Dark photon theory landscape

Stefania Gori
UC Santa Cruz

"Roadmap of Dark Matter models for Run 3" workshop

CERN,
May 15, 2024

The dark photon

Nature seems well described by a SU(3) x SU(2)$_L$ x U(1)$_{em}$ gauge theory. We need to check this assumption!

Additional gauge symmetries in Nature? **U(1)'?**

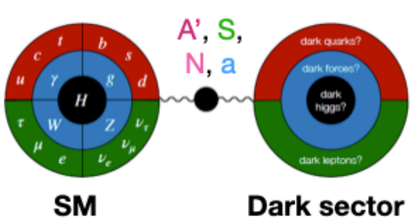
Okui, '82
Holdom, '86

$$\mathcal{L} \subset \epsilon Z^{\mu\nu} A'_{\mu\nu} + m^2_{A'} A'_\mu A'^\mu$$ + couplings within the dark sector

Mixing with the SM hyper-charge gauge boson

arising from
* dark Higgs mechanism or
* Stueckelberg mechanism

⇒ **Massive photon**



One of the four low dimensional portals

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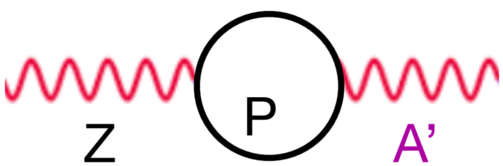
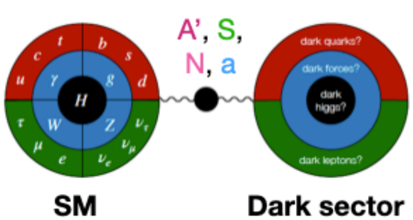
It is allowed by symmetries and, in general, it is generated





One of the four low dimensional portals

For example, if we gauge the L_μ - L_τ number

$$\epsilon \simeq \frac{e^2 (g')^2}{6\pi^2} \log\left(\frac{m_\tau^2}{m_\mu^2}\right)$$

- 1-loop suppression: $\varepsilon \sim (10^{-1} - 10^{-2}) g'$
- ε can be smaller than this, if generated at higher orders

Model independently…

The dark photon changes several electroweak precision observables (EWPO)

Curtin, Essig, SG, Shelton, 1412.0018

- Tree level shift in the Z mass (compared to the W mass)

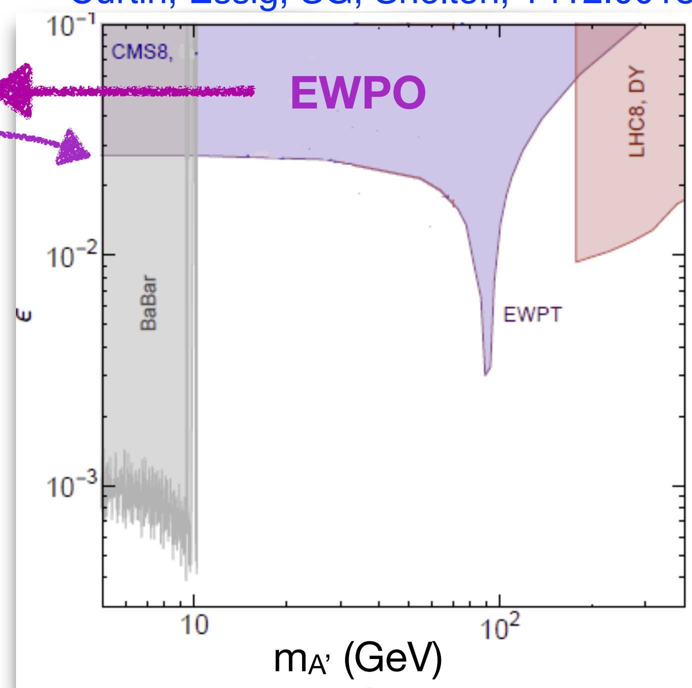
$$m_Z^2 \simeq m_{Z_0}^2 (1 + \epsilon^2 \tan^2 \theta)$$

- Modification of the Z couplings

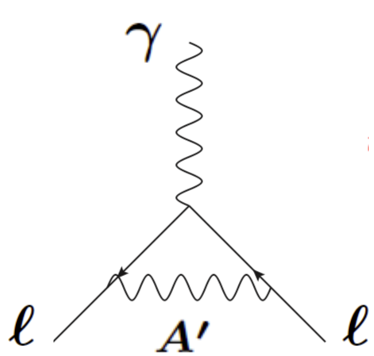
$$\simeq (Z f \bar{f})_{\rm SM} \left(1 + \epsilon^2 \frac{\tan^2 \theta}{2} \times \mathcal{O}(1) \right)$$

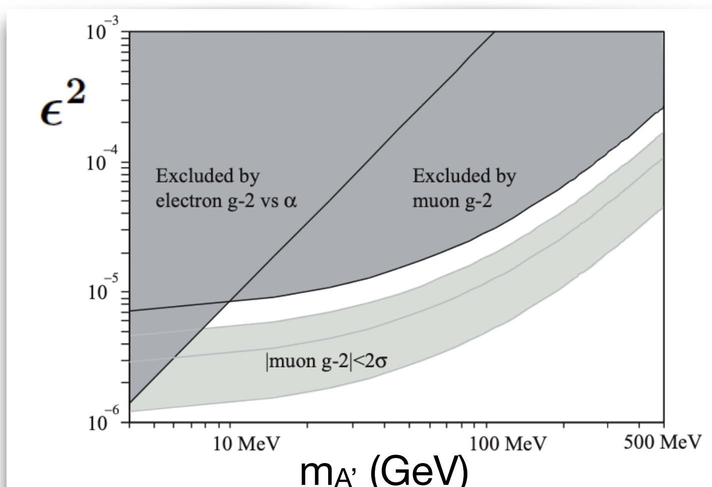
Bounds from LEP!

improvement by up to an order of magnitude expected at FCC-ee



(g-2)$_\ell$ gets modified as well:

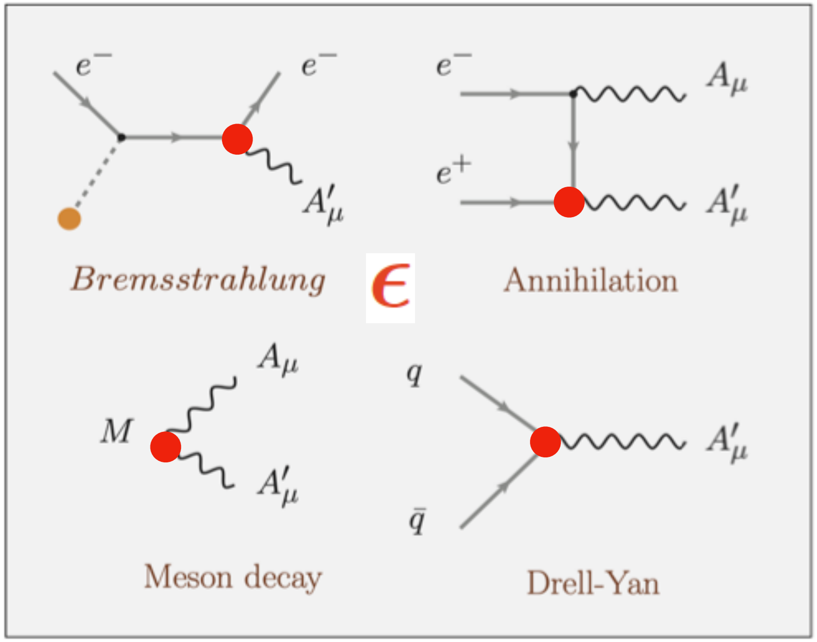




Pospelov, Phys.Rev.D80 (2009) 095002

Producing dark photons at accelerator experiments

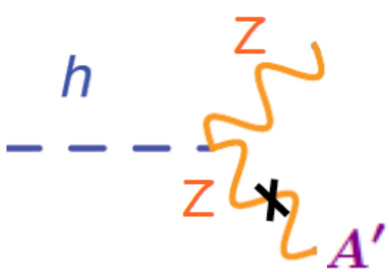
Several processes produce dark photons at accelerator experiments:



from Fabbrichesi et al., 2005.01515

+ at high energy colliders:

Higgs exotic decays,



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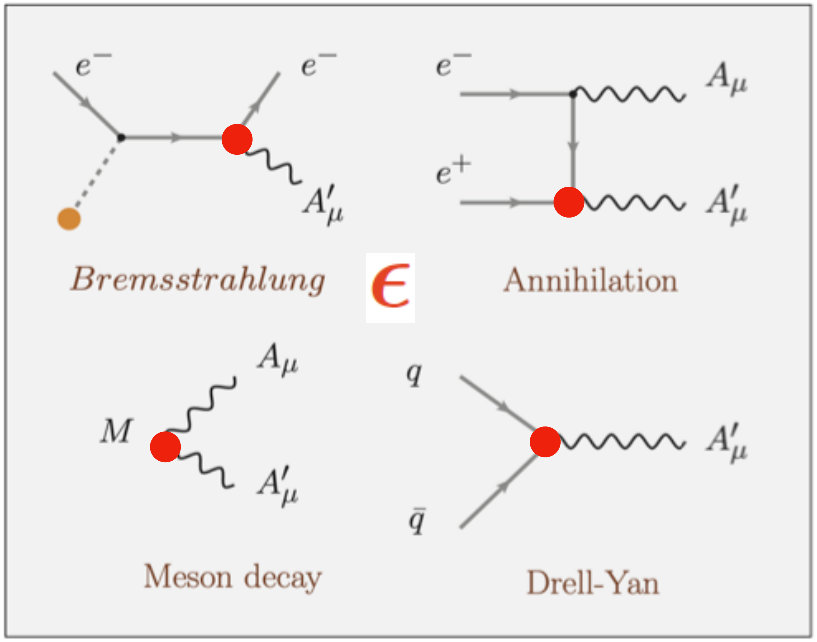

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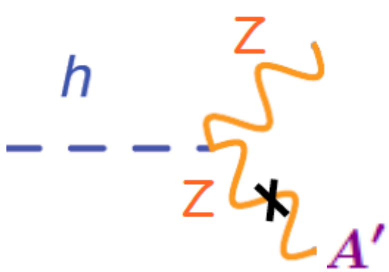
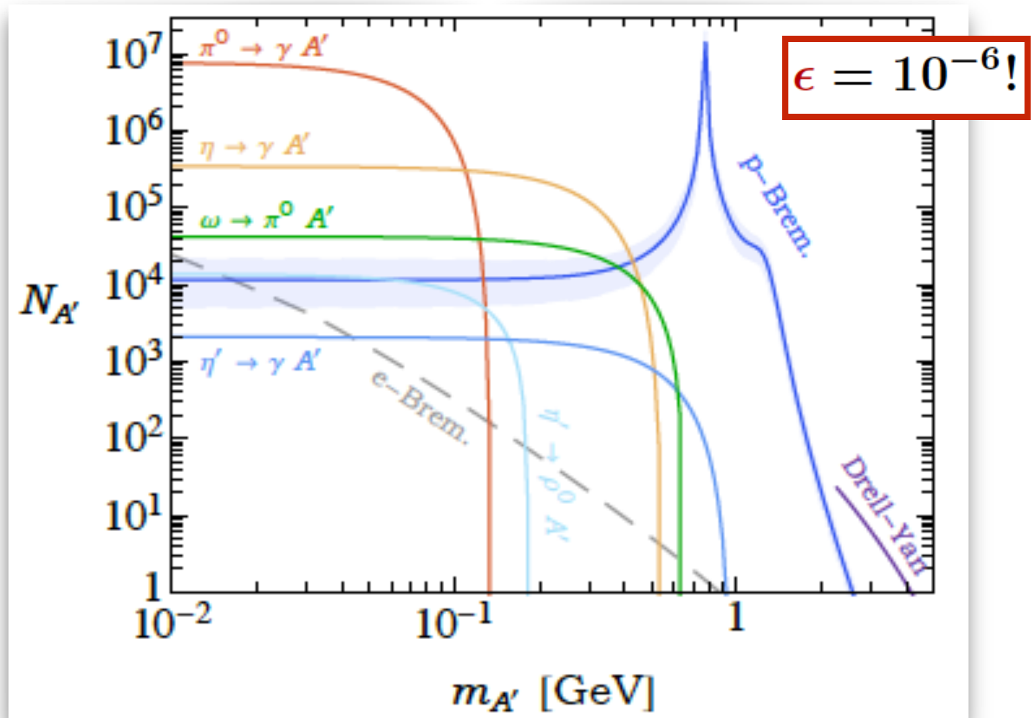


Rates can be quite large.

