Dark sector searches at fixed-target experiments

Nhan Tran, Fermilab

Light Dark World International Forum 2021

December 14, 2021

Outline

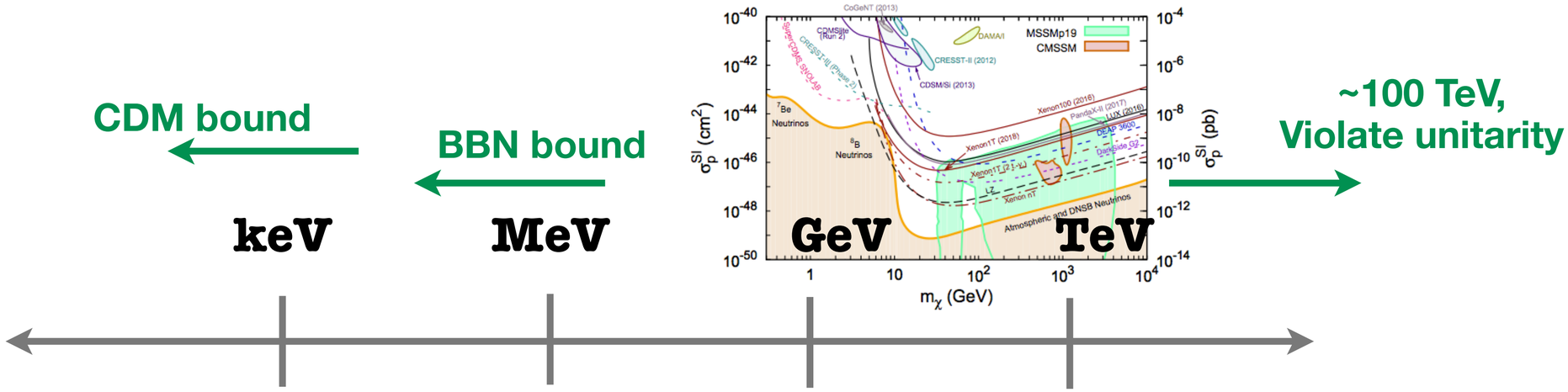
- Opportunities for dark matter below ~GeV at accelerators
  - Complementarity between direct detection and accelerators

- Towards a taxonomy of the accelerator dark matter search landscape
  - Pick one from every category
  - Selected examples

- Discussion - guiding principles for systematic prioritizing and coverage

See also talks from Luigi Corona, Doojin Kim!

Thermal, but not WIMP



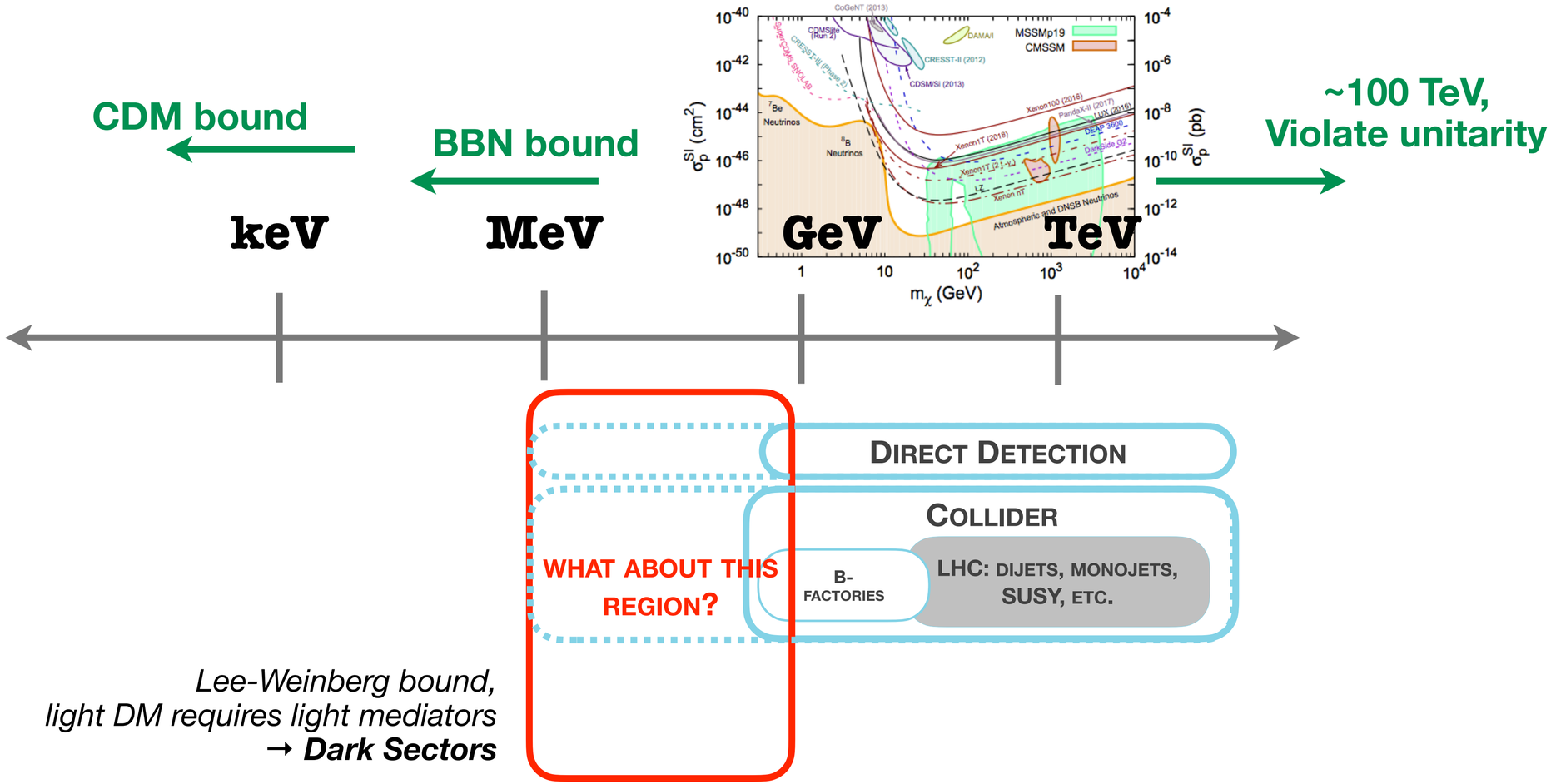
DIRECT DETECTION

COLLIDER

B-FACTORIES

LHC: DIJETS, MONOJETS, SUSY, ETC.

Thermal, but not WIMP



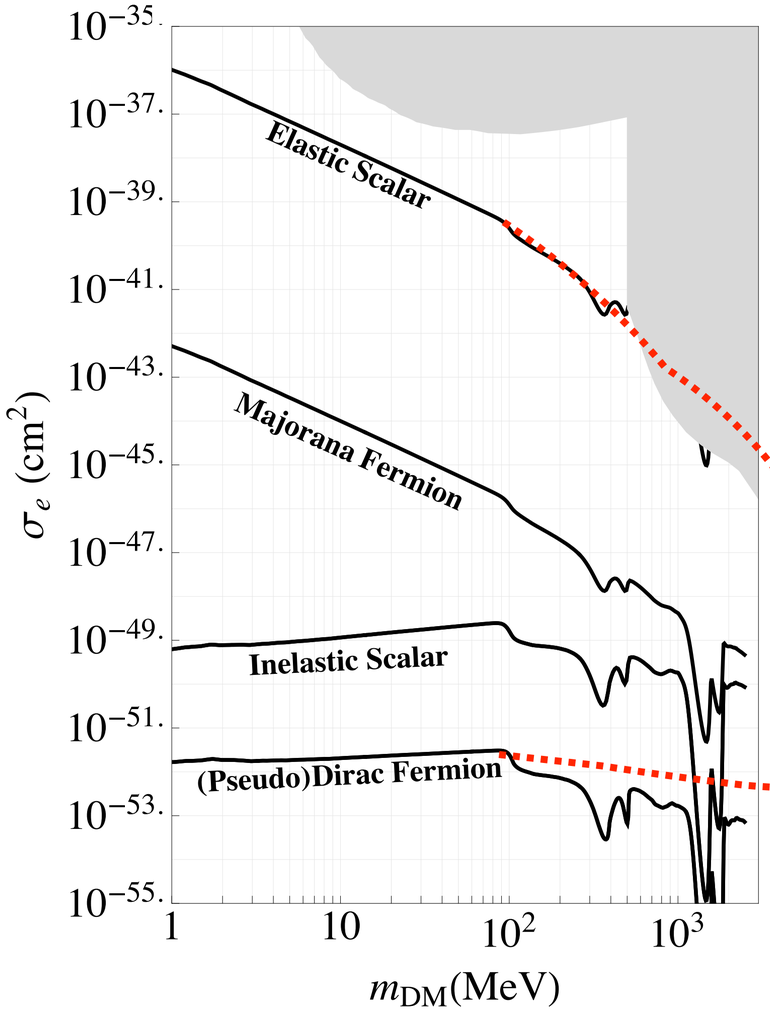
Lee-Weinberg bound,
light DM requires light mediators
*→ **Dark Sectors***

NORMAL MATTER LIVES HERE. WHY NOT DM?

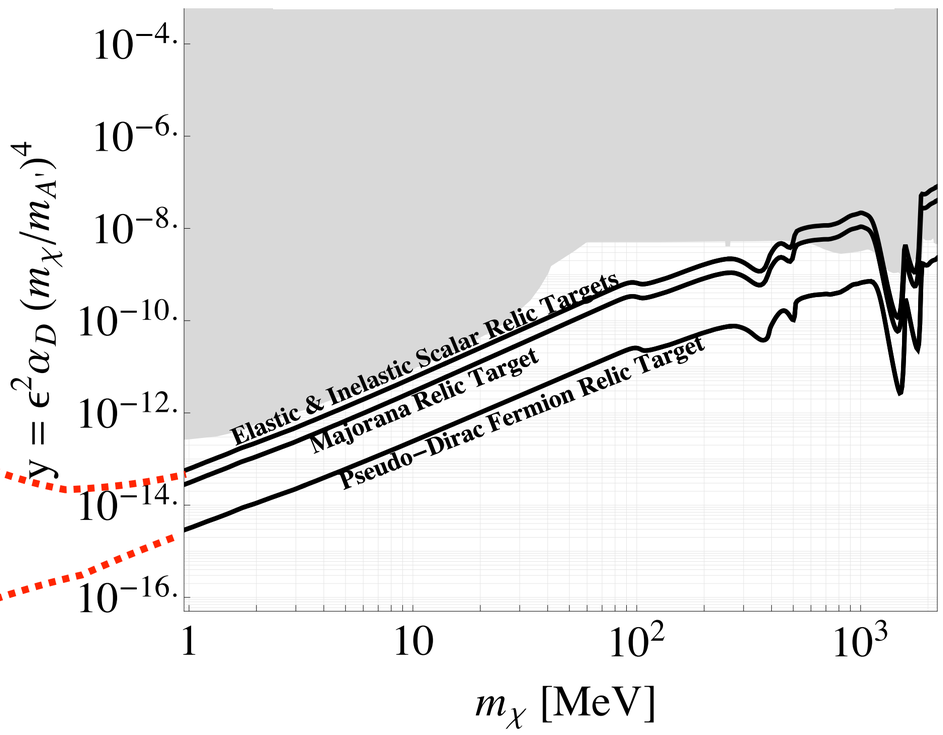
+ Curious results…
muon g-2, proton radius puzzle, KTEV excess, astrophysical inconsistencies

Why accelerators?

Direct Detection Milestones



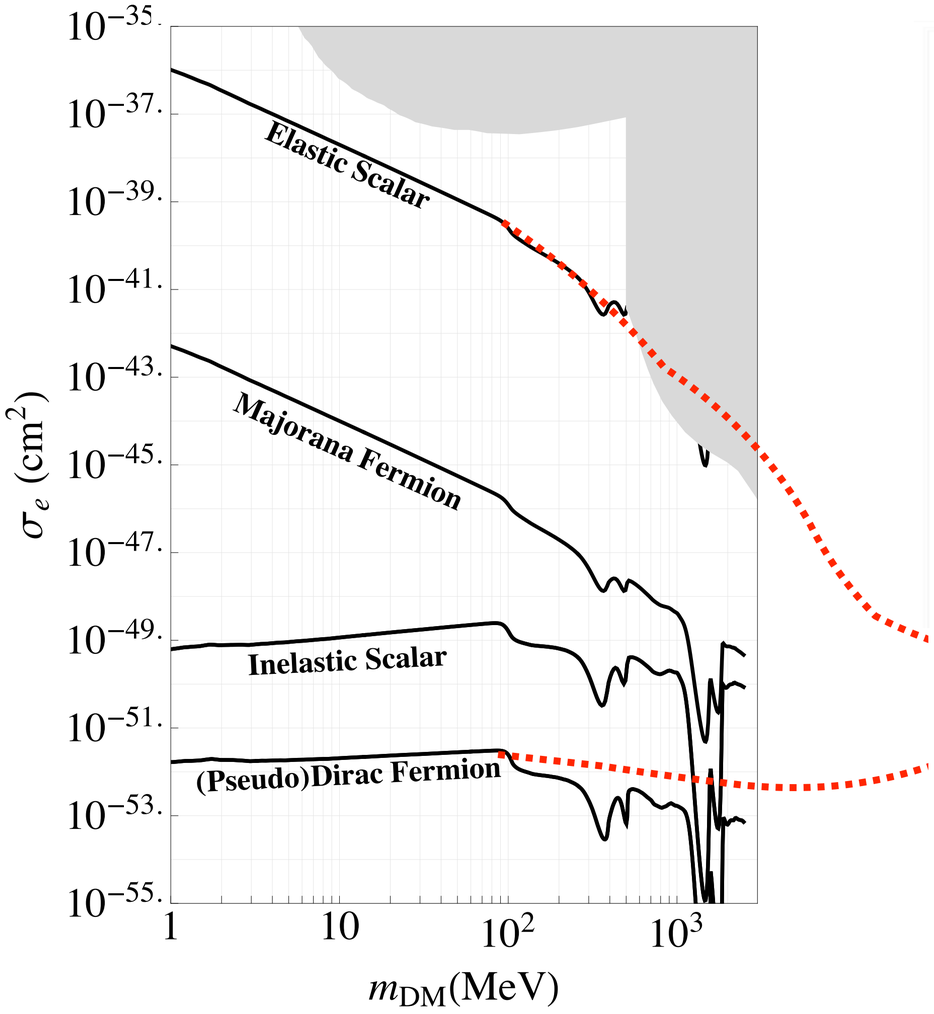
Accelerator milestones

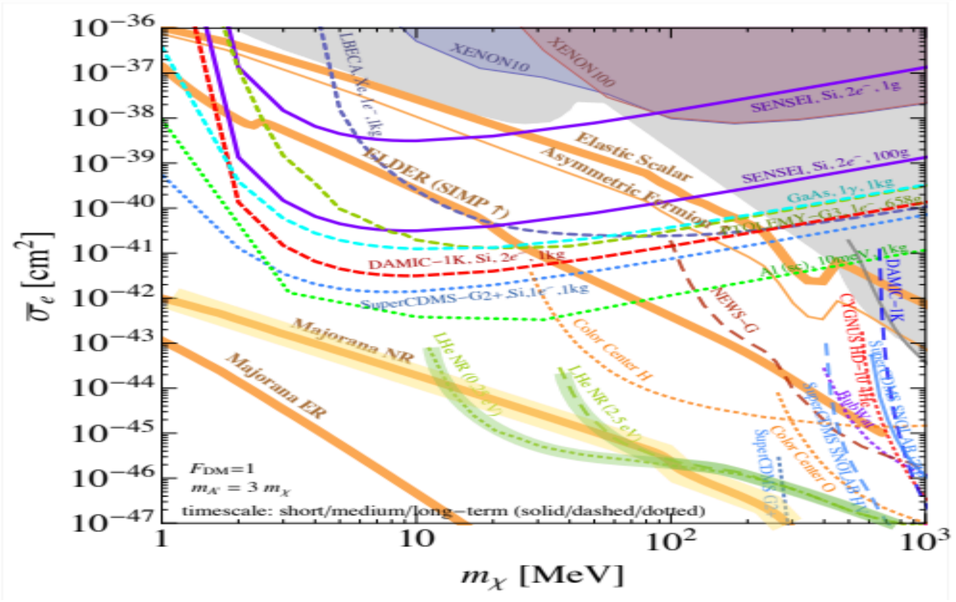


Relativistic production of dark sectors is less sensitive to loop- or velocity-suppression

Why accelerators?

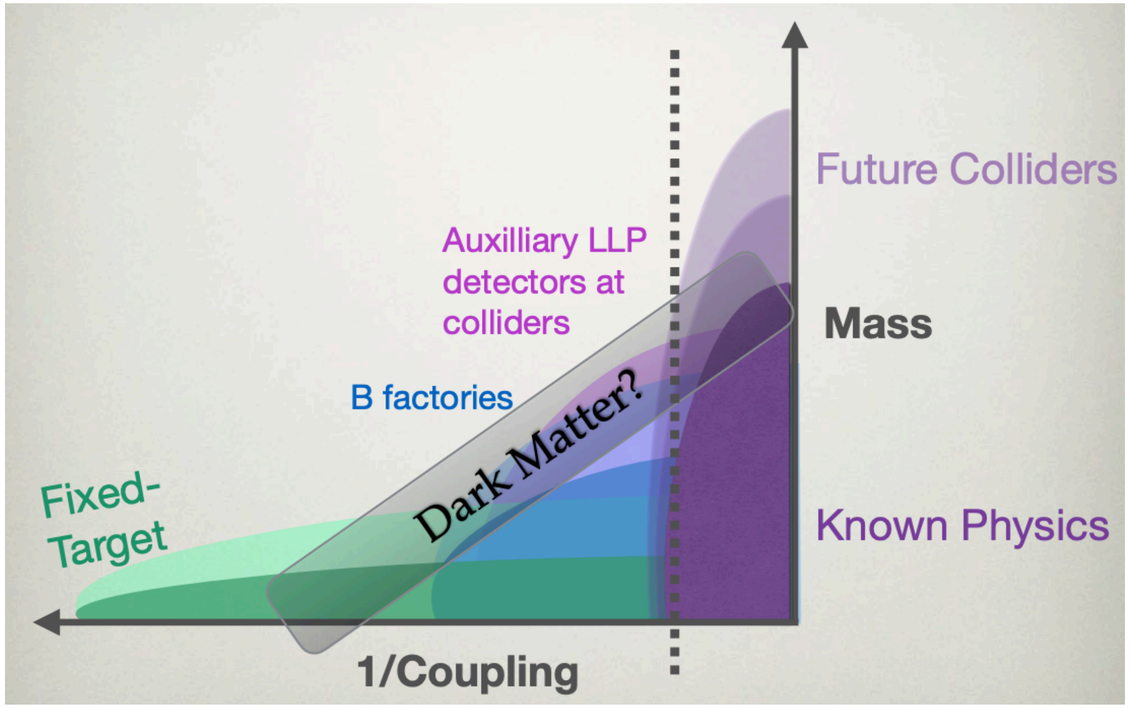
Direct Detection Milestones



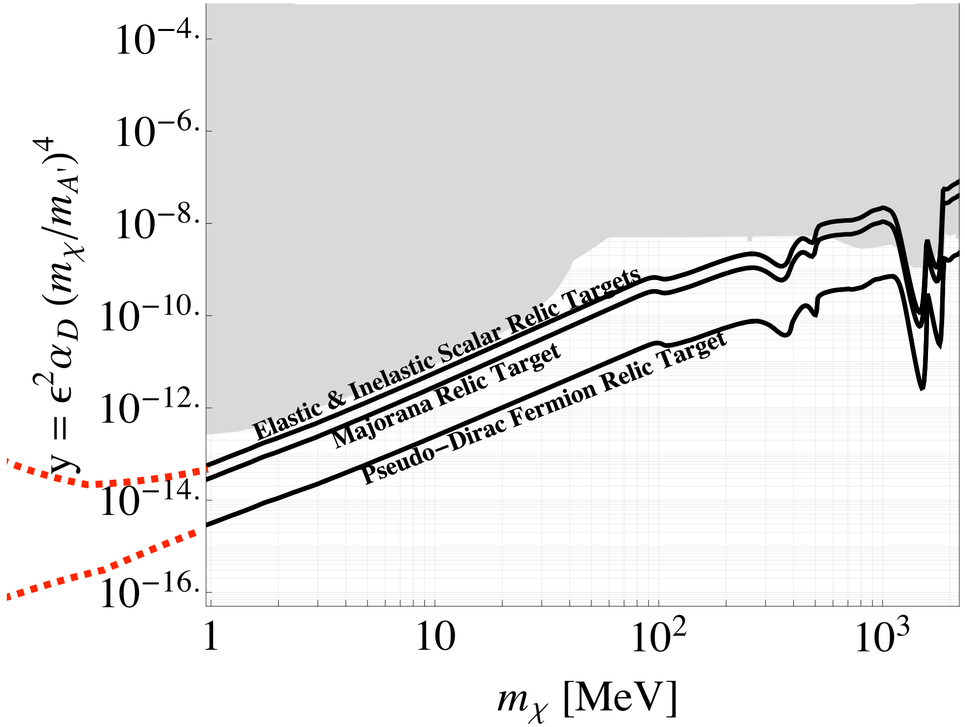


Why accelerators?

