UNIVERSITÀ DEGLI STUDI DI GENOVA

INFN

The search for dark photons

13th European Research Conference on Electromagnetic Interactions with Nucleons and Nuclei

L. Marsicano (INFN Genova, Università di Genova)

Overview

- **Introduction**
- **Dark photon visible searches**

  E137-visible

  HPS
- **Dark photon invisible searches**

  E137-invisible

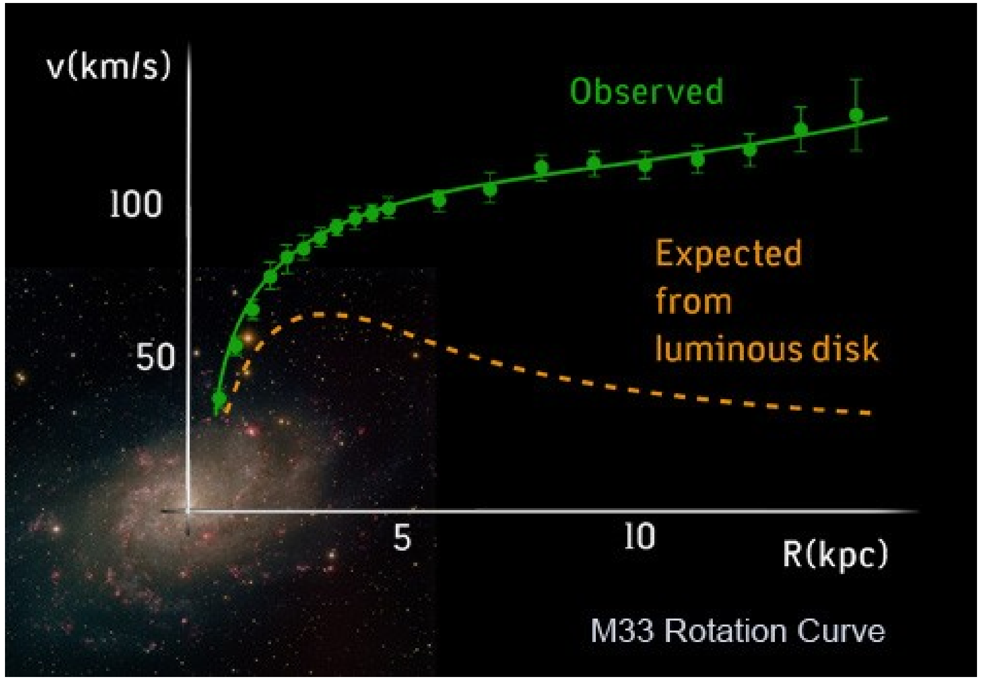
  BDX

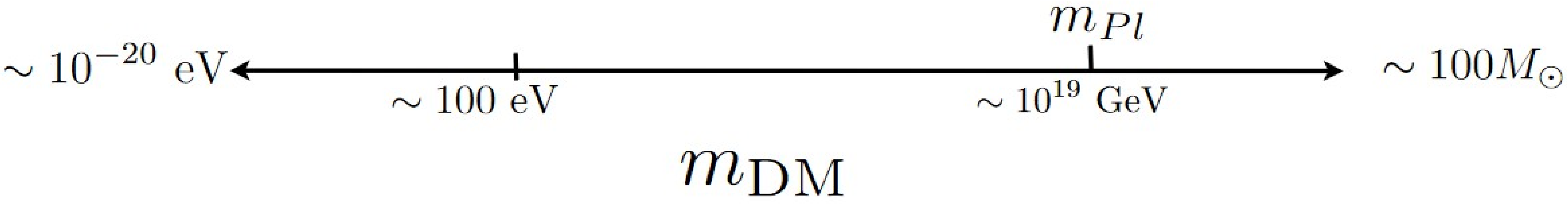
  NA64

  LDMX
- **Conclusions**

Dark Matter Search

- Dark Matter (DM) existence is highly motivated by various **astrophysical-cosmological** evidences (Galaxy Rotation Curves, CMBR fluctuations, collisions between galaxy clusters…)
- All DM evidences come from the observation its gravitational effects. No hints on DM particle properties (mass, cross section) from particle physics experiment
- The viable DM mass window is dauntingly large:





Theoretical guidance needed to narrow the search

Thermal Dark Matter

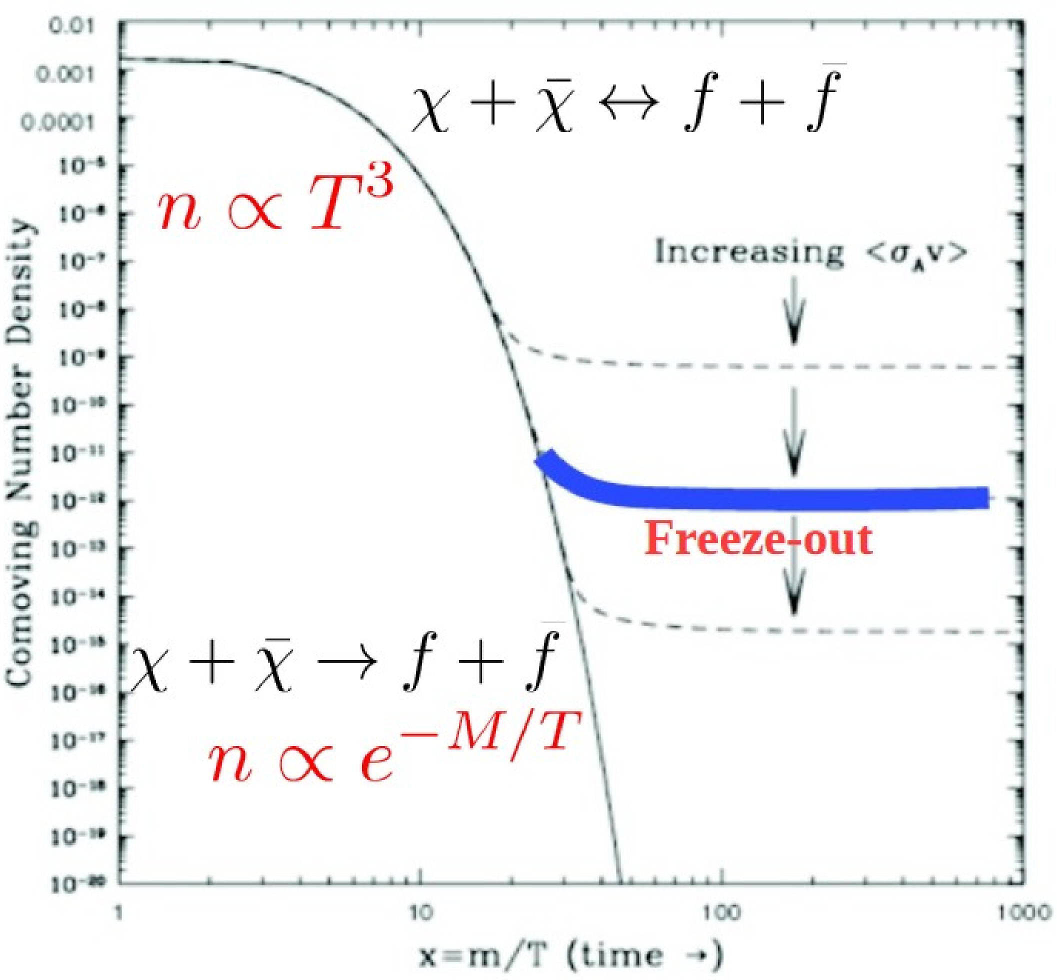
Cosmological Hypotesis: DM particles in **equilibrium** with early universe

$$\chi + \bar{\chi} \leftrightarrow f + \bar{f}$$

DM-SM decoupling due to Universe cooling (*Freeze-out*)

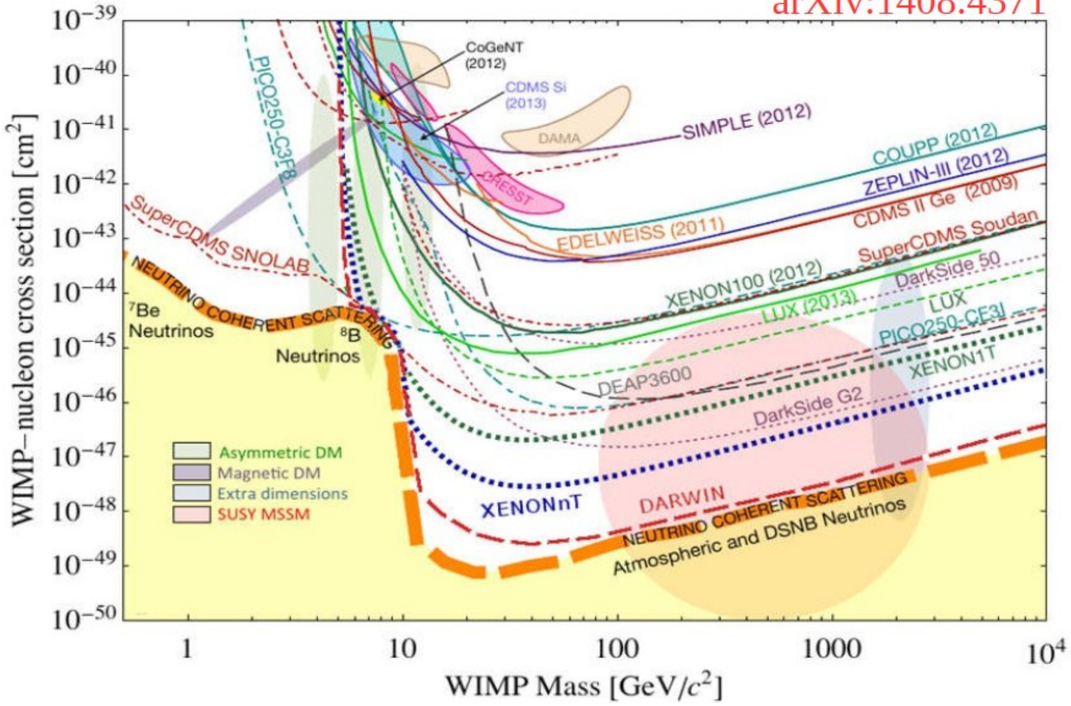
- DM relic density depends on DM-SM interaction properties
- DM mass and interaction cross section are bound

If m_{DM} ~ 100 GeV → typical weak Interaction cross section: "**WIMP → Miracle**"



From WIMPs To Dark Sector

arXiv:1408.4371



- WIMPs search: detectors made of large volumes of active materials to detect cosmogenic DM scattering over nuclei

  - low sensitivity to "light" DM candidates (<1 GeV)

- **NO evidence of WIMP to date**

  → Search for lower mass candidates

- Preserve DM thermalization with lower DM mass → new force necessary

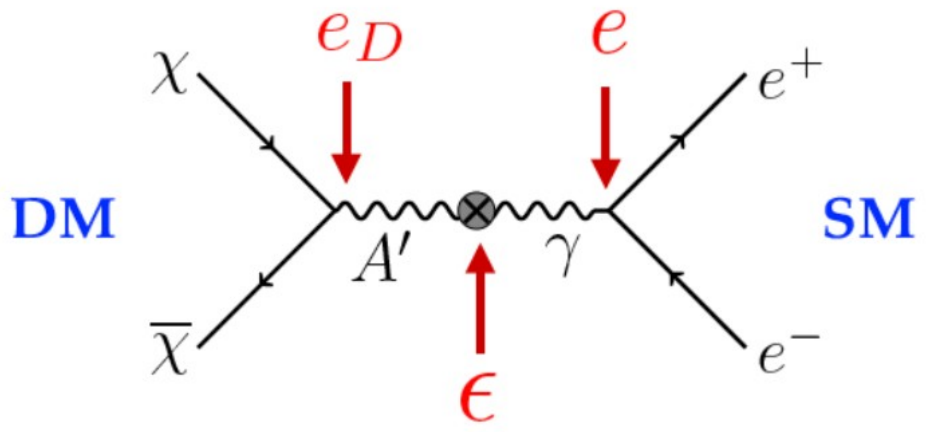
- Simplest Model: **Dark Sector** (χ particles) coupled to SM through a U(1) massive gauge boson, the **Dark Photon (A')**, kinetically mixed with SM photon:

$$\mathcal{L} = -\frac{1}{4} F'_{\mu\nu} F'^{\,\mu\nu} + \frac{\epsilon}{2} F'_{\mu\nu} F_{\mu\nu} + \frac{m^2_{A'}}{2} A'_\mu A'^{\,\mu} + g_D A'_\mu J^\mu_D$$

