Cosmology and Accelerator Tests of Strongly Interacting Dark Matter

ASHER BERLIN

New Probes for Physics Beyond the Standard Model, KITP,
April 9, 2018

collaboration with Nikita Blinov, Stefania Gori, Philip Schuster, & Natalia Toro

based on arXiv:1801.05805

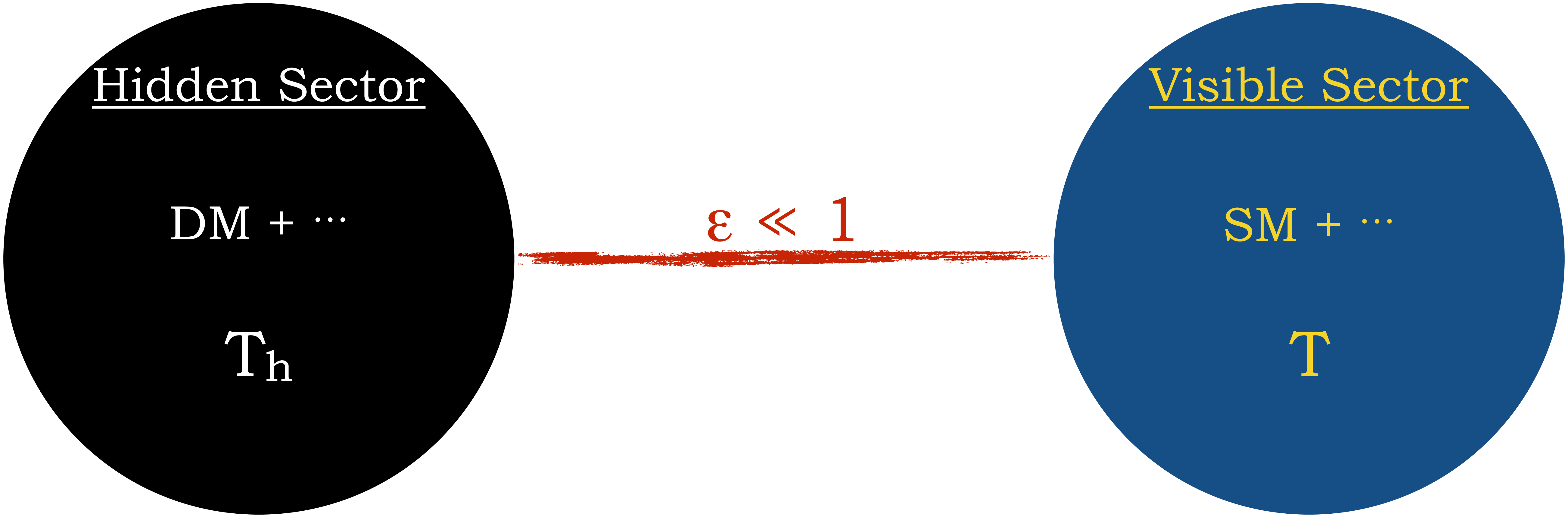
Outline

I. Review of Strongly Interacting Dark Matter

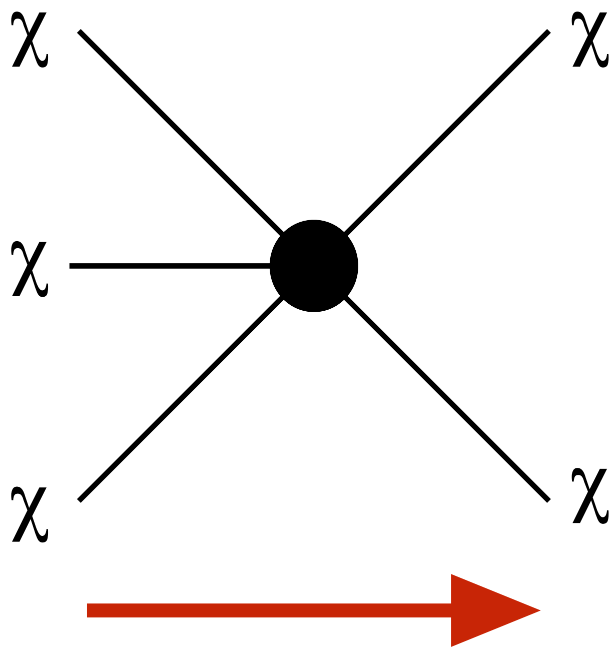
II. SIMP Cosmology

III. The GeV-Scale: Fixed-Target Experiments

Hidden Sector

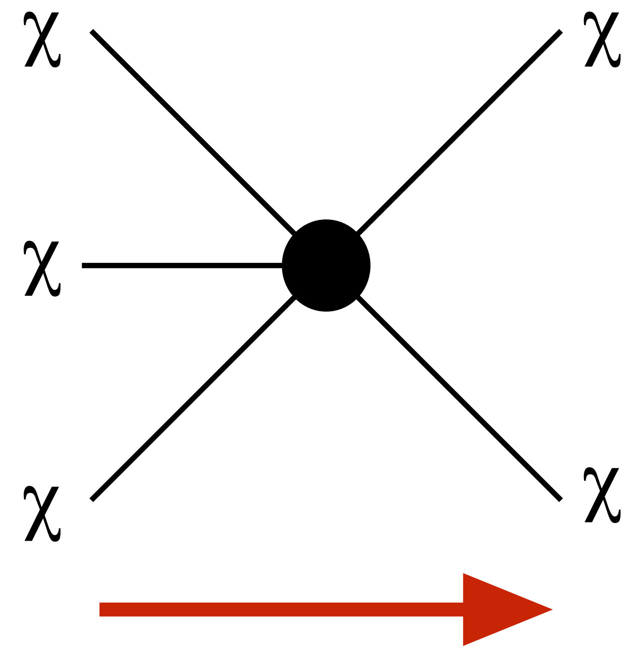


Kinetically Decoupled



Carlson, Machacek and Hall (1992)

Kinetically Decoupled



$$T_h < m_\chi \implies s_h \simeq \frac{\rho_\chi}{T_h} \simeq \frac{m_\chi n_\chi}{T_h} \propto e^{-m_\chi/T_h}$$

Carlson, Machacek and Hall (1992)

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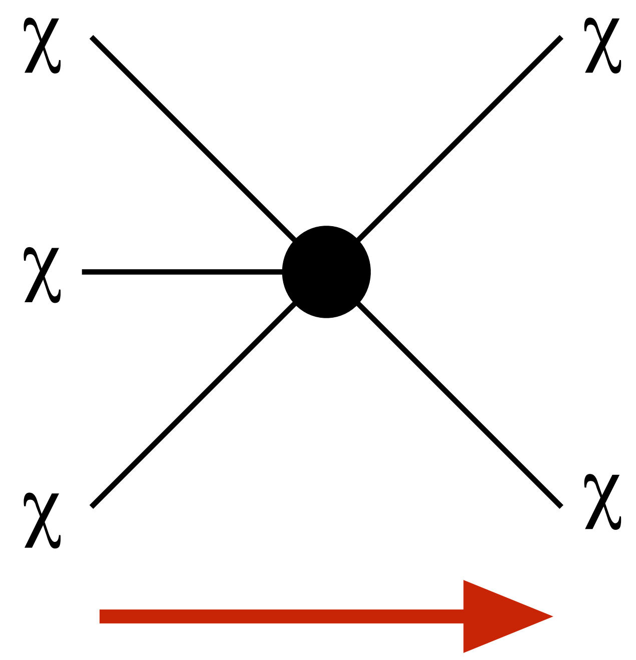

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$$S_h \propto e^{-m_\chi/T_h}\, a^3 \sim \text{constant} \implies T_h \sim \frac{m_\chi}{\log a}$$

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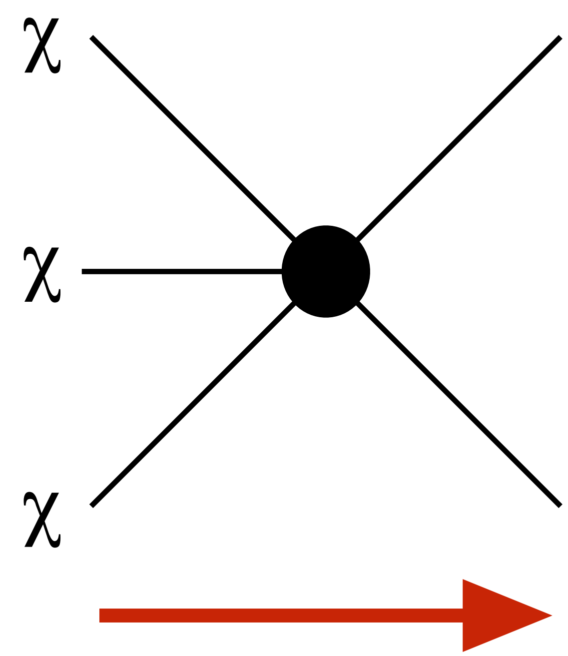

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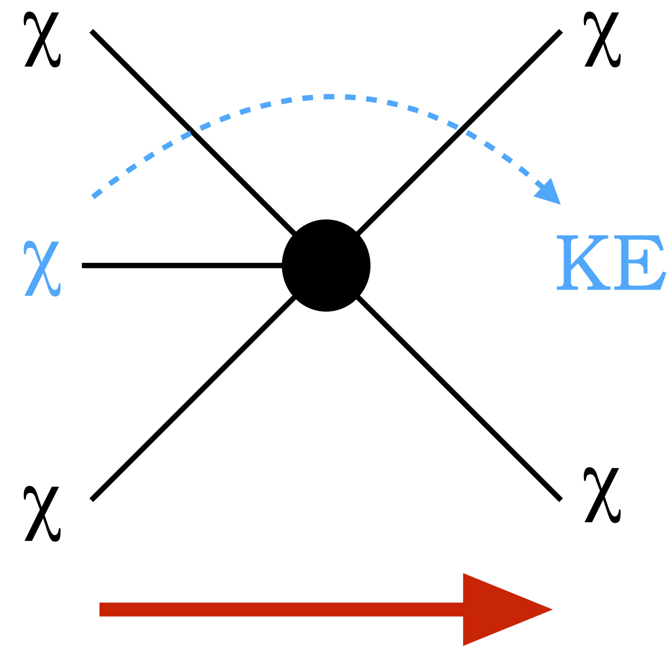
$$\rho_h \simeq s_h\, T_h \sim \frac{1}{a^3\ \log a} \gg \frac{1}{a^{3/2}\ e^a}$$ $\Rightarrow m_\chi \ll \text{keV}$ (warm)

Carlson, Machacek and Hall (1992)

Kinetically Decoupled



(Need to expel heat)

$$T_h < m_\chi \implies s_h \simeq \frac{\rho_\chi}{T_h} \simeq \frac{m_\chi n_\chi}{T_h} \propto e^{-m_\chi/T_h}$$

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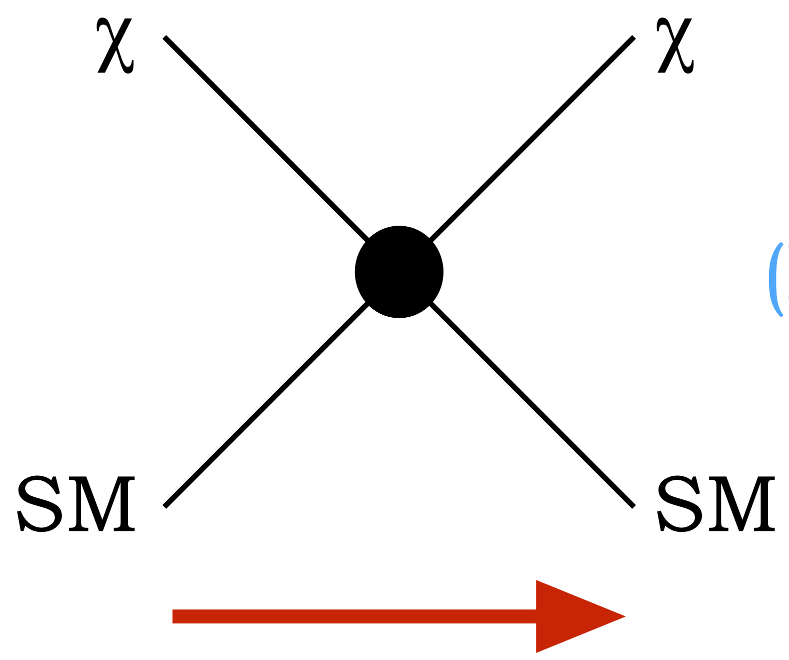
Carlson, Machacek and Hall (1992)

Kinetically Coupled

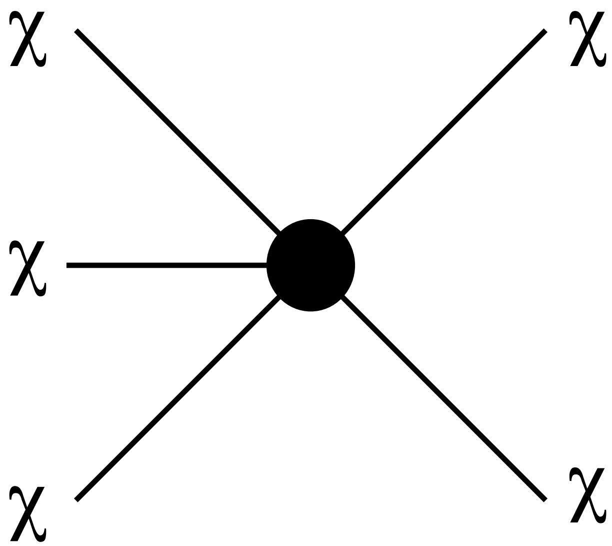


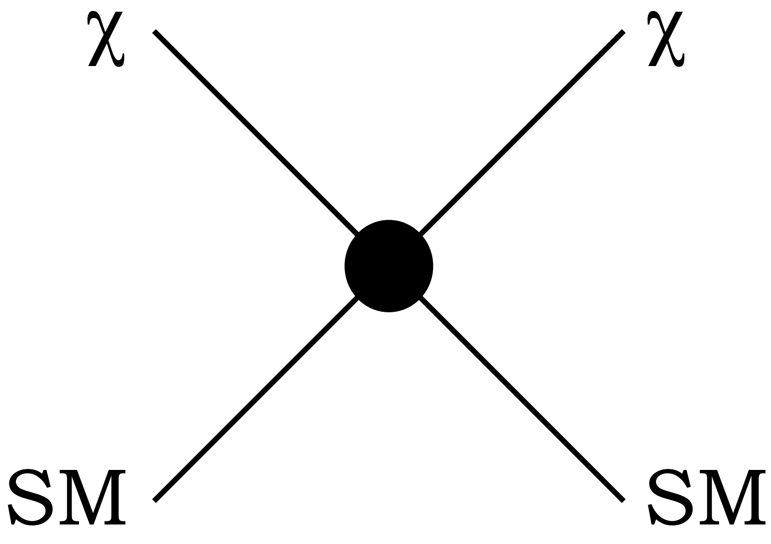
(heat dumped into SM)

$$T_h = T$$

Carlson, Machacek and Hall (1992)

The SIMP Miracle

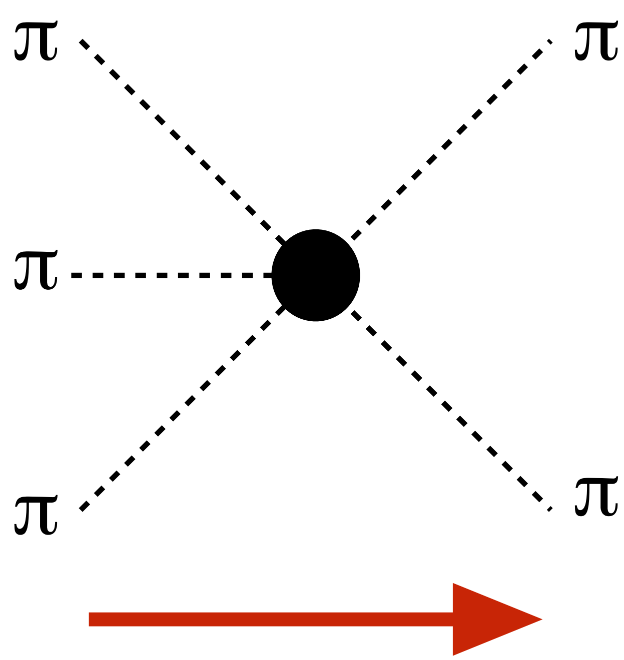




$$m_\chi \sim \alpha_\chi \left(T_{\rm eq}^2 m_{\rm pl}\right)^{1/3} \sim \alpha_\chi \times 1\ \mathrm{GeV}$$

