Dipole Dark Matter (v2)

- The Dipole DM model extends the SM by adding three Dirac Fermions and a real scalar, all singlets under the SM gauge group:

$$\chi_2,\ \chi_1,\ \chi_0 \text{ and } \phi$$

- The Lagrangian of the model is given by:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\phi} + \mathcal{L}_{\chi} + \mathcal{L}_{H\chi} + \mathcal{L}_{\rm dipole},$$

$$\mathcal{L}_{\phi} = (\partial^{\mu}\phi)^2 - \mu_2^2|\phi|^2 - \lambda_2\phi^4 - \lambda_3\phi^2|H|^2\,,$$

$$\mathcal{L}_{\chi} = i\overline{\chi}_i\partial\chi_i - \tilde{M}_{ij}\overline{\chi}_i\chi_j - (y_{\chi})_{ij}\,\overline{\chi}_i\chi_j\phi\,,$$

$$\mathcal{L}_{H\chi} = \frac{(C_{H\chi\chi})_{ij}}{\Lambda}\overline{\chi}_i\chi_j|H|^2\,.$$

$$\mathcal{L}_{\rm dipole} = \frac{(C_{\gamma\chi\chi})_{ij}}{\Lambda}\overline{\chi}_i\sigma^{\mu\nu}\chi_j F_{\mu\nu}$$

Dipole Dark Matter (v2)

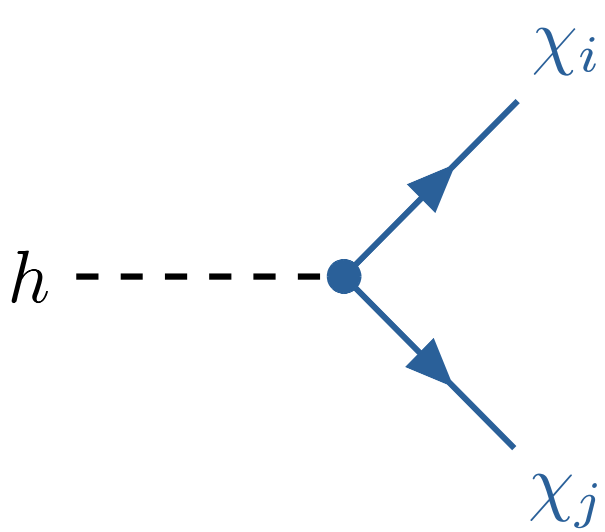
- Mass eigenstates: $\chi_2,\ \chi_1,\ \chi_0,\ S$

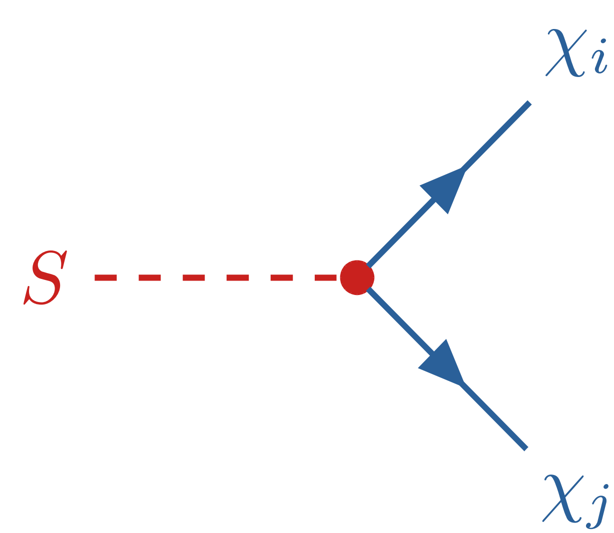
$$h = (\sqrt{2}H^0 - v)\cos\alpha - (\sqrt{2}\phi - v_D)\sin\alpha\,,$$
$$S = (\sqrt{2}\phi - v_D)\cos\alpha + (\sqrt{2}H^0 - v)\sin\alpha\,.$$

