Dark Sectors at the Fermilab SeaQuest Experiment

Stefania Gori
University of Cincinnati

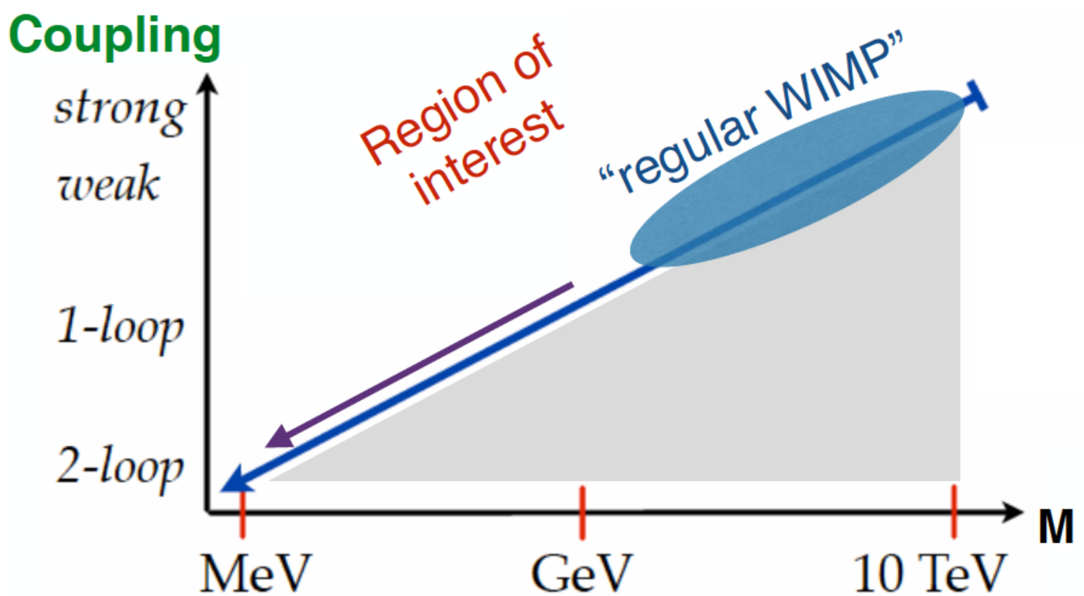
New Probes for Physics Beyond the Standard Model

KITP

April 9, 2018

Dark sectors

Dark matter (DM) exists!



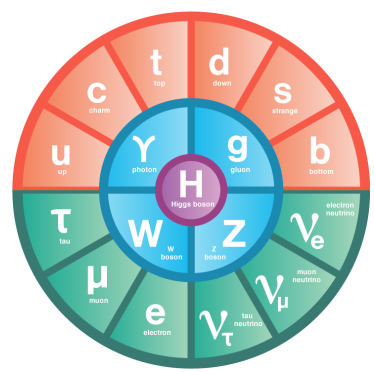
DM needs lighter mediators

Dark sector!

(in principle) mediated by the Z or Higgs boson

The stronger and stronger bounds from DM direct detection experiments may suggest that DM couples to SM with couplings weaker than weak

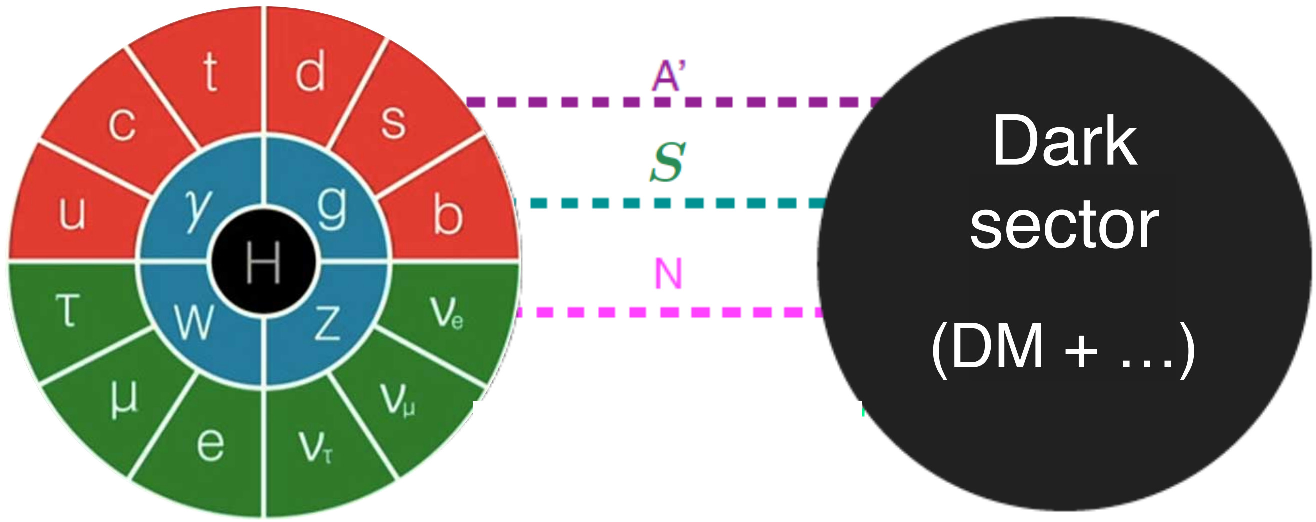
The Standard Model (SM) is highly non-minimal



Already some evidence? DM self interactions

Mediating DM interactions

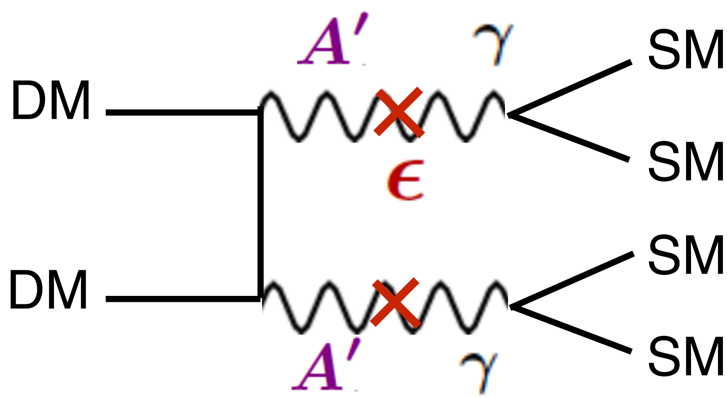
The “most simplified” models



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

$$\kappa |H|^2 |S|^2$$

$$y H L N$$



Secluded scenario

$m_{\rm DM} > m_{A'}$

More hidden to direct detection and collider Pospelov, Ritz, Voloshin, 0711.4866

Bounds from cosmology: CMB, $N_{\rm eff}$

Long lived particles

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

$$\kappa |H|^2 |S|^2$$

$$y H L N$$

Depending on the strength of the connection between the SM and the dark sector, mediators can

- decay promptly back to the SM
- be long lived
- be stable

Long lived particles

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

$\kappa |H|^2 |S|^2$

$y H L N$

Depending on the strength of the connection between the SM and the dark sector, mediators can

- decay promptly back to the SM
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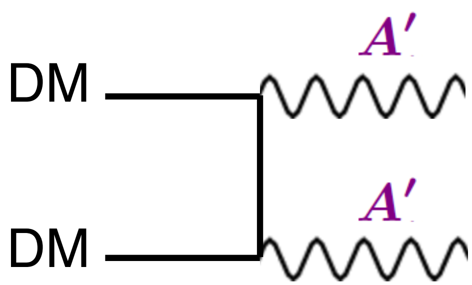
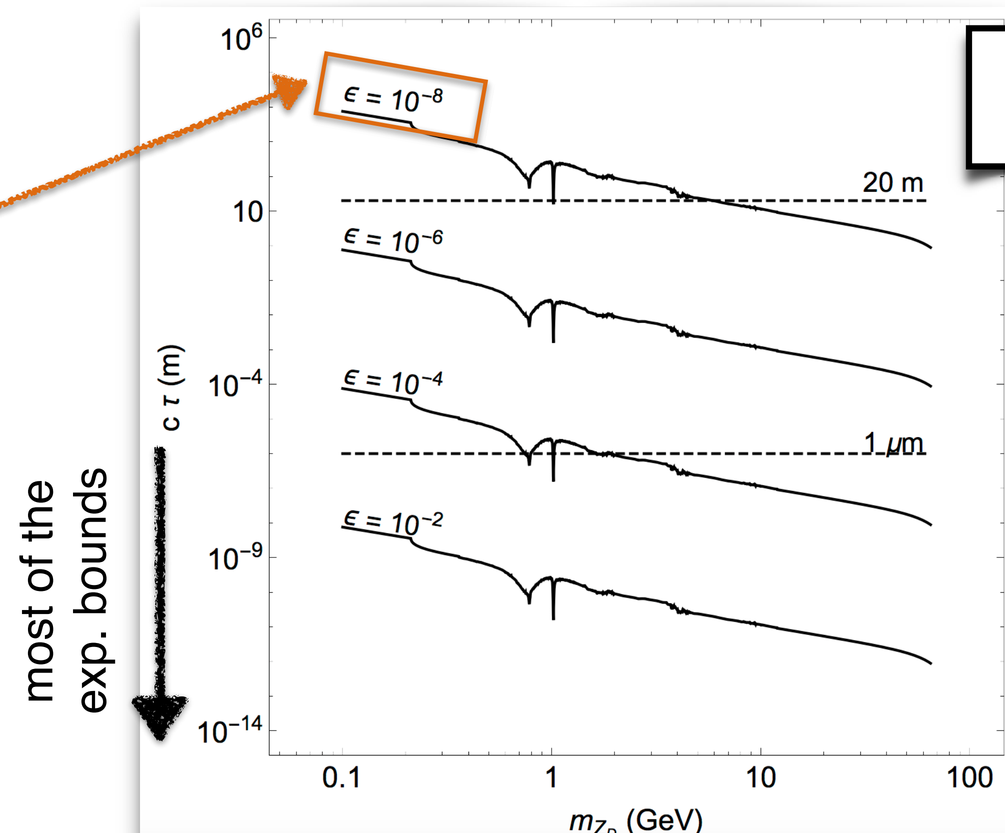
~ Lower bound from thermalization



$m_{\text{DM}} > m_{A'}$

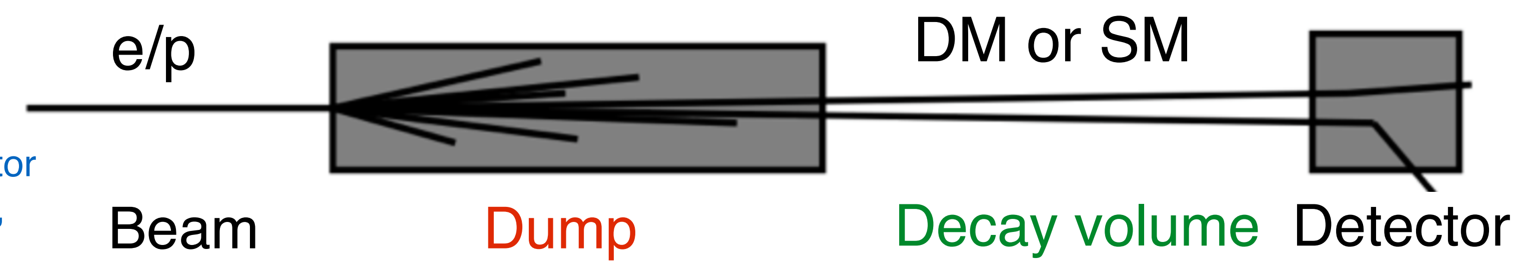
Evans, SG, Shelton, 1712.03974

Curtin, Essig, SG, Shelton, 1412.0018



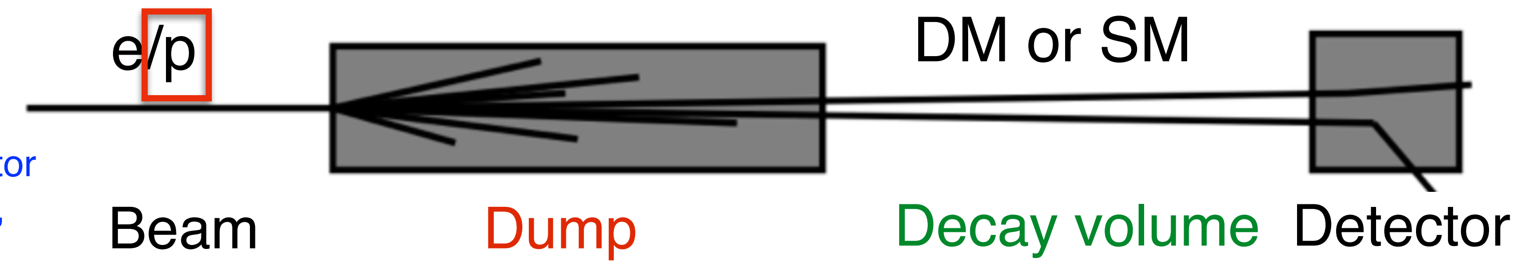
A'

Fixed target experiment program



See eg. Dark sector community report, 1608.08632

Fixed target experiment program



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Past

Experiment	Proton energy	POT	Dump	Decay volume
CHARM	400 GeV	2.4×10^{18}	480 m	35 m
LSND	800 MeV	10^{22}	30 m	10 m

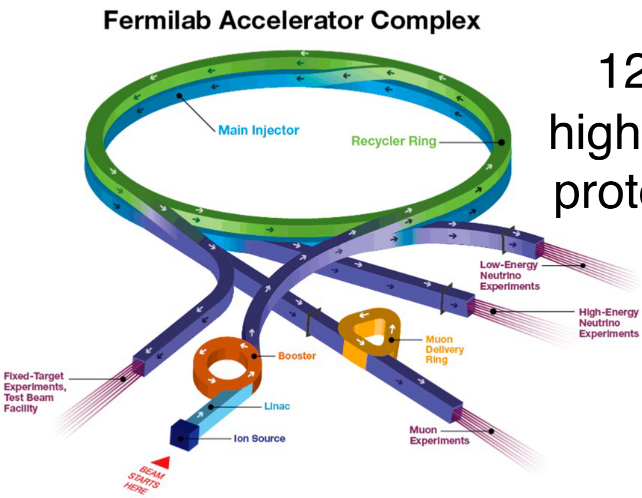
It corresponds to ~ O(100 ab^{-1}) data!

