Probing the dark sector with electron beam experiments at the intensity frontieer

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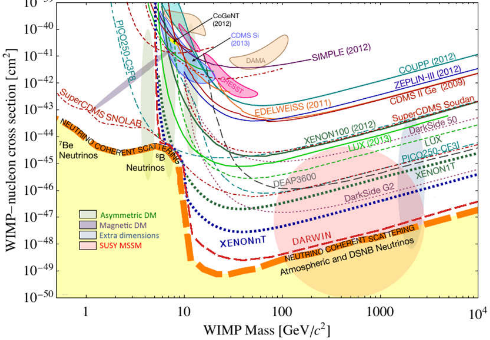
Outline

The dark sector

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. 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 $\div$ 1 GeV?

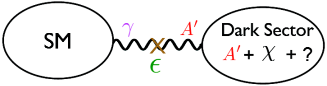
arXiv:1408.4371



Light dark matter

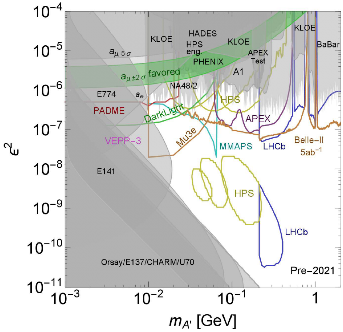
The light dark matter hypothesis can explain the (gravitationally) observed relic abundance, **provided a new interaction mechanism between SM and dark sector exists**[1].

- Simplest possibility: "vector-portal". DM-SM interaction trough a new U(1) gauge-boson ("dark-photon") coupling to electric charge.



Model parameters:

- Dark-photon mass, M'_A and coupling to electric charge ε.
- Dark matter mass, M_χ and coupling to dark photon, g_D ($\alpha_D \equiv g_D^2/4\pi$).

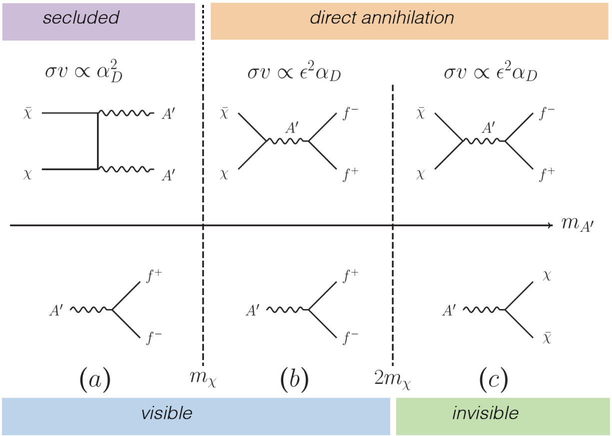


Experimental searches:

- A comprehensive LDM experimental program must investigate **both** the existence of χ particles and of dark photons.
- A collection of complementary searches sensitive to all possible A' decays is required, visible & invisible.

[1] For a comprehensive review: 1707.04591

Light dark matter signatures



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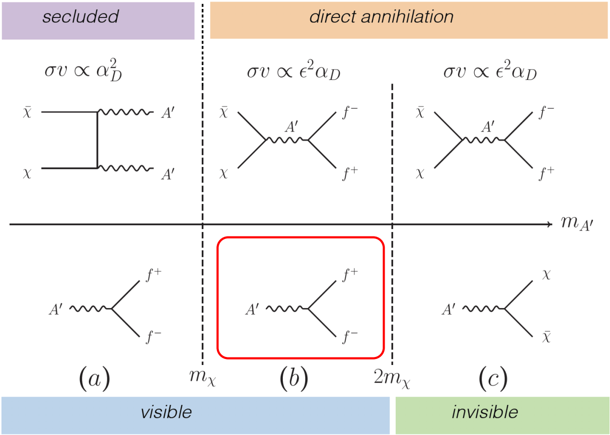

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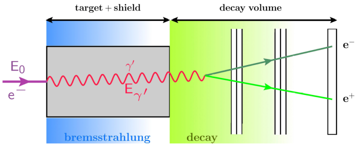
A' production and visible decay detection in a fixed thick-target setup

Reaction topology:

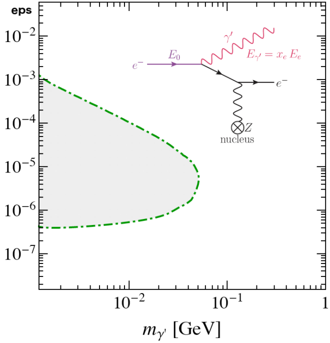
- A' production: radiative A' emission $e^- N \to e^- N A'$
- A' propagation: for low ε values ($\lesssim 10^{-5}$) the A' is long-lived, resulting to a detached decay vertex.
- A' detection: measurement of the e^+ e^- decay pair in a downstream detector.



Number of events:
Dependence on main parameters[2]:

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

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



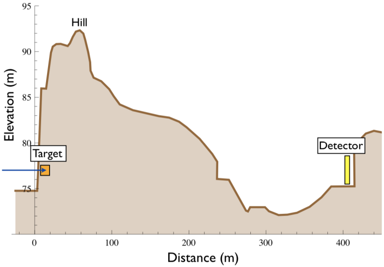
[2] For a review: S. Andreas, Phys.Rev. D86 (2012) 095019

E137 at SLAC

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

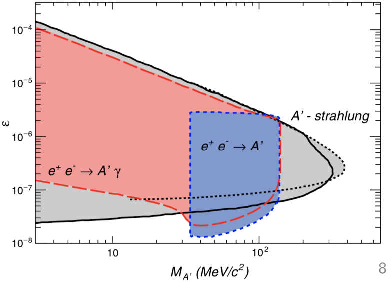
Experiment Parameters:

- **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:

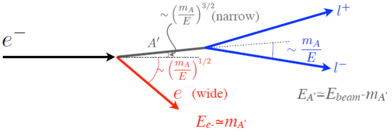
- Experiment observed 0 events, exclusion limits at 95% CL $= 2.3$ signal events.
- Two re-analysis with different approximations (Miller, Andreas) resulting in a similar exclusion limit.
- Recent limits extension (Marsicano) considering secondary positrons annihilation on atomic e^-

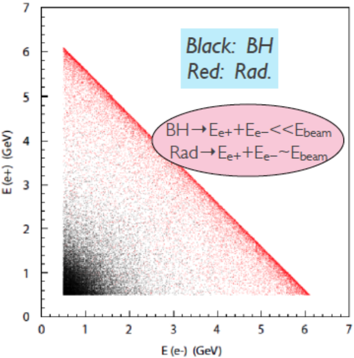


A' production and visible decay detection in a fixed thin-target setup

Radiative production mechanism:
$e^- N \to e^- N A' \to e^- N e^+ e^-$, $e^+ e^-$ pairs detected through a downstream particle spectrometer.
Two detection strategies:

- High ε: **resonance search**, look for a "bump" in the $M_{e^+e^-}$ spectrum over the continuos QED background
- Low ε: **detached-vertex search**



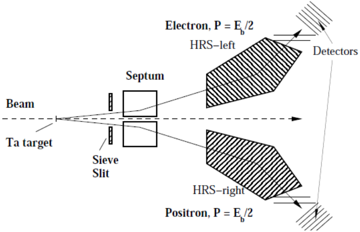


APEX: setup

JLab Hall-A experiment[3]: two-arms spectrometers resonance search ("bump-hunting") for $50 - 500$ MeV A' decaying promptly to e^+e^-.

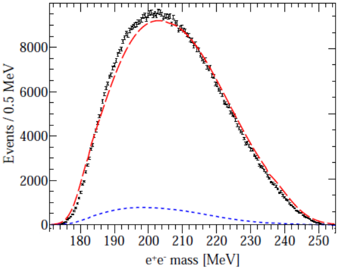
Setup:

- 2.26 GeV, 150 μA e^- beam impinging on a thin Ta target.
- e^+e^- detection: Hall-A HRS
  - Momentum reconstruction: drift chambers
  - Triggering and PID: Cerenkov and scintillator counters
  - Central momenta: 1.131 GeV. Momentum acceptance: $\pm 4.5\%$.



