LLPs at the Rare Processes Frontier

Stefania Gori
UC Santa Cruz

Searching for long-lived particles at the LHC and beyond:
11th workshop of the LLP Community

June 2, 2022

The Snowmass Rare Processes Frontier

https://snowmass21.org/rare/

Frontier conveners:

Name	Institution	email
Marina Artuso	Syracuse University	martuso[at]syr.edu
Bob Bernstein	Fermi National Accelerator Lab	rhbob[at]fnal.gov
Alexey A Petrov	Wayne State University	apetrov[at]wayne.edu

Topical conveners:

- RF1: Weak decays of b and c quarks (Angelo Di Canto/Stefan Meinel)
- RF2: Weak decays of strange and light quarks (Evgueni Goudzovski/Emilie Passemar)
- RF3: Fundamental Physics in Small Experiments (Tom Blum/Peter Winter)
- RF4: Baryon and Lepton Number Violating Processes (Pavel Fileviez Perez/Andrea Pocar)
- RF5: Charged Lepton Flavor Violation (electrons, muons and taus) (Bertrand Echenard/Sacha Davidson)
- RF6: Dark Sector Studies at High Intensities (Mike Williams/Stefania Gori)
- RF7: Hadron Spectroscopy (Tomasz Skwarnicki/Richard Lebed)

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Overview of RF6
“Dark sectors at high intensities”

RF6: dark sectors at high intensities

Conveners: Stefania Gori (sgori@ucsc.edu), Mike Williams (mwill@mit.edu)

- mailing list (SNOWMASS-RPF-06-DARK-SECTOR@fnal.gov)
- SLACK channel (#rpf-06-dark-sector)
- webpage: https://snowmass21.org/rare/dark

Key questions:

- Why are dark sectors a compelling opportunity for the next decade?
- What are the needed theoretical developments to guarantee a broad exploration of the dark sector?
- Which set of benchmark models comprehensively covers the interesting signatures we can look for?
- How will experiments confront the dark sector landscape? (RF6 involves experiments from small to large, both dedicated and multi-purpose).

Goal: to achieve a broad theoretical and experimental exploration of the physics of dark sectors at or below the GeV scale.

RF6 “Big ideas” solicited papers

- Organization around science goals/questions.
- Arrange the breadth of RF6 science so that all the main techniques have a chance to shine.
- Span ≳95% of white-paper interests

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1. Detect dark matter particle production (production reaction or through subsequent DM scattering), with a focus on exploring sensitivity to thermal DM interaction strengths.
Editors: Gordan Krnjaic, Natalia Toro

2. Explore the structure of the dark sector by producing and detecting unstable dark particles: Minimal Portal Interactions.
Editors: Brian Batell, Chris Hearty

3. New Flavors and Rich Structures in Dark Sectors.
Editors: Phil Harris, Philip Schuster, Jure Zupan

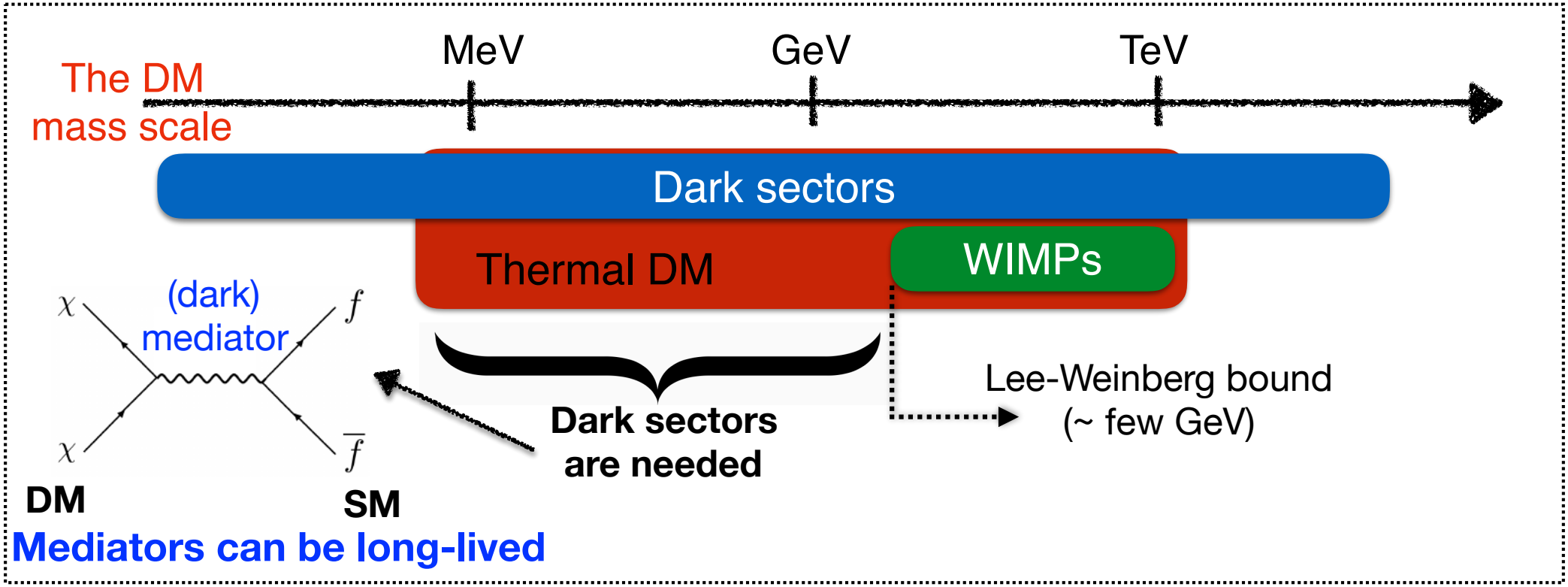
4. Experiments/facilities
Editors: Phil Ilten, Nhan Tran

Each big idea white paper contains the discussion of models with LLP particles

More details: https://docs.google.com/document/d/1R0O23wjGLxRzsc93a4pJlFn17yW9TCTq
(in our google drive folder, https://drive.google.com/drive/folders/1sMn1cWl2ddqzu46Yi4TcMIX7Cm2GUxO)

Motivations for a dark sector

(especially with LLPs)



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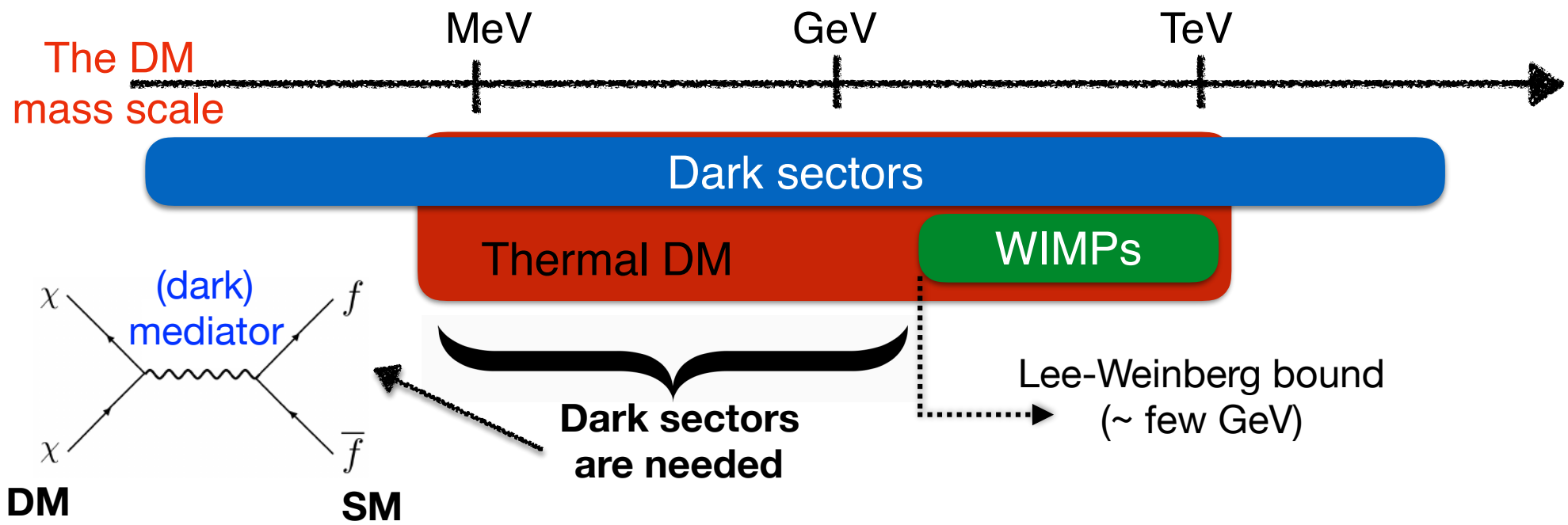