Present
Future

Experiment	Proton energy	p_{min}	POT	Dump	Decay volume
SeaQuest	120GeV	10 GeV	$10^{18} - 10^{20}$	5 m	10 m
NA62	400 GeV	-	10^{18}	100 m	250 m
SHiP	400 GeV	100 GeV	10^{20}	65 m	125 m
(*) FASER	6500 GeV	1 TeV	$10^{16} - 10^{17}$	390 m	400 m

(*) talk by J.Feng

Fermilab intensity frontier



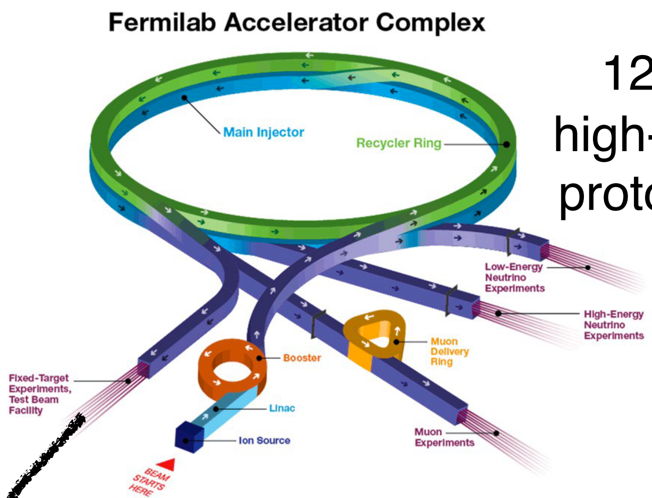
120 GeV
high-intensity
proton beam

Fermilab has a very high intensity proton beam!

Proton Improvement Plan
to get very high intensity (PIP, PIP II, PIP III)

Final goal: ~2 MW of proton beam power (now ~700 KW)

Fermilab intensity frontier



120 GeV high-intensity proton beam

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Proton Improvement Plan

to get very high intensity (PIP, PIP II, PIP III)

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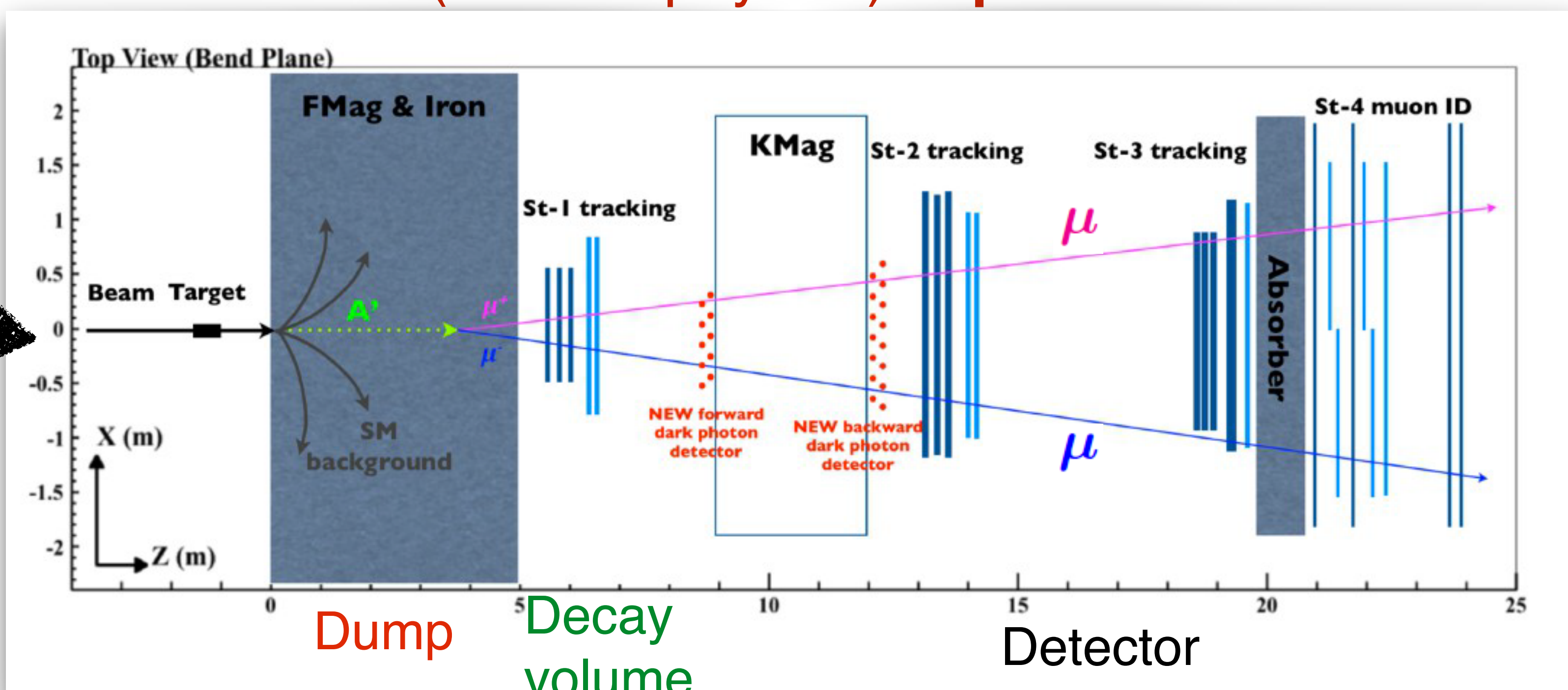
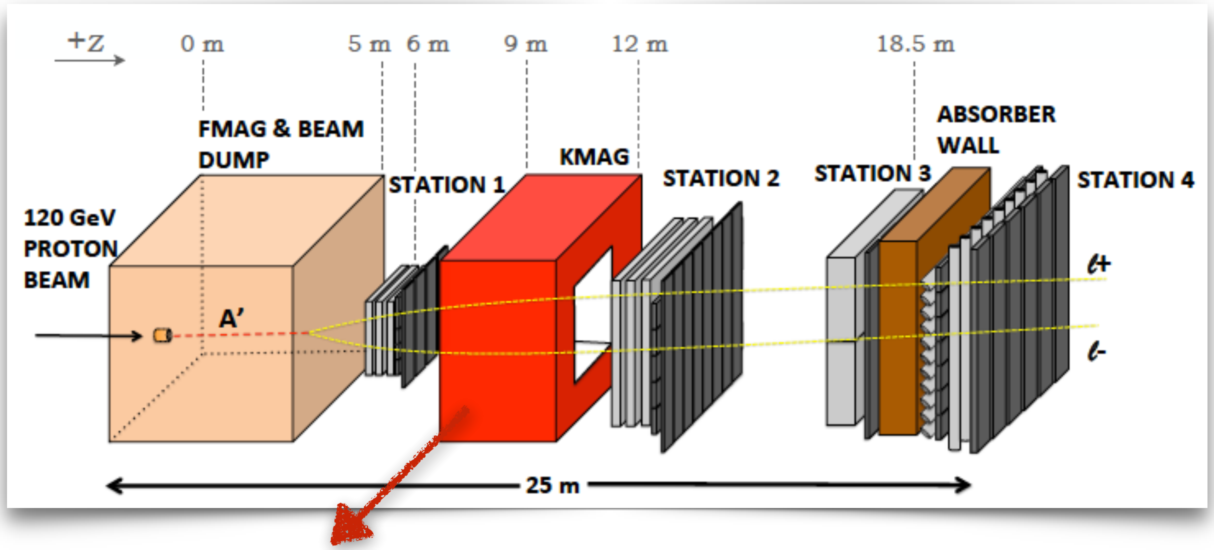
5% main injector beam

The SeaQuest (nuclear physics) experiment



SeaQuest in a nutshell



1. Compact geometry

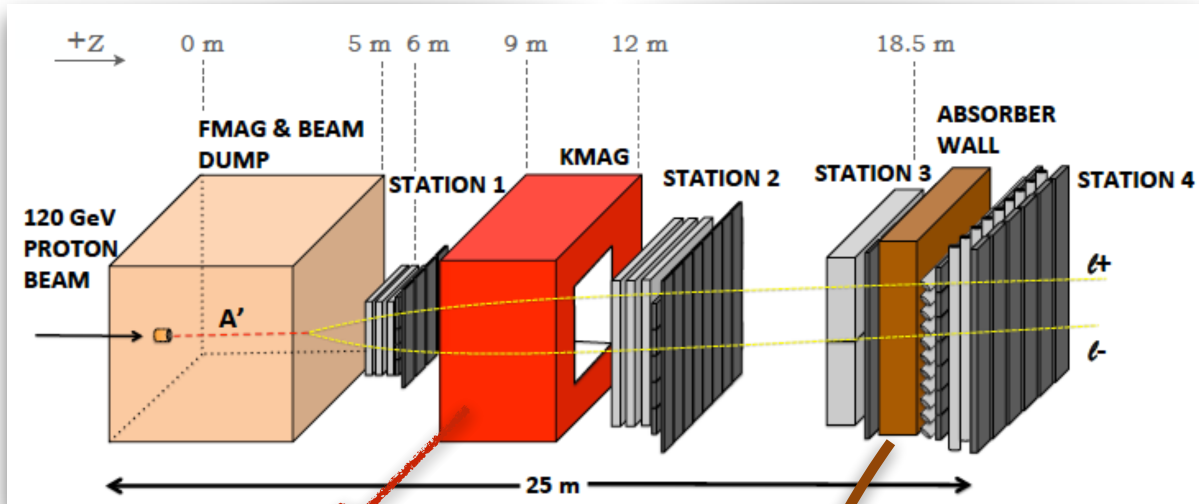
Sensitivity to slightly displaced dark particles with d > 5m

2. KMAG separating even very forward muons

($\Delta p_T \sim 0.4$ GeV)

Identification of very light dark particles/squeezed spectra

SeaQuest in a nutshell



1. Compact geometry

Sensitivity to slightly displaced dark particles with d > 5m

2. KMAG separating even very forward muons

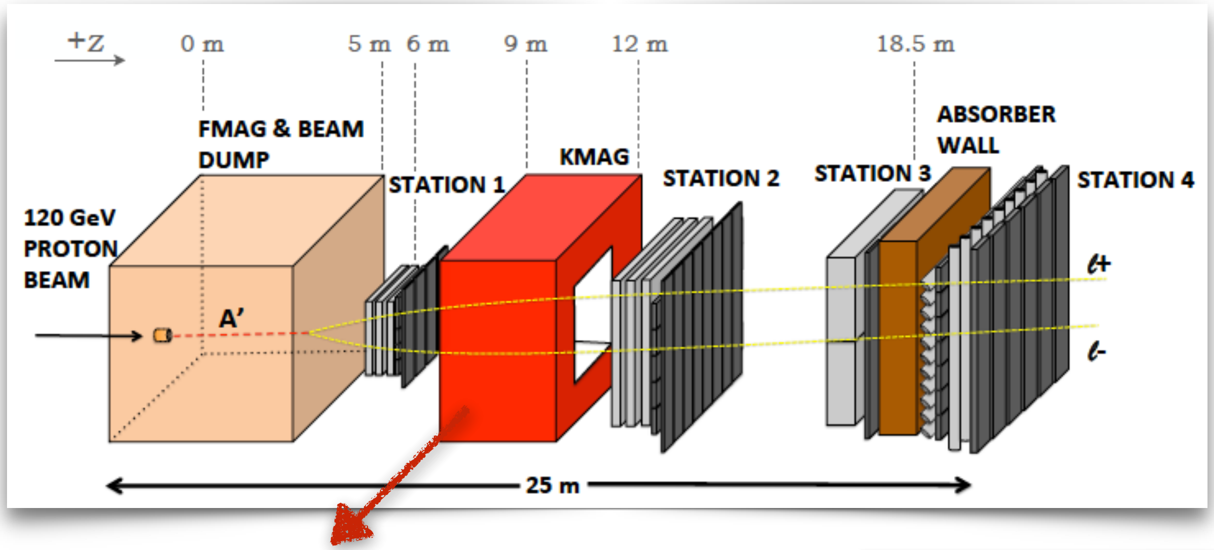
($\Delta p_T \sim 0.4$ GeV)

Identification of very light dark particles/squeezed spectra

3. A bit of history

- previous runs (since 2012) dedicated to prompt μ
- April 2017:
  installation of displaced di-muon trigger
  3 x 10^{16} POT collected in 5 running days
- Approved: physics run for ~10^{18} POT by 2019
- Work in progress: proposal for installation of ECAL (from the Phenix experiment)

SeaQuest in a nutshell



1. Compact geometry

Sensitivity to slightly displaced dark particles with d > 5m

2. KMAG separating even very forward muons

$(\Delta p_T \sim 0.4 \text{ GeV})$

Identification of very light dark particles/squeezed spectra

Questions for this talk

Physics-case for the ECAL?

Future runs with larger luminosities?

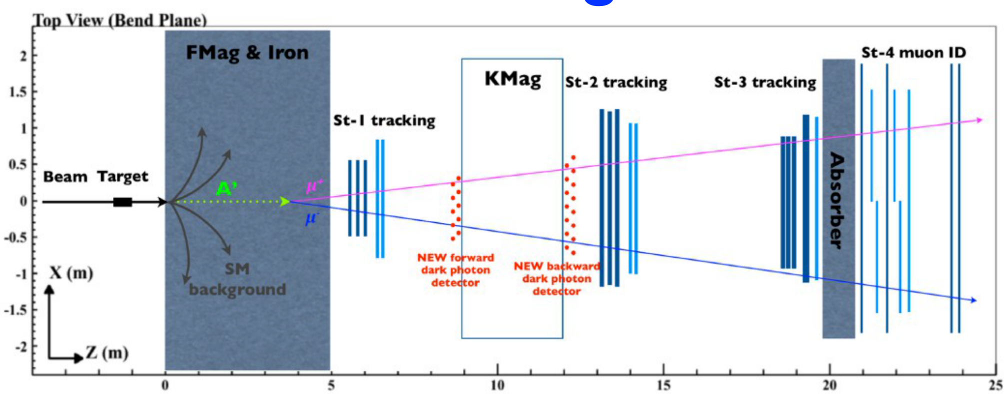
<u>What is the reach for</u>

- dark photons,
- dark matter models,
- dark scalars,
- axions, …

Berlin, SG, Schuster, Toro, 1804.00661

Visible displaced signatures

Fiducial regions



1. (5-6)m
2. (5-9)m
3. (5-12)m

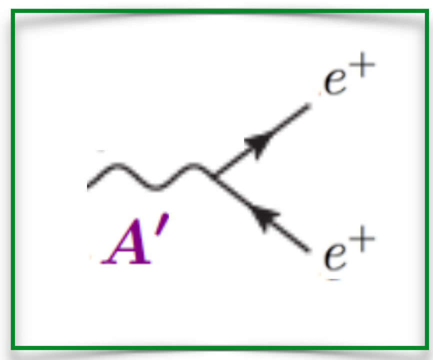
Backgrounds for electron signatures

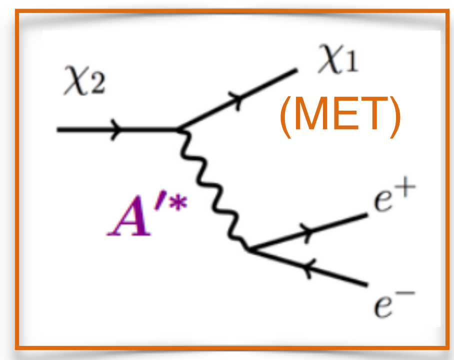
- The (5-6)m region has negligible $K_L \to \pi^\pm e^\mp \nu$ background
- The largest decay region will probably have backgrounds. Experimental studies needed!