E.g., at a proton fixed target with E_{beam} = 120 GeV:



Berlin, SG, Schuster, Toro, 1804.00661

$$\begin{cases} N_{A'}(e\ \text{Brem.}) \sim \left(\frac{\epsilon}{10^{-6}}\right)^2 \left(\frac{m_{A'}}{\text{GeV}}\right)^{-2} \left(\frac{\text{EOT}}{10^{18}}\right) \\ N_{A'}(p\ \text{Brem.}) \sim 10^4 \times \left(\frac{\epsilon}{10^{-6}}\right)^2 \left(\frac{\text{POT}}{10^{18}}\right) \end{cases}$$

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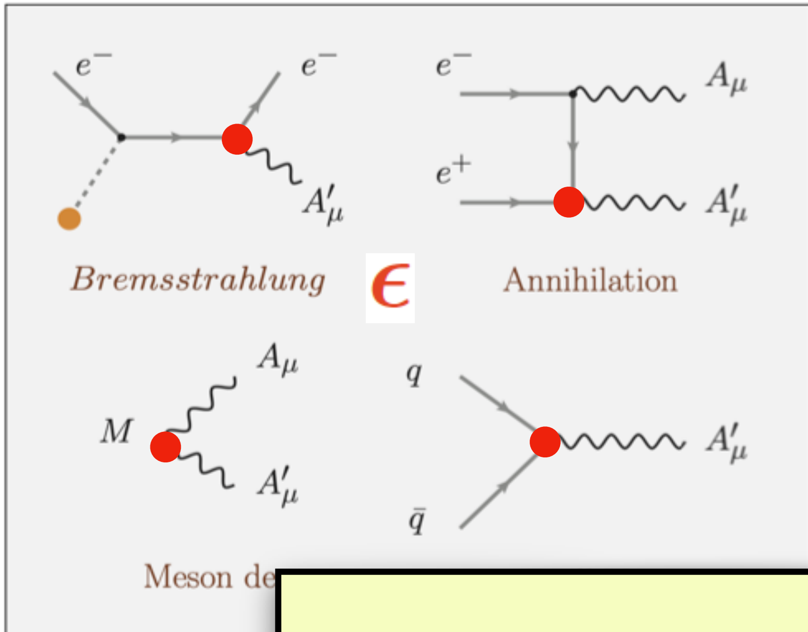
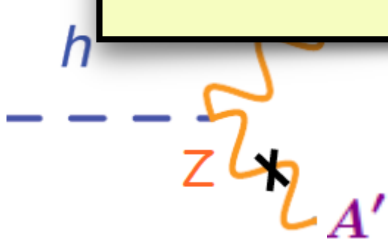


from Fabb

+ at high

Higgs



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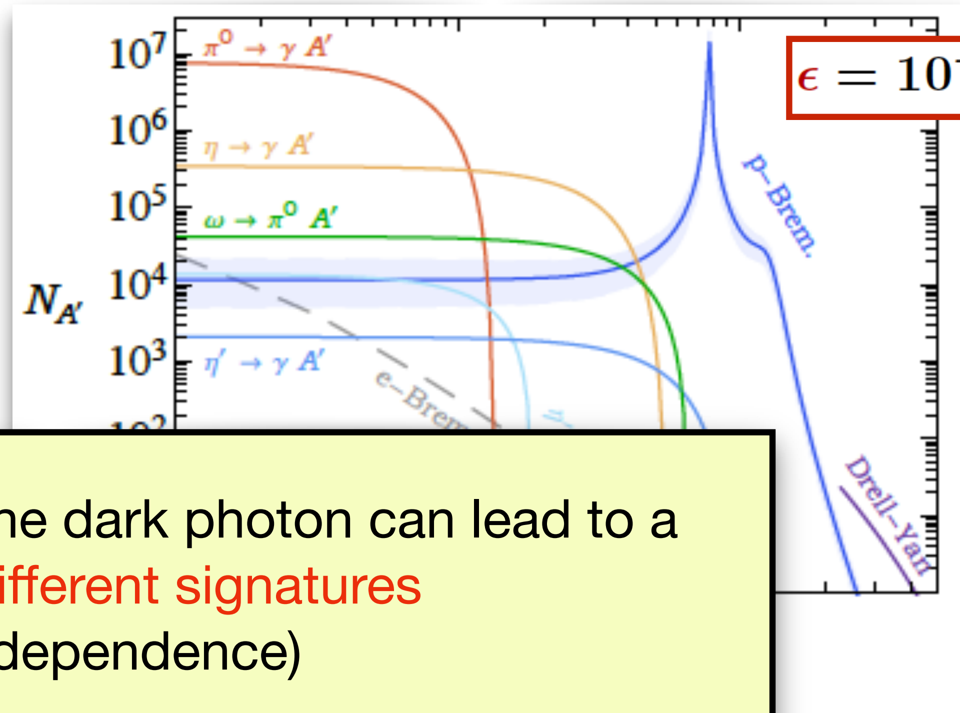


661

After being produced, the dark photon can lead to a plethora of different signatures (model dependence)

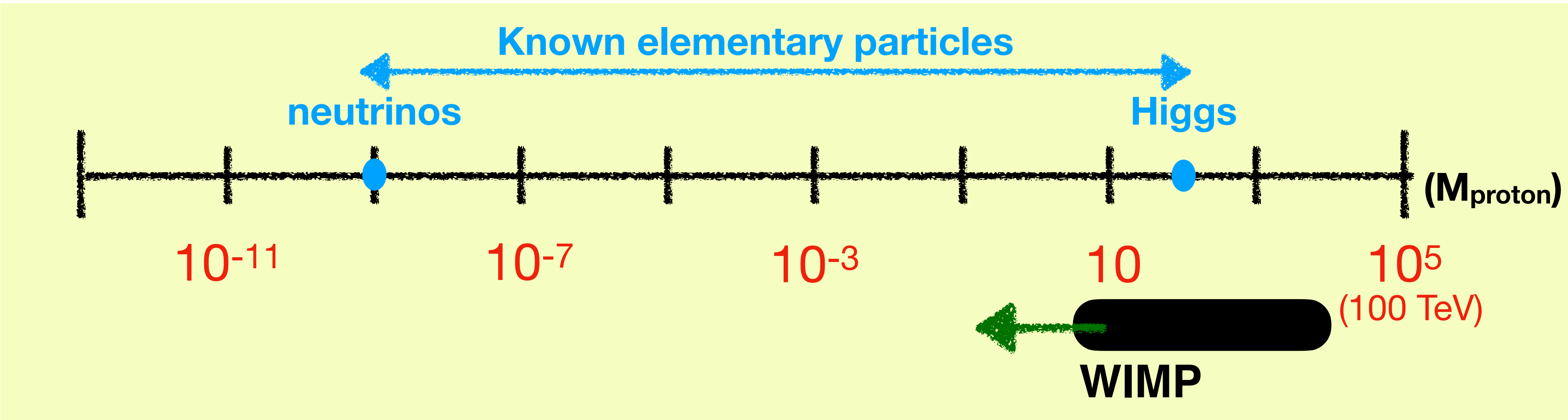
Let's discuss some models and their motivation…

$$N_{A'}(e\ \text{Brem.}) \sim \left(\frac{\epsilon}{10^{-6}}\right)^2 \left(\frac{m_{A'}}{\text{GeV}}\right)^{2} \left(\frac{\text{EOT}}{10^{18}}\right)$$

$$N_{A'}(p\ \text{Brem.}) \sim 10^4 \times \left(\frac{\epsilon}{10^{-6}}\right)^2 \left(\frac{\text{POT}}{10^{18}}\right)$$

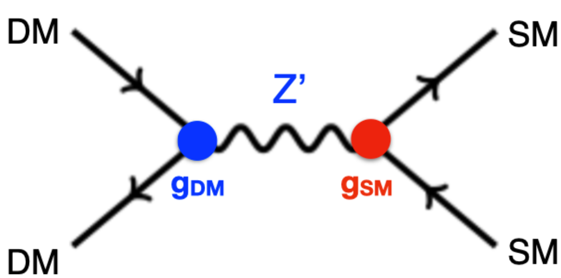
The dark photon and dark matter

What is the Dark Matter scale?



WIMP is a beautiful and predictive framework.

Can we extend it to lower masses? YES



for the measured relic abundance

$$\langle \sigma v \rangle \sim 1\text{pb} \times \left(\frac{g_{DM}}{0.5}\right)^2 \left(\frac{g_{SM}}{0.001}\right)^2 \left(\frac{m_{DM}}{100\text{ MeV}}\right)^2 \left(\frac{1\text{ GeV}}{m_{Z'}}\right)^4 \sim 1\text{pb}$$

<u>Lee Weinberg bound</u>: $m_{DM} \geq O(1\text{ GeV})$,

or **existence of a "Dark Sector"**

(in this case a light Z')

Additional motivations for dark particles

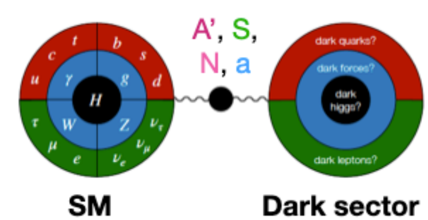
Beyond the Dark Matter motivation, dark sectors arise in many theories beyond the Standard Model:

* Theories motivated by the hierarchy problem:
  - Supersymmetric theories (Next-to-Minimal-Supersymmetric-Standard-Model)
  - Neutral Naturalness
  - Relaxion theories

* Theories that explain the baryon-antibaryon asymmetry
* Theories for the generation of neutrino masses
* Theories to address the strong CP problem (axions and ALPs)

* Several anomalies in data can be addressed by dark sectors (eg. $(g\text{-}2)_\mu$, B-physics anomalies, short-baseline neutrino anomalies, …)

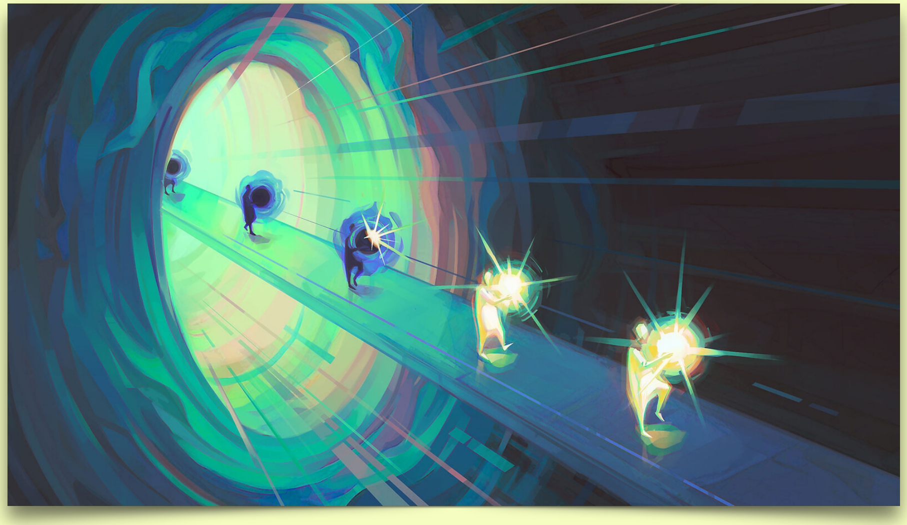
From a phenomenological point of view, the signatures to search for are often similar



$$\epsilon B^{\mu\nu} A'_{\mu\nu}$$

Minimal
dark photon models

Invisible and visible dark photons

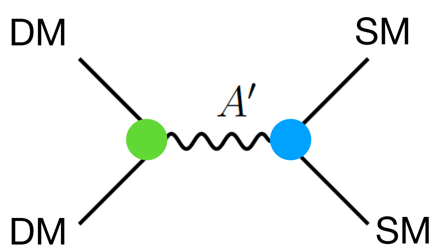


From symmetry magazine

A minimal dark matter model (1)

if $m_{A'} > 2m_{DM}$

Cosmological history:
thermal freeze-out



$$\sigma \propto \frac{y}{m_{\rm DM}^2},$$

$$y \equiv \epsilon^2 \alpha_D \left(\frac{m_{\rm DM}}{m_{A'}}\right)^4$$

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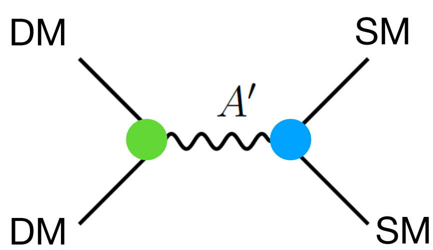

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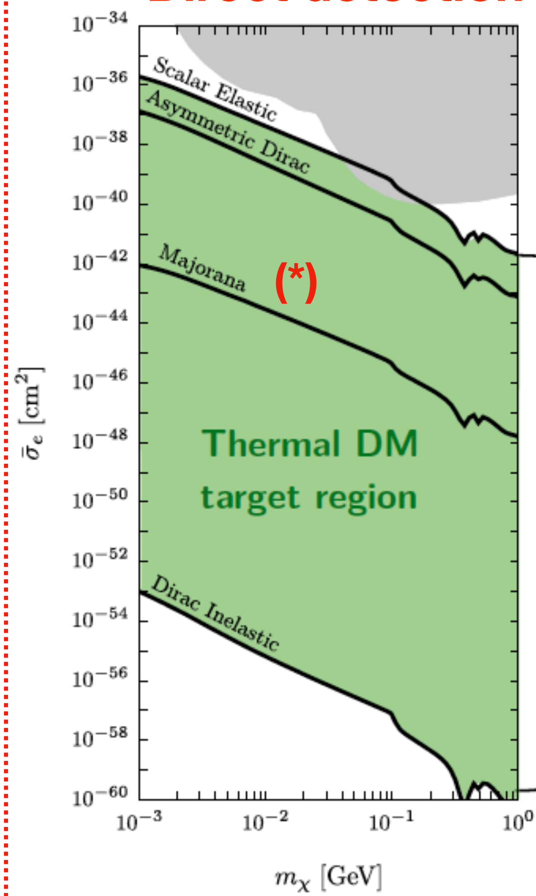
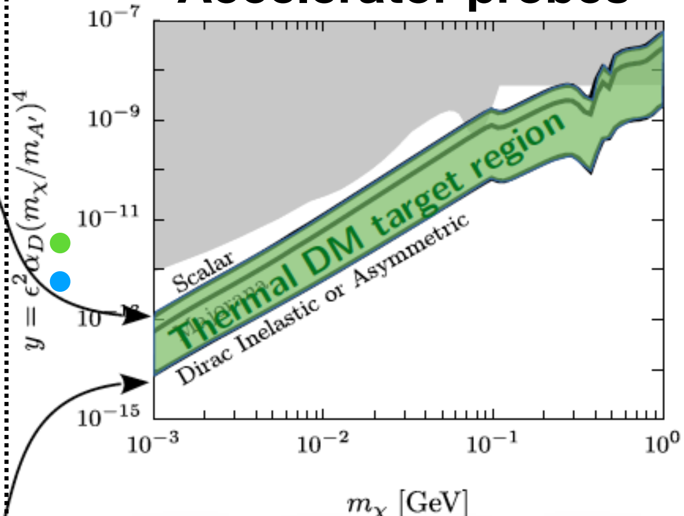
Direct detection