Hochberg, Kuflik, Volansky, Wacker
arXiv:1402.5143

The SIMP Miracle



(π = Dark Matter)

$$m_\pi \sim \alpha_\chi \ \left(T_{\rm eq}^2 m_{\rm pl}\right)^{1/3} \sim \alpha_\chi \times 1 \ \mathrm{GeV}$$

A Theory of Pions

$$SU(N_c) \text{ confines at } \Lambda \implies SU(N_f)_L \times SU(N_f)_R \to SU(N_f)_{L+R} \implies N_f^2 - 1 \text{ pions, } \pi^a\, T^a$$

A Theory of Pions

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$$\frac{2\,N_c}{15\pi^2\,f_\pi^5}\;\epsilon^{\mu\nu\rho\sigma}\;\mathrm{Tr}\left[\pi\partial_\mu\pi\partial_\nu\pi\partial_\rho\pi\partial_\sigma\pi\right]$$

(Wess-Zumino-Witten)

A Theory of Pions

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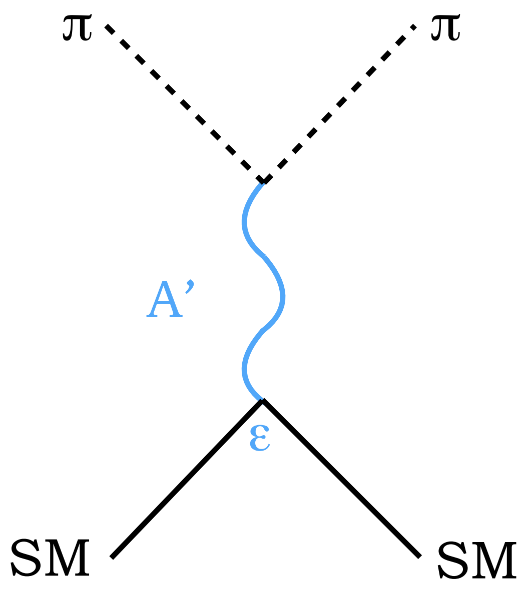
(Wess-Zumino-Witten)

$$\boxed{\Gamma(3 \to 2) = n_\pi^2\,\langle \sigma v^2 \rangle\ ,\ \langle \sigma v^2 \rangle \sim \left(\frac{m_\pi}{f_\pi}\right)^{10}\frac{1}{m_\pi^5}}$$

$N_f = 3$ (minimum for pion number changing processes)

+ Dark Photons

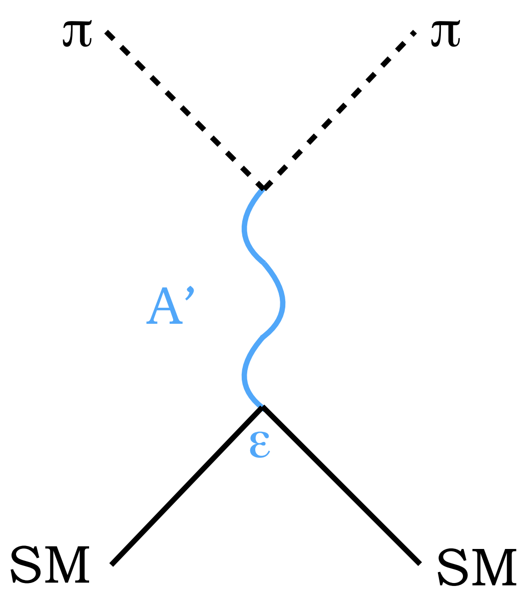


(ε ≪ 1)

$$\frac{\epsilon}{2\,\cos\theta_W}\;A'_{\mu\nu}\,B^{\mu\nu}$$

(Kinetic mixing)

+ Dark Photons



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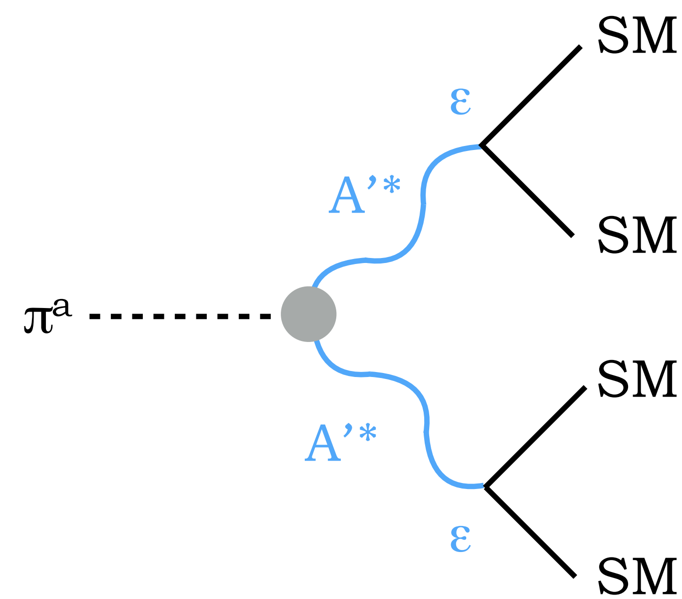
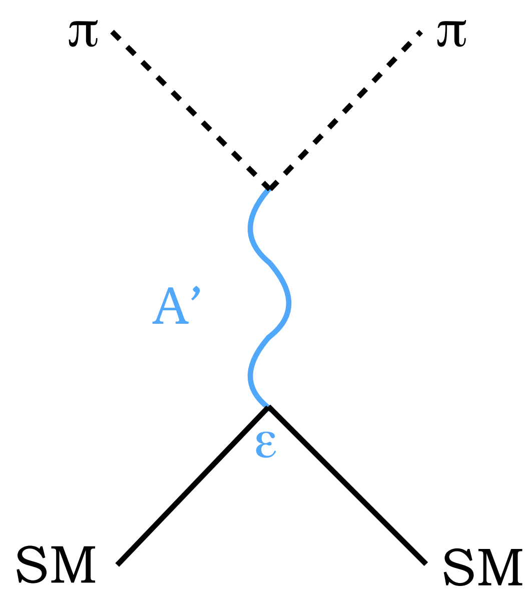


$$i\mathcal{M} \sim \epsilon^2\;\mathrm{Tr}\left[Q^2\,T^a\right]$$

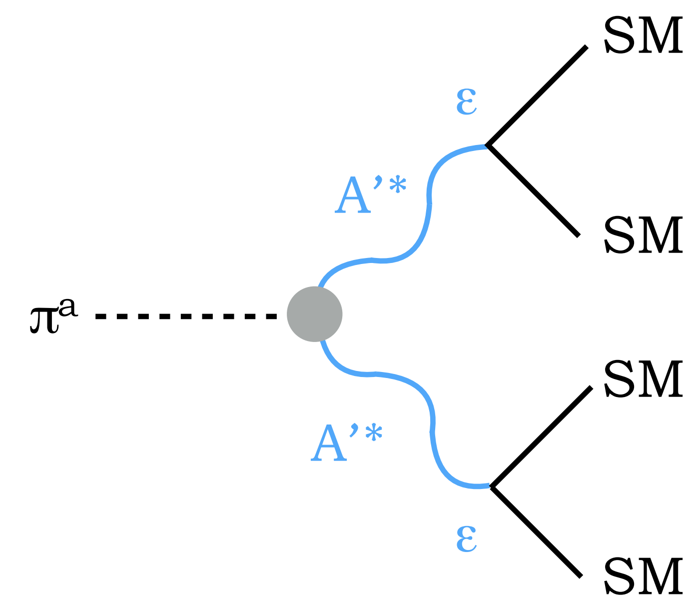
+ Dark Photons



$(\varepsilon \ll 1)$

$$\frac{\epsilon}{2\,\cos\theta_W}\;A'_{\mu\nu}\,B^{\mu\nu}$$

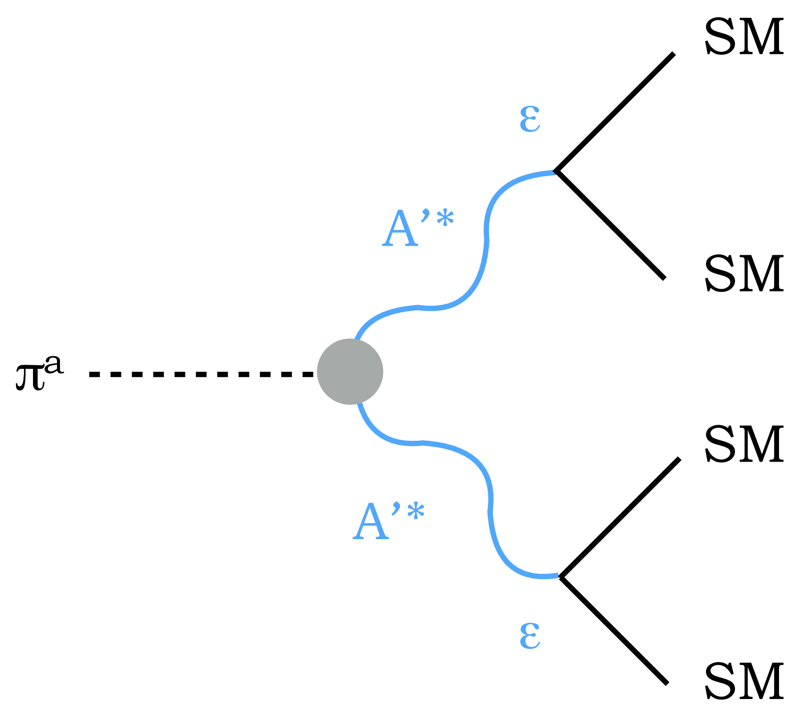
(Kinetic mixing)



$$i\mathcal{M} \sim \epsilon^2\ \mathrm{Tr}\left[Q^2\,T^a\right] \quad \sim 0$$

$$Q = \begin{pmatrix} \overbrace{+1 & & }^{N_1} & & & \\ & \ddots & & & & \\ & & +1 & & & \\ & & & \overbrace{-1 & & }^{N_2} \\ & & & & \ddots & \\ & & & & & -1 \end{pmatrix}$$

Decay



chiral limit $\Rightarrow$ $i\mathcal{M} \sim \epsilon^2 \ \mathrm{Tr}\left[Q^2\, T^a\right]$

$\Gamma_\pi > H_f \implies$ sink for entire DM abundance

$\Gamma_\pi < H_f \implies$ potential issues with BBN + CMB

Effective Field Theory $\Rightarrow$ nothing preventing decay $\Rightarrow$ will decay

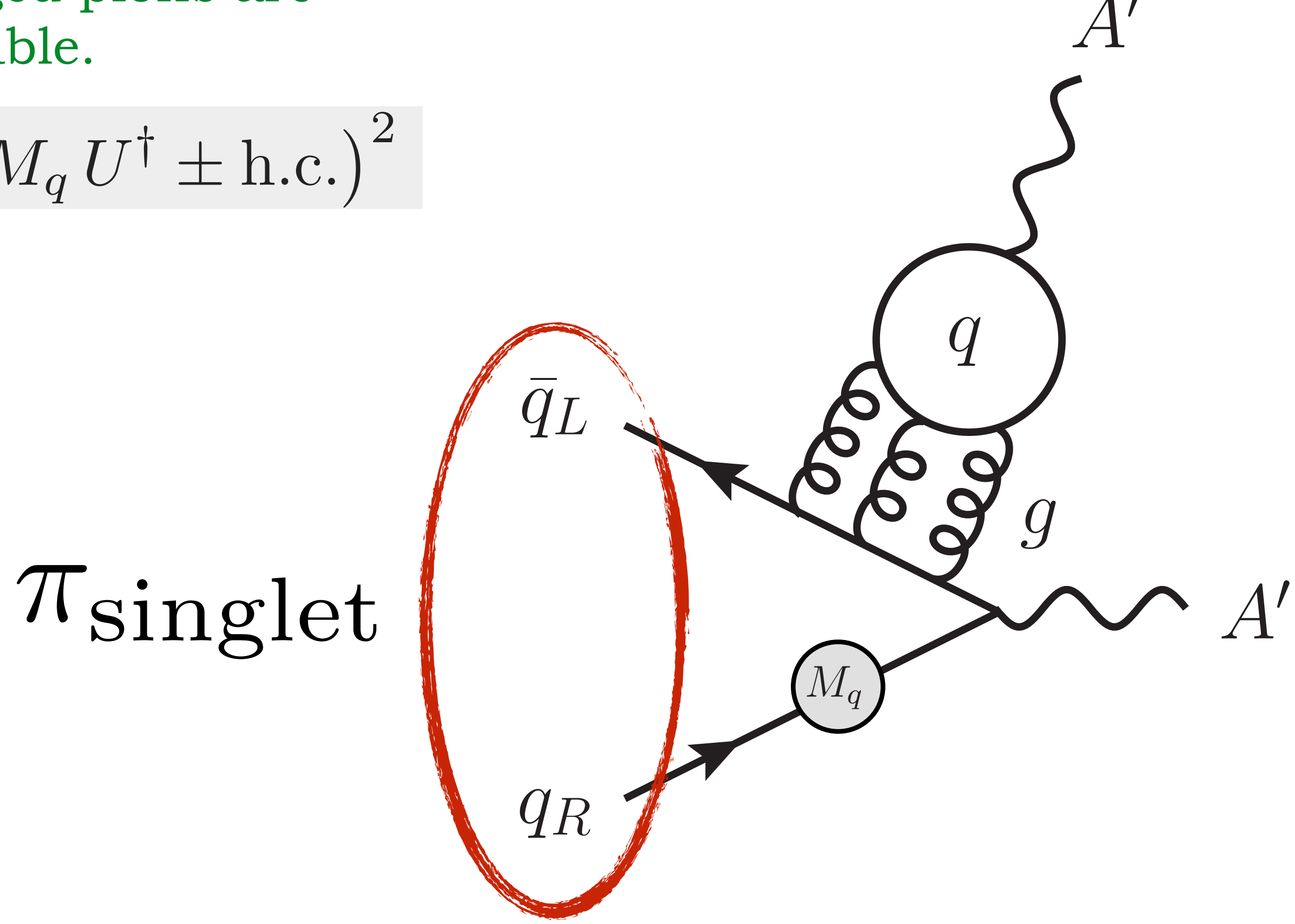
Decay

Can potentially depopulate through 2→2 scattering. U(1)D charged pions are stable.

$$\alpha_{6,7}\, B_0^2 \, \left(\mathrm{Tr}\, M_q\, U^\dagger \pm \mathrm{h.c.}\right)^2$$