We will show the reach corresponding to 10 signal events

Signatures

- Di-electrons (resolved & not resolved)
- Mesons
- Di-photons





Luminosity

- 10^{18} POT (approved luminosity)
- 10^{20} POT (luminosity accumulated by MiniBooNE)

Dark photon models

1. Minimal dark photon model
2. Inelastic Dark Matter (IDM)

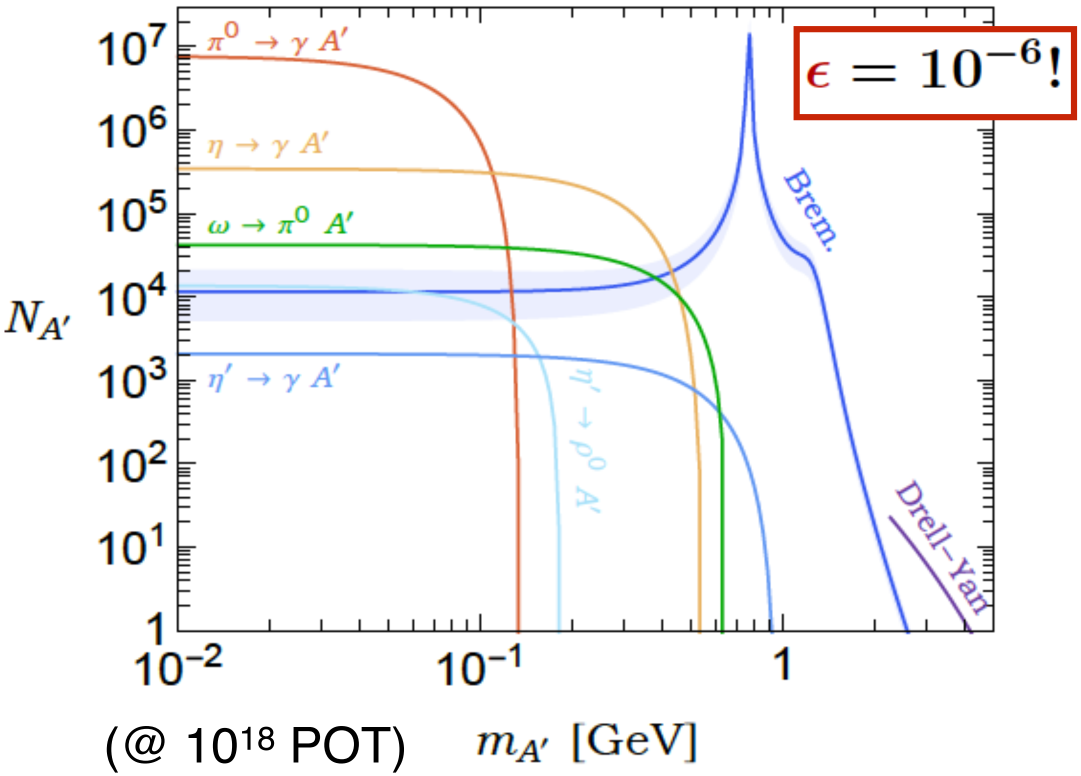
See also talk by A.Berlin on SIMPs
Berlin, Blinov, SG, Schuster, Toro, 1801.05805

A huge dark photon production

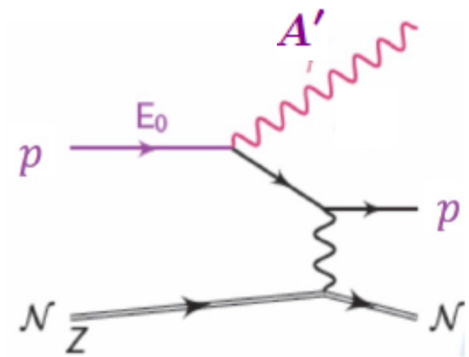
if we take the **120 GeV Fermilab proton beam**:

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

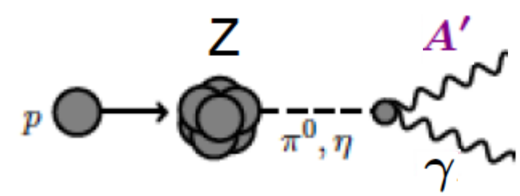
Berlin, SG, Schuster, Toro, 1804.00661



(@ 10^{18} POT)



brems-strahlung



meson decay

A huge dark photon production

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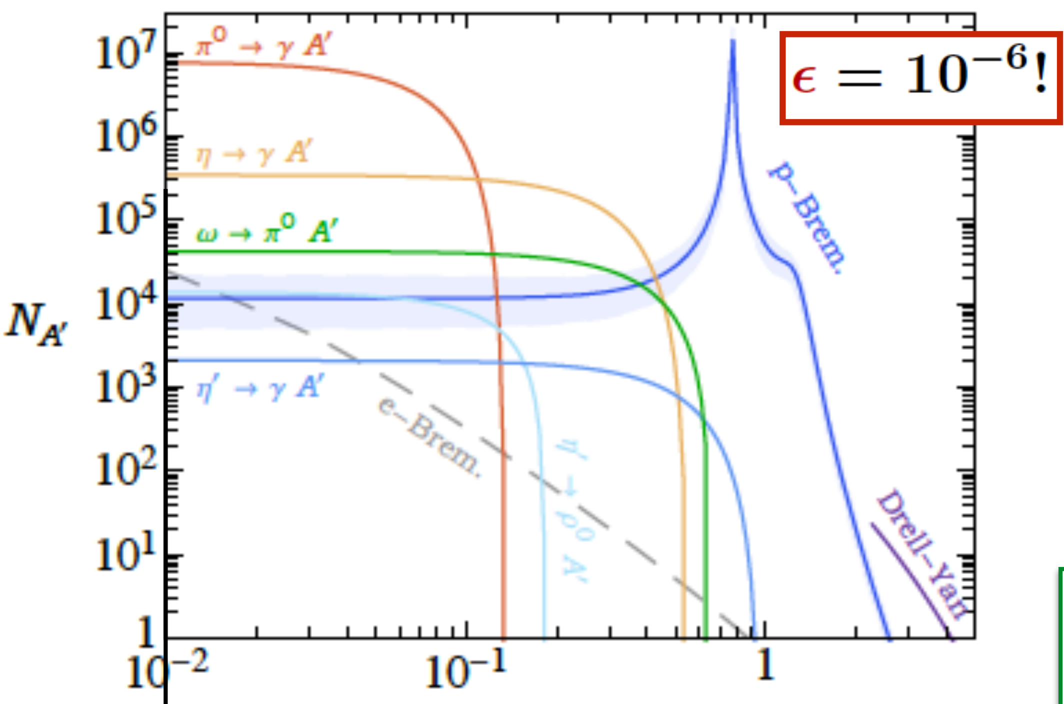
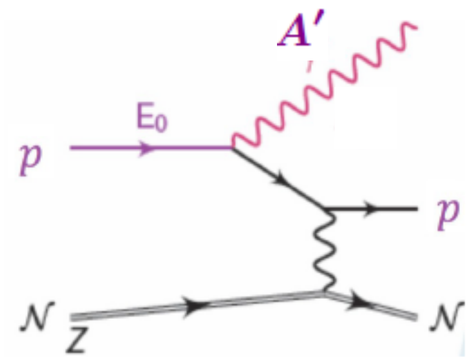
Berlin, SG, Schuster, Toro, 1804.00661



(@ 10^{18} POT)



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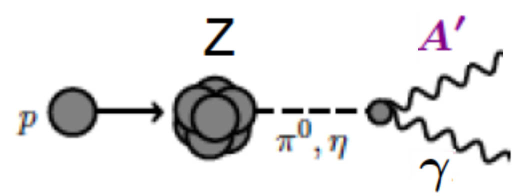


meson decay

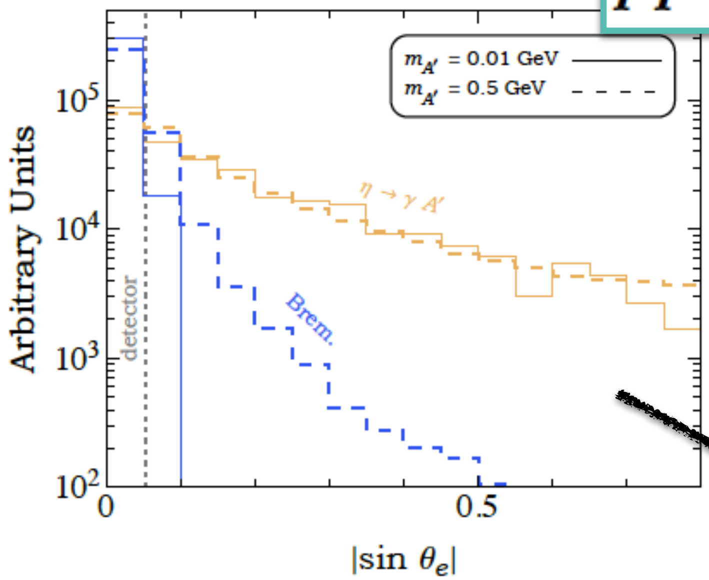
Generically larger rates than at electron fixed target experiments

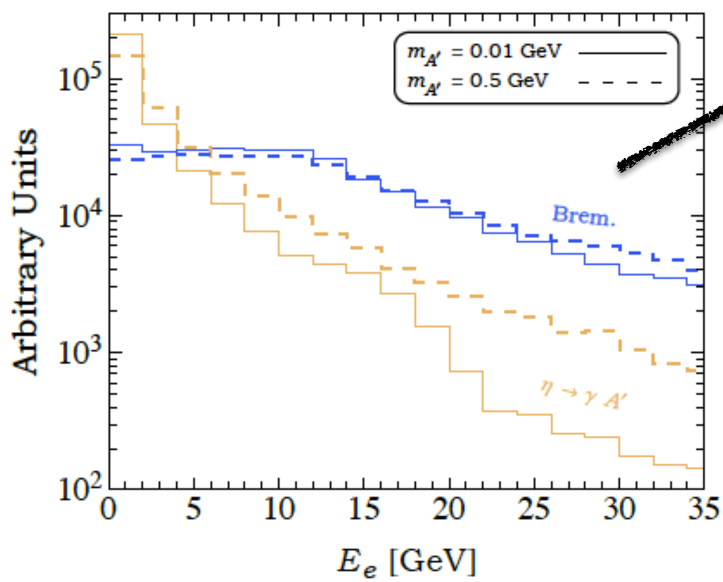
$$N_{A'}(e\ \text{Brem.}) \sim \left(\frac{\epsilon}{10^{-6}}\right)^2 \left(\frac{m_{A'}}{\text{GeV}}\right)^{-2} \left(\frac{\text{EOT}}{10^{18}}\right)$$

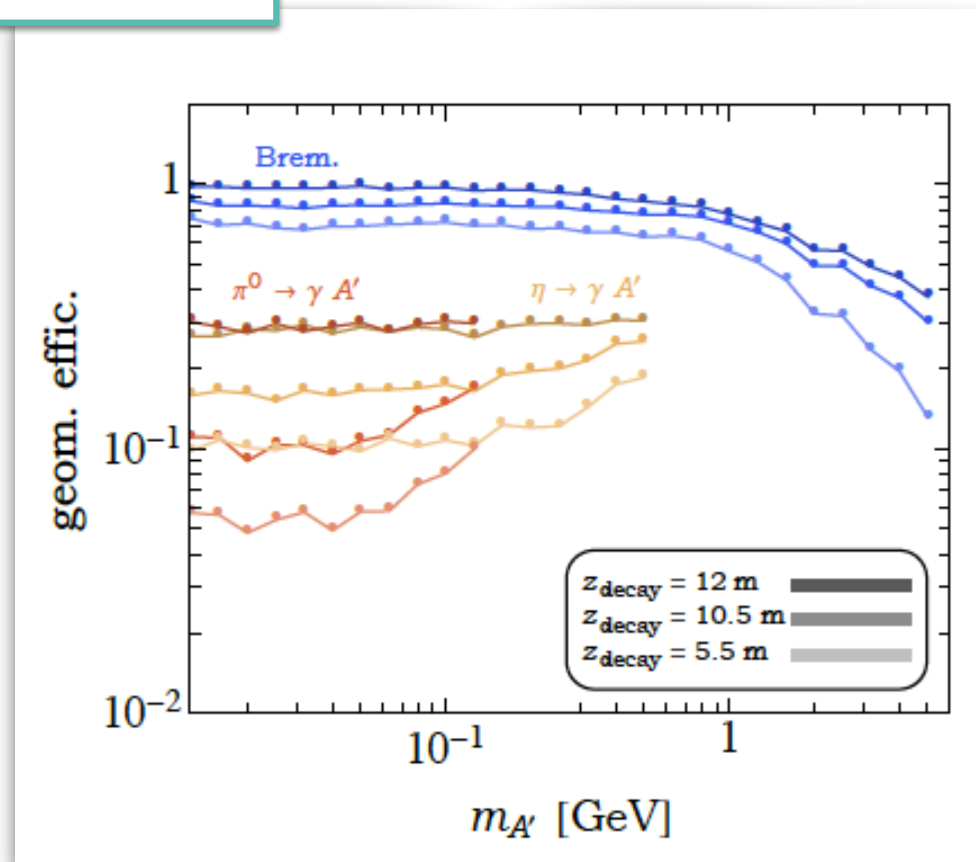
$$N_{A'}(p\ \text{Brem.}) \sim 10^4 \times \left(\frac{\epsilon}{10^{-6}}\right)^2 \left(\frac{\text{POT}}{10^{18}}\right)$$