Mediators can be long-lived

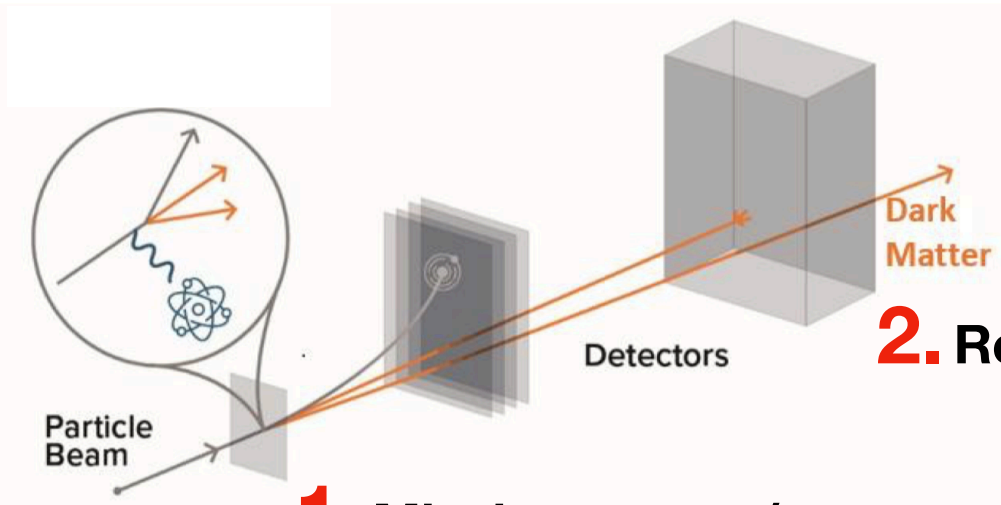
Extended DM models with **long-lived excited DM states**

Several anomalies in data can be addressed by **long-lived dark sector particles** (eg. $(g\text{-}2)_\mu$);

Many other motivations: neutrino mass model building, baryon-antibaryon asymmetry problem, strong CP problem, …

Search techniques for dark sectors at high intensities

Production of dark matter



2. Re-scattering

1. Missing energy/ momentum

Several experiments, but the experimental techniques are only 3

Basic Research Needs for
DM Small projects New Initiatives (DMNI),
2018

https://science.osti.gov/-/media/hep/pdf/Reports/Dark_Matter_New_Initiatives_rpt.pdf

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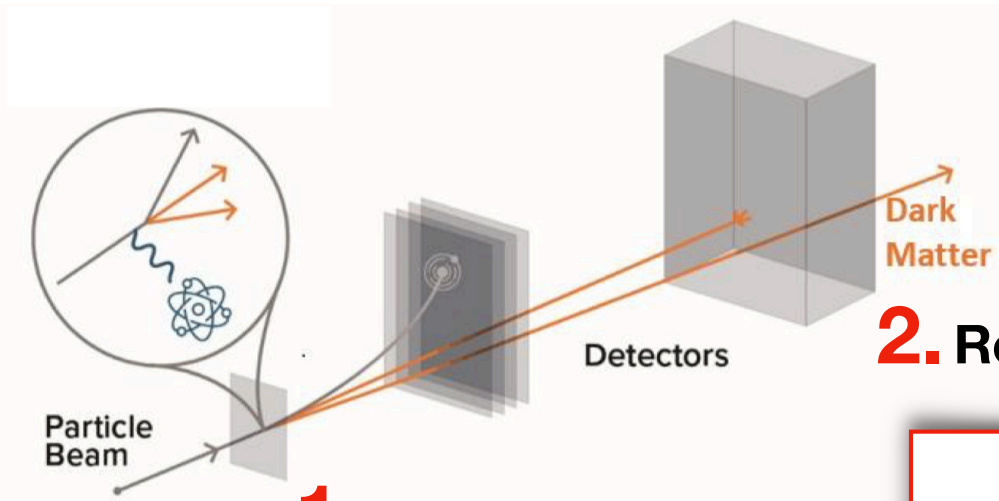

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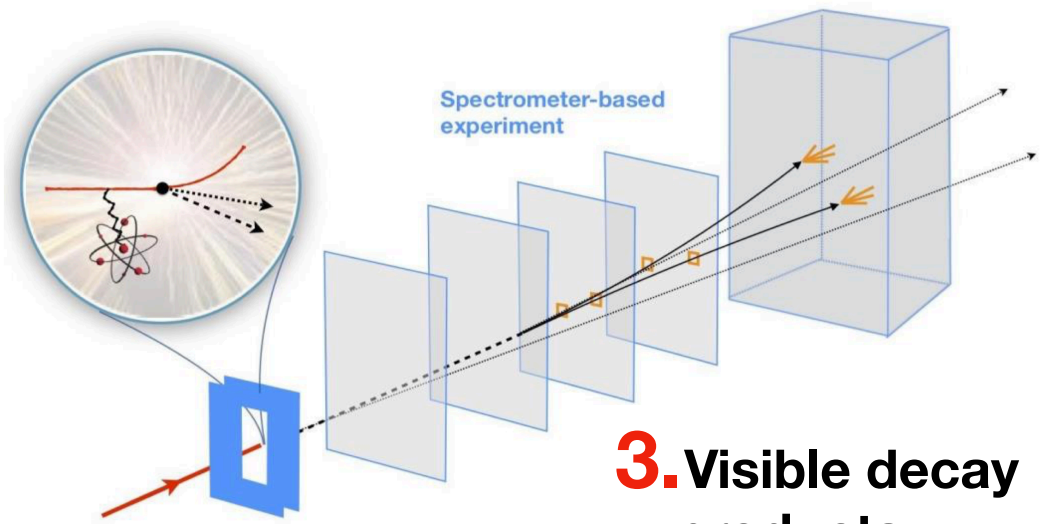
Production of unstable dark sector particles



3. Visible decay products

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Search techniques for dark sectors at high intensities

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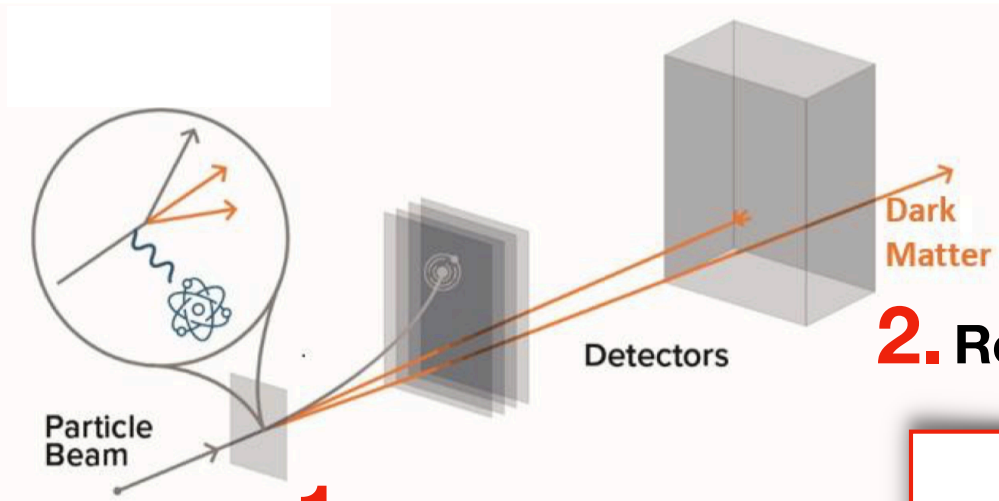

