Dark sectors at fixed-target experiments

(focused on U.S.-based facilities)

Nhan Tran
Fermilab

Aug 10, 2023
Windows on the Universe, Rencontres du Vietnam

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See Matt Citron's complementary talk on worldwide efforts!

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Outline

- Motivations and some context
- How to make the dark sector
- How to see the dark sector
- Some unique (, well-motivated but biased, US) examples

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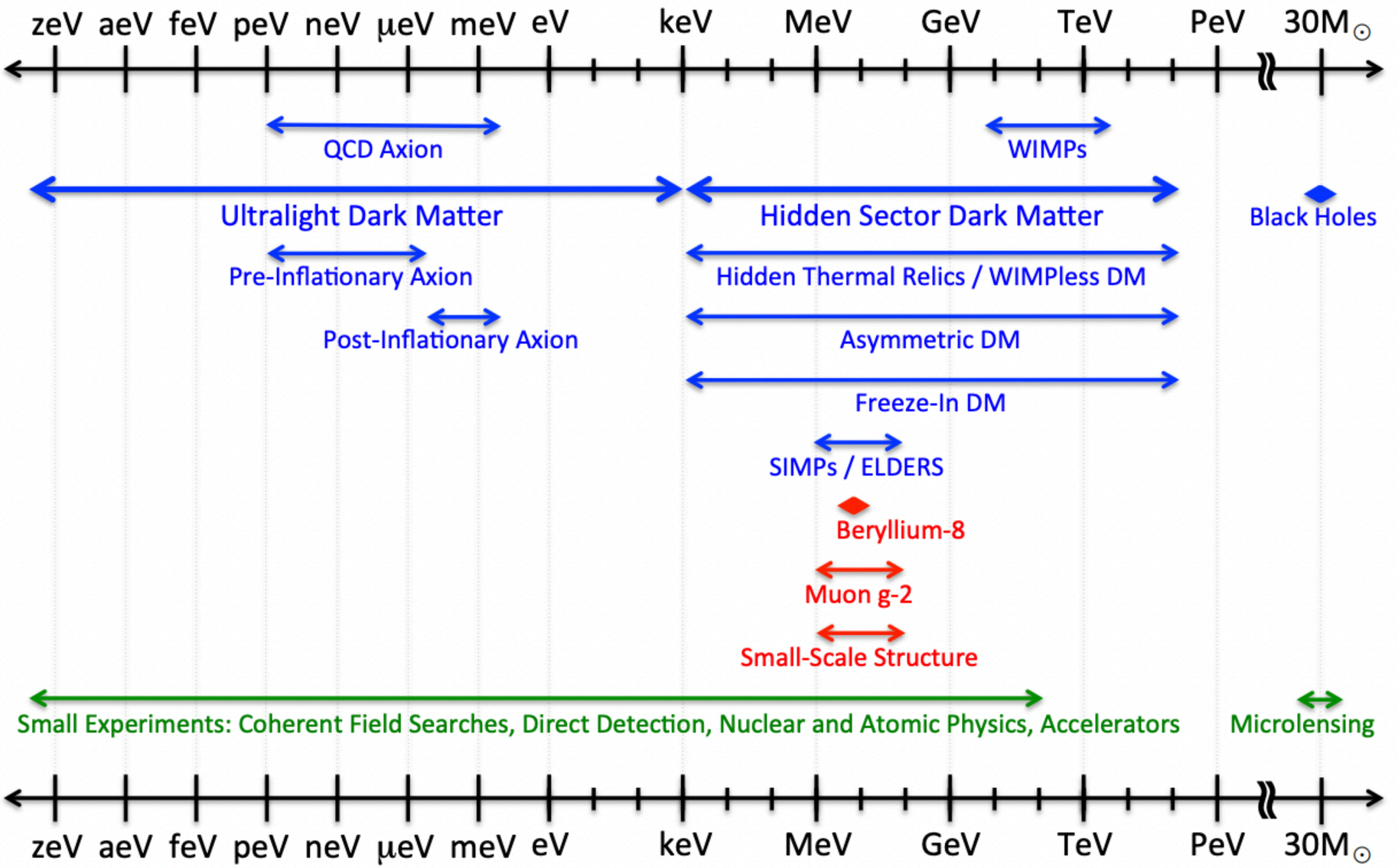
High level reference material:

Dark Sectors at high intensity Snowmass report: https://arxiv.org/pdf/2209.04671.pdf

FIPS 2022 report: https://arxiv.org/pdf/2305.01715.pdf

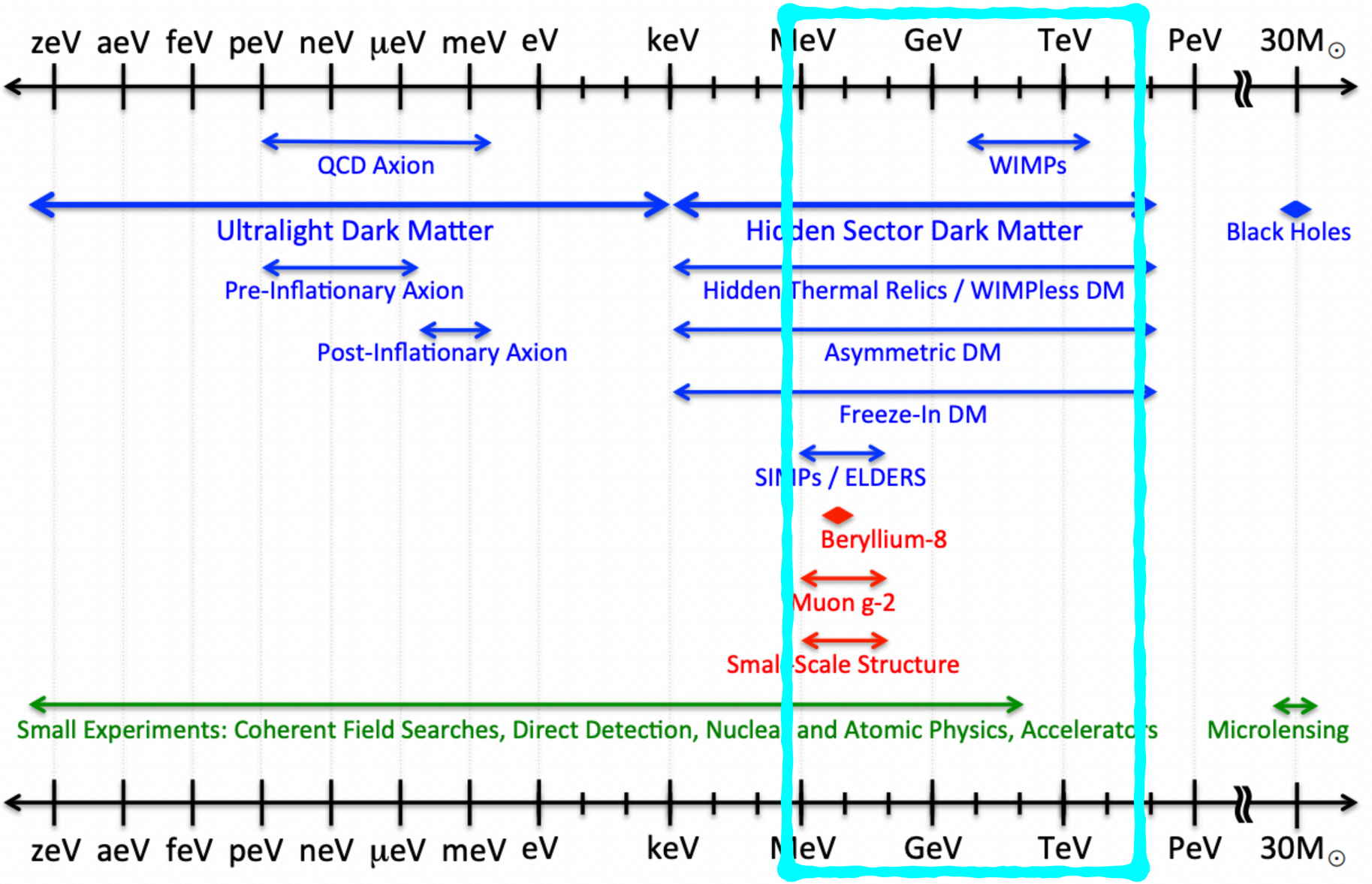
Motivations & context

Dark Sector Candidates, Anomalies, and Search Techniques



Cosmic Visions, https://arxiv.org/abs/1707.04591

Dark Sector Candidates, Anomalies, and Search Techniques



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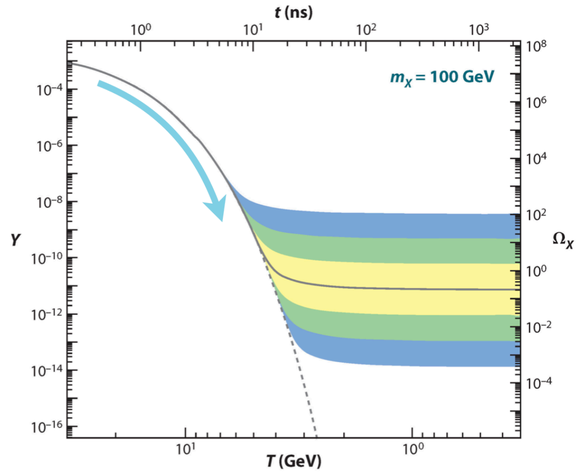
Narrowing the mass range

See Céline Boehm's great talk!

Cosmic Visions, https://arxiv.org/abs/1707.04591

Physics drivers

- **Dark matter** exists
  - Thermal freeze-out DM narrows the mass range to ~MeV-TeV
    - **Predictive**: relic density provides clear milestones
    - UV insensitive, easily realized
  - WIMP searches — thus far no discovery
- **Dark sectors** can solve many experimental/theoretical puzzles
  - Dark sectors mean SM-neutral forces (typically < ~GeV)
    - Can include dark matter
  - For parts of phase space, visible (SM) final states needed for discovery



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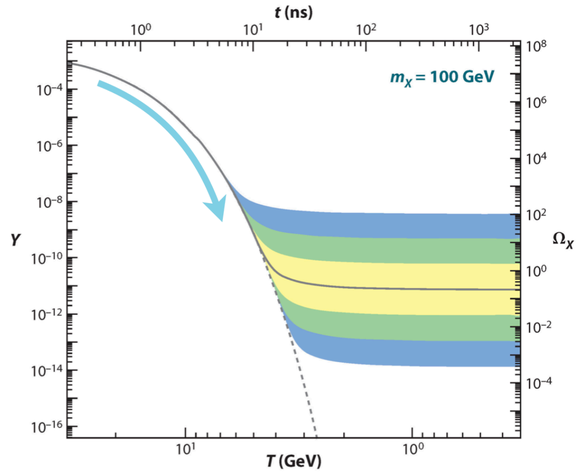


Can we develop a comprehensive worldwide program for sub-GeV dark sectors?

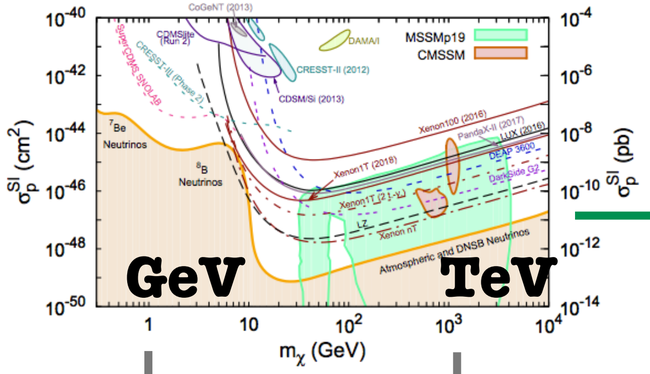
Thermal, but not WIMP

CDM bound

BBN bound

~100 TeV,
Violate unitarity

keV MeV GeV TeV



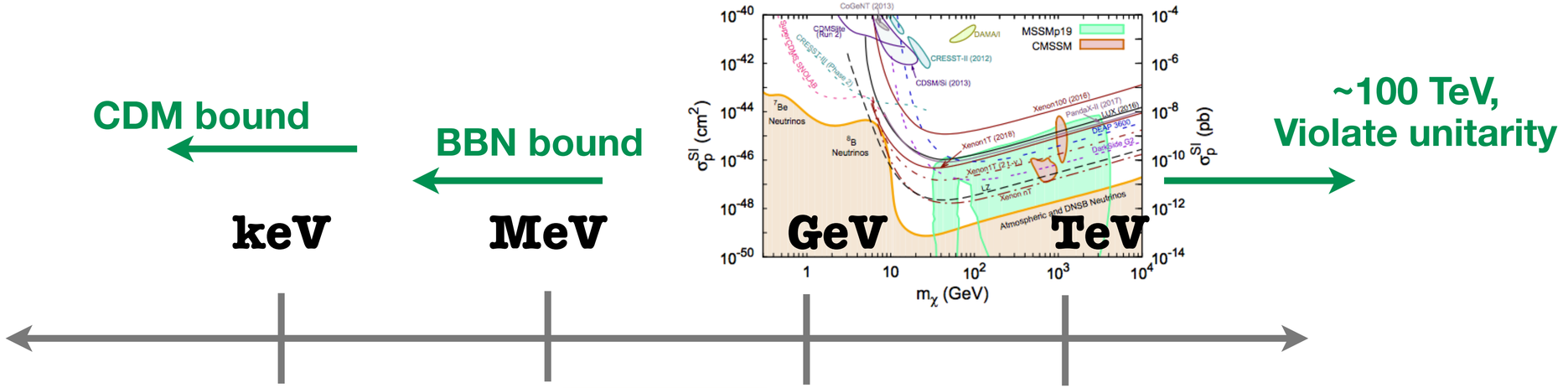
DIRECT DETECTION

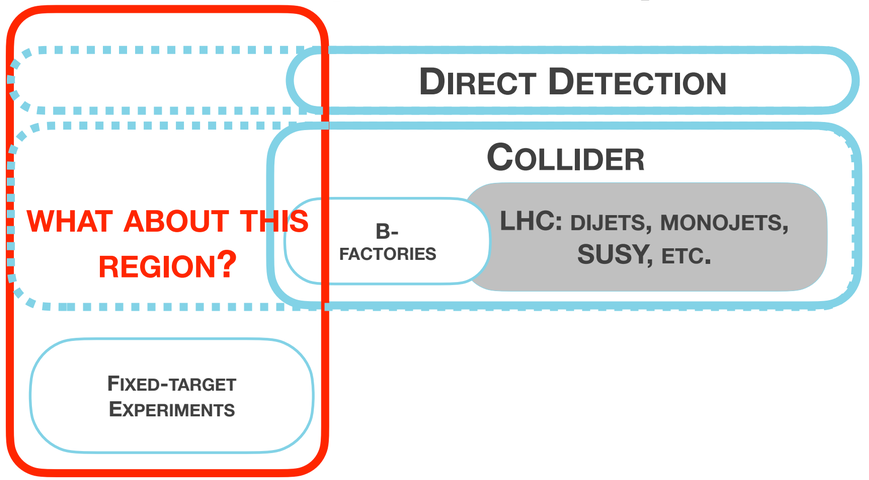
COLLIDER

B-FACTORIES

LHC: DIJETS, MONOJETS, SUSY, ETC.

