Dark Sectors at the Fermilab SeaQuest Experiment

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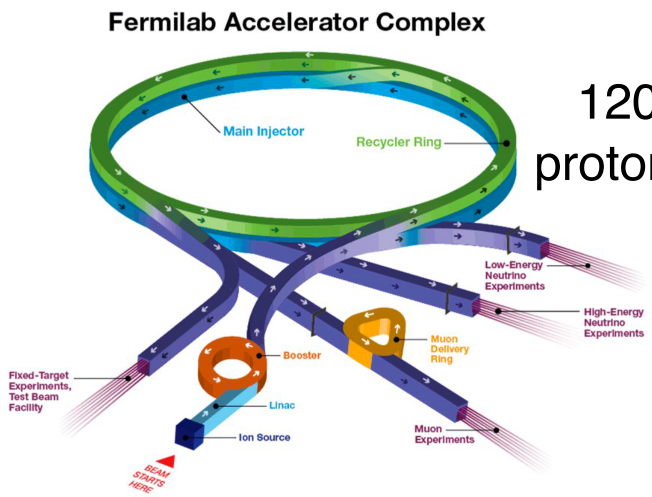
University of Cincinnati

Searching for long-lived particles at the LHC:
3rd workshop of the LHC LLP Community

CERN
May 17, 2018

The SeaQuest experiment

2012 - now



120 GeV
proton beam

Very high intensity proton beam

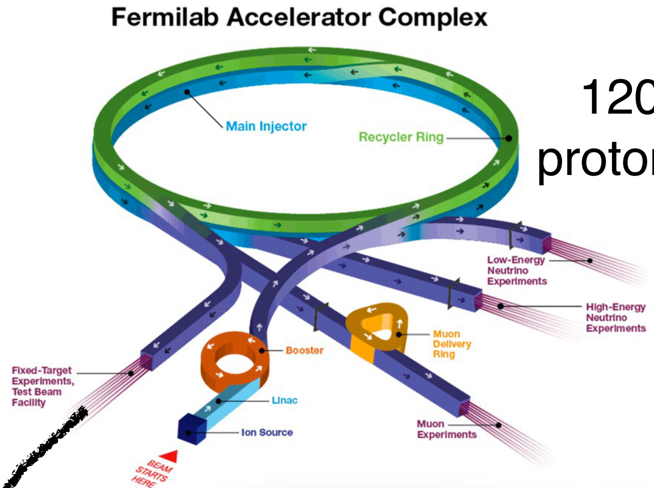
Proton Improvement Plan
to get very high intensity (PIP, PIP II, PIP III)

