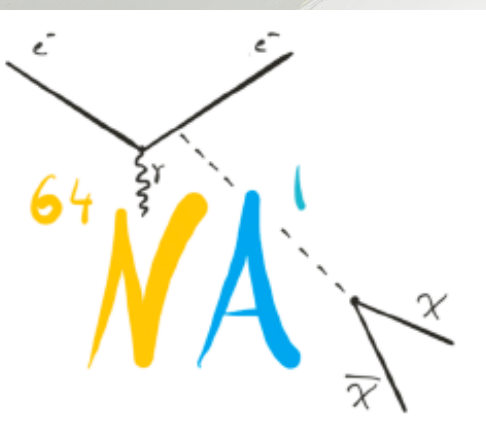




Light Dark Matter searches at fixed target experiments

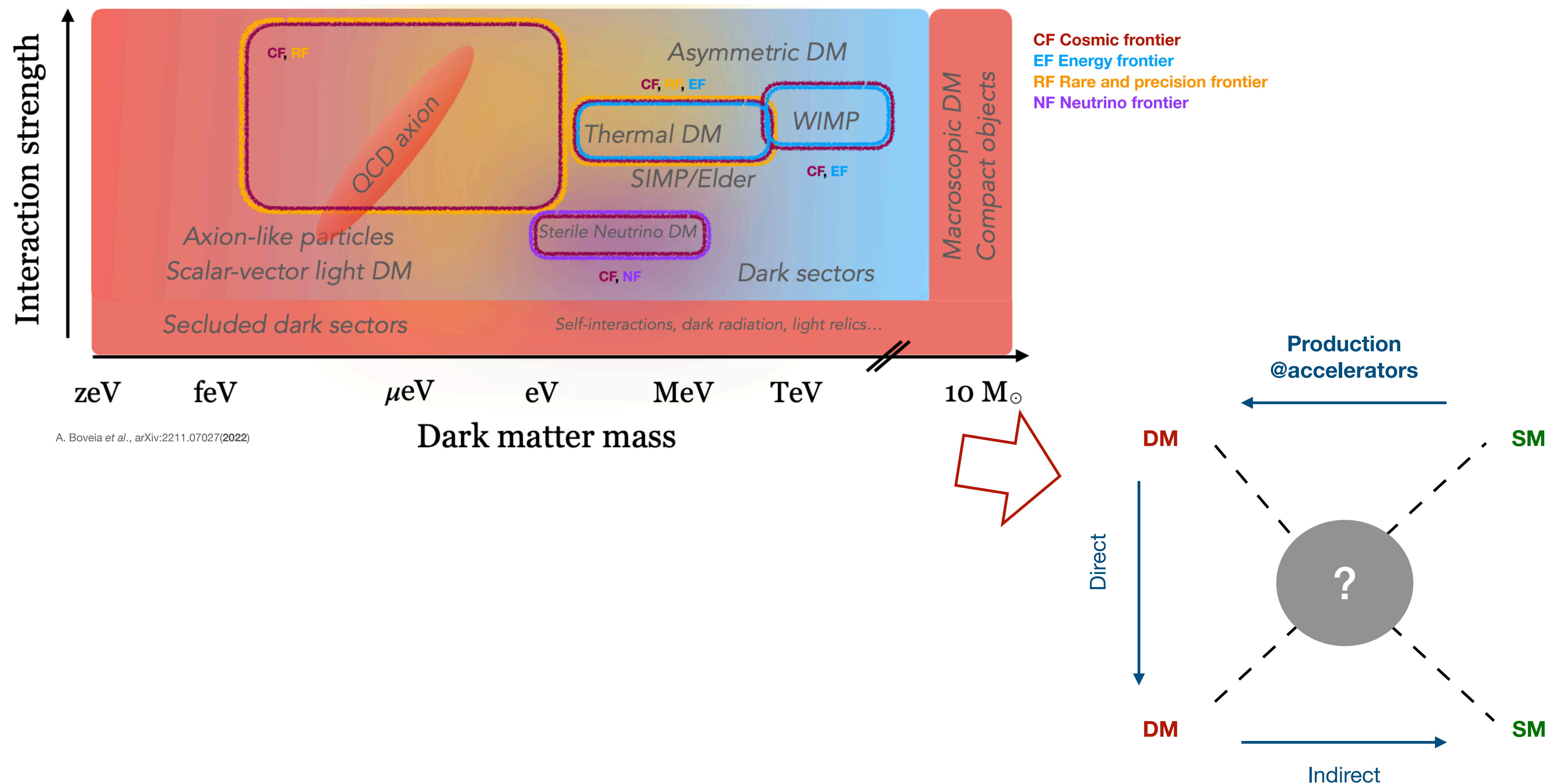
Laura Molina Bueno
laura.molina@ific.uv.es



16th International Workshop on the
Identification of Dark Matter 2026



Dark matter candidates



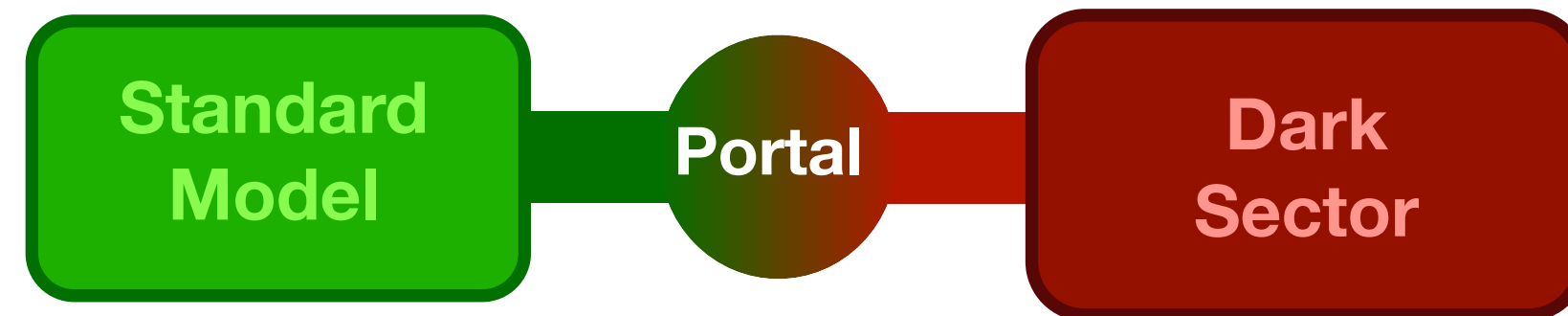
A. Boveia et al., arXiv:2211.07027(2022)

Dark sectors

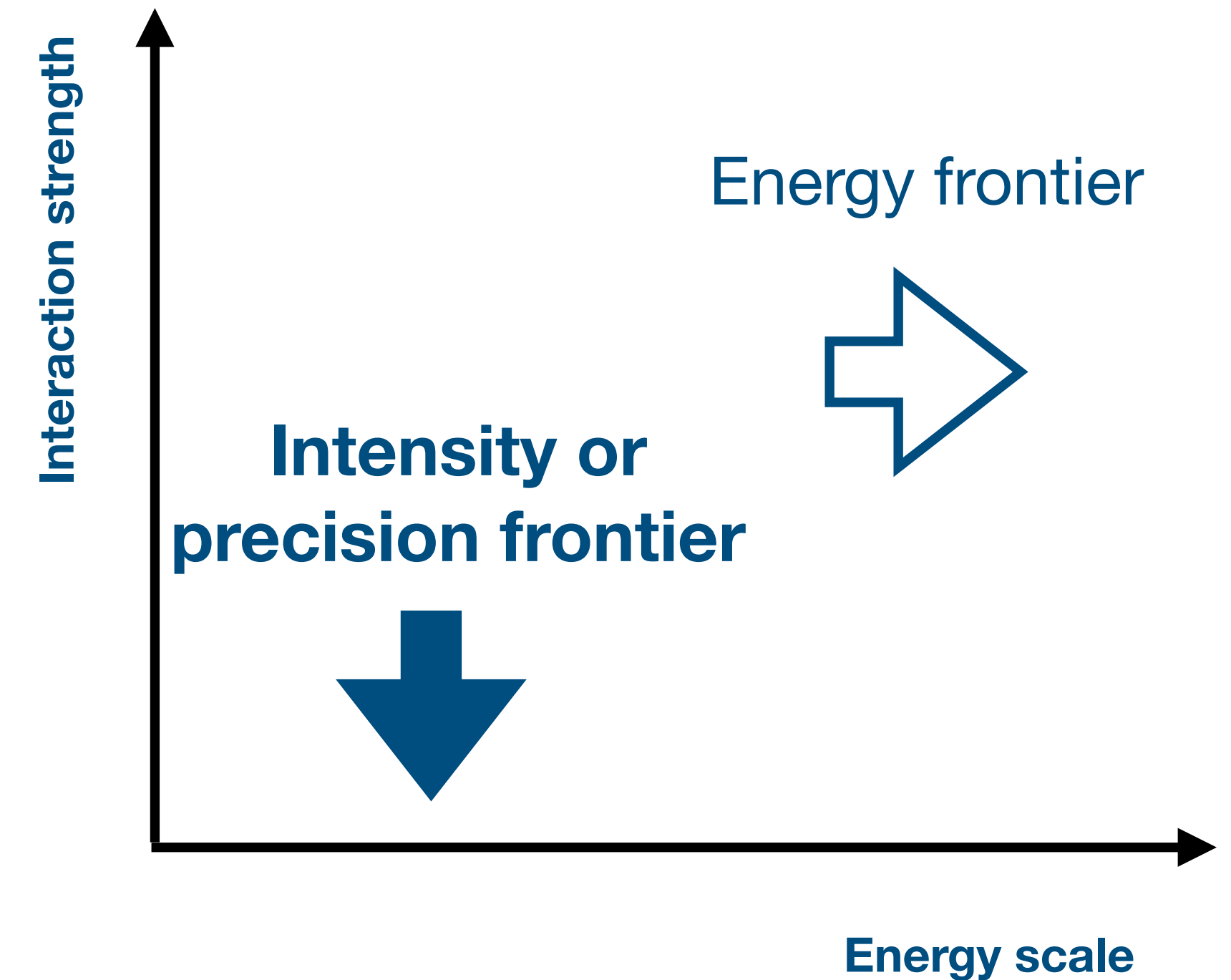
J. Jaeckel, M. Lamont and C.Vallée, "The quest for new physics with the Physics Beyond Colliders programme," Nature Phys. 16 (2020) no.4, 393-401
C. Antel, *et al.* "Feebly-interacting particles: FIPs 2022 Workshop Report", Eur. Phys. J. C 83, 1122 (2023)
F. Kahlhoefer, "PBC BSM vision" at Physics Beyond Colliders Annual Workshop 25-27 Marzo 2024

The existence of dark sectors (DS) (or feebly interacting particles FIPs) is an interesting framework to explain some of the most pressing questions in particle physics with New Physics at low energy scales as:

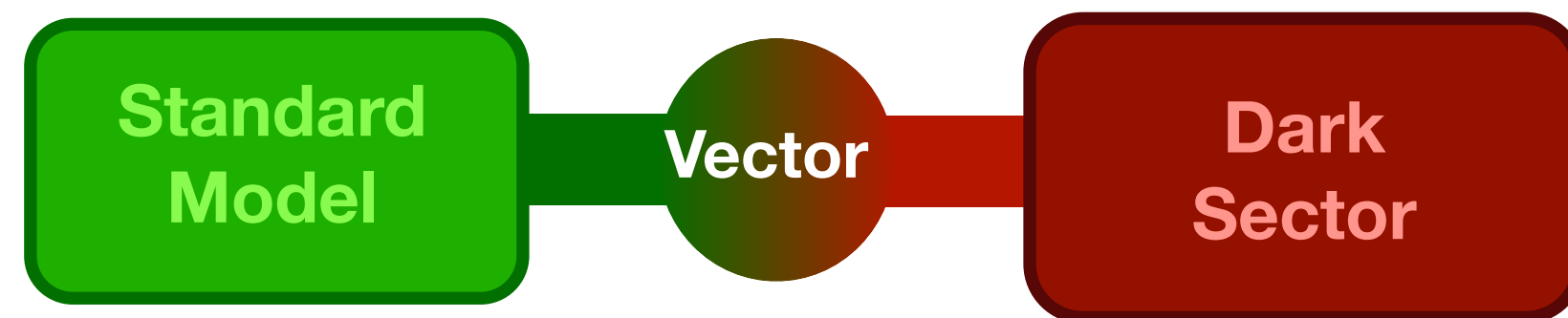
- **The composition of Dark Matter**
- *The origin of neutrino masses*
- *The baryon asymmetry of the universe*
- ...



$$L_{Total} = L_{SM} + L_{DS} + L_{Portal}$$



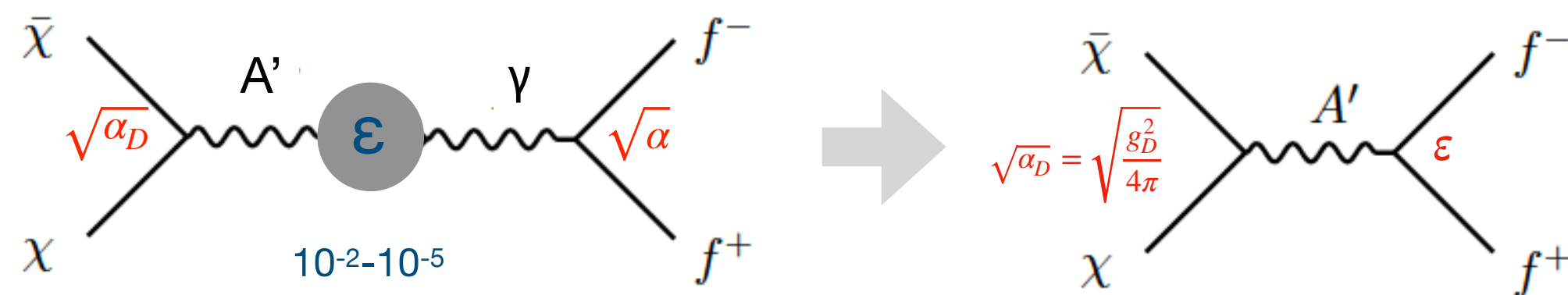
The vector portal and Light Dark Matter



Dark Photon, A'

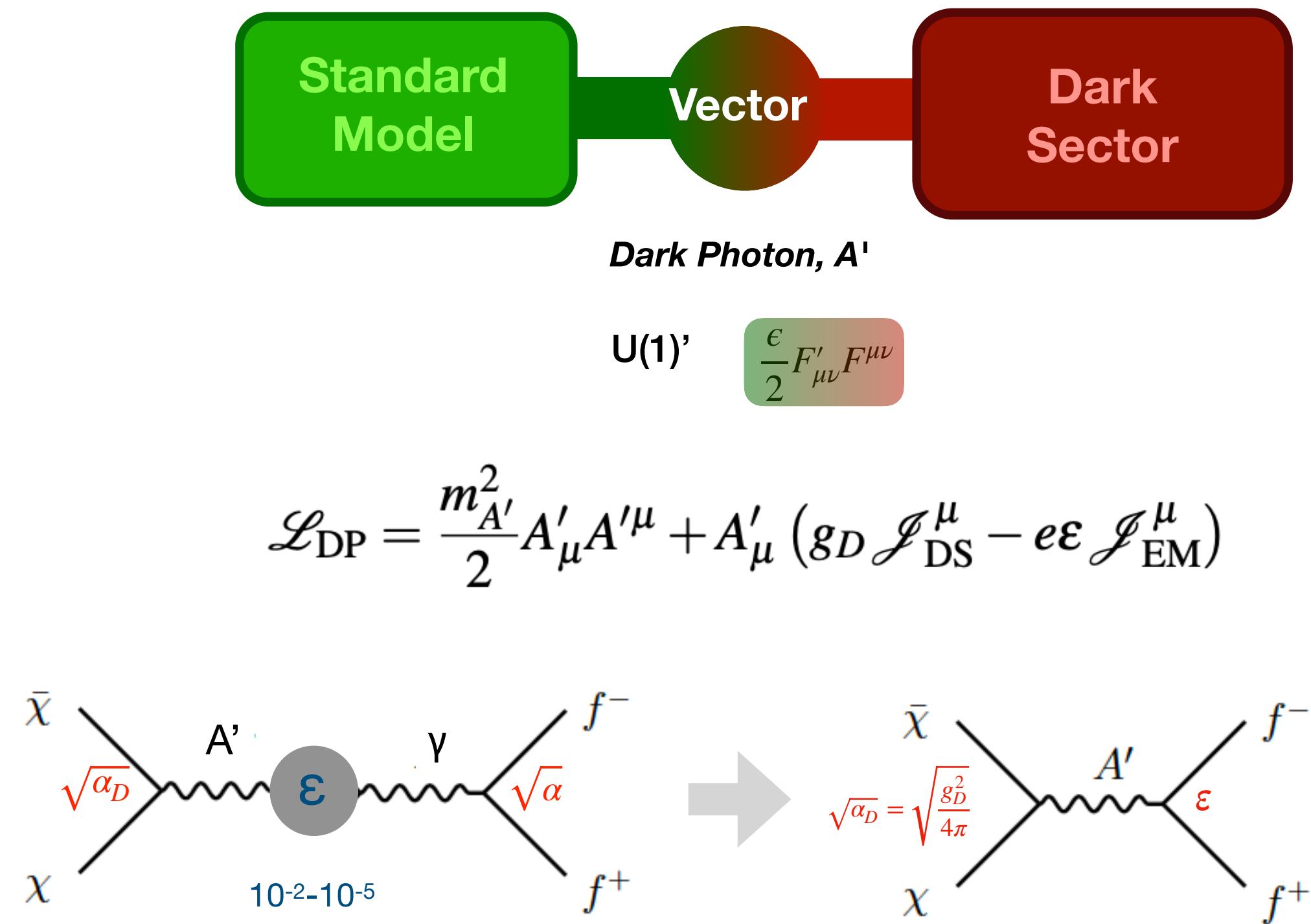
$U(1)'$ $\frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu}$

$$\mathcal{L}_{\text{DP}} = \frac{m_{A'}^2}{2} A'_\mu A'^\mu + A'_\mu (g_D \mathcal{J}_{\text{DS}}^\mu - e\epsilon \mathcal{J}_{\text{EM}}^\mu)$$



Parameter space defined by: $m_{A'}$, m_χ , ϵ , α_D

The vector portal and Light Dark Matter

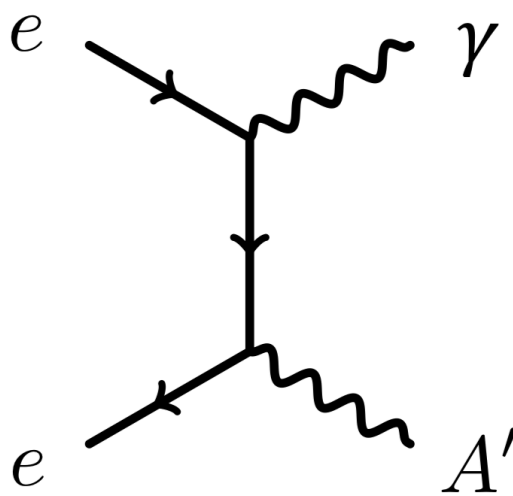


Parameter space defined by: $m_{A'}$, m_χ , ϵ , α_D

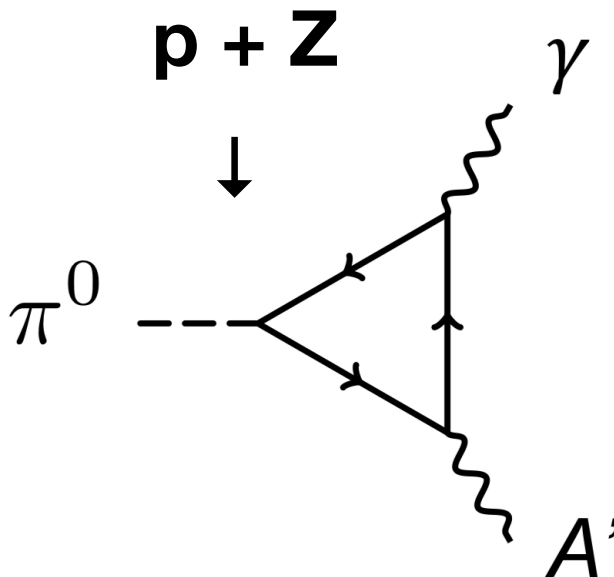
Production mechanisms

Example: Dark Photon (applicable for other mediators)

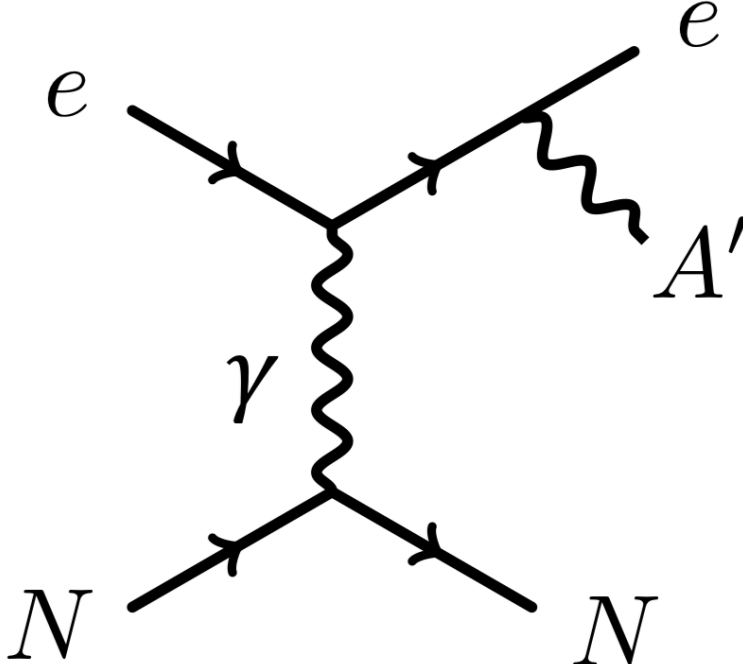
Annihilation



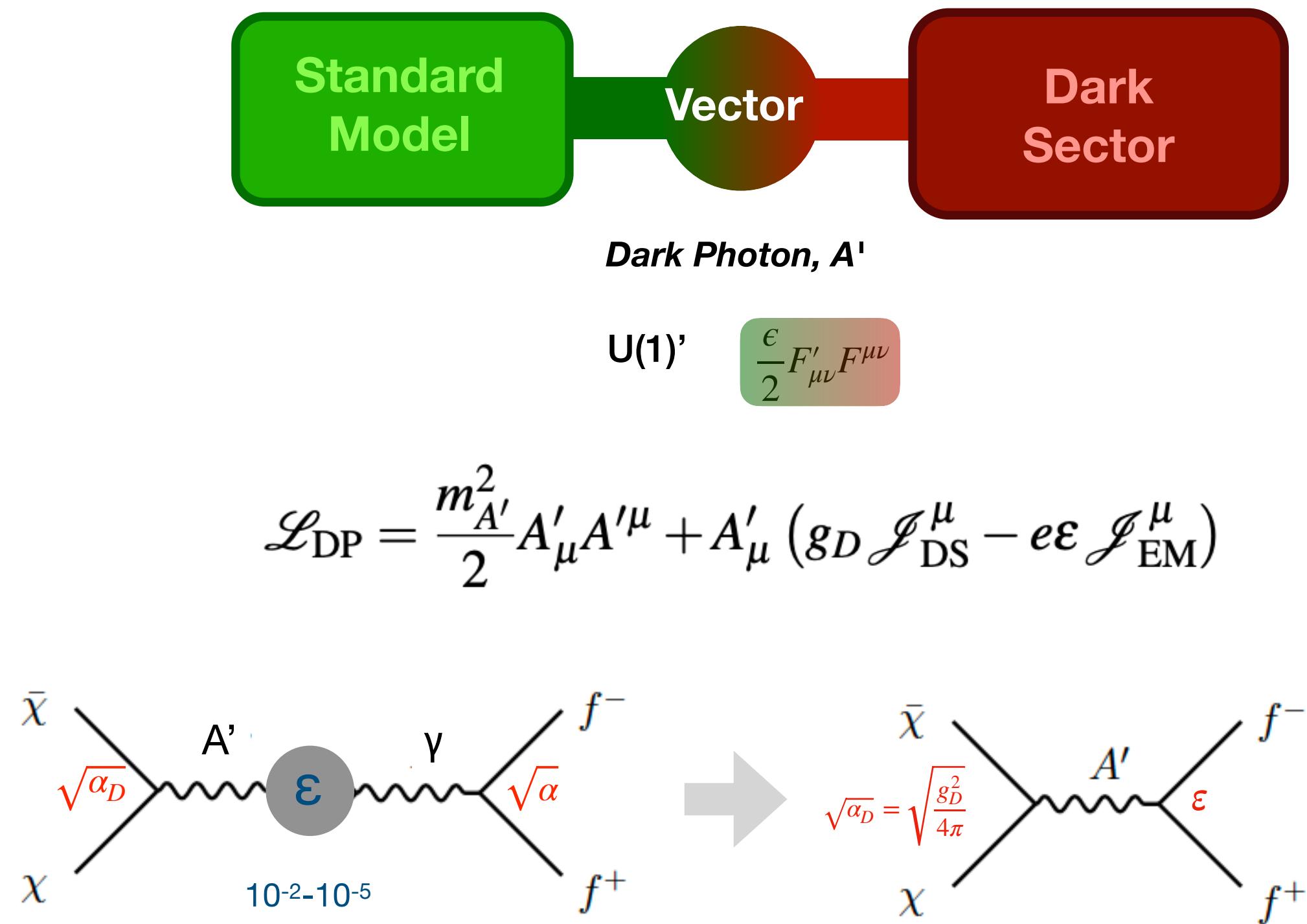
Meson decay



Bremsstrahlung



The vector portal and Light Dark Matter

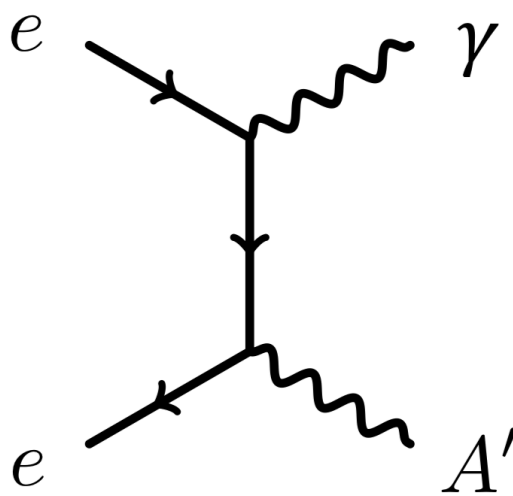


Parameter space defined by: $m_{A'}$, m_χ , ϵ , α_D

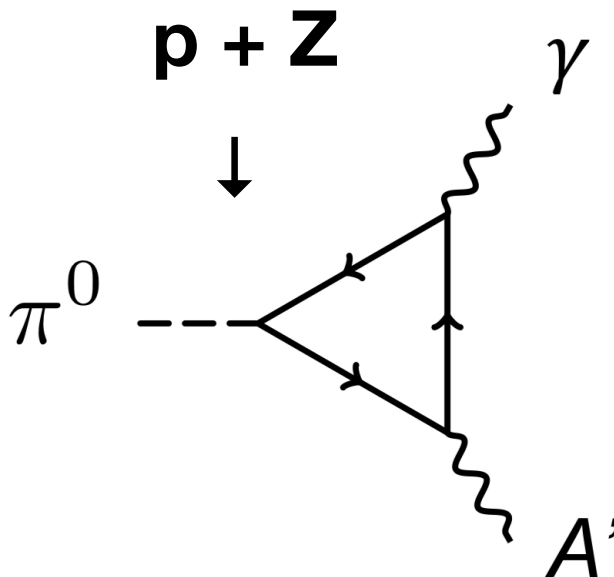
Production mechanisms

Example: Dark Photon (applicable for other mediators)

