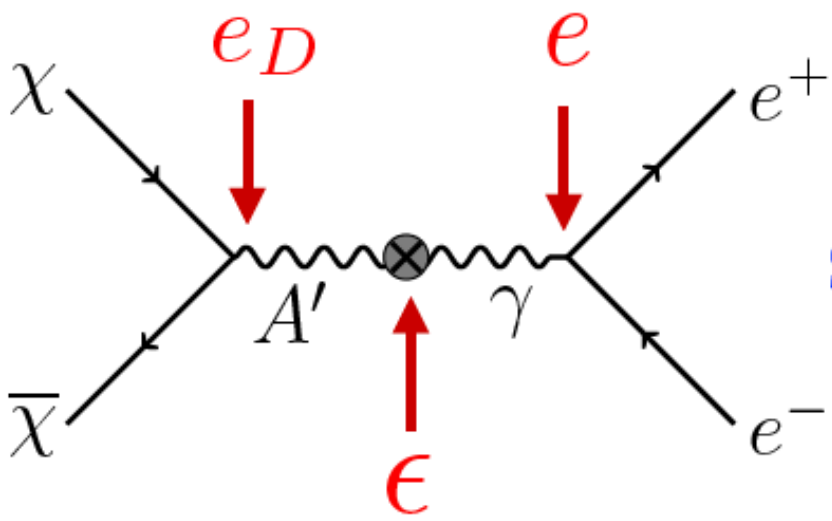
Dark Sectors Searches with electron/positron beams
Other Science Opportunities at the FCC-ee - CERN 28.11.2024

Paolo Crivelli, ETH Zurich, Institute for Particle Physics and Astrophysics

THE VECTOR PORTAL & Light Dark Matter (LDM)

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



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

In this framework DM can be produced thermally in the early Universe

OBSERVED **AMOUNT OF DARK MATTER** TODAY

$$\Omega_X \propto \frac{1}{< v\sigma >} \sim \frac{m_X^2}{y}$$

WHERE $$y = \epsilon^2 \alpha_D \left(\frac{m_X}{m_{A'}}\right)^4$$

The WIMPless MIRACLE

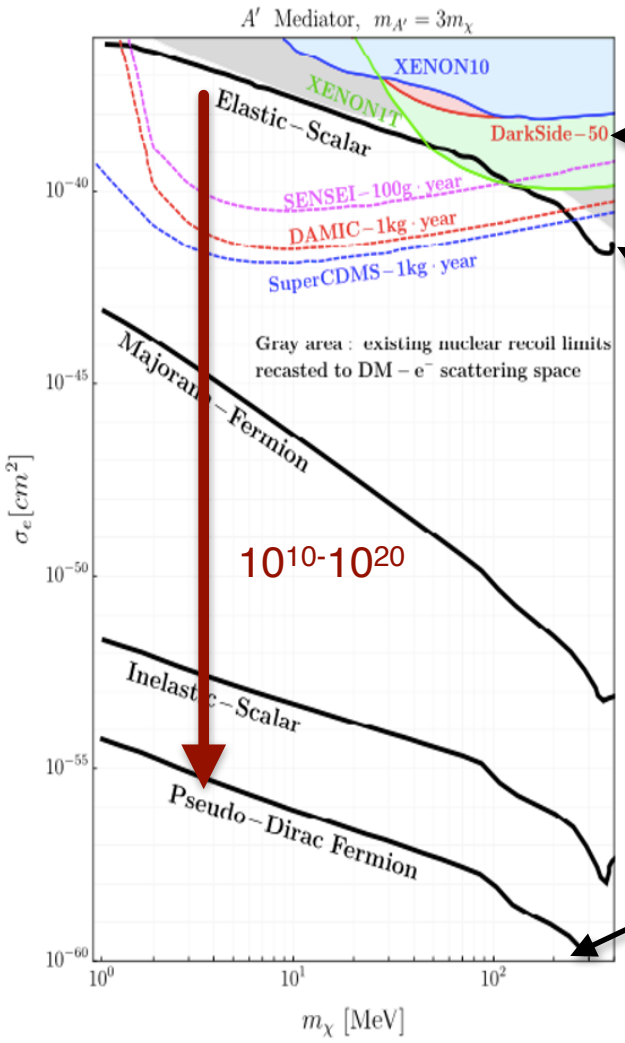
$$\frac{m_X}{g_X^2} \sim \frac{m_{\text{weak}}}{g_{\text{weak}}^2}$$

J. Feng and J. Kumar Phys.Rev.Lett.101:231301,2008

Complementarity of direct detection and accelerators experiments

R. Essig, J. Mardon, and T. Volansky, PRD85, 076007 (2012), 1108.5383.

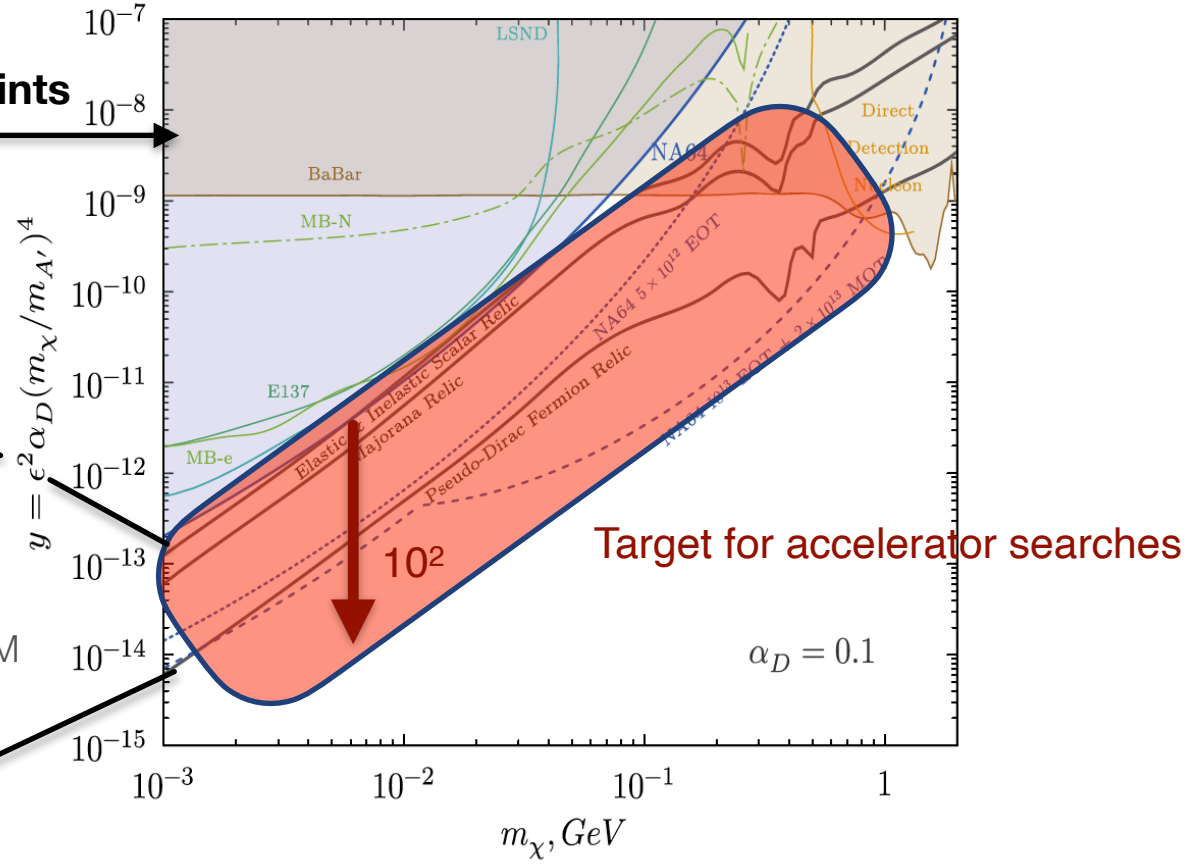
Direct Detection Targets



Current constraints

Solid lines predictions from DM relic abundance

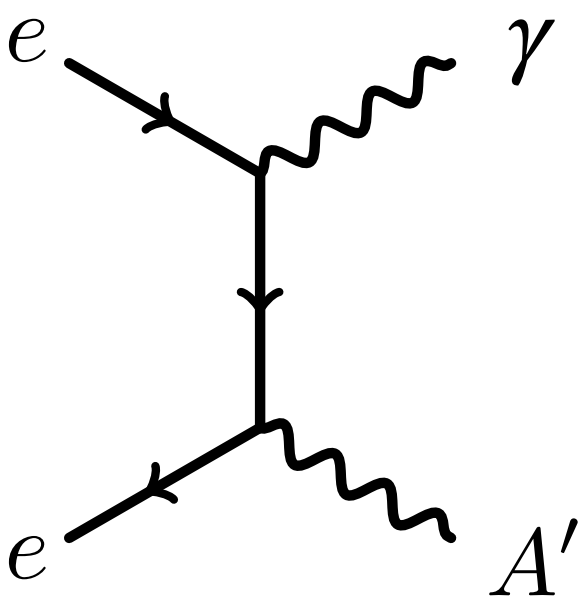
Accelerator Targets



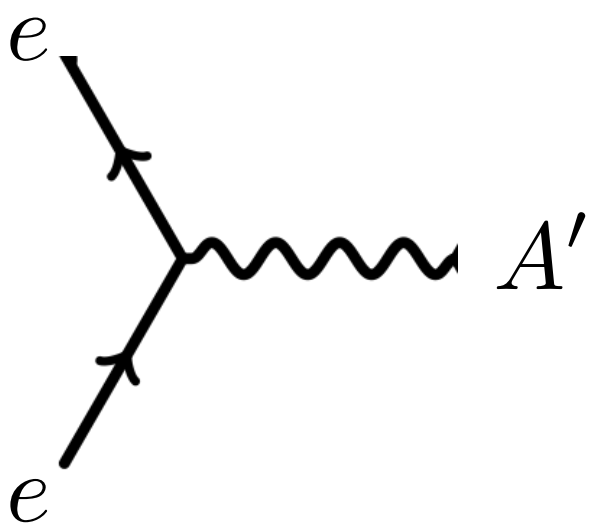
Target for accelerator searches

NA64 collaboration, PRL 123, 121801 (2019)

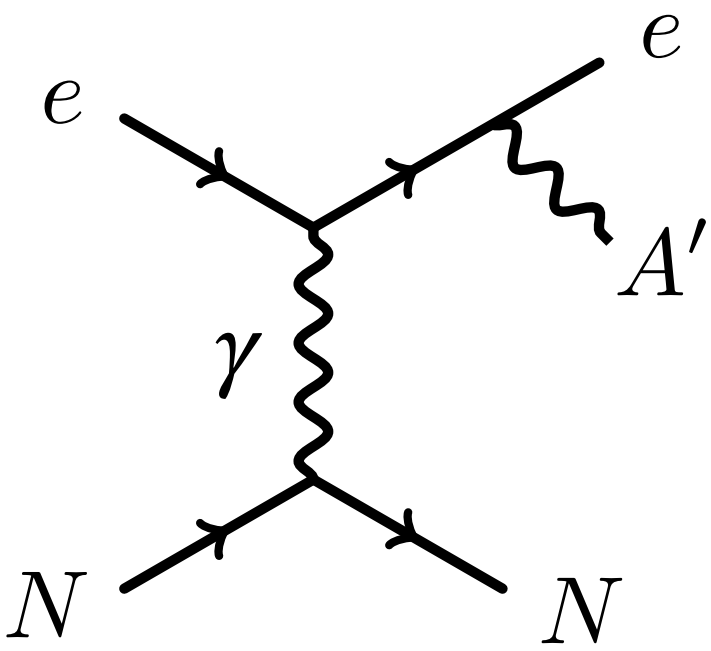
Production mechanisms for Dark Photons in e+/e- beams