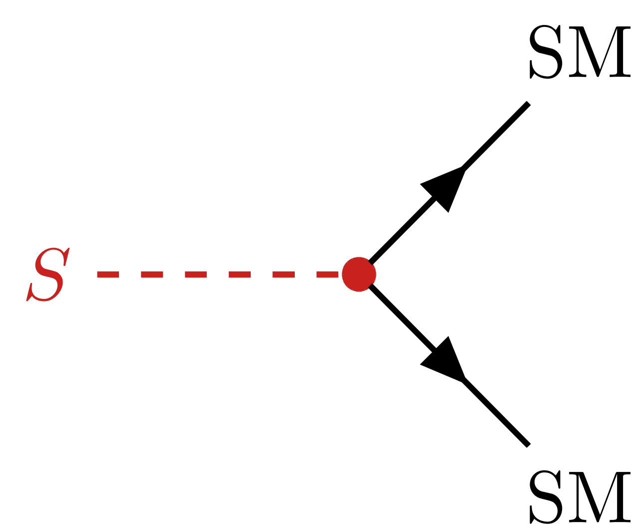
- We assume the following mass hierarchy:

$$m_S > m_{\chi_2} > m_{\chi_1} > m_{\chi_0} > m_h/2$$

- Vertices:







$$\frac{i}{\sqrt{2}}(y_\chi)_{ij}\sin\alpha - i\frac{v}{\Lambda}(C_{H\chi\chi})_{ij}\cos\alpha$$

$$-\frac{i}{\sqrt{2}}(y_\chi)_{ij}\cos\alpha - i\frac{v}{\Lambda}(C_{H\chi\chi})_{ij}\sin\alpha$$

$$\propto \sin\alpha$$

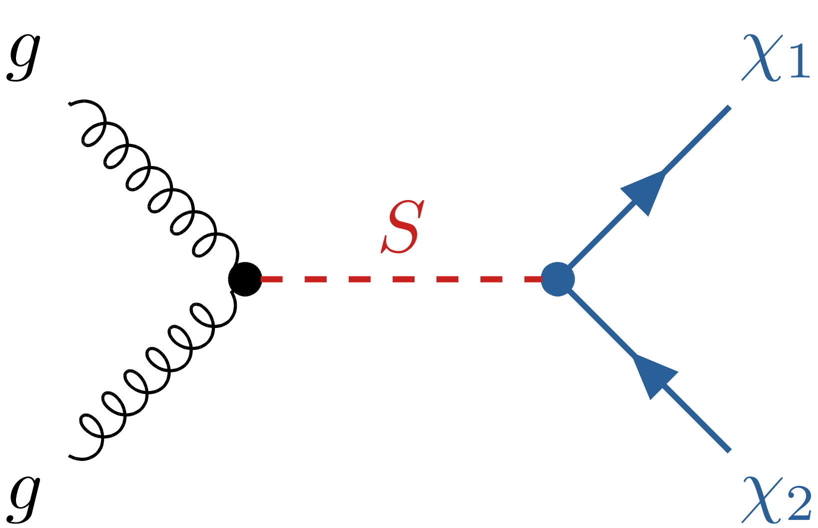
Dipole Dark Matter (v2)

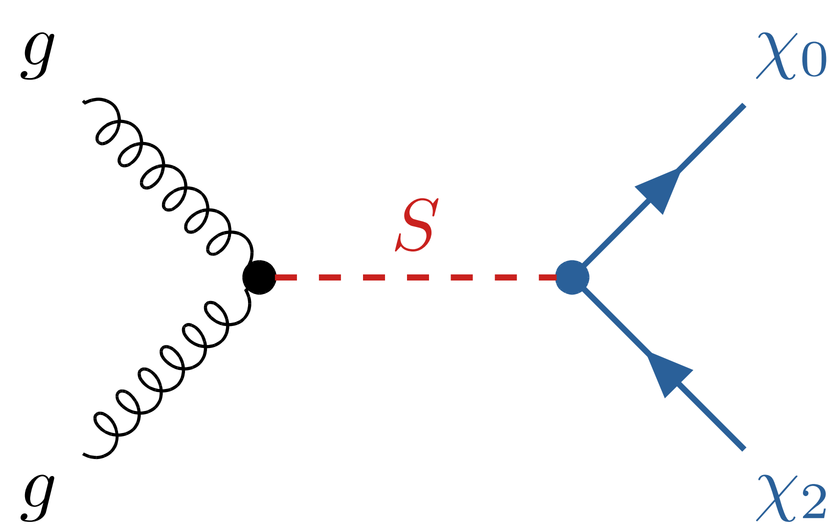
- Minimal "12"-Model:

$$(C_{H\chi\chi})_{ij} = 0 \text{ , if } i = j \text{ or } i = 2 \text{ or } j = 2$$
$$(y_\chi)_{ij} = 0 \text{ , if } i = j \text{ or } i = 1, j = 0$$

$$\mathcal{L}_\chi = \overline{\chi}_i \left(i\partial\!\!\!/ - M_i \right) \chi_i - \left[(y_\chi)_{21}\, \overline{\chi}_2 \chi_1 \phi + (y_\chi)_{20}\, \overline{\chi}_2 \chi_0 \phi + \frac{(C_{H\chi\chi})_{01}}{\Lambda} \overline{\chi}_0 \chi_1 |H|^2 + h.c. \right]$$

- "Leading" Production: $(v/\Lambda \ll 1, \alpha < 1)$





$-\frac{i}{\sqrt{2}}(y_\chi)_{21} \cos\alpha \sin\alpha$

$-\frac{i}{\sqrt{2}}(y_\chi)_{20} \cos\alpha \sin\alpha$

Dipole Dark Matter (v2)

- Minimal "12"-Model:

$$(C_{H\chi\chi})_{ij} = 0 \ , \text{ if } i = j \text{ or } i = 2 \text{ or } j = 2$$
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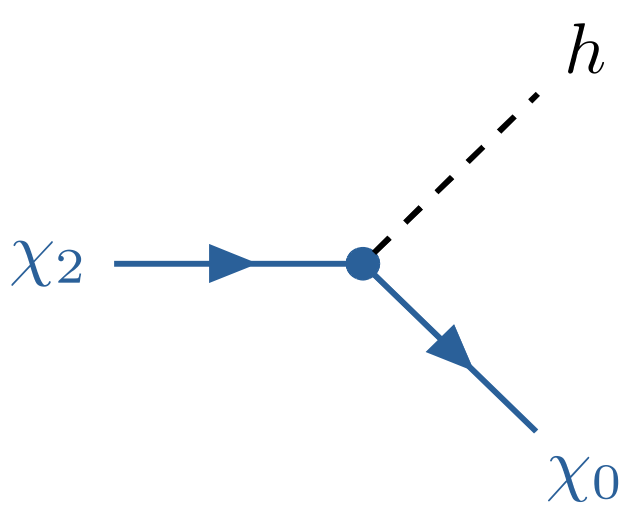
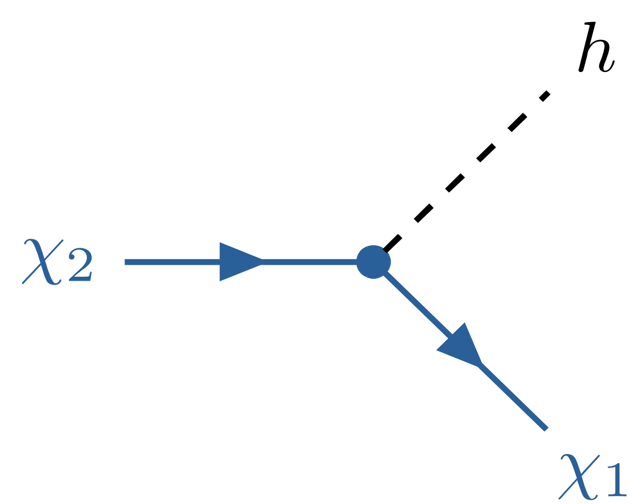
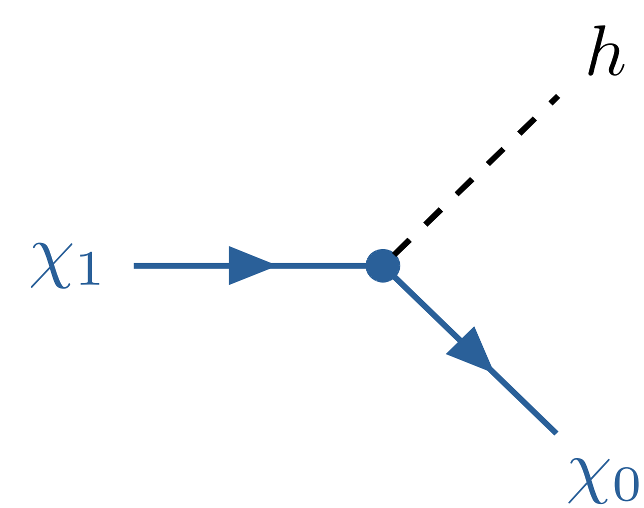
- "Leading" Decays: $(v/\Lambda \ll 1, \alpha < 1)$