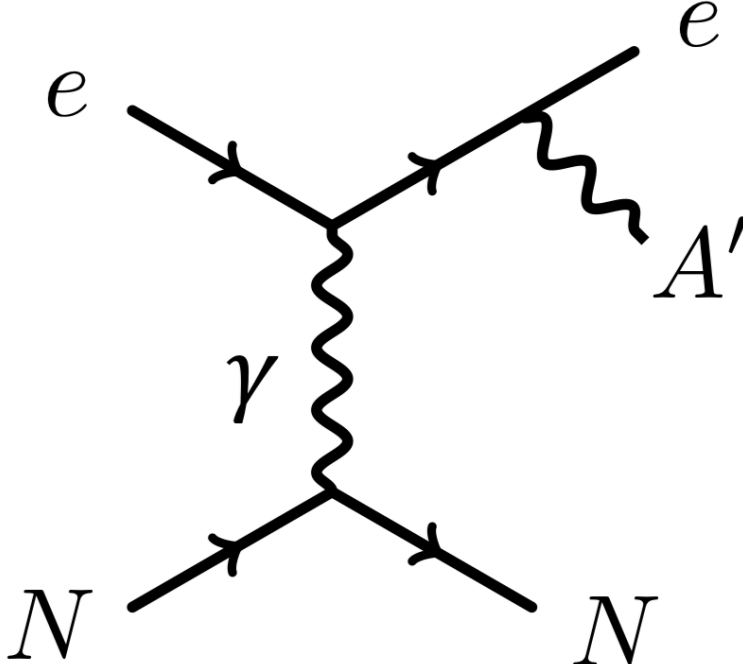
Annihilation



Meson decay



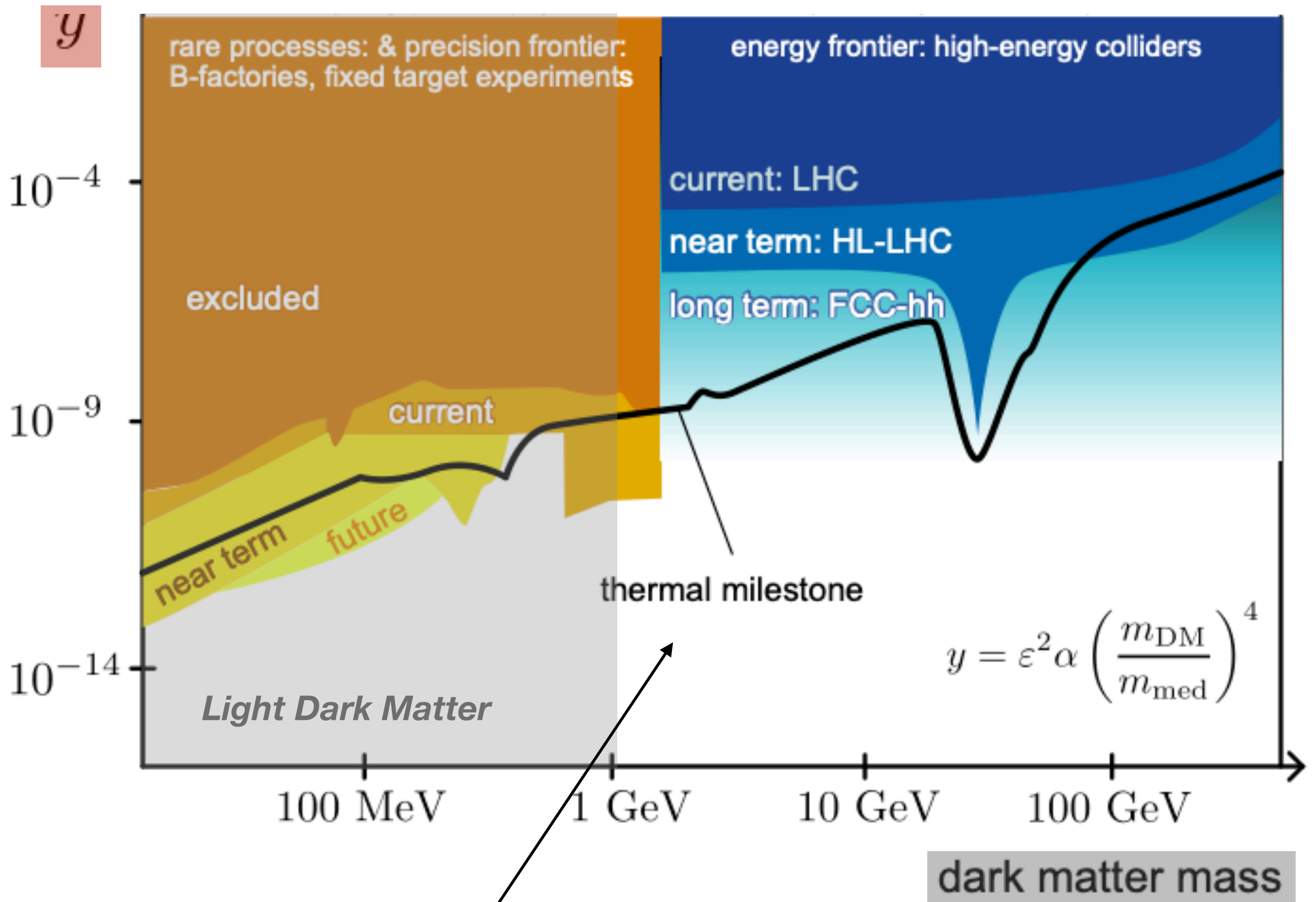
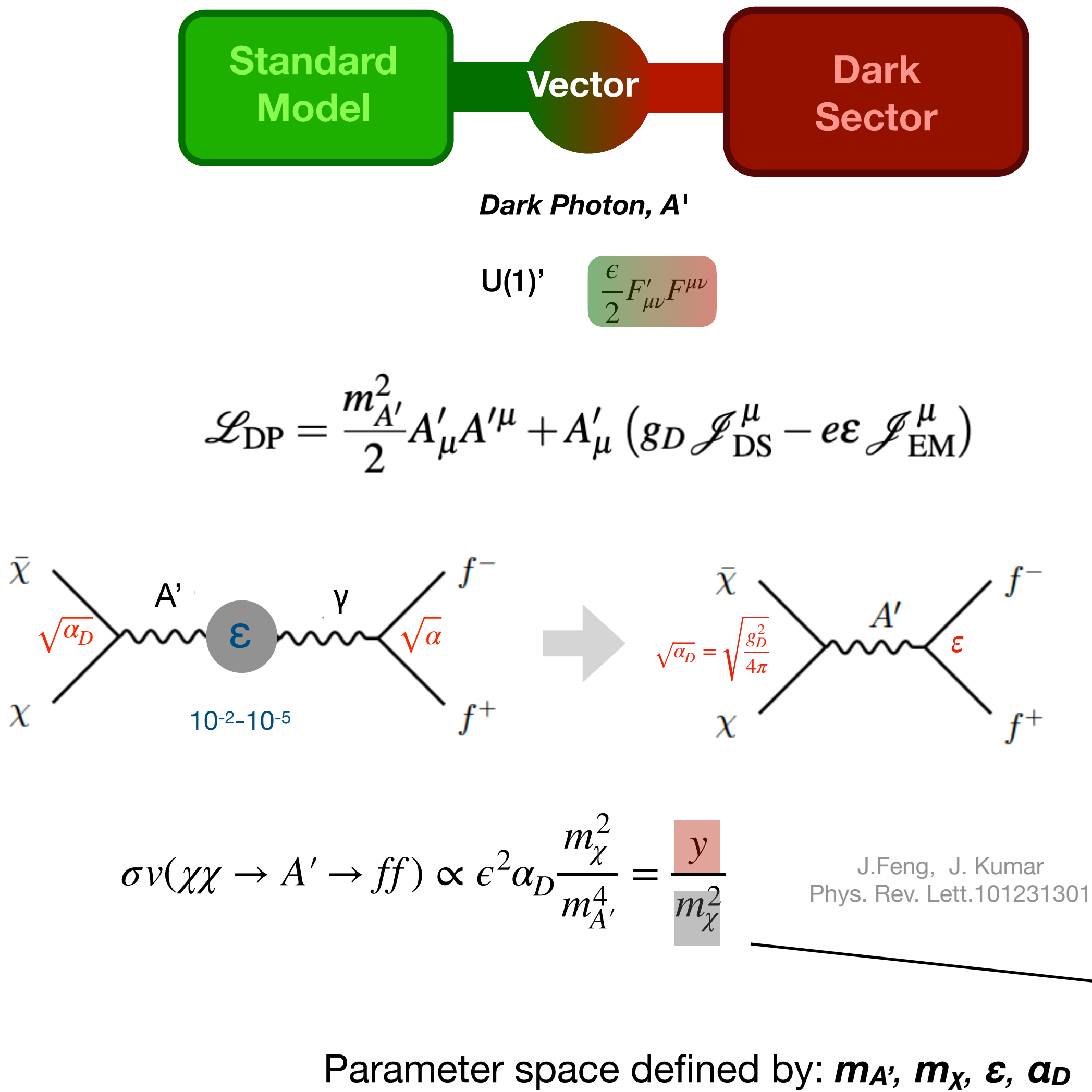
Bremsstrahlung



Colliders, Fixed target, and Neutrino experiments

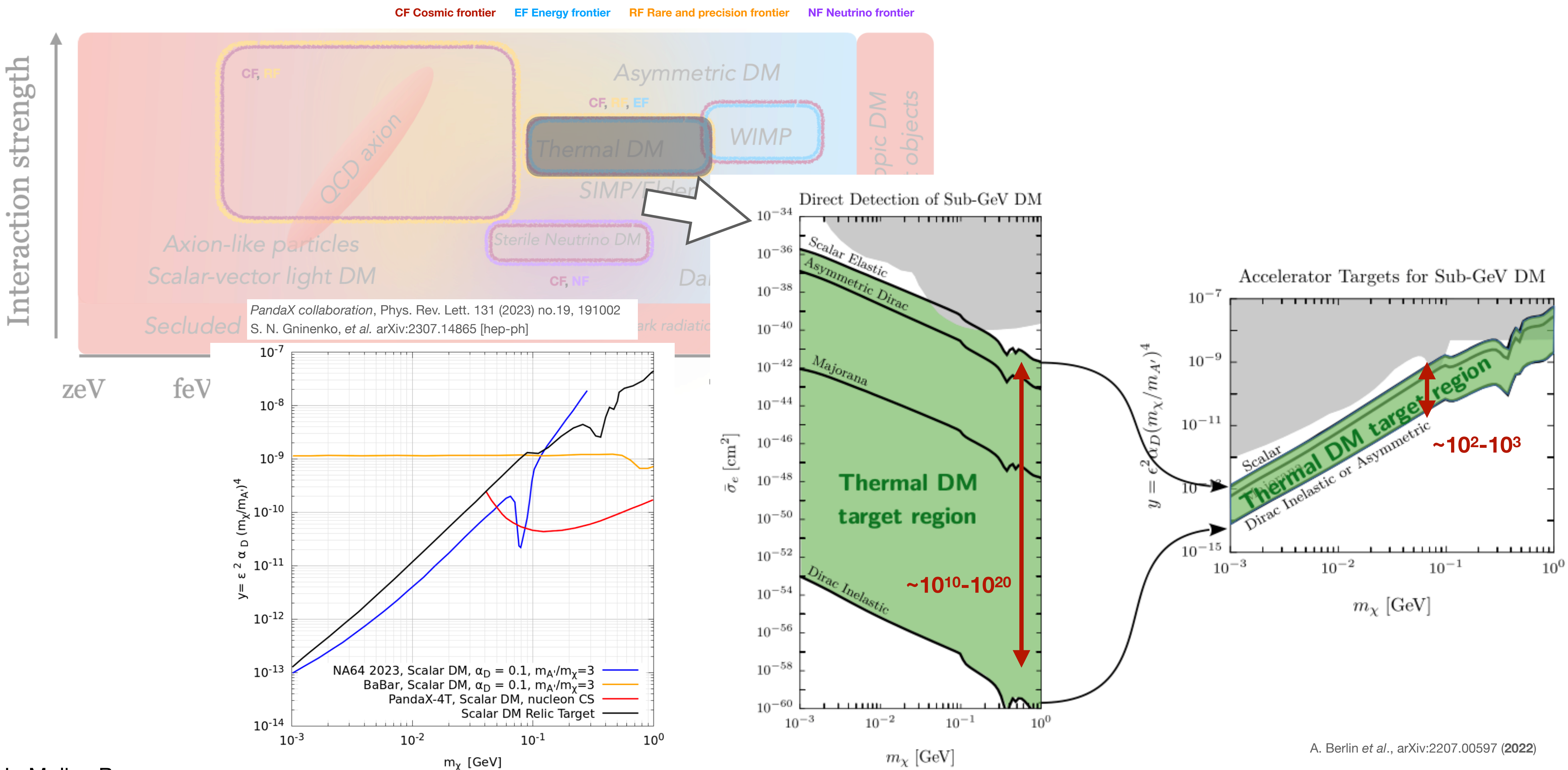
The vector portal and Light Dark Matter

A. Boveia et al., arXiv:2211.07027(2022)



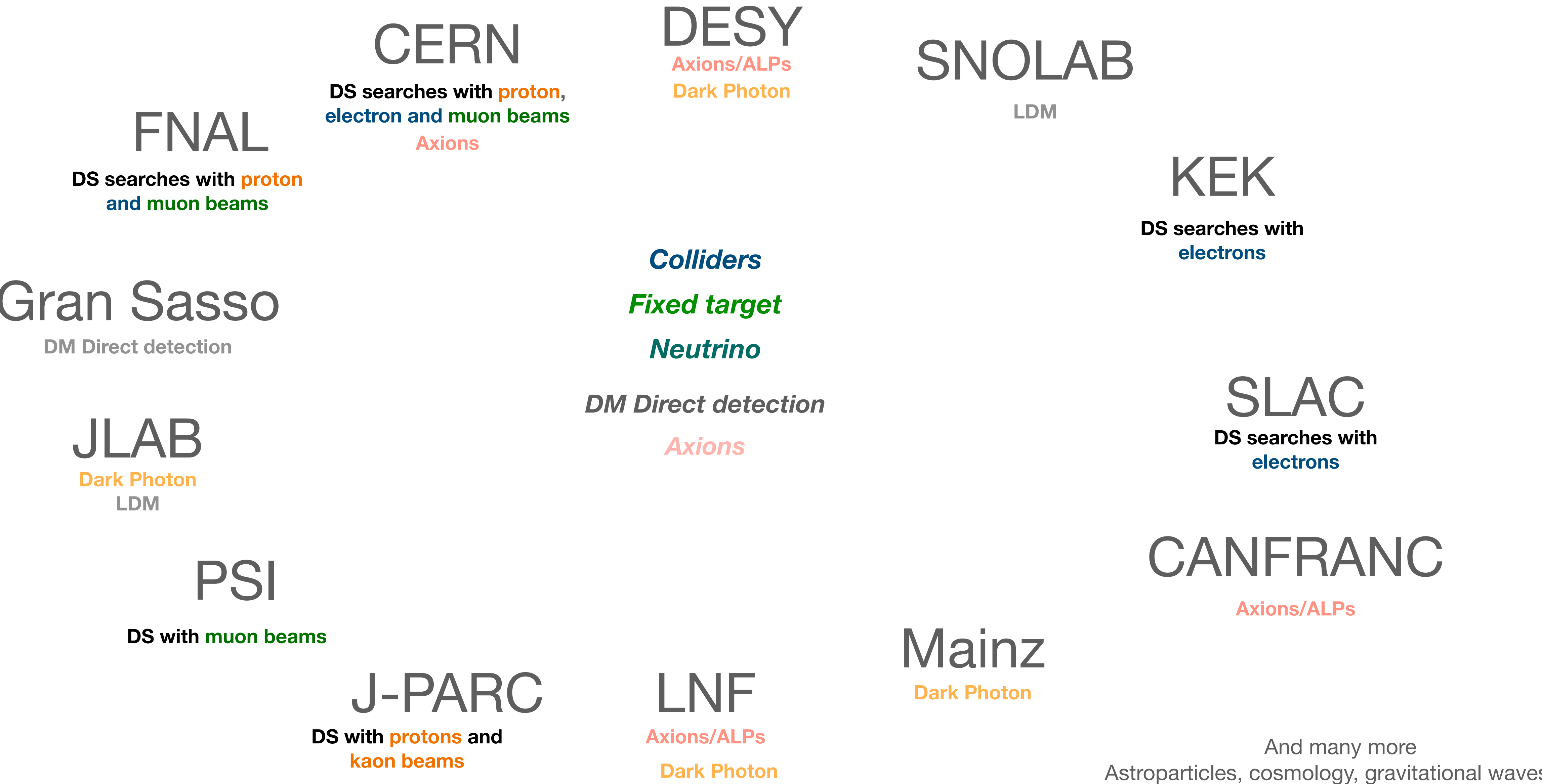
$$\Omega_\chi \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_\chi^2}{g_\chi^4}$$

Complementarity with direct detection experiments

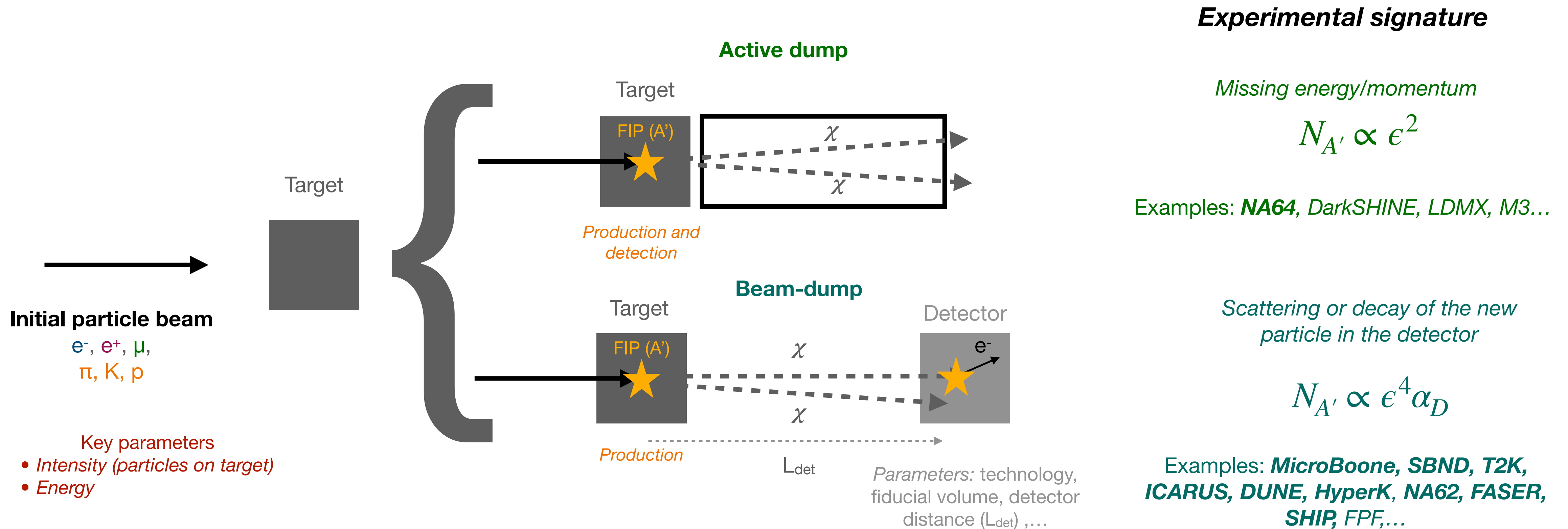


Worldwide effort @laboratories

Adapted from:
• C. Vallée et al., “Overview of PBC past studies and current focus”, *Physics Beyond Colliders Annual Workshop March 2024*.
• G. Lanfranchi, *Dark Matter 2023*, “The search for MeV-GeV Dark Matter and other feebly interacting particles (FIPs) at accelerators”



Fixed-target experiments in a nutshell



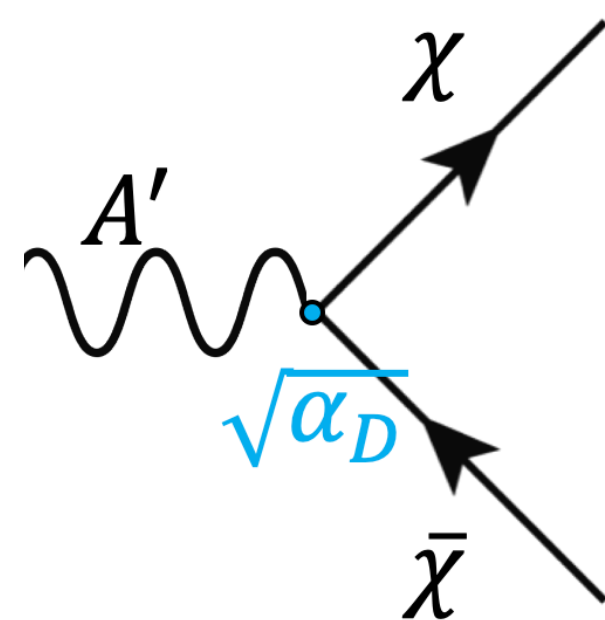
Example: *Dark Photon A' (applicable for other mediators)*

Fixed-target experiments in a nutshell

Decay

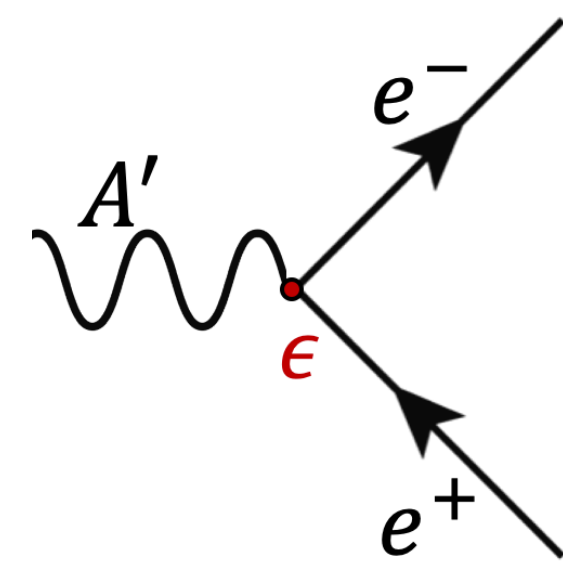
• Invisible

$$m_{A'} > 2m_\chi$$



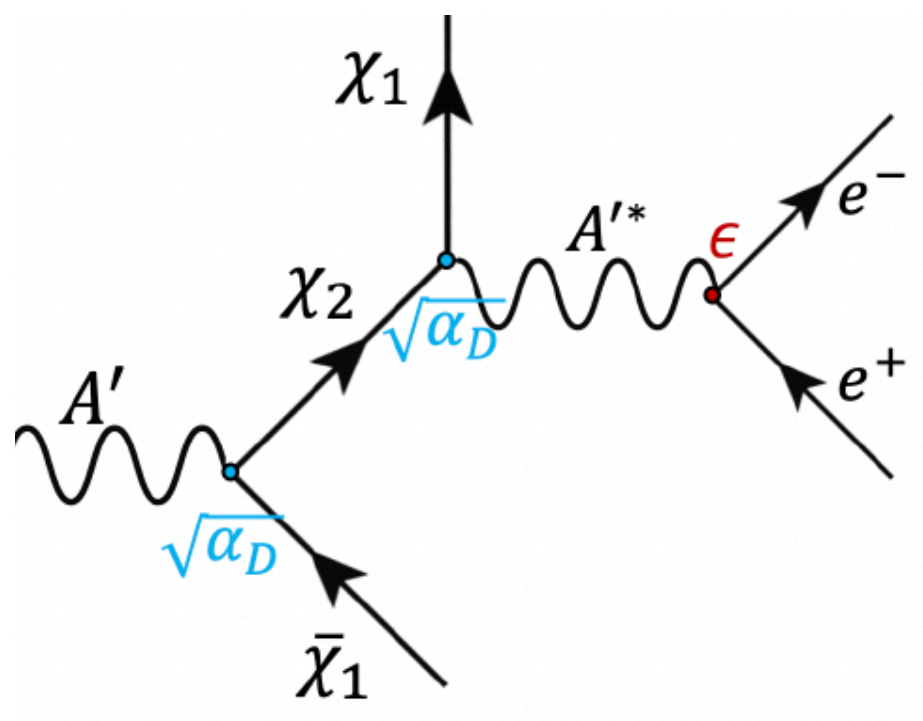
• Visible

$$m_{A'} < 2m_\chi$$



• Semi-Visible (or displaced)

$$m_{A'} > m_{\chi_1} \gg m_e$$



Experimental Signature

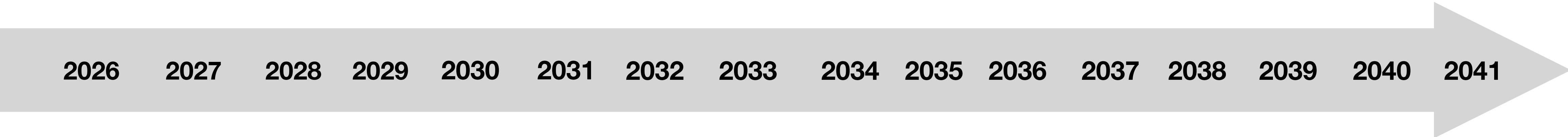
Missing energy/momentum

SM pair particles

Missing energy
+
SM pair particles

Timeline using accelerators

[More details in C. Antel, *et al.* Eur. Phys. J. C 83 (2023) no.12, 1122]



- **NA64, NA62, FASER, DarkQuest, PADME, LUXE, MiliQan...**
- **SBND, Microboone, T2K, ICARUS, COHERENT...**
- **Belle II, ATLAS, CMS, LHCb,...**

Beyond

- **DarkSHINE, LDMX, BDX, M3,...**
- **Phase 1 of DUNE, HyperK, COHERENT, ProtoDUNE@SPS,...**
- **HL-LHC,...**

- **SHIP, Forward Physics Facility (FASER2, FORMOSA, FLARE,...),
Mathusla, Codex-B, Anubis,...**

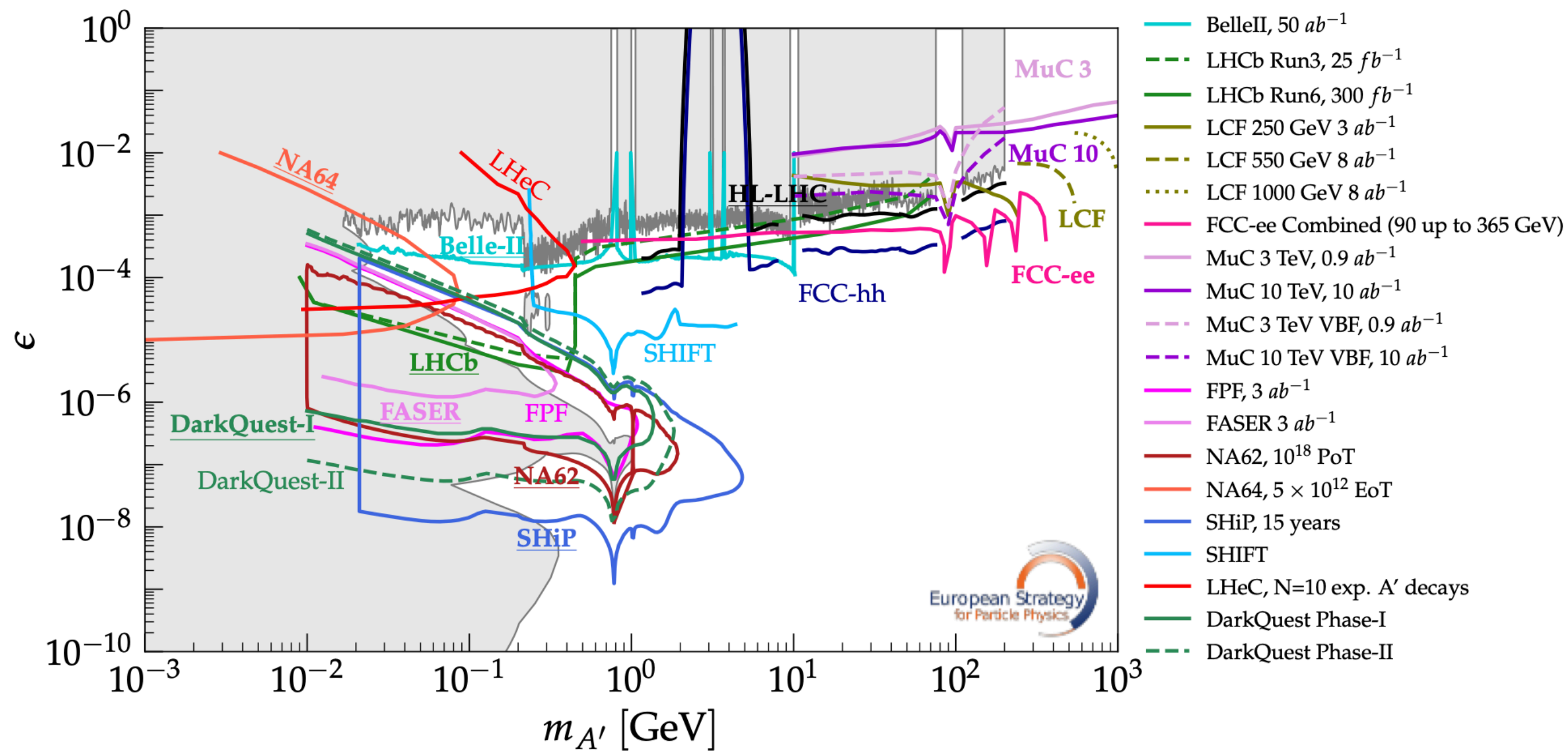
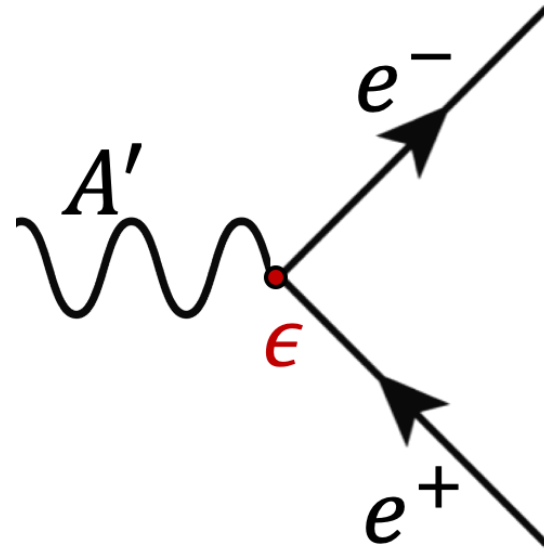
- **FCCee, FCChh,...**

Colliders
Fixed target
Neutrino experiments

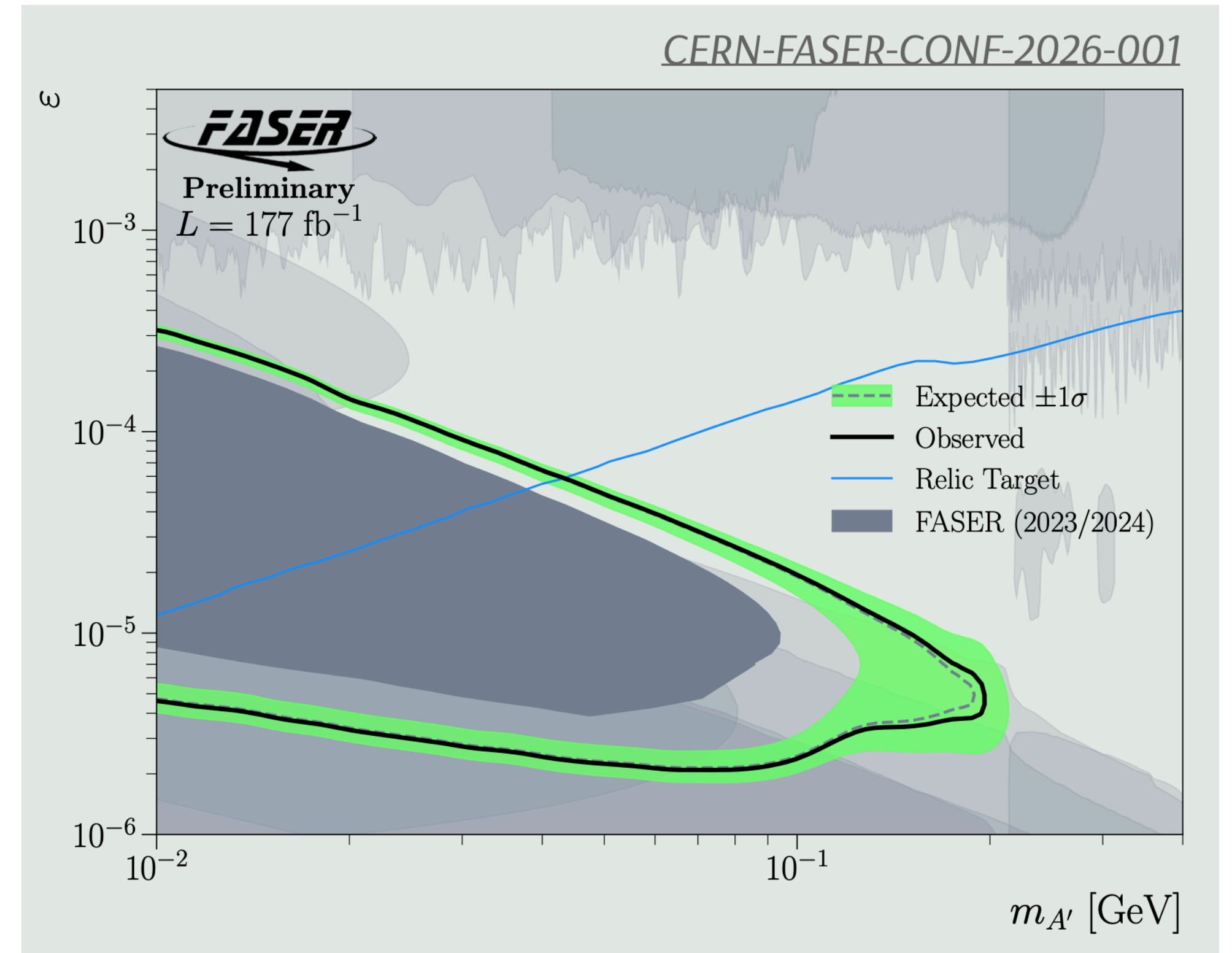
- *And many more...*
- *Complementary to (Baby) laXo, CADEX,..., LZ, PANDAX, XenonNT,..., km3net, icecube,...*

