Dark Sector Searches with the NA64 Experiment at CERN

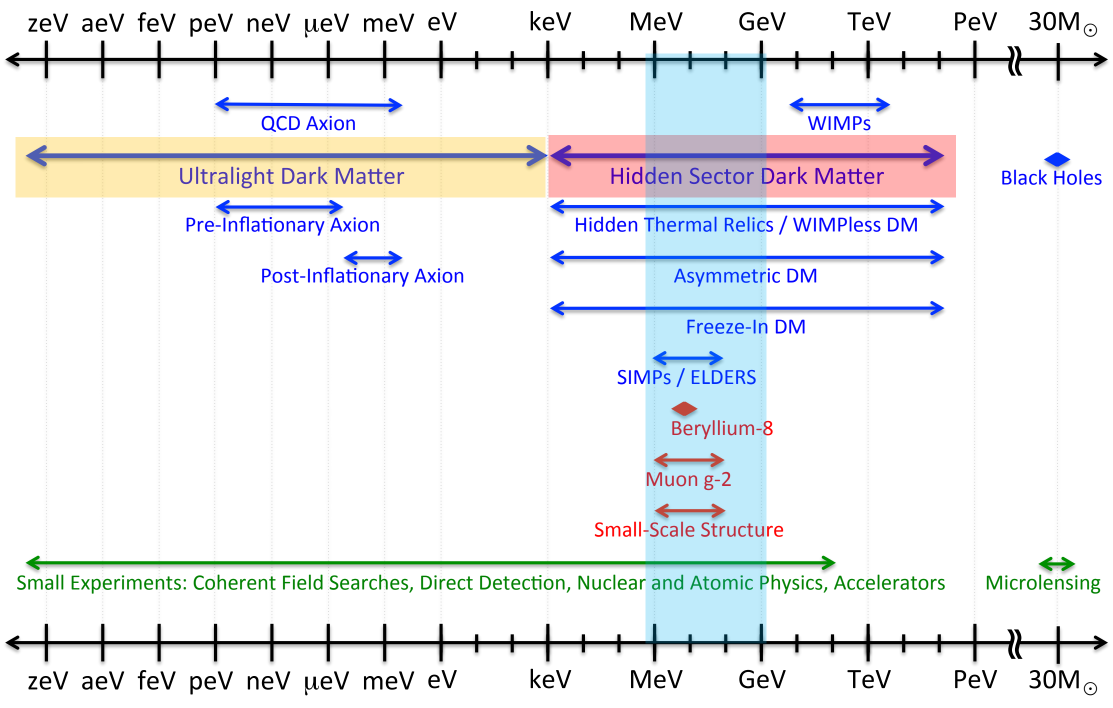
16th Patras Workshop on Axions, WIMPs and WISPs

Henri Sieber on behalf of the NA64 Collaboration

Dark Matter (DM) framework overview

Broad spectrum of **DM candidates** and well motivated effort towards its probing

Dark Sector Candidates, Anomalies, and Search Techniques



M. Battaglieri et al., arXiv:1707.04591 **[hep-ph]**

WIMP hypothesis largely studied, the **WIMP miracle** and DM relic density:

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

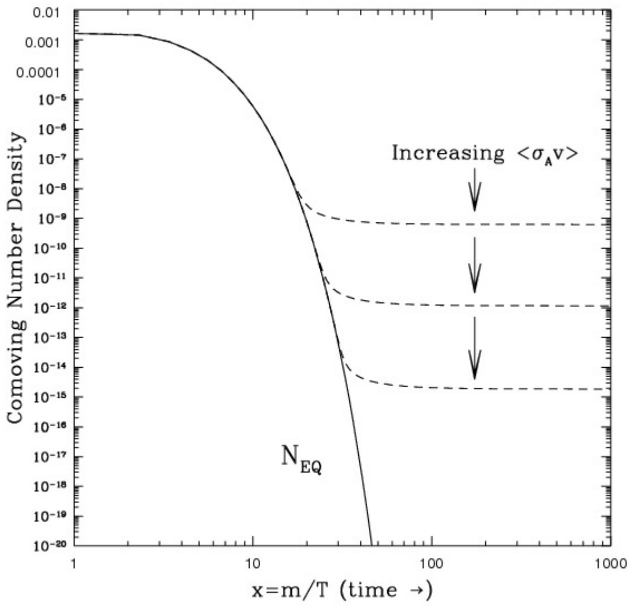
$$(m_\chi, g_D) \sim (m_{\text{weak}}, g_{\text{weak}})$$