Accelerator probes



Main signature:
invisible decay of A'

Example:
for Majorana fermion (*)

$$\sigma v \propto v^2$$

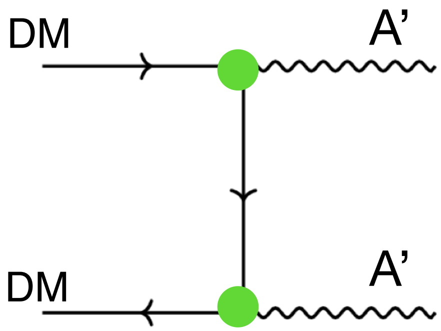
To connect these two probes, one need to make model assumptions on the nature of DM

Snowmass white paper,
Krnjaic, Toro et al, 2207.00597

A minimal dark matter model (2)

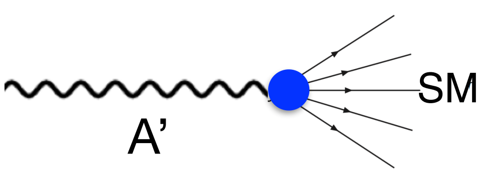
Pospelov, Ritz, Voloshin, 0711.4866

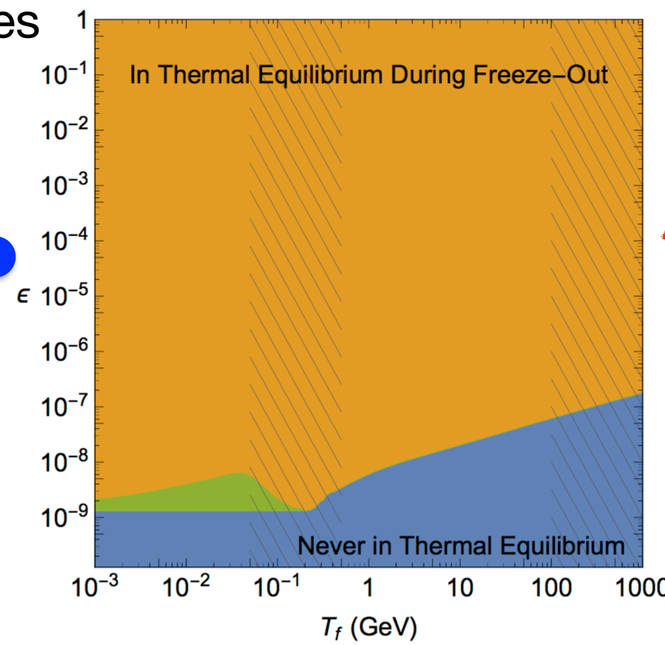
if $m_{A'} < m_{DM}$
("secluded" case)



$$\langle \sigma v \rangle \propto \frac{\alpha_D^2}{m_X^2}$$

The thermalization condition requires a minimum coupling to the SM





Lower bound

Evans, SG, Shelton, 1712.03974
+ work in progress with Alenezi and Cesarotti

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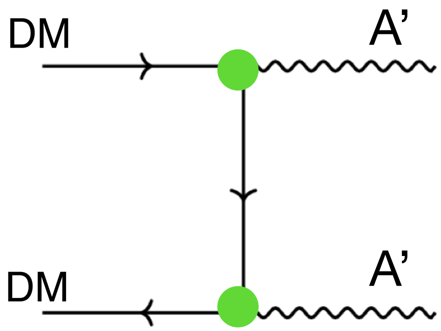

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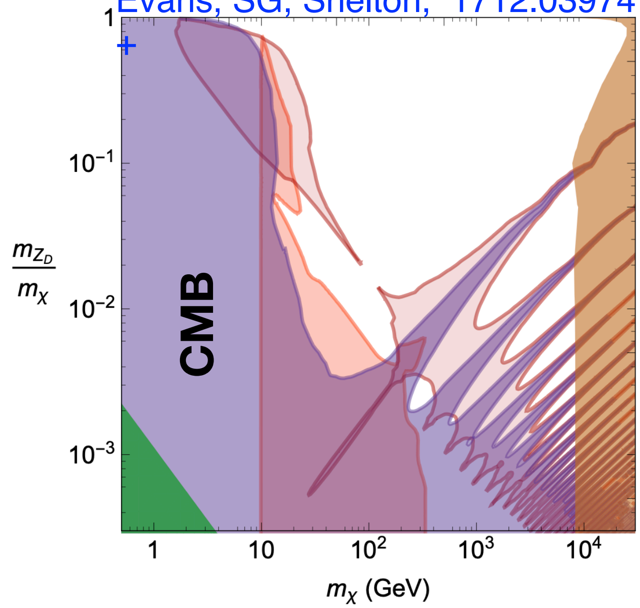


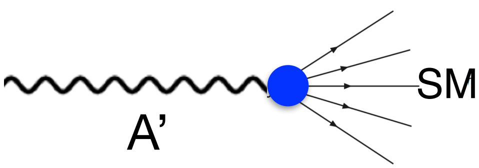
Pospelov, Ritz, Voloshin, 0711.4866

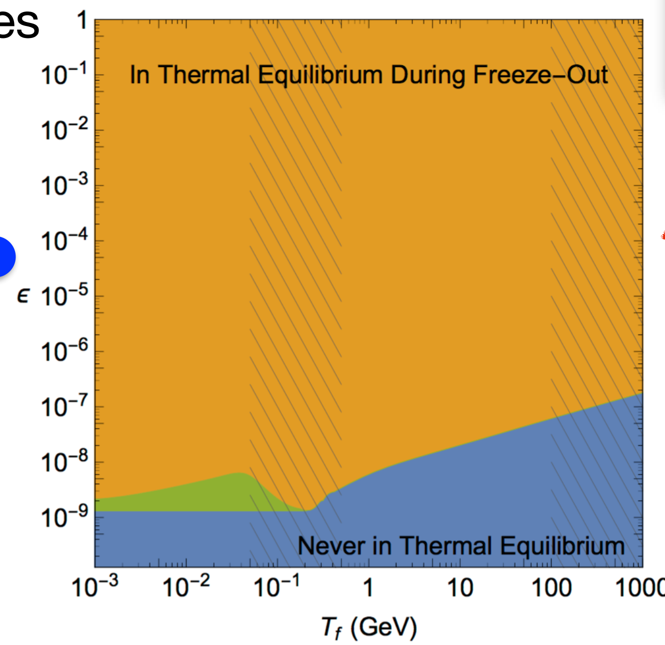
if $m_{A'} < m_{DM}$ ("secluded" case)

Several constraints especially at low DM mass (m_{DM} < 10 GeV) from indirect detection & cosmology (CMB). **A sub-GeV dark photon is still possible though**

Main signature: **visible** decay of A'

The thermalization condition requires a minimum coupling to the SM





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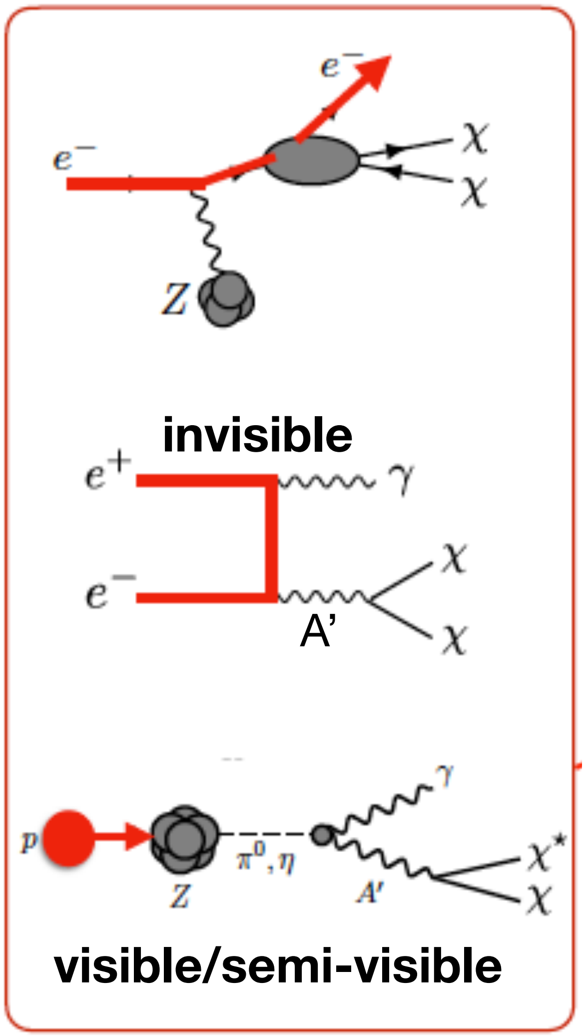
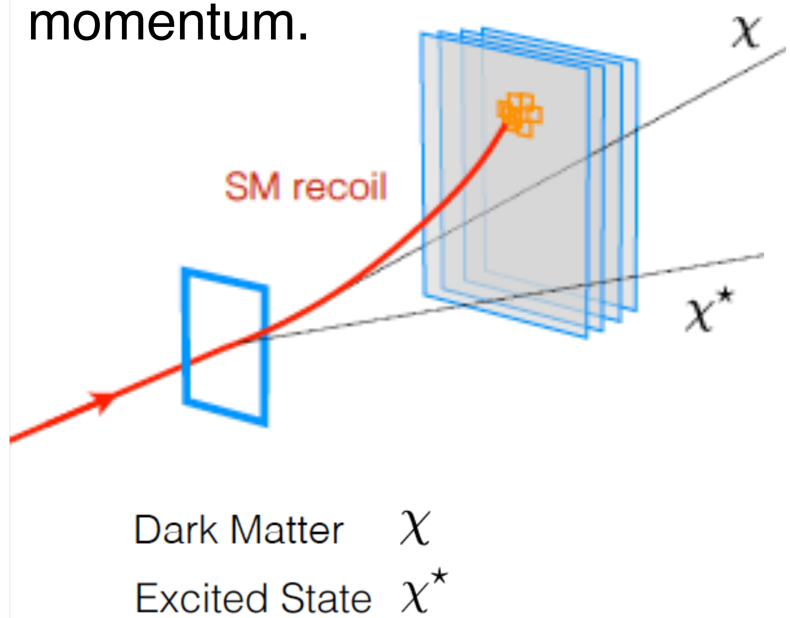
DM/dark sector production at fixed-targets

https://arxiv.org/abs/2207.00597



(1)
"Missing" a sizable fraction of the beam energy/ momentum.



Synergy with main & auxiliary detectors at collider experiments

DM/dark sector production at fixed-targets

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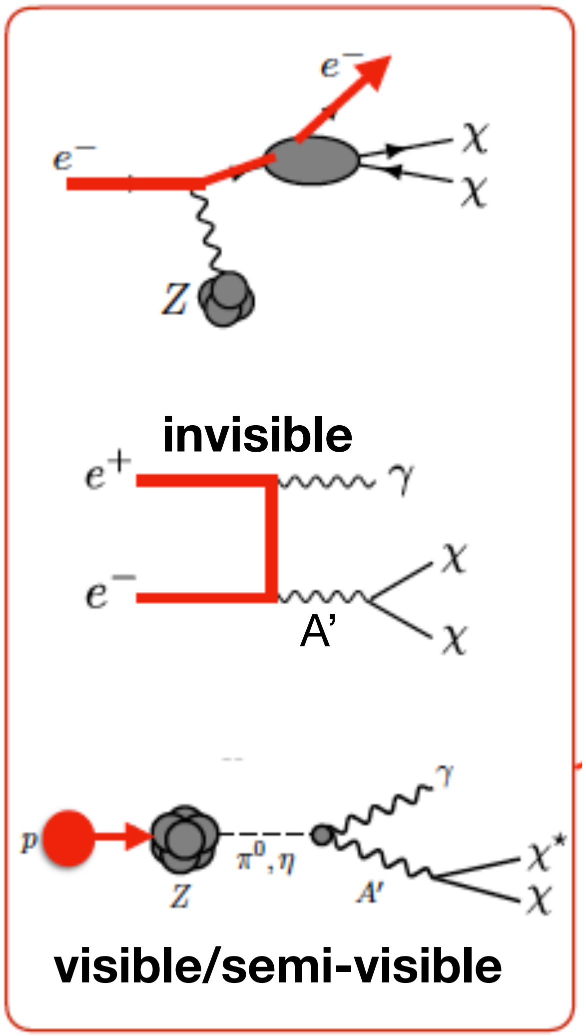

(proton beam: synergistic with the accelerator-based **neutrino physics program**)