A' visible decays and LDM

• Visible



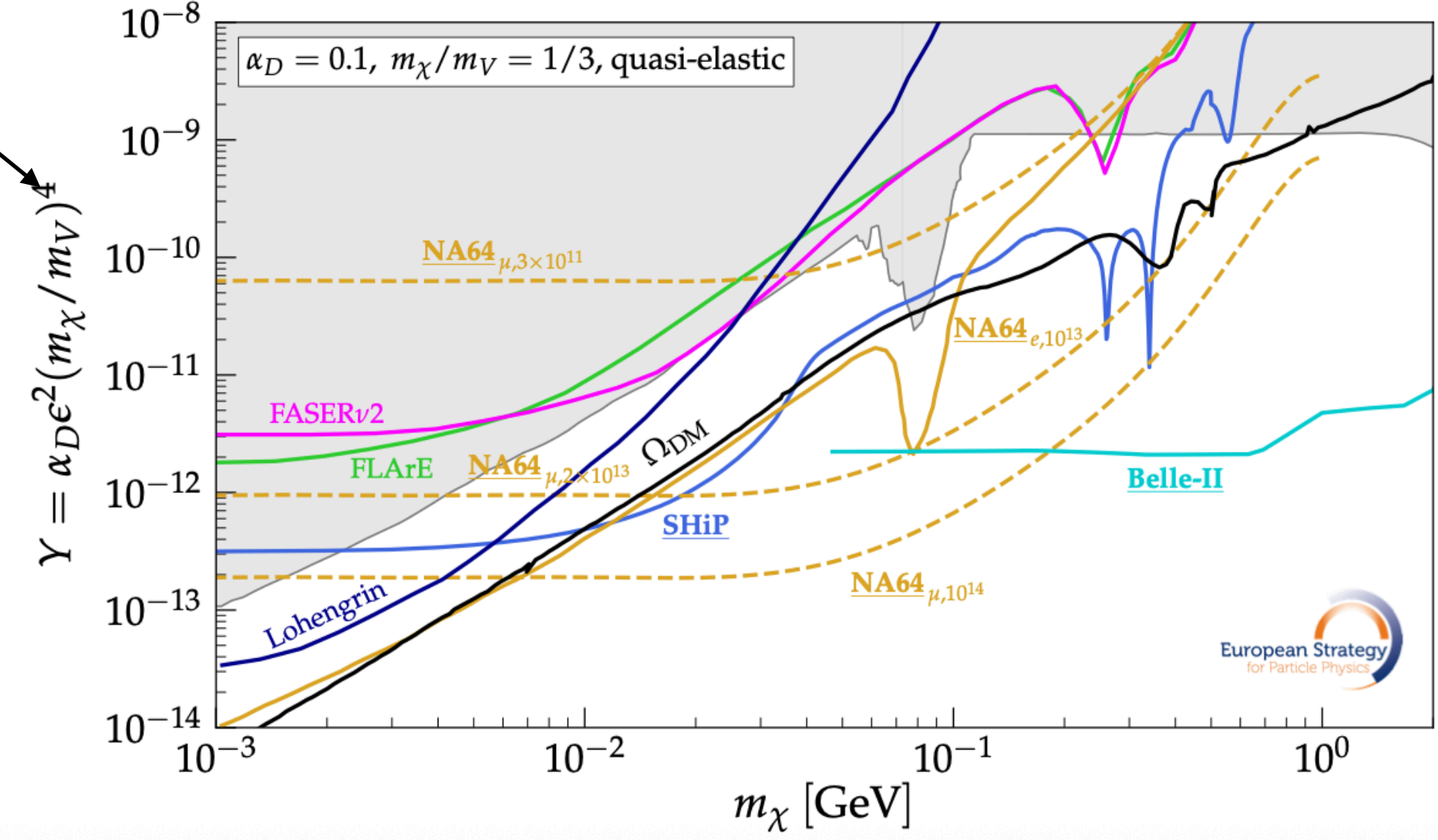
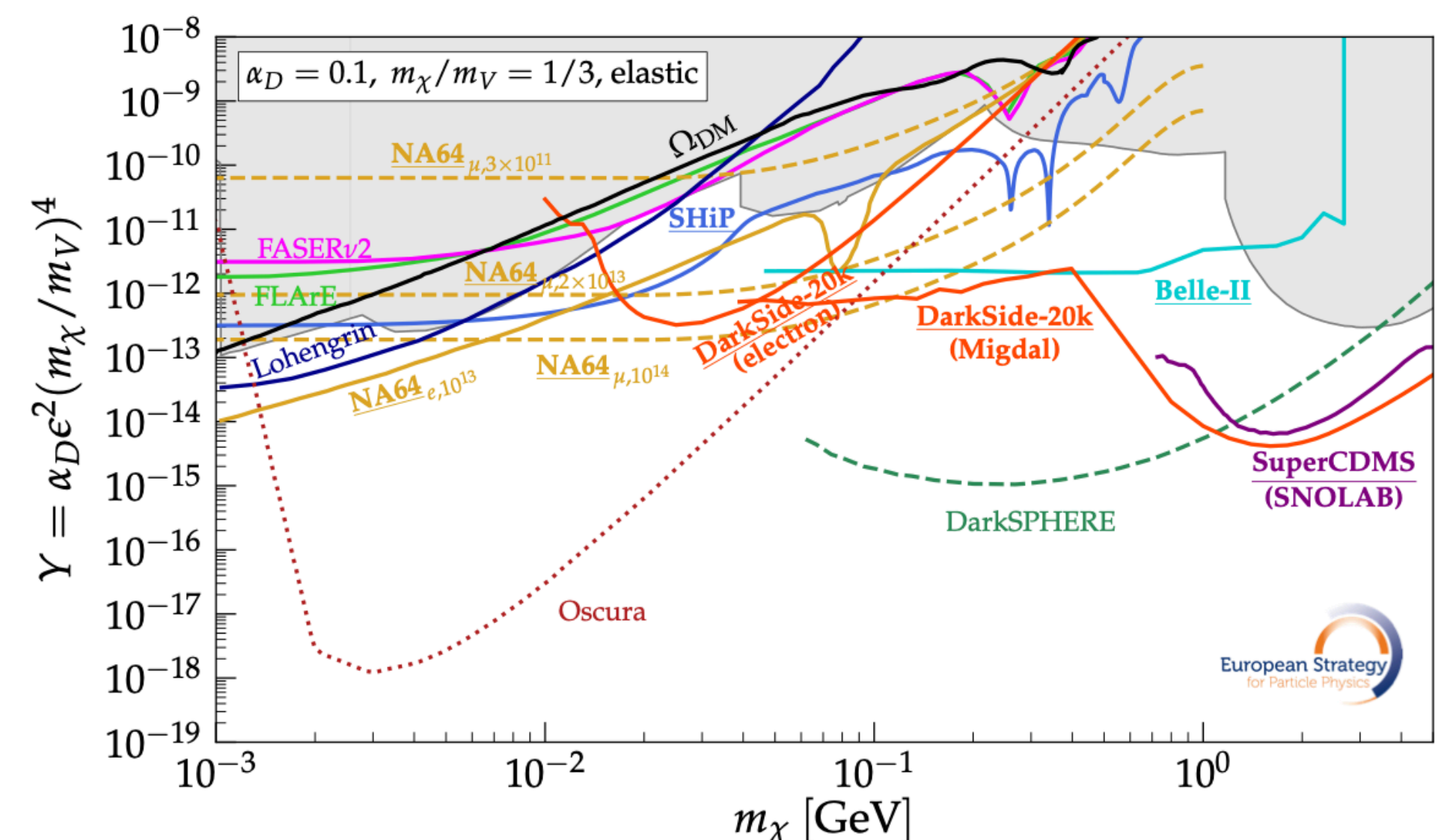
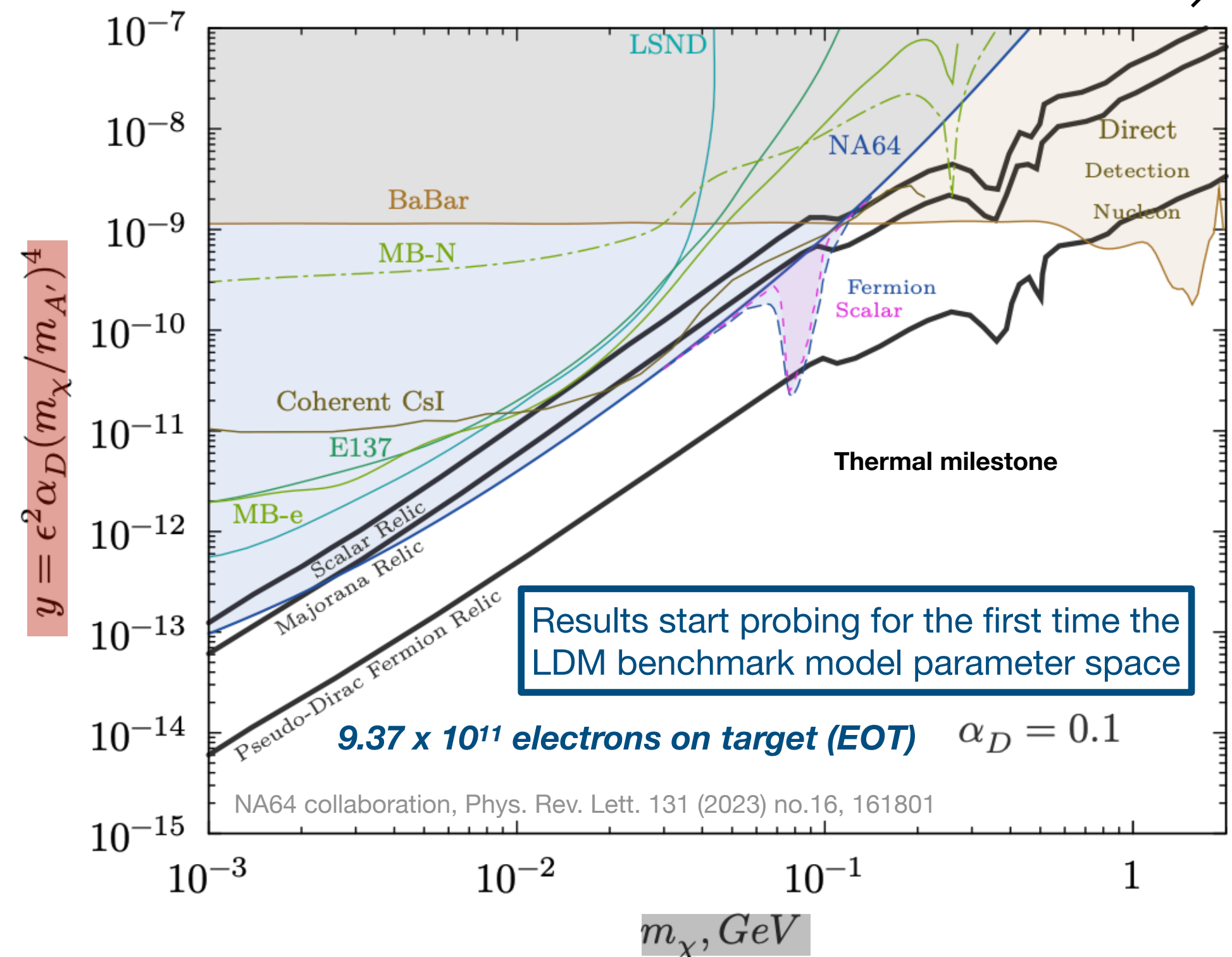
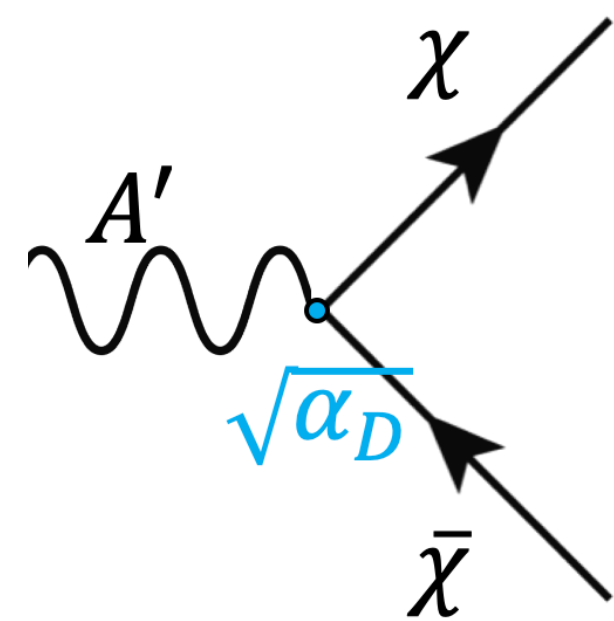
From: A. Desai, "Latest DS results from the FASER experiment"



See more details in the Light Dark Matter session

A' invisible decays and LDM

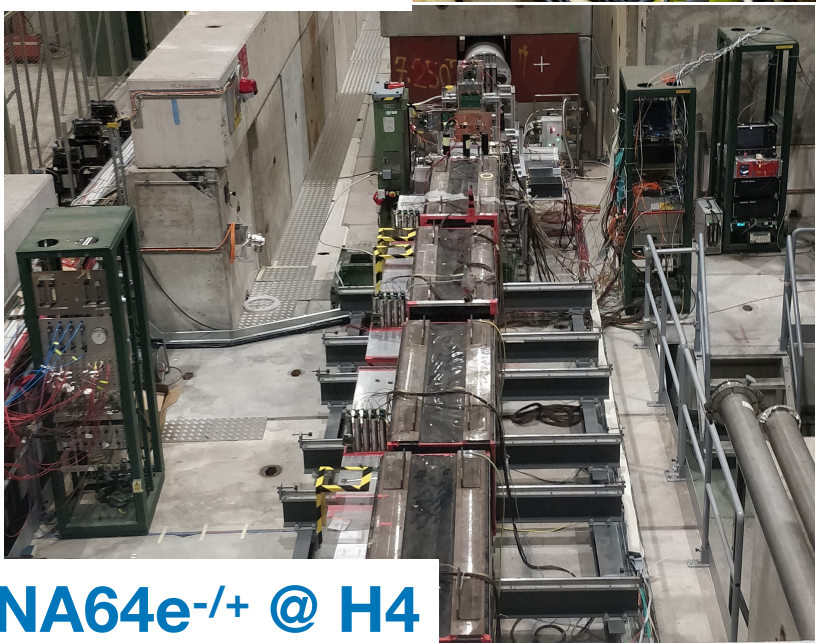
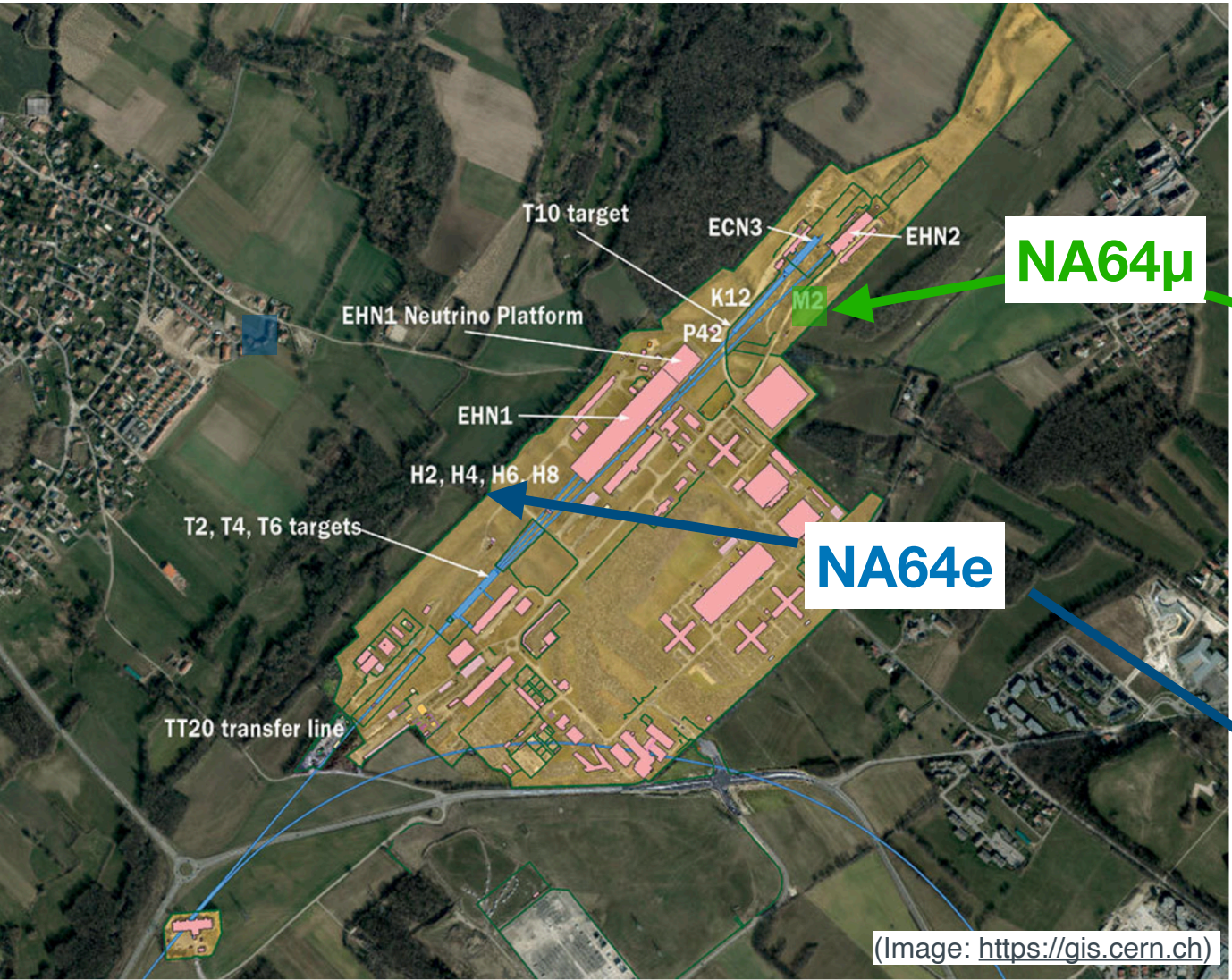
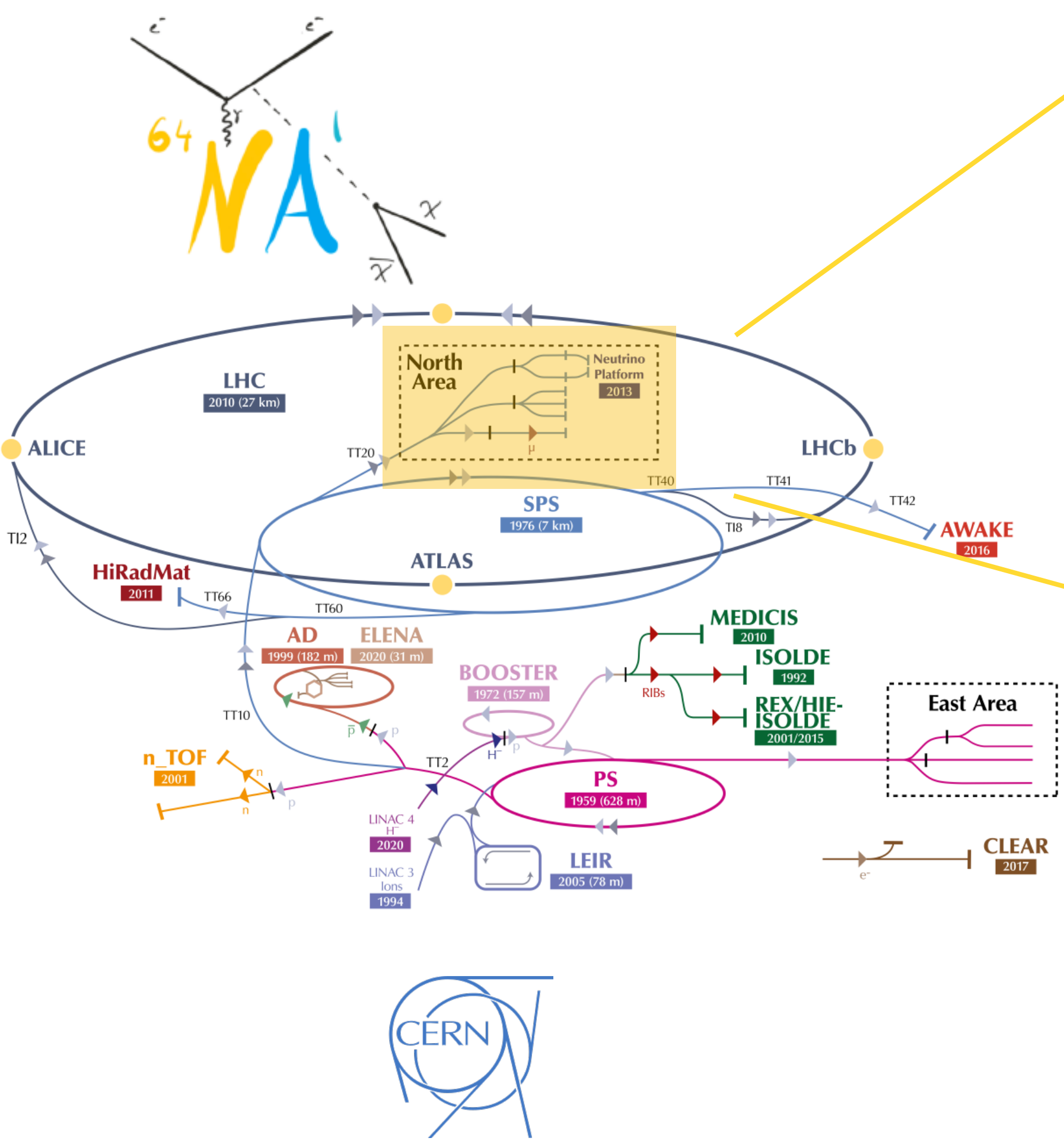
• Invisible



See more details in the Light Dark Matter session

The NA64 experiment

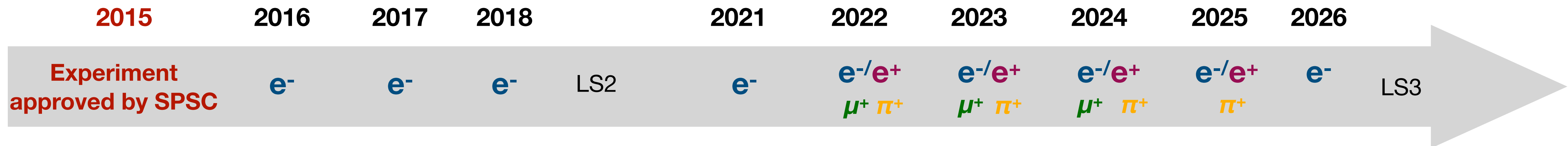
Fixed target experiment devoted to exploit unequivocally Dark Sector physics combining complementary and different beams from the CERN SPS (e^- , e^+ , μ and hadron)



International collaboration: 53 researchers from 9 institutions

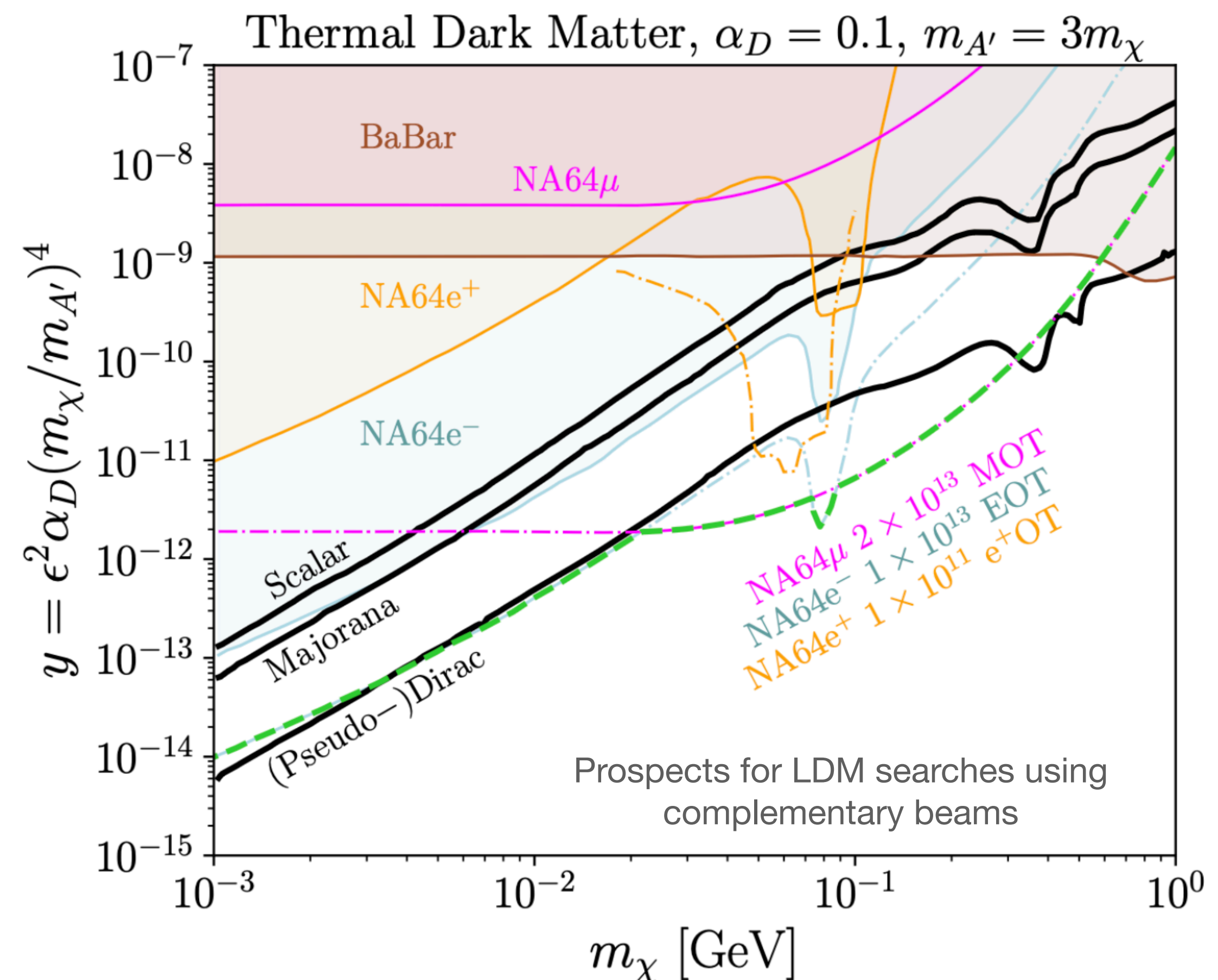
The NA64 program

NA64 10th anniversary! 🎉🎂

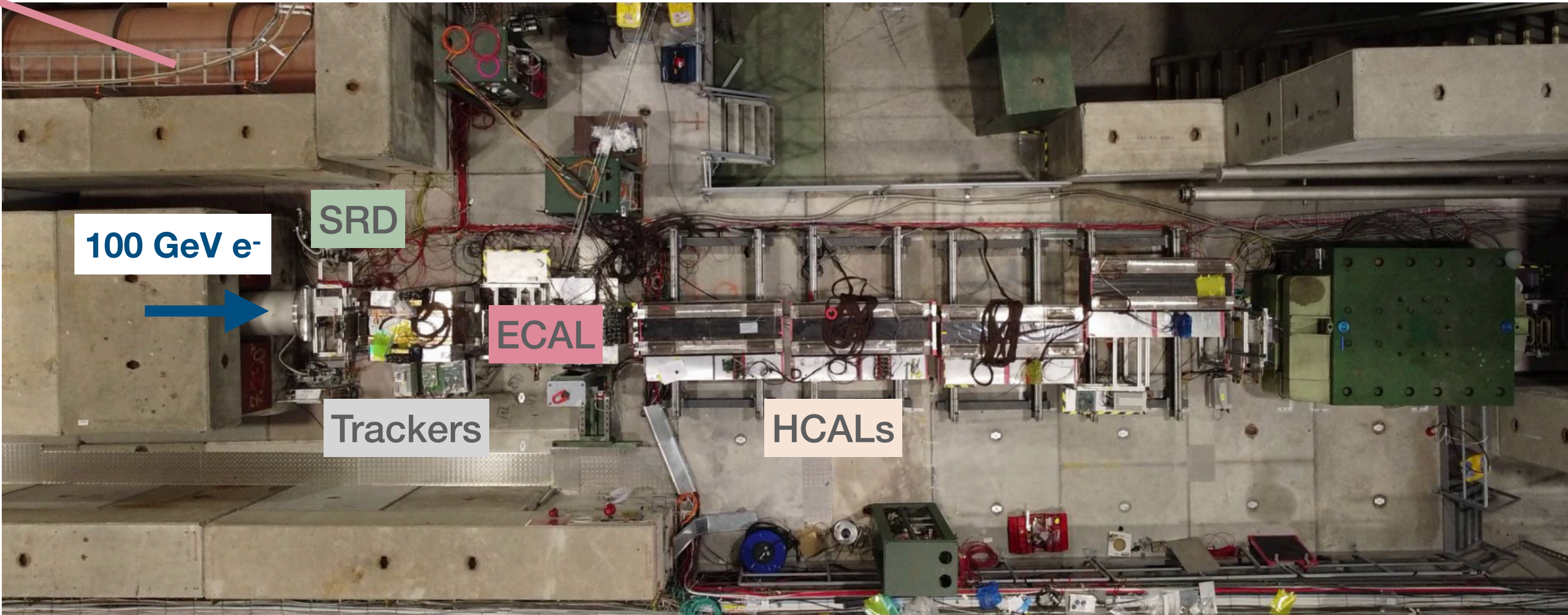
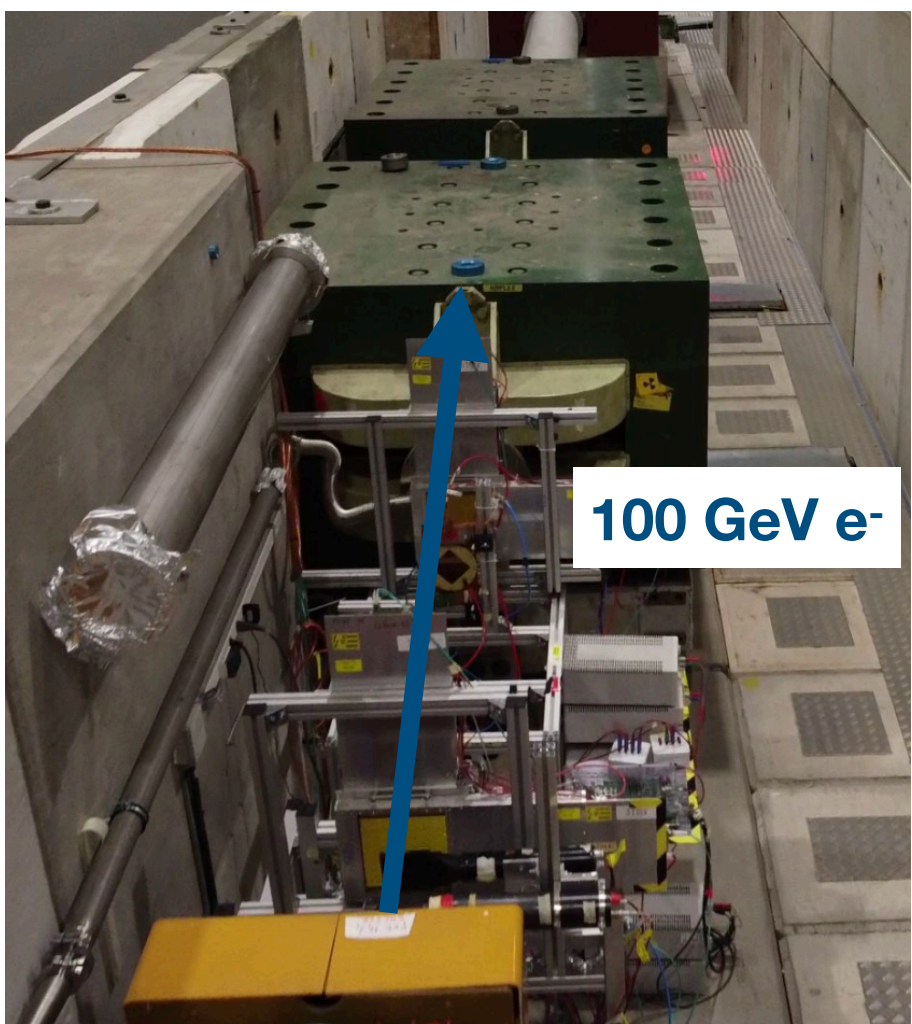
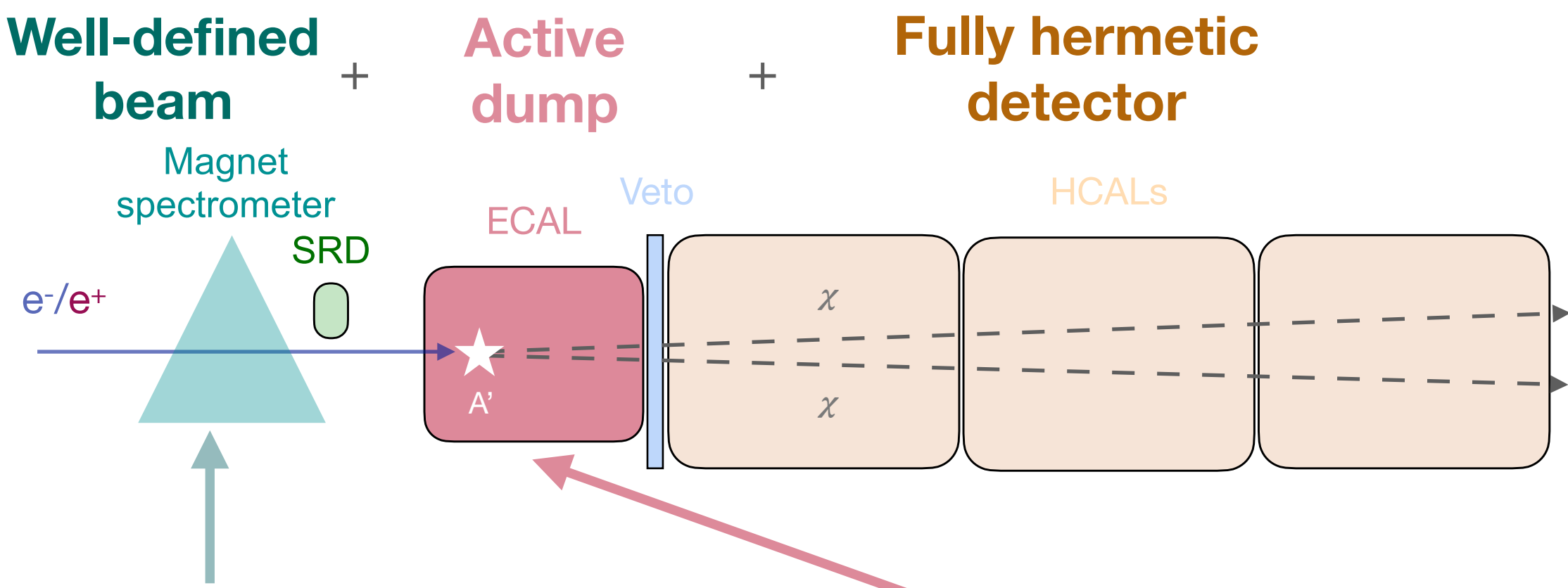
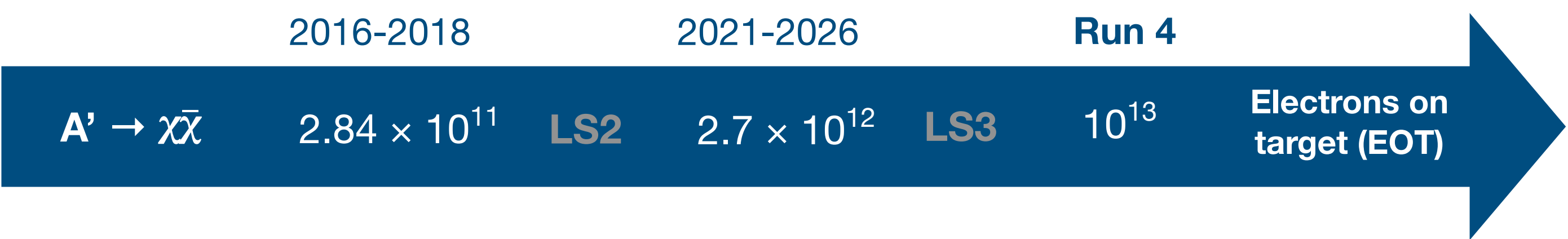


