Beam dump experiment with the proton driver

International
MUON Collider
Collaboration

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Muon Collider Synergies Workshop
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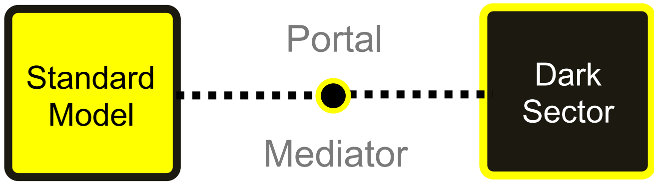
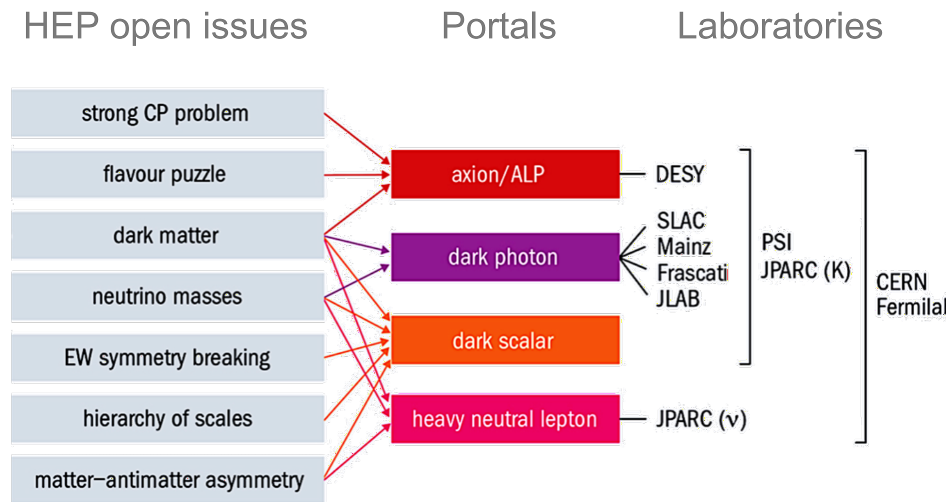
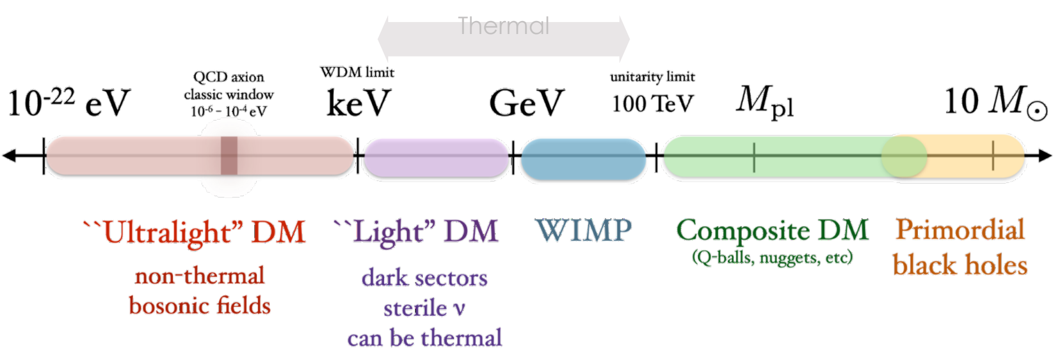
The dark sector paradigm



Feeble, non-gravitational interaction with ordinary matter

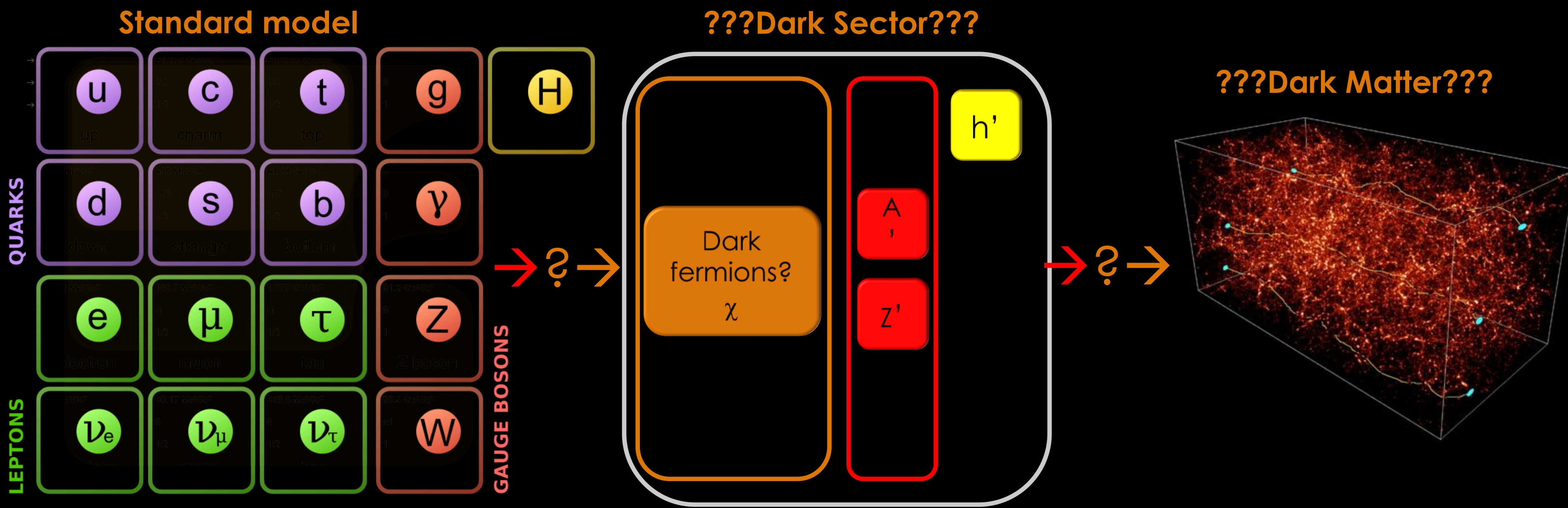
- **Dark matter**
- Dark forces
- Other dark particles





- Dark sector candidates can explain SM anomalies: (g-2)μ, ^{8}Be, proton radius
- The mediator can have a **small mass (MeV -100 MeV)**
- Due to its **small mass** the mediator can be **produced at low energy accelerators**
- It can **decay back to ordinary matter “visible”** on **not “invisible”**

Dark sectors a possible solution



- Standard model only includes <20% of the matter in the universe
  - We only know dark matter interacts gravitationally
- Many open questions
  - What is dark Matter made of?
  - How dark matter interact, if it does, with SM particles?
  - Does one or more new dark force exist?
  - How complex is the dark sector spectrum?

