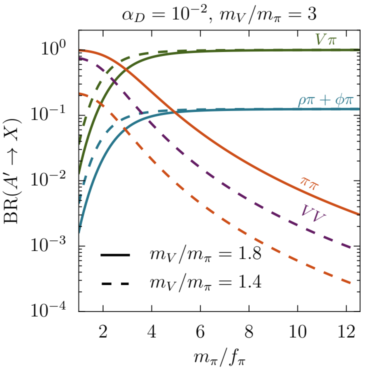
- $\sigma_{A'}$ largest for $m_{A'} \ll E_{\text{beam}}$
- A' carries away $\sim E_{\text{beam}}$

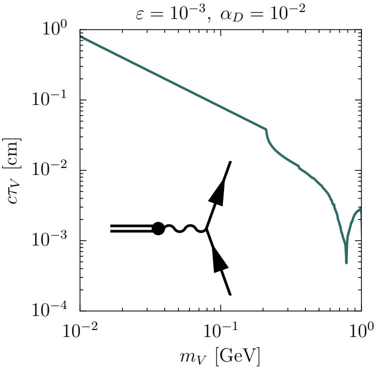
  Decay products boosted $\sim E_{\text{beam}}/m_{A'}$

- Emitted forward with $\theta_{A'} \ll 1$



Decay Modes and Lifetimes



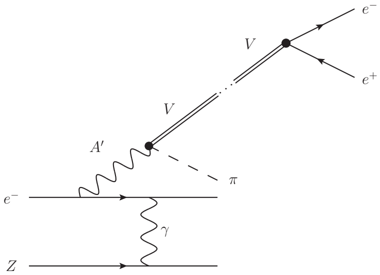


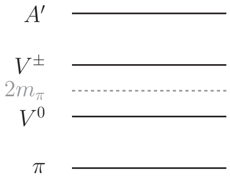
$A' \to V\pi$, $V \to \mathrm{SM}$ with $\mathcal{O}(10\%)$ branching fraction!

Vector mesons naturally long-lived

Signals at Fixed Target Experiments

Resonant e^+e^-



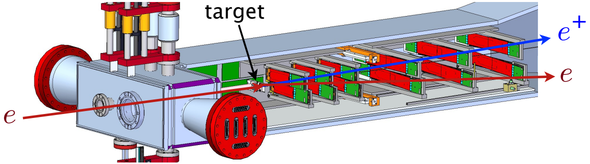


A' decays promptly, V gives displaced vertex

Can have DVs and large production rate

Heavy Photon Search

HPS looks for $A' \to e^+ e^-$ at JLab



Uemura (2013)

2016 data set:

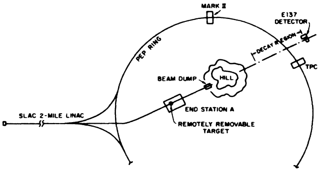
$$E_{\mathrm{beam}} = 2.3 \text{ GeV}, \ 4 \ \mu\text{m W target}, \ 10^{17} \text{ EOT} \Rightarrow \mathcal{L} \approx 0.01 \text{ fb}^{-1}$$

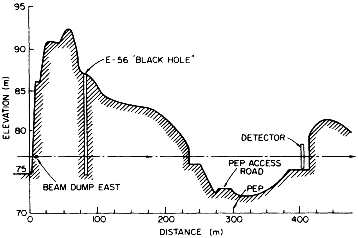
possible future run (~ 2018):

$$E_{\mathrm{beam}} = 6.6 \text{ GeV}, \ 8 \ \mu\text{m W target}, \ 10^{19} \text{ EOT} \Rightarrow \mathcal{L} \approx 0.3 \text{ fb}^{-1}$$

SLAC $E137$

- 20 GeV e^- beam on Al target w/ downstream ECAL
- 30 C (!) dumped $\Rightarrow \sim 10^{20}$ EOT
- ~ 200 m absorber, ~ 200 m decay region





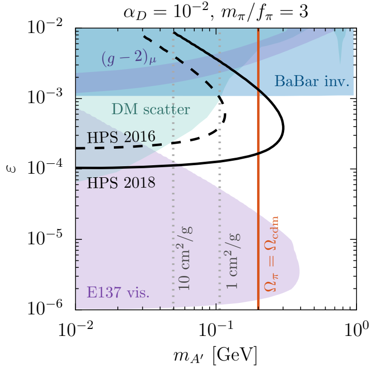
Bjorken et al (1988)