Well-defined beam + Active dump + Fully hermetic detector

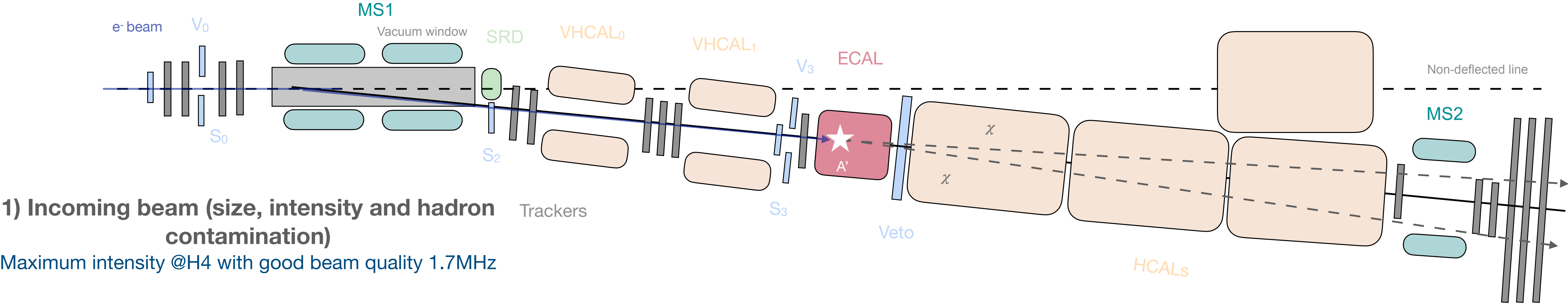
- **NA64 e^- , NA64 e^+**
 - Search for vector-mediated (A') LDM, inelastic DM, ALPs, scalar, millicharge...
- **NA64 μ :**
 - Leptophilic DS coupled to μ
 - Phase 1: $L_\mu-L_\tau$ Z' as a solution to the (g-2) μ anomaly and LDM
 - Phase 2: Complementary A' LDM searches, ALPs, scalar, inelasticDM, millicharge, ...
- **NA64 h :**
 - Use lower energy hadron charge-exchange scattering on heavy target as a source of neutral mesons ($\eta, \eta', \dots$) followed by their invisible decays, or transitions to DS state.



Searches for LDM using e^-



Searches for LDM using e^-



1) Incoming beam (size, intensity and hadron contamination)

Maximum intensity @H4 with good beam quality 1.7MHz

2) Reconstruction of the incoming particle ID and momentum

Magnetic spectrometer (MS1): Momentum (100 ± 5 GeV)

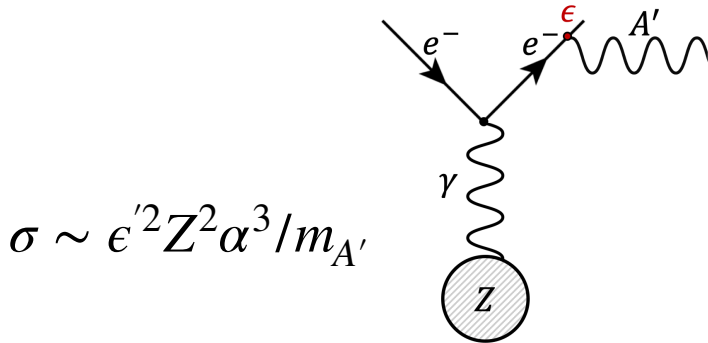
Synchrotron Radiation Detector (SRD): 95% e^- identification, 10^{-5} hadron suppression

3) Active target

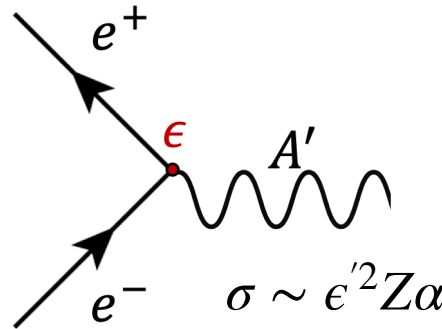
Electromagnetic calorimeter, ECAL

$$N_{A'} \propto \epsilon^2$$

A' -Bremsstrahlung



Resonant A' production



4) Hermeticity

Hadronic calorimeter (HCAL), veto hadron calorimeter (VHCAL) + Veto

5) Trigger:

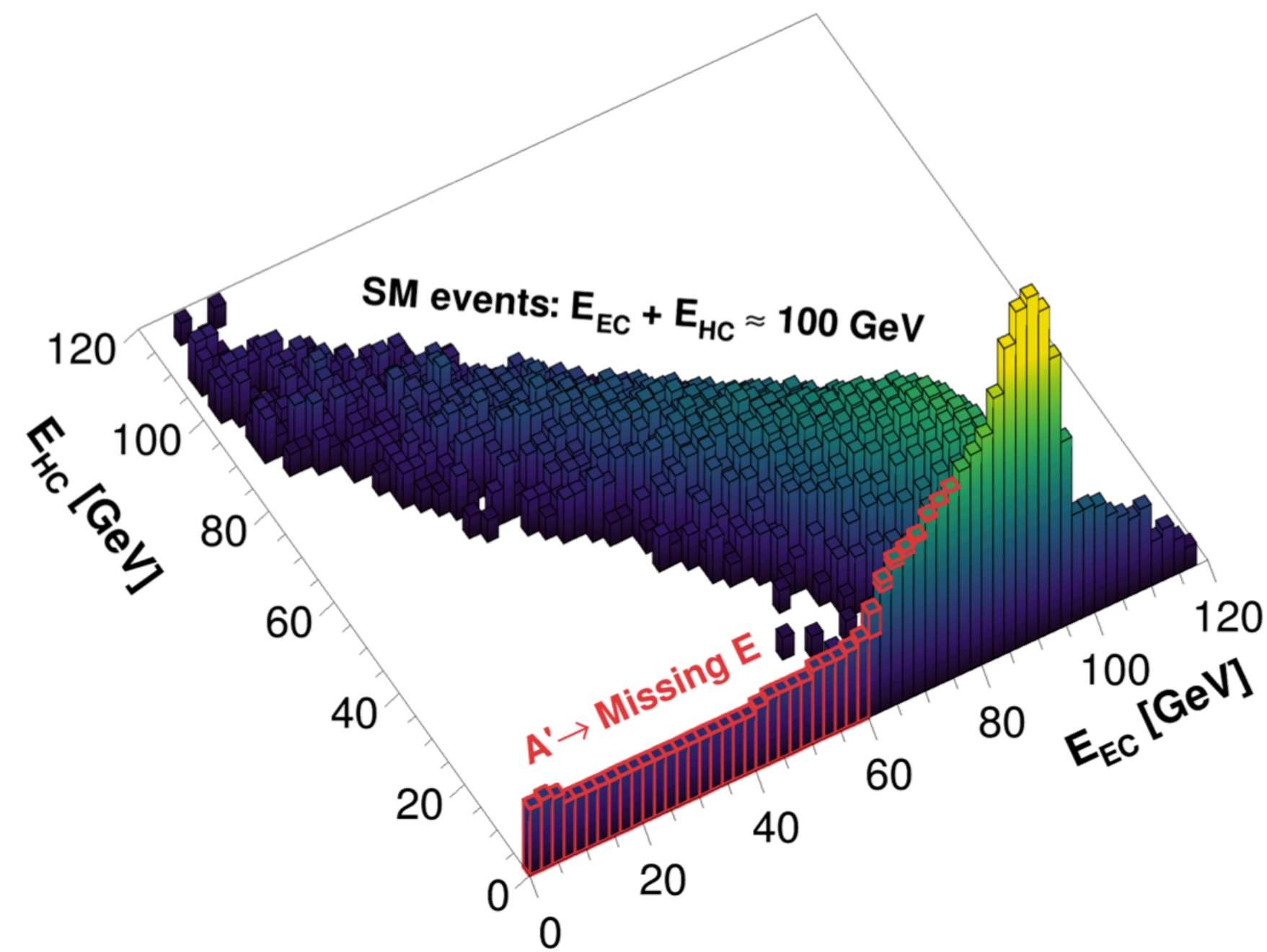
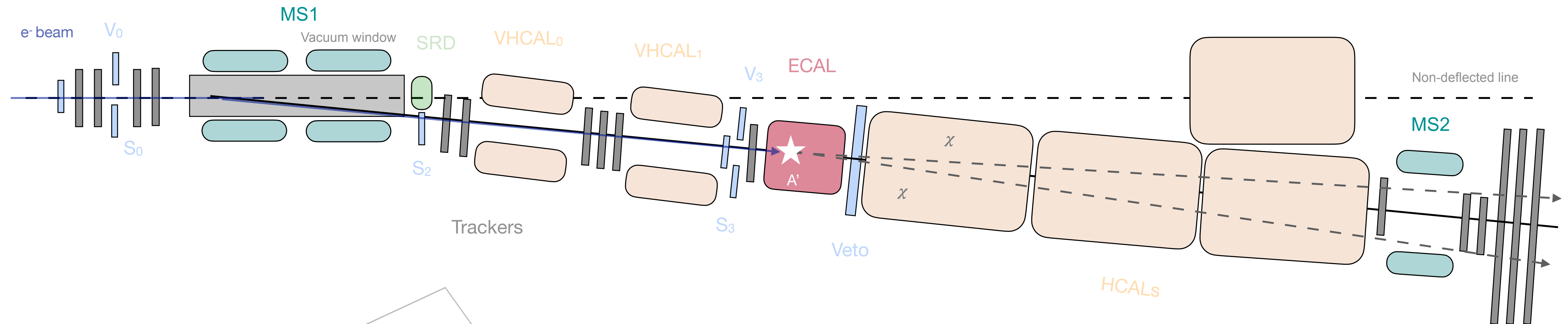
$$\Pi S_i \cdot \bar{V}_1 \cdot E_{PS} > 0.2 \text{ GeV} \cdot E_{ECAL} < 90 \text{ GeV}$$

+ Dedicated Dark Matter open-access simulation package in fixed target experiments **DMG4** interfacing GEANT4 toolkit

M.Bondi *et al.* Comput. Phys. Commun. 269, 108129 (2021)

B. Banto Oberhauser *et al.* Comput. Phys. Commun. 300 (2024), 109199

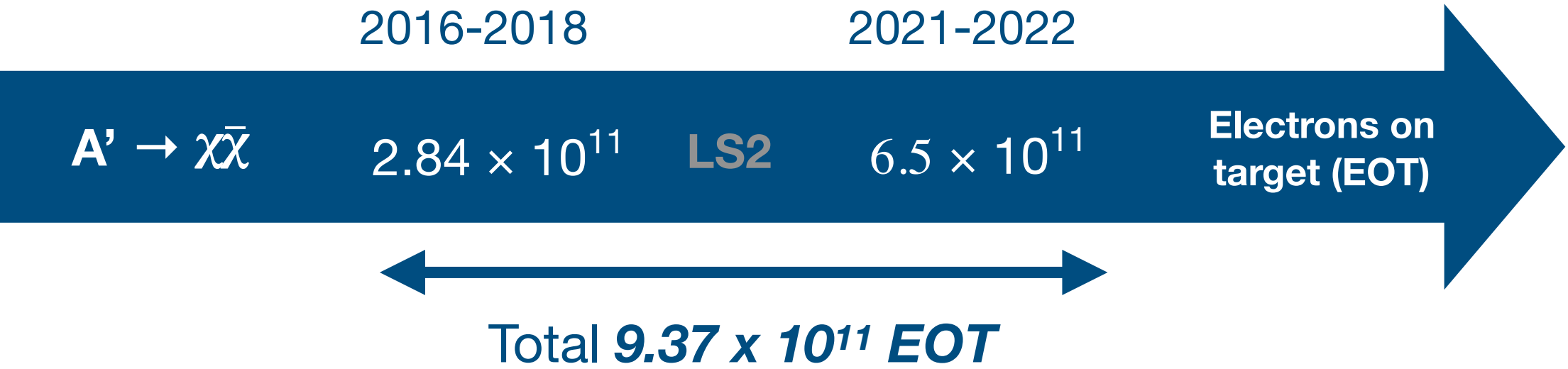
Searches for LDM using e^-



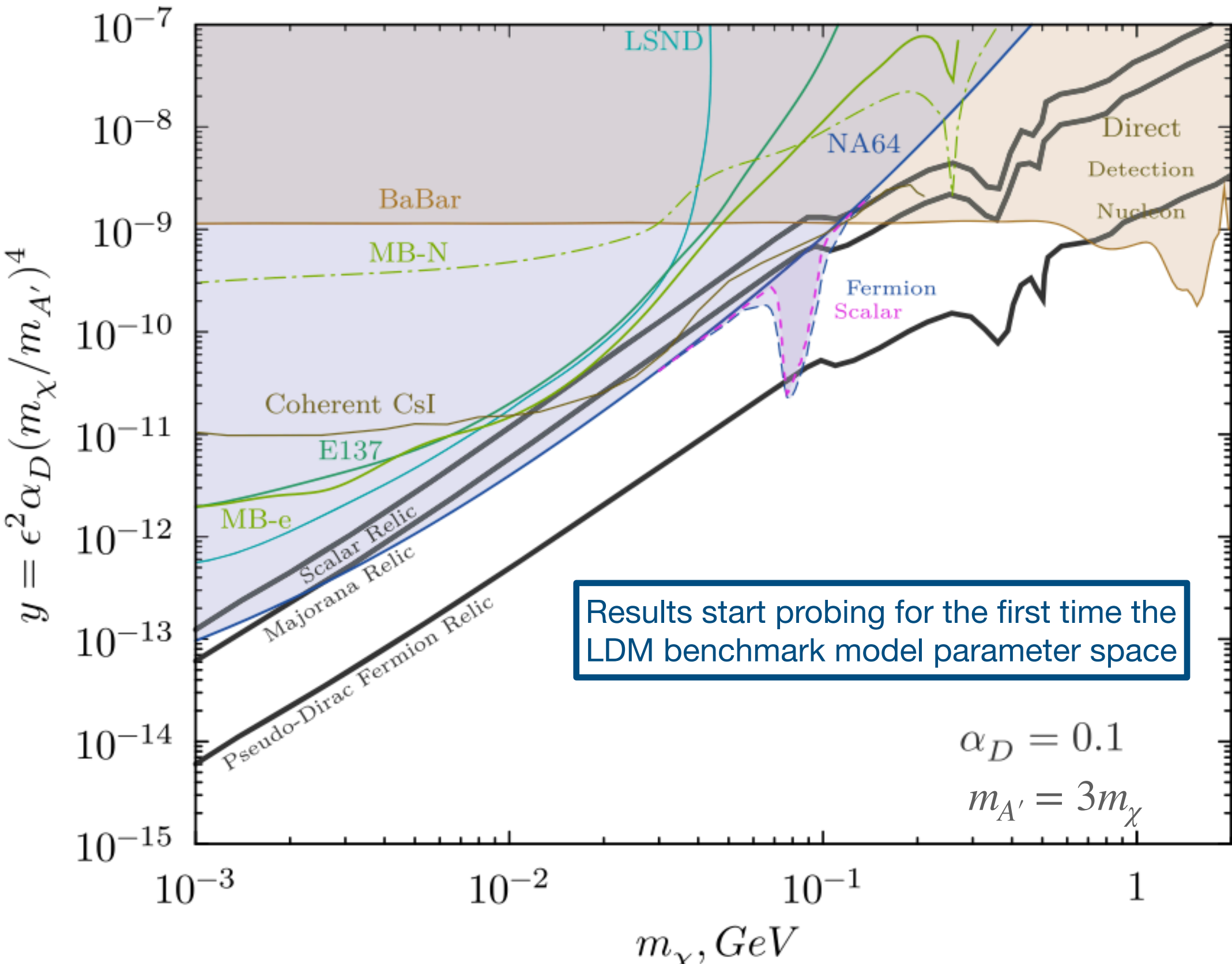
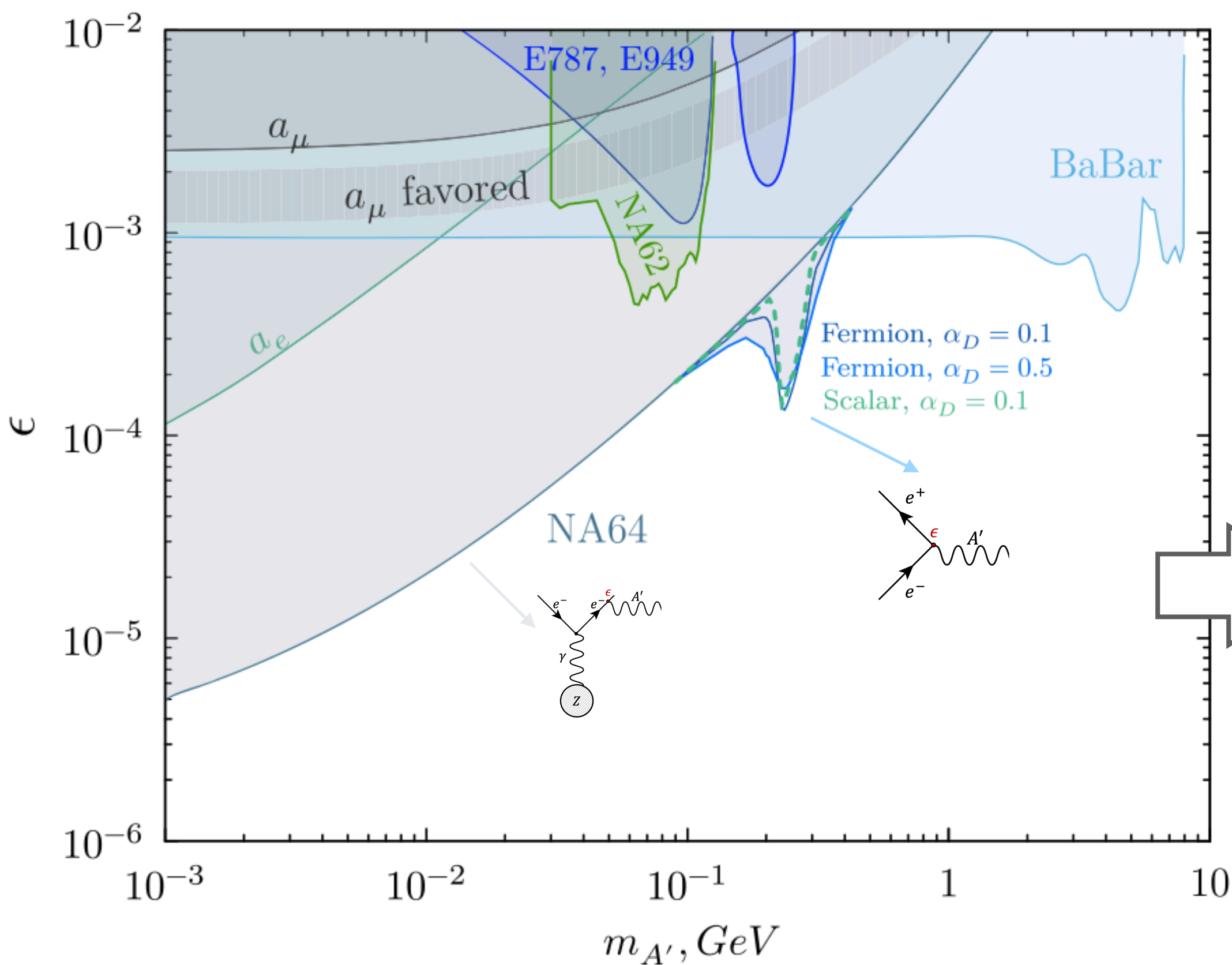
Signature:

- ♦ *Timing information*
- ♦ *Clean incoming track: angle + momentum ~100 GeV*
- ♦ *Electron identification: Synchrotron radiation + Shower profile compatible with e^- in ECAL*
- ♦ *No activity in Veto and in HCAL*

Searches for LDM using e^-

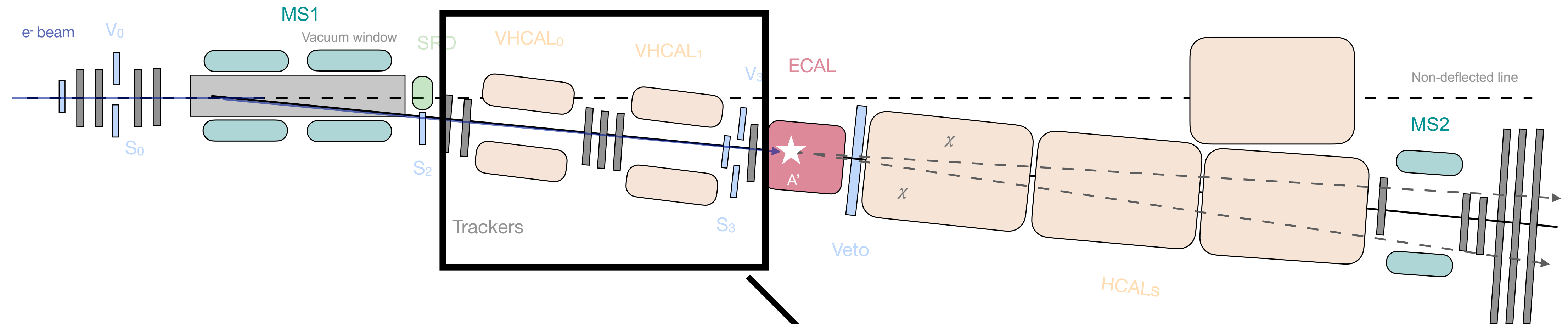


Background source	Background, n_b
1. Di-muons losses or decays in the target	0.04 ± 0.01
2. $\mu, \pi, K \rightarrow e + \dots$ decays in the beam line	0.3 ± 0.05
3. lost neutrals (γ, n, K^0) from upstream interactions	0.16 ± 0.12
4. Punch-through leading n, K_L^0	< 0.01
Total (conservatively) n_b	0.51 ± 0.13



NA64 collaboration, Phys. Rev. Lett. 131 (2023) no.16, 161801

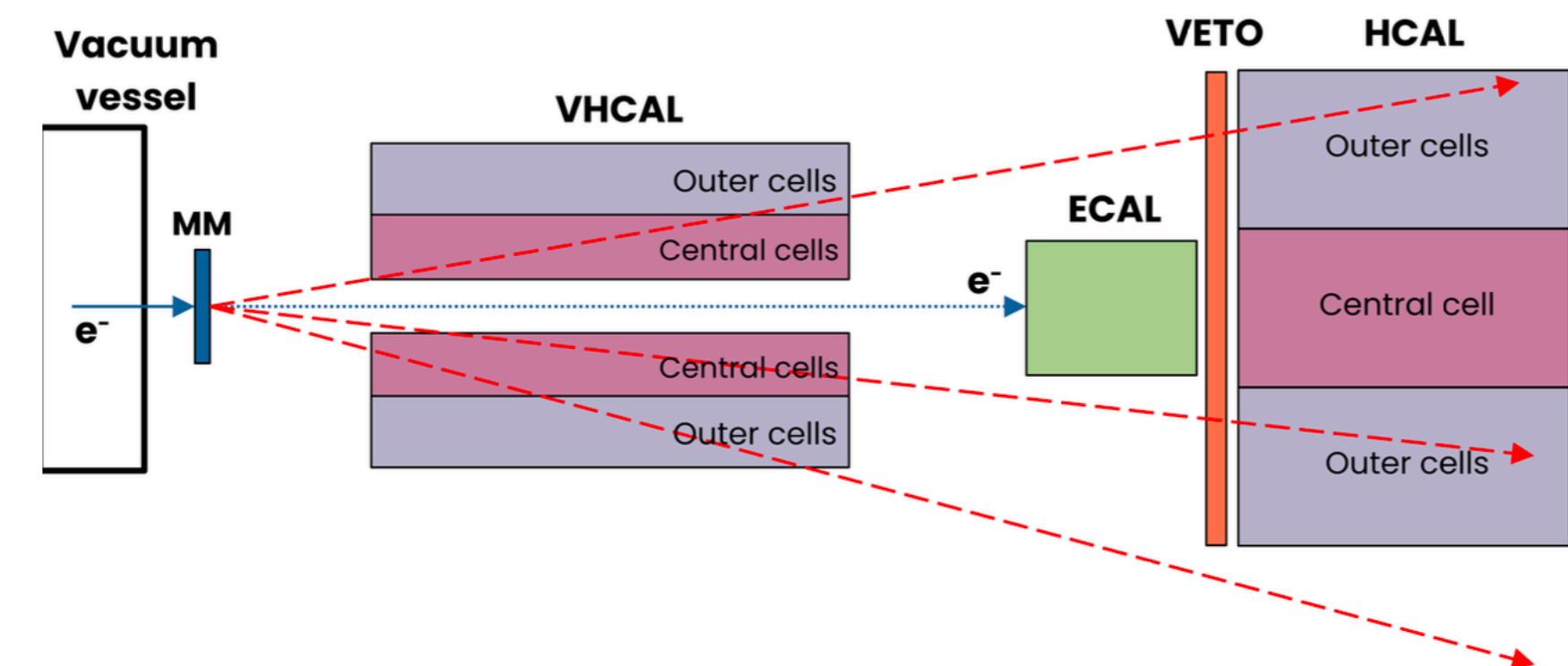
Searches for LDM using e^-



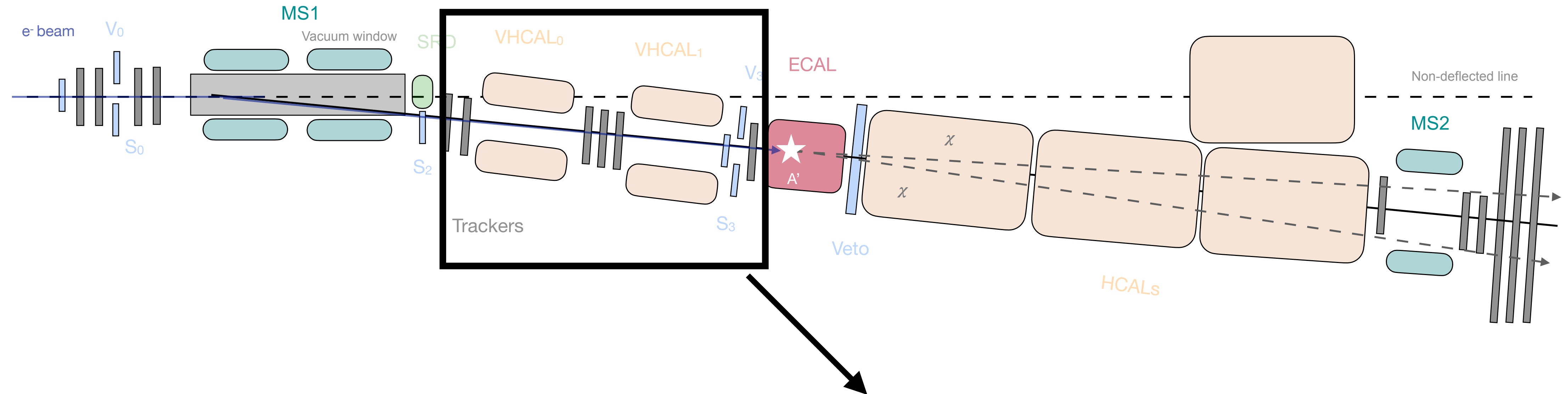
Setup improvements

Most dangerous background for invisible searches: large pt secondaries escaping the setup resulting from electro-nuclear interactions along the beamline