Stabilize for even flavors

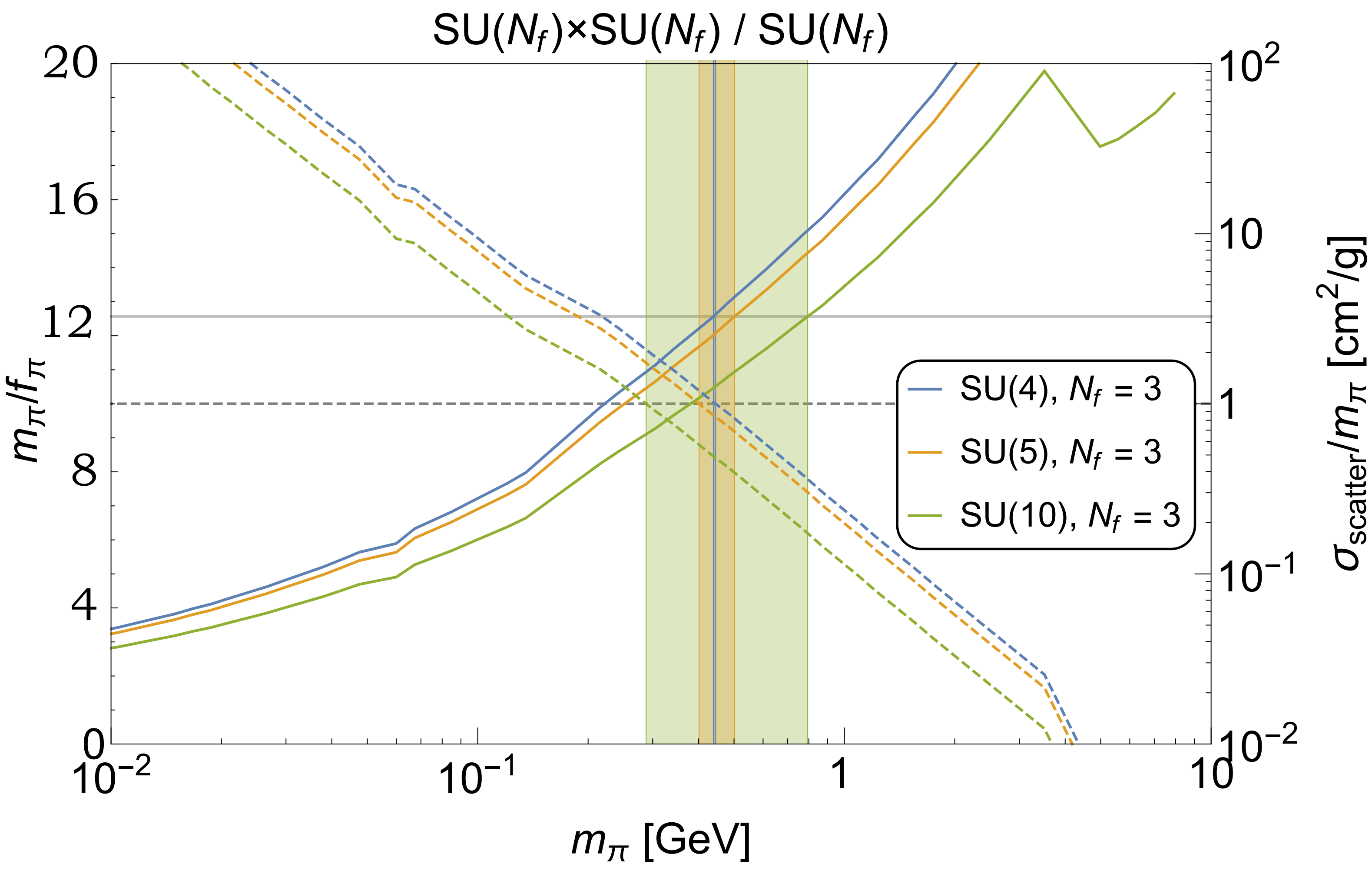
$$G \equiv C \times \mathbb{Z}_2^{A'} \times U_q$$



$$\frac{\alpha_D}{4\pi f_\pi}\, i\, \epsilon^{\mu\nu\alpha\beta}\, A'_{\mu\nu}\, A'_{\alpha\beta}\; \mathrm{Tr}\, Q\;\, \mathrm{Tr}\left(Q\, M_q\, U^\dagger\right) + \mathrm{h.c.}$$

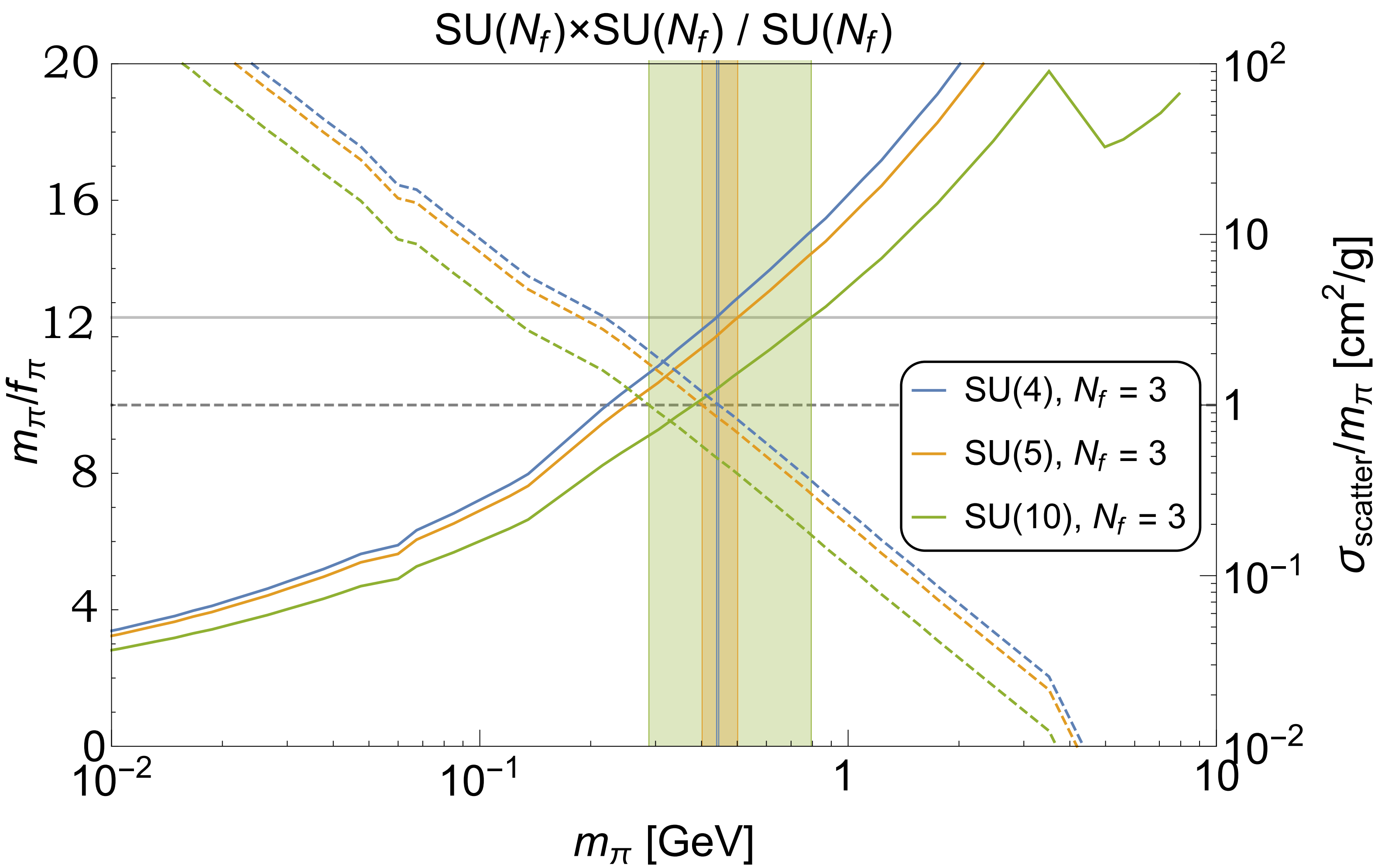
Berlin, Blinov, Gori, Schuster, Toro
arXiv:1801.05805

The SIMP Miracle



Hochberg, Kuflik, Murayama, Volansky, Wacker
arXiv: 1411.3727

The SIMP Miracle



$m_\pi/f_\pi \gg 1 \Rightarrow$ vector mesons nearby in mass

$m_V \sim 4\pi f_\pi / N_c^{1/2}$

Hochberg, Kuflik, Murayama, Volansky, Wacker
arXiv: 1411.3727

Outline

I. Review of Strongly Interacting Dark Matter

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III. The GeV-Scale: Fixed-Target Experiments

Mass Spectrum

A’

~ GeV

Prevent
$\pi\,\pi \rightarrow A'\ A'$
(CMB)

$2\,m_\pi$

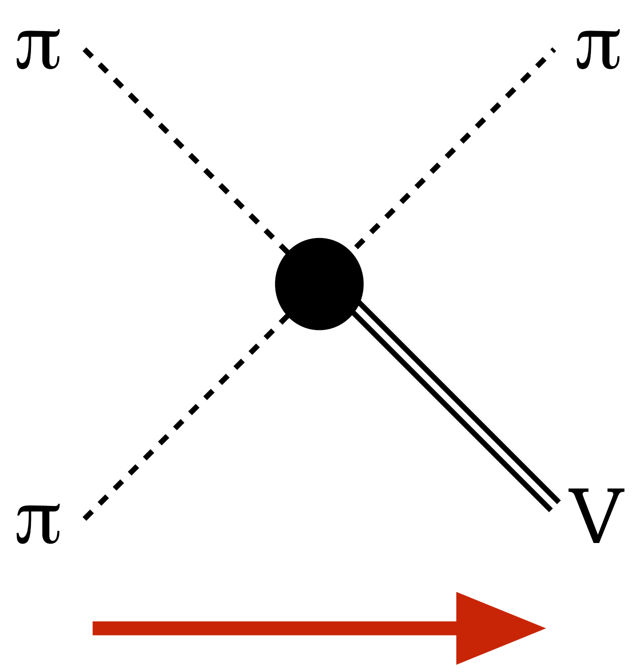
Vector Mesons, V

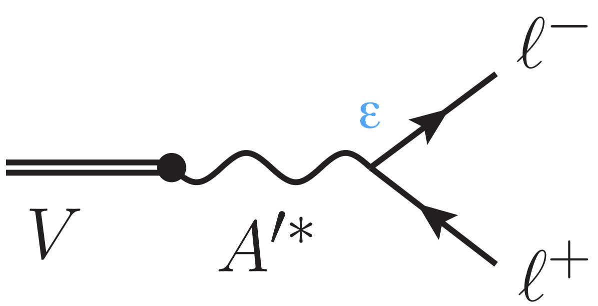
Pions, π

$m_\pi / f_\pi \gtrsim 3$

Forbidden Semi-Annihilation

Forbidden Semi-Annihilation





$m_V < 2\, m_\pi$

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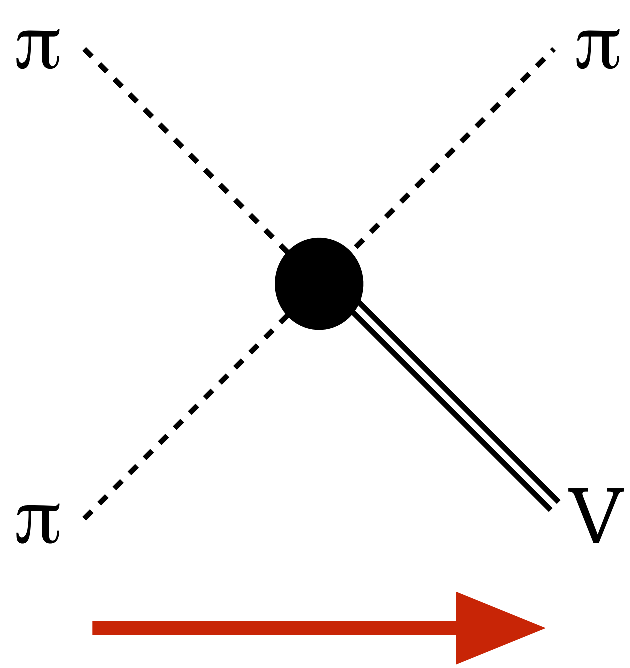
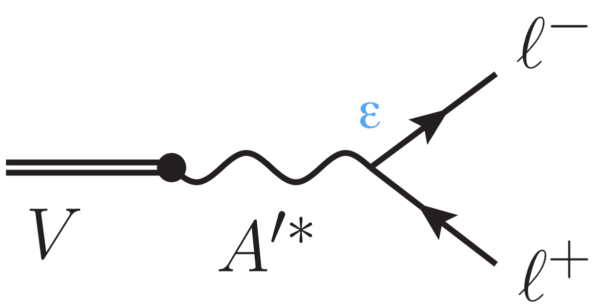
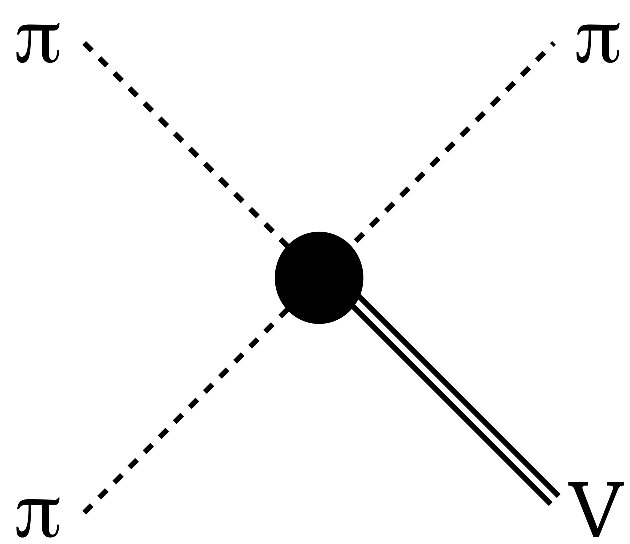


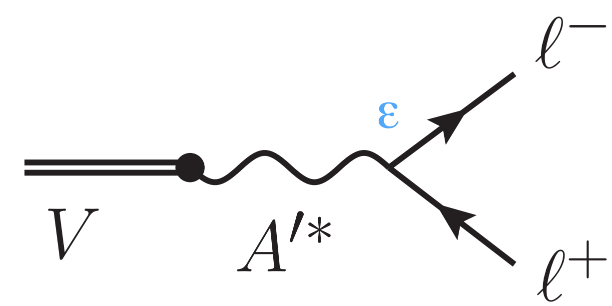


$m_V < 2\, m_\pi$

$$\langle \sigma v \rangle \sim \frac{e^{-(m_V - m_\pi)/T}}{m_\pi^2} \gtrsim \frac{e^{-m_\pi/T}}{m_\pi^2}$$

Forbidden Semi-Annihilation





$m_V < 2\ m_\pi$

(3 → 2)

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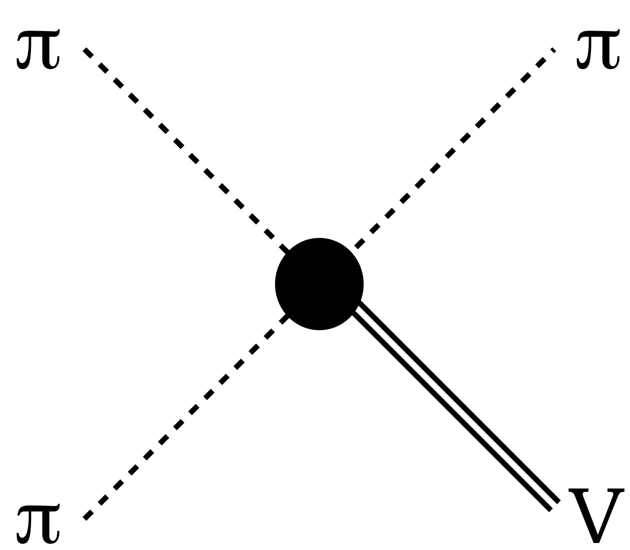

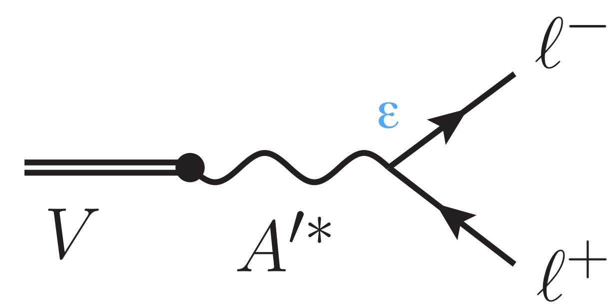

$m_V < 2\, m_\pi$

$(3 \to 2)$

$$\langle \sigma v \rangle \sim \frac{e^{-(m_V - m_\pi)/T}}{m_\pi^2} \gtrsim \frac{e^{-m_\pi/T}}{m_\pi^2}$$

$m_V \sim 4\pi f_\pi \Rightarrow m_V / m_\pi \sim 4\pi / (m_\pi / f_\pi)$

$$\frac{m_\pi}{f_\pi} \sim 3 \left(1 + 0.1 \log \frac{m_\pi}{10\ \mathrm{MeV}}\right)$$