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

The SeaQuest experiment

2012 - now

SeaQuest E906



120 GeV proton beam

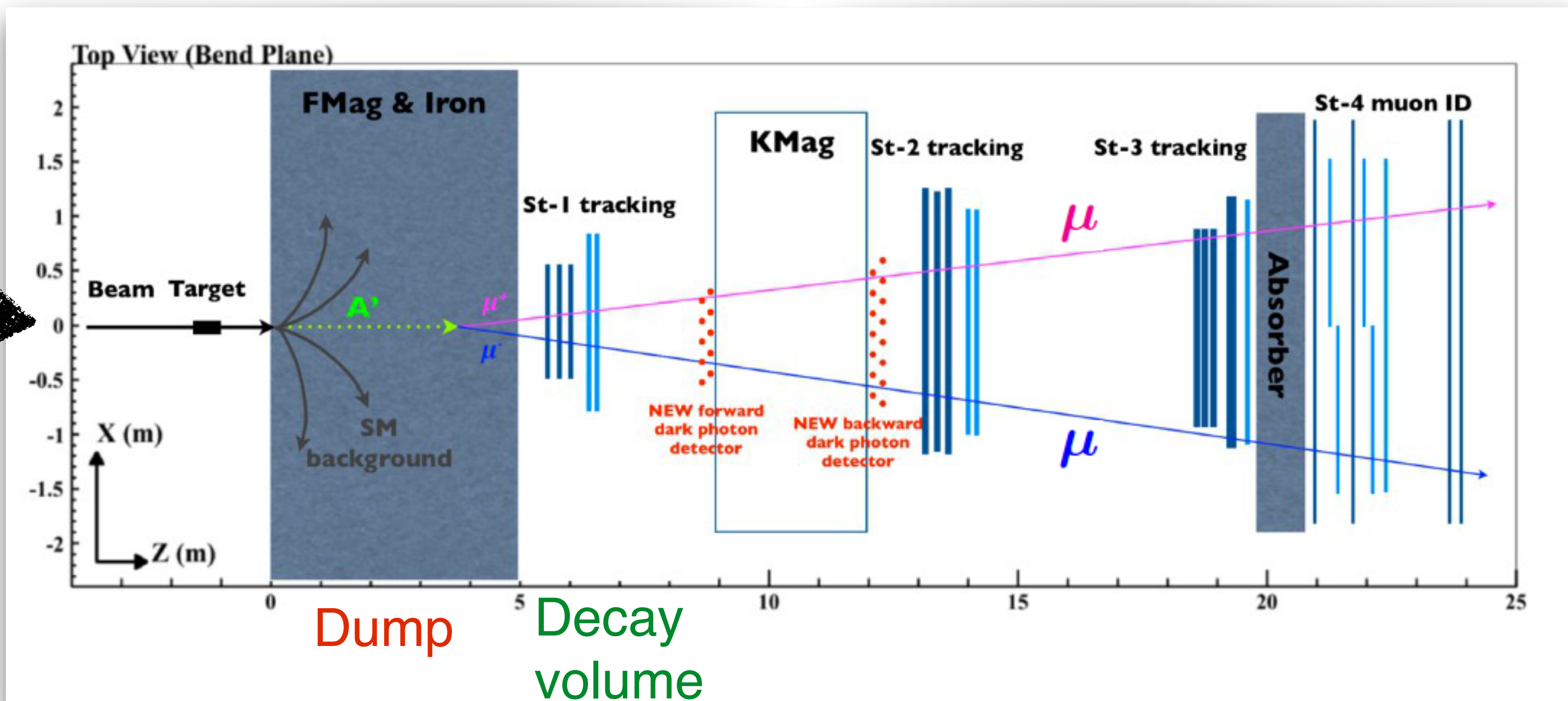
Very high intensity proton beam

Proton Improvement Plan

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

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

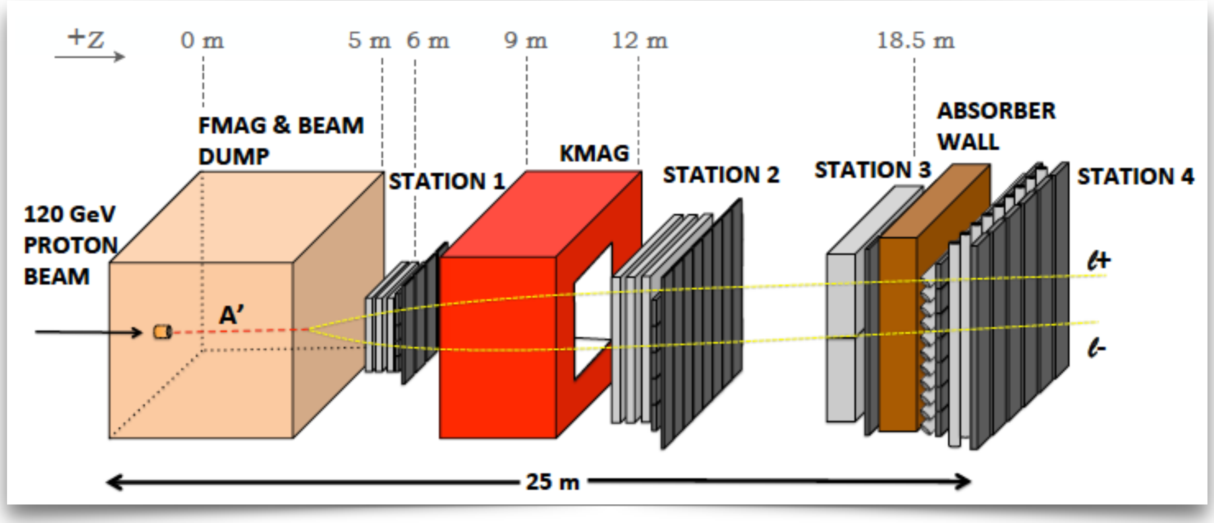
5% main injector beam



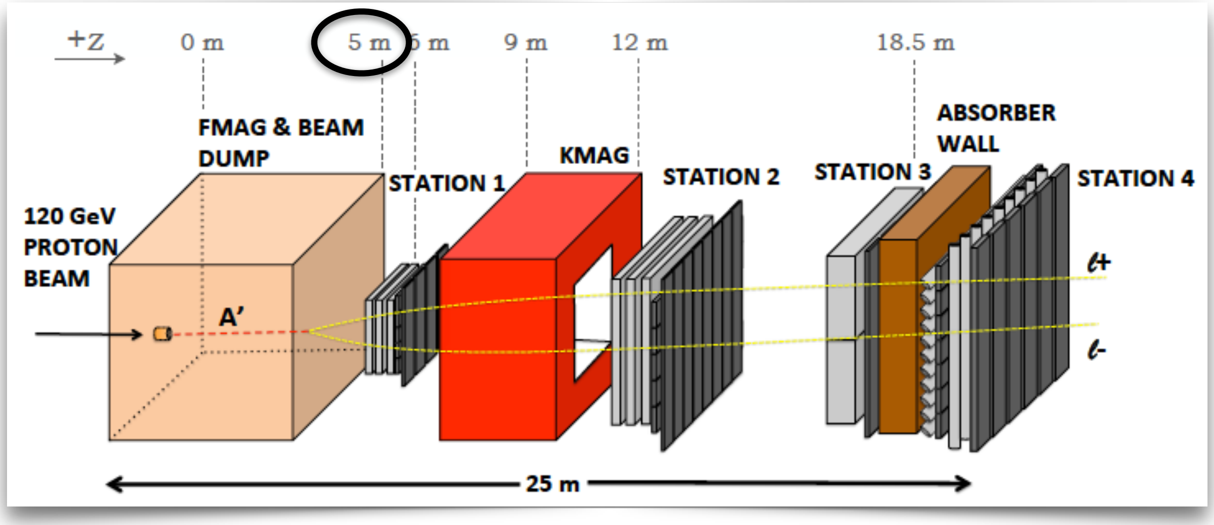
Dump

Decay volume

SeaQuest in a nutshell



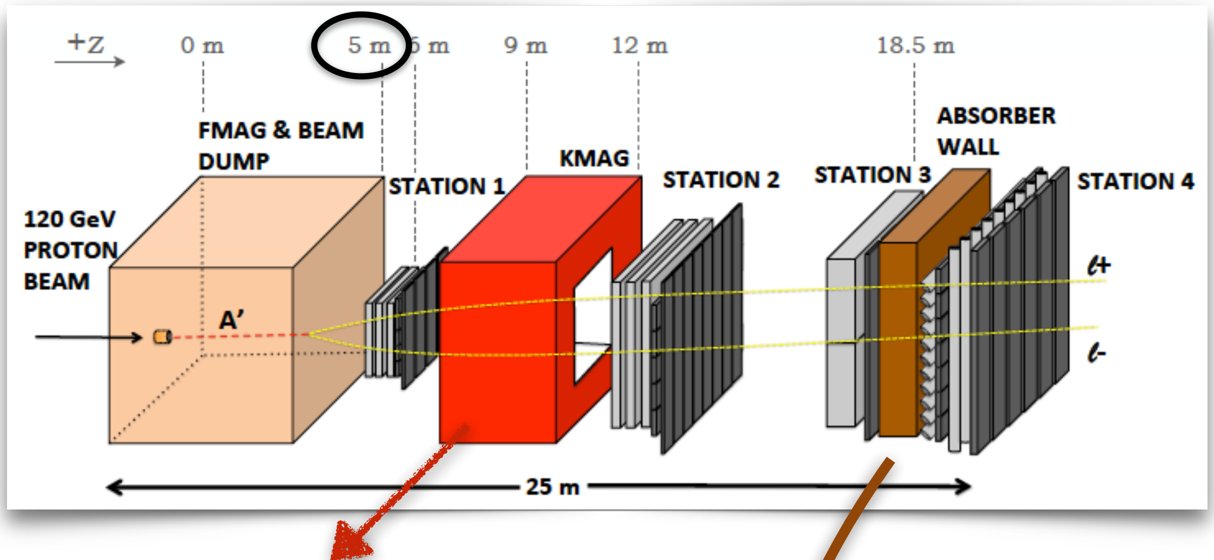
SeaQuest in a nutshell



1. Compact geometry

Sensitivity to (slightly) displaced dark particles with **d > 5m**

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)

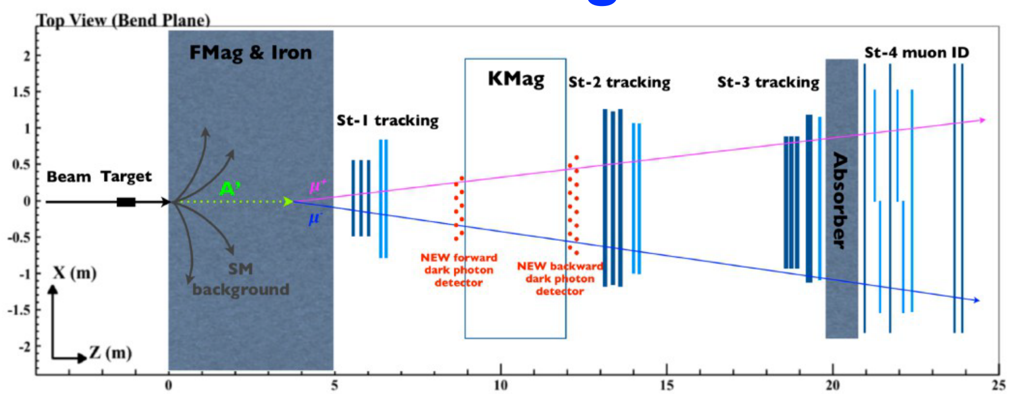
Identification of very light dark particles/squeezed spectra

3. A bit of history

- Previous runs (since 2012) dedicated to prompt μ. Nuclear physics program. Drell-Yan measurements
- April 2017: installation of displaced di-muon trigger $\sim 10^{16}$ POT collected in 5 days run
- Approved: physics run for $\sim 10^{18}$ POT (2018 - 2021)
- Work in progress: proposal for installation of ECAL (from the Phenix experiment)

