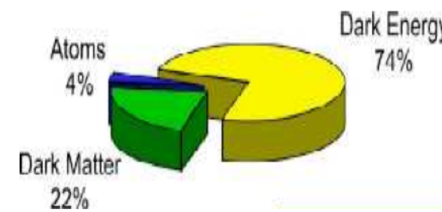
SEARCH FOR DARK SECTOR AT FIXED-TARGET EXPERIMENTS

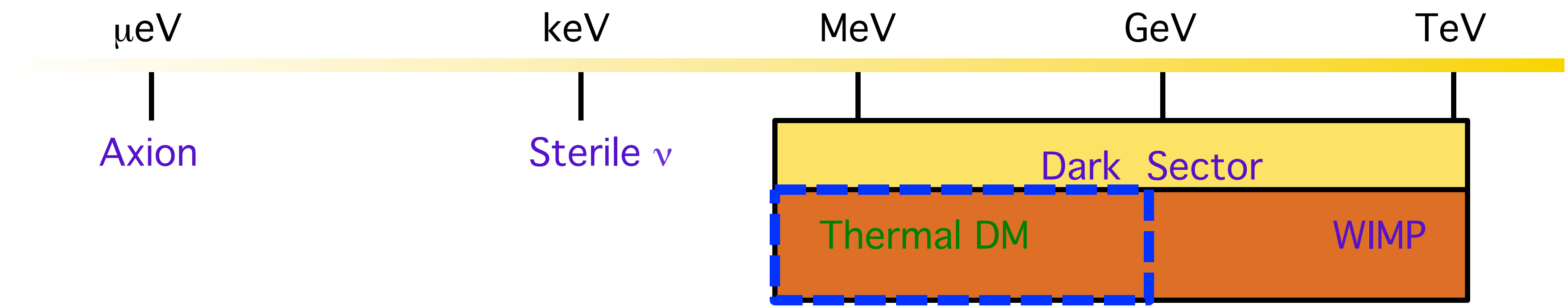
S.N. Gninenko (INR, Moscow)

Outline

- sub-GeV Dark Matter from Dark Sector
- search methods
- recent results and projections
- summary

Dark Matter (DM)



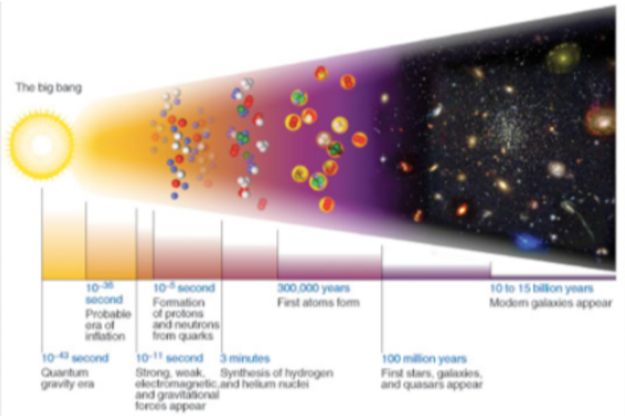


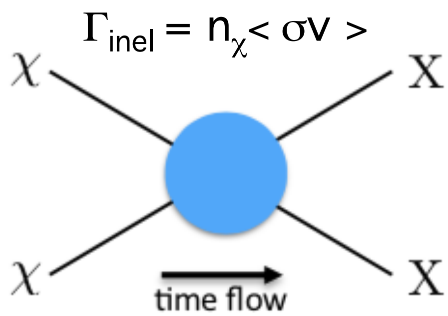
What makes up most of the Universe's mass?

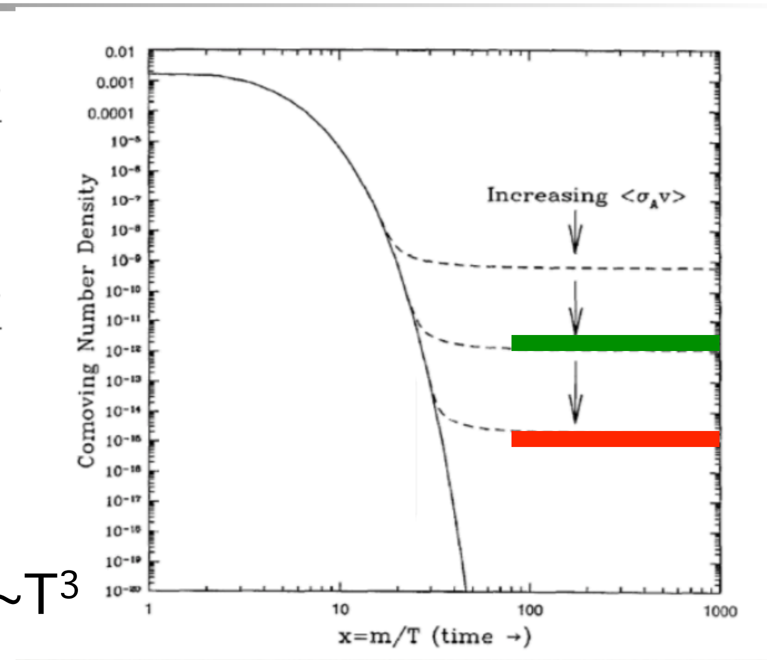
Possible answer: sub-GeV thermal DM from Dark Sector.

Dark(hidden) sector consists of particles and fields which are singlets with respect to the gauge group of the SM and interacts with visible matter presumably only via gravity.

Thermal Dark Matter: Evolution of the Density

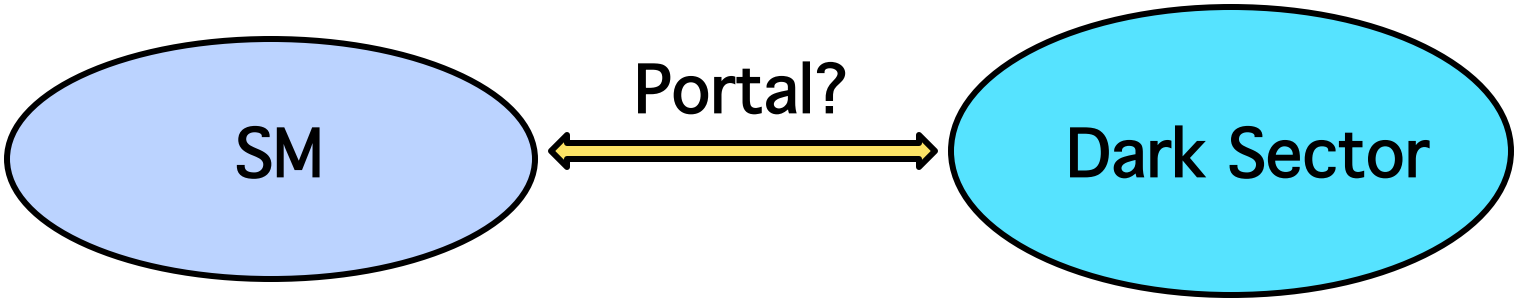






- For $T >> m_\chi$, $\chi\chi$<->SM is in equilibrium, $n_\chi \sim T^3$
- Hubble expansion, T & n_χ decrease
- For $T < m_\chi$ $\chi\chi$<->SM gets suppressed, $n_\chi \sim T^{3/2} e^{-m_\chi /T}$
- Finally $\chi\chi$<->SM stops, $n_\chi \sim$ frozen in time $\Gamma_{inel} = n_\chi < \sigma v > \sim H$
- $< \sigma v > \cong 3\text{x}10^{-26}\ \text{cm}^3/\text{s} \cong (1/20\ \text{TeV})^2$
- If DM is in sub-GeV range it must be SM neutral
- Thermal freeze-out motivate new interaction to mediate DM←→SM annihilation. New force in additional to gravity is required!

Interaction between the Visible and Dark Sectors



The most important portals are dictated by Standard Model symmetries:

- Vector
- Higgs
- Axions
- Sterile Neutrinos

Focus of this talk: vector mediator

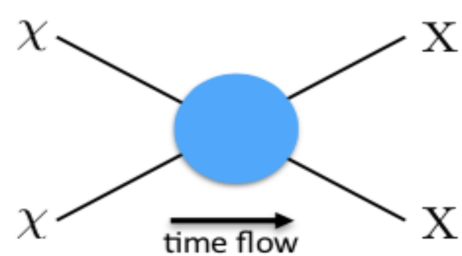
Vector portal to Dark Sector

Okun, Holdom' 86 ..

- new massive (dark) photon with γ–A´ kinetic mixing: $\Delta L = \varepsilon/2\, F^{\mu\nu} A'_{\mu\nu}$
- GUT prediction for the size of the γ-A´ mixing strength ($\varepsilon \ll 1$):
  1-loop: $\varepsilon \sim 10^{-4} - 10^{-2}$; 2 loops: $\varepsilon \sim 10^{-5} - 10^{-3}$, $m_{A'} \sim \varepsilon^{1/2} M_Z$
- A´ decays:

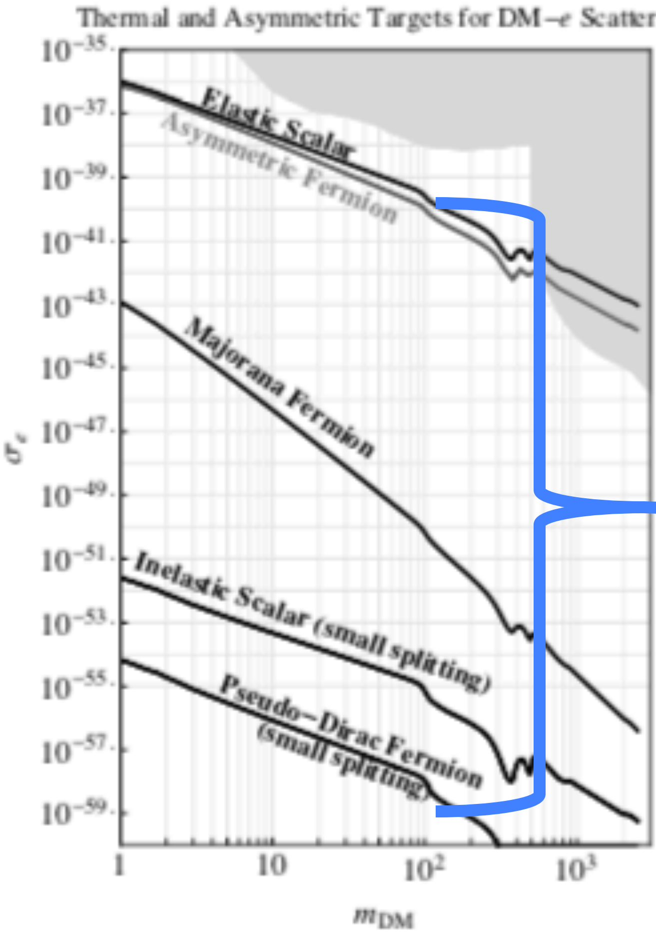
- $m_{A'} < 2m_\chi$: visible decays into SM, A´ → e^+e^-, $\mu^+\mu^-$, hadrons,..
- $m_{A'} > 2m_\chi$: invisible decays into DM: A´ → $\chi\chi$, $\alpha_D \gg \varepsilon$, $\alpha_D = e_D^2/4\pi$

- Cross section for χ–DM annihilation:
  $\Gamma_{inel} = n_\chi < \sigma v >$
  $\sigma v \approx [\alpha_D\, \varepsilon^2 (m_\chi/m_{A'})^4]\, \alpha/m_\chi^2 = y\, \alpha/m_\chi^2$;
  $y = [\alpha_D\, \varepsilon^2 (m_\chi/m_{A'})^4]$ - useful variable to compare FTE sensitivities

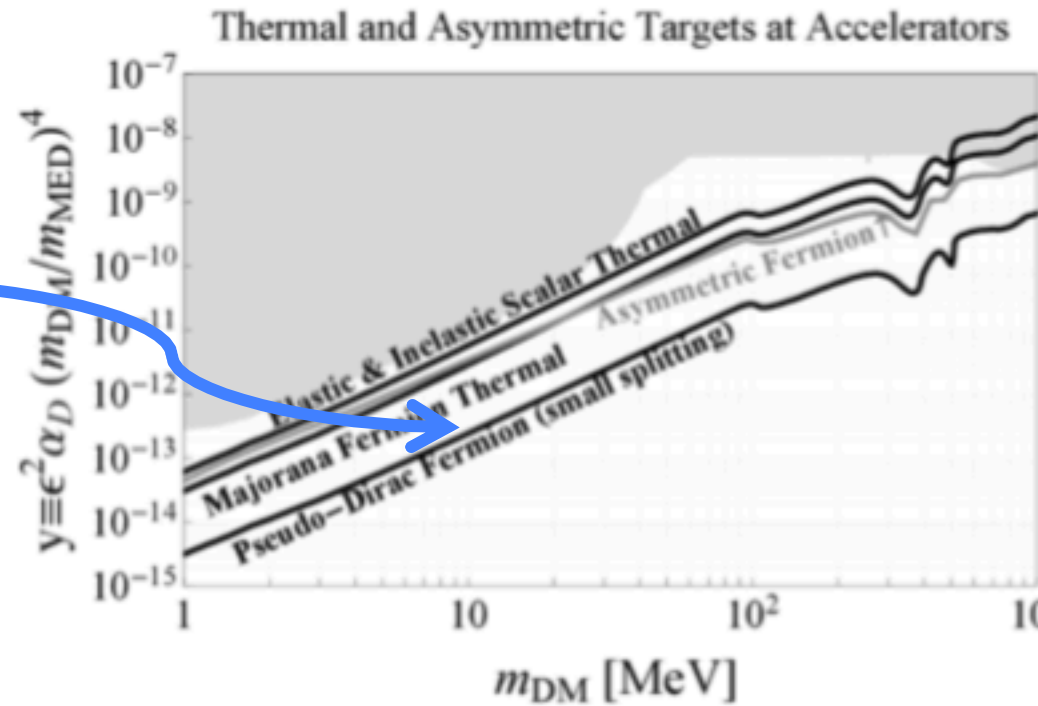


Sub-GeV Thermal DM scenarios

Direct detection almost unfeasible



Searching on accelerators more preferable



The TDM candidates χ : scalars, Majorana, pseudo-Dirac fermions. Required SM<->DM annihilation rate give exciting target for the $(\varepsilon, \alpha_D, m_\chi, m_A)$ parameter space which can be probed at F-T experiments. The dark coupling is typically assumed to be $\alpha_{e\text{-}m} < \alpha_D < \alpha_S$.