Natalia Toro

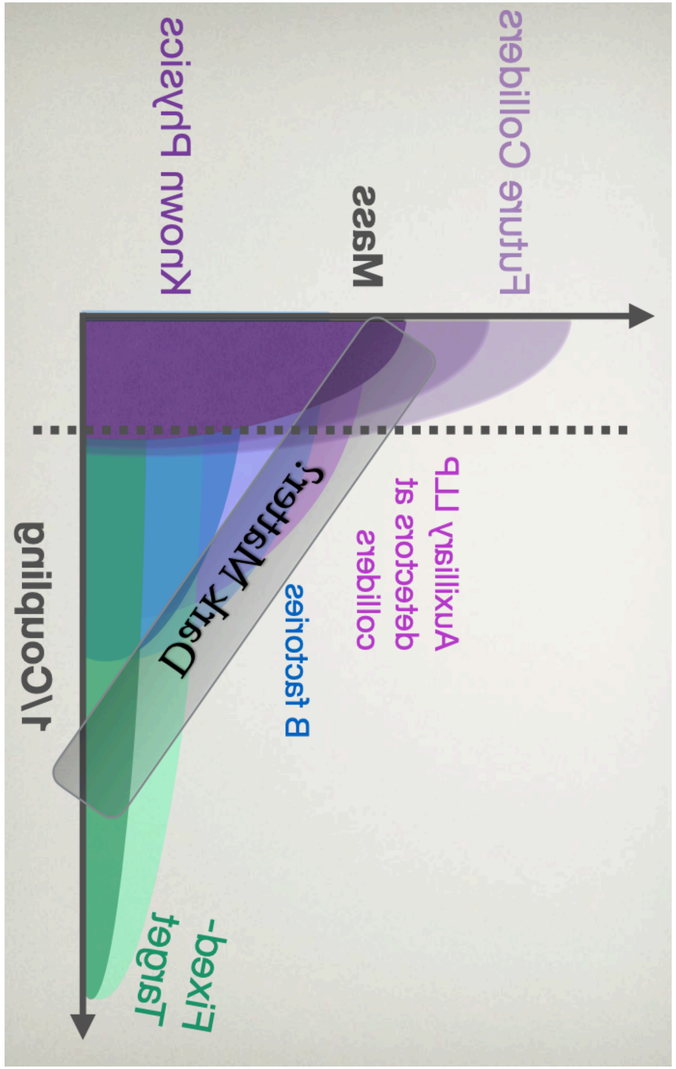


Accelerator milestones



Lighter DM
↓
Smaller cross section
↓
Freezes out earlier
↓
Larger number density

Why accelerators?



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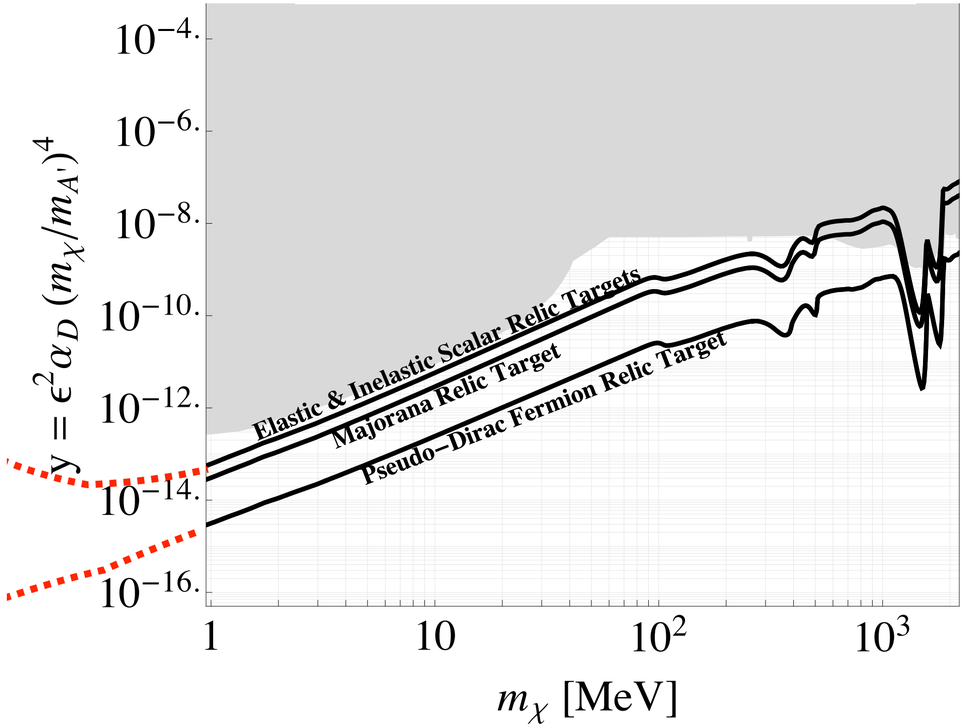

Lighter DM

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Smaller cross section

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Freezes out earlier

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Larger number density

Accelerators & Complementarity

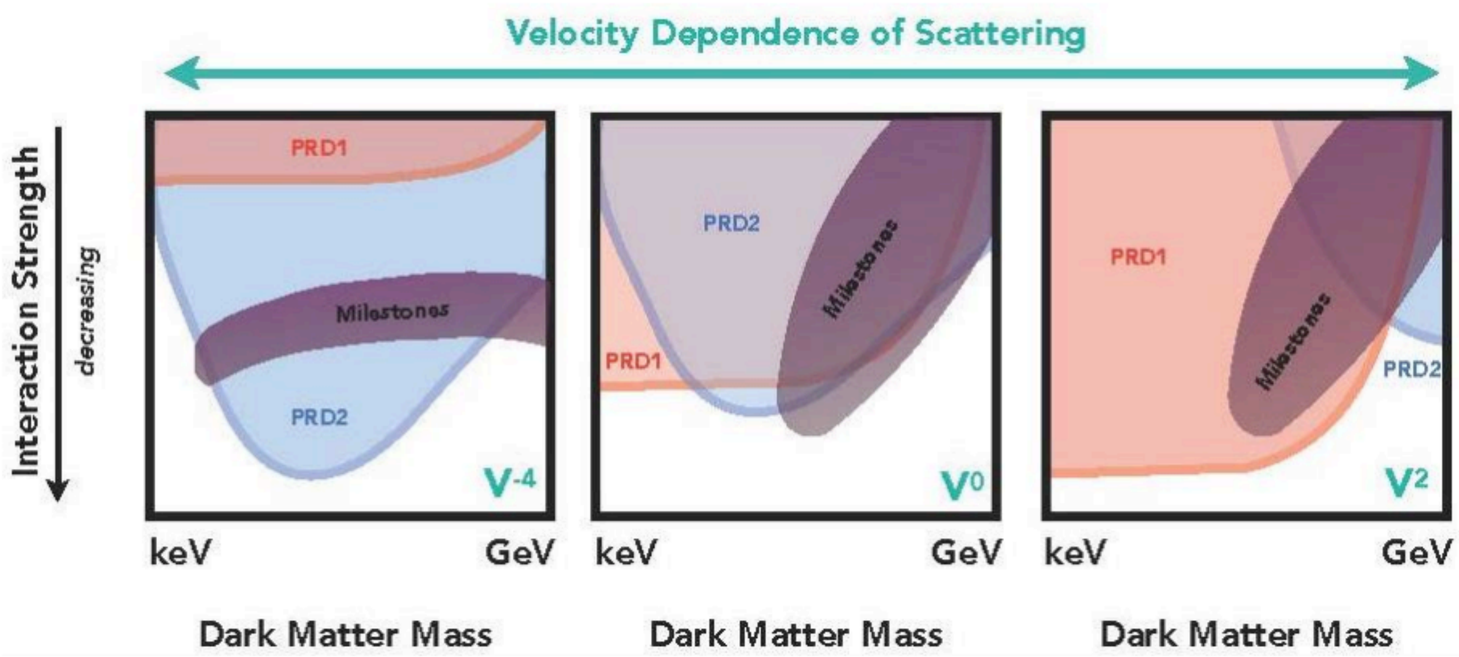
Dark Matter New Initiatives report

Thermal relic sub-GeV dark matter compelling

Accelerators important complementarity with direct detection

New opportunities for small scale experiments

PRD1 = accelerators
PRD2 = direct detection



Towards a (lightning fast) taxonomy of the accelerator dark matter search landscape

Disclaimer: I will describe things schematically and give a few examples, this is a very rich and highly complementary area!

Snowmass and dark sectors

Welcome
Speaker: Mike Williams (MIT)

RF6 overview
Speaker: Stefania Gori (UC Santa Cruz)
RF6RareKickoffOve...

Theory session, introduction
Speakers: Brian Batell (University of Pittsburgh), Philip Schuster (SLAC
Snowmass-RF6-the...

Dark Matter Production at High Intensities
Speaker: Gordan Krnjaic (Fermilab)
RF6-Kickoff-DM-Pro...

Portal Production at High Intensities
Speaker: Adam Ritz (University of Victoria)
Snowmass_RF6_po...

Rich Dark Sectors at High Intensities
Speaker: Asher Berlin (SLAC)
SnowmassRF6_Berl...

Dark sectors at e+e- colliders
Speaker: Christopher Hearty (U. British Columbia / IPP)
RF6 kickoff epem c...

Dark sectors at the LHC and heavy ions
Speaker: Jacob Salfeld-Nebgen (Princeton Uni)
RF6DarkSector_jSal...

LLPs at CODEX-b, FASER, MATHUSLA
Speaker: Dean Robinson (lbl)
llp_rf6.pdf

Millicharged particles
Speaker: Matthew Citron (Univ. of California Santa Barbara (US))
exoticCharge_MC_S...

Facilities for dark sectors
Speaker: Mike Lamont (CERN)
DS-facilities-RF6-kic...

Dark sectors at PIENU
Speaker: Shintaro ito (Okayama University)
DarkSector_Shintar...

Dark sectors at neutrino experiments
Speaker: Brian Batell (University of Pittsburgh)
RF6-neutrino-experi...

Sterile Sector Searches at Neutron Facilities
Speaker: Joshua Barrow (The University of Tennessee)
Sterile Sector Searc...

Dark sectors at Kaon experiments
Speaker: Diego Redigolo (CERN)
snowmass_talkRedi...

Dark sectors from eta decays
Speaker: Sean Tulin (U Michigan)
Snowmass_tulin_20...

Visible and Invisible Dark Sectors with Electron Beams
Speaker: Tim Nelson (SLAC)
RF6_overview_TKN....

Dark Sectors with Electron Beam Dumps and Positron Beams
Speaker: Marco Battaglieri (INFN-GE)
battaglieri-SnowM-...

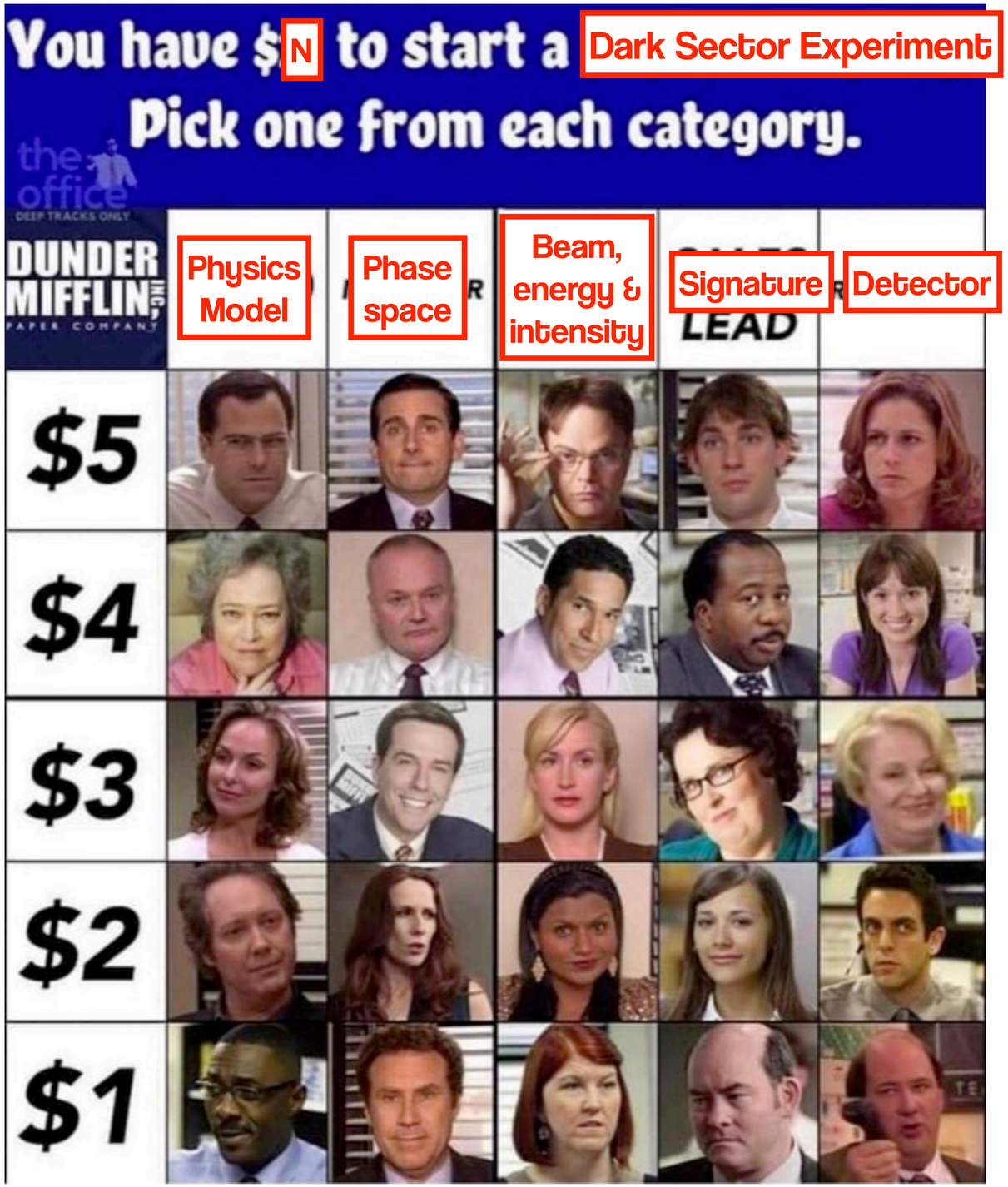
Dark sectors in muon and proton beams
Speaker: Nhan Tran (FNAL)
rf6-ntran.pdf

RF6 kickoff, https://indico.fnal.gov/event/44819/

Sometimes it feels like this...

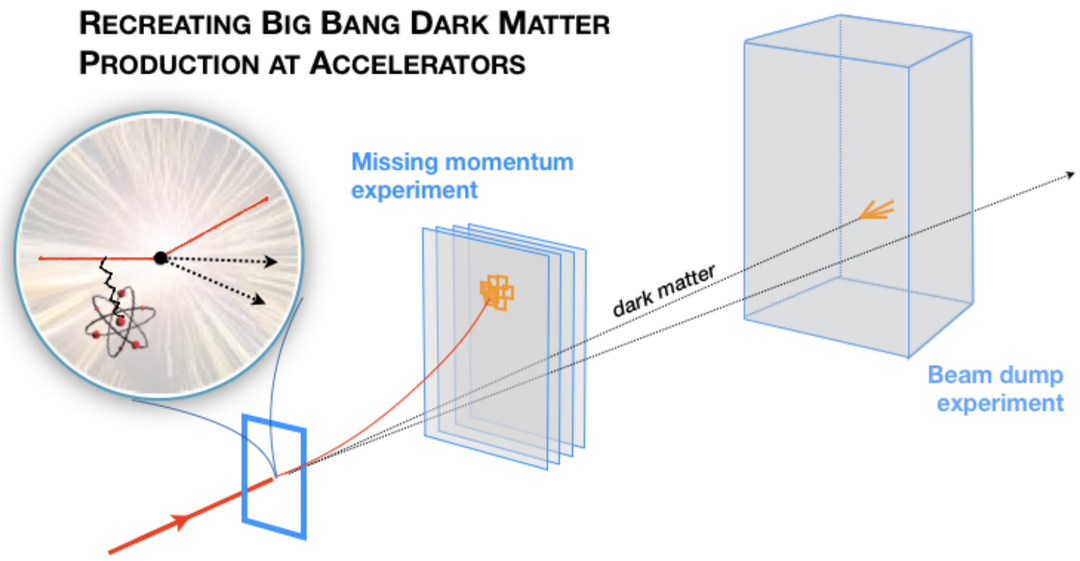
Credit: link

Sometimes it feels like this...



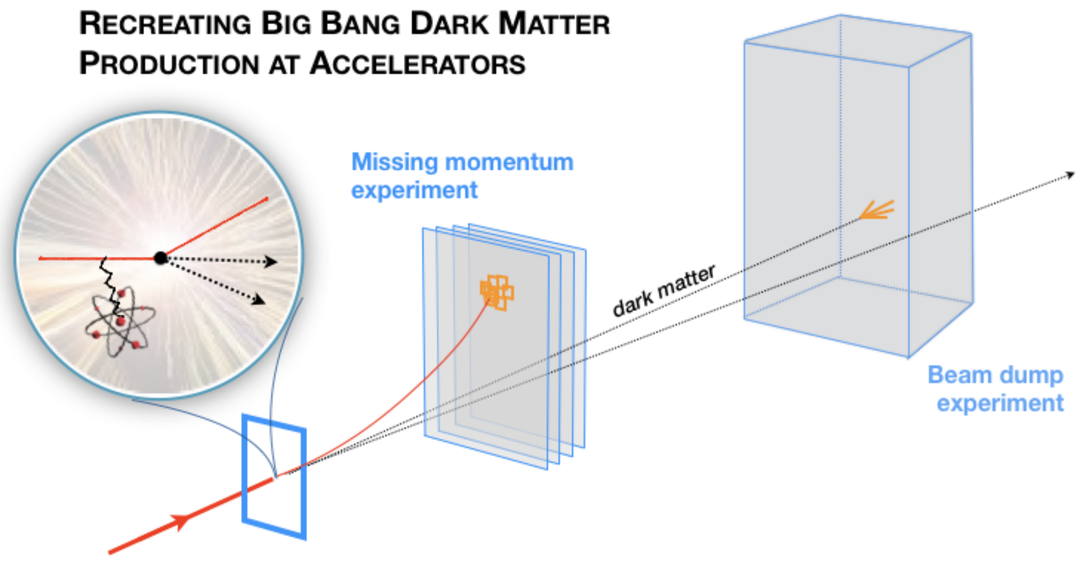
Credit: link

Dark matter and dark sectors



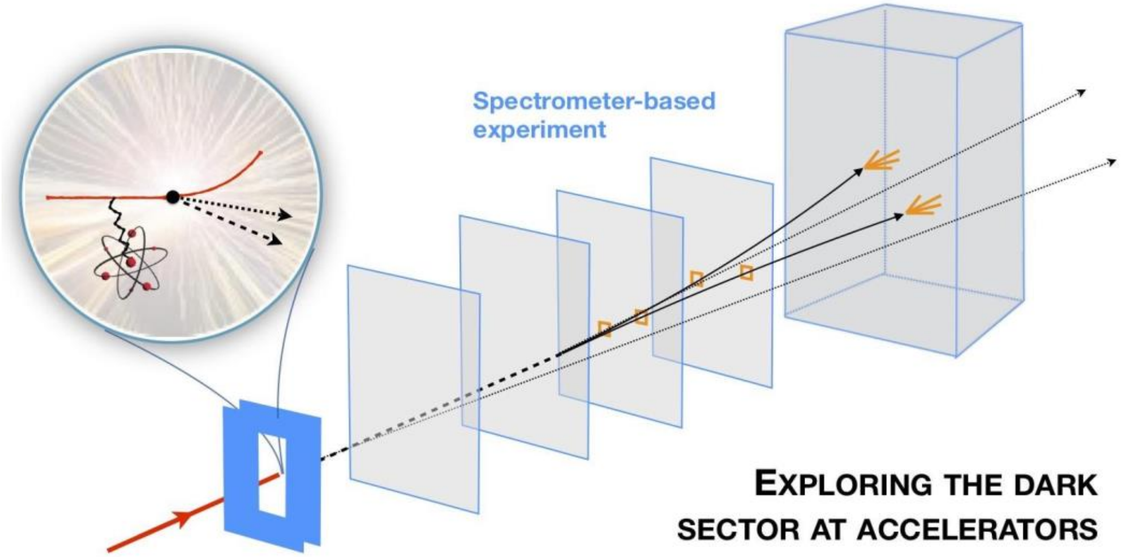
Dark matter searches provide sharp milestones to meet in the near term because couplings can be related to the dark matte relic abundance