… but also the correct relic density can be obtained by lighter particles, the **WIMPless miracle** (see J. L. Feng and J. Kumar, PRL 101, 231301 (2008)) :

$$\frac{m_\chi}{g_D^2} \sim \frac{m_{\text{weak}}}{g_{\text{weak}}^2}$$

→ Generalisation of the WIMP miracle outside the weak scale

Freeze-out scenario



E. Kolb, ISBN: 978-0201626742

Light thermal DM (LTDM): Hidden-sector DM and the portal formalism

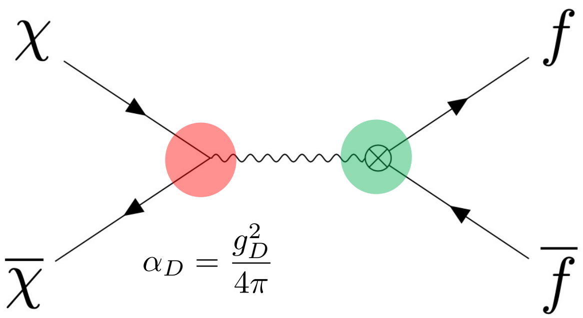
Particle model: interaction of DM with SM through a **new force** carried by a light mediator

$$\mathcal{L}_{\text{total}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DS}} + \mathcal{L}_{\text{Portal}}$$

Vector portal (Dark photon, A')
Scalar portal (Dark Higgs, S)
Fermion portal (Heavy Neutral Lepton, N)
Pseudo-scalar portal (ALPs, a) (generic case)

The **vector** portal: a massive U(1)' vector mediator, A', interacts with SM particles through kinetic mixing ε with SM photons

$$\mathcal{L}_V \supset g_D A'_\mu \bar{\chi}\gamma_\mu \chi + m_\chi \bar{\chi}\chi + \frac{1}{2} m^2_{A'} (A'_\mu)^2 + \frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu}$$



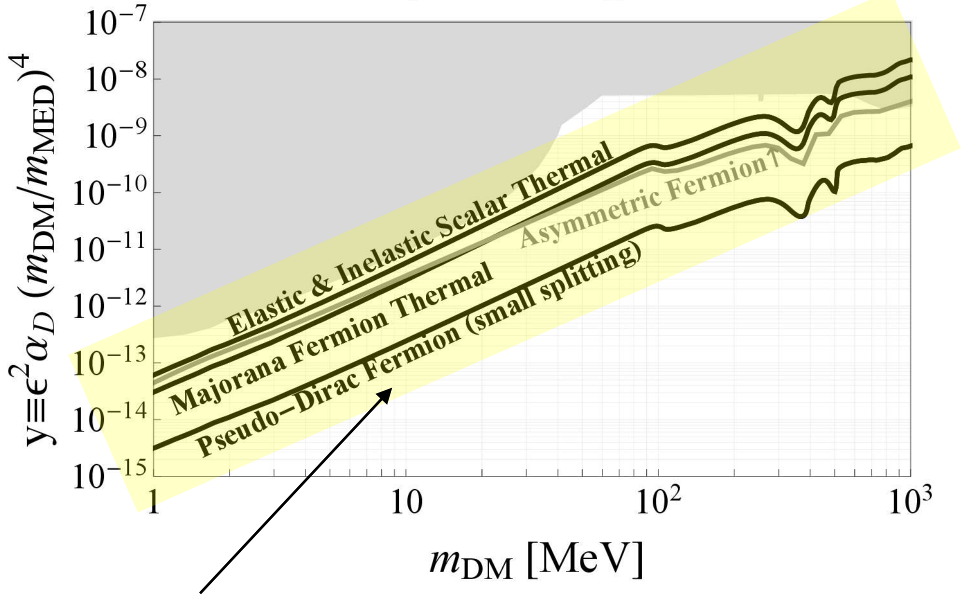
$$\alpha_D = \frac{g_D^2}{4\pi}$$

The relic abundance can be expressed in terms of the model **4 parameters**

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

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

for which the correct abundance is obtained through fine –tuning of the **y parameter**.