Thermal, but not WIMP



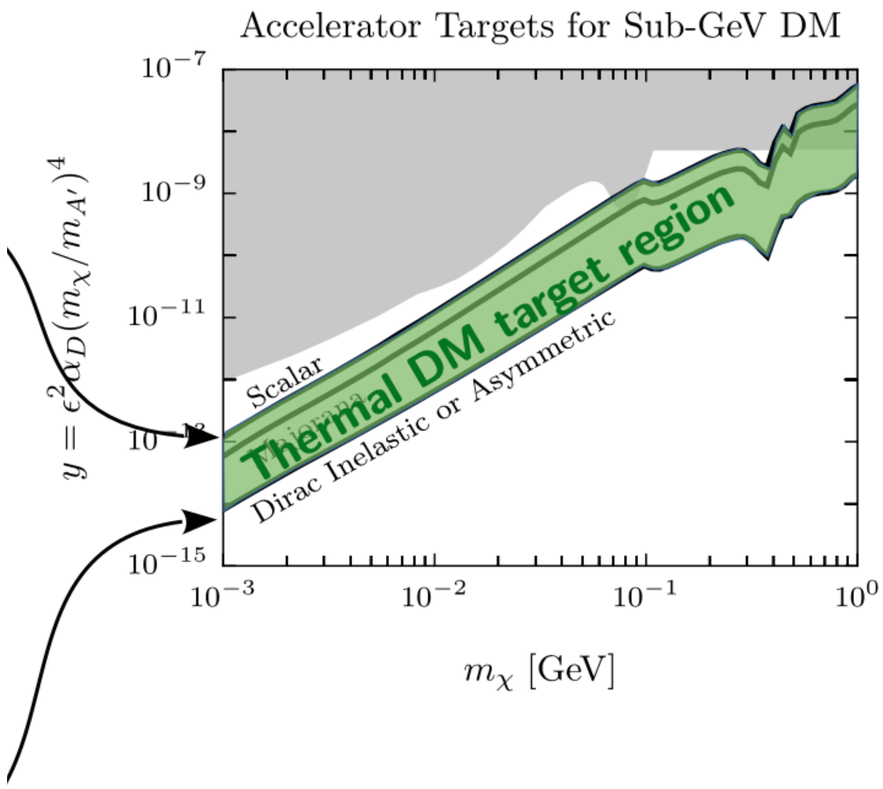


Lee-Weinberg bound,
light DM requires light mediators
→ ***Dark Sectors***

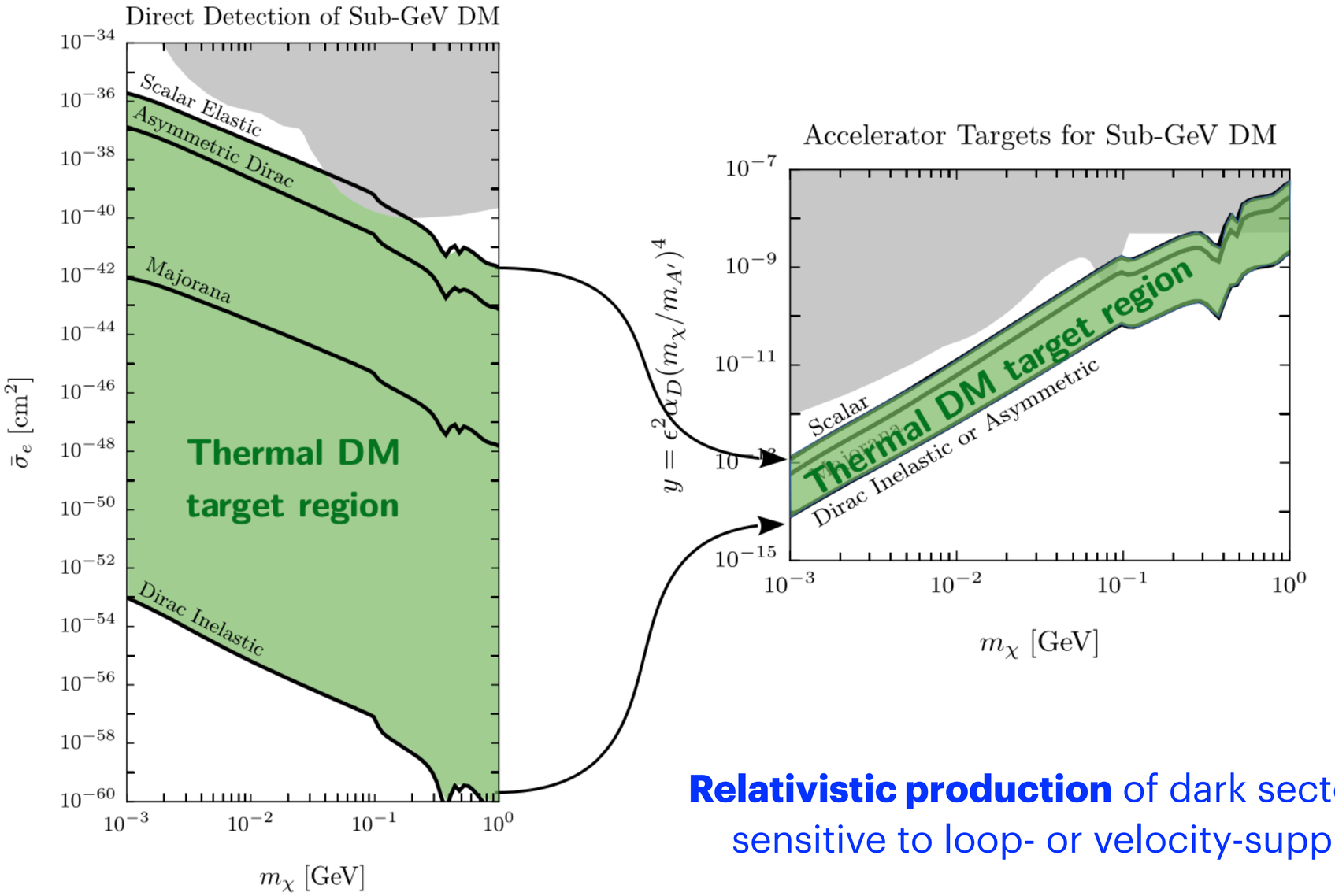
NORMAL MATTER LIVES HERE. WHY NOT DM?

+ Curious results…
muon g-2*, proton radius puzzle, MiniBooNE/MicroBooNE excess, Xenon-1T excess, flavor anomalies, neutron lifetime anomaly*

Accelerators and complementarity



Accelerators and complementarity



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

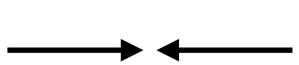
How to make the dark sector

How to make the dark sector 101

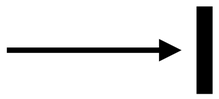
Particle beams
$e^{\pm}$,p,μ

+

Collider



Fixed Target

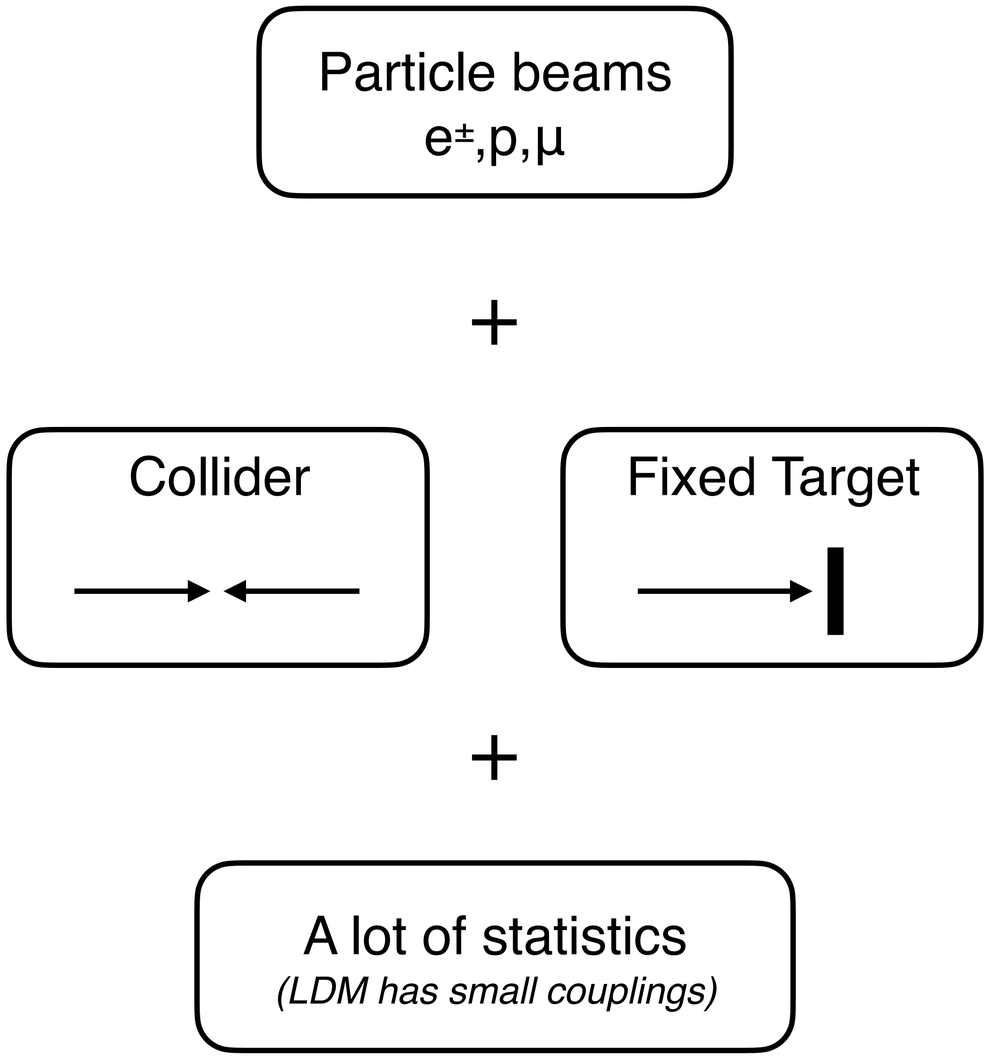


+

A lot of statistics
(LDM has small couplings)

In freeze-out: A lighter DM particle means higher number density means smaller coupling

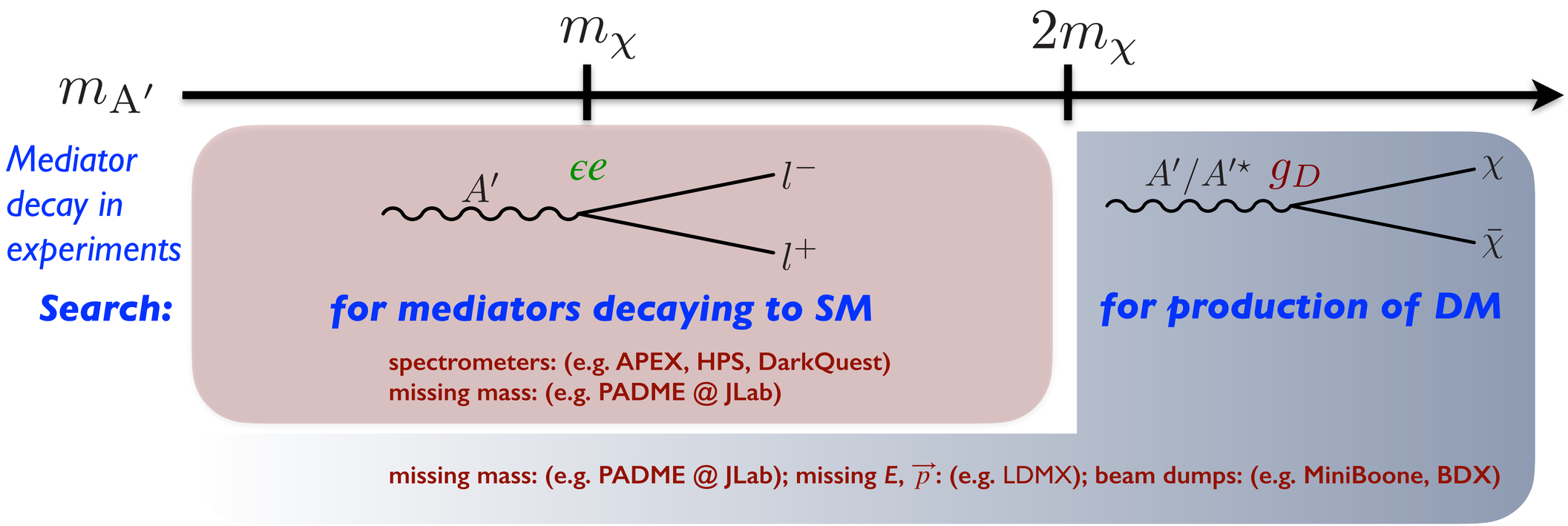
How to make the dark sector 101



- **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

How to “see” the dark sector

Visible and invisible - a simple schematic



T Nelson

A schematic taxonomy

Stefania Gori, Mike Williams

Invisible, non-SM

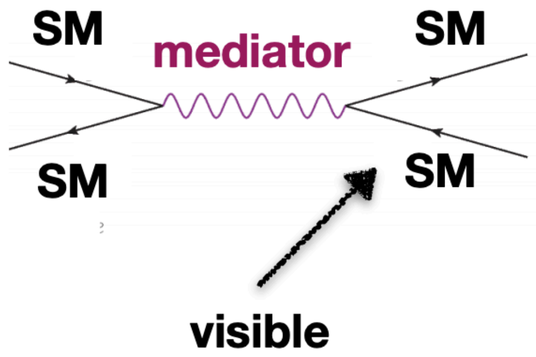
Dark Matter production

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

Visible, SM

Production of portal-mediators that decay to SM particles

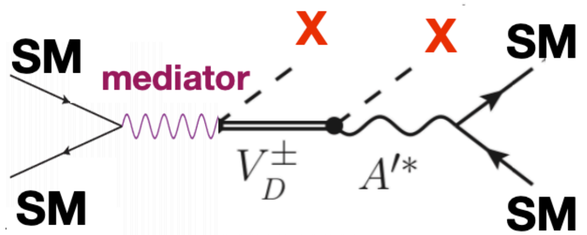
Systematically exploring the portal coupling to SM particles