Visible displaced signatures

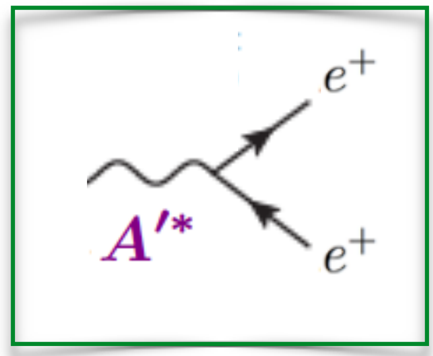
Fiducial regions

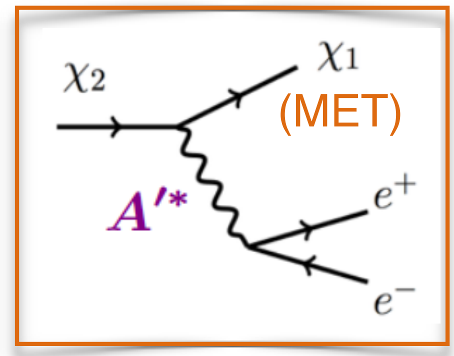


1. (5-6)m
2. (5-9)m
3. (5-12)m

Signatures

- Di-electrons (resolved & not resolved)

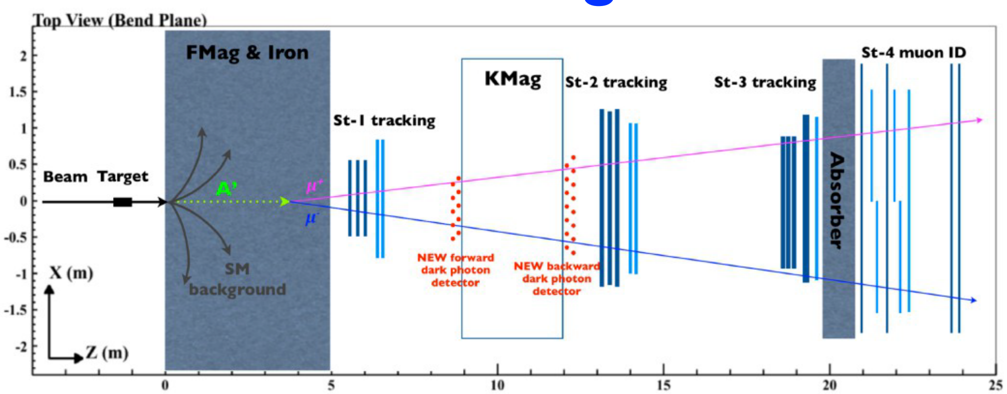




- Di-Muons
- Di-photons
- …

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

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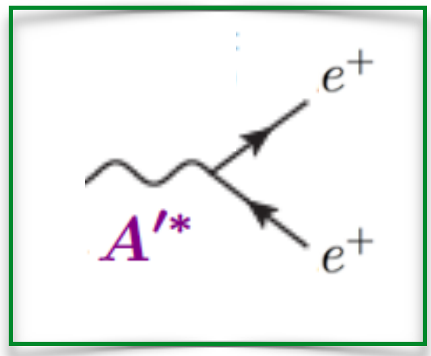
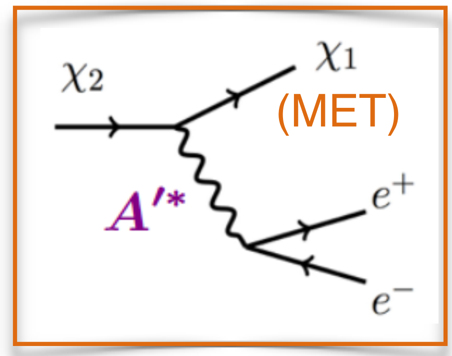




- Di-Muons
- Di-photons
- …

Luminosity

- 10^{18} POT (approved luminosity)
- 10^{20} POT (futuristic)

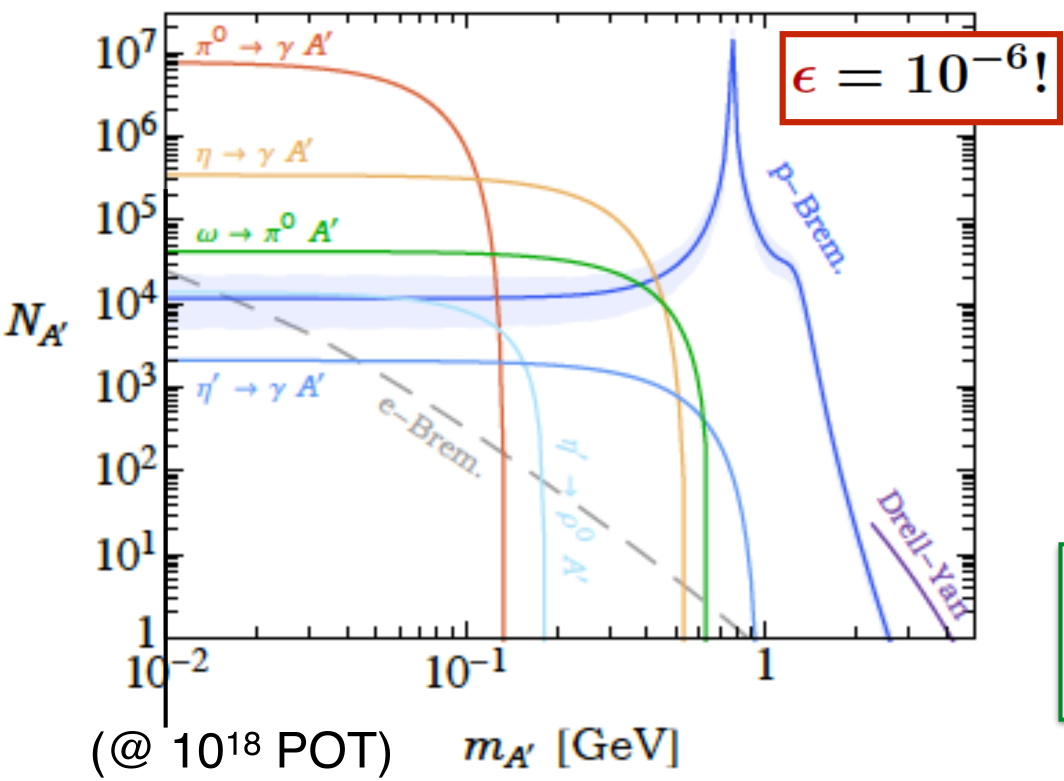
Dark photon models

1. Minimal dark photon model
2. Inelastic Dark Matter (IDM)
   Berlin, SG, Schuster, Toro, 1804.00661
3. Strongly interacting DM
   Berlin, Blinov, SG, Schuster, Toro, 1801.05805