The Dark Photon Scenario

- Dark QED:

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



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

DM charged under new mediator: $e_D \sim e$
Small A'-photon mixing: $\varepsilon \ll 1$

- By requiring that freeze-out mechanism reproduces today's relic abundance, a **target in the parameters space** can be derived:
- Define a new variable optimized for thermal targets:

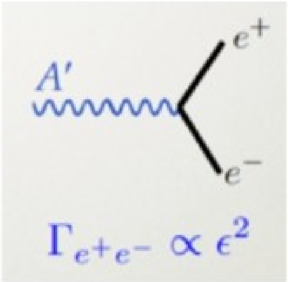
$$\langle \sigma v \rangle \propto \frac{\varepsilon^2 e_D^2 m_\chi^2}{m_{A'}^4} = [e_D^2 \varepsilon^2 (\frac{m_\chi}{m'_A})^4] \frac{1}{m_\chi^2} \equiv \frac{y}{m_\chi^2}$$

For a given value of m_χ, thermal origin imposes one value of "y"

Dark Photon Signatures

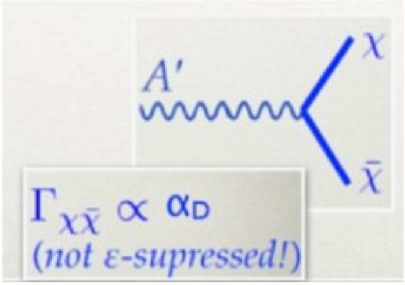
Visible: A'→e+e-

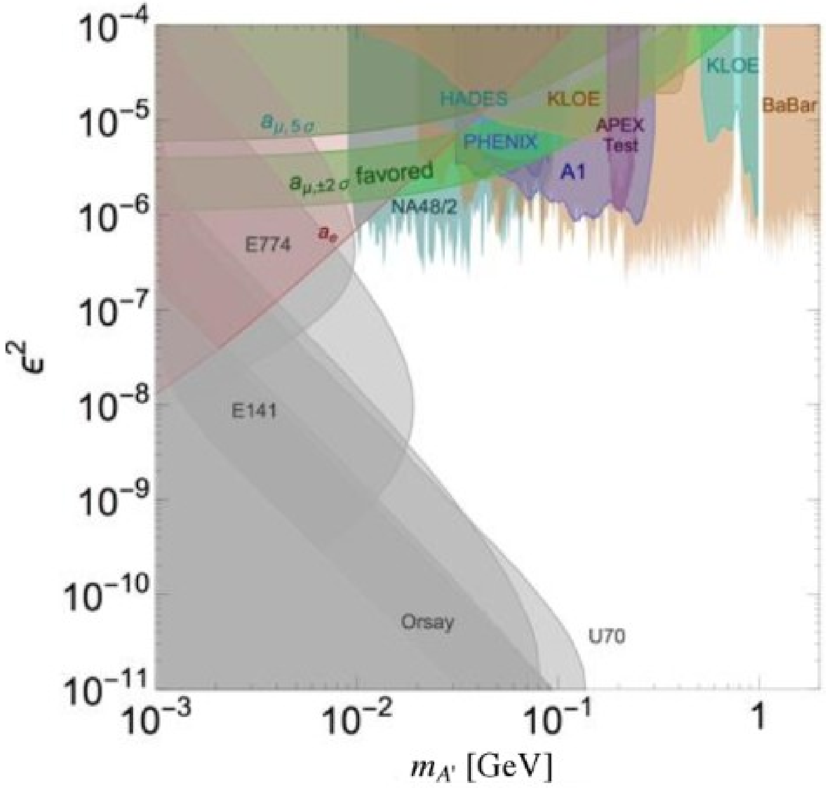
- $m_{A'} < 2m_\chi$
- Decay time depending on ε^2

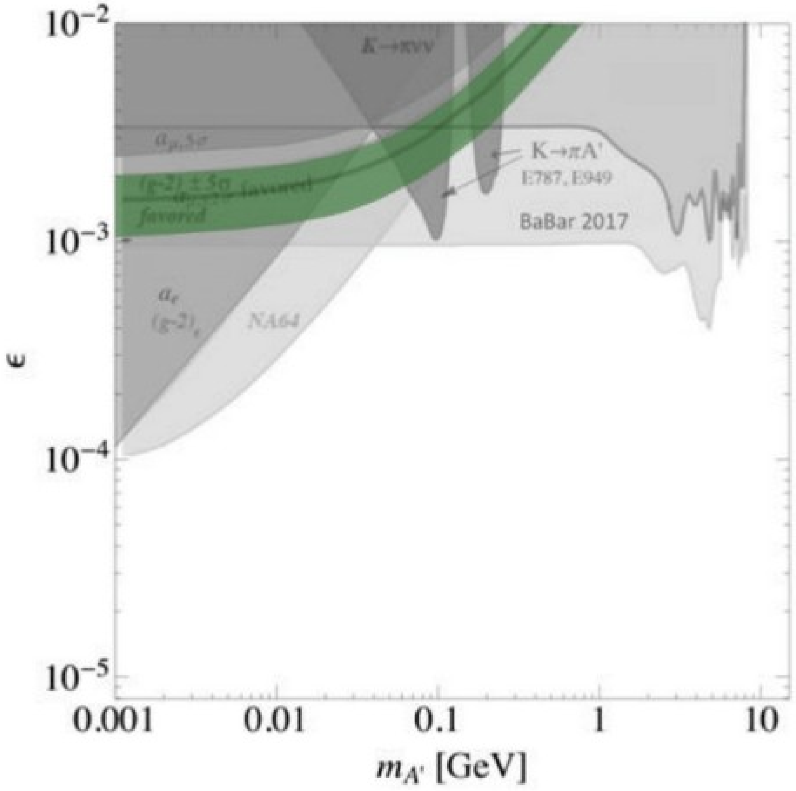


Invisible: A'→χχ

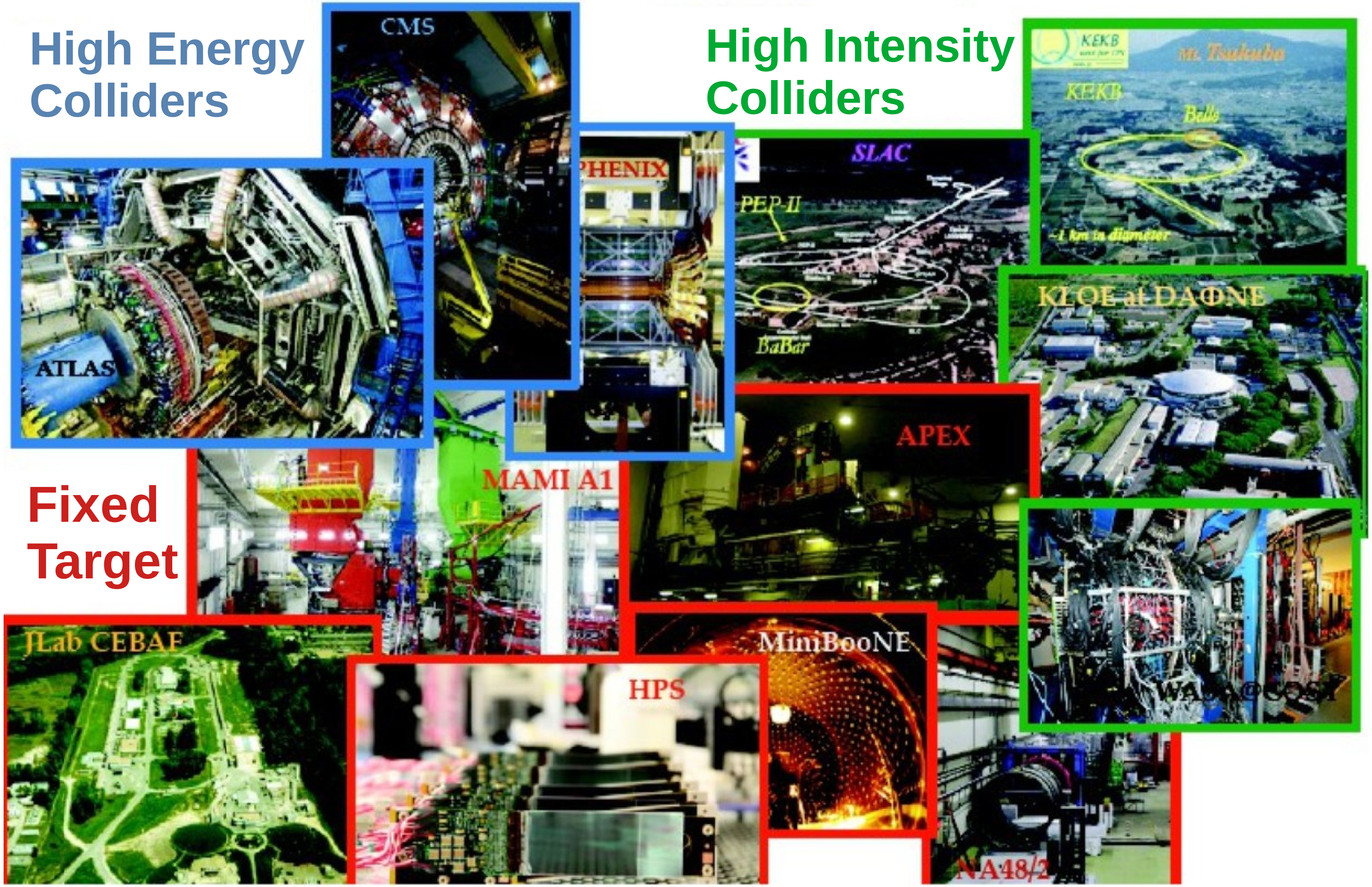
- $m_{A'} > 2m_\chi$
- Not depending on ε







