Light dark matter search with fixed-target experiments at accelerators

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POsitron resonant annihilation into darK mattER

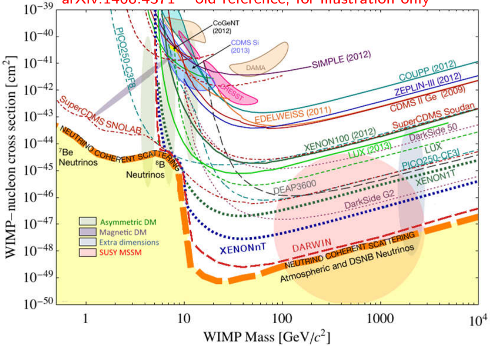
Outline

The dark sector: introduction

Dark matter: it is there, but very little is known about it! What is it? Where did it came from?

- "WIMP miracle:" electroweak scale masses ($\simeq$100 GeV) and DM annihilation cross sections (10^{-36} cm^2) give correct dark matter density / relic abundances ($\rho_{DM} \simeq 2 \cdot 10^{-27} kg/m^3$). No need for a new interaction!
- Intense experimental program searching for a signal in this mass region. So far, no positive evidences have been found.
- What about **light dark matter**, in the mass range 1 MeV ÷ 1 GeV?

arXiv:1408.4371 – old reference, for illustration only

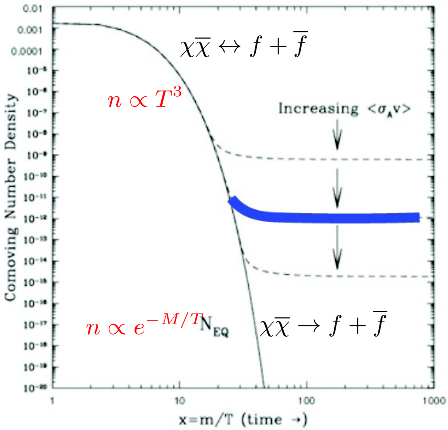


The dark sector - cosmological prior

Cosmological hypothesis: dark matter particles were in equilibrium with the primordial thermal bath in early Universe.
Reaction: $\chi + \overline{\chi} \leftrightarrow f + \overline{f}$

Thermal history:

- Early Universe: high-T, relativistic regime. Both reactions ($\leftarrow$ and $\rightarrow$) were permitted
- As Universe expands and cools down ($T < m_\chi$), only the $\rightarrow$ reaction occurs. DM number density is exponentially suppressed: Boltzmann regime
- Eventually, DM particles can't find each other to annihilate further, thermal equilibrium breaks: **freeze-out**



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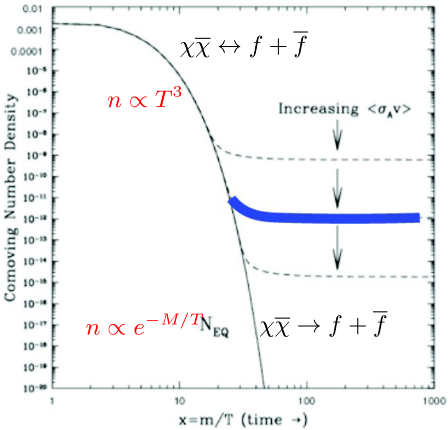
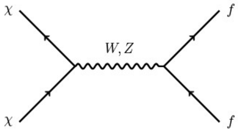
Thermal history:

- If annihilation cross section is too high (too small), DM particles would survive for a longer (shorter) in equilibrium in the Boltzmann regime, resulting in a lower (higher) density at present
- Observed relic abundance requires: $\langle \sigma v \rangle_{ann} \simeq 3 \cdot 10^{-26}$ cm^{-3}s^{-1}
- **This number corresponds to the scale of weak-force cross sections**



The dark sector - particle physics prior

WIMP miracle: weak-scale DM particle interacting with SM through weak force reproduces the presently observed DM relic density.
If DM is made of WIMPs, no necessity for new interactions.



$$\langle \sigma v \rangle_{\text{WIMP}} \sim 3 \times 10^{-26} \text{cm}^3 \text{s}^{-1} \left(\frac{\text{TeV}}{m_\chi} \right)^2$$

Successful thermal freeze-out for weak scale-masses and cross sections

- Predicts direct-detection cross section
- Driven main experimental efforts so far in the DM field

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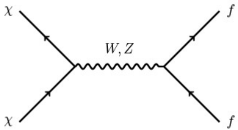

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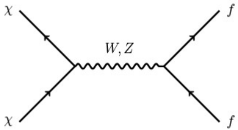
So far, no clear WIMP signals. Where to look next?

The dark sector - particle physics prior revisited

- WIMPs are natural DM candidates if DM has $\simeq O(1)$ coupling to SM through the EW force
- Sub-GeV scale arises if the coupling is $\ll 1 \rightarrow$ search for sub-GeV **Light Dark Matter**

A light WIMP does not reproduce the correct relic abundance:

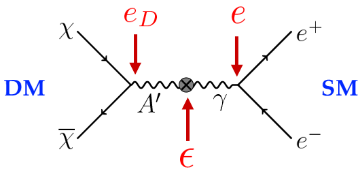


$$\langle\sigma v\rangle_{\rm WIMP} \sim 3\times10^{-26}{\rm cm}^3{\rm s}^{-1}\left(\frac{\rm TeV}{m_\chi}\right)^2$$

If $m_\chi \simeq 1$ GeV, $\langle\sigma v\rangle_{ann} \ll \langle\sigma v\rangle_{relic}$
A new SM-DM interaction mechanism is necessary.
Different mechanisms are possible - in the following, I'll focus on the so-called "dark-photon" hypothesis.