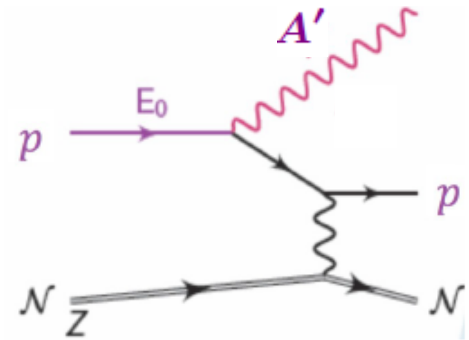
A huge dark photon production

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

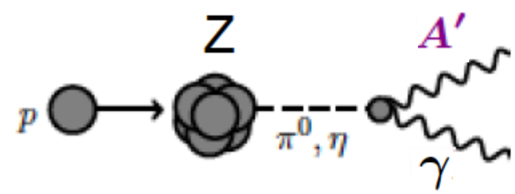
Berlin, SG, Schuster, Toro, 1804.00661



(@ 10^{18} POT)



brems-strahlung



meson decay

Generically larger rates than at electron fixed target experiments

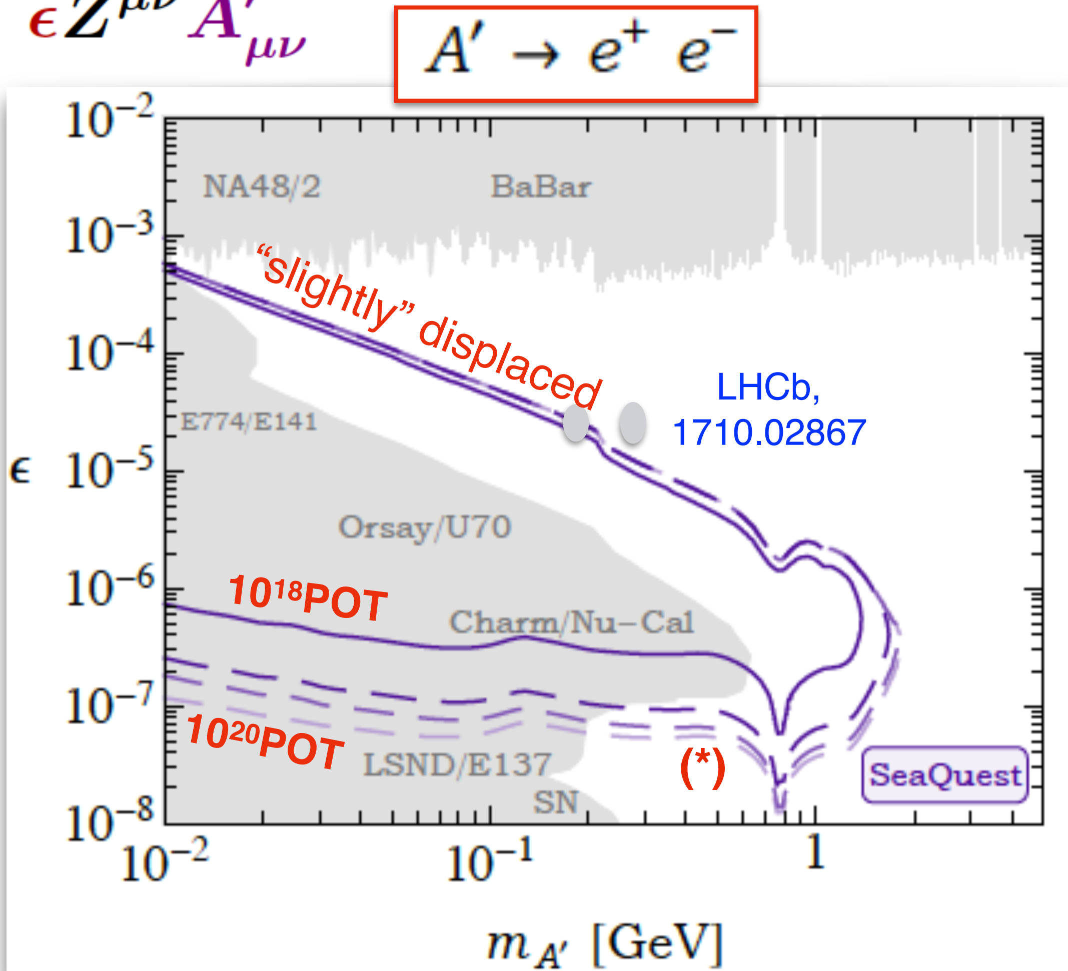
$$N_{A'}(e\ \mathrm{Brem.}) \sim \left(\frac{\epsilon}{10^{-6}}\right)^2 \left(\frac{m_{A'}}{\mathrm{GeV}}\right)^{-2} \left(\frac{\mathrm{EOT}}{10^{18}}\right)$$

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

1. 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

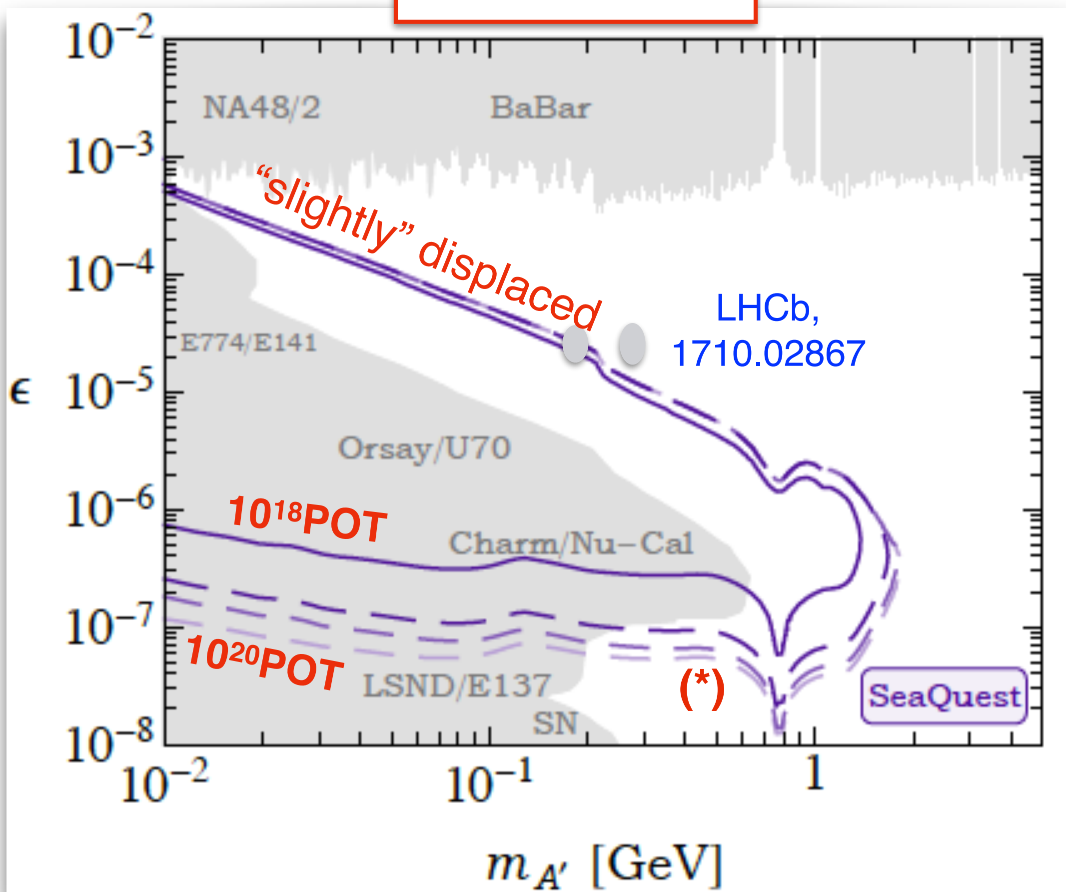
See Gardner, Holt, Tadepalli, 1509.00050 for the muon reach as well