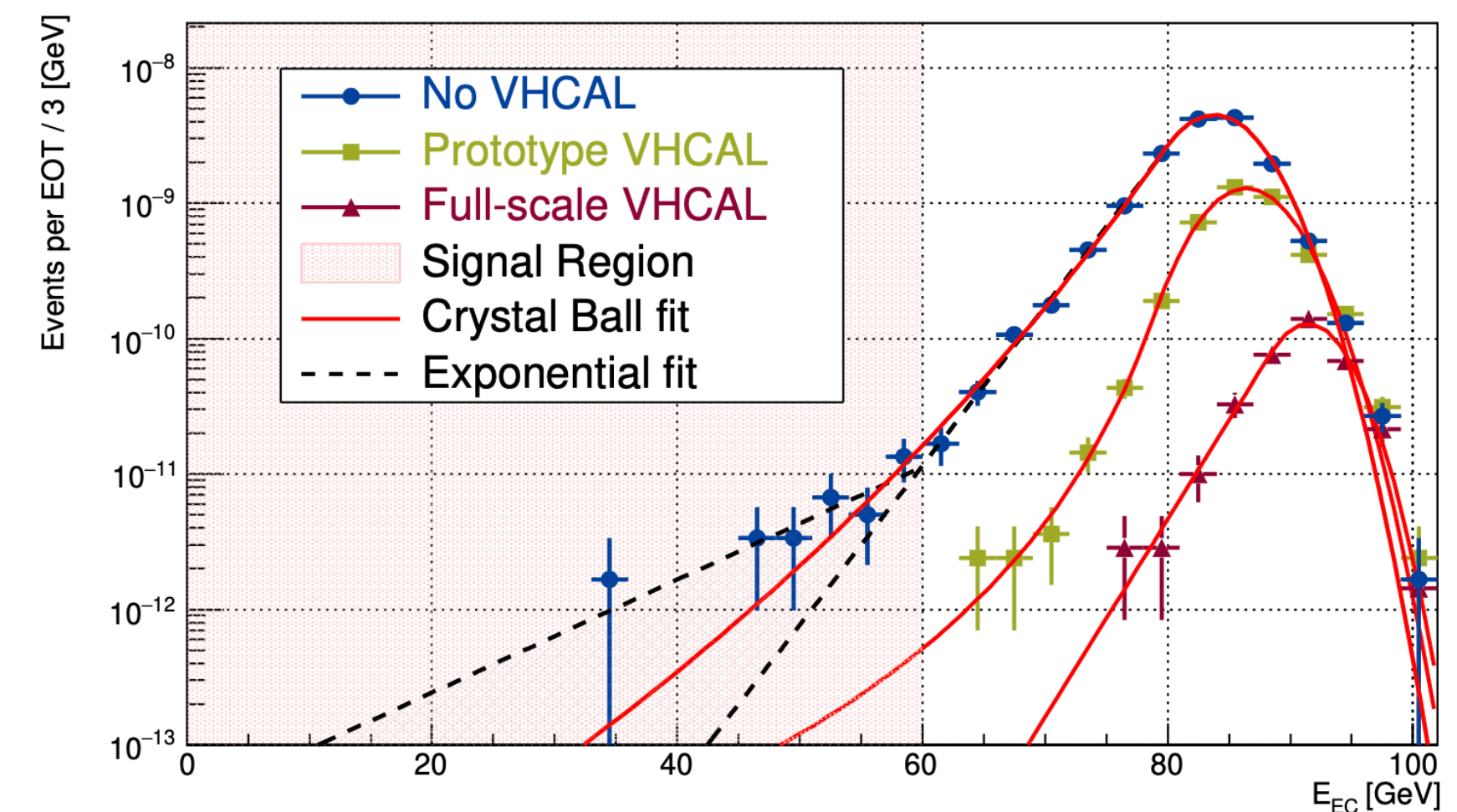
+ new Lyso-based SRD detector with lower synchrotron radiation threshold to reduce remaining μ , π ,... contaminants



Searches for LDM using e^-



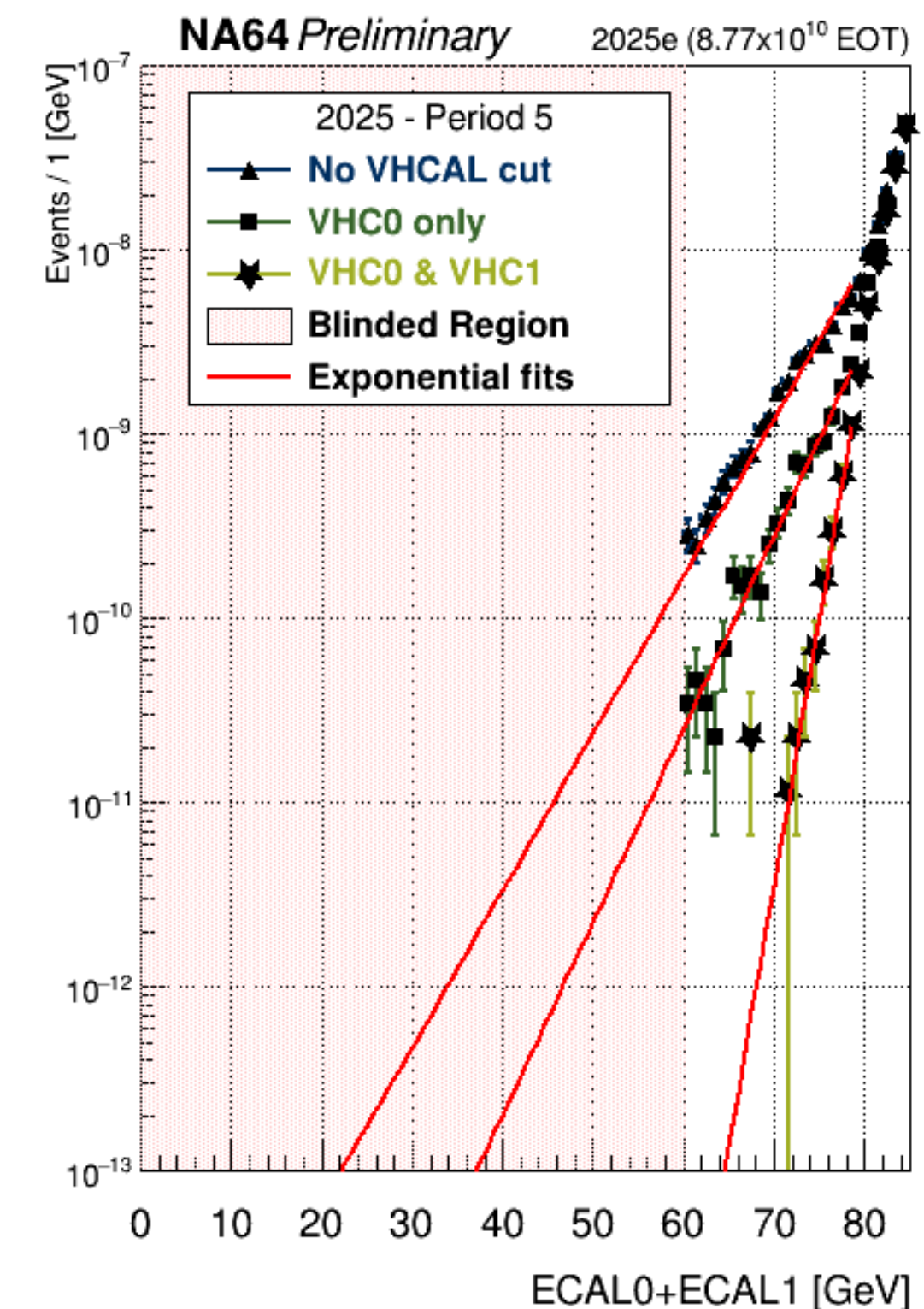
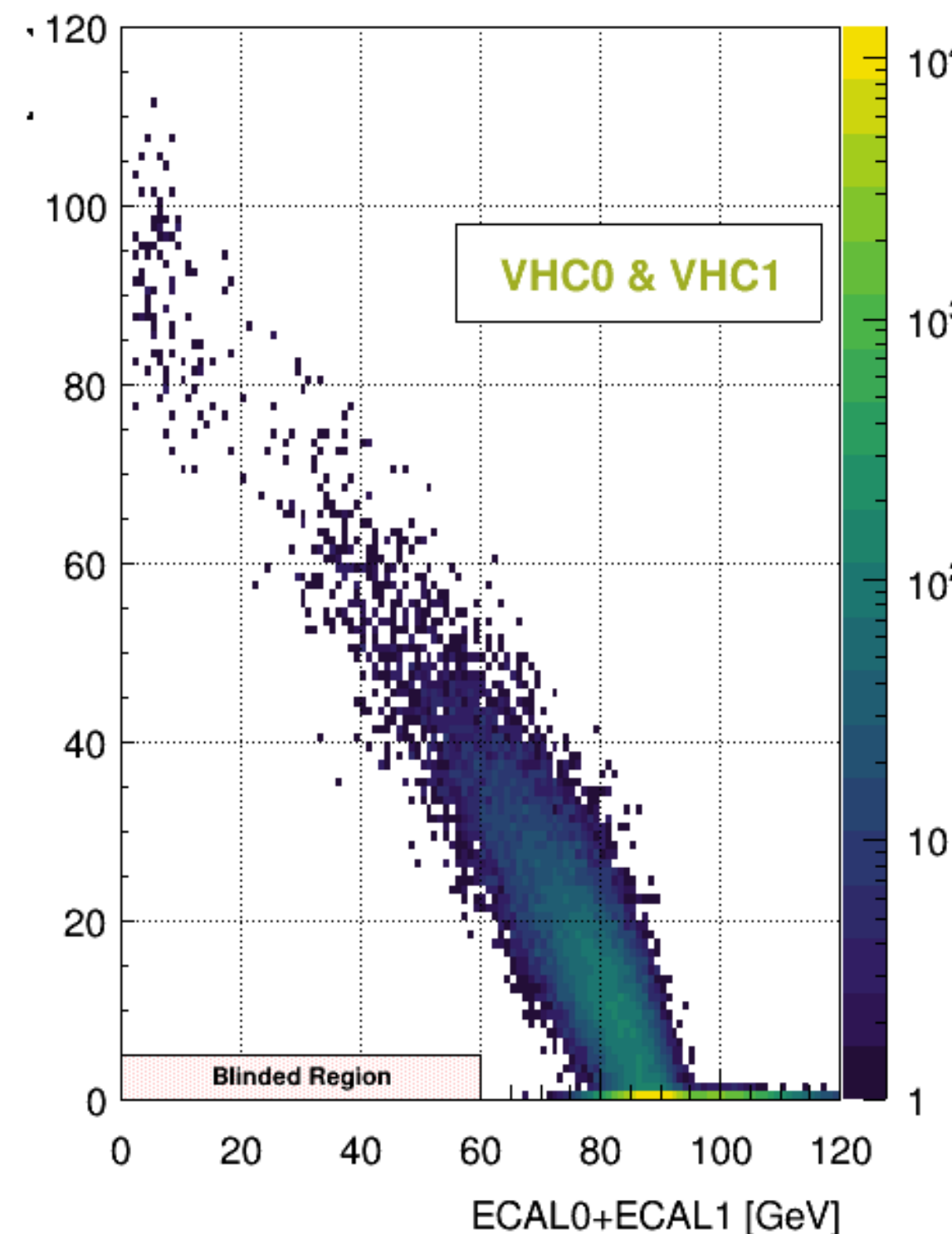
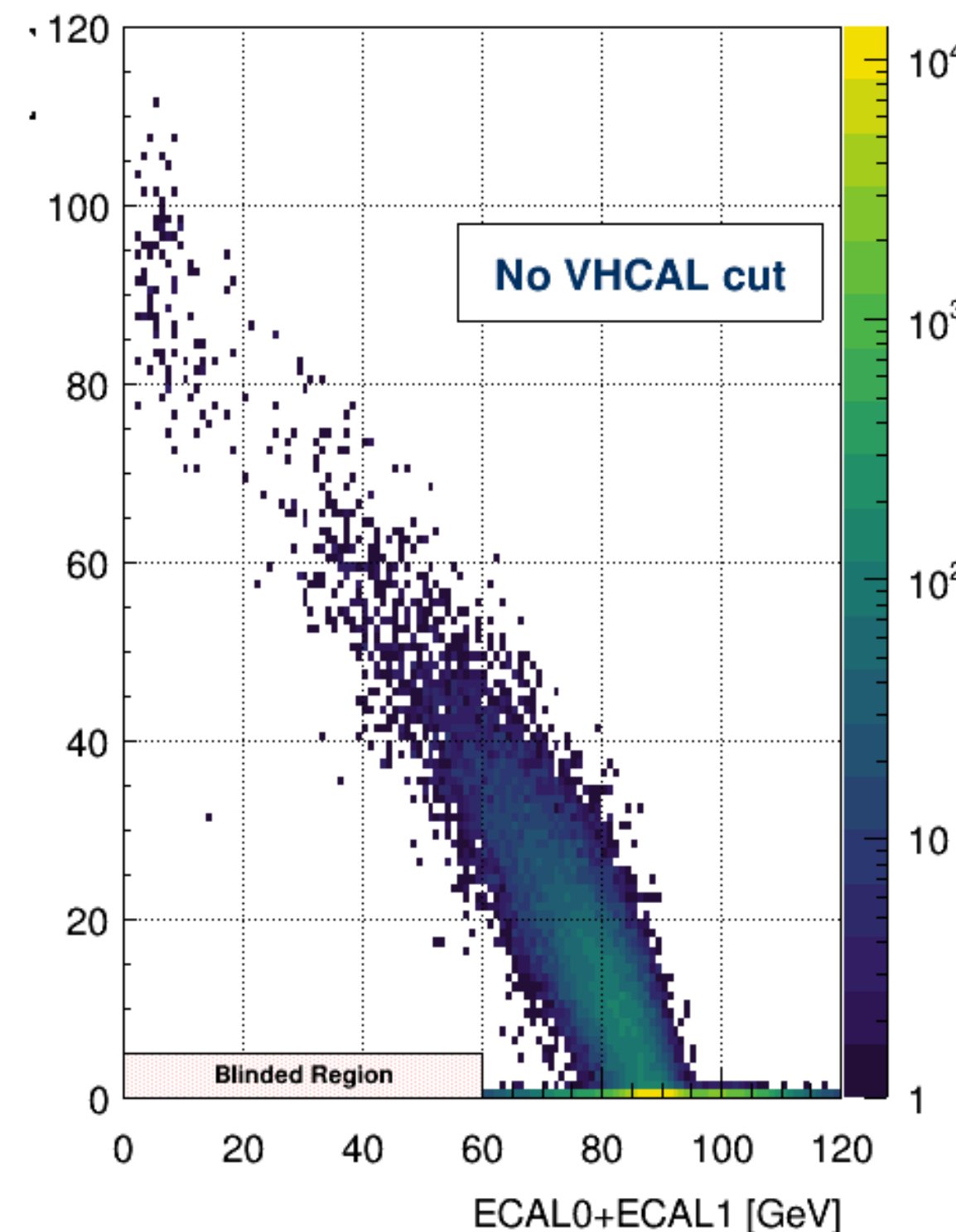
- 2023/2024 setup upgraded with a VHCAL prototype
- Monte Carlo (MC) developments to further understand the electro-nuclear processes: **NIM A 1081 (2026), 170830**



Searches for LDM using e^-

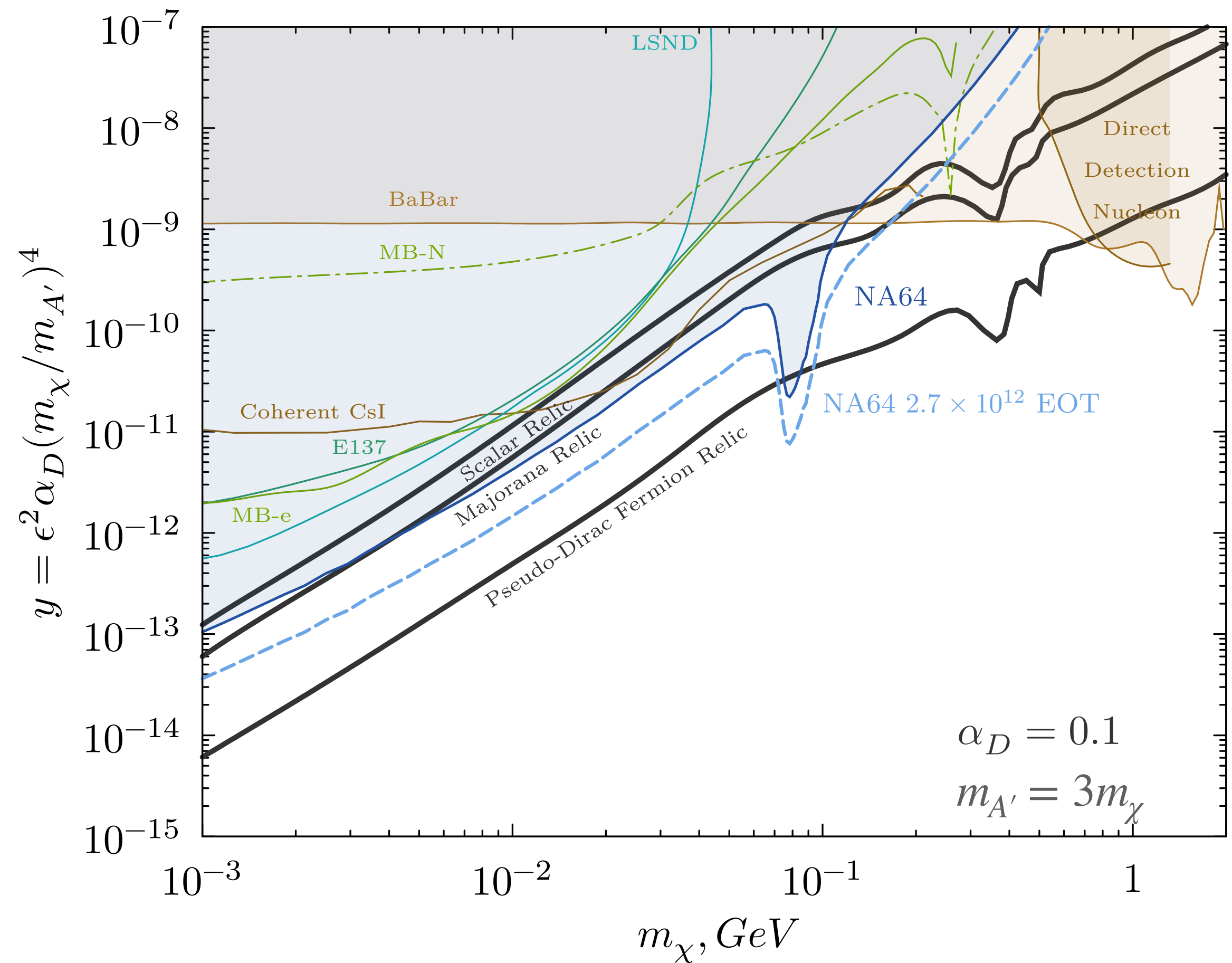
- ➔ **Optimisation of 2025 setup:** two VHCAL prototypes to improve detector hermeticity and to confirm our MC prediction.
- ➔ **Strategy:** compare performance between 1 VHCAL (2023/2024 samples) and 2 VHCAL (2025/2026 samples)
- ➔ *Data taking before LS3 successfully completed.*

PRELIMINARY RESULTS FROM 2025 ANALYSIS

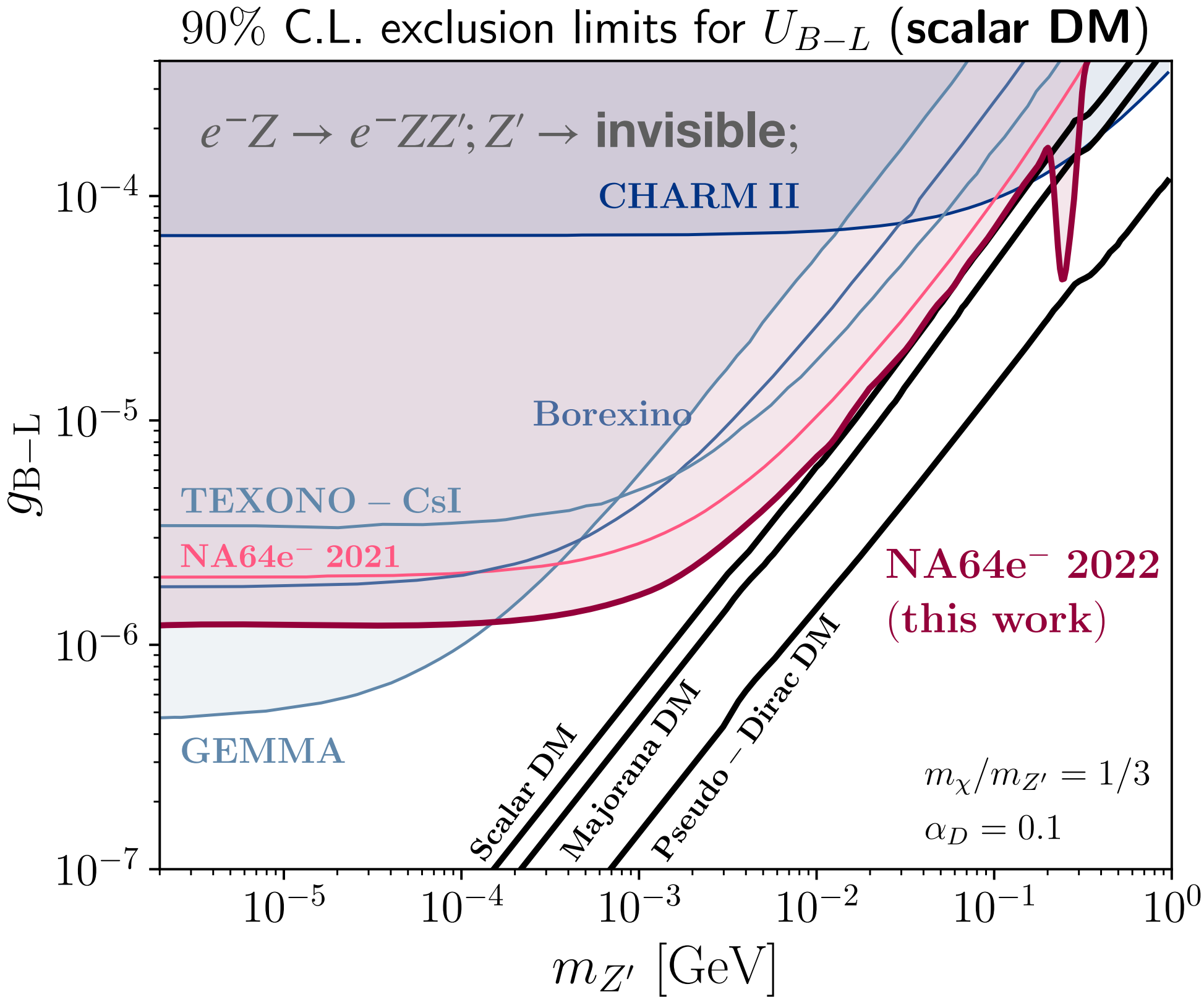
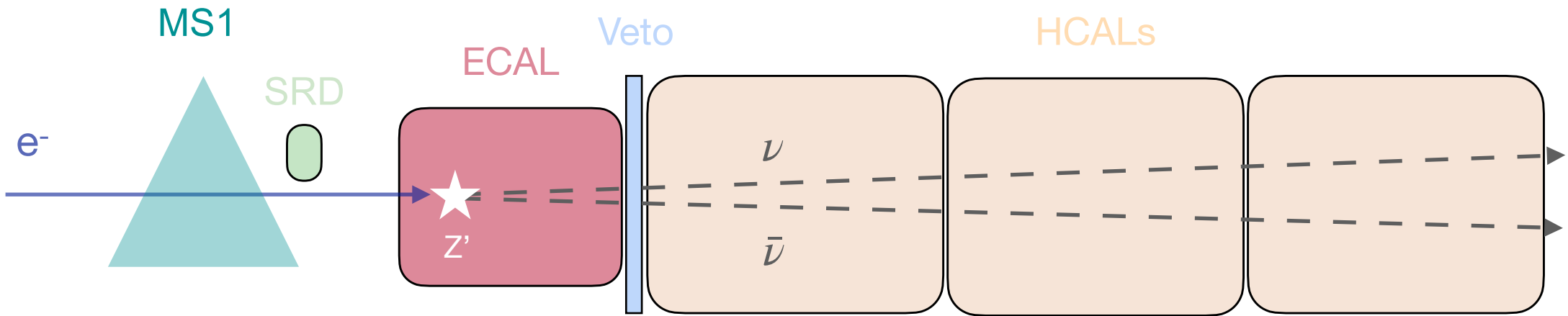


Searches for LDM using e^-

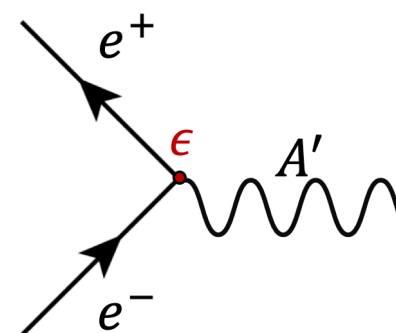
LDM projections for the statistics collected until 2026



NEW: “Improved limits on a new Z' in $B-L$ scenarios with the NA64 experiment at CERN” (paper accepted as CERN document)



Prospects for LDM searches: *NA64e⁺*

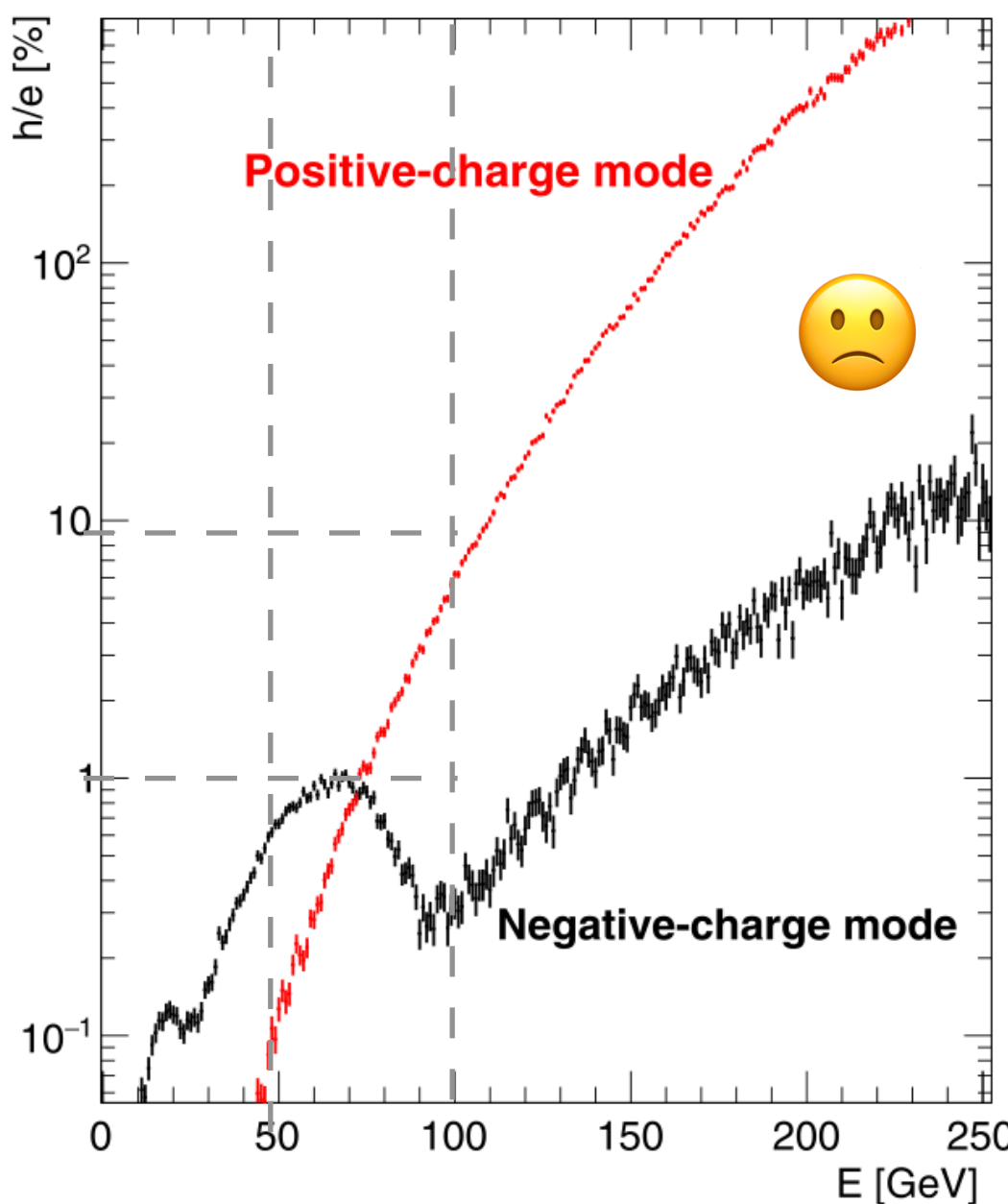
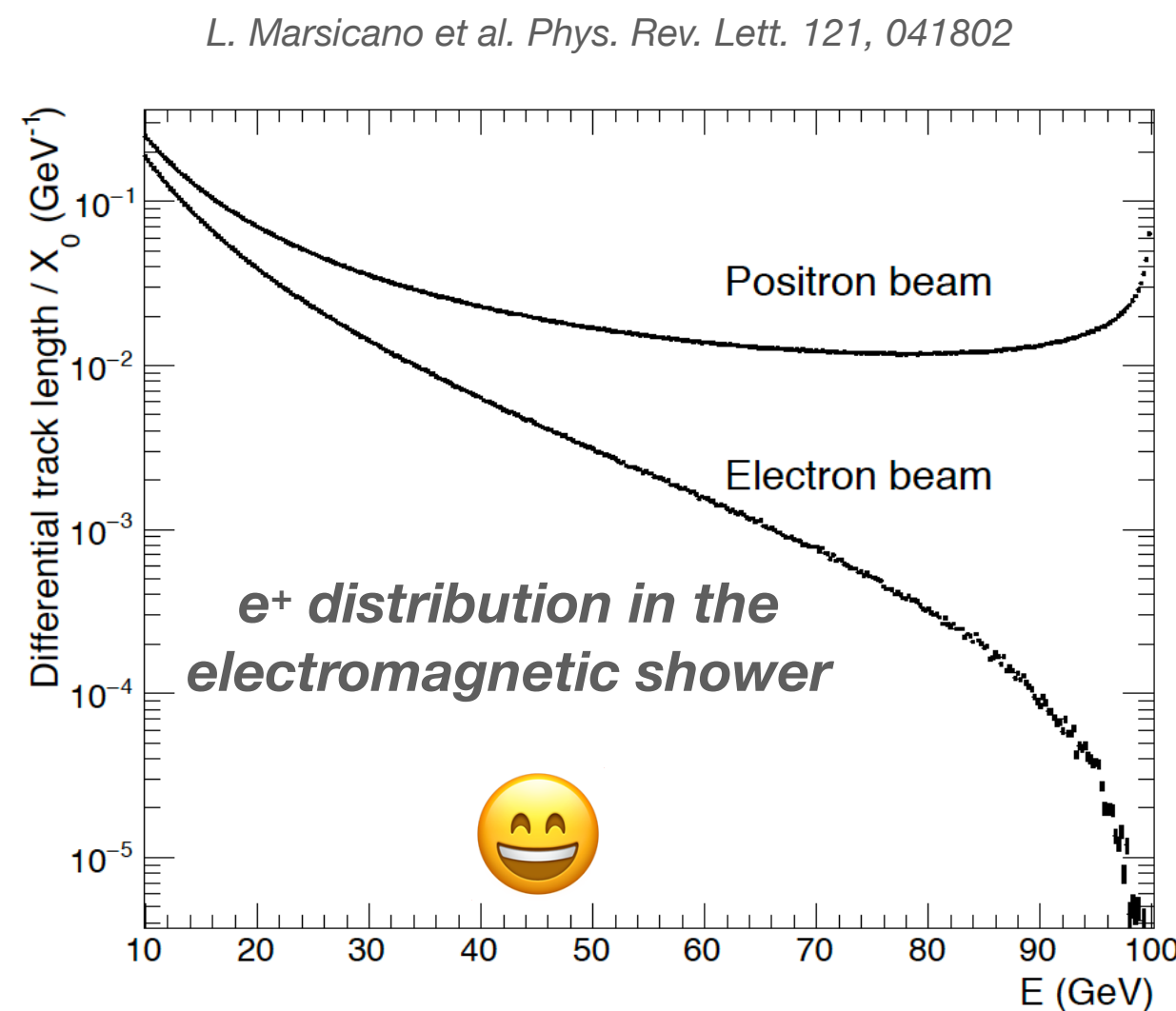