annihilation



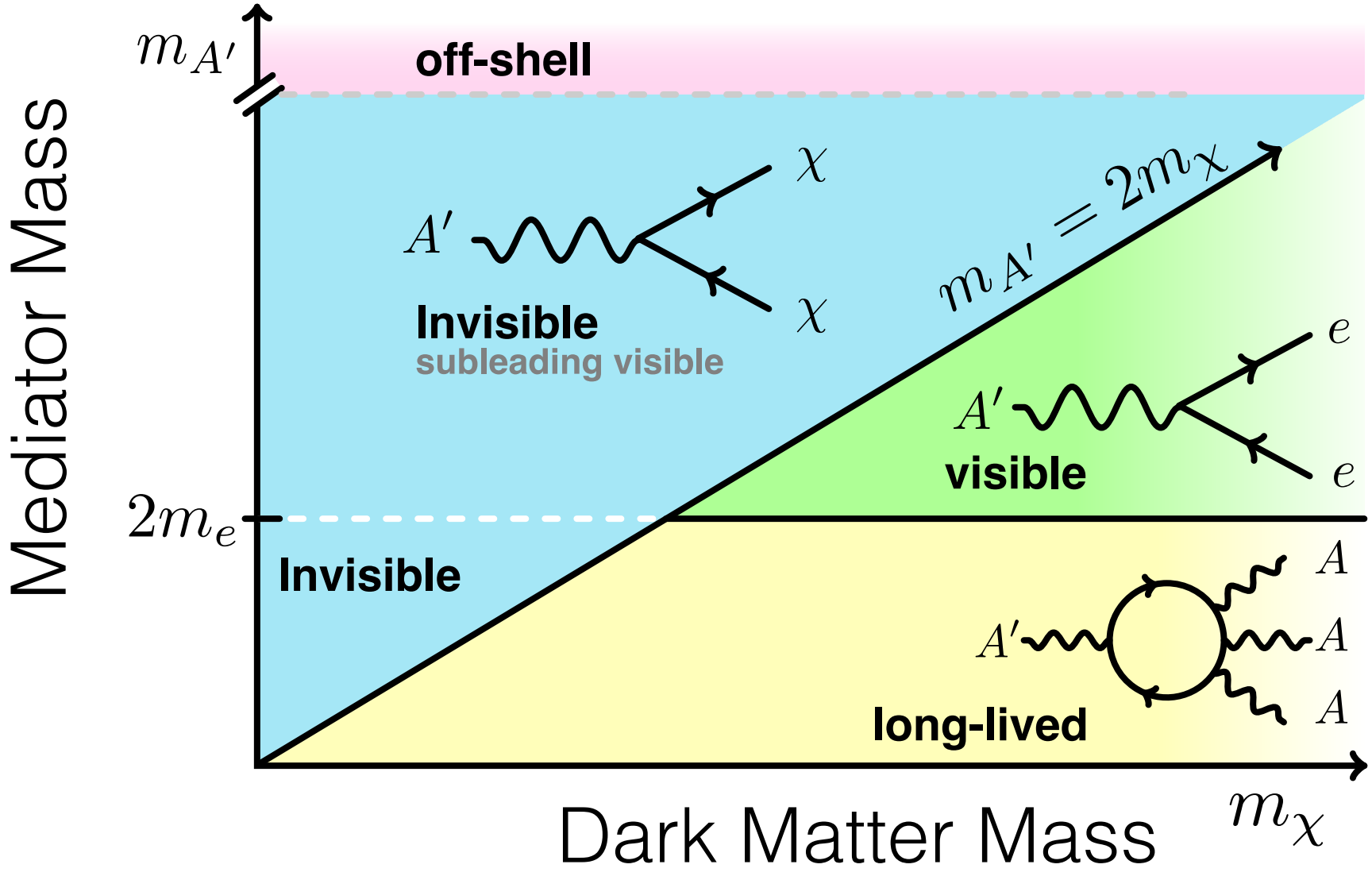
Resonant annihilation



Bremsstrahlung

Decays of Dark Photons

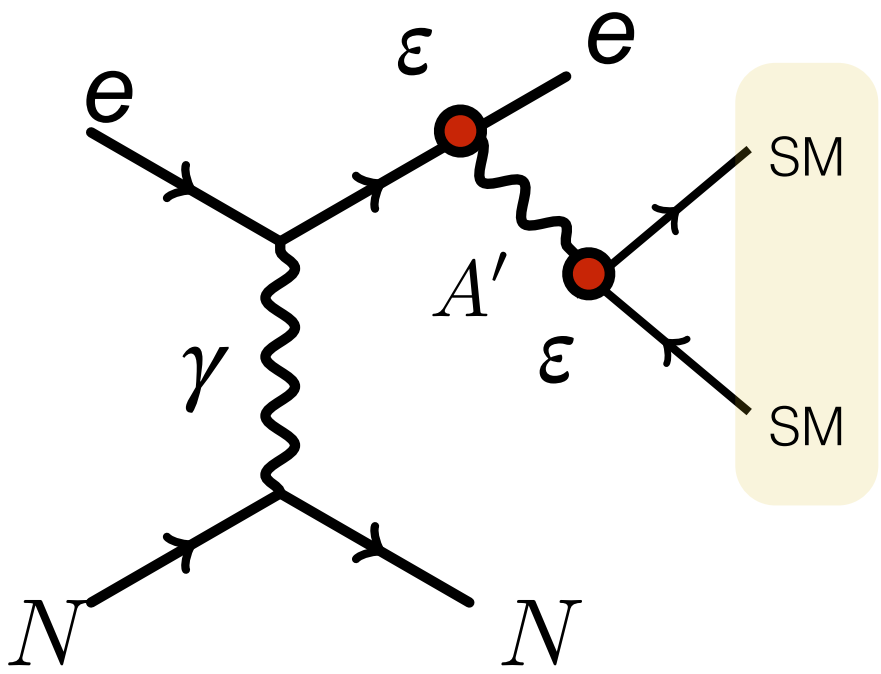
Adapted from Natalia Toro, Dark Sectors 2017 (1608.03591)



Visible searches for A' → e^+e^- in accelerators

$$m'_A < 2m_\chi$$

VISIBLE DECAY MODE

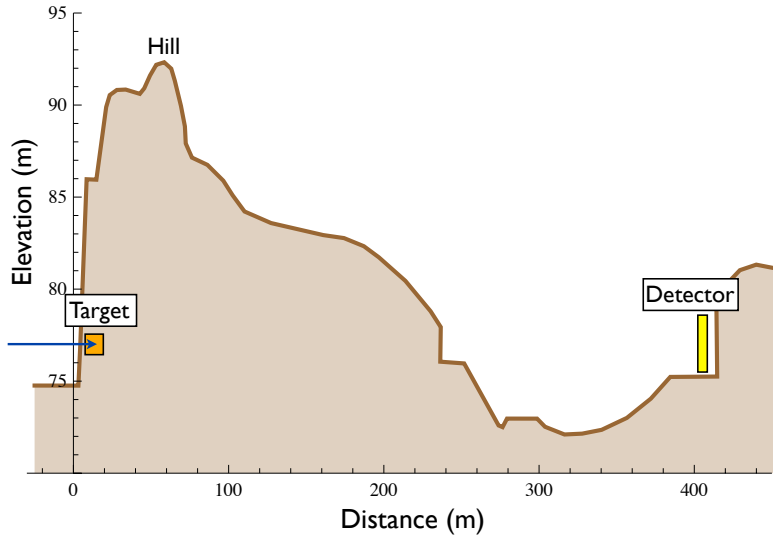


Pair production of SM particles

Example 1: search A' → e⁺e⁻ with electron beam: E137@SLAC

Proposed for ALPs search (1980-1982)

- **Beam: 20-GeV e– beam, ≃ 2 x10²⁰ 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

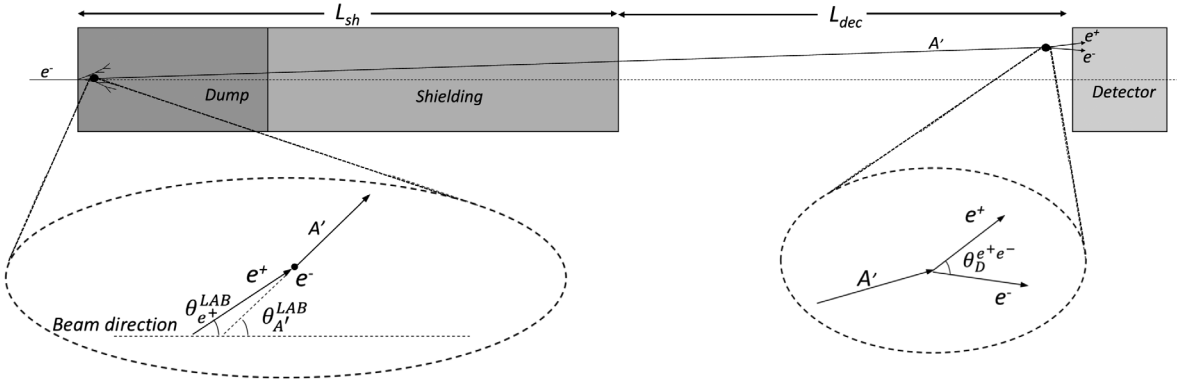


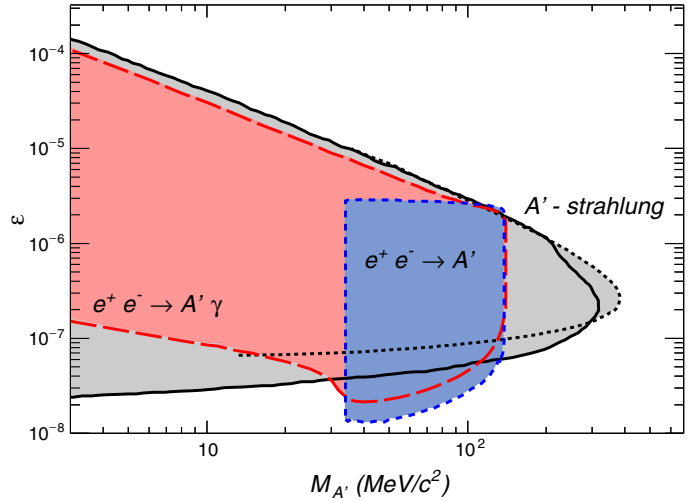
- Limits considering A' bremsstrahlung

  S. Andreas et al., PRD 86, 095019 (2012) , Y.-S. Liu et al. PRD 96, 016004 (2017).

- Limits extended considering secondary e+ annihilation on atomic e–

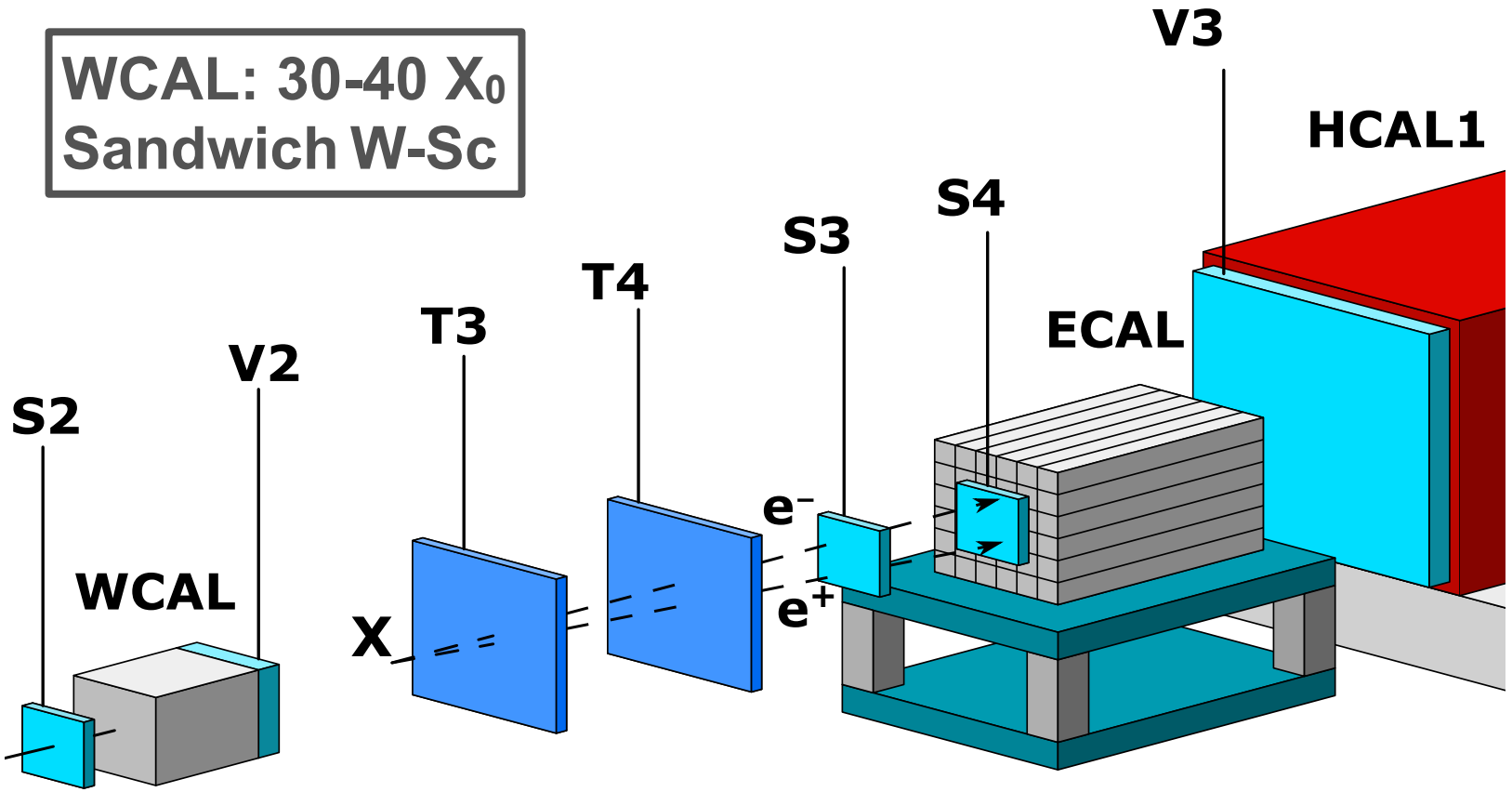
  Marsicano et al., PRD 98, 015031 (2018)