Dark matter and dark sectors



On the other hand, dark mediator searches may be our only glimpse into the dark sector... any hint of new physics could be connected to dark matter

Dark matter searches provide <u>sharp milestones</u> to meet in the near term because couplings can be related to the dark matte relic abundance



Snowmass and dark sectors

Invisible, non-SM

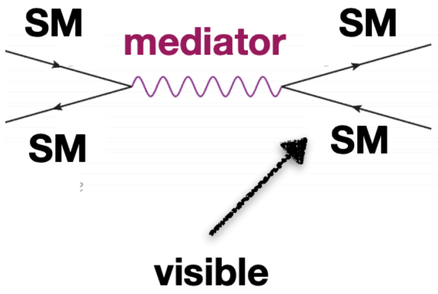
Dark Matter production

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

Visible, SM

Production of portal-mediators that decay to SM particles

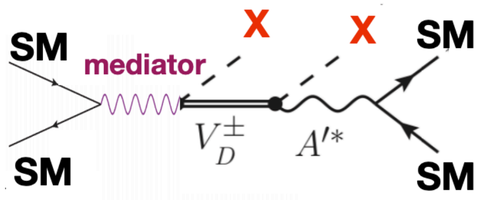
Systematically exploring the portal coupling to SM particles



Mixed visible-invisible

Production of "rich" dark sectors

Testing the structure of the dark sector



Stefania Gori, Mike Williams

Model Zoo

initiated by N.Toro

Benchmarks in Final State x Portal Organization

	DM Production	Mediator Decay Via Portal	Structure of Dark Sector
Vector	*m_χ vs. y [$m_{A'}/m_\chi$=3,α_D=.5]* **$m_{A'}$ vs. y** [α_D=0.5, 3 m_χ values] m_χ vs.α_D [$m_{A'}/m_\chi$=3, y=y_{fo}] m_χ vs. m_A [α_D=0.5, y=y_{fo}] *Millicharge m vs. q*	$m_{A'}$ vs. ϵ [decay-mode agnostic] ***$m_{A'}$ vs. ϵ [decays]***	**iDM m_χ vs. y** [$m_{A'}/m_\chi$=3,α_D=.5] (anom connection) **SIMP-motivated cascades [slices TBD]** $U(1)_{B-L\,/\,\mu-\tau\,/\,B-3\tau}$ (DM or SM decays)
Scalar	m_χ vs. sinθ [λ=0, fix m_S/m_χ, g_D] (thermal target excluded 1512.04119, should still include) Note secluded DM relevance of S→SM of mediator searches	*m_S vs. sinθ* [λ=0] *m_S vs. sinθ* [λ=s.t. Br(H→ϕϕ ~10^{-2})]?	Dark Higgssstrahlung (w/vector) scalar SIMP models? Leptophilic/leptophobic dark Higgs?
Neutrino	e/μ/τ a la1709.07001? Batell, Han, McKeen, Es Haghi	*m_N vs. U_e* *m_N vs. U_μ* *m_N vs. U_τ* Think more about reasoanble flavor structures	Sterile neutrinos with new forces?
ALP	m_χ vs. fq/l [λ=0, fix m_a/m_χ, g_D] (thermal target excluded) What about f_γ, f_G?	*m_a vs. f_γ* *m_a vs. f_G* *m_a vs. f_q=f_l* (separate?) Think more about reasoanble coupling relations including $f_{W/Z}$	FV axion couplings

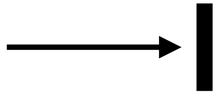
How to make the dark sector 101

Particle beams
$e^{\pm}$,p,μ

+

Collider

Fixed Target



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A lot of statistics
(LDM has small couplings)

How to make the dark sector 101

Particle beams
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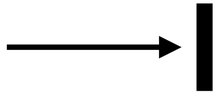

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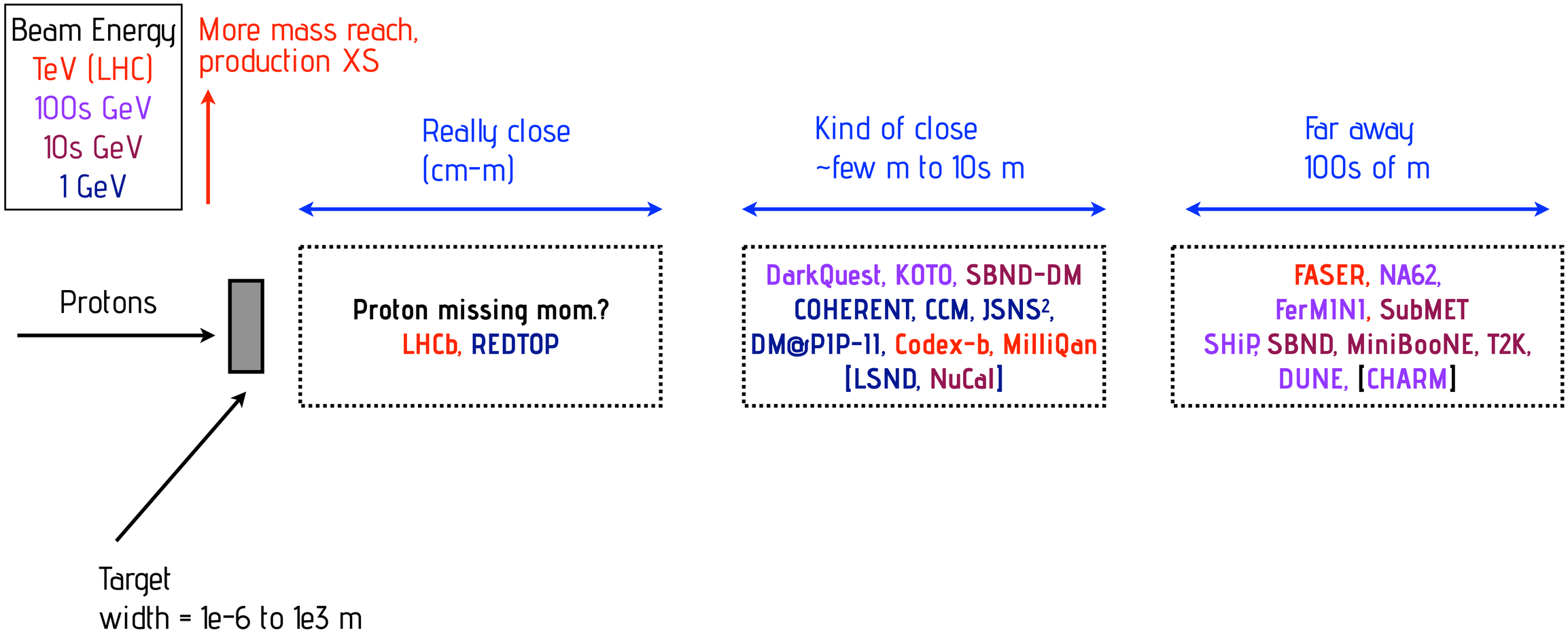
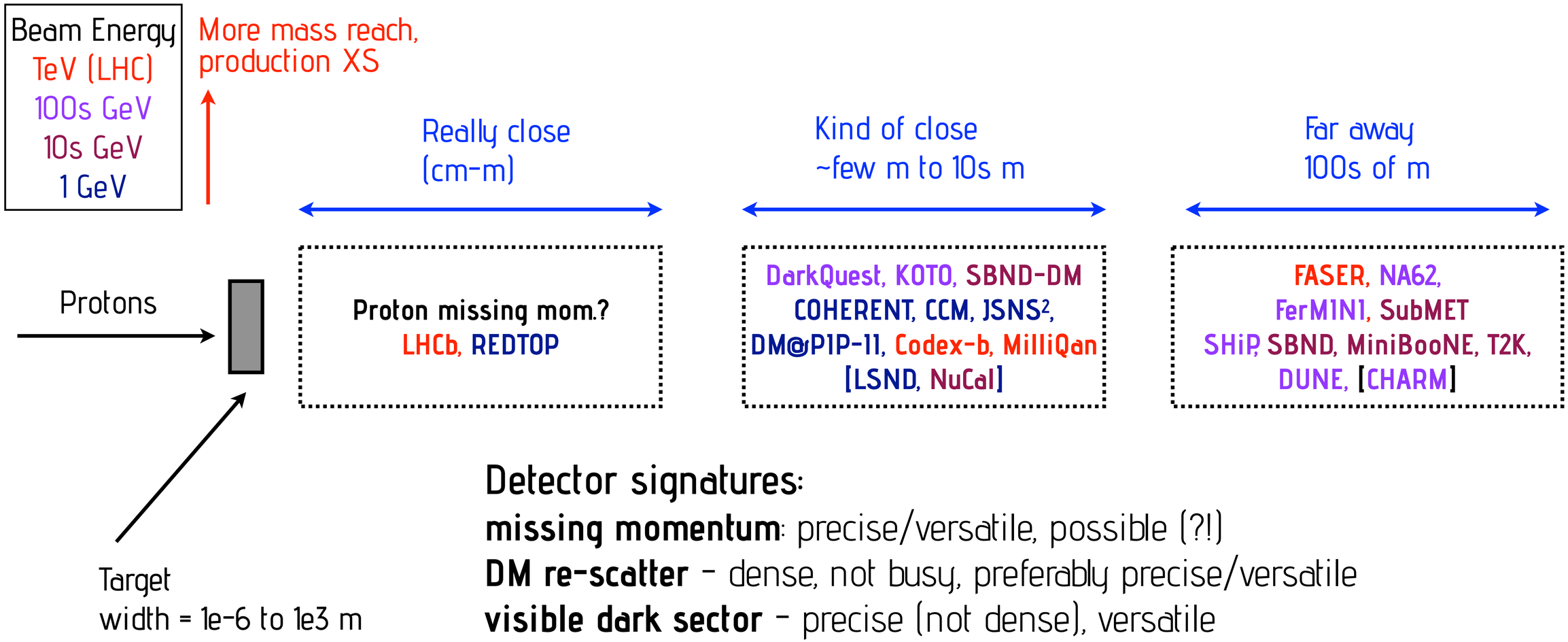
A lot of statistics
(LDM has small couplings)

- **Electrons/positrons** are easy to make and very **precise**
  - You can make a lot of them and control them very well
- **Protons** make all kinds of stuff, **versatile** production mechanism
  - e.g. mesons, muons, taus, heavy quarks,...
  - Cons: protons make all kinds of stuff, including neutrinos
- **Muons** are **unique window** to 2nd generation
  - Heavy (than electrons), clean (minimum ionizing)
  - Cons: muon beams are harder to come by and control

Proton beam fixed target cross-cutting examples



Proton beam fixed target cross-cutting examples



Detector signatures:

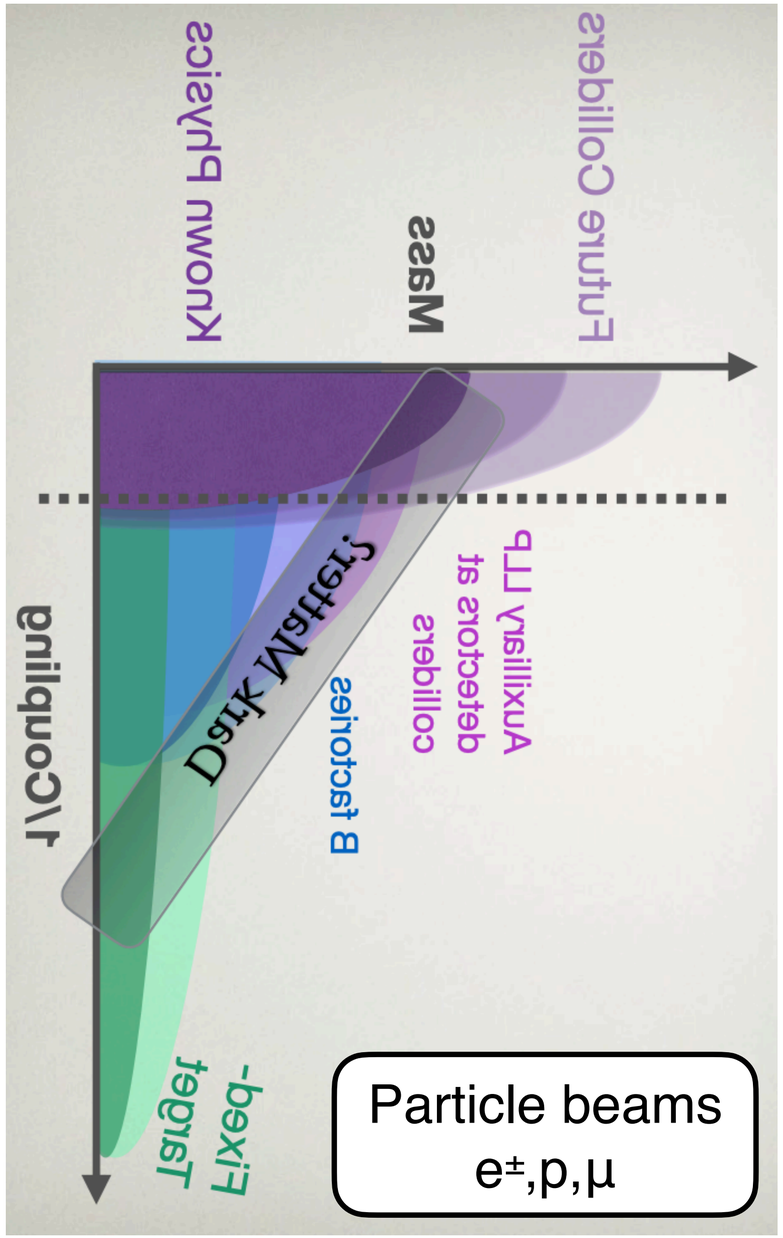
missing momentum: precise/versatile, possible (?!)

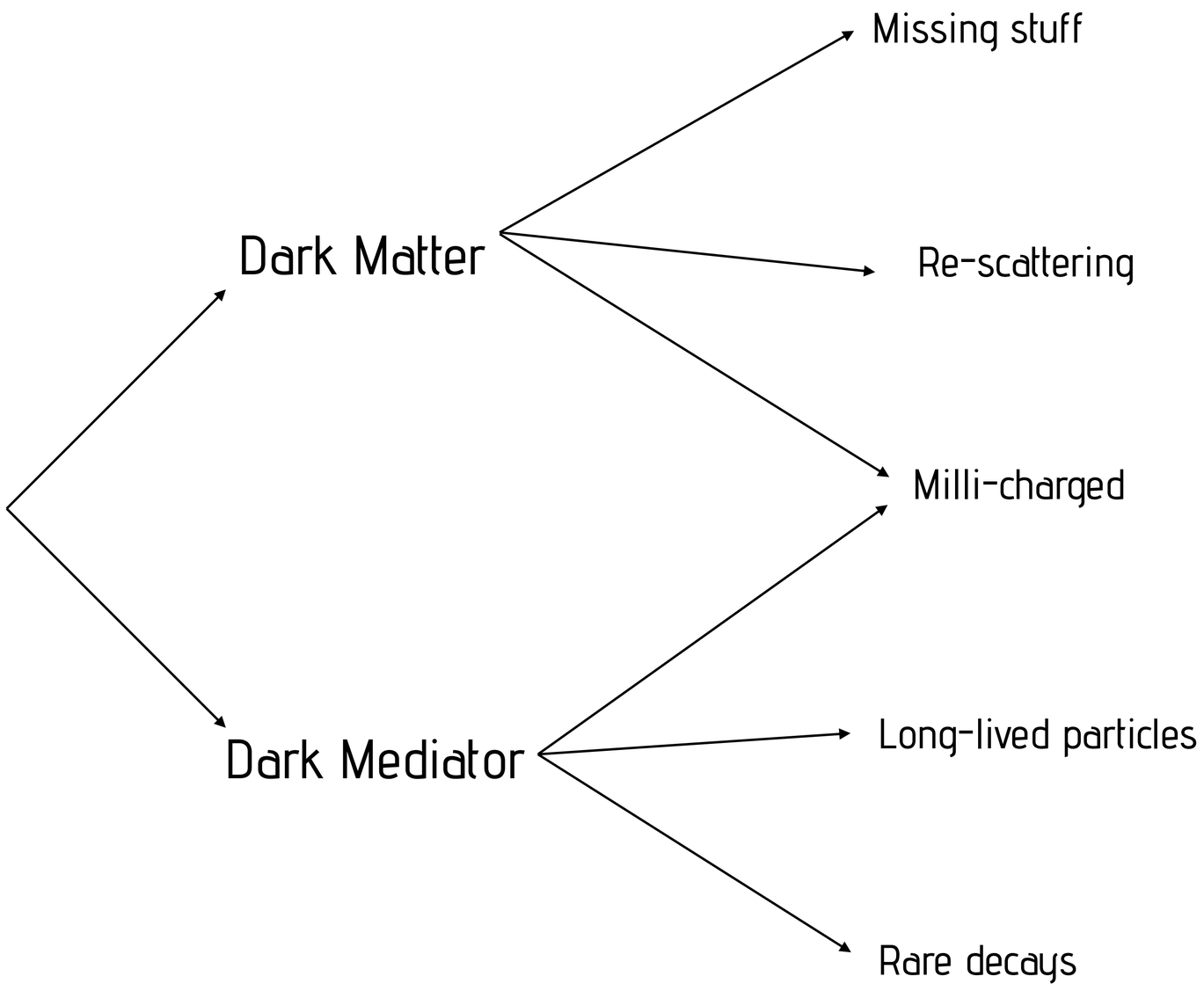
DM re-scatter - dense, not busy, preferably precise/versatile

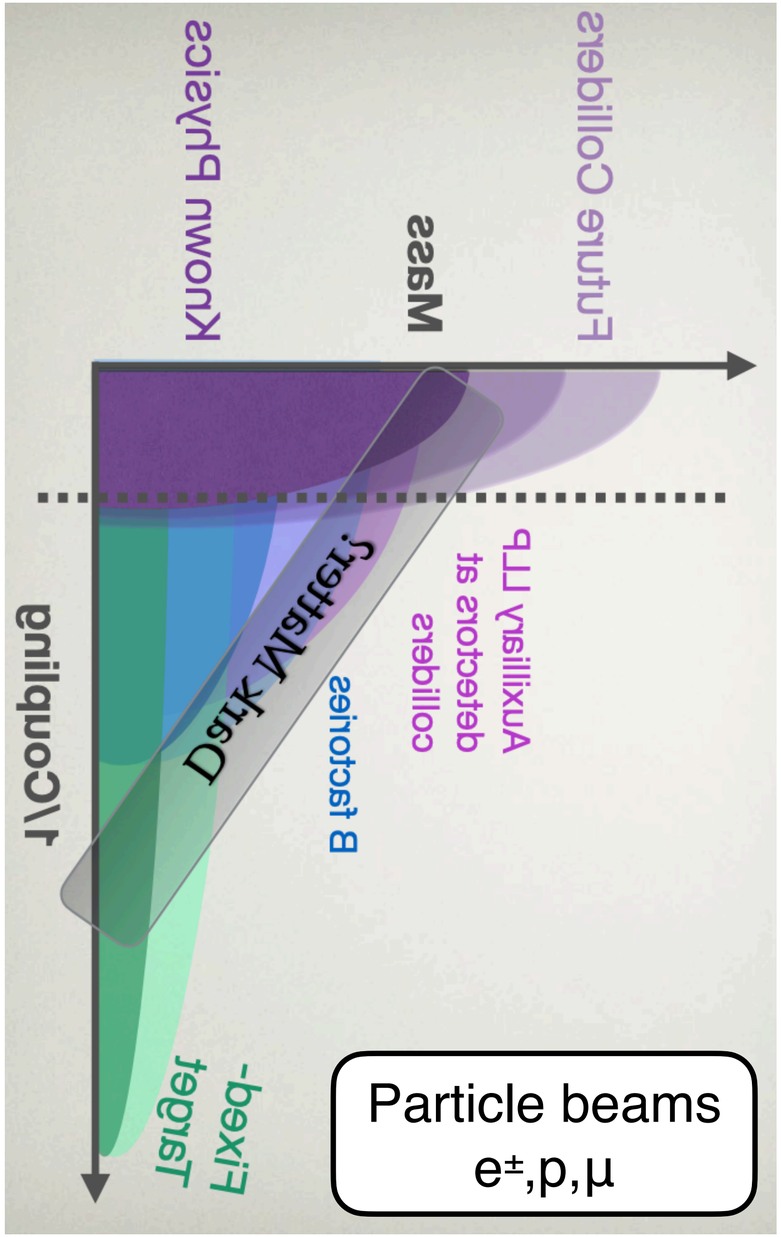
visible dark sector - precise (not dense), versatile

fractional charge - low noise, not busy

N.B. Need to combine beam energy and distance to get displacement sensitivity ($\gamma c\tau$)


Future Colliders
Known Physics
Mass
Auxilliary LLP detectors at colliders
B factories
Dark Mighty
Fixed-target
Particle beams
e±,p,μ

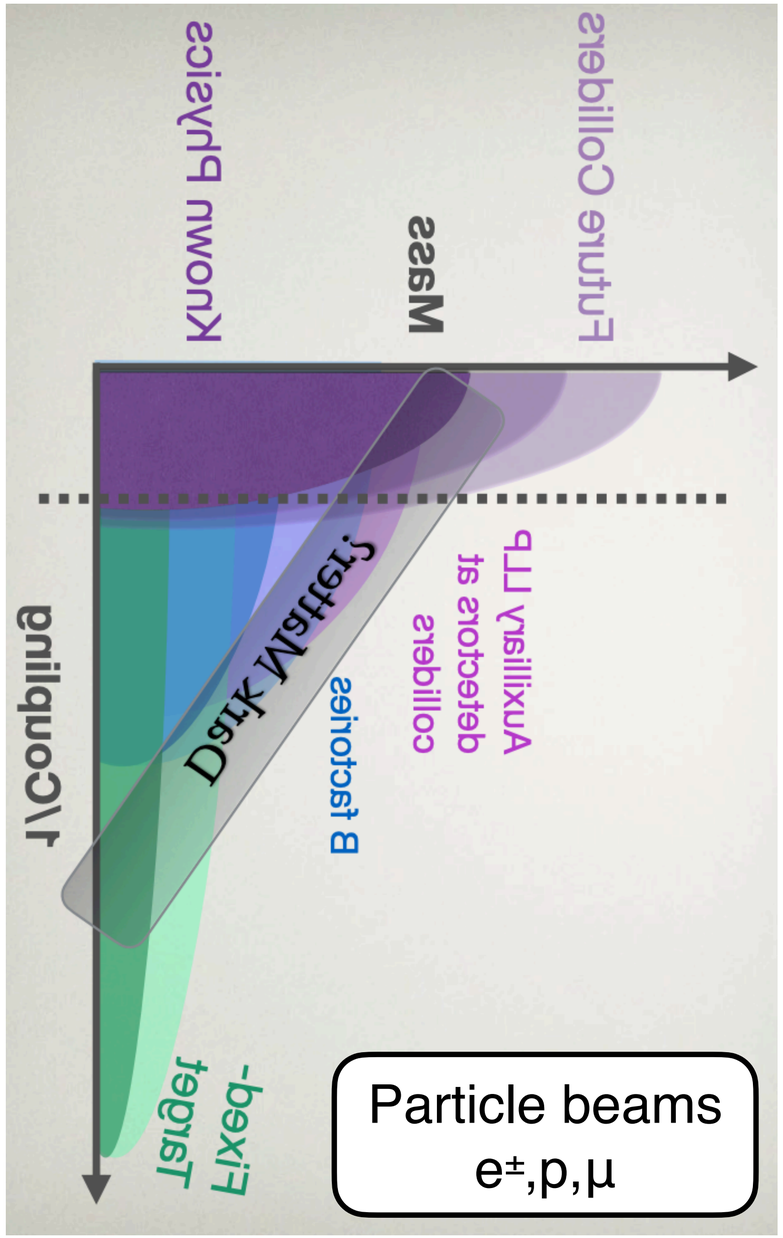

Dark Matter
Dark Mediator
Missing stuff
Re-scattering
Milli-charged
Long-lived particles
Rare decays



In this basis, I will give a few (biased) examples

Coming to some organizing principle will be important part of Snowmass and at the forefront of my mind!

