Cosmology and Accelerator Tests of Strongly Interacting Dark Matter

ASHER BERLIN

SLAC
NATIONAL ACCELERATOR LABORATORY

Lattice for BSM Physics, CU Boulder,
April 5, 2018

Collaborations with Nikita Blinov, Stefania Gori, Philip Schuster, & Natalia Toro
based on arXiv:1801.05805

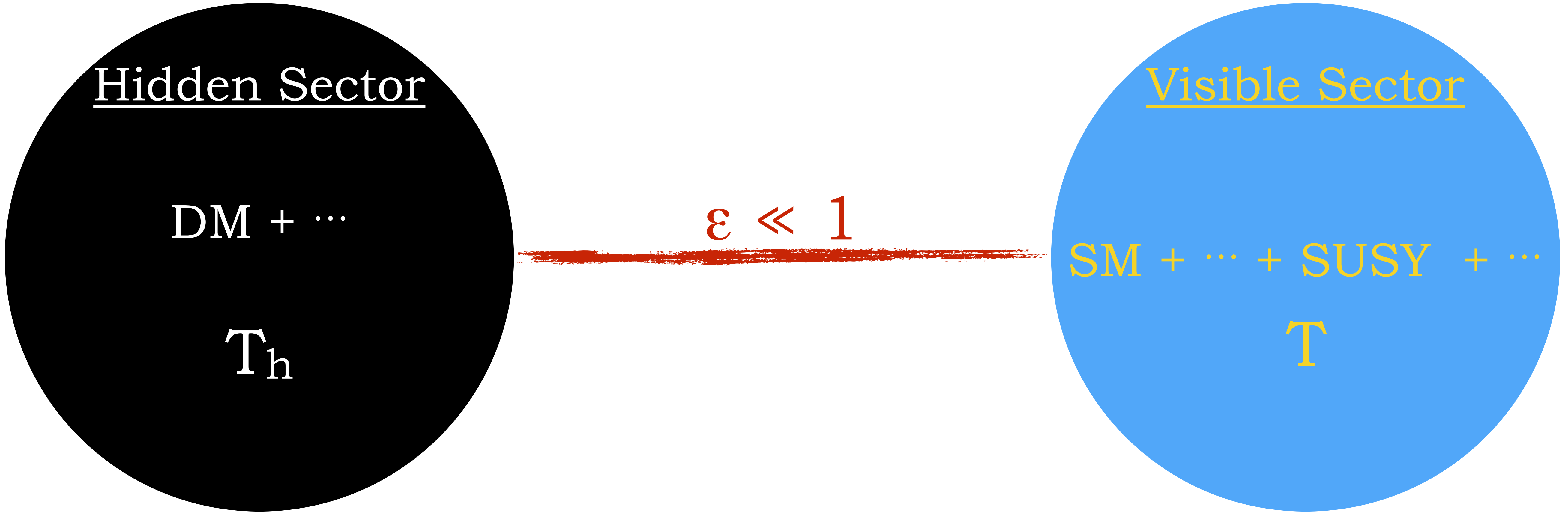
Outline

I. Review of Strongly Interacting Dark Matter

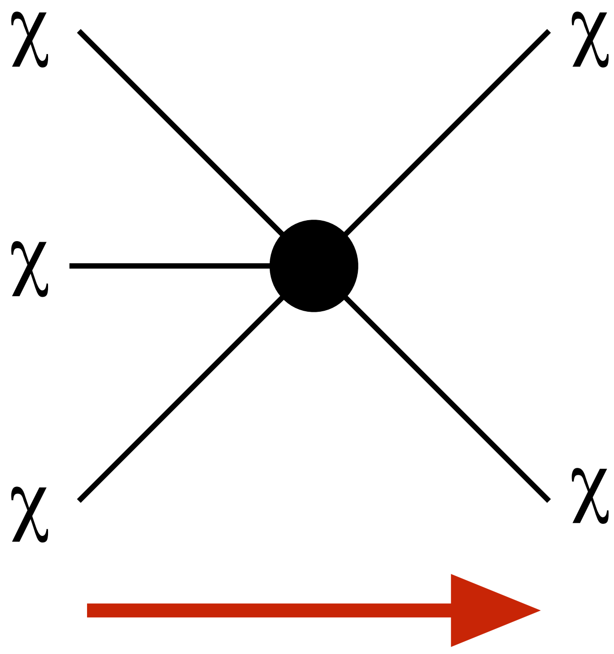
II. SIMP Cosmology

III. The GeV-Scale: Fixed-Target Experiments

Hidden Sector

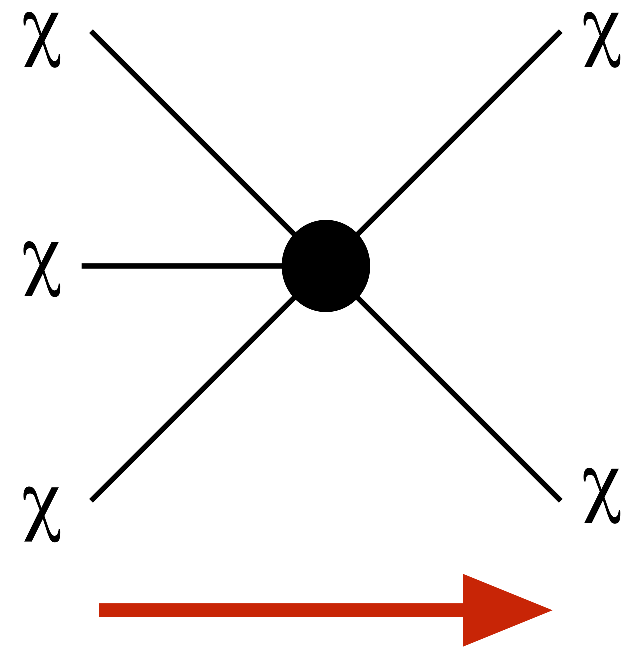


Kinetically Decoupled



Carlson, Machacek and Hall (1992)

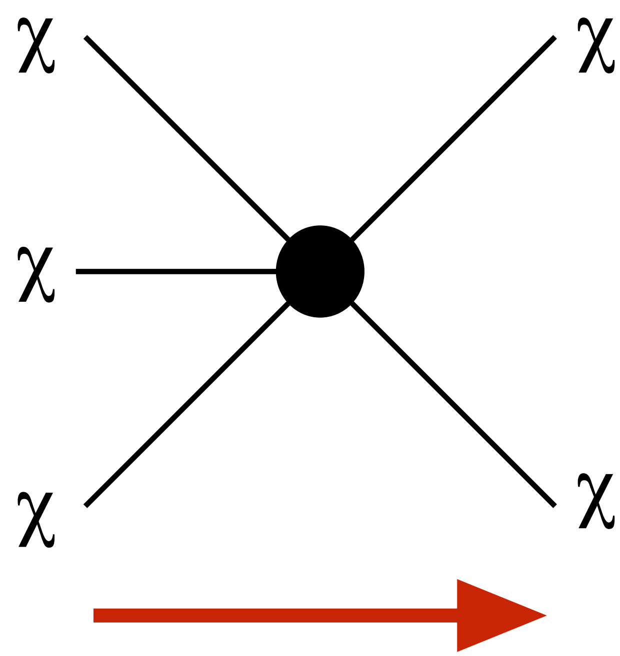
Kinetically Decoupled



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

Carlson, Machacek and Hall (1992)

Kinetically Decoupled

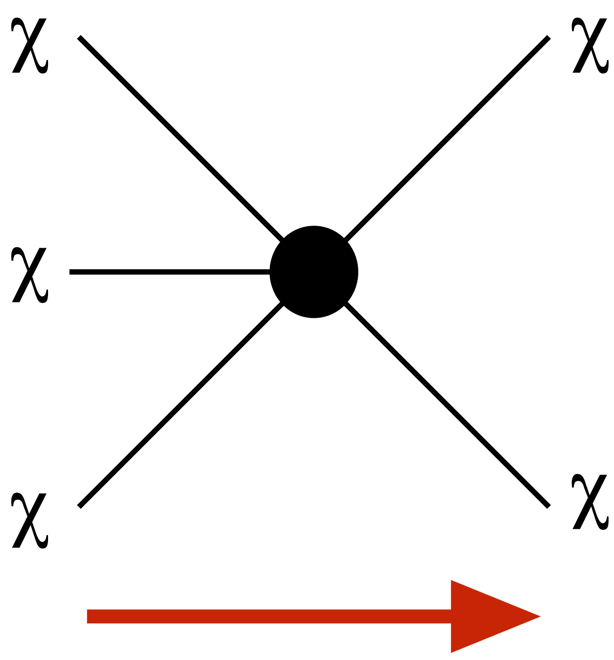


$$T_h < m_\chi \implies s_h \simeq \frac{\rho_\chi}{T_h} \simeq \frac{m_\chi n_\chi}{T_h} \propto e^{-m_\chi/T_h}$$

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

Carlson, Machacek and Hall (1992)

Kinetically Decoupled



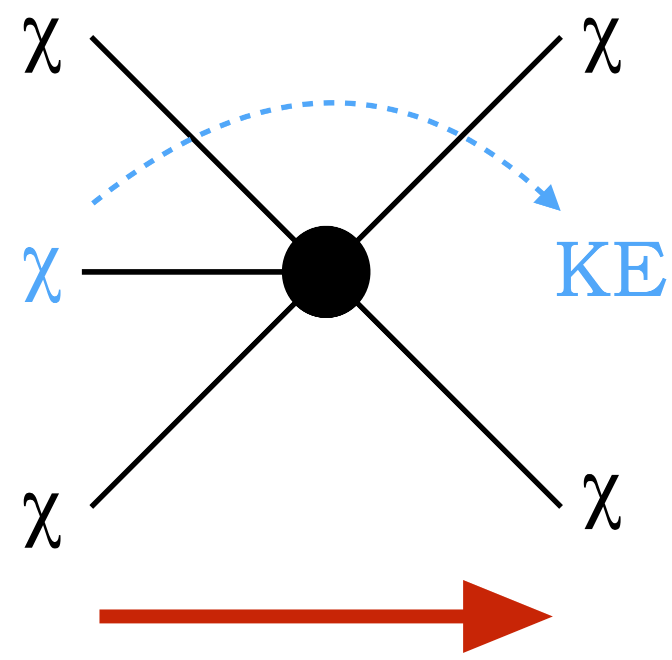
$$T_h < m_\chi \implies s_h \simeq \frac{\rho_\chi}{T_h} \simeq \frac{m_\chi n_\chi}{T_h} \propto e^{-m_\chi/T_h}$$

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

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

Carlson, Machacek and Hall (1992)

Kinetically Decoupled



(Need to expel heat)

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

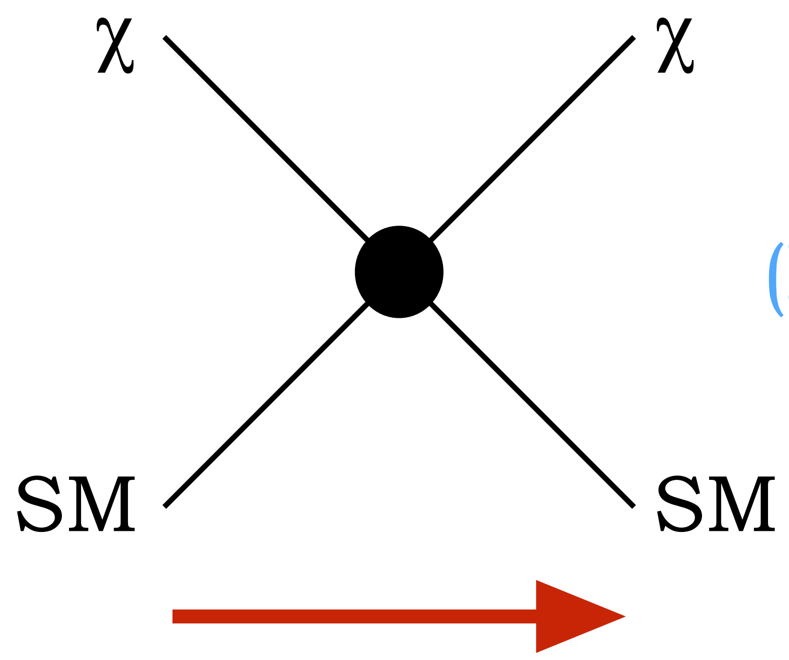
$$S_h \propto e^{-m_\chi/T_h}\, a^3 \sim \text{constant} \implies T_h \sim \frac{m_\chi}{\log a}$$

$$\rho_h \simeq s_h T_h \sim \frac{1}{a^3 \log a} \gg \frac{1}{a^{3/2} e^a}$$

$\Rightarrow m_\chi \ll$ keV (warm)

Carlson, Machacek and Hall (1992)

Kinetically Coupled

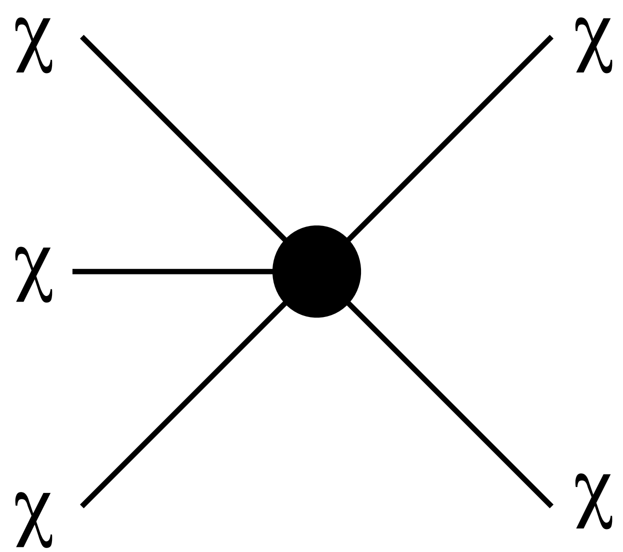


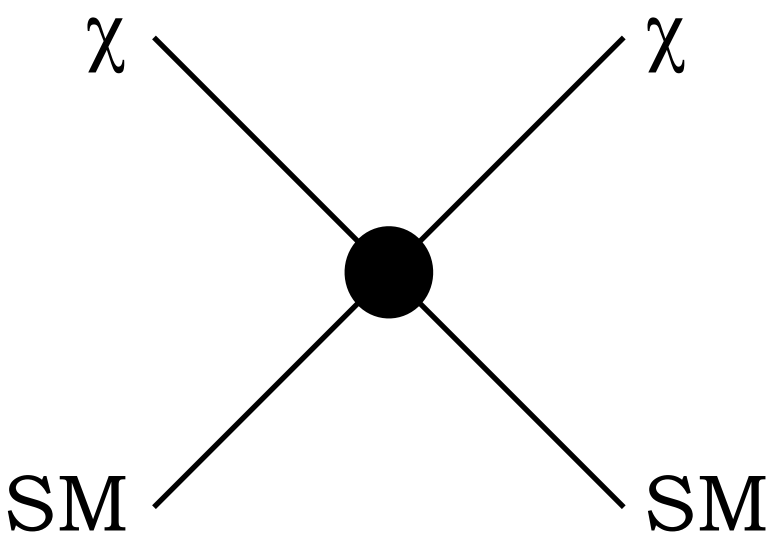
(heat dumped into SM)

$$T_h = T$$

Carlson, Machacek and Hall (1992)