The dark sector - dark photon prior

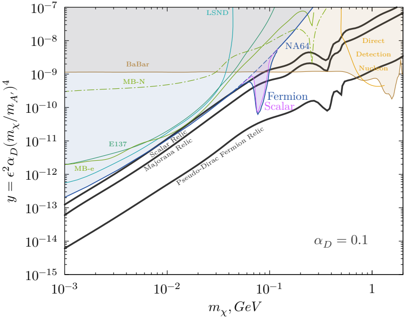
$$\alpha_D \equiv \frac{e_D^2}{4\pi}$$



$$\alpha \equiv \frac{e^2}{4\pi}$$

- Model parameters:
  - Dark photon and dark matter masses (sub-GeV)
  - $A' - \chi$ coupling $e_D \simeq 1$
  - $A' - SM$ coupling via kinetic mixing, $\varepsilon \ll 1$
- Annihilation cross section reads:

$$\langle \sigma v \rangle \propto \frac{\varepsilon^2 \alpha_D m_\chi^2}{m_{A'}^4} = \frac{\varepsilon^2 \alpha_D m_\chi^4}{m_{A'}^4} \frac{1}{m_\chi^2} \equiv \frac{y}{m_\chi^2}$$



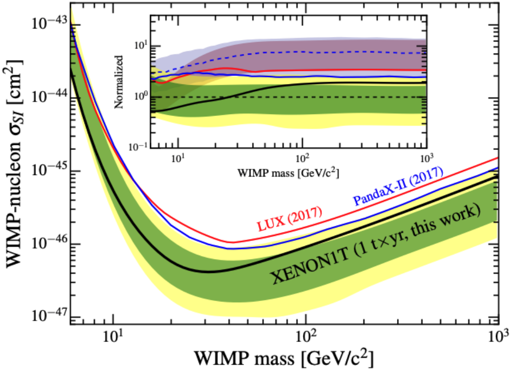
For a fixed m_χ value, the thermal origin hypothesis imposes a unique value of y

Light dark matter searches at accelerators

- Dark Matter direct detection experiments, typically optimized for $M_\chi \geq 1$ GeV, have a limited sensitivity in the sub-GeV range
  - $E_R \propto v^2 M_\chi^2 / M_N$, $v \simeq 220$ km/s $\sim 7 \cdot 10^{-4}$c (*Try to derive this yourself!*)
  - Many ongoing efforts to overcome this limitation
- LDM-SM interaction cross section at low energy has a sizable dependence on the impinging particle velocity, with a drastic reduction for specific models

Latest Xenon1T WIMP results - 1805.12562

$E_R \gtrsim 5$ keV$_{NR}$, $M_N \simeq 122$ GeV



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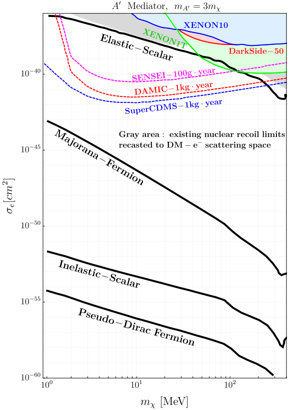

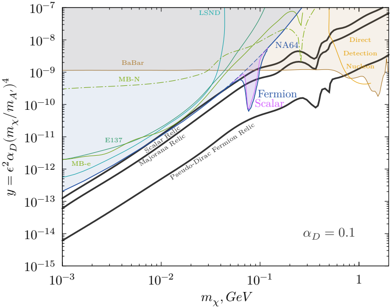

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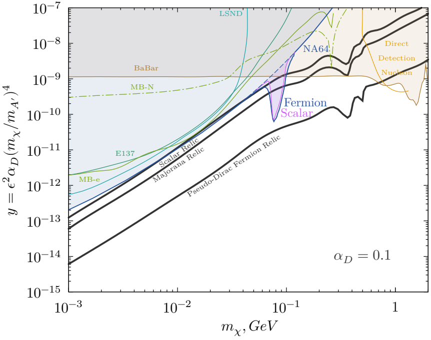


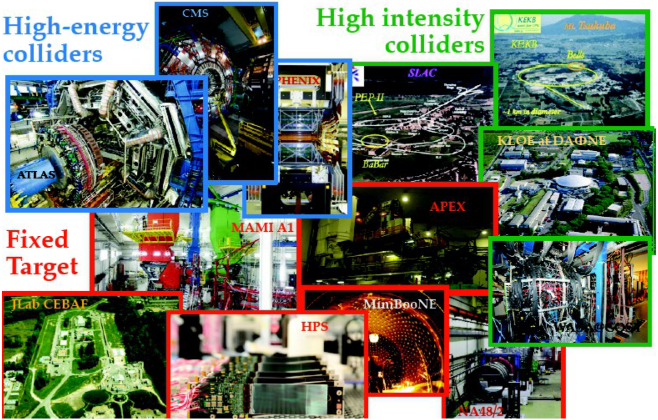
LDM at accelerators

Accelerator-based experiments are uniquely suited to explore the light dark matter hypothesis: high intensity / high energy.

Complementarity is crucial!