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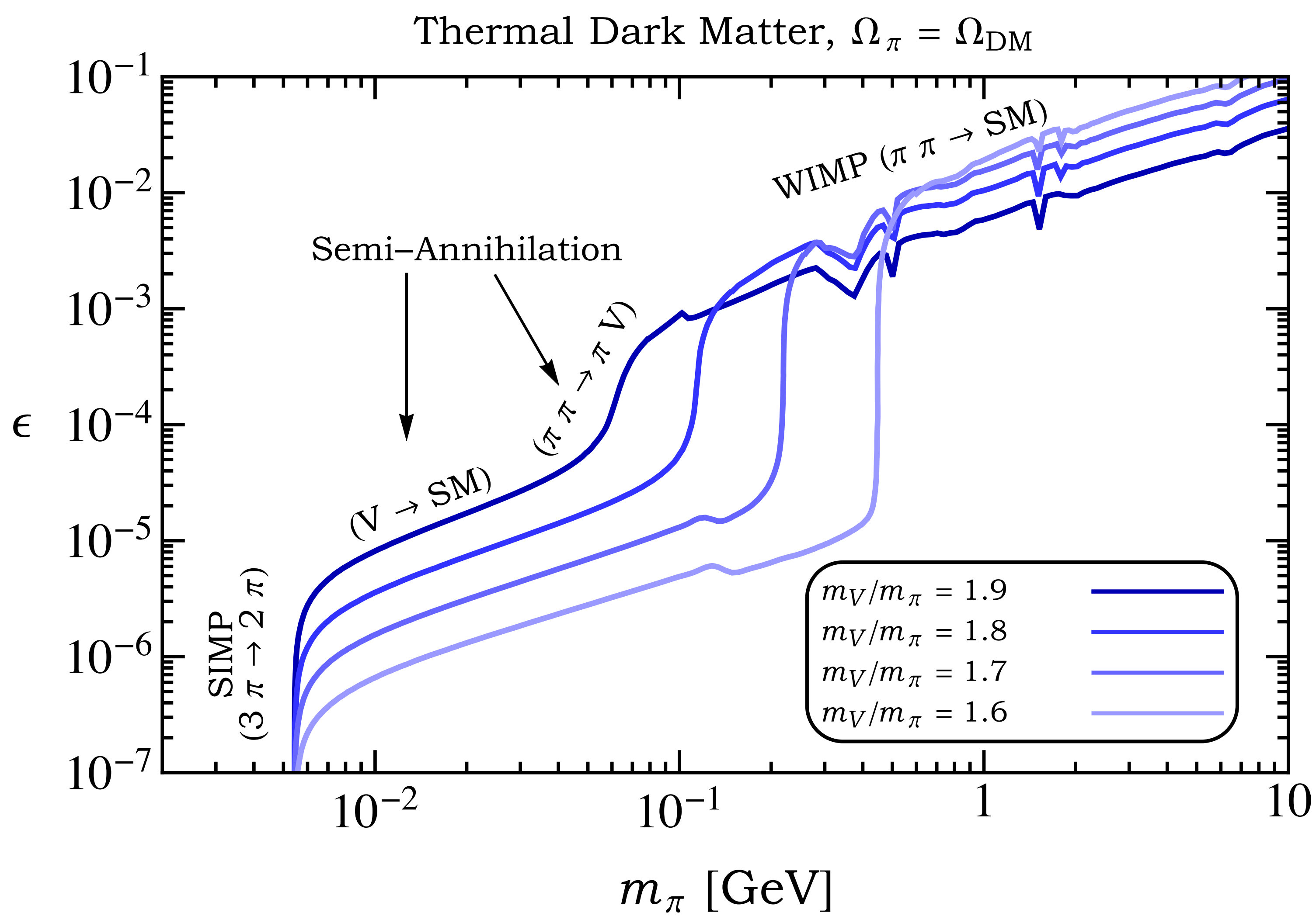

m_π / f_π = 3

$m_{A'}$ / m_π = 3

Berlin, Blinov, Gori, Schuster, Toro
arXiv:1801.05805

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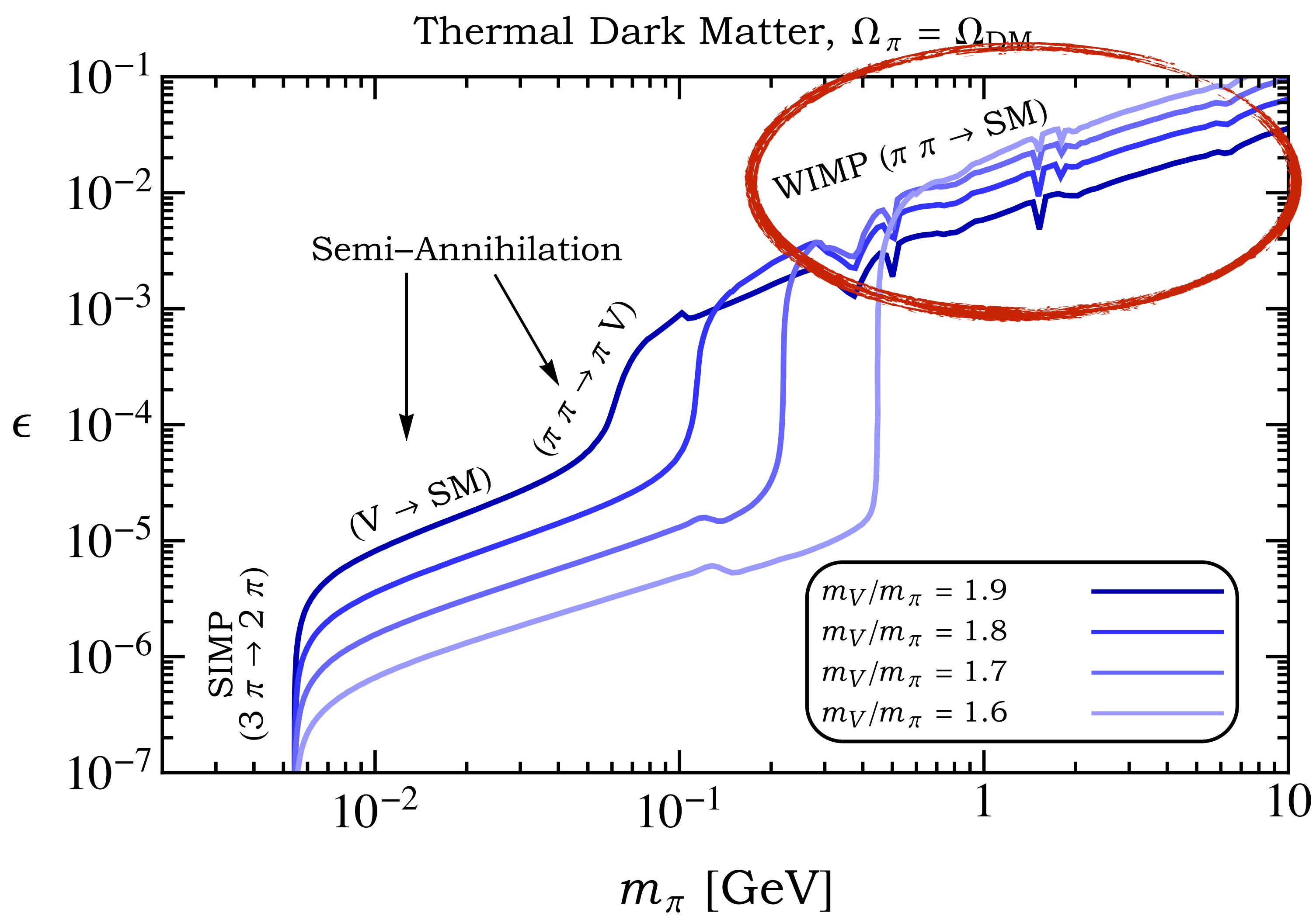
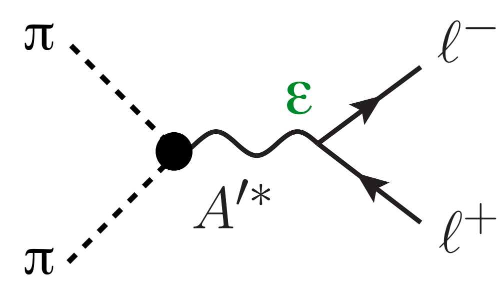


m_π / f_π = 3

$m_{A'}$ / m_π = 3

controlling rate:



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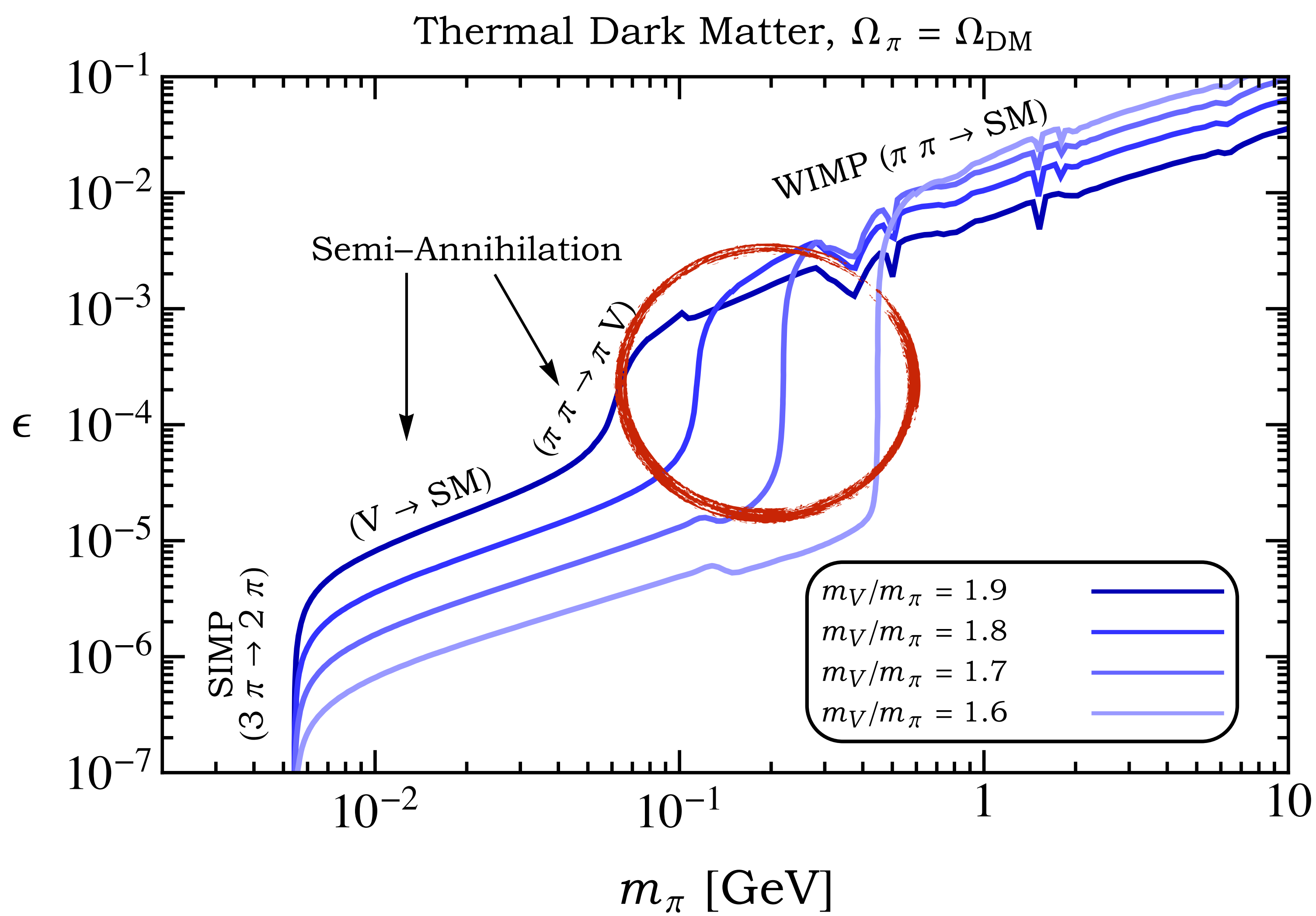
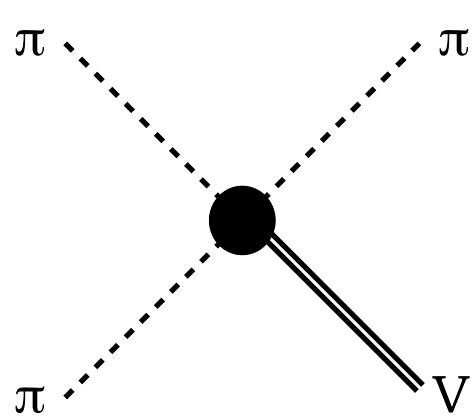


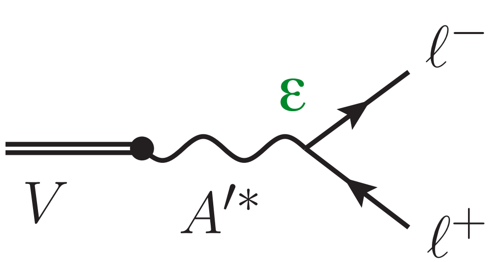
$m_\pi \,/\, f_\pi = 3$

$m_{A'} \,/\, m_\pi = 3$

controlling rate:



$\ll$



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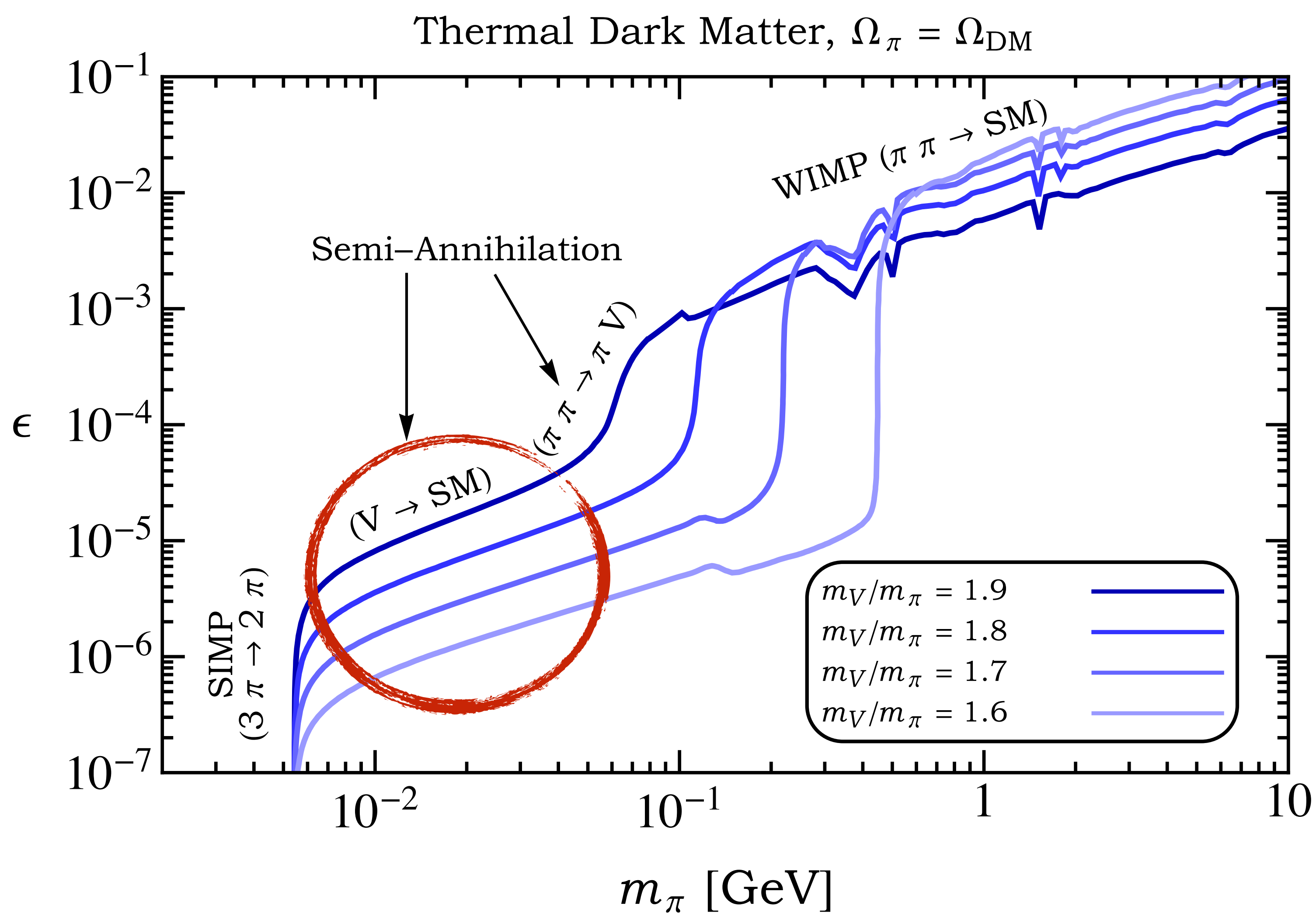
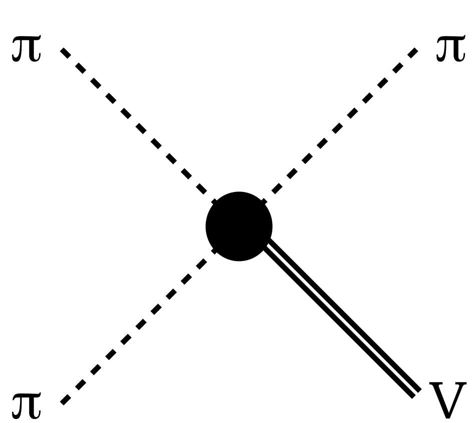