Summary table of current and future light-DM experiments.

arXiv:1707.04591
+more from
PBC at CERN

Experiment Class	Production Modes	Detection
B-factory	$e^+e^- \to \gamma A'$	missing mass
Electron fixed-target	$e^-Z \to e^-ZA'$	DM scatter or missing energy/mass
Hadron collider	$pp \to (\text{jet}/\gamma)A'$	missing energy
Positron fixed-target	$e^+e^- \to \gamma A'$	missing mass
Proton fixed-target	$\pi^0/\eta/\eta' \to \gamma A'$, $q\bar{q} \to A'$, $pZ \to pZA'$	DM scatter downstream

Experiment	Machine	Type	E_{beam} (GeV)	Detection	Mass range (GeV)	Sensitivity	First beam	Ref.
Future US initiatives								
BDX	CEBAF @ JLab	electron BD	2.1-11	DM scatter	$0.001 < m_\chi < 0.1$	$y \gtrsim 10^{-13}$	2019+	[211, 212]
COHERENT	SNS @ ORNL	proton BD	1	DM scatter	$m_\chi < 0.06$	$y \gtrsim 10^{-13}$	started	[213, 214]
DarkLight	LERF @ JLab	electron FT	0.17	MMass (& vis.)	$0.01 < m_{A'} < 0.08$	$\epsilon^2 \gtrsim 10^{-6}$	started	[215]
LDMX	DASEL @ SLAC	electron FT	4 (8)*	MMomentum	$m_\chi < 0.4$	$\epsilon^2 \gtrsim 10^{-14}$	2020+	[216]
MMAPS	Synchr @ Cornell	positron FT	6	MMass	$0.02 < m_{A'} < 0.075$	$\epsilon^2 \gtrsim 10^{-8}$	2020+	[217]
SBN	BNB @ FNAL	proton BD	8	DM scatter	$m_\chi < 0.4$	$y \sim 10^{-12}$	2018+	[218, 219]
SeaQuest	MI @ FNAL	proton FT	120	vis. prompt	$0.22 < m_{A'} < 9$	$\epsilon^2 \gtrsim 10^{-8}$	2017	[220]
				vis. disp.	$m_{A'} < 2$	$\epsilon^2 \sim 10^{-14} - 10^{-8}$		
Future international initiatives								
Belle II	SuperKEKB @ KEK	e^+e^- collider	~ 5.3	MMass (& vis.)	$0 < m_\chi < 10$	$\epsilon^2 \gtrsim 10^{-9}$	2018	[203]
MAGIX	MESA @ Mami	electron FT	0.105	vis.	$0.01 < m_{A'} < 0.060$	$\epsilon^2 \gtrsim 10^{-9}$	2021-2022	[205]
PADME	DAΦNE @ Frascati	positron FT	0.550	MMass	$m_{A'} < 0.024$	$\epsilon^2 \gtrsim 10^{-7}$	2018	[206, 207]
SHIP	SPS @ CERN	proton BD	400	DM scatter	$m_\chi < 0.4$	$y \gtrsim 10^{-12}$	2026+	[208, 209]
VEPP3	VEPP3 @ BINP	positron FT	0.500	MMass	$0.005 < m_{A'} < 0.022$	$\epsilon^2 \gtrsim 10^{-8}$	2019-2020	[210]
Current and completed initiatives								
APEX	CEBAF @ JLab	electron FT	1.1-4.5	vis.	$0.06 < m_{A'} < 0.55$	$\epsilon^2 \gtrsim 10^{-7}$	2018-2019	[197, 198]
BABAR	PEP-II @ SLAC	e^+e^- collider	~ 5.3	vis.	$0.02 < m_{A'} < 10$	$\epsilon^2 \gtrsim 10^{-7}$	done	[191, 229, 230]
Belle	KEKB @ KEK	e^+e^- collider	~ 5.3	vis.	$0.1 < m_{A'} < 10.5$	$\epsilon^2 \gtrsim 10^{-7}$	done	[231]
HPS	CEBAF @ JLab	electron FT	1.1-4.5	vis.	$0.015 < m_{A'} < 0.5$	$\epsilon^2 \sim 10^{-7}$**	2018-2020	[232]
NA/64	SPS @ CERN	electron FT	100	MEnergy	$m_{A'} < 1$	$\epsilon^2 \gtrsim 10^{-10}$	started	[186]
MiniBooNE	BNB @ FNAL	proton BD	8	DM scatter	$m_\chi < 0.4$	$y \gtrsim 10^{-9}$	done	[188]
TREK	K^+ beam @ J-PARC	K decays	0.240	vis.	N/A	N/A	done	[201, 202]

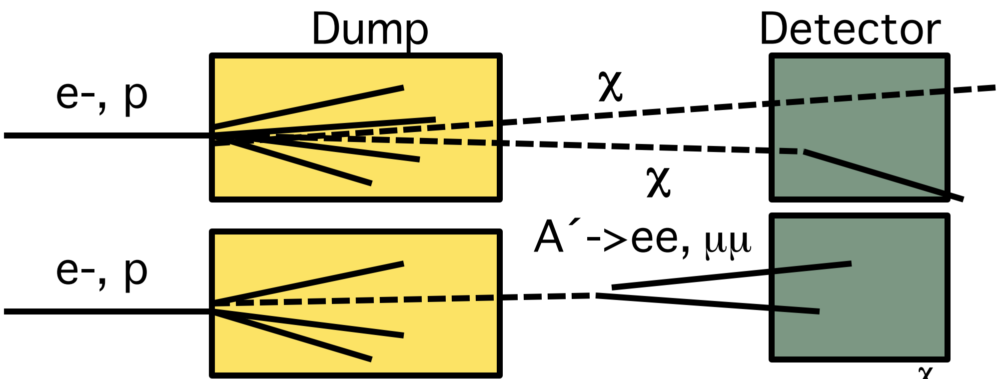
Some fixed-target experiments on sub-GeV TDM

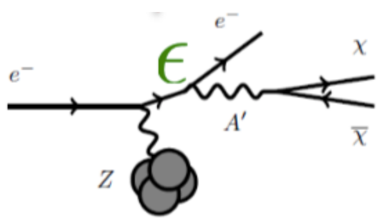
	Experiment	Energy, GeV	POT	DUMP, m	Decay Volume, m	Physics Run
A´-> invis	NA64e,μ	100	$5\text{x}10^{12-13}$ e^-, μ^-	0.5	5	running
	LDMX	4–10	~10^{16} e^-	<0.1		2022
	MiniBooNE	8	$2\text{x}10^{20}$ p	~500		2013/14
A´-> visible	SeaQuest	120	10^{18}-10^{20} p	5	10	2018
	NA62D	400	10^{18} p	10	200	2021(?)
	SHIP	400	10^{20} p	65	120	2026(?)
	HPS	1	$4.5\text{x}10^{16}$ ~$5\text{x}10^{18}$ e^-	-	~1	2d eng.run +180 d run
	PADME	0.55	10^{13} e^+	-		2018

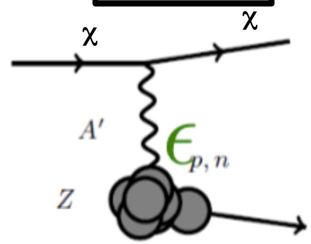
Two approaches for searching for LTDM at FTE

BEAM DUMP

BDX, NA62D, SeaQuest,...







A´ production:

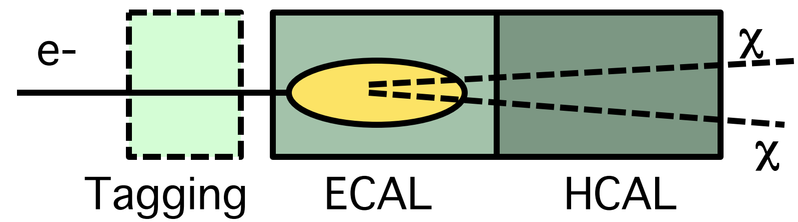
A´- bremsstrahlung $e^- Z \rightarrow e^- Z A'$, $\sigma \sim Z^2 \varepsilon^2 / m_{A'}^2$;

or π^0, η, η' ... $\rightarrow \gamma A'$, $A' \rightarrow \chi\chi$, ee, $\mu\mu$, ..

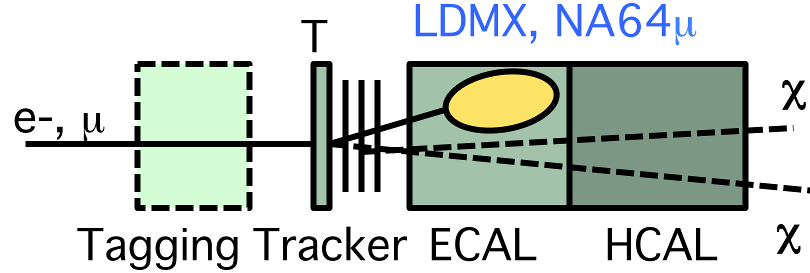
$n_S \sim \alpha_D \varepsilon^4 n_{eot}$ for both
- visible, A´->ee, $\mu\mu$, or
- invisible A´->$\chi\chi$ decays.

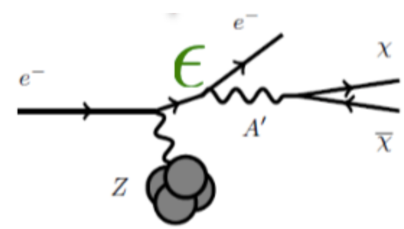
MISSING ENERGY/MOMENTUM

NA64e (active dump)



LDMX, NA64μ



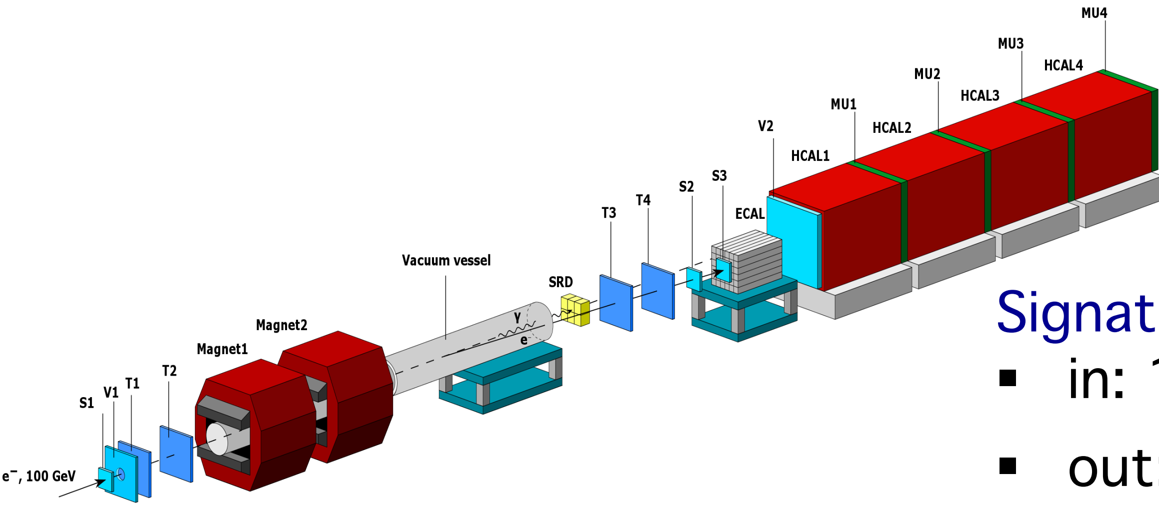


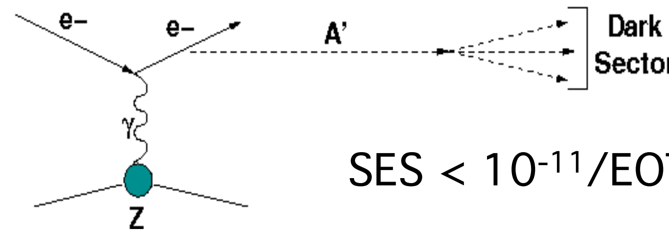
$n_S \sim \varepsilon^2 n_{eot}$

More signal events

Searches for A´->invisible decays: NA64@CERN SPS

NA64 is designed to search for new, in particular Dark Sector physics in missing energy events. Broad research program with e^-, μ, π, K, and p beams at SPC (PBC'16/17). Approved in March'16.