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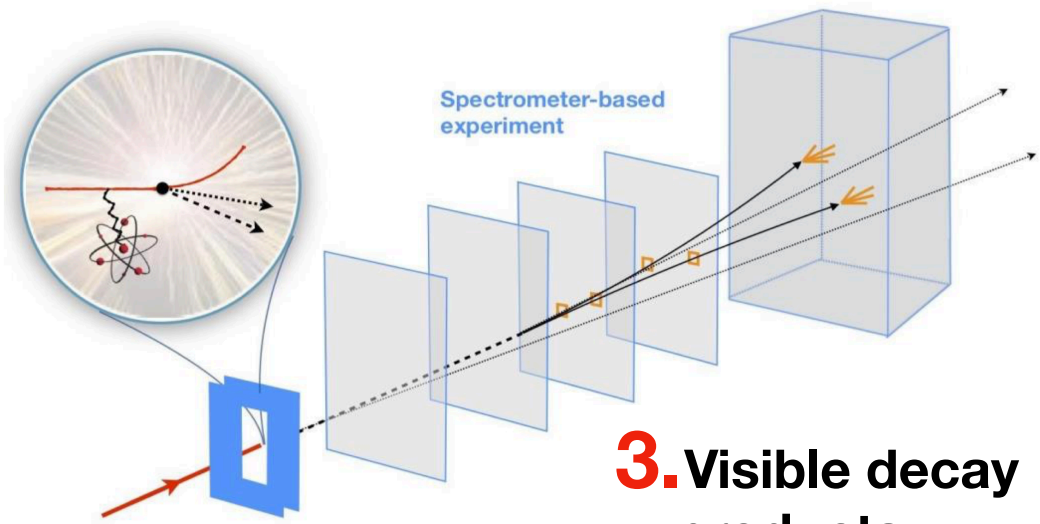
Let's focus on this

Production of unstable dark sector particles



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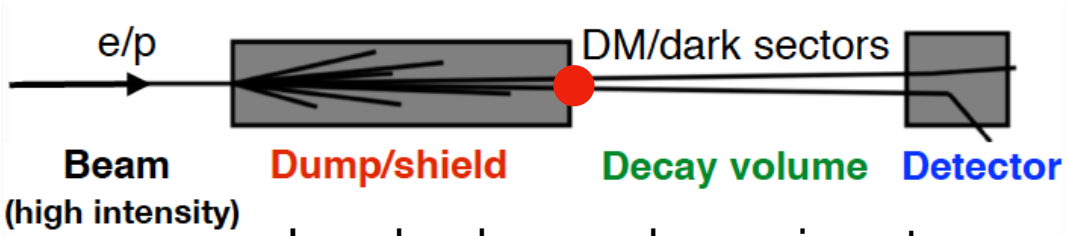
https://science.osti.gov/-/media/hep/pdf/Reports/Dark_Matter_New_Initiatives_rpt.pdf

High-intensity experiments for LLPs

Beam-dump experiments



Low background experiments
(depending on the size of the dump)

Production of an unstable dark sector particle in the dump and detection of its SM decay products in forward detectors.

Detection strategy

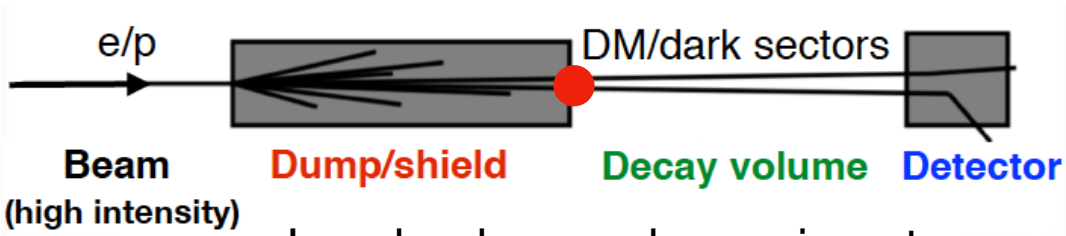
p beam for the SeaQuest/DarkQuest experiment at Fermilab
p beam for the NA62, KLEVER experiments at CERN
e- beam for the HPS experiment at JLAB
e- beam for the DarkLight experiment at TRIUMF

Running experiments

Future experiments

High-intensity experiments for LLPs

Beam-dump experiments



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Running experiments

Future experiments

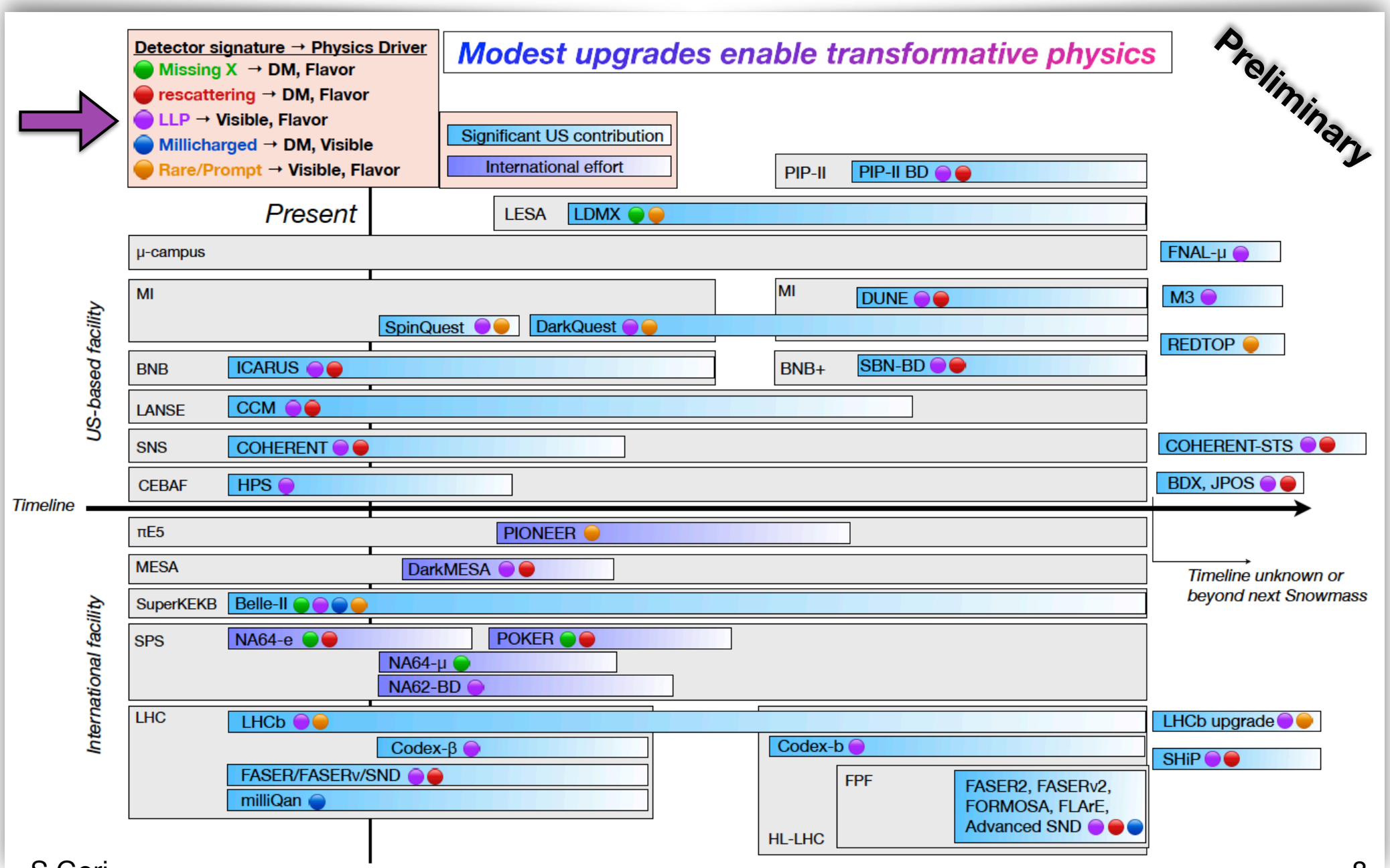
Flavor factories

B-factories: LHCb, Belle II
Kaon factories: NA62, KOTO
Pion factories: PIONEER

Production of an unstable dark sector particle from meson decays and detection of its SM decay products