Mixed visible-invisible

Production of "rich" dark sectors

Testing the structure of the dark sector



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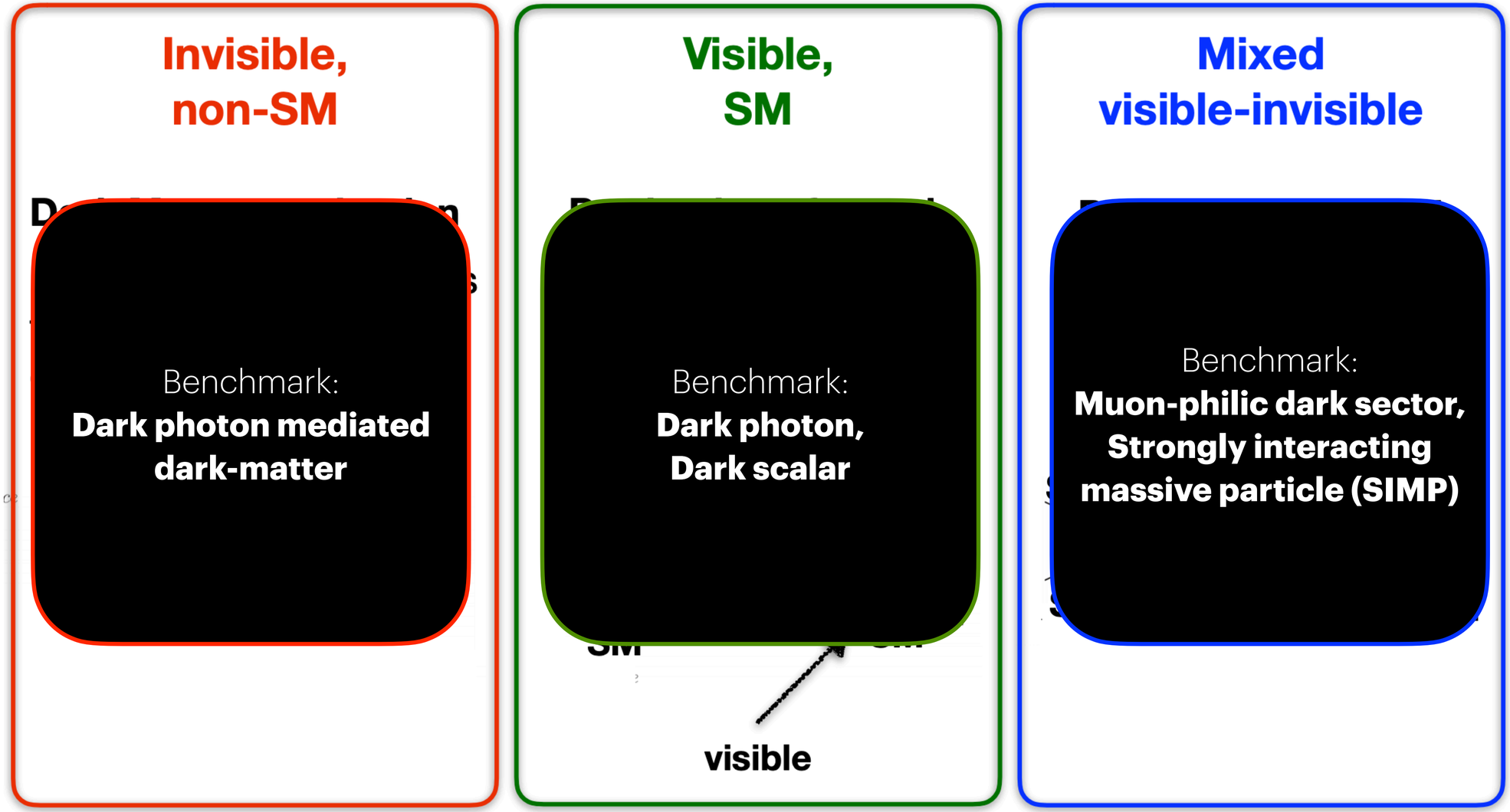
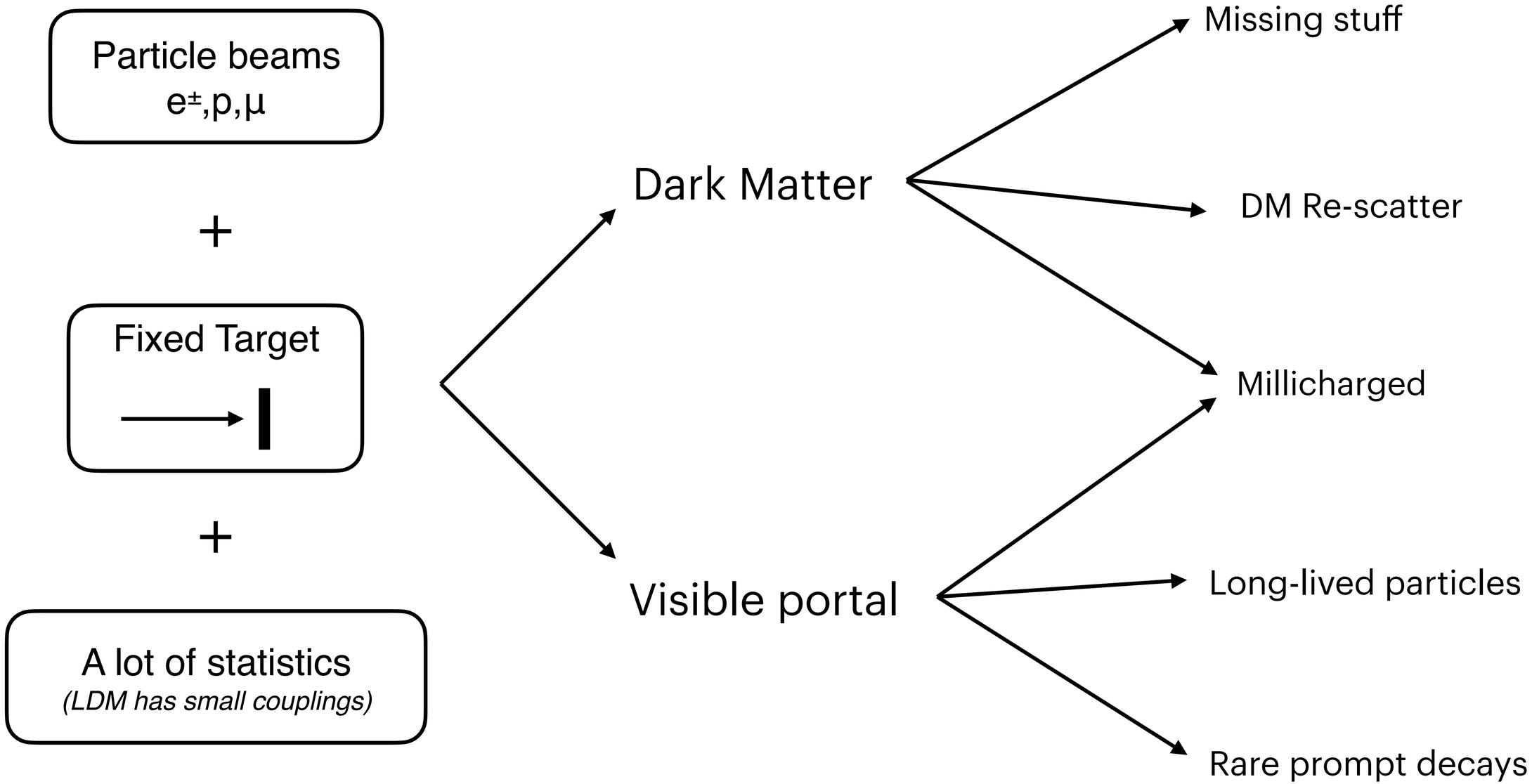
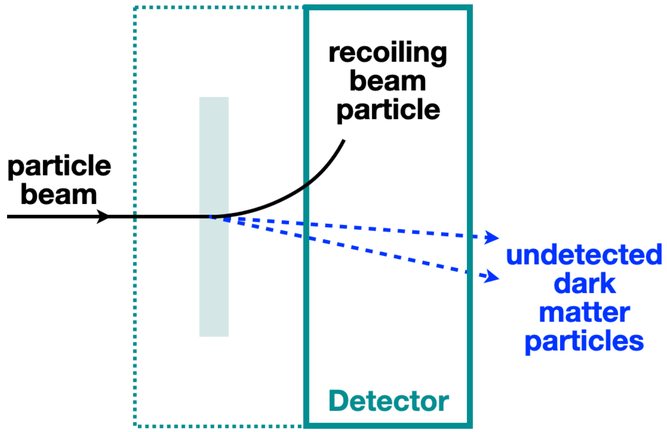


** Chosen from a finite number of possible portals: Vector, Higgs, Neutrino, Axion*


Particle beams
e±,p,μ
+
Fixed Target
+
A lot of statistics
(LDM has small couplings)
Dark Matter
Visible portal
Missing stuff
DM Re-scatter
Millicharged
Long-lived particles
Rare prompt decays

Schematic experiments

Missing stuff



Schematic experiments

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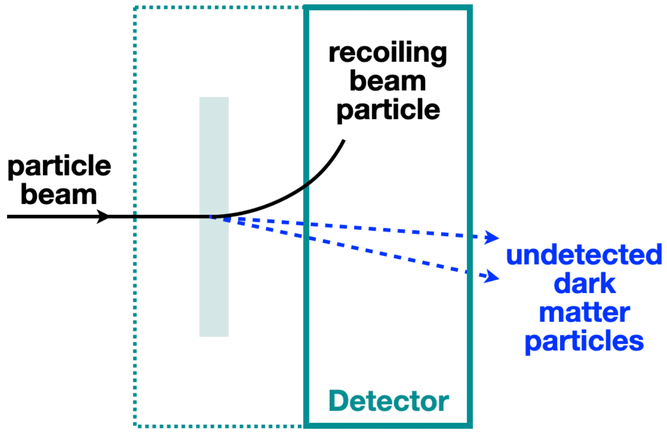
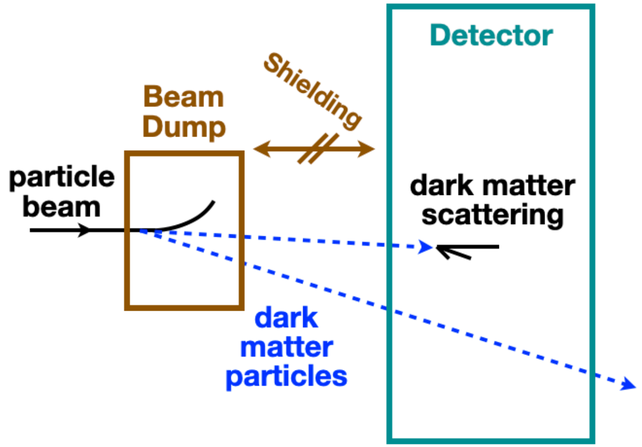
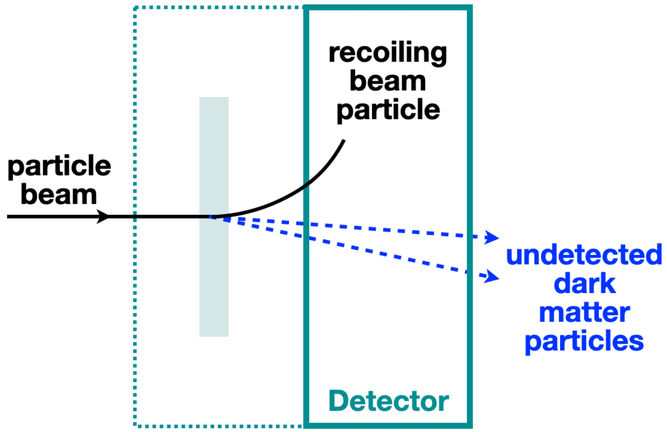


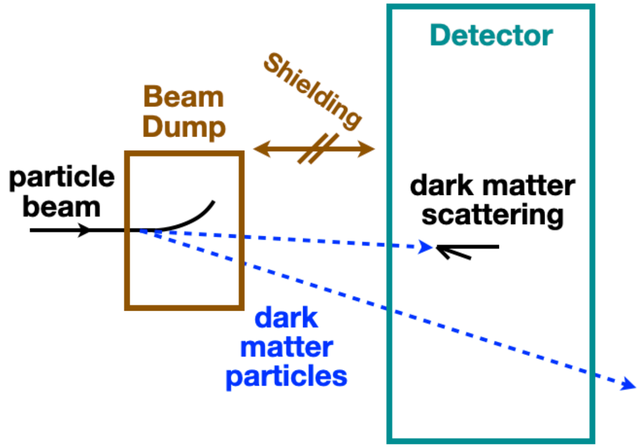


Re-scattering/ Millicharged

Schematic experiments

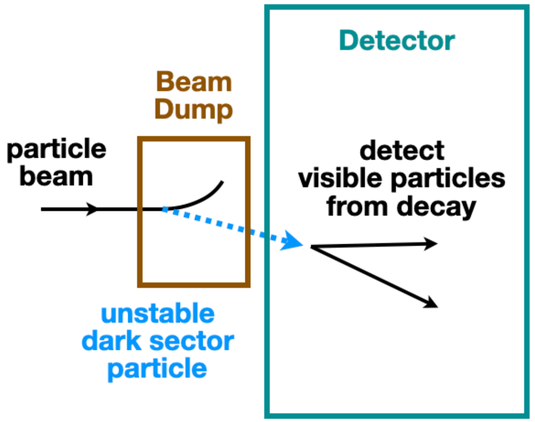
Missing stuff





Re-scattering/ Millicharged

Long-lived



Schematic experiments

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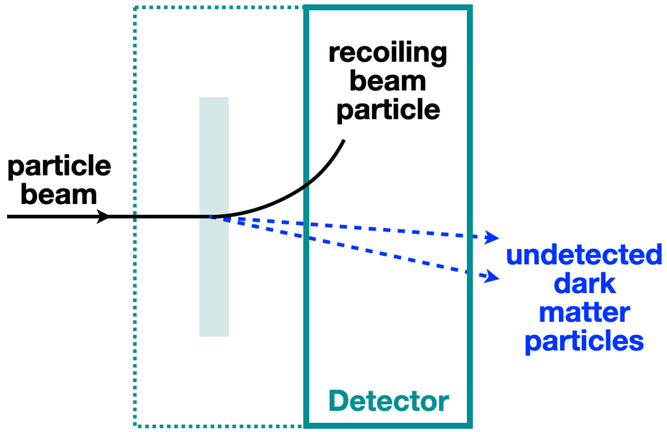