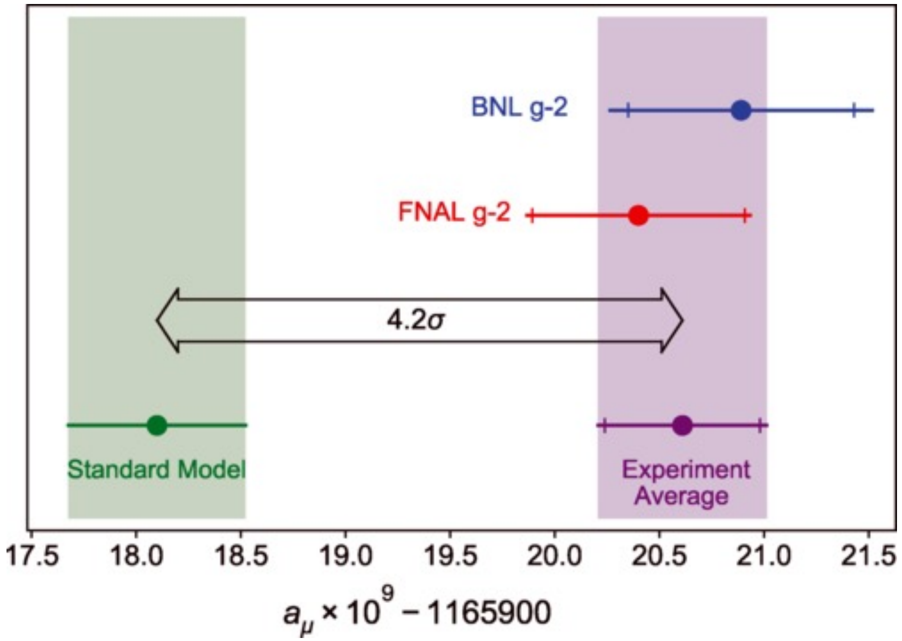
"thermal target" in {m, y} plane

M. Battaglieri et al., arXiv:1707.04591 **[hep-ph]**

DM and Standard Model (SM) anomalies: the muon $(g\text{-}2)_\mu$ anomalous magnetic moment

Recently published results from Muon (g-2) Experiment @Fermilab indicates:

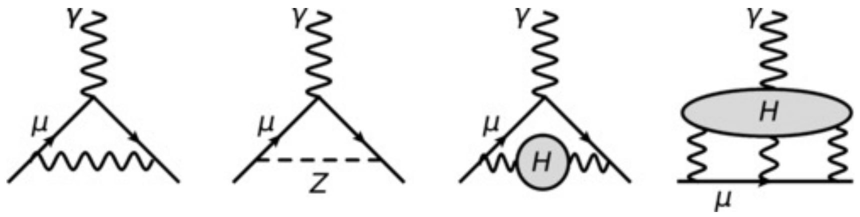
$$a_\mu(\text{Exp}) = 116\ 592\ 061(41) \times 10^{-11}$$



B. Abi et al., PRL 126, 141801 (2021)

Note: recent precise Lattice QCD calculations reduce discrepancy (see S. Borsanyi et al., Nature 593 (2021) 51-55). Hadronic loop contributions to be measured by MUonE @CERN (G. Abbiendi. PoS ICHEP2020, 223 (2021))

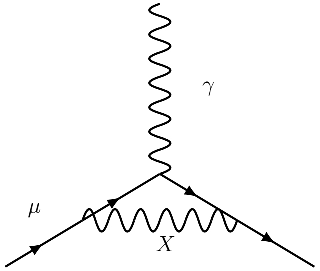
T. Ayoma et al., PR 887, 1-66 (2020)



$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{HVP} + a_\mu^{HLbL} = 116\ 591\ 810(43) \times 10^{-11}$$

$$a_\mu(\text{Exp}) - a_\mu(\text{SM}) = (251 \pm 59) \times 10^{-11}$$

?