Data selection (2010 test run):

- Tight time coincidence between two spectrometers
- Track-quality cut / energy sum cut
- **Final data set:** 770k e^+e^- events, O(7.5%) accidentals contamination. Mass resolution: 0.85÷1.11 MeV



[3] Phys. Rev. Lett. **107** (2011) 191804

APEX: results and status

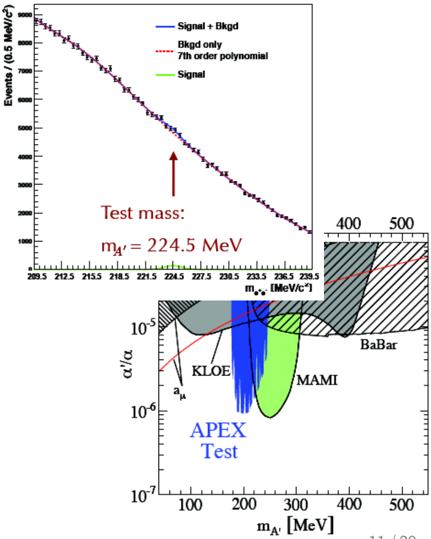
APEX 2010 test run: no signals were observed. Exclusion limits were set for $m'_A = 178\ldots250$ MeV, $\varepsilon^2 > 10^{-6}$.

Analysis: search for a small, narrow resonance over a smooth background

- Multiple fits to mass spectrum in narrow windows (30.5 MeV): signal (gaussian) + background (7^{th} order pol.)
- Extract local and global $p-$value trough Likelihood-ratio test
- Determine 2σ exclusion limit on ε

Status - future plans:

- Test run results published in PRL
- Full experiment just completed (Fall 2019):
  - Run with several energies and spectrometer settings
  - Multi-foil Ta-target to enhance acceptance at large m'_A values

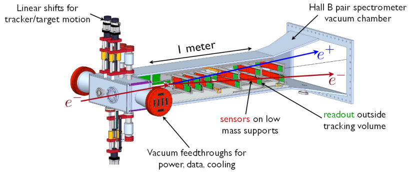


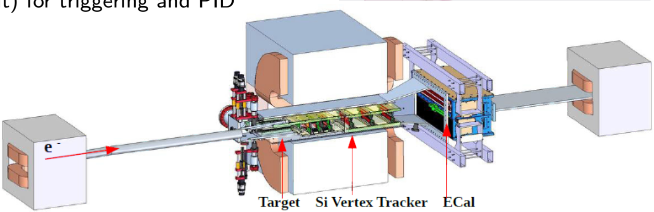
HPS: setup

HPS experiment in Hall-B: fixed-target A' search, with two complementary approaches, "bump-hunting" and "detached vertexing".

Setup: compact forward spectrometer matched to the A' kinematics

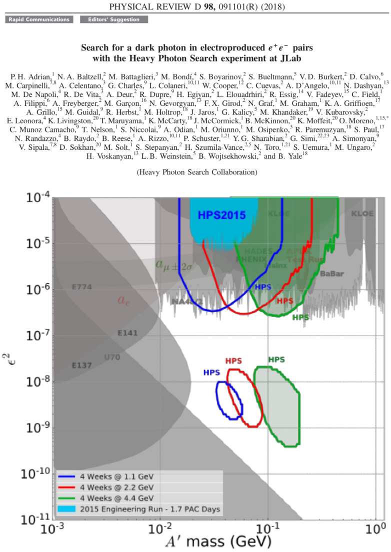
- Detector mounted in Hall-B "alcohove", behind CLAS12
- Thin W target ($\simeq 10^{-3} X_0$)
- Dipole magnet and 6-layers Si-tracker for momentum analysis and vertexing
- $PbWO_4$ calorimeter (442 crystals, APD readout) for triggering and PID