Dark Sector Searches

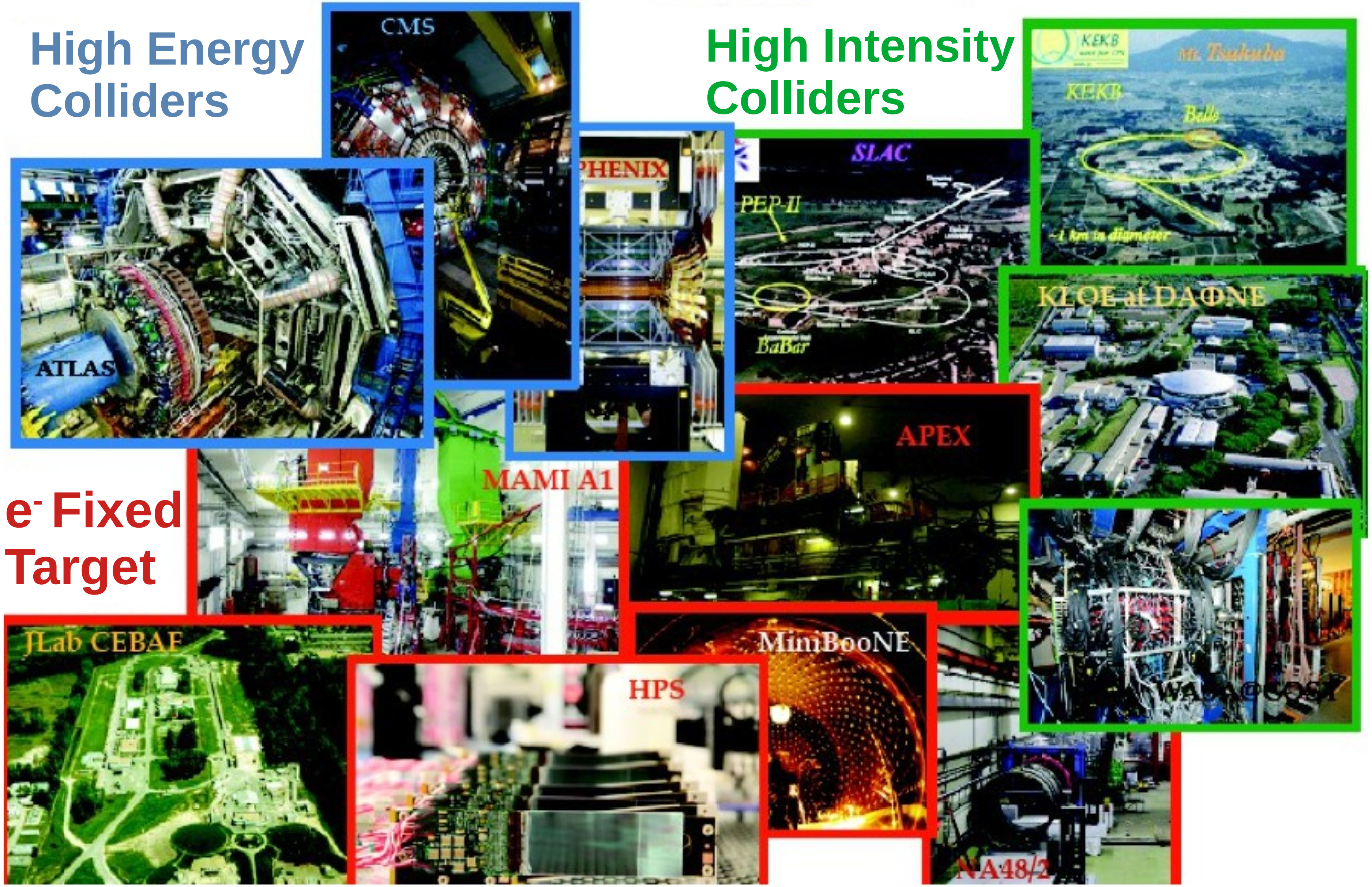


Dark Sector Searches

High Energy Colliders

High Intensity Colliders

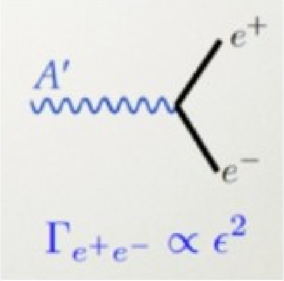
This Talk ➡ e^- Fixed Target



Dark Photon – Visible Searches

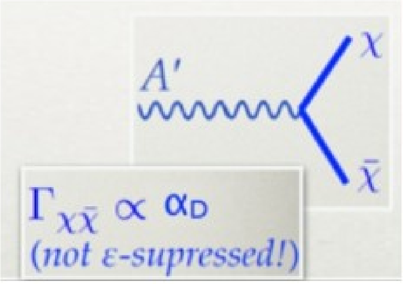
Visible: $A' \to e^+e^-$

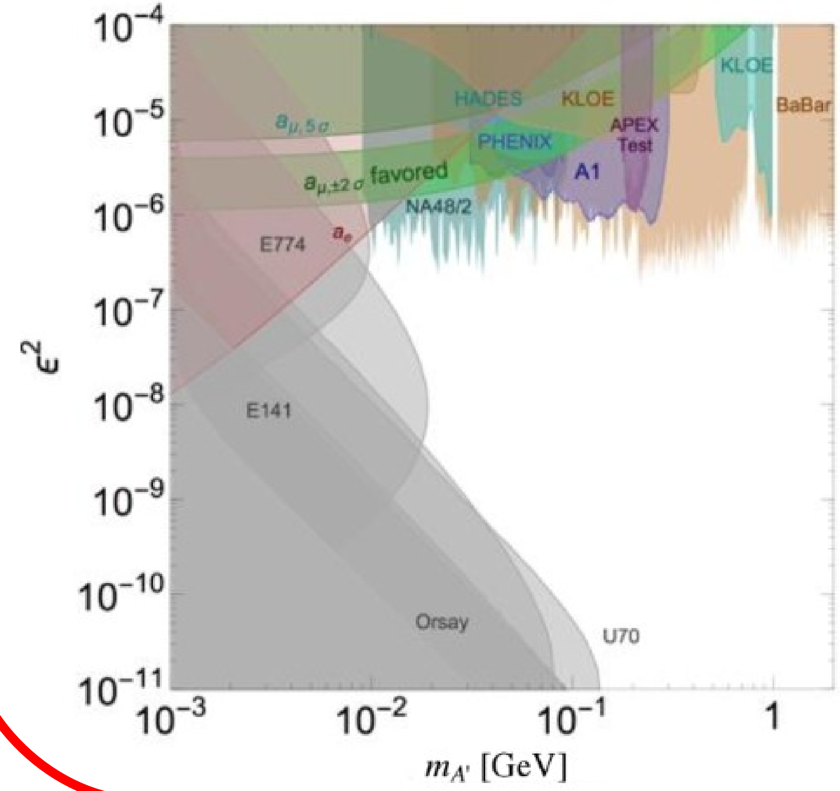
- $m_{A'} < 2m_\chi$
- Decay time depending on ε^2

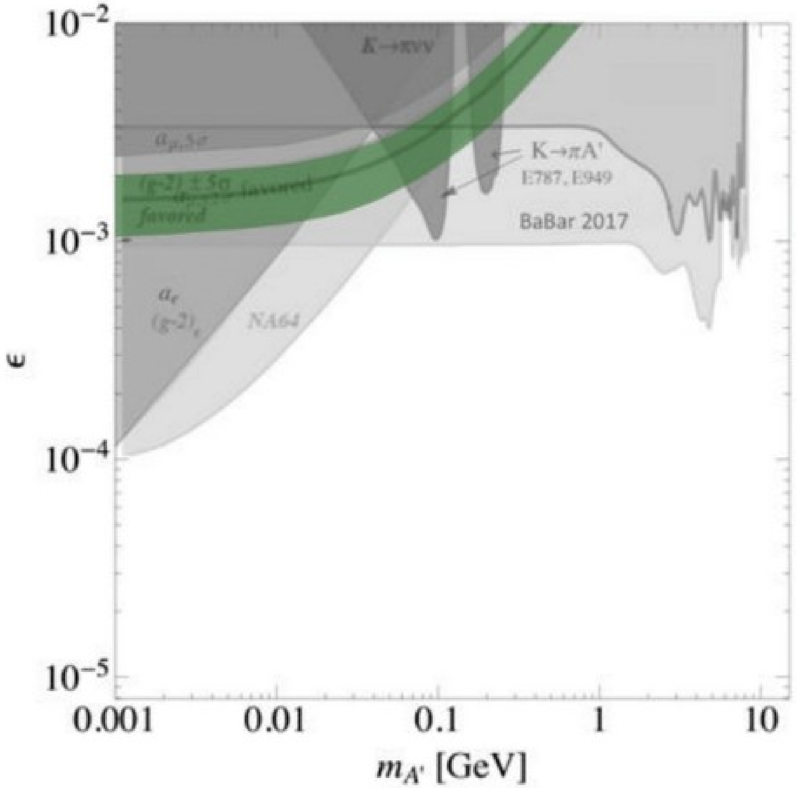


Invisible: $A' \to \chi\chi$

- $m_{A'} > 2m_\chi$
- Not depending on ε

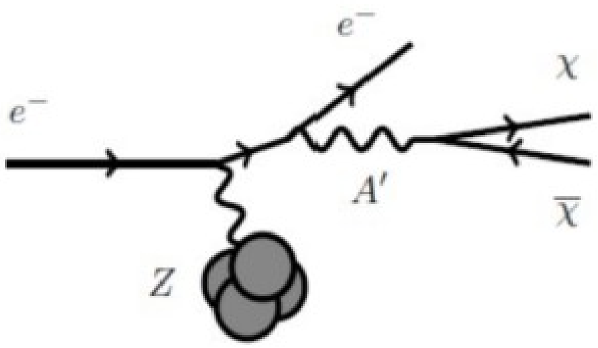






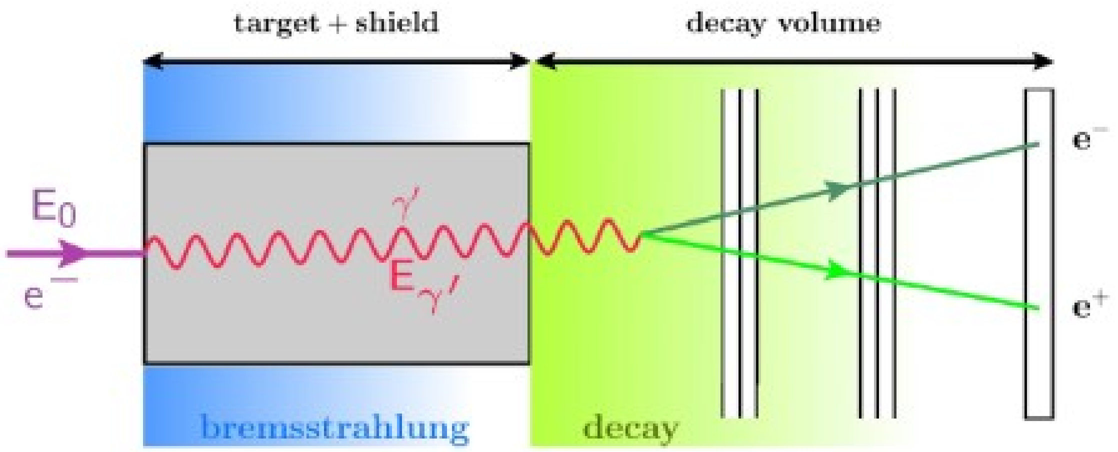
Beam Dumps - Visible Decay

- **Production:** radiative A' emission (A'-strahlung)
- **Propagation:** if $\varepsilon < 10^{-5}$, A' is long lived → detached decay vertex
- **Detection:** e^+e^- pair result of A' decay is measured in a downstream detector

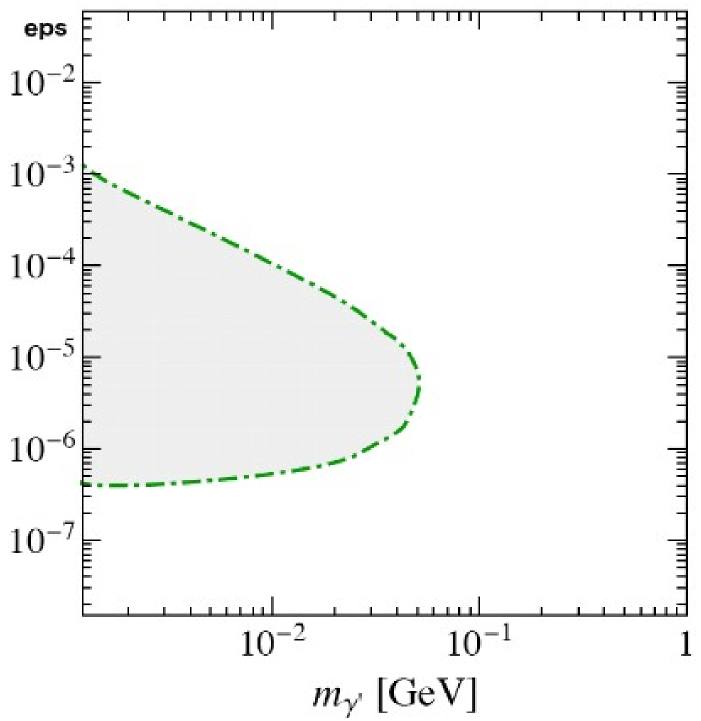


Upper bound: $N_{evt} \propto \varepsilon^2 e^{-L_{sh}/l_{A'}}$, $l_{A'} \propto E_0/\varepsilon^2$

Lower bound: $N_{evt} \propto \varepsilon^2 L_d/l_{A'} \propto \varepsilon^4$



Long lived A'