Example 2: NA64 search at SPS for A'/*X17*→ e^+e^- - *exp. signature*

WCAL: 30-40 X_0
Sandwich W-Sc

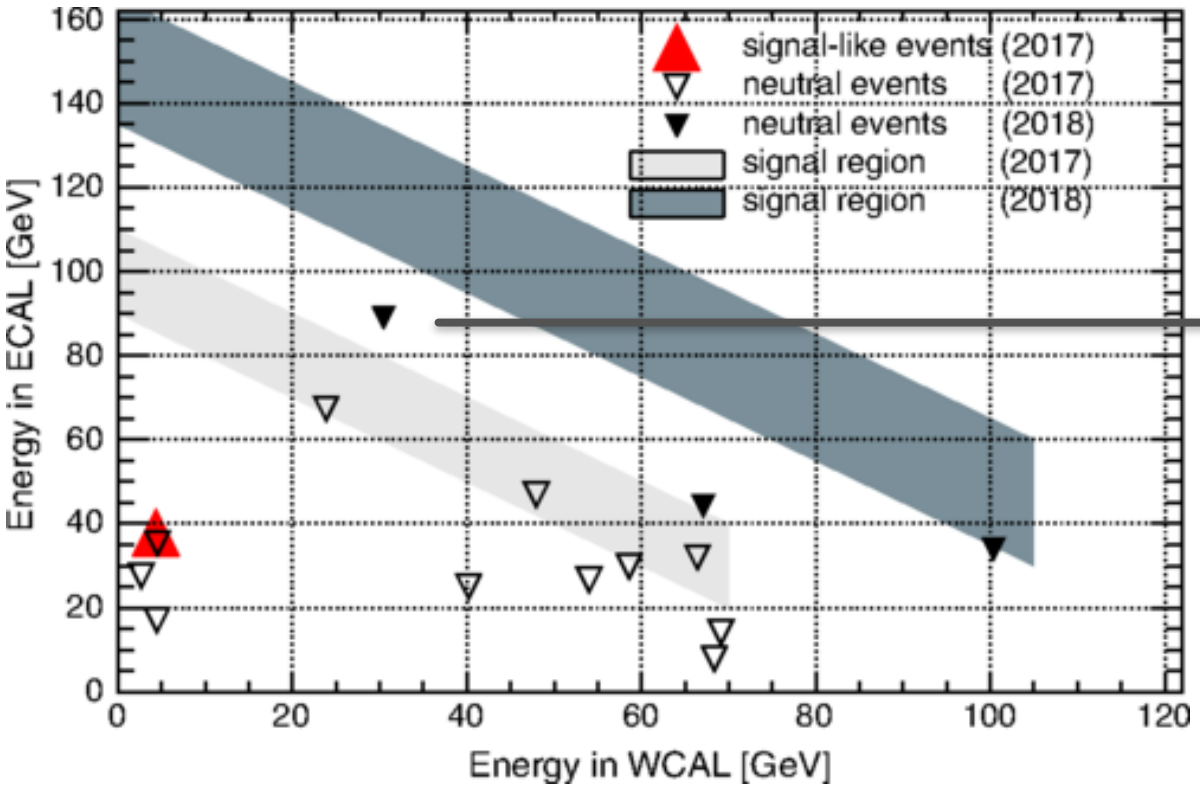


Signature:
1) $E_{WCAL}+E_{ECAL}$ = 100 GeV
2) No activity in $V_{2,3}$ and HCAL
3) Signal in S3, S4
4) e-m shower in ECAL

100/150 GeV electrons from SPS H4

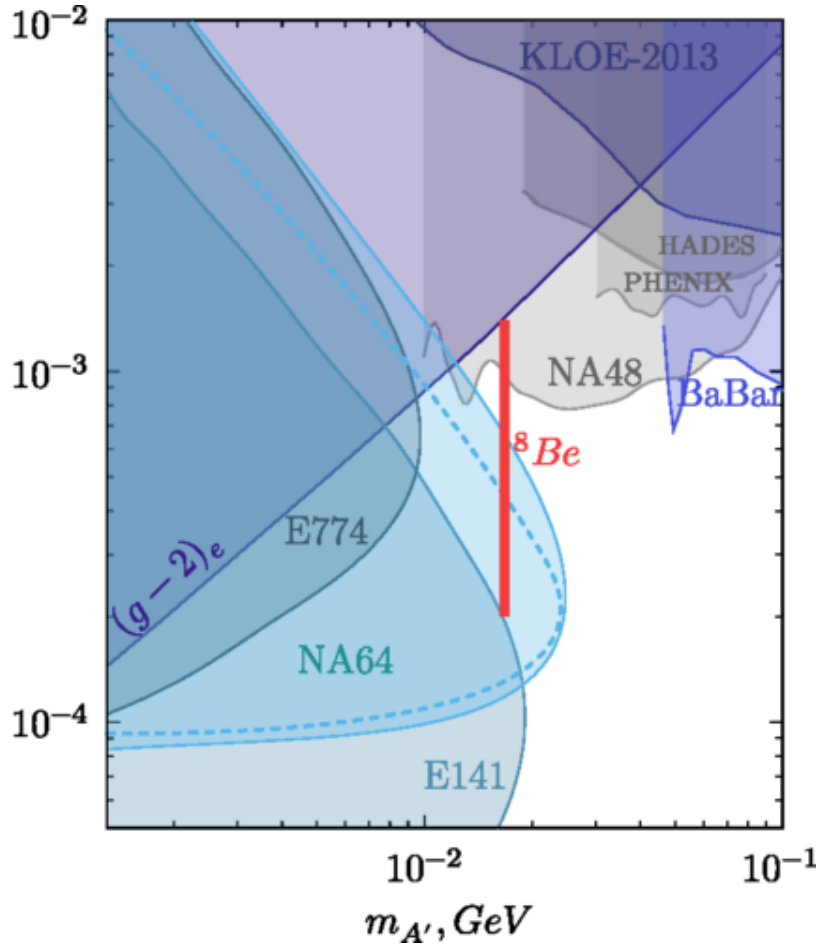
3 m

Example 2: NA64 search at SPS for A'/*X17*→ e^+e^- - *results (2017-2018)*



No signal-like event in signal box

~ 8×10^{10} EOT



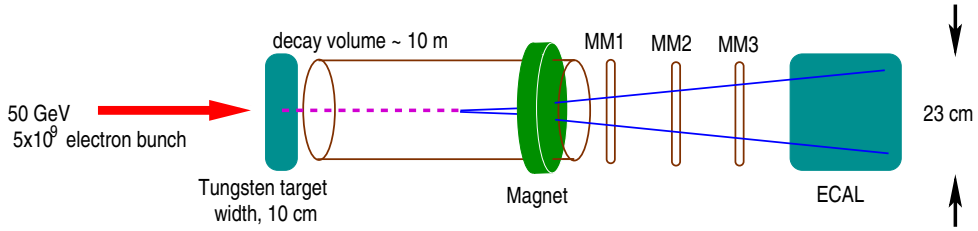
NA64 collaboration, PRL 120, 231802 (2018), PRD 107, 071101 (R) 2020

Reach of FCC-e- injector at 20 GeV for A' → e^+e^-

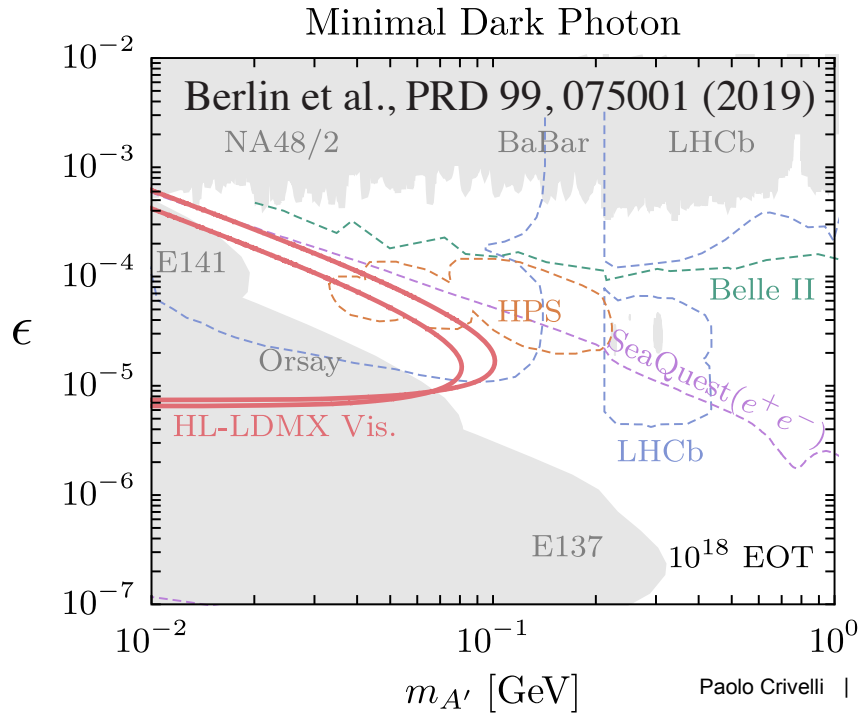
Running mode	PBC users
Beam energy at exit of injector	≤20
Maximum bunch charge	4
Maximum bunch intensity	0.1-2.5 x10^{10}
Number of bunches per pulse	1-4 (more?)
Linac repetition rate	100
Normalized emittance (x, y) (rms)	≤20,2
Physical emittance (x,y)	≤0.5,0.05
Bunch length (rms)	1-4
Energy spread (rms)	0.1-0.75
Bunch spacing from injector	25-50
Injector duty cycle	27-95

