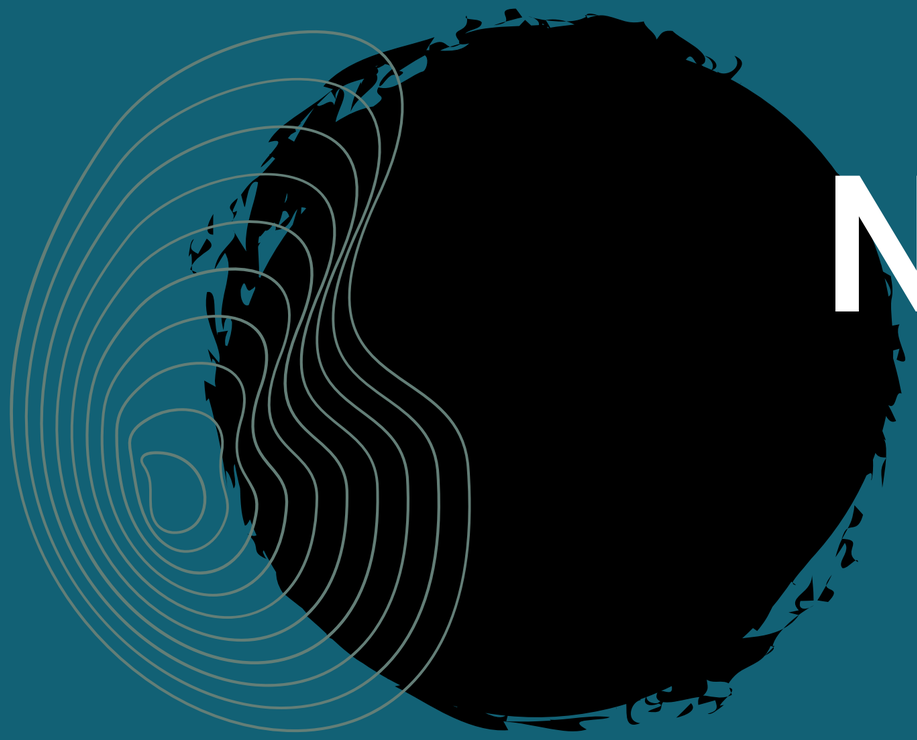


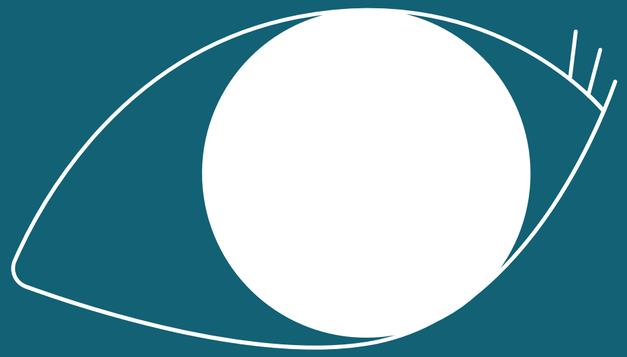
Not-so-inelastic Dark Matter

arXiv:2405.08081

Giovani Dalla Valle Garcia, Felix Kahlhoefer,
Maksym Ovchynnikov and Thomas Schwetz

DAAD KIT KSETA

10.10.2024
BLV 2024



OUTLINE

A model to be searched:

Not-so-inelastic Dark Matter

Dark Matter Production, (In)Direct detection

Signals at Colliders

Conclusion

Not-so-inelastic Dark Matter (niDM)

~~Not-so-inelastic~~ Dark Matter (~~ni~~DM)

~~Not so~~ inelastic Dark Matter (~~ni~~DM)

Basic principles

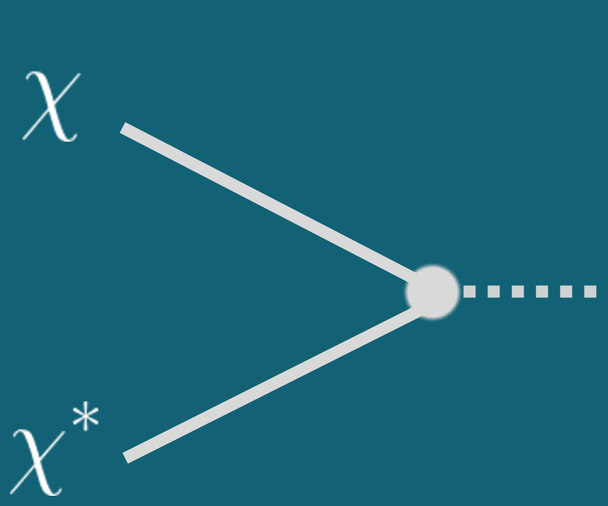
dark matter states with only off-diagonal interactions

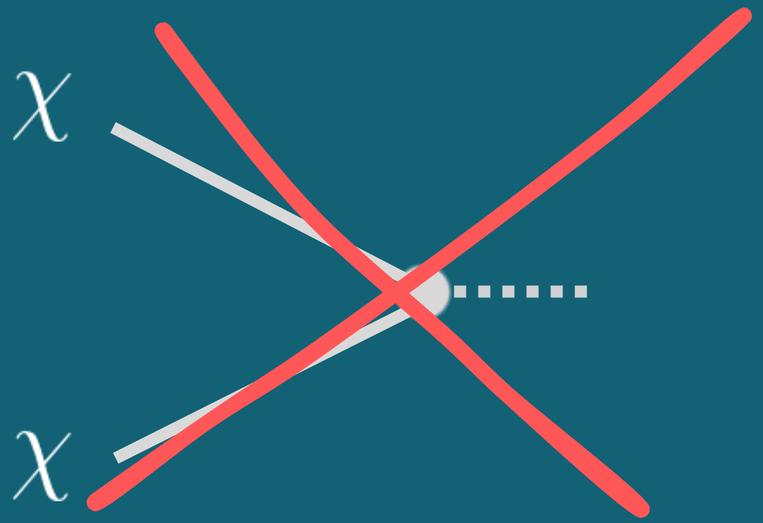
Two DM states

$$\chi \quad \chi^*$$

with a mass splitting

$$\frac{m_{\chi^*} - m_\chi}{m_\chi} = \Delta_m$$





~~Not so~~ inelastic Dark Matter (~~ni~~DM)

Two DM states

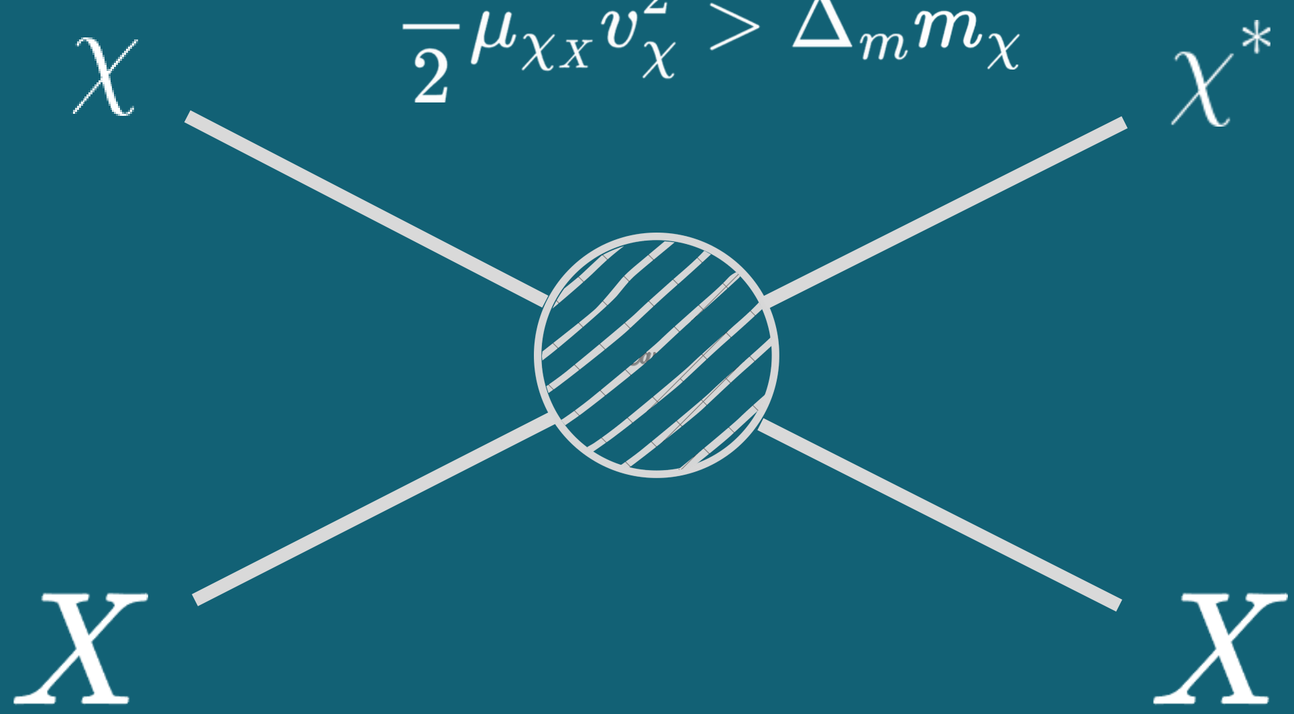
$$\chi \quad \chi^*$$

with a mass splitting

$$\frac{m_{\chi^*} - m_\chi}{m_\chi} = \Delta_m$$

Direct Detection

$$\frac{1}{2}\mu_{\chi X} v_\chi^2 > \Delta_m m_\chi$$



~~Not so~~ inelastic Dark Matter (~~ni~~DM)