1. High acceptance for minimal A’

$$pp \to A' \to e^+e^-$$





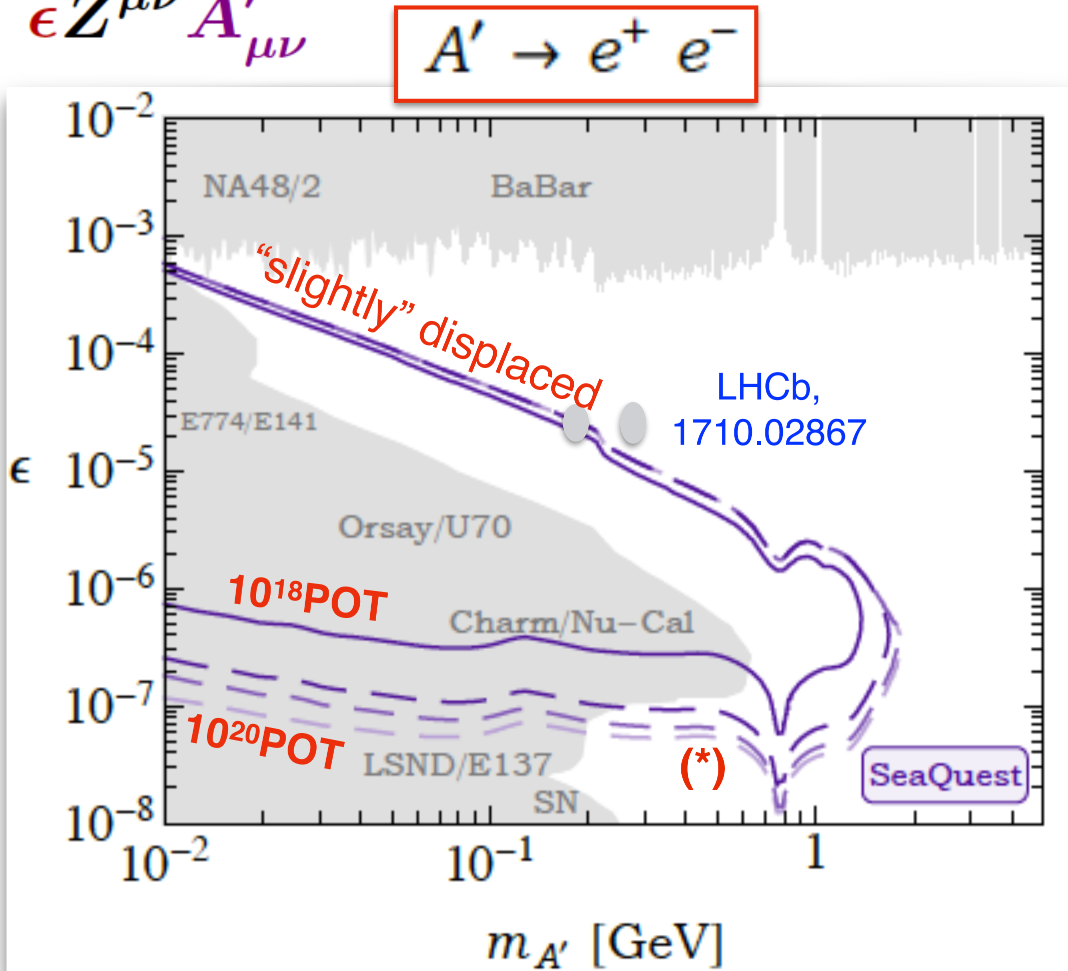


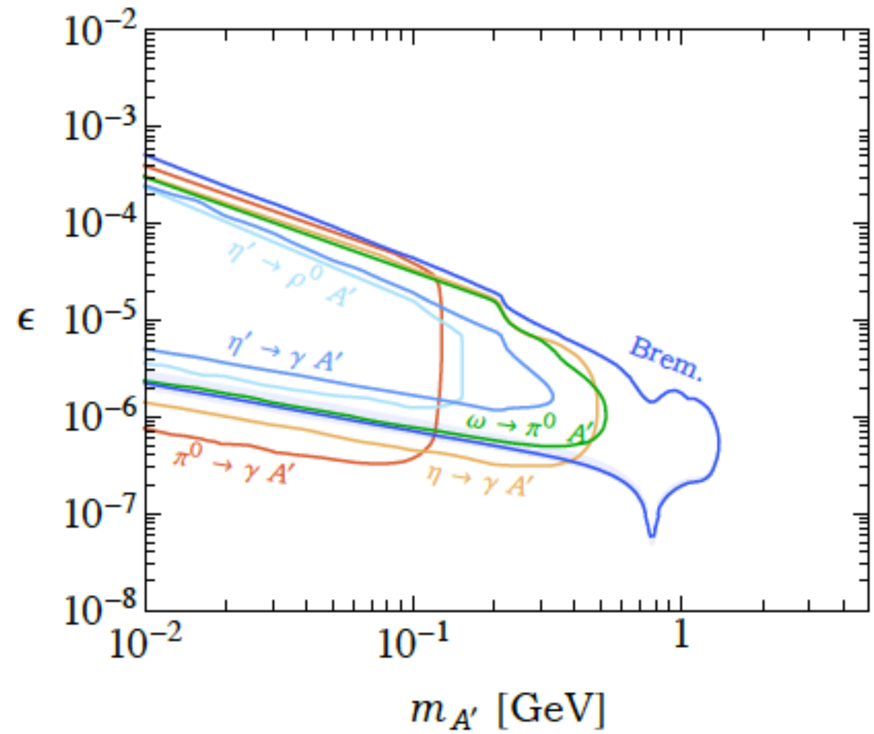
High acceptance
for boosted particles

The reach for the minimal A' model

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

Berlin, SG, Schuster, Toro, 1804.00661



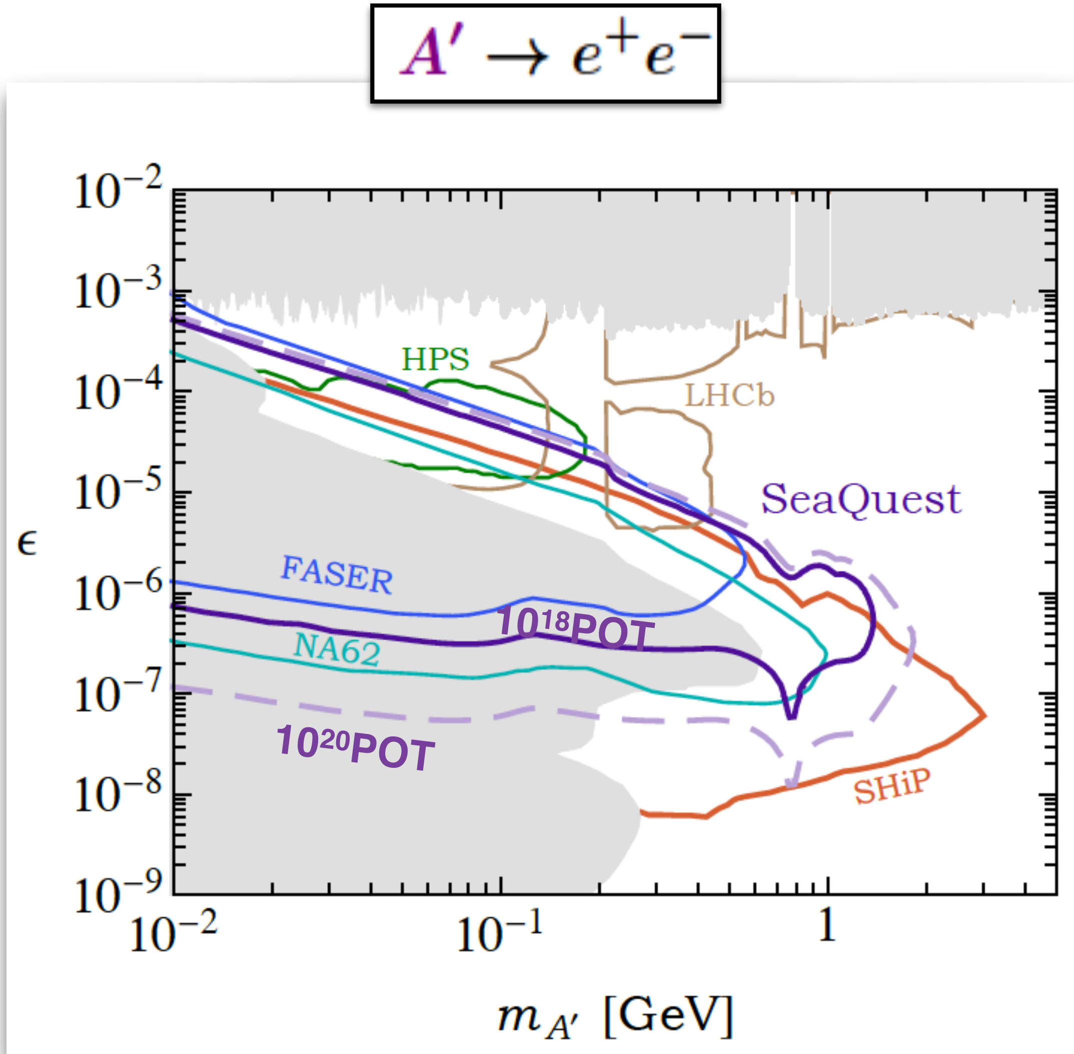


(*) decay regions: (5-6)m, (5-9)m, (5-12)m
1 2 3

See Gardner, Holt, Tadepalli, 1509.00050 for the muon reach as well

Comparison with future experiments

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



FASER: Feng et al., 1708.09389

NA62: Lanfranchi @ CERN-EPFL-Korean theory institute

SHiP: Alekhin et al., 1504.04855

Berlin, SG, Schuster, Toro, 1804.00661

2. Inelastic DM

Inelastic DM (IDM) models were initially proposed to explain the DAMA anomaly, while being consistent with Dark Matter direct detection bounds from CDMS

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)'

$$\chi_1 = i(\eta - \xi)\sqrt{2}\,, \qquad \chi_2 = (\eta + \xi)\sqrt{2}$$

The only relevant interaction is inelastic:

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

The elastic piece is very small $(\delta_{\eta,\xi} \ll m_D)$:

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

Two states close in mass: $\Delta \equiv \frac{m_2 - m_1}{m_1} \sim \frac{\delta_\xi + \delta_\eta}{m_D} \ll 1$

$(\Delta^{\rm DAMA} \sim 10^{-6},\ m_1^{\rm DAMA} \sim 50\ {\rm GeV})$

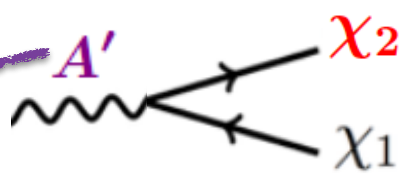
Easy to get it small since it is a U(1)' breaking effect

High-intensity probes of IDM

IDMs are rather hidden to <u>direct detection experiments</u>
Also <u>CMB</u> constraints are relaxed
The prime avenue to probe IDM is at high intensity experiments?

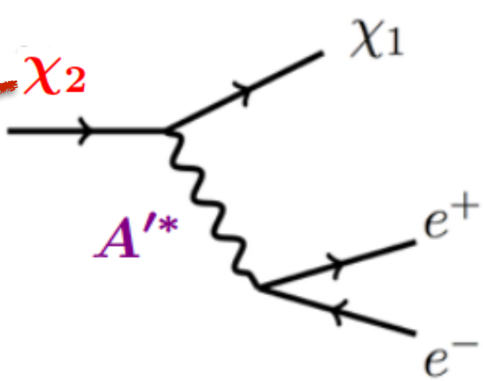
(see, however, Bramante et al., 1608.02662)

$m_X < m_{A'}$



Copiously produced at fixed target experiments

with



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

Non-resonant decays

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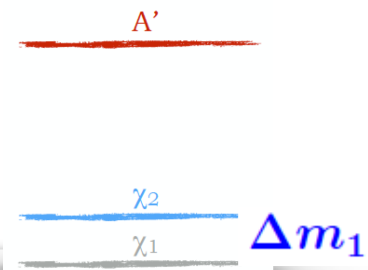
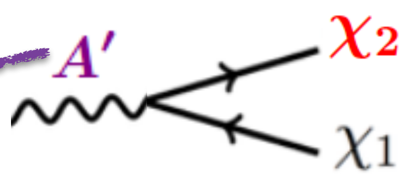


$m_\chi < m_{A'}$



Copiously produced at fixed target experiments

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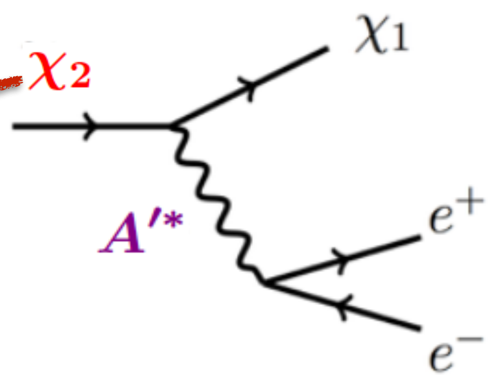