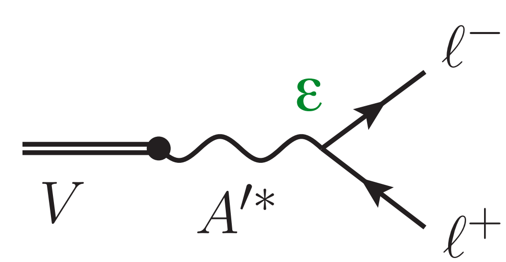
m_π / f_π = 3

$m_{A'}$ / m_π = 3

controlling rate:



$\gg$



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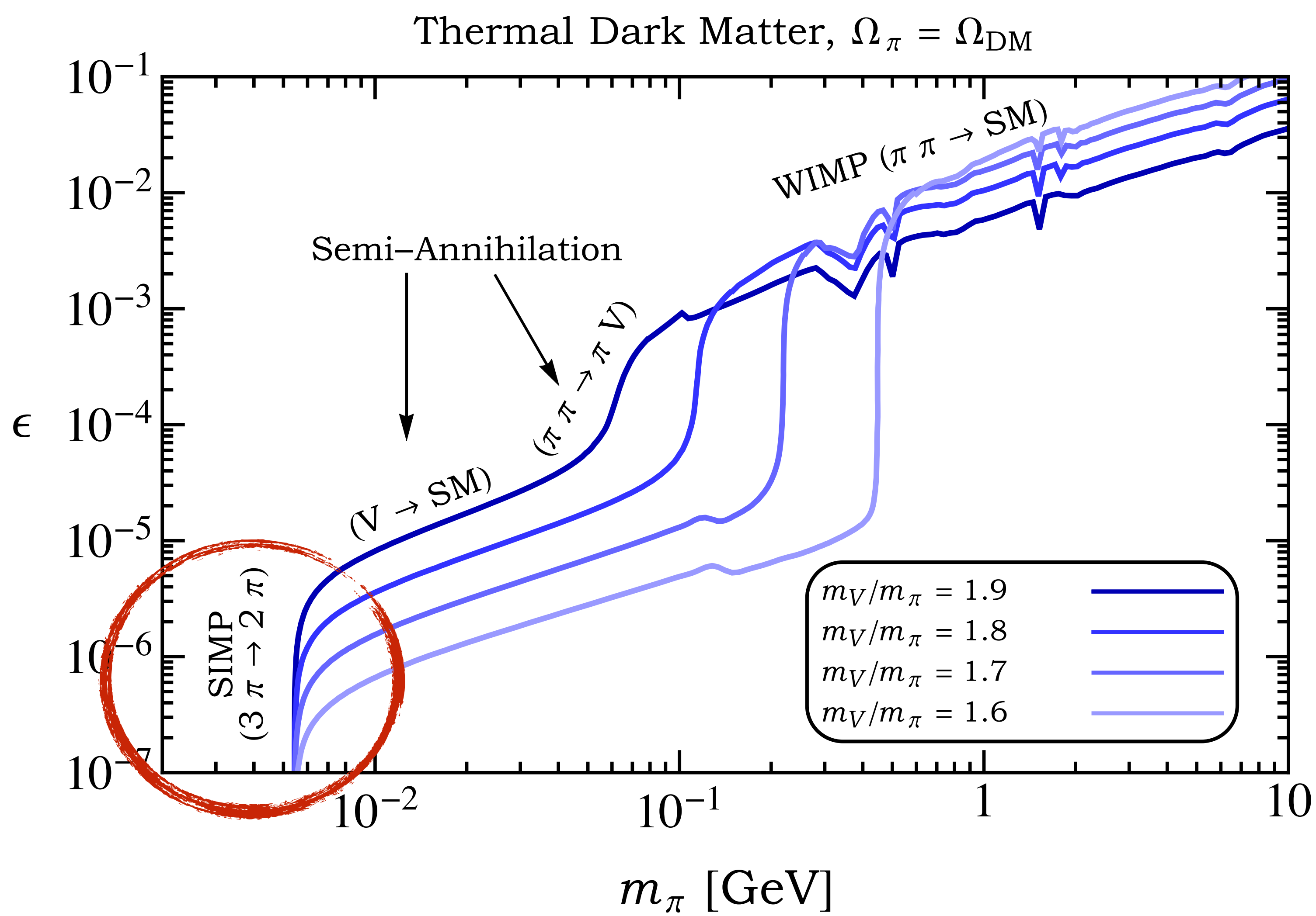
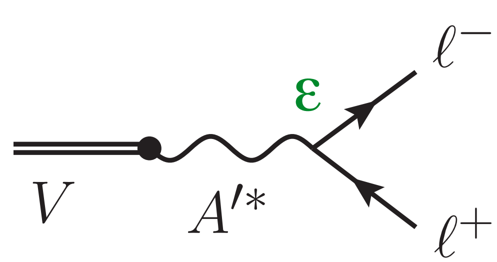


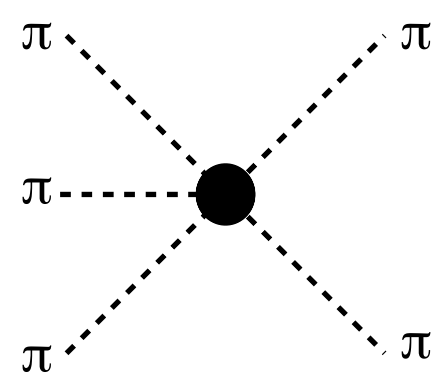
m_π / f_π = 3

$m_{A'}$ / m_π = 3

controlling rate:



$\ll$



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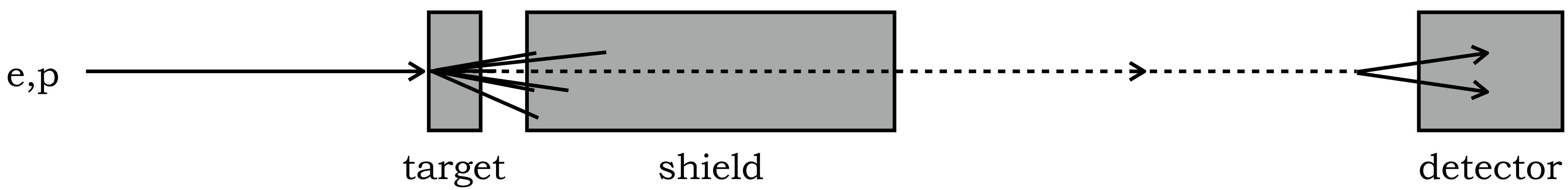
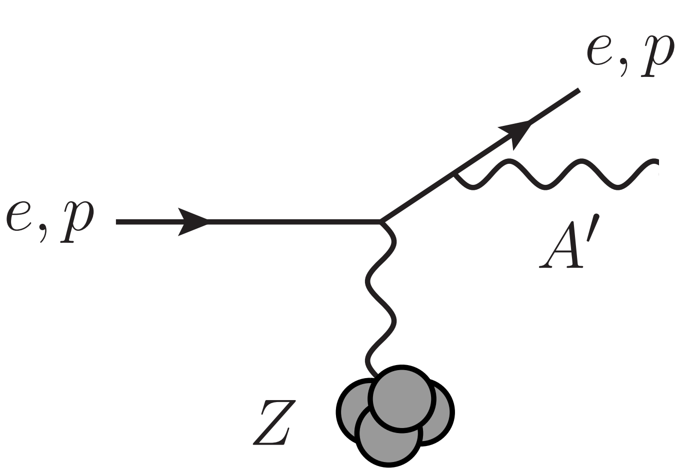
Fixed-Target Search

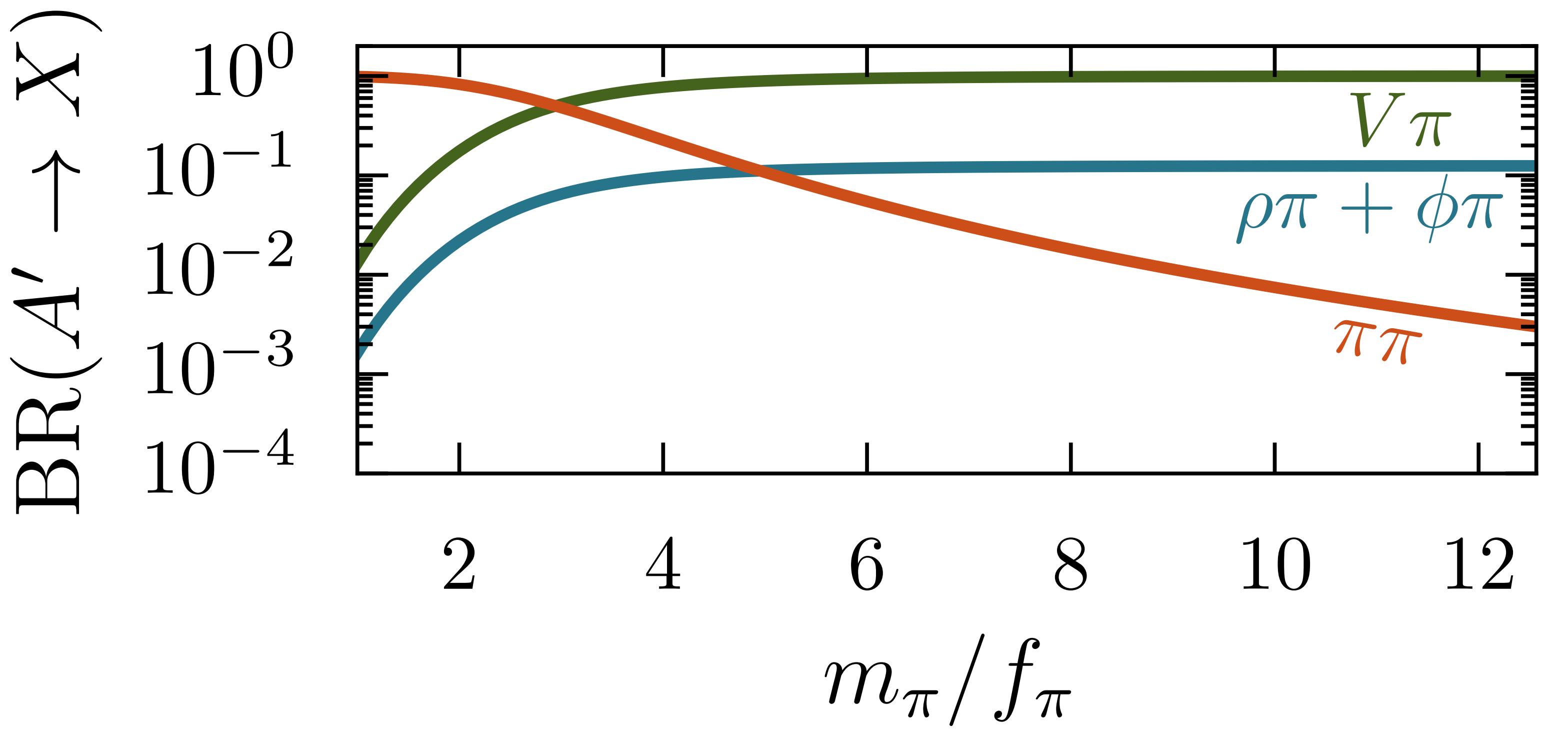




e.g. SeaQuest (see Stefania Gori's talk)

A' Decays

($\varepsilon \ll 1$)



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A' Decays

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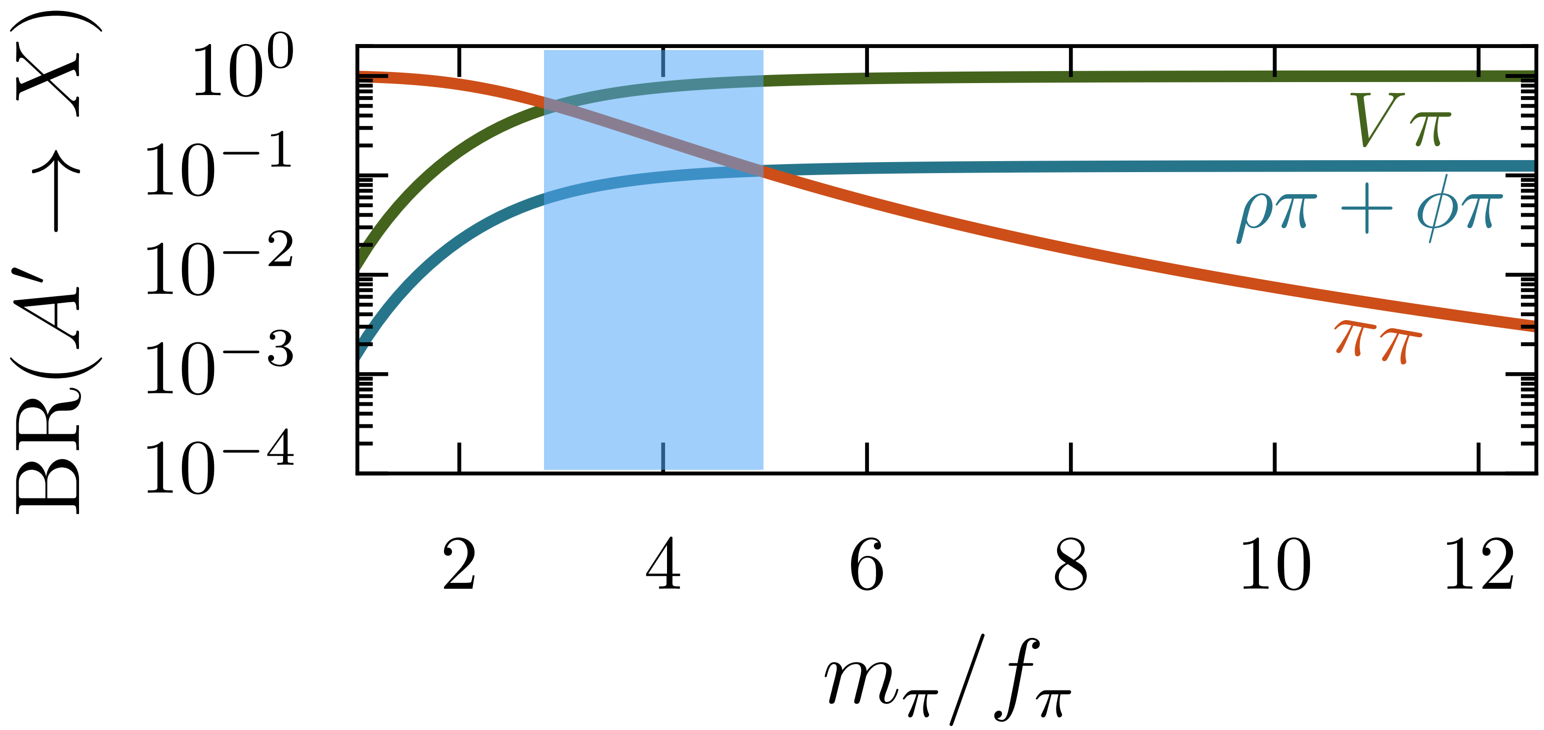