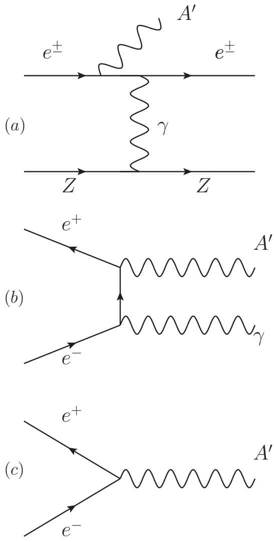
Light dark matter searches at accelerators

In the past few years, many different and complementary programs were proposed (and some already started) to search for LDM at accelerators, looking both for LDM particles and for mediators



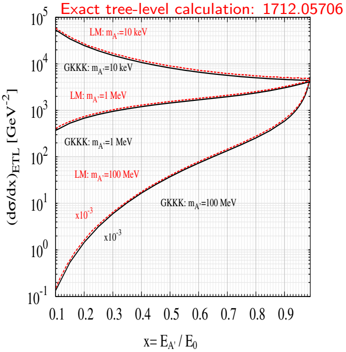
LDM production with lepton-beam experiments

Three main LDM production mechanisms in fixed-target, lepton-beam experiments



a) A'-strahlung

- Radiative A' emission in nucleus EM field followed by $A' \to \chi\overline{\chi}$
- Scales as $Z^2\alpha_{EM}^3$
- Forward-boosted, high-energy A' emission



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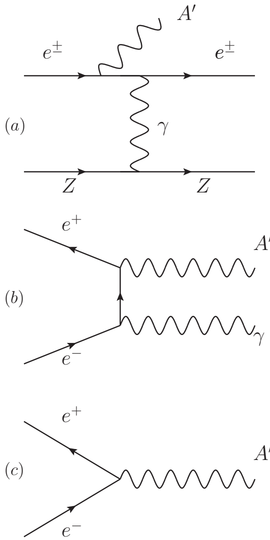
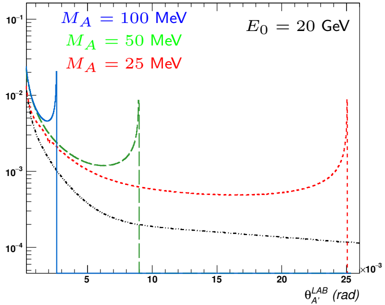


b) Non-resonant e^+e^- annihilation

- $e^+e^- \to A'\gamma$ followed by $A' \to \chi\overline{\chi}$
- Scales as $Z\alpha^2_{EM}$
- Forward-backward emission, $E^{AVG}_{A'} = \frac{E_0}{2}(1 + \frac{M^2_A}{2m_e E_0})$



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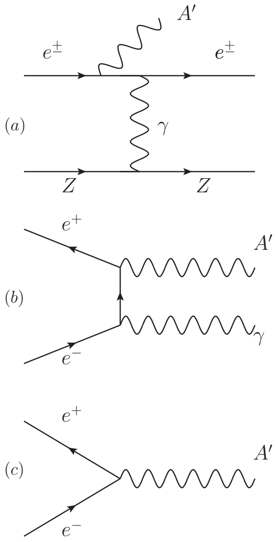
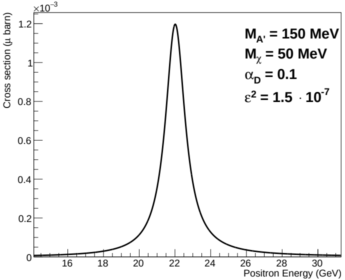
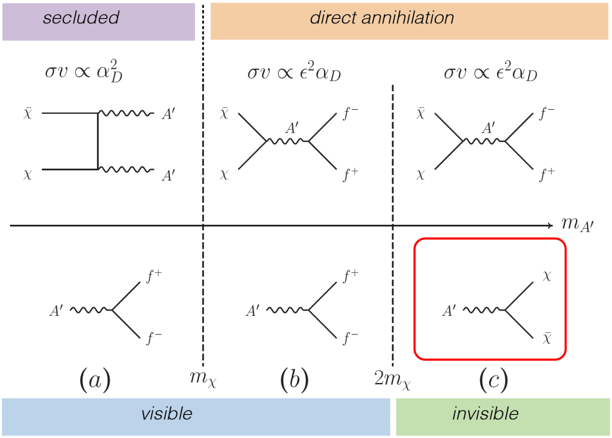


c) Resonant e^+e^- annihilation

- $e^+e^- \to A' \to \chi\overline{\chi}$
- Scales as $Z\alpha_{EM}$
- Closed kinematics: $P_\chi + P_{\overline{\chi}} \simeq P_{e^+}$
- Resonant, Breit-Wigner like cross section with $M_{A'} = \sqrt{2m_e E_R}$



Light dark matter signatures



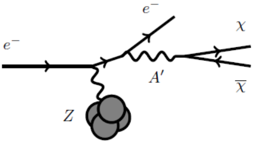
- ⓐ $m_{A'} < m_\chi$: **secluded** scenario. Provides no thermal target for accelerator-based experiments: **any** ε value is allowed.
- ⓑ $m_\chi < m_{A'} < 2m_\chi$: **visible decay** scenario (although off-shell $\chi - \overline{\chi}$ production is allowed!)
- ⓒ $m_{A'} > 2m_\chi$: **invisible decay** scenario.