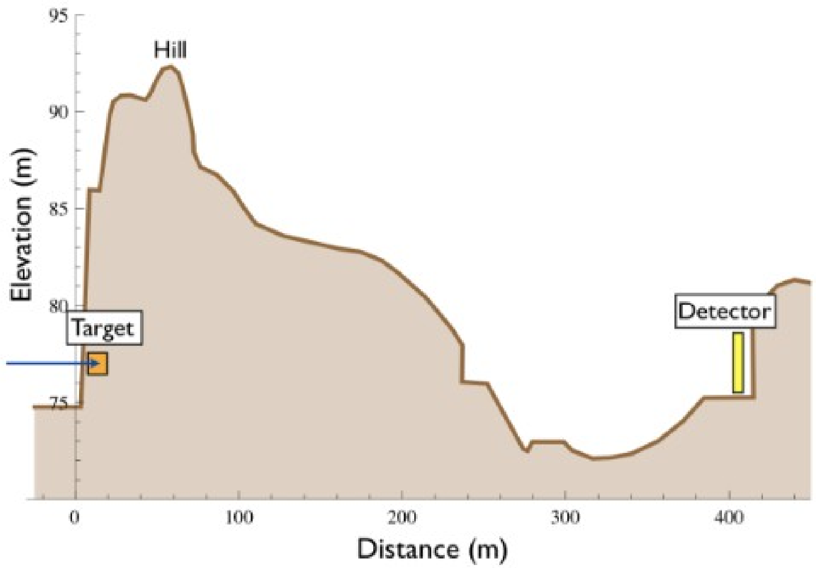
SLAC E137 -Visible

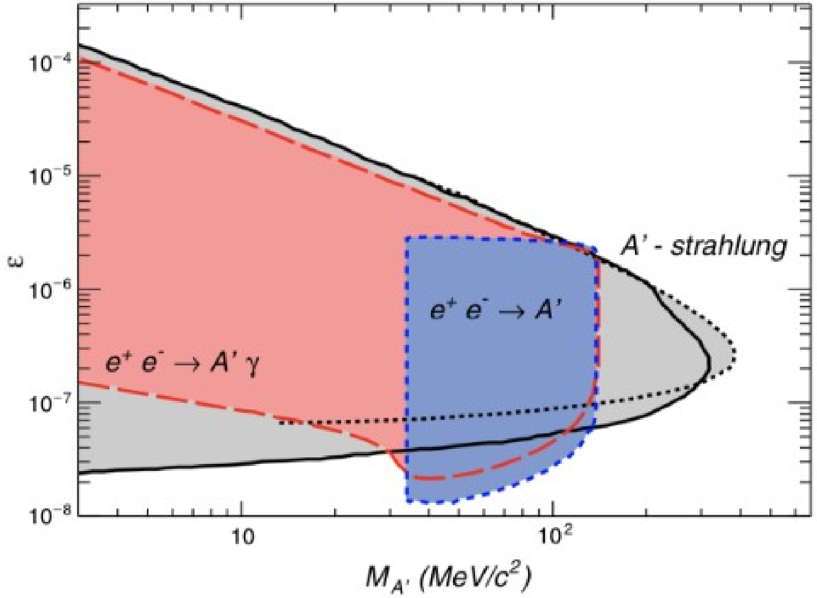
SLAC E137: electron beam-dump experiment from the ‘80s searching for axion-like particles

- Beam: 20 GeV, ~2 X10^{20} EOT
- Target: Aluminum-water beam-dump
- Shielding: 179 m of dirt (hill)
- Decay length: 204 m (air)
- Detector: EM calorimeter + MWPC

Results:

- No events observed: exclusion limits at 95% CL at 2.3 signal events
- Two reanalysis (Miller,Andreas) resulting in similar exclusion limit in the dark photon parameter space
- Recent limit exstension (Marsicano) considering secondary positron contribution to A’ production





Thin Target Visible Decay

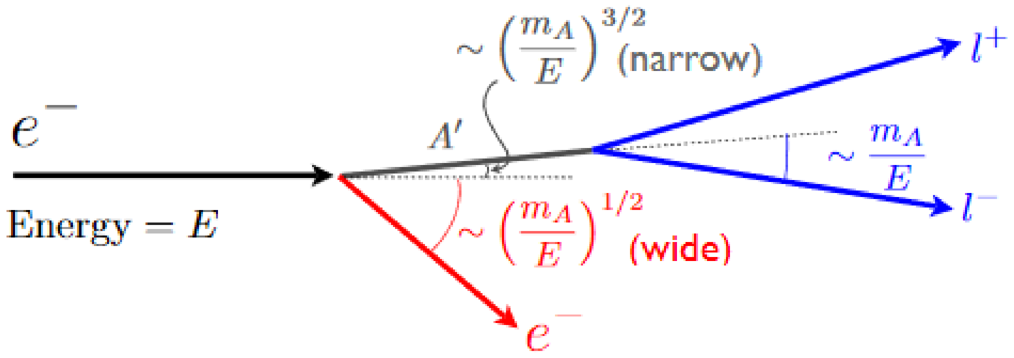
- Radiative production mechanism
- e^+e^- pairs detected through a downstream **particle spectrometer**
- Detection strategies:

  resonant search in the e^+e^- invariant mass spectrum

  detached-vertex search

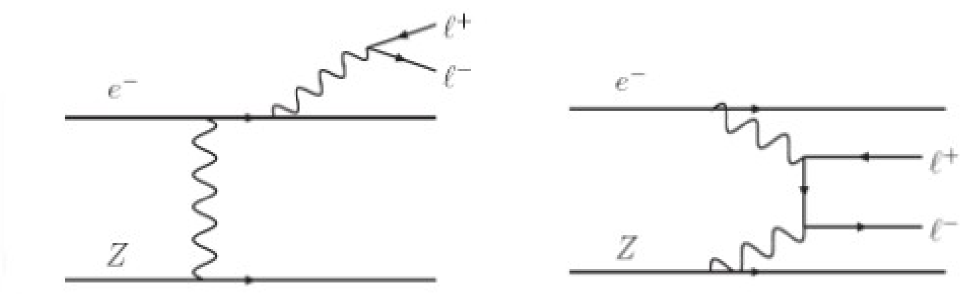
Thin target experiments searching for A': **Jlab** (APEX,HPS) and **MESA**

Signal Kinematics



- Very forward A' emission: $E_A \sim E_{beam}$
- Decay prod. opening angle: $m_{A'}/E_{beam}$

Trident Backgrounds



"Radiative" "Bethe-Heitler"

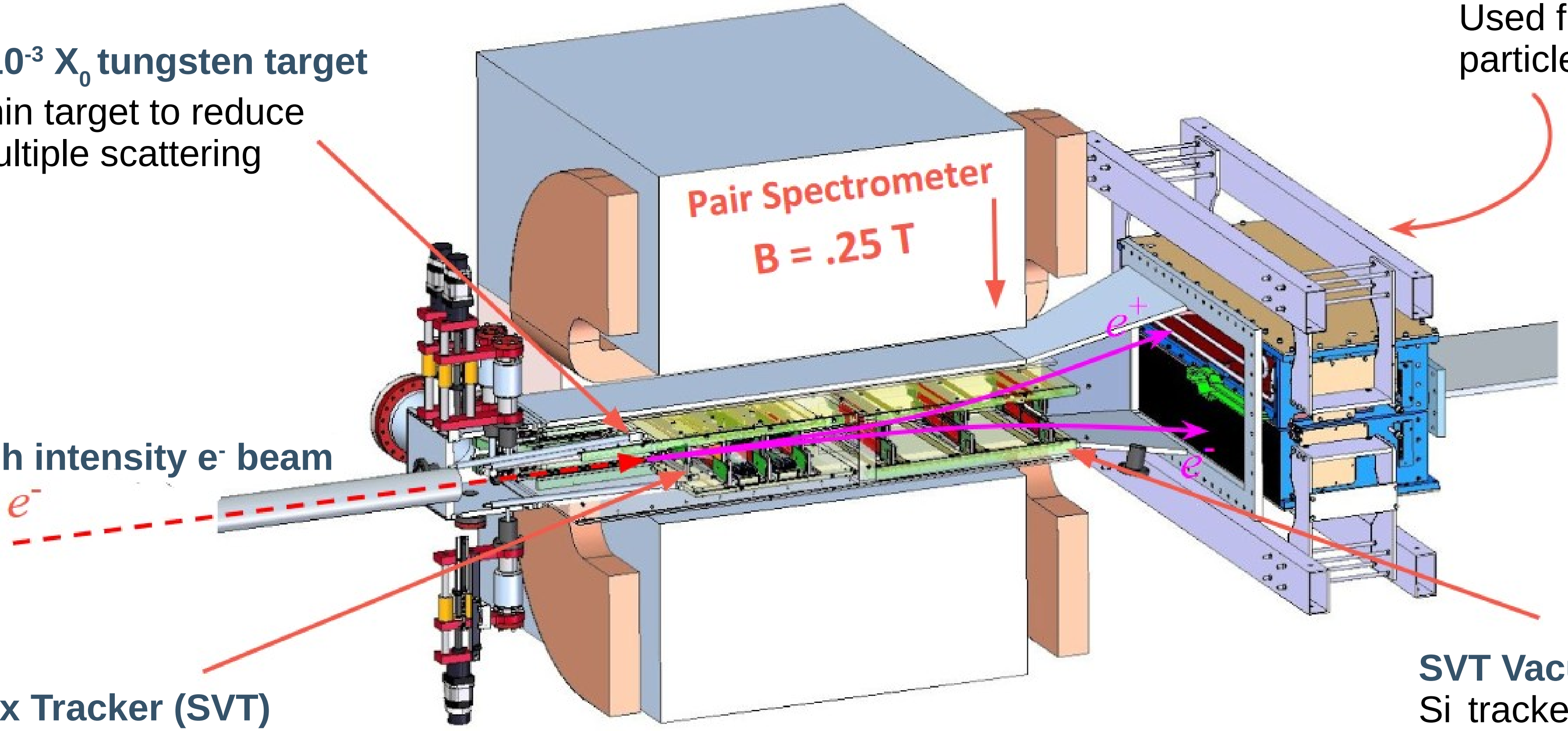
- "Radiative" kinematically identical to A'

The HPS Experiment

HPS experiment at Jefferson Lab Hall-B: fixed-target A′ search, with two complementary approaches, **“bump-hunting”** and **“detached vertexing”**

Eelectromagnetic calorimeter
Used for triggering and particle ID

~10^{-3} X_0 tungsten target
Thin target to reduce multiple scattering



CEBAF high intensity e^- beam

Silicon Vertex Tracker (SVT)
Split into two volumes to avoid intense flux of scattered beam electrons. Used for precise momentum and vertex determination

SVT Vacuum Chamber
Si tracker placed in vacuum in order to avoid backgrounds due to beam-gas interactions

HPS Results And Status

- July 2012: HPS demonstrated the feasibility of the measurement and the operation of the detector in a test run
- Spring 2015: 1.7 PAC days @ 1.06 GeV. Results published in PRD rapid communications
- Spring 2016: 5 PAC days @ 2.3 GeV
- Summer 2019: 2 months running @ 4.55 GeV – about 10^5 nbarn^{-1} accumulated.

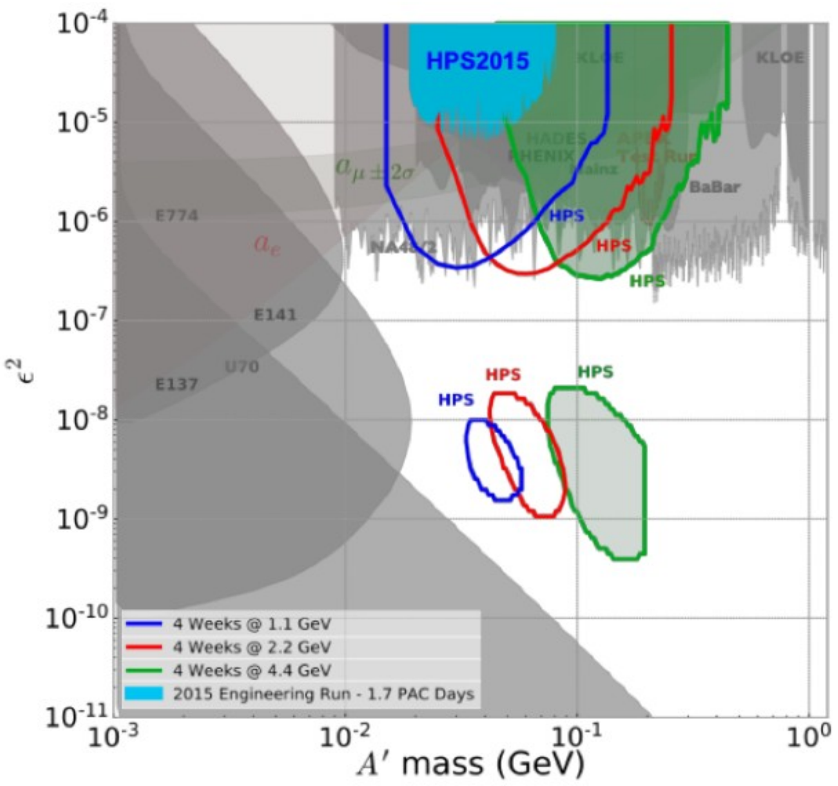
PHYSICAL REVIEW D **98**, 091101(R) (2018)

Rapid Communications Editors' Suggestion

Search for a dark photon in electroproduced e^+e^- pairs with the Heavy Photon Search experiment at JLab