- Dark Matter
  - Re-scattering
  - Milli-charged
- Dark Mediator
  - Milli-charged
  - Long-lived particles
  - Rare decays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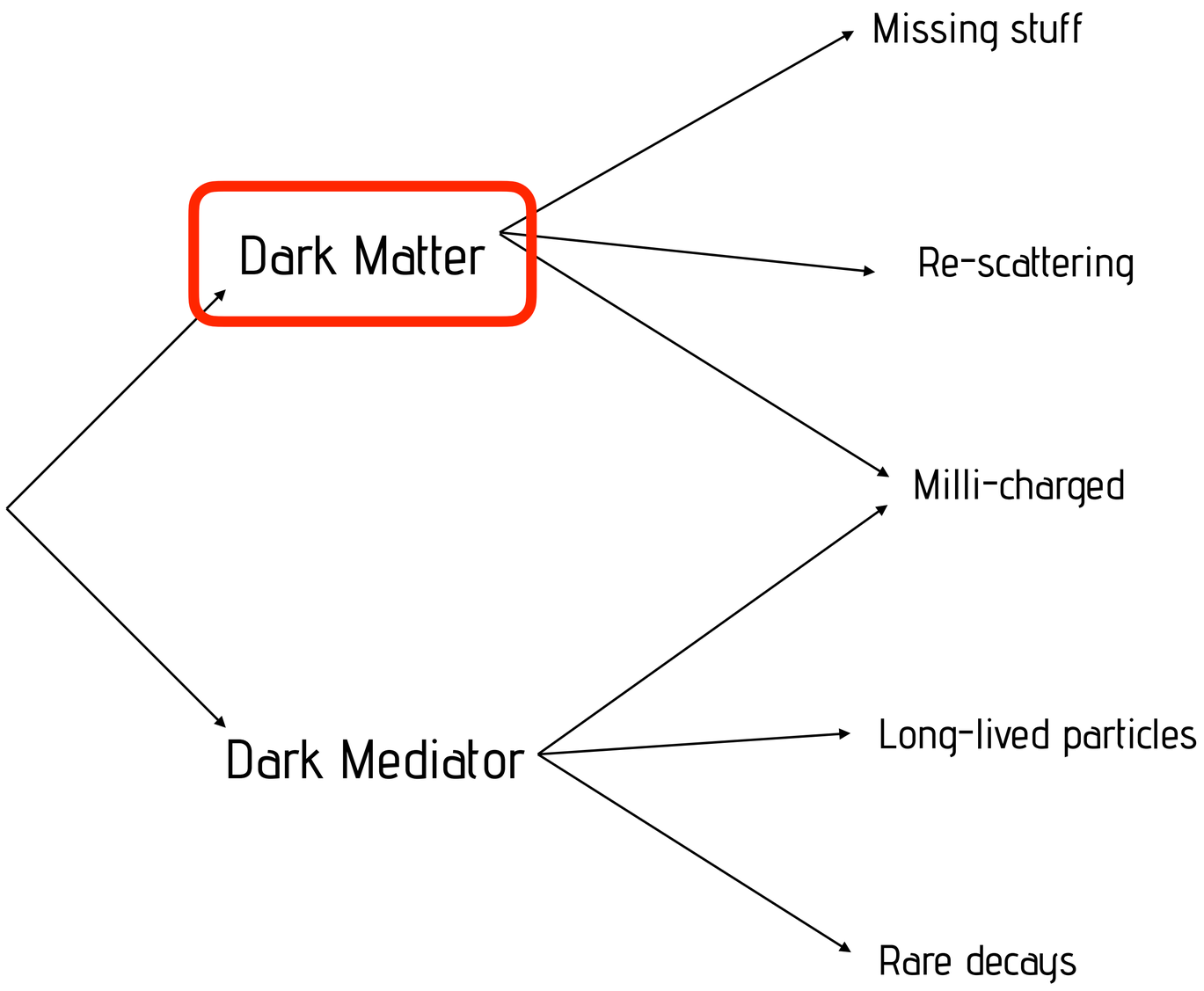
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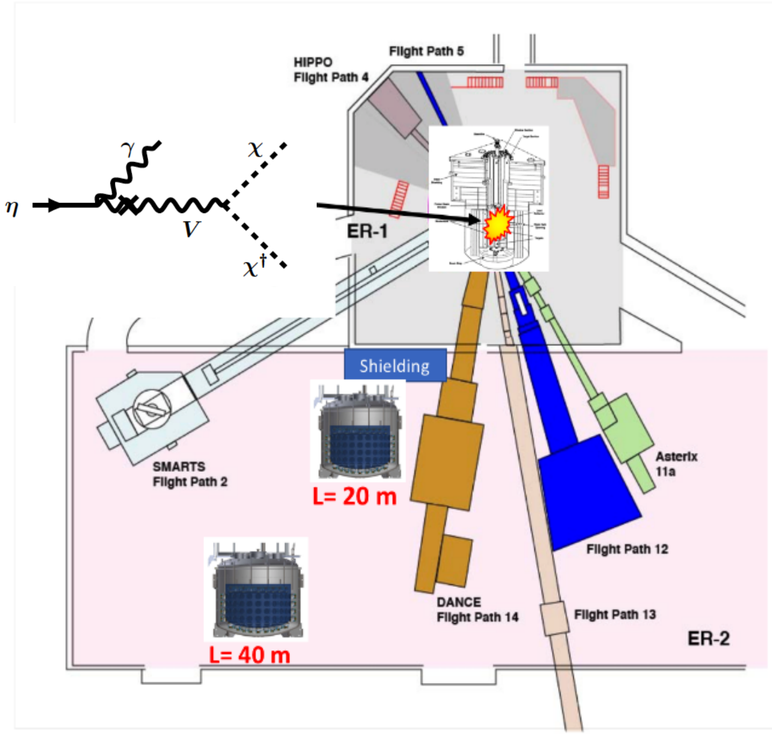
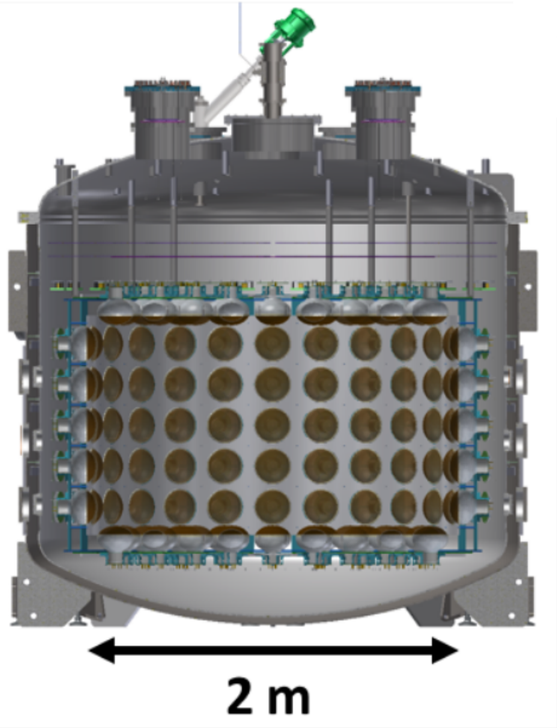
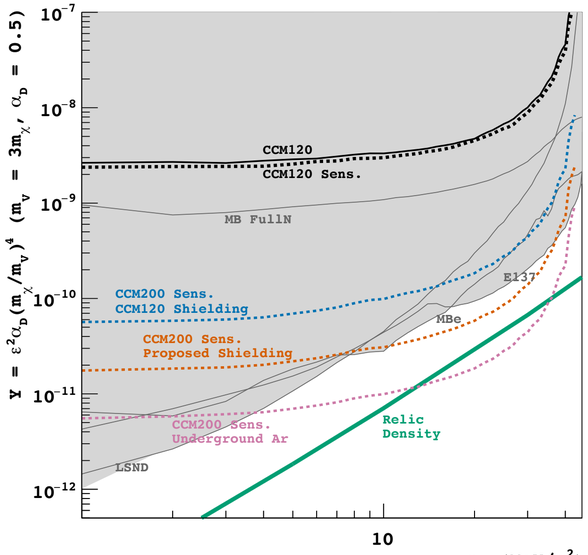
Rescattering example: low energy proton fixed target

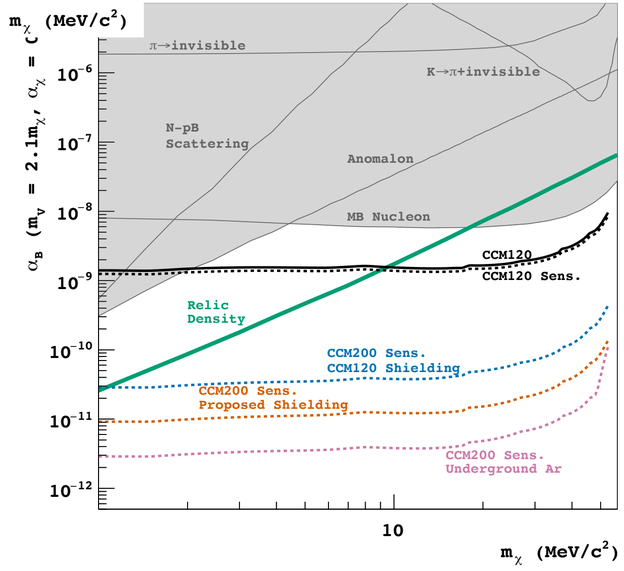
- CCM @ LANL: 800 MeV protons on tungsten target
- Also capable of measuring CEvNS and searching for sterile neutrinos
- Example: DM production through pion production
  - Timing important to distinguish from neutrino signatures







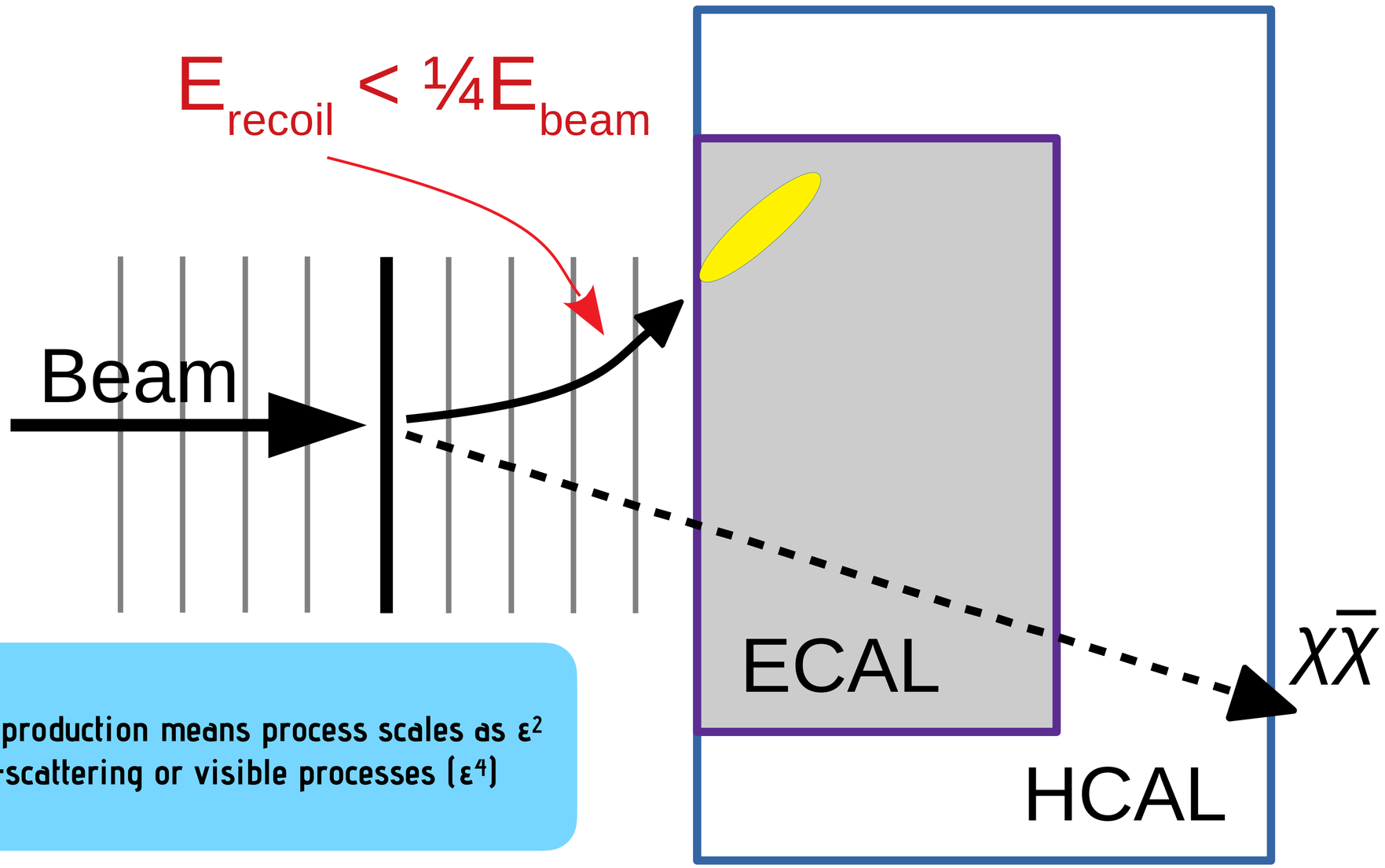
(a) vector portal



(b) leptophobic

First DM search!
https://arxiv.org/abs/2105.14020

(Electron) missing momentum



Requiring only dark production means process scales as ε^2 as opposed to re-scattering or visible processes (ε^4)

The Light Dark Matter eXperiment

https://arxiv.org/abs/1808.05219
https://arxiv.org/abs/1807.01730
https://arxiv.org/abs/1912.05535
https://arxiv.org/abs/2112.02104
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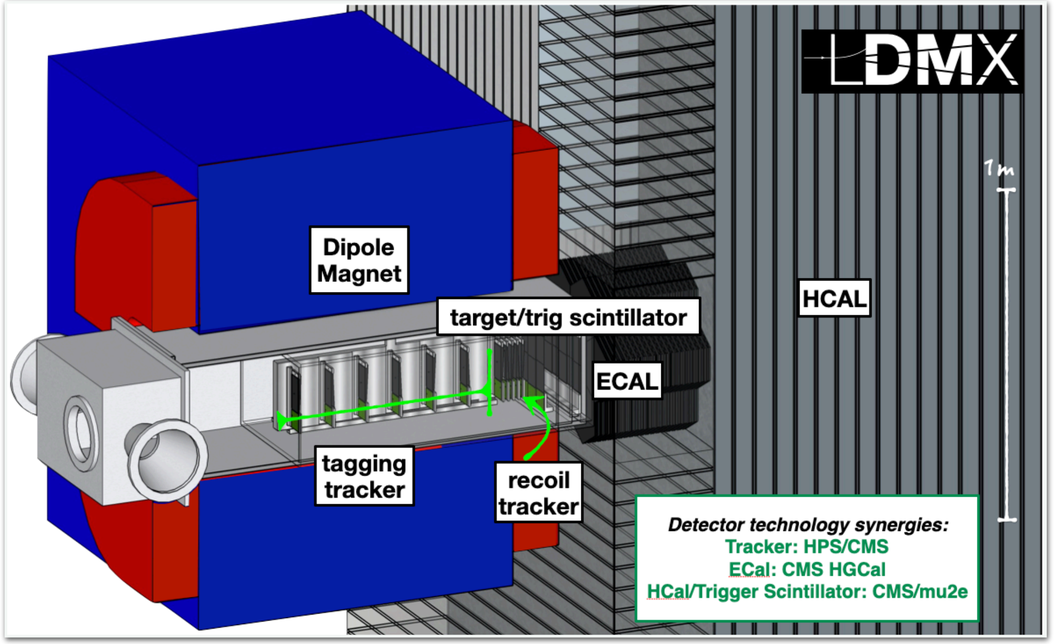
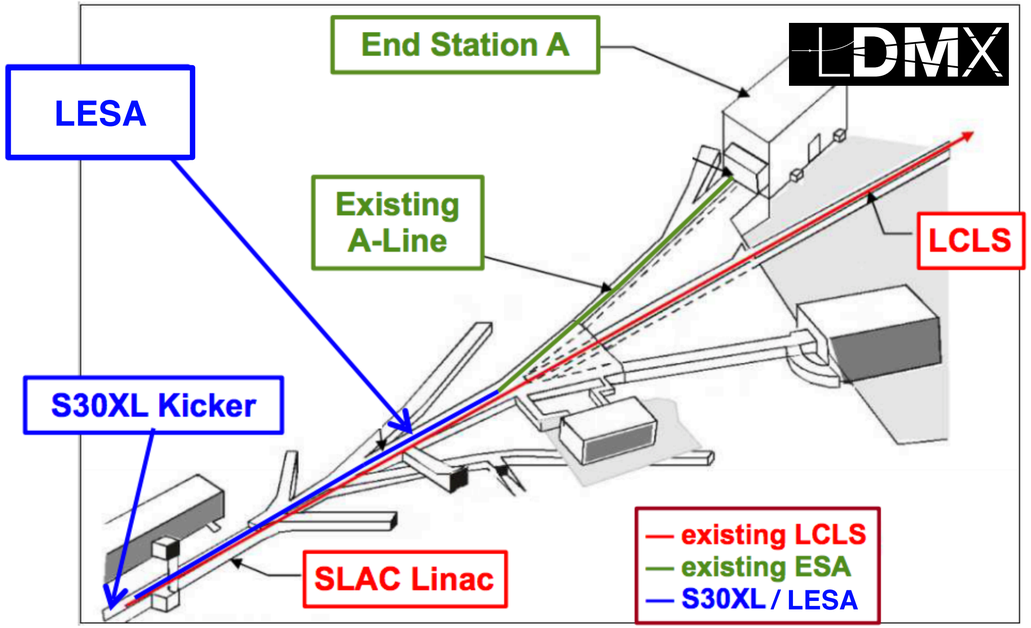
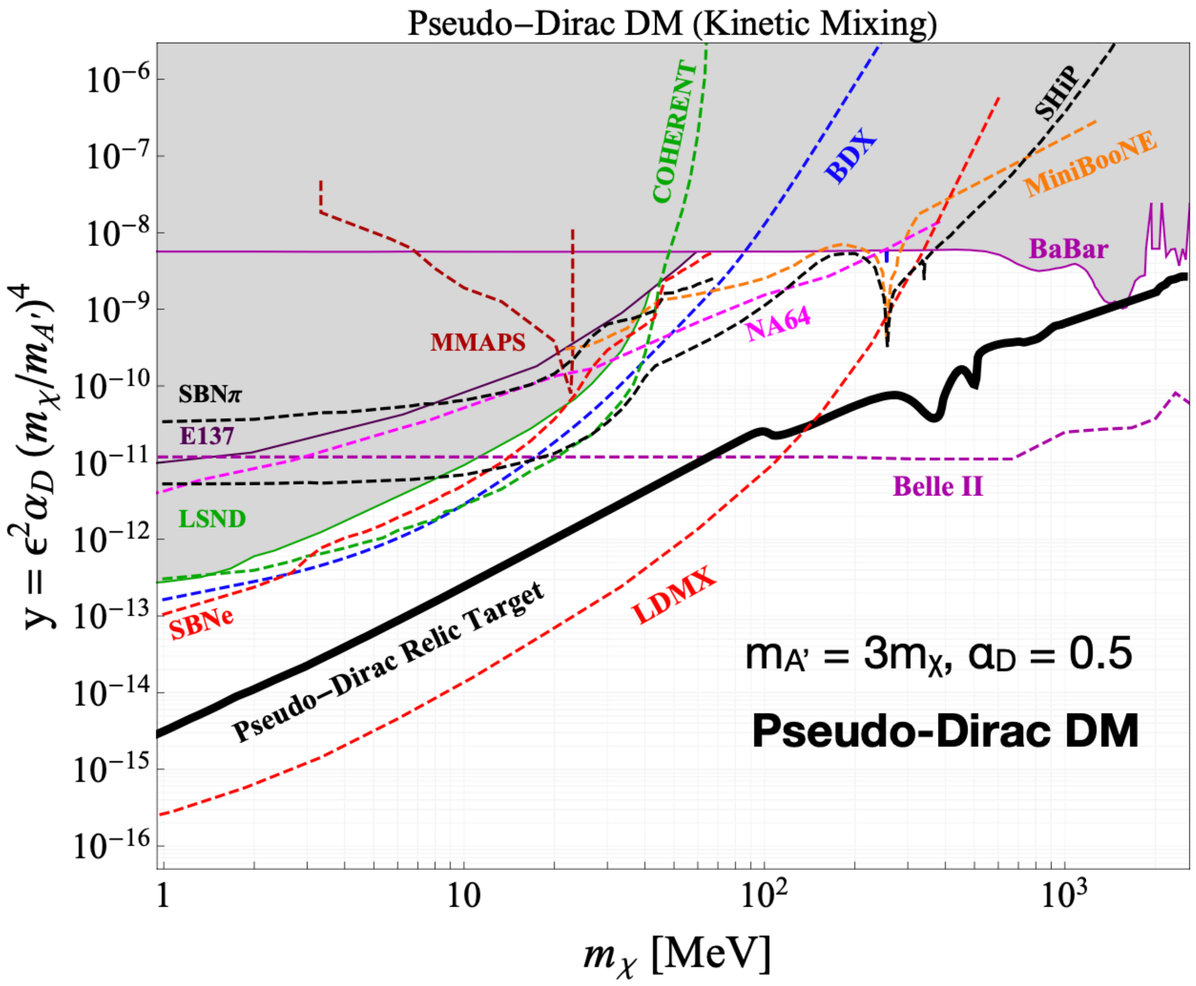