Fixed *passive* thick-target LDM searches: beam-dumps

Beam dump experiments: LDM direct detection in a e^- beam, fixed-target setup[1]

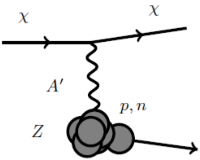
χ production

- High-energy, high-intensity e^- beam impinging on a dump
- χ particles production: radiative A' emission (both on-shell or off-shell) / via e^+e^- annihilation

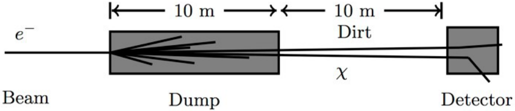


χ detection

- Detector placed behind the dump, O(10-100) m
- Neutral-current χ scattering trough A' exchange, recoil releasing visible energy
- Different signals depending on the interaction (most promising channel: $\chi - e^-$ elastic scattering)



Number of events scales as: $N \propto \frac{\alpha_D \varepsilon^4}{m_A^4}$



[1] For a comprehensive introduction: E. Izaguirre *et al*, Phys. Rev. D 88, 114015

LDM production: thick-target effects

Thin target kinematics (on-shell A'):

- A' emitted forward, $E_A \simeq E_0$
- χ beam forward peaked

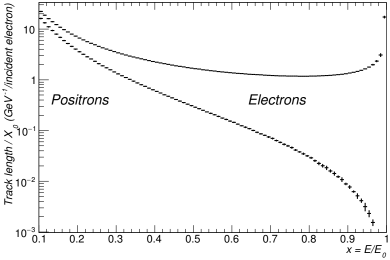
e^- in the dump:

- Energy loss: χ kinematics gets broader
- Secondary e^-/e^+ are produced: more χ particles are emitted

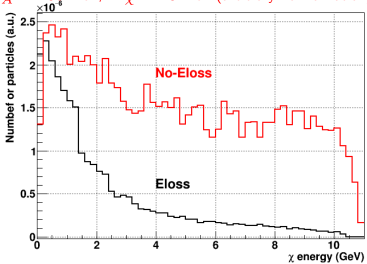
To account for this:

$$\frac{dN}{dE_{A'}} \propto \int_{E_{min}}^{E_0} dE_e T(E_e) \frac{d\sigma(E_e)}{dE_{A'}}$$

- "Traditional" approach: $T_+ = X_0 \delta(E_0 - E_e)$
- Correct approach: account for shower development in the thick target.
  - Evaluate $T(E_e)$ with MonteCarlo (Geant4)
  - Compute DM yield for each electron energy
  - Sum yields with weight $T_+(E_e)$



χ energy distribution for $E_0 = 11$ GeV
$M_A = 100$ MeV, $M_\chi = 10$ MeV (arbitrary normalization)



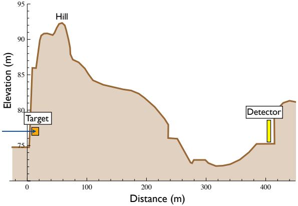
E137 at SLAC

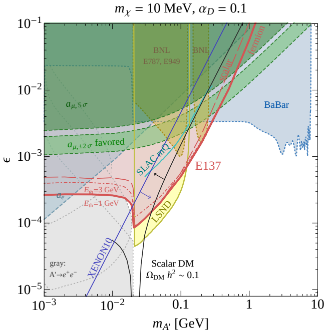
ALPs search experiment, results re-interpreted as LDM search.

- **Beam:** 20-GeV e^- beam, $\simeq 2 \cdot 10^{20}$ EOT
- **Target:** Water-filled Al beam dump
- **Shielding:** 179 m of ground (hill)
- **Decay:** 204 m of open air
- **Detector:** 8-X_0 EM calorimeter + MWPC

Different production mechanisms have been considered:

- First analysis focused on A'-strahlung production mechanism (Phys. Rev. Lett. 113, 171802 (2014))
- New analysis focused on secondary *positrons*: new resonant production mechanism $e^+e^- \to \chi\overline{\chi}$ (Phys. Rev. Lett. 121, 041802 (2018))





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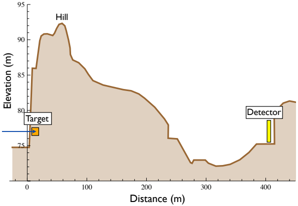
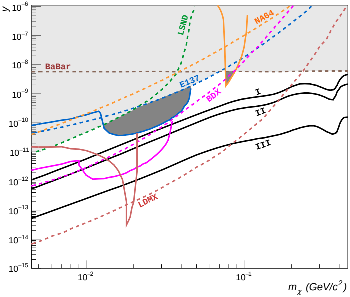


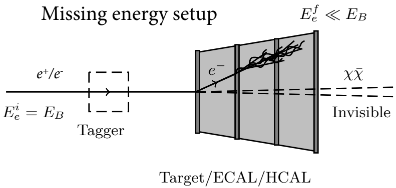


Fixed *active* thick-target LDM searches: missing energy experiments

Beam-dump experiments pay a penalty $N_S \propto \varepsilon^4$ in the event yield: production $\times$ detection
New approach: missing energy measurement - the *active thick target* is the detector, $N_S \propto \varepsilon^2$

Missing Energy Experiments

- Specific beam structure: impinging particles impinging "one at time" on the active target
- Deposited energy E_{dep} measured event-by-event
- Signal: events with large $E_{miss} = E_B - E_{dep}$
- Backgrounds: events with ν / long-lived (K_L) / highly penetrating (μ) particles escaping from the detector