$\simeq \frac{i}{\sqrt{2}} (y_\chi)_{20} \sin\alpha$



$\simeq \frac{i}{\sqrt{2}} (y_\chi)_{21} \sin\alpha$

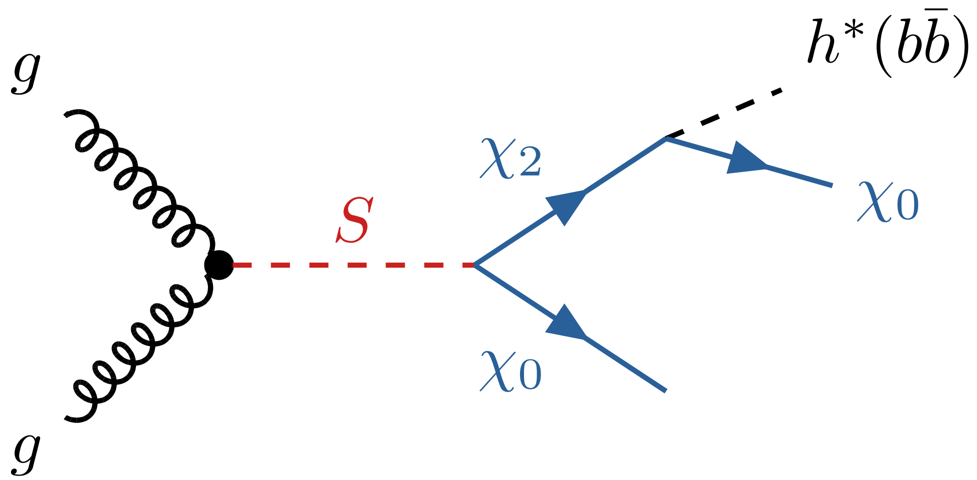


$\simeq -i\frac{v}{\Lambda} (C_{H\chi\chi})_{10} \cos\alpha$

- Note that chi2 → chi0+h dominates over chi2→chi1+h, if mchi2 ~ mchi1

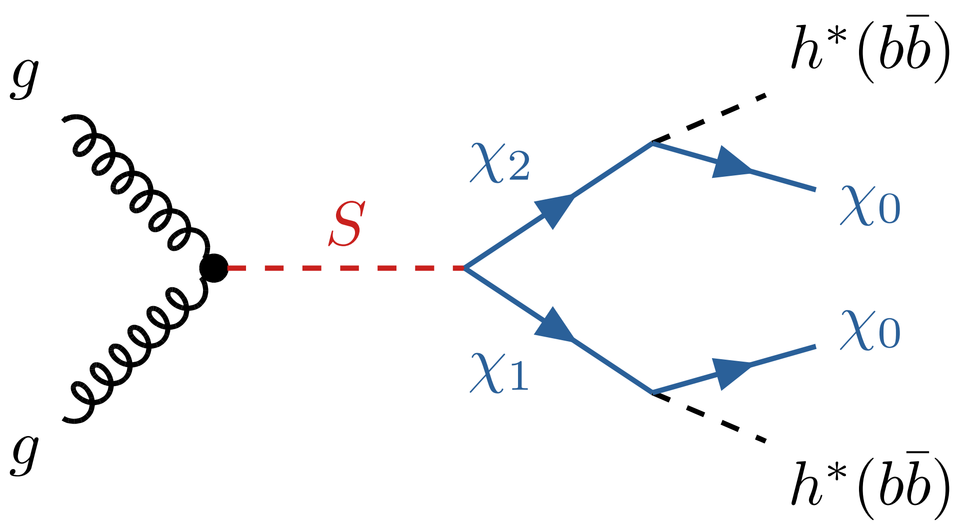
Dipole Dark Matter (v2)

- Leading channels:



Prompt $\left((y_\chi)^2_{20}\,\sin\alpha\right)$

$$\sigma \propto \left[(y_\chi)_{20}\cos\alpha\ \sin\alpha\right]^2$$



Prompt $\left((y_\chi)^2_{20}\,\sin\alpha\right)$

$$\sigma \propto \left[(y_\chi)_{21}\cos\alpha\ \sin\alpha\right]^2$$

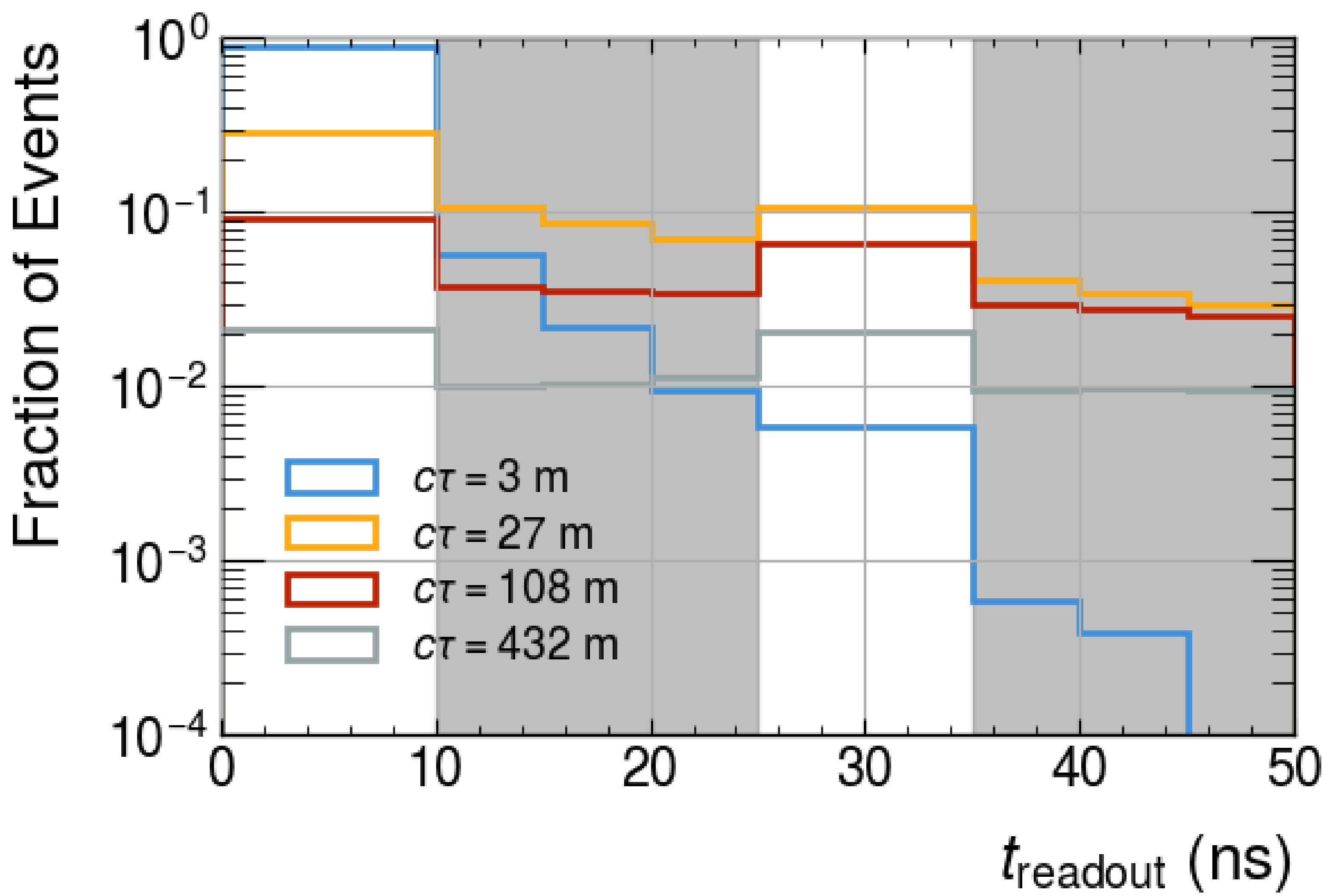
Displaced $\left(\frac{v}{\Lambda}(C_{H\chi\chi})_{10}\cos\alpha\right)$