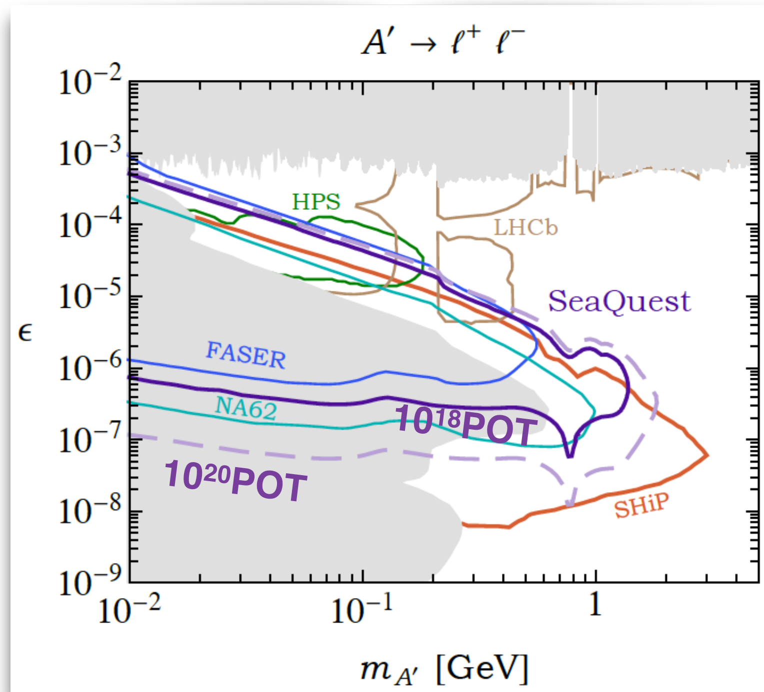
1. The reach for the minimal A' model

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

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

Berlin, SG, Schuster, Toro, 1804.00661





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FASER: Feng et al., 1708.09389

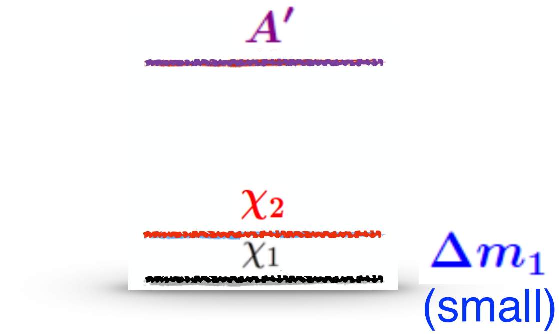
NA62: Lanfranchi @ CERN-EPFL-Korean theory institute

SHiP: Alekhin et al., 1504.04855

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

2. Inelastic DM & displaced decays

Spectrum of Inelastic DM (IDM) models:
χ_1 (DM), χ_2 (DM excited state), A' (mediator)



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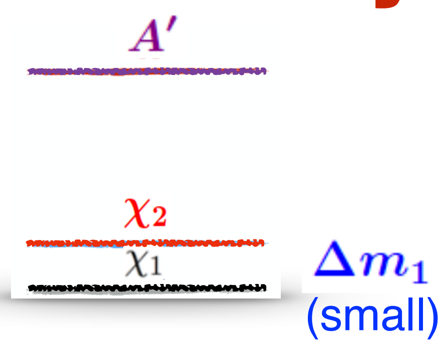
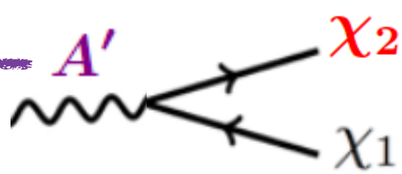
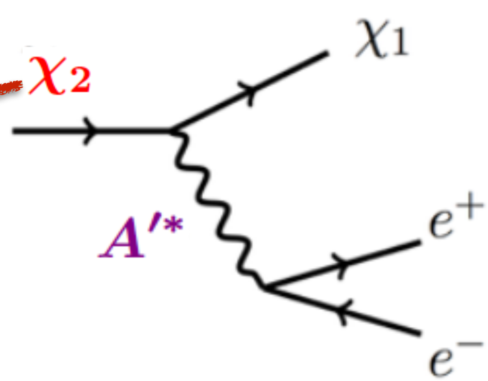




Copiously produced at
fixed target experiments

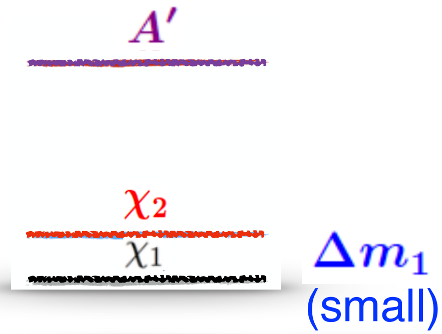
with



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

Non-resonant decays

2. Inelastic DM & displaced decays



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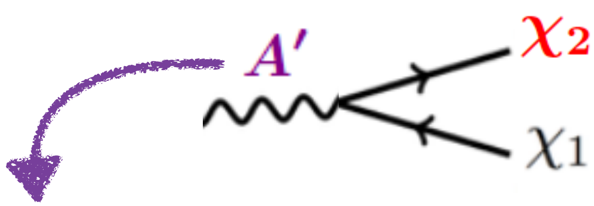

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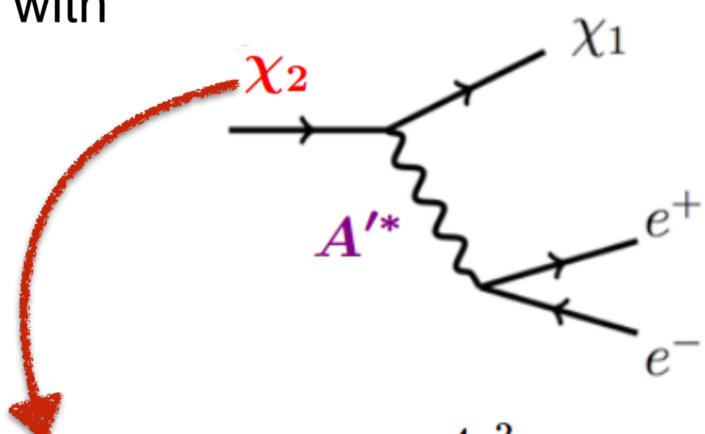