From Hannes Bartosik presentation -10^{13} electrons/s

Similar to AWAKE proposal: A .Caldwell et al arXiv 1812.11164v1

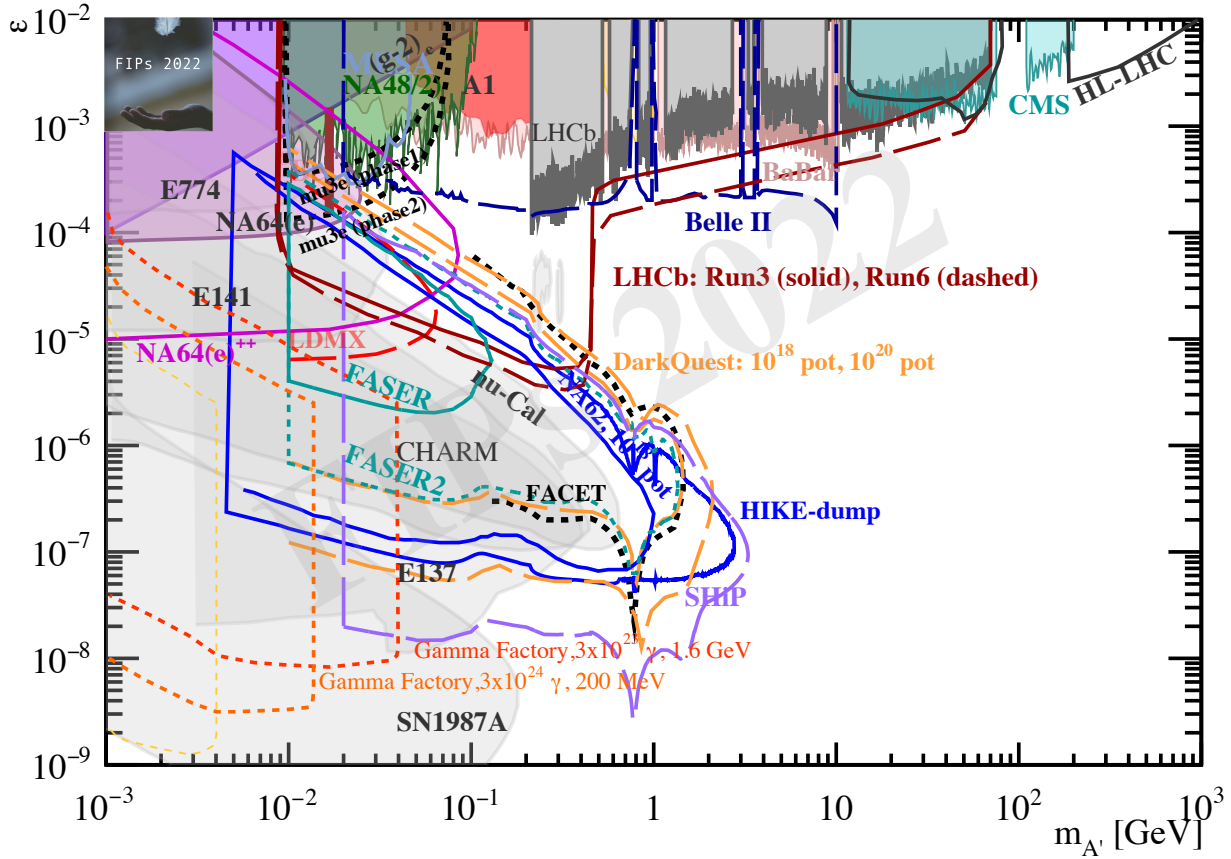


Projection for HL-LDMX with 10^{18} EOT at 16 GeV

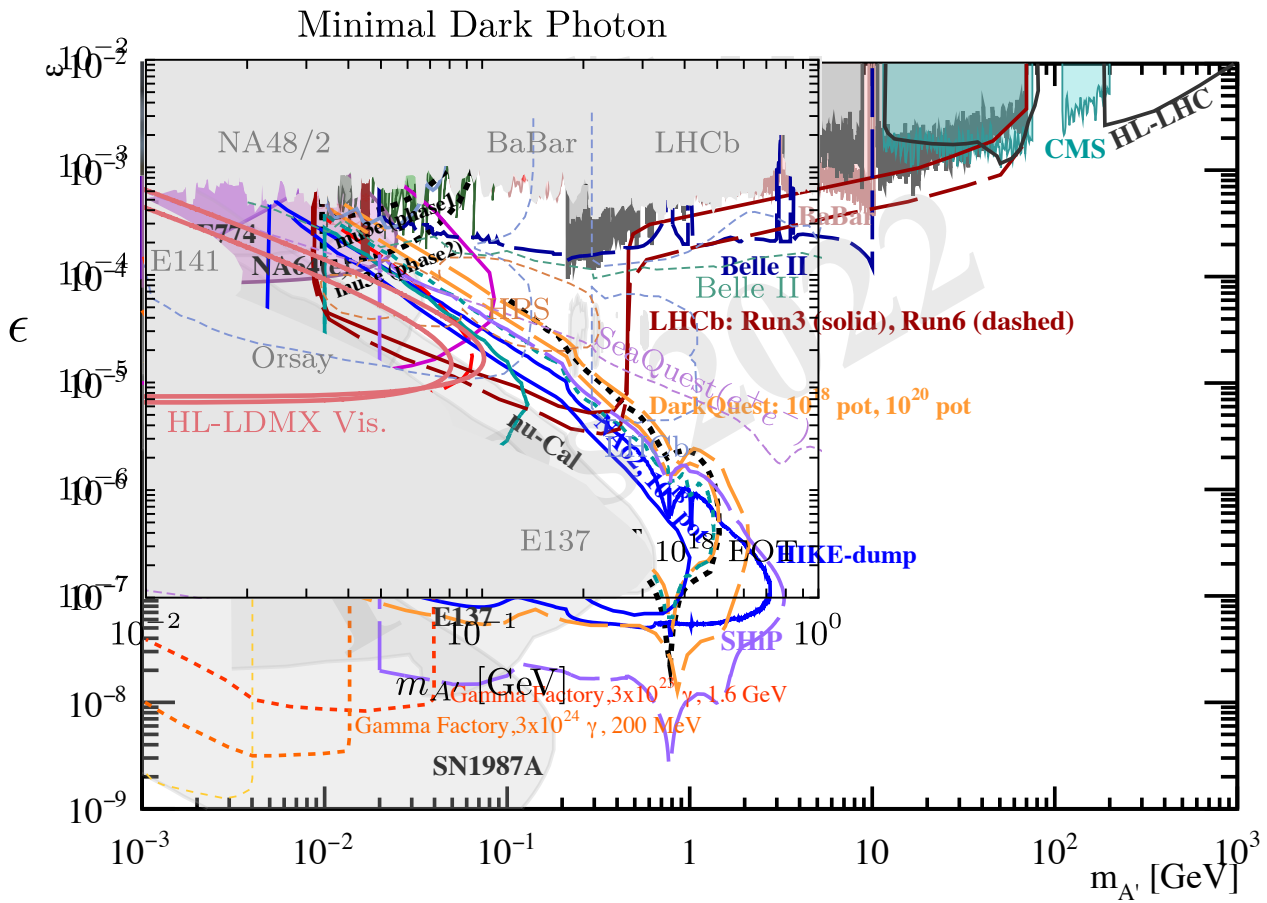


Current landscape and future prospects for A’ → e⁺e⁻

FIPs 2022 workshop at CERN, 2305.01715



Reach of FCC-e- injector at 20 GeV for A' → e⁺e⁻

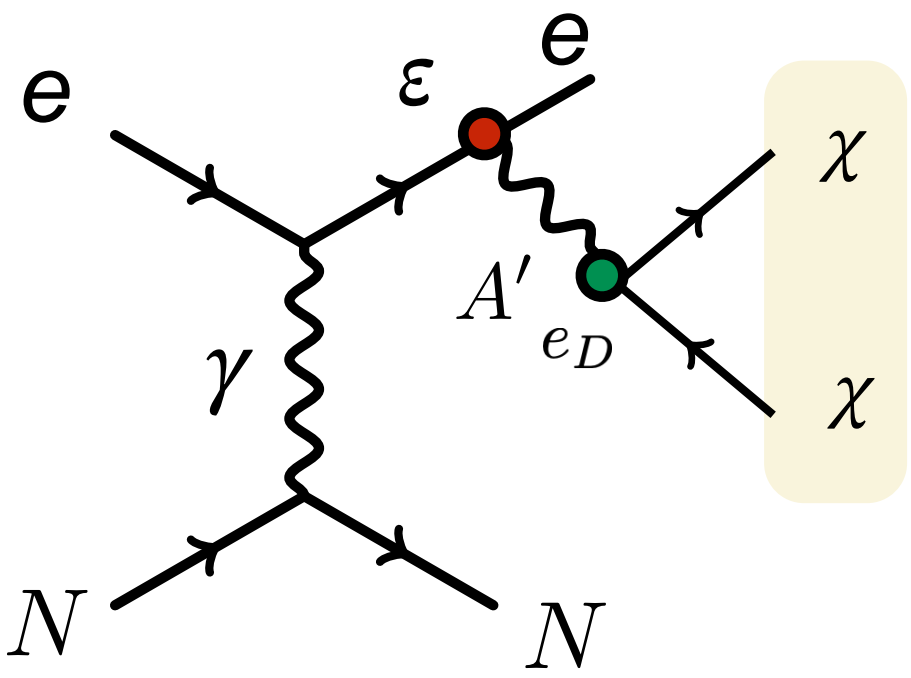


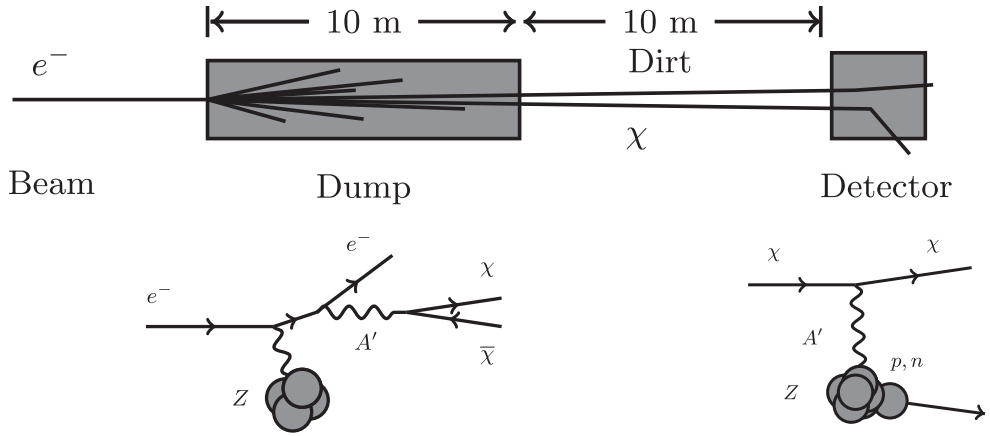
Even for 10^{20} EOT at 20 GeV difficult to compete with LHCb and SHiP because of the different time scales …

2.1) Beam dump searches for A' → $\chi\bar{\chi}$ in accelerators

INVISIBLE DECAY MODE $m'_A > 2m_\chi$

1) BEAM DUMP APPROACH (E137,MiniBooNE, LSND, NA62…)



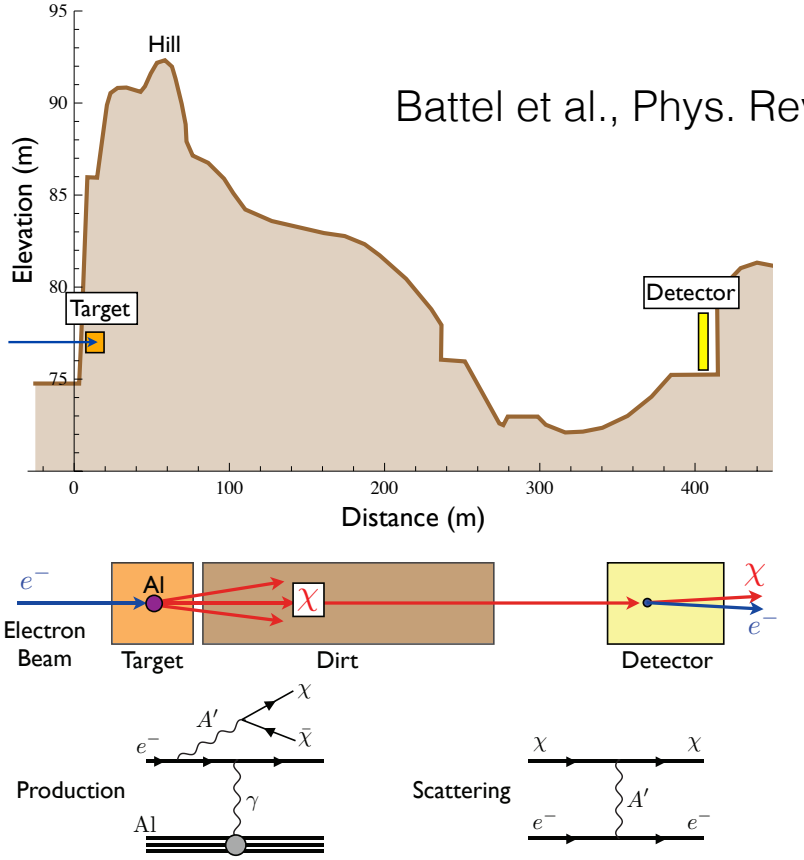


From E. Izaguirre *et al*, Phys. Rev. D 88, 114015 (2013)

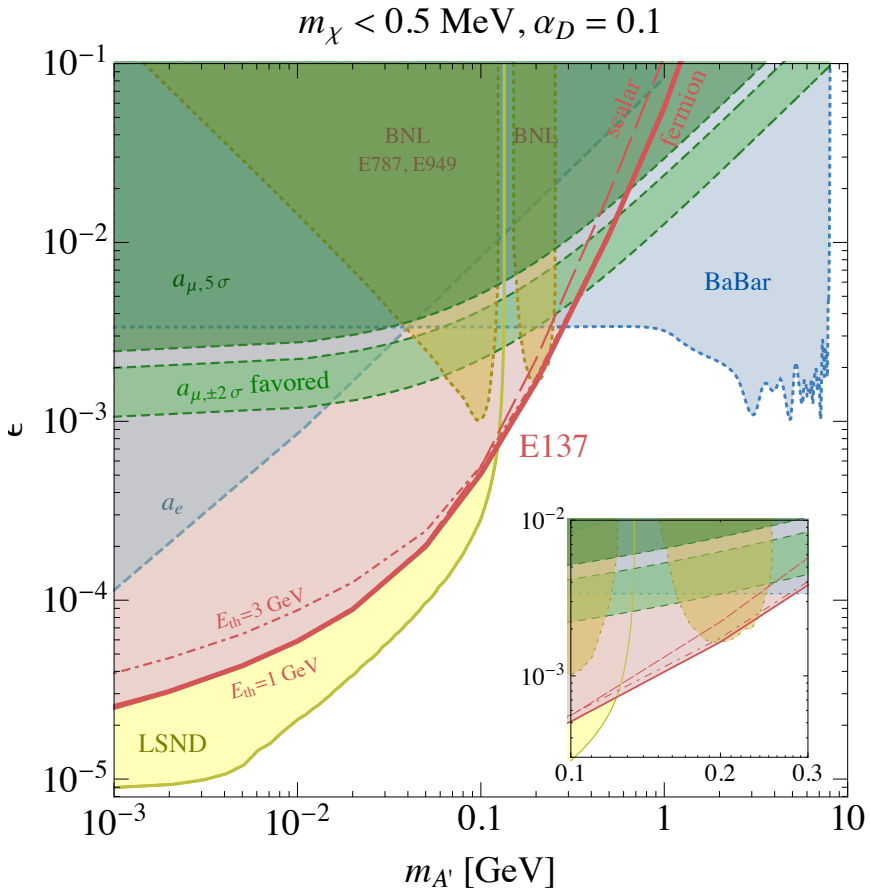
Flux of X generated by decays of A's produced in the dump. **Signal:** X scattering in far detector

$$\sigma \propto \epsilon^4 \alpha_D$$

Example of a search A' → $\chi\bar{\chi}$ with electron beam: E137@SLAC



Battel et al., Phys. Rev. D 91, 094026 (2015)