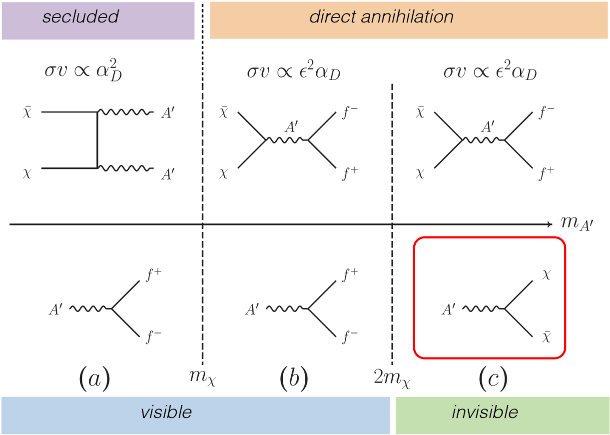
HPS: results and status

- July 2012: HPS demonstrated the feasibility of the measurement and the operation of the detector in a test run[3]
- Spring 2015: 1.7 PAC days @ 1.06 GeV. Results published in PRD rapid communications[4]
- Spring 2016: 5 PAC days @ 2.3 GeV. Results expected next few months
- Summer 2019: 2 months running @ 4.55 GeV - $\simeq 10^5$ nbarn^{-1} accumulated.



[3] Nucl. Instrum. Meth. A **777** (2015) 91
[4] Phys. Rev. D 98, 091101 (2018)

Light dark matter signatures



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Missing mass searches

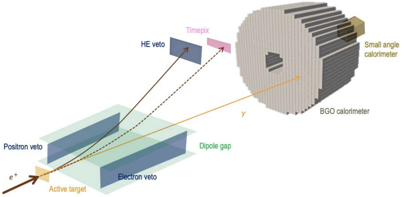
Positron beam impinging on a thin-target: mono-photon missing mass resonance search in the reaction $e^+e^- \to A'\gamma$. Limiting factor: $M_{A'} < \sqrt{2m_e E_{e^+}}$

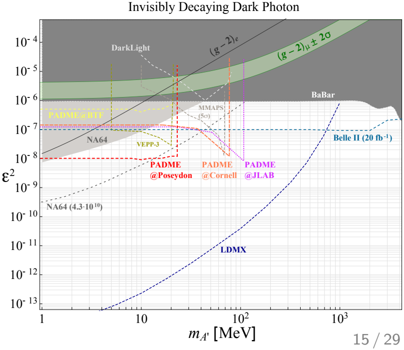
The PADME experiment at LNF-BTF:

- 550 MeV e^+ beam, 50 Hz rep. rate.
  - $M_{A'}$ max: 23.7 MeV/c^2
- 100 μm C *active* target
- BGO calorimeter, 616 crystals
- First run **completed** in 2019, $7.4 \cdot 10^{12}$ POT

Other proposals:

- VEPP3: $E_{e+} = 500$ MeV, $10^{15} - 10^{16}$ POT/year
- Cornell: $E_{e+} = 5.3$ GeV, $10^{17} - 10^{18}$ POT/year
- JLAB: $E_{e+} = 11$ GeV, $10^{18} - 10^{19}$ POT/year



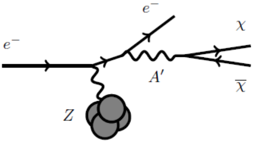


Fixed *passive* thick-target LDM searches: beam-dumps

Beam dump experiments: LDM direct detection in a e^- beam, fixed-target setup[4]

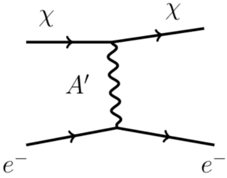
χ production

- High-energy, high-intensity e^- beam impinging on a dump
- χ particles pair-produced radiatively, trough A' emission (both on-shell or off-shell).

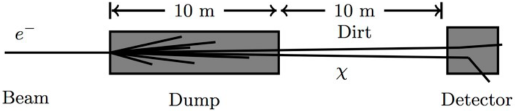


χ detection

- 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)



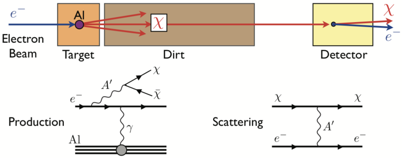
Number of events scales as: $N \propto \frac{\alpha_D (\alpha_D^2) \varepsilon^4}{m_A^4}$



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

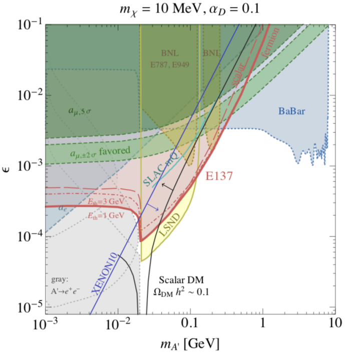
E137

Experiment results *also* re-interpreted as *invisible* A' search - exclusion limits derived.