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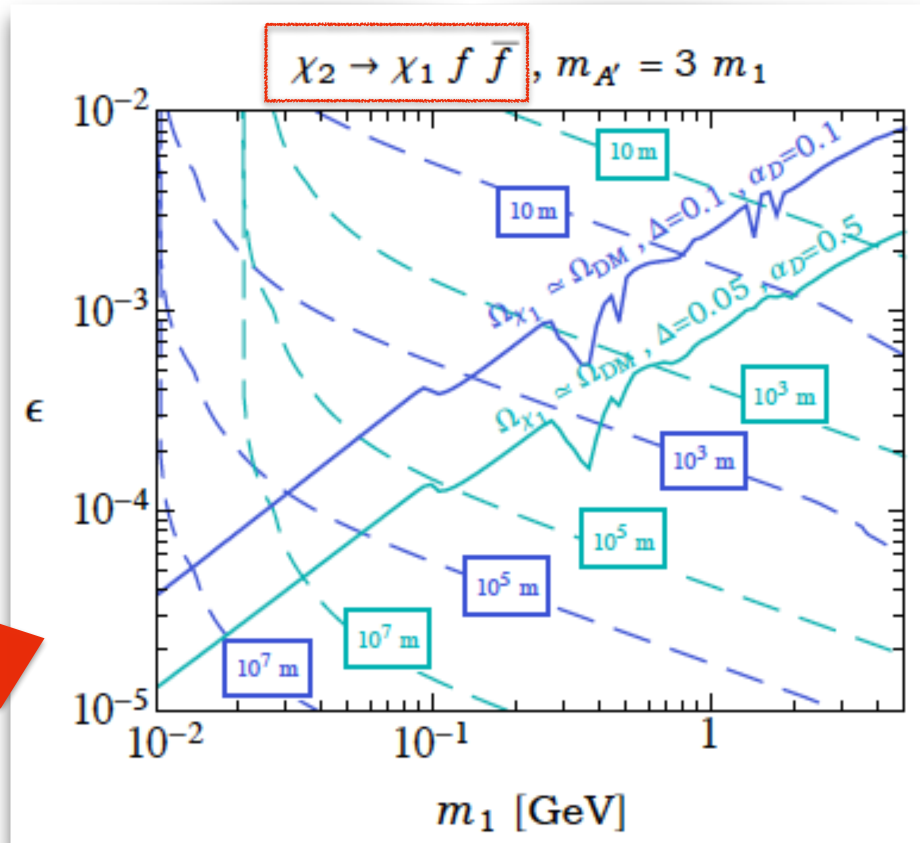
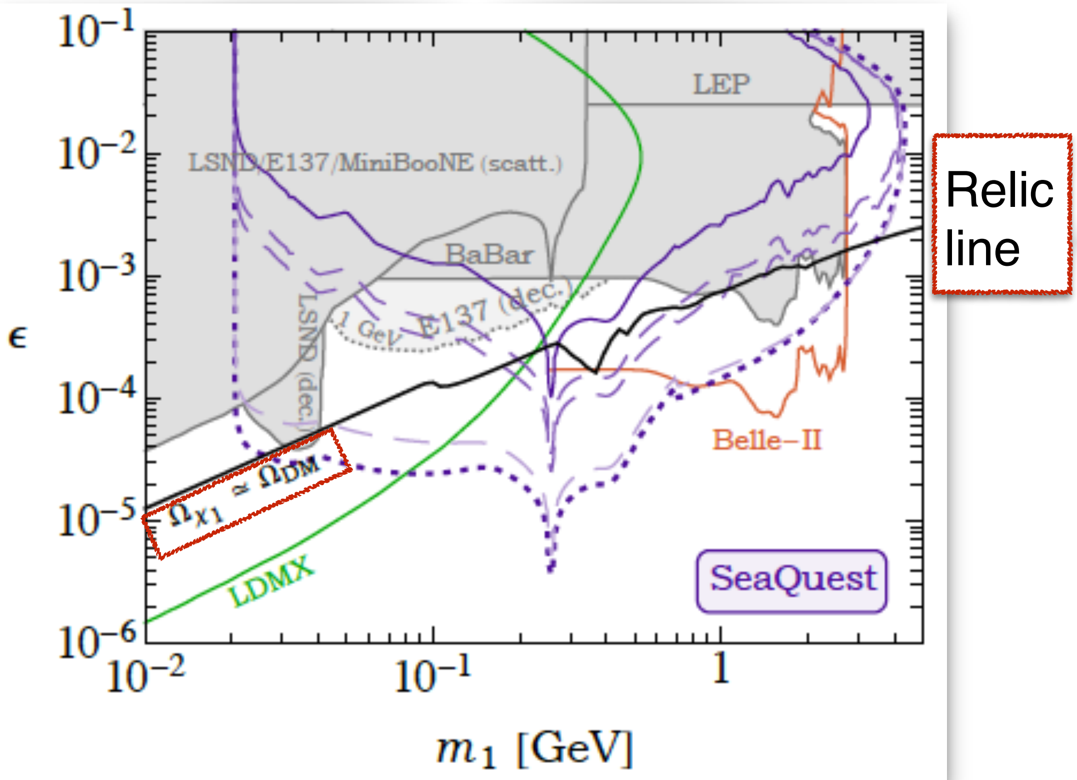


Displaced decays

2. The reach for IDM



see also Izaguirre et al. 1703.06881

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

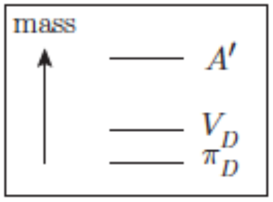
10^{18} POT

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!)

3. SIMPs & displaced decays



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

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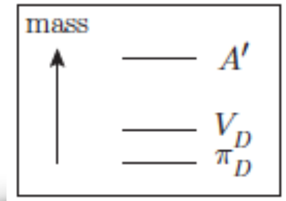
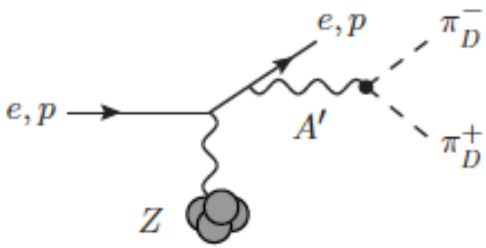
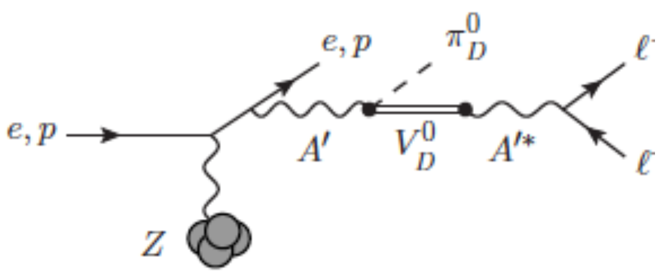
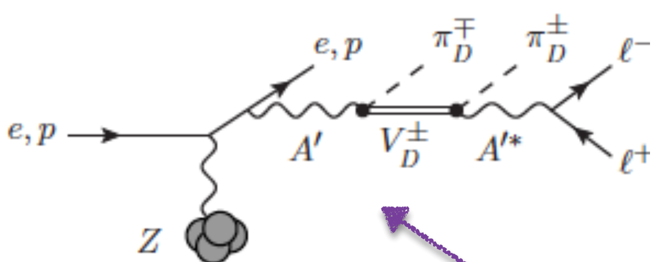