The SIMP Miracle

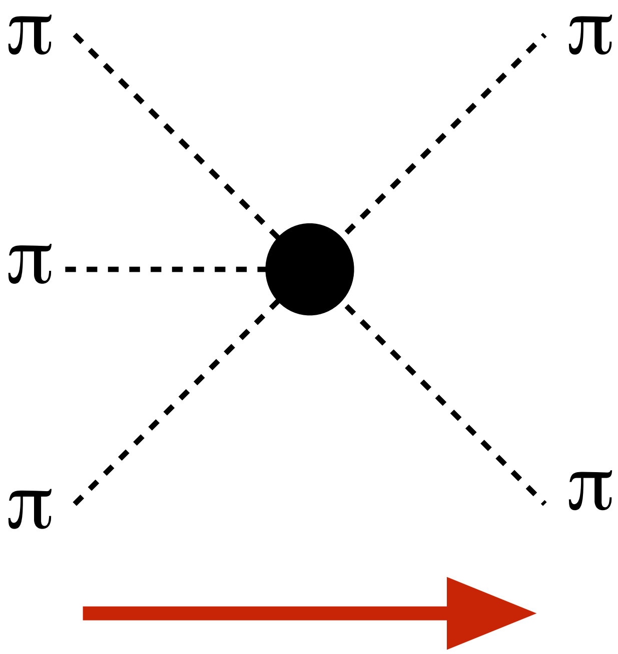




$$m_\chi \sim \alpha_\chi \left(T_{\rm eq}^2 m_{\rm pl}\right)^{1/3} \sim \alpha_\chi \times 1 \text{ GeV}$$

Hochberg, Kuflik, Volansky, Wacker
arXiv:1402.5143

The SIMP Miracle



(π = Dark Matter)

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

A Theory of Pions

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

A Theory of Pions

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

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

(Wess-Zumino-Witten)

A Theory of Pions

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

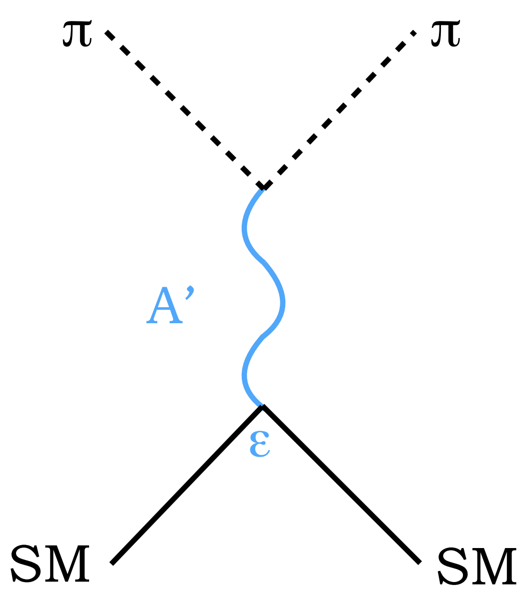
$$\frac{2\,N_c}{15\pi^2\, f_\pi^5}\ \epsilon^{\mu\nu\rho\sigma}\ \mathrm{Tr}\left[\pi\partial_\mu\pi\partial_\nu\pi\partial_\rho\pi\partial_\sigma\pi\right]$$

(Wess-Zumino-Witten)

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

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

+ Dark Photons

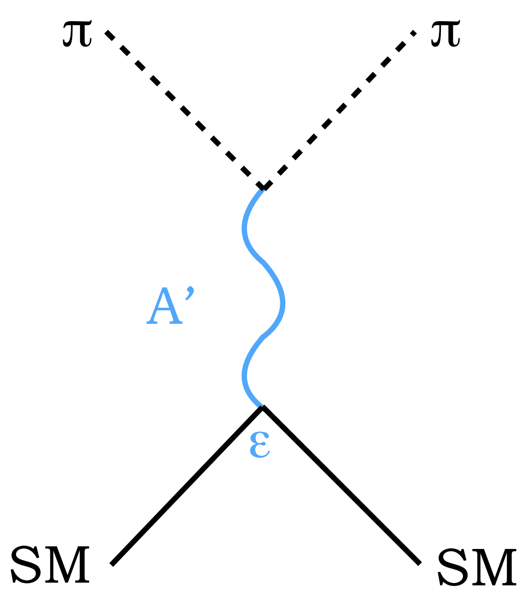


$(\varepsilon \ll 1)$

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

(Kinetic mixing)

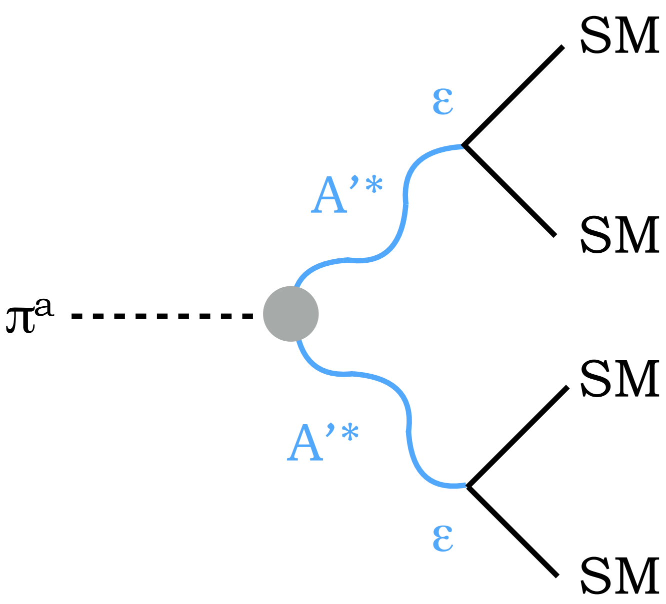
+ Dark Photons



(ε ≪ 1)

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

(Kinetic mixing)

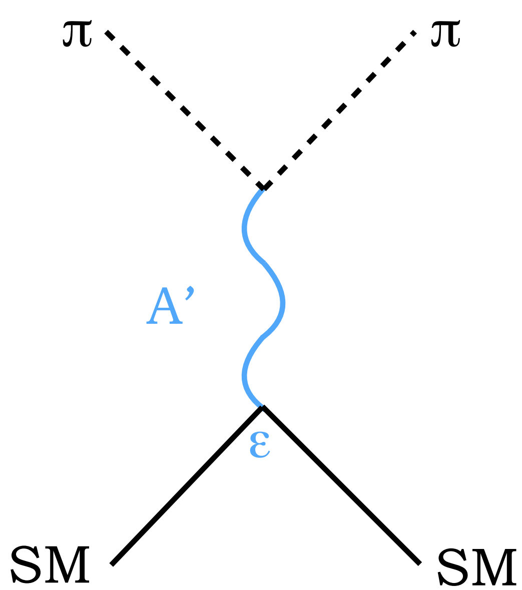


$$i\mathcal{M} \sim \epsilon^2 \,\mathrm{Tr}\left[Q^2 T^a\right]$$

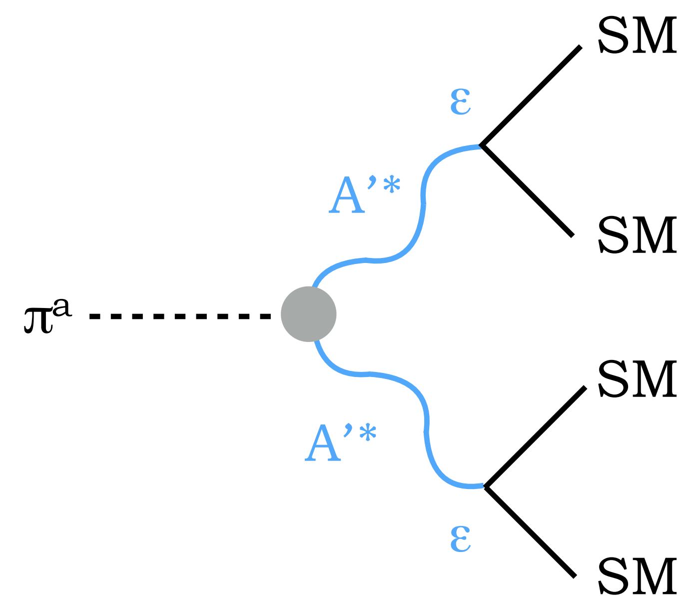
+ Dark Photons

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

(Kinetic mixing)



(ε ≪ 1)

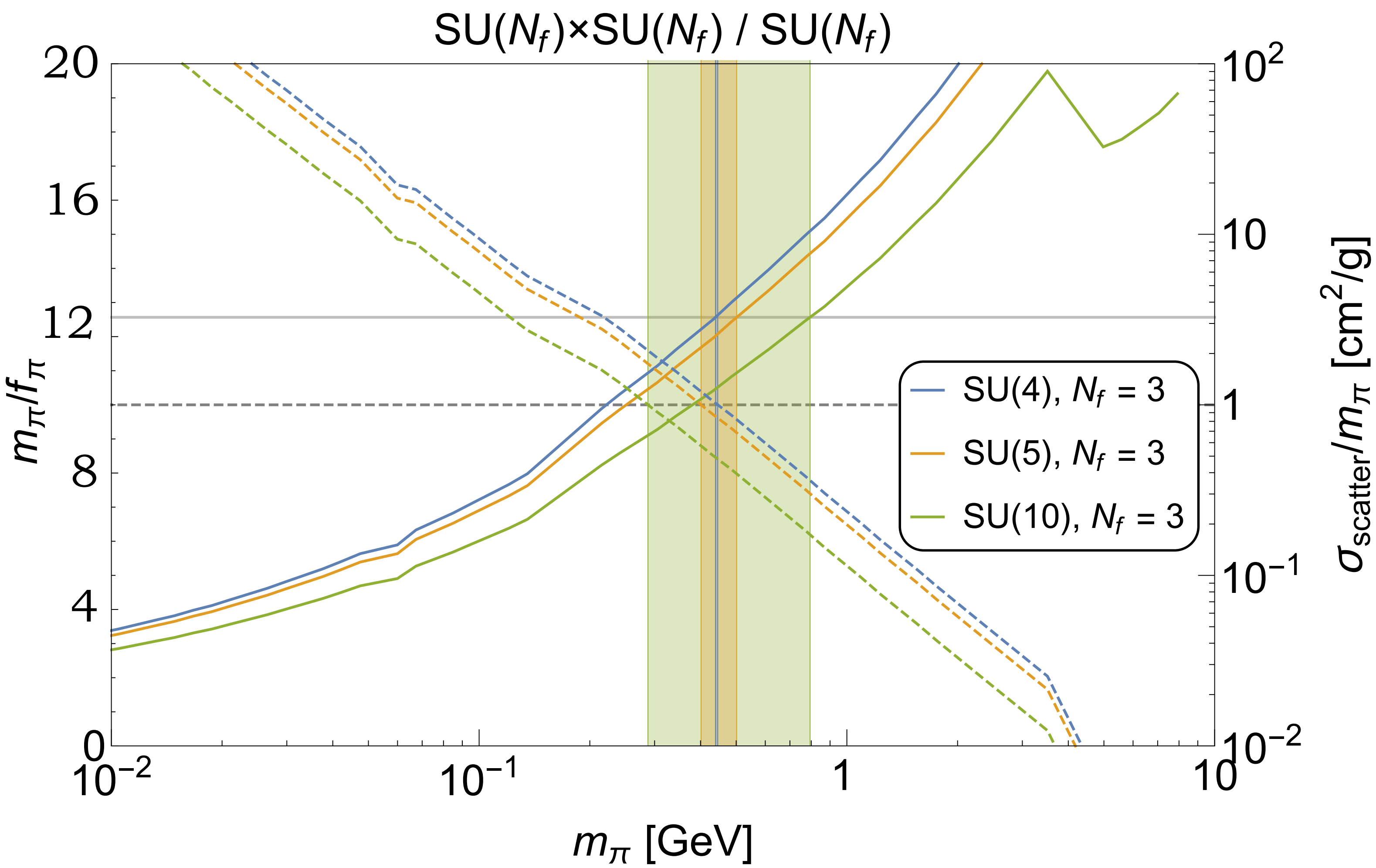


$$i\mathcal{M} \sim \epsilon^2 \, \mathrm{Tr}\left[Q^2 T^a\right]$$ ~ 0

(fully stabilize via G-parity)

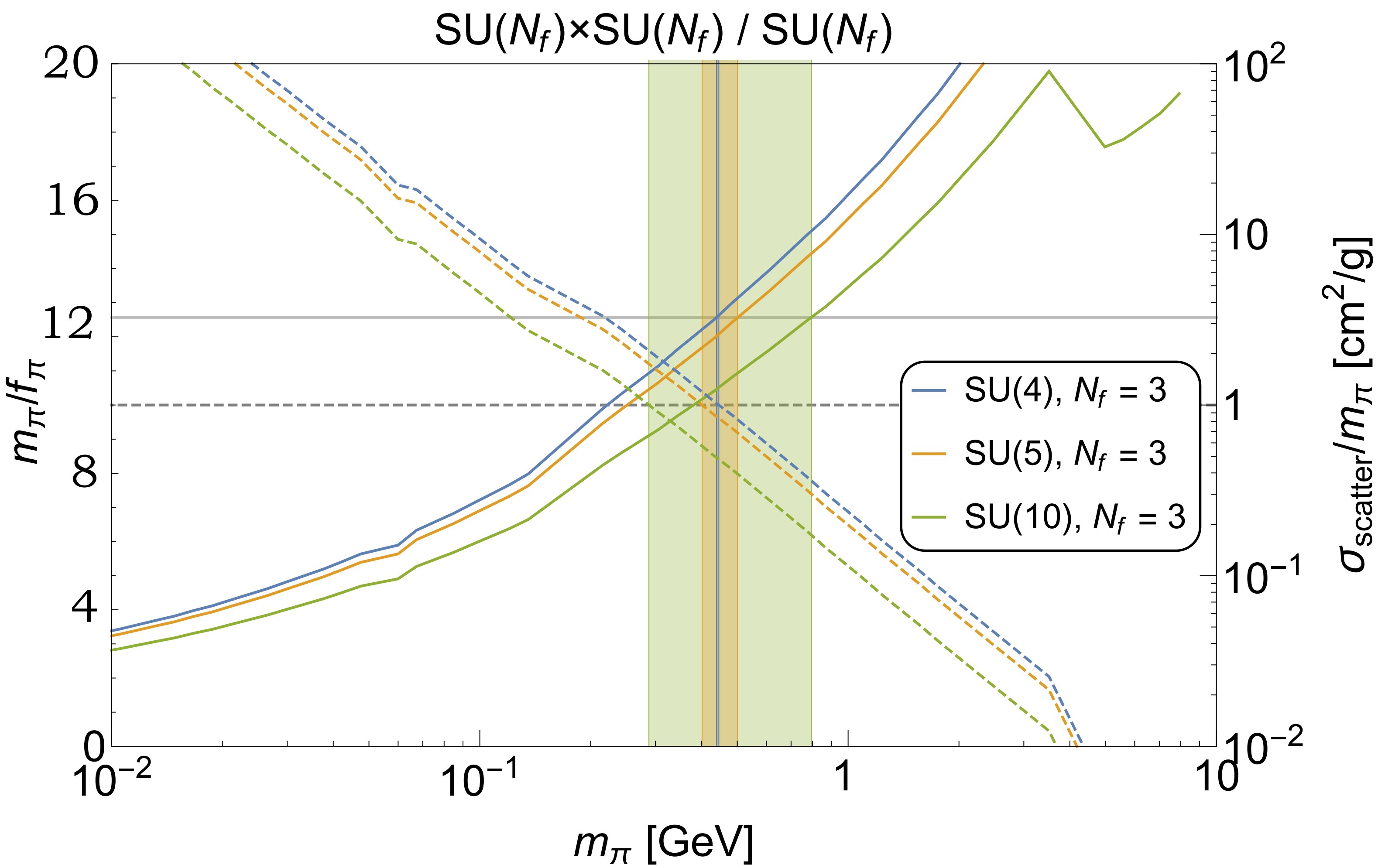
$$Q = \begin{pmatrix} \overbrace{+1 & & }^{N_1} & & & \\ & \ddots & & & & \\ & & +1 & & & \\ & & & \overbrace{-1 & & }^{N_2} \\ & & & & \ddots & \\ & & & & & -1 \end{pmatrix}$$

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

II. SIMP Cosmology

III. The GeV-Scale: Fixed-Target Experiments

Mass Spectrum

A’