Two DM states

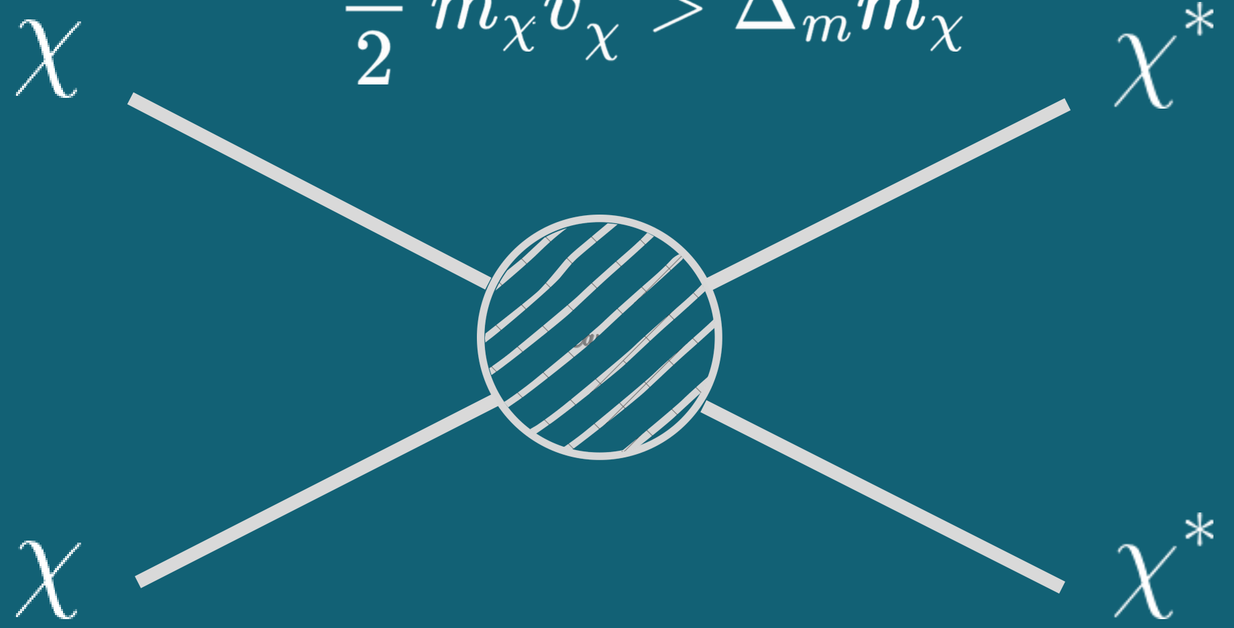
$$\chi \quad \chi^*$$

with a mass splitting

$$\frac{m_{\chi^*} - m_\chi}{m_\chi} = \Delta_m$$

Indirect Detection

$$\frac{1}{2} m_\chi v_\chi^2 > \Delta_m m_\chi$$



~~Not so~~ inelastic Dark Matter (~~ni~~DM)

Two DM states

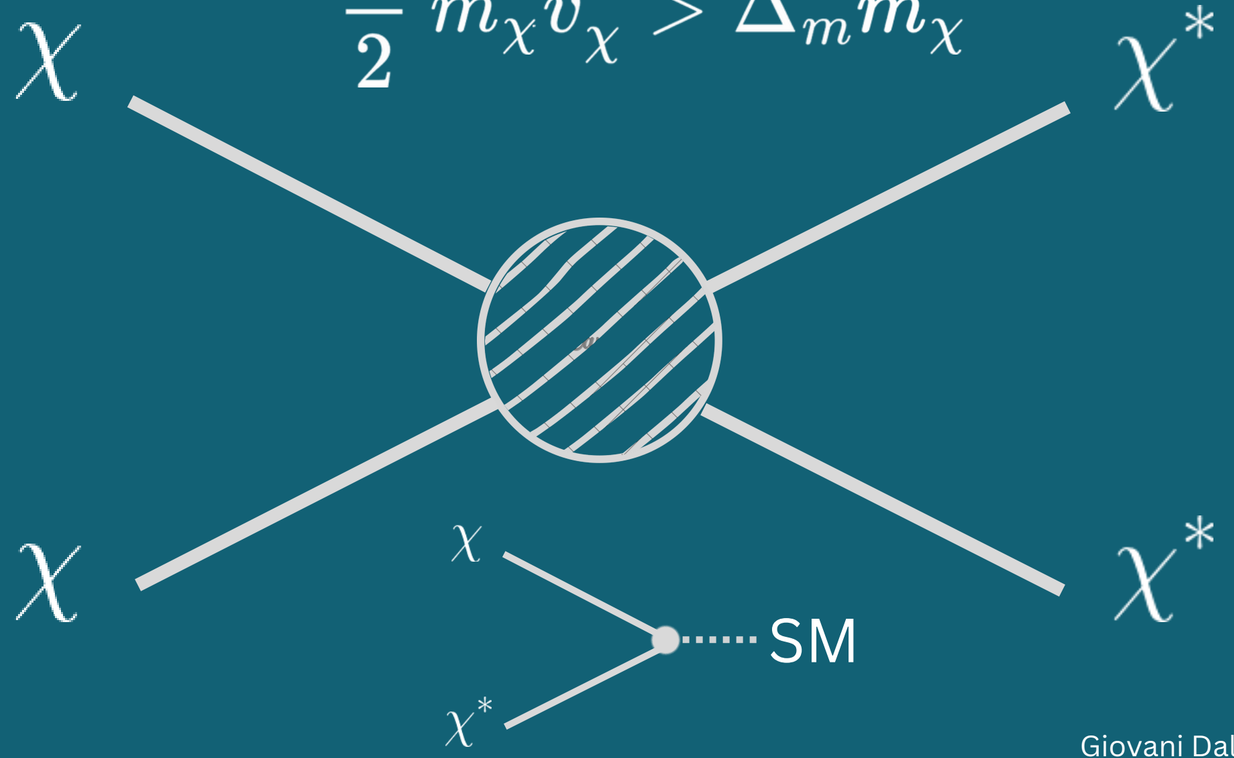
$$\chi \quad \chi^*$$

with a mass splitting

$$\frac{m_{\chi^*} - m_\chi}{m_\chi} = \Delta_m$$

Indirect Detection

$$\frac{1}{2} m_\chi v_\chi^2 > \Delta_m m_\chi$$

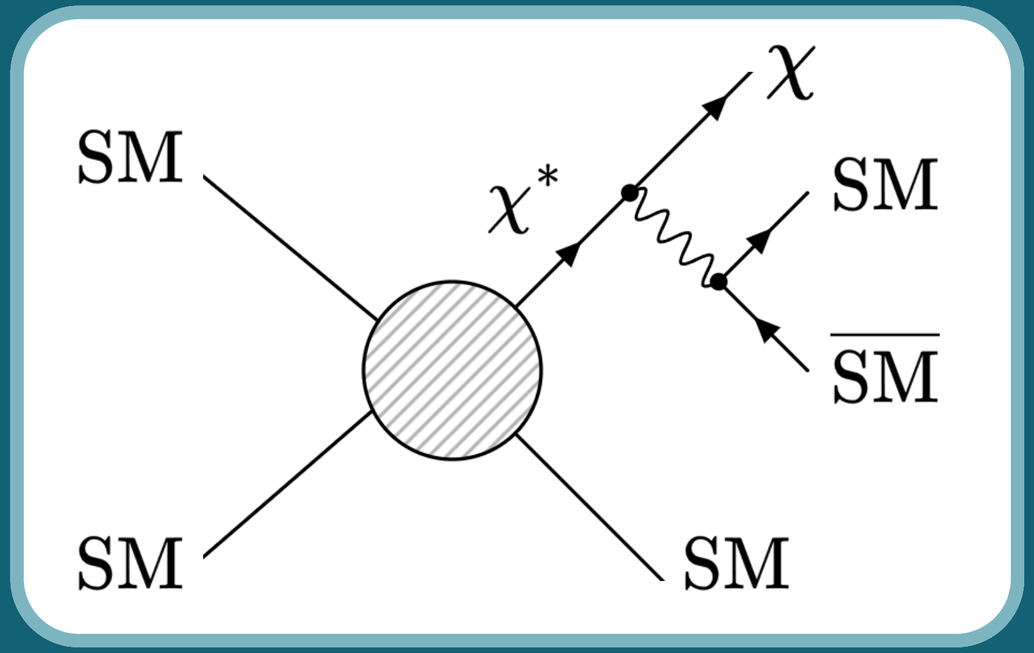


~~Not so~~ inelastic Dark Matter (~~ni~~DM)

A sub-GeV DM candidate

Non-trivial dark sector $\Longrightarrow$

- long-lived particles
- new signatures: displaced vertices



Not-so-inelastic Dark Matter (niDM)

Dirac Fermion DM

$$\chi = \chi_L + \chi_R$$

NEW FORCE: $U'(1)$

a Dark Photon

$$A'$$

a simple UV-complete sub-GeV WIMP model

Not-so-inelastic Dark Matter (niDM)

a simple UV-complete sub-GeV WIMP model

Majorana Fermions DM

$\chi \quad \chi^*$

NEW FORCE: $U'(1)$

a massive Dark Photon

A'

Parameters

$m_{\chi^*} = (1 + \Delta_m) m_\chi$

$m_R = (1 + \delta_y) m_L$

Parity breaking

$U'(1)$ eigenstates

$$\mathcal{L} \supset \frac{1}{2} \begin{pmatrix} \chi_L \\ \chi_R^c \end{pmatrix}^T C^\dagger \begin{pmatrix} m_L & m_D \\ m_D & m_R \end{pmatrix} \begin{pmatrix} \chi_L \\ \chi_R^c \end{pmatrix}$$