Invisible
A’ decay



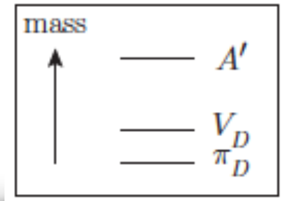


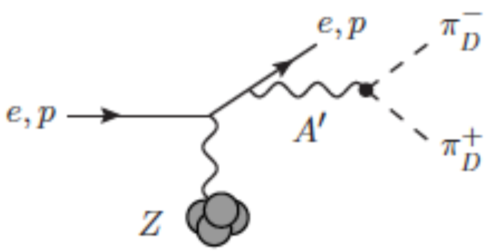
Visible
A’ decay

Similar to the
IDM signature

3. SIMPs & displaced decays

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





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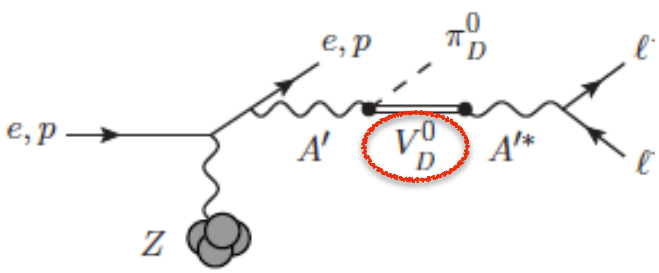
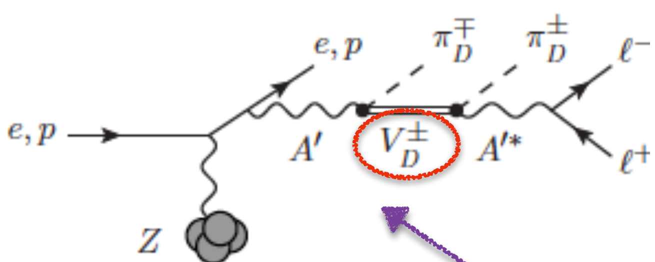
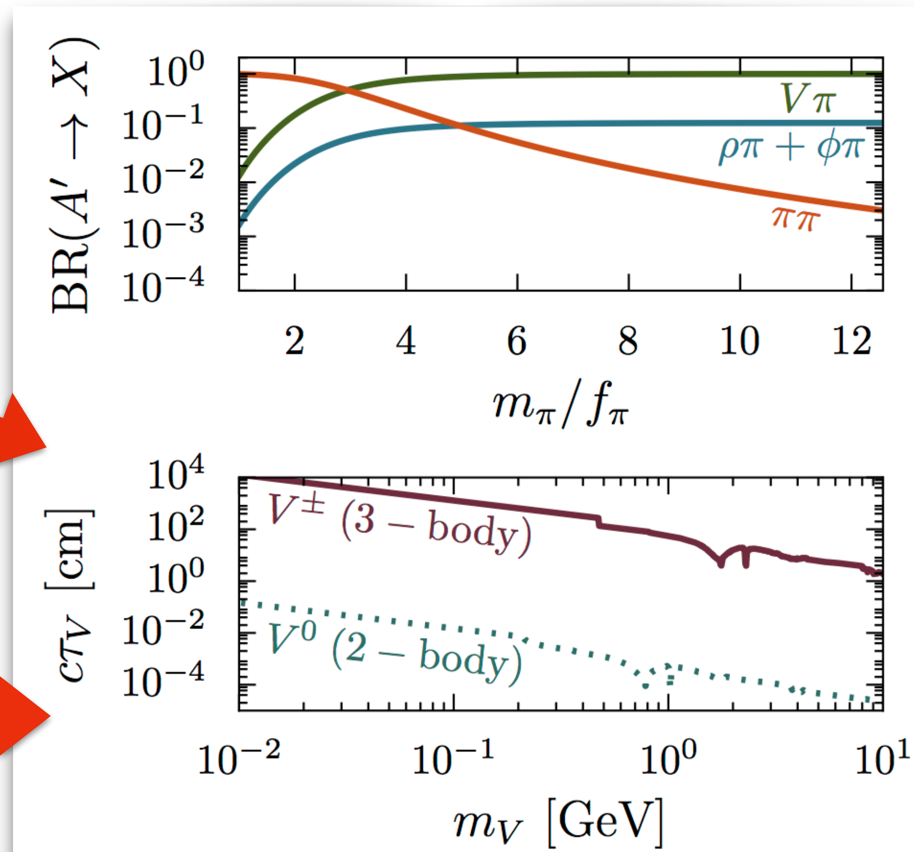




Visible A’ decay

Similar to the IDM signature

Berlin, Blinov, SG, Schuster, Toro, 1801.05805



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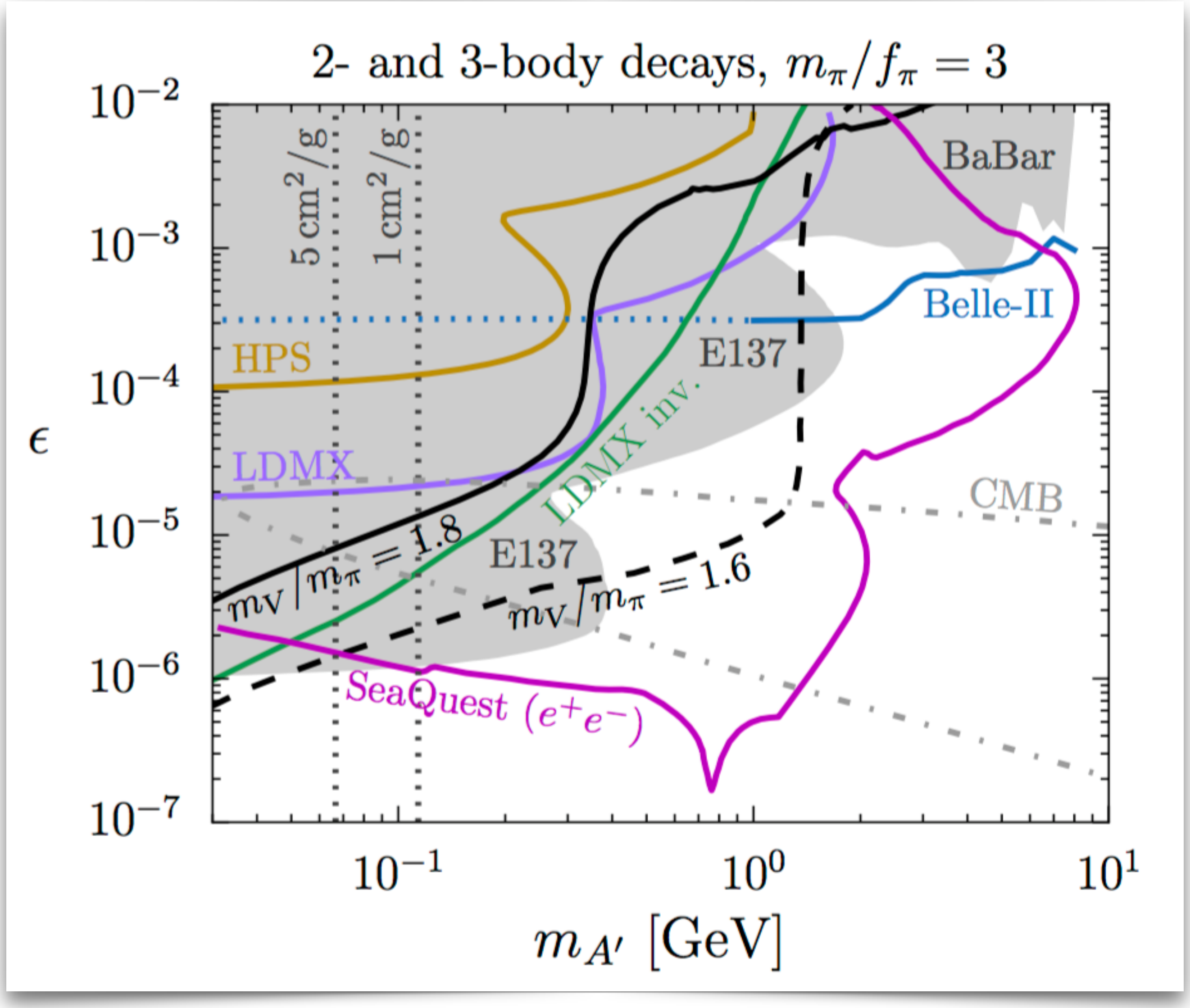


