Hidden sectors & dark photons

Stefania Gori
University of Cincinnati

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Dark Matter (DM) is there!

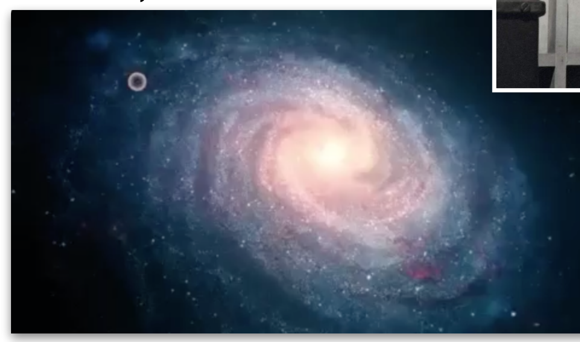
What do we know about it? Not much

1. It gravitates

1933 Fritz Zwicky

Coma cluster (of galaxies)

1970, Vera Rubin



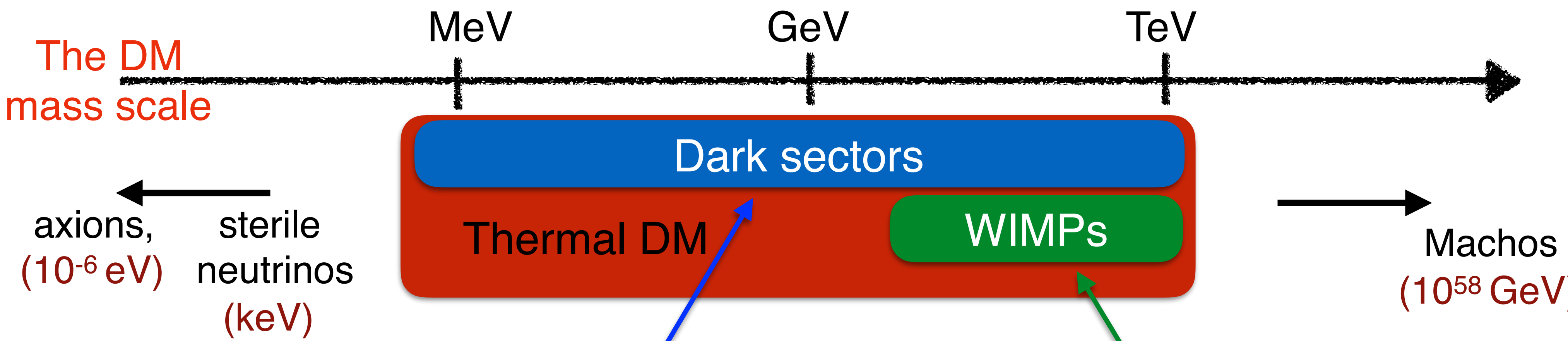
Andromeda Galaxy

2. It is dark (i.e. it does not interact with photons)

3. It is stable on cosmological scales

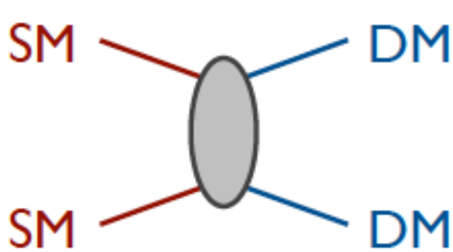
Fun fact: There is lots of DM in the Universe, but for DM particles weighing several hundred times the mass of the proton, there should be about one DM particle per coffee-cup-sized volume of space.

Thermal dark matter



Neutral under the SM interactions.
Annihilate through new interactions

Annihilate through
weak interactions



This coupling cannot be too small
for DM to be in thermal equilibrium
with the SM in the early universe

Detectability?

Dark sectors … beyond Dark Matter

Further motivations?

- Several anomalies in data can be addressed by dark sectors (eg. $(g\text{-}2)_{\mu}$, B-physics anomalies, Dark Matter anomalies (galactic center excess), …);
- Neutrino mass model building

What theories?

DM theories, Supersymmetric theories (NMSSM), neutral naturalness theories, theories for baryogengesis, …

Dark sectors … beyond Dark Matter

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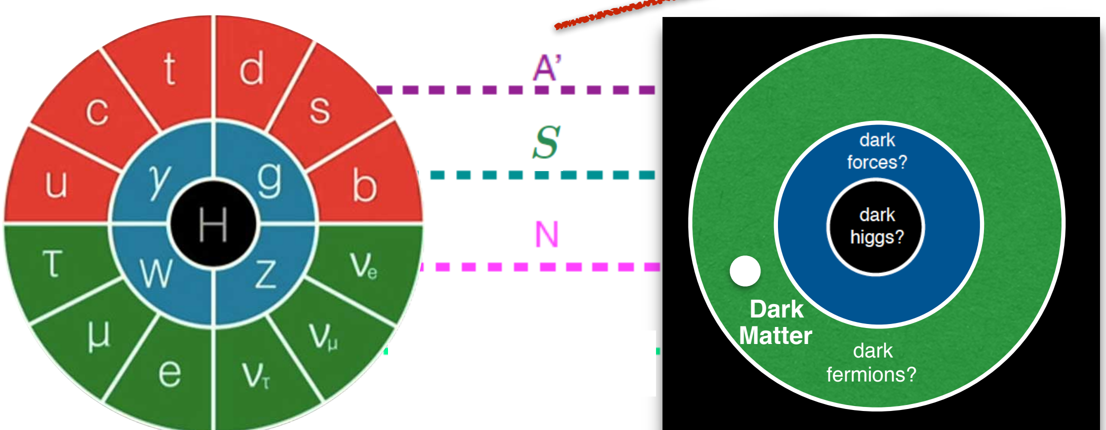
How to test this emerging paradigm?



Not charged under the SM gauge symmetries

"Portals":

Dark photon	$\epsilon Z^{\mu\nu} A'_{\mu\nu}$
Higgs	$\kappa \|H\|^2 \|S\|^2$
Neutrino	$y H L N$

generically small parameters

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)'?**

Holdom, '86

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

Mixing with the SM hyper-charge gauge boson

arising from
* dark Higgs mechanism or
* Stueckelberg mechanism

⇒ **Massive photon**

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→ **Massive photon**

The SM Z boson is affected

Mass of the Z boson:

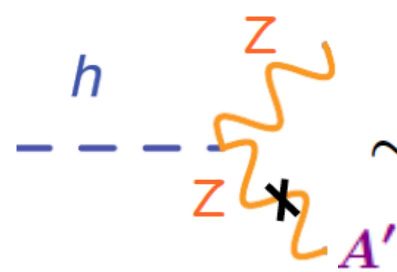
$$m_Z^2 \sim m_{Z0}^2 (1 + \epsilon^2 \sin^2\theta)$$