Different models and different portals

- **A’:** new **vector** state mixing to SM photon
  - Produced by dark proton strahlung
  - or decays of secondary mesons π^0,η,ρ
  - free parameters are $m_{A'}$ and ε

Portal	FIPs
Vector	Dark photon, A'
Scalar	Dark Higgs/scalar, S
Fermion	Heavy neutral lepton (HNL), N
Pseudoscalar	Axion/axion-like particle (ALP), a

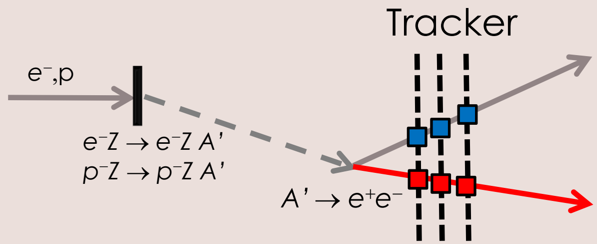
- **S:** new **scalar** state S mixing with SM Higgs
  - produced in FCNC B mesons decays (B->K$^{(*)}$S)
  - free parameters of are m_S and θ

- **HNL:** new **heavy fermions** interacting with the SM lepton doublets
  - Produced in semi-leptonic decays of charmed mesons or τ leptons
  - Decay to meson-lepton or meson-neutrino two-body final states
  - free parameters of the models are m_N $U_{e,\mu,\tau}$

- **ALP:** a new pseudoscalar **Axion Like Particle** interacting with the SM field
  - Produced by primakoff interaction by photons from meson decays π^0,η,ρ
  - free parameters m_a coupling to photons($g_{a\gamma}$) electrons (g_{ae}) gluons (g_{aY})

How to search for A' visible decays?

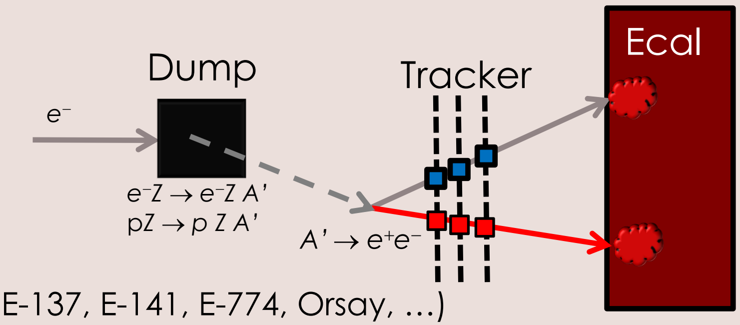
A) Thin target experiments



(APEX, HPS, A1)

N∝ε² ~10$^{14-16}$ EOT (ε²,M$_{A'}$)

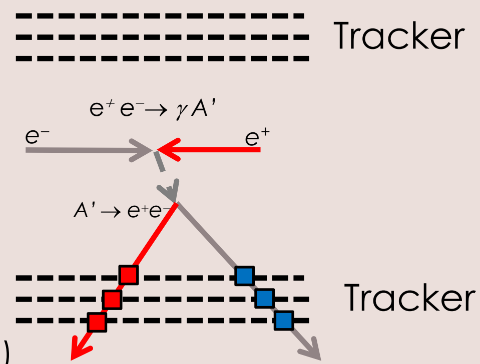
B) e⁻,p dump experiments



(E-137, E-141, E-774, Orsay, …)
(charm, NA62, U70)

N∝ε² ~10$^{19-20}$ EOT (ε²,M$_{A'}$)

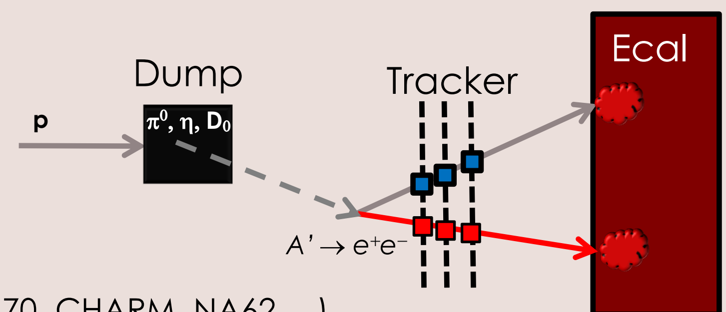
C) Collider experiments



(KLOE, BaBar, A1)

N∝ε² sensitive to (ε,A') mass
Limited by M$_{A'}$<sqrt(s)

D) Proton dump experiments

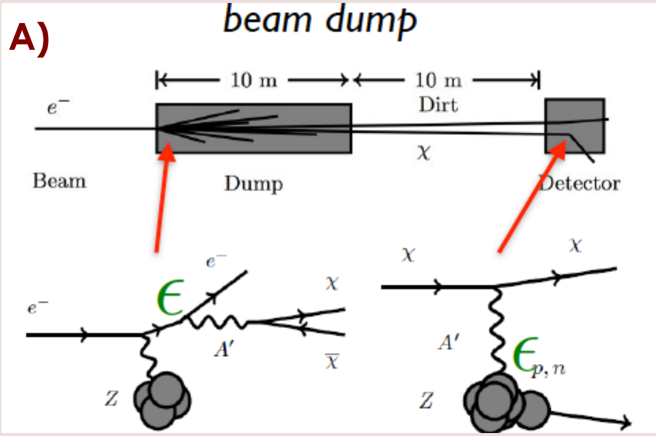


(U70, CHARM, NA62 …)

N∝ε² ~10$^{19-20}$ POT (ε²,M$_{A'}$)

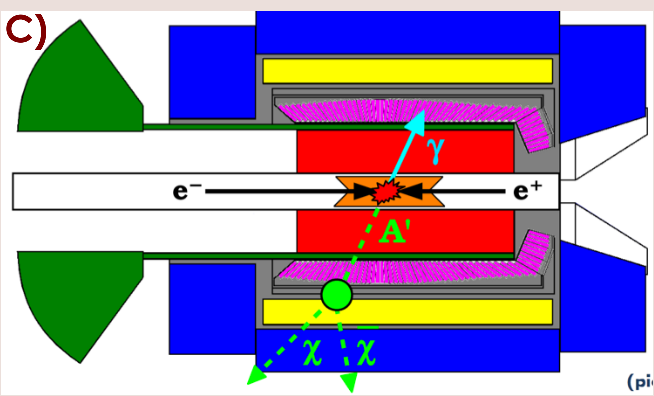
How to search for A' invisible decays?