Dipole Dark Matter (v2)

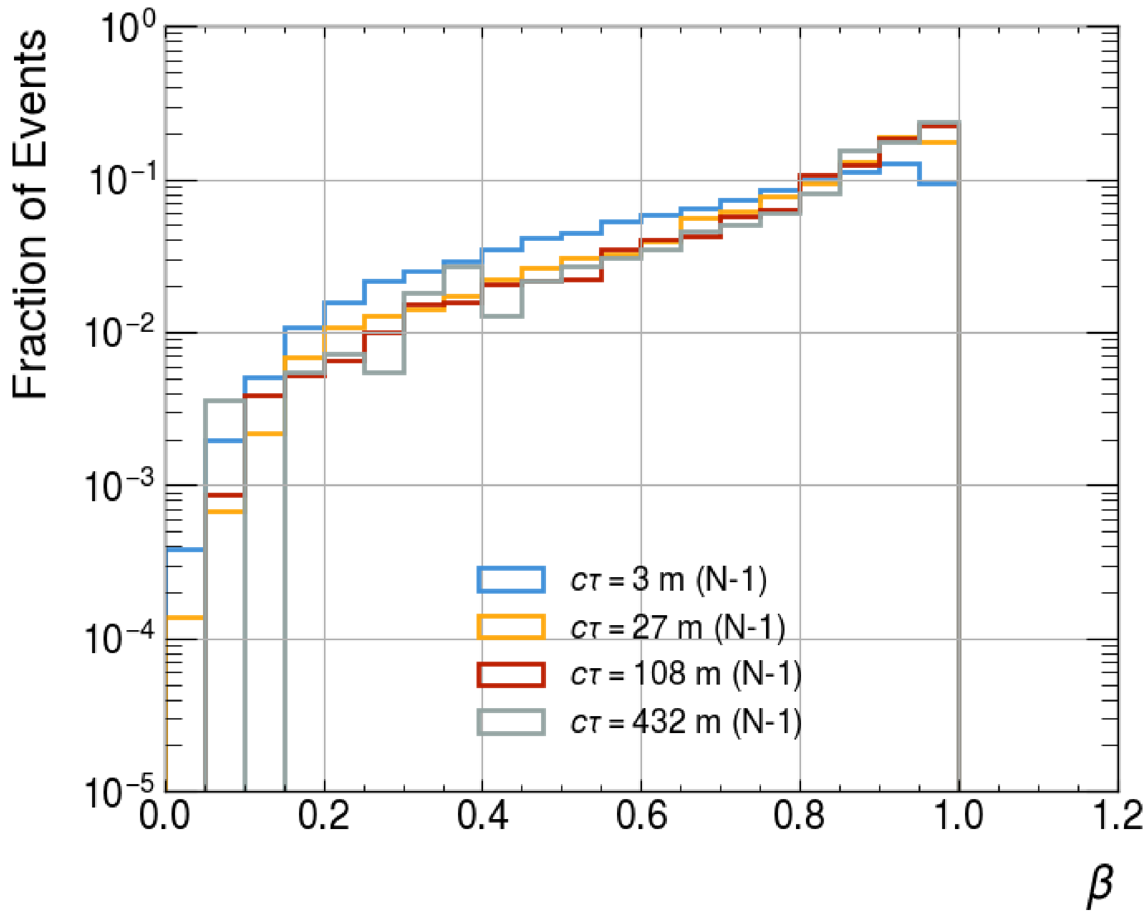
- Benchmark: $pp \to \chi_1\chi_2,\ \chi_1 \to b\bar{b}\chi_0,\ \chi_2 \to b\bar{b}\chi_0,$