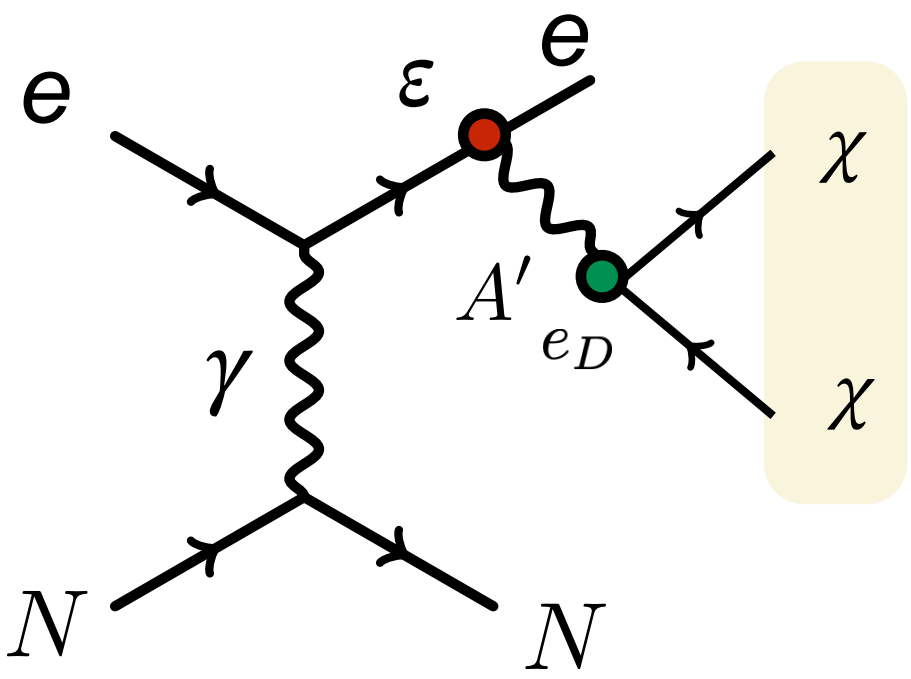
Results re-interpreted as a invisible A′ search.

Experiment observed 0 events, exclusion limits at 95% CL = 2.3 signal events.

2.2) Missing energy/momentum searches for A' → $\chi\bar{\chi}$ in accelerators

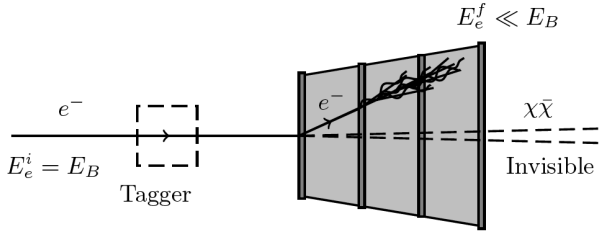
INVISIBLE DECAY MODE $m'_A > 2m_\chi$

2) NA64/LDMX APPROACH

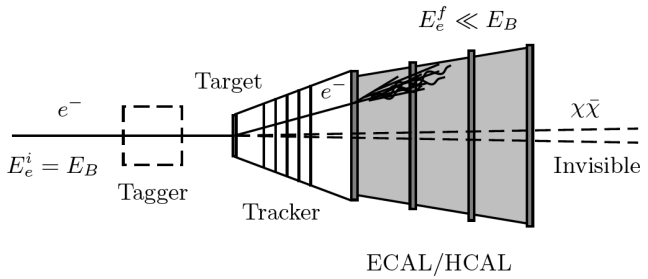


From E. Izaguirre *et al*, Phys. Rev. D **91**, 094026 (2015)

missing energy



missing momentum



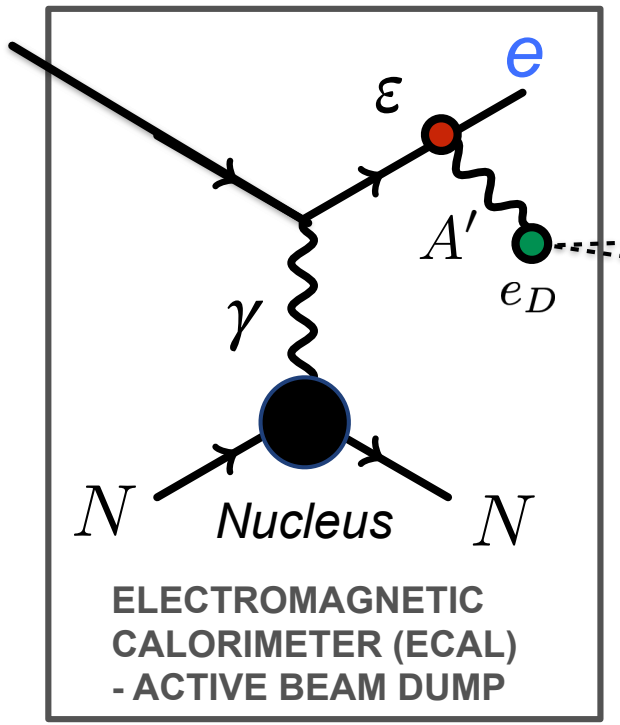
Missing energy: produced A's carry away energy from the **active dump** used to measure recoil e- energy