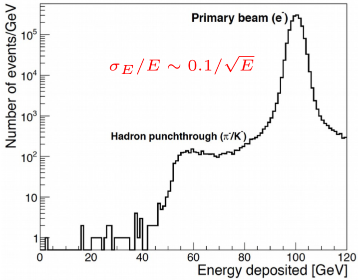


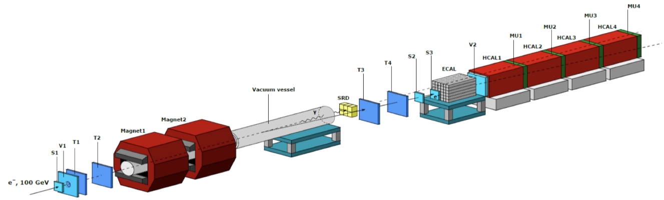
NA64-e: setup

Missing energy experiment at CERN North Area, 100 GeV e^- beam[2]

Experiment Setup

- EM-Calorimeter: $40X_0$, Pb/Sc Shashlik
- Hadron calorimeter: 4 m, 30 λ_I
- Beam identification system: SRD + MM trackers
- Plastic scintillator counters for VETO / beam tagging





[2] Phys.Rev.Lett. 123 (2019) 121801

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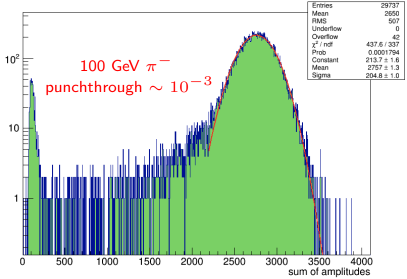

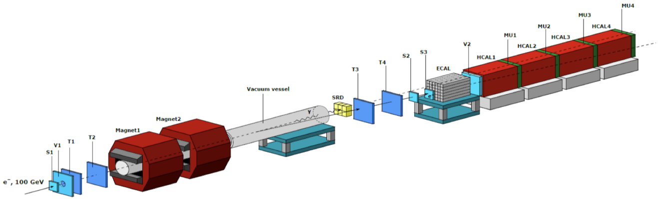

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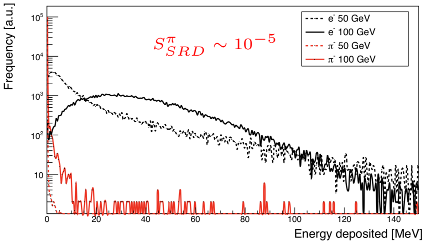
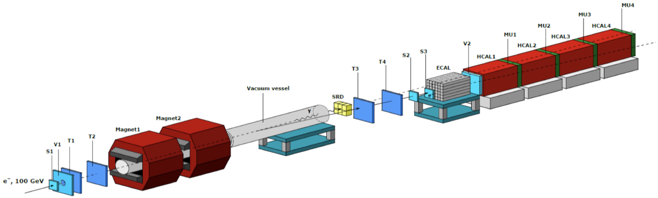




2 Phys.Rev.Lett. 123 (2019) 121801

NA64-e: backgrounds

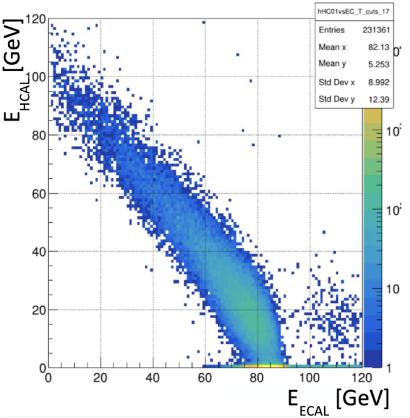
Possible background sources: production of long-lived and highly penetrating neutral SM particles upstream / within ECAL (neutrons, kaons)

(i) Di-muon events: $eZ \to eZ\mu^+\mu^-$, with one or both muons decaying or escaping without being detected by VETO/HCAL.

(ii) Decay of mis-identified contaminating hadrons to $e\nu_e$ final state.

(iii) Electro- / photo-nuclear interactions with upstream beamline materials. Critical contribution, yield estimated directly from data by side-band extrapolation.

(iv) Hadron productions in the ECAL undetected by VETO/HCAL.



Background yield for 2021-2022 runs

Background source	Background, n_b
(i) dimuons losses or decays in the target	0.04 ± 0.01
(ii) $\mu, \pi, K \to e + ...$ decays in the beam line	0.3 ± 0.05
(iii) lost γ, n, K^0 from upstream interactions	0.16 ± 0.12
(iv) Punch-through leading n, K^0_L	< 0.01
Total n_b (conservatively)	0.51 ± 0.13

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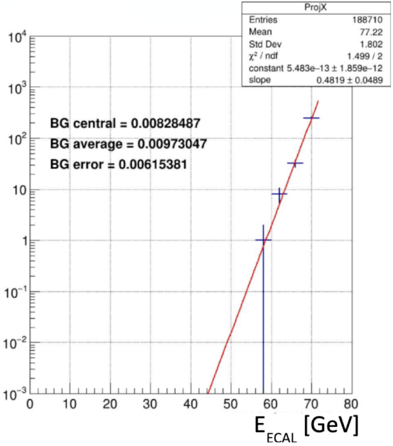