Couplings of the Z boson with fermions:

$$(Zf\bar{f})\,(1 + \epsilon^2 \sin^2\theta F(T_3, Q))$$

→ LEP bounds

The SM Higgs boson is affected



$$\sim 2\epsilon \sin\theta \frac{m^2_{A'}}{v}$$

Novel Higgs decays

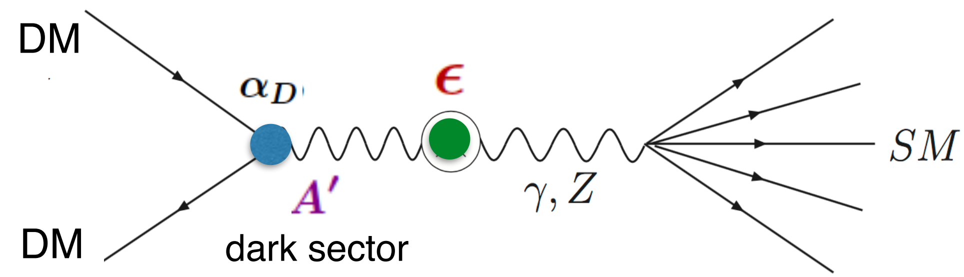
→ New opportunities for the LHC

“Thermal goals”

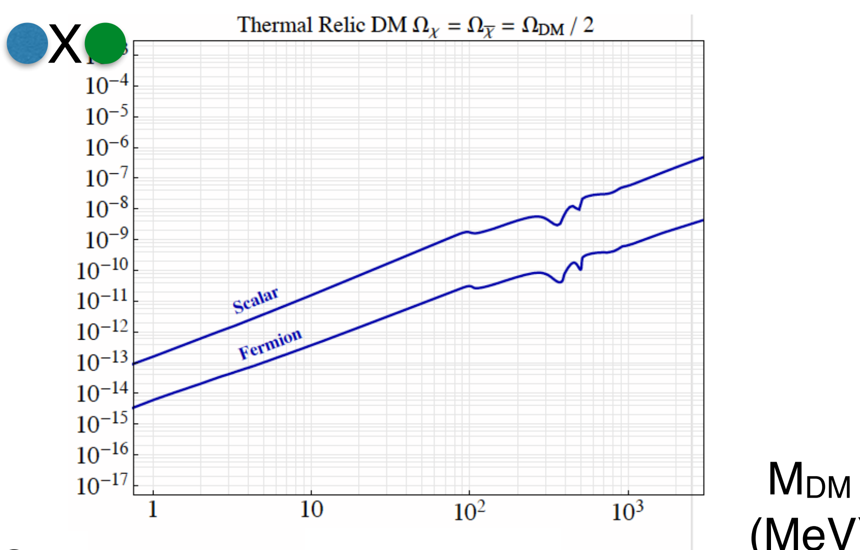
Two general classes of thermal DM:

(“non-secluded” case)

DM is the lightest state of the dark sector



Relic abundance regulated by ,



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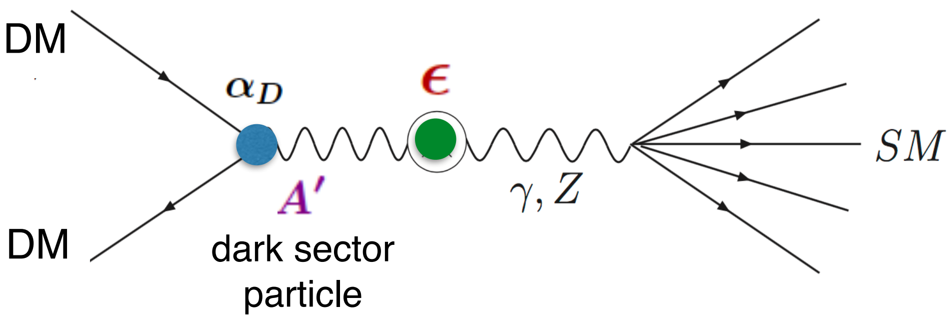

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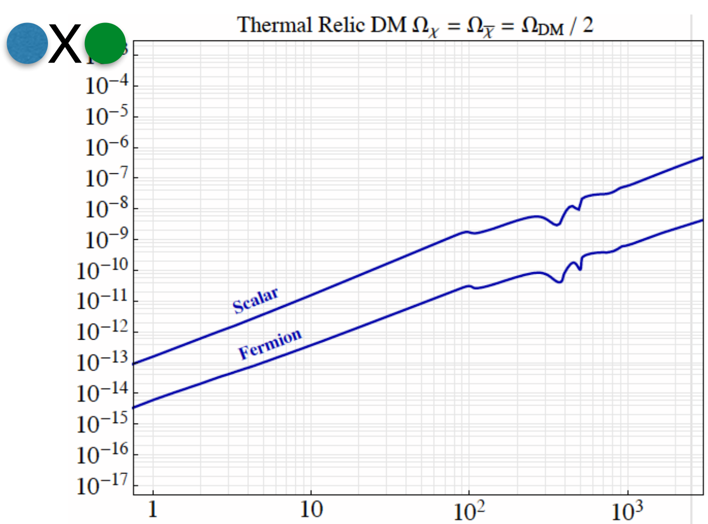
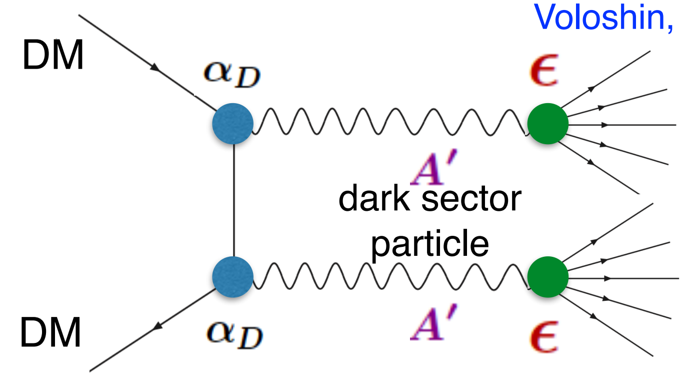


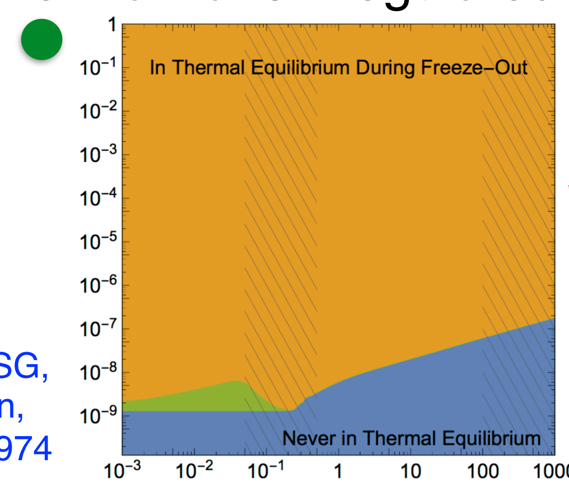
M_{DM} (MeV)