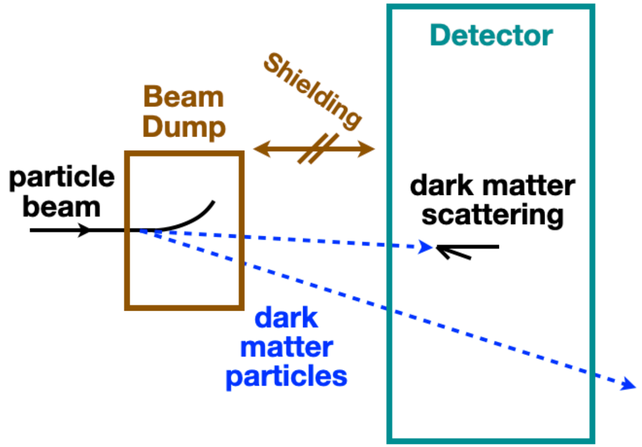

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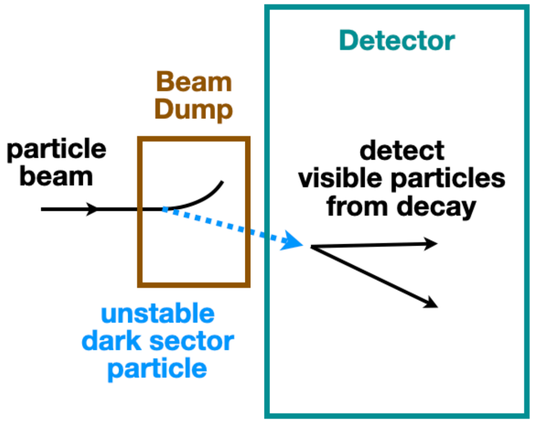
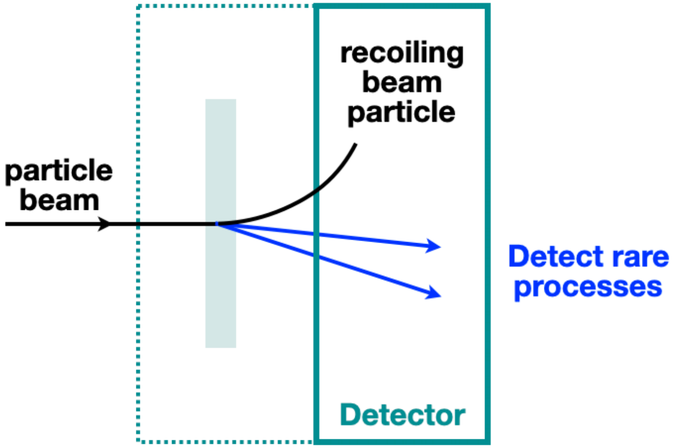




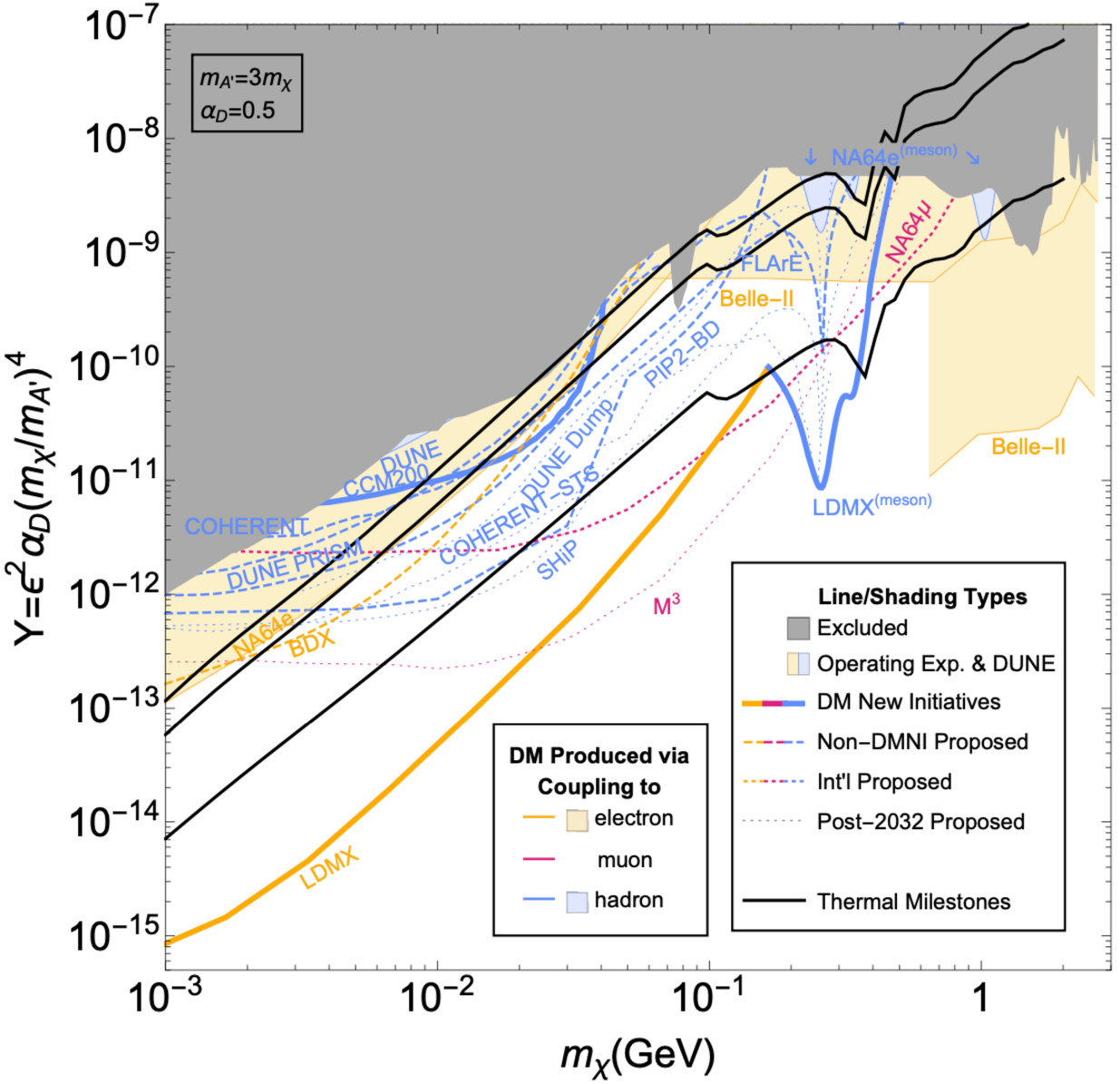
Rare, prompt

Some unique (, well-motivated but biased, US) examples

No shortage of ideas!

Experiment	Facility	Beam Config	Beam Energy	Det Signature	Timeline	Refs.
US-based						
HPS	CEBAF @ JLab	electron FT	1-6 GeV	LLP	running	section 3.15, [16]
COHERENT	SNS @ ORNL	proton FT	1 GeV	rescattering	running	section 4.5, [17]
CCM	LANSE @ LANL	proton FT	0.8 GeV	rescattering	running	[18]
SpinQuest/DarkQuest	MI @ FNAL	proton FT	120 GeV	LLP	construction, proposed upgrade	section 3.5, [19]
LDMX	LESA @ SLAC	electron FT	4-8 GeV	Missing X	R&D funding, 2024	section 3.17, [20]
BDX	CEBAF @ JLab	electron BD	11 GeV	rescattering, Millicharged	proposed	section 3.1, [21]
JPOS	CEBAF @ JLab	positron FT	11 GeV	Missing X	proposed	section 3.16, [22]
PIP-II BD	PIP-II @ FNAL	proton FT	1 GeV	rescattering, LLP	proposed (2029)	section 3.23, [23]
SBN-BD	Booster @ FNAL	proton BD	8 GeV	rescattering	proposed (2029)	[24]
REDTOP	TBD	proton FT	1-5 GeV	Missing X, LLP, Prompt	proposed	section 3.25, [25]
M^3	MI @ FNAL	muon FT	15 GeV muons	Missing X	proposed	[26]
FNAL-μ	muon campus @ FNAL	muon FT	3 GeV	LLP	proposed	section 3.13, [27]
International						
Belle-II	SuperKEKB @ KEK	e+e- collider	150 MeV	Missing X, LLP, Prompt	running	section 3.2, [28]
CODEX-β	LHC @ CERN	pp collider	6.5-7 TeV	LLP	construction (2023)	section 3.4, [29]
CODEX-b	LHC @ CERN	pp collider	6.5-7 TeV	LLP	proposed (2026)	section 3.3, [30]
LHCb	LHC @ CERN	pp collider	6.5-7 TeV	LLP, Prompt	running, future upgrade planned	section 3.18, [31]
NA62	SPS-H4 @ CERN	proton BD	400 GeV	LLP	dedicated running planned	[32]
FASERnu	LHC @ CERN	pp collider	6.5-7 TeV	rescattering	running	section 3.9, [33]
milliQAN	LHC @ CERN	pp collider	6.5-7 TeV	Millicharged	running	section 3.19, [34]
DarkMESA	MESA @ Mainz	Electron FT	150 MeV	rescattering, LLP	construction (2023)	section 3.6
NA64-e	SPS-H4 @ CERN	electron FT	100-150 GeV	Missing X, Prompt	running	section 3.20, [35]
NA64-mu	SPS-M2 @ CERN	muon FT	100-160 GeV	Missing X	commissioning	section 3.21
NA64/POKER	SPS-H4 @ CERN	positron FT	100 GeV	Missing X	planned (2024)	section 3.24, [35]
PIONEER	πE5 @ PSI	proton FT	10-20 MeV pions	Prompt	planned (2028)	section 3.22, [36]
FASER2	FPF @ CERN	pp collider	6.5-7 TeV	LLP	proposed (2029)	section 3.8 [37]
FORMOSA	FPF @ CERN	pp collider	6.5-7 TeV	Millicharged	proposed (2029)	section 3.14, [38]
FASERnu2	FPF @ CERN	pp collider	6.5-7 TeV	rescattering	proposed (2029)	section 3.10, [33]
FLArE	FPF @ CERN	pp collider	6.5-7 TeV	rescattering	proposed (2029)	section 3.12, [39]
SND@LHC	LHC @ CERN	pp collider	6.5-7 TeV	rescattering	running	section 3.27, [40]
Advanced SND@LHC	FPF	pp collider	6.5-7 TeV	rescattering	proposed (2029)	section 3.27, [40]

DM production: LDMX



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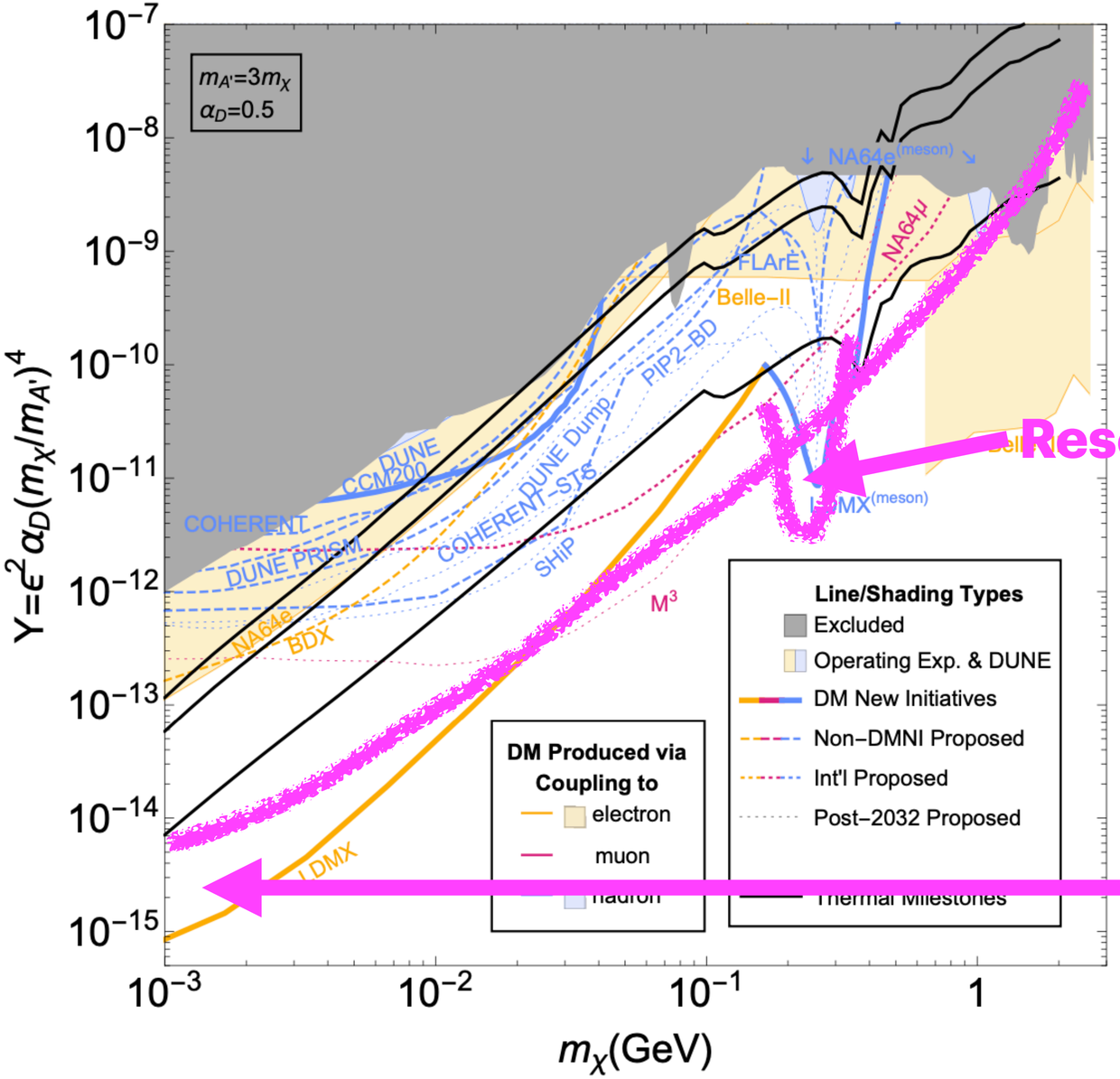
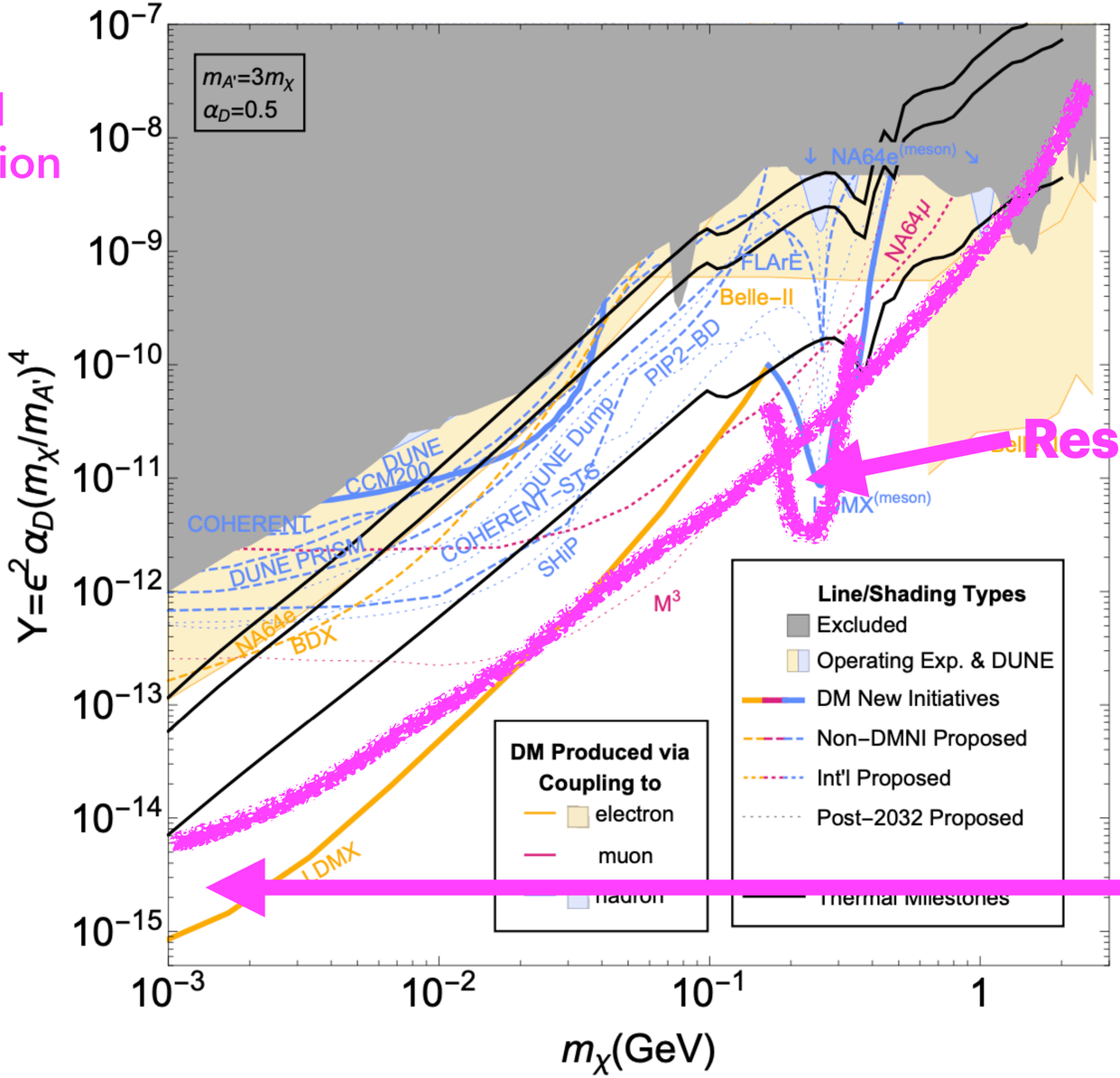