Resonant annihilation channel + e^+ beam to enhance the signal yield for A' masses > 100 MeV

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

$$\sqrt{2m_e E_{thr}} \leq m_{A'} \leq \sqrt{2m_e E_0}$$

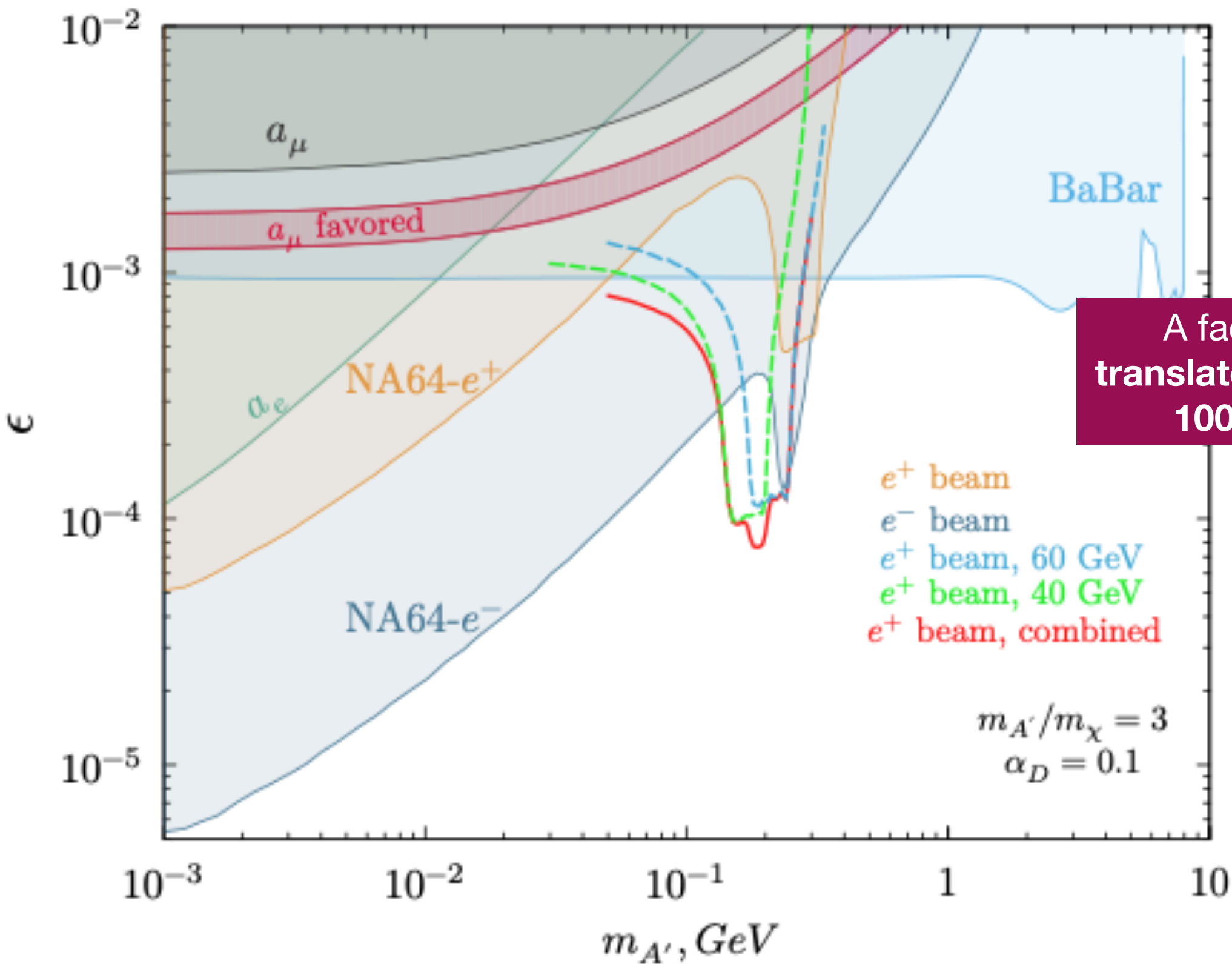
Key aspects: demonstrate the scanning of different A' masses using different initial e^+ energies, hadronic contamination at the different energies and hermeticity



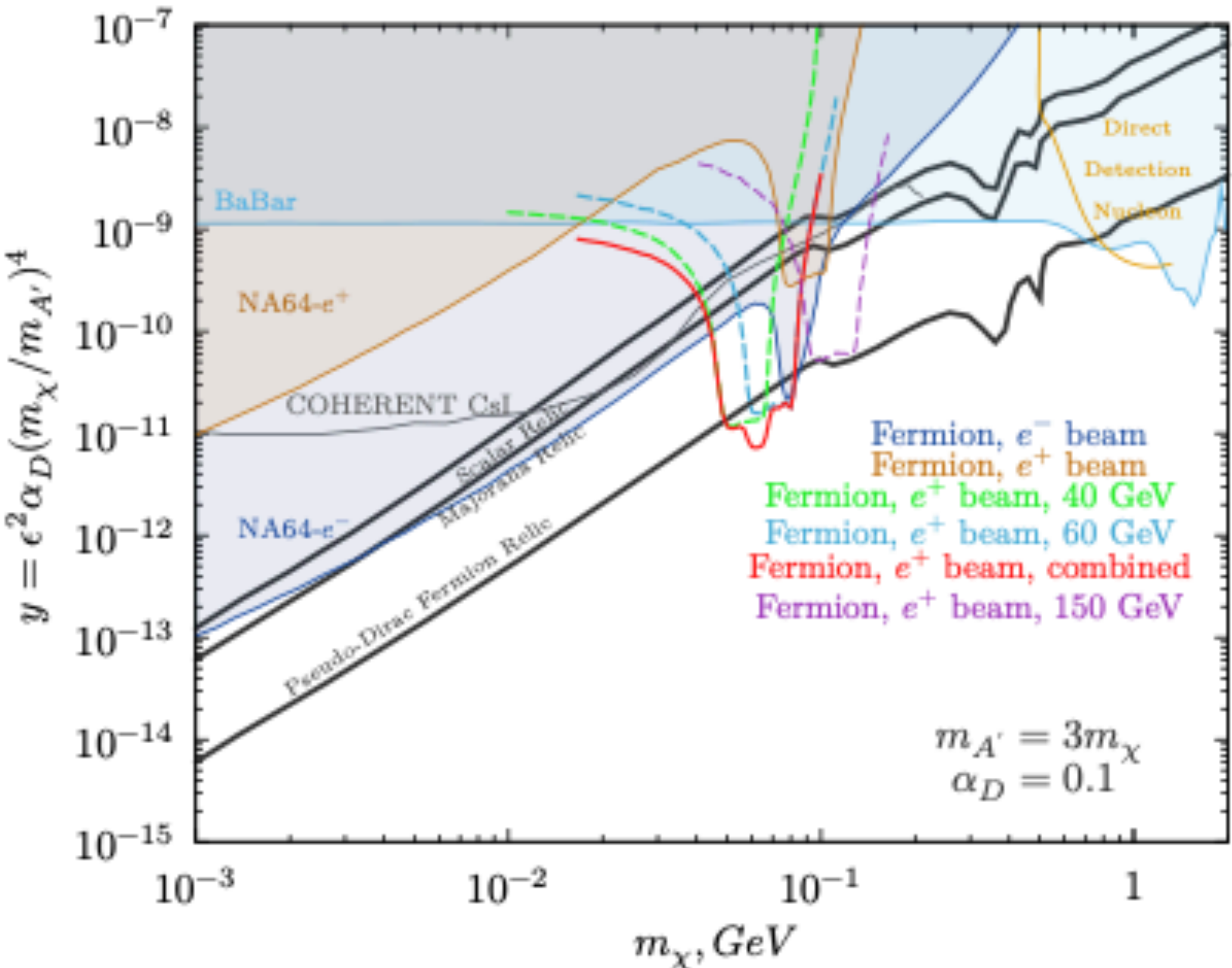
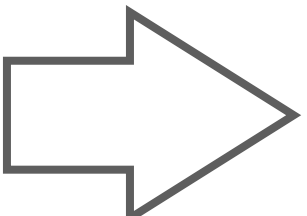
Hadron contamination at the H4 beamline for e^+ and e^- beams

Prospects for LDM searches: *NA64e⁺*

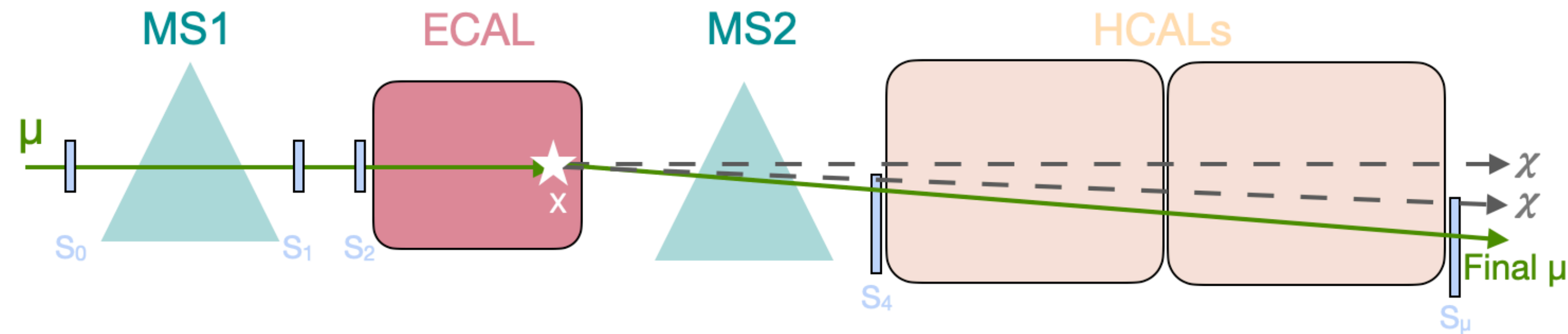
- **Goal:** scan different energies (40-100 GeV) to improve the sensitivity in the region $140 \leq m_\chi \leq 250$ MeV ($> 10^{11}$ e⁺oT per energy)
- ➔ **Ongoing setup optimisation:** new lyso-based SRD (already tested in 2024), hermeticity, hadron contamination,...
- ➔ **First results:** @100 GeV (Phys. Rev. D 109, L031103 (2024) and @ 70 GeV (JHEP 06 (2025), 256)



A factor 10 on ϵ
translates into a factor
100 on y ($\sim \epsilon^2$)



Prospects for LDM searches: *NA64μ*



$$\sigma \sim g'^2 Z^2 \alpha^2 / m^2$$

$X = A', Z', \dots$

1) **M2: unique** high energy (up to 250 GeV) and high intensity (up to $10^7 \mu/s$) muon beam 😊

2) Measure p_{in} (~ 160 GeV)

3) Increased signal yield (full length of the target contributing to the yield)

4) Measure p_{out} (< 80 GeV)

5) Tag muons and catch secondaries

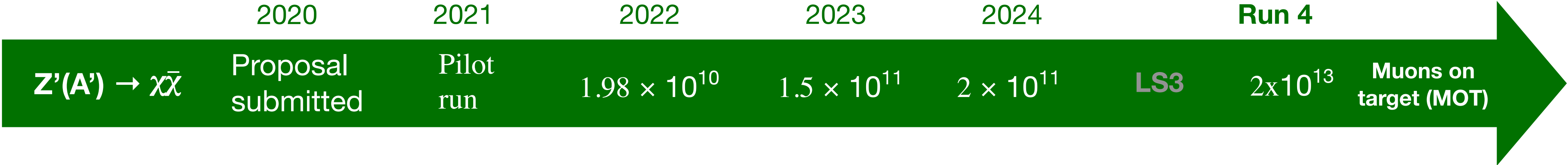
Experimental signature: *missing energy* + *missing momentum*



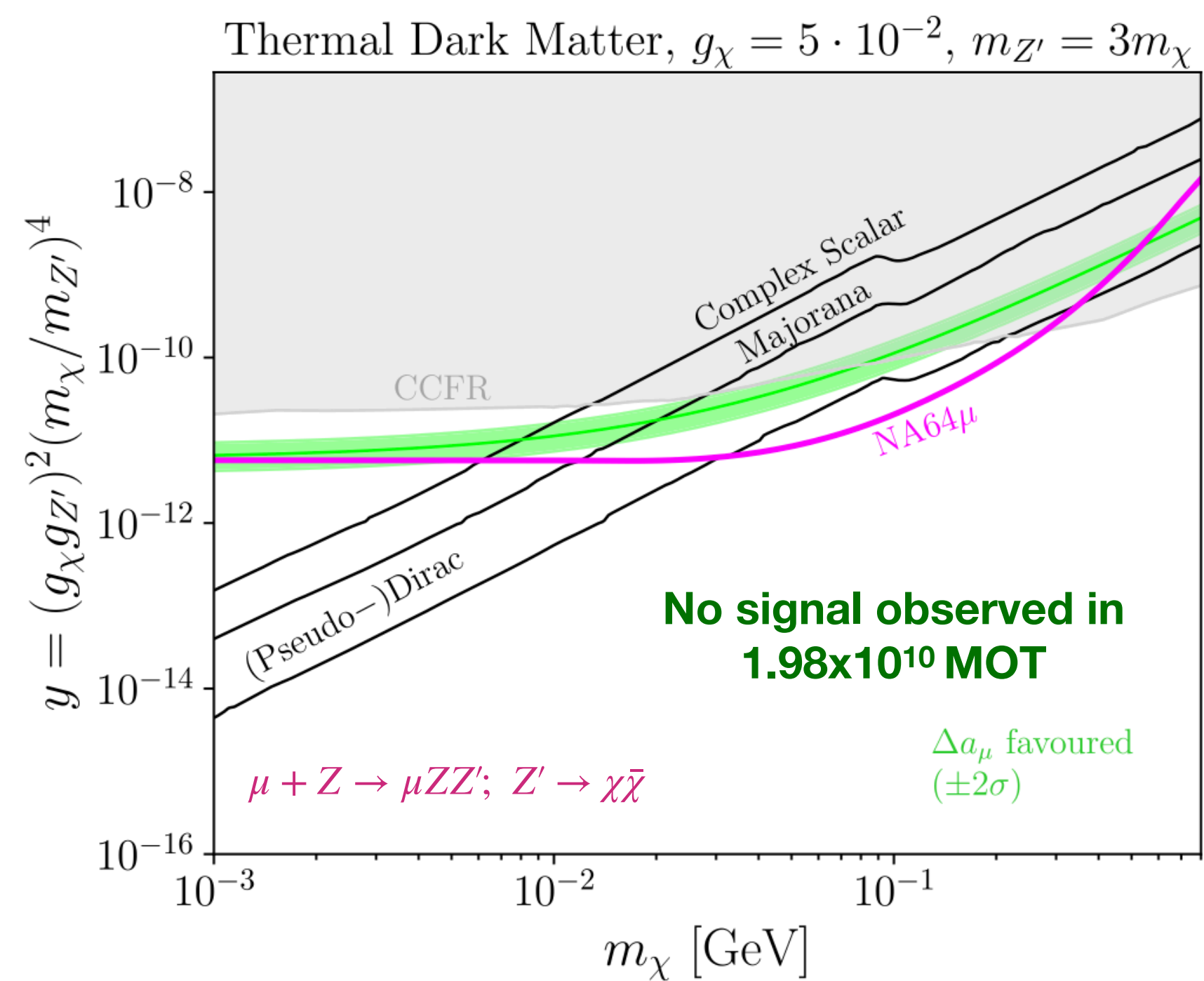
Prospects for LDM searches: *NA64μ*

NA64 collaboration, Phys. Rev. Lett. 132 (2024) no.21, 211803

NA64 collaboration Phys. Rev. D **110** (2024) no.11, 112015



Strategy: two analysis in 2023 and 2024 data



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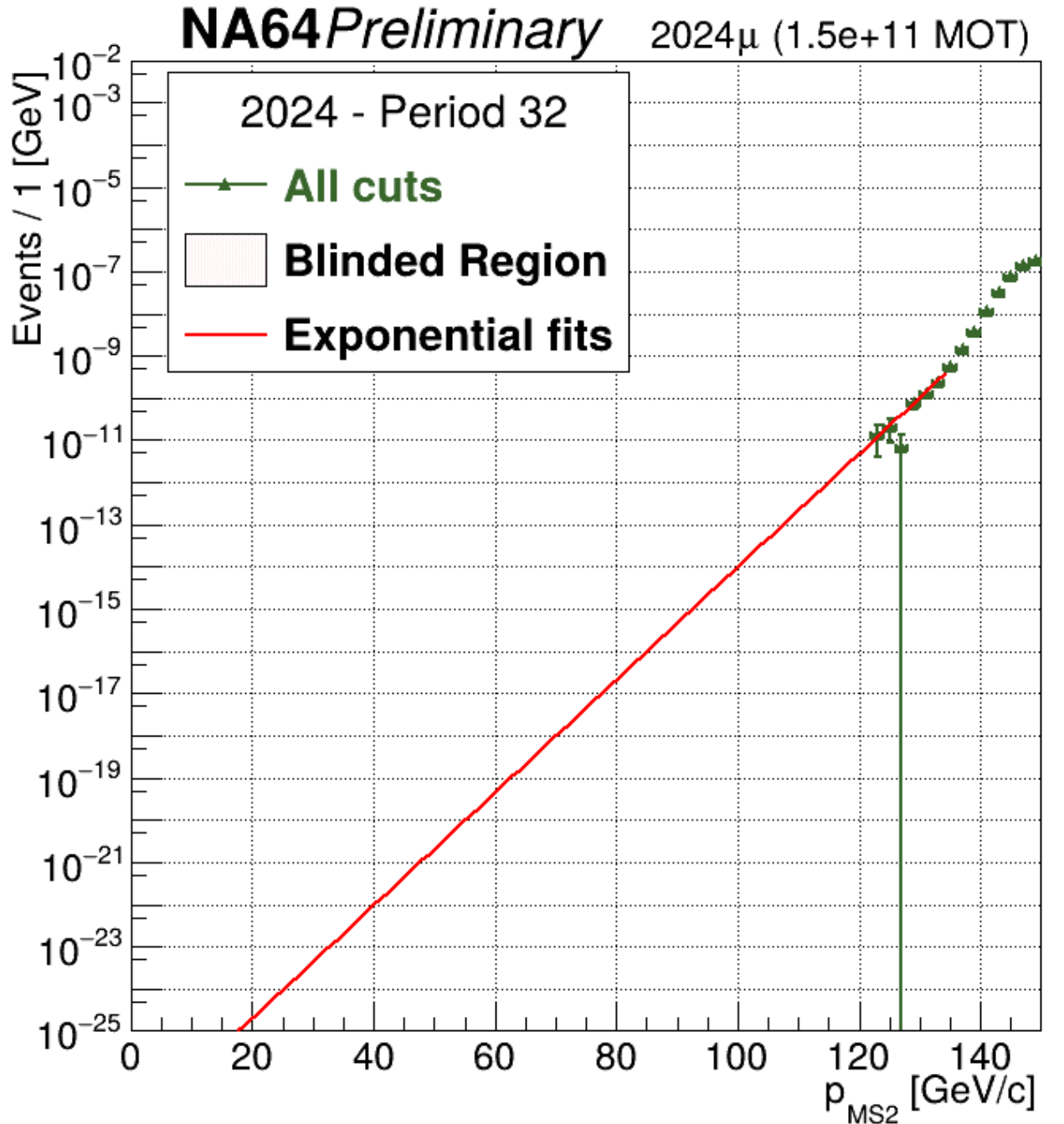
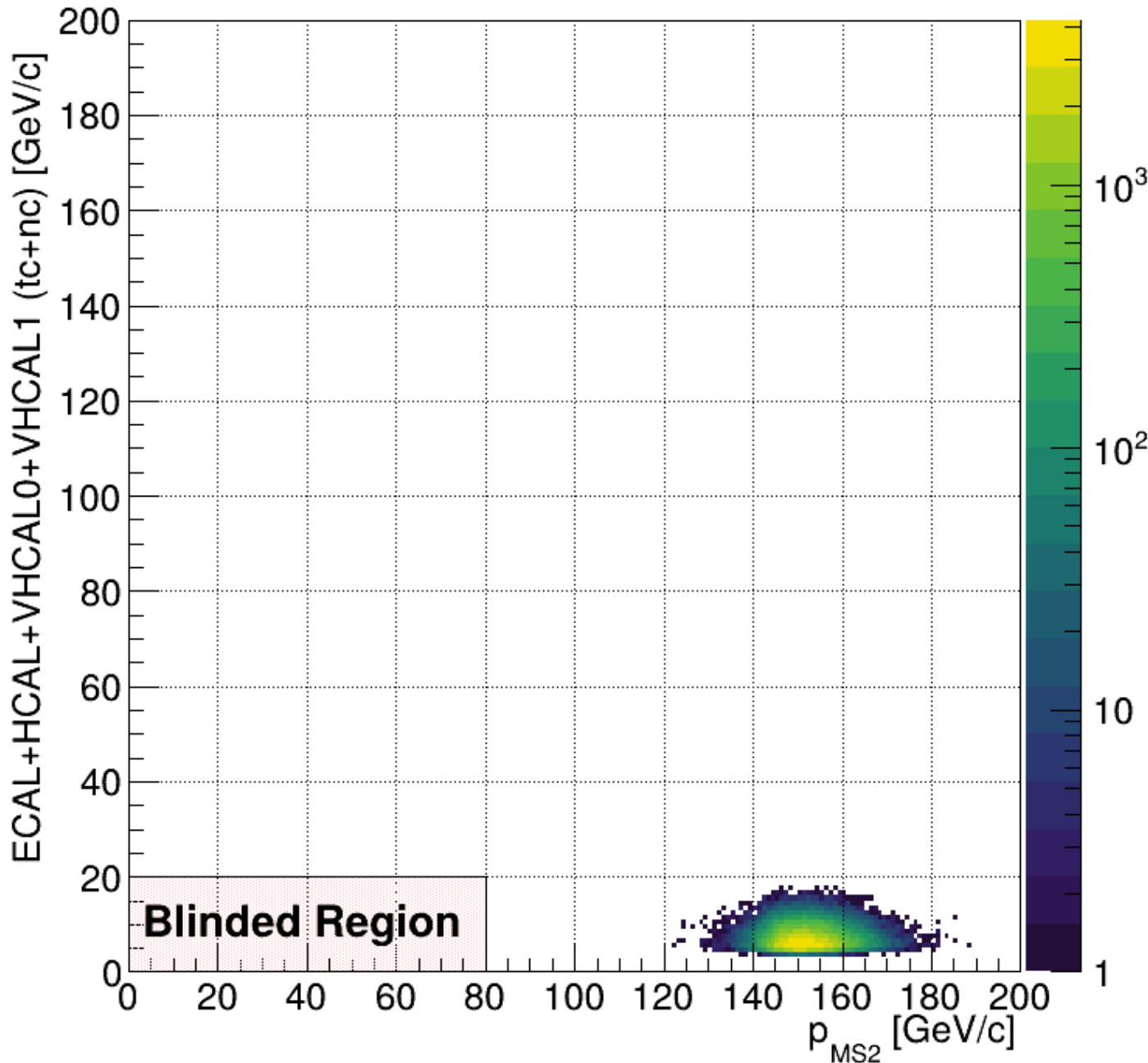
First Results in the Search for Dark Sectors at NA64 with the CERN SPS High Energy Muon Beam

Yu. M. Andreev *et al.*
Phys. Rev. Lett. **132**, 211803 – Published 21 May 2024

PhysiCS See synopsis: [Careful Accounting Could Reveal the Dark Sector](#)

Background source	Background, n_b
(I) Momentum misreconstruction	0.05 ± 0.03
(II) $K \rightarrow \mu + \nu, \dots$ in-flight decays	0.010 ± 0.001
(III) Calorimeter non-Hermiticity	< 0.01
Total nb (conservatively)	0.07 ± 0.03