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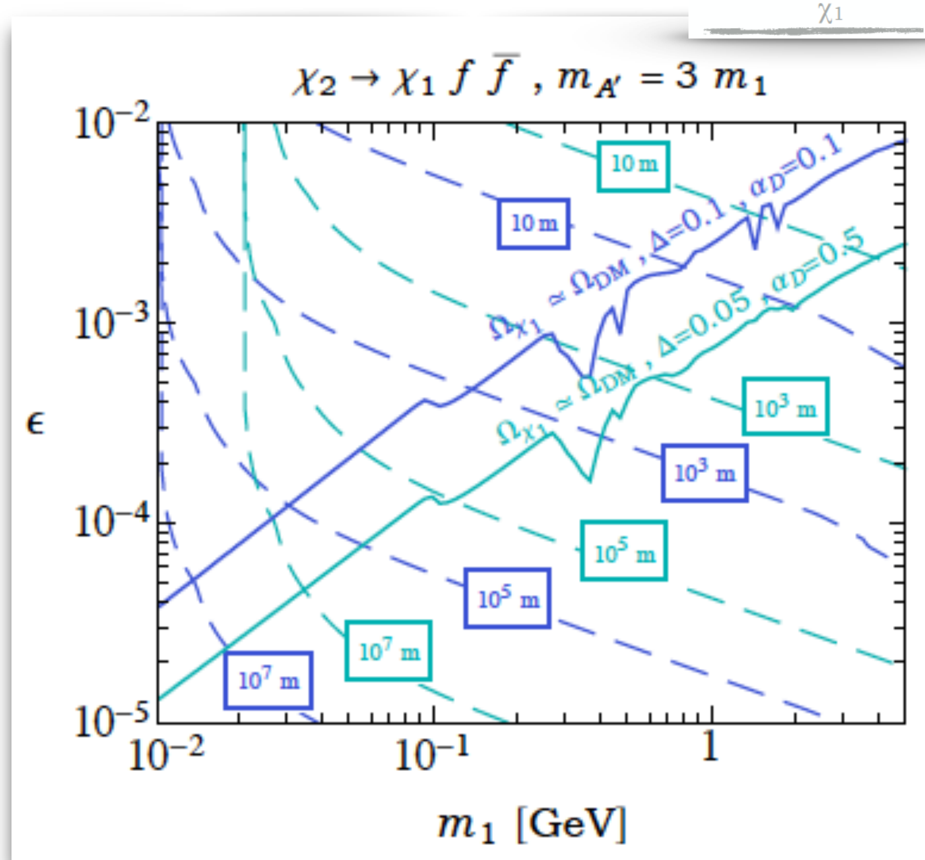
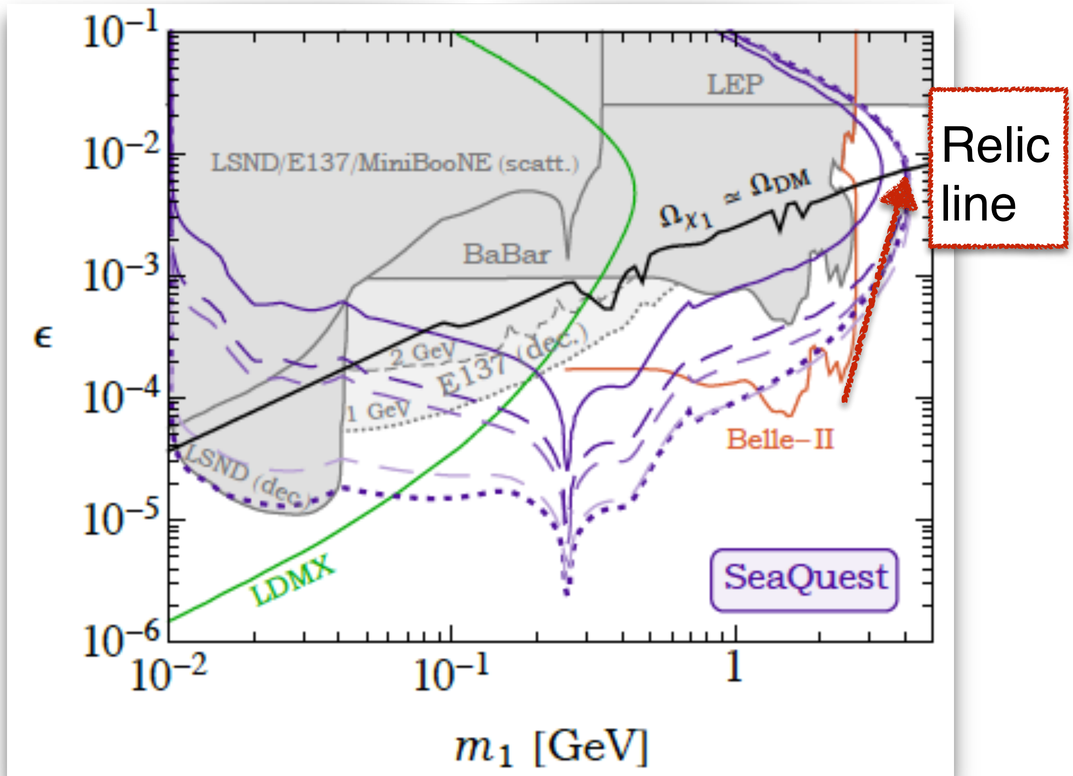


Displaced decays

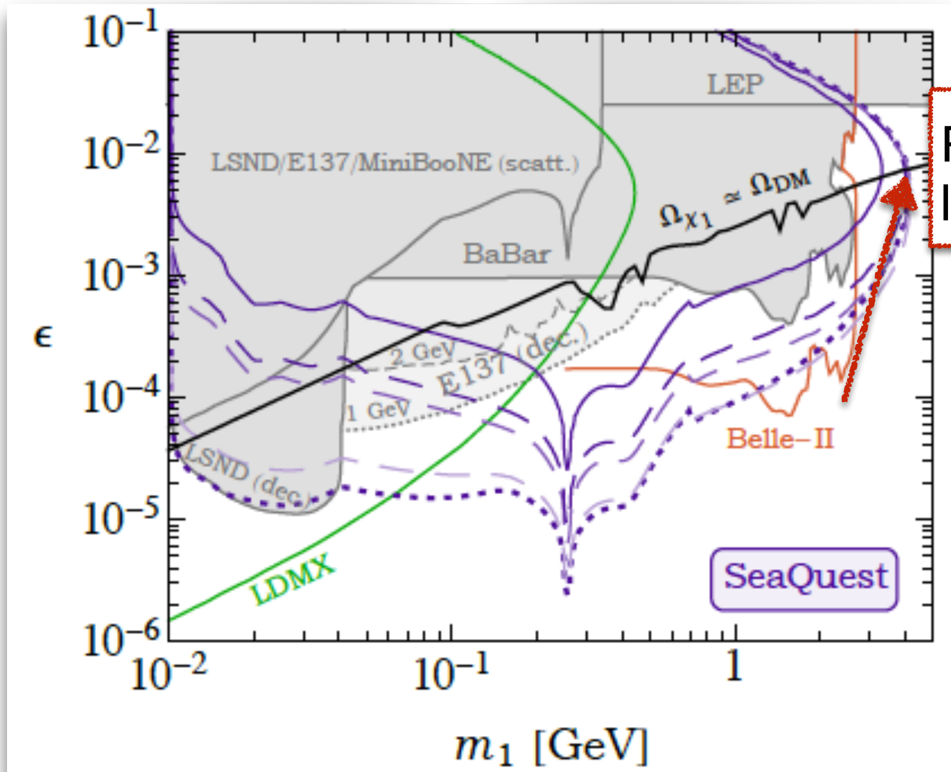
IDM @ fixed target experiments



Good coverage from past experiments for sizable mass splittings ($\Delta = 0.1$) (in gray)

see also Izaguirre et al. 1703.06881

IDM @ fixed target experiments



Relic line

Good coverage from past experiments for sizable mass splittings ($\Delta = 0.1$) (in gray)

see also Izaguirre et al. 1703.06881

☑ Babar (inv.)

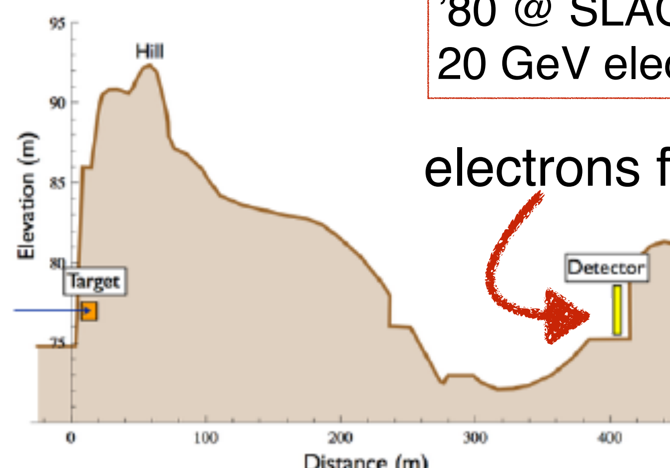
$$e^+e^- \to \gamma A', \;\; A' \to \chi_1\chi_2$$

not detected

☑ E137 (dec.)

'80 @ SLAC
20 GeV electron beam

electrons from χ_2 decay



Bjorken et al. (1988)

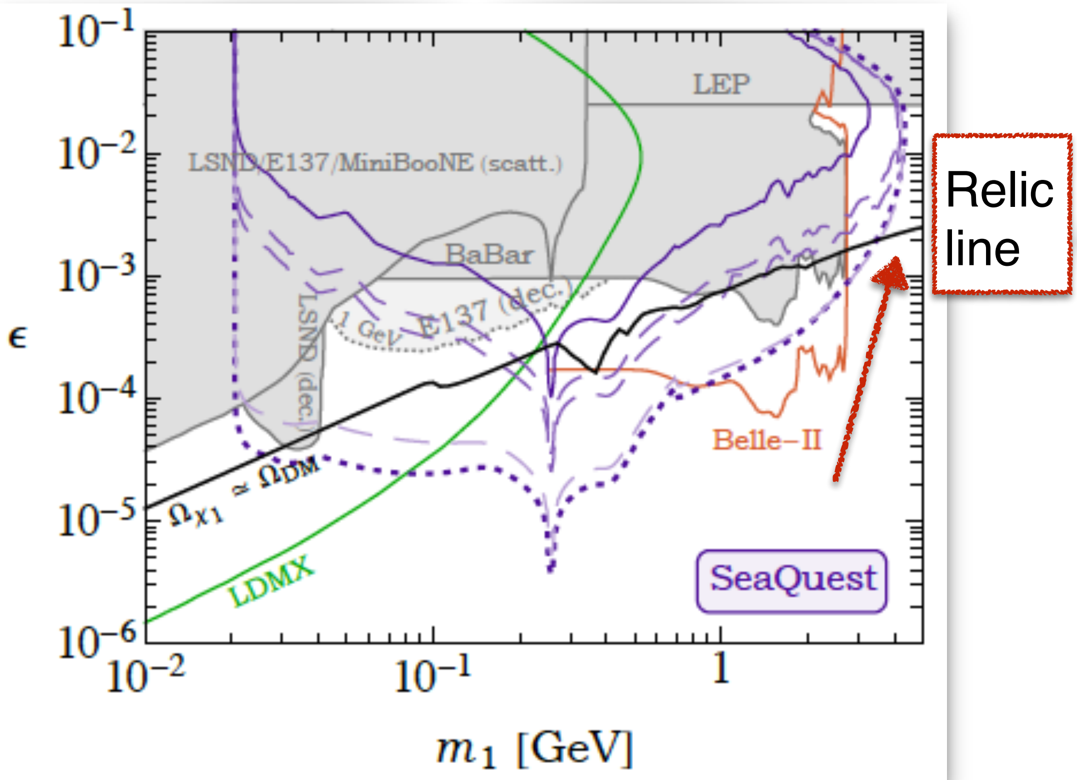
☑ LSND (dec.)

'90 @ Los Alamos
800 MeV proton beam

$$\pi \to \gamma A', \;\; A' \to \chi_1\chi_2$$

visible

IDM @ fixed target experiments



see also Izaguirre et al. 1703.06881

Less coverage from past experiments for smaller mass splittings ($\Delta = 0.05$) (in gray)

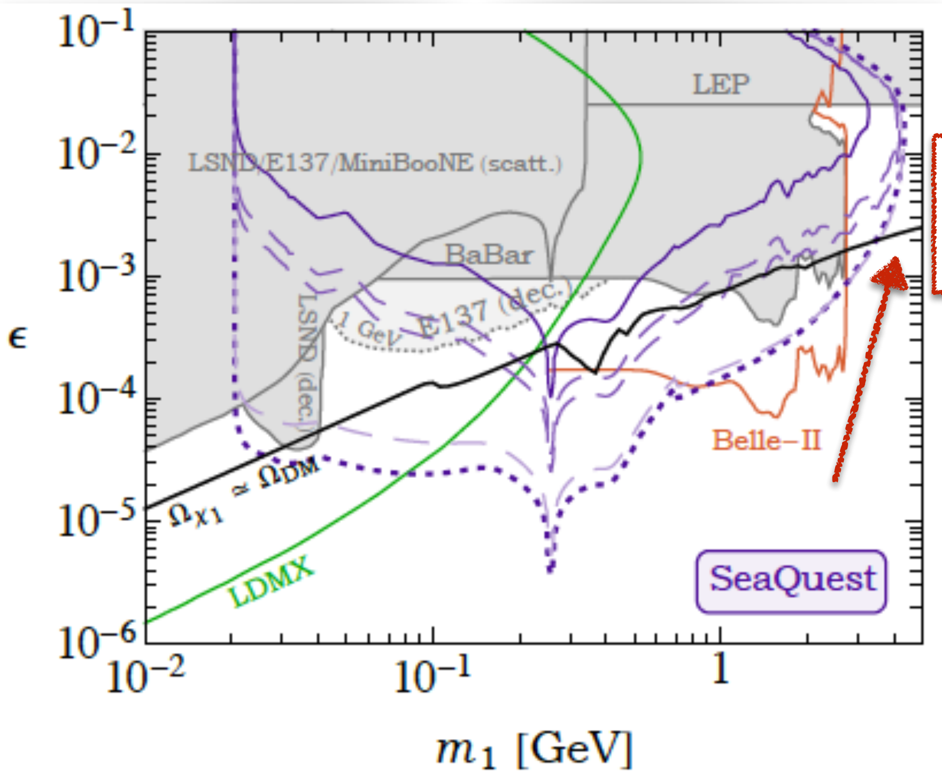
10^{18} POT

10^{20} POT
(5-6)m
(5-9)m
(5-12)m
From darker to lighter

10^{20} POT
(5-6)m, no KMAG

The SeaQuest acceptance remains relatively high even for smaller mass splittings
((5-12)m fiducial region!)

IDM @ fixed target experiments



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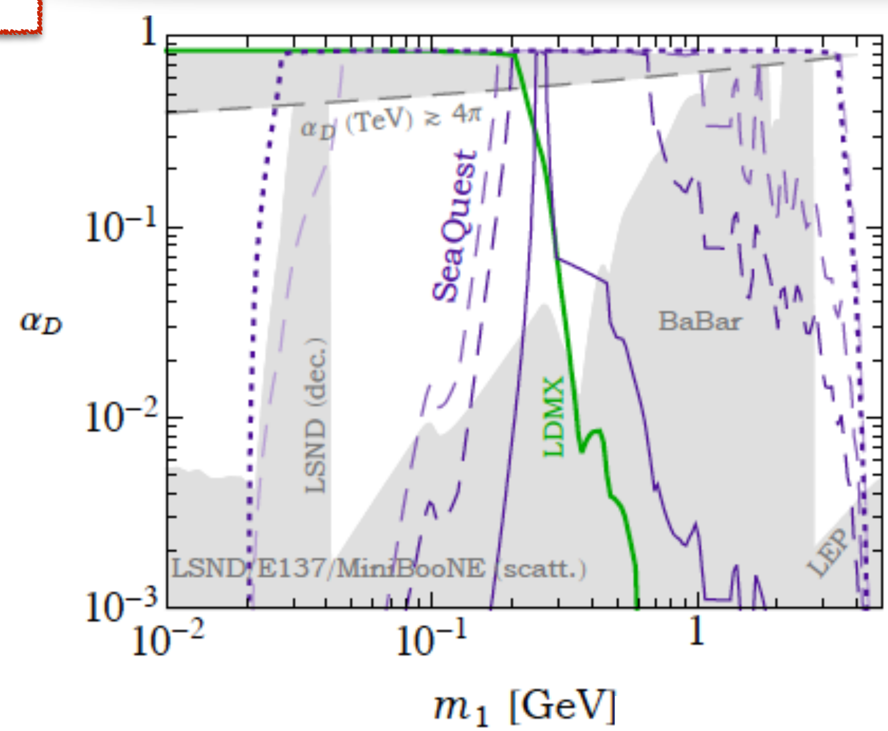


The SeaQuest acceptance remains relatively high even for smaller mass splittings ((5-12)m fiducial region!)