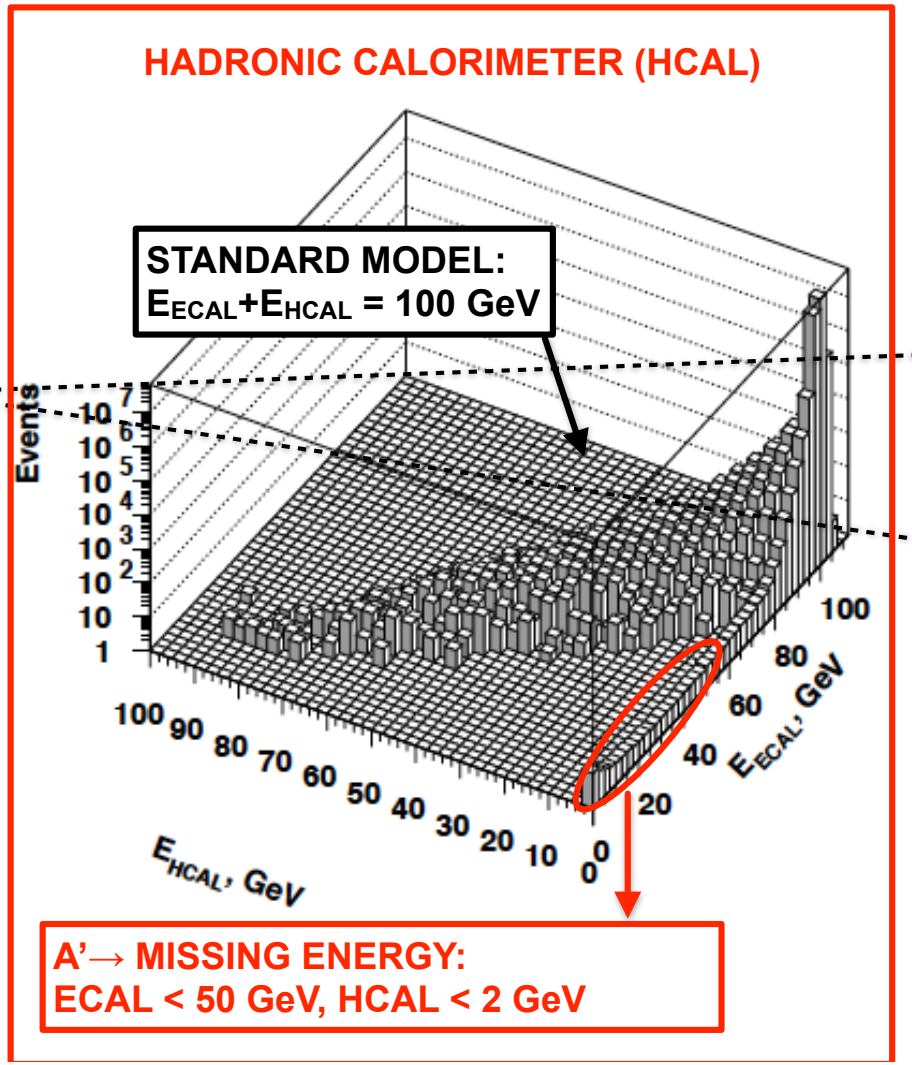
$$\sigma \propto \epsilon^2$$

The NA64 method to search for A' → $\chi\bar{\chi}$

Incoming 100 GeV electron

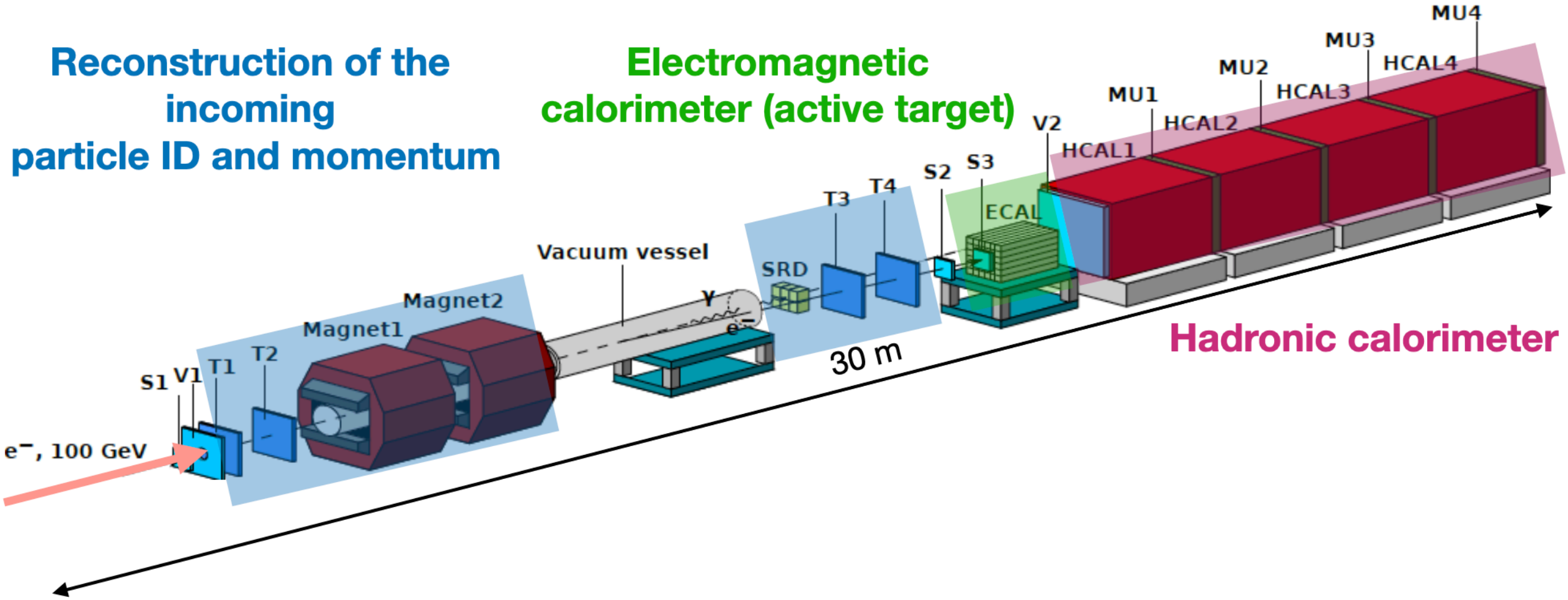
Detected scattered electron





DM particles escaping detection

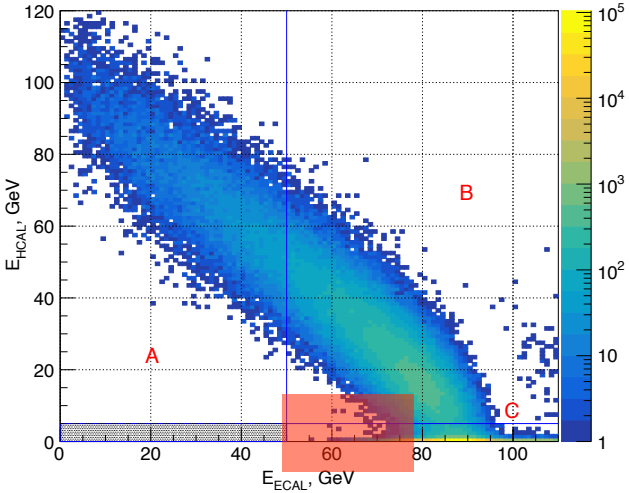
The CERN SPS H4 electron beam

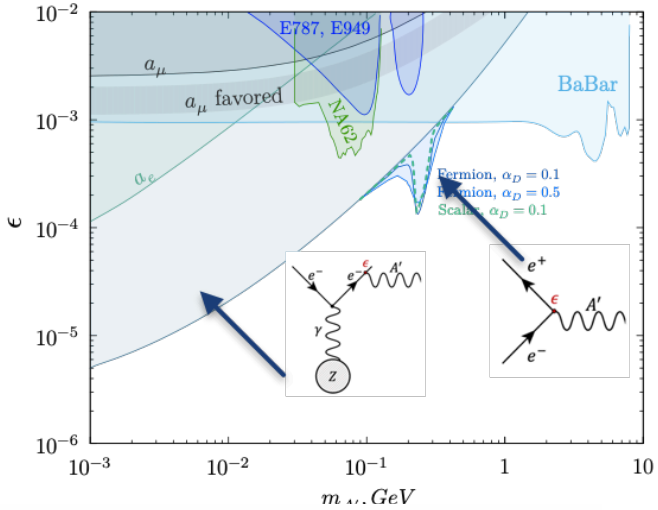


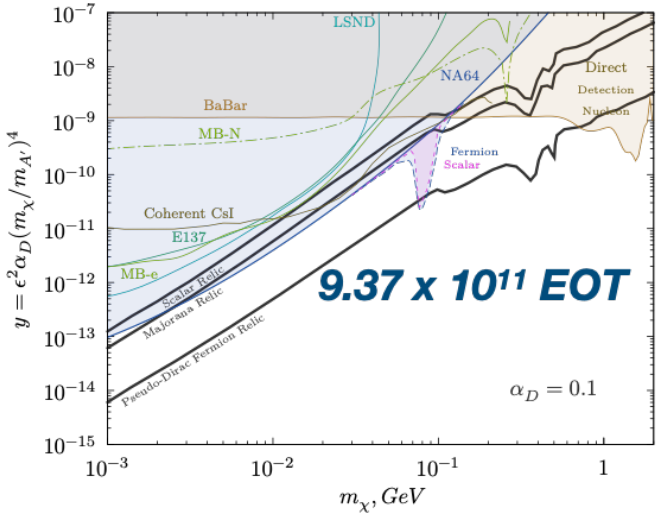
NA64 LDM latest results (2016-2022)

NA64, Phys. Rev. Lett. **131**, 161801 (2023)

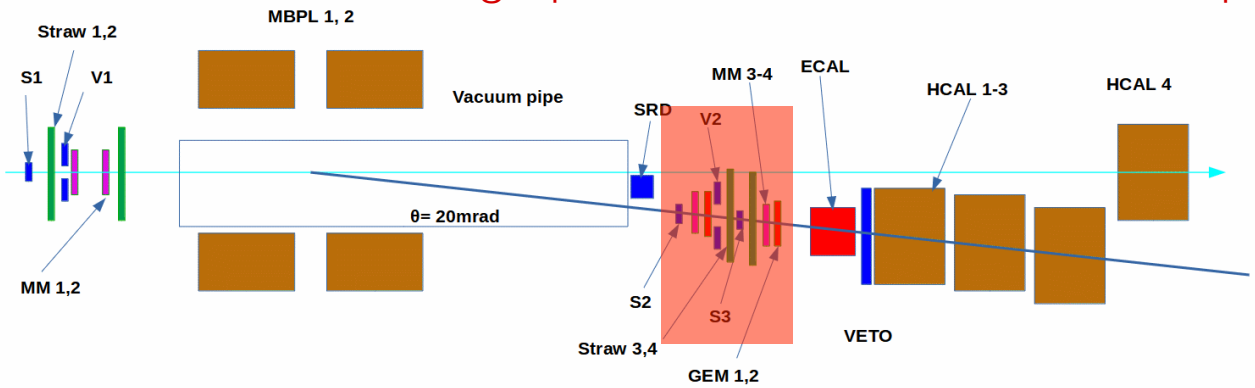
For **α_D=0.1**, NA64 excludes the **Scalar and Majorana scenarios** for almost all m_χ values. Exploiting the e^+e^- resonant enhancement, we also exclude the **Pseudo-Dirac Fermion scenario** for a narrow m_χ interval.



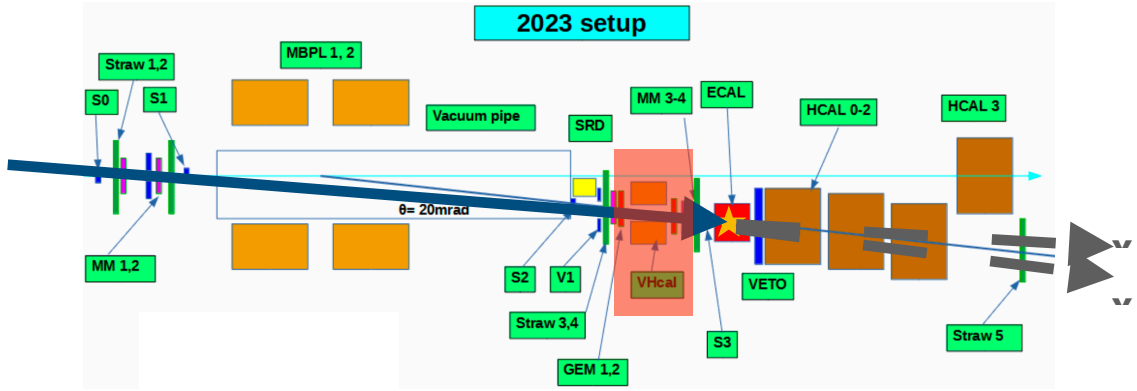




Main background from interaction high-pt hadronic secondaries from upstream electroproduction



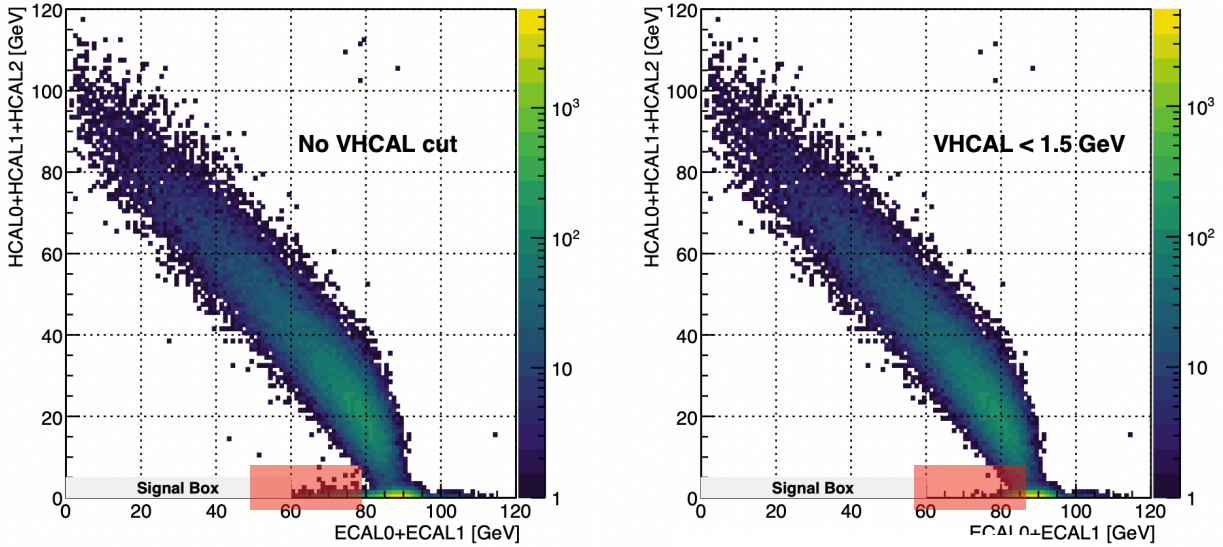
NA64 LDM prospects before LS3



VHCAL prototype: to suppress high-pt hadronic secondaries from upstream electroproduction

Very promising results!
Step forward towards the design and construction of the optimised VHCAL during LS3

Preliminary results from 2023 analysis



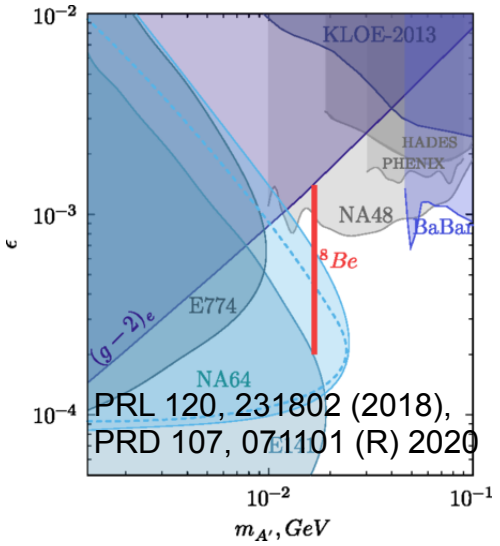
High-pt background suppressed by a factor > 10!

2016-2018	2021	2022	2023	2024	2025	LS3
NA64e	2.84 × 10^{11} EOT	6 × 10^{10} EOT	~6.3 × 10^{11} EOT	**~5.1× 10^{11} EOT**	**~ 3× 10^{12} EOT**	

1.5 x 10^{12} EOT **Improved set-up**

Additional new physics scenarios

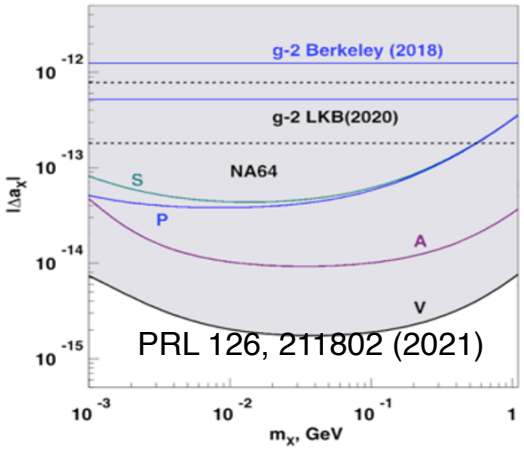
A' -> visible and X17



PRL 120, 231802 (2018),
PRD 107, 071101 (R) 2020

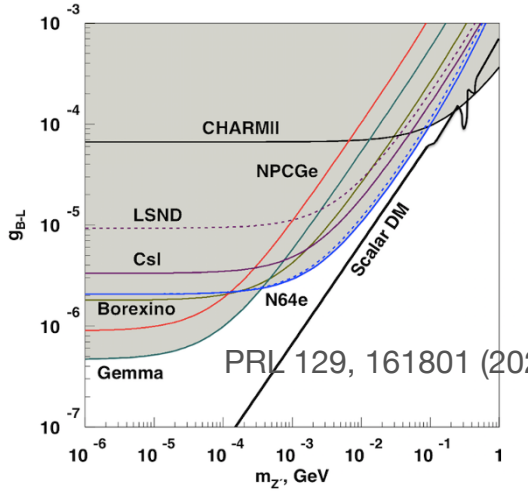
$e^-Z \to e^-ZX; X \to$ invisible

New Physics in $(g-2)_e$ vs $(g-2)_e$ from measurement of alpha

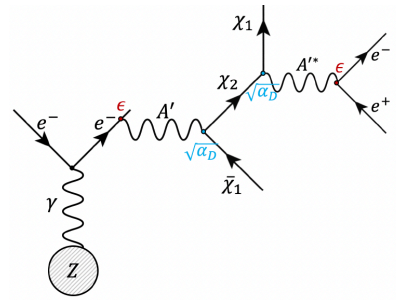


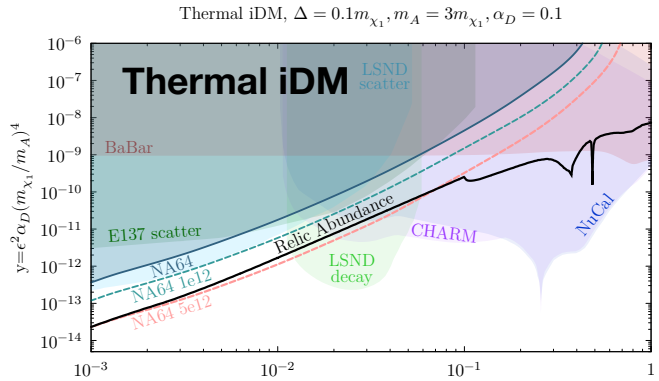
PRL 126, 211802 (2021)