One (or more) particles of the dark sector are lighter than DM

Pospelov, Ritz, Voloshin, 0711.4866



Thermalization regulated by

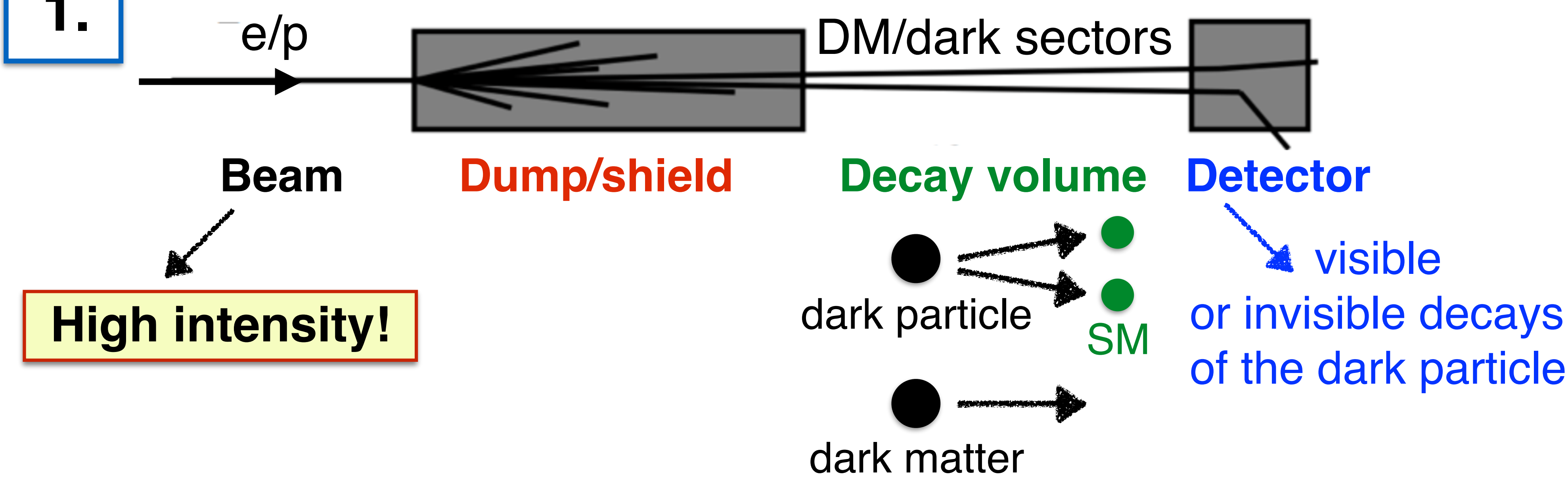


Lower bound

Evans, SG, Shelton, 1712.03974

Fixed target & colliders experiments

1.



2. Electron and proton colliders

High energy!

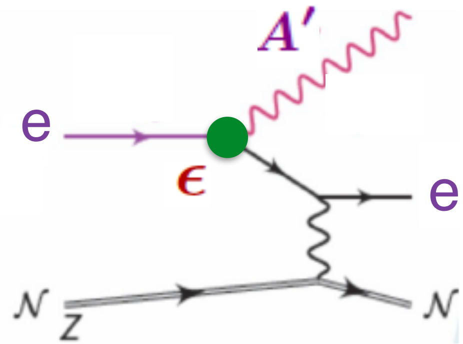
Production of dark particles through high energy

- electron-positron collisions (Babar, Belle, …)
- proton-proton collisions (LHC, future colliders, …)

The production of dark photons

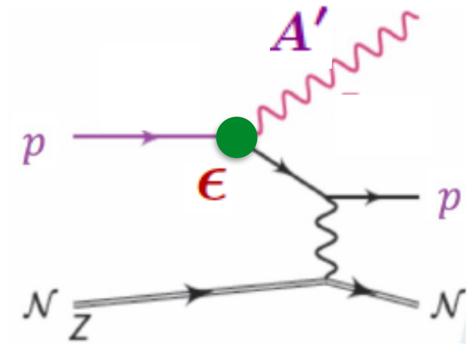
$\epsilon Z^{\mu\nu} A'_{\mu\nu}$

Electron fixed target experiments



brems-
strahlung

Proton fixed target experiments



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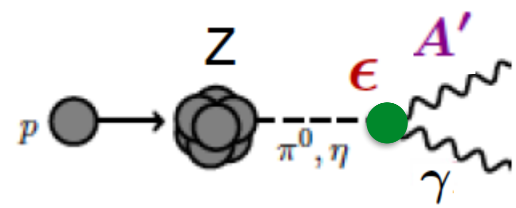
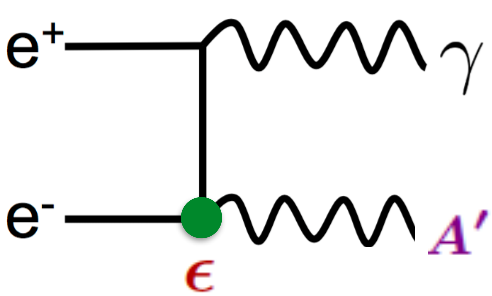
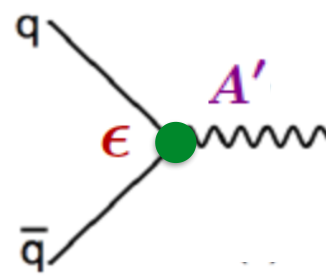


meson
decay

Electron-positron colliders



Proton-proton colliders:



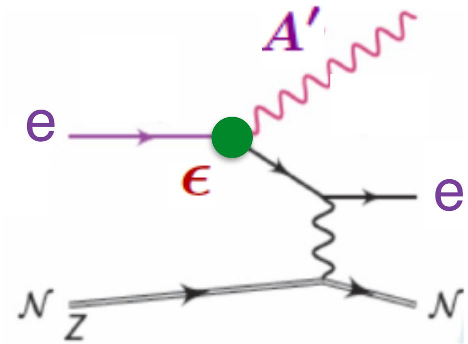
Drell-Yan

High intensity High energy

The production of dark photons

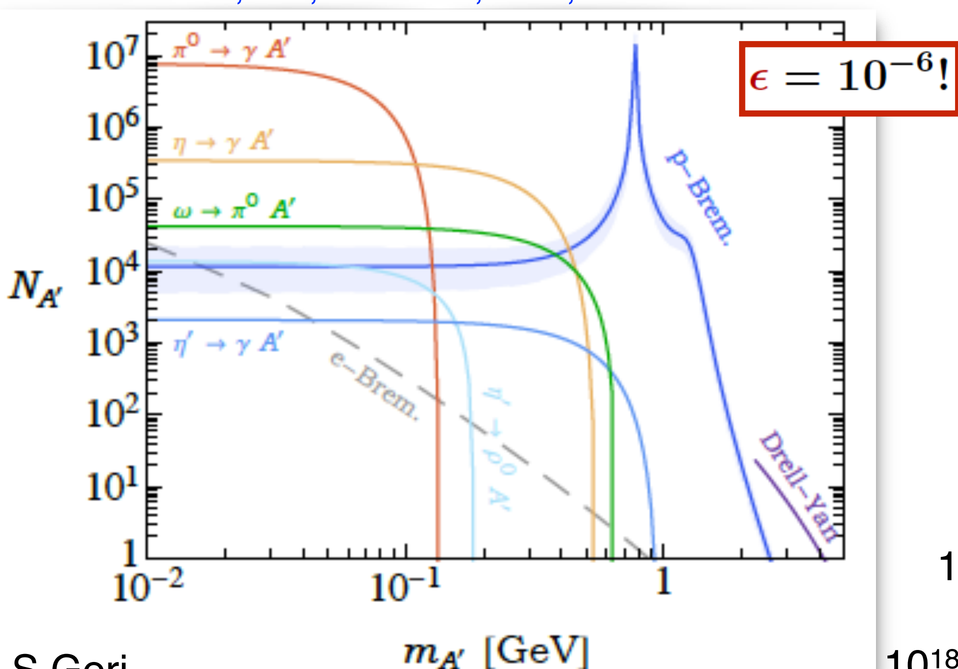
$\epsilon Z^{\mu\nu} A'_{\mu\nu}$

Electron fixed target experiments

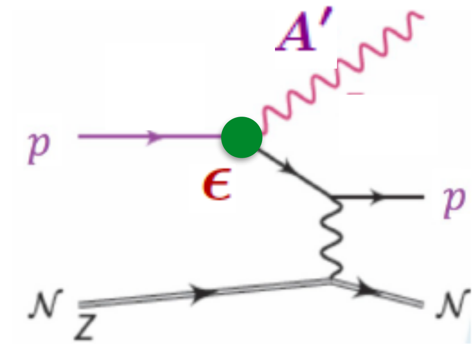


brems-strahlung

Berlin, SG, Schuster, Toro, 1804.00661



Proton fixed target experiments



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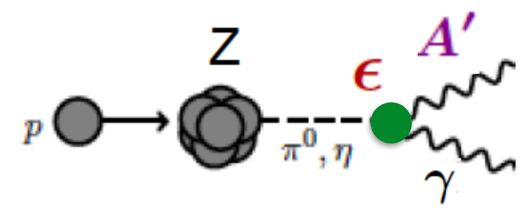
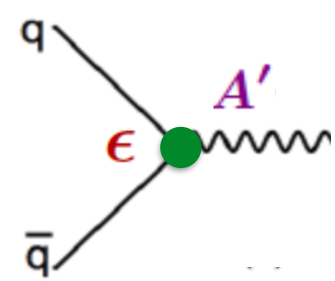


meson decay



Drell-Yan

120 GeV beam, 10^{18} POT/EOT

Protons:

typically higher energies

but larger backgrounds

Minimal dark photon signatures

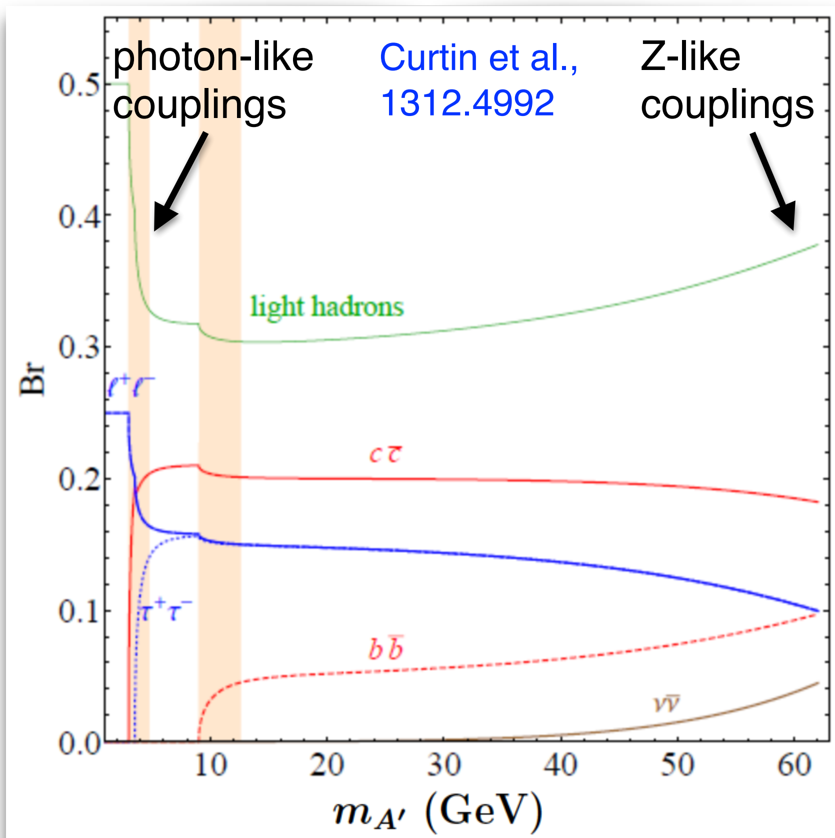
(secluded*)

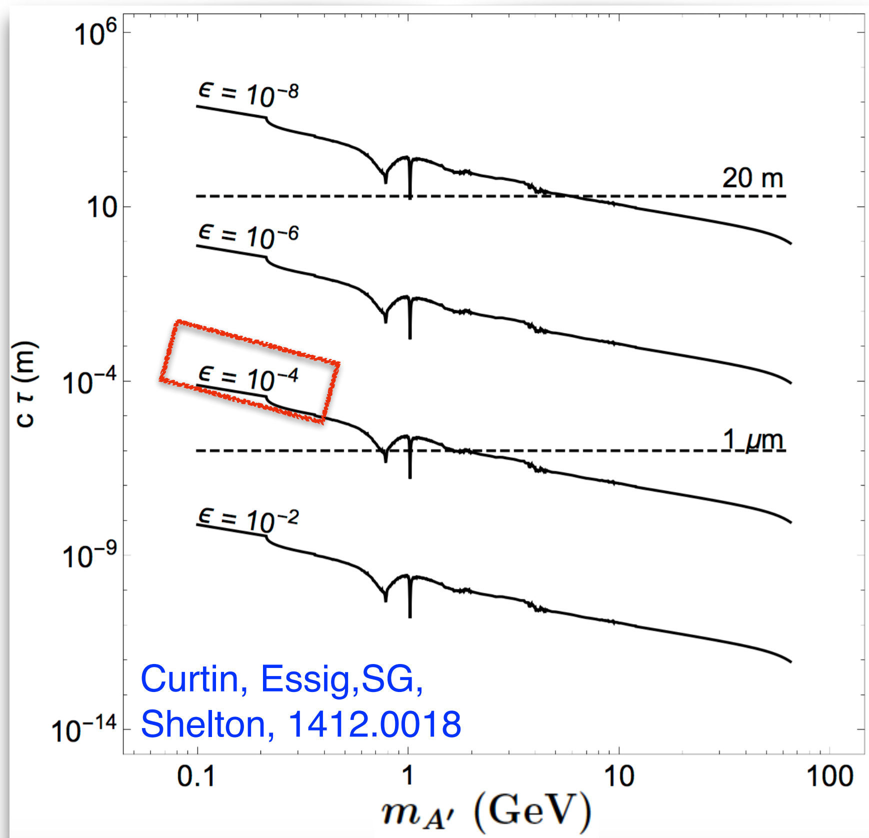
*DM is heavier

Lifetime and decay mode dictates search strategy

Only relevant free parameters of the minimal model: $\epsilon, \; m_{A'}$

The dark photon can only decay to SM particles (visible decays)





No ϵ dependence

Present & future reach

(secluded*)