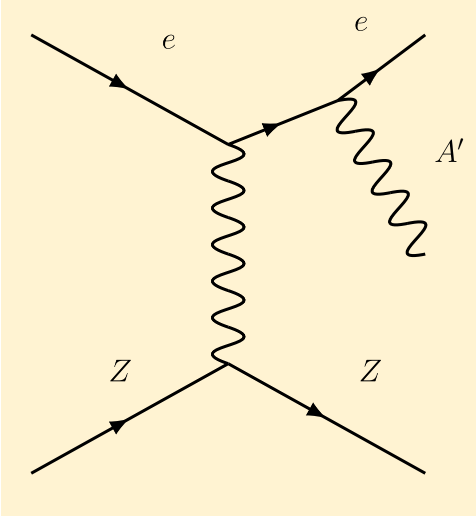


M. Pospelov et al., PLB 662, 53-61 (2008)

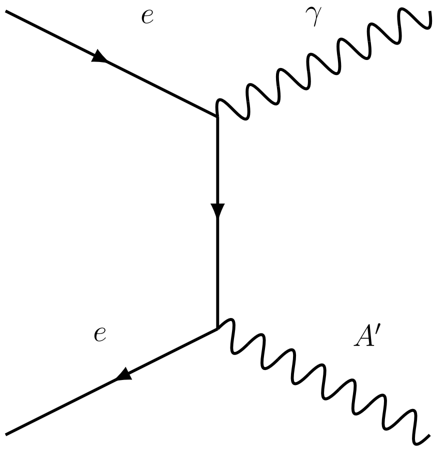
As a **New Physics contribution**, generic X (e.g. A', Z') boson vertex corrections could serve as possible explanation of $(g\text{-}2)_\mu$ discrepancy

Accelerator-based searches for light vector mediators

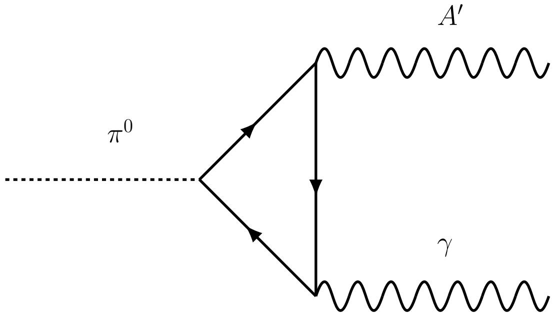
Accelerator experiments search for DM produced in a relativistic regime in the **mass range MeV-GeV** → great advantage for probing energy scales similar to thermal freeze-out



A’ bremsstrahlung



Annihilation



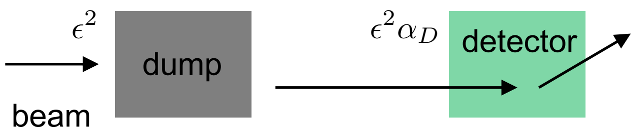
Meson decay

Search techniques for light DM at NA64

NA64 relies on **missing energy/momentum** techniques to identify DM, using an **active beam dump**

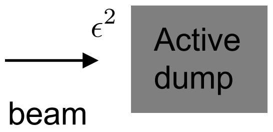
NA64 operates in two distinct modes: **visible** and **invisible**