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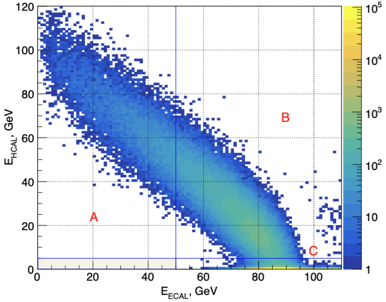
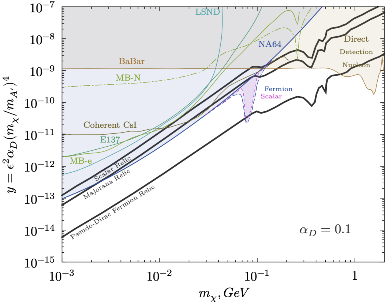
NA64-e: results

Latest results from NA64-e

- Accumulated statistics $\simeq 10^{12}$ EOT
- After applying all selection cuts, no events are observed in the signal region $E_{ECAL} < 50$ GeV, $E_{HCAL} < 1$ GeV
- Expected number of background events ~ 0.5 compatible with null observation
- **Today, the most competitive exclusion limits** in large portion of the LDM parameters space

In the large-mass region, $m_{A'} \gtrsim 100$ MeV, the NA64-e yield - and thus the exclusino limit - suffers a penalty from the $\sigma^{rad}_{A'} \propto 1/m^2_{A'}$ dependency. How to overcome this limitation?





NA64-e: results

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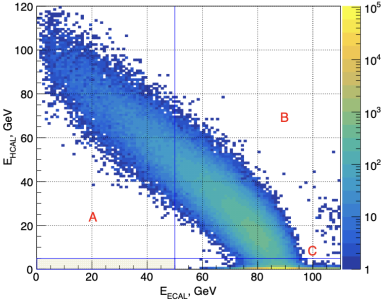
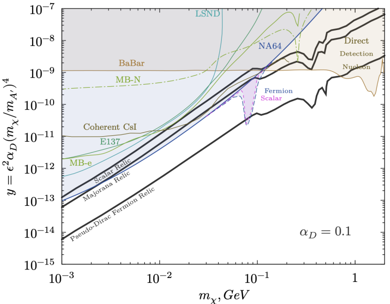




POKER (NA64-e^+): **PO**sitron resonant annihilation into dar**K** matt**ER**

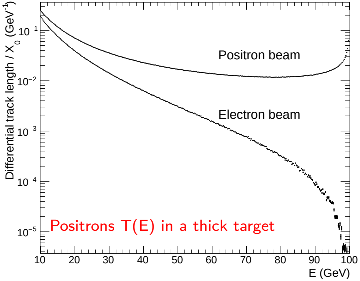
A missing-energy, active thick-target, light dark matter search with positrons

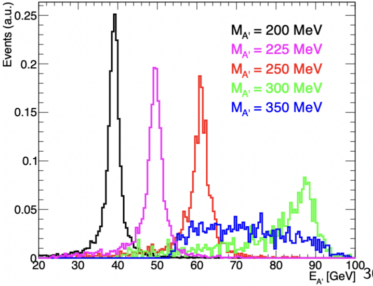
Why positrons?

Signal production reaction: $e^+e^- \to A' \to \chi\overline{\chi}$

- Large event yield: $N_s^{annihil} \propto Z\alpha_{EM}$ vs $N_s^{brem} \propto Z^2\alpha_{EM}^3$
- Missing energy distribution shows a **peak** around $E_R = \frac{M_{A'}^2}{2m_e}$

Thanks to the resonant enhancement, the use of a positron beam allows to effectively explore the large A' mass range ($\gtrsim$ 100 MeV)





POKER (NA64-e^+): current status

A first proof-of-concept measurement was completed in 2022 (10^{10} E$^+$OT at 100 GeV)

Goals: backgrounds study (higher beam hadronic contamination), resonant production characterization via the $e^+e^- \to \mu^+\mu^-$ reaction, extraction of the first upper limit with an analysis optimized for resonant LDM production.

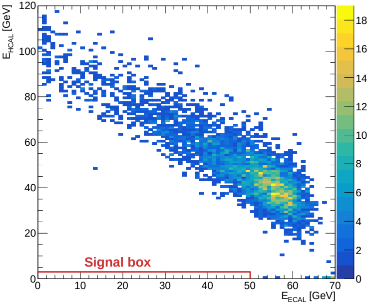
Experimental setup: as in NA64-e^-.

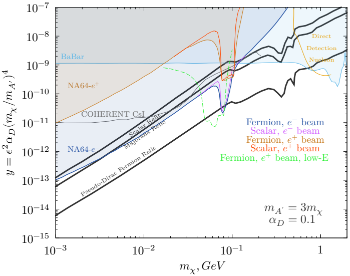
Analysis strategy: blind-analysis (signal-like region $E_{ECAL} < 50$ GeV, $E_{HCAL} < 3$ GeV).

Main backgrounds:

- $\pi^+ \to e^+\nu_e$ + fake-SRD tag
- Upstream hadrons electro-production, soft e^+ in ECAL
- Overall yield: < 0.1 events.

Results: no events observed in the signal region after unblinding, new upper limits set to the LDM parameters space.