P. H. Adrian,[1] N. A. Baltzell,[2] M. Battaglieri,[3] M. Bondí,[4] S. Boyarinov,[2] S. Bueltmann,[5] V. D. Burkert,[2] D. Calvo,[6] M. Carpinelli,[7,8] A. Celentano,[3] G. Charles,[9] L. Colaneri,[10,11] W. Cooper,[12] C. Cuevas,[2] A. D'Angelo,[10,11] N. Dashyan,[13] M. De Napoli,[4] R. De Vita,[3] A. Deur,[2] R. Dupre,[9] H. Egiyan,[2] L. Elouadrhiri,[2] R. Essig,[14] V. Fadeyev,[15] C. Field,[1] A. Filippi,[6] A. Freyberger,[2] M. Garçon,[16] N. Gevorgyan,[13] F. X. Girod,[2] N. Graf,[1] M. Graham,[1] K. A. Griffioen,[17] A. Grillo,[15] M. Guidal,[9] R. Herbst,[1] M. Holtrop,[18] J. Jaros,[1] G. Kalicy,[5] M. Khandaker,[19] V. Kubarovsky,[2] E. Leonora,[4] K. Livingston,[20] T. Maruyama,[1] K. McCarty,[18] J. McCormick,[1] B. McKinnon,[20] K. Moffeit,[20] O. Moreno,[1,15,*] C. Munoz Camacho,[9] T. Nelson,[1] S. Niccolai,[9] A. Odian,[1] M. Oriunno,[1] M. Osipenko,[3] R. Paremuzyan,[18] S. Paul,[17] N. Randazzo,[4] B. Raydo,[2] B. Reese,[1] A. Rizzo,[10,11] P. Schuster,[1,21] Y. G. Sharabian,[2] G. Simi,[22,23] A. Simonyan,[9] V. Sipala,[7,8] D. Sokhan,[20] M. Solt,[1] S. Stepanyan,[2] H. Szumila-Vance,[2,5] N. Toro,[1,21] S. Uemura,[1] M. Ungaro,[2] H. Voskanyan,[13] L. B. Weinstein,[5] B. Wojtsekhowski,[2] and B. Yale[18]

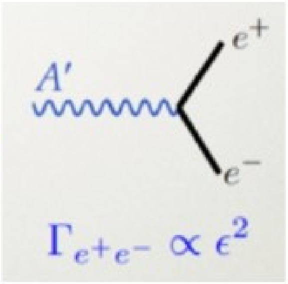
(Heavy Photon Search Collaboration)

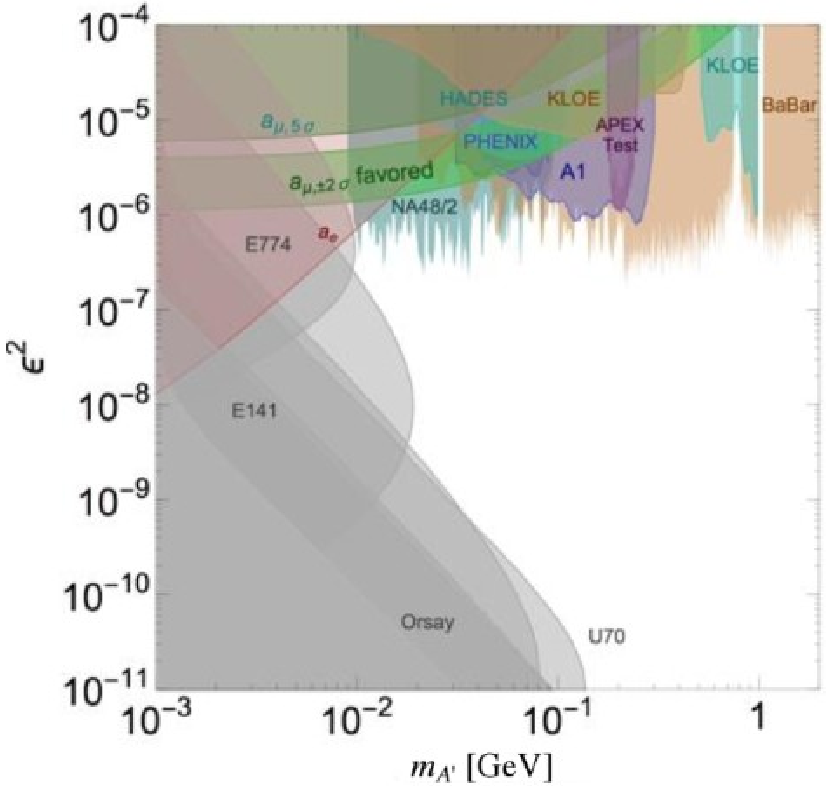


Dark Photon - Invisible

Visible: A'→e+e-

- $m_{A'} < 2m_\chi$
- Decay time depending on ε^2





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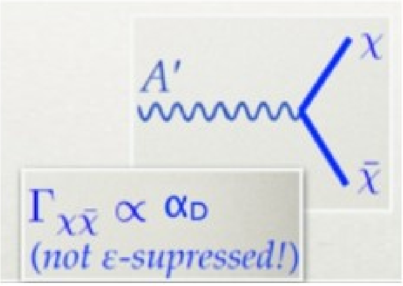
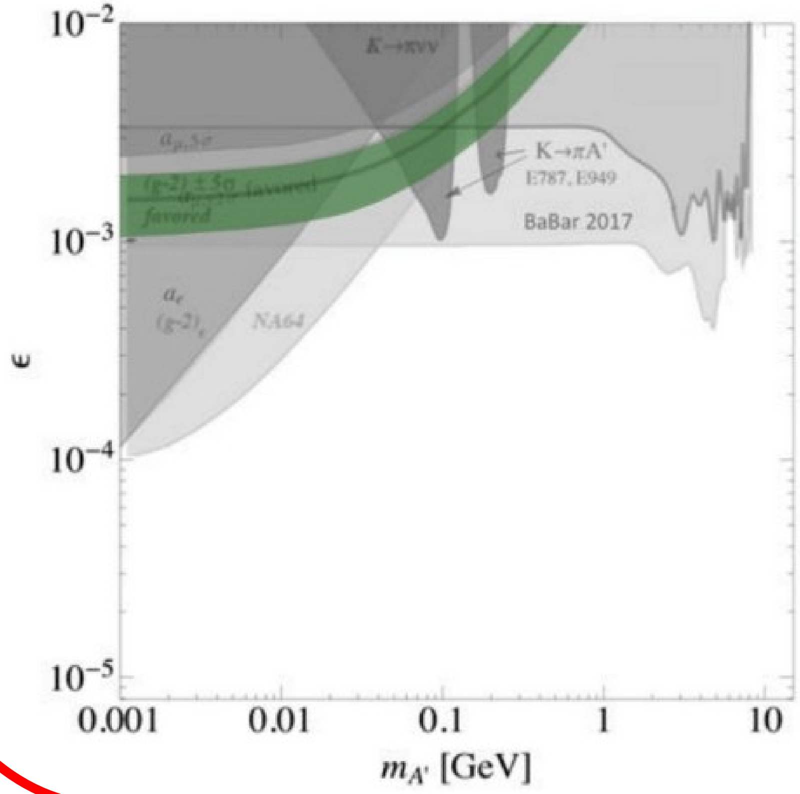


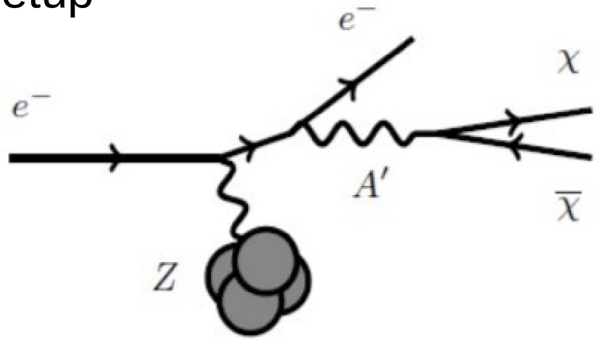


Beam Dumps

Beam-dump experiment: LDM detection in a e- beam, fixed target setup

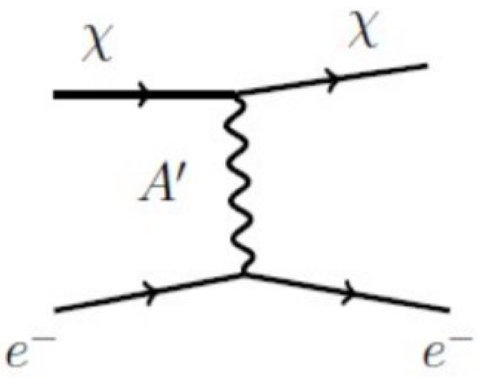
LDM Production:

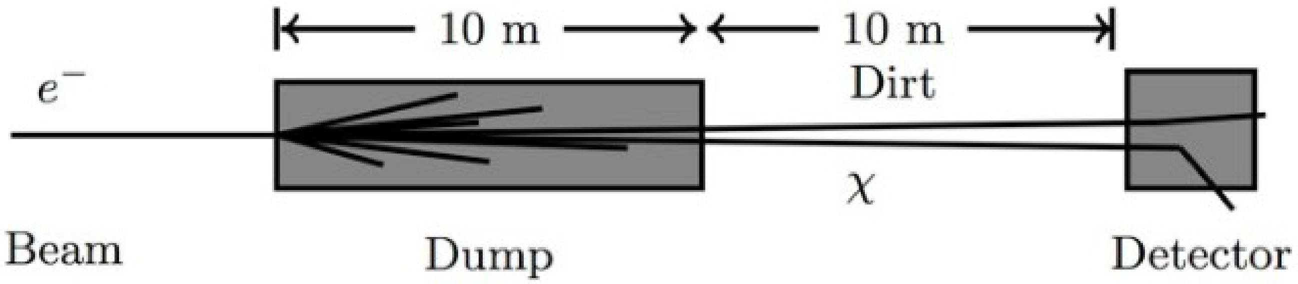
- High-energy, high-intensity e^- beam impinging on the dump
- LDM particles pairs produced radiatively, through A' emission (***A'-strahlung***), both on-shell or off-shell



LDM Detection:

- Detector placed O(20-100 m) behind the dump
- Neutral-current scattering on atomic e- through A' exchange, recoil releasing visible energy
- Signal O(100 MeV) electromagnetic shower





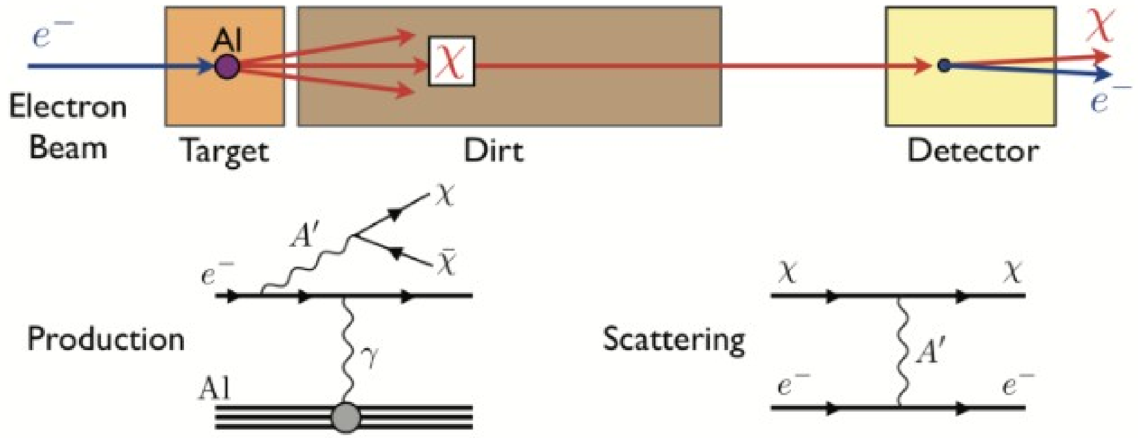
A' yield: $N_{A'} \propto \frac{\varepsilon^2}{m_{A'}^2}$