Detection strategy

From the experiments/facilities white paper…

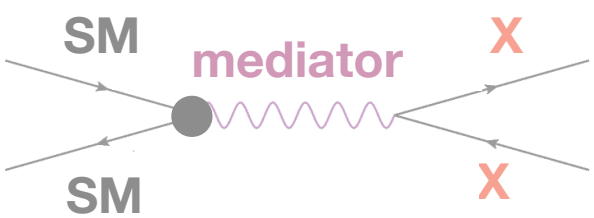


Final states to look for

a. Invisible, non-SM

Dark Matter production

Producing stable particles that could be (all or part of) Dark Matter

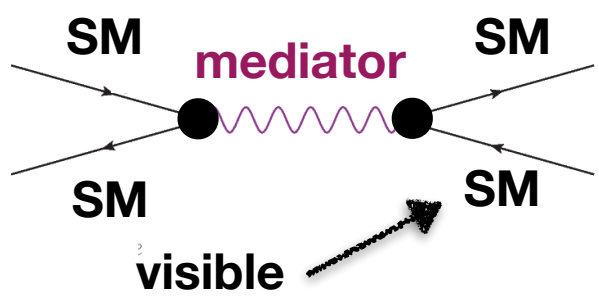


1. Missing energy/ momentum
2. Scattering

b. Visible, SM

Production of portal-mediators that decay to SM particles

Systematically exploring the portal coupling to SM particles

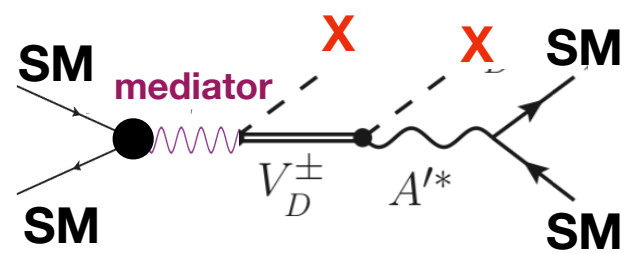


3. Visible decay products

c. Mixed visible-invisible

Production of "rich" dark sectors

Testing the structure of the dark sector



1. Missing energy/ momentum
2. Scattering
3. Visible decay products

A few example benchmarks
that we discuss in our RF6 report:

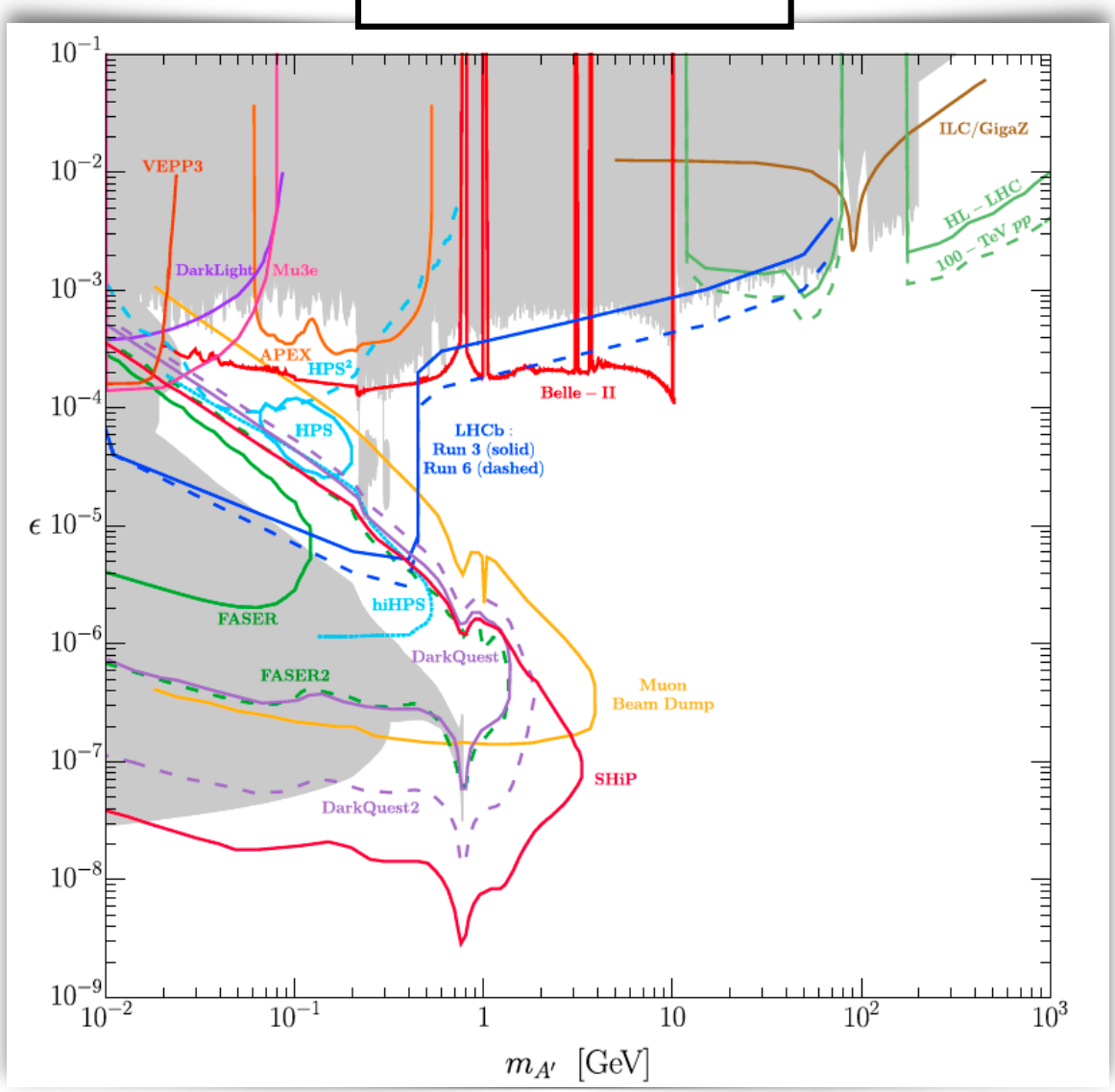
1. long-lived mediators (big idea 2)
2. long-lived particles in $(g - 2)_\mu$ motivated models (big idea 3)
3. SIMP and IDM models with long-lived DM excited states (big idea 3)