More broadly,

- Additional production mechanisms of dark particles?
- what type of searches (beyond e^+e^-) can be carried over by the SeaQuest experiment in the future?
- Is there some upgrade we need?

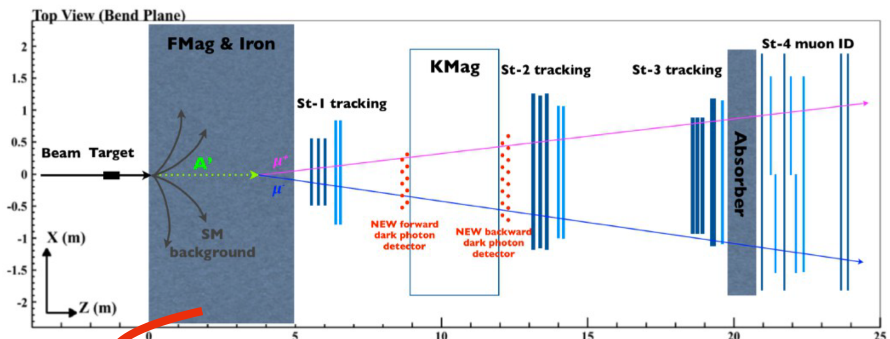
Scalars, axions, …

Leptophilic scalars

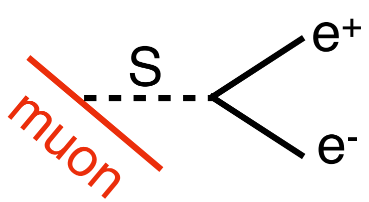
$$-\mathcal{L} \supset \sum_{\ell=e,\mu,\tau} \frac{m_\ell}{\Lambda} S\,\bar{\ell}\,\ell \quad \Rightarrow \quad -\mathcal{L} \supset g_\mu \sum_{\ell=e,\mu,\tau} \frac{m_\ell}{m_\mu} S\,\bar{\ell}\ell$$

These scalars are **not copiously** produced from "standard" mechanisms

BUT



huge production of (relatively energetic) muons



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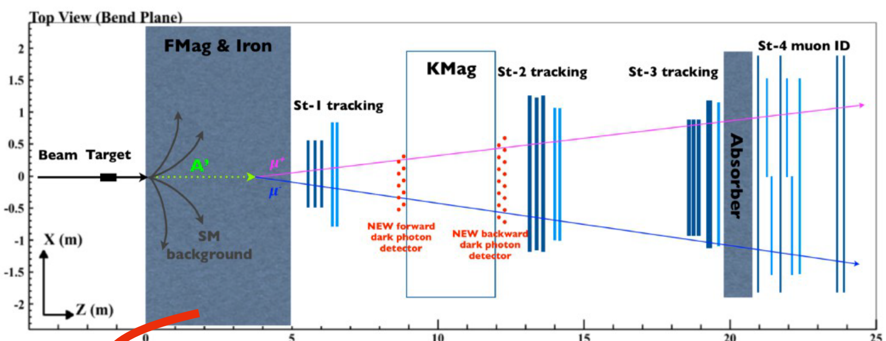
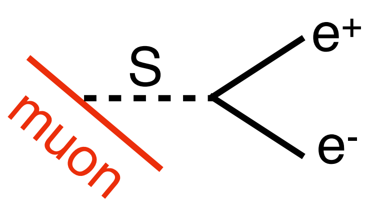
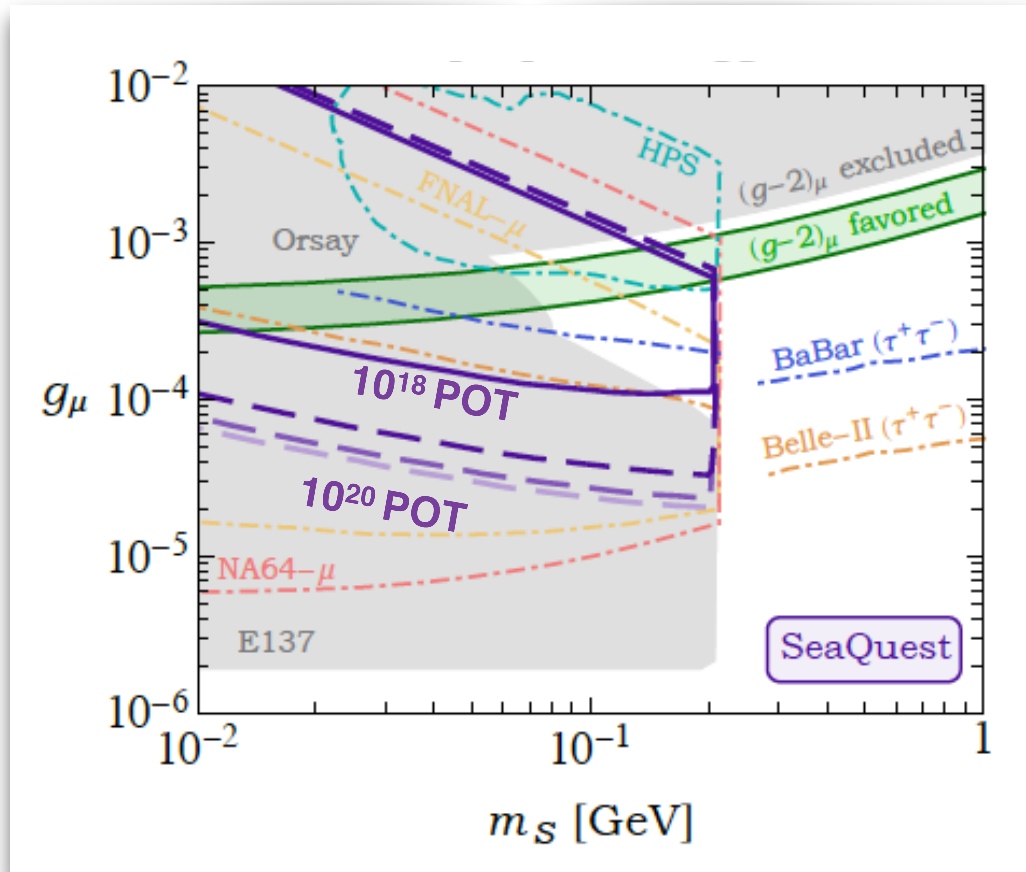


huge production of (relatively energetic) muons

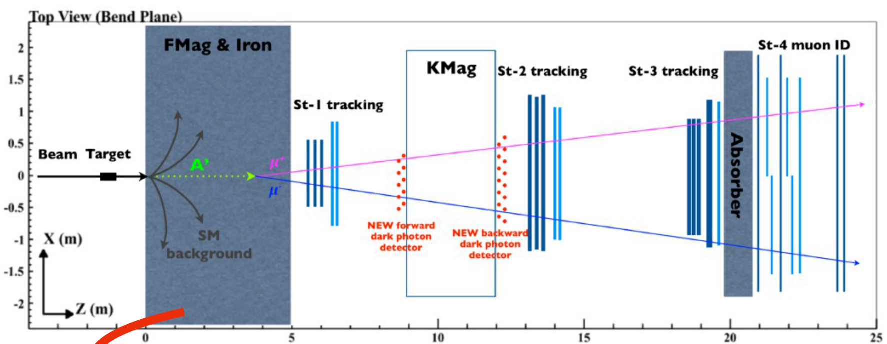




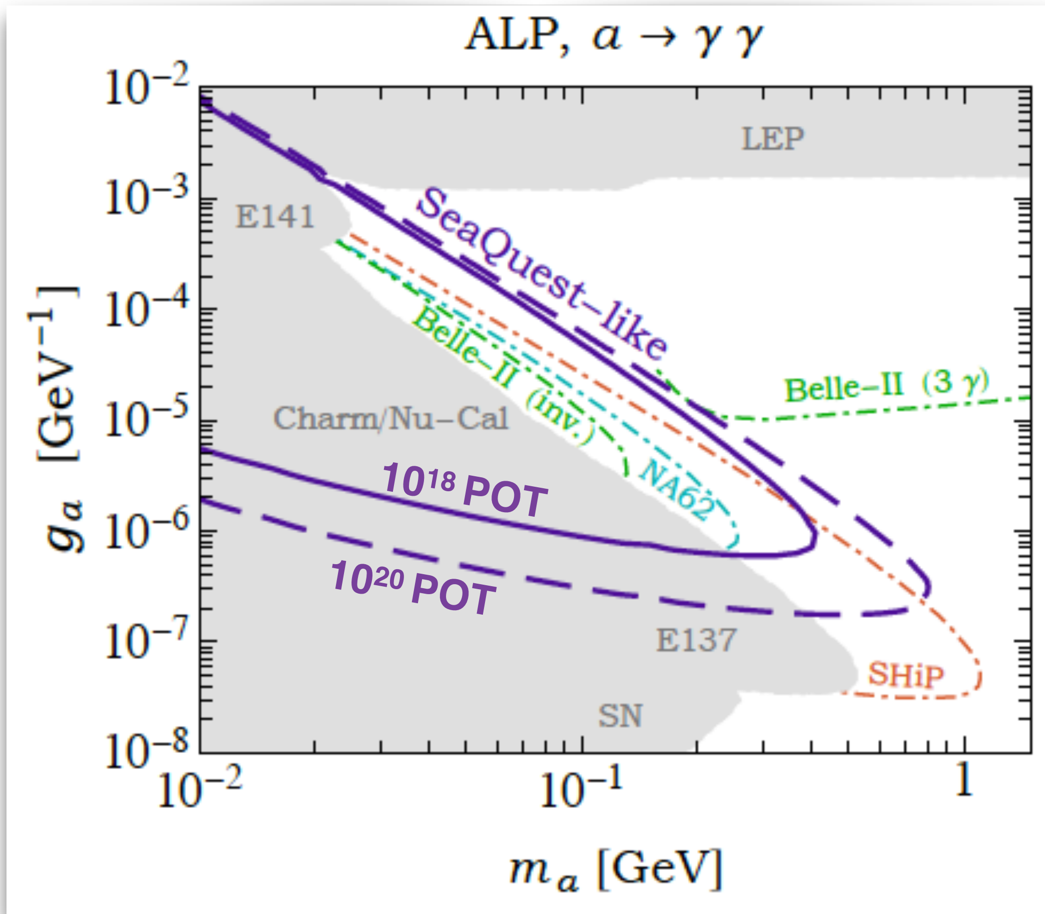
NA64-μ and FNAL-μ experiments proposed in Chen, Pospelov, Zhong, 1701.07437

Opportunities for axions

$$\mathcal{L} \supset g_a \, a \, F_{\mu\nu} \, \tilde{F}^{\mu\nu} \quad \Rightarrow \quad \Gamma(a \to \gamma\gamma) = \frac{g_a^2 \, m_a^3}{4\pi}$$



huge production of (relatively energetic) photons



10 events, (7-8)m

Backgrounds for photon signatures?

$K_L \to \gamma\gamma$ few more meters of iron?

Conclusions & Outlook

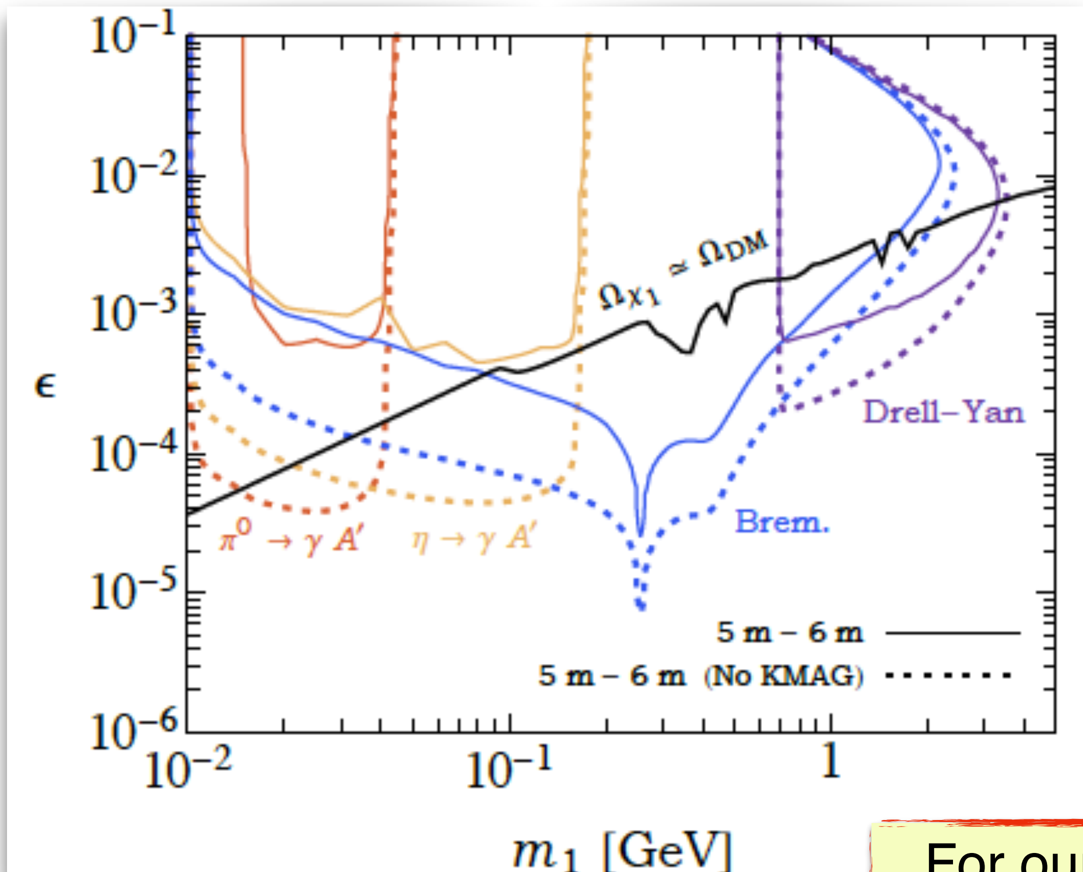
- Past, present & future fixed target experiments play a crucial role in testing interesting dark sector models

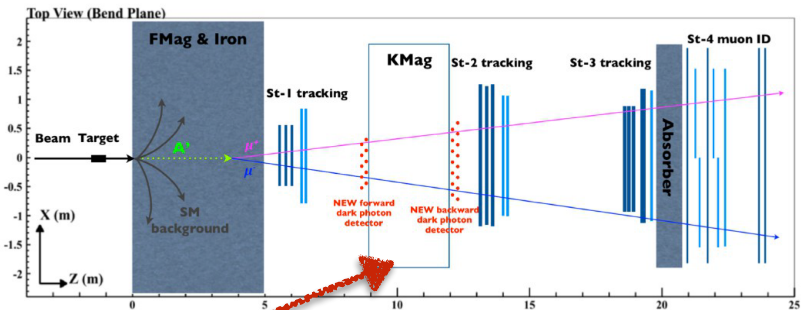
- A special role can be covered by Fermilab: SeaQuest (nuclear physics) experiment
  ⇨ **obvious advantage: <u>Existing experiment!</u>**

Minimal dark photon & dark scalar; Inelastic DM; axions (and Strongly-interacting DM) models can be broadly explored

Additional models that SeaQuest can explore? (Particle) physics case?