SES < 10^{-11}/EOT

S.Andreas et al., arXiv: 1312.3309
S.G., PRD(2014)

Signature:

- in: 100 GeV e- track
- out: $E_{ECAL} < E_0$ shower in ECAL
- no energy in Veto and HCAL

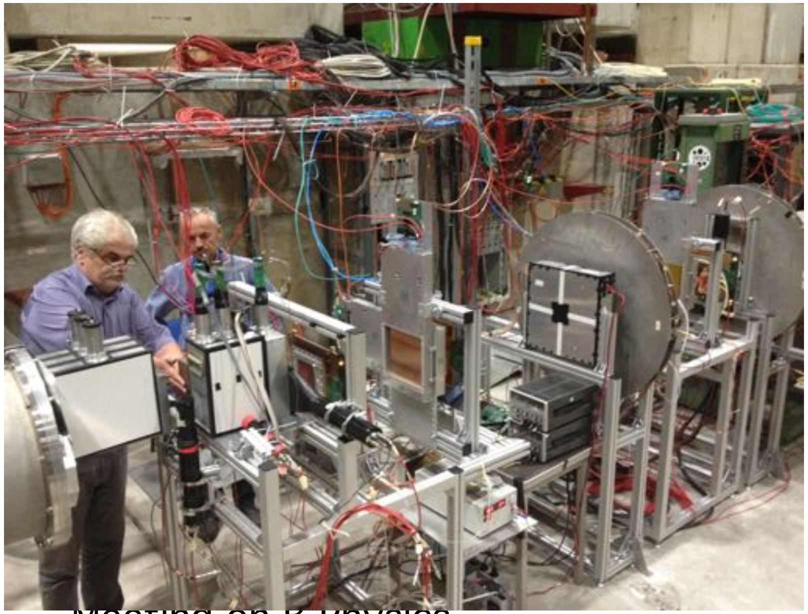
Main components :

- clean 100 GeV e- beam
- e- tagging system: tracker+SRD
- 4π fully hermetic ECAL+ HCAL

Background:

- μ, π, K decays in flight
- Tail < 50 GeV in the e- beam
- Energy leak from ECAL+HCAL

2018 run



NA64 results from 2016 run, 2.75x10^9 EOT

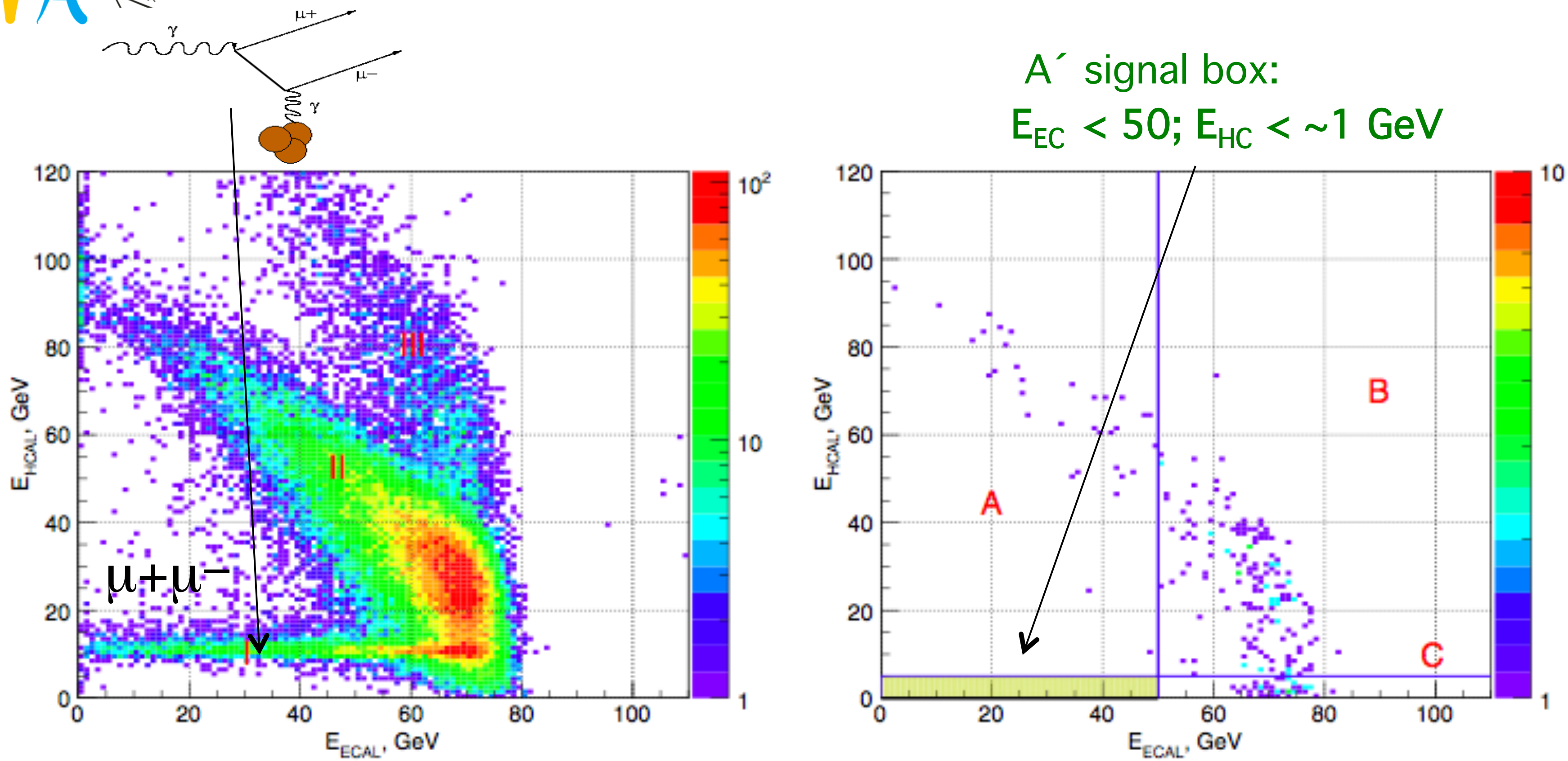


FIG. 2. The left panel shows the measured distribution of events in the (E_{ECAL}; E_{HCAL}) plane from the combined BGO and PbSc run data at the earlier phase of the analysis. Another plot shows the same distribution after applying all selection criteria. The dashed area is the signal box region which is open. The side bands A and C are the ones used for the background estimate inside the signal box. For illustration purposes the size of the signal box along the E_{HCAL} axis is increased by a factor of 5.

Systematics errors are dominated by the uncertainties in the A´ yield ~20%. Cross checked with dimuon production.

A´explanation of $(g-2)_\mu$ anomaly is ruled out

CERN Courier April 2017

News

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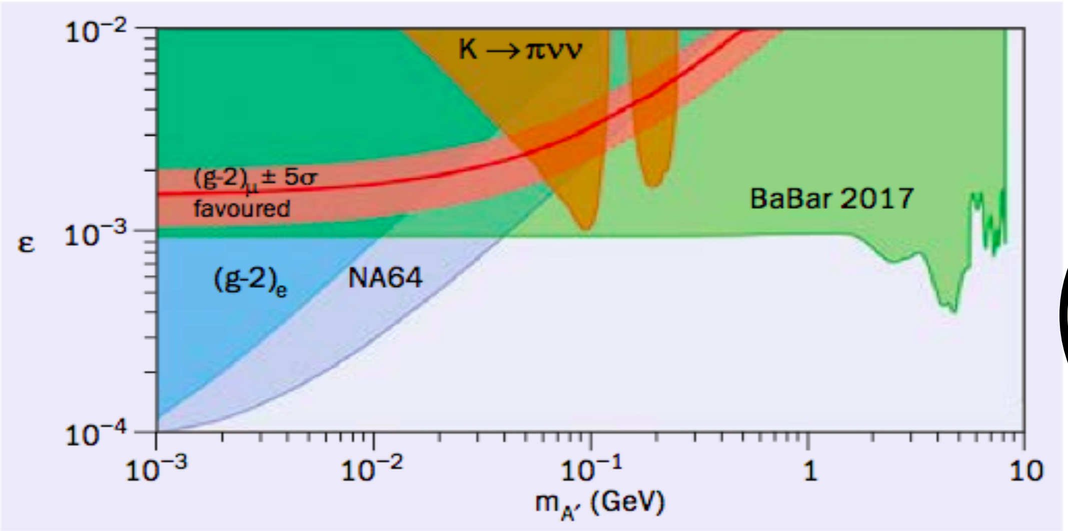


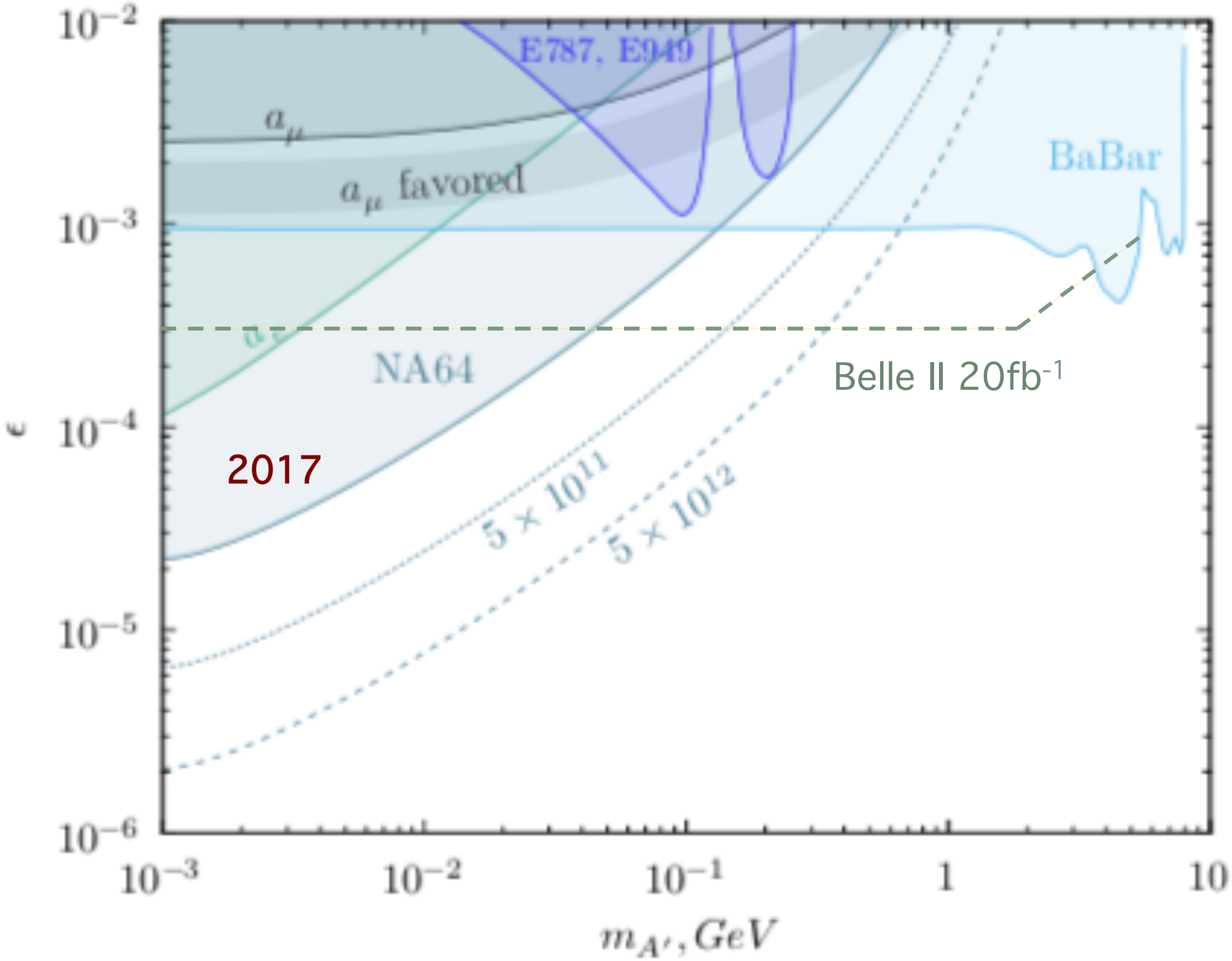
Regions of the dark-photon parameter space (mixing strength versus mass) excluded by BaBar (green) compared with the previous constraints. The new analysis rules out dark-photon coupling as the explanation for the muon (g-2) anomaly and places stringent constraints on dark-sector models.

of Caltech, who has worked on dark-photon models. "In contrast to massless dark photons, which are analogous to ordinary photons, this experiment constrains a slightly different idea of dark force-carrying particles that are associated with a broken symmetry, which therefore get a mass and then can decay. They are more like 'dark Z bosons' than dark photons."

- **Further reading**

BaBar Collaboration 2017 arXiv:1702.03327.
NA64 Collaboration 2017 *Phys. Rev. Lett.* **118** 011802.