Detection of DM scattering in forward detectors. **(2)**

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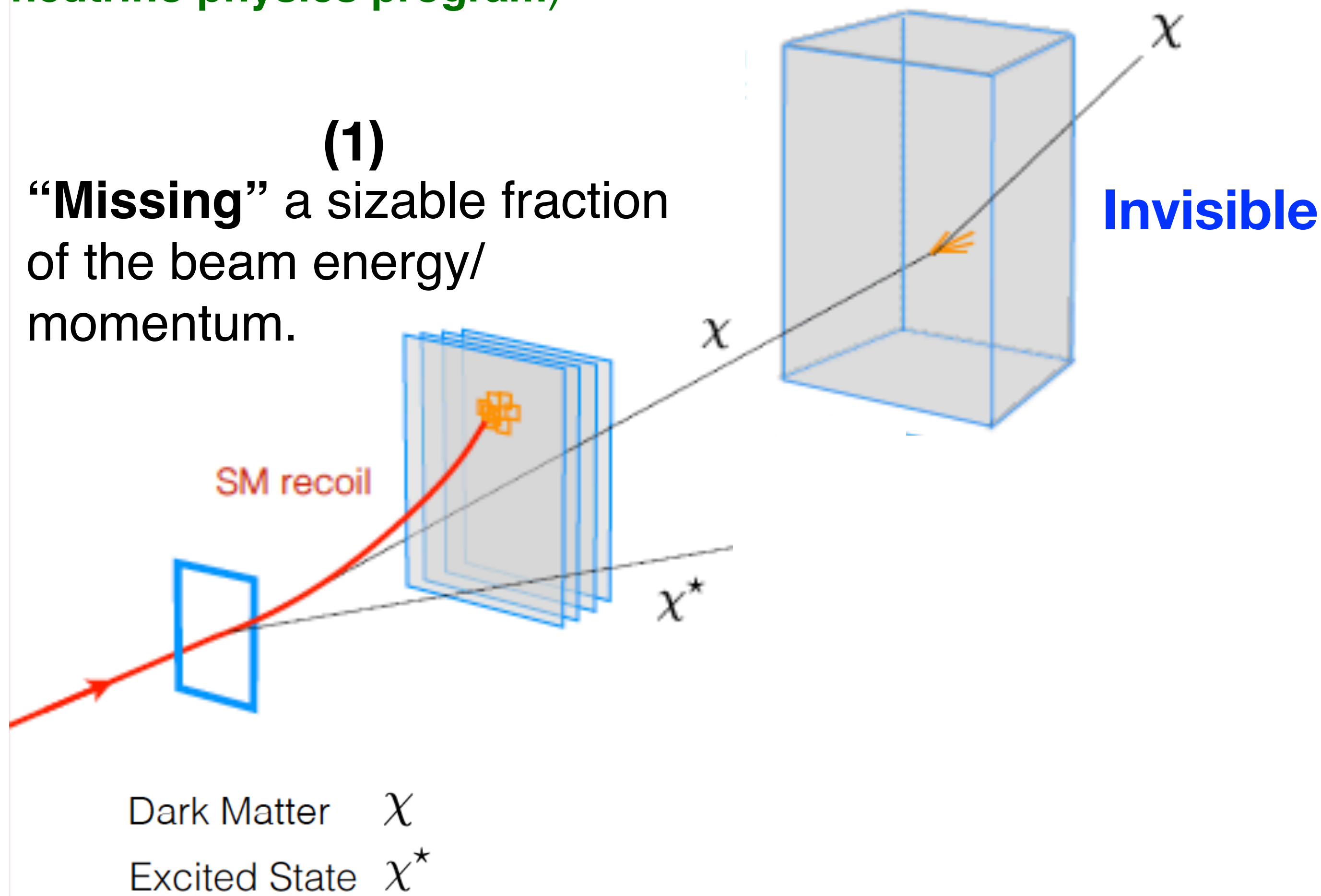

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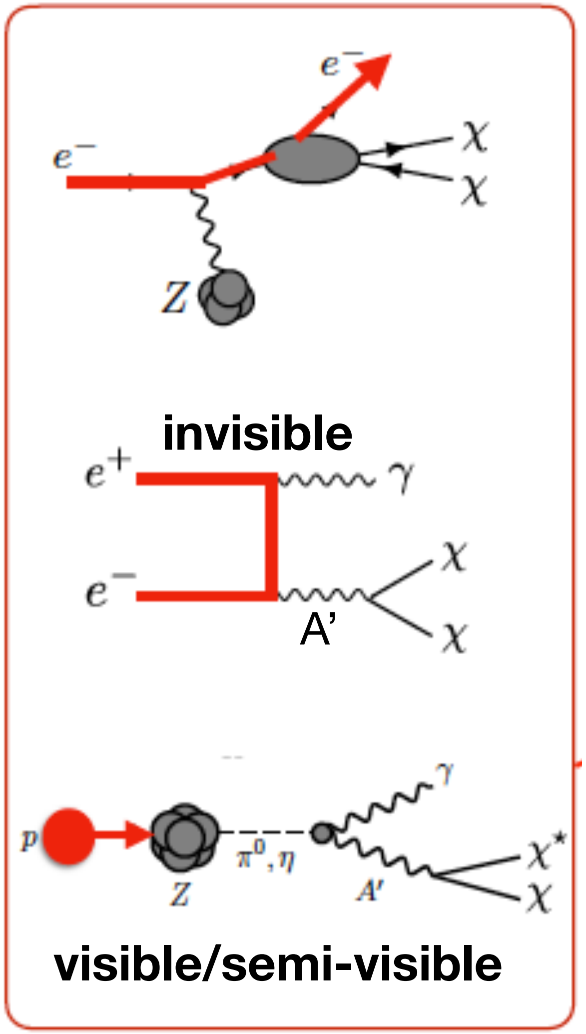

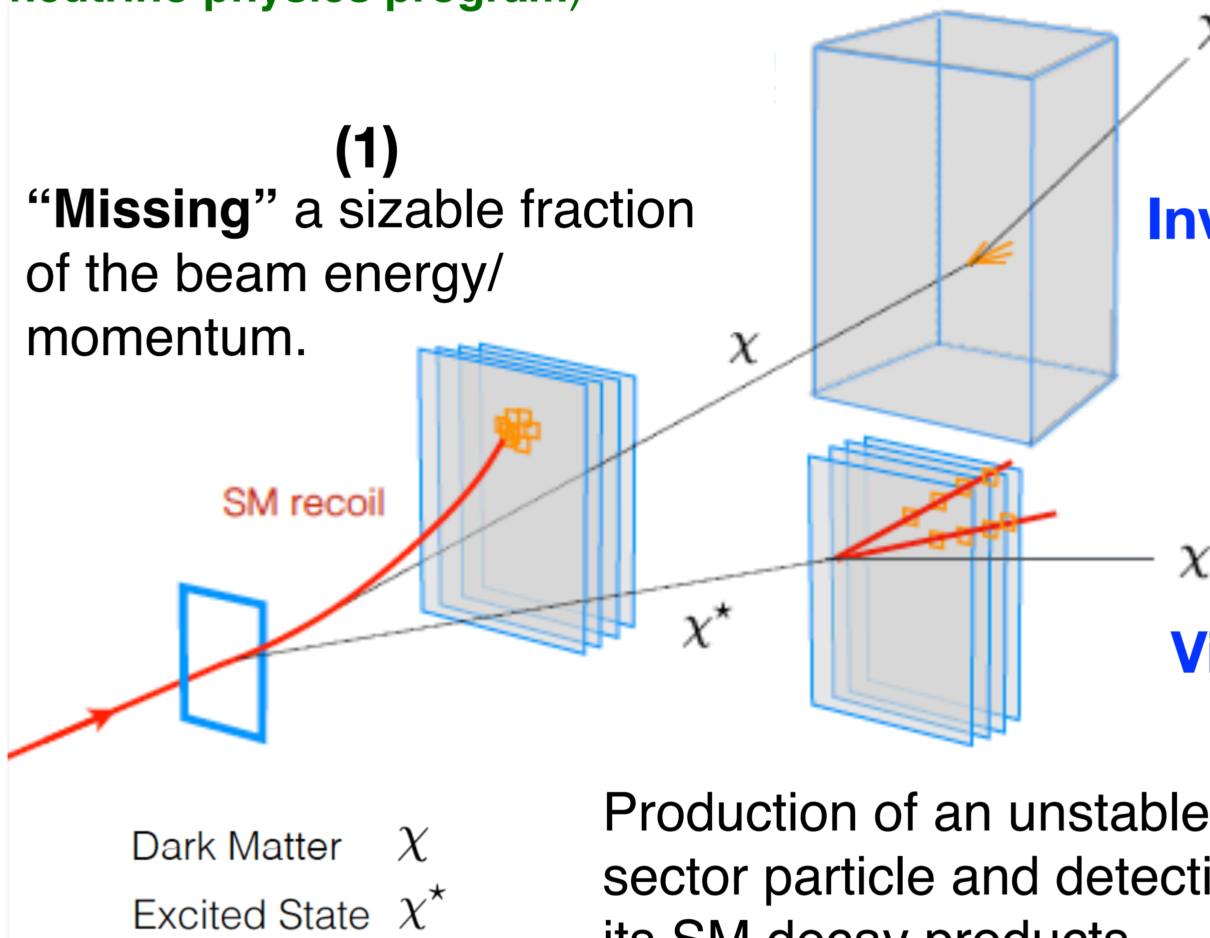

Invisible

Visible

(3)
Production of an unstable dark sector particle and detection of its SM decay products.

Synergy with main & auxiliary detectors at collider experiments

Accelerator probes, minimal model 1

If $m_{A'} > 2m_{DM}$,

the dark photon decays invisibly

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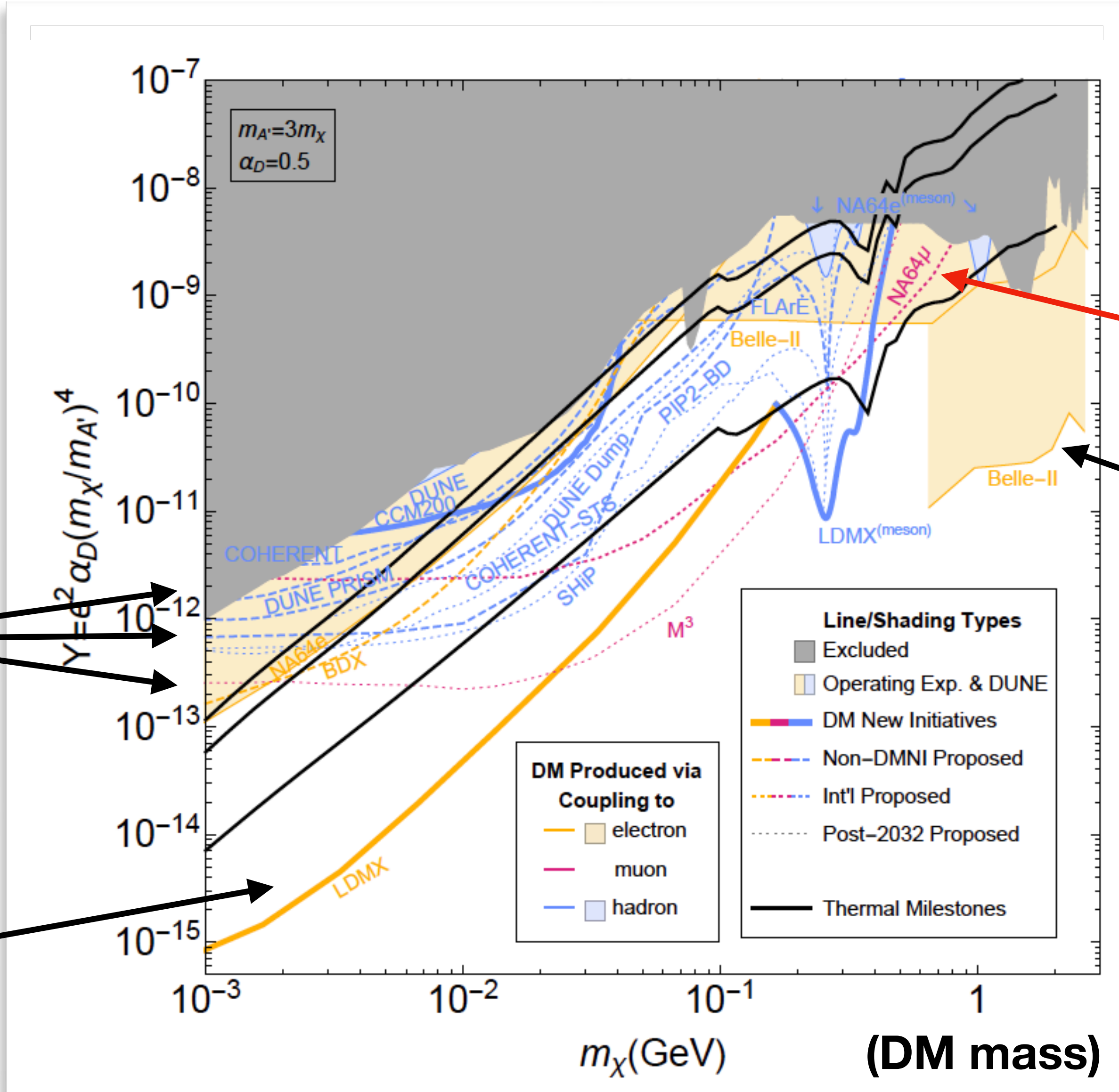
(1) Missing momentum (fixed target)



(DM mass)