Positive evidence



N∝ε⁴ ~10²⁰ EOT (α_D and ε²)

Missing Mass

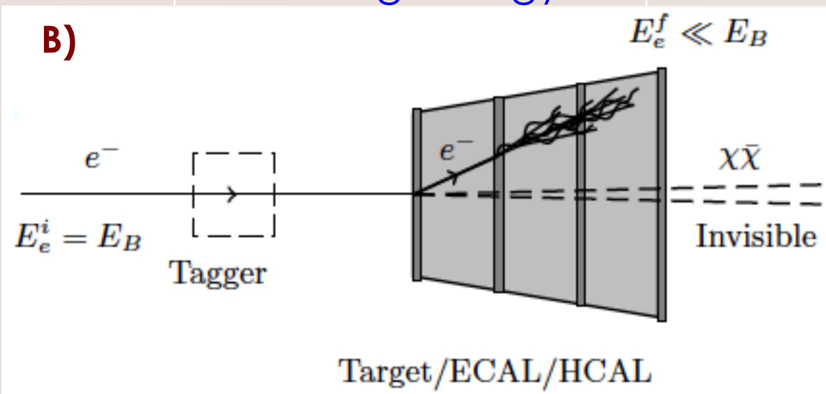


N∝ε² sensitive to (ε,A') mass

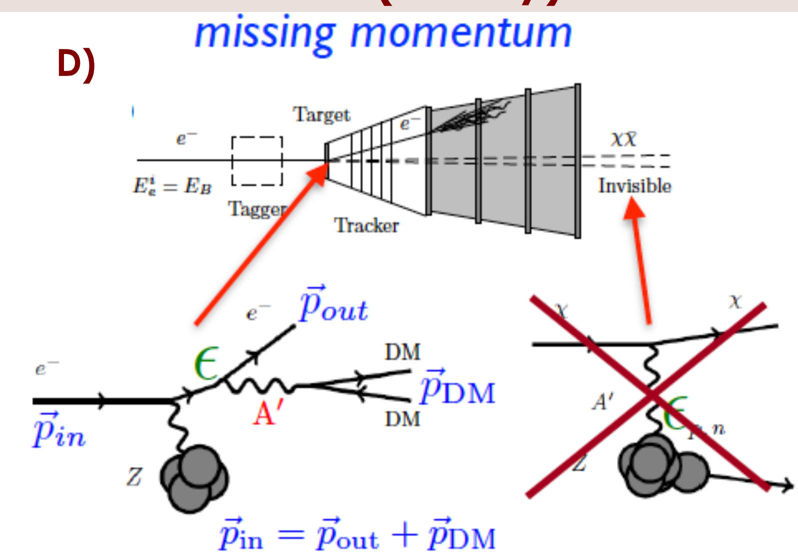
Limited by M^A'<sqrt(s)

Negative evidence

Missing energy



N∝ε² (ε² only)

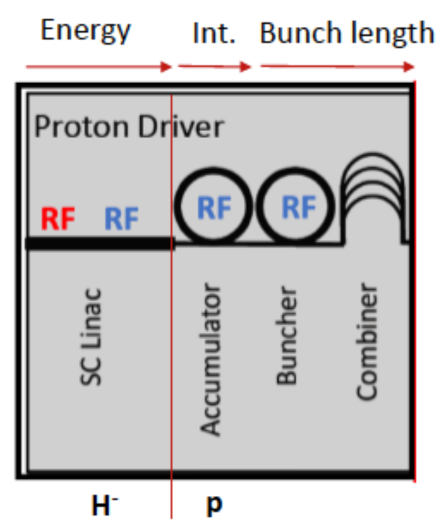


N∝ε² contains E_{miss} exp.

The Muon Collider proton driver

- Beam Power: 2 MW
- Rep. rate: 10 Hz
- Beam spot size: ~ 5 mm (1σ)
- Bunch length: 2 ns = 0.6 m (rms)
- Beam Energy: 8 GeV
- Linac + 2 rings (initial design)
  - Combine 4 bunches on target

H- source and **accumulator and combiner complex**
10^{14}-10^{15} protons in ns-long bunch S. Nagaitsev | 06/14/23



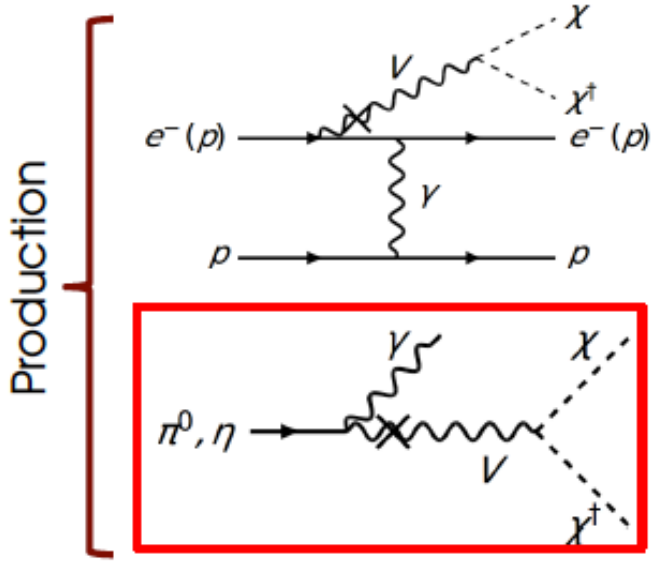
Assuming in the following consideration that we are using the bunched beam at 10Hz.

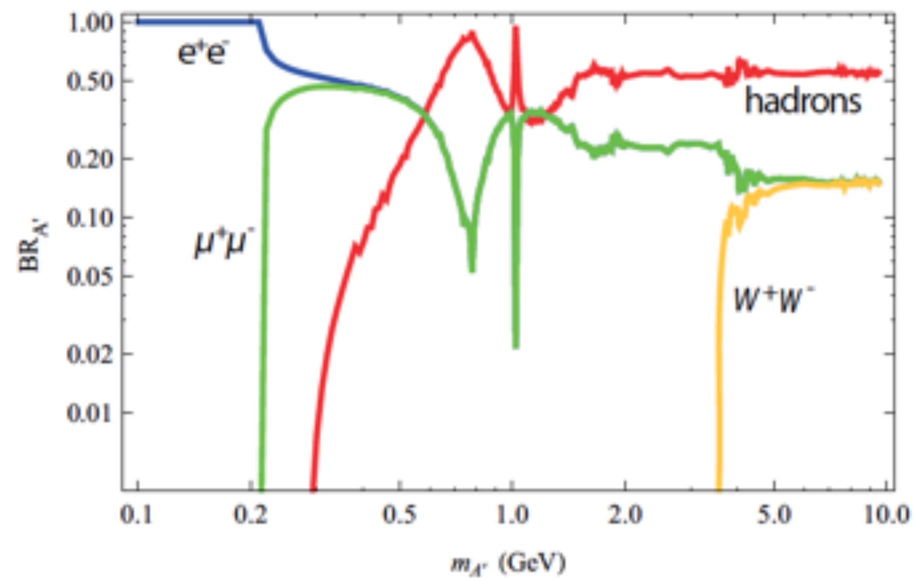
Is there any option for a continuous beam?