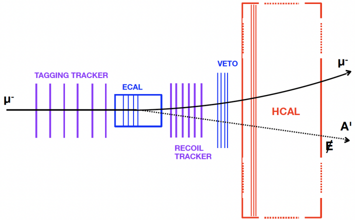




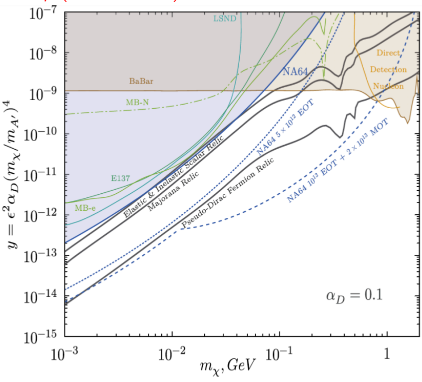
Fixed *active* thick-target LDM searches: missing momentum experiments

Missing-momentum search with a **muon beam** impinging on a fixed target, complementary to $e^{\pm}$ searches in the high-mass region.

- **Signal production:** A' radiative emission by beam muons impinging on an active target (ECAL).
- **Signal signature:** well-identified impinging beam track and final-state low-energy deflected track. No additional activity in downstream detectors (VETO / hadronic calorimeters).



Combined sensitivity of NA64-e (10^{13} EOT) and NA64-μ (2×10^{13} MOT).



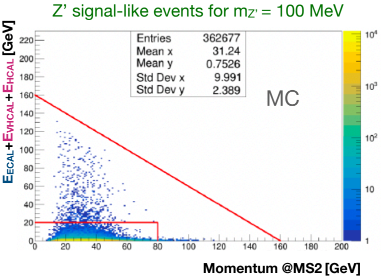
NA64$-\mu$: experimental setup

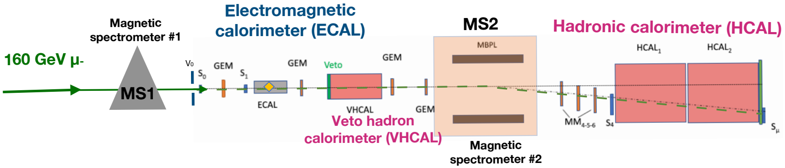
NA64-μ experiment: muon beam missing energy + momentum search

Beam: M2 beamline at CERN SPS, 160 GeV μ^-, $10^5 - 10^7$ μ/s.
Detector:

- Two magnetic spectrometers, MS1 (impinging μ) / MS2 (scattered μ)
- Three calorimeters: ECAL (active target), VHCAL, HCAL
- Beam-defining plastic scintillator counters

Signal signature: $P_1 \simeq 160$ GeV, $P_2 < 80$ GeV, $E_{CAL} \simeq$MIP.





NA64$-\mu$: status

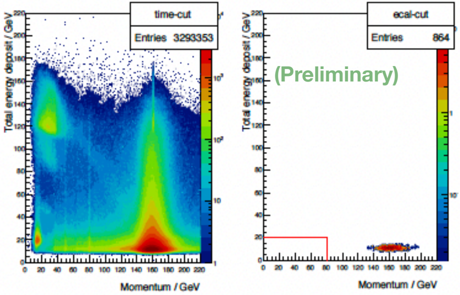
Three test runs have already been performed in 2021 (5x10^9 MOT), 2022 (5x10^{10} MOT), and 2023 (10^{11} MOT)

- First results from 2021 data analysis: less than 10^{-11} background events expected per MOT. No events observed in the signal region.
- 2022/2023 data analysis in progress.

Long physics run foreseen in 2024

- Detector optimization in progress.
- Final goal: 10^{12} MOT.

Source of background	Level per MOT
Hadron in-flight decay	$\lesssim 10^{-11}$
Momentum mismatch	$\lesssim 10^{-12}$
Detector non-hermeticity	$\lesssim 10^{-12}$
Single-hadron punch through	$\lesssim 10^{-12}$
Dimuon production	$< 10^{-12}$
Total (conservatively)	$\lesssim 10^{-11}$



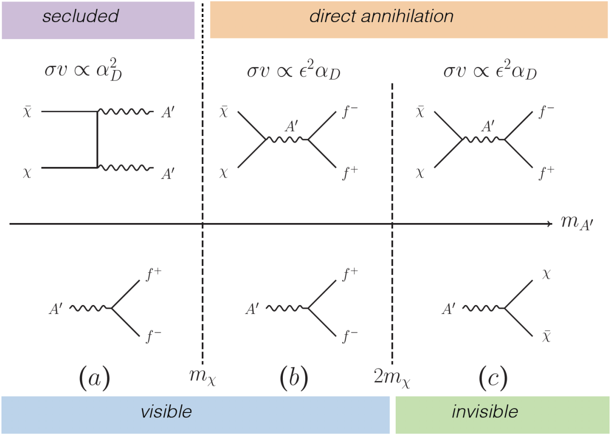
Conclusions

- Many different experiments searching for light dark matter at accelerators started in the last few years, with complementary methodologies and techniques.
- Each experiment is characterize by its own advantages and difficulties - I think that only a complete experimental program will be allow to explore this field.
- I hope this lecture gave you a "tasting" of this large variety of efforts, with few "hints" of the (very interesting and broad) technical aspects behind. For any further question or comment, do not hesitate to ask me!