1. Long-lived mediators (dark photon)

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

$$A' \to \text{visible}$$

energy frontier



Preliminary

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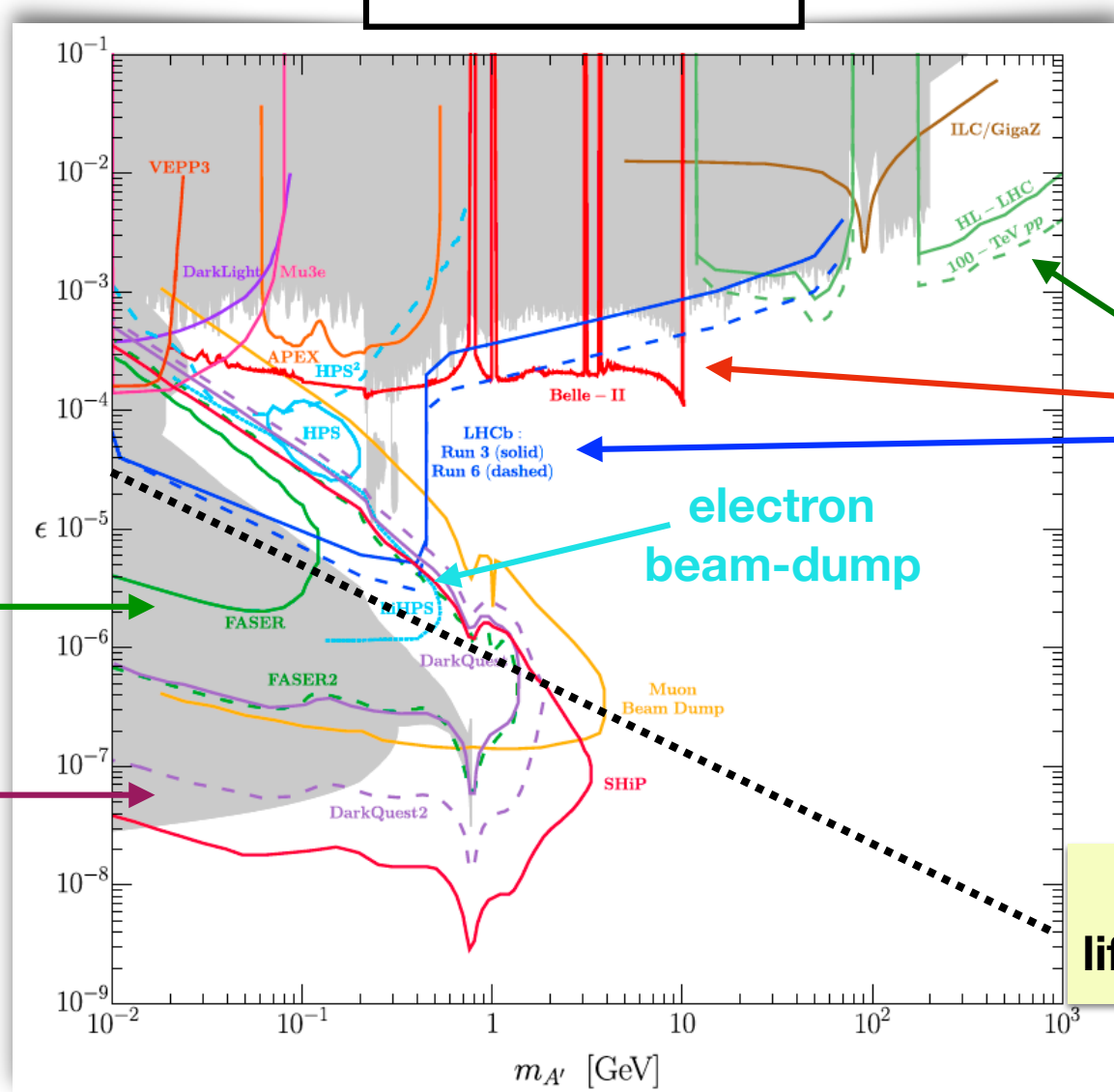


Colliders

electron beam-dump

forward detectors

proton beam-dump

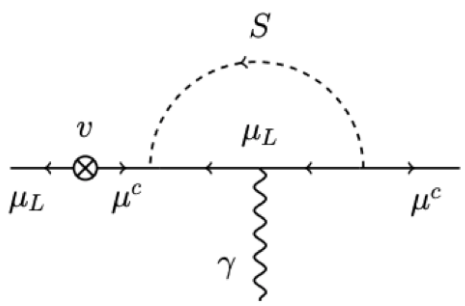
roughly:
life time ~ cm

Preliminary

2. LLPs in $(g-2)_\mu$ motivated models

"Flavor-specific" dark sectors

$$\mathcal{L} = -g_S\, S\, \overline{\mu}\mu$$



- S decays to muons if $m_S > 2\, m_\mu$
- S decays to photons if $m_S < 2\, m_\mu$

(loop suppressed → eventually displaced)

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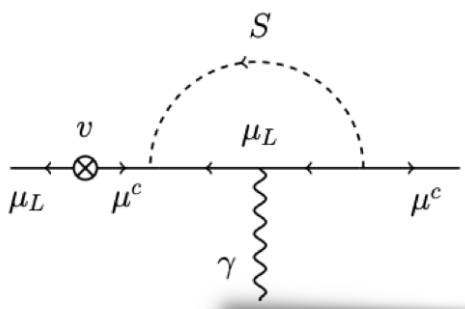

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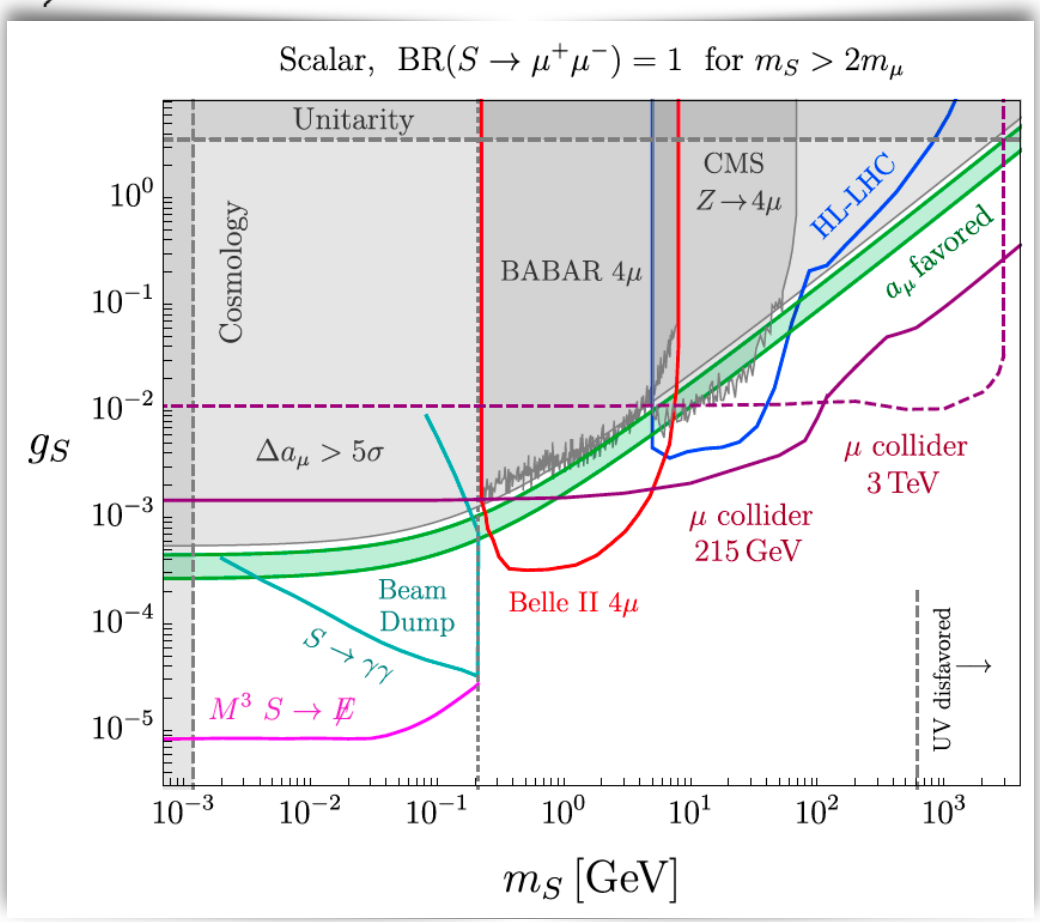