Resonant enhancements

Lighter DM, smaller coupling

DM production: LDMX

Complementarity in hadronic, electron and muon couplings exploration with rescattering and missing X

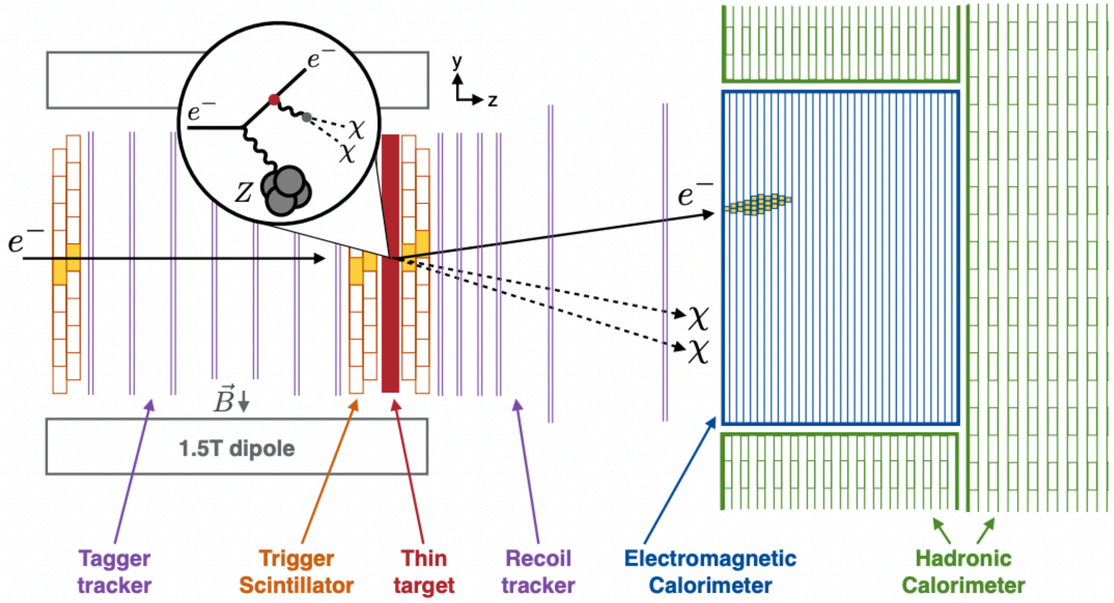


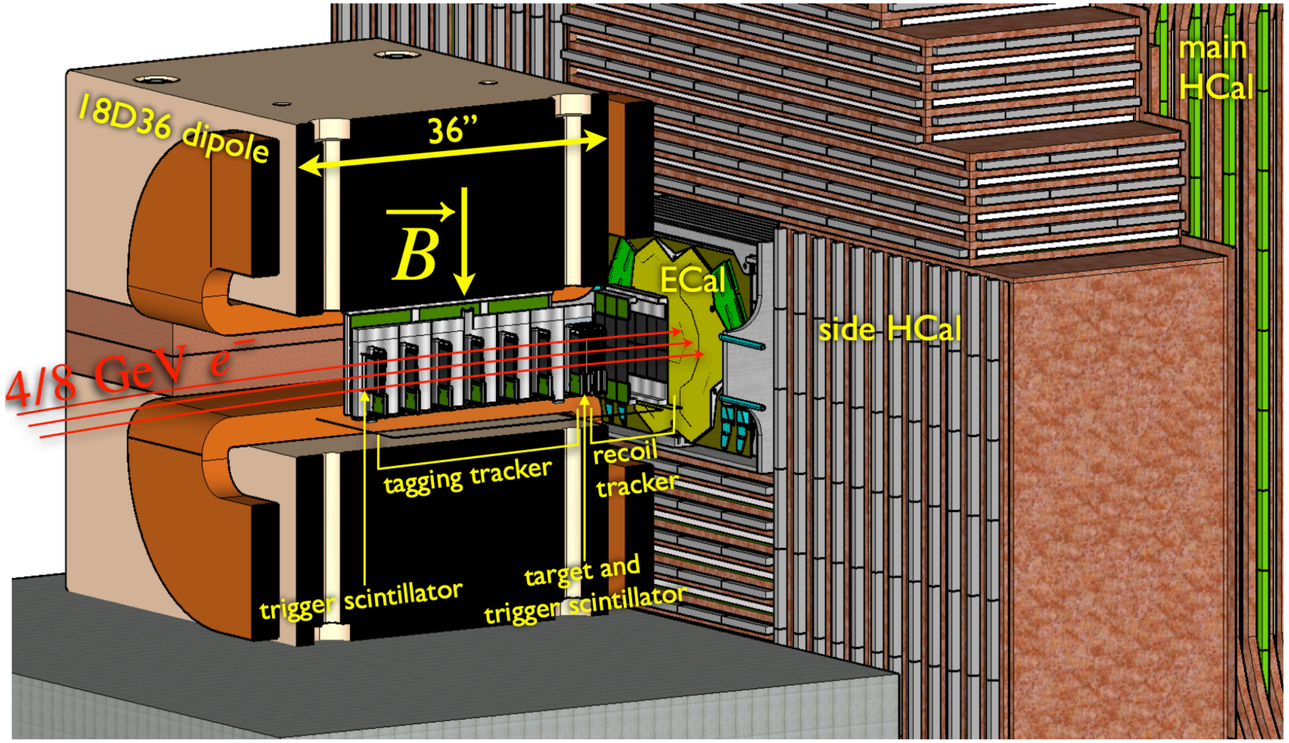
Resonant enhancements

Lighter DM, smaller coupling

LDMX @ SLAC

Missing momentum: electron loses significant momentum through the target





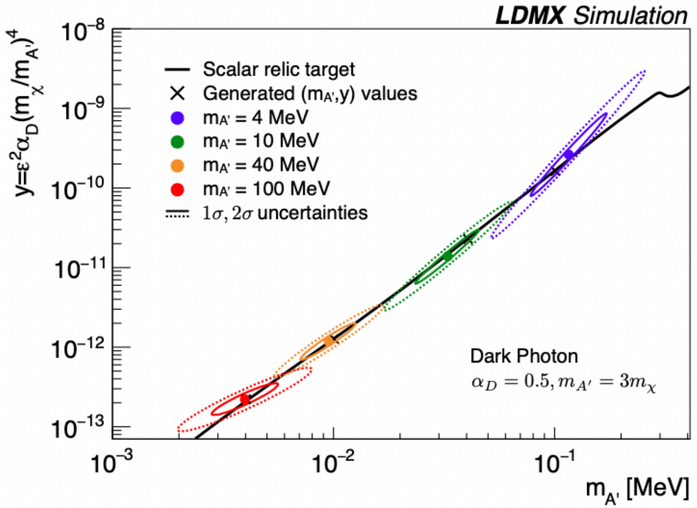
Key features:

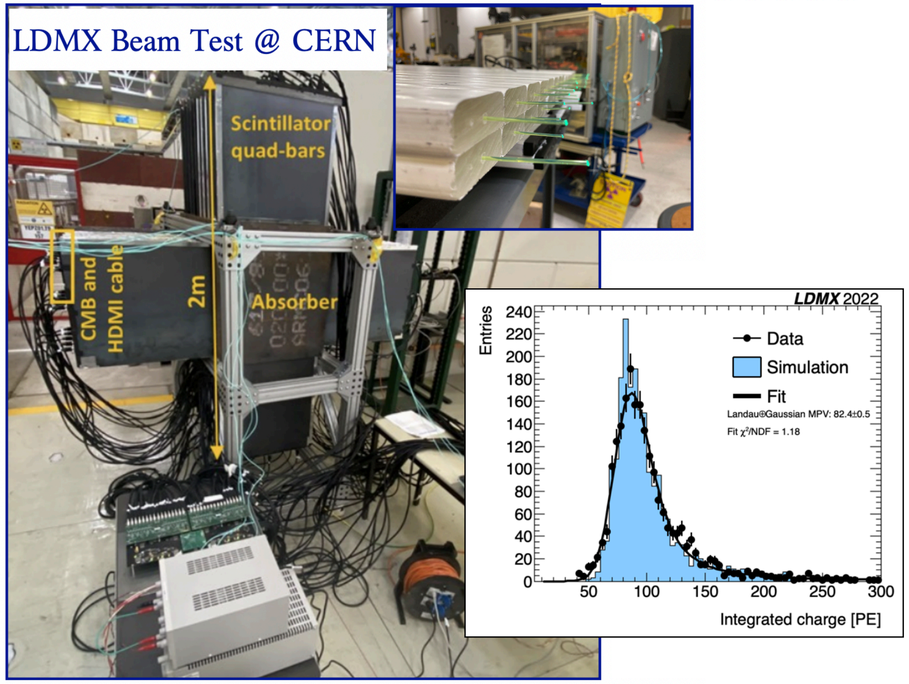
- A lot of electrons (> 1e14), but 1-at-a-time (low current)
- Tagging tracker with good resolution at beam energy
- Recoil tracker with good resolution at lower momentum
- Deep ECal with ***good granularity, resolution, radiation hard***
- Deep HCal with low threshold for veto
- Fast data acquisition system with efficient missing energy trigger

LDMX

https://arxiv.org/abs/2203.08192

- Recent progress in Snowmass white paper
  - Test beam campaign at CERN, more results coming!
  - New strategies for data-driven bkg estimation, missing energy analysis, signal characterization, etc.
- LDMX has received DOE R&D funding (DMNI)
  - Planning for operation ~3 years after construction funding available

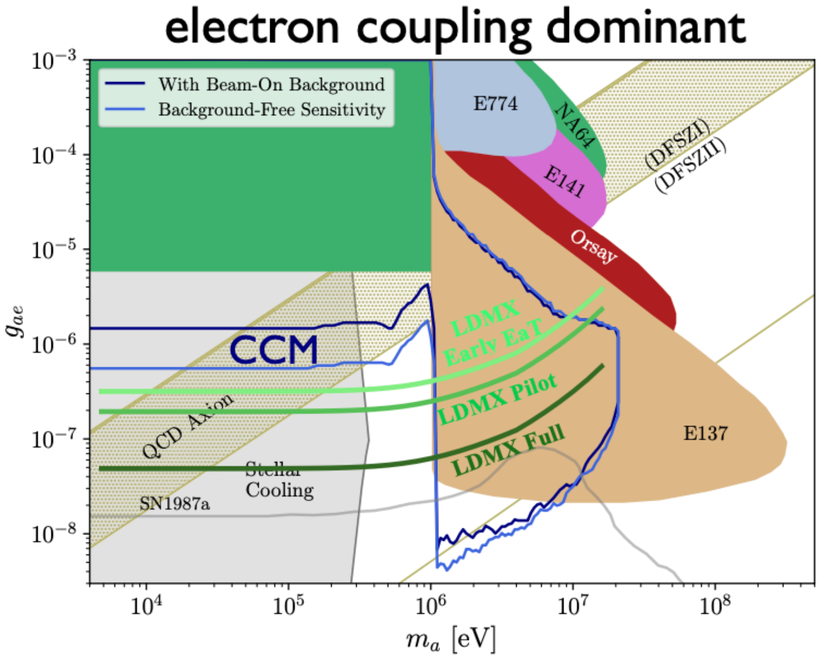




More LDMX physics

Can cover other scenarios in the **invisible final state** such as QCD axion, millicharged, inelastic DM, etc.