3-body decay

$V_D^\pm \to \pi_D^\pm \ell^+\ell^-$

2-body decay

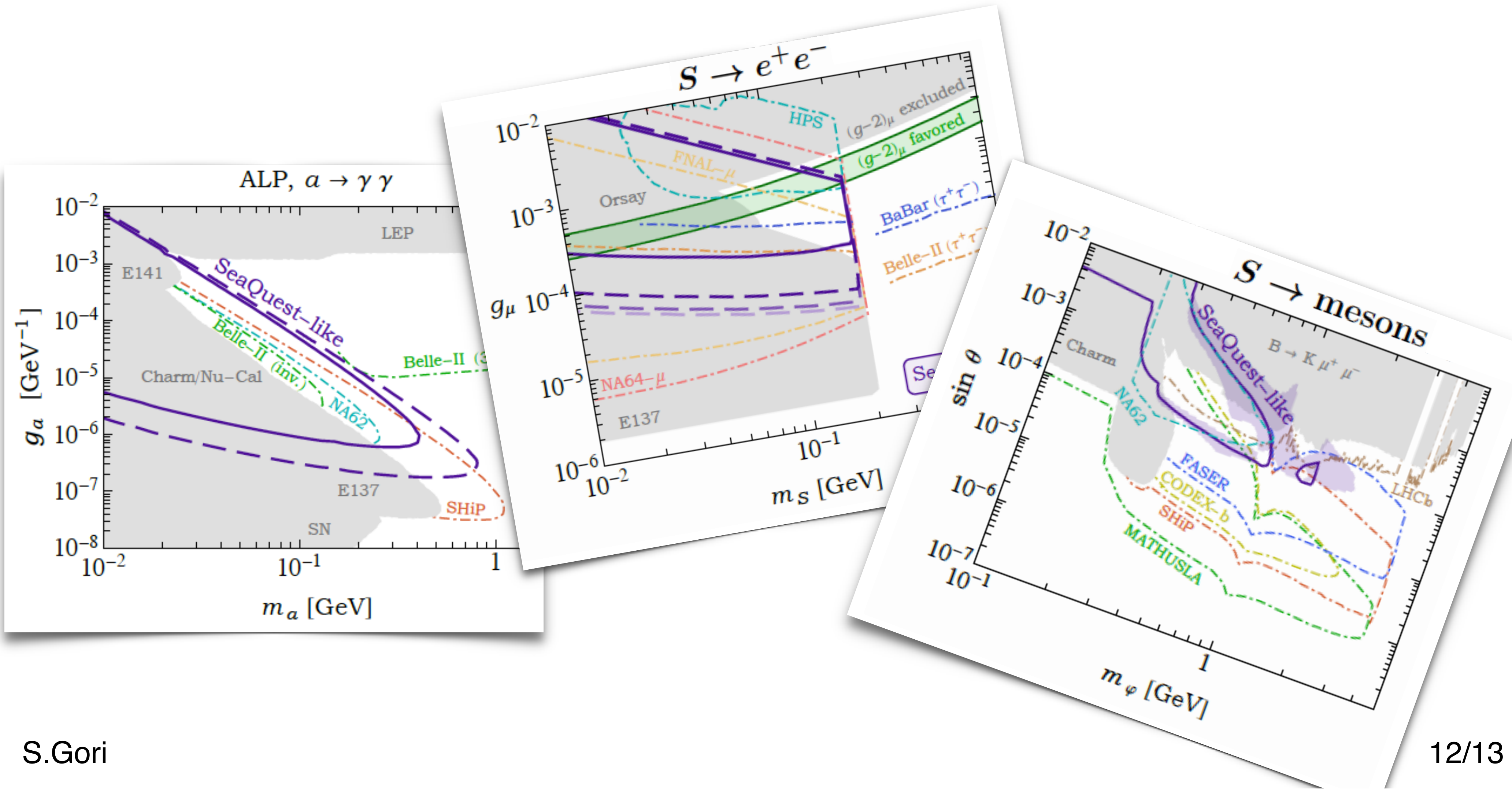
$V_D^0 \to \ell^+\ell^-$

Berlin, Blinov, SG, Schuster, Toro, 1801.05805

From Berlin, SG, Schuster, Toro, 1804.00661

Beyond dark photon models

Scalars, axions, …many additional signatures



Conclusions & Outlook

- Fermilab will cover a very important role in the search for displaced dark sectors: the SeaQuest experiment

→ **obvious advantage: <u>existing experiment</u>**

Minimal dark photon & dark scalar;
Inelastic DM; axions; strongly-interacting DM
models can be broadly explored

Complementarity with other fixed target experiments

Additional models that SeaQuest can explore?
Particle physics case?
Larger luminosities? Upgrades?

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 $(\delta_{\eta,\xi} \ll m_D)$:

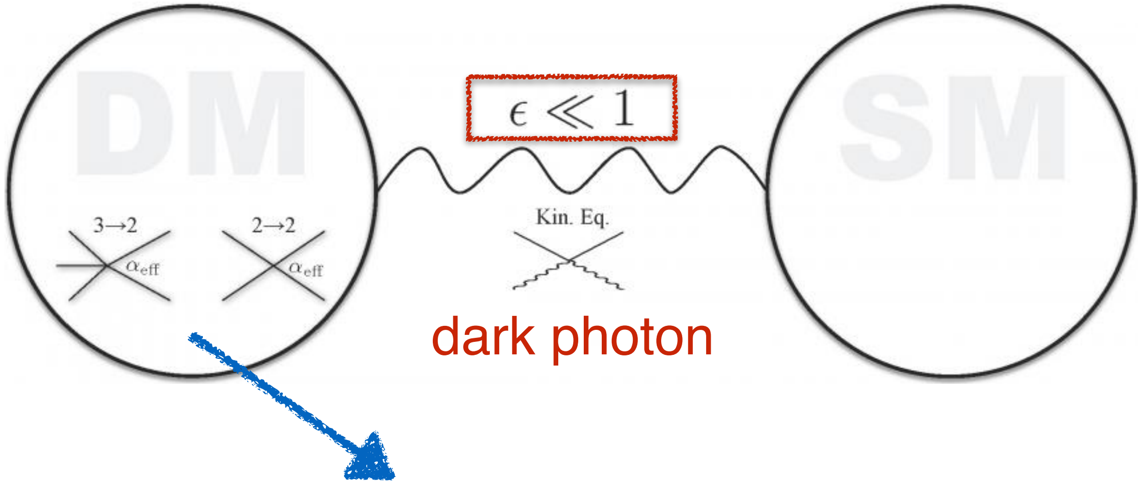
$$\mathcal{L} \supset \frac{e_D\,(\delta_\xi - \delta_\eta)}{\sqrt{4m_D^2 + (\delta_\xi - \delta_\eta)^2}}\, A'_\mu\, (\bar{\chi}_2\gamma^\mu\chi_2 - \bar{\chi}_1\gamma^\mu\chi_1)$$

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

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

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

3. Strongly interacting DM (SIMP)



Hochberg, Kuflik, Volansky, Wacker, 1402.5143,

Hochberg, Kuflik, Murayama, Volansky, Wacker, 1411.3727

A new scale for DM?

WIMP	SIMP
$2 \to 2$	$3 \to 2$
$m_{\rm DM} \sim \alpha_{\rm ann}(T_{\rm eq} M_{\rm pl})^{1/2} \sim \text{TeV}$	$m_{\rm DM} \sim \alpha_{\rm ann}(T_{\rm eq}^2 M_{\rm pl})^{1/3} \sim 100\ \text{MeV}$

Realized in eg. QCD-like theories

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

❖ DM candidates: U(1)$_D$ charged pions

❖ Cosmology depends heavily on the mass of the dark vectors (V_D)

- $3\pi_D \to 2\pi_D$ annihilation
- $\pi_D\pi_D \to V_D\pi_D$ semi-annihilation