Not-so-inelastic Dark Matter (niDM)

a simple UV-complete sub-GeV WIMP model

Majorana Fermions DM

$\chi \quad \chi^*$

NEW FORCE: $U'(1)$

a massive Dark Photon

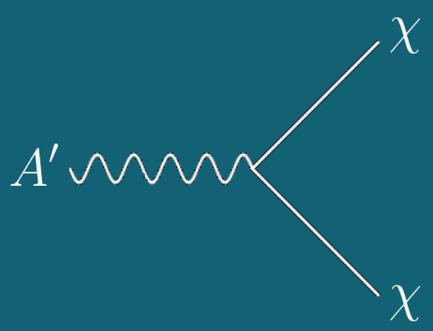
A'

Parameters

$m_{\chi^*} = (1 + \Delta_m) m_\chi$

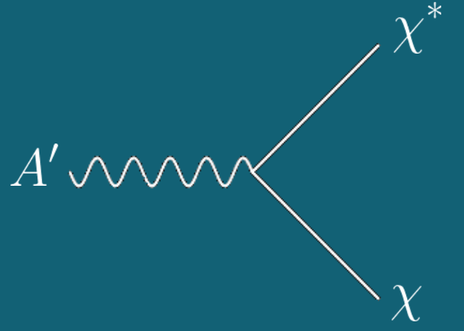
$m_R = (1 + \delta_y) m_L$

elastic



$\alpha'_{\text{el}} = \alpha' \cos^2 2\theta$

inelastic



$\alpha'_{\text{inel}} = \alpha' \sin^2 2\theta$

Not-so-inelastic Dark Matter (niDM)

a simple UV-complete sub-GeV WIMP model

Majorana Fermions DM

$\chi \quad \chi^*$

NEW FORCE: $U'(1)$

a massive Dark Photon

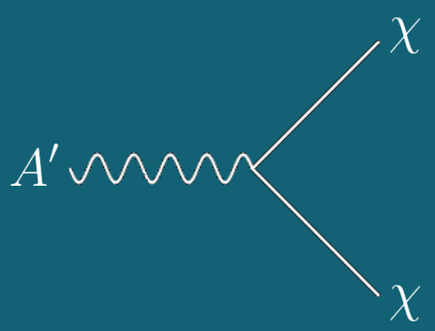
A'

Parameters

$m_{\chi^*} = (1 + \Delta_m) m_\chi$

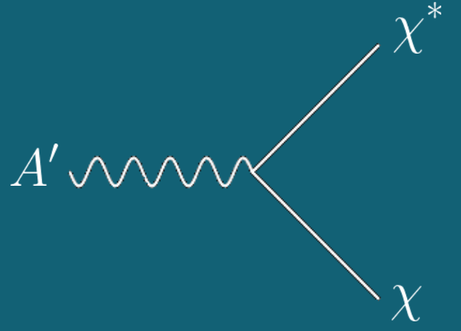
$m_R = (1 + \delta_y) m_L$

elastic



$\alpha'_{\text{el}} = \alpha' \cos^2 2\theta$

inelastic



$\alpha'_{\text{inel}} = \alpha' \sin^2 2\theta$

$$\cos 2\theta = -\frac{\delta_y \Delta_m}{(2 + \delta_y)(2 + \Delta_m)}$$

Not-so-inelastic Dark Matter (niDM)

a simple UV-complete sub-GeV WIMP model

Majorana Fermions DM

$\chi \quad \chi^*$

NEW FORCE: $U'(1)$

a massive Dark Photon

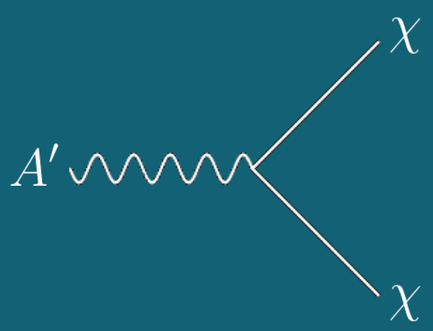
A'

Parameters

$m_{\chi^*} = (1 + \Delta_m) m_\chi$

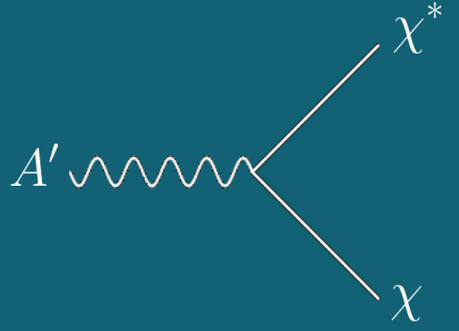
$m_R = (1 + \delta_y) m_L$

elastic



$\alpha'_{\rm el} = \alpha' \cos^2 2\theta$

inelastic



$\alpha'_{\rm inel} = \alpha' \sin^2 2\theta$

$$\cos 2\theta = -\frac{\delta_y \Delta_m}{(2 + \delta_y)(2 + \Delta_m)}$$

iDM: $\delta_y = 0$

Not-so-inelastic Dark Matter (niDM)

a simple UV-complete sub-GeV WIMP model

Majorana Fermions DM

$\chi \quad \chi^*$

NEW FORCE: $U'(1)$

a massive Dark Photon

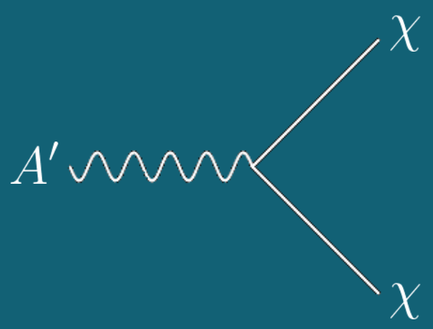
A'

Parameters

$m_{\chi^*} = (1 + \Delta_m) m_\chi$

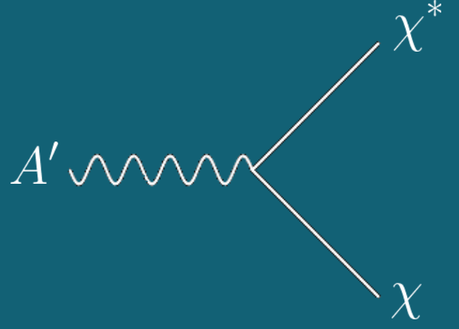
$m_R = (1 + \delta_y) m_L$

elastic



$\alpha'_{\rm el} = \alpha' \cos^2 2\theta$

inelastic



$\alpha'_{\rm inel} = \alpha' \sin^2 2\theta$

$$\cos 2\theta = -\frac{\delta_y \Delta_m}{(2 + \delta_y)(2 + \Delta_m)}$$

iDM: $\delta_y = 0$

niDM: $\delta_y \neq 0$

Not-so-inelastic Dark Matter (niDM)

a simple UV-complete sub-GeV WIMP model

Majorana Fermions DM

$\chi \quad \chi^*$

NEW FORCE: $U'(1)$

a massive Dark Photon

A'

Parameters

$m_{\chi^*} = (1 + \Delta_m) m_\chi$

$m_R = (1 + \delta_y) m_L$

SM-DM mediation

$$Q'^{\mathrm{SM}} = -\epsilon Q_{\mathrm{em}}$$

Not-so-inelastic Dark Matter (niDM)

a simple UV-complete sub-GeV WIMP model

Majorana Fermions DM

$\chi \quad \chi^*$

NEW FORCE: $U'(1)$

a massive Dark Photon

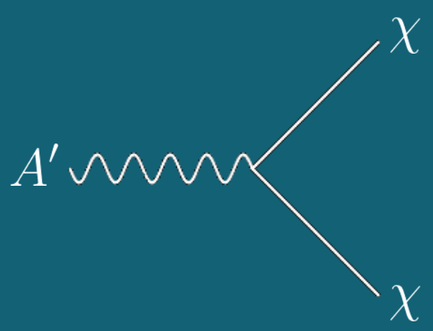
A'

Parameters

$m_{\chi^*} = (1 + \Delta_m) m_\chi$

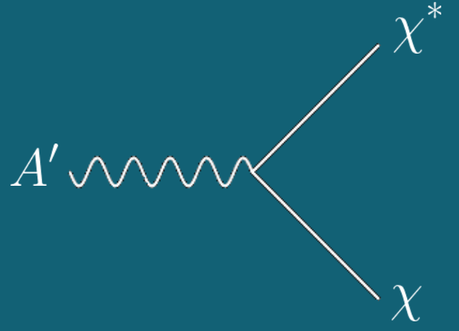
$m_R = (1 + \delta_y) m_L$

elastic



$\alpha'_{\text{el}} = \alpha' \cos^2 2\theta$

inelastic



$\alpha'_{\text{inel}} = \alpha' \sin^2 2\theta$

$$\cos 2\theta = -\frac{\delta_y \Delta_m}{(2 + \delta_y)(2 + \Delta_m)}$$

SM-DM mediation

iDM: $\delta_y = 0$

niDM: $\delta_y \neq 0$

Not-so-inelastic Dark Matter (niDM)