Info about KMAG, IDM





KMAG

10 signal events with 10^{18} POT

with ——

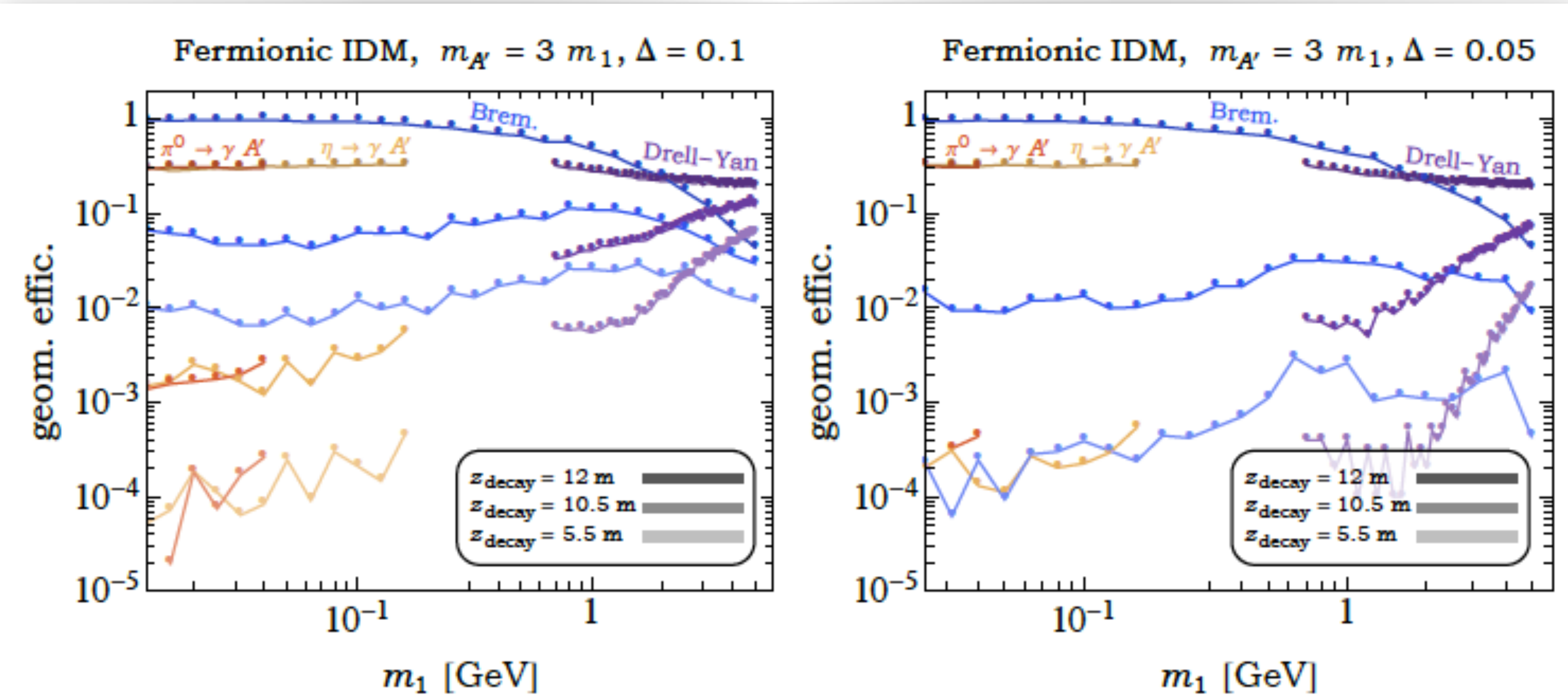
or without ········

KMAG

For our SeaQuest experimental colleagues: is the search without KMAG feasible? backgrounds?

IDM acceptance at SeaQuest

Berlin, SG, Schuster, Toro



Dark scalars mixed with the Higgs

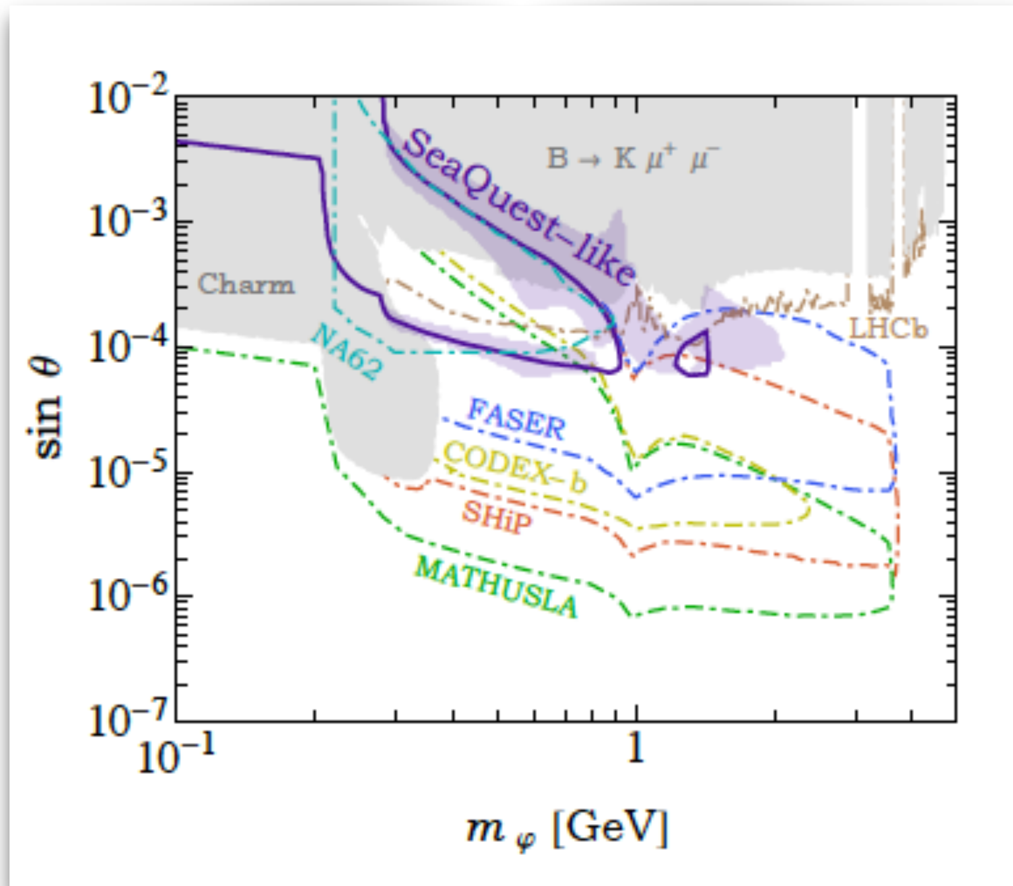
$$-\mathcal{L} \supset \sin\theta \, \frac{m_f}{v} \, \varphi \bar{f} f \quad \Rightarrow \quad \Gamma(\varphi) \propto \sin^2\theta \, m_\varphi$$

At SeaQuest, scalars produced from the decay of heavy mesons:

$$K \to \pi\varphi, \ B \to K\varphi$$

Scalars decaying to

Kaons (small region of parameters)
pions (backgrounds from $K_L \to \pi\pi$?)
electrons (typically small BR)
muons (backgrounds?)



10 events, (7-12)m, inclusive decays

Computing the efficiency at SeaQuest

Total efficiency=

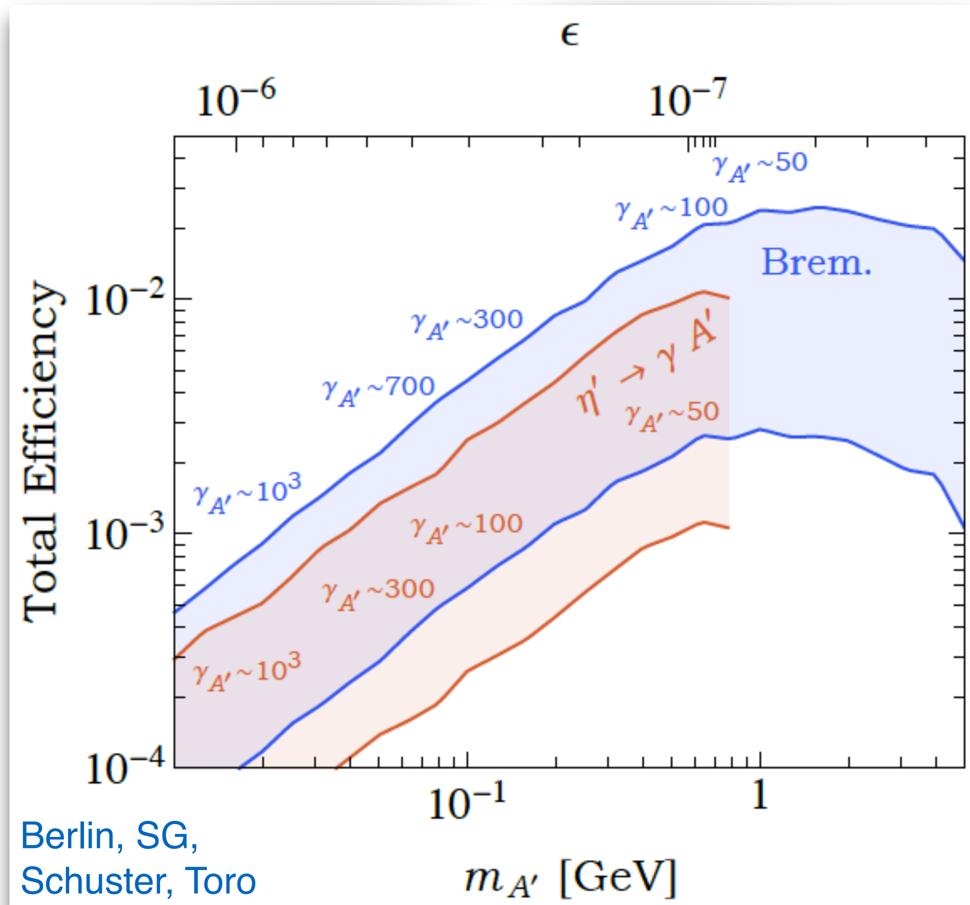
$$\frac{m\Gamma}{N_{tot}}\int_{\ell_{min}}^{\ell_{max}} d\ell \sum_{i\,\in\,\text{geom. criteria}(\ell)} \frac{e^{\frac{-\ell\ \Gamma\ m}{p_{\ell_i}}}}{p_{\ell_i}}$$

(and not

$$\text{Exp}\left[-\frac{\ell_{min}\Gamma}{\langle\gamma\rangle}\right]\left(1-\text{Exp}\left[-\frac{\ell_{max}\Gamma}{\langle\gamma\rangle}\right]\right)\sum_i \frac{N_i}{N_{tot}}$$!)

mean boost

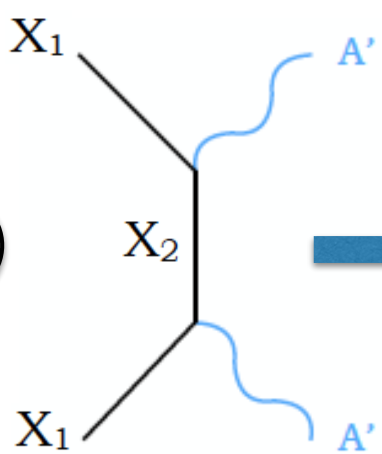
For the minimal dark photon model:



Indirect detection of IDM

CMB constraints:

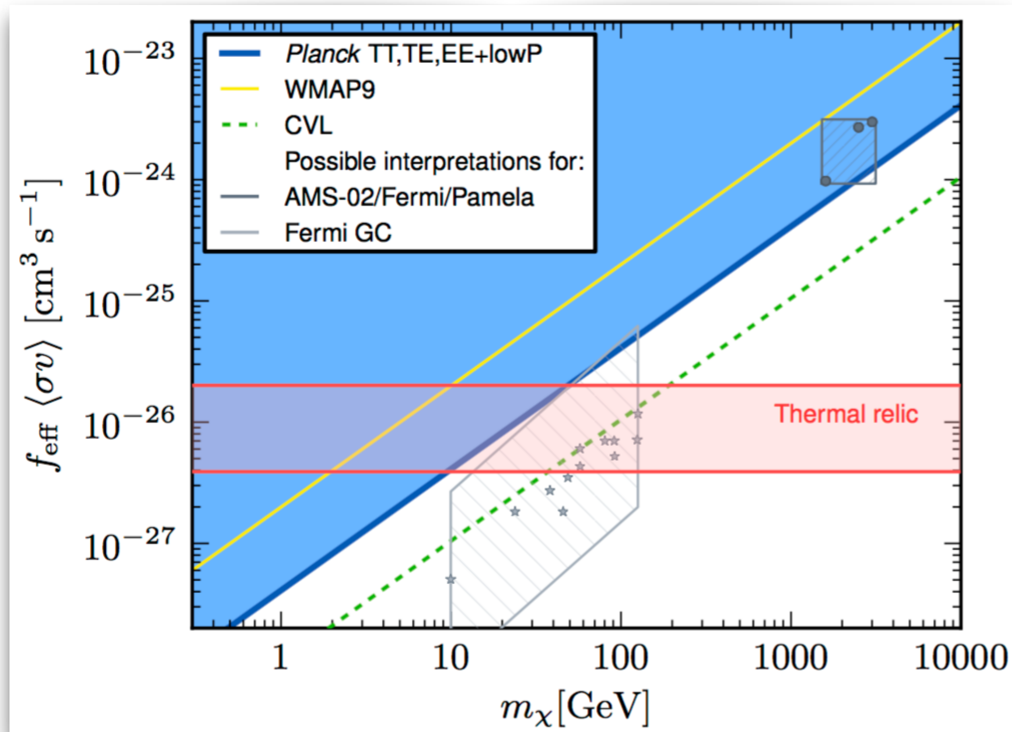
1.