~ GeV

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

$2\ m_{\pi}$

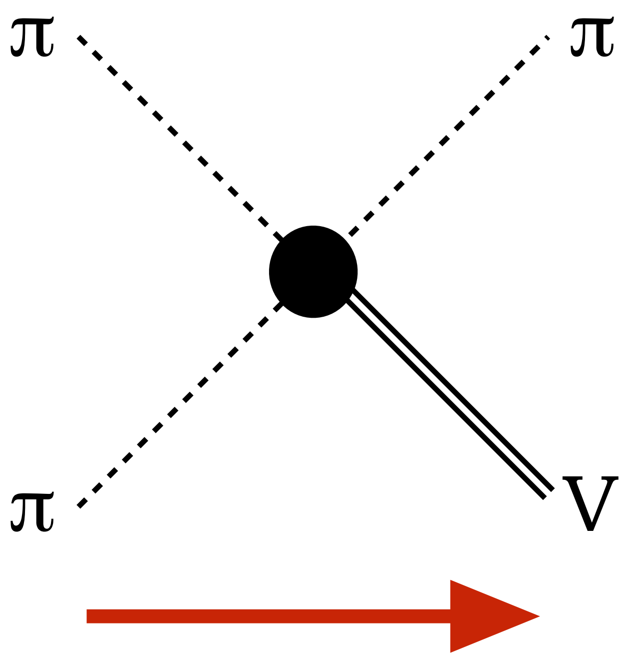
Vector Mesons, V

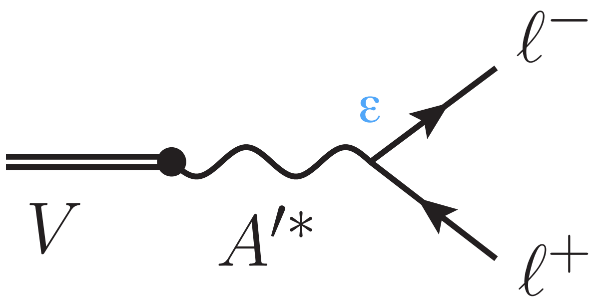
Pions, π

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

Forbidden Semi-Annihilation

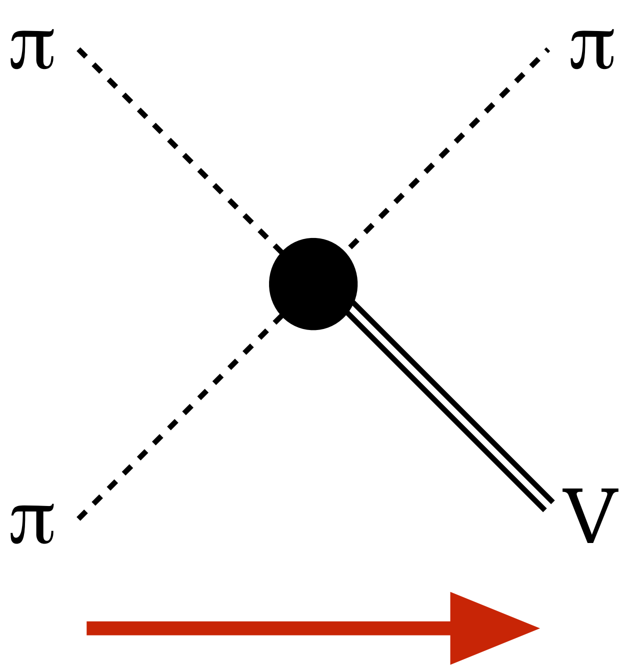
Forbidden Semi-Annihilation

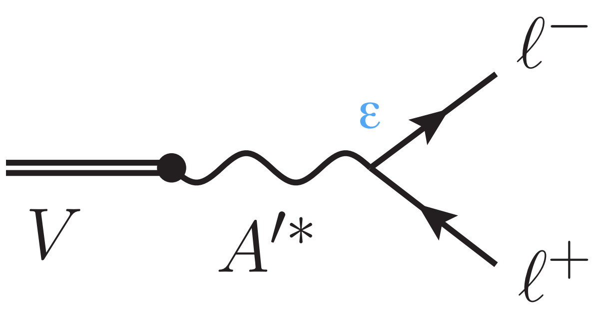




$m_V < 2\, m_\pi$

Forbidden Semi-Annihilation

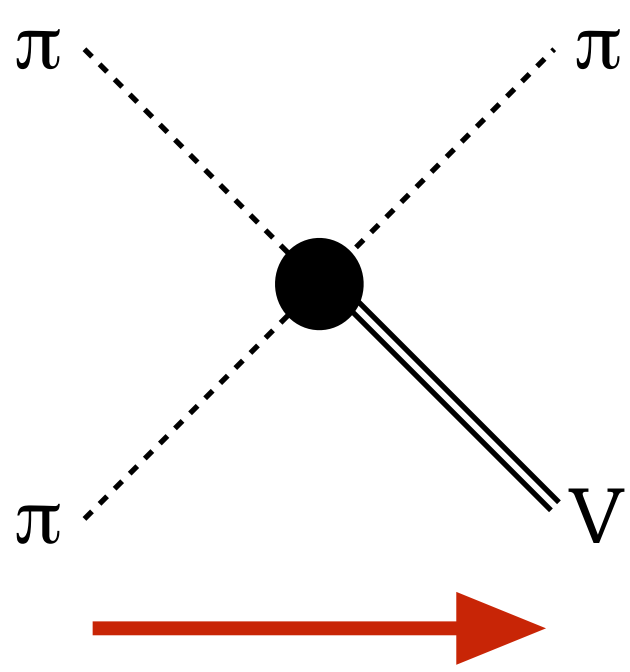


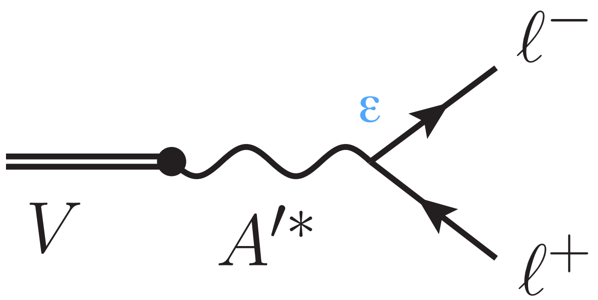


$m_V < 2\ m_\pi$

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

Forbidden Semi-Annihilation



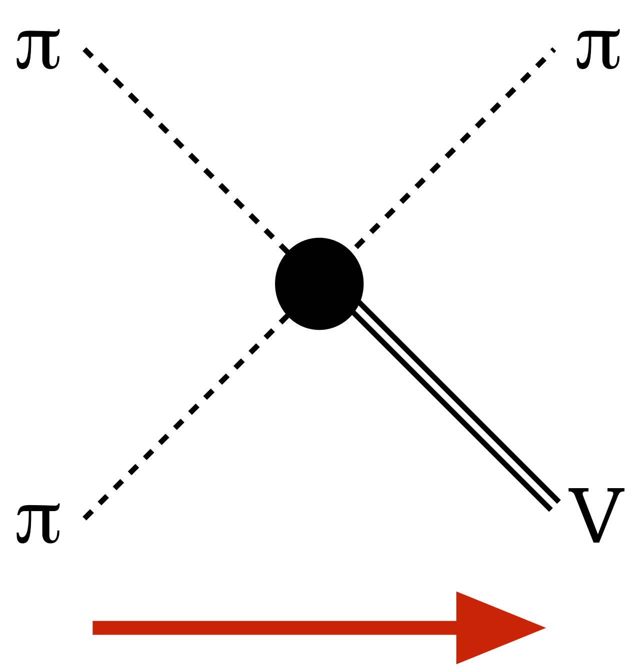


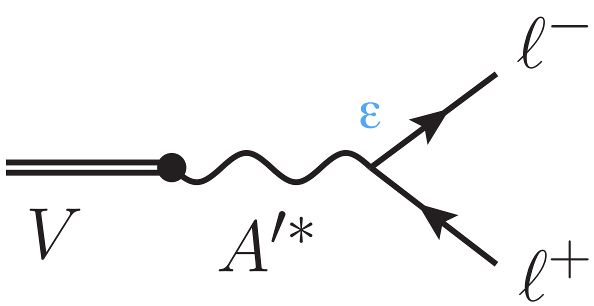
$m_V < 2\, m_\pi$

(3 → 2)

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

Forbidden Semi-Annihilation





$m_V < 2\, m_\pi$

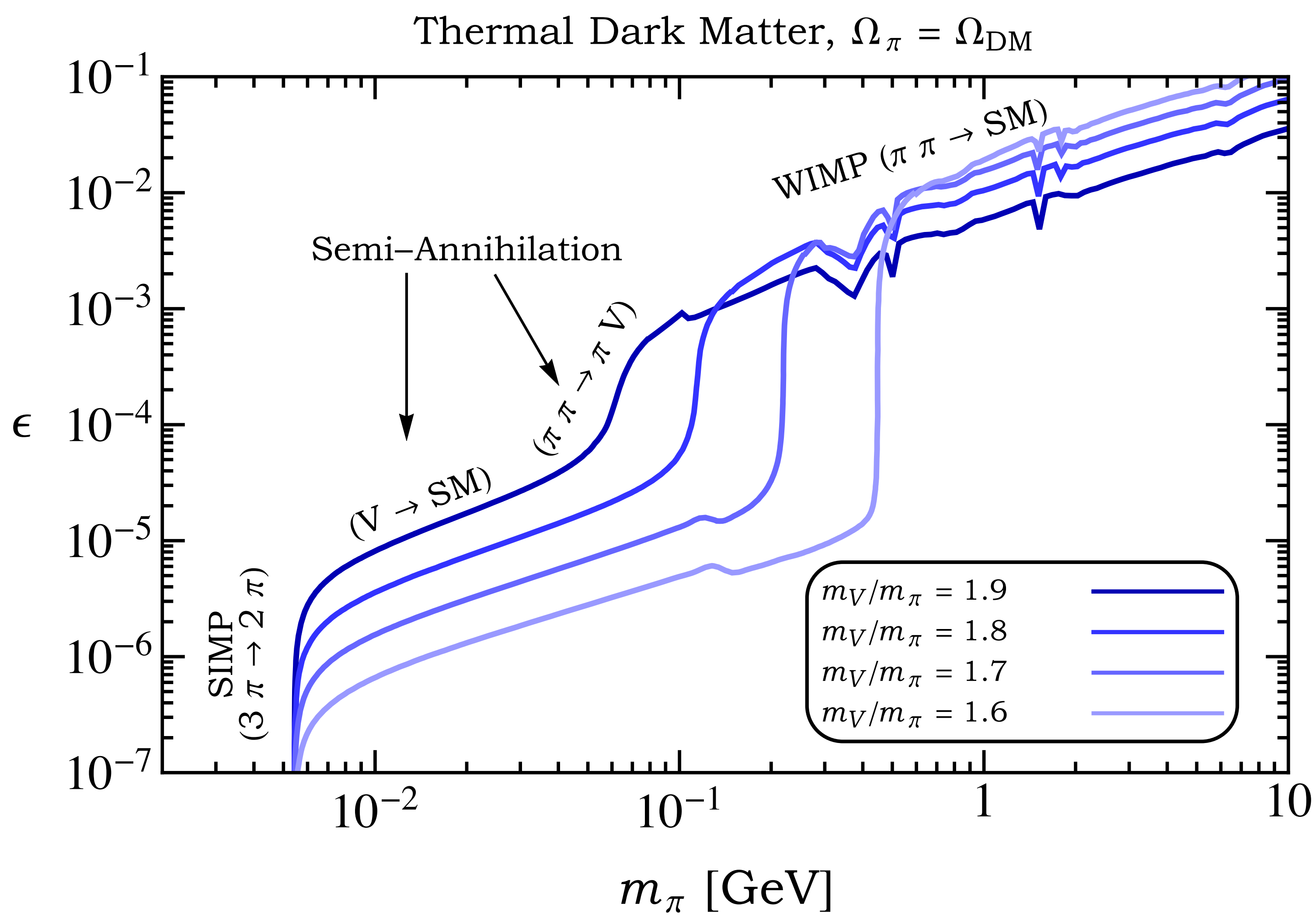
(3 → 2)