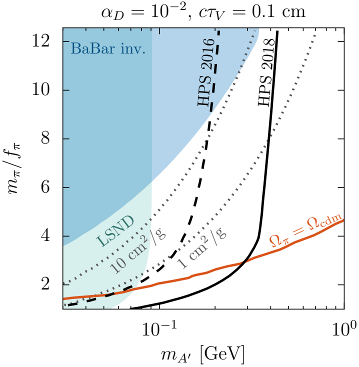
HPS Reach

100 DVs in $1 \text{ cm} < z < 8 \text{ cm}$ from target, assuming 100% efficiency

Acceptances are $\mathcal{O}(5\%)$ - thanks to Takashi Maruyama & Bradley Yale

$m_\pi : m_V : m_{A'} = 1 : 1.8 : 3,\ m_{V^\pm} > 2m_\pi$

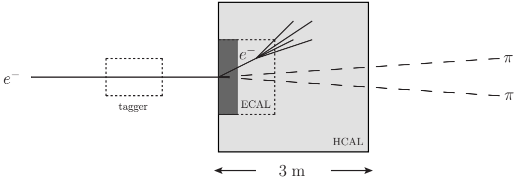




Future runs of HPS can probe cosmologically interesting models!

Future Experiments: LDMX

Invisible channels can be extremely powerful

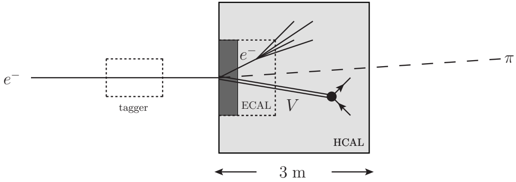


- Measure $p_e^{\rm in}$ and $p_e^{\rm out}$; signal: scattered e^- and nothing else $\Rightarrow \not{p}$
- Phase 1: $E = 4$ GeV, $4 \times 10^{14}\ e^-$, Phase 2: $E = 8$ GeV, $4 \times 10^{16}\ e^-$
- Timeline: > 2020 (see Dark Sectors 2016 report)

Izaguirre et al (2014), Dark Sectors 2016

Future Experiments: LDMX

Potential sensitivity to visible signal



- Significant MET + displaced EM shower

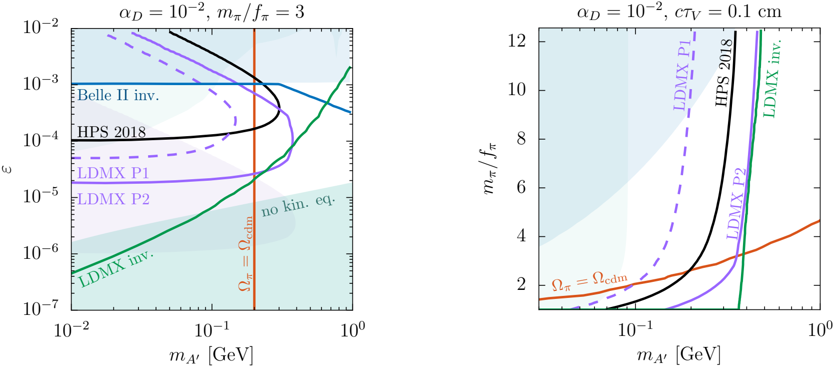
$$E_e^{\text{out}} < 0.3 E_{\text{beam}},$$

- Use large detector to range out background EM showers

DV $> 20X_0$ (7 cm in W) from target

Visible and Invisible Signals at LDMX

$$m_\pi : m_V : m_{A'} = 1 : 1.8 : 3,\ m_{V^\pm} > 2m_\pi$$



LDMX will test even more cosmologically interesting models!