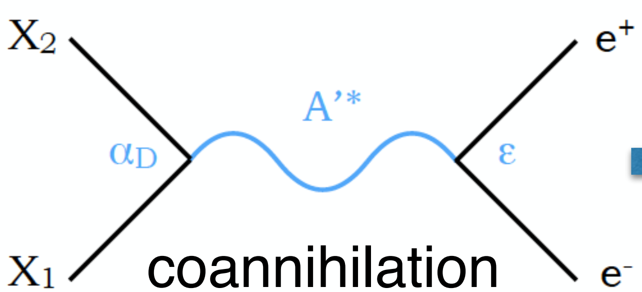
$m_X > m_{A'}$

$\rightarrow$ $m_X \gtrsim 10$ GeV

1502.01589



2.

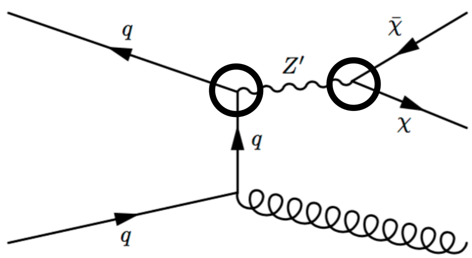


$m_X < m_{A'}$

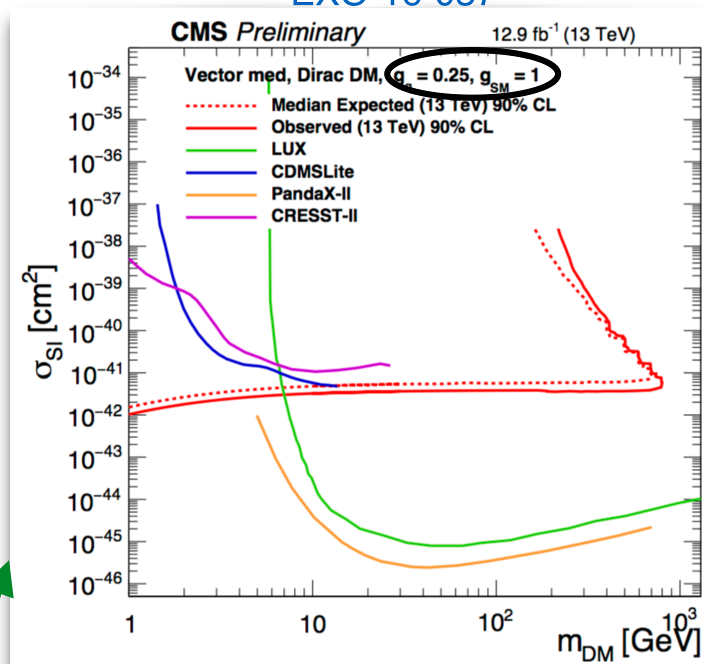
$\rightarrow$ No significant constraint

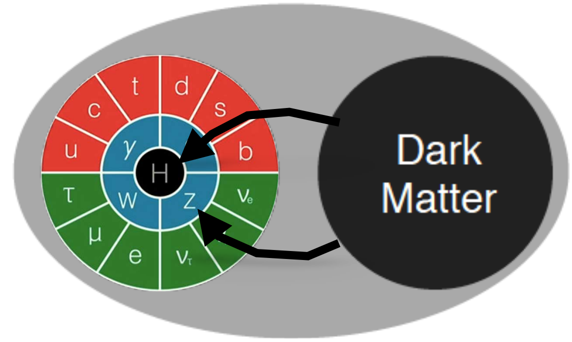
The DM candidate in IDM models can be thermal and below 10 GeV!

Experimental program for WIMPs



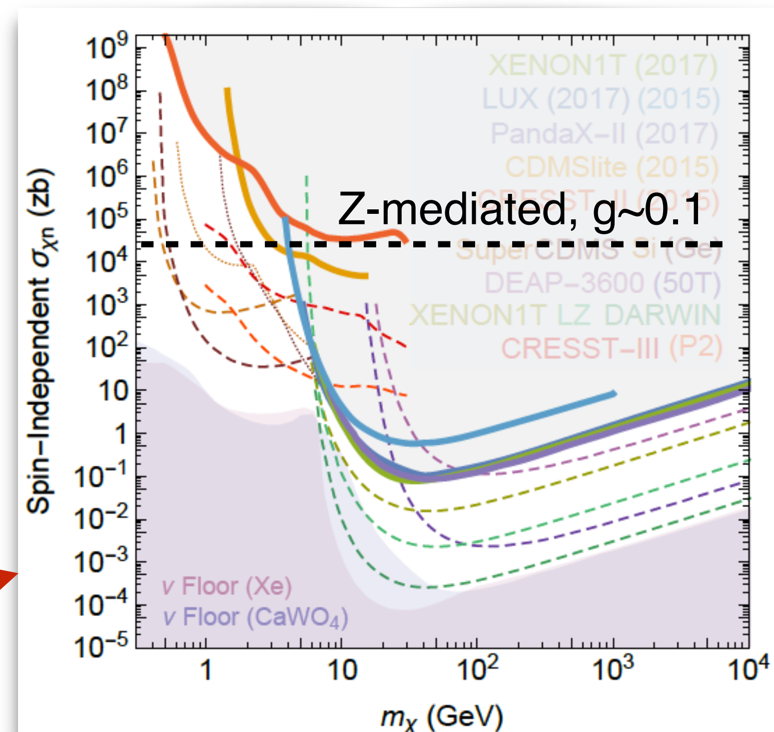
EXO-16-037

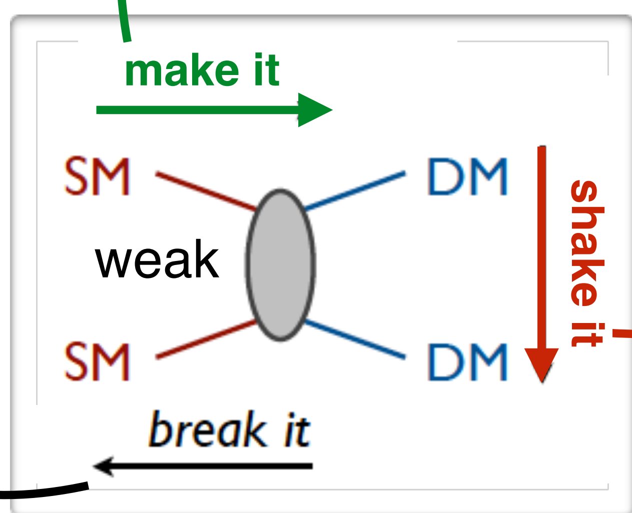




$$m_\chi \sim \alpha_\chi \times 10\ \mathrm{TeV}$$

Evans, SG, Shelton, 1712.03974





CMB,
Dwarf galaxies,
Cosmic rays, …

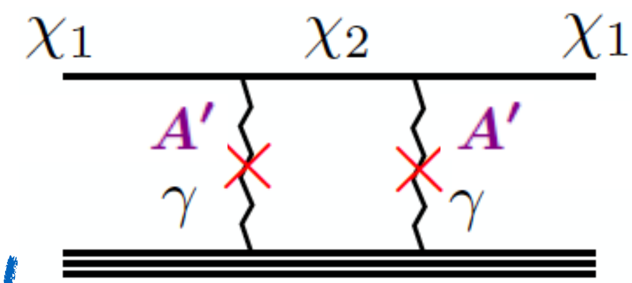
S.Gori

Backup

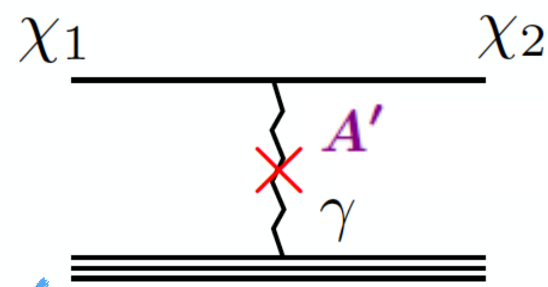
Direct detection of IDM

Direct detection signals are suppressed even for EW-scale DM

Hall, Moroi, Murayama, 9712515



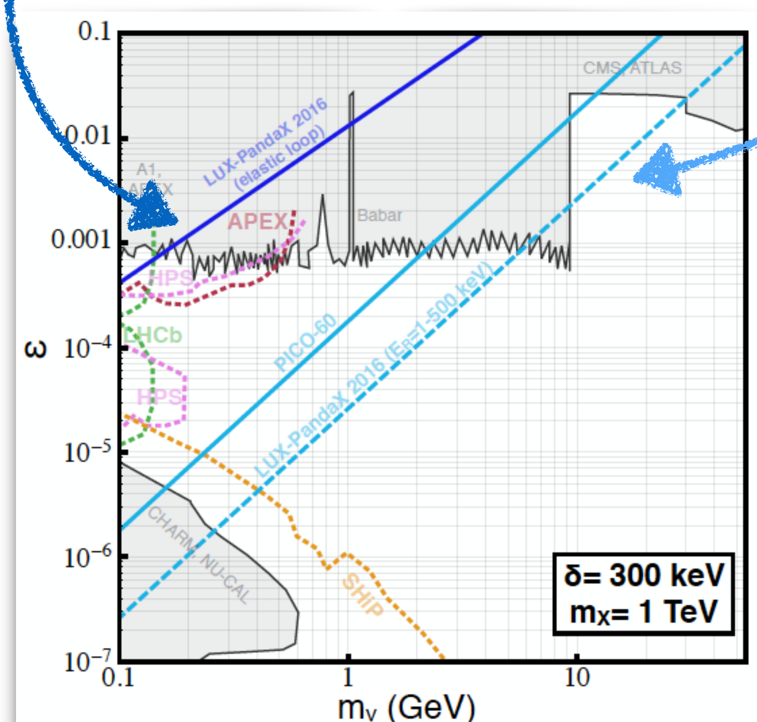
loop suppressed



dominant process

larger recoil energy

Data is not analyzed!



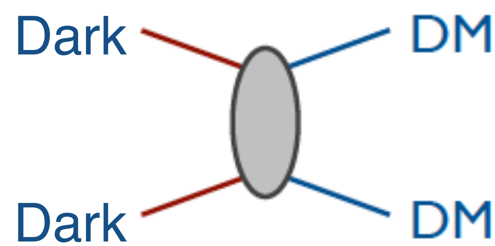
Bramante, Kribs, Fox, Martin, 1608.02662

<u>Proposal:</u>
extend Xenon and Tungsten experiment analysis to **high recoils data**

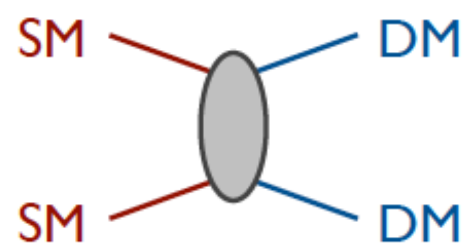
The "WIMP next door"

Even in more "pessimistic" scenarios, there is a lower bound on the DM-SM interaction strength.

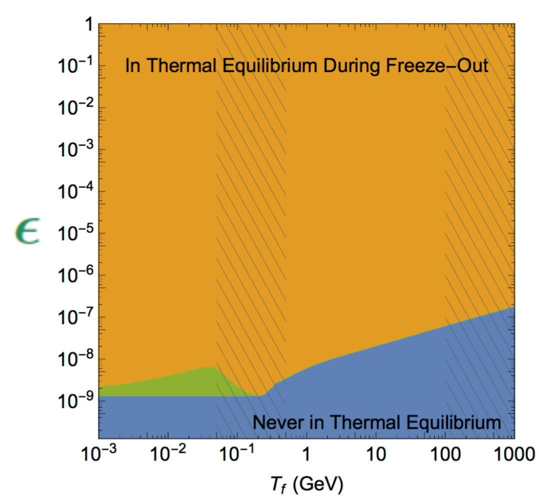
- Dark matter can reach the measured relic density via its interactions with the dark sector:



- Nevertheless, to achieve thermal contact between the SM and the dark sector, a minimum interaction strength is required:

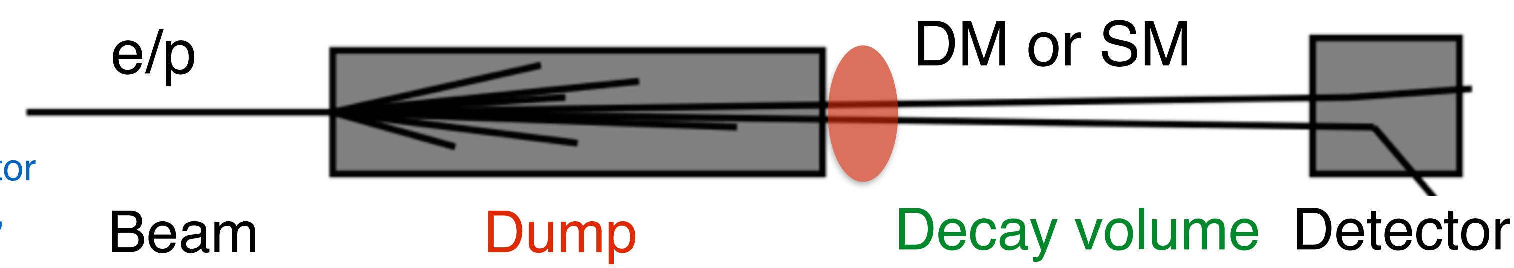


This bound will depend on the equilibration temperature



Evans, SG, Shelton, 1712.03974

Fixed target experiment program



See eg. Dark sector community report, 1608.08632

	Experiment	Proton energy	POT	Dump	Decay volume
Past	CHARM	400 GeV	2.4×10^{18}	480 m	35 m
Past	LSND	800 MeV	10^{22}	30 m	10 m
Present	NA62 (dump mode)	400 GeV	5×10^{18}	80 m	200 m
Future	ShiP	400 GeV	2×10^{20}	65 m	60 m

Generically higher mass reach

and many more…

	Experiment	Electron energy	EOT	Dump	Decay volume
Past	E137	20 GeV	10^{20}	179 m	204 m
Present	HPS	2 GeV; 7 GeV	5.6×10^{17}; 6.8×10^{18}	–	$\mathcal{O}(10\text{ cm})$
Future	LDMX	4 GeV; 8 GeV	4×10^{14}; 10^{16}	–	$\mathcal{O}(3\text{ m})$

Other experiments to probe dark sector models?

From nuclear to particle physics

SeaQuest started in 2010 as a nuclear physics experiment

Nuclear physics goal of the experiment:

3-dimensional proton tomography in momentum space through the precise measurement of Drell-Yan production.

More in particular: understanding the origin of the nucleon spin
Non-vanishing sea angular momentum distribution?

The experiment can also be used for **particle physics**!

Recent (April 2017) installation of a displaced trigger
→ Searches for displaced dark sectors **decaying after the dump**

In the near future, possibility of inserting a EMCAL between Station III and Station IV → sensitivity to electrons

A particle physics program to be written!