B-L Z´ vs neutrino scattering



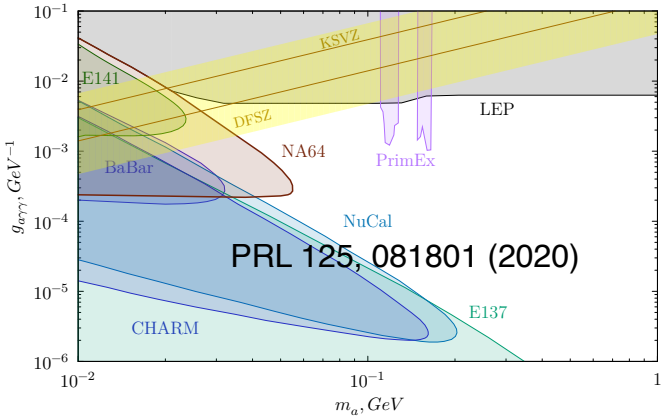
PRL 129, 161801 (2022)





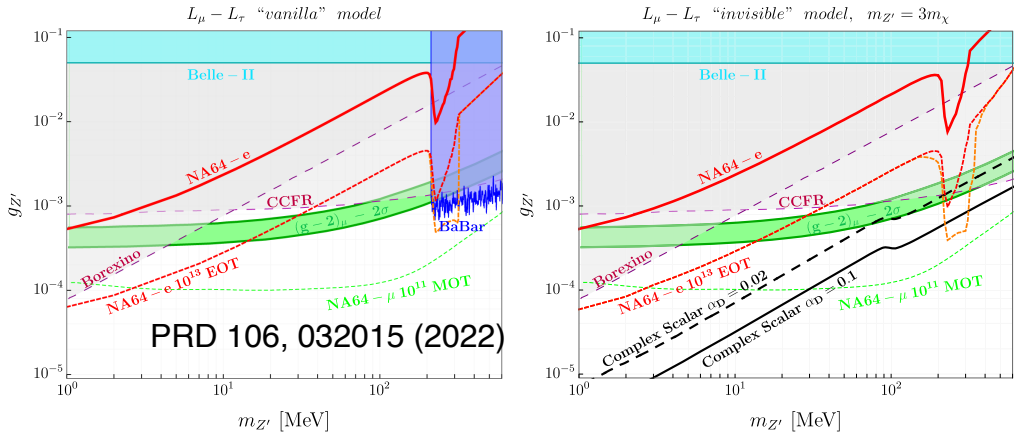
Eur. Phys. J. C (2021) **81**: 959
Eur. Phys. J. C (2023) **83**: 391

QCD axion and ALPs



PRL 125, 081801 (2020)

Lmu-Ltau Z' models

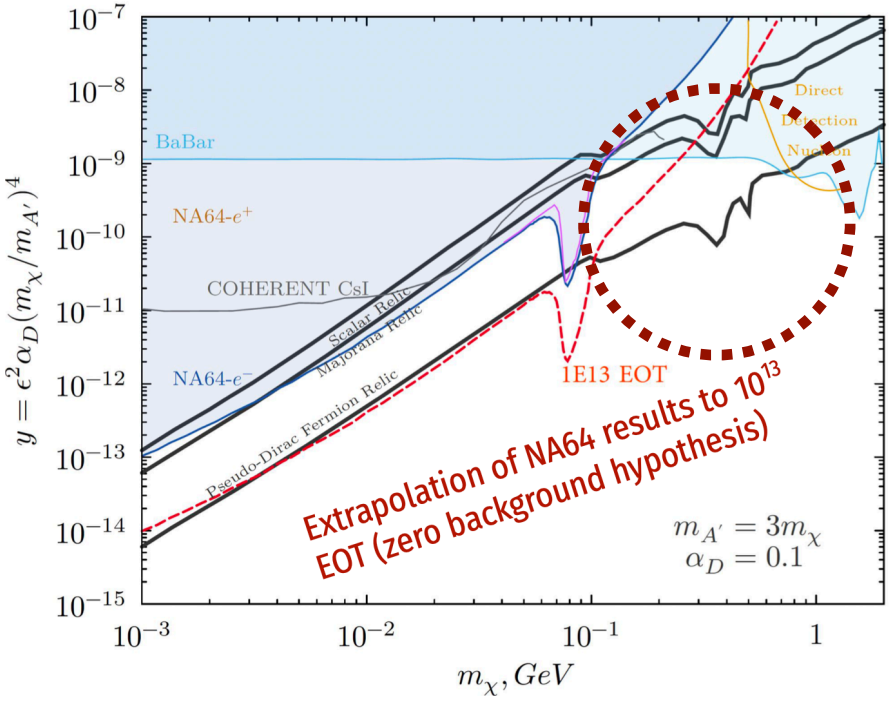


PRD 106, 032015 (2022)

Results obtained with
3x10¹¹ EOT
(2016-2018 statistics)
Analysis in progress of
10 x more data on "tape"

Post LS3 prospects for LDM searches at NA64

GOAL > 1× 10^{13} EOT



Planned upgrades include:

i) Increase the e- beam intensity up to >~ 10^7 e-/spill

- new readout electronics: 80-> 250 MHz digitisers, trackers APV ->VMM
- DAQ speed up to 30-40 kevent/ spill

ii) Improve detector hermeticity and performance

ECAL: radiation hard central part, improve stability,…

HCAL:, larger acceptance modules, longitudinal segmentation

VHCAL: to reject high P_t hadronic secondaries, 2023 prototype test was successful

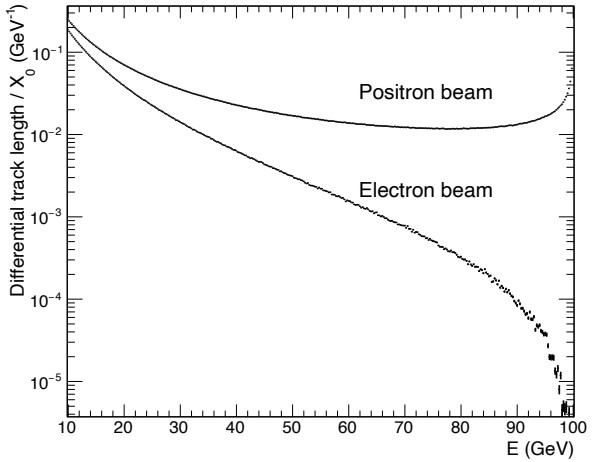
New LYSO based SRD: higher granularity, lower SR threshold

To improve our sensitivity in the (high) mass range and on scenarios with $alpha_D$=0.5 →use positron and muon beams

First results of LDM searches at NA64 with positrons

Resonance annihilation channel with 100 GeV e+beam $e^+e^- \to A' \to \chi\bar{\chi}$

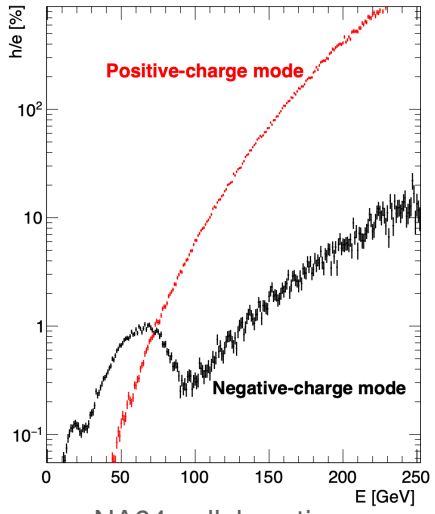
Positrons track-length distribution



Total signal yield $N_S \simeq \Gamma\sigma^P_{res}T(E_R) \propto T(E_R)/m_{A'}$

where $E_R = m^2_{A'}/(2m_e)$ is the resonant energy.

Challenge: Hadron contamination in H4 beam in e+ mode is significantly higher at 100 GeV

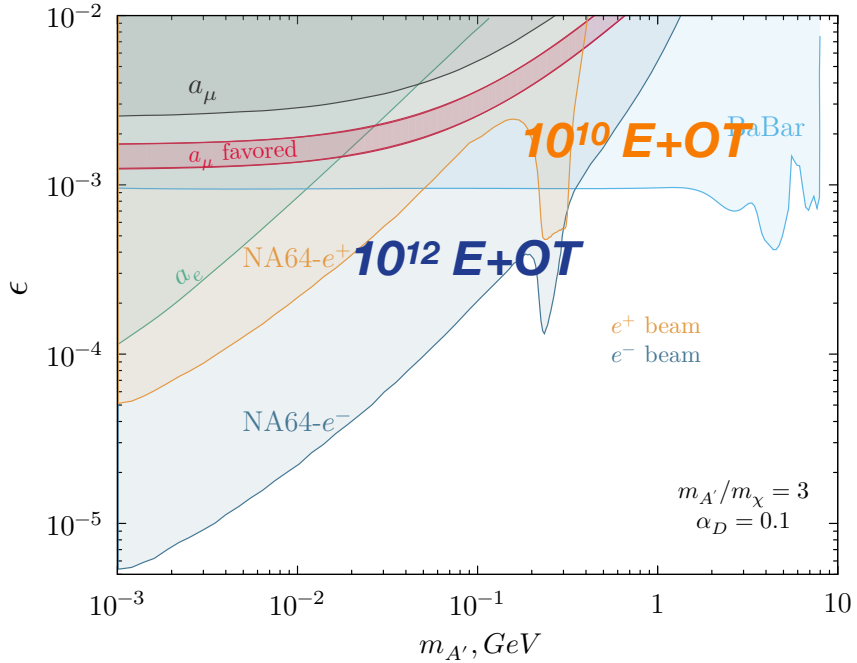


NA64 collaboration, NIM. A 1057 (**2023**), 168776

Positron-beam measurement, T(E+) **enhancement** for E+ → E0

→ sensitivity to ε is almost flat for all accessible A′ masses,

$$\sqrt{2m_eE^{thr}_{miss}} \div \sqrt{2m_eE_0}$$



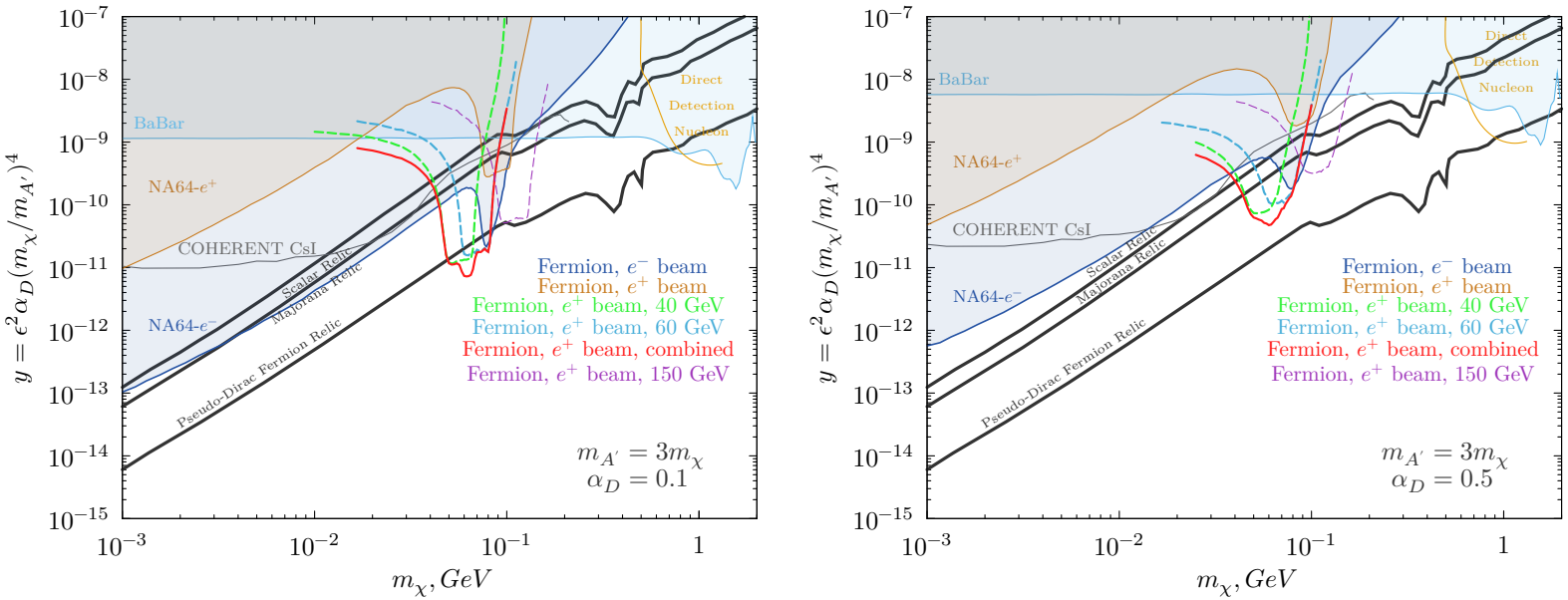
NA64 collaboration, ***Phys.Rev.D*** **109 (2024) 3, L031103**

Post LS3 prospects for LDM searches at NA64 with positrons

Resonance annihilation channel scanning e+beam.