Conclusion

- Strongly interacting dark sectors – another paradigm for thermal DM

  novel production mechanisms in early universe

- Unique signals at *current* and future fixed target experiments

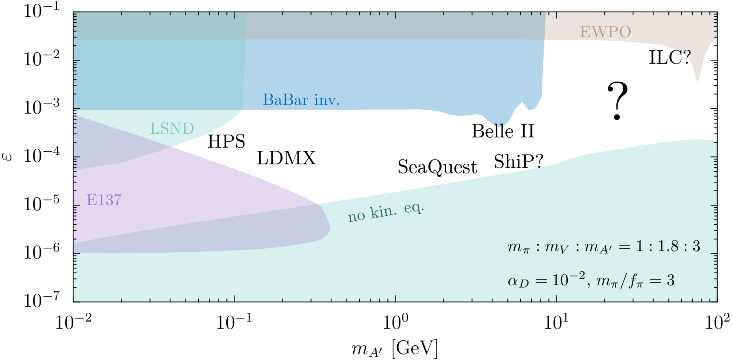
  displaced vertex + inv. mass peak

- Kinetic equilibrium implies minimum coupling to SM

  Is there a set of realistic experiments to decisively probe these scenarios?

Thank you!

Complementarity of Future Searches



Backup

Cannibalization (I)

If DS completely decoupled, $T \neq T'$ and

- Dark sector entropy *independently* conserved:

$$\frac{d(s' a^3)}{dt} = 0 \;\Rightarrow\; s' \propto a^{-3}$$

- DM is the lightest state and $3 \to 2$ in equilibrium:

$$n \sim (mT')^{3/2} e^{-m/T'},\; s' \approx \frac{mn}{T'}$$

- Solving for $T'(a)$:

$$T' \sim 1/\ln a^3$$

compare with $T' \sim 1/a$ when $s' \sim (T')^3$.

Carlson, Machacek and Hall (1992)

Cannibalization (II)

- While $3 \to 2$ active, energy density also drops slowly

$$\rho' = T's' \sim \frac{1}{a^3 \ln a}$$

compare with species in equilibrium with radiation: $\rho \propto \exp(-m/T)$.

- After freeze-out of $3 \to 2$ number density is conserved and

$$mn = T'_{\rm fo} s'_{\rm fo} \;\Rightarrow\; \Omega_{\rm dm} = \frac{T'_{\rm fo} s_0}{(s_{\rm fo}/s'_{\rm fo})\rho_c}$$

- Correct relic density then implies

$$T'_{\rm fo} \left(\frac{s'_{\rm fo}}{s_{\rm fo}}\right) \sim 10^{-10}\ {\rm GeV}$$

Carlson, Machacek and Hall (1992)

Not So Fast

$$T'_{\text{fo}}\left(\frac{s'_{\text{fo}}}{s_{\text{fo}}}\right) \sim 10^{-10}\ \text{GeV}$$

$T' \sim T \Rightarrow m \sim 1\text{eV}$

$T' \ll T$

Carlson, Machacek and Hall (1992)

Entropy conservation in DS $\Rightarrow$ DM is too light, does not have time to redshift

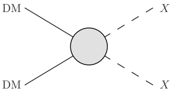
DM free-streaming length too long, small scale structure washed out

De Laix, Scherrer and Schaefer (1995)

Characteristic Scales in More Detail

$\rho_R = \rho_{\rm dm}$ at $T_{\rm eq} \approx 1$ eV $\Rightarrow n_{\rm dm} \sim T_{\rm eq} s/m$

Annihilation



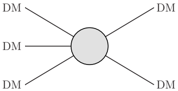
$$\langle \sigma v \rangle = \frac{\alpha_{\rm eff}^2}{m^2}$$

$$n\langle \sigma v \rangle = H \sim \frac{T_{\rm fo}^2}{M_{\rm Pl}}$$

For $\alpha_{\rm eff} \sim 10^{-1} - 10^{-2}$

$$m \sim \alpha_{\rm eff} \left(T_{\rm eq} M_{\rm Pl} \right)^{1/2} \lesssim {\rm TeV}$$

Cannibalization



$$\langle \sigma v^2 \rangle = \frac{\alpha_{\rm eff}^3}{m^5}$$

$$n^2\langle \sigma v^2 \rangle = H \sim \frac{T_{\rm fo}^2}{M_{\rm Pl}}$$

For $\alpha_{\rm eff} \sim 1$

$$m \sim \alpha_{\rm eff} \left(T_{\rm eq}^2 M_{\rm Pl} \right)^{1/3} \sim 0.1 \ {\rm GeV}$$

Anomalies and $3 \to 2$

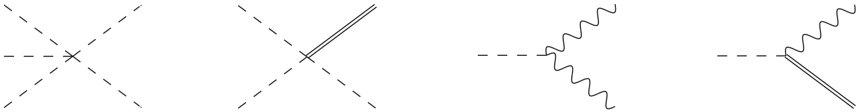
Chiral Lagrangian preserves "Bose" symmetry: $\pi(x) \to -\pi(x)$

Not a symmetry of the underlying theory!