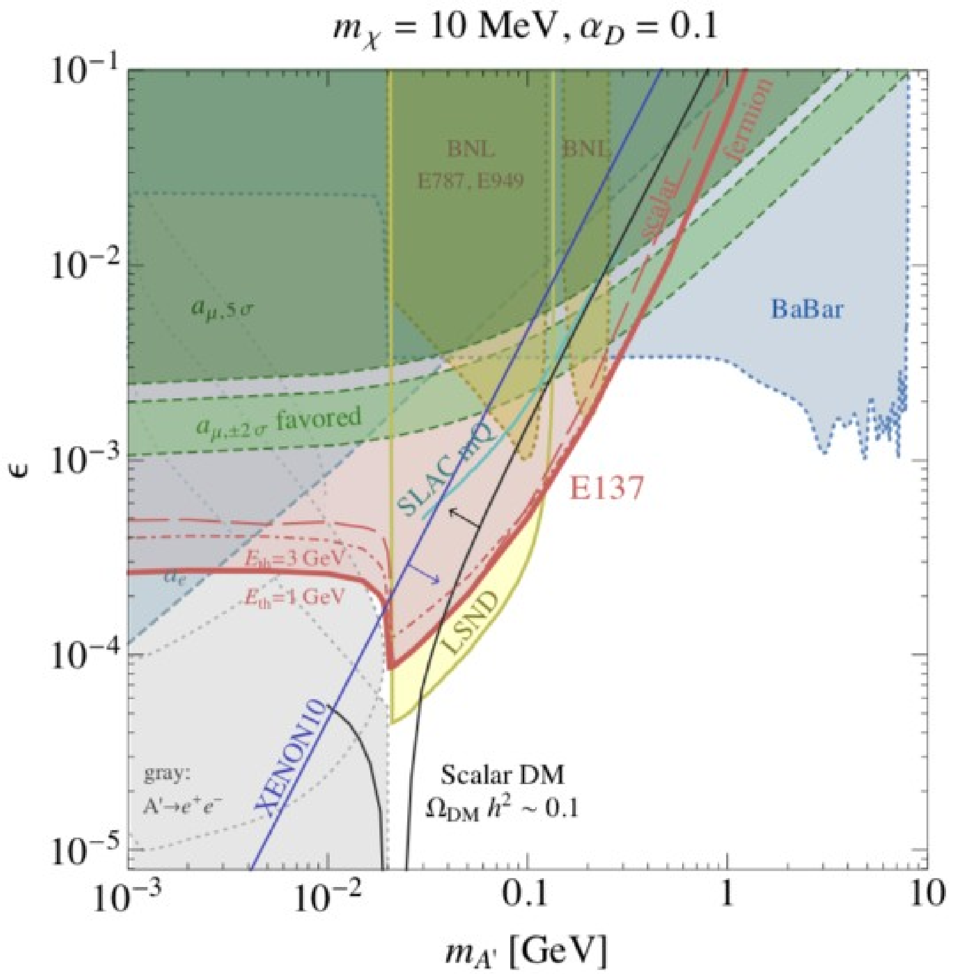
χ cross-section: $\sigma_{\chi e} \propto \frac{\alpha_D \varepsilon^2}{m_{A'}^2}$

Number of events: $N_\chi \propto \frac{\alpha_D \varepsilon^4}{m_{A'}^4}$

E137

- **E137** results have been reanalyzed also in the invisible A’ scenario
- First analysis (Batell) focused on A′-strahlung production mechanism
- Analysis included detailed simulation of original E137 detection threshold and trigger

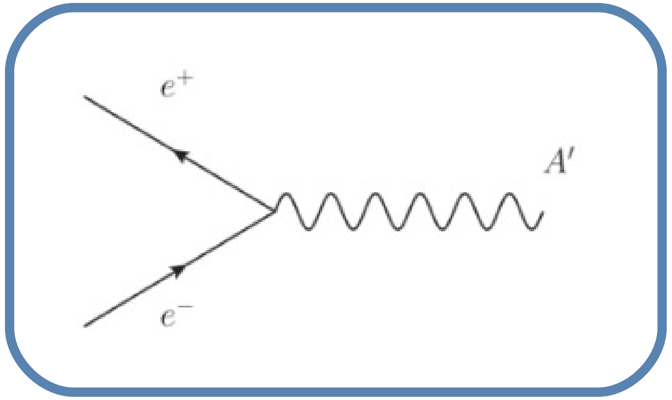


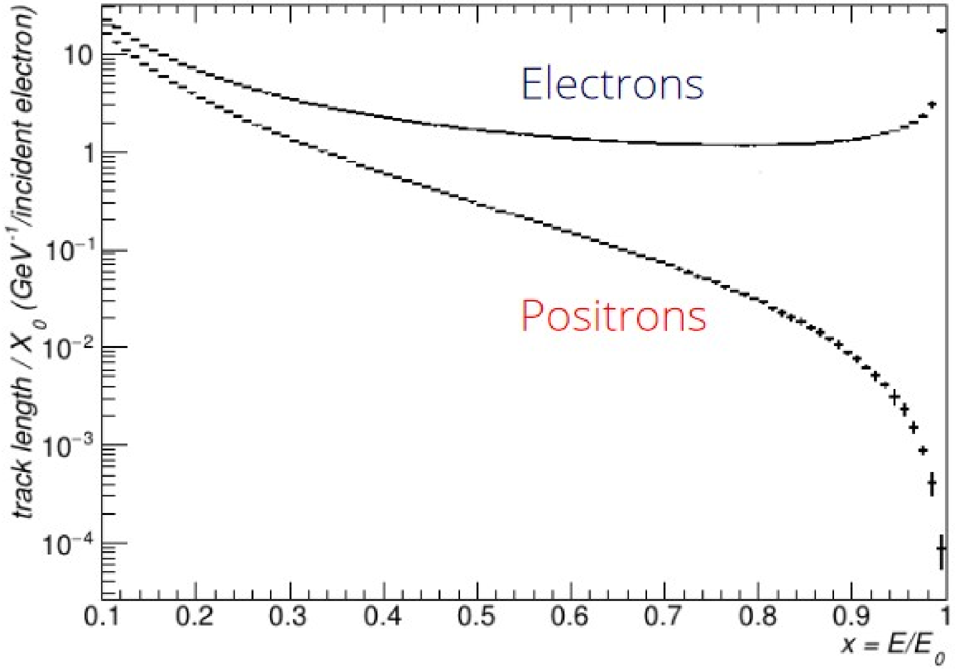


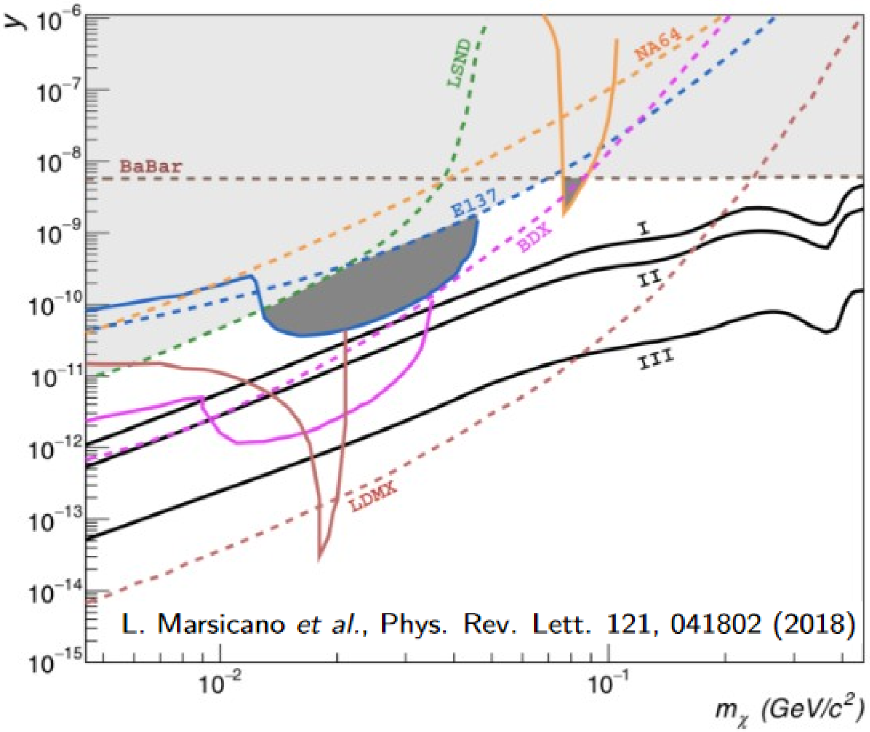
B. Batell *et al.*, Phys. Rev. Lett. 113, 171802 (2014)

E137

- New analysis (Marsicano) included the contribution of secondary positron annihilation **$e^+e^- \rightarrow A'$** to the total A' yield
- Due to EM showering, an electron beam-dump is a positron rich environment
- The contribution of positron resonant annihilation is sizable



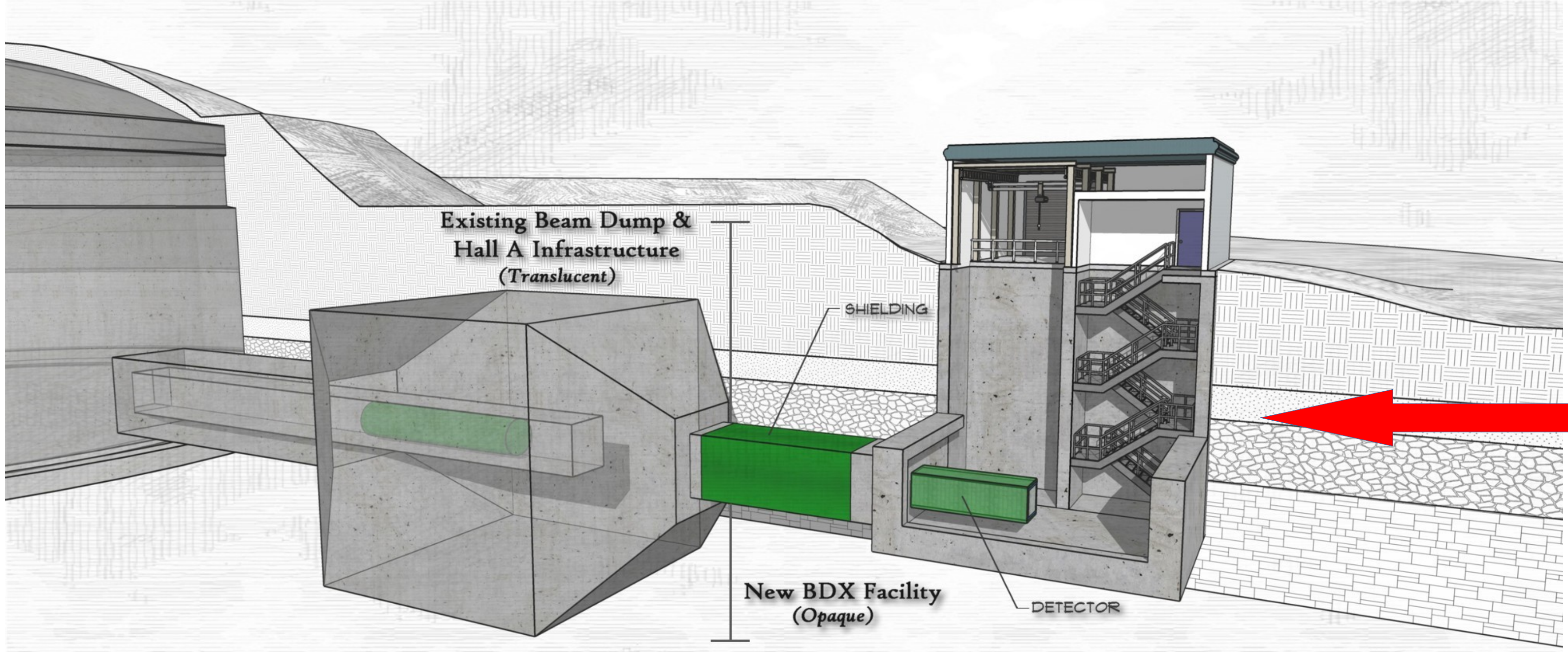


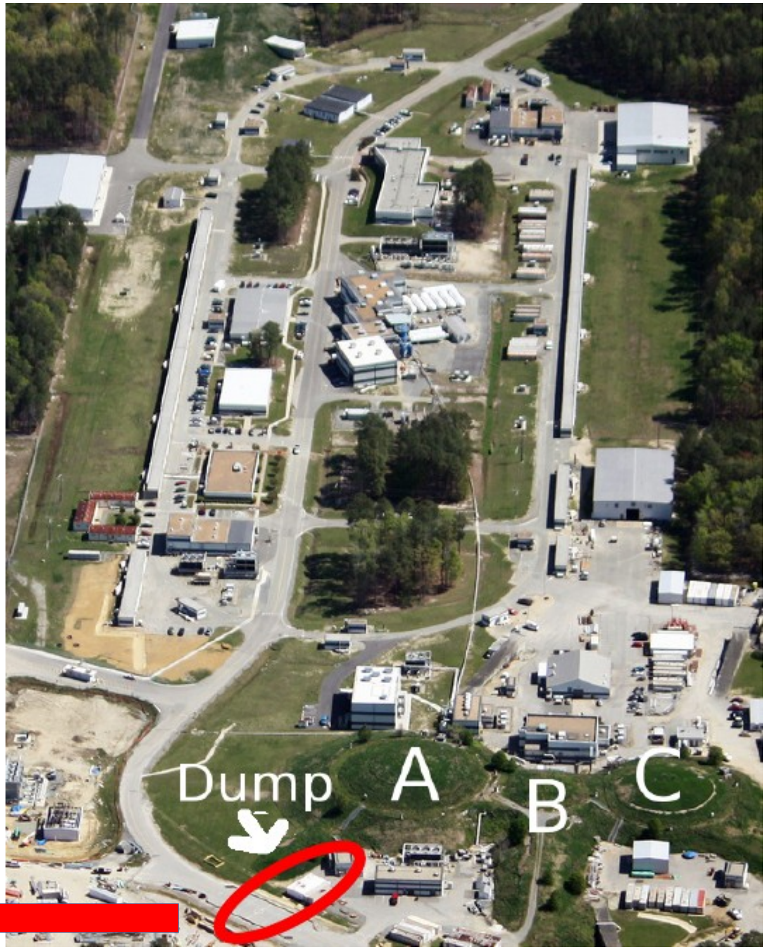


The Beam Dump eXperiment

BDX: modern beam-dump experiment at **Jefferson Lab** - 11 GeV e- beam, Al-H_2O beam-dump. 10^{22} EOT in 285 days.