NA64 projections for ε

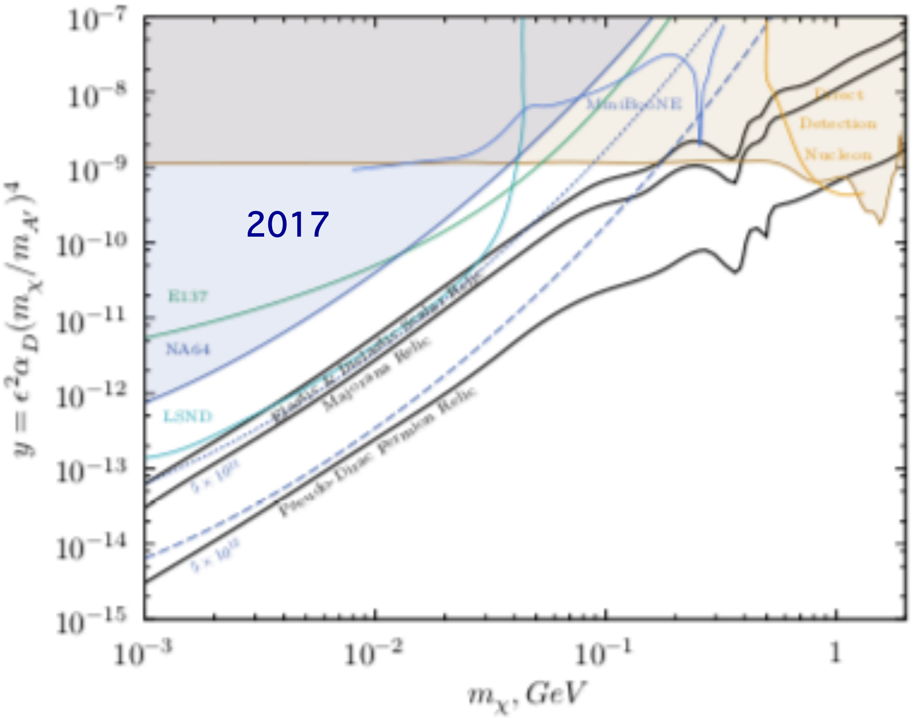


(background free case)

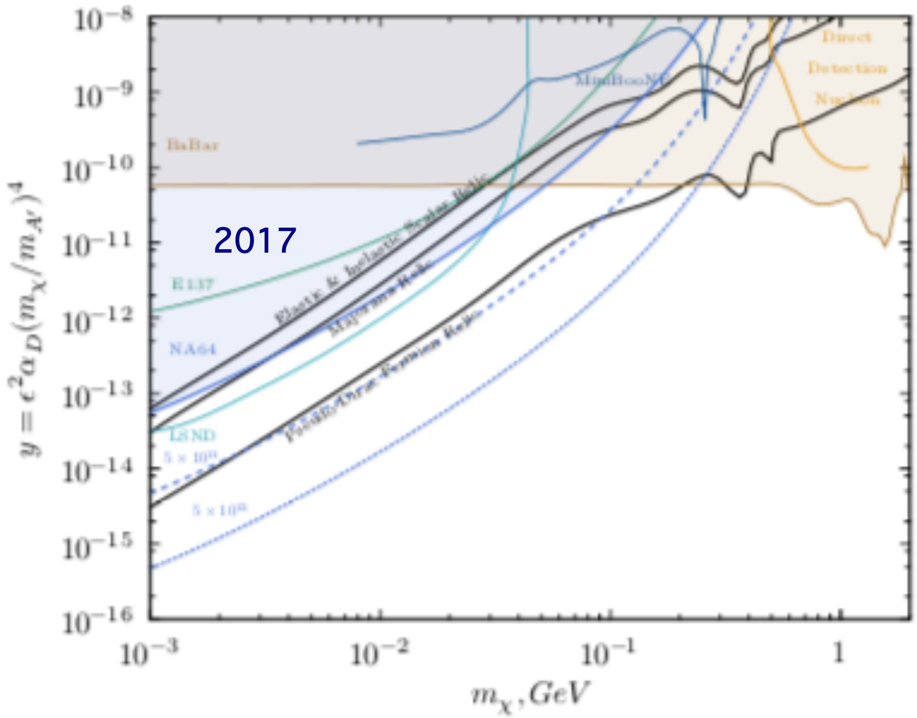
Expected limits on sub-GeV TDM

$m_{A'} = 3\ m_\chi$

$\alpha_D = 0.1(\sim\alpha_S)$

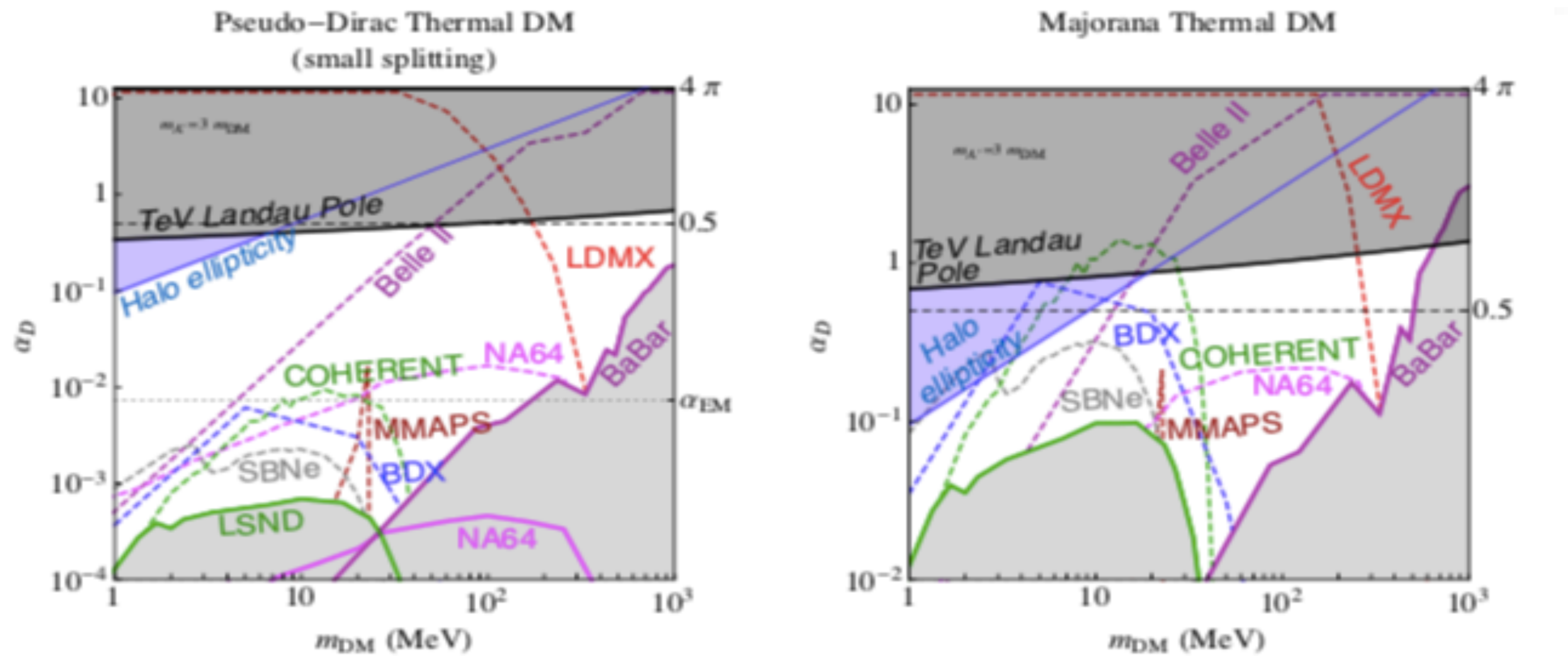


$\alpha_D = 0.01\ (\sim\alpha_{e\text{-}m})$

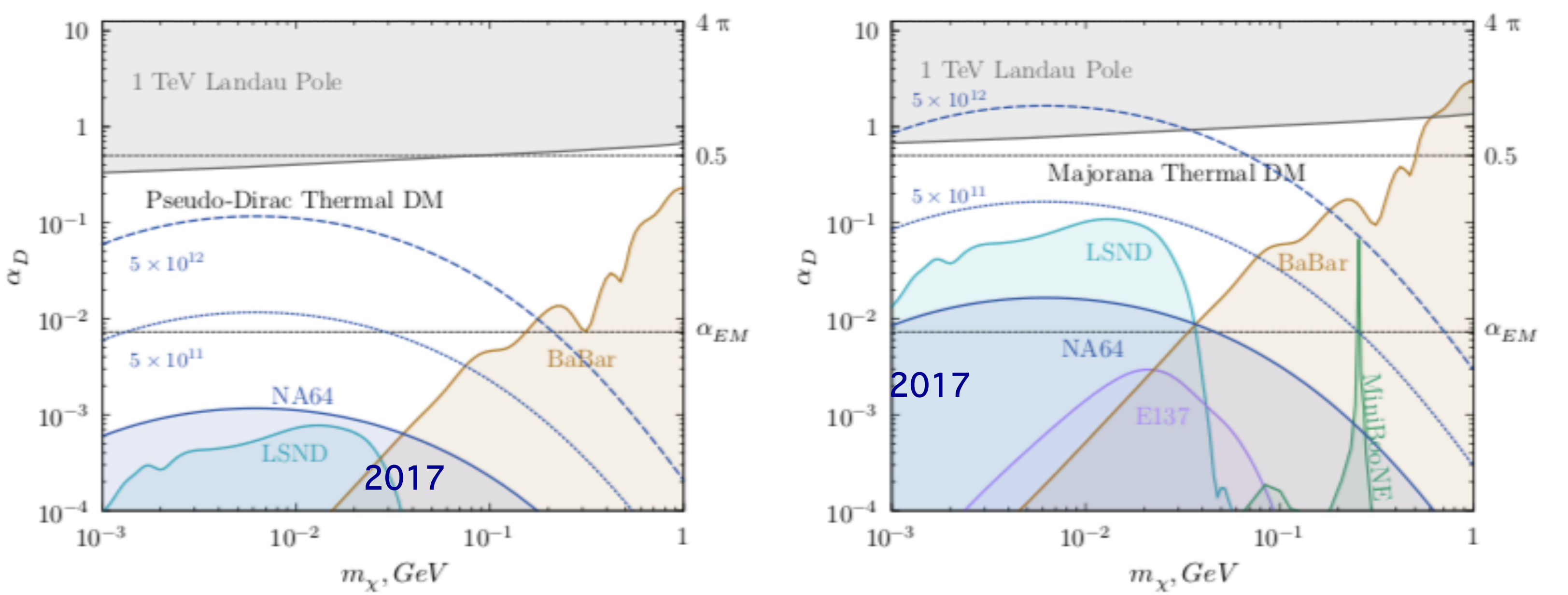


Expected limits on α_D

US Cosmic Visions, arXiv:1707.04591



NA64 projections, arXiv:1710.00971



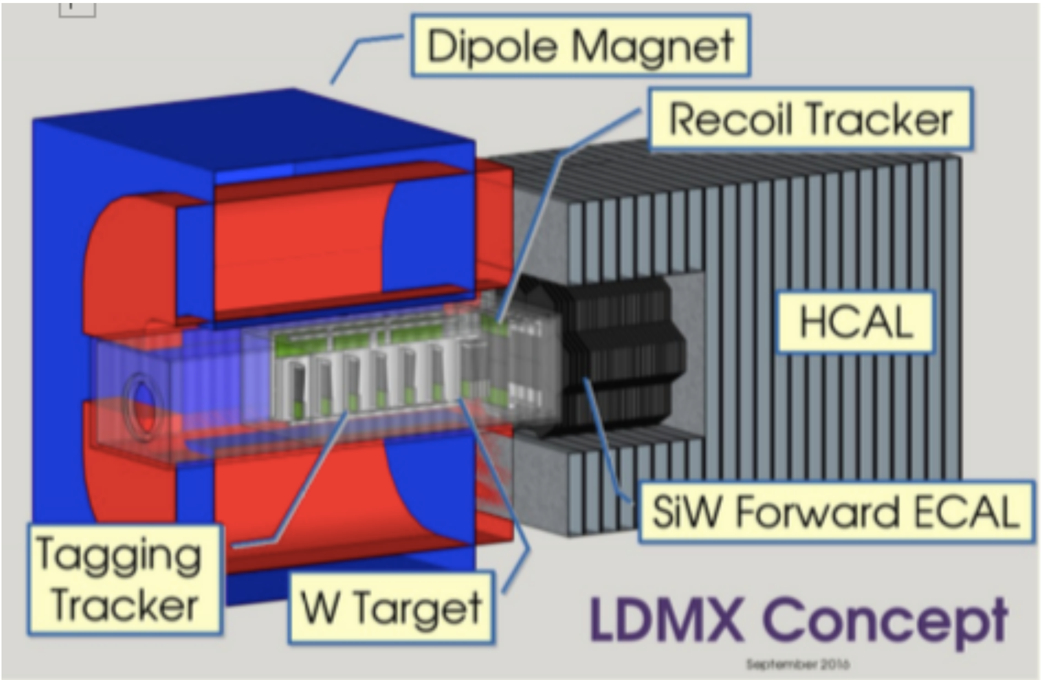
A´->invisible: Light Dark Matter eXperiment (LDMX)