Witten (1983)

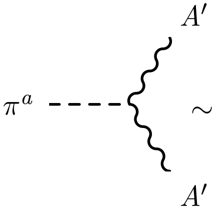
$$\mathscr{L}_{\mathrm{WZW}} \supset \frac{N_c}{240\pi^2 f_\pi^5} \epsilon^{\mu\nu\rho\sigma}\, \mathrm{Tr}(\pi\partial_\mu\pi\partial_\nu\pi\partial_\rho\pi\partial_\sigma\pi) + \ldots$$

Wess and Zumino (1971)



Anomalies and DM Stability

For general charge assignments neutral pions are unstable:



$$\sim \mathrm{Tr}(Q^2 T^a)$$

Stability during freeze-out $\Rightarrow$ choose $Q^2 \propto \mathbb{1}$

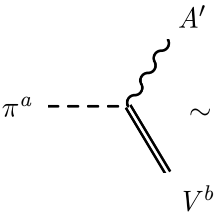
For example, for $N_f = 3$:

$$Q = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix}$$

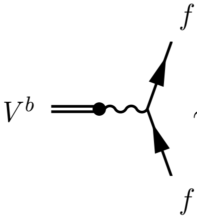
Hochberg, Kuflik and Murayama (2015)

Anomalies and DM Stability

Even with $Q^2 = \mathbb{1}$, still have



$\sim \mathrm{Tr}(QT^a T^b)$



$\sim \mathrm{Tr}(QT^b)$

Only π protected by a symmetry stable!

Dark Matter Production

$$\dot{n}_\pi + 3Hn_\pi = -\langle \sigma v^2 \rangle (n_\pi^3 - n_\pi^2 n_\pi^{\rm eq})$$

- Rate from anomaly

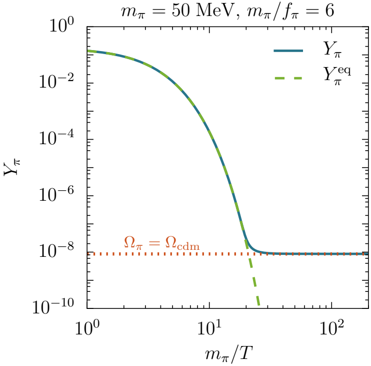
$$\langle \sigma v^2 \rangle = \frac{a(m_\pi/f_\pi)^{10}}{x^2 m_\pi^5},$$

$x = m_\pi/T$ and $a \sim 10^{-4}$

Hochberg et al (2014)

- Large coupling needed to compensate for a, n_π^2 in rate:

$$\Gamma_{3\to 2} = \langle \sigma v^2 \rangle n_\pi^2$$



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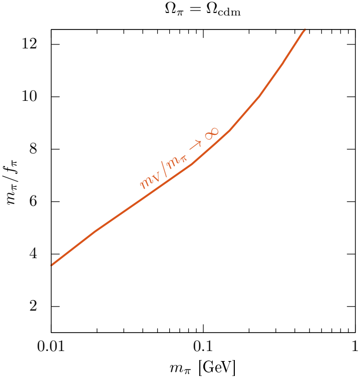
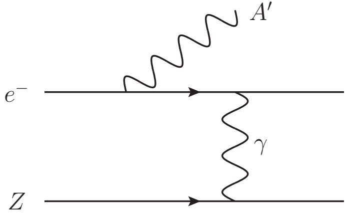
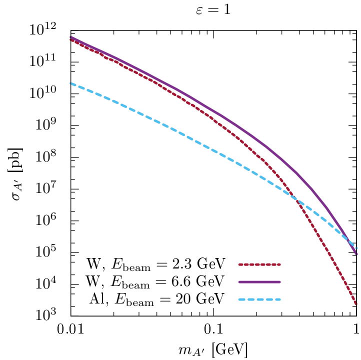


A' Production Cross-Section





Schematic Experimental Reach

Factors that determine signal yield:

1. Number of A' produced

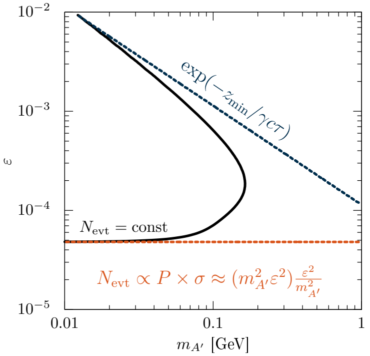
$$\sigma_{A'} \sim \frac{\epsilon^2 \alpha^3}{m_{A'}^2}$$

2. A' decays in detector volume

$$P \sim e^{-z_{\min}/\gamma c\tau}\left(1 - e^{-z_{\max}/\gamma c\tau}\right),$$

with decay length

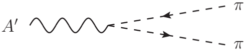
$$\gamma c\tau \sim (E_{\text{beam}}/m_{A'})(\epsilon^2 m_{A'})^{-1}$$

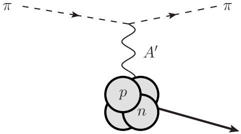


Some Existing Constraints

SIMPs constrained by DM scattering, colliders and astro:

- LSND, MiniBooNE, E137





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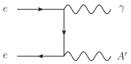


$\mathcal{L} = 53\ \text{fb}^{-1}$ mono-γ $\Rightarrow$ sensitivity to $\varepsilon \sim 10^{-3}$

Some Existing Constraints

SIMPs constrained by DM scattering, colliders and astro:

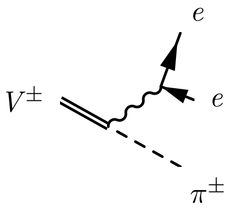
- LSND, MiniBooNE, E137
- BaBar: $e^+ e^- \to \gamma A'$, $A' \to \text{inv.}$
- Large self-scattering rates

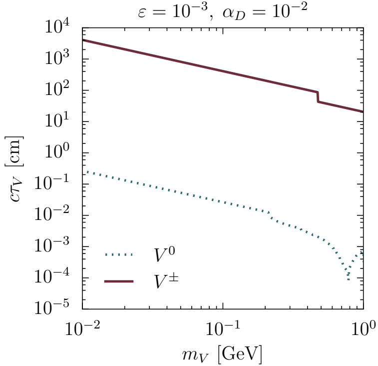
$$\sigma_{\text{scatt}} = \frac{(m_\pi / f_\pi)^4}{128 \pi m_\pi^2}$$

can aid small scale structure anomalies

Charged Vector Mesons

If $m_{V^\pm} < 2m_\pi$, $V^\pm$ decays introduce a second length scale

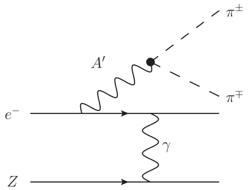




$V^\pm$ decay length $\sim 10^4$ times longer $\Rightarrow$ long-baseline experiments important

Resonant Signal at Fixed Target Experiments

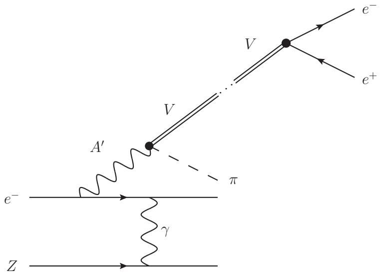
Invisible



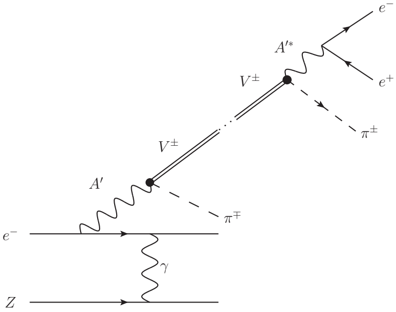
Missing mass/momentum, DM scattering in downstream detector

Resonant Signal at Fixed Target Experiments

Resonant e^+e^-



Non-resonant



A' decays promptly, V gives displaced vertex

Can have DVs and large production rate

$m_{V^0,\ V^\pm} < 2m_\pi$

For $\varepsilon \sim 10^{-3} - 10^{-4}$, $c\tau_{V^\pm}$ in perfect range for E137