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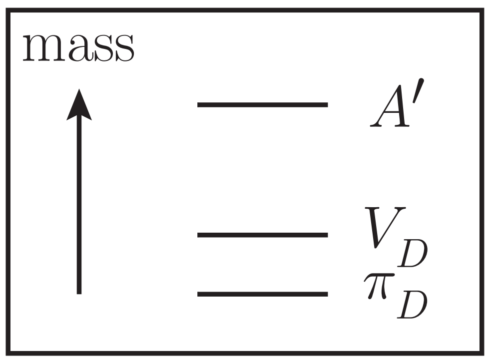
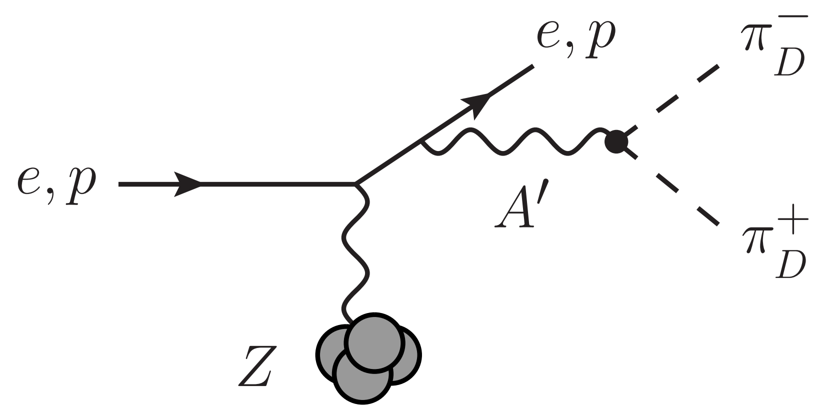
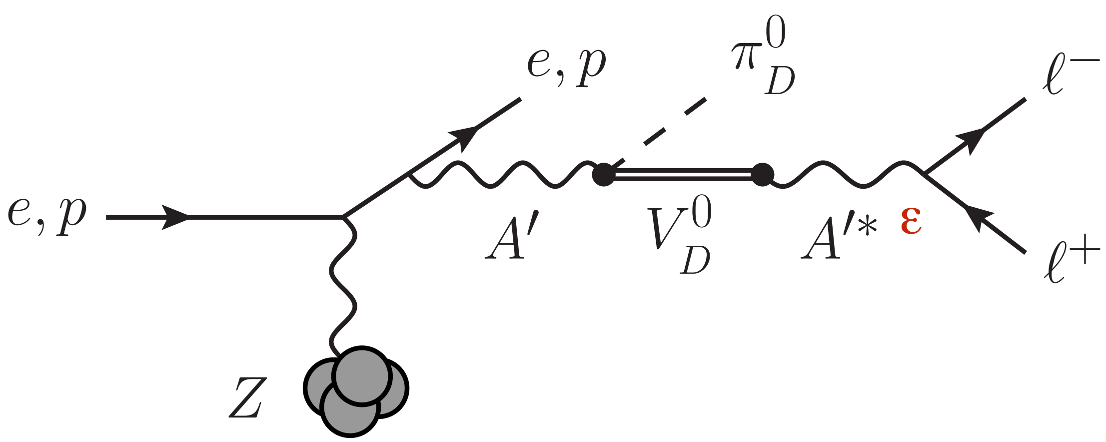
Production and Decay

(vector mesons are long-lived)

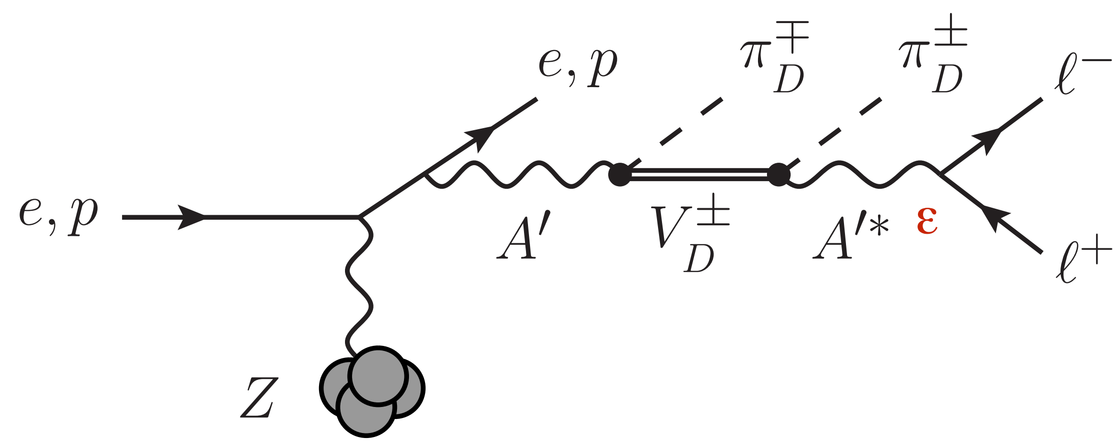




invisible decay



2-body V^0 decay



3-body $V^\pm$ decay

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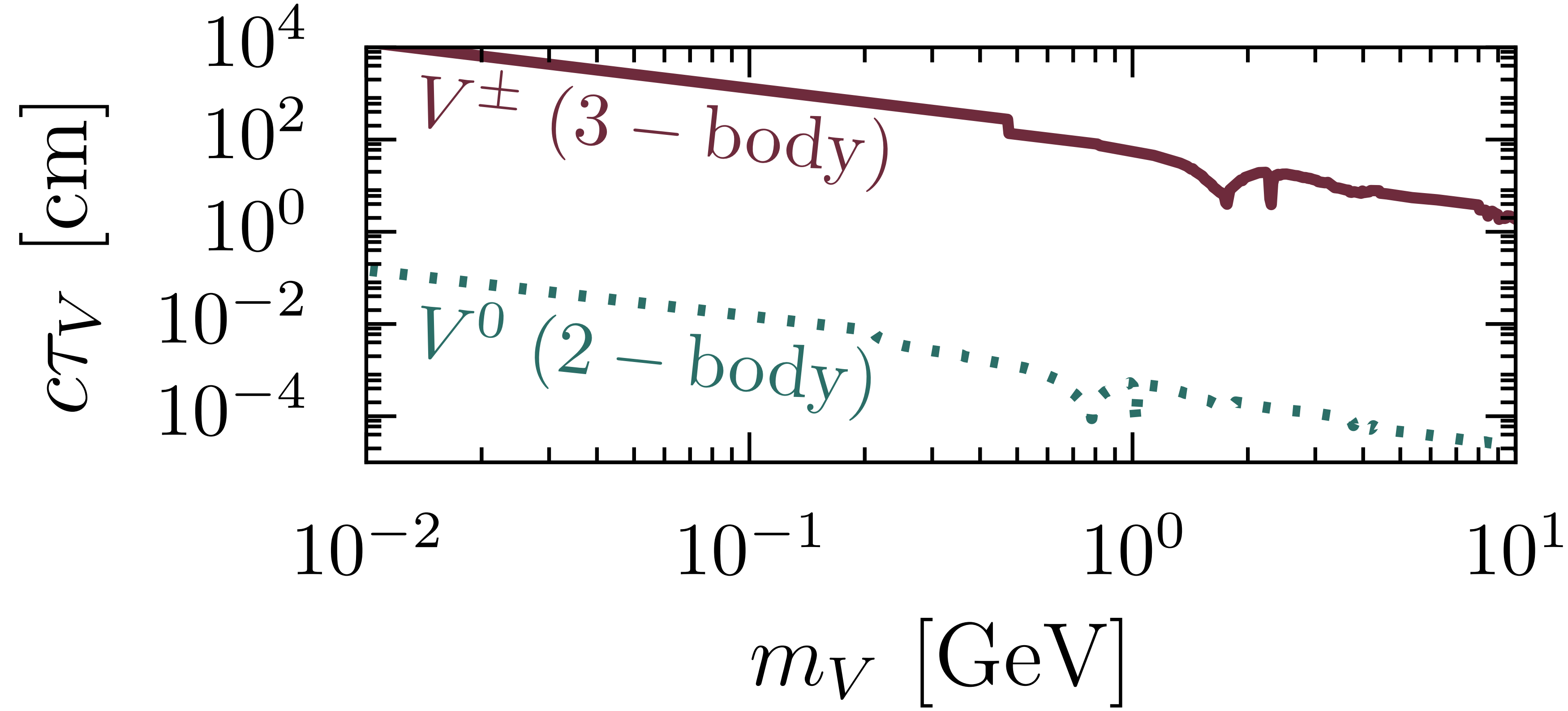
V Decays



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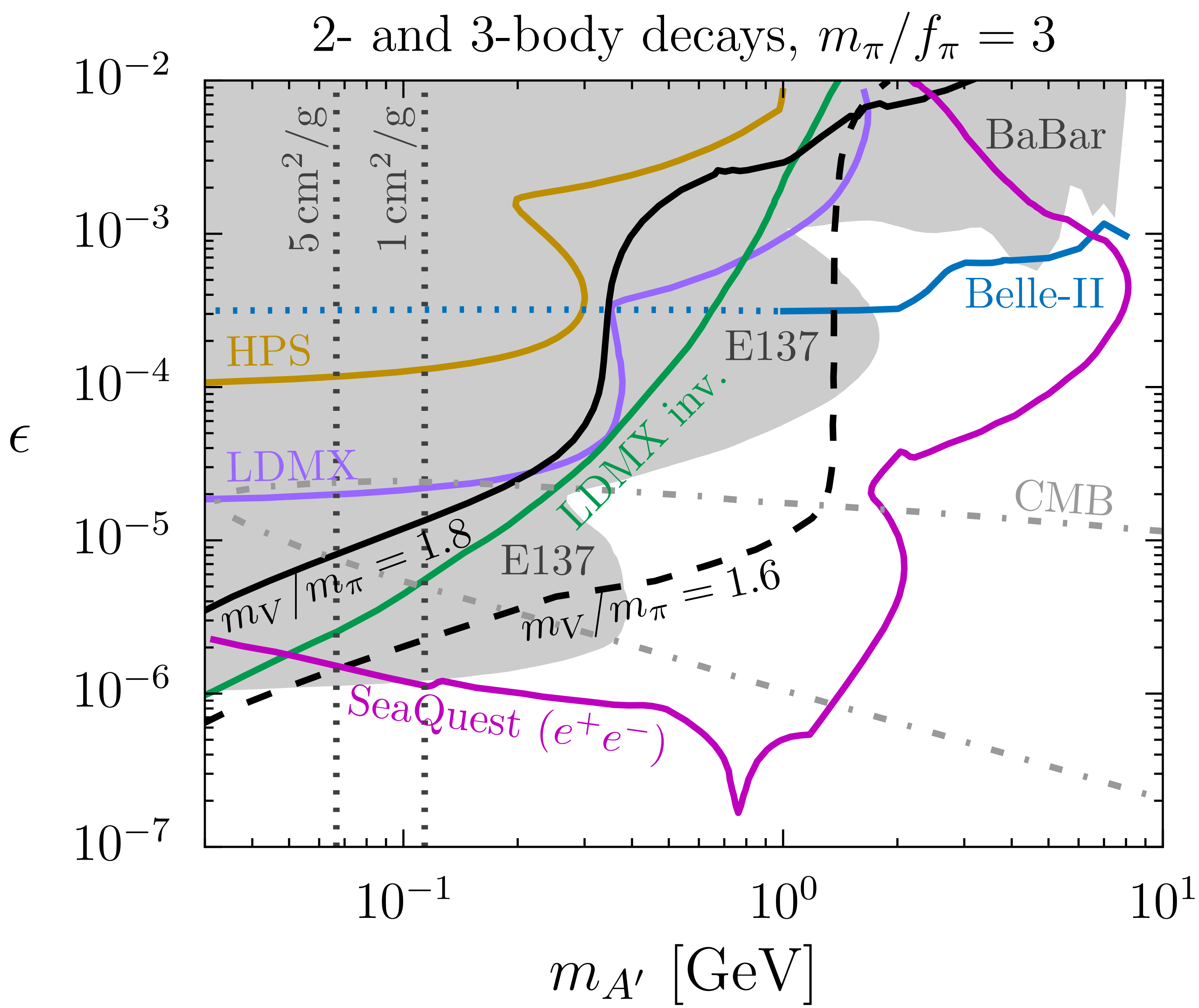
arXiv:1801.05805

Signals

$(m_{A'} \ / \ m_\pi = 3)$



Berlin, Blinov, Gori, Schuster, Toro
arXiv:1801.05805

Summary

- dark matter = hidden sector pions
- cosmology motivates significant chiral symmetry breaking
- pions are nearby in mass to the lowest spin-1 excitations
- new freeze-out dynamics in the hidden sector
- visible signatures at low-energy accelerators
- Above the muon threshold, possibilities include searches at BaBar, Belle-II, LHCb, FASER.

Back Up Slides

Production and Decay

Invisible

m_V

$2\ m_\pi$

m_π

$2\ m_e$

Visible $(m_\pi\ /\ f_\pi \gg 1)$

$2\ m_\pi$

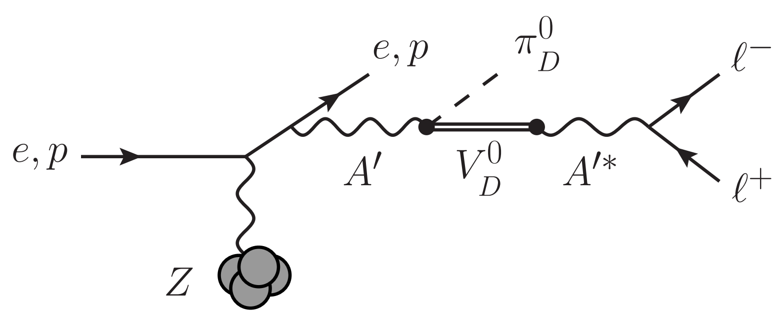
m_V

m_π

$2\ m_e$

Invisible

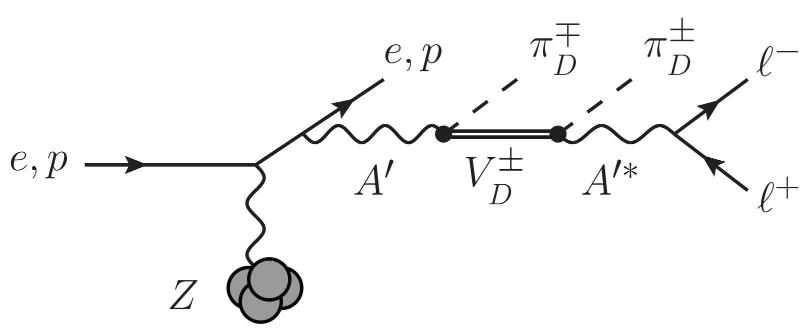
$V^\pm$

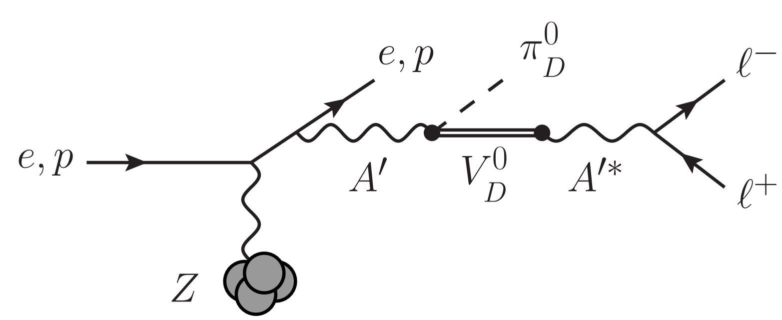


Visible

V^0

(2-body visible decays)





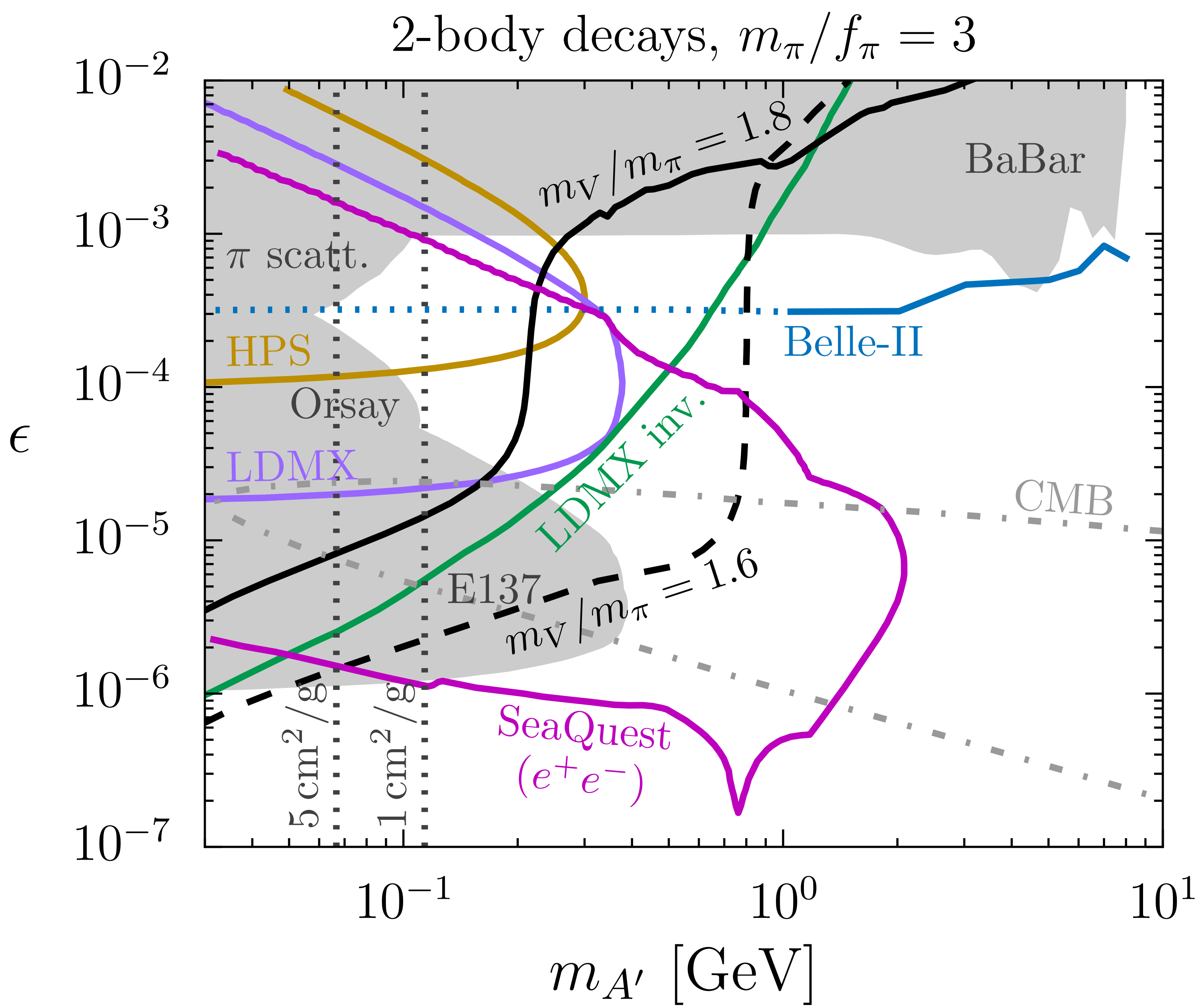
Visible

$V^0\ \ V^\pm$

(2-body and 3-body visible decays)