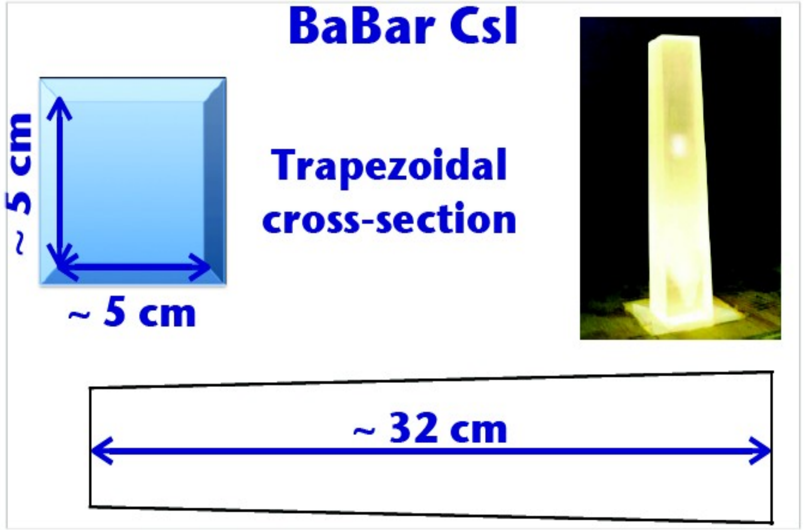
- Detector installed O(20 m) behind Hall-A beam-dump, in a **new experimental hall**
- Passive shielding layer between beam-dump and detector to reduce SM beam-related background
- Sizable overburden (10 m water-equivalent) to reduce cosmogenic background





The BDX Detector

BDX detector: state-of-the-art EM calorimeter, CsI(Tl) crystals with SiPM-based readout, surrounded by active veto layers and a passive lead shielding to reduce cosmic background



Detector design:

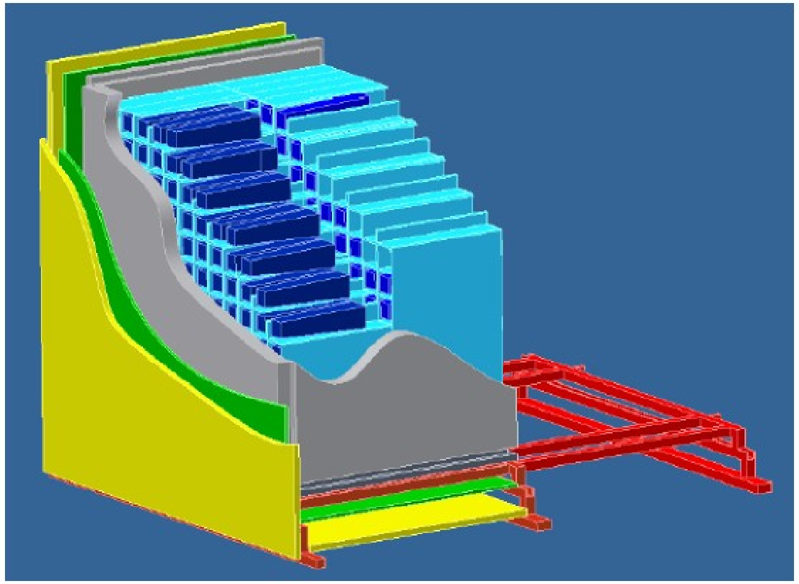
- 800 CsI(Tl) crystals, total interaction volume 0.5 m^3
- 5 cm thick lead shielding
- Dual active-veto layer (IV and OV), made of plastic scintillator counters with SiPM readout

Calorimeter arrangement:

- 1 module: 10x10 crystals, 30-cm long; front face: 50x50 cm^2
- 8 modules: interaction length 2.6 m

Signal:

- EM-shower, (threshold: 300 MeV), anticoincidence with IV and OV
- Efficiency (conservative): O(10% – 20%) – dominated by EM shower splash back to veto counters



BDX: Sensitivity 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:

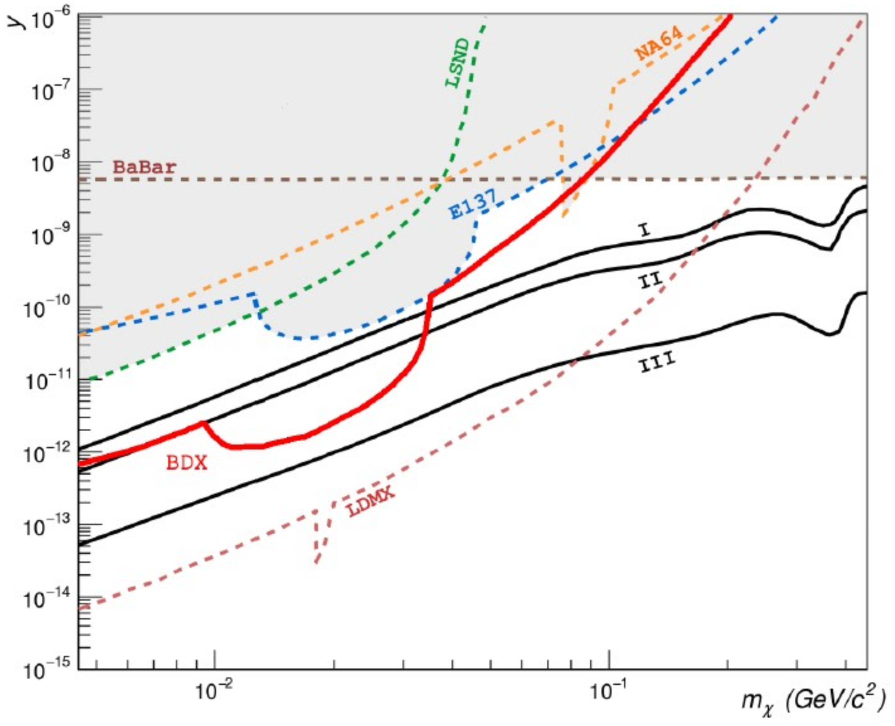
- Experiment approved by JLab PAC in 2018 with the highest scientific rating

Beam Request:

- 10^{22} EOT (285 days @ 65 μA)

Expected Backgrounds:

- Energy threshold: 350 MeV
- Neutrino background events: ~5 ev.
- Cosmic background events: ~0 ev.



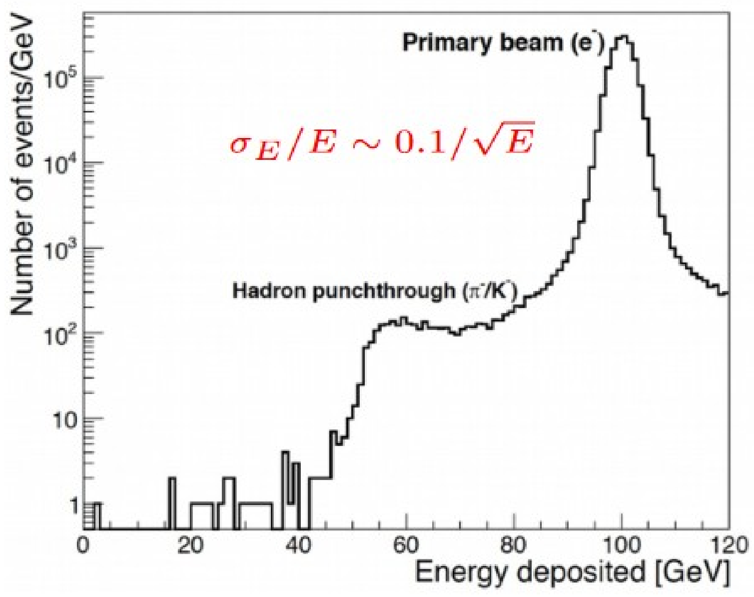
Missing Energy - NA64

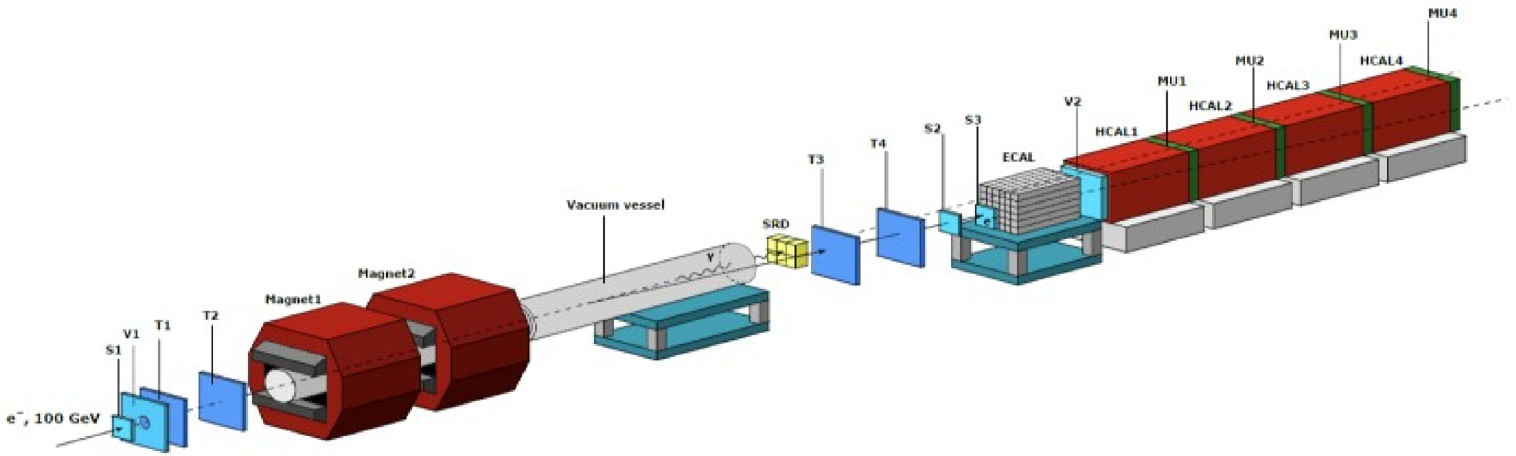
- **NA64:** missing energy experiment at CERN North Area; 100 GeV e- beam
- **Tagged** 100 GeV e- impinges on active target
- A’ produced radiatively, leave the detector with high kinetic energy

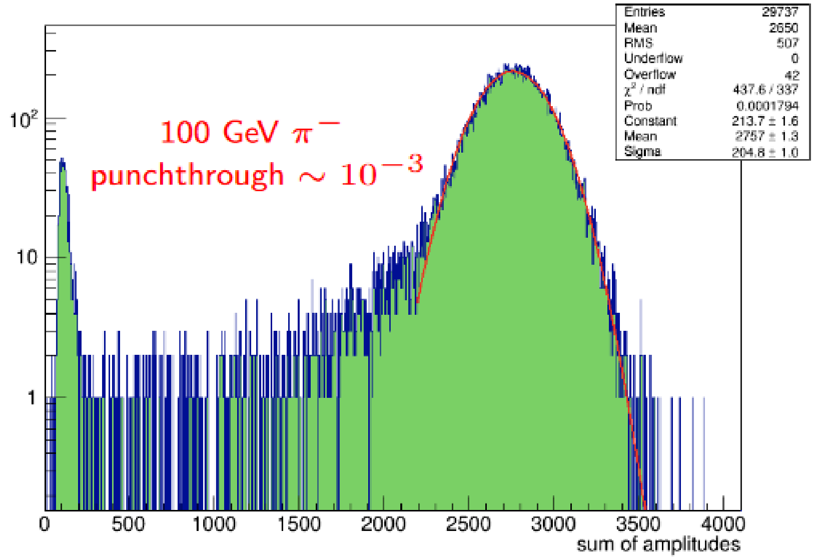
  → search for **missing energy search for missing energy events with no activity in the downstream hadron calorimeter**