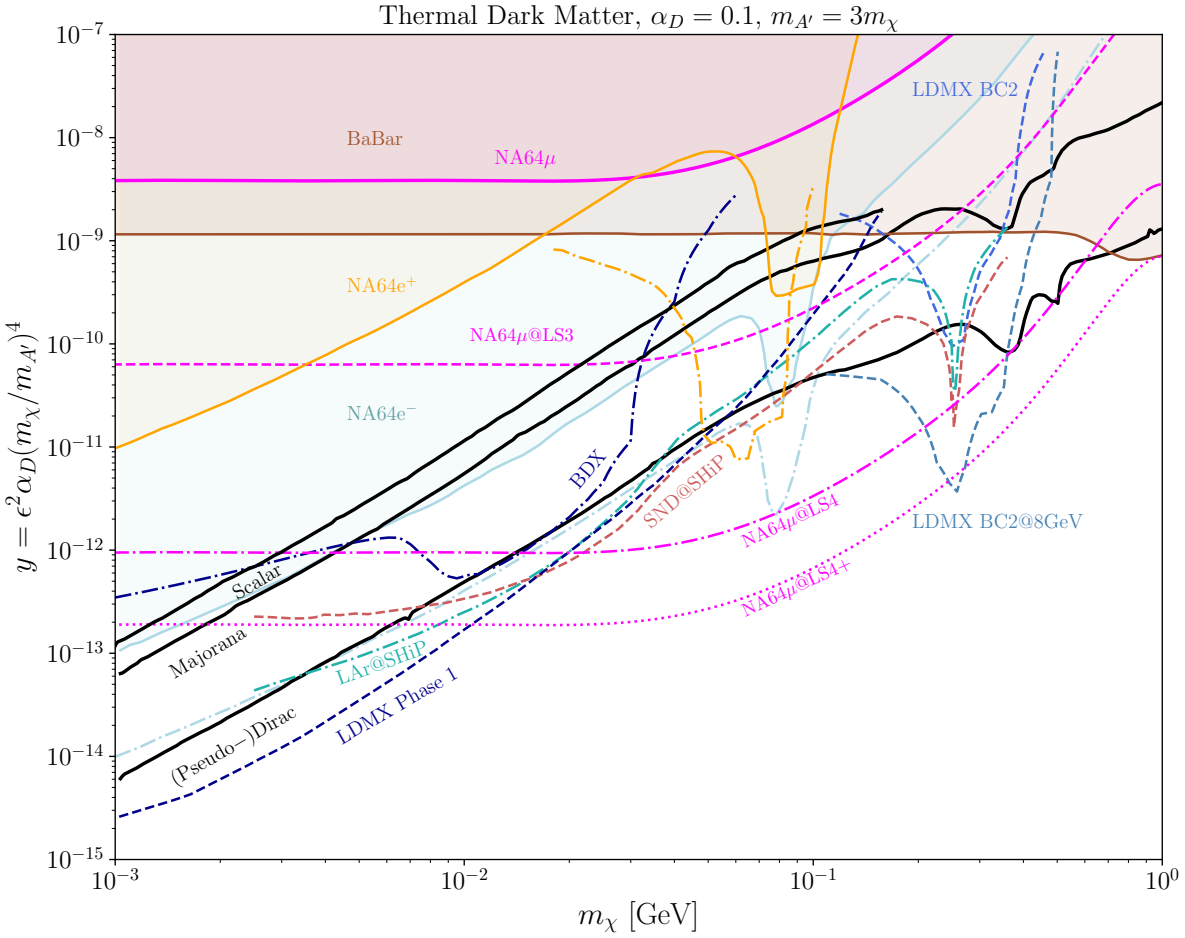
$$e^+e^- \rightarrow A' \rightarrow \chi\bar{\chi}$$

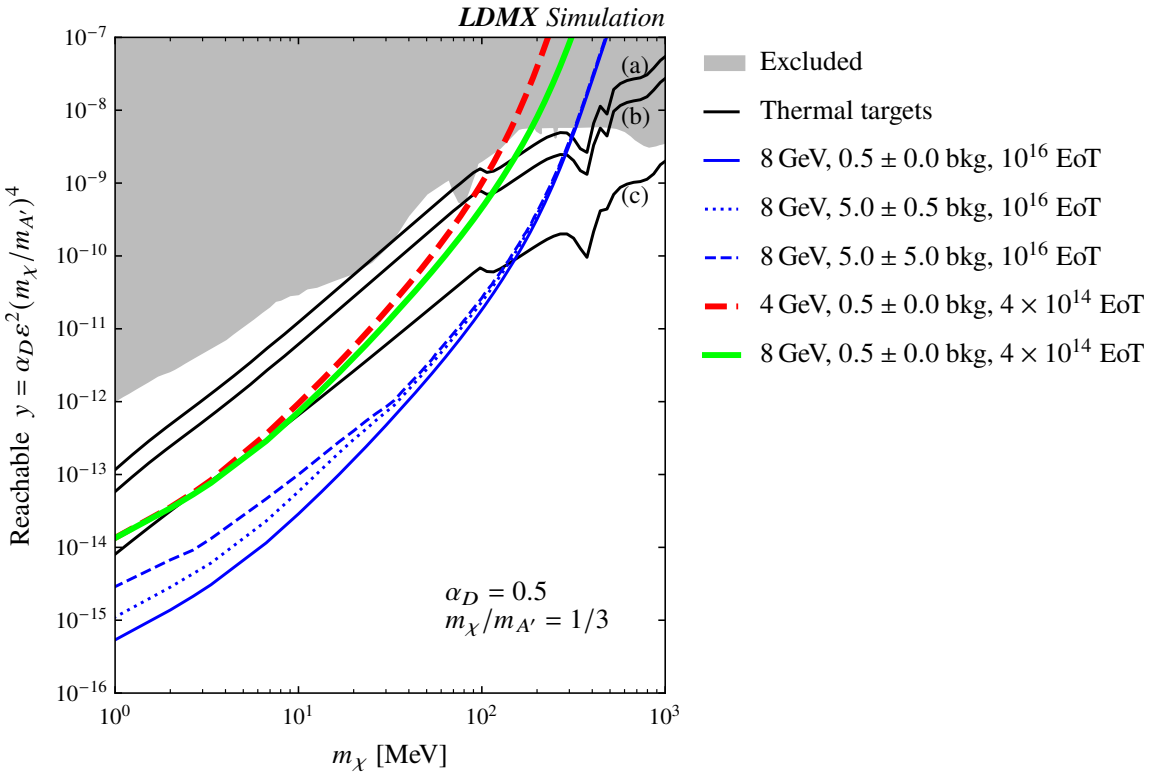
CERN-SPSC-2024-003 ; SPSC-P-348-ADD-4



	2028	2029	2030	2031	2032
NA64e+	@ 60 GeV 10^{10} E+OT	@ 40 GeV 10^{11} E+OT	@ 60 GeV 5×10^{11} E+OT	@ 40 GeV 5×10^{11} E+OT	@ 150 GeV 10^{11} E+OT

Current landscape and future prospects for A' → $\chi\bar{\chi}$ searches





https://link.springer.com/article/10.1007/JHEP12(2023)092

Missing energy searches a la NA64/LDMX with FCC-ee injectors?

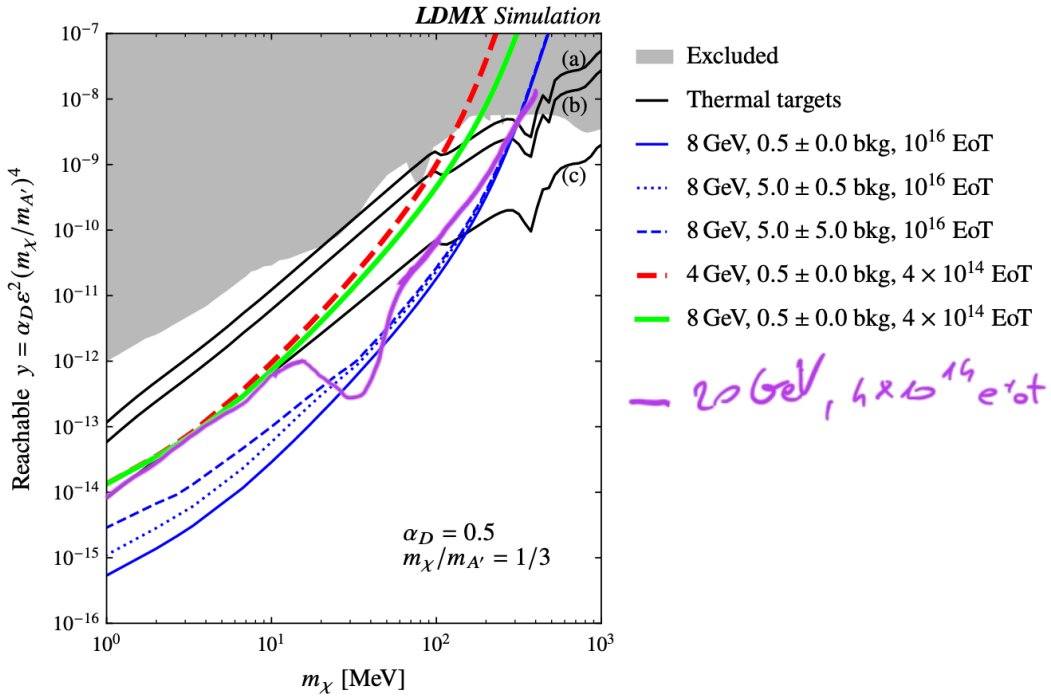
From Hannes Bartosik presentation, Other Science Opportunities at the FCC-ee, 28.11.2024, CERN (UPDATED 07/12/24)

	Option I: 20 GeV e^+ (high energy linac)	Option II: 11.8 GeV e^+ (high energy linac)	Option III: 2.86 GeV e^+/e^- (slow extr. from DR)	Option IV: 20 GeV e^+/e^- (slow extr. from booster)
Bunch spacing	2.5 ns (or 1.0 ns)	2.5 ns	2.5 ns	1.25 ns
Pulse length	75 ns	3 us	100 ms	~ seconds
Number of "single positrons" per pulse	31 (76)	1200	40e+6	800e+6 (for a 1 s pulse)
Repetition rate	100 Hz	100 Hz	5 Hz	cycles in the booster
Duty cycle	25-90%	25-90%	25-90%	40% in H and ttbar (20% WW)
Energy	20 GeV	11.8 GeV	2.86 GeV	20 GeV
Pot / day	2e+8 (5e+8) (70% duty cycle)	7e+9 (70% duty cycle)	1e+13 (70% duty cycle)	2.7e+13 during H and ttbar (1.3e+13 during WW)
Required hardware		• extraction kickers with ~few us flat top • slow extr. (DR)	• injection kickers with ~few us flat top • slow extr. (DR)	• Slow extr. (booster)

Unfortunately, for Options I and II do not seem competitive…
Option III and IV could explore a new region of LDM parameter space (more detailed studies are required).

Conclusions

If a **slow extraction of 20 GeV positrons** from the **FCCee booster** could be realised an **experiment a la NA64** would be **competitive** with 8GeV beam LDMX projections allowing to **probe all the remaining parameter space from LDM of the canonical dark photon model down to alpha_D=0.5.** The advantage of using positron is that exploiting the resonant annihilation channel as we do in NA64 (Phys. Rev. D 109, L031103 (2024)), one requires 10x less statistics for the mass range between the maximal beam energy and the missing energy threshold so 101 MeV < $M_{A'}$ < 143 MeV and 33 MeV < M_X< 47 MeV. A statistics of 10^{14} positrons on target could be achieved in 40 days (see "educated guess" projection" in the plot).



"Once you have a collider, every problem starts to look like a particle."