Thanks for your attention

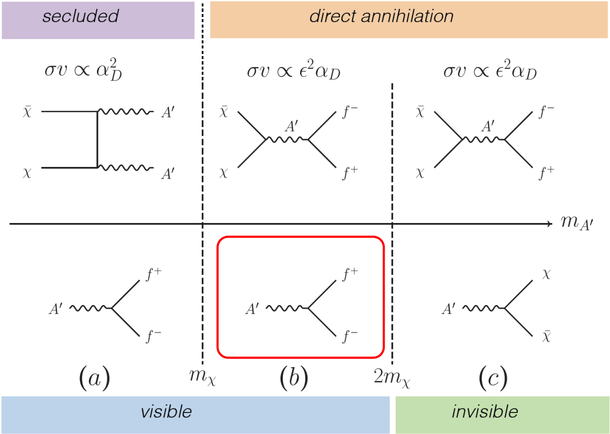
Backup slides

Light dark matter signatures



- (a) $m_{A'} < m_\chi$: **secluded** scenario. Provides no thermal target for accelerator-based experiments: **any** ε value is allowed.
- (b) $m_\chi < m_{A'} < 2m_\chi$: **visible decay** scenario (although off-shell $\chi - \overline{\chi}$ production is allowed!)
- (c) $m_{A'} > 2m_\chi$: **invisible decay** scenario.

Light dark matter signatures



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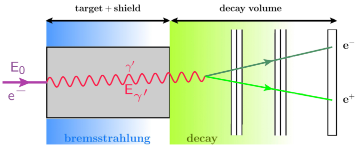
A' production and visible decay in a e^- beam, fixed thick-target setup (Phys.Rev. D86 (2012) 095019)

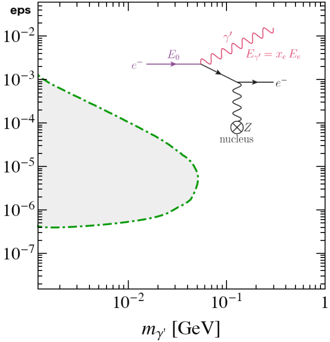
- A' production: radiative A' emission
  $e^- N \to e^- N A'$
- A' propagation: for low ε values ($\lesssim 10^{-5}$) the A' is long-lived, resulting to a detached decay vertex.
- A' detection: measurement of the e^+ e^- decay pair in a downstream detector.



Signal yield dependence on main parameters:

$$N \sim N_{eot} n_{sh} \int dE' dE_e dt I_e(E_e, t) \frac{d\sigma}{dE'} e^{-L_{sh}/l_{A'}} (1 - e^{-L_d/l_{A'}})$$

- Upper bound:
  $N_{evt} \propto \varepsilon^2 e^{-L_{sh}/l_{A'}}$, $l_{A'} \propto E_0/\varepsilon^2$
- Lower bound:
  $N_{evt} \propto \varepsilon^2 L_d / l_{A'} \propto \varepsilon^4$



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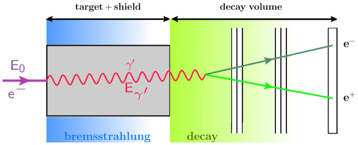

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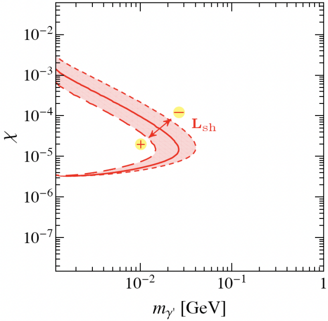

Target/shielding length L_{sh}

$N \propto e^{-L_{sh}/l_{A'}}$

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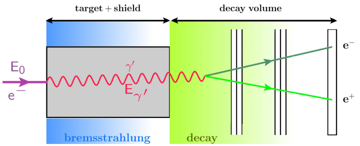

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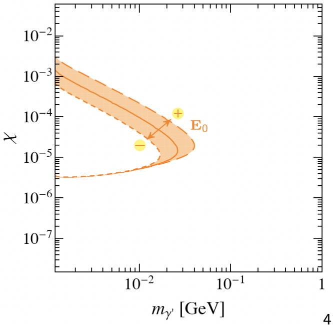

Beam energy

$N \propto e^{-L_{sh}/l_{A'}}$, $l_{A'} \propto E$
(smooth production cross section dependence)

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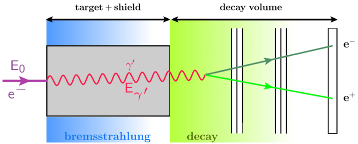

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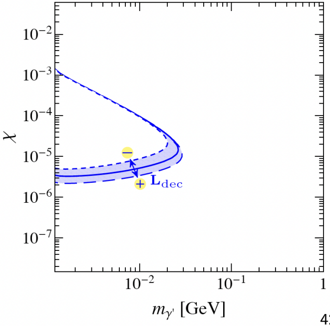


Detector/decay length L_d

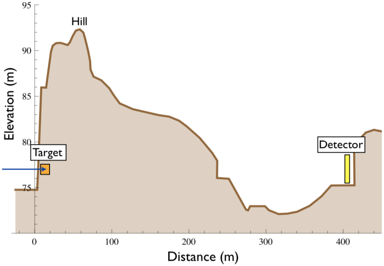
$N \propto L_d$

E137 at SLAC

Experiment originally proposed for ALPs search, results re-interpreted as a visible A' search.

Experiment Parameters:

- **Beam:** 20-GeV e^- beam, $\simeq 2 \cdot 10^{20}$ EOT
- **Target:** Water-filled Al beam dump
- **Shielding:** 179 m of ground (hill)
- **Decay:** 204 m of open air
- **Detector:** 8-X_0 EM calorimeter + MWPC



Results:

- Experiment observed 0 events, exclusion limits at 90% CL $=$ 2.3 signal events.
- Two re-analysis with different approximations (Miller, Andreas) resulting in a similar exclusion limit.
- Recent limits extension (Marsicano) considering secondary positrons annihilation on atomic e^-