1) Beam dump (DM scattering off electron) $\sigma \propto \epsilon^4 \alpha_D$



$eZ \to eZA'; A' \to \bar{\chi}\chi$ $\quad e\chi \to e\chi$

2) Active beam dump (missing energy/momentum) $\sigma \propto \epsilon^2$

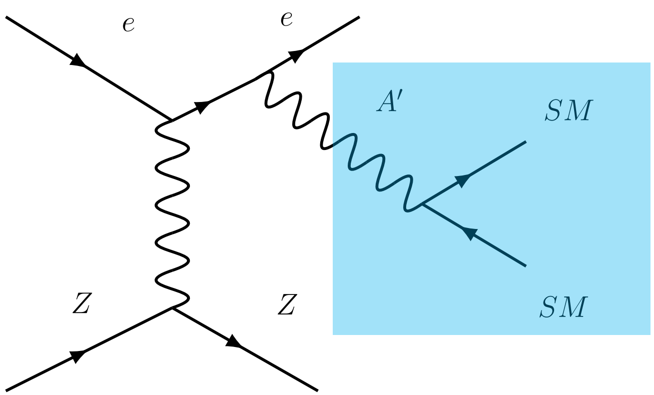


$eZ \to eZA'$

NA64 approach !

Visible

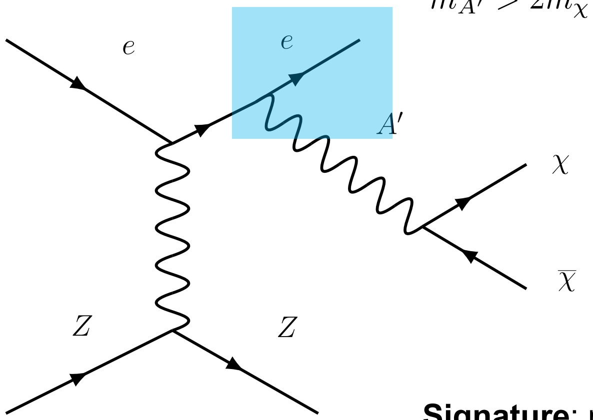
$m_{A'} < 2m_\chi$



Signature: SM pair production

Invisible

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



Signature: missing energy

A fixed-target set-up: the NA64 experiment

A fixed-target experiment at the CERN Super-Proton Synchrotron (SPS) aiming at probing **Dark Sector physics**

International collaboration with **50 researchers** from **16 institutions**

2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024

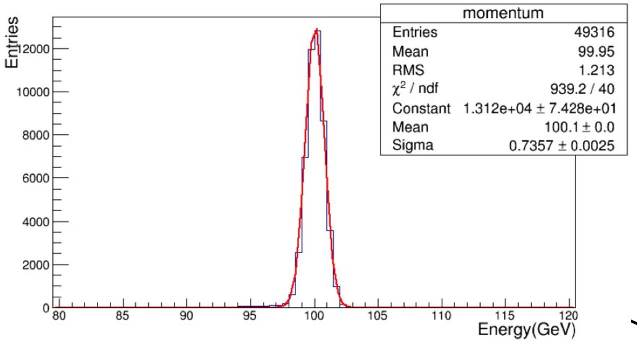
- 2014: Proposed as P348
- 2015: First test run
- 2016: Approved as NA64; Invisible run
- 2017: Invisible + visible runs
- 2019: CERN Long Shutdown 2 (LS2)
- 2021: Invisible run; Muon test run; Approved to continue running
- 2022: Invisible + visible runs; Muon first physics run
- 2023: Muon physics runs
- 2024: CERN LS3