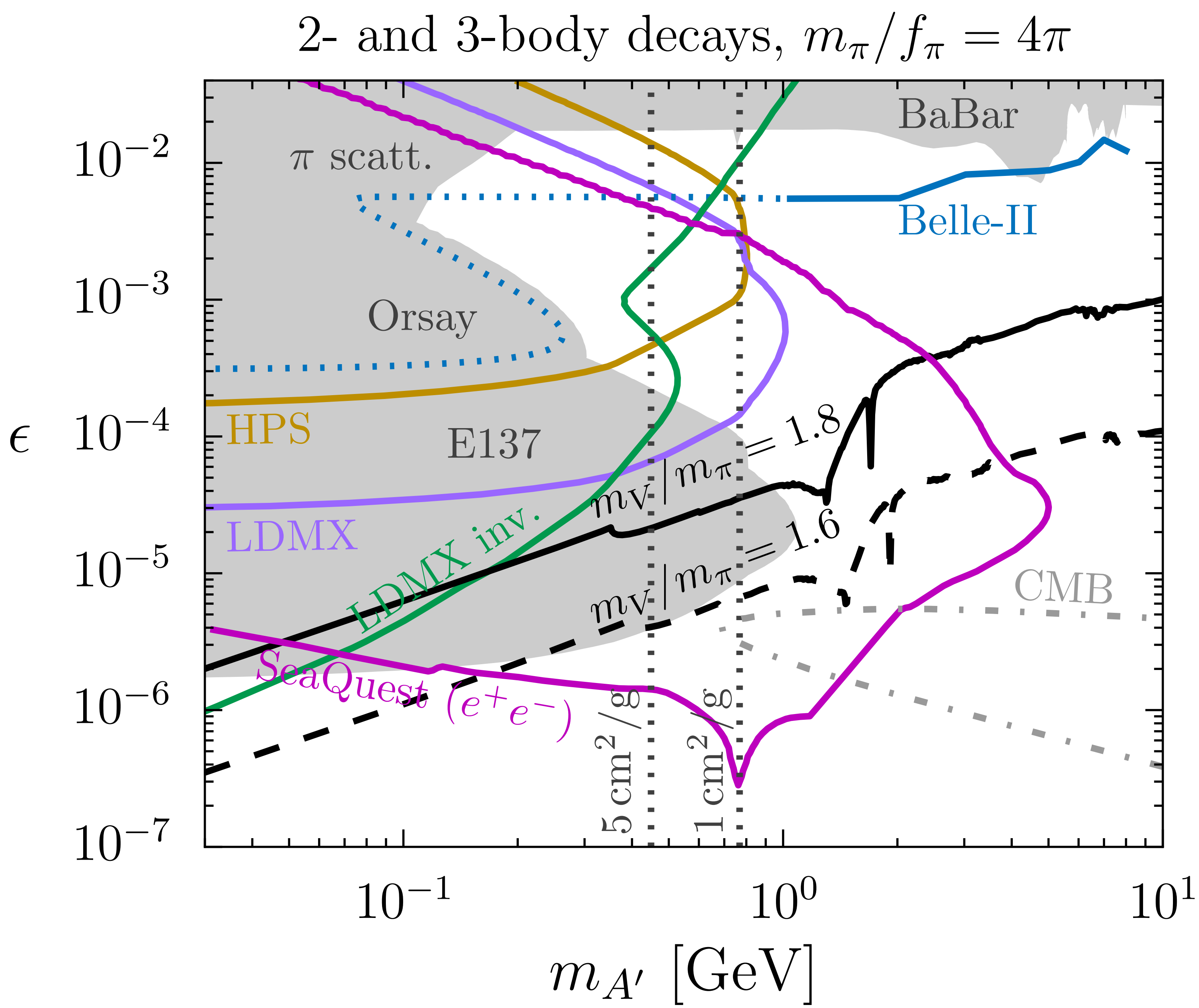
Signals

$(m_{A'} / m_{\pi} = 3)$



Berlin, Blinov, Gori, Schuster, Toro
arXiv:1801.05805

Signals

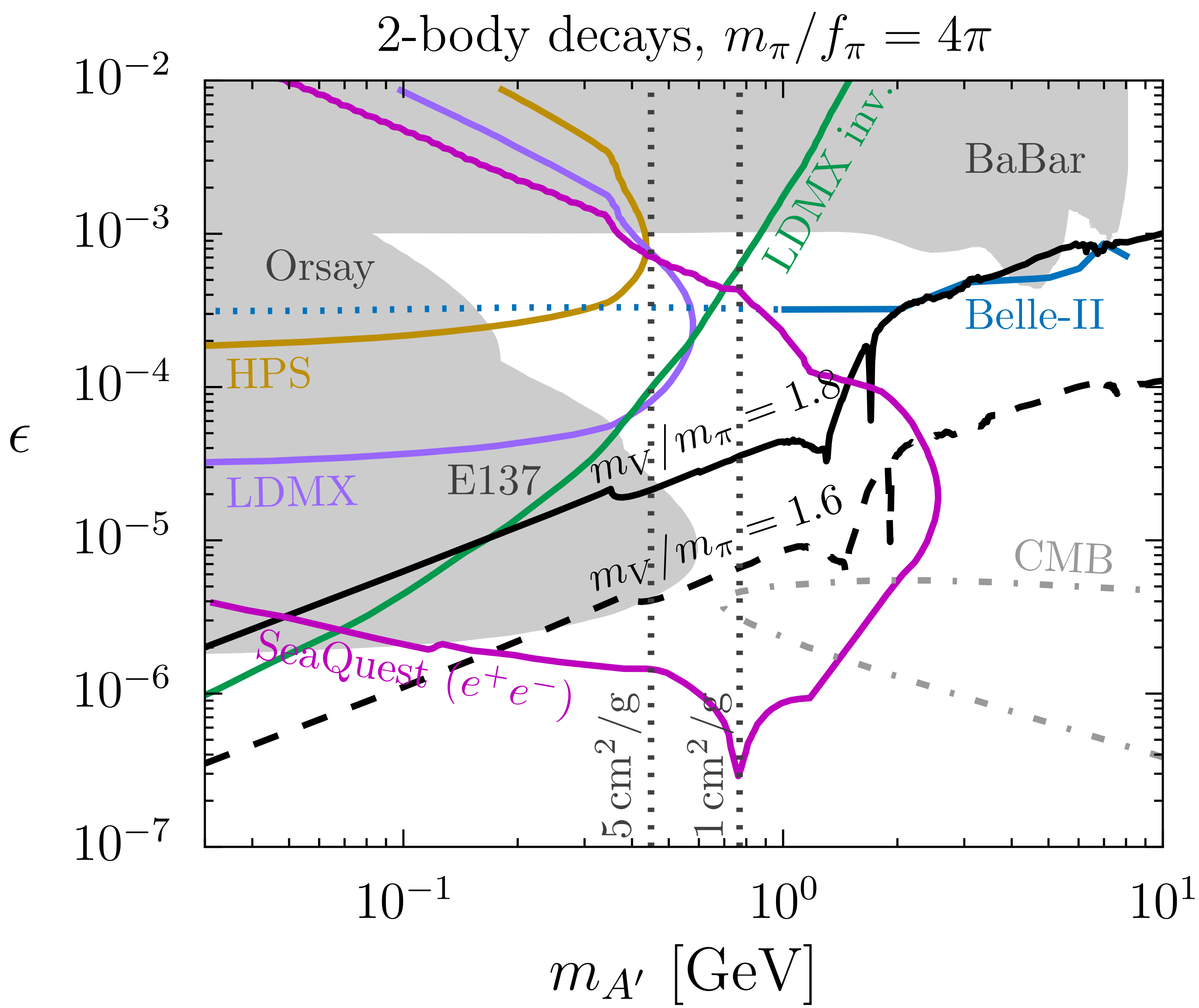


($m_{A'}$ / m_π = 3)