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

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

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

Forbidden Semi-Annihilation

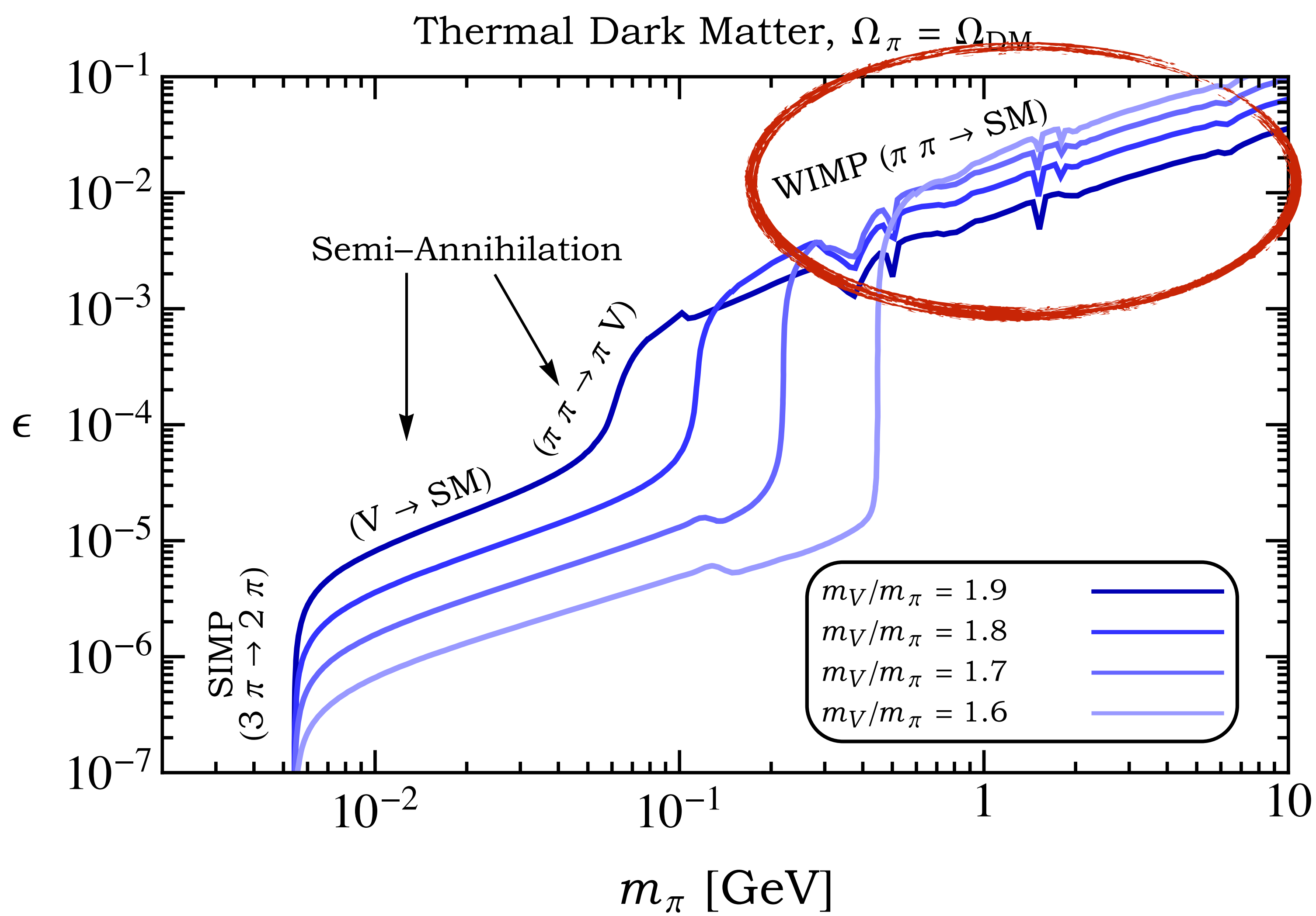


m_π / f_π = 3

$m_{A'}$ / m_π = 3

Berlin, Gori, Schuster, Toro
arXiv:1801.05805

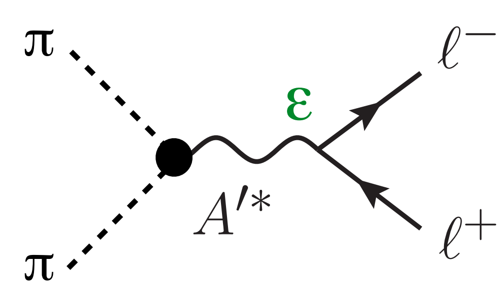
Forbidden Semi-Annihilation



m_π / f_π = 3

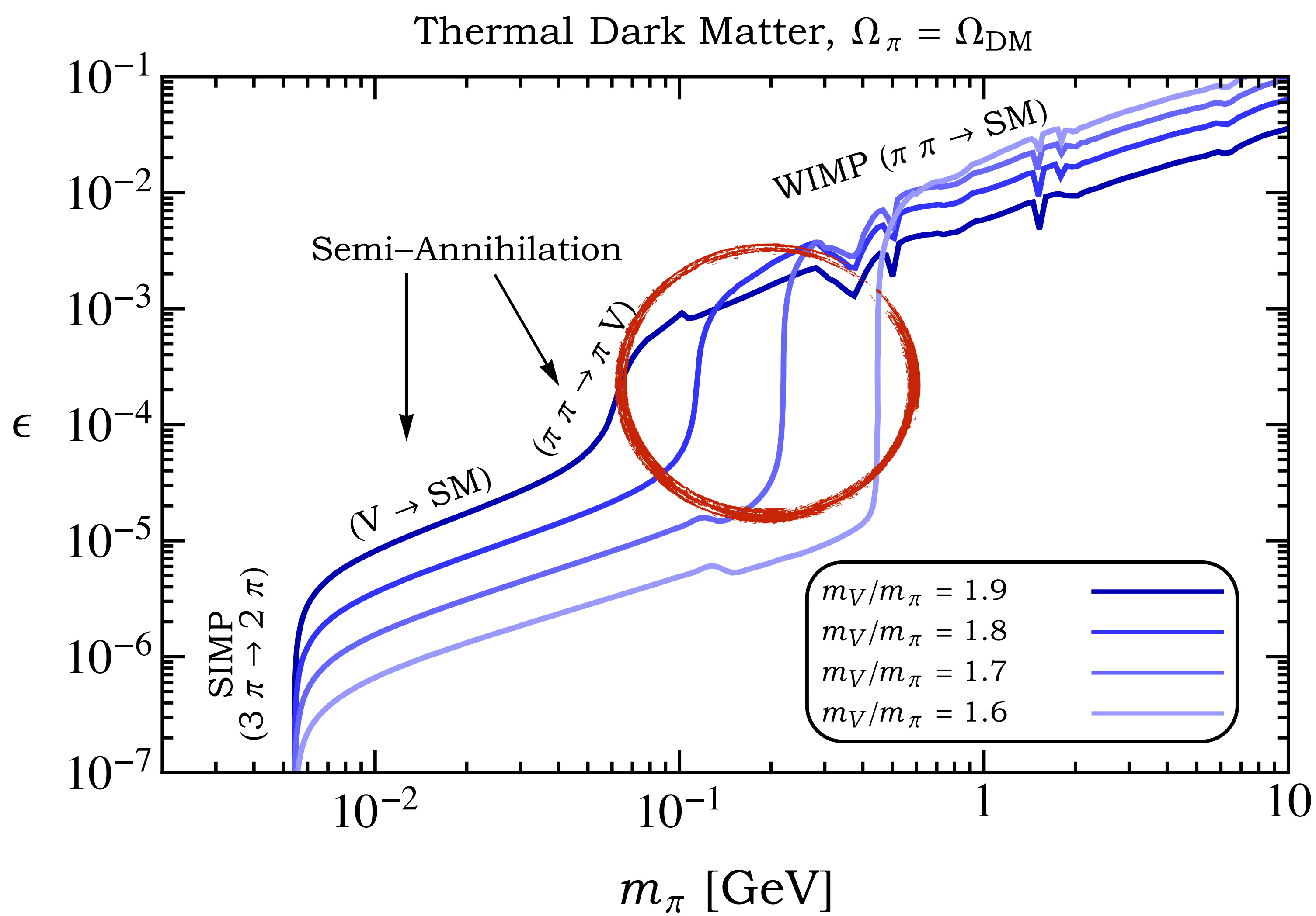
$m_{A'}$ / m_π = 3

controlling rate:



Berlin, Gori, Schuster, Toro
arXiv:1801.05805

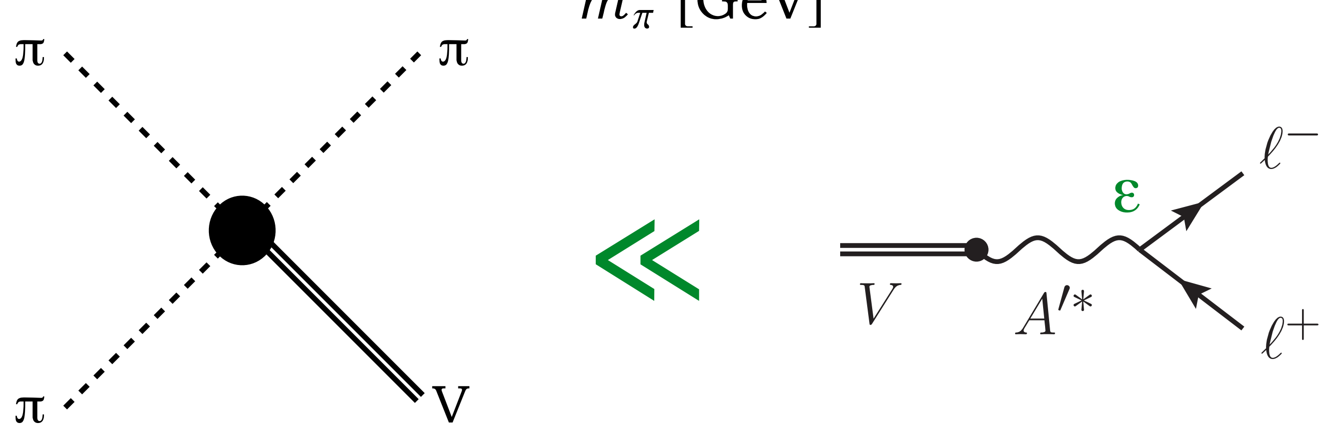
Forbidden Semi-Annihilation



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

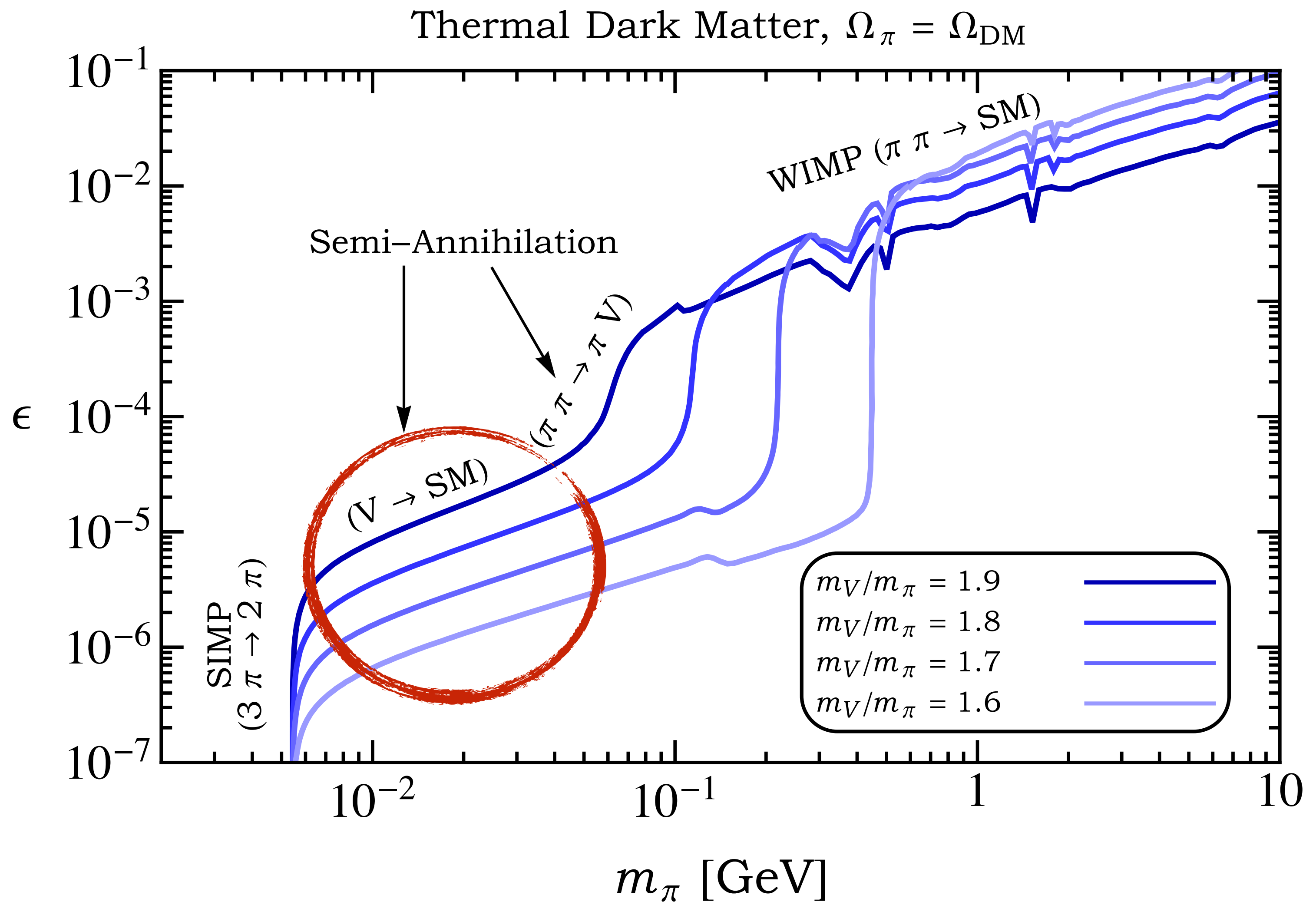
$m_{A'} \,/\, m_\pi = 3$

controlling rate:



Berlin, Gori, Schuster, Toro
arXiv:1801.05805

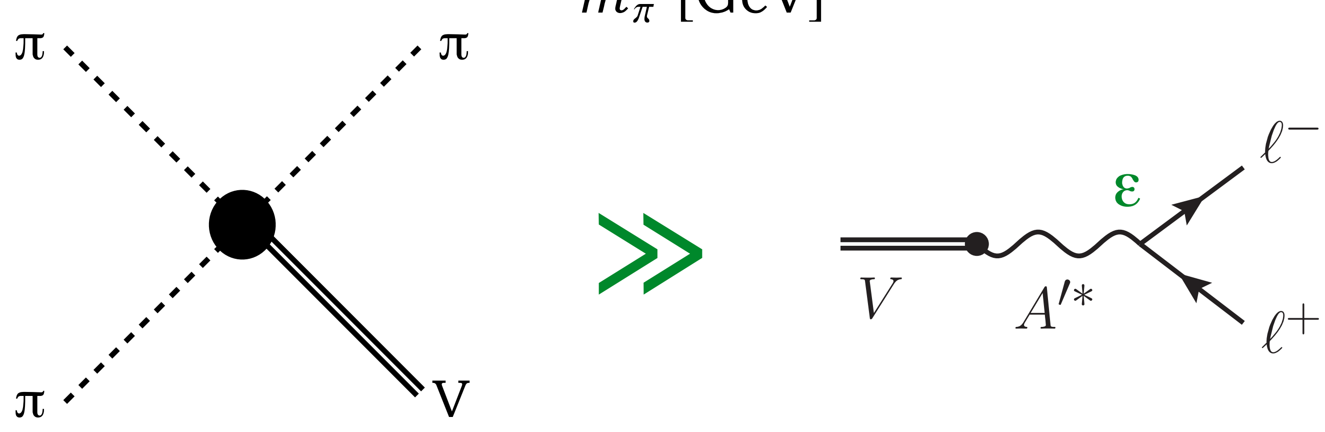
Forbidden Semi-Annihilation



m_π / f_π = 3

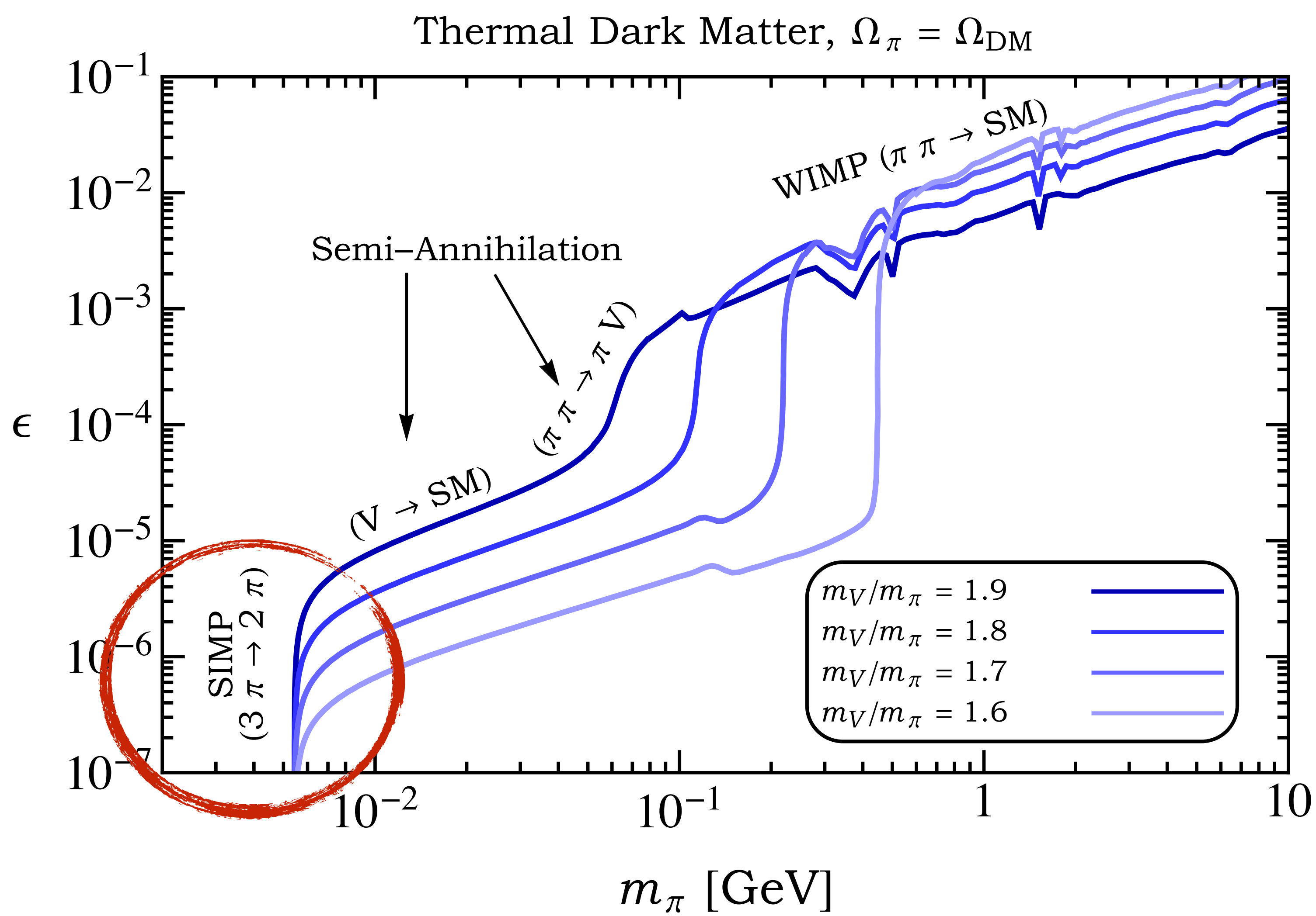
$m_{A'}$ / m_π = 3

controlling rate:



Berlin, Gori, Schuster, Toro
arXiv:1801.05805

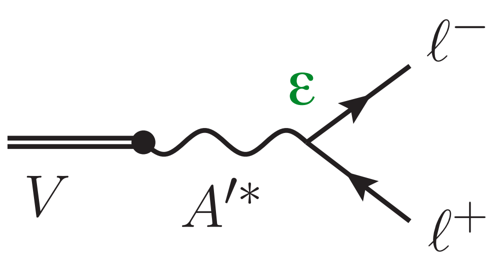
Forbidden Semi-Annihilation



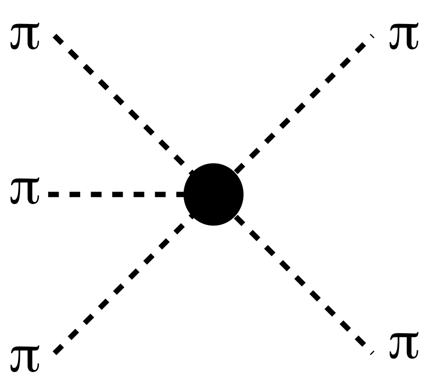
m_π / f_π = 3

$m_{A'}$ / m_π = 3

controlling rate:



$\ll$



Berlin, Gori, Schuster, Toro
arXiv:1801.05805

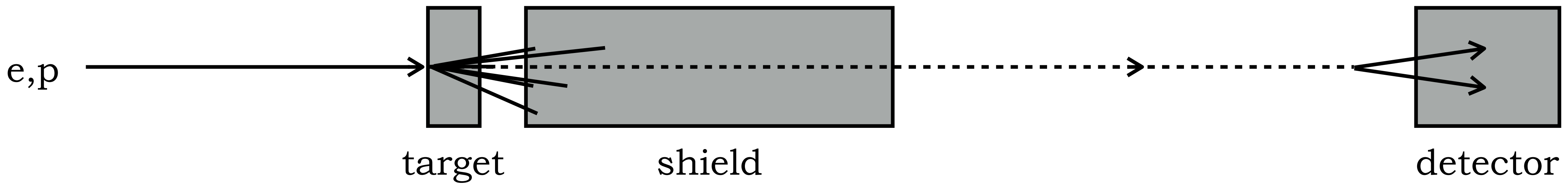
Outline

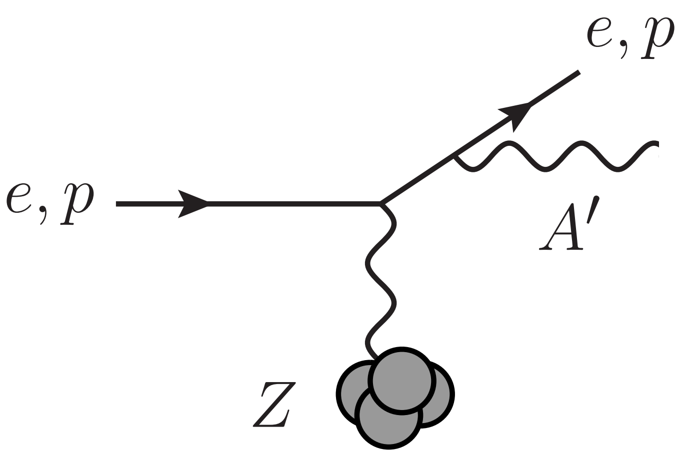
I. Review of Strongly Interacting Dark Matter

II. SIMP Cosmology

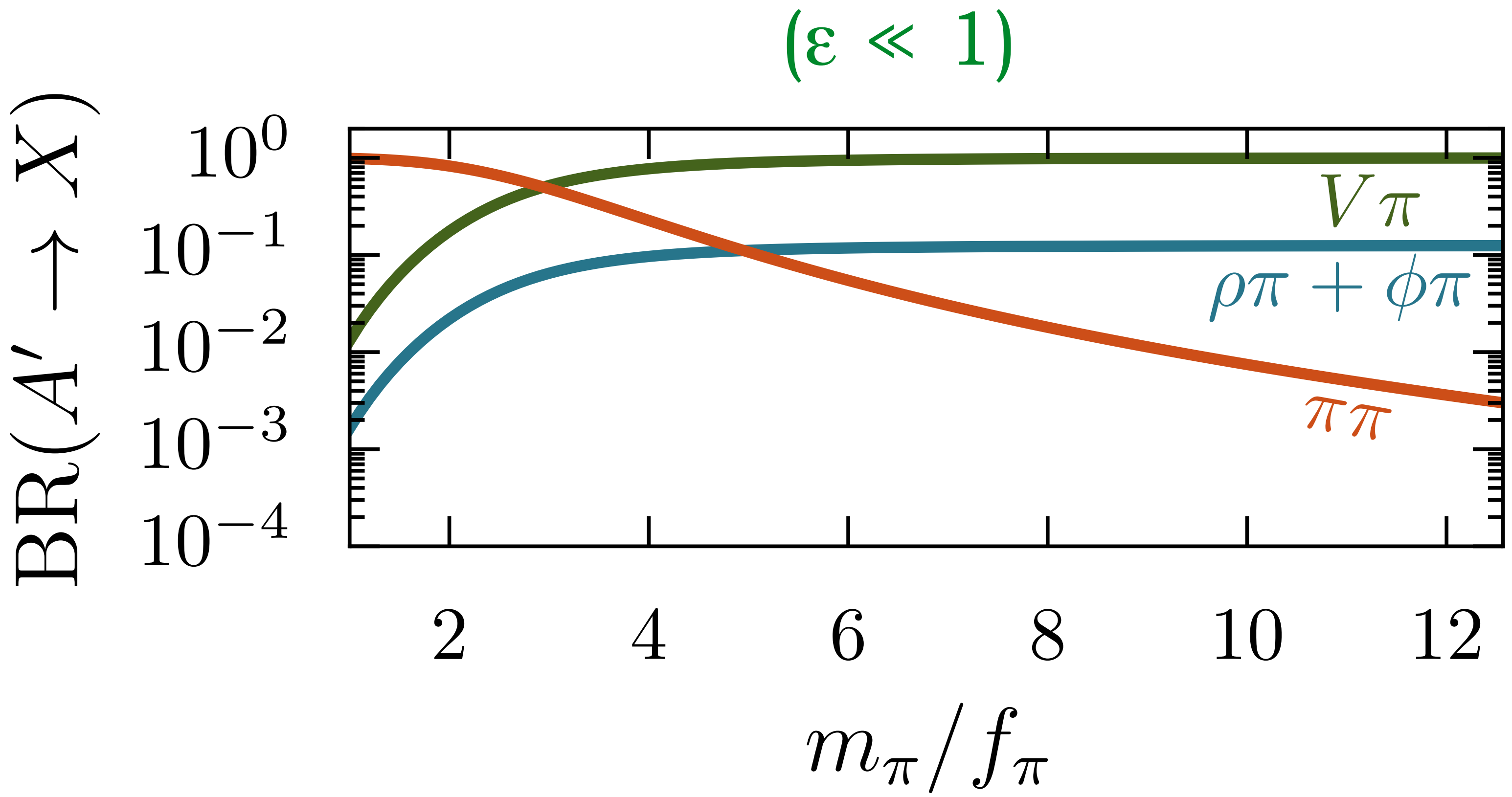
III. The GeV-Scale: Fixed-Target Experiments

Fixed-Target Search



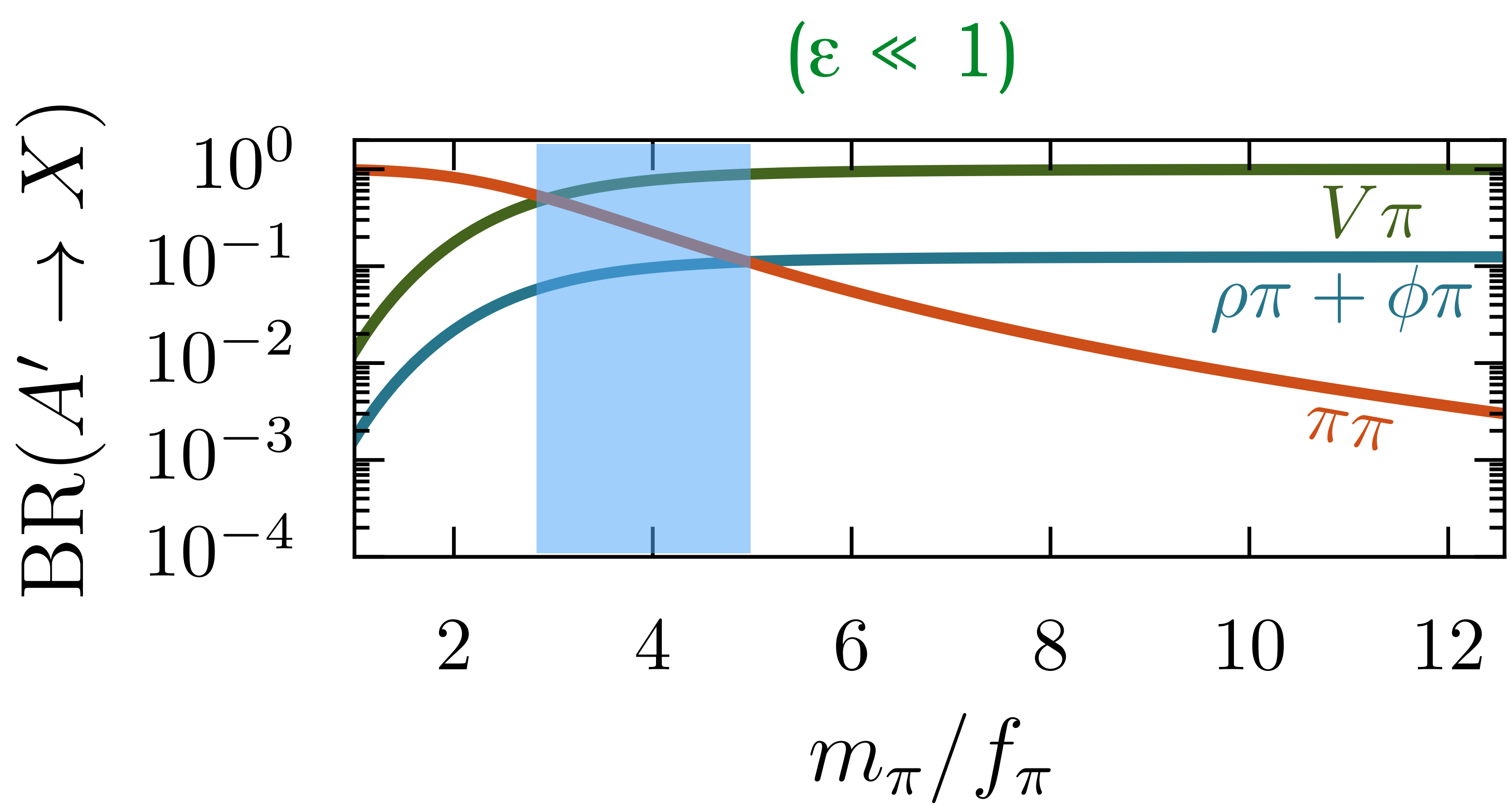


A’ Decays



Berlin, Gori, Schuster, Toro
arXiv:1801.05805

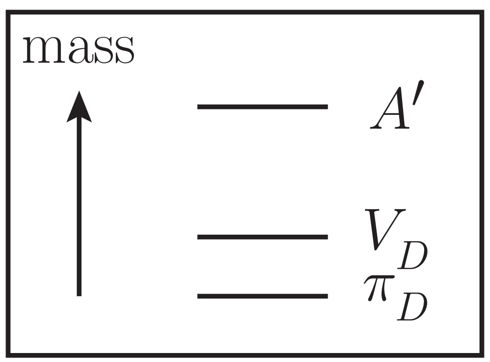
A' Decays

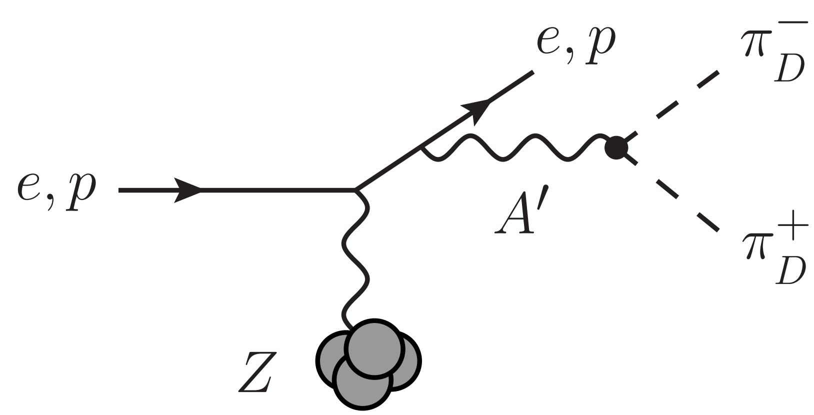


Berlin, Gori, Schuster, Toro
arXiv:1801.05805

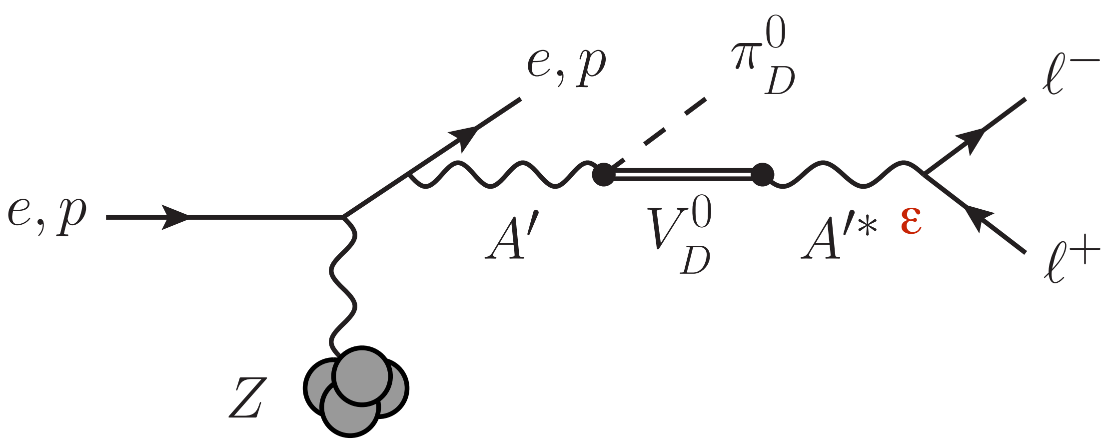
Production and Decay

(vector mesons are long-lived)