Some prospects also for visible final states (ALPs, dark photon)
https://arxiv.org/abs/1807.01730



Adapted from:
https://arxiv.org/abs/2112.09979

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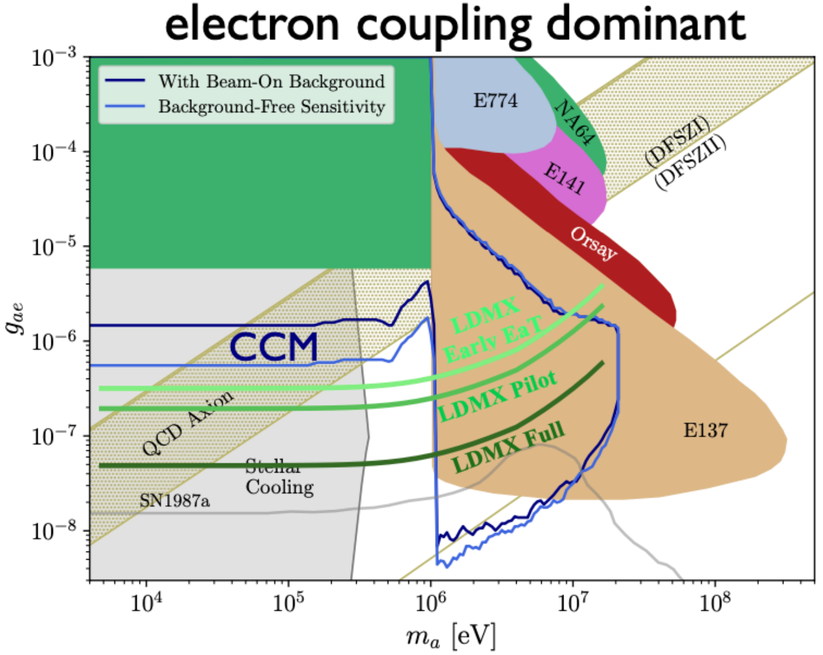

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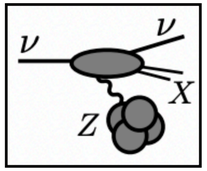
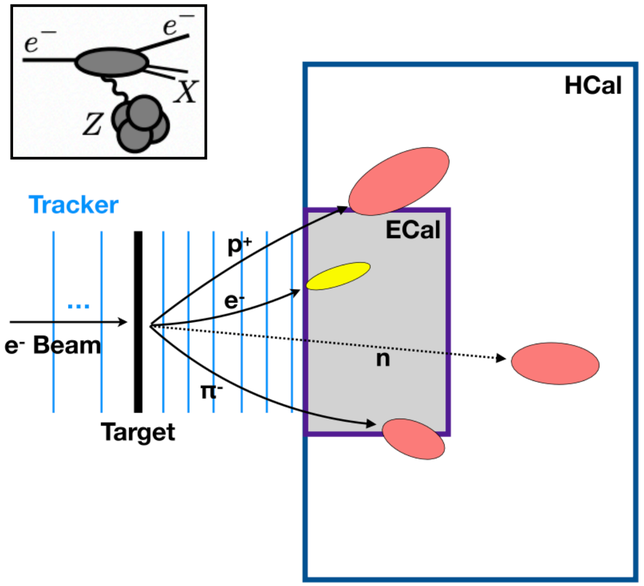
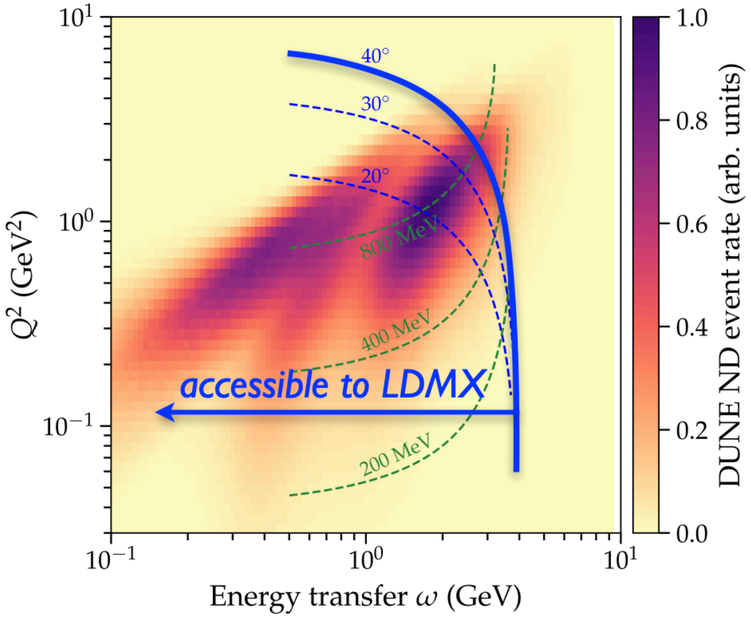
https://arxiv.org/abs/1912.06140
https://arxiv.org/abs/2203.06853





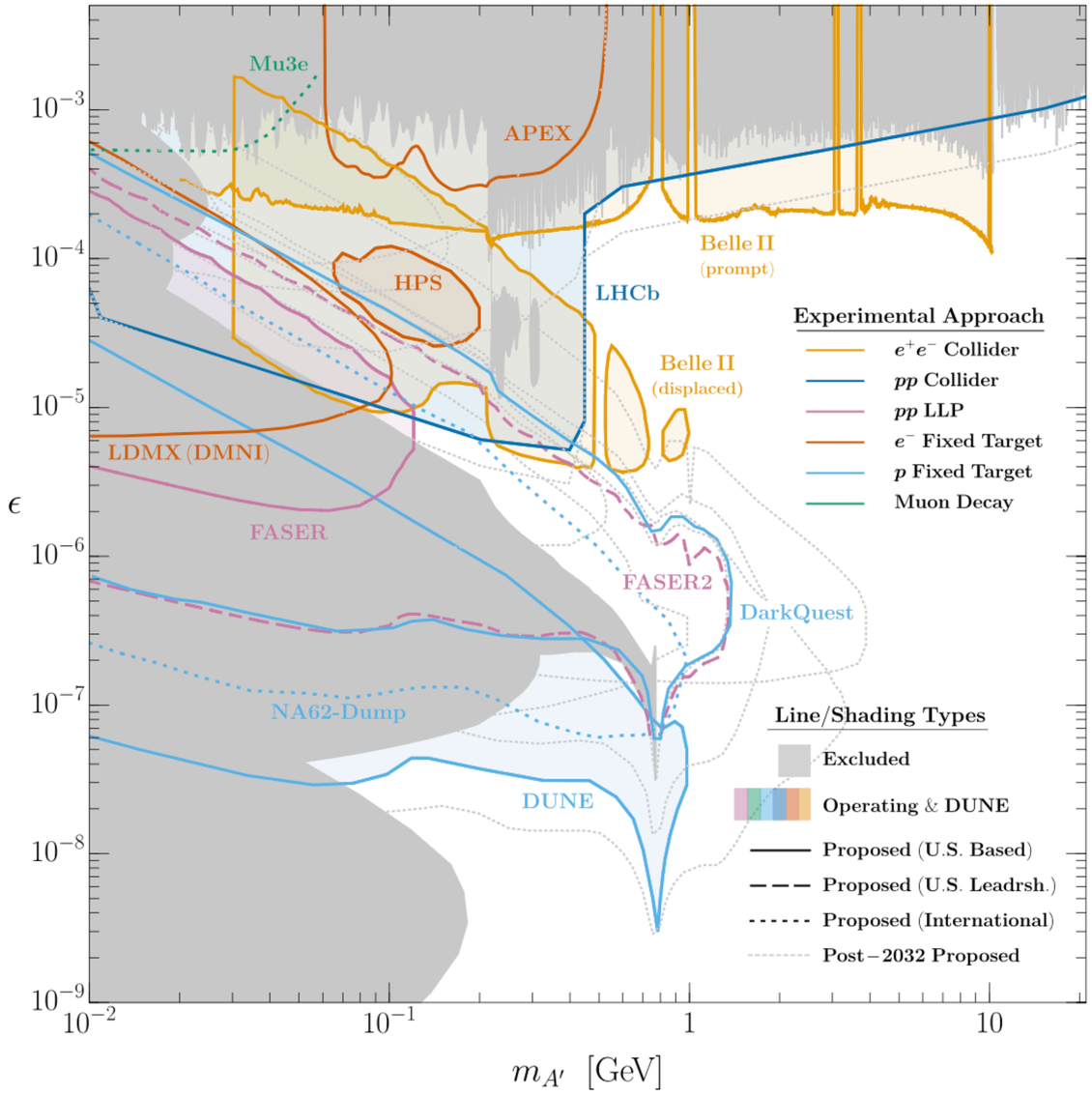


Electron scattering experiments and connection to neutrino physics: landscape and complementarity

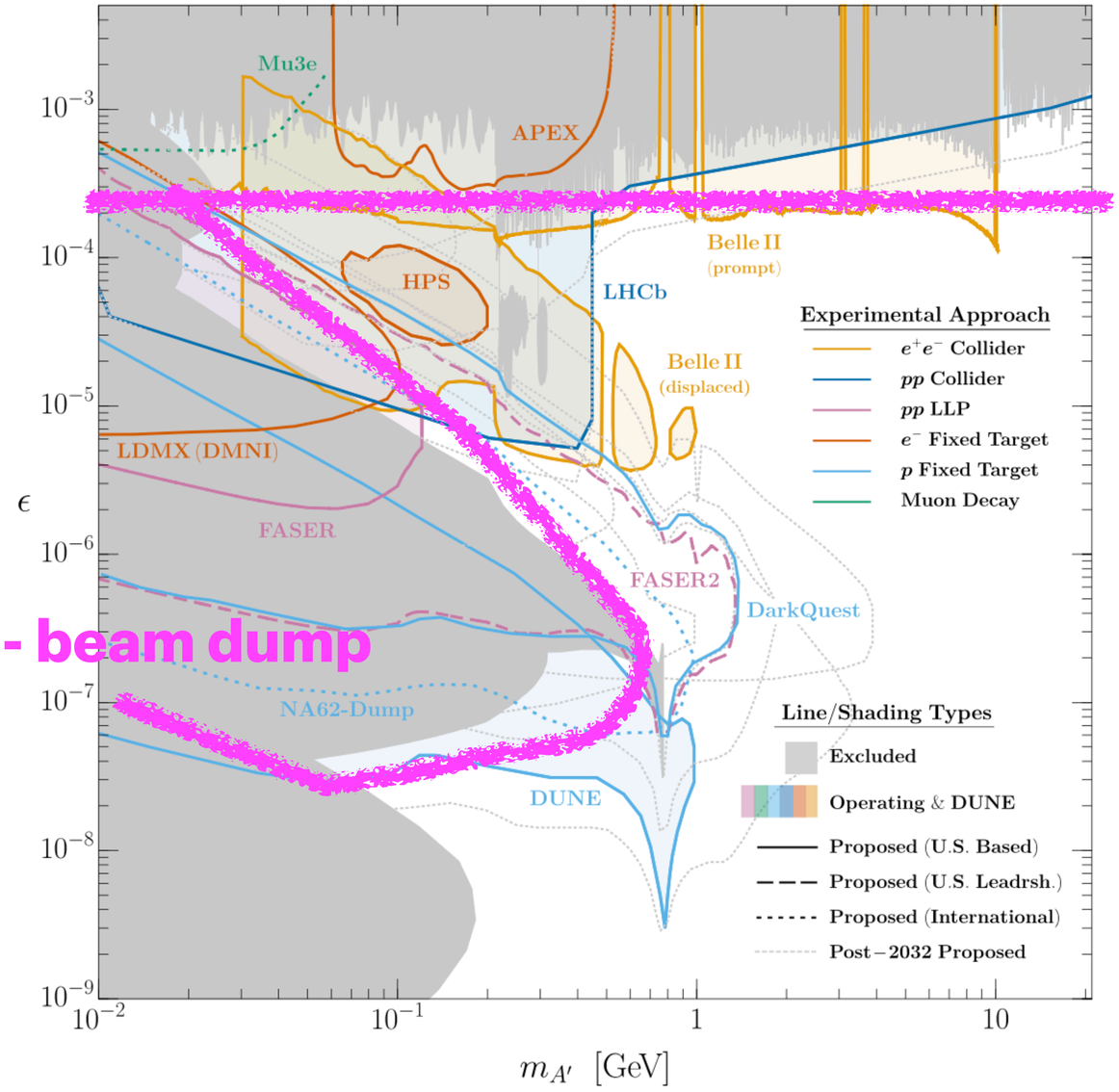
Collaborations	Kinematics	Targets	Scattering
E12-14-012 (JLab) (Data collected: 2017)	$E_e = 2.222$ GeV $15.5° \leq \theta_e \leq 21.5°$ $-50.0° \leq \theta_p \leq -39.0°$	Ar, Ti Al, C	(e,e') e,p in the final state
e4nu/CLAS (JLab) (Data collected: 1999, 2022)	$E_e = 1, 2, 4, 6$ GeV $\theta_e > 5°$	H, D, He, C, Ar, ^{40}Ca, ^{48}Ca, Fe, Sn	(e,e') e,p,n,π,γ in the final state
LDMX (SLAC) (Planned)	$E_e = 4.0, 8.0$ GeV $\theta_e < 40°$	W, Ti, Al	(e,e') e,p,n,π,γ in the final state
A1 (MAMI) (Data collected: 2020) (More data planned)	50 MeV $\leq E_e \leq 1.5$ GeV $7° \leq \theta_e \leq 160°$	H, D, He C, O, Al Ca, Ar, Xe	(e,e') 2 additional charged particles
A1 (eALBA) (Planned)	$E_e = 500$ MeV - few GeV	C, CH Be, Ca	(e,e')

Table 5: Current and planned electron scattering experiments.