(1) Missing energy

(1) Collider, mono-photon search

Krnjaic, Toro et al, 2207.00597

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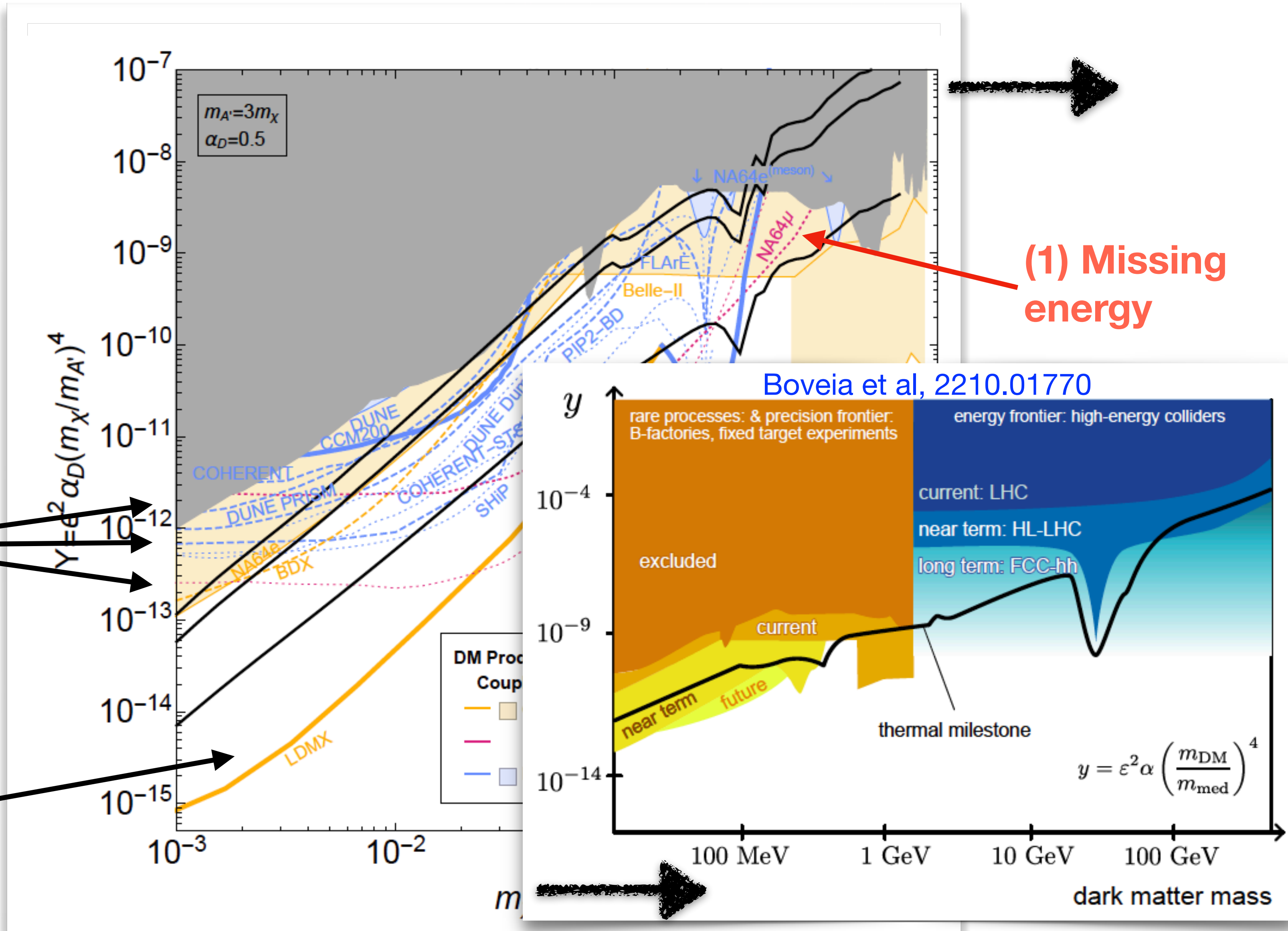

(1) Missing energy

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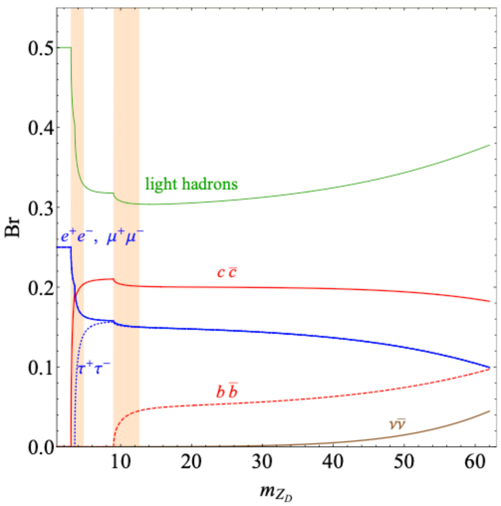
Krnjaic, Toro et al, 2207.00597

Accelerator probes, minimal model 2

If $m_{A'} < m_{DM}$,

the dark photon decays back to the SM



Curtin, et al., 1312.4992

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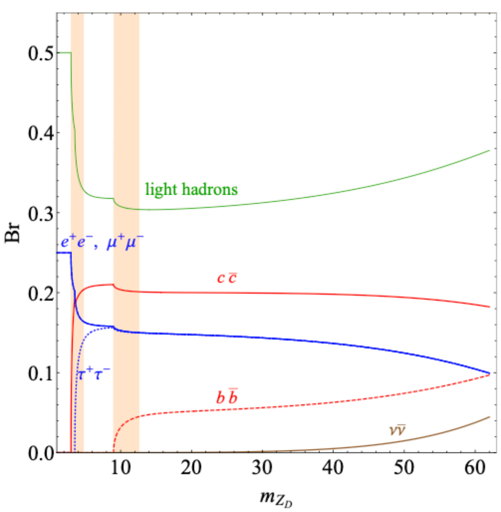
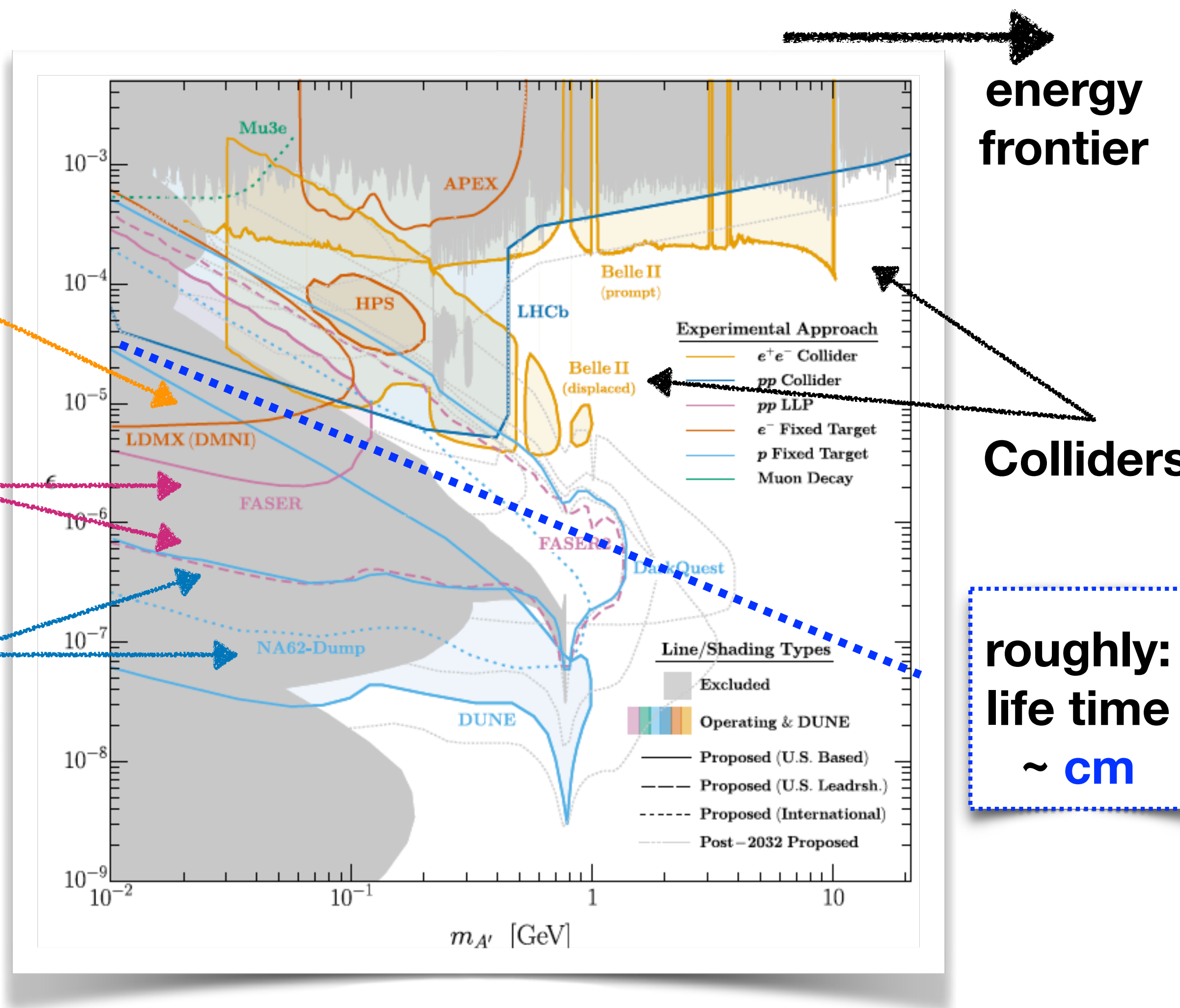


Curtin, et al., 1312.4992



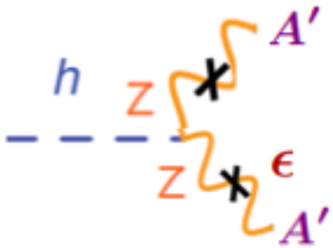
Batell et al., 2207.06905

roughly: life time ~ cm

Higgs exotic decays

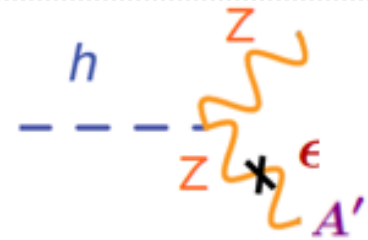
Many opportunities for the LHC to produce dark photons from Higgs (exotic) decays

Even small couplings will lead to sizable Higgs exotic branching ratios
(the SM Higgs width is tiny!)

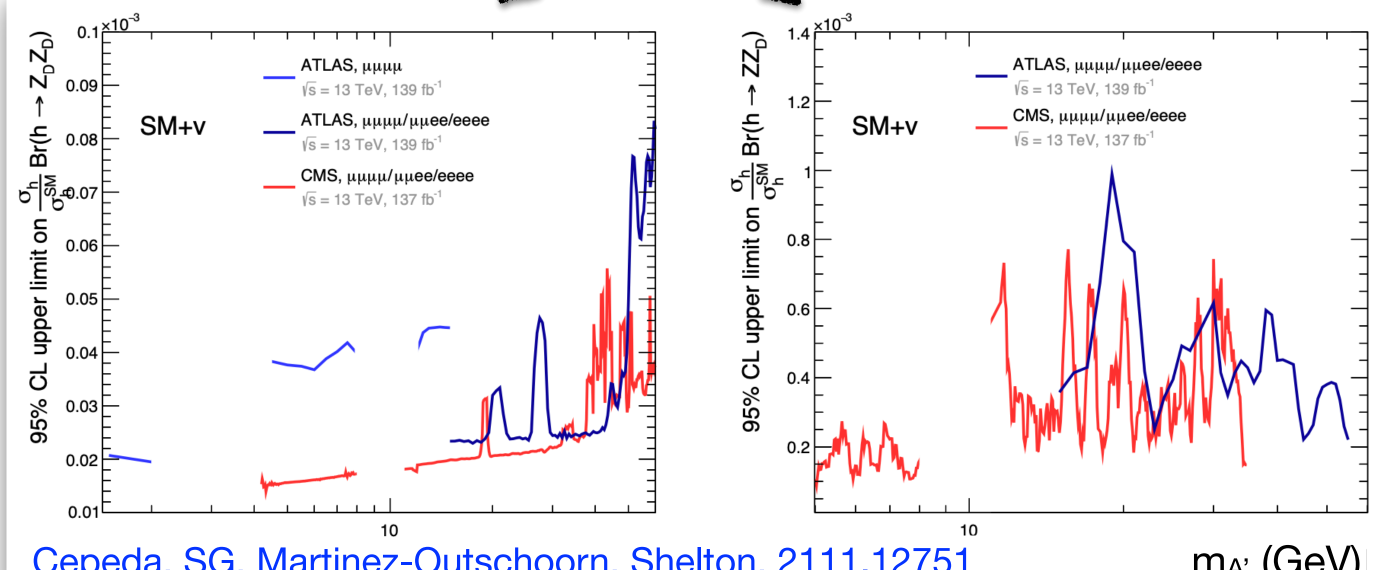


$$h \to A'A' \to 2\ell\, 2\ell'$$

The decay of A' can be
both **prompt** or **displaced**



$$h \to ZA' \to 2\ell\, 2\ell'$$



Cepeda, SG, Martinez-Outschoorn, Shelton, 2111.12751

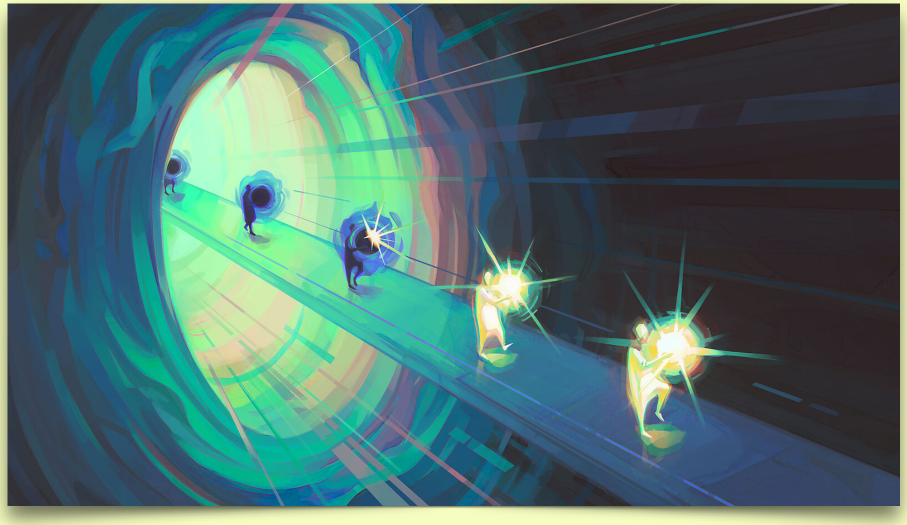
$$\epsilon B^{\mu\nu} A'_{\mu\nu}$$

Non - Minimal dark photon models

Depending on the specific dark sector theory, the dark photon can decay to a mixture of visible and invisible particles.