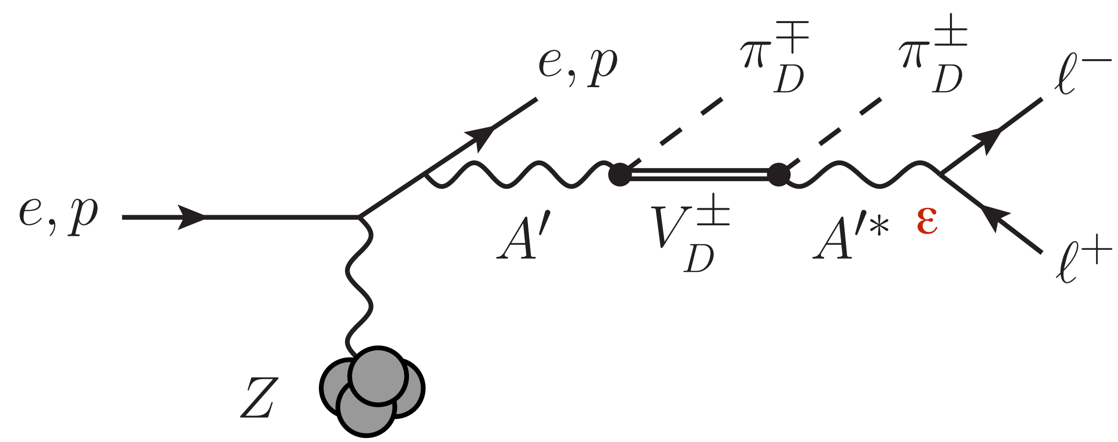




invisible decay



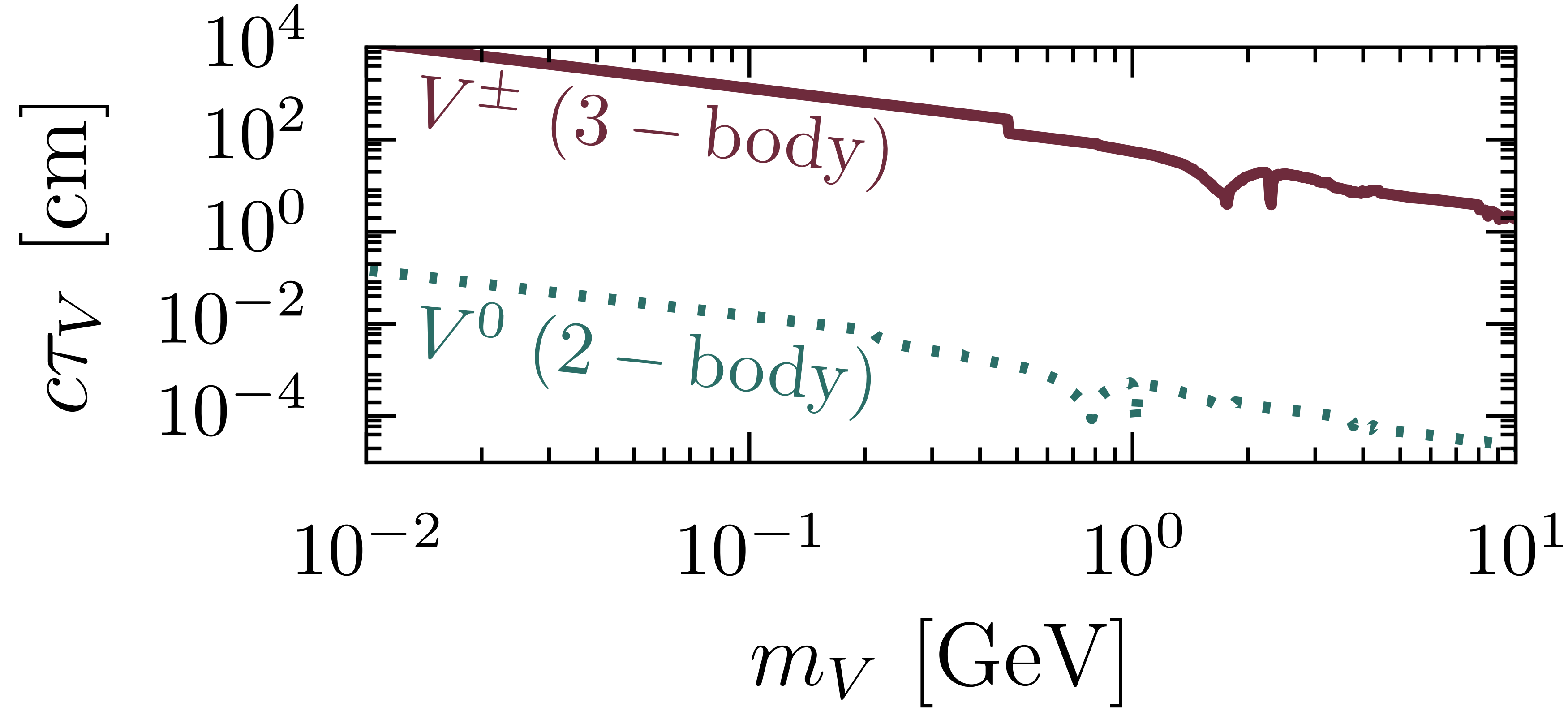
2-body V^0 decay



3-body $V^\pm$ decay

Berlin, Gori, Schuster, Toro
arXiv:1801.05805

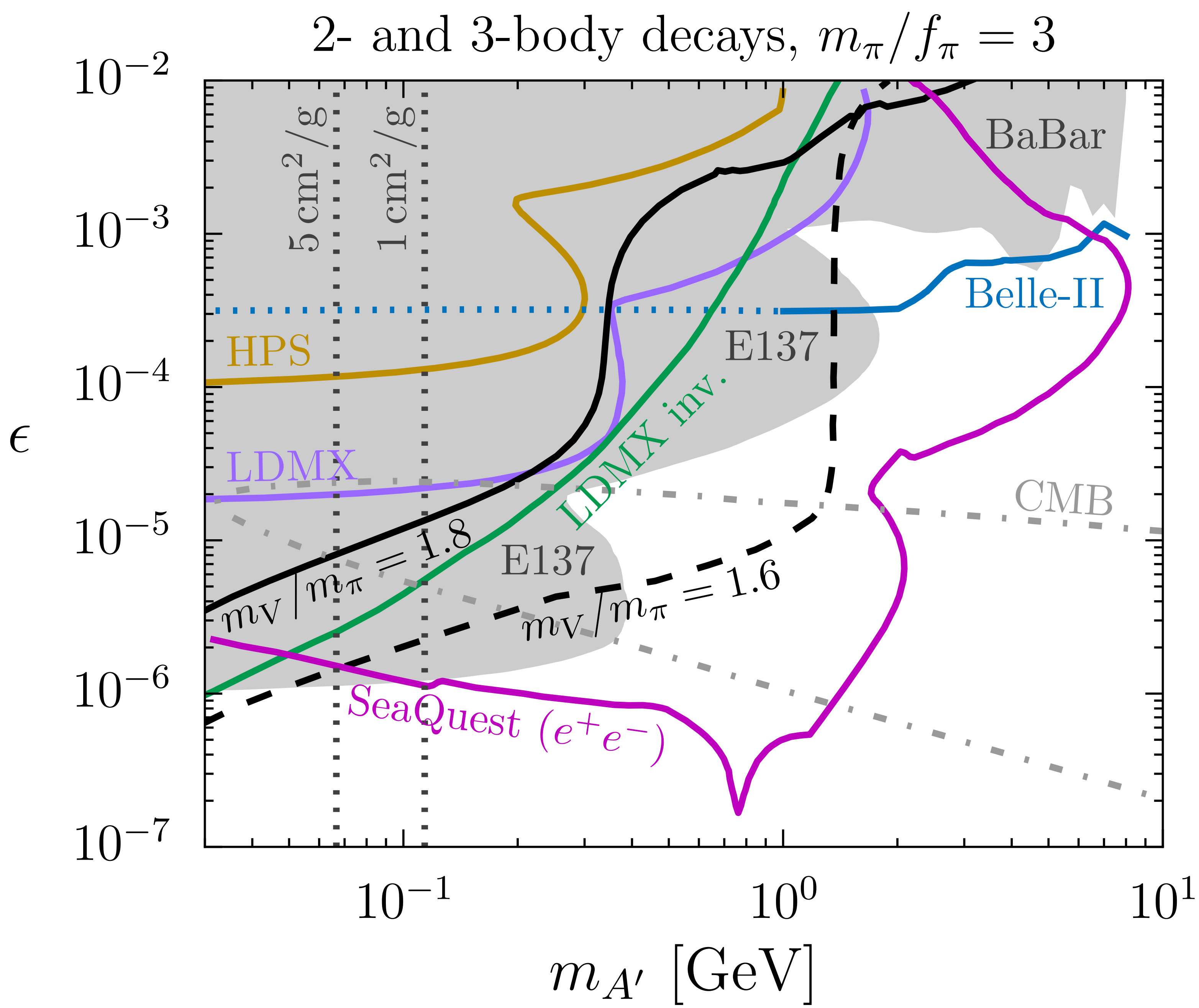
V Decays



Berlin, Gori, Schuster, Toro
arXiv:1801.05805

Signals

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



Berlin, Gori, Schuster, Toro
arXiv:1801.05805

Outlook

- Cosmology favors $m_\pi / f_\pi \gg 1$, i.e., $m_\pi \sim m_V$ parametrically true.
- Vector mesons significantly modify cosmology; widen the viable mass range. Vector mesons also lead to striking signals at low-energy accelerators.

vector-pion spectrum

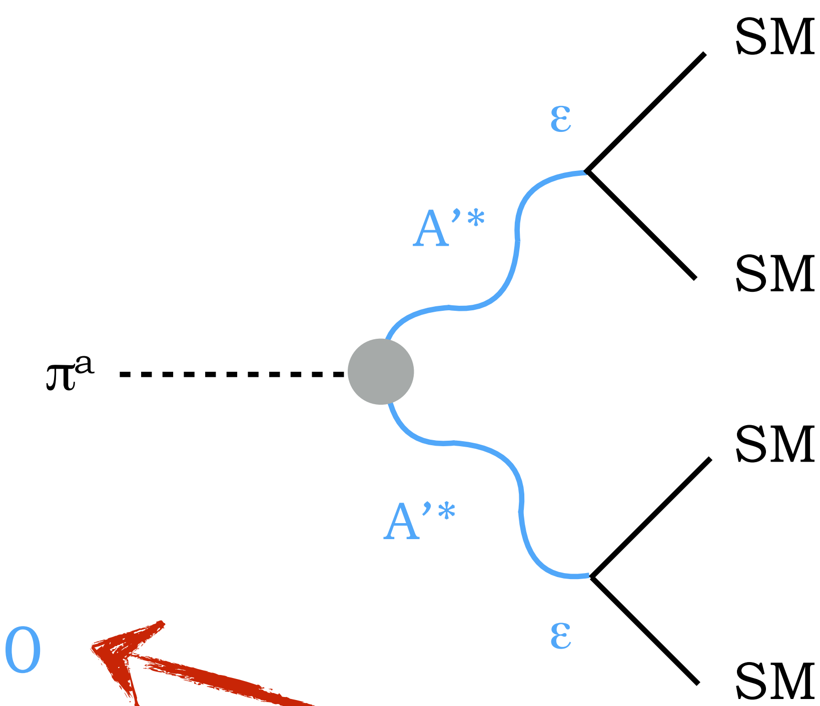
- Cosmology is exponentially sensitive to vector meson-pion mass difference.
- Phenomenology is qualitatively sensitive to vector meson-pion mass difference.

pion spectrum

- Cosmological/astrophysical signals from unstable sub-population.
- Exponentially sensitive to pion mass differences.

Back Up Slides

Decay



only true for $m_q = 0$

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 ⇒ nothing preventing decay ⇒ will decay

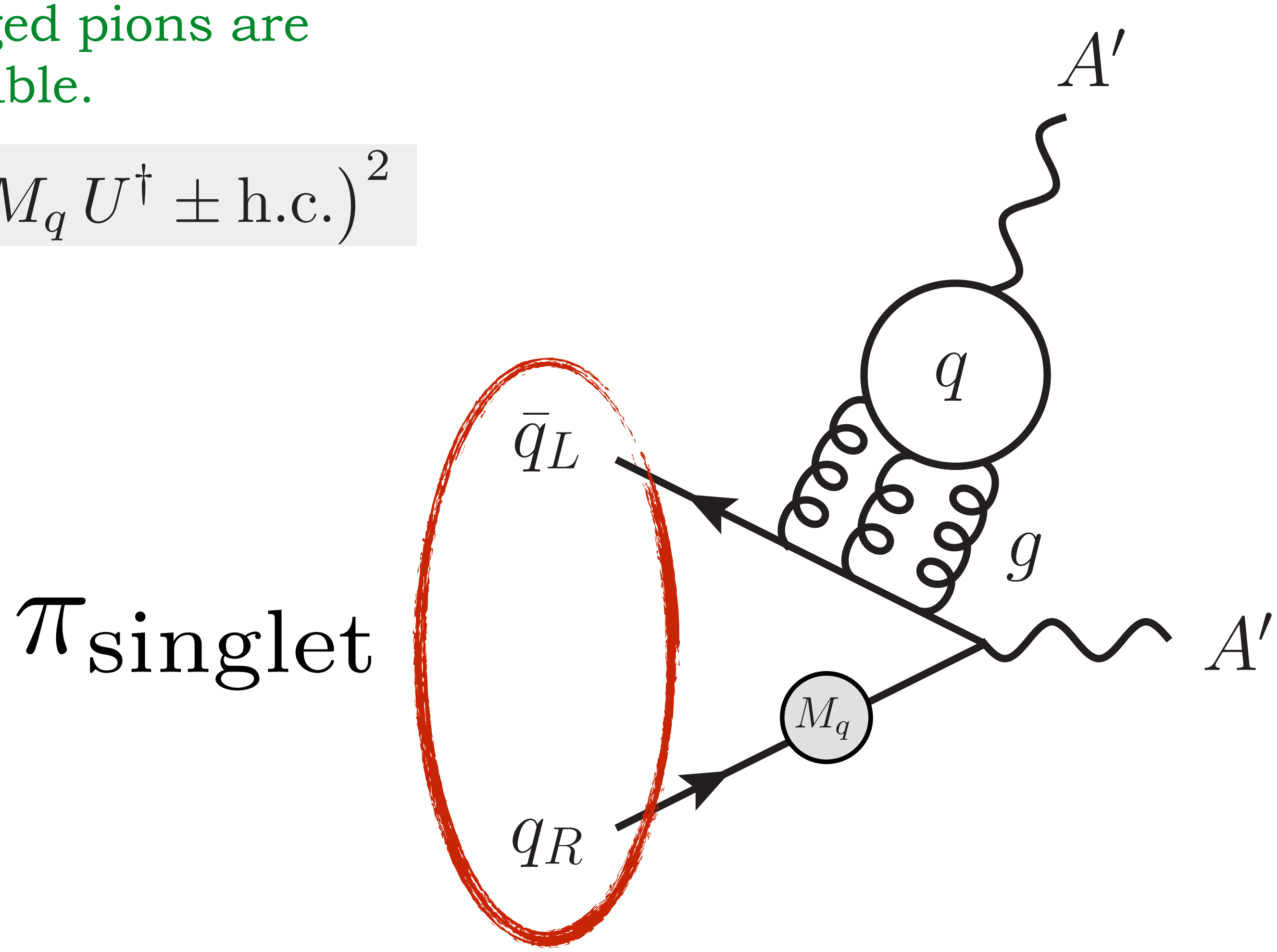
Decay

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

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

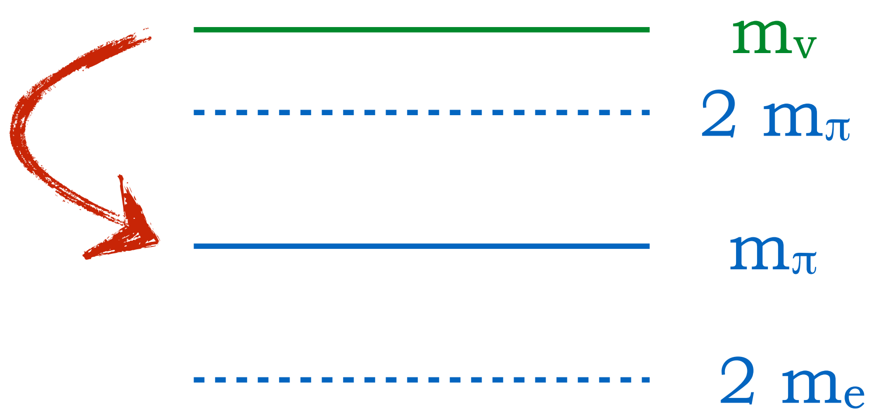


$$\frac{\alpha_D}{4\pi f_\pi}\, i\,\epsilon^{\mu\nu\alpha\beta}\, A'_{\mu\nu}\, A'_{\alpha\beta}\; \mathrm{Tr}\, Q\; \mathrm{Tr}\left(Q\, M_q\, U^\dagger\right) + \mathrm{h.c.}$$