- Repetition rate very low: only 10 Hz
- Luminosity extremely high
  - Particle density protons on target (pot) ~10^{14}/ns
  - Thin target experiments impossible
- Energy Ok to obtain a reasonable mass production limit.
- Power very high for any small mass target.

Dark photon signature at the PD

- Production dominated by π^0 and η decays to photons
  - A' visible decays to lepton pairs (ee,$\mu\mu$) or invisible to DM (χ,χ)
- A' strahlung from primary protons or electrons in the showers
  - A' visible decays to lepton pairs (ee,$\mu\mu$) or invisible to DM (χ,χ)





Option for a dark sector experiment

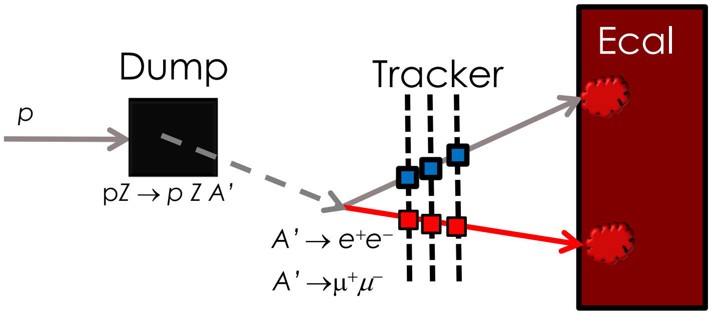
- Two main options are available
  - Thin active target experiments
  - Thick target experiments (DUMP)
- **Thin targets** with the proton driver
  - Too high density of protons/ns due to bunched structure
  - Productions rates per single proton non competitive with leptons (e,μ)
  - Too high Standard Model background
- **Thick target** experiments with the proton driver
  - **Density of protons/ns not a issue** (missing experiment impossible)
  - **No Standard Model background** (for thick enough dump)
  - Very high number of protons

which thick target experiment?

- Active thick target: **missing mass/momentum** (NA64 of LDMX)
  - Impossible due to **too high number of protons/ns**.
  - Need to measure single particles momentum or energy
- Beam Dump experiments
  - Ok: **nothing will survive the dump**
  - Visible decays: search for di leptons after the dump (NA62 dump)
  - Invisible decays: search for DM scattering (MiniBoone dump)

what will potentially work at MuColl?

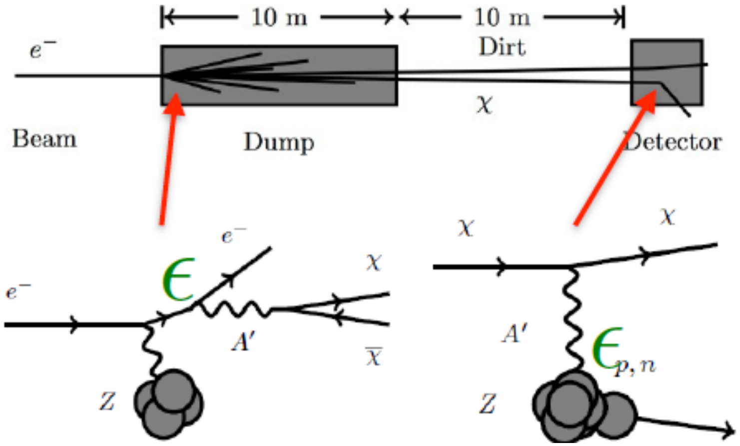
p dump experiment visible



(charm, NA62, U70)

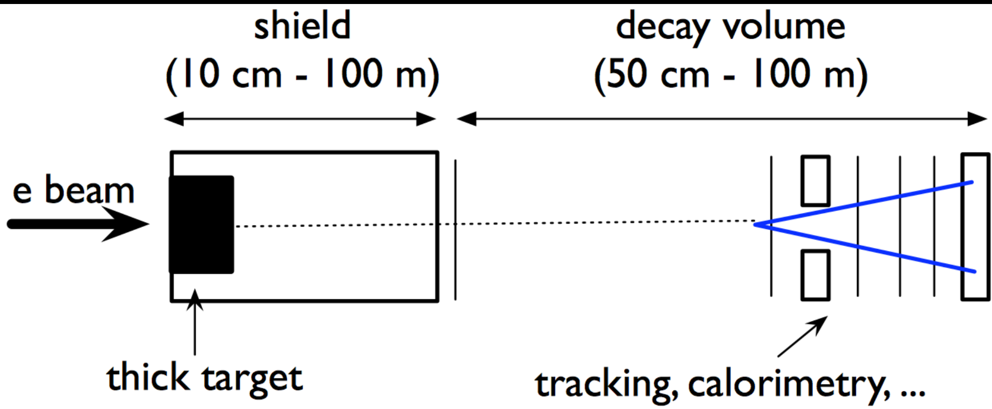
$N_{DS} \propto \varepsilon^2$ ~10^{18-20} POT (ε^2,$M_{A'}$)

p dump experiment invisible



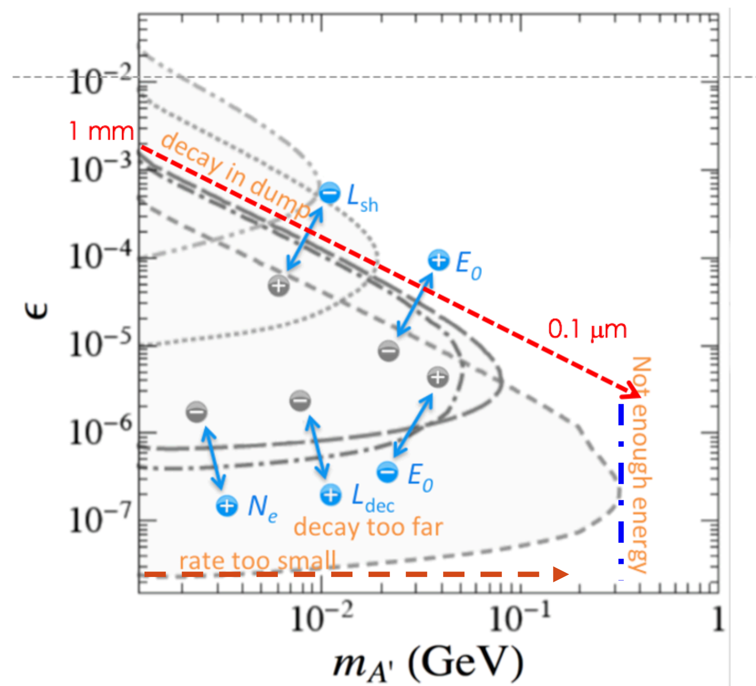
$N_{DS} \propto \varepsilon^4$ ~10^{20} POT ($M_{A'}$,α_D , ε^2)