Examples:

- **Inelastic Dark Matter**
- **Strongly interacting massive particles**



From symmetry magazine

Inelastic Dark Matter models

Tucker-Smith, Weiner, 0101138

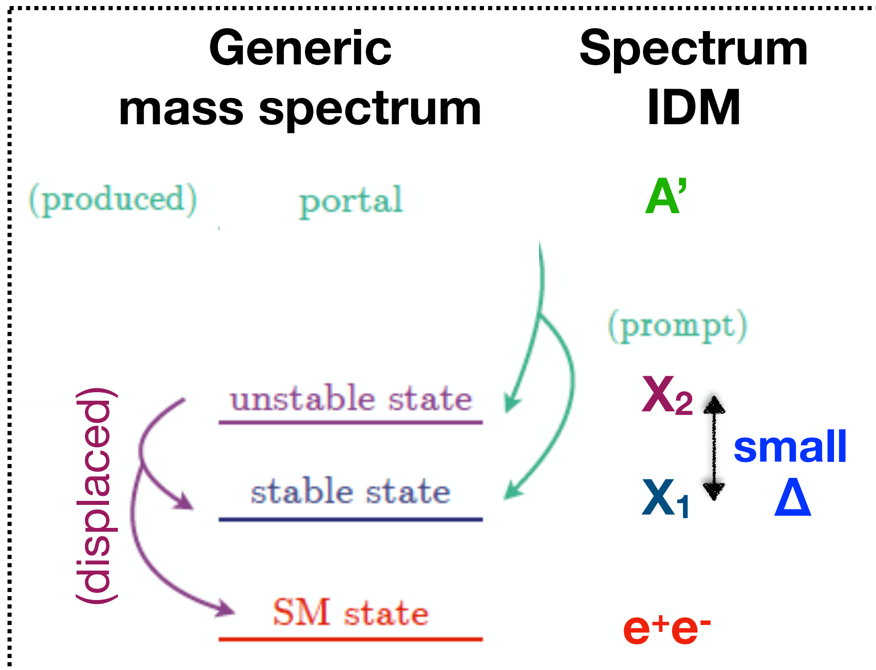
$$-\mathcal{L} \supset m_D\,\eta\,\xi + \frac{1}{2}\,\delta_\eta\,\eta^2 + \frac{1}{2}\,\delta_\xi\,\xi^2 + \text{h.c.}$$

2-component Weyl spinors with opposite charge under U(1)’

$$\mathcal{L} \supset \frac{ie_D\,m_D}{\sqrt{m_D^2 + (\delta_\xi - \delta_\eta)^2/4}}\,A'_\mu\,(\bar{\chi}_1\gamma^\mu\chi_2 - \bar{\chi}_2\gamma^\mu\chi_1)$$

* Freeze-out: $X_1\,X_2 \to$ SM

CMB constraints are relaxed because of the exponential suppression of this process at the time of recombination



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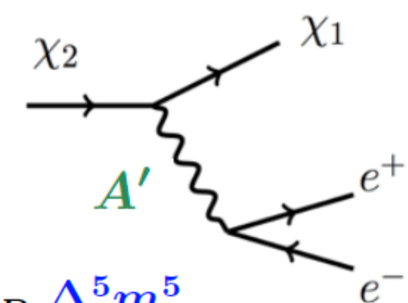
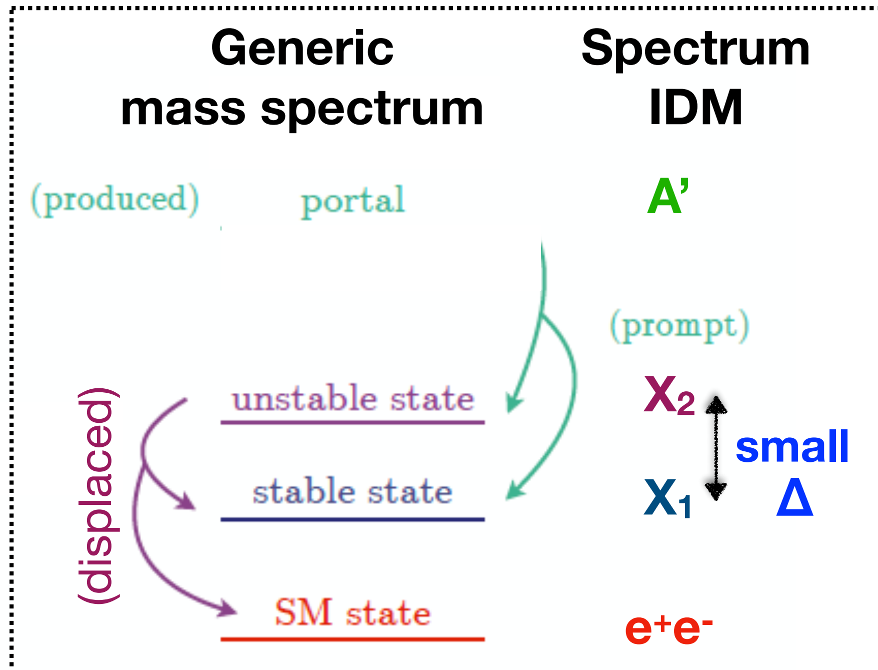
CMB constraints are relaxed because of the exponential suppression of this process at the time of recombination

* <u>Signatures</u> in our labs:



$$\Gamma(\chi_2 \to \chi_1 e^+ e^-) = \frac{4\epsilon^2 \alpha_{\rm em}\, \alpha_D\, \Delta^5 m_1^5}{15\pi m_{A'}^4}$$

generically displaced



$$A' \to \chi_2 \chi_1,\ \chi_2 \to e^+ e^- \chi_1$$

Inelastic Dark Matter models

Tucker-Smith, Weiner, 0101138

$$-\mathcal{L} \supset m_D\,\eta\,\xi + \frac{1}{2}\,\delta_\eta\,\eta^2 + \frac{1}{2}\,\delta_\xi\,\xi^2 + \text{h.c.}$$

2-component Weyl spinors with opposite charge under U(1)’

$$\mathcal{L} \supset \frac{ie_D\, m_D}{\sqrt{m_D^2 + (\delta_\xi - \delta_\eta)^2/4}}\, A'_\mu\, (\bar{\chi}_1 \gamma^\mu \chi_2 - \bar{\chi}_2 \gamma^\mu \chi_1)$$

* Freeze-out: $X_1\, X_2 \to$ SM

CMB constraints are relaxed because of the exponential suppression of this process at the time of recombination

* Signatures in our labs:

$$\Gamma(\chi_2 \to \chi_1 e^+ e^-) = \frac{4\epsilon^2 \alpha_{em}\, \alpha_D\, \Delta^5 m_1^5}{15\pi m_{A'}^4}$$

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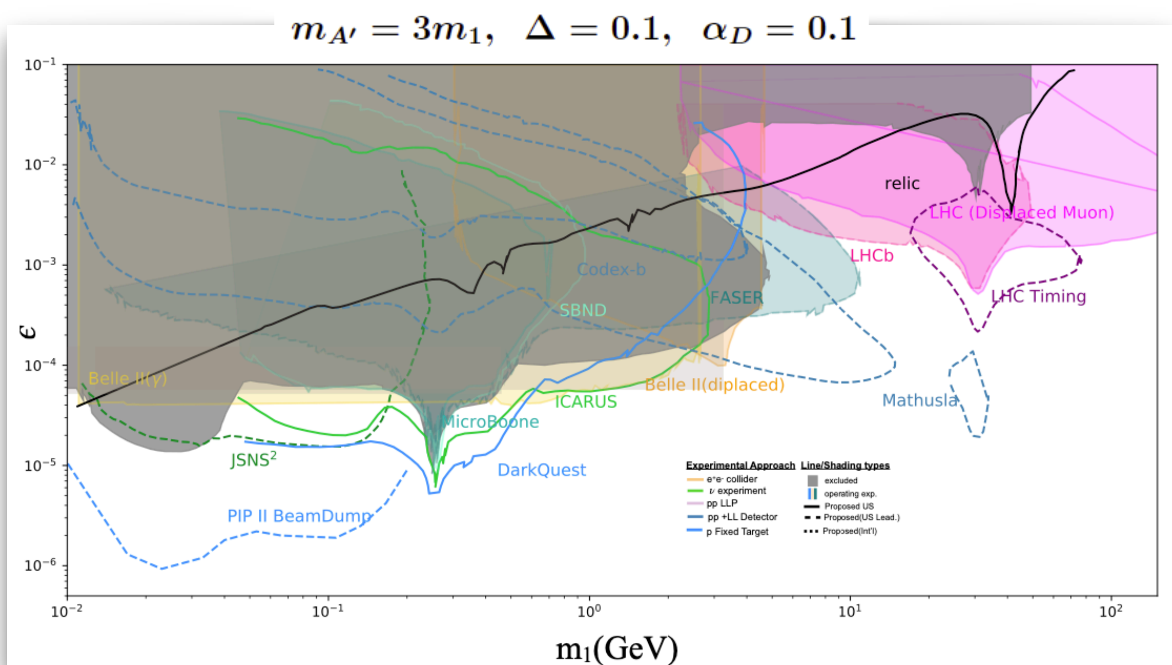
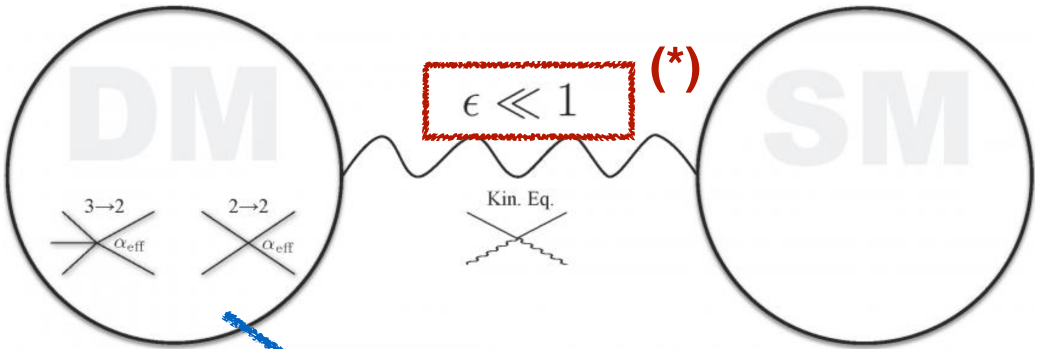


Harris et al., 2207.08990

Strongly interacting massive particles



Hochberg, Kuflik, Volansky, Wacker, 1402.5143,

Hochberg, Kuflik, Murayama, Volansky, Wacker, 1411.3727

(*) Needed to maintain thermalization between the two sectors

A new scale for DM?

(**WIMP**

$2 \to 2$

$m_{DM} \sim \alpha_{ann}(T_{eq} M_{pl})^{1/2} \sim$ TeV)

SIMP

$3 \to 2$

$m_{DM} \sim \alpha_{ann}(T_{eq}^2 M_{pl})^{1/3} \sim$ 100 MeV

Possibly realized in a QCD-like theory SU(N_c) with

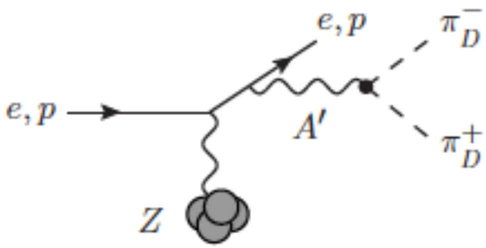
$SU(N_f) \times SU(N_f) \to SU(N_f)$

N_f^2-1 pions Light pions

$$\mathcal{L}_{WZW} = \frac{2N_c}{15\pi^2 f_\pi^5} \epsilon^{\mu\nu\rho\sigma} \mathrm{Tr}(\pi \partial_\mu \pi \partial_\nu \pi \partial_\rho \pi \partial_\sigma \pi)$$

If the portal operator is not too small, the dark pions can be in thermal equilibrium with the SM → **Detection?**

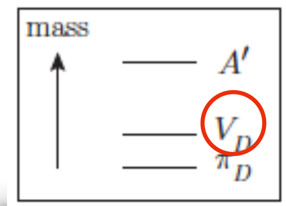
SIMP signatures at accelerator experiments



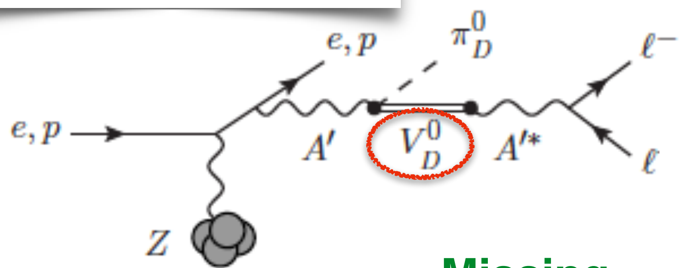
Invisible
A' decay

New dark vectors
(arising in dark QCD)

spectrum

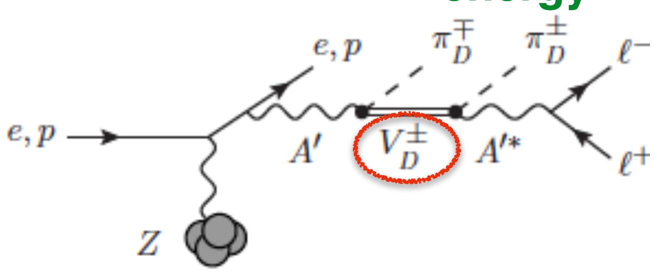


$$A' \to \pi_D^0 (V_D^0 \to \ell^+ \ell^-)$$



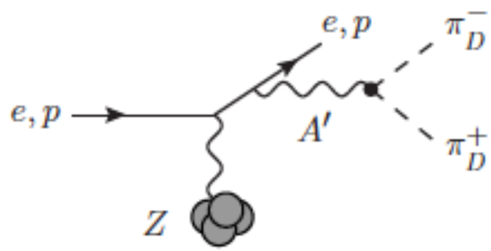
Missing
energy

Visible
A' decay



$$A' \to \pi^\pm (V_D^\mp \to \pi_D^\mp \ell^+ \ell^-)$$

SIMP signatures at accelerator experiments



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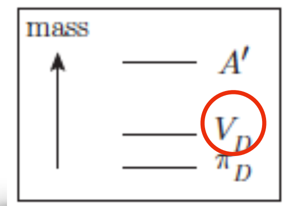