Majora

model

NEV

a mas

DM
ation

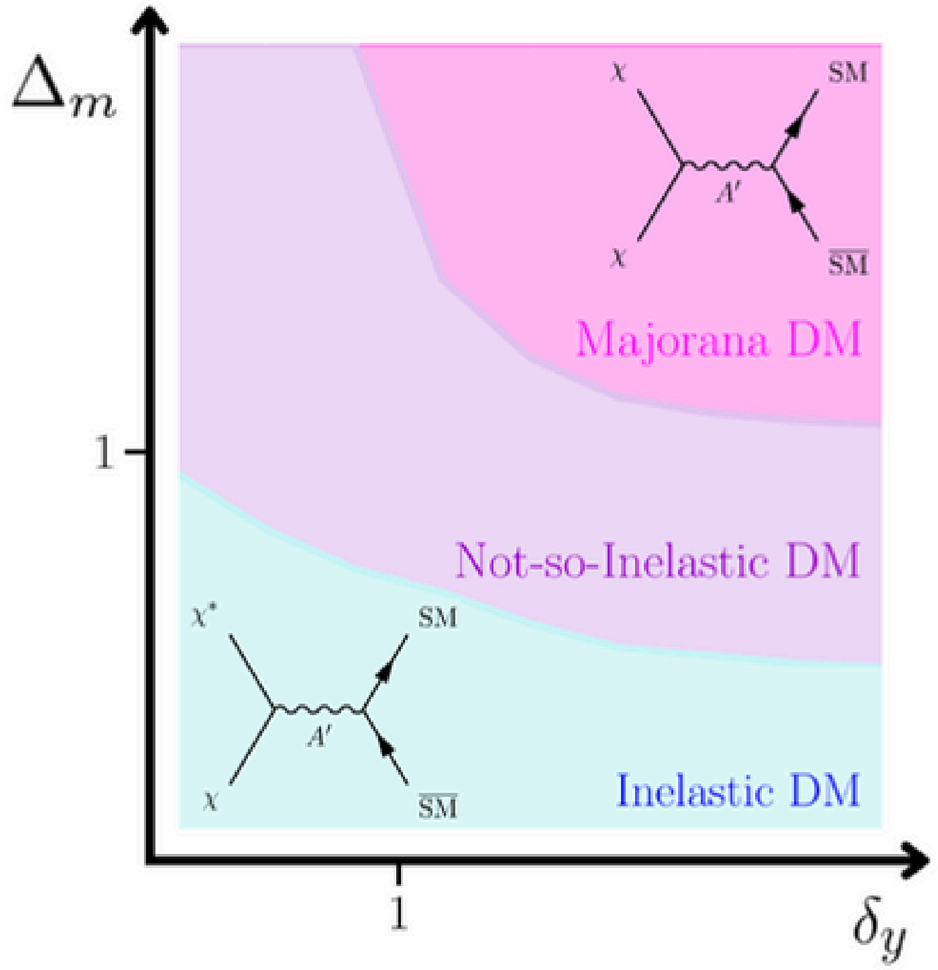
A'

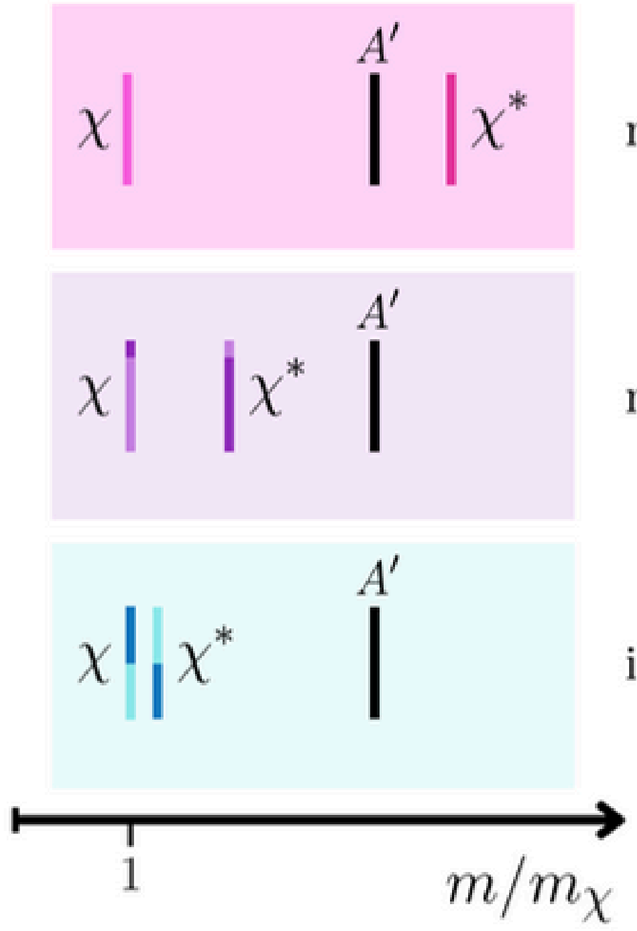
m_{χ^*} =

m_R

$\delta_y = 0$

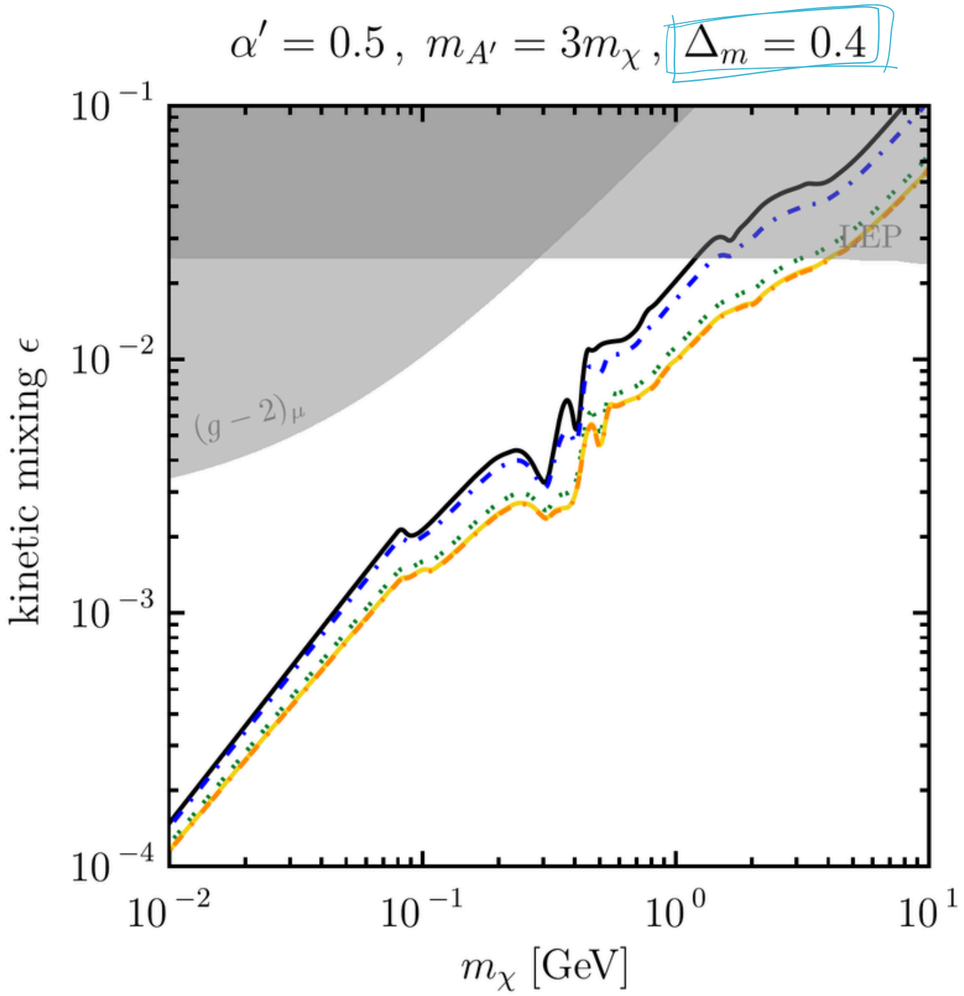
$\delta_y \neq 0$

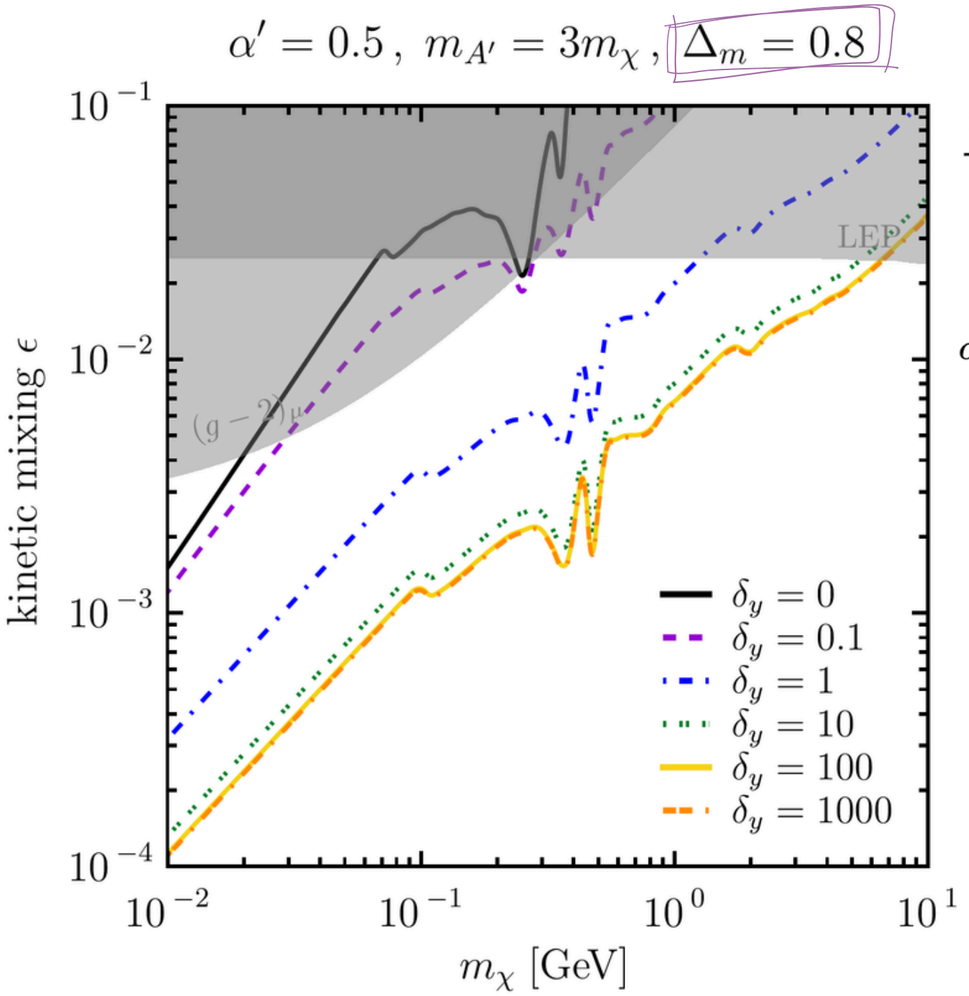




niDM - Relic abundance

Standard Freeze-out

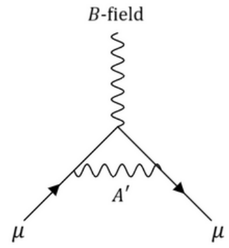




$$\frac{n_{\chi^*}}{n_\chi} \propto e^{-\Delta_m x_f}\,, x_f \approx 20$$

$$\alpha'_{\rm el} = \alpha' \left(\frac{\delta_y \Delta_m}{(2+\delta_y)(2+\Delta_m)} \right)^2$$