A variety of production mechanisms have been considered:

- First analysis focused on A'-strahlung production mechanism[5]
  - Detailed simulation of original E137 detection threshold and trigger, including systematic studies
- New analysis focused on secondary *positrons*[6]
  - New resonant production mechanism $e^+e^- \to \chi\overline{\chi}$
- Secondary *muons* provide a viable tool to search for muon-coupling light dark scalars[7]



[5] B. Batell *et al.*, Phys. Rev. Lett. 113, 171802 (2014)

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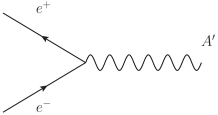

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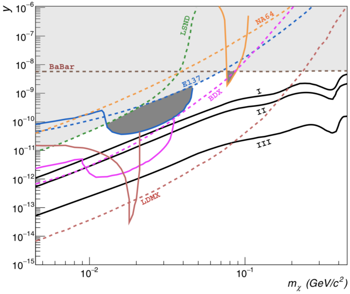

[6] L. Marsicano *et al.*, Phys. Rev. Lett. 121, 041802 (2018)

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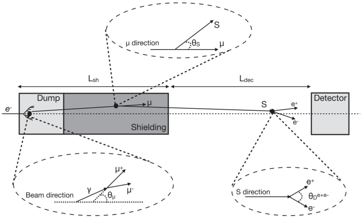
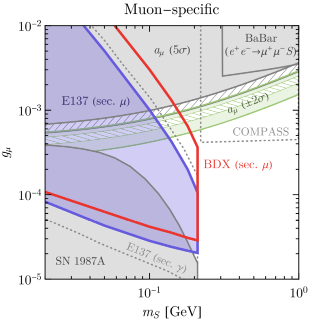




[7] L. Marsicano *et al.*, Phys. Rev. D 98, 115022 (2018)

BDX

Modern beam-dump experiment at JLab: 11-GeV e^- beam, Al/H_2O beam-dump

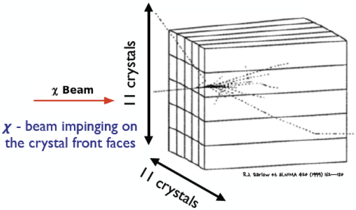
Experimental setup

- Detector installed O(20 m) behind Hall-A beam dump, in a new experimental hall
- Passive shielding layer between beam dump and detector to reduce SM beam-related background
- Sizable overburden ($\simeq$ 10 m water-equivalent) to reduce cosmogenic background

Detector design

- EM calorimeter: CsI(Tl) crystals+SiPM readout
- Two plastic-scintillator active-veto layers
- Passive lead layer between inner and outer veto

Total active volume: $\simeq 0.5\ m^3$



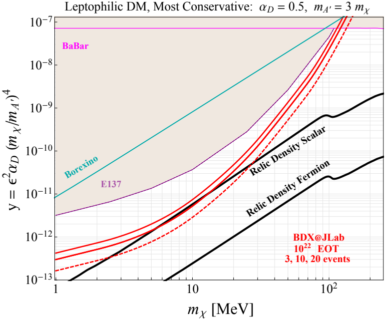
BDX: reach and status

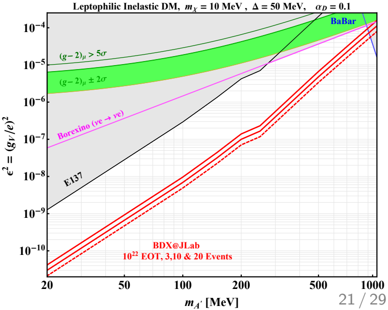
BDX reach:

- With O(10^{22}) EOT, BDX can explore an unique region in the MeV-GeV LDM mass region, with a discovery potential up to two orders of magnitude better than existing or planned experiments
- Final reach is limited by the beam-related irreducible ν background