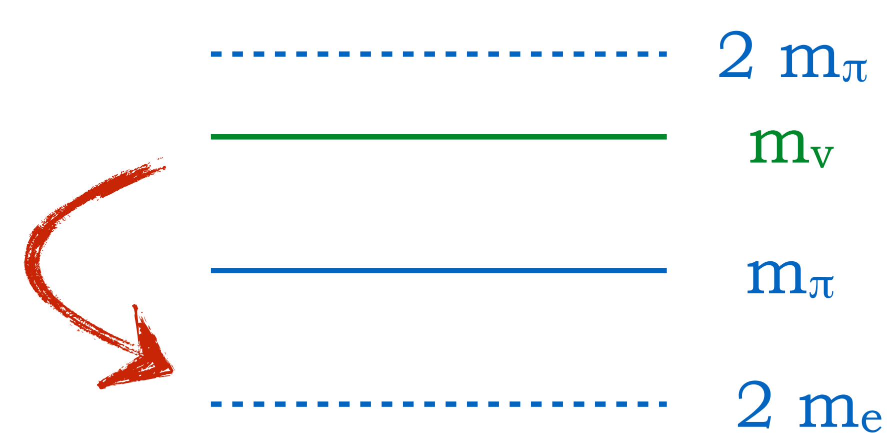
Berlin, Gori, Schuster, Toro
arXiv:1801.05805

Production and Decay

Invisible

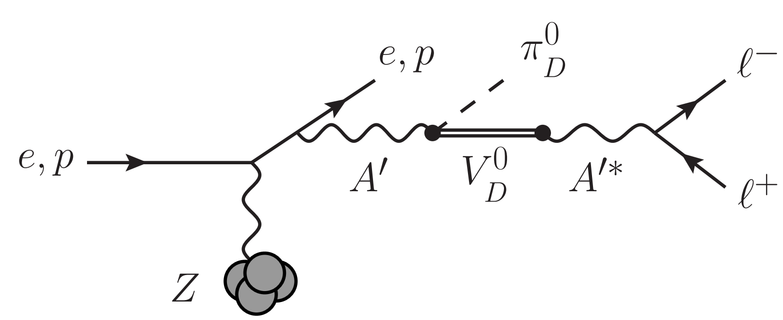


Visible $(m_\pi\ /\ f_\pi \gg 1)$



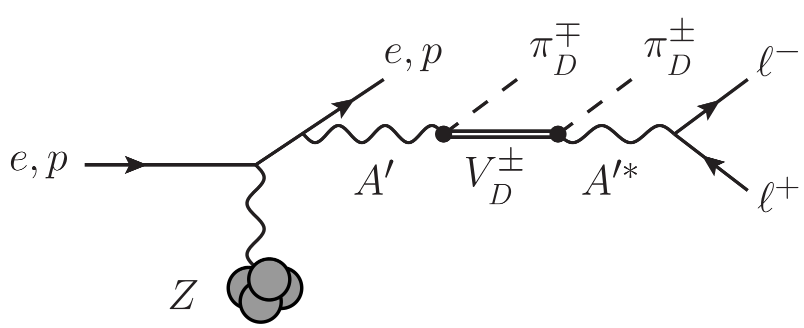
Invisible

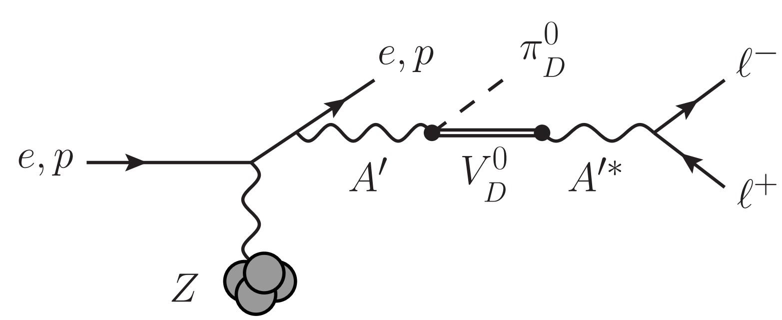
$V^\pm$



Visible

V^0 (2-body visible decays)

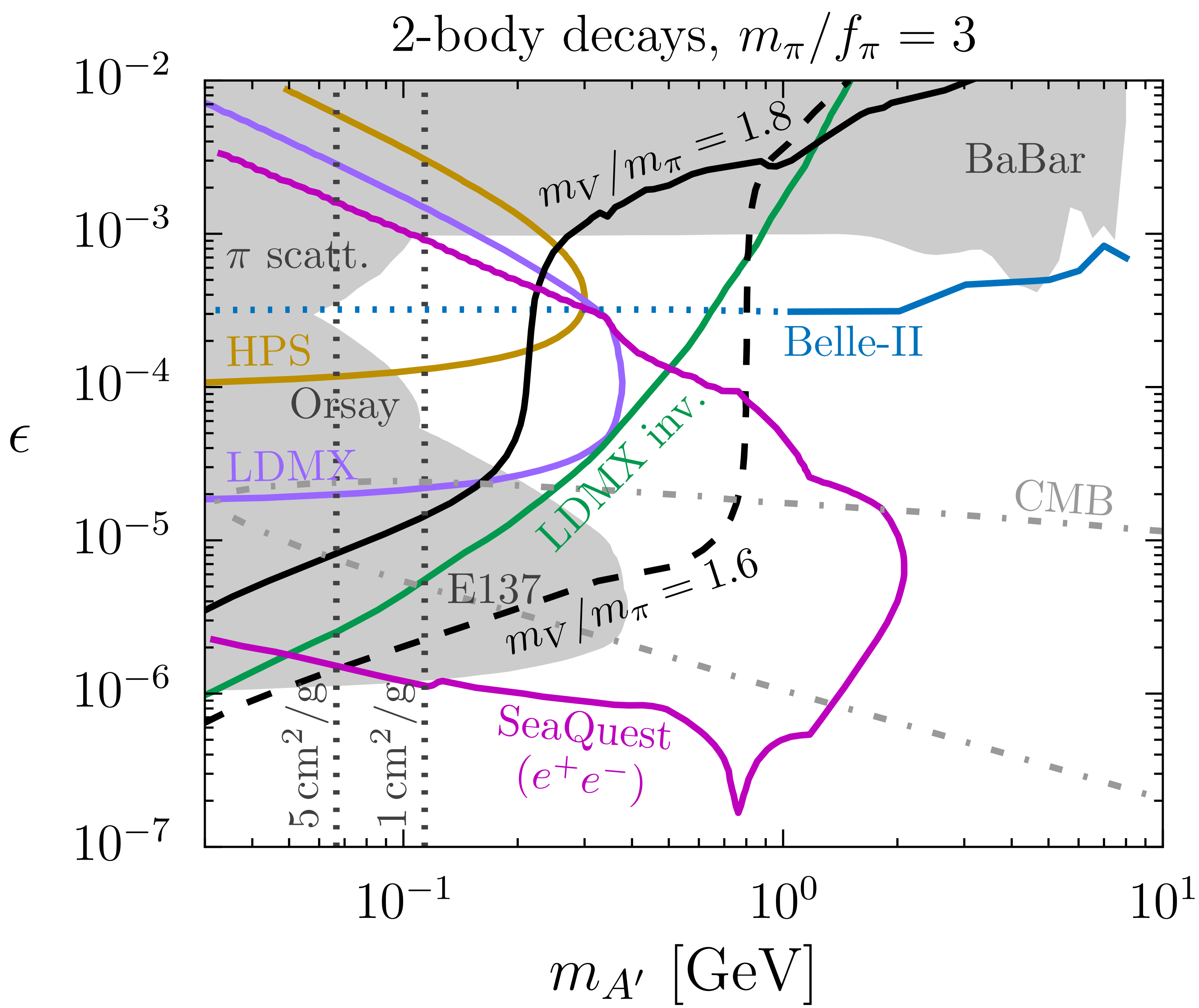




Visible

$V^0\ \ V^\pm$ (2-body and 3-body visible decays)

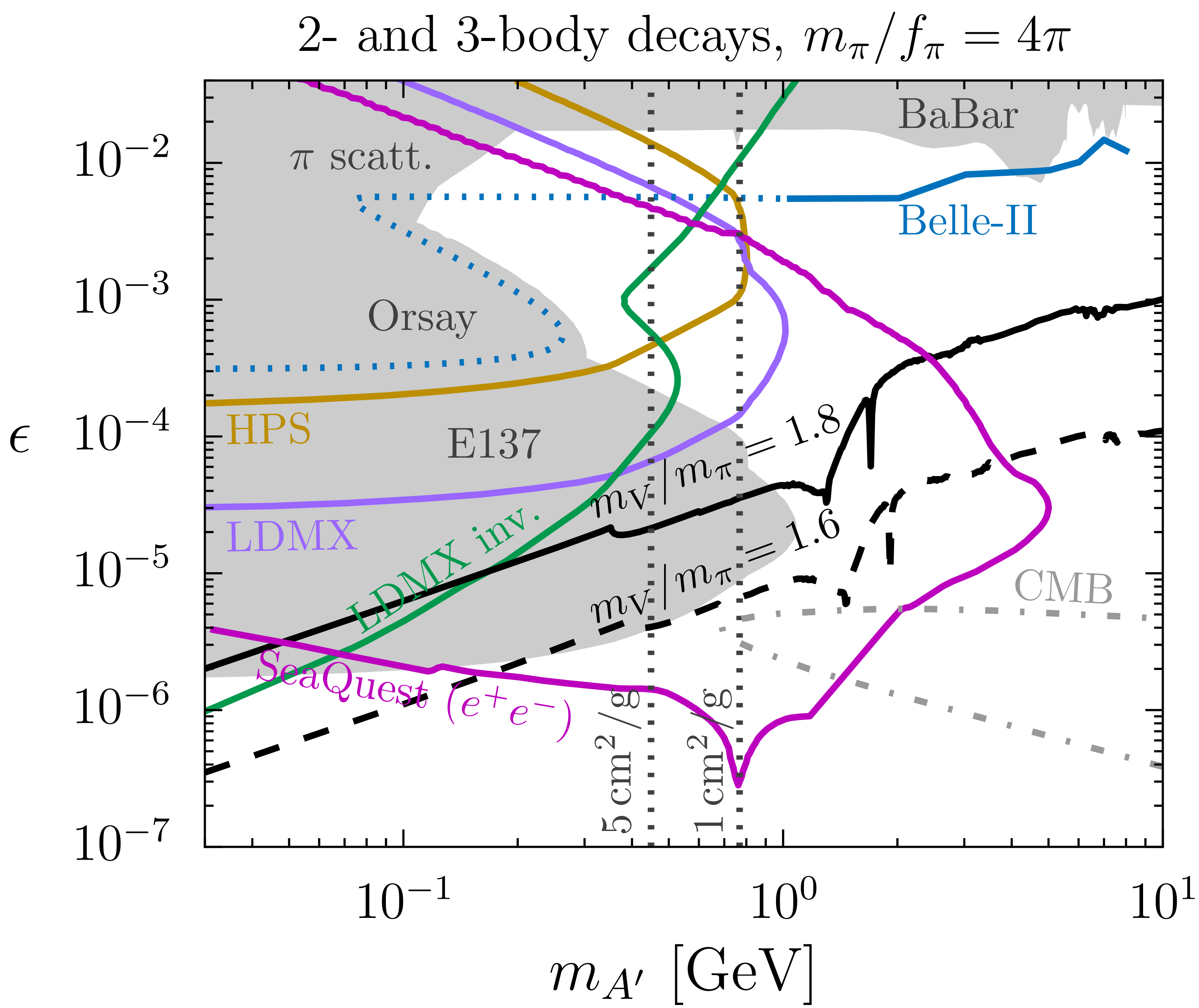
Signals



($m_{A'}$ / m_π = 3)

Berlin, Gori, Schuster, Toro
arXiv:1801.05805

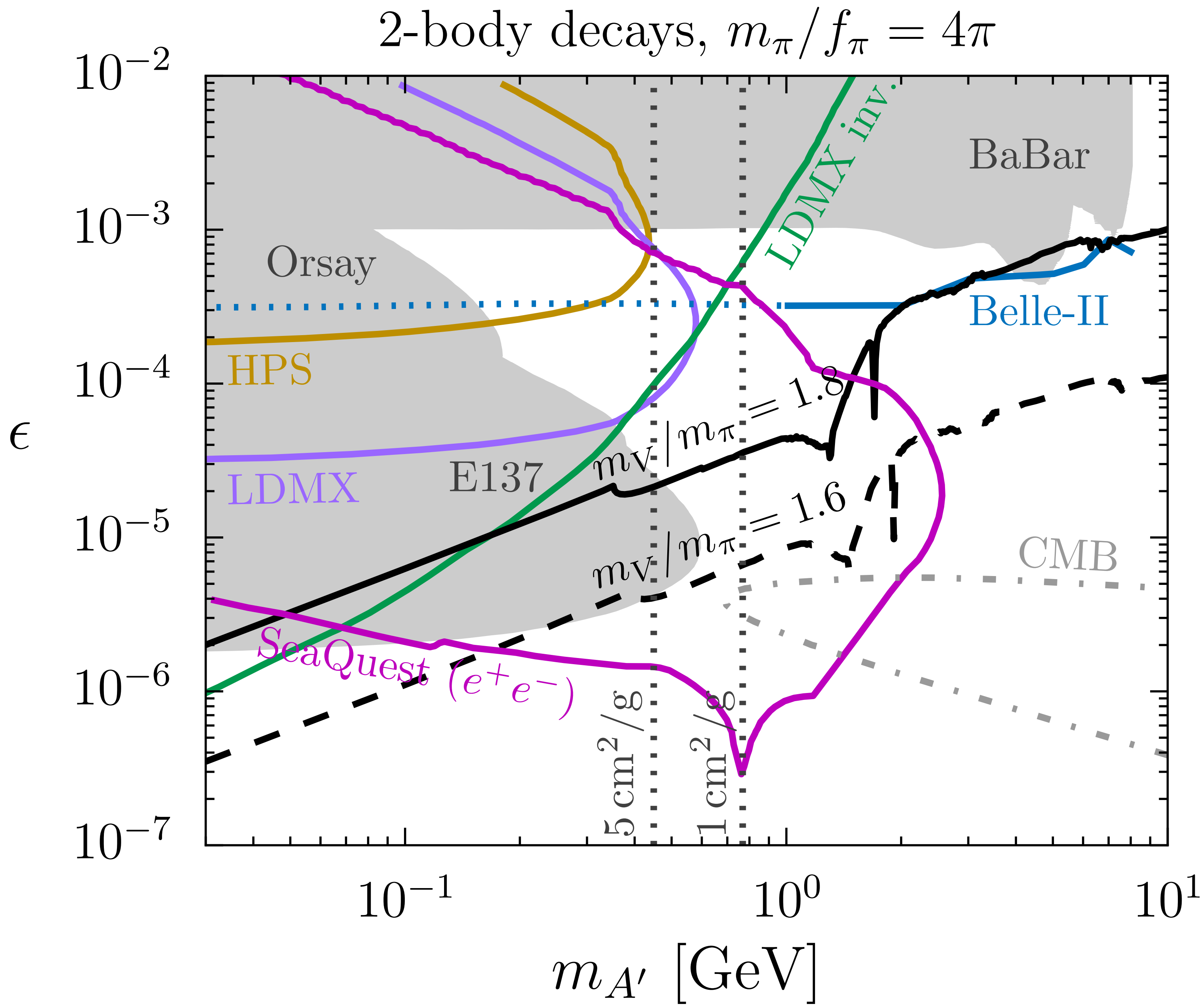
Signals



($m_{A'}$ / m_π = 3)