Detector:

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







NA64 -Results

- NA64 just published the analysis of 2.84· 10^{11} EOT
- After applying all selection cuts, no events are observed in the signal region E_{ECAL}<50 GeV, E_{HCAL}<1GeV
- Expected number of background events ~ 0.5 compatible with null observation
- Most competitive exclusion limits in large portion of the LDM parameters space

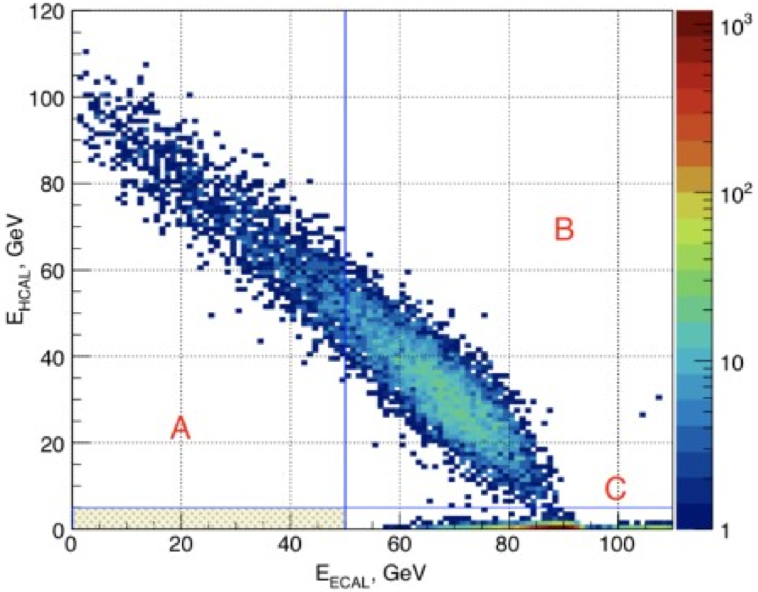
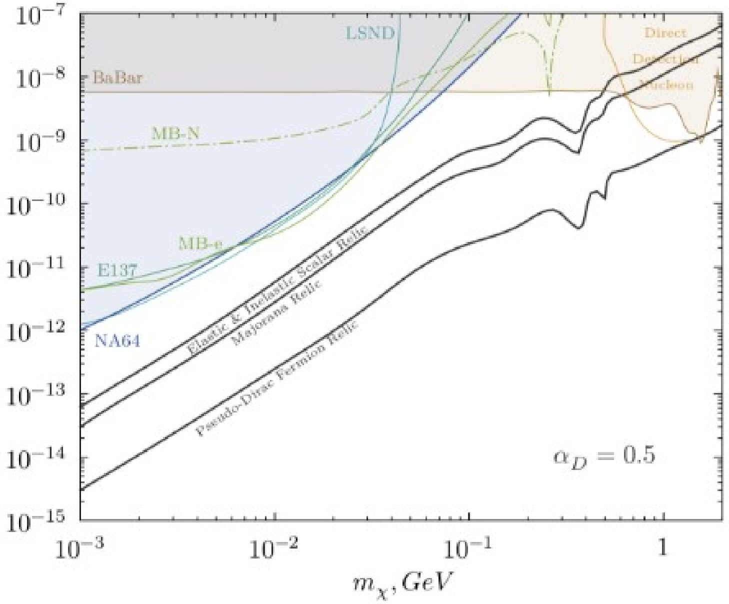


TABLE I: Expected background for 2.84×10^{11} EOT.

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



Missing Momentum - LDMX

LDMX: Proposed missing monentum experiment with muti-GeV electron beam – 10^{16} EOT in few years measurement run → very fast detector required

Fast Si tracker

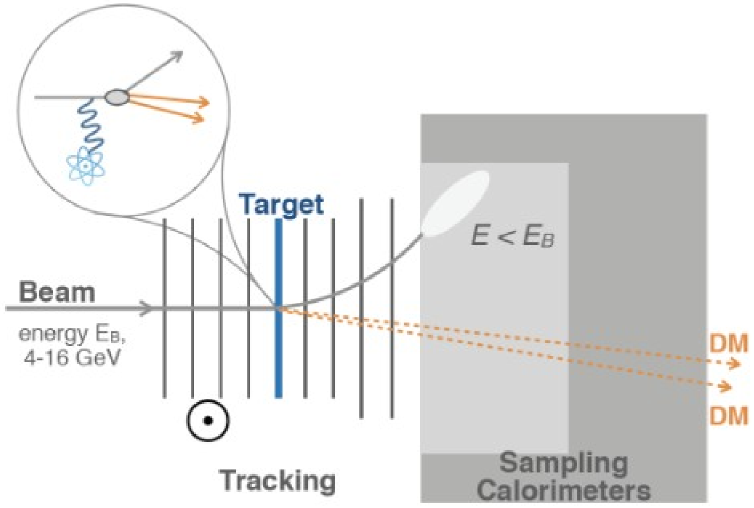
- Tagging tracker in 1.5 T field
- Recoil tracker in fringe field
- W (0.1-0.3 X_0) target in between

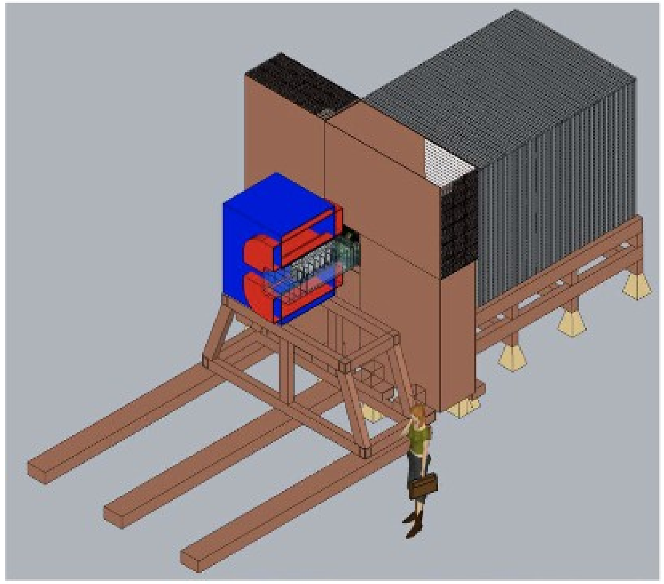
EM Calorimeter

- 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

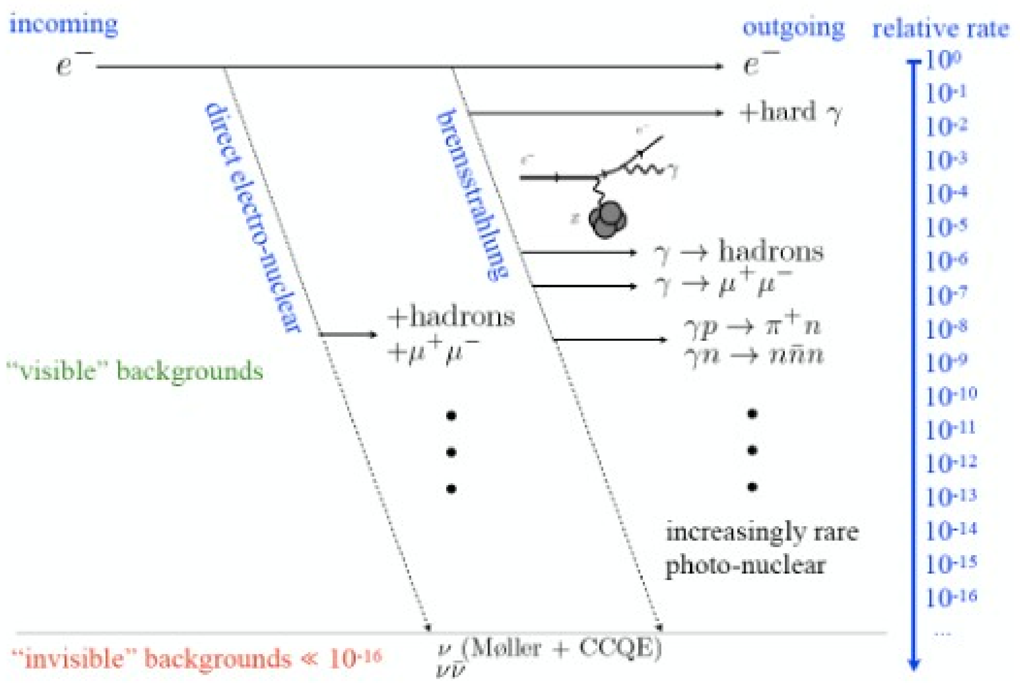


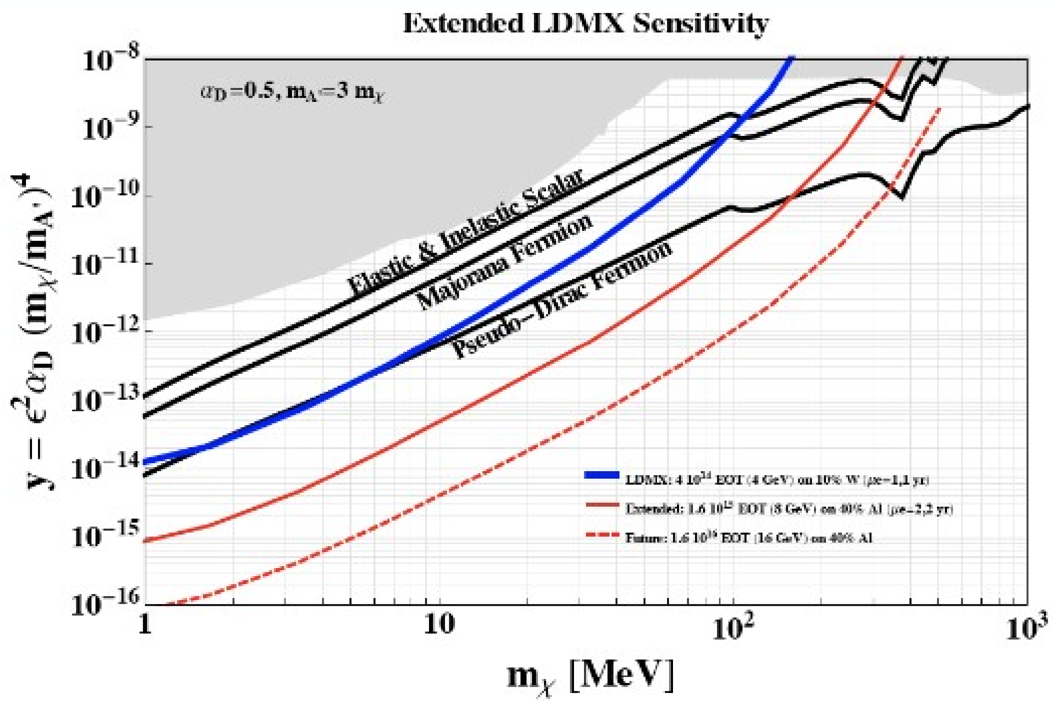


LDMX Status

Background studies and detector design efforts are currently ongoing...

- close to 0 background events are expected for a preliminary run of 10^{14} EOT
- Particular care for non-trivial hadronic backgrounds (e.g. n pairs, backward particles,…) is required
- Large statistics run optimization: pT signature / HCAL design / beam energy...





Conclusions

- Vector mediated light Dark Matter in the MeV-GeV mass range is largely unexplored
- Theoretically, it is as founded as the more “traditional” WIMP paradigm, since it can efficiently explain DM relic density, assuming the existence of a new force
- Medium-small size fixed-target experiments can make a great contribution to the exploration of this paradigm, both in the “visible” and “invisible” dark photon decay scenario
- Visible Searches:

  Beam-dumps

  Spectrometer-search: invariant mass or detached vertex technique
- Invisible searches:

  Beam-dumps

  Missing energy / momentum