$(g-2)_\mu$:



PROBING OUR CANDIDATE

- Indirect&Direct detection
  - inelastic : $\Delta_m m \gg E_\chi^{\text{kin}}$
  - elastic : $\langle \sigma v \rangle_{\text{ann}} \propto v_\chi^2 \, , v_\chi \sim 10^{-3}$

$$\mathcal{L}_{\text{direct}}^{\text{eff}} = \sum_f \frac{Q_f}{\Lambda^2} (\bar{\chi} \gamma_\mu \gamma_5 \chi)(\bar{f} \gamma^\mu f)$$

$$\mathcal{O}_8^N = \left(\vec{S}_\chi \cdot \vec{v}_\perp\right) \mathbb{1}_N \, , \mathcal{O}_9^N = \vec{S}_\chi \cdot \left(\frac{i\vec{q}}{m_N} \times \vec{S}_N\right)$$

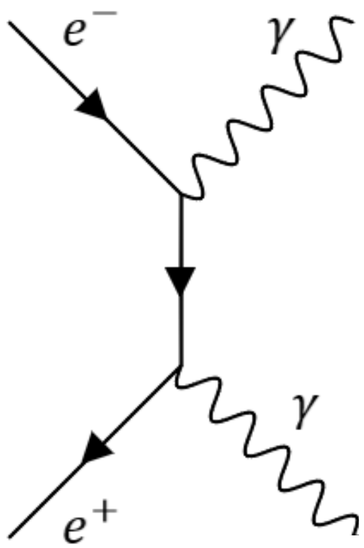
- Collider searches

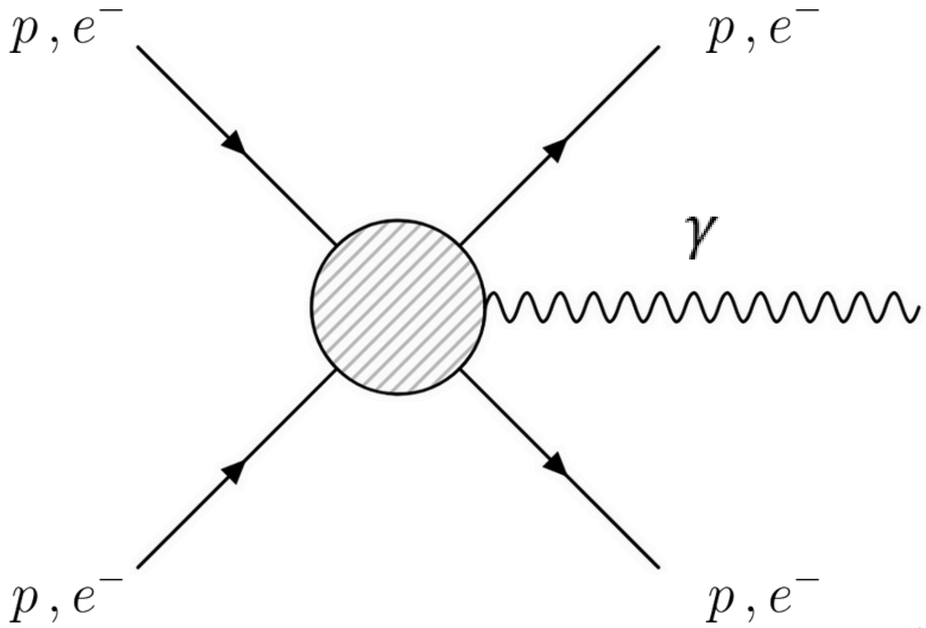
$$E_{\text{colliders}} > m_{\chi^{(*)}}$$

$$\Longrightarrow \; \chi^* \to \chi + \text{SM}, v_\chi \sim c$$

COLLIDER SEARCHES

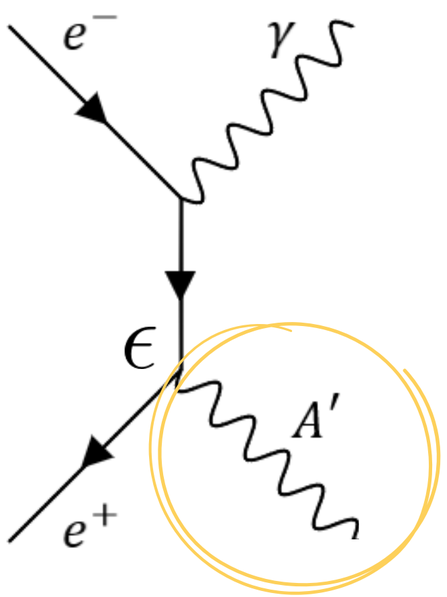
- A' produced just like photons - $E > m_{A'}$

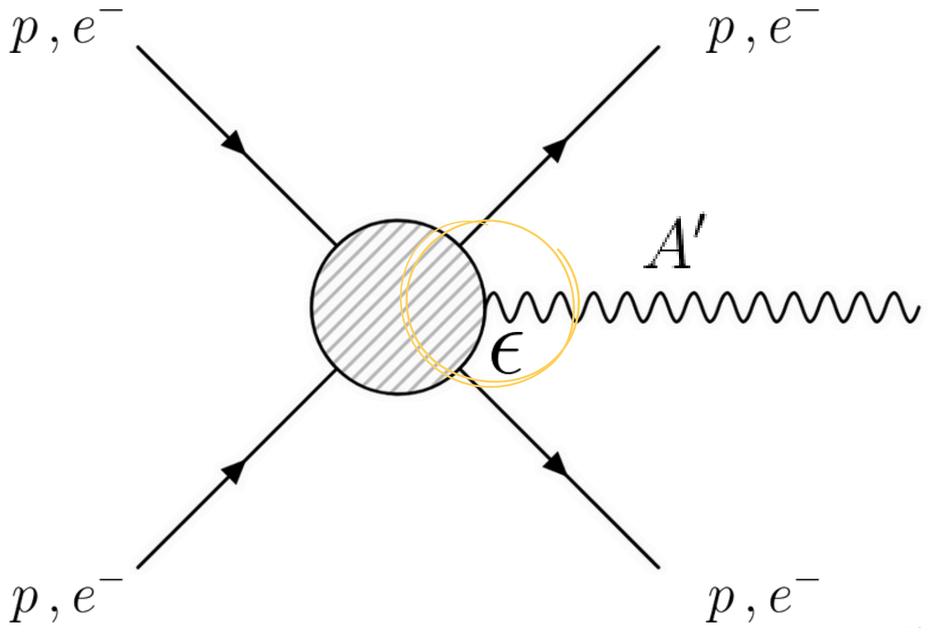




COLLIDER SEARCHES

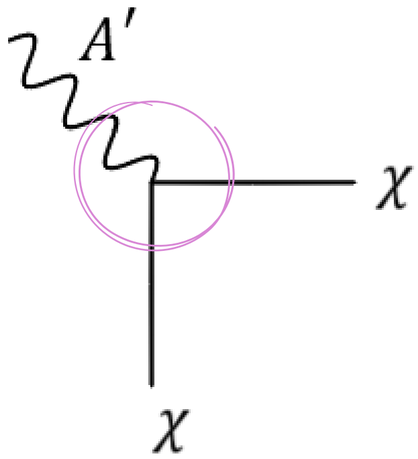
- A' produced just like photons - $E > m_{A'}$