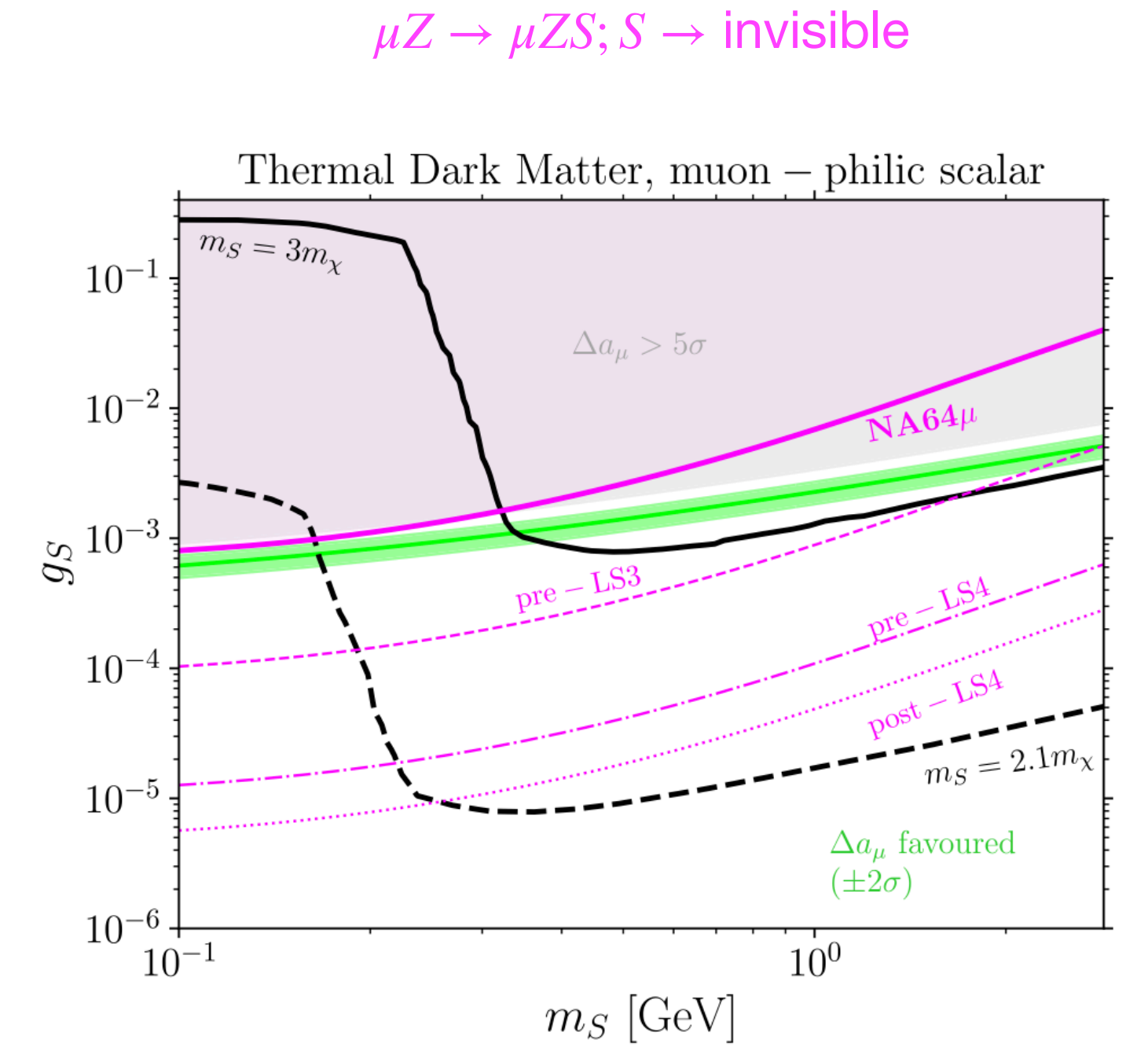
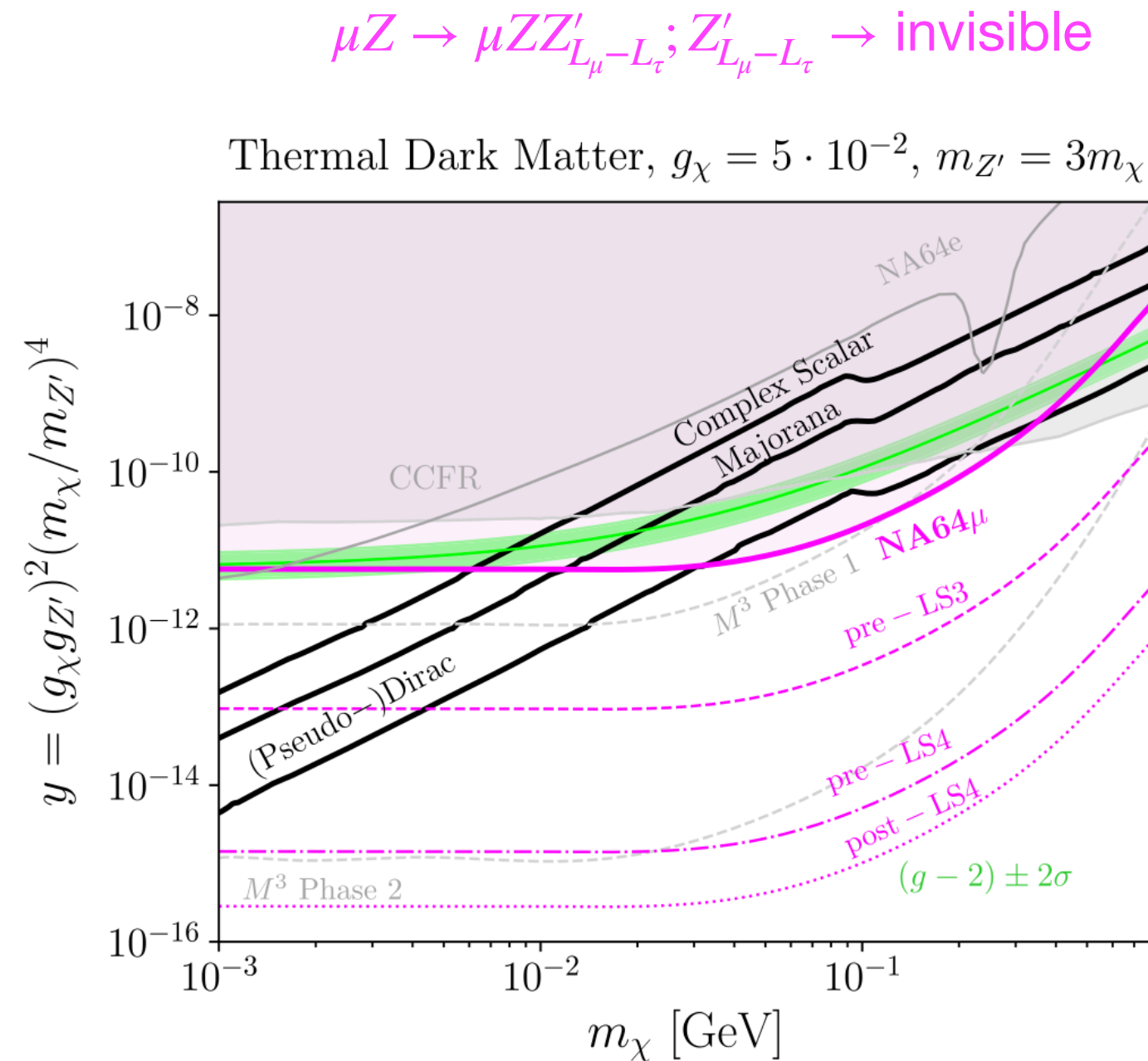
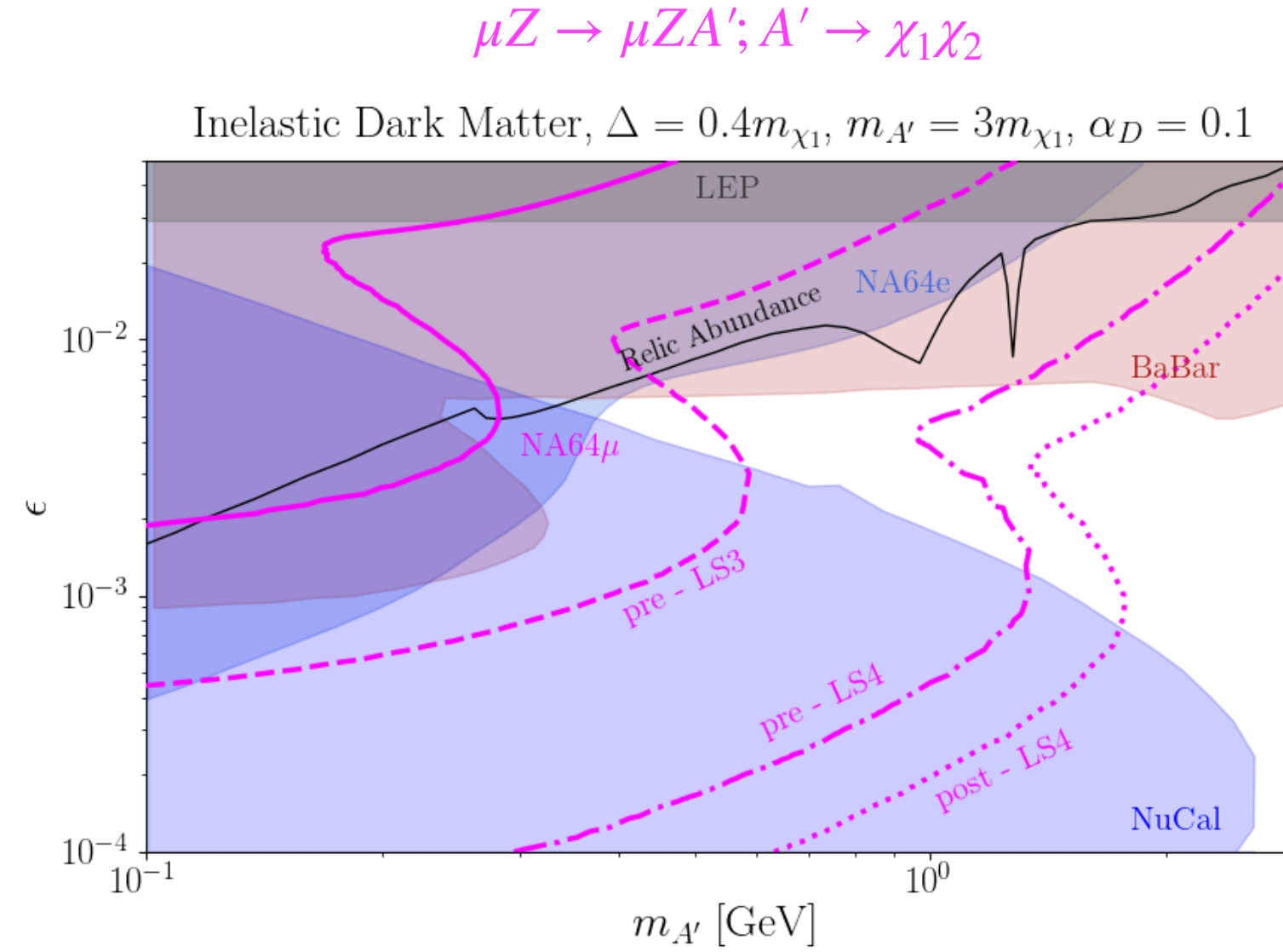
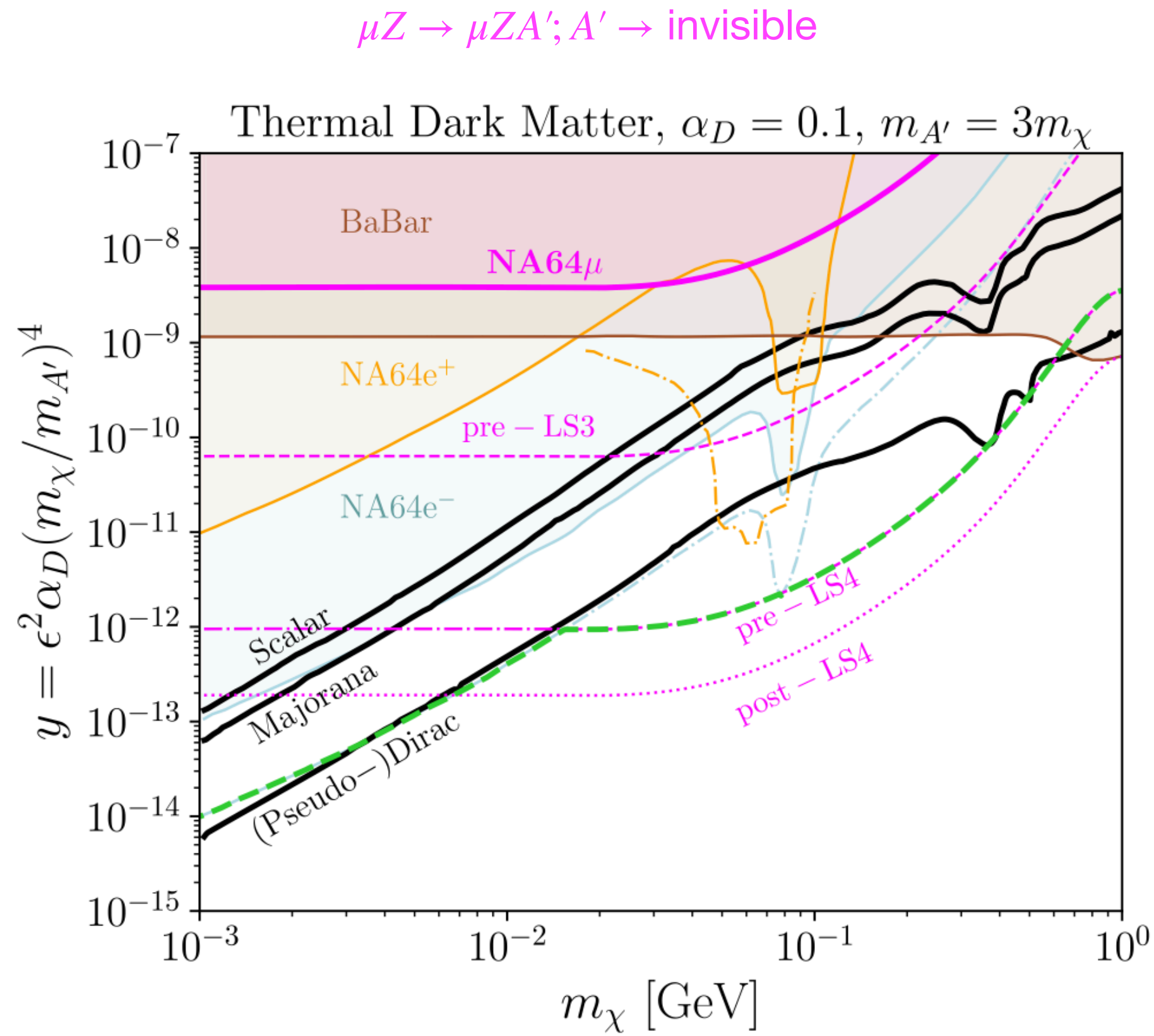
—> **Goal in 2023/2024:** optimise the setup to further suppress background and increase intensity



Prospects for LDM: *NA64μ*

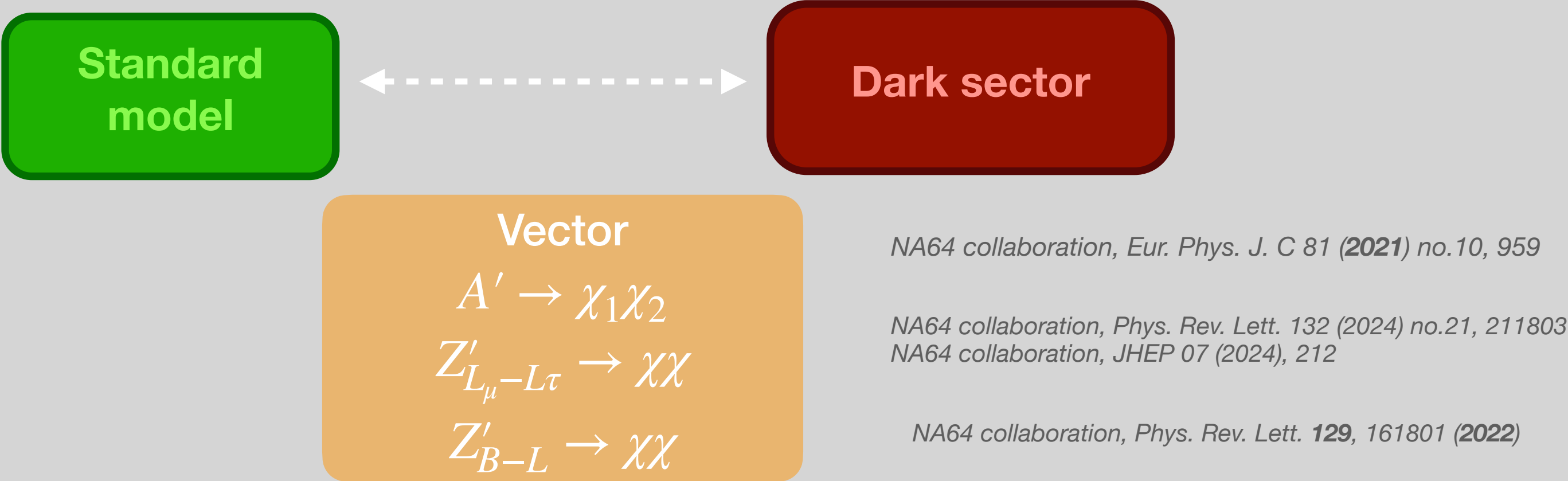
NA64 collaboration Phys. Rev. D **110** (2024) no.11, 112015

LDM projections with the 2023-2024 statistics

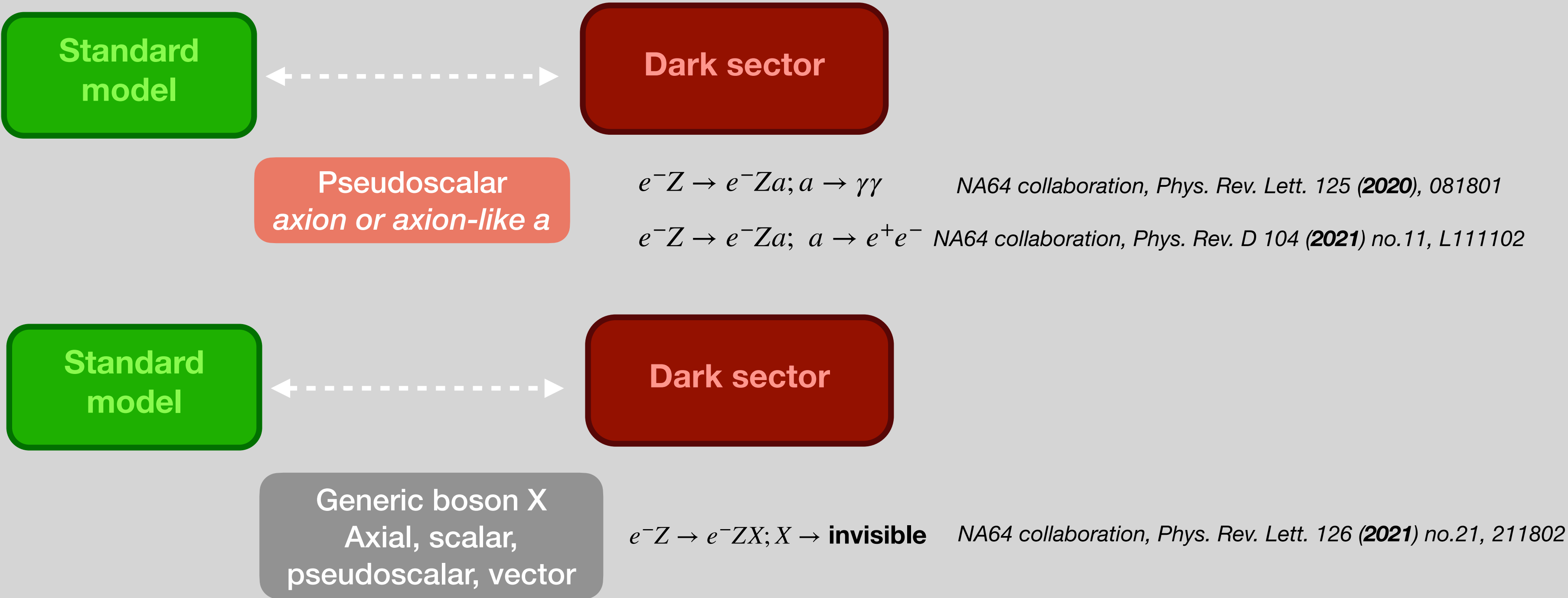


We are currently designing the upgrade of the setup for the next phase after CERN shutdown.

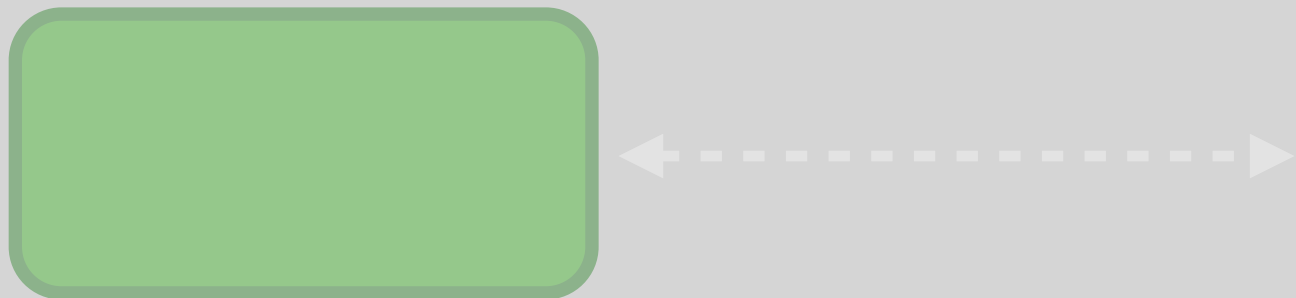
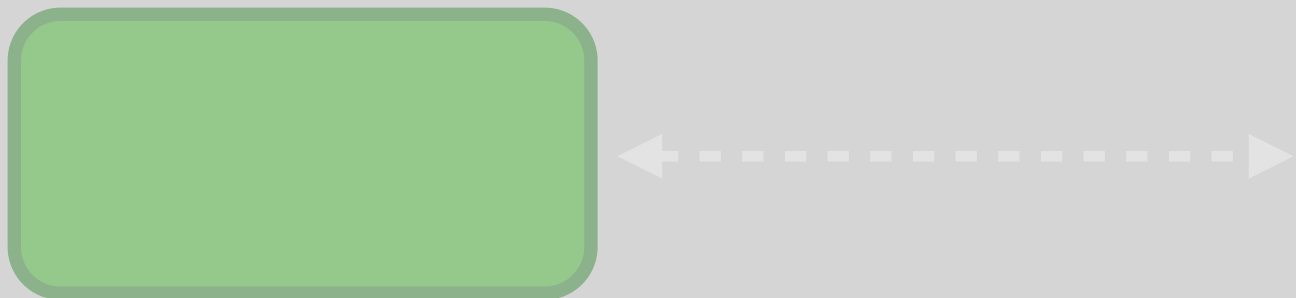
Beyond $A' \rightarrow invisible$ searches



NA64e⁻
Results obtained
with 2016-2018 data
(2.84x10¹¹ EOT)



Beyond $A' \rightarrow \text{invisible}$ searches



Work in progress

- 2016-2026 data: factor 10 more statistics
- NEW: complementarity of these scenarios and new ones with a muon beam

S.N. Gninenko, *et al.* “Probing millicharged particles with NA64μ and LDMX,” Eur. Phys. J. C 86 (2026) no.2, 140

P. Crivelli, J. Hernandez-Garcia, J. Lopez-Pavon, V. Martin Lozano and L. Molina Bueno,, “First bounds on effective muon interactions using the NA64μ experiment at CERN,”

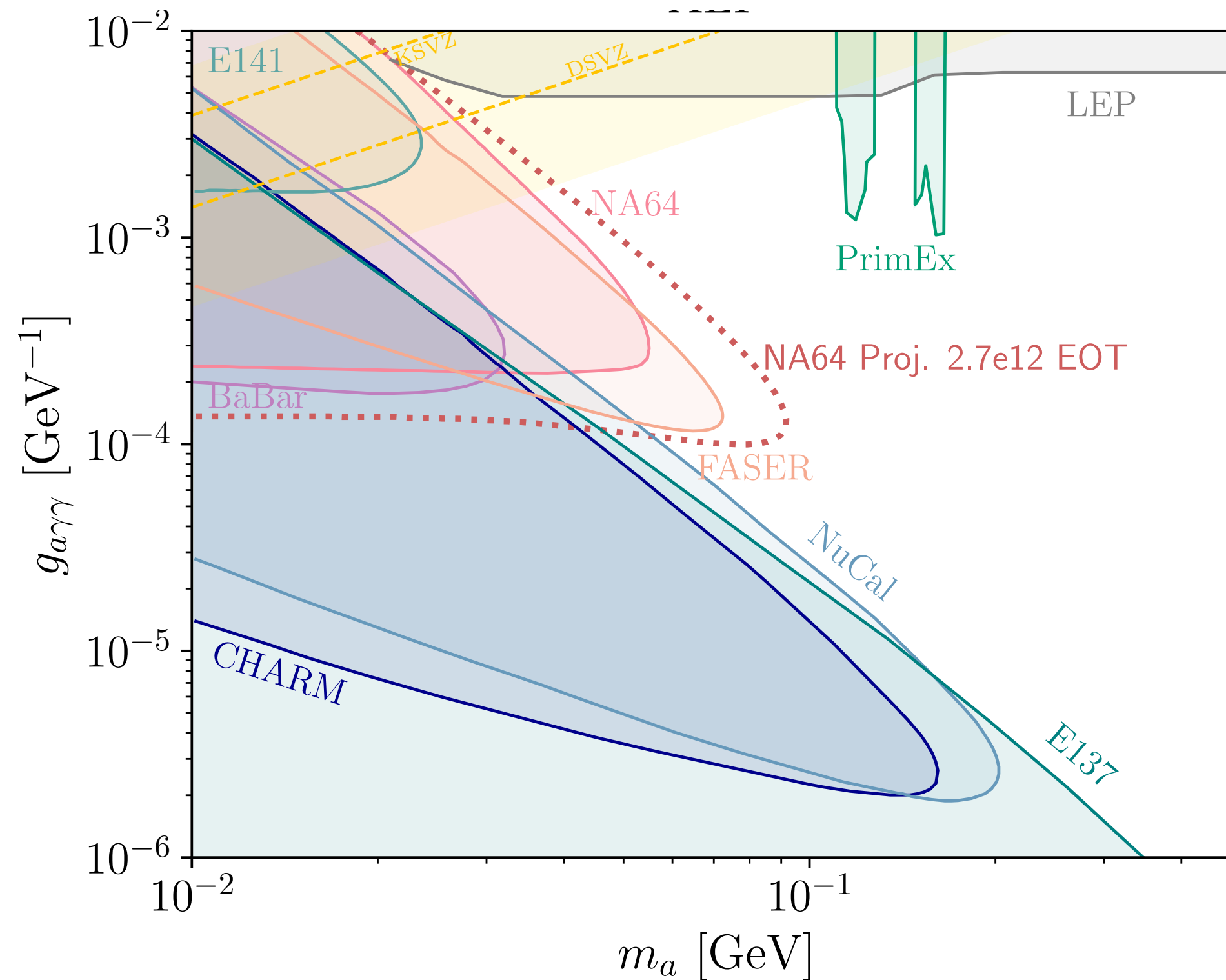
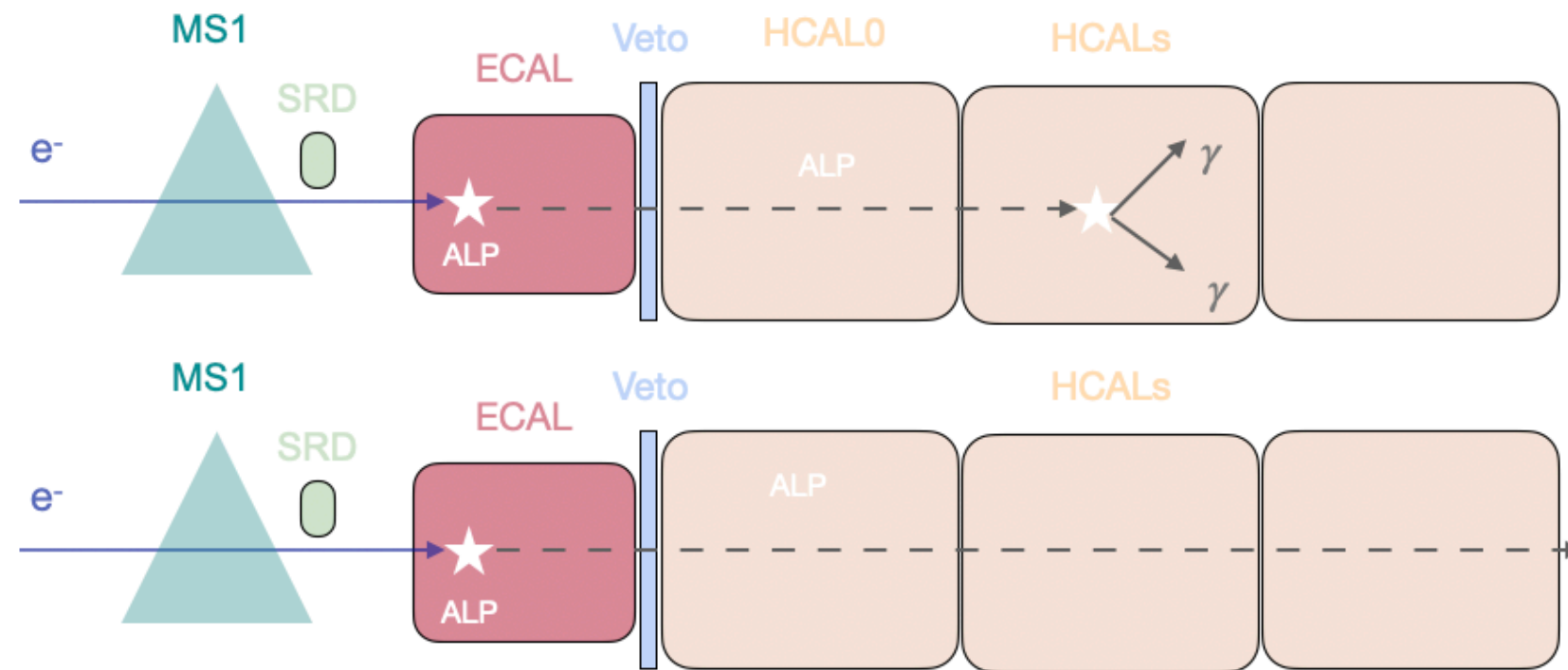
$e^-Z \rightarrow e^-Z\alpha$, $\alpha \rightarrow e^-e^+$

See also more details about the future prospects of these searches and many others at Belle II, SHIP and LDMX experiments in the Light Dark Matter session.

$e^-Z \rightarrow e^-ZX$; $X \rightarrow \text{invisible}$

Axion and Axion-like particles

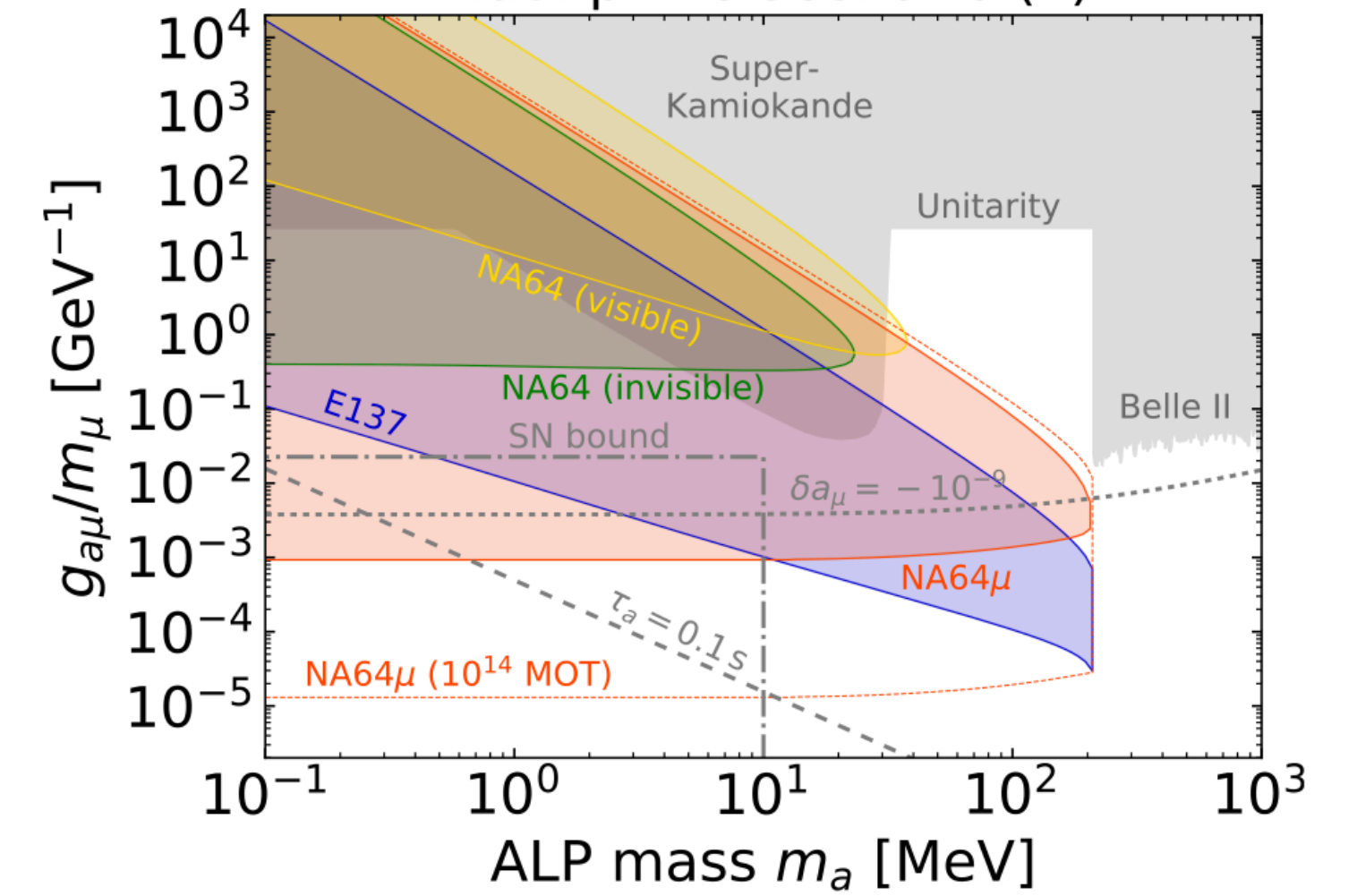
$$e^-Z \rightarrow e^-Za; a \rightarrow \gamma\gamma$$



A. Eberhart *et al.*, [arXiv:2504.05873 [hep-ph]].

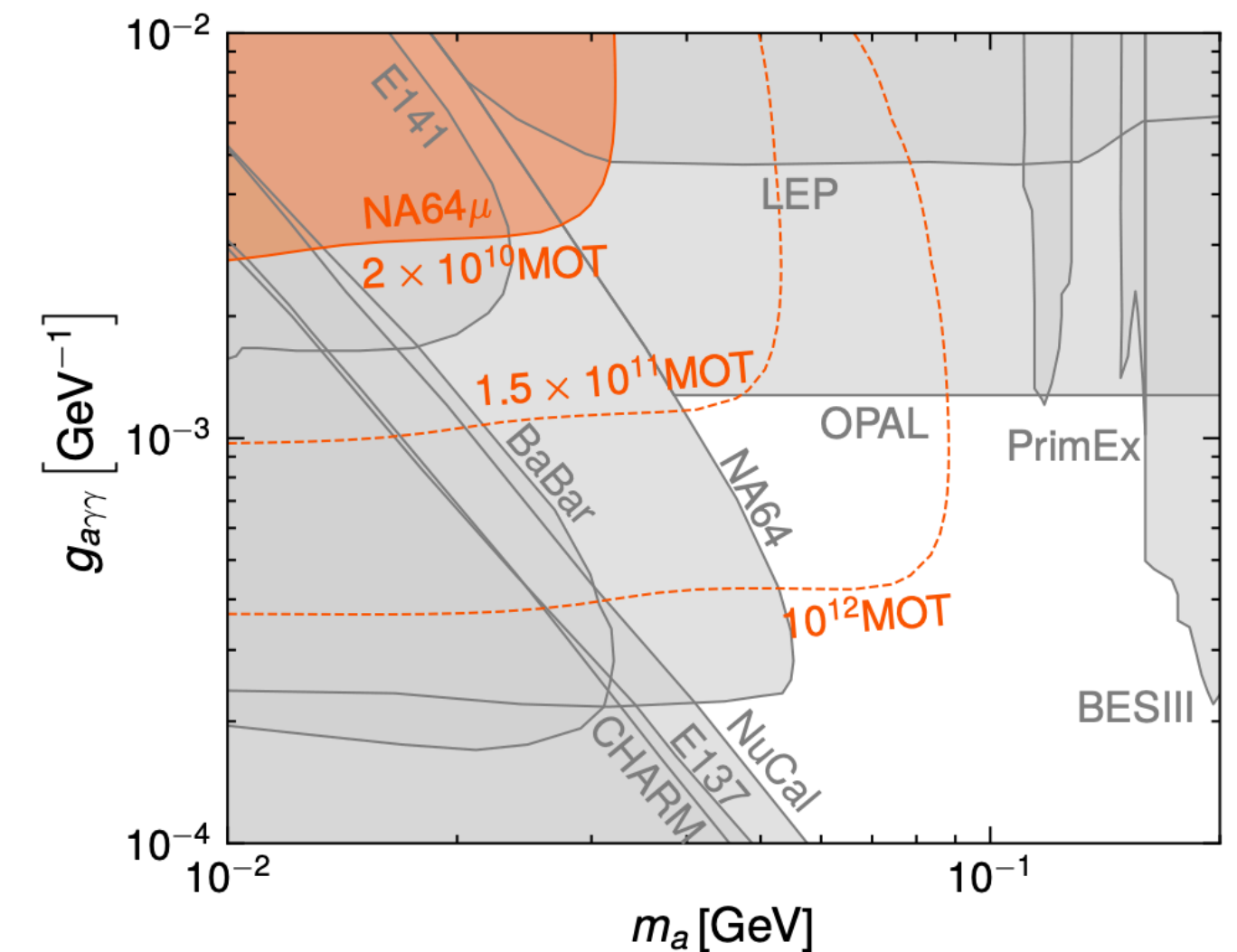
$$\mu Z \rightarrow \mu Z a; a \rightarrow \mu\mu$$