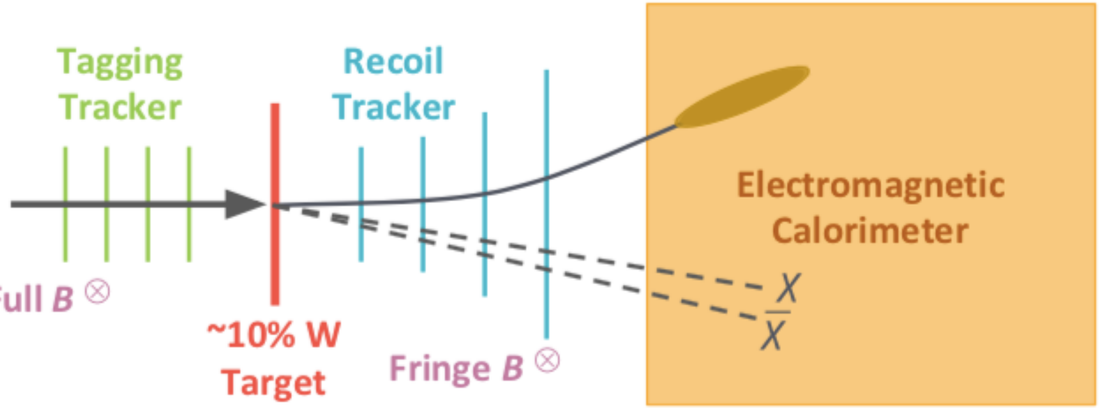
Location possibilities

- DASEL@SLAC at 4/8 GeV
- CEBAF@JLab up to 11 GeV
- SPS@CERN ~10 GeV

Plans

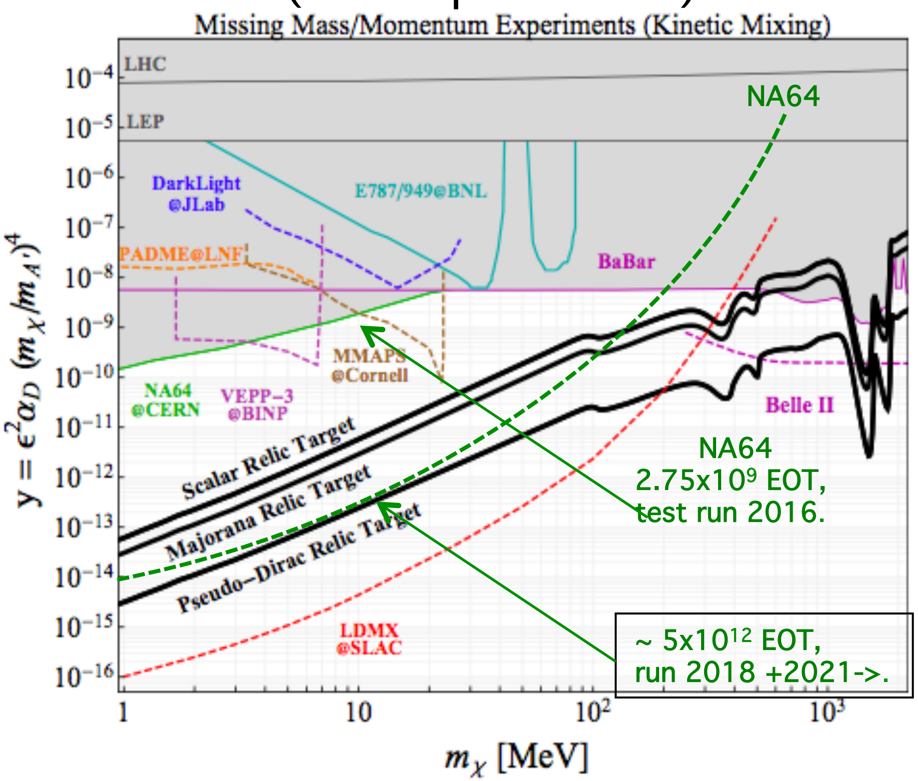
- Rate 1 e-/3 ns, 10^{16}/year
- Phase I: ~ 4×10^{14} EOT
- Phase II: ~ 10^{16} EOT
- 1st Physics run ~ 2022



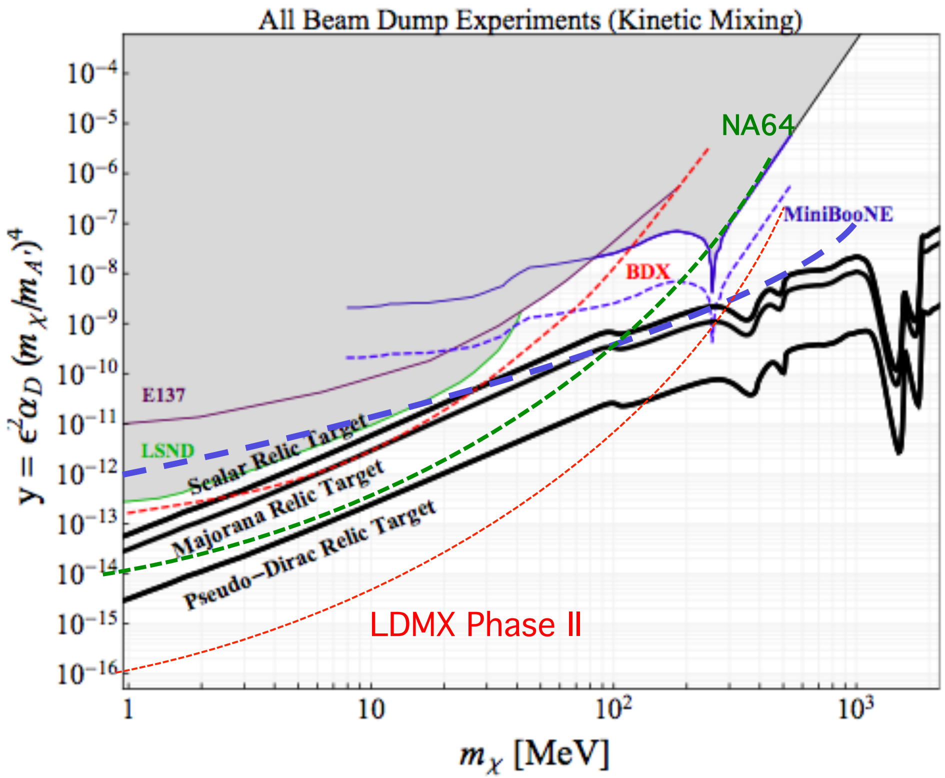


Existing and projected limits on sub-GeV TDM

Missing mass / momentum / energy
(assumption free)



Beam dump

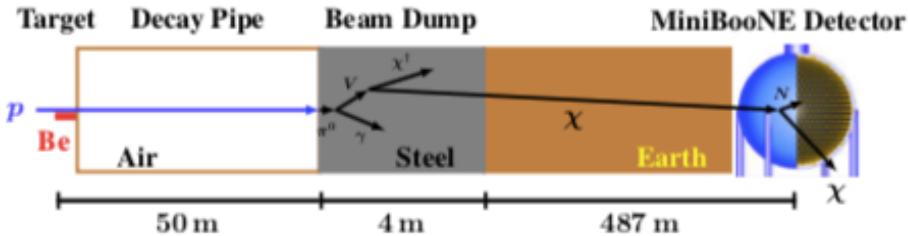


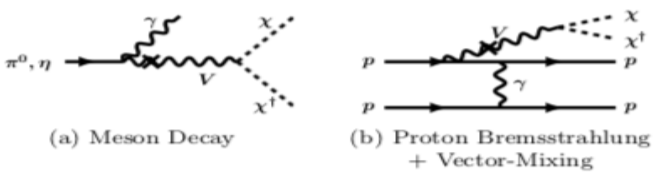
NA64 has a good potential to cover region sub-GeV thermal DM targets.

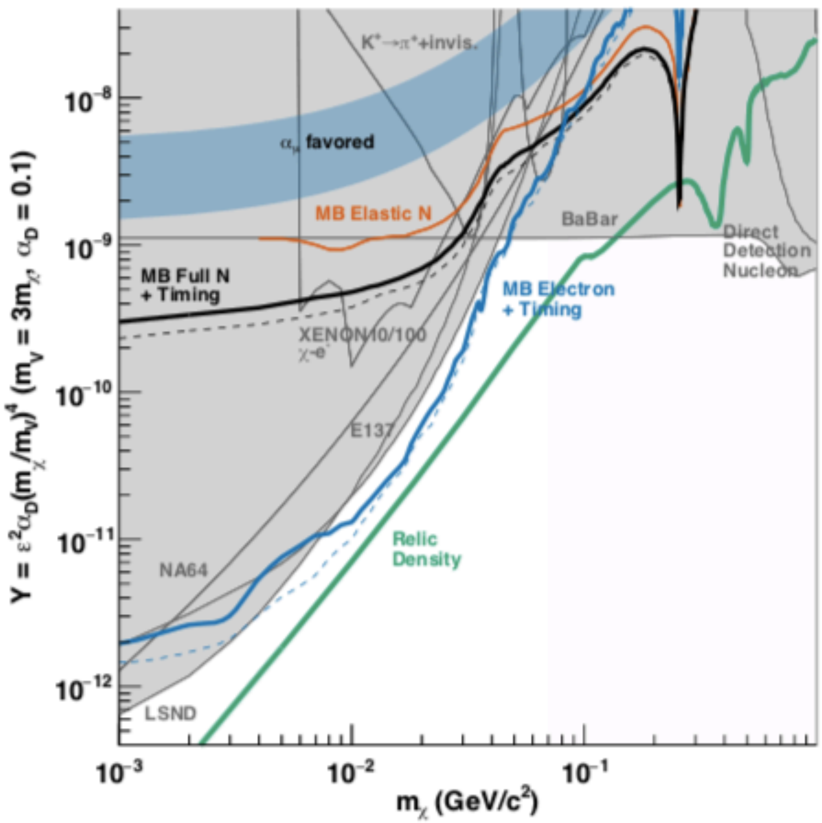
(from US Cosmic Visions Workshop 2017)

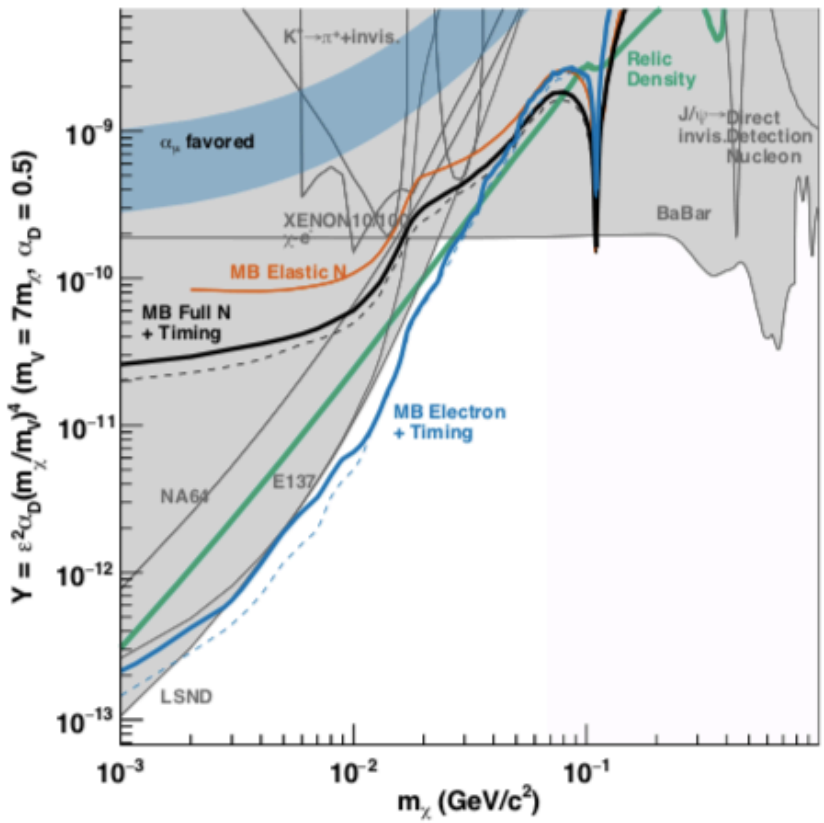
A´->χχ: MiniBooNE-DM@FNAL

arXiv:1807.06137



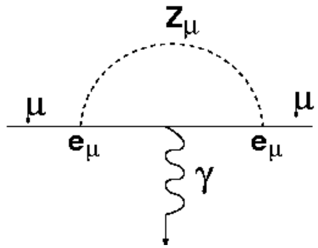






$(g\text{-}2)_\mu$ and DM: what's about 2^{nd} L -generation?

Strong motivation for a search for leptophobic mediator Z_μ in a near future NA64μ experiment with a muon beam at CERN.



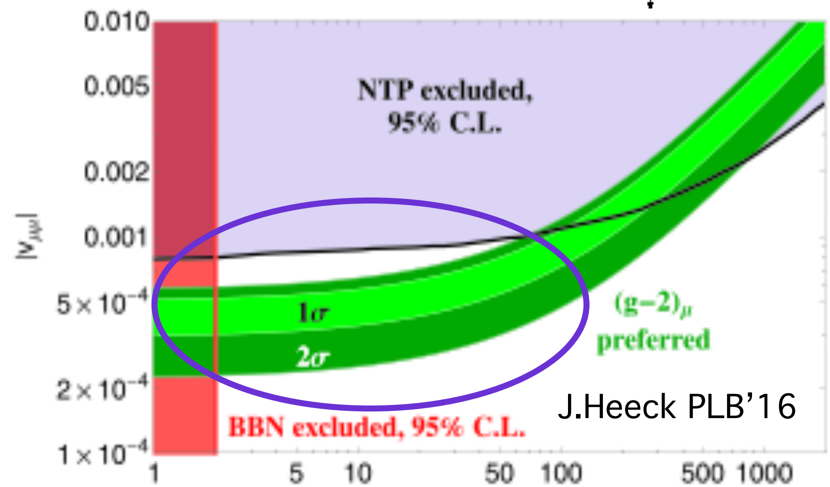
E.g.: leptonic $Z_\mu \to \nu\nu$, DM from (broken) gauged $L_\mu - L_\tau$ symmetry

- explanation of $(g-2)_\mu$
- mediator of new force, sub-GeV TDM
- Impact on ν-physics,

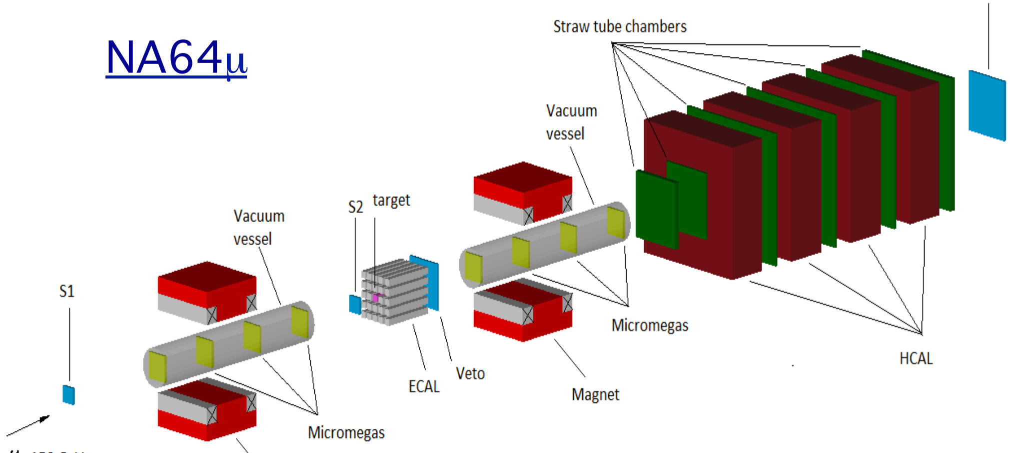
Currently NA64μ proposal under preparation