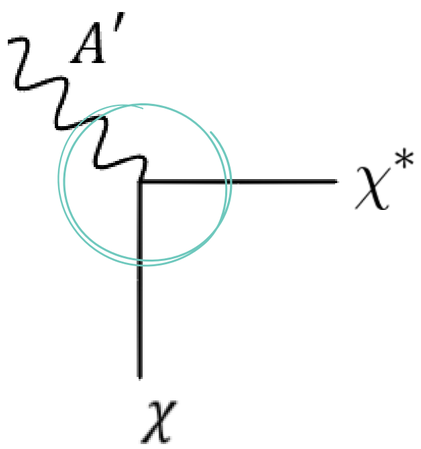


COLLIDER SEARCHES

- Missing energy searches

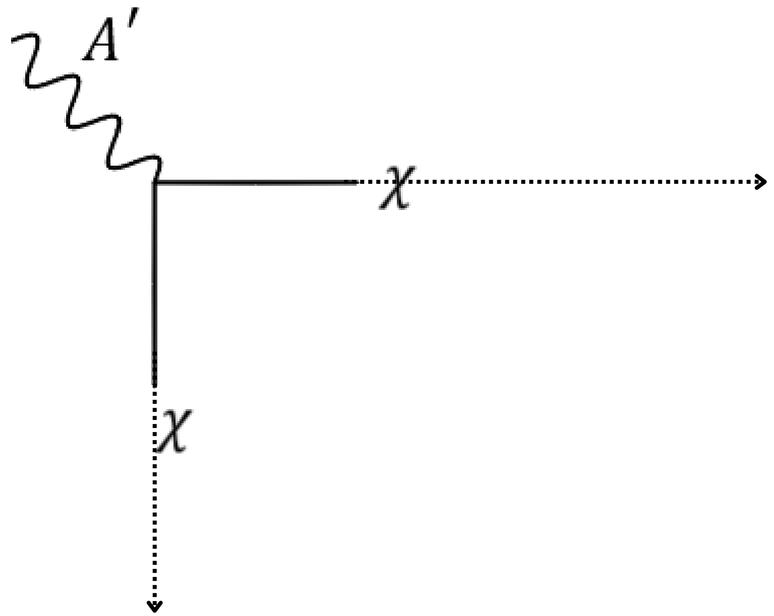


- Decays inside the detector

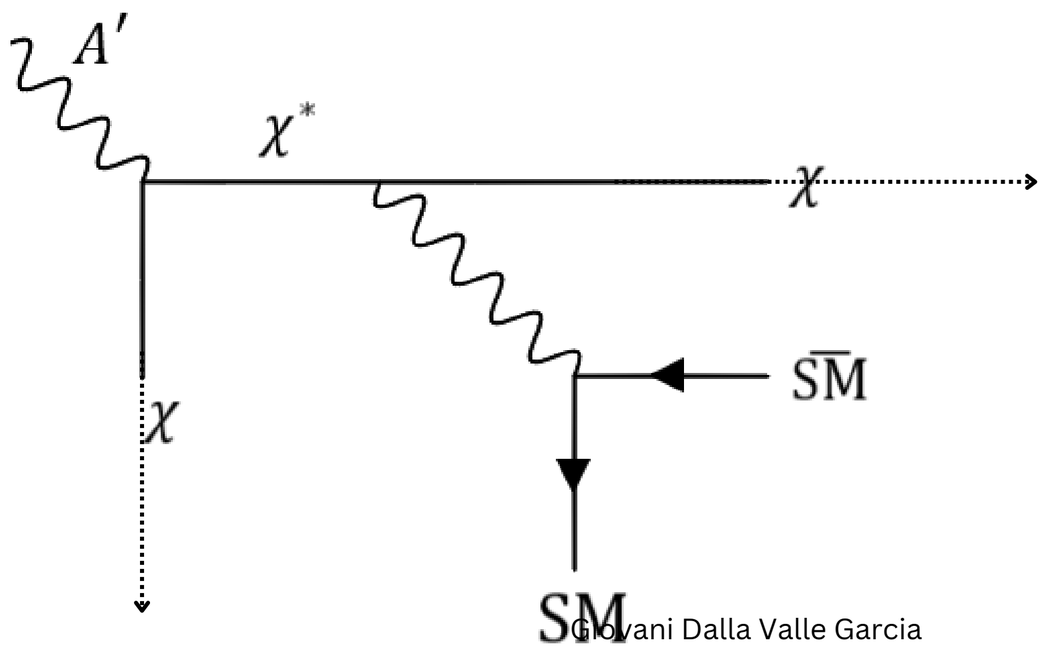


COLLIDER SEARCHES

- Missing energy searches

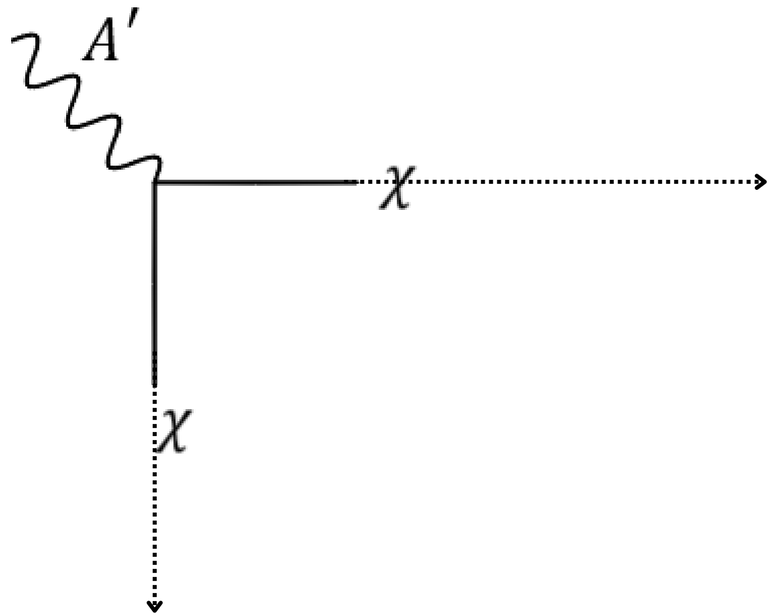


- Decays inside the detector

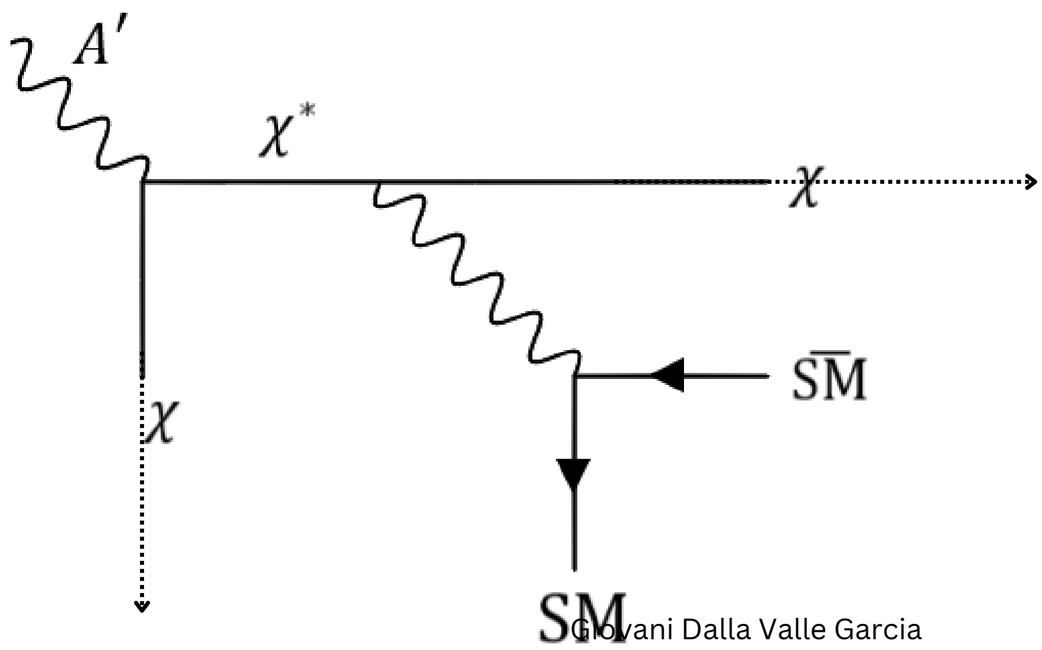


COLLIDER SEARCHES

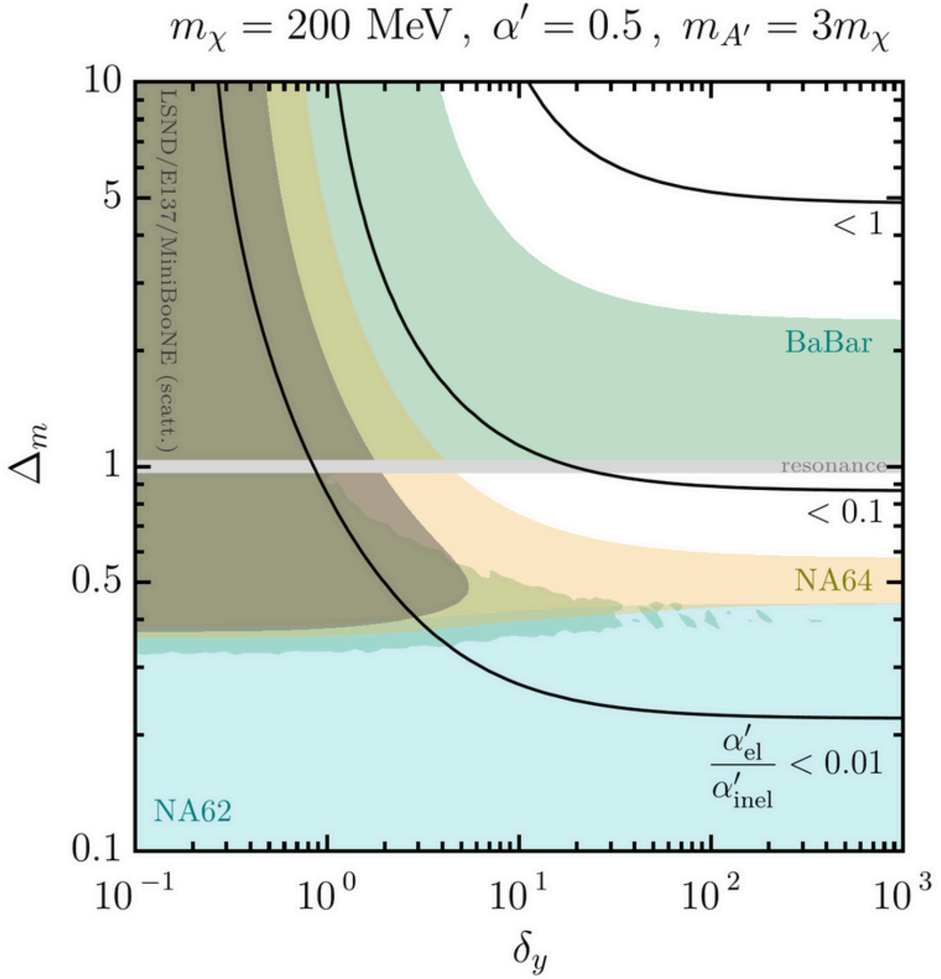
- Scattering

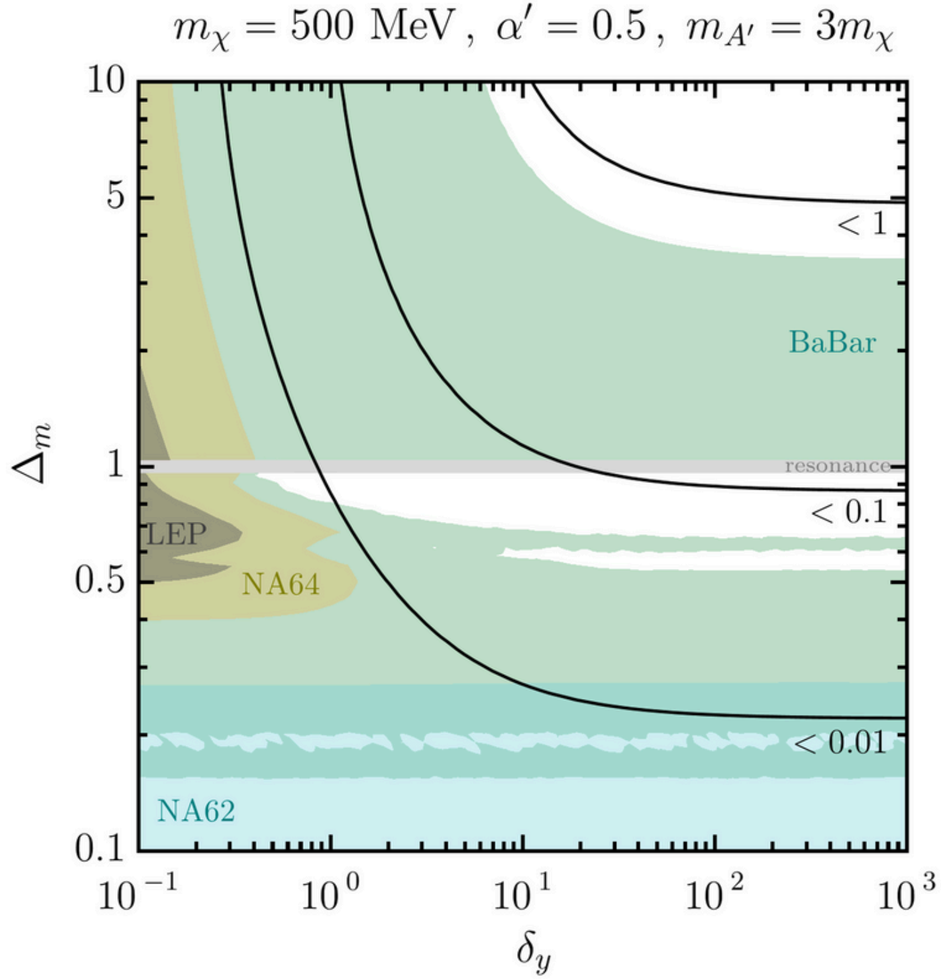


- Scattering

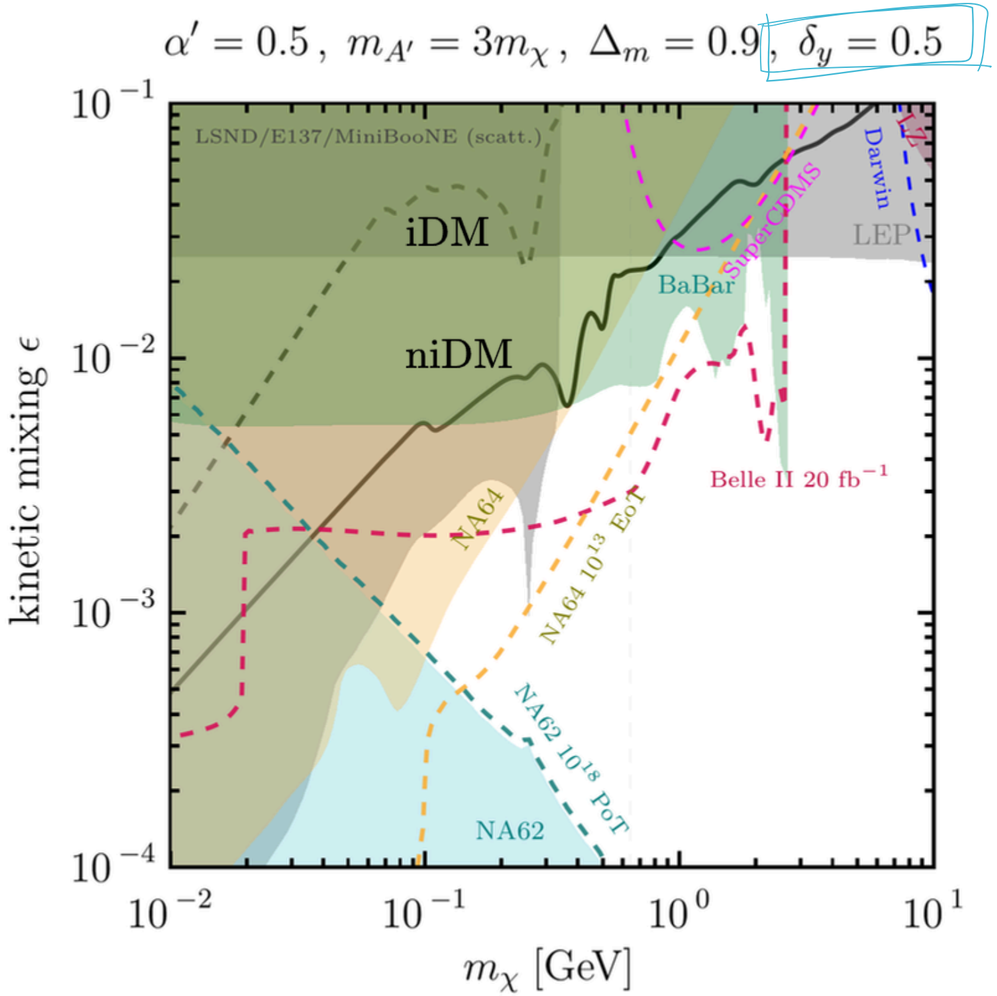


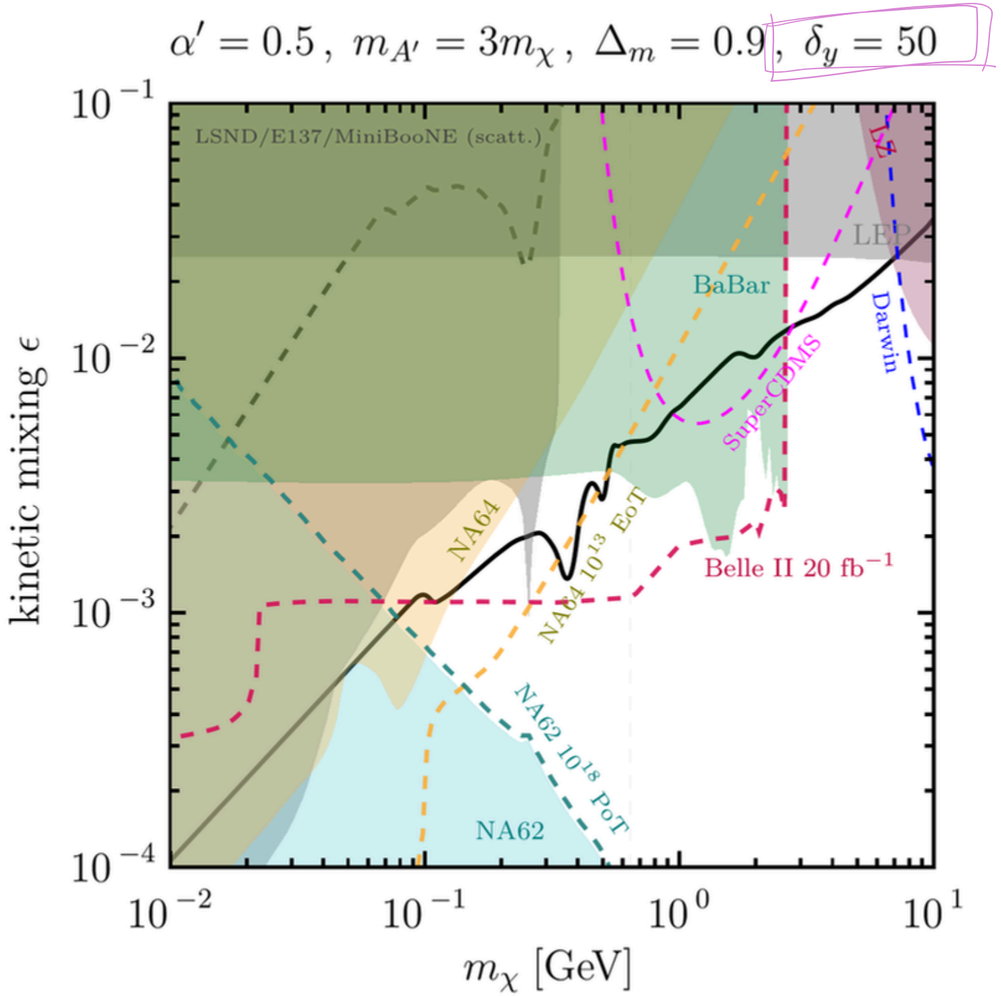
COLLIDER SEARCHES

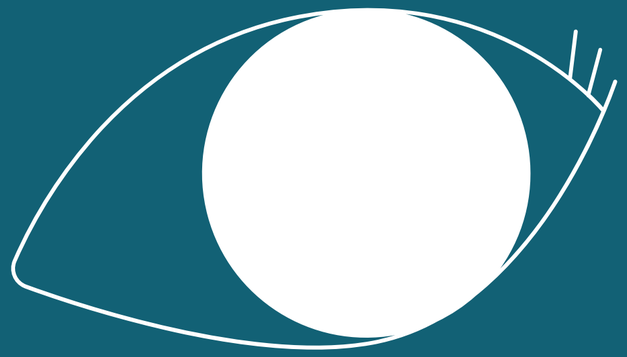




COLLIDER SEARCHES







FUTURE SEARCHES

Future exploration

DM masses around 5 GeV with future colliders and direct detection experiments

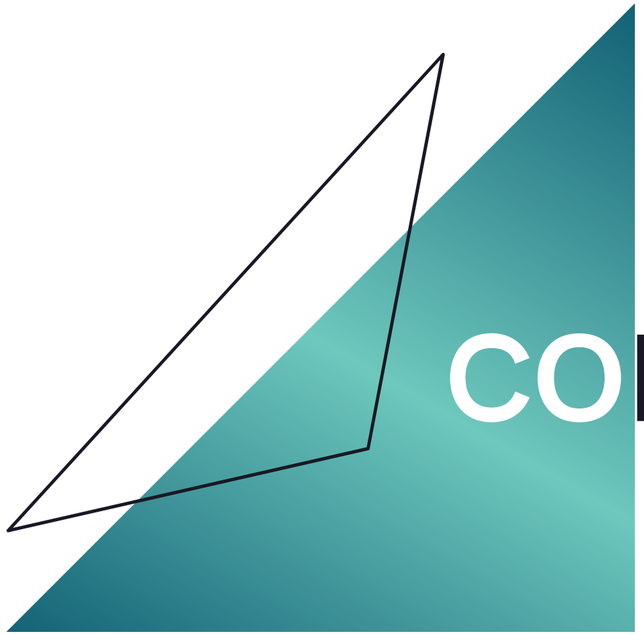
New signatures

displaced vertices

double-bang

New experiments

NA64 muons



CONCLUSION

New directions explored

parity violation also in the dark sector
inelastic Dark Matter with large mass spliting

Thank you!

Questions?