Muonphilic Scenario (P)



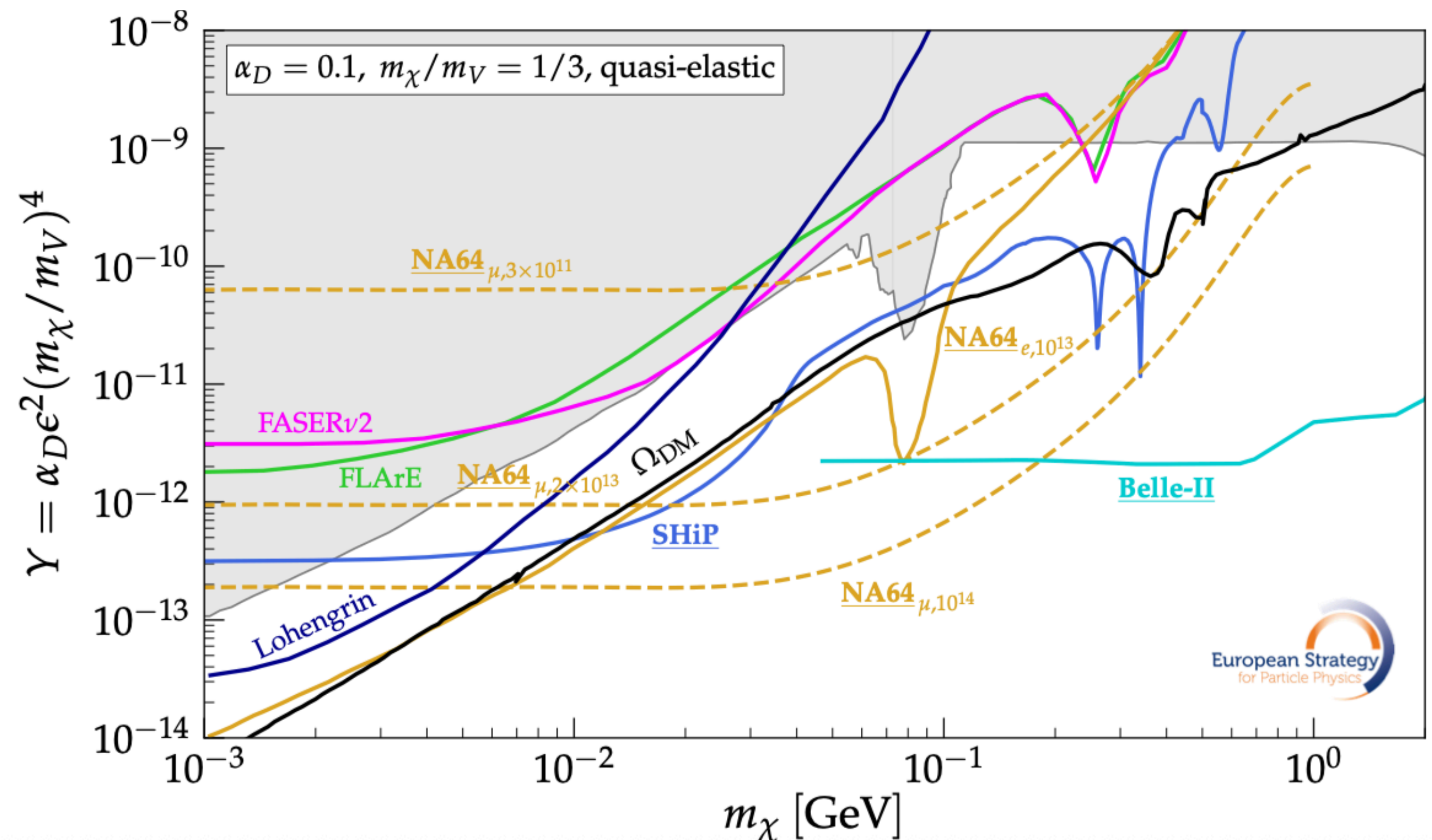
$$\mu Z \rightarrow \mu Z a; a \rightarrow \gamma\gamma$$

H. Li, Z. Liu and N. Song, [arXiv:2501.06294 [hep-ph]].



Summary and outlook

- The existence of Dark Sectors is an excellent framework to explain the composition of Dark Matter.
- Accelerator-based experiments offer unique opportunities to probe complementary to direct detection experiments the Light Dark Matter parameter space.
- Present and future fixed-target experiments offer unique sensitivity in probing the origin of DM and many other well-motivated New Physics scenarios below the electroweak scale such as ALPs, scalar, HNLs, ...



Thanks for your attention

Acknowledgements

NA64 collaboration in particular **P.Crivelli** and **S.Gninenko**

ETH Zürich group in particular P. Crivelli, B.Banto, M. Mongillo, M. Tuzi (PhD student at IFIC)

CERN BE-EA group in particular D. Banerjee and N. Charitonidis

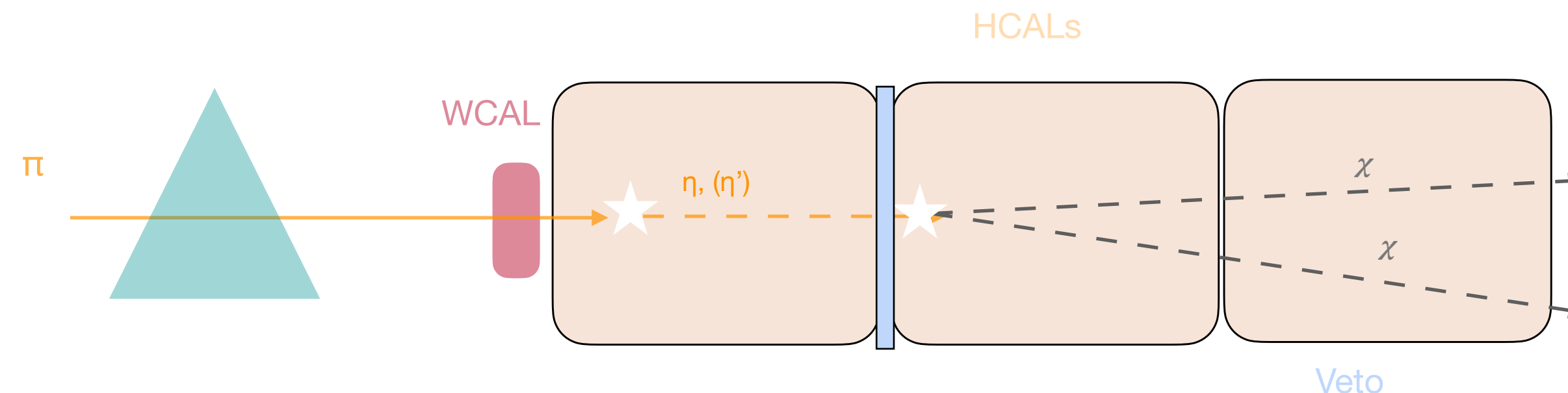


Back-up

Exploration of Dark Sector searches coupled to quarks

NA64h: Search for Dark Sector predominantly coupled to quarks with pion, kaon, and proton beams at the CERN SPS

- Sensitive to several models via missing-energy technique (invisible decays of η , η' , ω , ρ mesons, oscillations of neutral kaon into its “dark” partner, production of leptophobic LDM states)
- First proof-of-concept results from the the analysis of 2.9×10^9 π OT (1 day in 2022) with a simple setup: Phys. Rev. Lett. 133, 121803 (2024)



Most stringent constraints on η, η' invisible decay
Additional data collected in 2025 with improved setup

- **First tests at PS in T9 performed from the 24th of September until October 8th**
- The main goal of this run was to characterize the area and the beam quality (available types of particles, intensity, spot size,...) to evaluate the feasibility of conducting physics measurements at the PS.

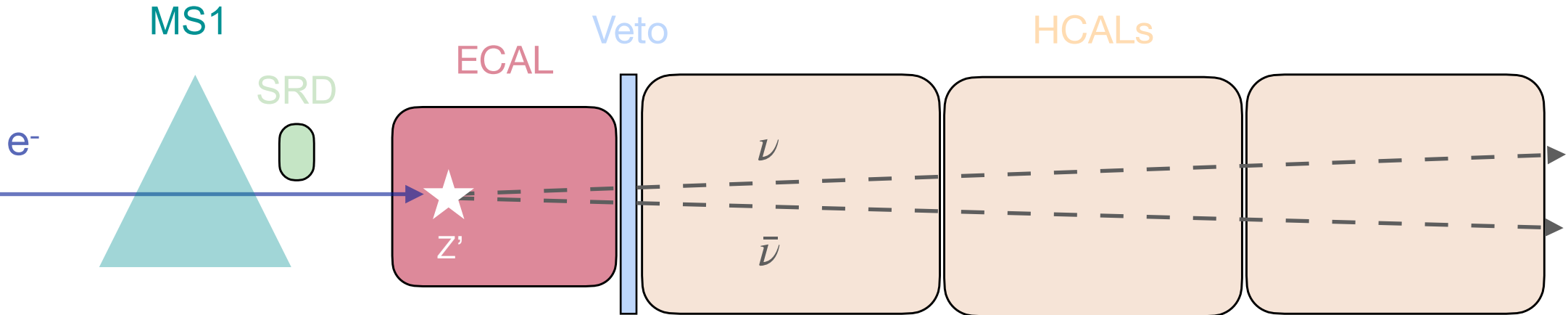
NA64μ: roadmap for Run 4

Aspect	Plan	Improvement
Beam and location	• Further suppress the beam hadron contamination	• K background
	• Is the initial energy optimal?	• Compromise between hermeticity and trigger efficiency
	• New semi-permanent area in M2 with ~25m available (under discussion with CERN BE-EA group, more details in D. Banerjee presentation)	• Reducing installation time
	• Vacuum in the line (ongoing for other users)	• Suppression of muon interactions along the line
Tracking detectors	• Optimisations ongoing (final design after 2023/2024 analysis)	Efficiency
Target	• Optimizations under study (length, material,..)	Increase the signal yield
Spectrometer	• Do we need two magnets in the downstream spectrometer?	More deflection (increase efficiency but trade off with hermeticity)
Hermeticity and acceptance	• New detectors under design and optimisation of the setup during CERN LS3 • New VHCAL and HCAL	No BKG up to 2×10^{-13}
Intensity	• New faster electronics for the calorimeters (developed by INFN Genova for electron and positron and to be included in the muon) • New electronics for the tracking detectors (VMM solution under study) • New trigger under development using the tracking as trigger via FPGA	Higher intensities up to a factor 20 Expand the physics case

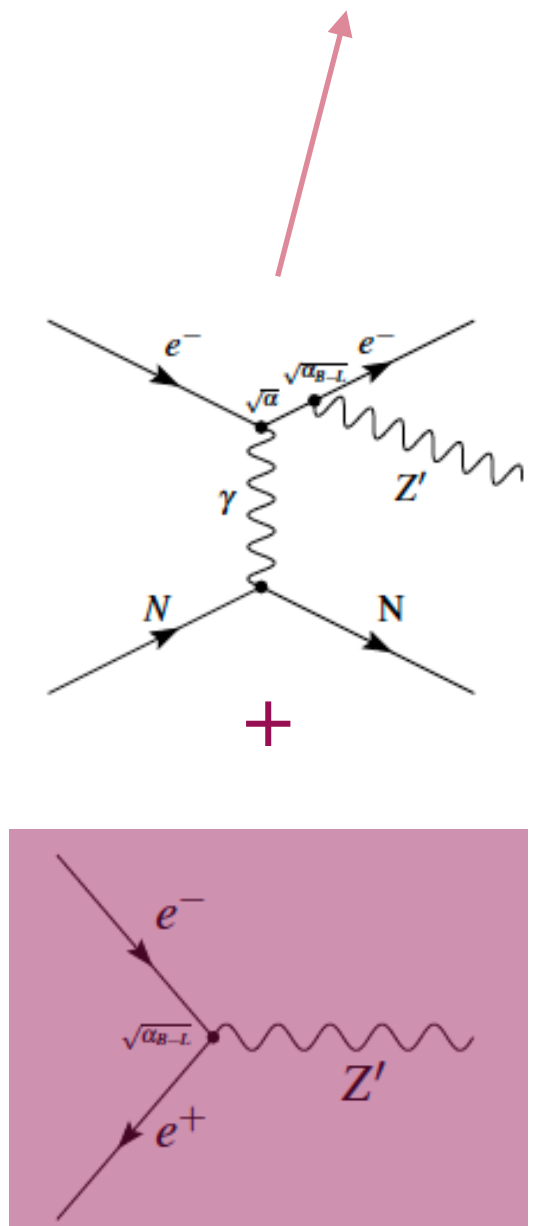
New results on B-L Z'

NEW: “Improved limits on a new Z' in B-L scenarios with the NA64 experiment at CERN” (paper accepted as CERN document)

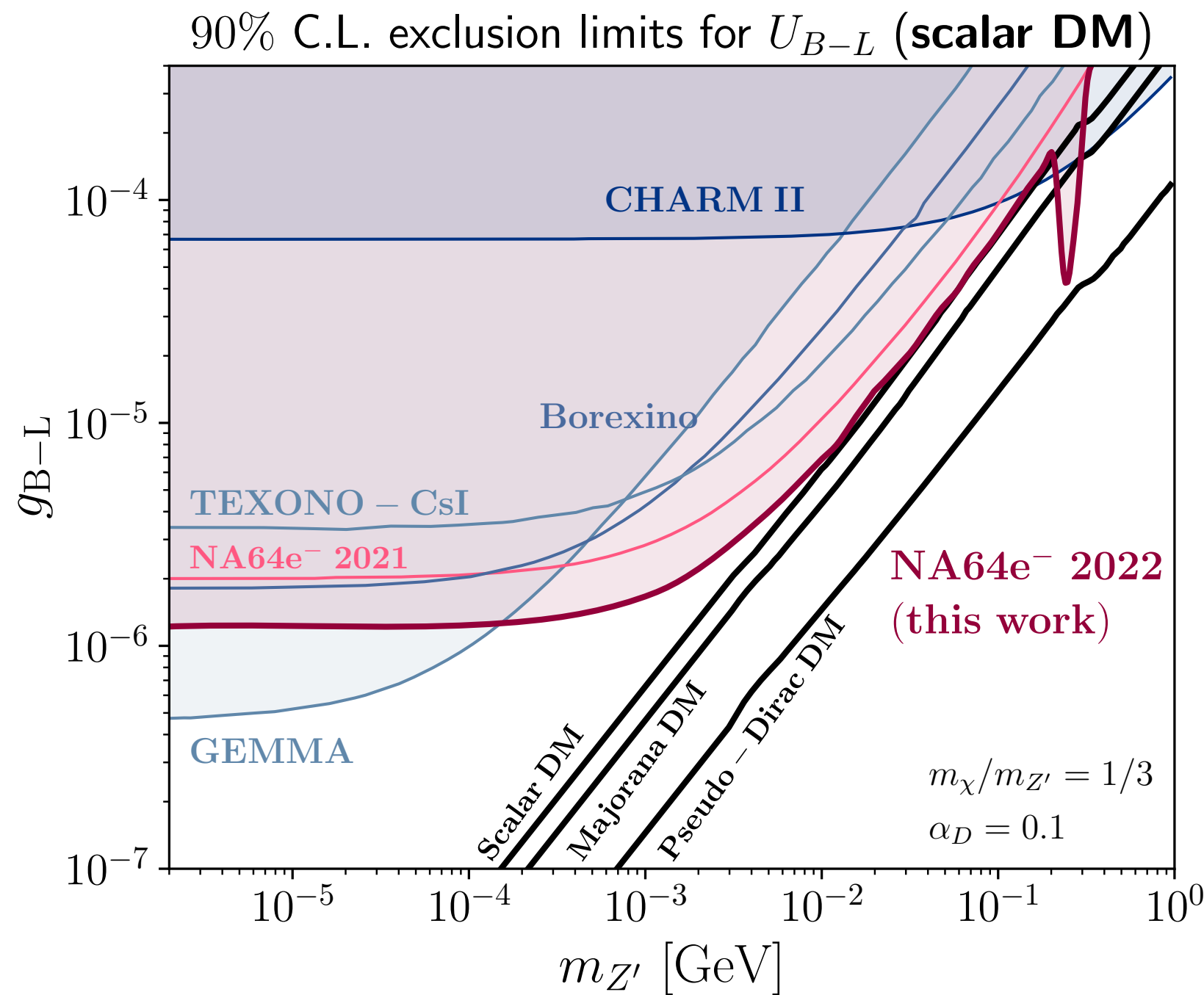
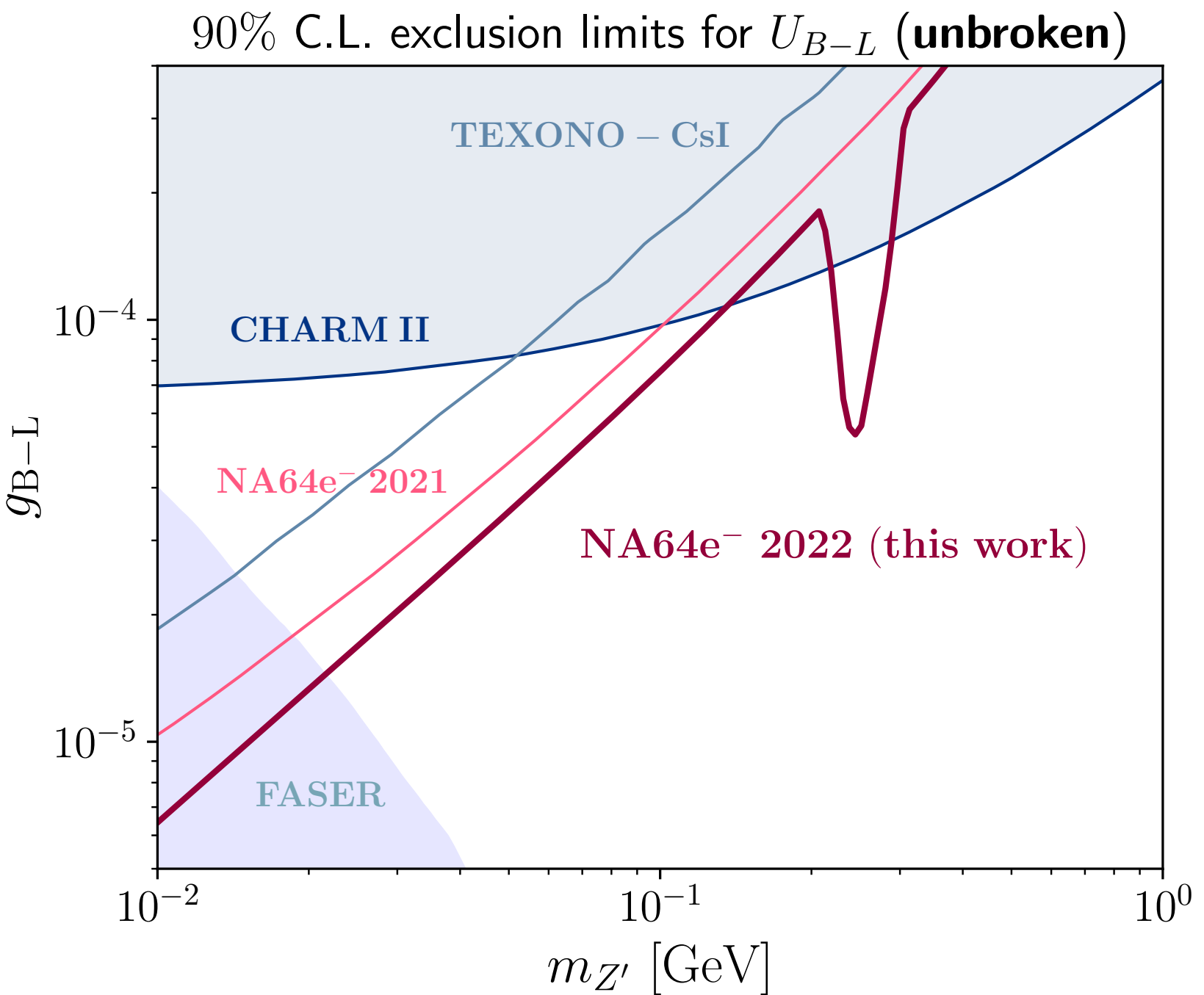
$$e^- Z \rightarrow e^- Z Z'; Z' \rightarrow \text{invisible};$$



- A sub-GeV Z' resulting from $U(1)'$ gauge symmetry generated by the difference between the Baryon and Lepton numbers, B-L. It can explain the **origin of neutrino masses** and the **DM composition**.
- Data sample 3 times larger than previous result (including 2023-2025 data will duplicate this sample).
- **Most stringent bounds on g_{B-L}** . The 90% C.L. exclusion limits obtained **go beyond the ones obtained by neutrino-electron scattering** experiments traditionally devoted to these searches.



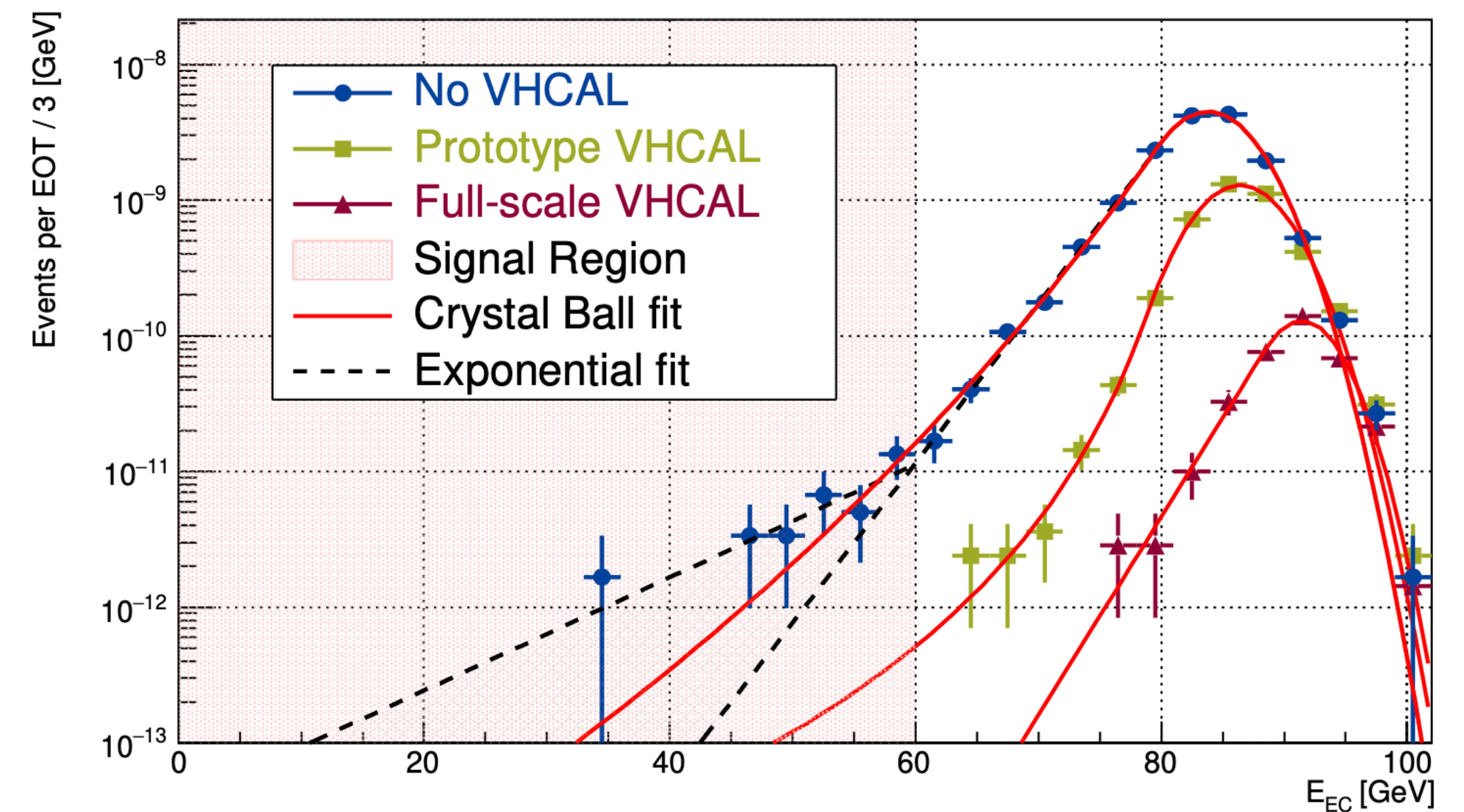
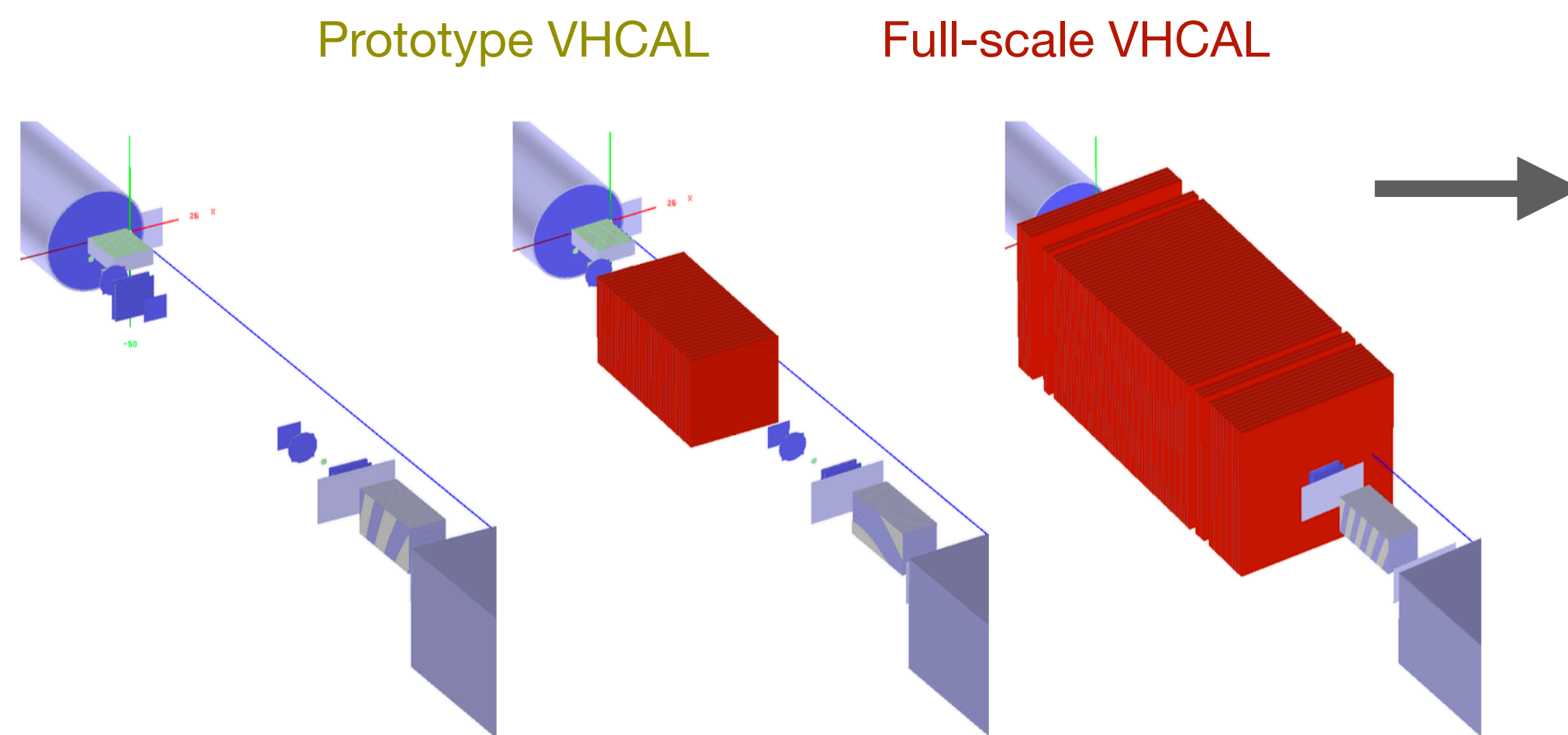
NEW! Annihilation channel included



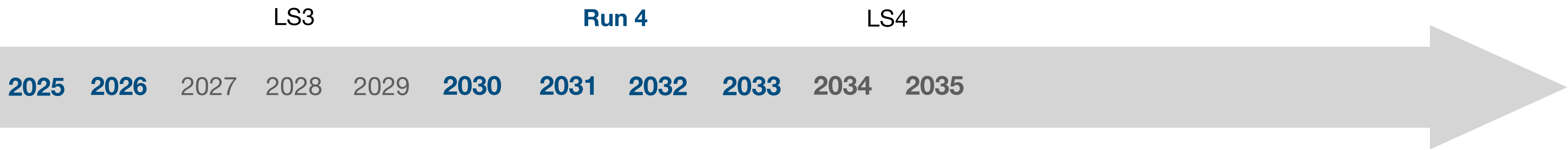
Searches for LDM using 100 GeV e^-

Roadmap:

- 2023/2024 setup upgraded with a VHCAL prototype
- Monte Carlo developments to further understand the electro-nuclear and photo-nuclear processes
 - ➔ NIM A 1081 (2026), 170830



The NA64 program



Beamline	Particle	Energy [GeV]	Motivation	Published	Current statistics	Run 4 [particles on target]
H4	NA64e ⁻	100	Leptophilic Dark Sectors coupled to e ⁻ : LDM, inelastic DM, ALPs, scalar, Z', X17 ...	0.937x10 ¹²	2.7x10 ¹²	10 ¹³
	NA64e ⁺	150-40	LDM (masses <0.25 GeV), several mediators: axial, vector, pseudoscalar, scalar, ...	10 ¹⁰ @100 GeV 1.3x10 ¹⁰ @100 GeV	10 ¹⁰ @100, 70, 40 and 45 GeV	> 10 ¹¹ for different energies
M2	NA64μ ⁺	160	Leptophilic DS coupled to μ: LDM (masses > 0.1 GeV), ALPs, Z', muon g-2, scalar, millicharge, μ→τ...	1.98x10 ¹⁰	3.5x10 ¹¹	2x10 ¹³
	NA64h	20-50	Hadrophilic DS Invisible η, η', K ₀ decays	Adenda to be prepared next year Proof-of-principle published! Phys. Rev. Lett. 133, 121803 (2024)		