Capdevilla, Curtin, Kahn, Krnjaic, 2112.08377

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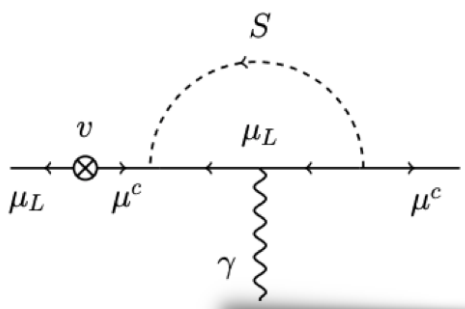

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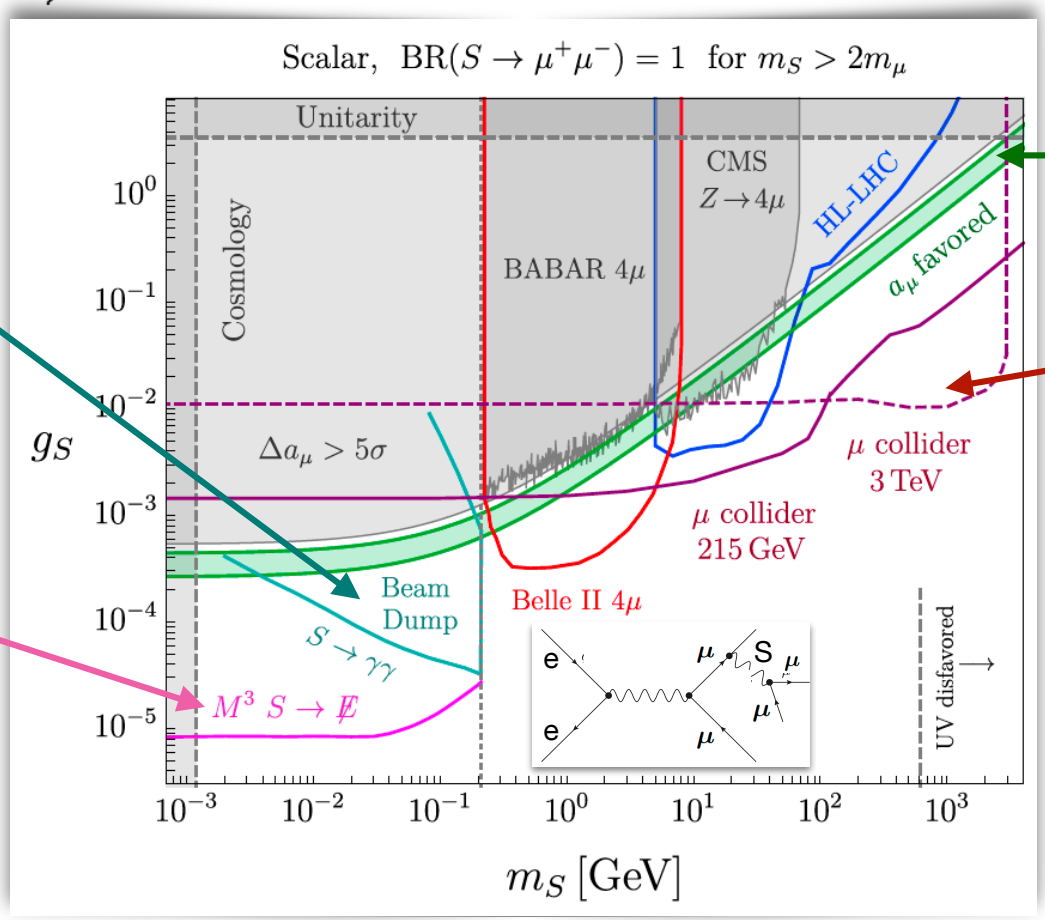
muon beam-dump
Chen, et al, 1701.07437

muon missing momentum
Kahn, Krnjaic, Tran, Whitbeck, 1804.03144



$(g-2)_\mu$ favored region

high energy muon colliders

Capdevilla, Curtin, Kahn, Krnjaic, 2112.08377

3. SIMP models for DM

SIMPs: strongly interacting massive particles. Realized in a QCD-like theory SU(N_c):

$SU(N_f) \times SU(N_f) \to SU(N_f)$ Light dark pions (some of them can be DM)

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

Relic abundance:	$3 \to 2$ annihilation

Right relic abundance if m_{DM} ~ O(100 MeV)!

Hochberg, Kuflik, Volansky, Wacker, 1402.5143

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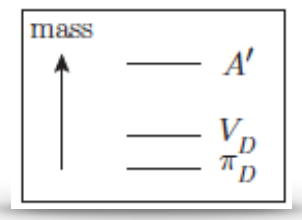
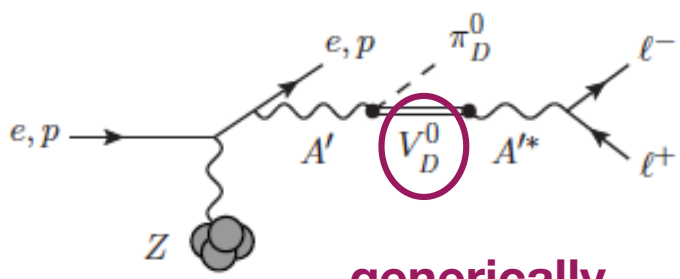
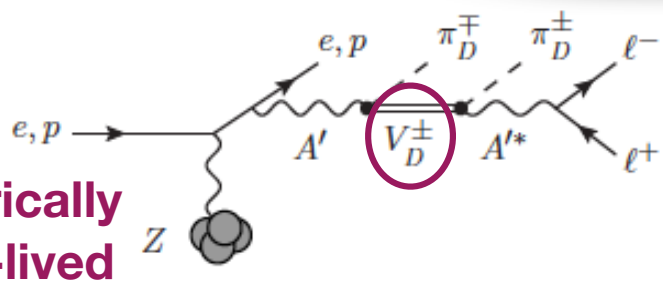