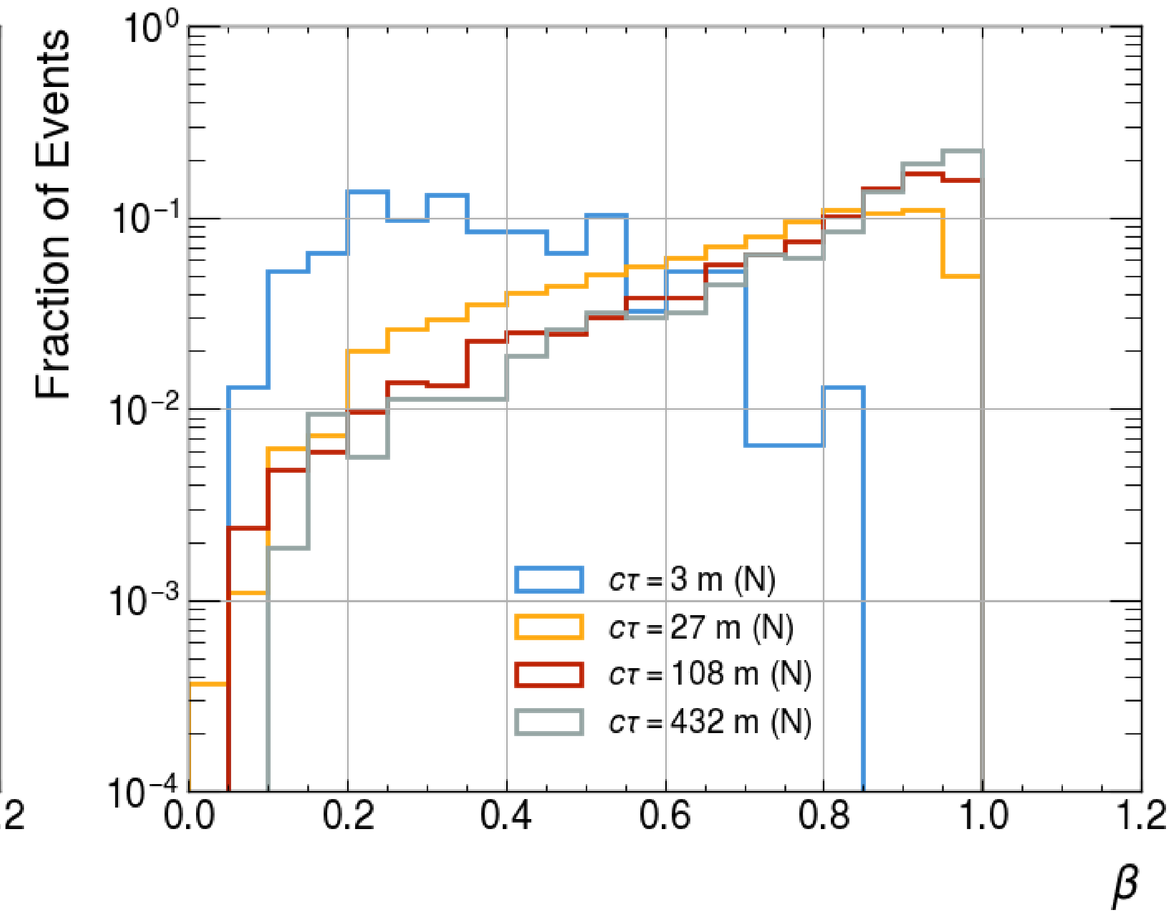
$$m_S = 500\,\text{GeV},\ m_2 = 250\,\text{GeV},\ m_1 = 244\,\text{GeV},\ m_0 = 154\,\text{GeV}$$

$$(y_\chi)_{21} = (y_\chi)_{20} = 1,\ (C_{H\chi\chi})_{10} = 0.1,\ \sin\alpha = 0.2 \qquad c\tau = 3, 27, 108, 432\,\text{m}$$



Dipole Dark Matter (v2)





The above behavior for the small lifetime in *N* events is due to the requirement that the readout time is given by:

$$t_r = t_d - L_d/c \sim t_d - c\beta t_d/c = t_d(1-\beta) \sim \gamma\tau_0(1-\beta) = \tau_0\sqrt{\frac{1-\beta}{1+\beta}}$$

Hence for small proper lifetime we need a small boost to achieve large readout times.

As a result, decays taking place in the *N* event record will correspond to small beta and therefore result in smaller traveled distance (when compare to scenarios with larger lifetimes). This enhances the fraction of *N*-decays within the HCAL.

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Dipole Dark Matter (v2)

- f(N-1) = # Events with the LLP decaying in N/(Total # Events)
- f(HCAL) = # Events with the LLP decaying in the HCAL/(f(N) or f(N-1))