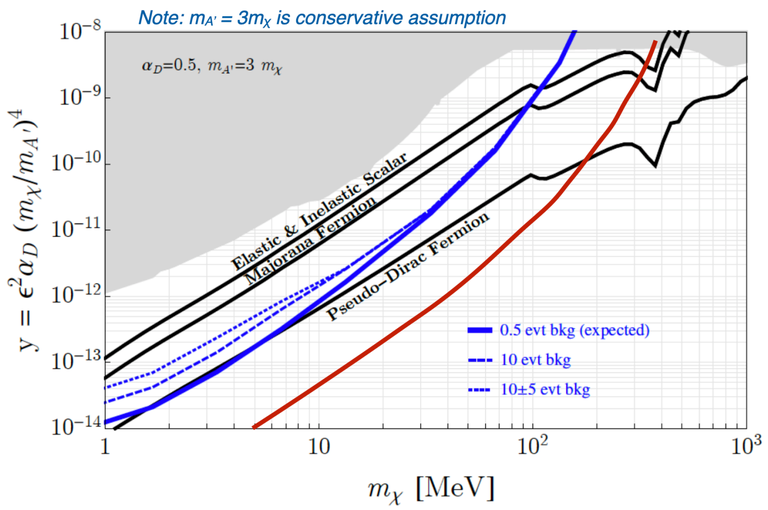


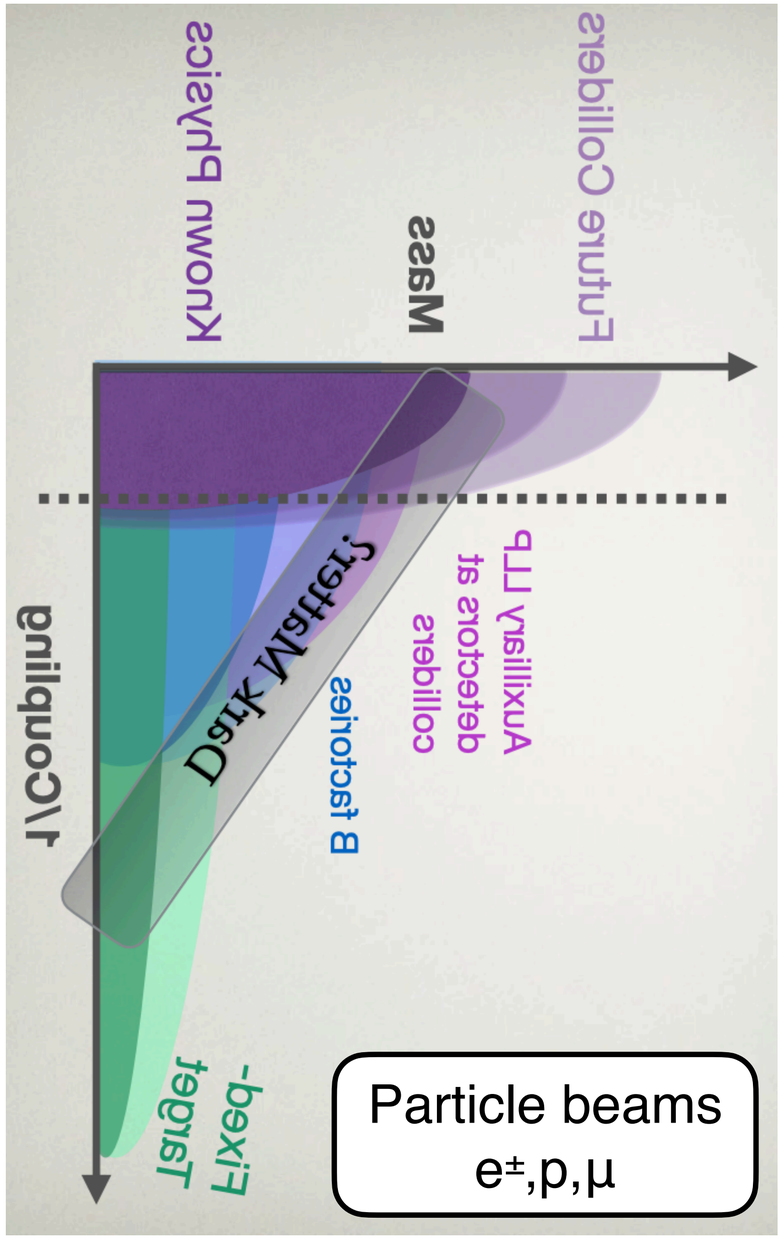
- **Electron missing momentum experiment 4/8 GeV**
- Primary physics goal: definitively explore thermal dark matter milestones
  - Potential for other dark sector signatures and eN scattering for DUNE program
- **Status**: R&D funded including 1st milestones - test beam and detector prototypes

Invisible search, projected sensitivity



See Luigi's talk from yesterday for a lot more details about Belle II

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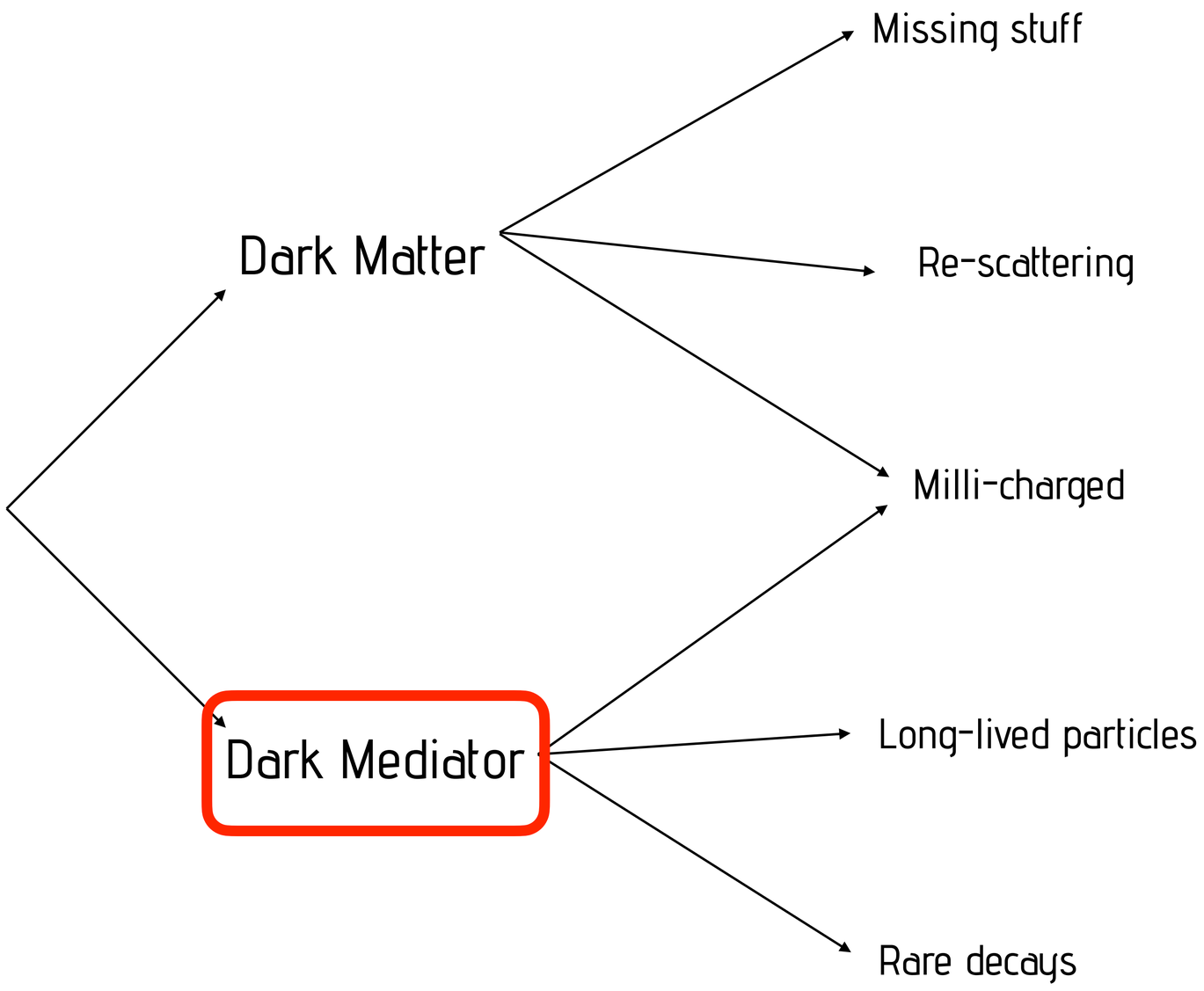
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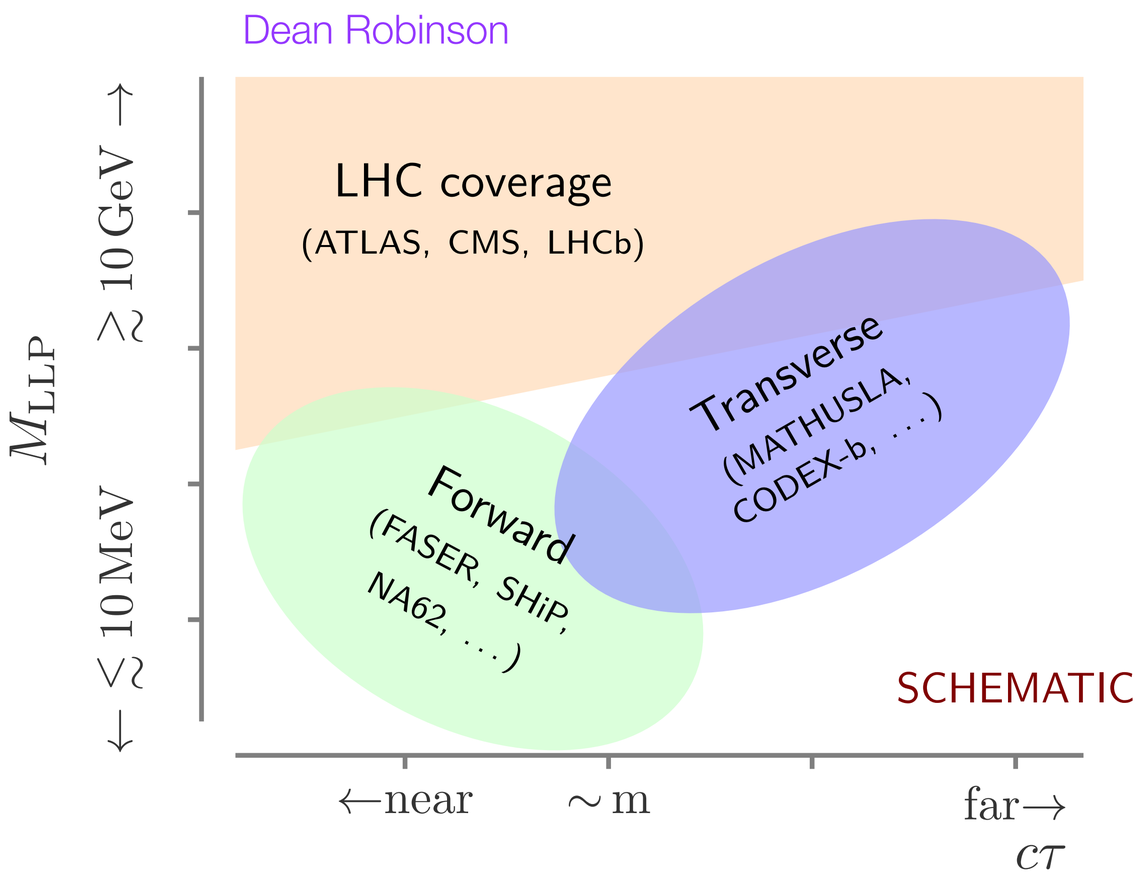
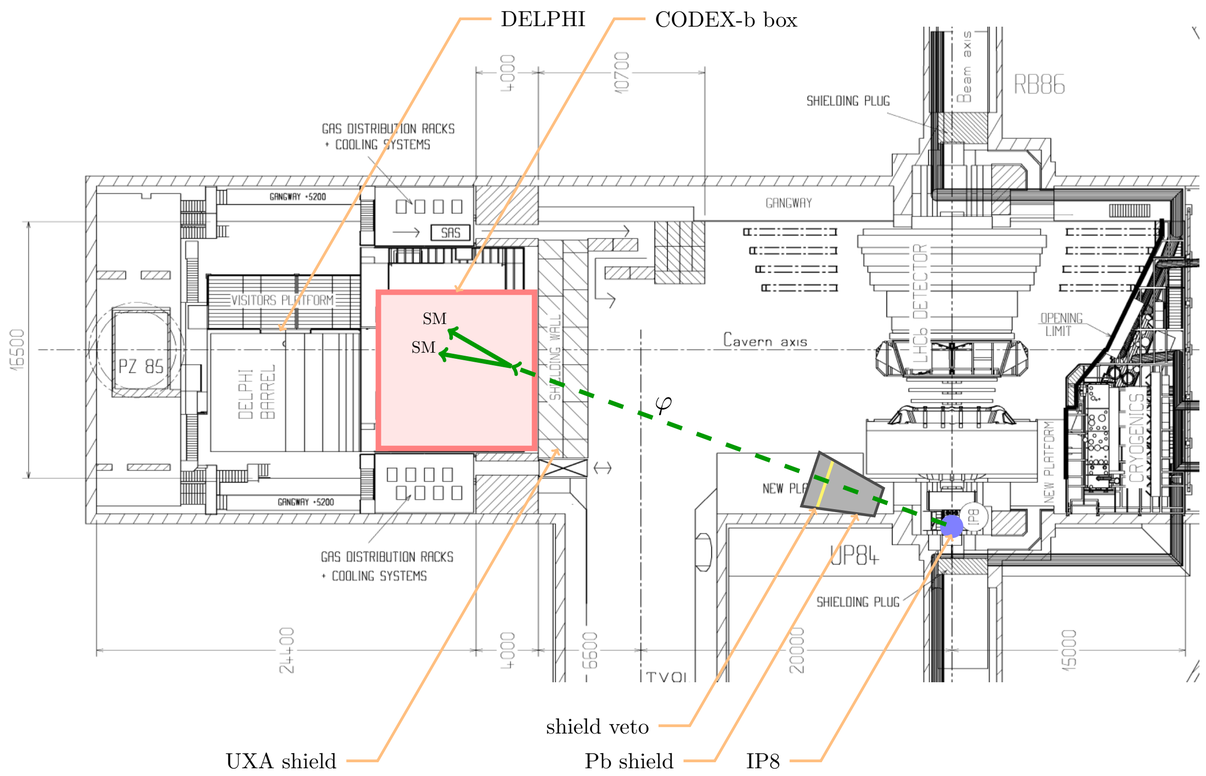
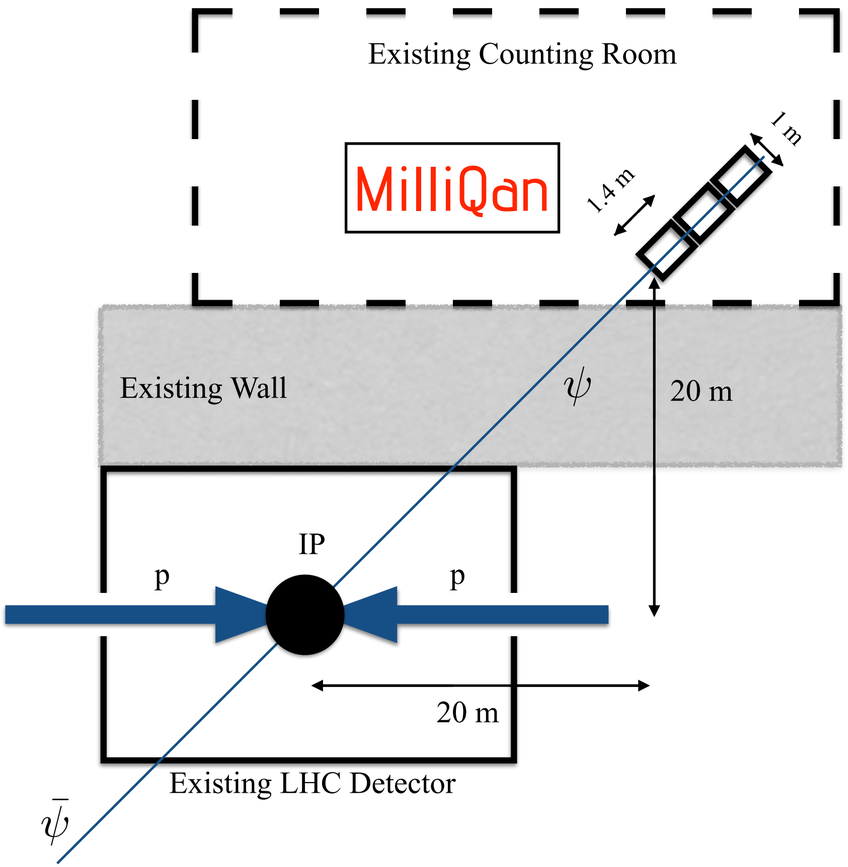
Opportunities near LHC