generically long-lived

$A' \to V_D\pi_D,\ V_D \to A'^* \to e^+e^-$



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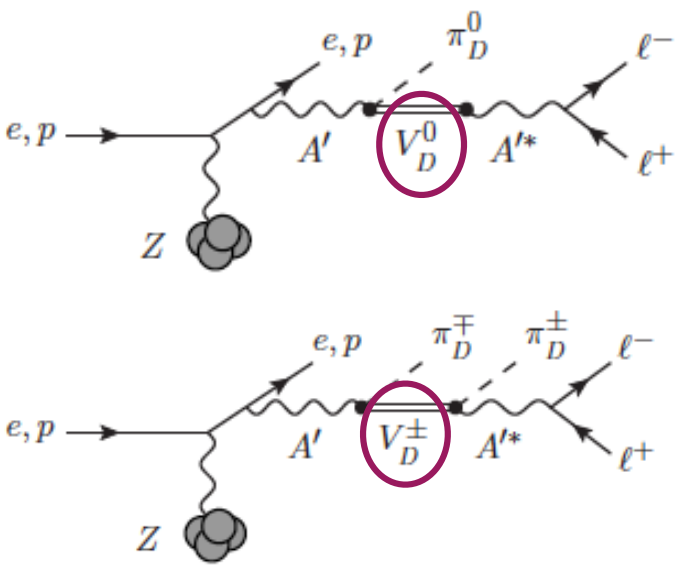
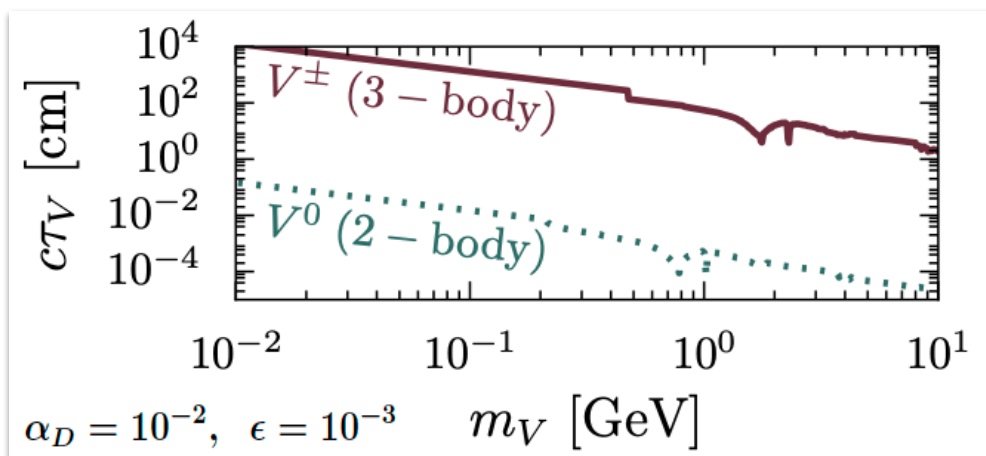
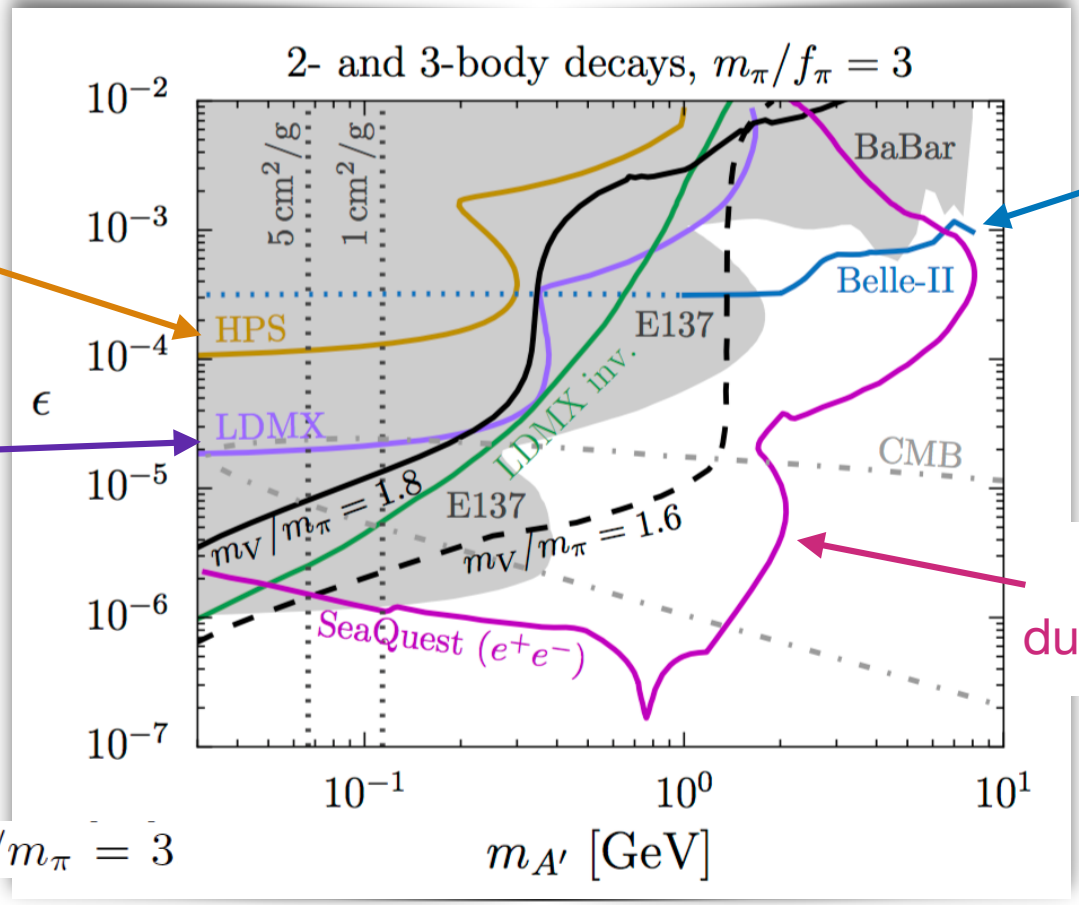


Berlin, Blinov, SG, Schuster, Toro, 1801.05805



3. Searching for SIMPs

Berlin, Blinov, SG, Schuster, Toro, 1801.05805

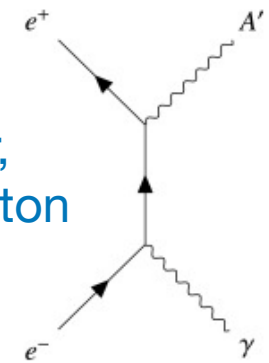


$\alpha_D = 10^{-2}$, $m_{A'}/m_\pi = 3$

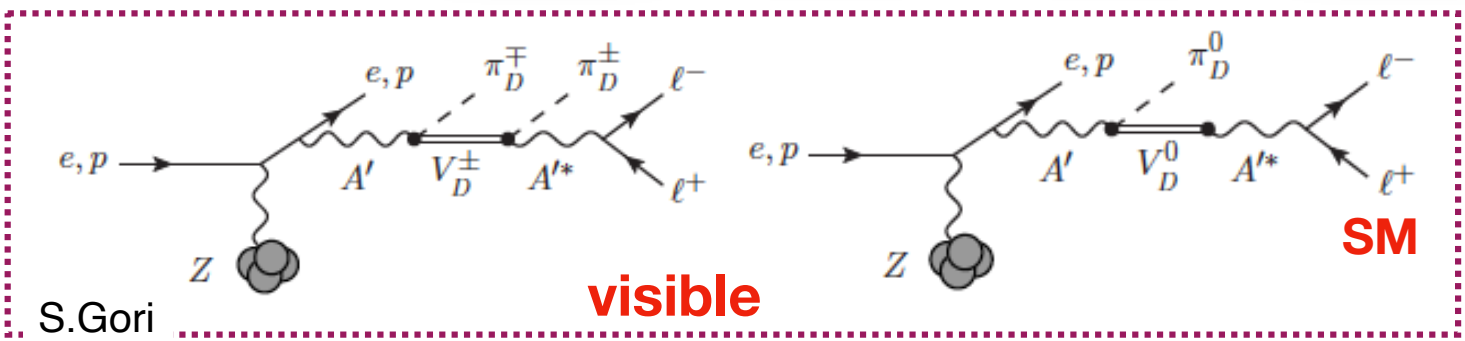
e-beam dump (visible)

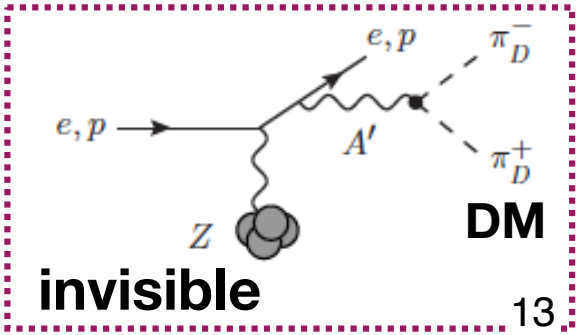
missing momentum

Collider, mono-photon



p-beam dump (visible)