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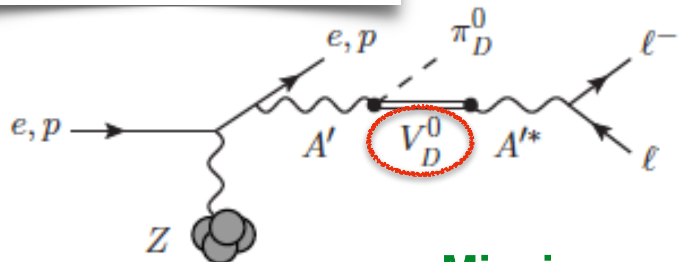

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Visible
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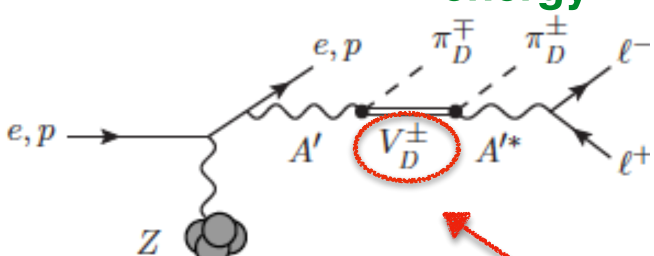
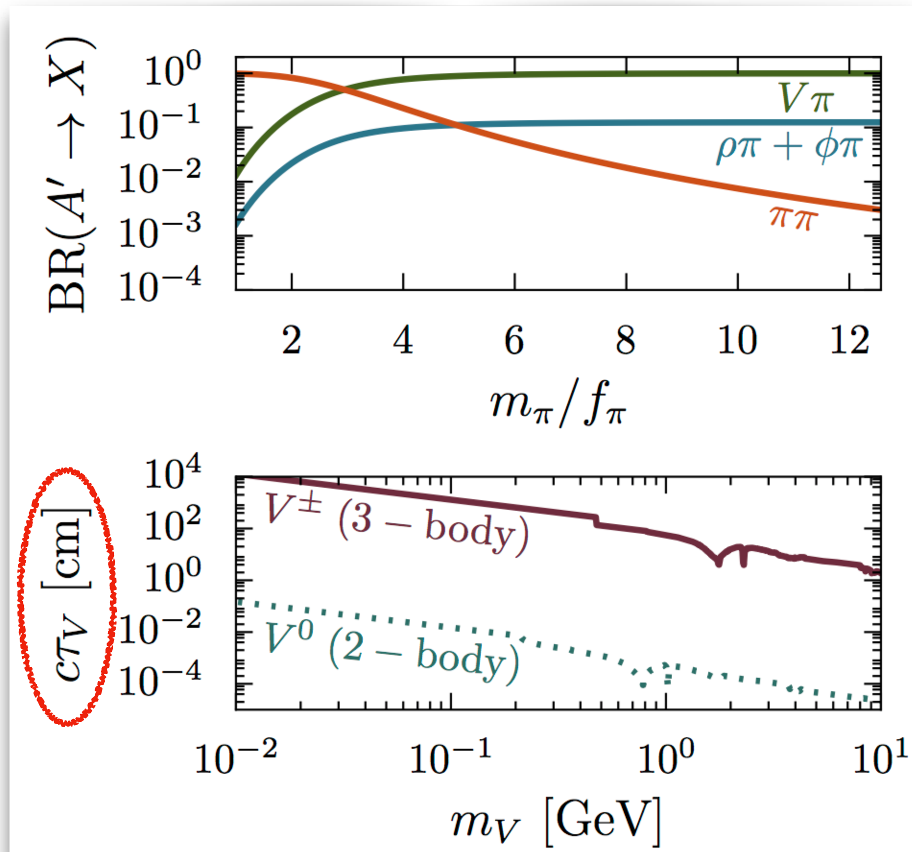


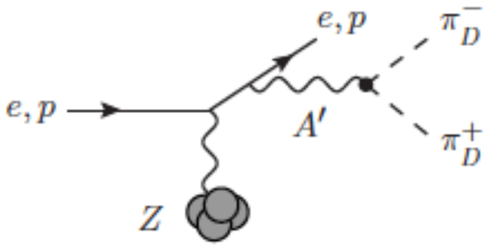
$A' \to \pi^\pm (V_D^\mp \to \pi_D^\mp \ell^+ \ell^-)$

generically
displaced

Berlin, Blinov, SG, Schuster, Toro, 1801.05805



SIMP signatures at accelerator experiments



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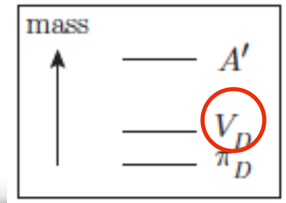

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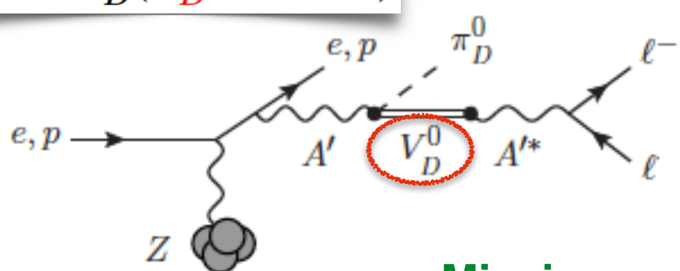
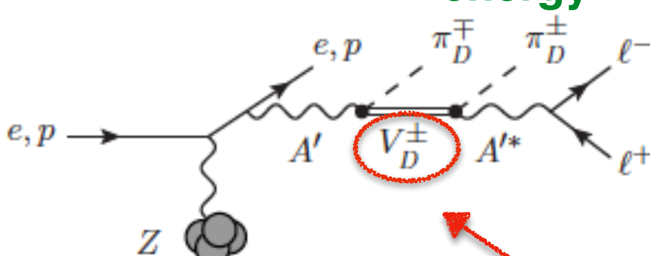


Missing energy

Visible
A' decay



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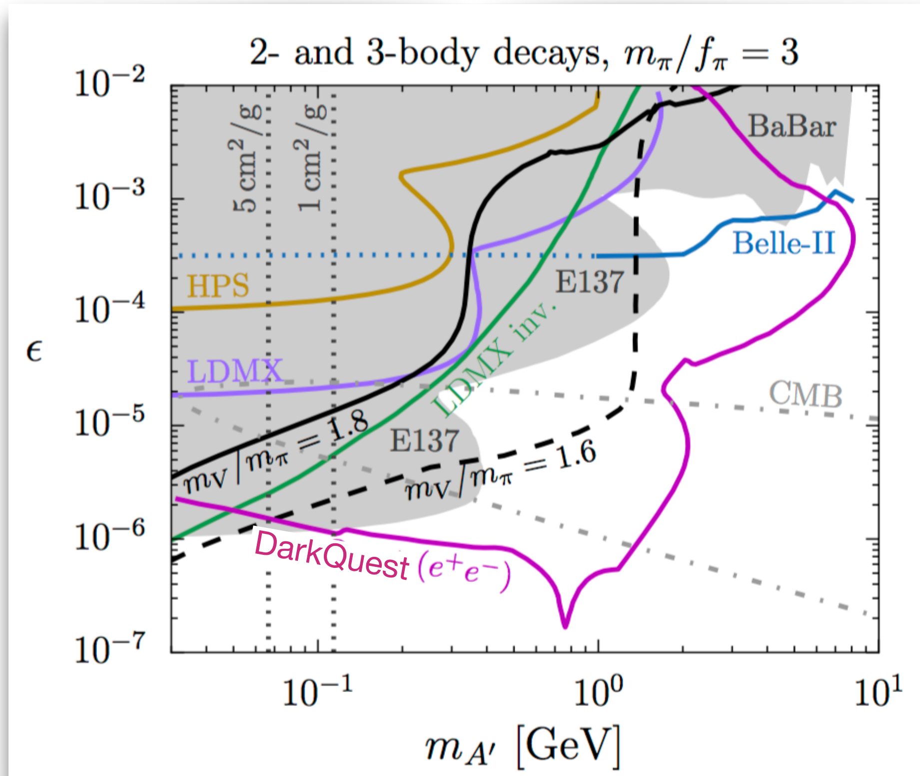


Berlin, Blinov, SG, Schuster, Toro, 1801.05805

Beyond dark photon models

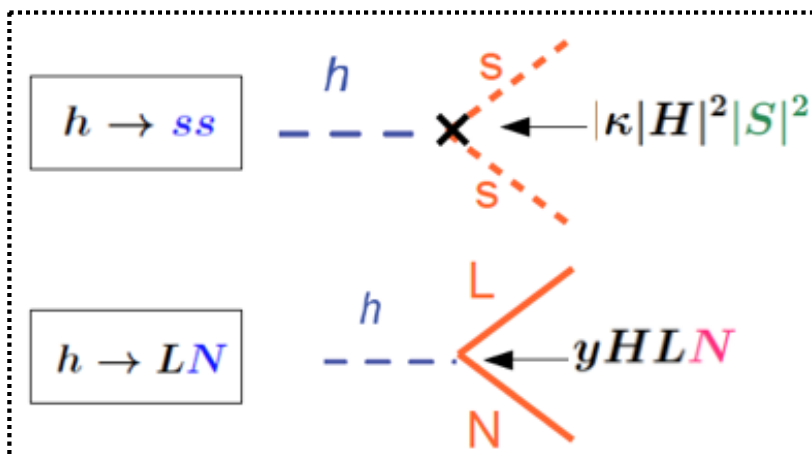
- **Invisible** signatures can be interpreted in terms of invisible ALPs or invisible dark scalars

- Additional **visible** signatures coming from ALP, scalar, or sterile neutrino models
  E.g.,
  - di-photon resonances produced from meson decays
    $B \to K(a \to \gamma\gamma), \quad K \to \pi(a \to \gamma\gamma), \ldots$
  - di-electron resonances from meson decays
    $B^+ \to e^+\nu(a \to e^+e^-), \quad K^+ \to e^+\nu(a \to e^+e^-), \quad \pi^+ \to e^+\nu(a \to e^+e^-), \ldots$

- Generic feature of dark sector models:
The **Higgs** can have a sizable branching ratio **into dark particles**

Plenty of (prompt+displaced) signatures to look for.

For a review,
see Cepeda, SG, Martinez-Outschoorn, Shelton, 2111.12751



Conclusions

Light dark photons are theoretically well-motivated particles, and they arise in many BSM theories.

They can be copiously produced at accelerator experiments.

Plethora of signatures can be searches for. Interesting complementarity between visible, invisible, and semi-visible signatures.

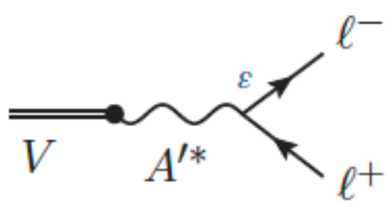
Complementarity between LHC searches (Higgs exotic decays!) and searches at high-intensity experiments.