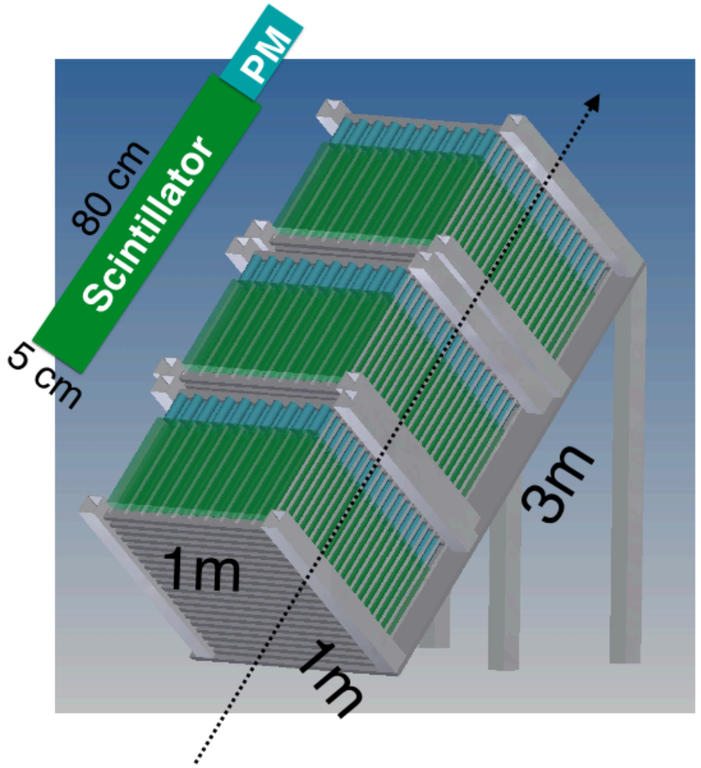


Scintillator arrays for millicharges



A portable setup of scintillator arrays

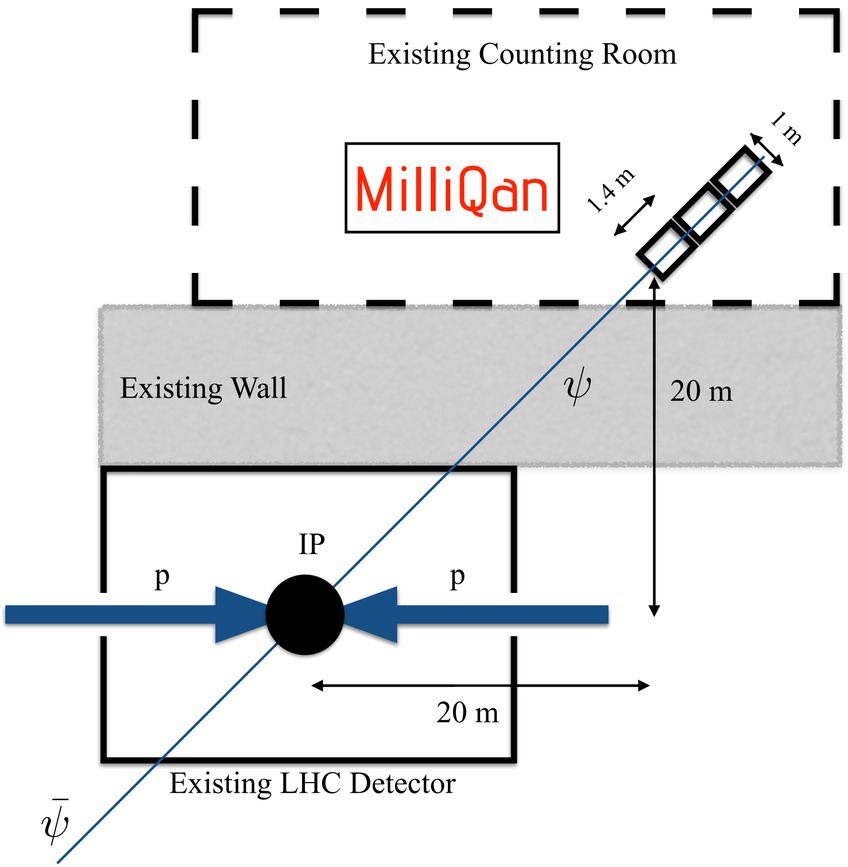
- inexpensive detector technology
- long, sensitive active material to detect Q ~ 10^{-3}e
- triple coincidence to reduce backgrounds



Phys.Lett.B 746 (2015) 117-120 (Haas, Hill, Izerquirre, Yavin)

Now running, MilliQan demonstrated near CMS

Scintillator arrays for millicharges



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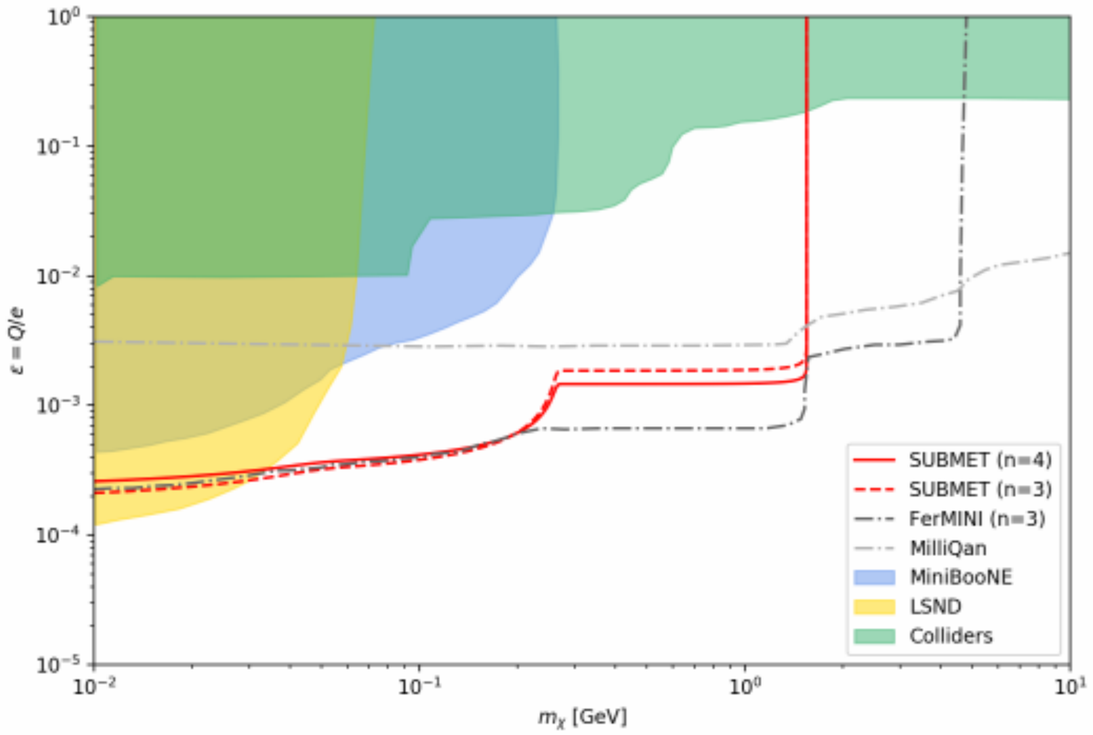
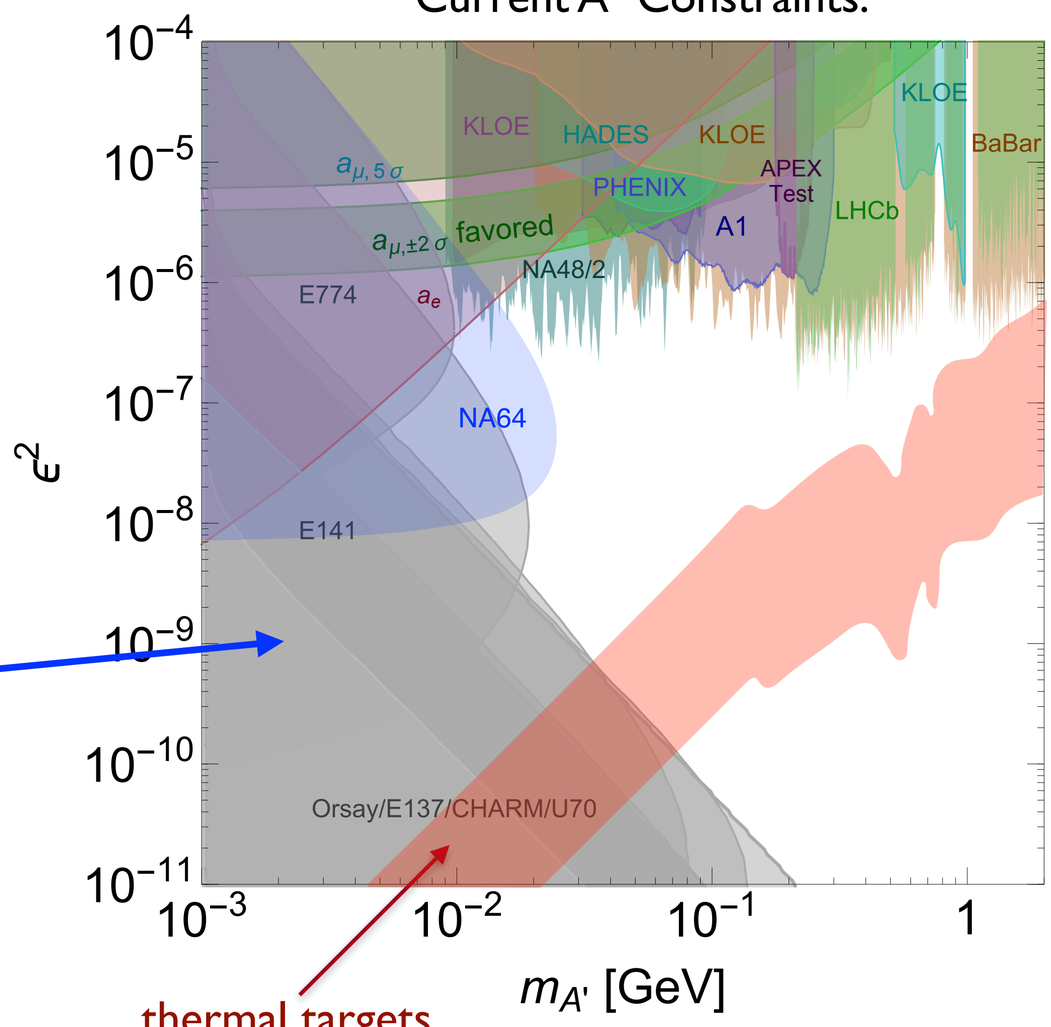


Phys.Lett.B 746 (2015) 117-120 (Haas, Hill, Izerquirre, Yavin)

Now running, MilliQan demonstrated near CMS

E.g. Minimal Dark Photon

Current A′ Constraints:



Prompt searches

Very long lived searches

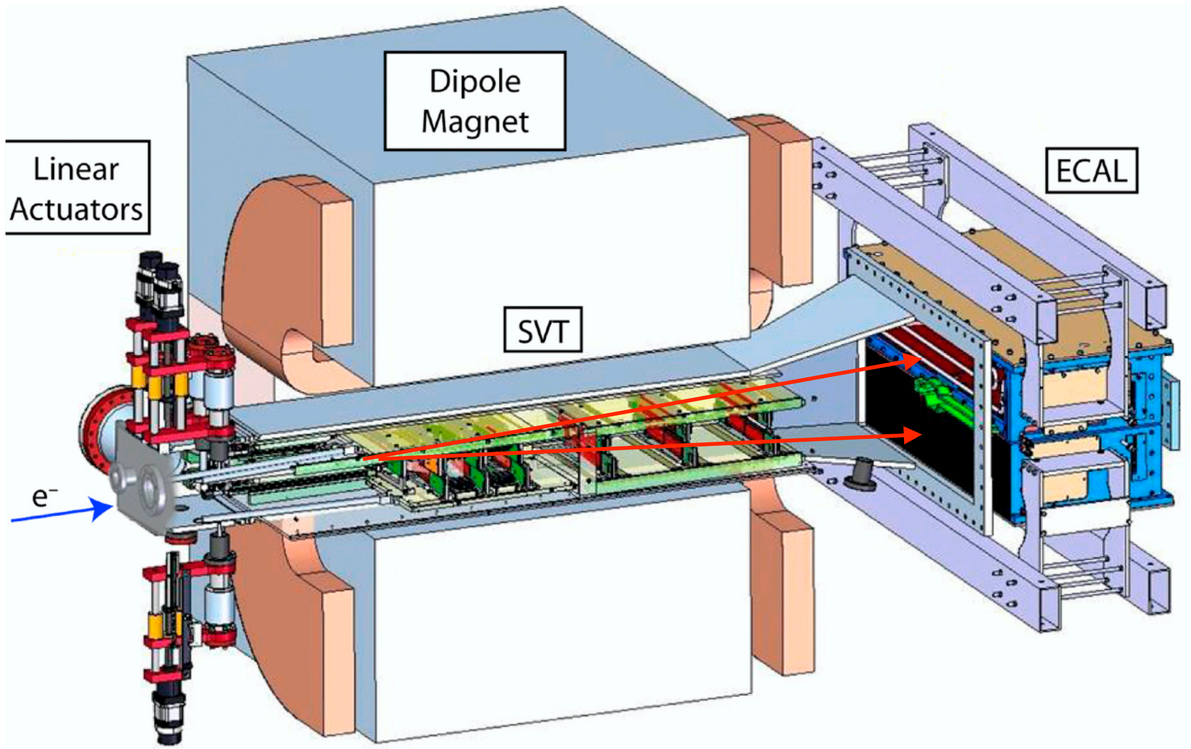
thermal targets

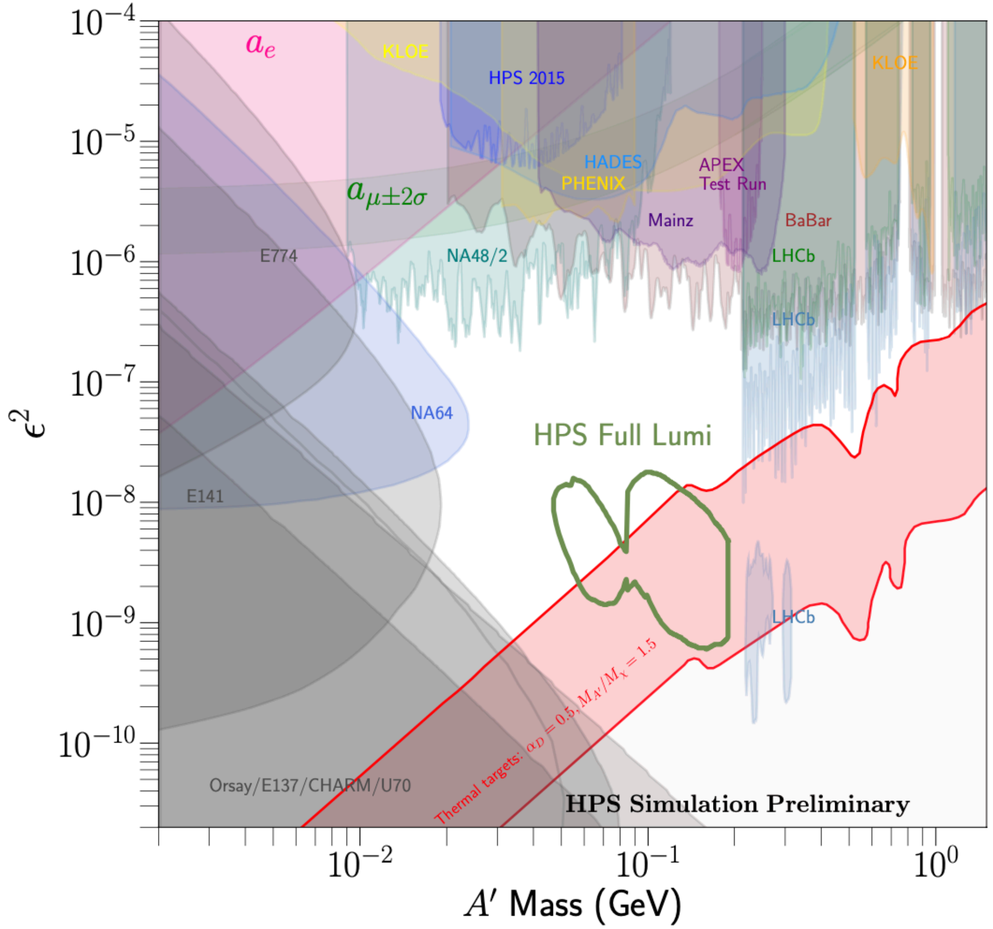
$\alpha_D = 0.5, M_{A'}/M_\chi = 1.5$

6

Electron fixed target

Heavy Photon Search (HPS) @ JLab CEBAF
Electron beam at 4.55 GeV, full lumi is 107 days

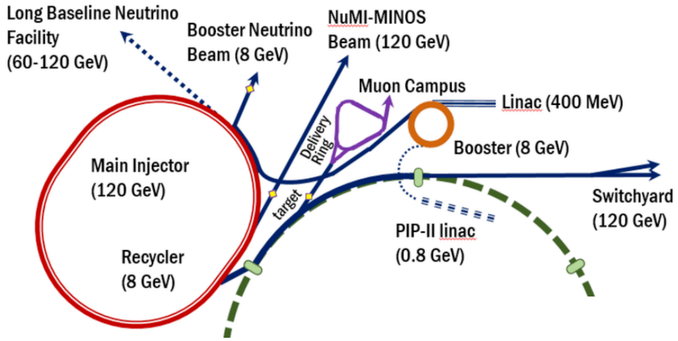




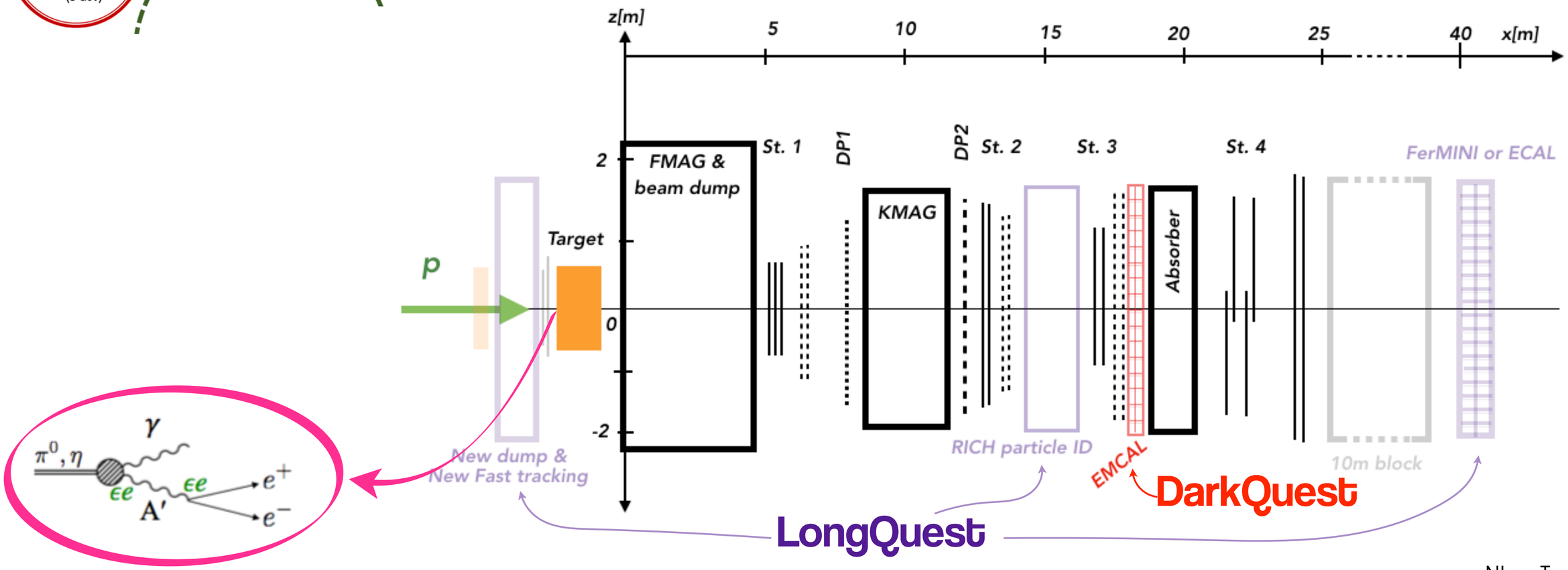
Proton beam dump: DarkQuest

Berlin, Gori, Toro, Schuster
http://arxiv.org/pdf/1804.00661.pdf

Y-D Tsai, deNiverville, M.X. Liu
https://arxiv.org/abs/1908.07525



SeaQuest: Original nuclear physics experiment
SpinQuest: Upgrade w/polarized target (& DP triggers)