Berlin, SG, Schuster, Toro, 1804.00661

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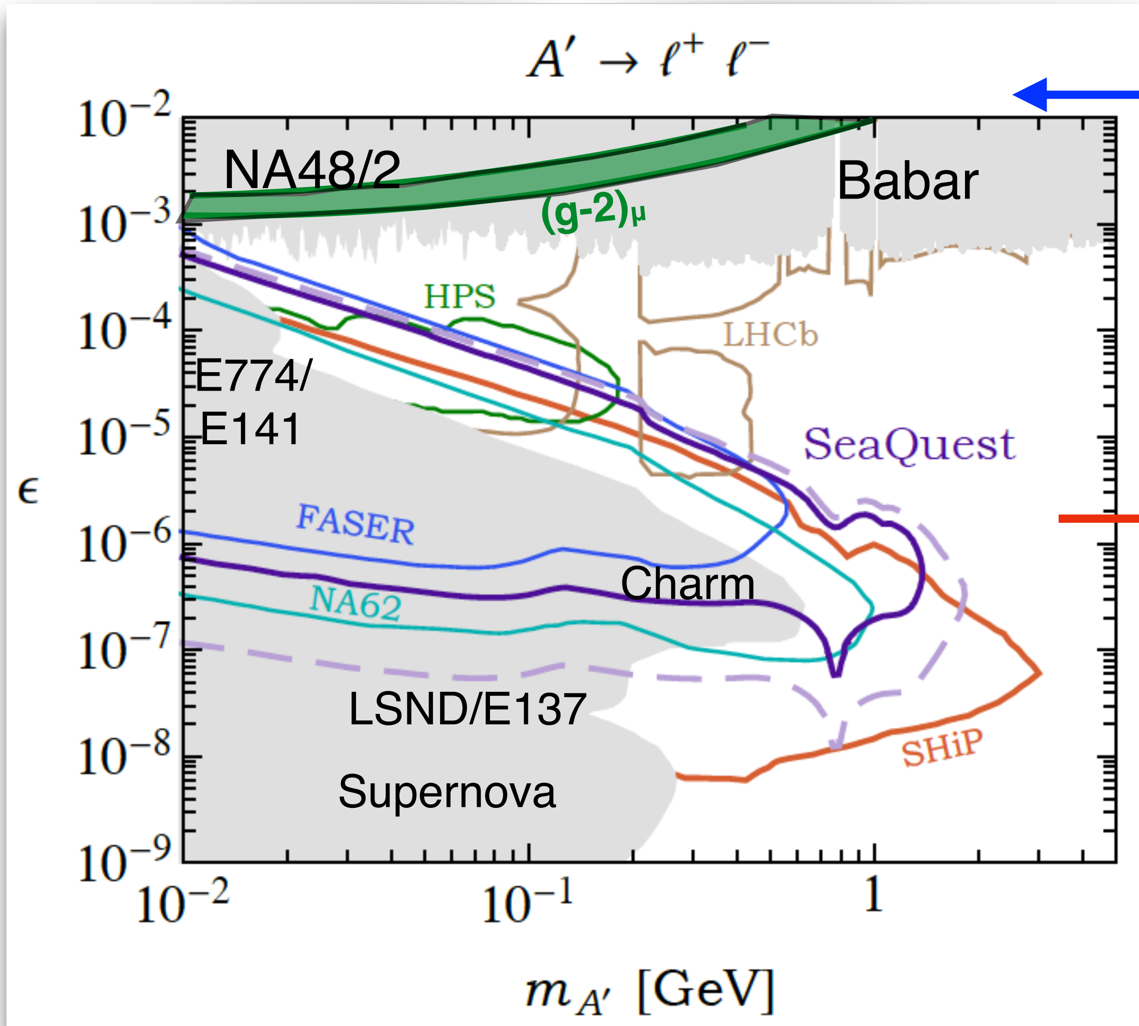

LEP bound is here

LHC

The entire parameter space
is motivated by thermal DM! (our goal)

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Berlin, SG, Schuster, Toro, 1804.00661

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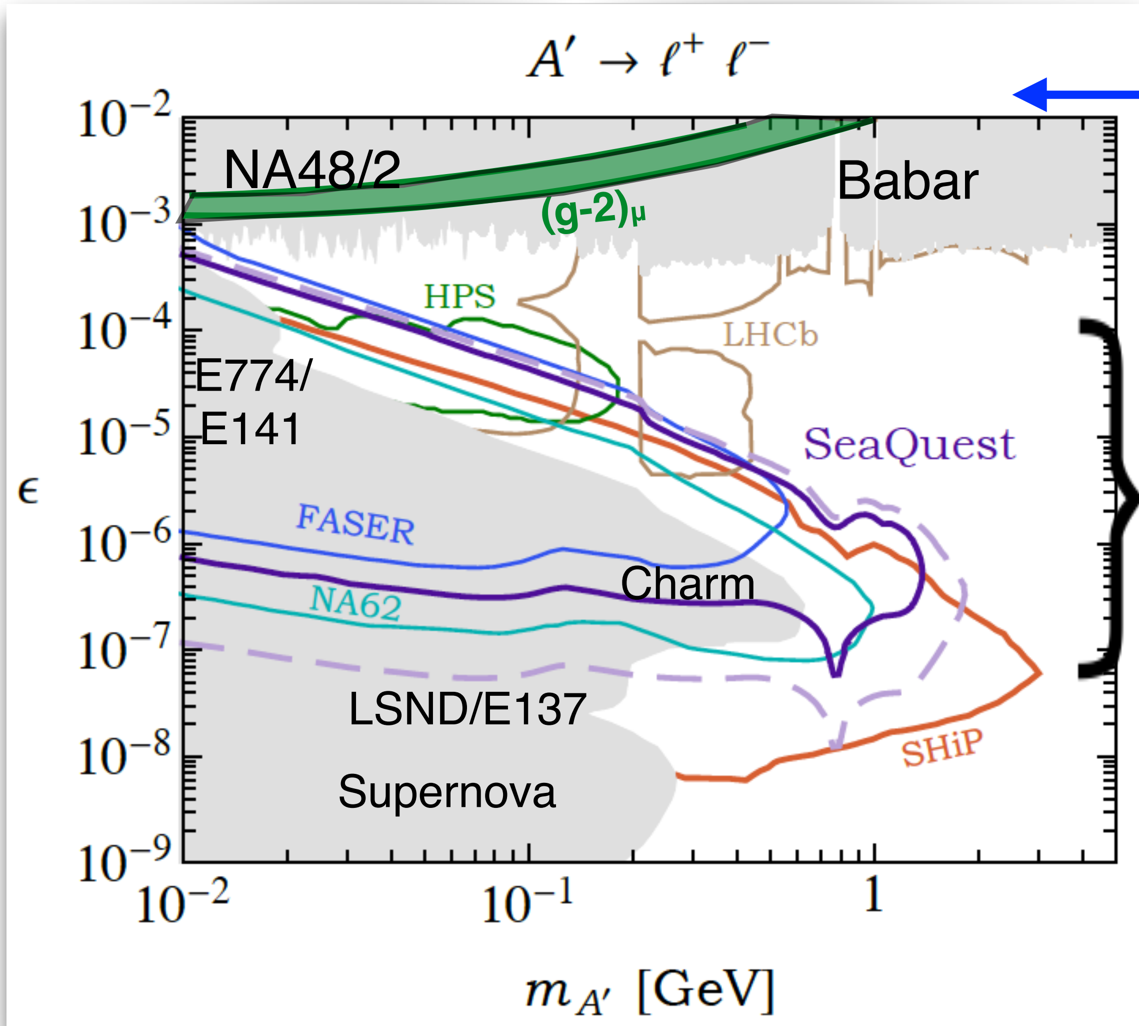