Berlin, Gori, Schuster, Toro
arXiv:1801.05805

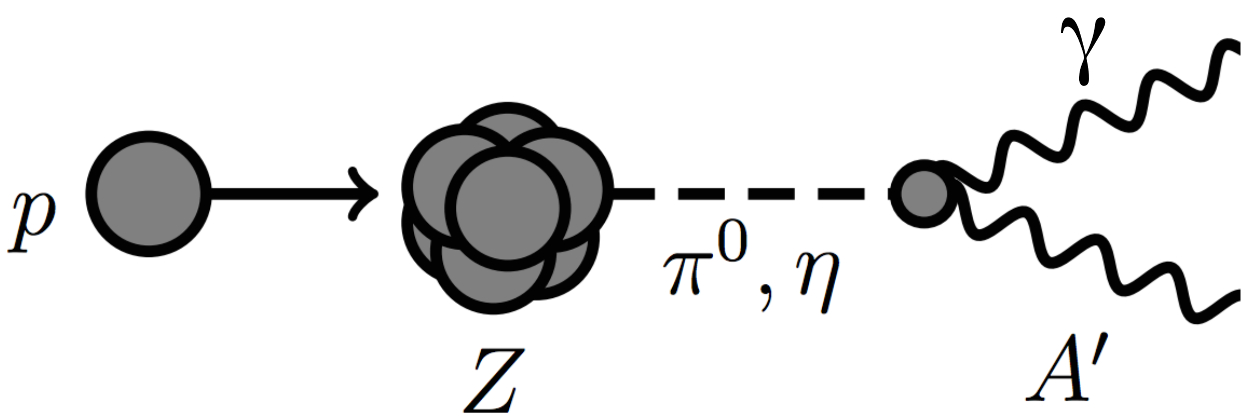
Signals

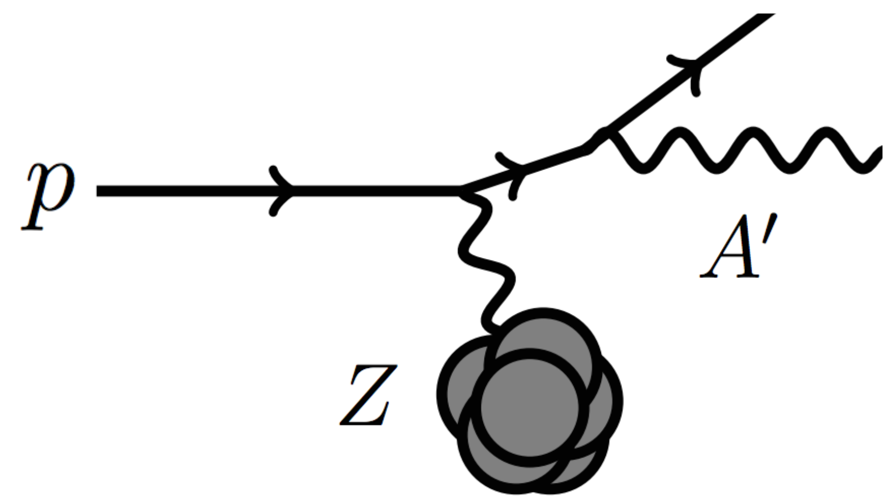


($m_{A'}$ / m_π = 3)

Berlin, Gori, Schuster, Toro
arXiv:1801.05805

Production from Protons





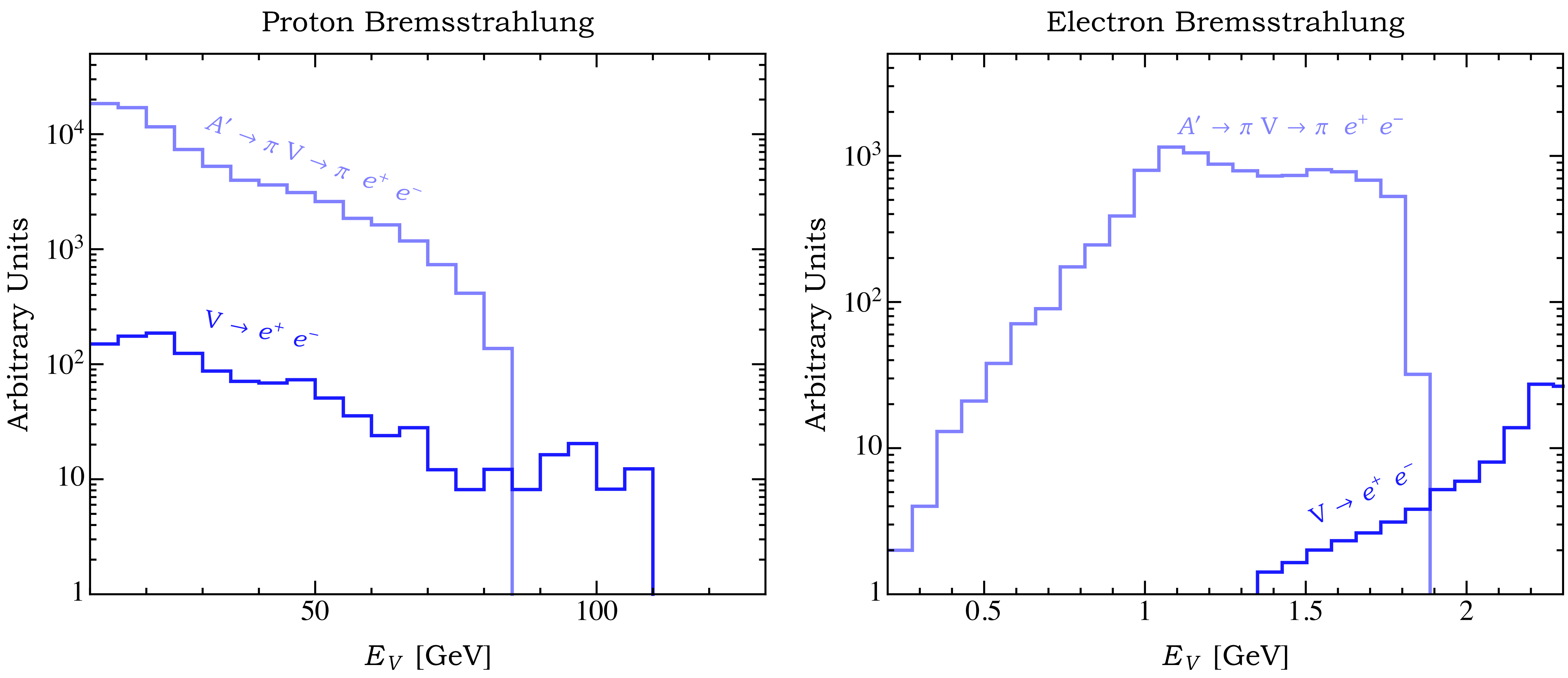
$m_{A'} \lesssim$ 100 MeV

$m_{A'} \lesssim$ 1 GeV

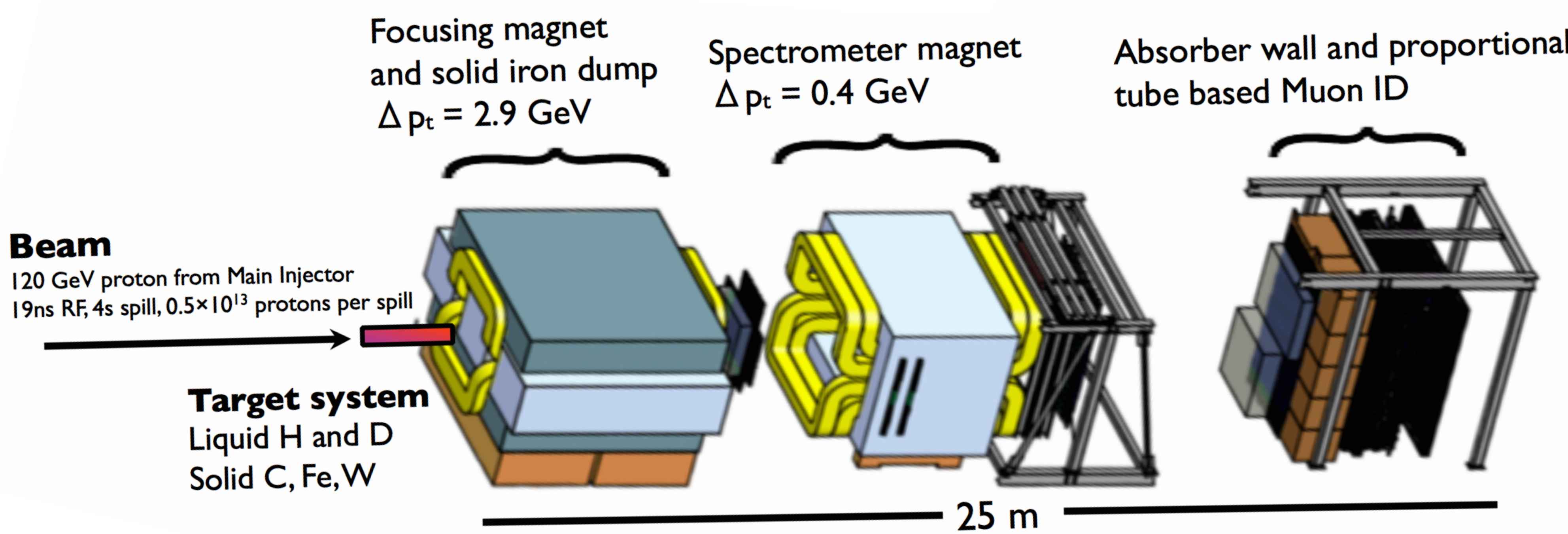
+ Drell-Yan at higher masses

arXiv:1504.04956

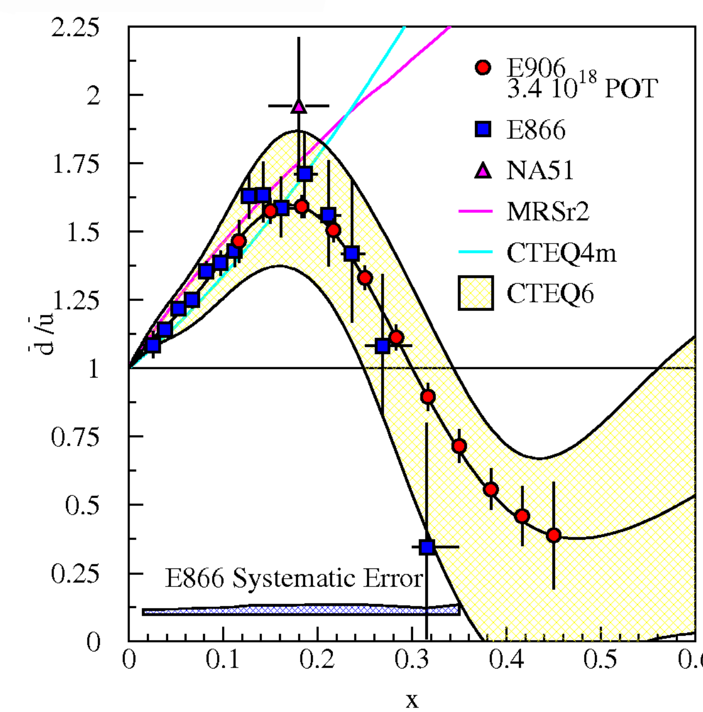
Signal Kinematics



SeaQuest

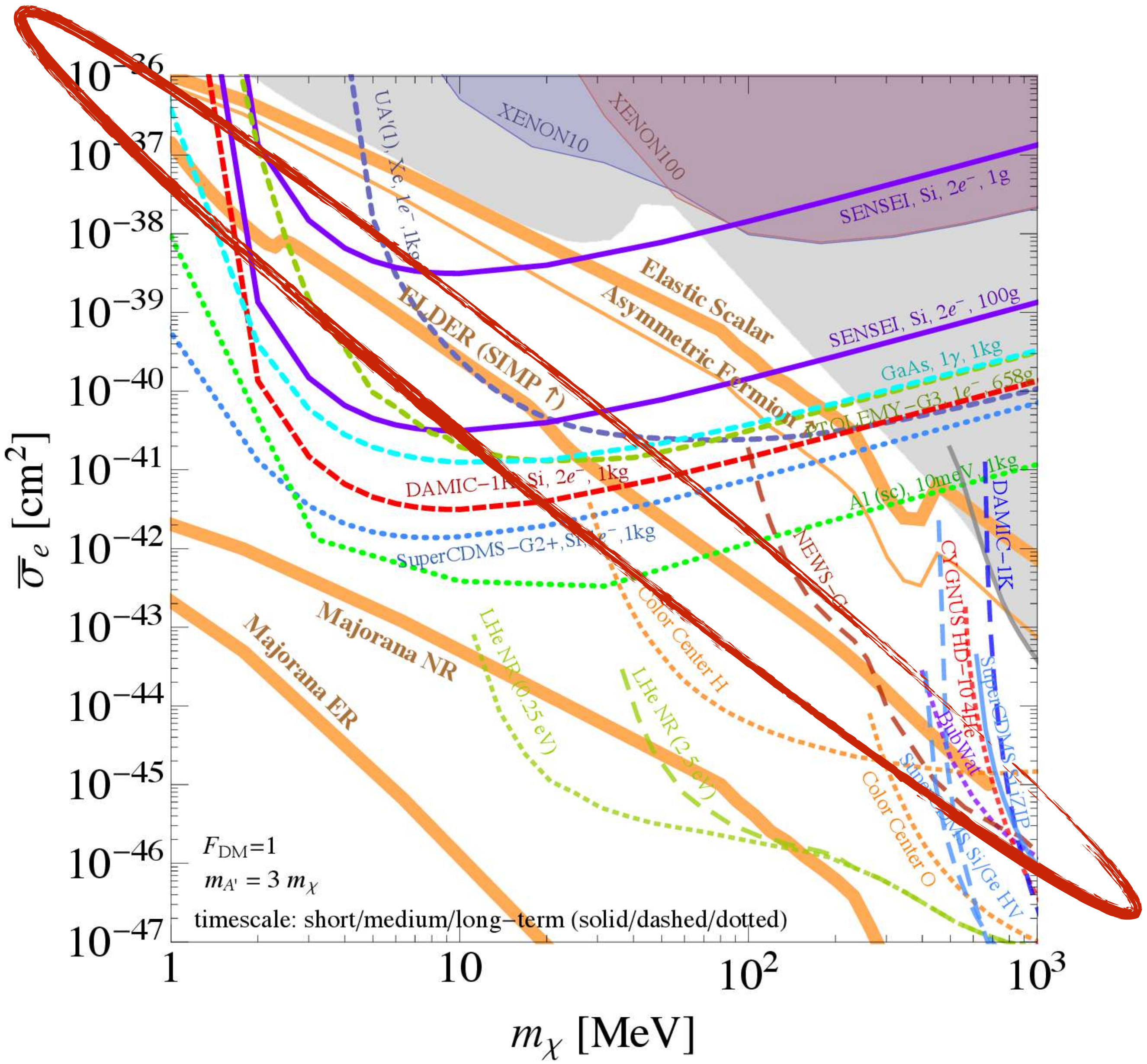


- Measure sea quark fractions at mid-x via Drell-Yan off of different targets.
- Started data taking on April 2nd.
- 10^{18} POT ~ 35,000 fb^{-1} in 2 year of parasitic run!
- Comparable luminosity to Belle-II in 2023.
- ECAL upgrade possible within the year.



(Ming X. Liu)

SIMP Target



US Cosmic Visions Community Report,
arXiv: 1707.04591

Decays

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

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

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

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

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

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

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

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

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

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

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

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

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