3. IDM models for DM

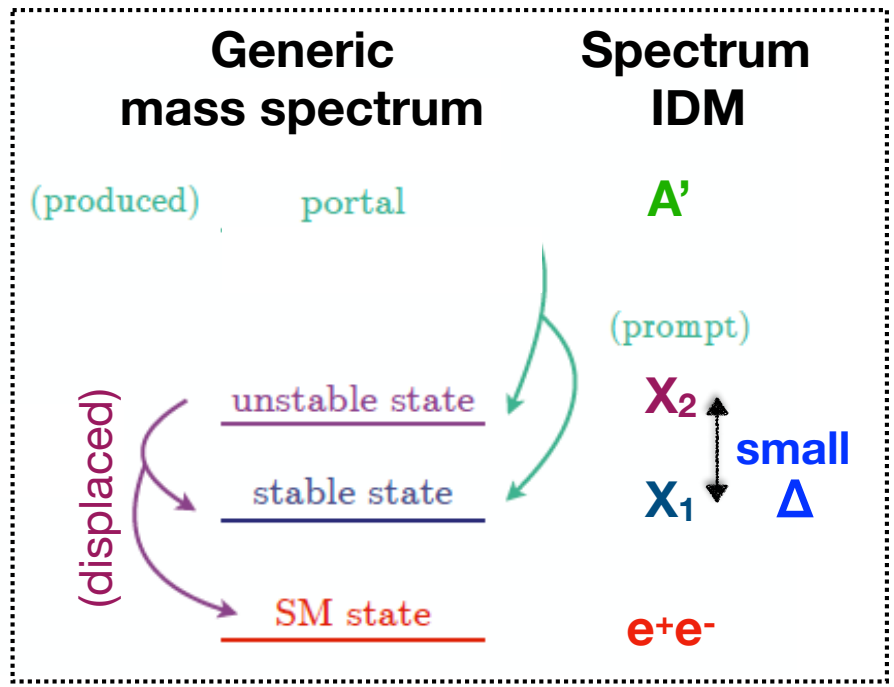
Inelastic Dark Matter (IDM) models:

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

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

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

* Freeze-out: X_1 X_2 → SM



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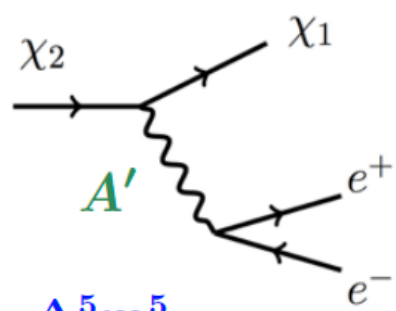
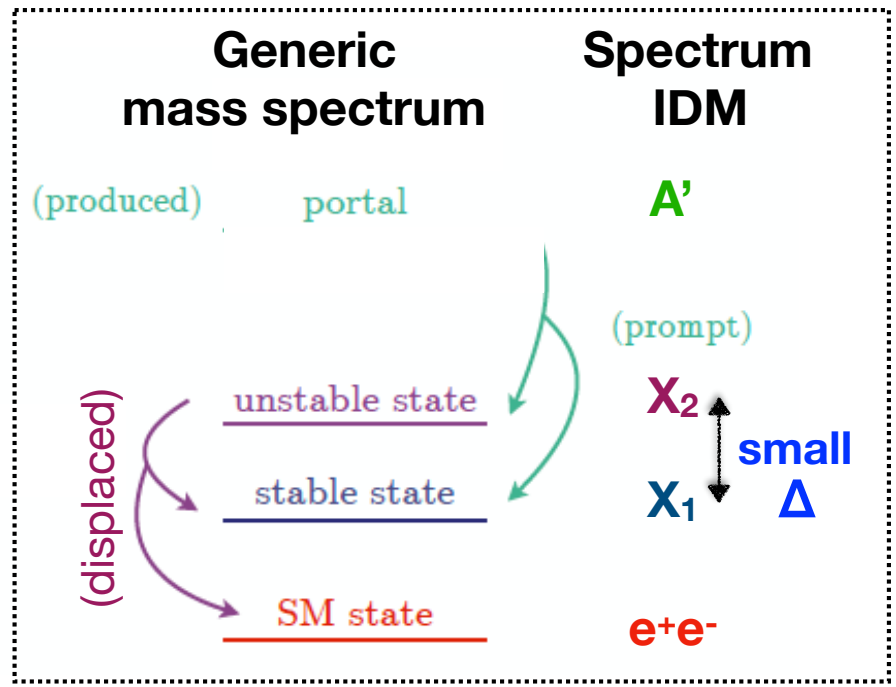


* Signatures in our labs:

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

generically displaced

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



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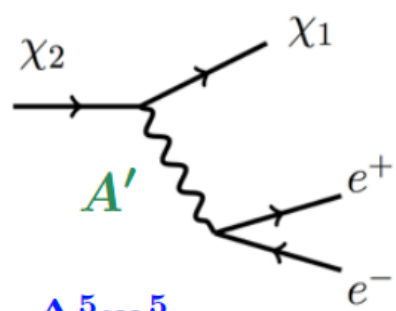
$$-\mathcal{L} \supset m_D\,\eta\,\xi + \frac{1}{2}\,\delta_\eta\,\eta^2 + \frac{1}{2}\,\delta_\xi\,\xi^2 + \text{h.c.}$$

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

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

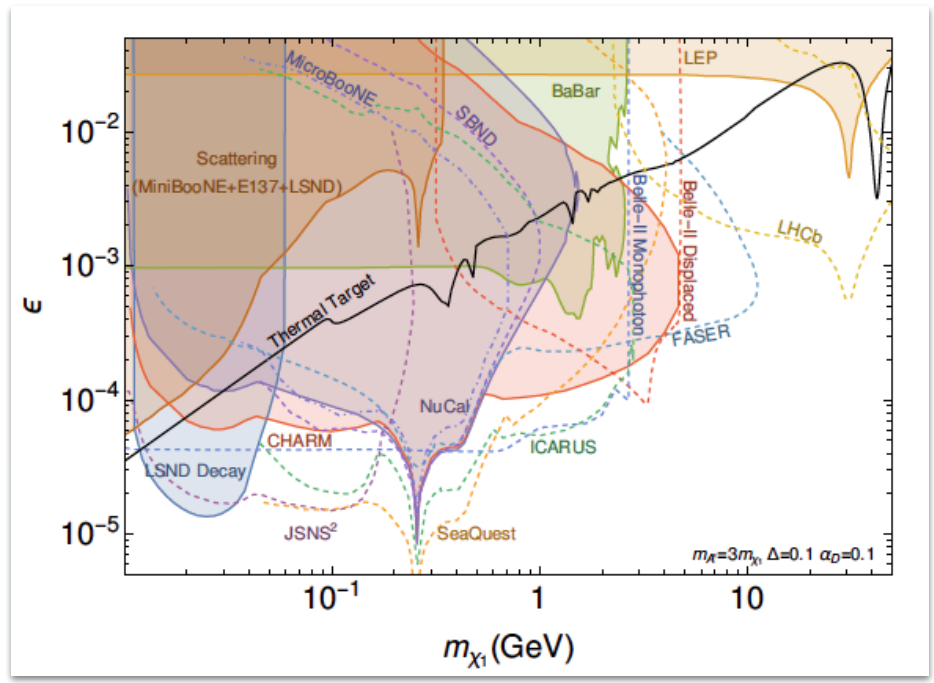
* Freeze-out: X_1 X_2 → SM

* Signatures 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



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

Conclusions & Outlook

Dark sector particles naturally appear in many well-motivated extensions of the Standard Model.

High-intensity experiments based on 3 different techniques:
- missing energy/momentum
- re-scattering
- searches for visible decay products

will offer an **unprecedented opportunity to test dark sectors at or below the GeV scale**

Snow mass

RF6

Full exploration of many LLP benchmarks is expected in the coming few years (beam dump experiments, flavor factories).

Crucial complementarity with
- high energy colliders
- neutrino experiments
- auxiliary detectors at colliders