BACKUP SLIDES

Not-so-inelastic

Dark Matter (DM)

A simplified sub-GeV WIMP model

Dirac Fermion DM
$\chi = \chi_L + \chi_R$

NEW FORCE: $U'(1)$
a massive Dark Photon
A'

SSB: $V(H')$
Dark Higgs
H'

$$\mathcal{L}_\chi^I \supset ig_\chi A'_\mu \bar{\chi}\gamma^\mu\chi - \sqrt{2}y_L S\bar{\chi}^c P_L\chi - \sqrt{2}y_R S\bar{\chi}^c P_R\chi + \text{h.c.}$$

$$g_\chi A'_\mu \bar{\Psi} R_{A'} \gamma^\mu \Psi + \Psi^T C^{-1}(M_\chi + h' R_{H'})\Psi + \text{h.c.}$$

$$\Psi = \begin{pmatrix} \chi_L \\ \chi_R^c \end{pmatrix} \qquad M_\chi = \begin{pmatrix} y_L w & m_D/2 \\ m_D/2 & y_R w \end{pmatrix}$$

Not-so-inelastic

Dark Matter (DM)

A simplified sub-GeV WIMP model

Dirac Fermion DM
$\chi = \chi_L + \chi_R$

NEW FORCE: $U'(1)$
a massive Dark Photon
A'

SSB: $V(H')$
Dark Higgs
H'

$$\mathcal{L}_\chi^I \supset ig_\chi A'_\mu \bar{\chi}\gamma^\mu\chi - \sqrt{2}y_L S\bar{\chi}^c P_L\chi - \sqrt{2}y_R S\bar{\chi}^c P_R\chi + \text{h.c.}$$

$$\Psi' = U\Psi$$

$$g_\chi A'_\mu \bar{\Psi} R_{A'} \gamma^\mu \Psi + \Psi^T C^{-1}(M_\chi + h' R_{H'})\Psi + \text{h.c.}$$