The dark pion relic abundance

$$SU(3)_L \times SU(3)_R \to SU(3)_D \supset U(1)_D, \quad N_f = 3$$

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

2. $\pi_D \pi_D \to V_D \pi_D$ semi-annihilation



$m_V < 2m_\pi$

(If the dark vectors (V) have a mass close to the mass of the dark pions)

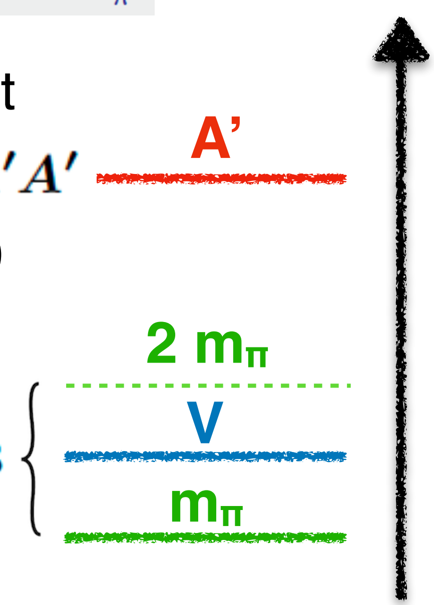
$$\langle \sigma v \rangle \sim \frac{e^{-(m_V - m_\pi)/T}}{m_\pi^2} \gtrsim \frac{e^{-m_\pi/T}}{m_\pi^2}$$

prevent

$\pi\pi \to A'A'$

(CMB)

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



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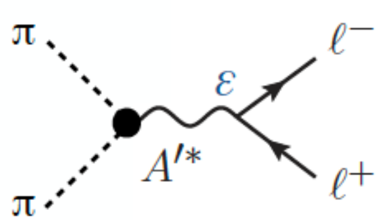

 Berlin, Blinov, SG, Schuster, Toro, 1801.05805

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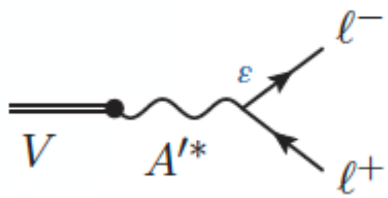

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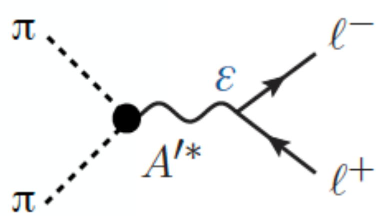
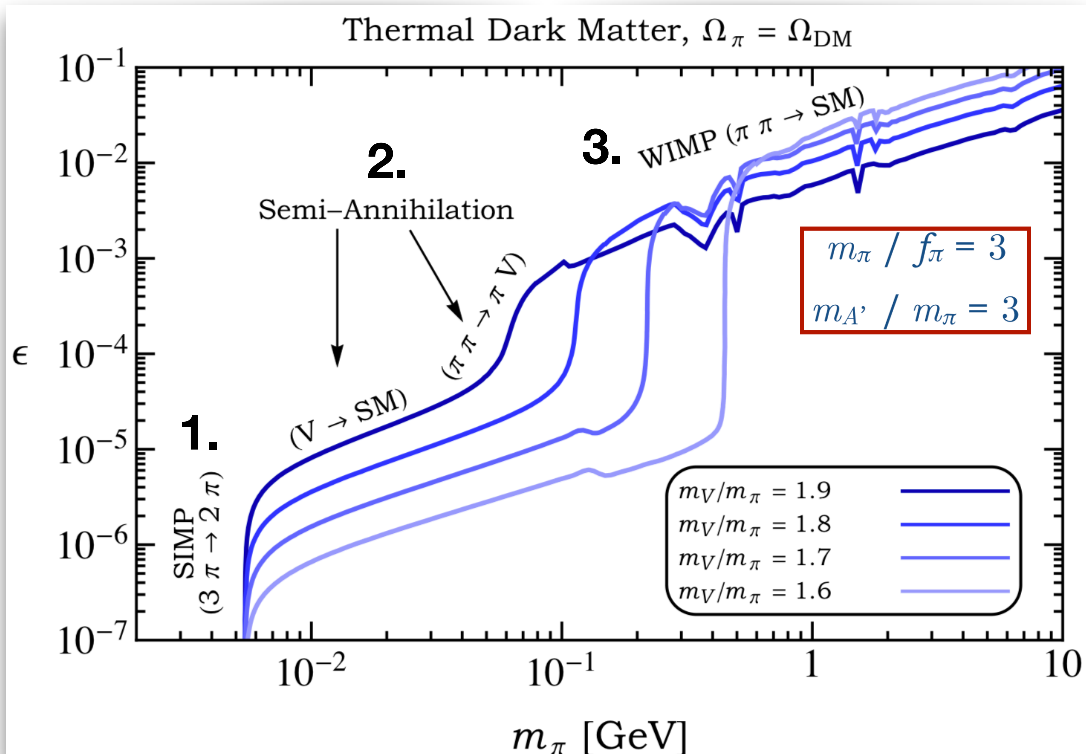
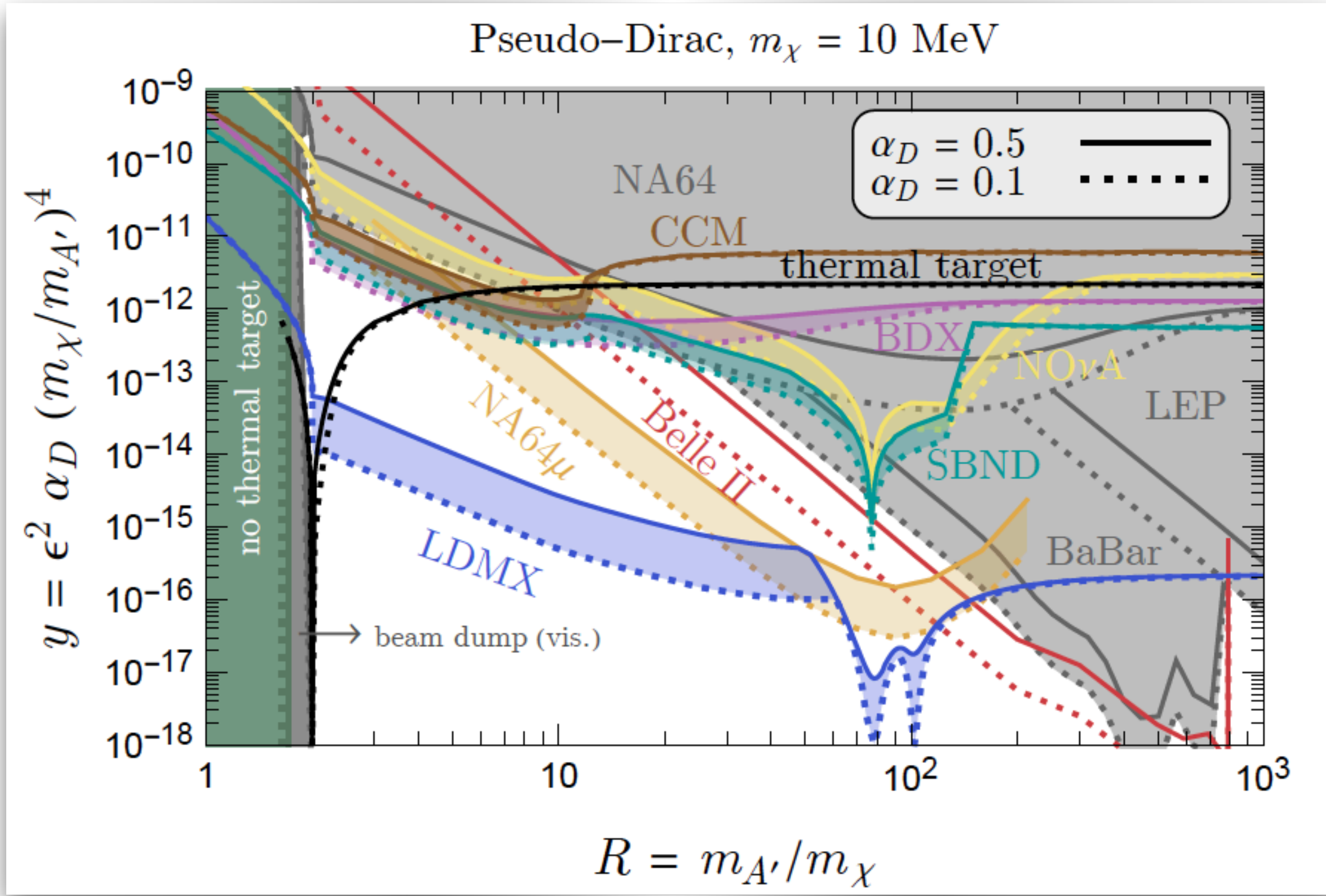




 Berlin, Blinov, SG, Schuster, Toro, 1801.05805 see also Bernreuther et al., 2311.17157

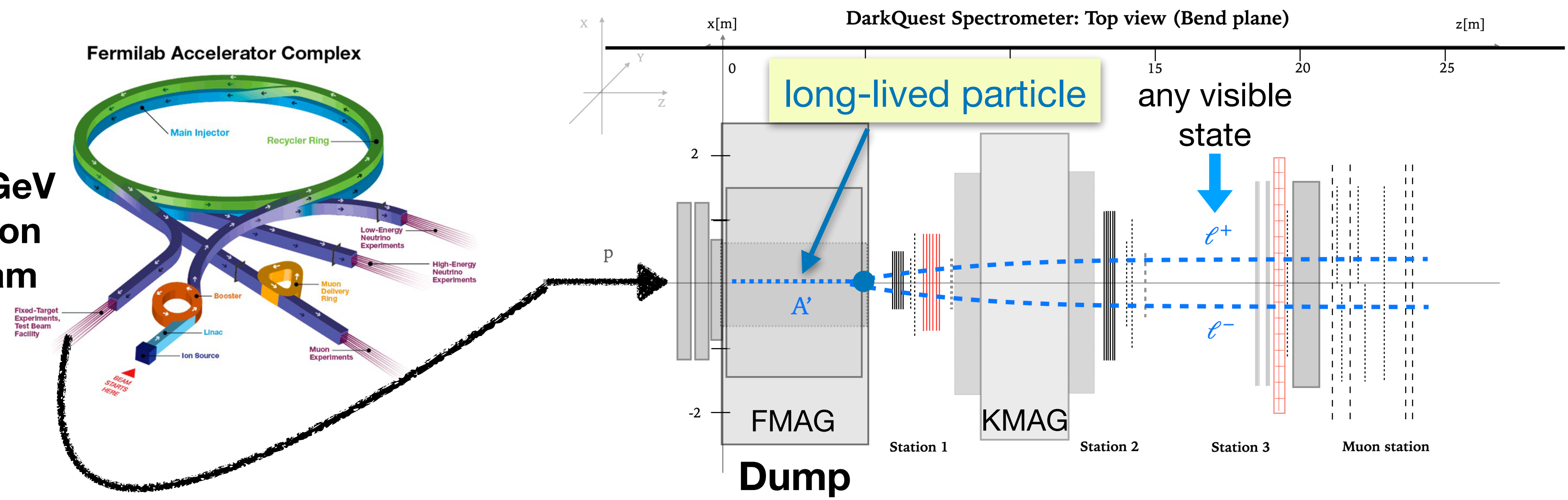
Variation of the minimal dark photon invisible model



Snowmass white paper, Krnjaic, Toro et al, 2207.00597

DarkQuest

120 GeV proton beam



Fermilab accelerator complex

SeaQuest → SpinQuest → DarkQuest

1706.09990

SpinQuest
polarized target
+ displaced trigger
muon signatures

DarkQuest
proposed upgrade
(calorimeter +
more tracking layers +
hodoscope for triggering)
all visible signatures

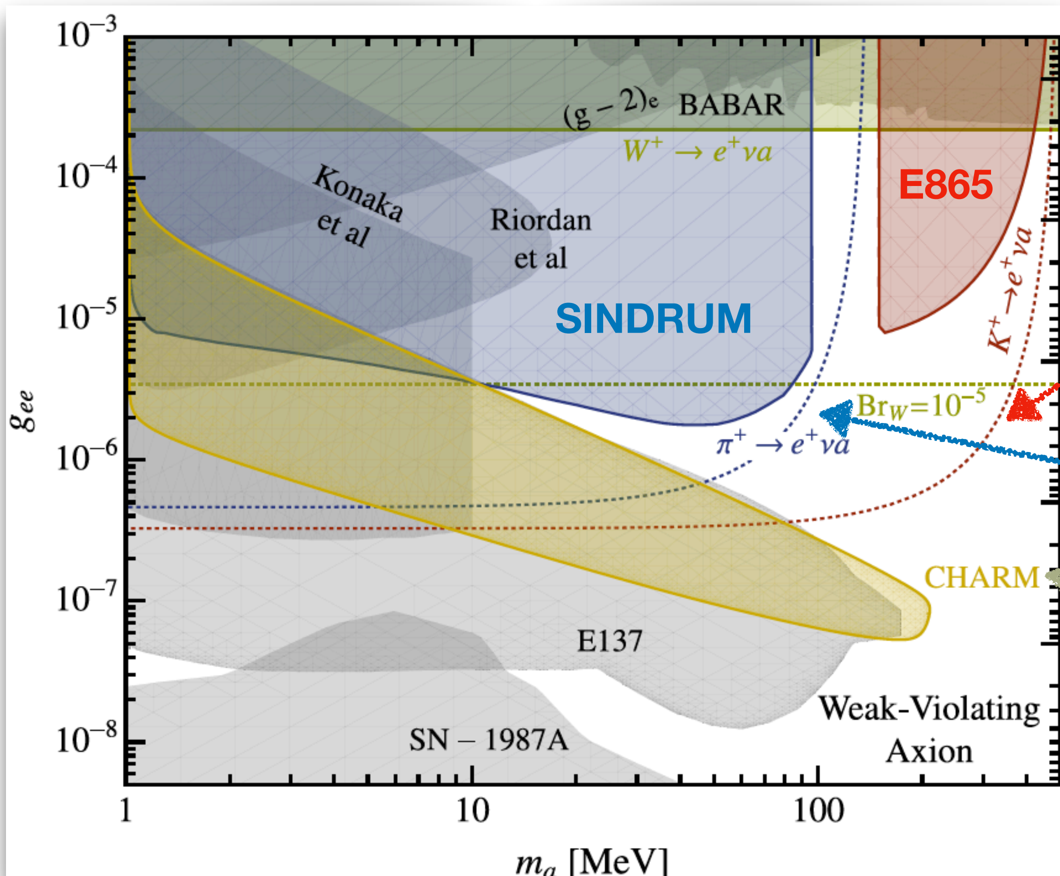
Initial proposal: Berlin, SG, Schuster, Toro, 1804.00661
Snowmass white paper: 2203.08322

Weak violating ALPs

Enhancement of meson decay rates to ALPs, $\pi \to e\nu a, \quad K \to e\nu a, \quad B \to e\nu a$

This is relevant for both meson (pion, Kaon, B-meson) factories and proton beam dumps like SeaQuest / DarkQuest (or the past CHARM experiment)

Altmannshofer, Dror, SG, 2209.00665



$$\frac{(\partial_\mu a)}{m_e}\left[\bar{e}\gamma^\mu\left(\bar{g}_{ee} + g_{ee}\gamma_5\right)e + g_\nu \bar{\nu}\gamma^\mu P_L \nu\right]$$

adding the new production modes to the CHARM reach