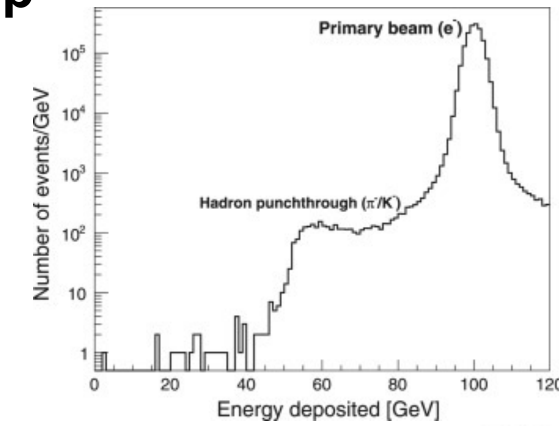
Broad physics program

Process	New Physics
e^- **beam**	
$A' \to e^+e^-$	Dark photon
$A' \to invisible$	
$A' \to \bar{\chi}\chi$	sub-GeV Dark Matter (χ)
$X \to e^+e^-$	new gauge $X-$boson
milliQ particles	Dark Sector, charge quantisation
$a \to \gamma\gamma,\ invisible$	Axion-like particle
μ^- **beam**	
$Z_\mu \to \bar{\nu}\nu$	gauge $Z_\mu-$boson of $L_\mu - L_\tau$, $< 2m_\mu$
$Z_\mu \to \bar{\chi}\chi$	$L_\mu - L_\tau$ charged Dark matter (χ)
milliQ	Dark Sector, charge quantisation
$a_\mu \to invisible$	non-universal ALP coupling
$\mu - \tau$ conversion	Lepton Flavour Violation
$\pi^-,\ K^-$ **beam**	Current limits, PDG 2018
$\pi 0 \to invisible$	$Br(\pi^0 \to invisible) < 2.7 \times 10^{-7}$
$\eta \to invisible$	$Br(\eta \to invisible) < 1.0 \times 10^{-4}$
$\eta' \to invisible$	$Br(\eta' \to invisible) < 5.0 \times 10^{-4}$
$K_S^0 \to invisible$	no limits
$K_L^0 \to invisible$	no limits
e^+ **beam**	