Visible dump experiment concept



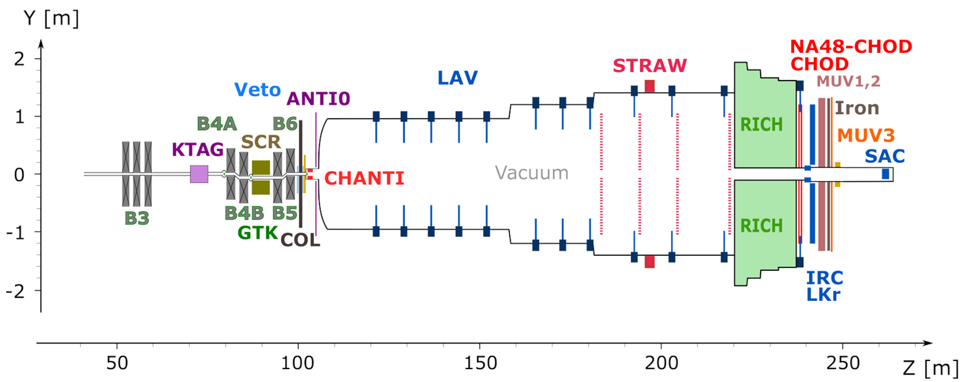
$$c\tau = \frac{1}{\Gamma} \simeq \frac{3}{N_{\rm eff} m_{A'} \alpha \epsilon^2} \simeq \frac{80\ \mu{\rm m}}{N_{\rm eff}} \left(\frac{10^{-4}}{\epsilon}\right)^2 \left(\frac{100\ {\rm MeV}}{m_{A'}}\right),$$

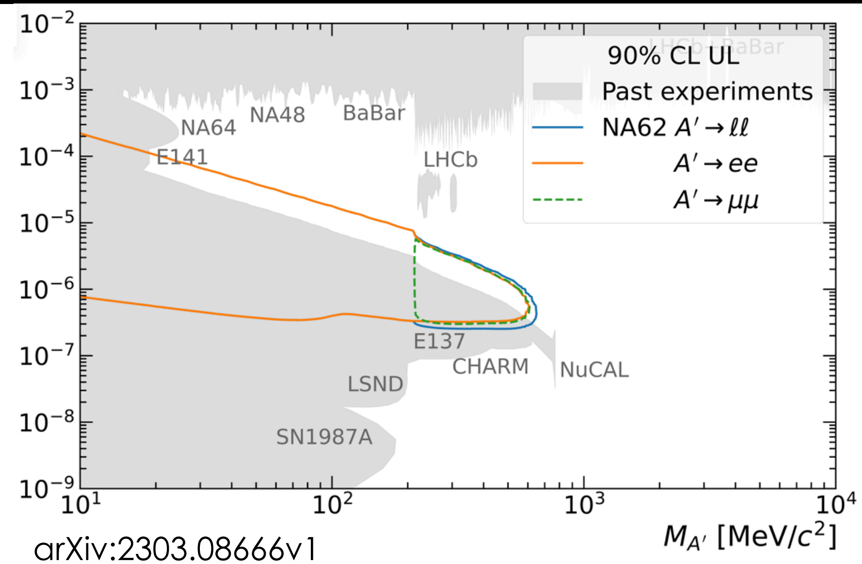
$$\frac{dP(l)}{dl} = \frac{1}{l_{\gamma'}} e^{-l/l_{\gamma'}}$$



- Key parameters for exclusion limit regions
  - **L_{shield}** = Length of the shield, decay inside dump (dominate at high ε values)
  - **L_{decay}**= Length of the decay region, decay outside(dominate at low ε values)
  - **N_p** = number of protons on target (dominate at low ε values)
  - **Beam Energy** = dominates in the mass region limit helps with lifetime for low ε