Experiment status:

- Experiment approved by JLab PAC in 2018 with the highest scientific rating
- Proposal submitted to 2019 DOE FOA call for initial foundings

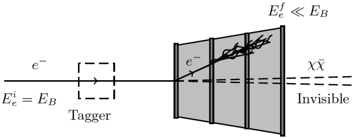




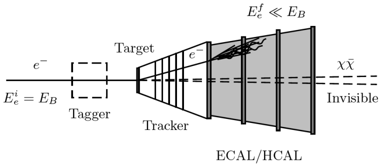
Fixed *active* thick-target LDM searches: missing energy/momentum

Two complementary approaches

missing energy



missing momentum



Missing Energy

- Higher yield (thick target)
- Higher acceptance

Missing Momentum

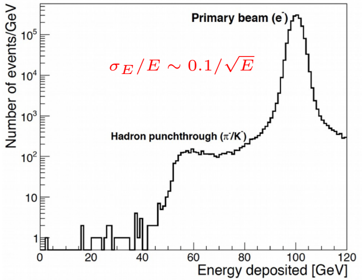
- Lower yield (thin target), but includes a missing energy experiment
- p_T as background discriminator and signal identifier

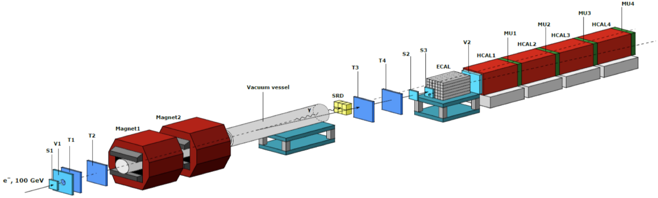
NA64

Missing energy experiment at CERN North Area, 100 GeV e^- beam[8]

Experiment Setup

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





8 Latest results: Phys.Rev.Lett. 123 (2019) 121801

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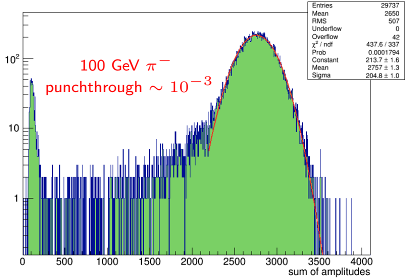

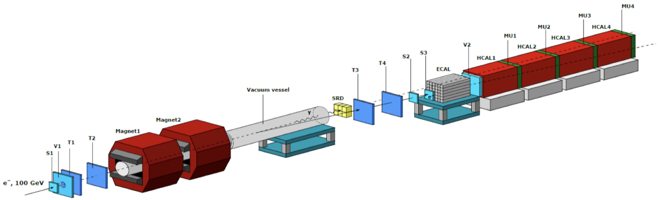

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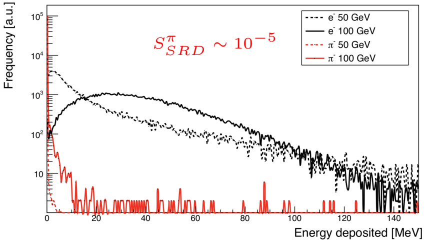

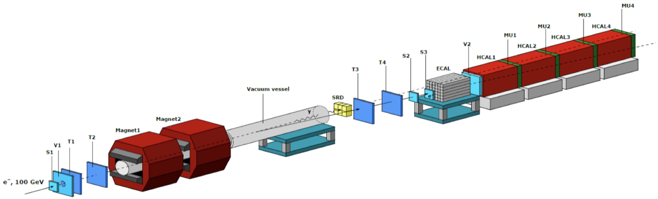

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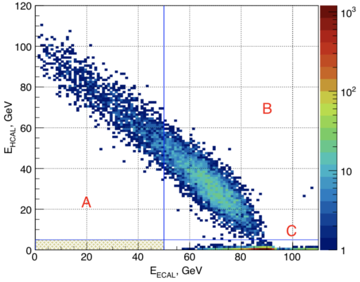
NA64

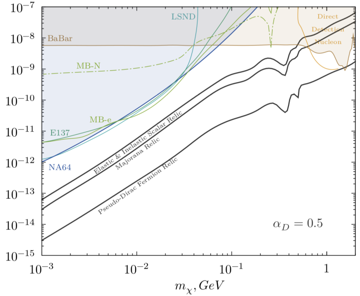
Latest results

- NA64 just published the analysis of $2.84 \cdot 10^{11}$ 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 $\sim$ 0.5 compatible with null observation
- **Most competitive exclusion limits** in large portion of the LDM parameters space

TABLE I: Expected background for 2.84×10^{11} EOT.