NA64 in invisible mode: set-up

Momentum reconstruction: dp/p ~ 1%

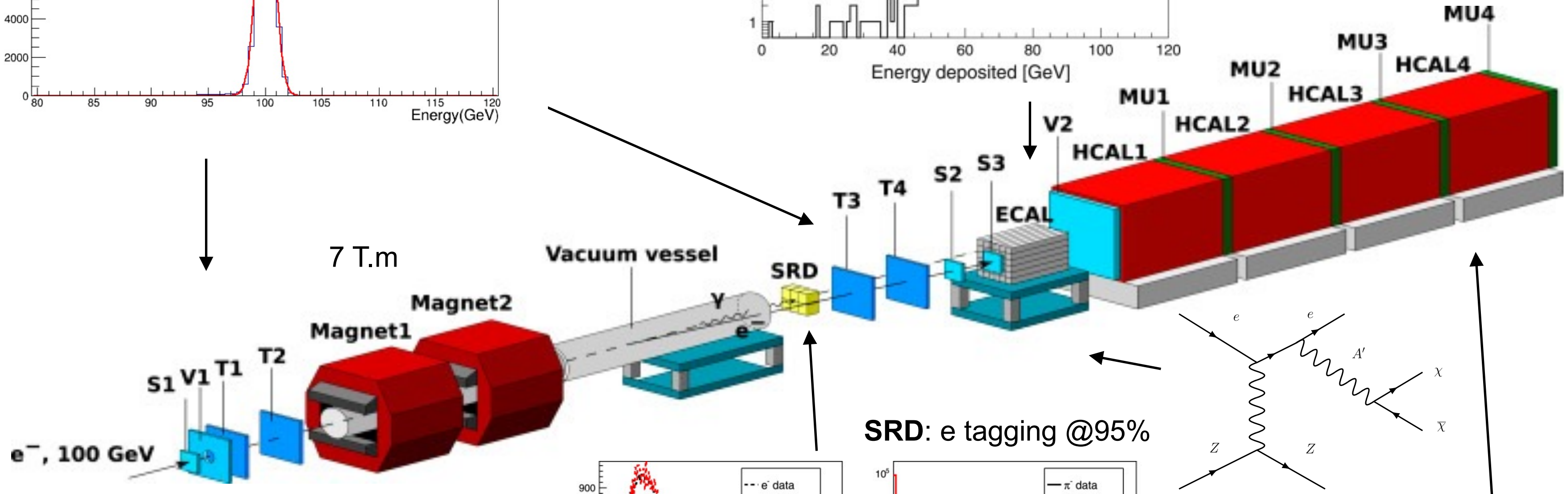


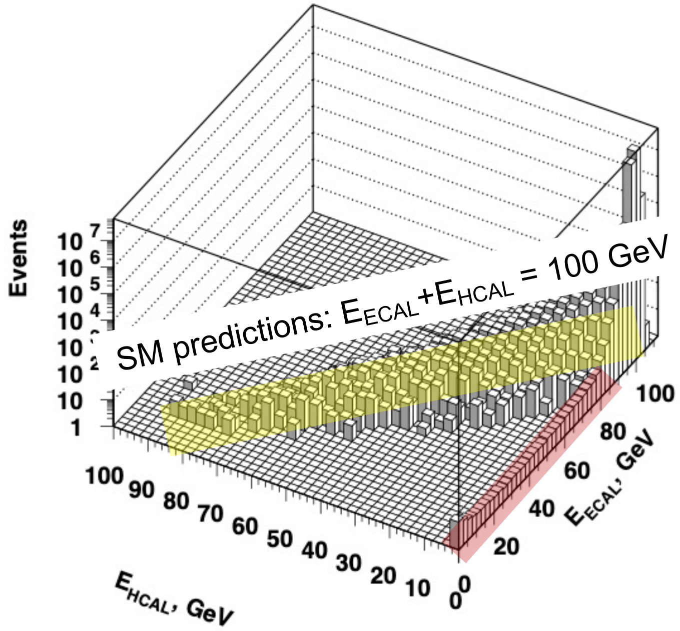


Electromagnetic Calorimeter (ECAL):
- Pb/Scintillator
- High hermeticity ($40X_0$)

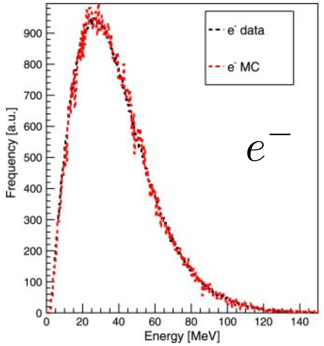
$\delta E_{\mathrm{ECAL}}/E_{\mathrm{ECAL}} \simeq 0.1/\sqrt{E_{\mathrm{ECAL}}}$

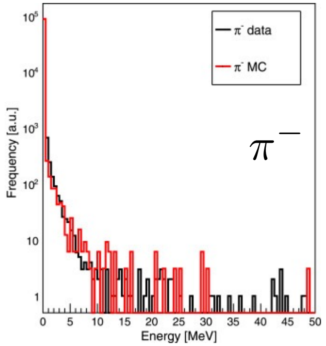
Signature as **missing energy**:
- Incoming e- with 100 GeV and good SRD tag
- ECAL shower with E < 50 GeV
- No energy deposit in Veto and HCAL (HCAL < 1 GeV)





SRD: e tagging @95%





E. Depero et al., NIM A 866,(2017) 196-201

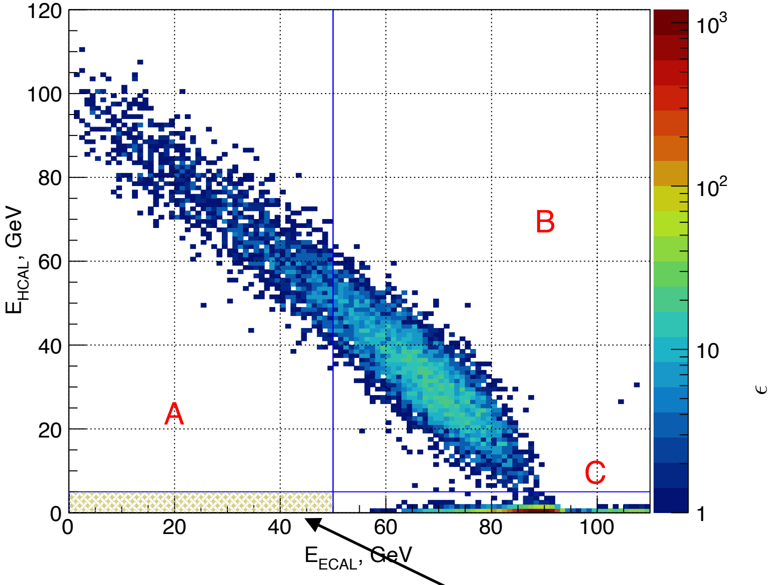
Beam:
- H4 100 GeV electron beam from CERN SPS
- ≤ 10^7 e^-/spill, 5s spill duration, 2-4 spill/min
- beam hadron contamination π/e ≤ 1%