LEP bound is here

- NA48/2: $\pi^0 \to \gamma A',\ A' \to e^+e^-$ (prompt)
  1504.00607
- Babar: 1406.2980
  $e^+e^- \to \gamma A',\ A' \to e^+e^-, \mu^+\mu^-$ (prompt)
- Fixed target beam-dump experiments
  SeaQuest: talk by S.Uemura
- HPS: see talk by O.Moreno
- LHCb:
  1. inclusive (prompt and displaced di-muon searches), 1603.08926
  2. $D^* \to D^0 A',\ A' \to e^+e^-$ 1509.06765

The entire parameter space is motivated by thermal DM! (our goal)

Minimal dark photon signatures

(non-secluded*)

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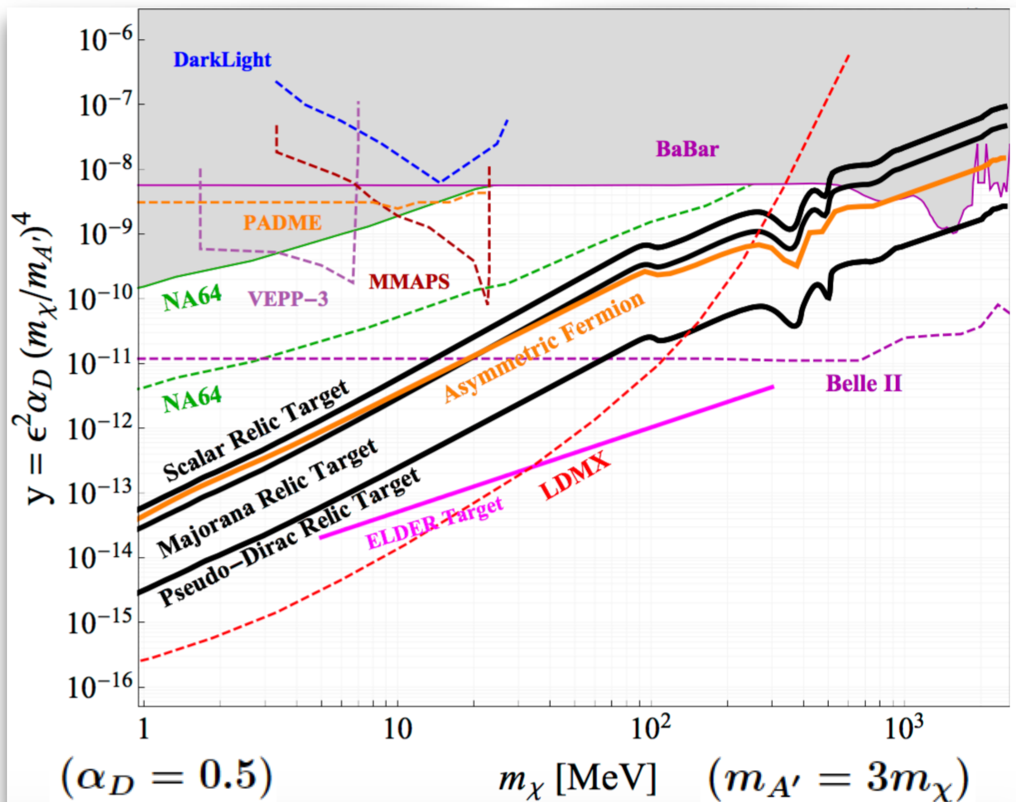
Lifetime and decay mode dictates search strategy

Only relevant free parameters of the minimal model: $\epsilon, \ \alpha_D, \ m_{A'}$

The dark photon decays mainly to dark matter (invisible decays), $\alpha_D \gg \epsilon$



Battaglieri et al., 1707.04591

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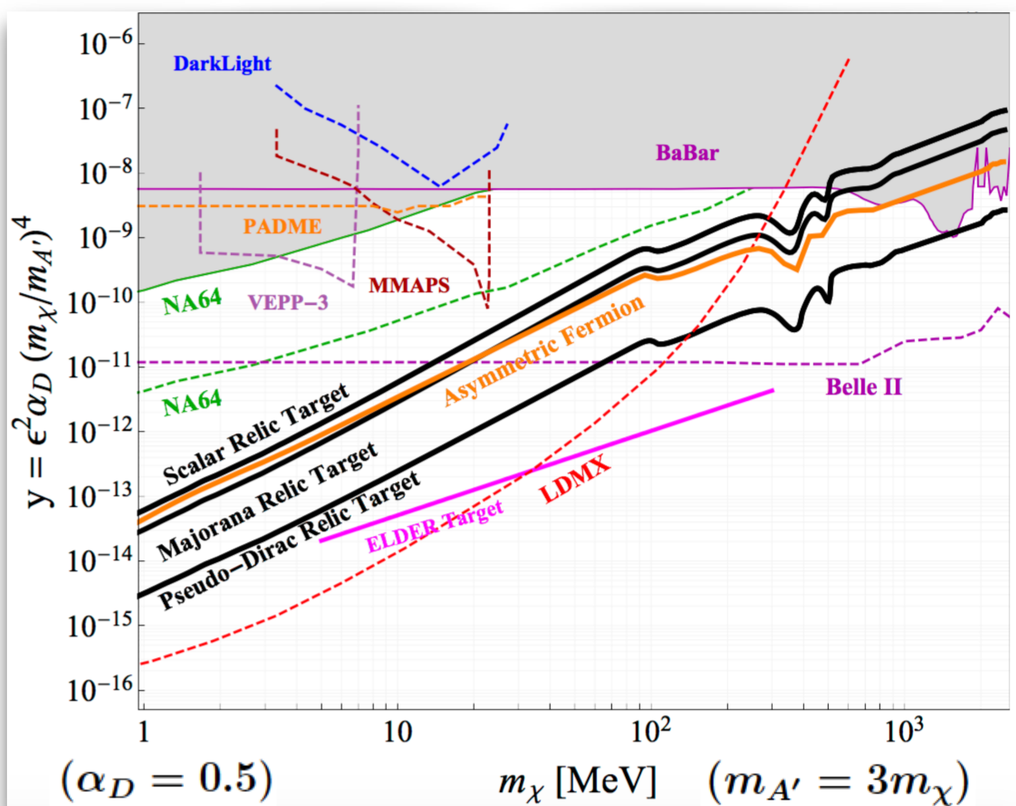