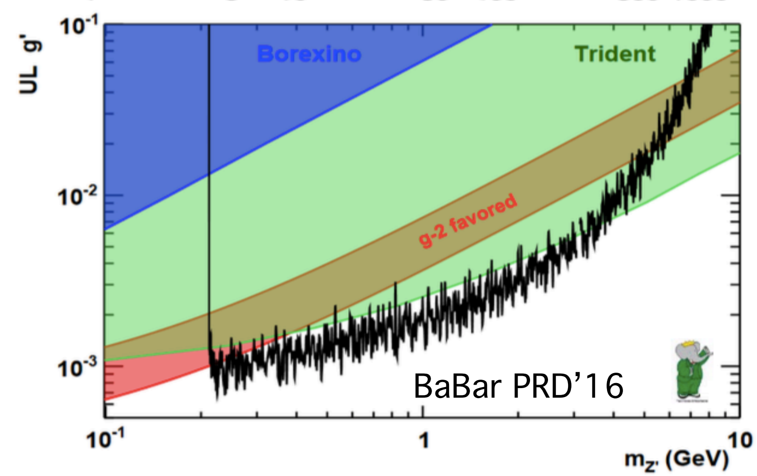
NA64μ- like initiative in US

- M^3@FNAL, arXiv:1804.03144
- Leptophilic TDM, arXiv:1807.03790
- Light scalars from DS, arXiv:1701.07437



NA64μ

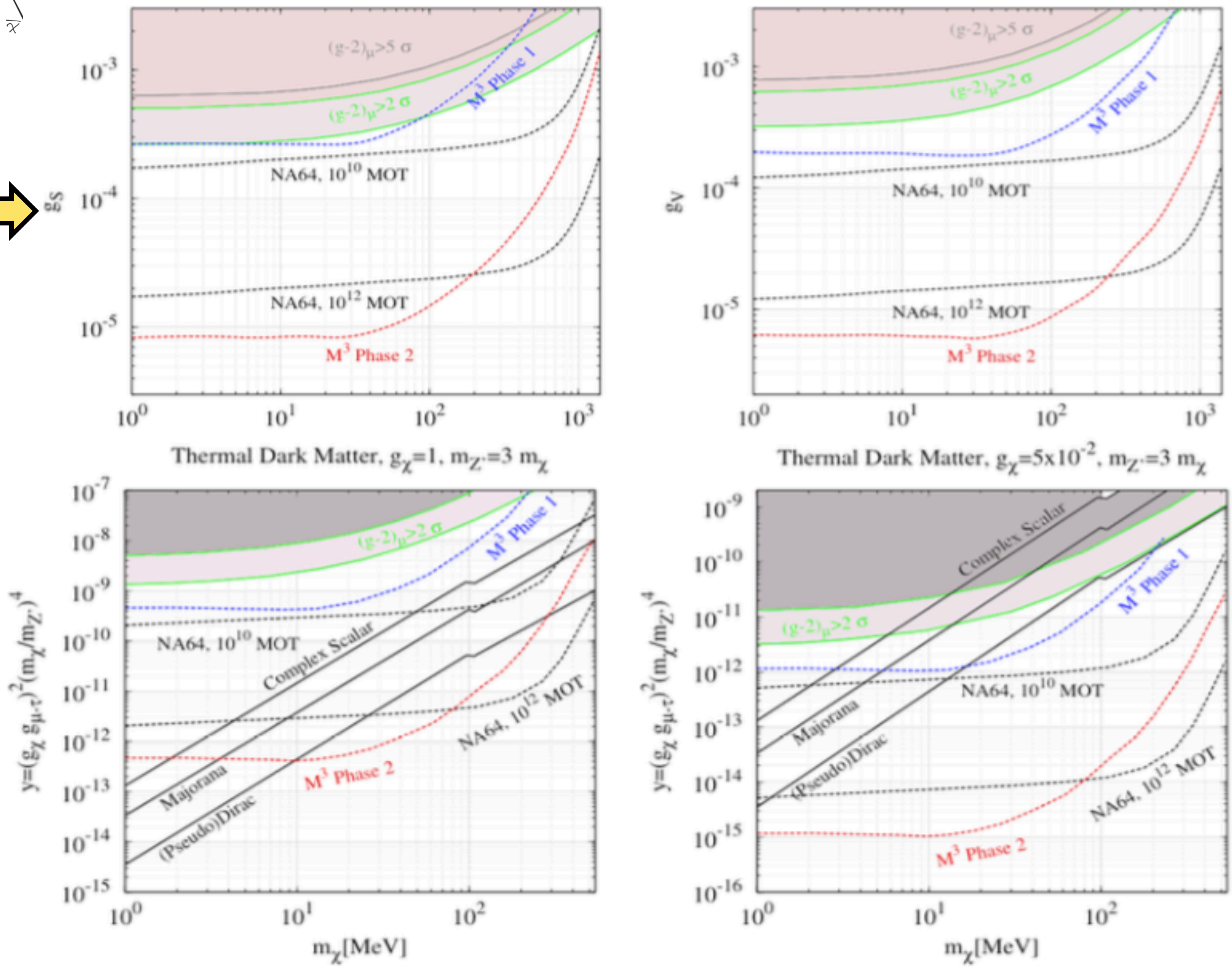




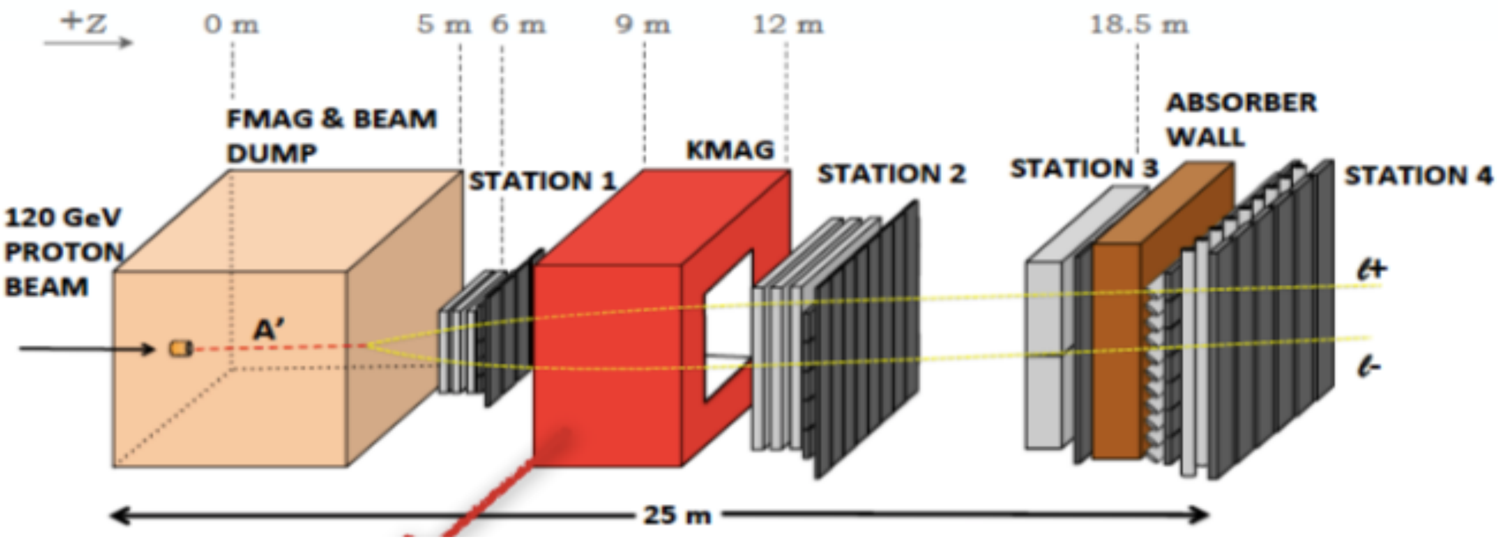
SG, Krasnikov, Matveev PRD'15

Sensitivities of NA64μ@CERN and M³@FNAL

NA64 need just <~ 10^{11} to probe muon g-2 region



A´->ee, μμ, ππ decays: SeaQuest@FNAL(E-906)



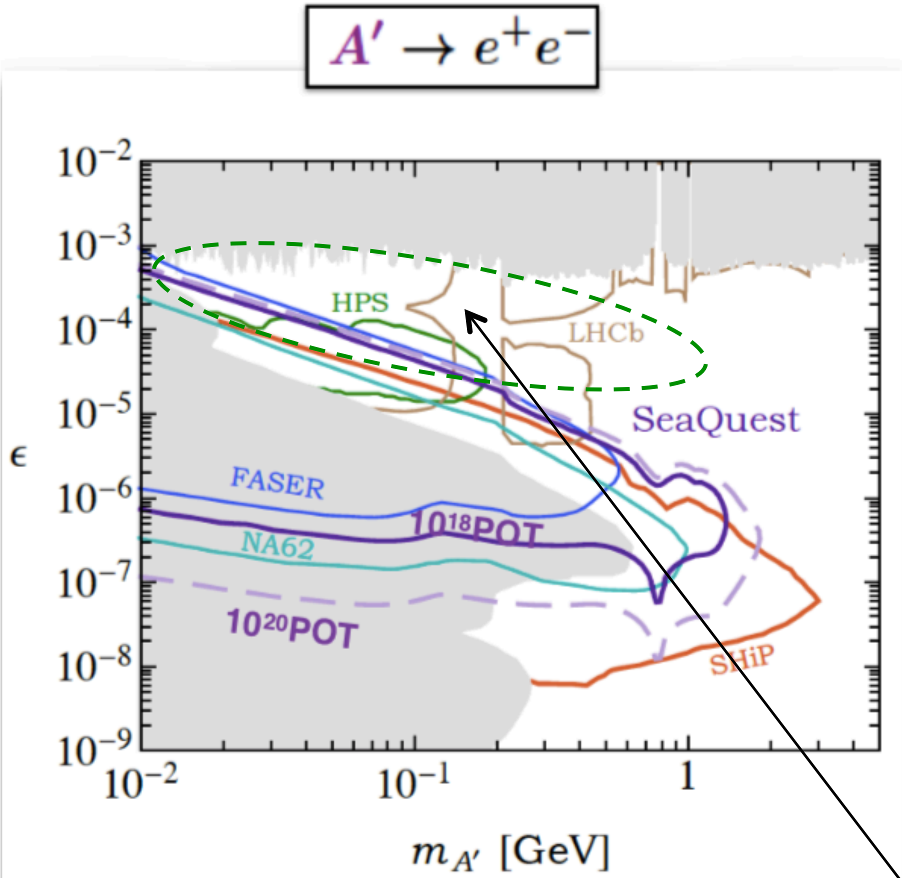
- Sensitivity to slightly displaced dark particles with d > 5m
- Separating KMAG, ID of very light particles
- Approved luminosity ~ 10^{18} pot by 2019

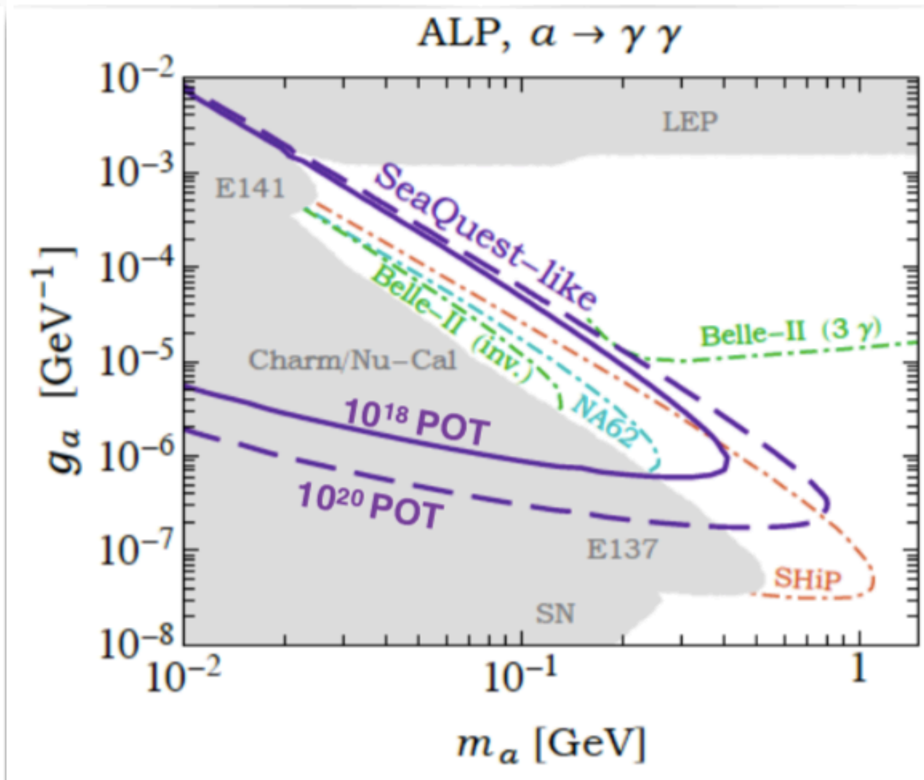
Models that can be explored

- Minimal dark photon & dark scalar
- Inelastic DM
- Axions
- Strongly-interacting DM