$$\Psi = \begin{pmatrix} \chi_L \\ \chi_R^c \end{pmatrix} \qquad M_\chi = \begin{pmatrix} y_L w & m_D/2 \\ m_D/2 & y_R w \end{pmatrix}$$

Not-so-inelastic

Dark Matter (DM)

A simplified sub-GeV WIMP model

Dirac Fermion DM
$\chi = \chi_L + \chi_R$

NEW FORCE: $U'(1)$
a massive Dark Photon
A'

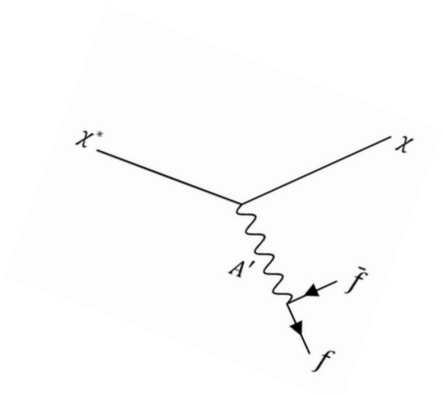
SSB: $V(H')$
Dark Higgs
H'

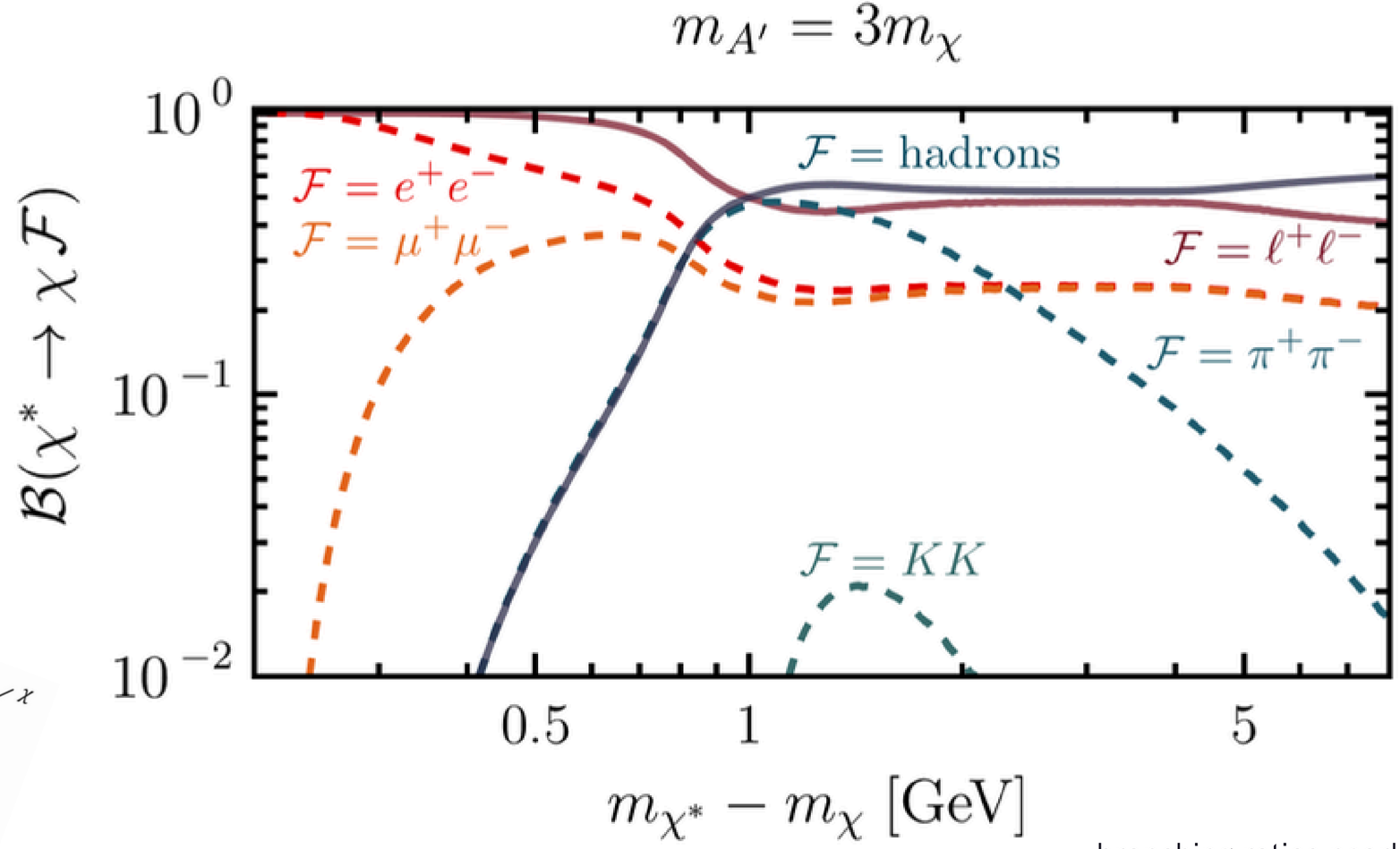
$$\mathcal{L}_\chi^I \supset ig_\chi A'_\mu \bar{\chi}\gamma^\mu\chi - \sqrt{2}y_L S\bar{\chi^c}P_L\chi - \sqrt{2}y_R S\bar{\chi^c}P_R\chi + \text{h.c.}$$

$$g_\chi A'_\mu \bar{\Psi} R_{A'}\gamma^\mu\Psi + \Psi^T C^{-1}(M_\chi + h' R_{H'})\Psi + \text{h.c.}$$

$$\Psi = \begin{pmatrix}\chi_L \\ \chi_R^c\end{pmatrix} \quad R_{A'} = \begin{pmatrix}1 & 0 \\ 0 & -1\end{pmatrix} \quad M_\chi = \begin{pmatrix}y_L w & m_D/2 \\ m_D/2 & y_R w\end{pmatrix} \quad R_{H'} = y_L \begin{pmatrix}1 & 0 \\ 0 & 1+\delta\end{pmatrix}$$

niDM - Excited states decays





branching ratios nearly independent of $m_{A'}$

COLLIDER SEARCHES