Berlin, Blinov, Gori, Schuster, Toro
arXiv:1801.05805

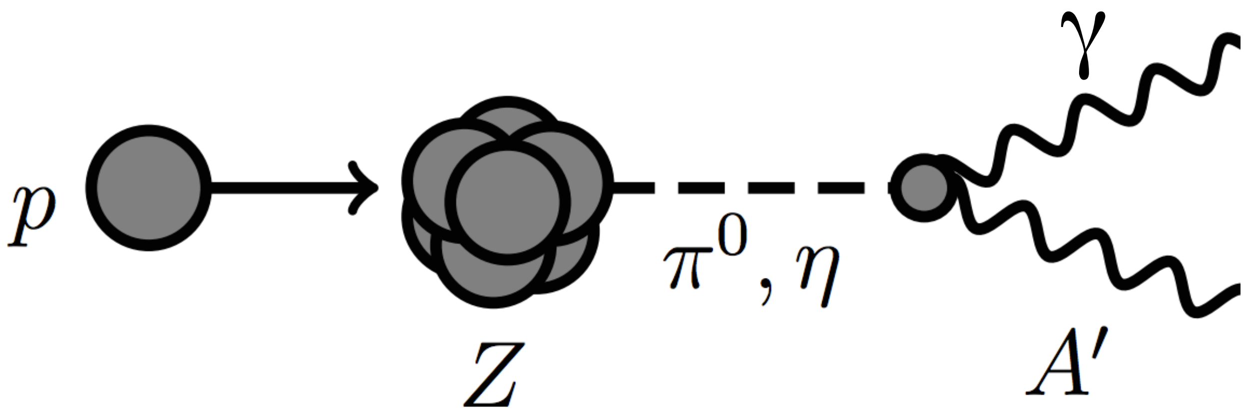
Signals

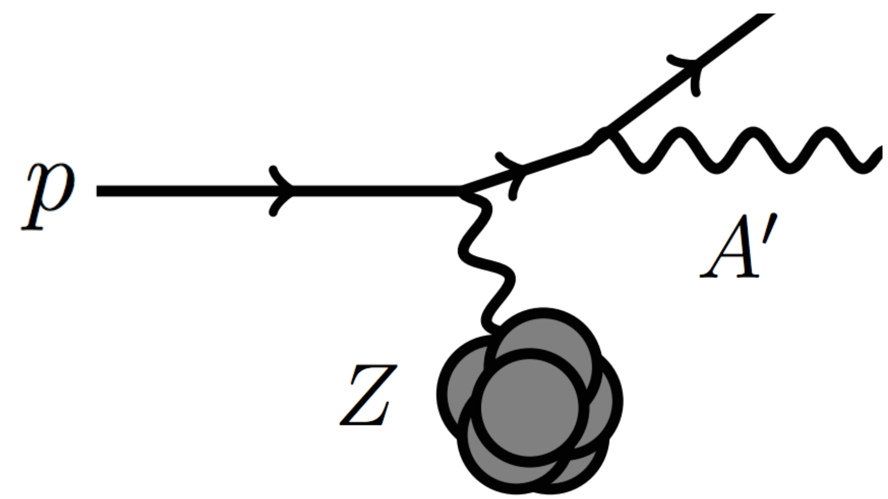
$(m_{A'} \;/\; m_{\pi} = 3)$



Berlin, Blinov, Gori, Schuster, Toro
arXiv:1801.05805

Production from Protons





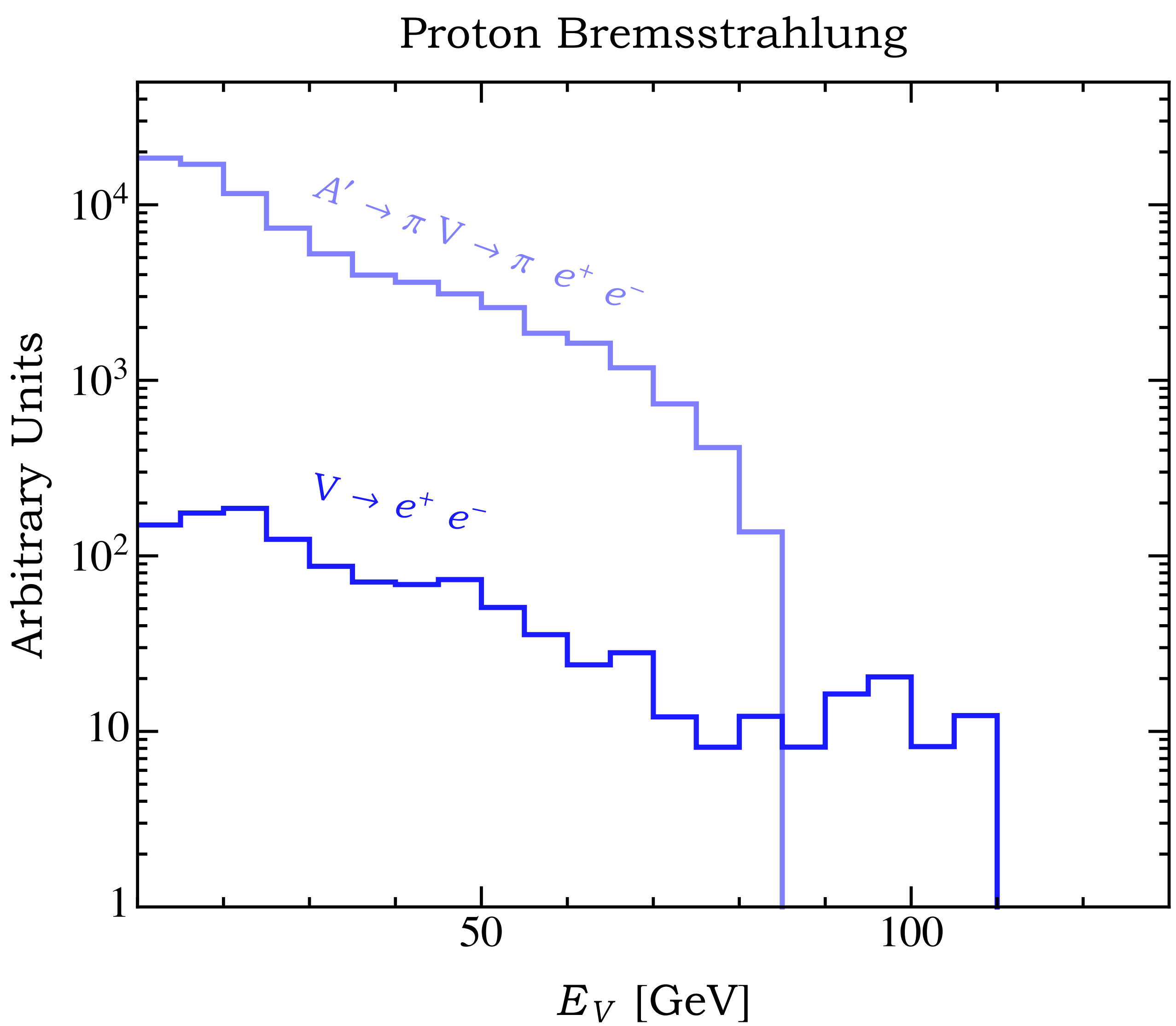
$m_{A'} \lesssim$ 100 MeV

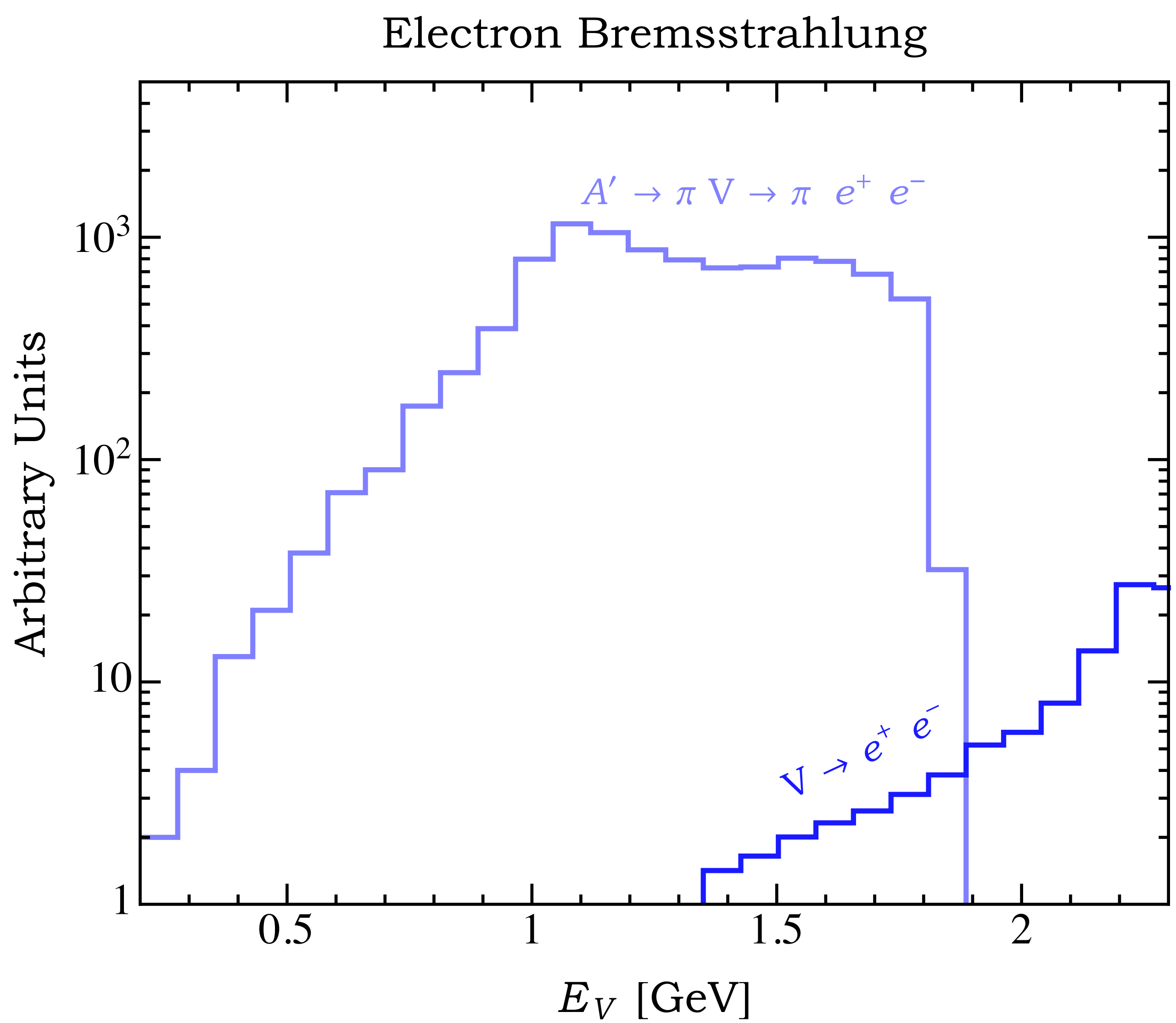
$m_{A'} \lesssim$ 1 GeV

+ Drell-Yan at higher masses

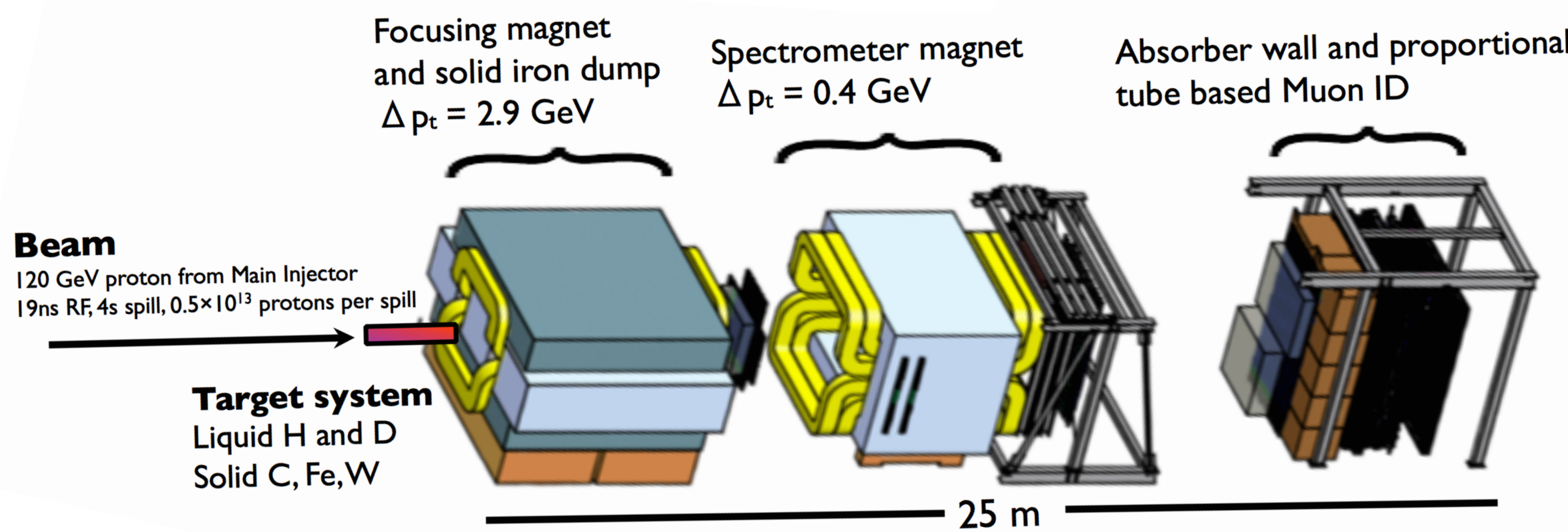
arXiv:1504.04956

Signal Kinematics

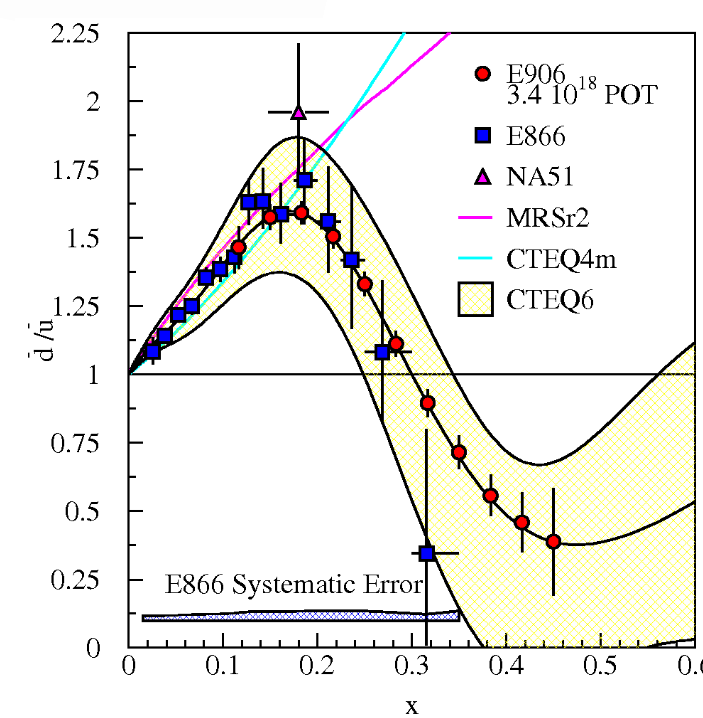




SeaQuest

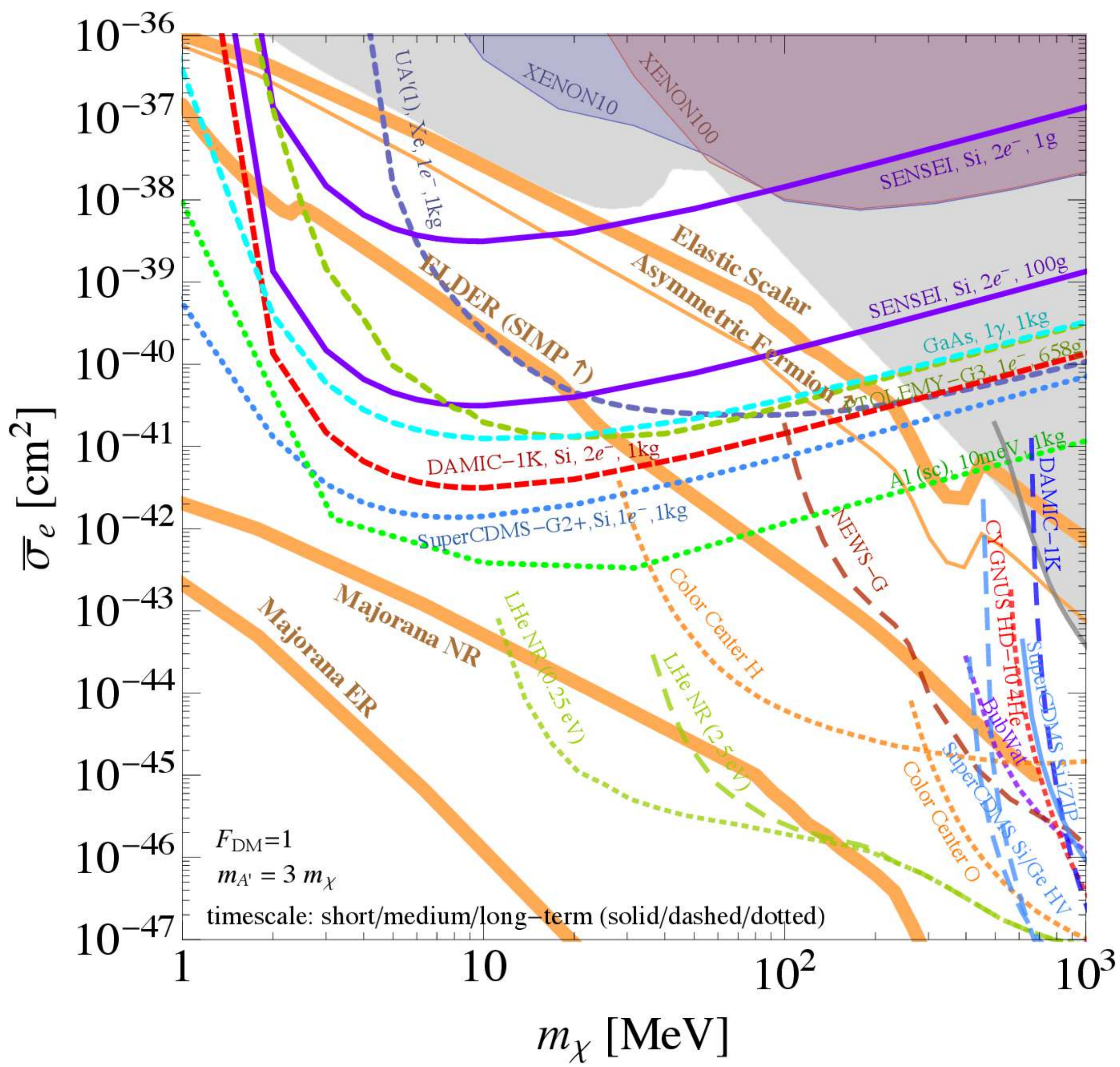


- Measure sea quark fractions at mid-x via Drell-Yan off of different targets.
- Started data taking on April 2nd.
- 10^{18} POT ~ 35,000 fb^{-1} in 2 year of parasitic run!
- Comparable luminosity to Belle-II in 2023.
- ECAL upgrade possible within the year.



(Ming X. Liu)

SIMP Target



US Cosmic Visions Community Report,
arXiv: 1707.04591

Decays

$$\Gamma(A' \to \ell^+\ell^-) = \frac{\alpha_{\rm em}\,\epsilon^2}{3}\,\left(1 - 4\,r_\ell^2\right)^{1/2}\,\left(1 + 2\,r_\ell^2\right) m_{A'}$$

$$\Gamma(A' \to \text{hadrons}) = R(\sqrt{s} = m_{A'})\,\Gamma(A' \to \mu^+\mu^-)$$

$$\Gamma(A' \to \pi\pi) = \frac{2\,\alpha_D}{3}\,\frac{(1-4r_\pi^2)^{3/2}}{(1-r_V^{-2})^2}\,m_{A'}$$

$$\Gamma(A' \to \eta^0\,\rho) = \frac{\alpha_D\,r_V^2}{256\pi^4}\,\left(\frac{m_\pi/f_\pi}{r_\pi}\right)^4\,\left[1 - 2(r_\pi^2 + r_V^2) + (r_\pi^2 - r_V^2)^2\right]^{3/2}\,m_{A'}$$

$$\Gamma(A' \to \eta^0\,\phi) = \frac{\alpha_D\,r_V^2}{128\pi^4}\,\left(\frac{m_\pi/f_\pi}{r_\pi}\right)^4\,\left[1 - 2(r_\pi^2 + r_V^2) + (r_\pi^2 - r_V^2)^2\right]^{3/2}\,m_{A'}$$

$$\Gamma(A' \to \pi^0\,\omega) = \frac{3\alpha_D\,r_V^2}{256\pi^4}\,\left(\frac{m_\pi/f_\pi}{r_\pi}\right)^4\,\left[1 - 2(r_\pi^2 + r_V^2) + (r_\pi^2 - r_V^2)^2\right]^{3/2}\,m_{A'}$$

$$\Gamma(A' \to K^0\,\overline{K^{*0}}\,,\,\overline{K^0}\,K^{*0}) = \frac{3\alpha_D\,r_V^2}{128\pi^4}\,\left(\frac{m_\pi/f_\pi}{r_\pi}\right)^4\,\left[1 - 2(r_\pi^2 + r_V^2) + (r_\pi^2 - r_V^2)^2\right]^{3/2}\,m_{A'}$$

$$\Gamma(A' \to \pi^\pm\,\rho^\mp) = \frac{3\alpha_D\,r_V^2}{128\pi^4}\,\left(\frac{m_\pi/f_\pi}{r_\pi}\right)^4\,\left[1 - 2(r_\pi^2 + r_V^2) + (r_\pi^2 - r_V^2)^2\right]^{3/2}\,m_{A'}$$

$$\Gamma(A' \to K^\pm\,K^{*\mp}) = \frac{3\alpha_D\,r_V^2}{128\pi^4}\,\left(\frac{m_\pi/f_\pi}{r_\pi}\right)^4\,\left[1 - 2(r_\pi^2 + r_V^2) + (r_\pi^2 - r_V^2)^2\right]^{3/2}\,m_{A'}$$

$$\Gamma(A' \to VV) = \frac{\alpha_D}{6}\,\frac{(1-4r_V^2)^{1/2}(1+16r_V^2 - 68r_V^4 - 48r_V^6)}{(1-r_V^2)^2}\,m_{A'}$$

$$\Gamma(\rho \to \ell^+\ell^-) = \frac{32\pi\,\alpha_{\rm em}\,\alpha_D\,\epsilon^2}{3}\,\left(\frac{r_\pi}{m_\pi/f_\pi}\right)^2\,(r_V^2 - 4r_\ell^2)^{1/2}\,(r_V^2 + 2r_\ell^2)\,(1-r_V^2)^{-2}\,m_{A'}$$

$$\Gamma(\phi \to \ell^+\ell^-) = \frac{16\pi\,\alpha_{\rm em}\,\alpha_D\,\epsilon^2}{3}\,\left(\frac{r_\pi}{m_\pi/f_\pi}\right)^2\,(r_V^2 - 4r_\ell^2)^{1/2}\,(r_V^2 + 2r_\ell^2)\,(1-r_V^2)^{-2}\,m_{A'}$$

$$\Gamma(\omega \to \ell^+\ell^-) = 0$$