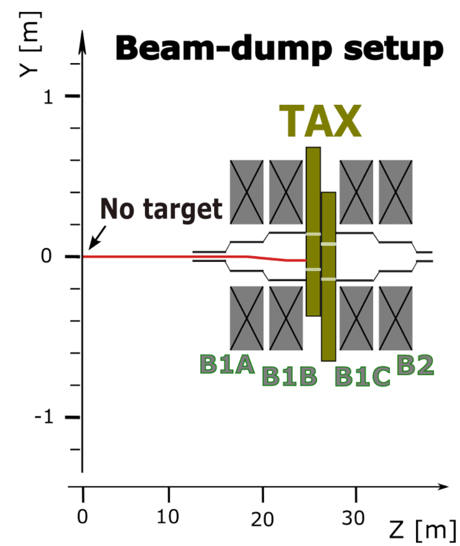
Visible p dump example: NA62-Hike



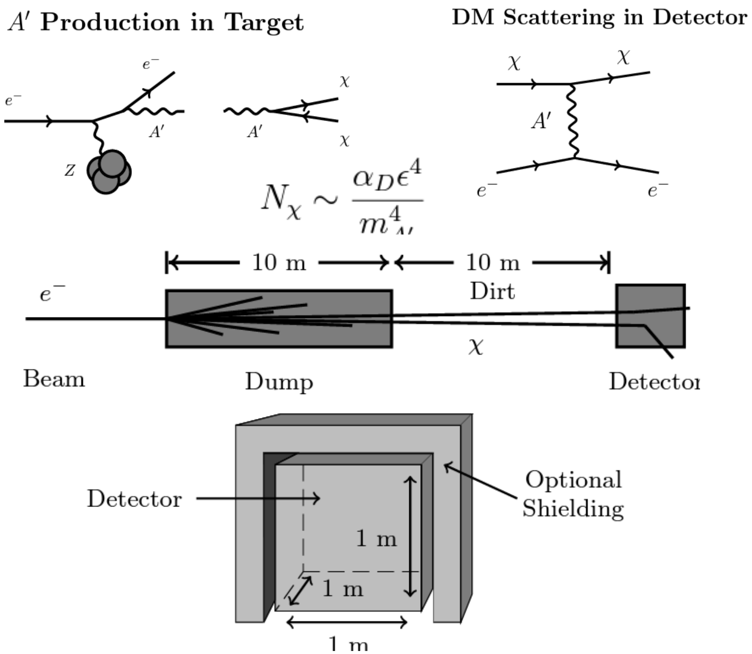


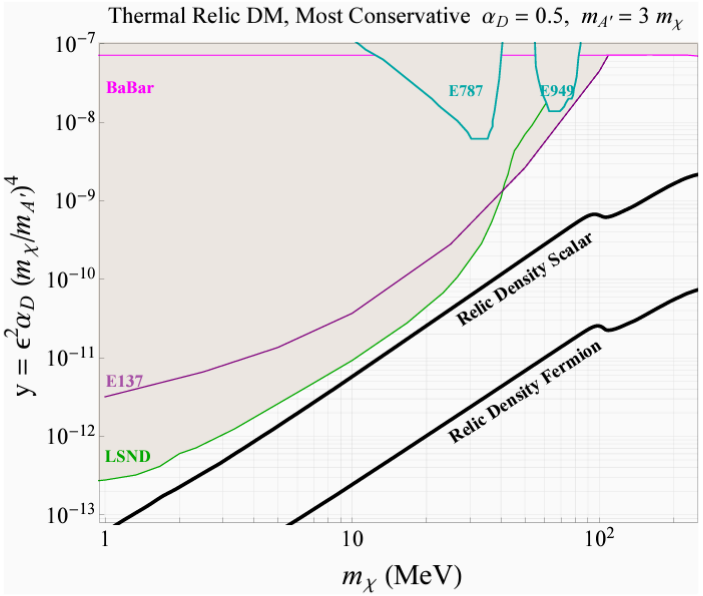
arXiv:2303.08666v1

- 400 GeV primary protons
- Thick dump TAX: 0.8m copper +2.4 m of iron
- ~100 m long decay region
- Searches for di-lepton final states
- New results expected in upcoming years from HiKe



Invisible dump concept

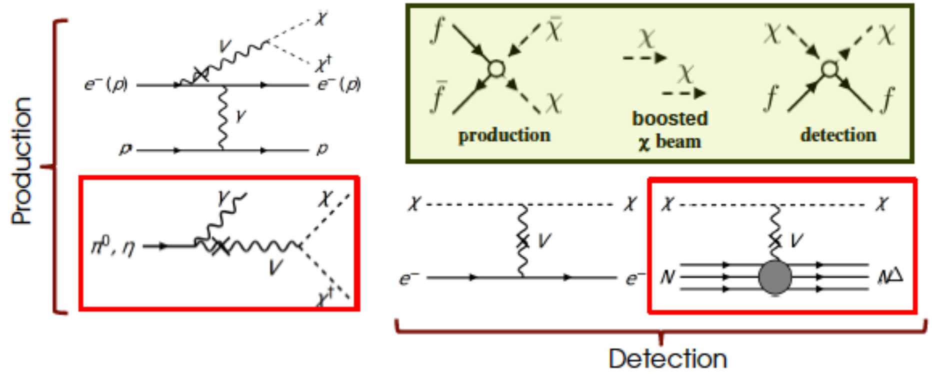


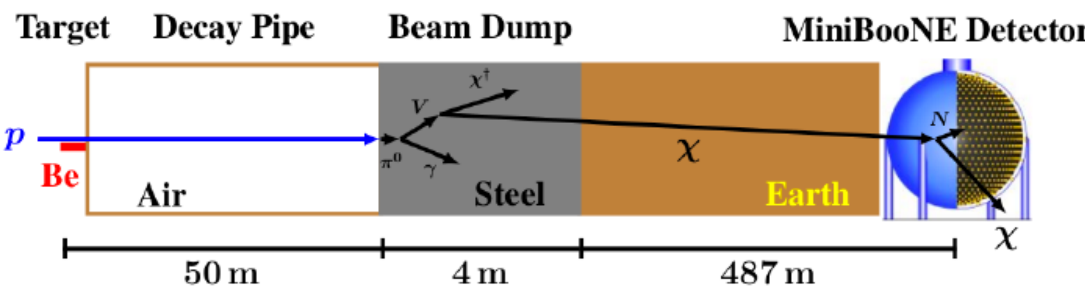


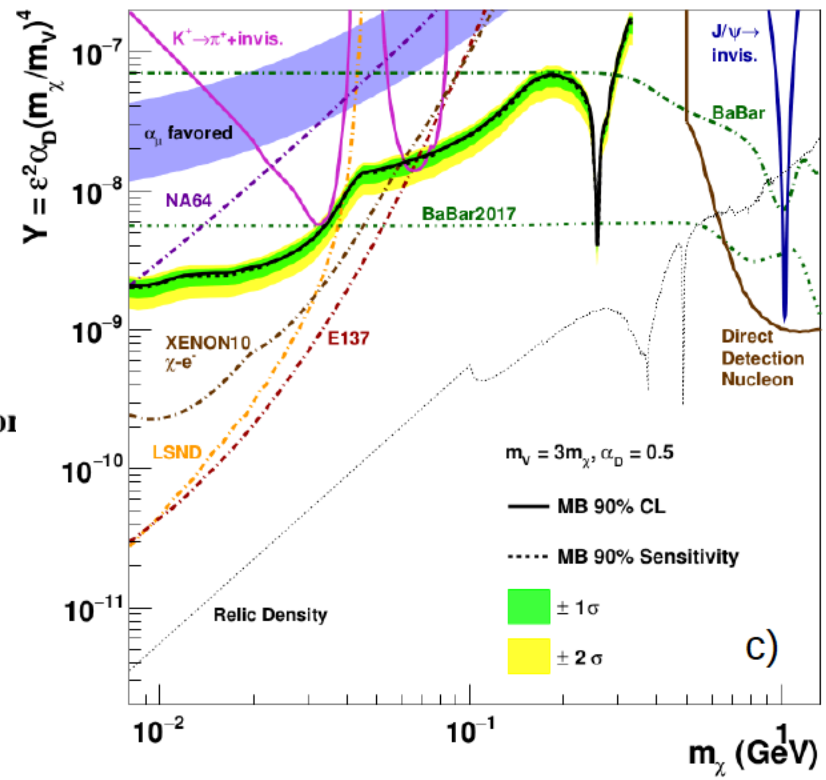
arXiv:1607.01390v1

- Key features for exclusion limit regions
  - Decay always prompt (α_D is order 1)
  - Need a lot of protons N_χ scale with ε^4 power
  - Need detector screening to reduce background
- Region on hundreds of MeV not very constrained yet.