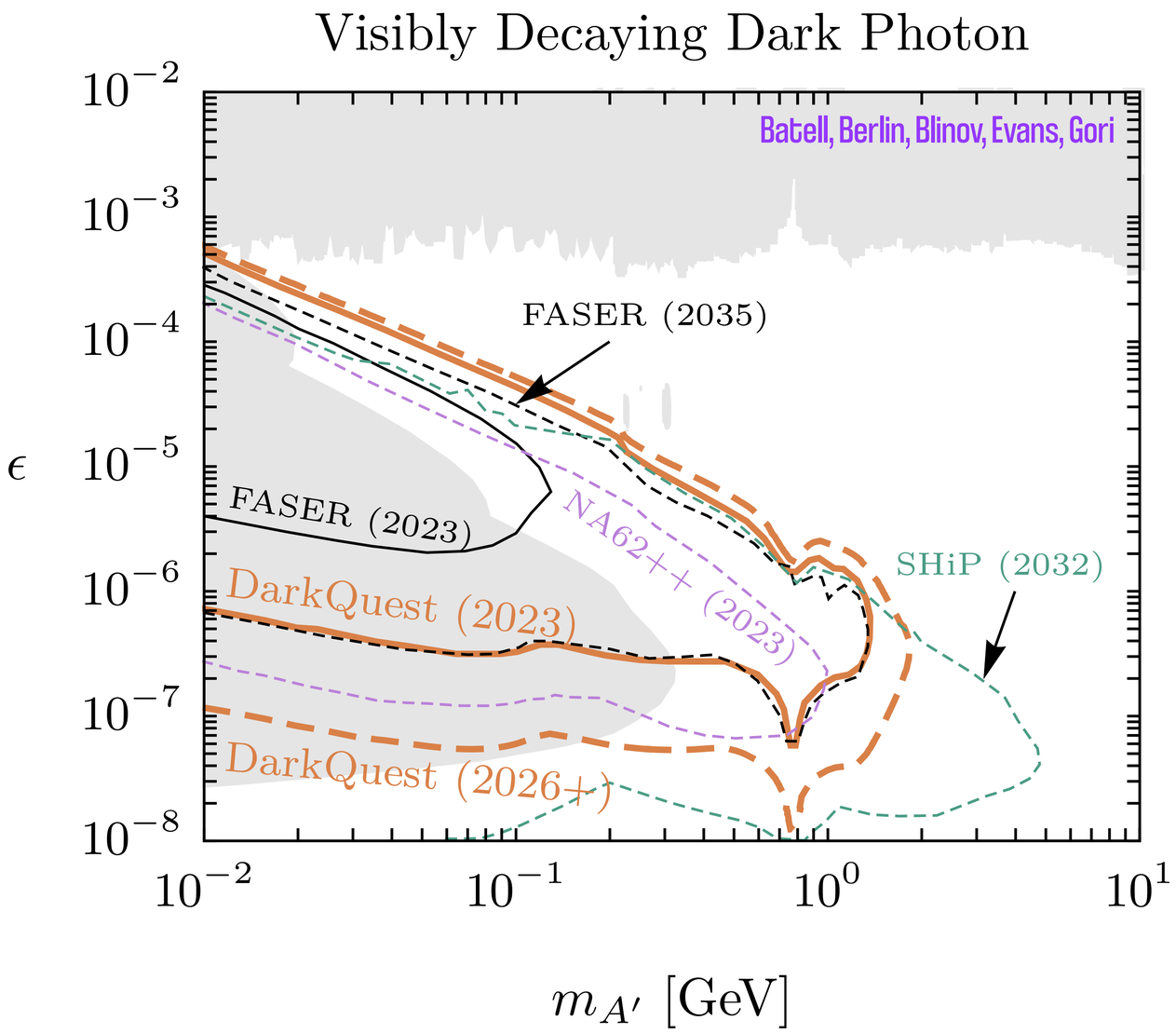


Nhan Tran, Fermilab

Proton beam dump sensitivity

Experiment	Beam Energy	POT	$L_{\text{dist.}}$	L_{dec}
CHARM	400 GeV	2.4e18	480 m	35 m
NuCal	70 GeV	1.7e18	64 m	23 m
NA62	400 GeV	*1.3e16/1e18	82 m	75 m
SQ/DQ	120 GeV	*1.4e18/1e20	5 m	*7 m
LongQuest	120 GeV	*1e20	5 m	*7/13 m

Probing areas of phase space with different types of long-lived particle searches and setups

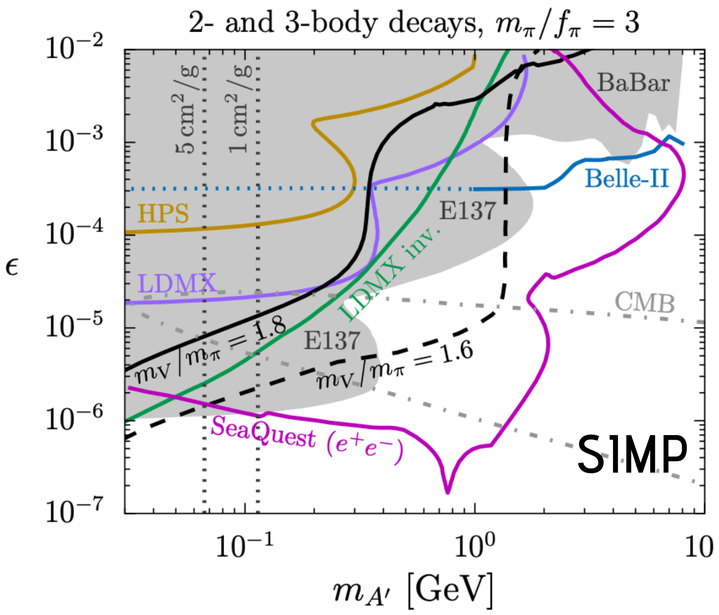


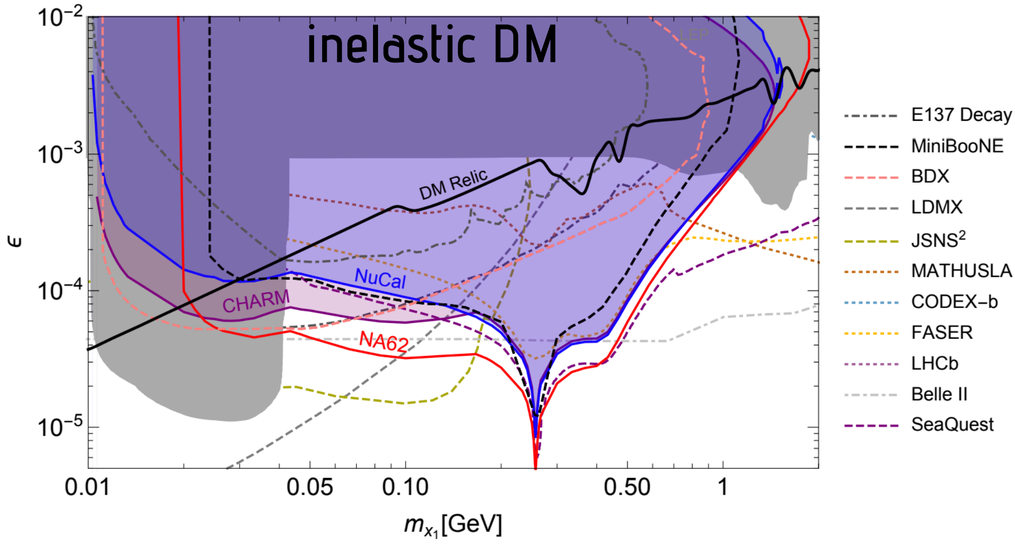
A variety of dark sector signatures

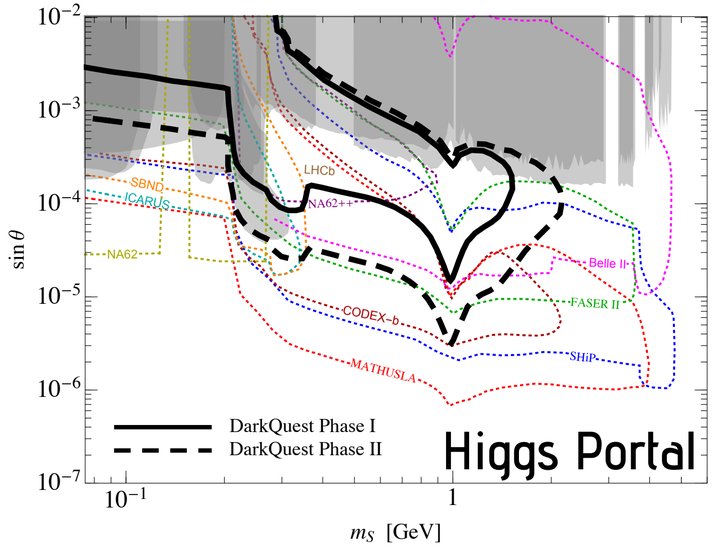
This is just a sampling of different types of benchmark scenarios under consideration

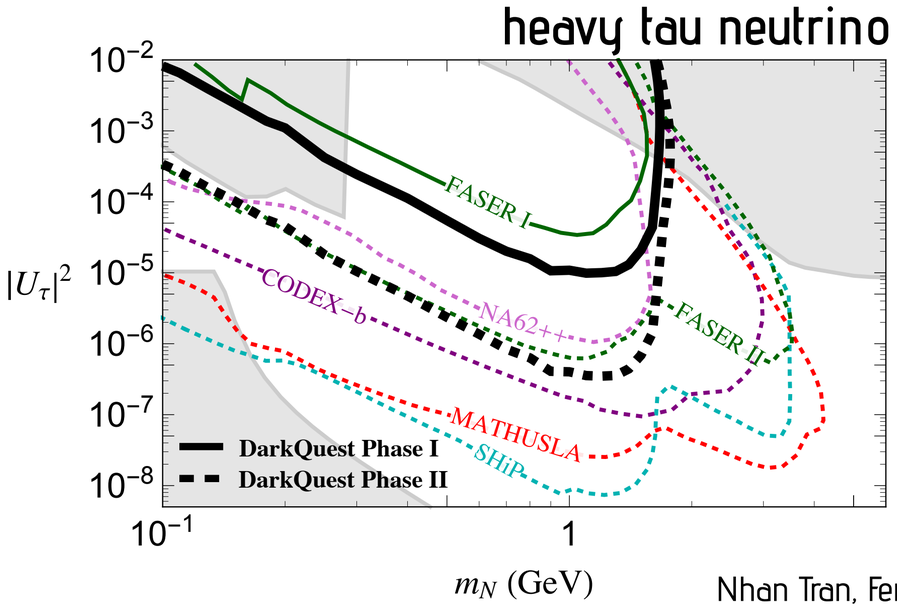
Open areas are generally around moderately long-lived, displaced particle signatures

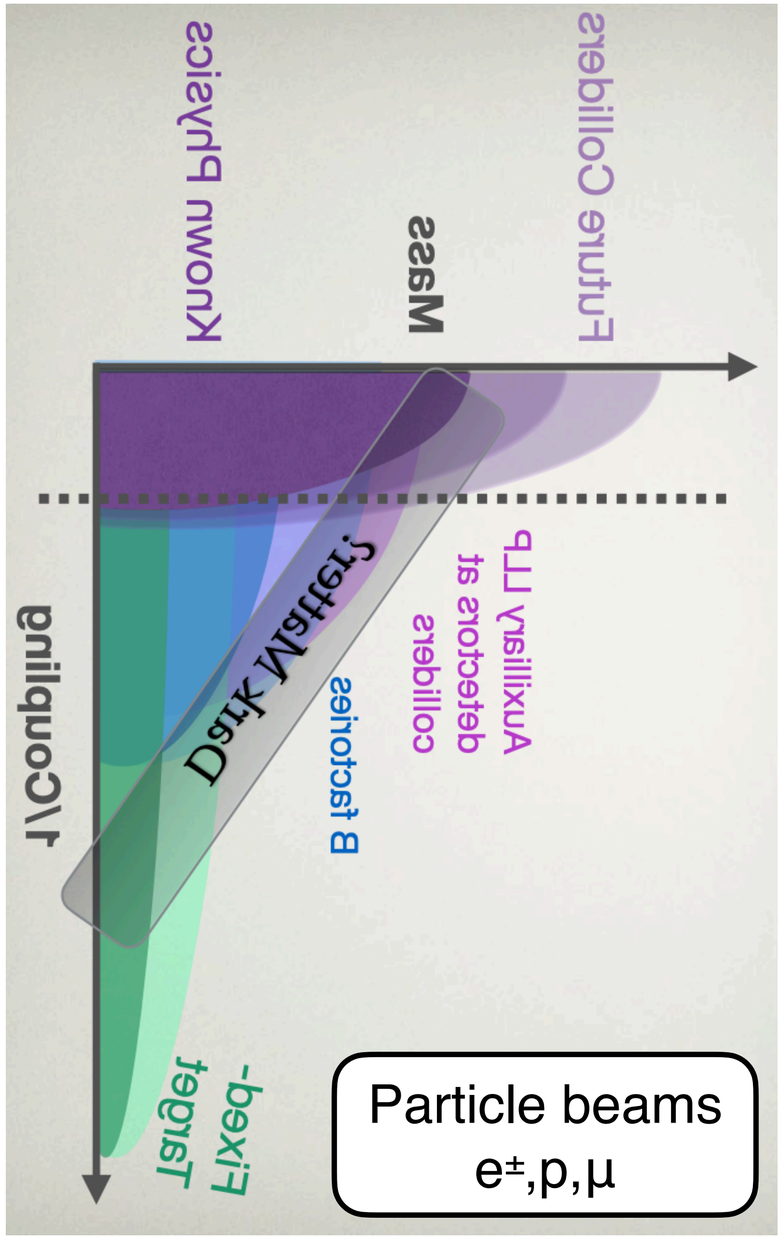
Snowmass process to help define dark sectors milestones





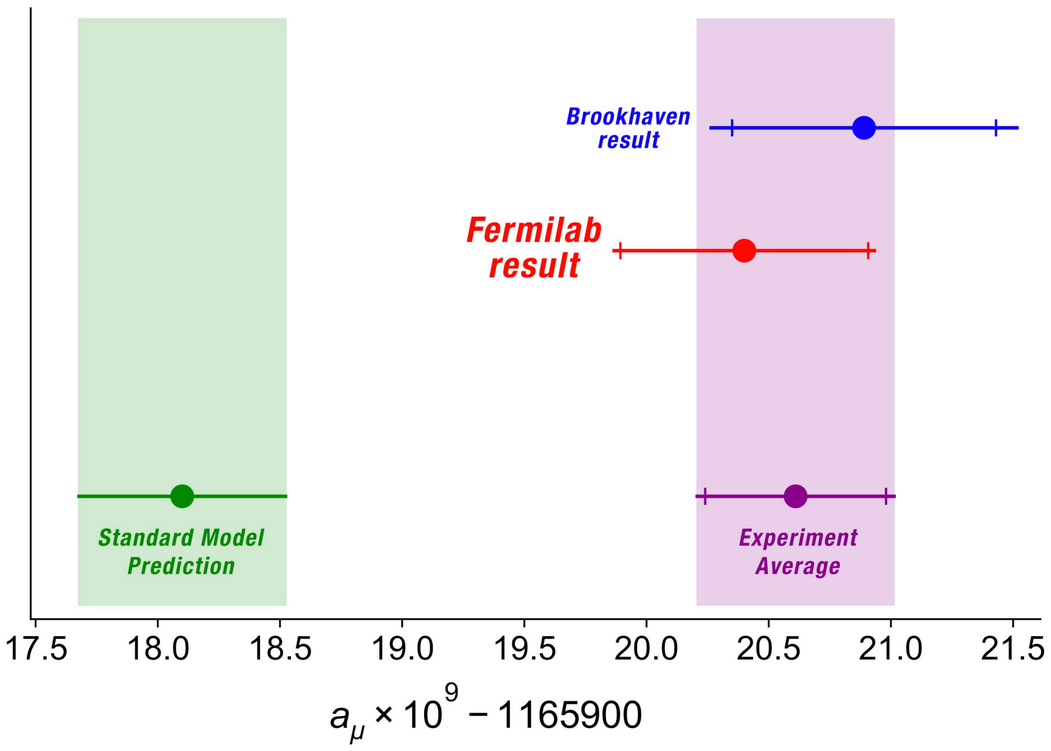






- Dark Matter
  - Missing stuff
    - B factories
    - Fixed target (missing X)
  - Re-scattering
    - Neutrino experiments
    - Other beam dumps
  - Milli-charged
    - pp Colliders
    - Beam dumps
- Dark Mediator
  - Long-lived particles
    - pp Colliders
    - Fixed target/beam dumps
    - Kaon factories
    - B factories
  - Rare decays
    - Eta factories

What about muons?



Models redux: muons

Credit: Brian Batell

	Invisible			Visible			
final state/ mediator	Long-lived	neutrinos $\nu\nu$	DM $\chi\chi$	photons $\gamma\gamma$	electrons e^+e^-	muons $\mu^+\mu^-$	hadrons $\pi\pi, \ldots$
vector	no(?)	yes	yes	no	no(?)	yes* ($m_V > 2m_\mu$)	no(?)
	• $L_\mu - L_\tau$ gauge boson: UV complete, automatic coupling to neutrinos, easy to couple to DM. (* $m_V > 2m_\mu$ constrained by dedicated *BABAR* search) • Challenging to build viable models with sizable couplings of vector mediator to electrons or hadrons (gauge anomalies, constraints from neutrino physics)						
scalar	yes ($m_S < 2m_\mu$)	yes	yes	yes ($m_S < 2m_\mu$)	yes ($m_S < 2m_\mu$)	yes ($m_S > 2m_\mu$)	yes ($m_S > 2m_\pi$)
	• All minimal signatures can be realized in scalar simplified models. • UV complete models require new SM-charged states above weak scale with special flavor structure (such states can in principle affect (g-2) • More phenomenological studies needed to chart the parameter space						
signature	missing momentum			prompt or displaced resonance			

https://indico.fnal.gov/event/48936

Discovering the new physics of g-2 with fixed target muon facilities at Fermilab

Tuesday Jun 22, 2021, 12:00 PM → 5:00 PM US/Central

Andrew Whitbeck (Texas Tech University), Christian Herwig (FNAL), Cristina Ana Mantilla Suarez (FNAL), Gordan Krnjaic (Fermilab), Nhan Tran (FNAL), Yonatan Kahn (University of Illinois at Urbana-Champaign)

Introduction
Introductory slides

Theory motivations
Speaker: Gordan Krnjaic (Fermilab)
MiniMuWorkshop.pdf

Theory phenomenology
Speaker: Brian Batell (University of Pittsburgh)
Batell-muon-pheno....

Muon beam options at Fermilab Accelerator Facility and discussion
Speaker: Nhan Tran (FNAL)
muon-beams-nt.pdf

(Minimal) M^3
Speaker: Cristina Ana Mantilla Suarez (FNAL)
CMS_M3_Jun22.pdf

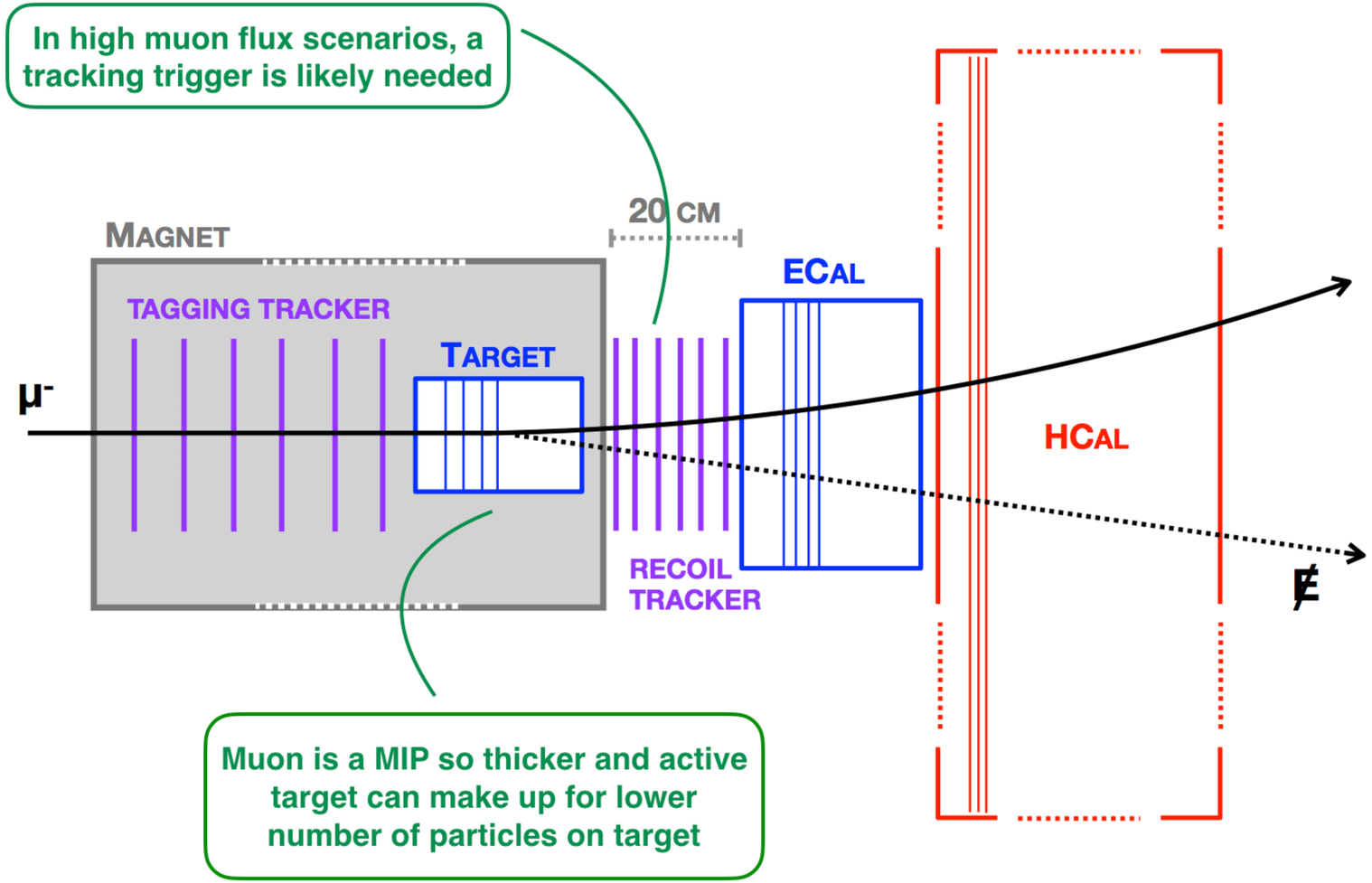
Muon beam dumps at muon campus
Speaker: Yiming Zhong (Boston University)
muon_beam_dump_...