Battaglieri et al., 1707.04591

- Babar/Belle (Babar, 1702.03327)
  $e^+e^- \to \gamma A', \ A' \to \text{inv}$
- NA64 (1610.02988)
  $e^-p \to e^-pA', \ A' \to \text{inv}$
  Missing energy measurement.
  100 GeV electron beam
- LDMX (1610.02988)
  $e^-p \to e^-pA', \ A' \to \text{inv}$
  Missing momentum measurement.
  few GeV electron beam, ~10^{16} EOT
- PADME, MMAPS, VEPP-3, DarkLight
  $e^+e^- \to \gamma A', \ A' \to \text{inv}$
  Missing mass measurement.

see talk by R.Corliss

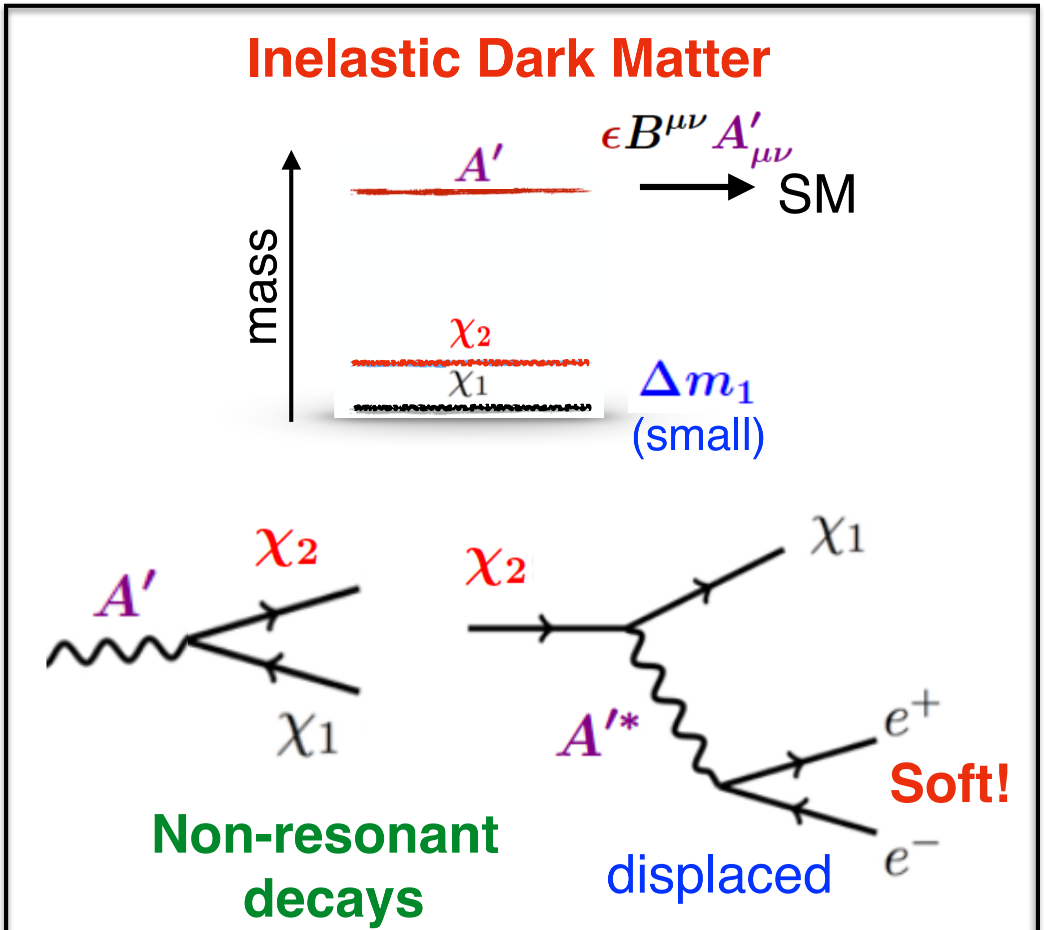
Beyond minimal dark photon models

(non-secluded*)

*DM is lighter

The non-secluded case can predict a richer phenomenology if the dark sector is not minimal

Examples:



 Izaguirre, Krnjaic, Shuve, 1508.03050

Beyond minimal dark photon models

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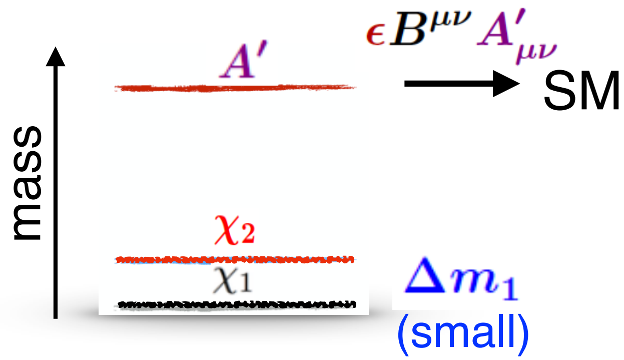
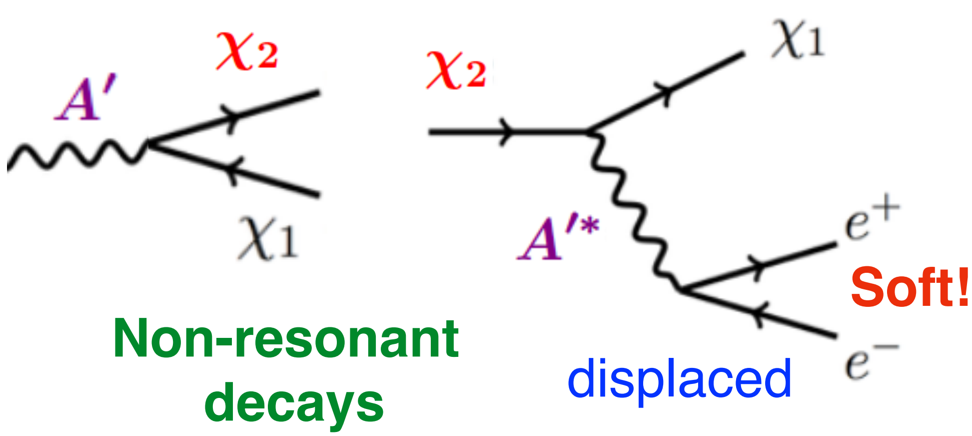
Examples:

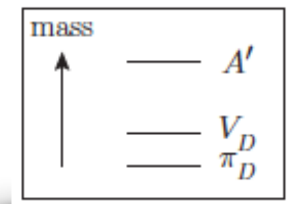
Inelastic Dark Matter

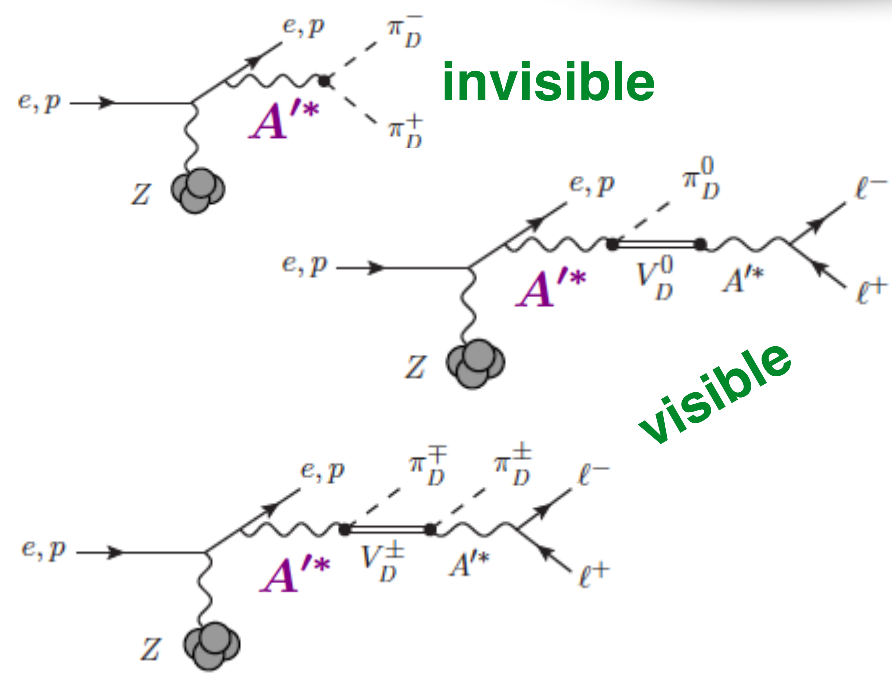




Strongly interacting Dark Matter

QCD-like theories with:
DM = lightest pions (π_D);
dark vectors (V_D)…





 Izaguirre, Krnjaic, Shuve, 1508.03050 Berlin, Blinov, SG, Schuster, Toro, 1801.05805

Beyond minimal dark photon models

(secluded*)

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The dark gauge boson can couple non-universally to the SM fermions

$$Z'e^+e^- \neq Z'\mu^+\mu^- \neq Z'\tau^+\tau^-$$

Example: models based on the L_μ - L_τ gauge symmetry ⇒ more hidden!

Motivations: B-physics anomalies, neutrino mass model building, …

Free parameters of the model: g’, $m_{Z'}$

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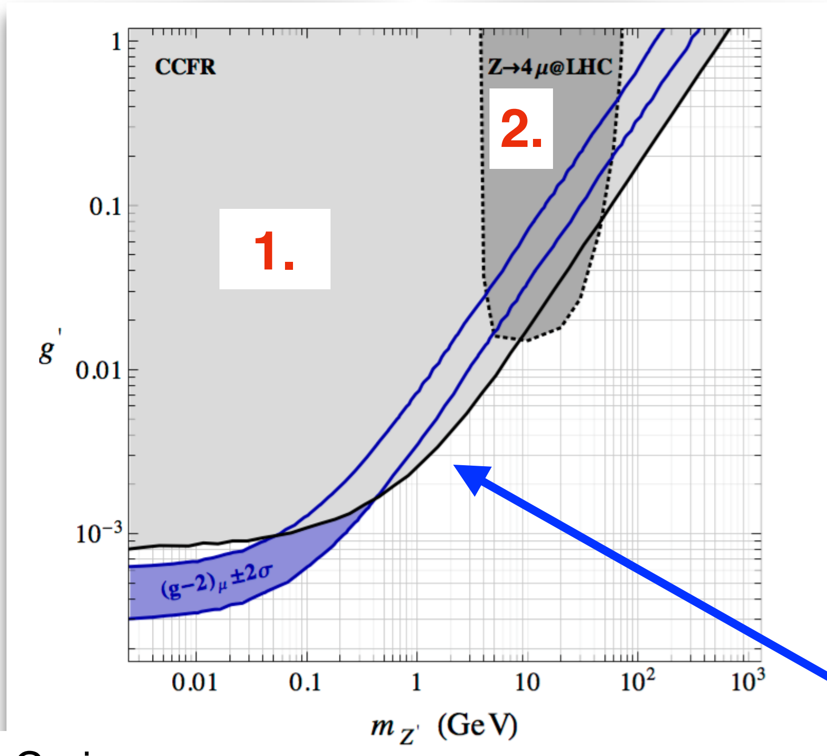
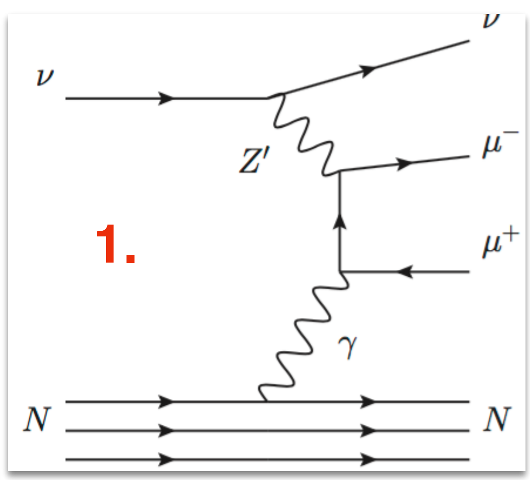
Altmannshofer, SG, Pospelov, Yavin, 1406.2332

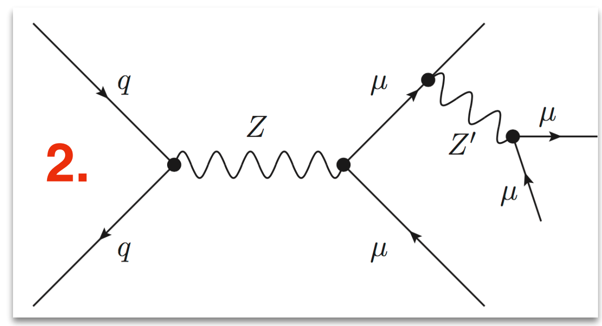


Additional probes by Babar, see talk by B.Shuve



high-intensity neutrino experiments

Free parameters of the model: g', $m_{Z'}$

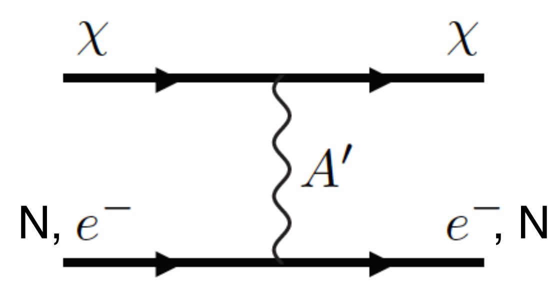


LHC

Many other probes of dark sectors

In this talk,
we have focused on the direct production and detection of dark photons

Additional probes include off-shell dark photon effects:



1. DM direct detection experiments:

Main challenge is that light (< 1GeV) DM deposits only a small recoil energy in detector

New dedicated experiments aim to see electron/nucleon recoils at lower energy than typical backgrounds (Sensei, Damic-1K, Ptolemy, SuperCDMS, …)

2. Beam-dump experiments: direct production of a dark photon $A' \to \chi\bar{\chi}$ and DM - electron & nucleon scattering in a downstream detector
(MiniBooNE, BDX (talk by M.Bondi), Coherent, Icarus, …)

Beyond dark photon models:

Many additional tests for model with dark scalars, right-handed neutrinos, axions, …

Conclusions & Outlook

Very rich program for dark sector searches at high intensity experiments

visible & prompt

scattering experiments

Dark photon

visible & displaced

invisible (missing mass, missing momentum, missing energy)

Complementarity with the high energy experimental program & the DM direct detection program