Background source	Background number, n_b
punchthrough γ's, cracks, holes	< 0.01
loss of dimuons	0.024 ± 0.007
$\mu \to e\nu\nu$, π, $K \to e\nu$, K_{e3} decays	0.02 ± 0.01
e^- interactions in the beam line	0.43 ± 0.16
μ, π, K interactions in the target	0.044 ± 0.014
accidental SR tag and μ, π, K decays	< 0.01
Total n_b	0.53 ± 0.17

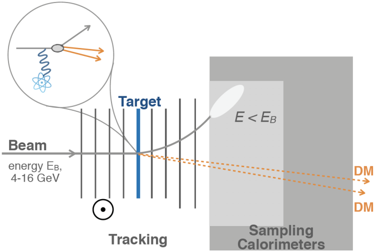


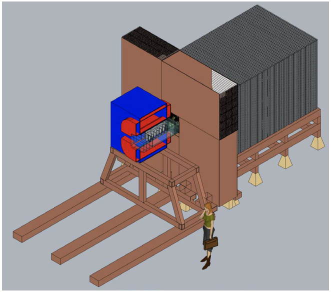


LDMX

Missing *momentum* experiment with multi-GeV electron beam[9]
Goal: 10^{16} EOT in few years $\sim 1e^{-}/10$ ns!
Very challenging detector design

- **Fast Si tracker**
  - Tagging tracker in 1.5 T field
  - Recoil tracker in fringe field
  - W (0.1-0.3 X_0) target in between
- **EM Calorimeter**
  - Design based on ongoing CMS forward Si/W calorimeter upgrade
- **Hadron Calorimeter**
  - Veto for penetrating hadrons (most critical: neutrons)
  - Sci/steel sampling design
  - Hermetic: surrounds ECAL on back and on sides



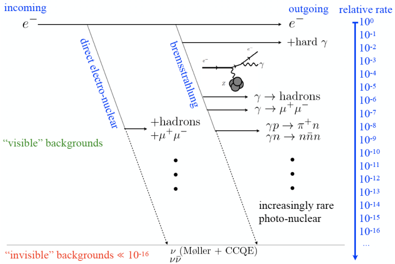


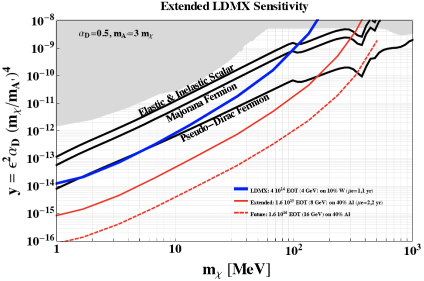
[9] Baseline design paper: arXiv:1808.05219

LDMX

On-going backgrounds study and detector design effort

- Close to 0 background target for pilot run - 10^{14} EOT
  - Particular care for non-trivial hadronic backgrounds (e.g. n pairs, backward particles, . . .)
- Large statistics run optimization: p_T signature / HCAL design / beam energy





Conclusions

- Light dark matter scenario (MeV-to-GeV range) is largely unexplored
  - Can efficiently explain DM relic density
  - Theoretically founded as the "traditional" DM paradigm, assuming a **new** DM-SM interaction mechanics, exists
- A comprehensive experimental program searching **both** for the A' and for its invisible decay products is required to explore the new hypothesis
- Visible searches:
  - Old-style beam-dumps
  - Spectrometer-search: invariant mass or detached vertex technique
  - Missing mass
- Invisible searches:
  - Beam-dumps **exploiting also secondary particles**
  - Missing energy / momentum

Backup slides