Invisible p dump example: Miniboone





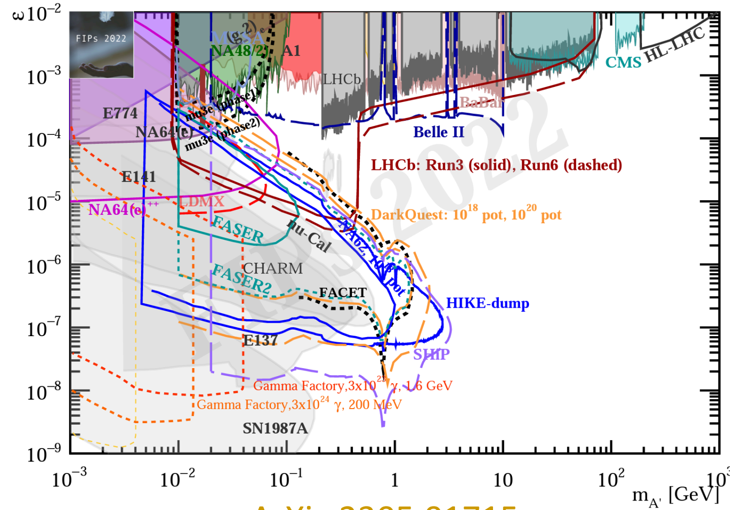


- 8 GeV proton beam
- Production dominated by π^0 decays
  - 4 m stainless still dump
  - ~ 500 m long decay region
- detection through scattering on nuclei

Near future competitors

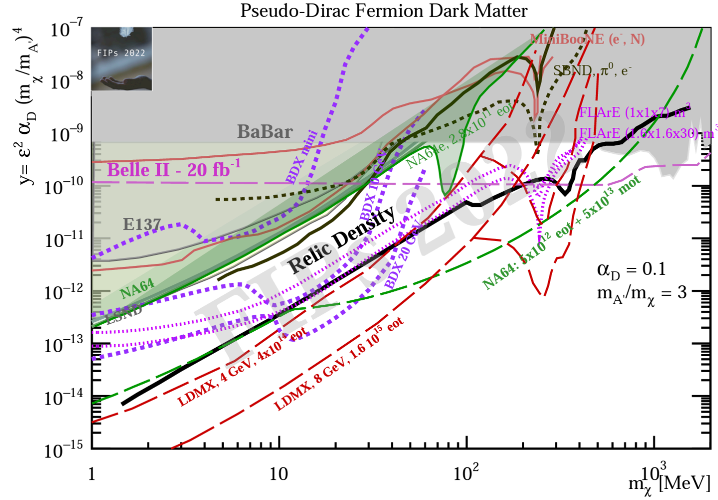
Experiment	lab	beam	particle yield/$\mathcal{L}$	technique	portals	timescale
current						
ATLAS [1382]	CERN	pp, 13-14 TeV	up to 3 ab^{-1}	visible, invis.	(1,2,3,4)	2042
Belle II [1219]	KEK	e^+e^-, 11 GeV	up to 50 ab^{-1}	visible, invis.	(1,2,3,4)	2035
CMS [1383]	CERN	pp, 13-14 TeV	up to 3 ab^{-1}	visible, invis.	(1,2,3,4)	2042
Dark(Spin)Quest [1256]	FNAL	p, 120 GeV	$10^{18} \to 10^{20}$	visible	(1,2,3,4)	2024
FASER [1052]	CERN	pp, 14 TeV	150 fb^{-1}	visible	(1,2,3,4)	2025
LHCb [1384]	LHC	pp, 13-14 TeV	up to 300 fb^{-1}	visible	(1,2,3,4)	2042
MicroBooNE [1385]	FNAL	p, 120 GeV (NuMi)	$\sim 7 \times 10^{20}$ pot	visible	(2,4)	2015-2021
NA62 [1174]	CERN	K^+, 75 GeV	a few 10^{13} K decays	visible, invis.	(1,2,3,4)	2025
NA62-dump [1386]	CERN	p, 400 GeV	$\sim 10^{18}$ pot	visible	(1,2,3,4)	2025
NA64$_e$ [1387]	CERN	e^-/e^+, 100 GeV	up to $1 \cdot 10^{13}$ e^-/e^+	$\not{E}$, visible	(1,3)	< 2032
PADME [1300]	LNF	e^+, 550 MeV	$5 \cdot 10^{12}$ e^+ot	missing mass	(1)	< 2023
T2K-ND280 [1388]	JPARC	p, 30 GeV	10^{21} pot	visible	(4)	running
proposed						
BDX [1389]	JLAB	e^-, 11 GeV	$\sim 10^{22}$ eot/year	recoil e	(1,3)	2024-2025
CODEX-b [1030]	CERN	pp, 14 TeV	300 fb^{-1}	visible	(1,2,3,4)	2042
Dark MESA [1390]	Mainz	e^-, 155 MeV	150 μA	visible	(1)	< 2030
FASER2 [1068]	CERN	pp, 14 TeV	3 ab^{-1}	visible	(1,2,3,4)	2042
FLaRE [1068]	CERN	pp, 14 TeV	3 ab^{-1}	visible, recoil	(1)	2042
FORMOSA [1068]	CERN	pp, 14 TeV	3 ab^{-1}	visible	(1)	2042
Gamma Factory [1391]	CERN	photons	up to 10^{25} γ/year	visible	(1,3)	2035-2038?
HIKE-dump [1392, 1191]	CERN	p, 400 GeV	$5 \cdot 10^{19}$ pot	visible	(1,2,3,4)	<2038
HIKE-K^+ [1392, 1191]	CERN	K^+, 75 GeV	10^{14} K decays	visible, inv.	(1,2,3,4)	<2038
HIKE-K_L [1392, 1191]	CERN	K_L, 40 GeV	10^{14} K decays	visible, inv.	(1,2,3,4)	<2042
LBND (DUNE) [1393]	FNAL	p, 120 GeV	$\sim 10^{21}$ pot	recoil e, N	(1,2,3,4)	< 2040
LDMX [1271]	SLAC	e^-, 4,8 GeV	$2 \cdot 10^{16}$ eot	$\not{p}$, visible	(1)	< 2030
M^3 [1394]	FNAL	μ, 15 GeV	10^{10} (10^{13}) mot	$\not{p}$	(1)	proposed
MATHUSLA [1395]	CERN	pp, 14 TeV	3 ab^{-1}	visible	(1,2,3,4)	2042
milliQan [1070]	CERN	pp, 14 TeV	0.3-3 ab^{-1}	visible	(1)	< 2032
MoeDAL/MAPP [1396]	CERN	pp, 14 TeV	30 fb^{-1}	visible	(4)	< 2032
Mu3e [1397]	PSI	29 MeV	$10^8 \to 10^{10}$ μ/s	visible	(1)	< 2038?
NA64$_\mu$ [1398]	CERN	μ, 160 GeV	up to 2×10^{13} mot	$\not{p}$	(1)	< 2032
PIONEER [1399]	PSI	55-70 MeV, π^+	$0.3 \cdot 10^6$ π/s	visible	(4)	phase I approved
SBND [1400]	FNAL	p, 8 GeV	$6 \cdot 10^{20}$ pot	recoil Ar	(1)	< 2030
SHADOWS [1401]	CERN	p, 400 GeV	$5 \cdot 10^{19}$ pot	visible	(2,3,4)	<2038
SHiP [1402]	CERN	p, 400 GeV	$2 \cdot 10^{20}$ pot	visible, recoil	(1,2,3,4)	<2038