S.Gardner at el., arXiv:1509.00050

SeaQuest projections

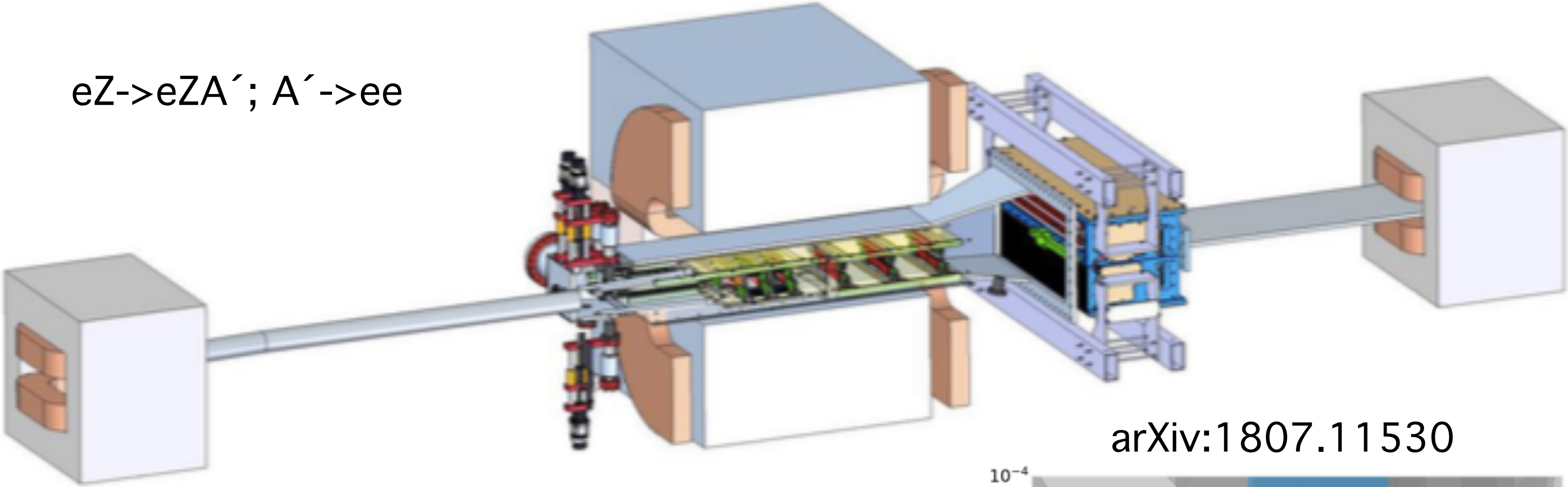




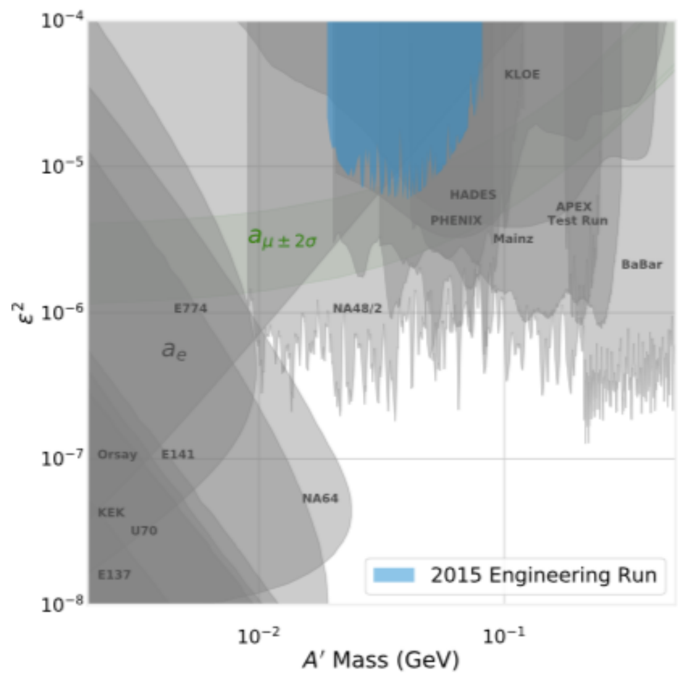
very short-lived A´ region
difficult to probe

A´->e⁺e⁻ decays: HPS@JLab

eZ->eZA´; A´->ee

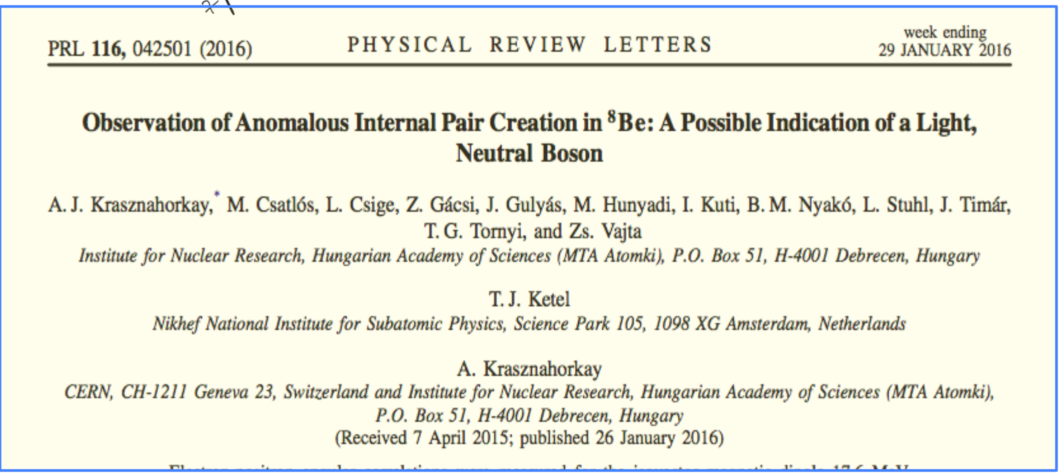


arXiv:1807.11530



- 3 dipole magnets
- 0.1% X_0 W target, 1 GeV e-
- 1m long Si tracker: tracks, vertex
- PWO ECAL: energy, timing, trigger
- Background: radiative, Bethe-Heitler
- Resonance search possible

A new light X boson from $^8Be^*$ transition ?


PRL 116, 042501 (2016) PHYSICAL REVIEW LETTERS week ending 29 JANUARY 2016

Observation of Anomalous Internal Pair Creation in ^{8}Be: A Possible Indication of a Light, Neutral Boson

A. J. Krasznahorkay,* M. Csatlós, L. Csige, Z. Gácsi, J. Gulyás, M. Hunyadi, I. Kuti, B. M. Nyakó, L. Stuhl, J. Timár, T. G. Tornyi, and Zs. Vajta
Institute for Nuclear Research, Hungarian Academy of Sciences (MTA Atomki), P.O. Box 51, H-4001 Debrecen, Hungary

T. J. Ketel
Nikhef National Institute for Subatomic Physics, Science Park 105, 1098 XG Amsterdam, Netherlands

A. Krasznahorkay
CERN, CH-1211 Geneva 23, Switzerland and Institute for Nuclear Research, Hungarian Academy of Sciences (MTA Atomki), P.O. Box 51, H-4001 Debrecen, Hungary
(Received 7 April 2015; published 26 January 2016)

$^7Li(p,\gamma)^8Be$, $M_X = 16.7$ MeV

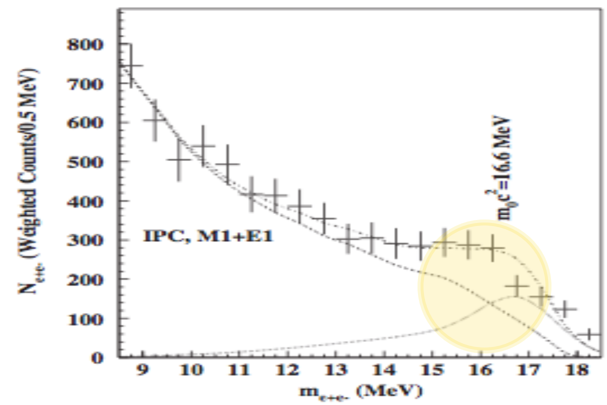
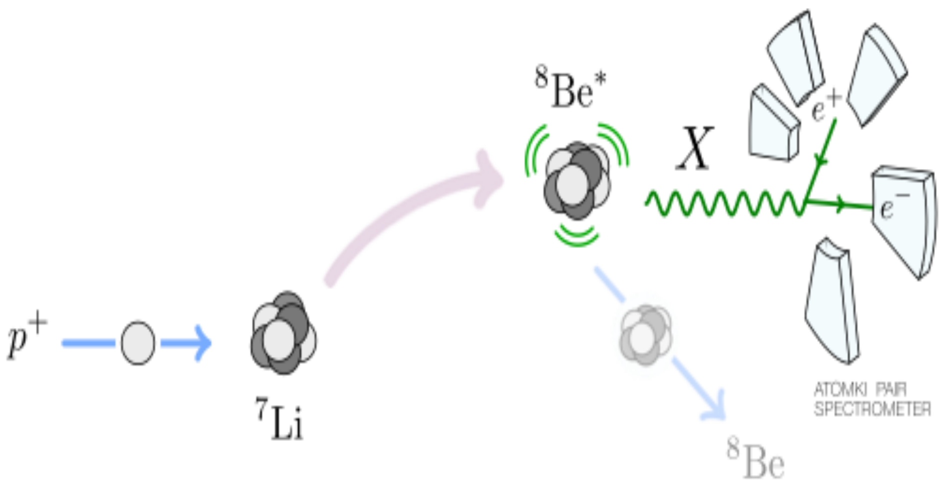
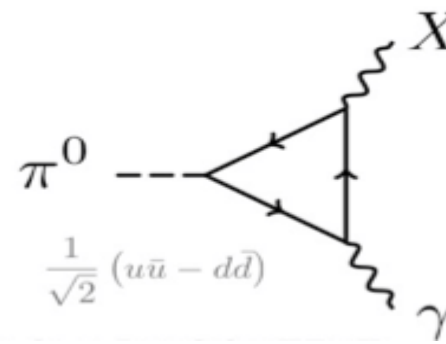


FIG. 5. Invariant mass distribution derived for the 18.15 MeV transition in ^{8}Be.



X cannot be A´ due to constraints from $\pi^0 \to X\gamma$ decay:



Feng et al, 2016

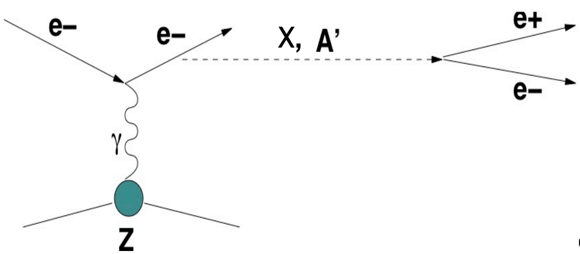
$2\times10^{-4} < \varepsilon_e < 1.4\times10^{-3}$

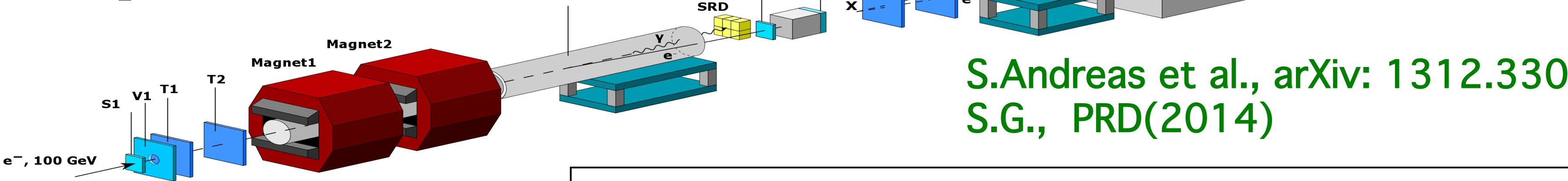
$\Gamma(\pi^0 \to X\gamma) \sim (\varepsilon_u q_u - \varepsilon_d q_d)^2 \sim 0$

if $2\varepsilon_u = -\varepsilon_d$ -> protophobic X

NA64e: $^8Be^*$ anomaly, $A' \to e^+e^-$ from 2017 run and beyond

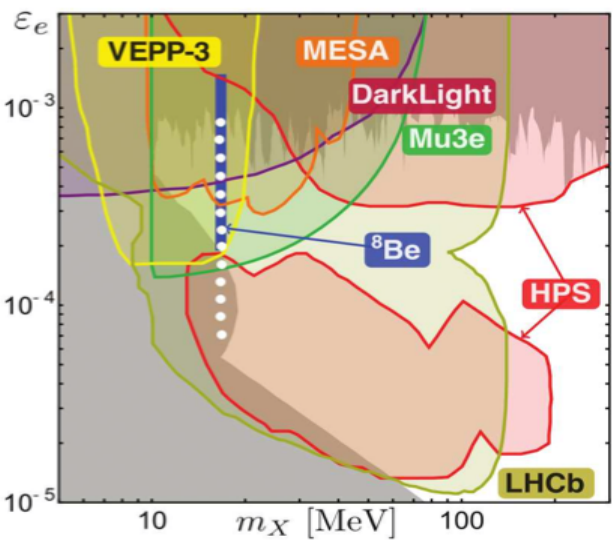
$\sigma_X/\sigma_\gamma \sim 10^{-10}$, $\tau_X \sim 10^{-13}$ s