Visible Dark Photon: DarkQuest



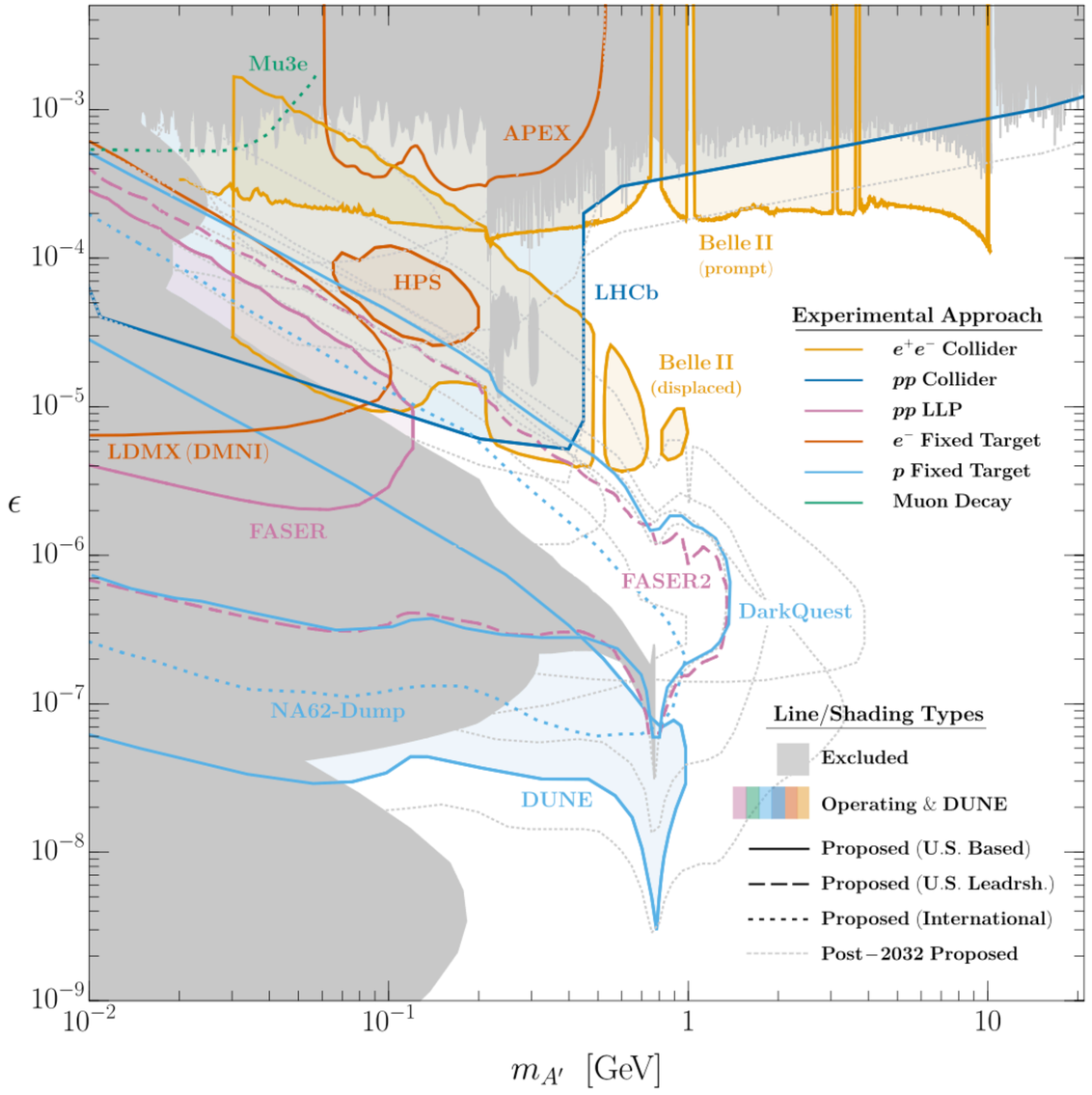
Visible Dark Photon: DarkQuest



Rare prompt

LLP - beam dump

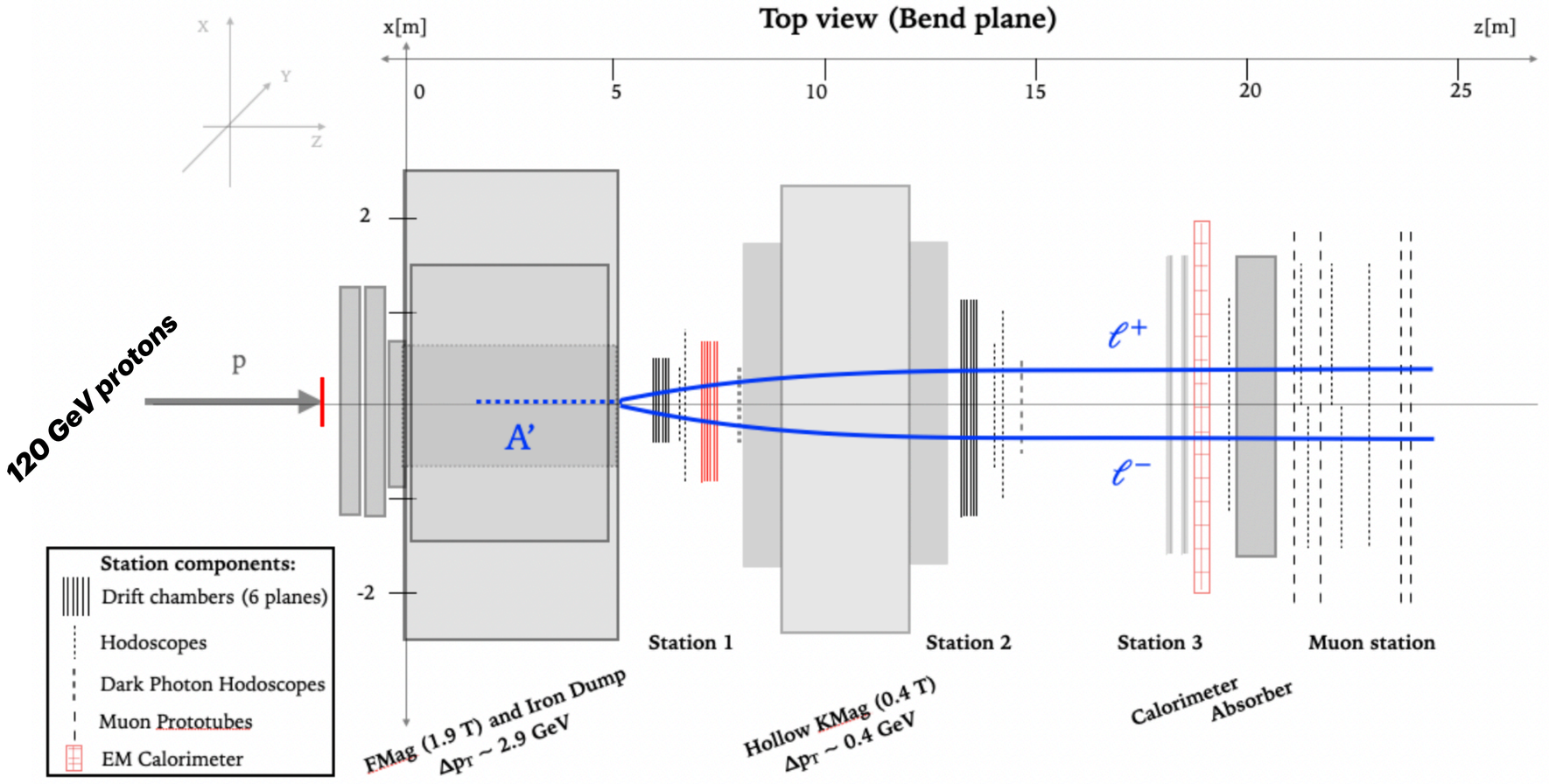
Visible Dark Photon: DarkQuest



Plot from 2022:

See talks by Alina Kleimenova and Ke Li from Tuesday — new results for NA62 and FASER!

SpinQuest/DarkQuest @ FNAL



Dark sector signature

SpinQuest: muon final states

DarkQuest: e,γ,π,...

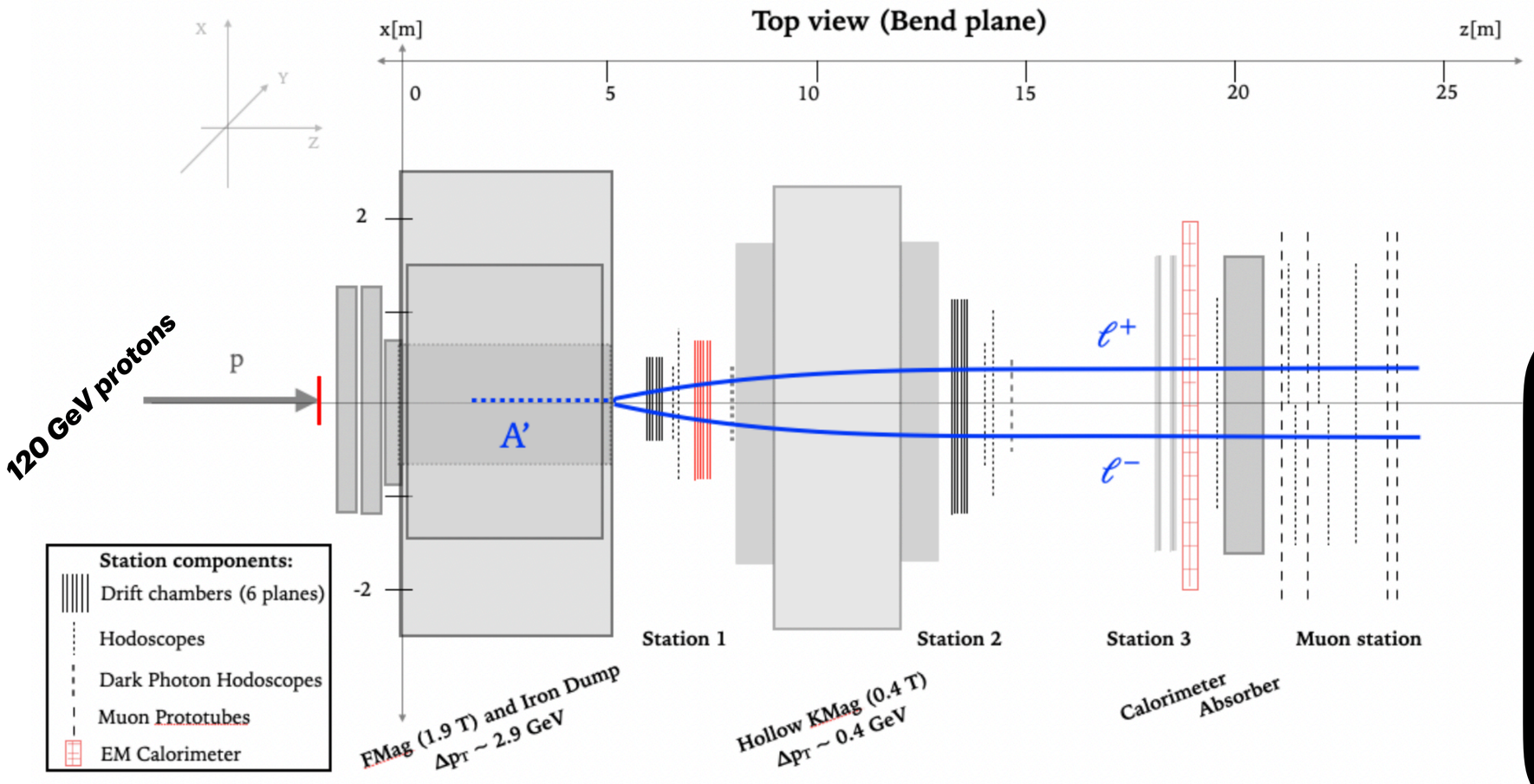
System upgrades

Existing EMCal from PHENIX

Tracking MWPC available

Tensor polarized deuteron target

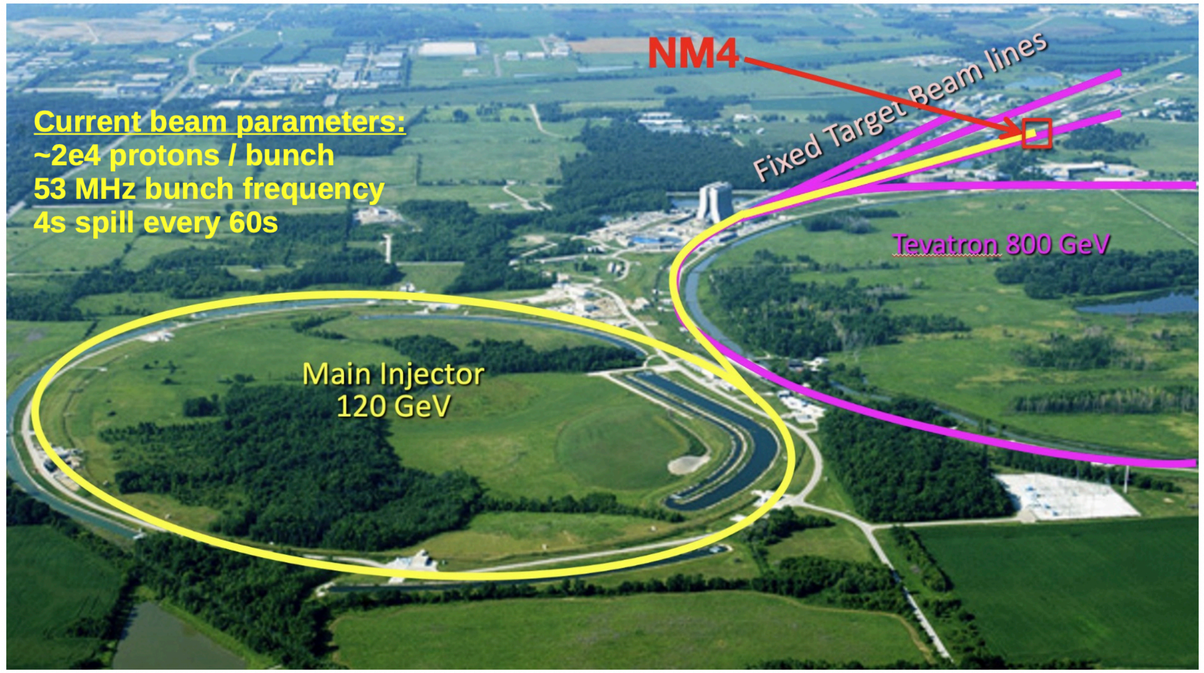
SpinQuest/DarkQuest @ FNAL

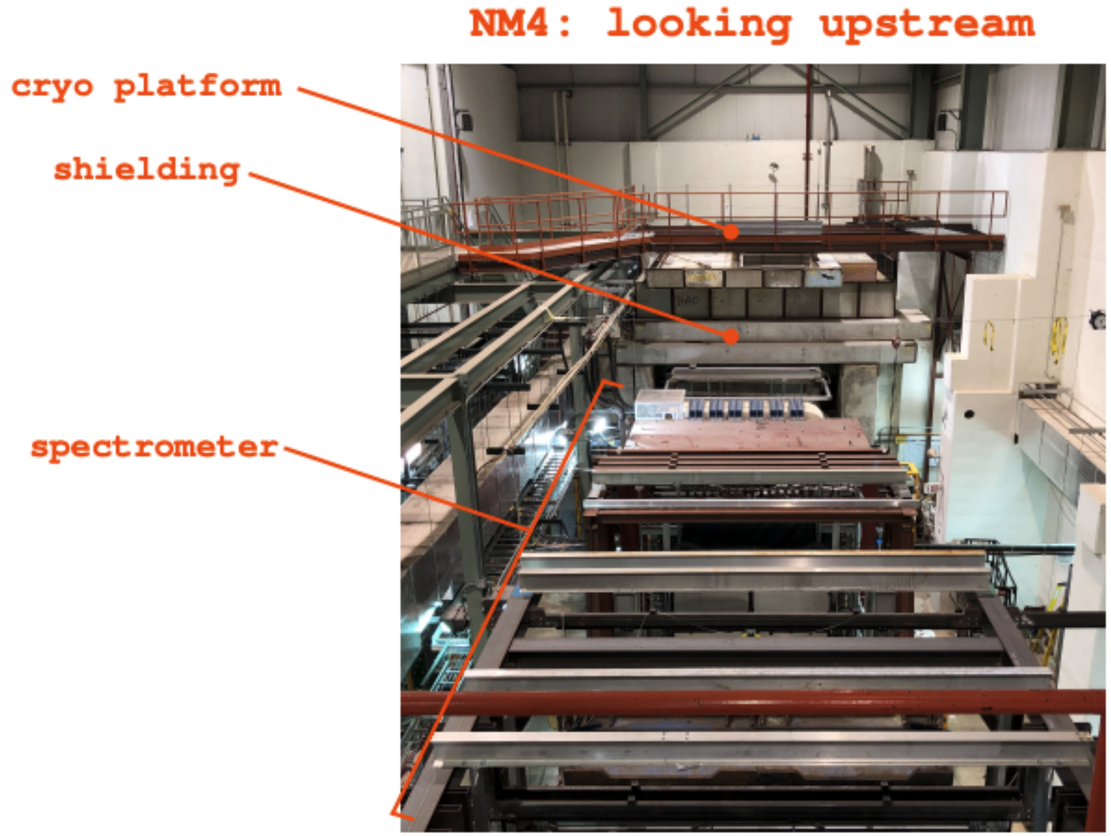


Attractive features:

- Short dump, interesting lifetime baseline
- Most of the stuff exists, low-cost
- Can happen soon

SpinQuest/DarkQuest @ FNAL



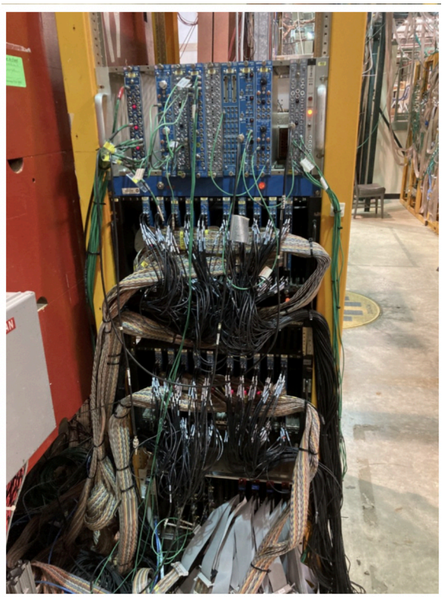


SpinQuest/DarkQuest defined

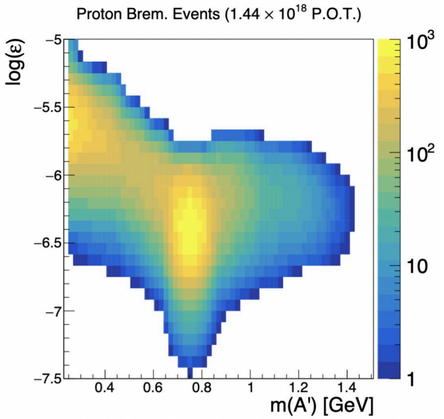
- **SpinQuest**: muon spectrometer looking at Drell-Yan from a polarized target to understand the Proton Spin puzzle
  - Can also do (displaced) dimuon dark sector searches (more later)
  - Plans to run in FY24
- **DarkQuest**: upgrade with additional EMCal, opens up electron, photon, and hadronic final states; other possible detector upgrades
  - Goal for data before PIP-II shutdown in FY26

Dark Sectors progress

- Latest status from Snowmass white paper: arXiv: 2203.08322
- **SpinQuest** displaced dimuon trigger in place
- **DarkQuest**: with additional EMCal, opens up electron, photon, and hadronic final states
  - Uses EMCal from PHENIX
    - Recent progress with EMCal electronics test stand at BU
  - GEANT-level dark sector sim. studies of tracking, vertexing, mass recon.

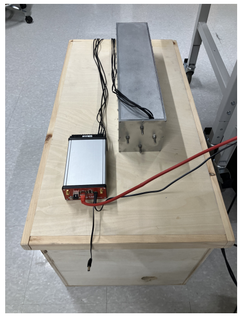


Displaced Dimuon trigger system in place for SpinQuest running



PHENIX EMCal

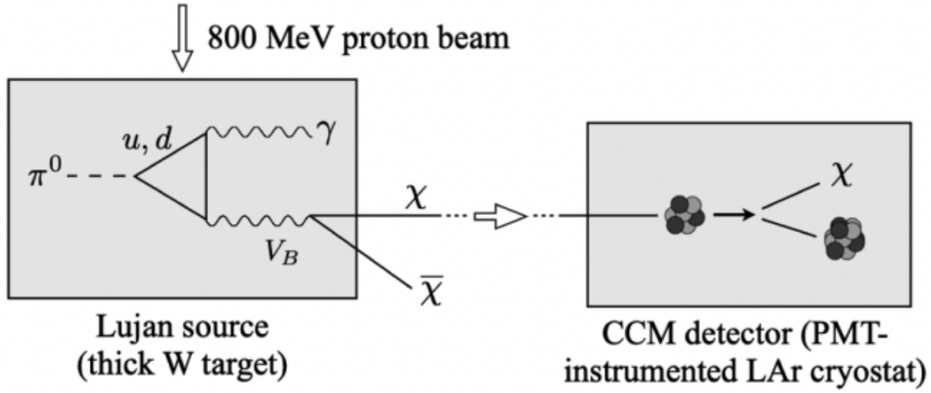
Module readout test stand

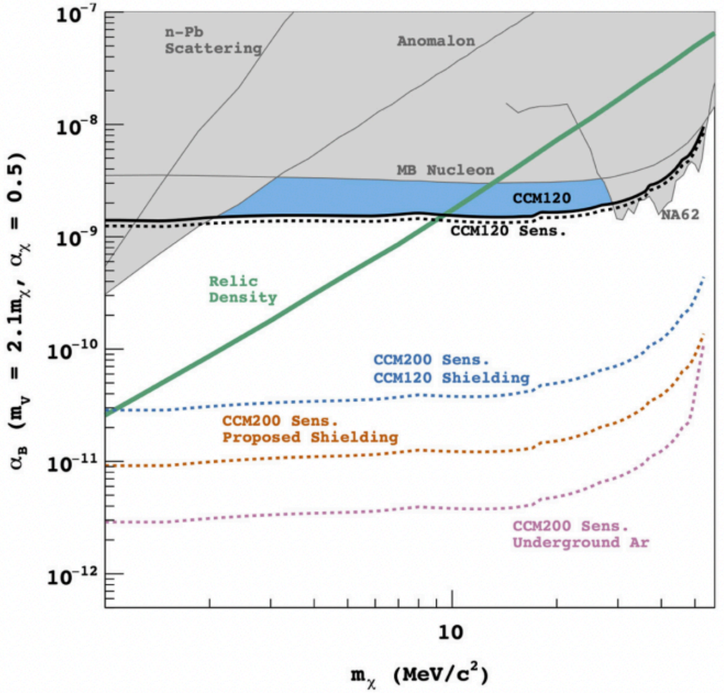


More interesting examples

PRL 129, 021801 (2022)

- Re-scattering experiments from stopped pion sources
  - **CCM, COHERENT, PIP-II BD**
- Millicharged - Sensei, ArgoNeut
- Muon-philic & g-2 - Darkquest





Supported by DOE DMNI

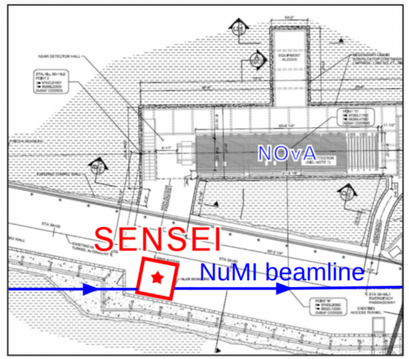
800 MeV protons, 1.8e21 Protons on Target at LANSCE @ LANL, 1.5 months of data
Already new phase space covered for leptophobic DM

Looking forward to new results soon!

https://arxiv.org/pdf/2305.04964.pdf

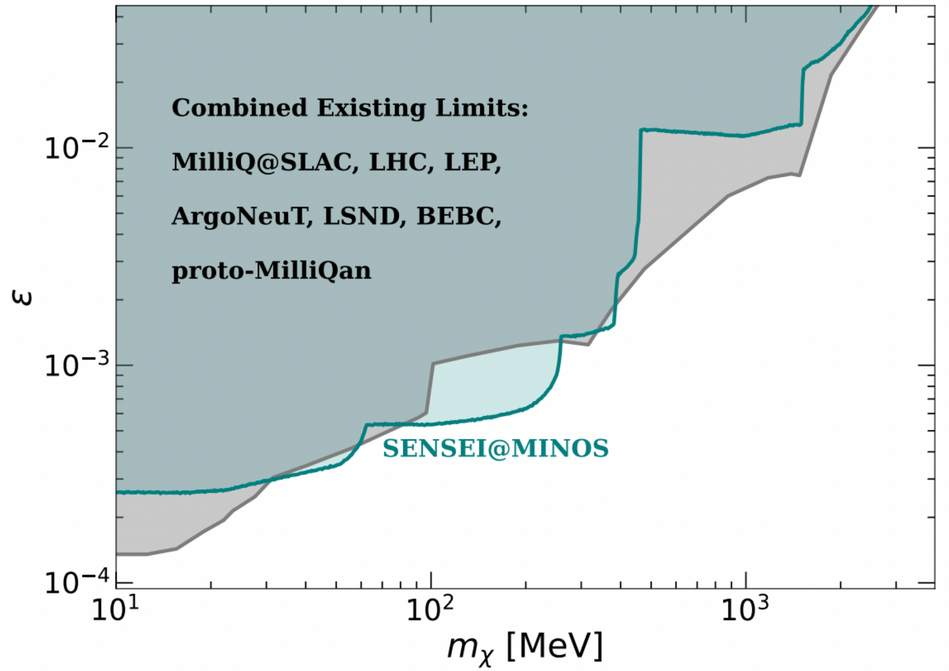
More interesting examples

- Re-scattering experiments from stopped pion sources
  - CCM, COHERENT, PIP-II BD
- Millicharged - **SENSEI, ArgoNeut**
- Muon-philic & g-2 - Darkquest



Deploys Skipper CCD (ultra-low noise CCD) to search for millicharged particles

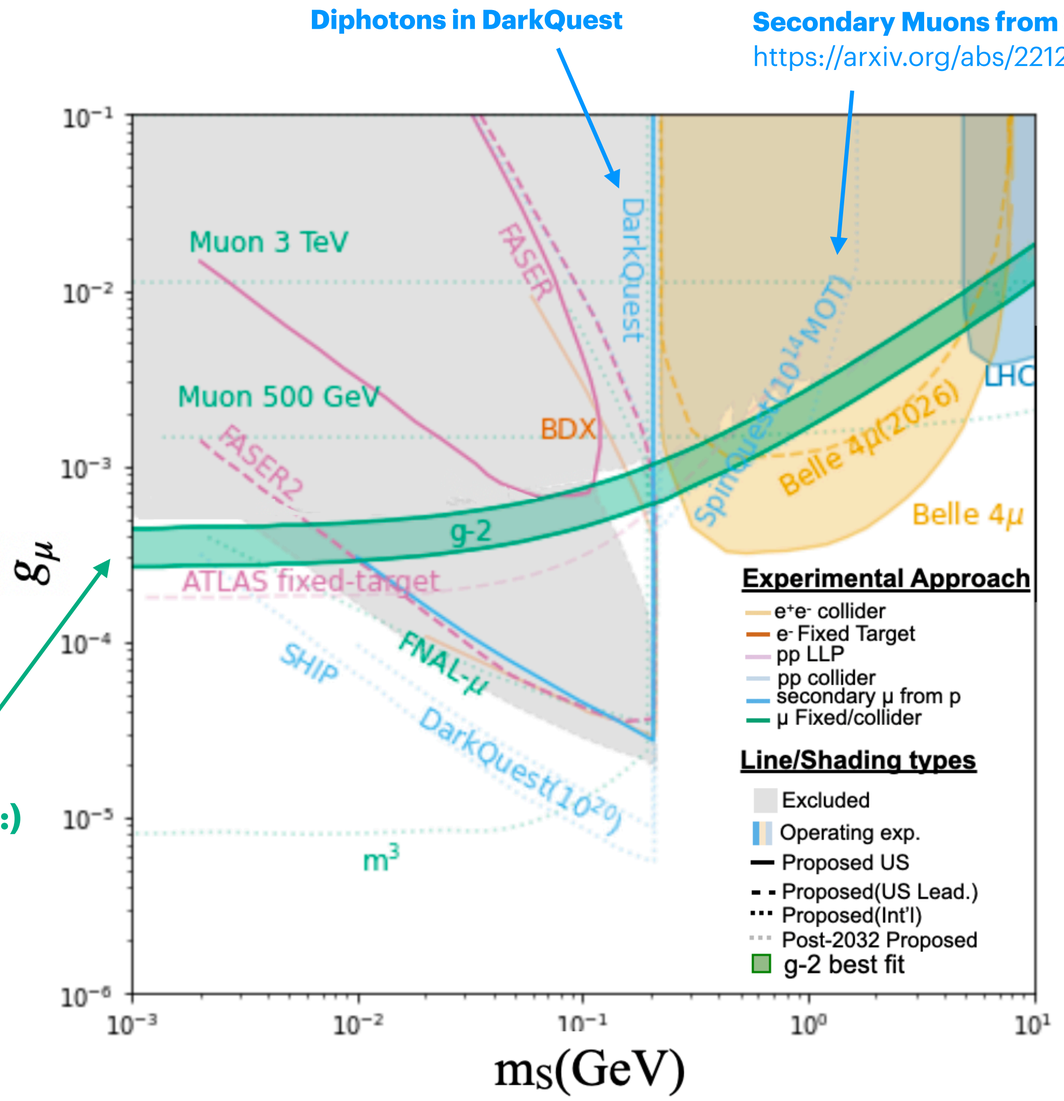
In the MINOS underground hall with 120 GeV protons, ~2g detector with 24 days of data taking in 2020 — already explores new parameter space!



More interesting examples

- Re-scattering experiments from stopped pion sources
  - CCM, COHERENT, PIP-II BD
- Millicharged - Sensei, ArgoNeut
- Muon-philic & g-2 - **DarkQuest**

True for ~5 more hours! :)



Takeaways

Takeaways

Can we develop a comprehensive worldwide program for sub-GeV dark sectors?

Yes! Modest investments in small experiments can enable transformative physics in the near term:
Covering DM relic density milestones & significant phase space for visible dark sectors

I've presented a few examples of experiments that bring new and/or unique sensitivity, see more in Matt's talk and looking forward to more discussion