DarkQuest
Speaker: David Sperka
DarkQuest_g2works...

M^3 in SpinQuest
Speaker: Philip Harris (MIT)
PCH_DQforM3_14_...

Muon missing momentum, M^3

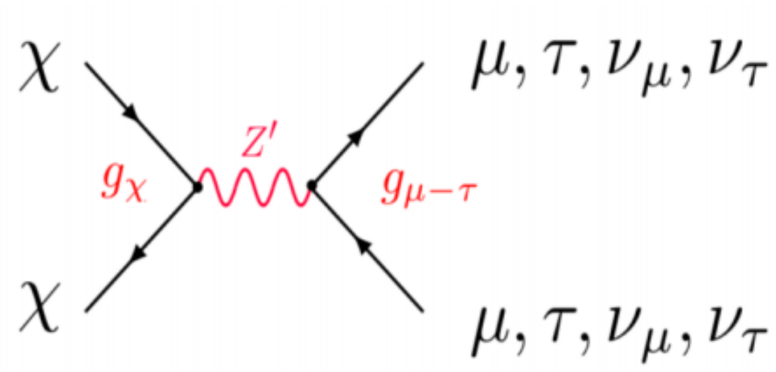
Y. Kahn, G. Krnjaic, N.T., A. Whitbeck
https://arxiv.org/abs/1804.03144

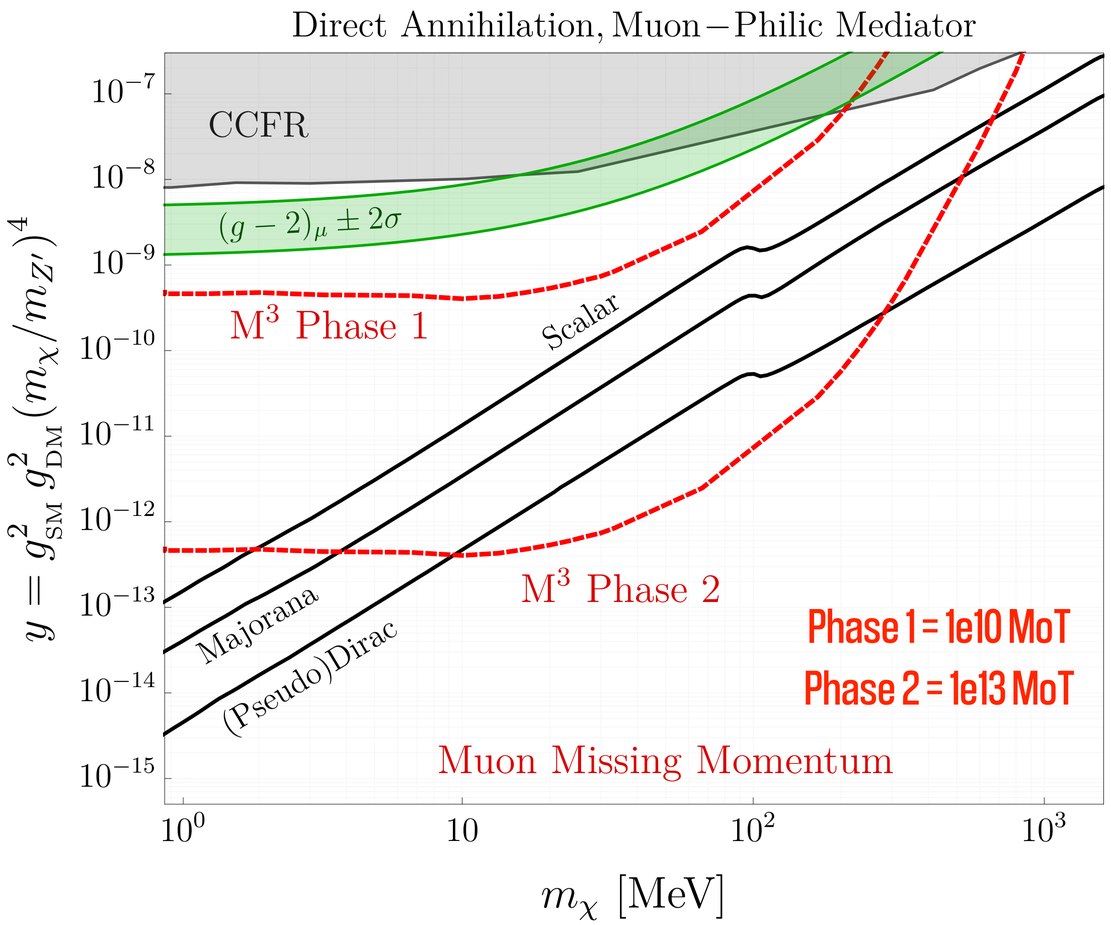


M³ sensitivity

Muon beams provide model-independent probe of light new physics contributing to $(g-2)_\mu$ anomaly

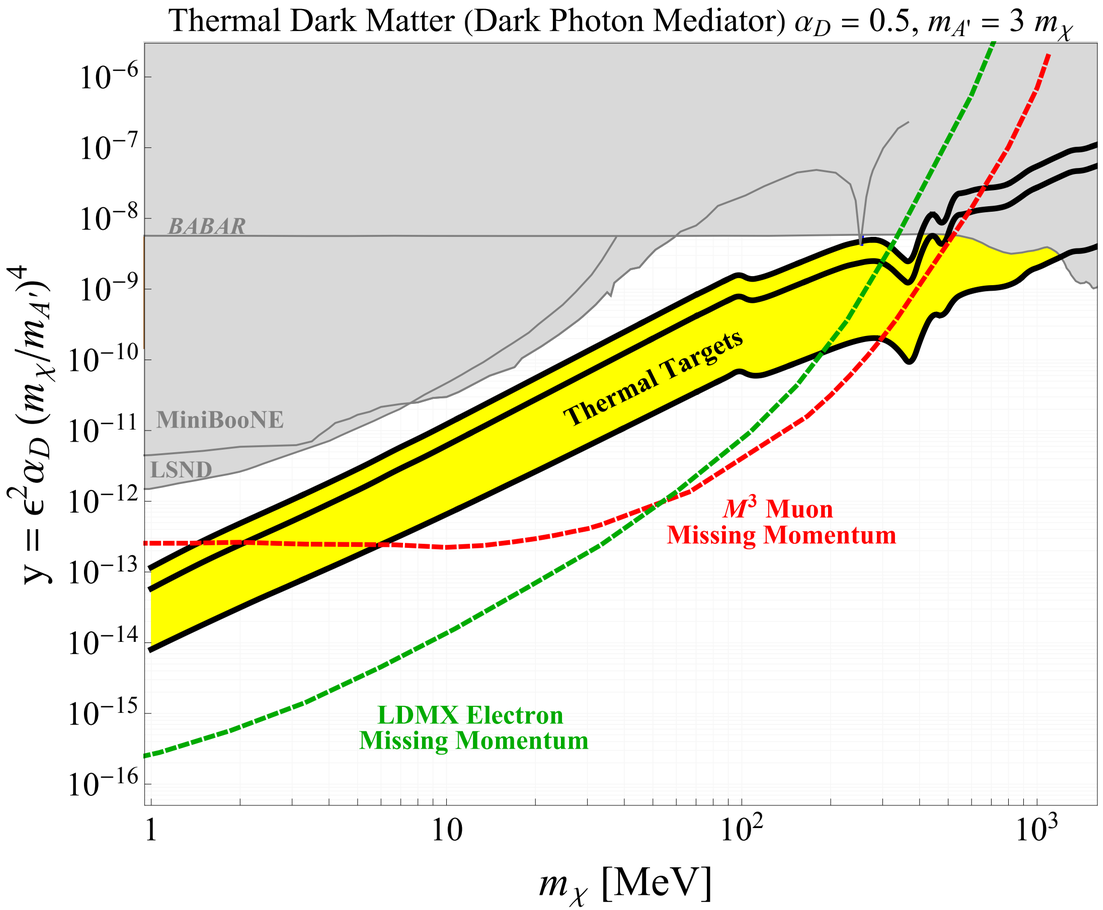
Muon-Philic Mediator, $L_{\mu-\tau}$





M³ sensitivity

Muon missing momentum has good sensitivity to m_χ > ~m_μ for flavor agnostics models too



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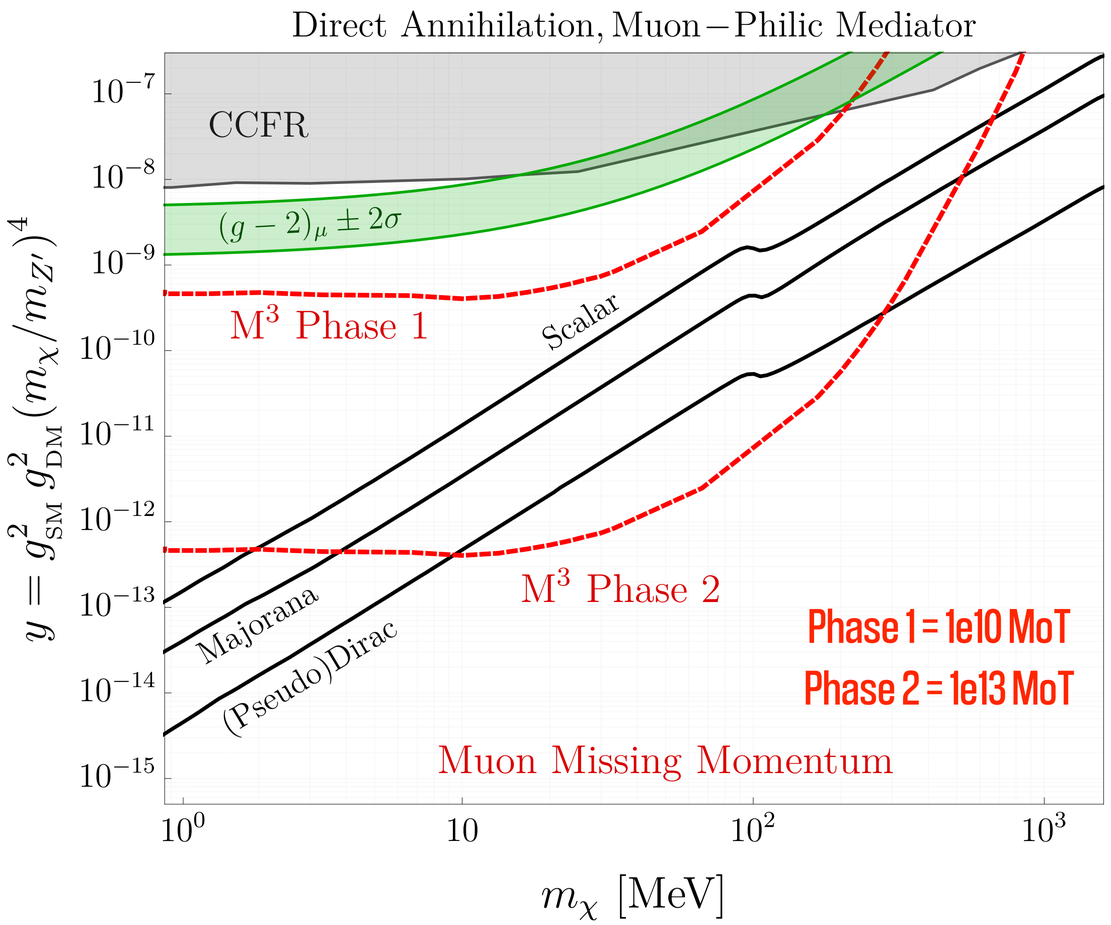
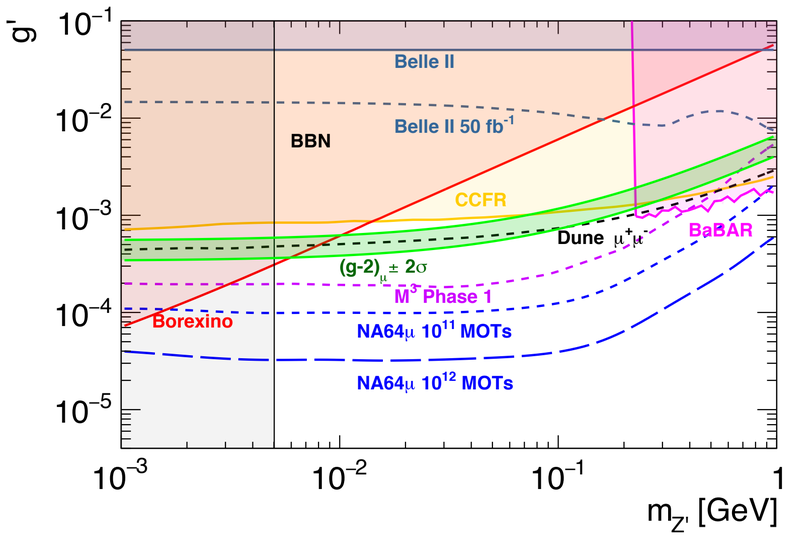


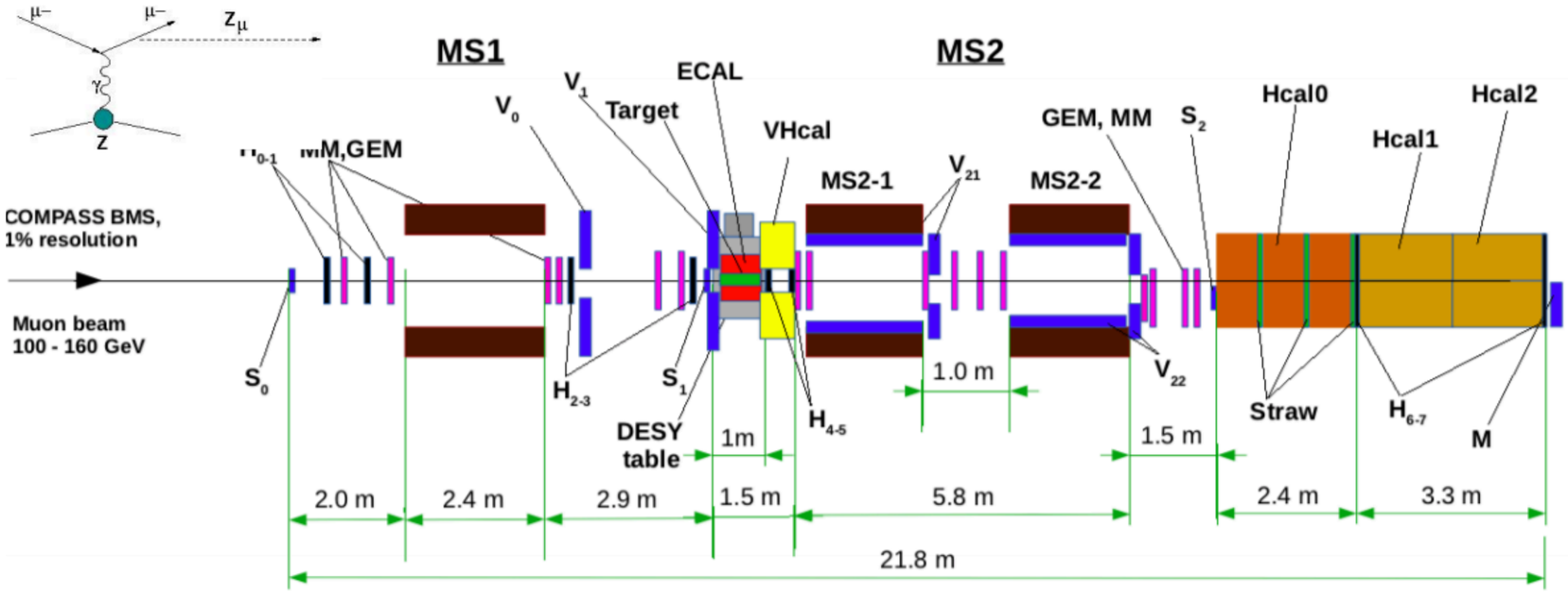
S. Gninenko talk at PBC
https://arxiv.org/abs/2110.15111

NA64-μ



- Proposed at the M2 beam line at CERN
- 100-160 GeV secondary muon beam
- Same missing momentum concept, but stretched out due to higher beam energy - **pilot run in 2021**

With similar phasing to M^3, NA64μ shows comparable sensitivity



"Muon beam dumps"

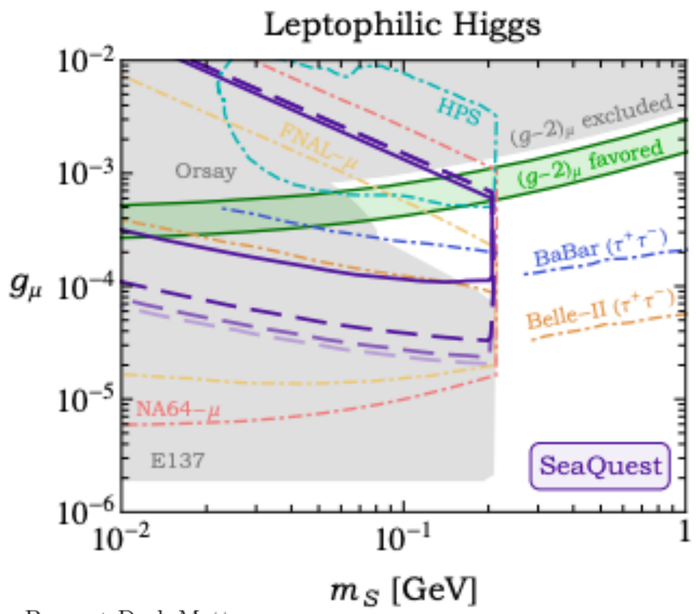
Berlin, Gori, Toro, Schuster
http://arxiv.org/pdf/1804.00661.pdf

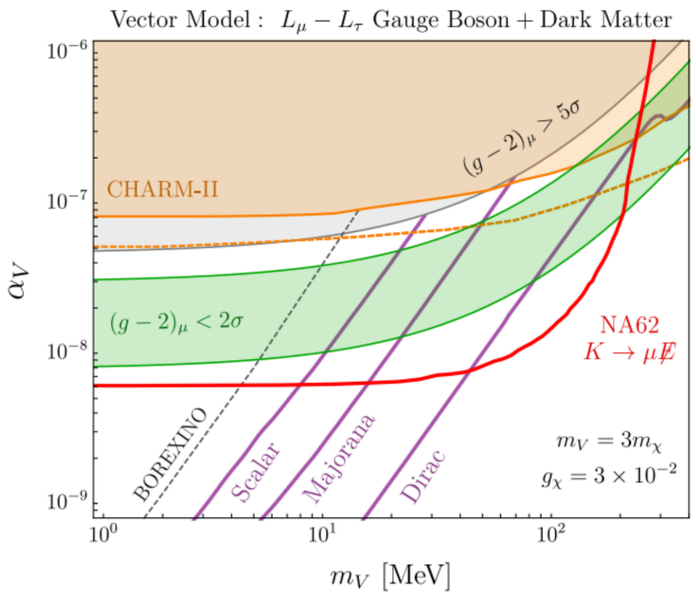
Redigolo
Snowmass talk

- Here the proton versatility shows
- Produces mesons which produce muons

- DarkQuest: muons are created in the dump via pion production and **effectively becomes another muon beam dump**

- NA62 makes muons through K → μ+ν
  - Sensitivity to g-2 as well
  - Improve sensitivity by upgrading trigger to collect more single muon events





Outlook

Outlook & Discussion

- A number of experiments plan to explore dark sectors landscape at accelerators in the next decade
  - Some exist, some are in R&D, and some are proposed

- We are at a critical stage in Snowmass where organizing principles can help better understand strengths, complementarity, and prioritization of experiments