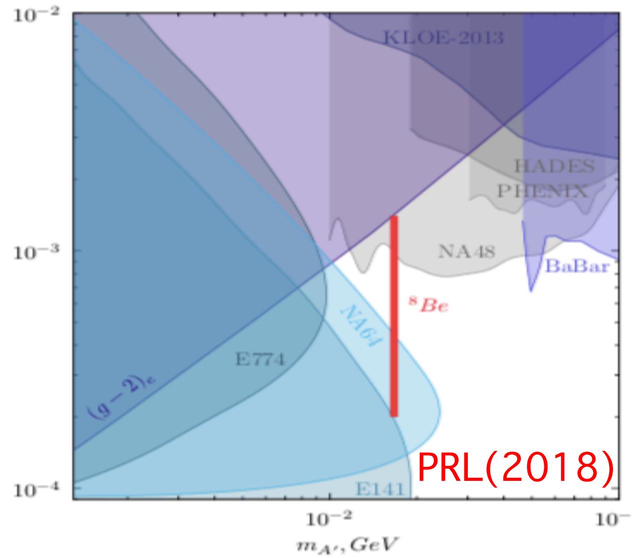


S.Andreas et al., arXiv: 1312.3309
S.G., PRD(2014)

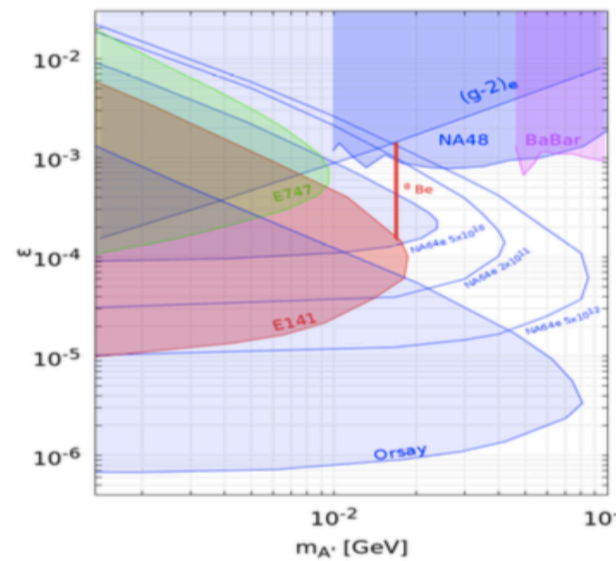
NA64e focus on short-lived $A' \to e^+e^-$, and $10^{-3} < \varepsilon < 10^{-5}$



Br($X \to e^+e^-$)=1, $\varepsilon^2 \sim 10^{-7}$



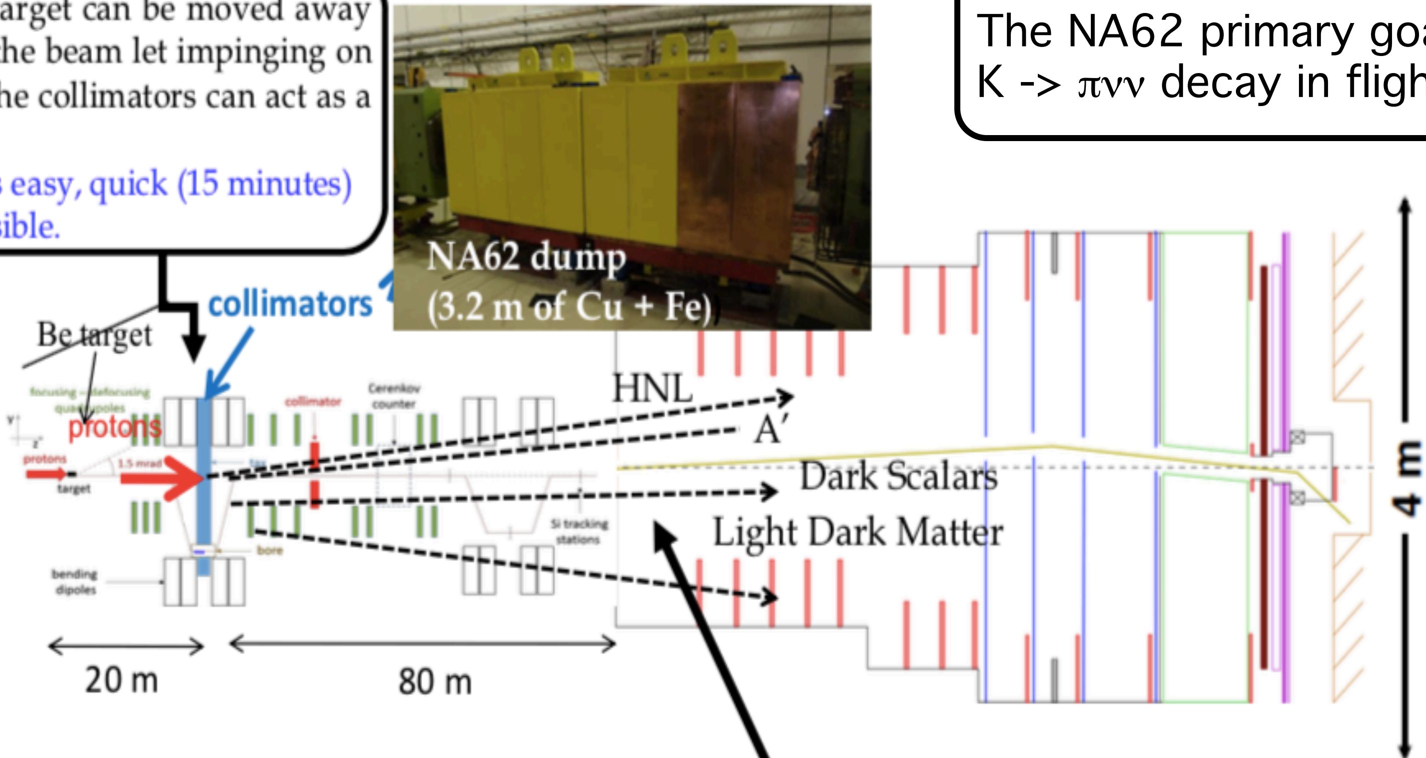
$A' \to e^+e^-$ vs EOT



NA62 in "dump" operation mode

In dump mode the target can be moved away from the beam and the beam let impinging on the copper. Hence: the collimators can act as a dump.
→ this operation is easy, quick (15 minutes) and fully reversible.

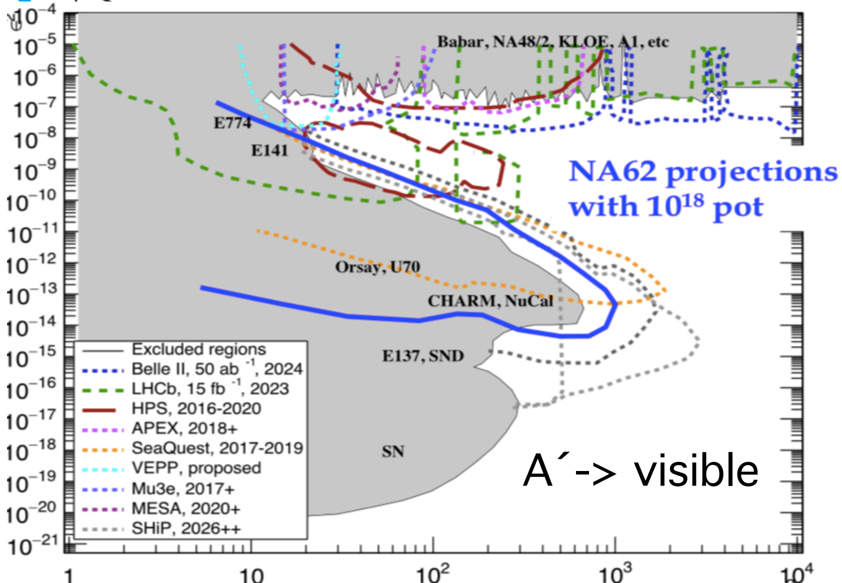
The NA62 primary goal: K -> $\pi\nu\nu$ decay in flight !

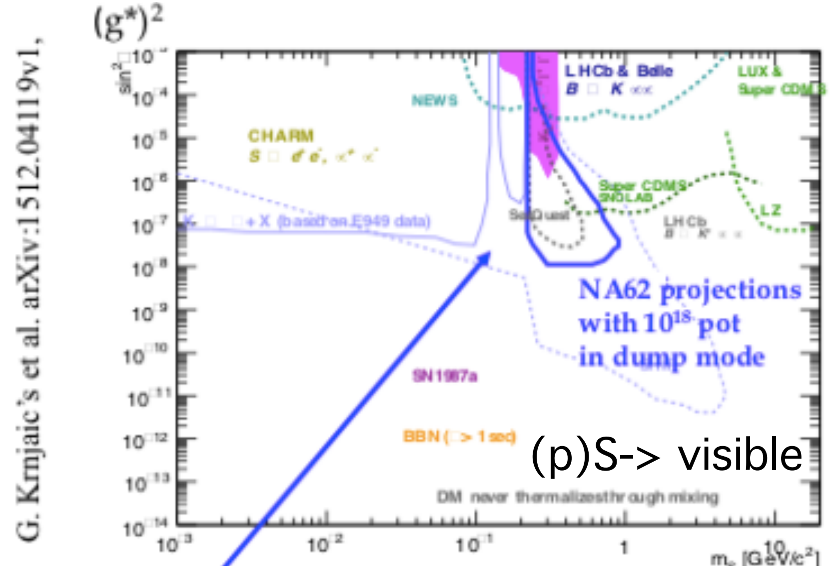


Heavy Neutrinos, Dark Photons, Dark scalars, and ALPS can be originated by charm, beauty and photons produced in the interaction of protons with the dump.

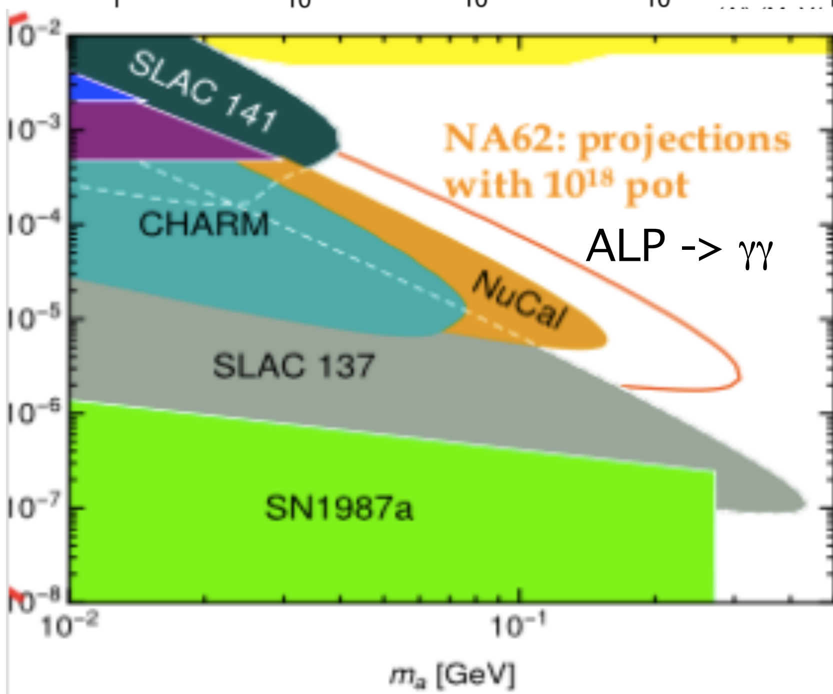
From the talk of
G. Lanfranchi

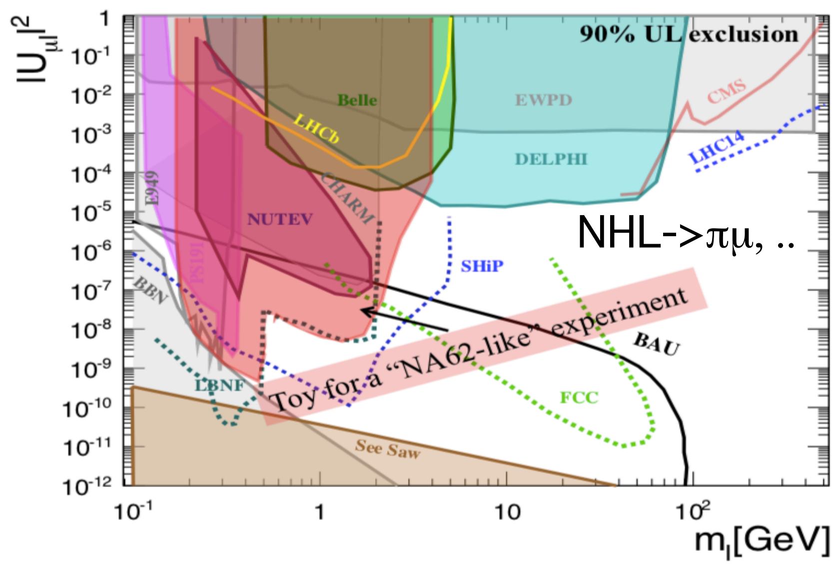
NA62D, SHIP projected sensitivities





In dump-mode, from b decays





Assume: 2×10^{18} pot, HNL → πμ/π e decays, trigger/acceptance/selection efficiencies, zero background

Summary

Fixed-target experiments – sensitive probe of Dark Sector physics.

Two complementary approaches to search for sub-GeV Dark Matter: beam-dump and missing energy/momentum

Feasible and exciting research program of experiments such as NA62D, NA64, SHIP at CERN and SeaQuest, HPS, LDMX,..in US

These experiments can efficiently

- look for signatures of visible and invisible decays of Dark Sector mediators;
- test large part of the remaining (ε, α_D, m_χ, m_A) parameter space of sub-GeV Thermal Dark Matter model
- test a large variety of other models: ALPs, NHL, SIMP, ...

  and possibly additional Dark Sector signatures