Feebly-Interacting Particles: FIPs 2022 Workshop Report



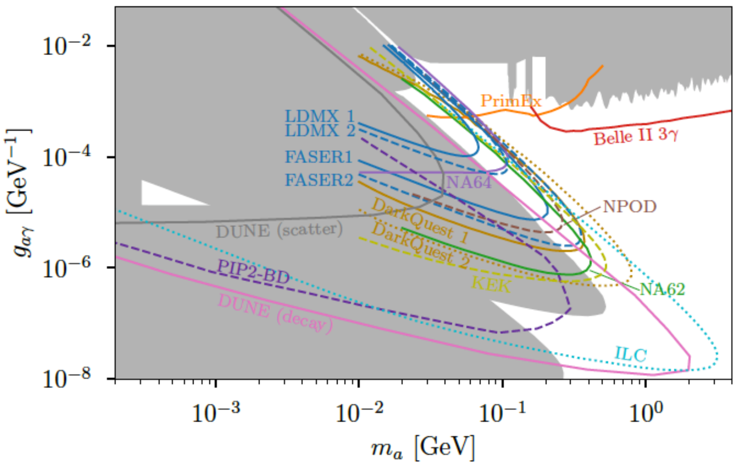
ArXiv 2305.01715

Pseudo-Dirac Fermion Dark Matter

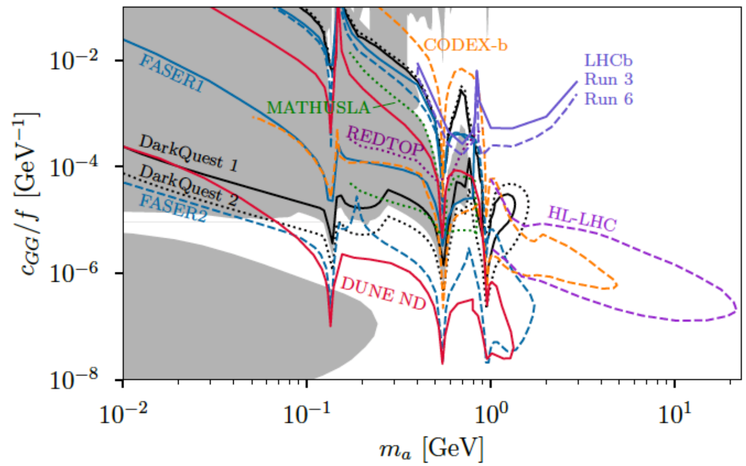


Potential for scalars and Neutrino

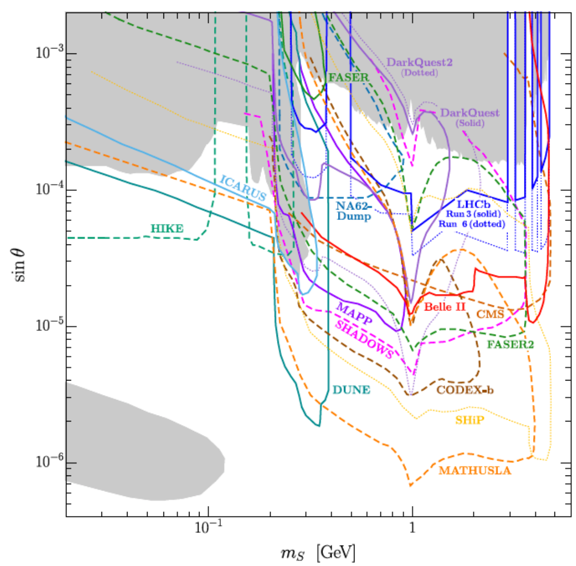
ALPs γ coupling



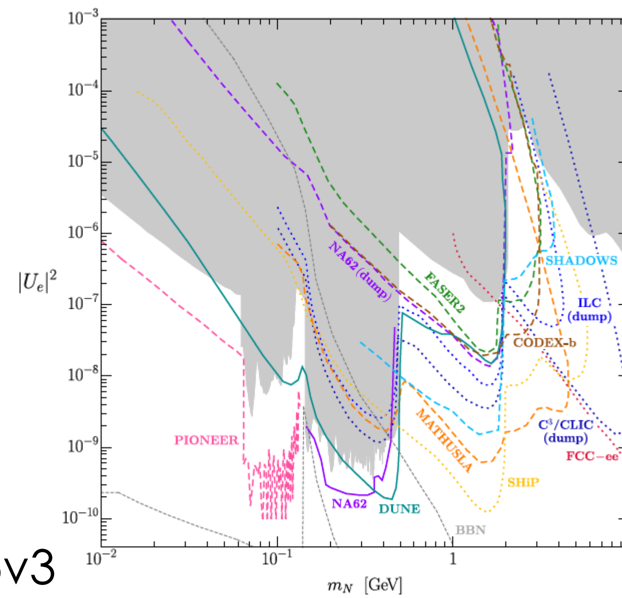
ALPs gluon coupling



Scalars visible



Neutrino e dominated



arXiv:2207.06905v3

Conclusions

- Muon collider proton driver can provide a **huge amount of p/year**
  - Lumi Proton driver = 1E15 p/s x 1E7 s/y x 10 Hz = **1x10^{23} pot/y**
  - This ~100 times higher of anything I heard about
- The beam bunching scheme limits the experimental strategies
  - Only passive beam dump experiments are feasible.
- Different portal interactions can be explored
- Both **visible and invisible DS candidate decays are accessible**
  - Main potential competitors are the neutrino facility (Dune)
  - Opportunities in all the different scenario are available.