Hadronic Calorimeter (HCAL):
- Fe/Scintillator sandwich
- High hermeticity (~28λ)

$\delta E_{\mathrm{HCAL}}/E_{\mathrm{HCAL}} \simeq 0.6/\sqrt{E_{\mathrm{HCAL}}}$

S. N. Gninenko et al., PRD 94, 095025 (2016)

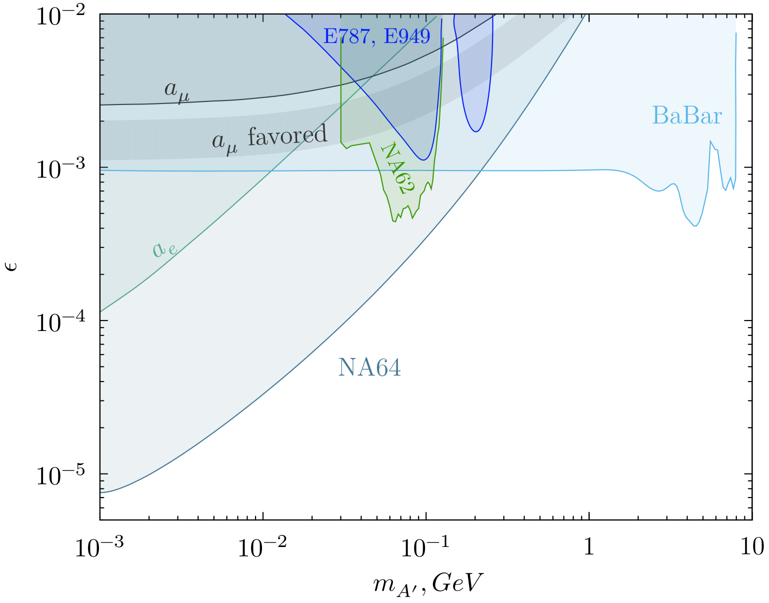
Combined 2016-2018 invisible searches results for LTDM and muon $(g\text{-}2)_\mu$



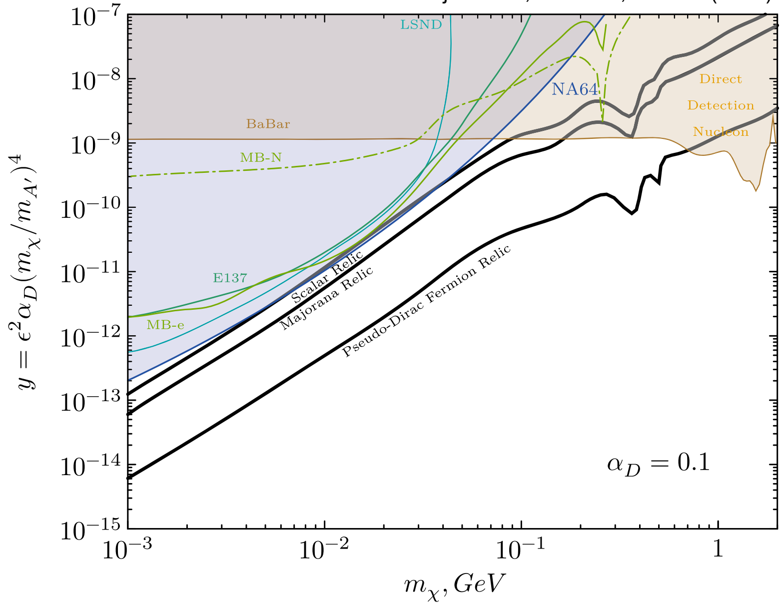
No event found in the signal box !

Background source	Background number, n_b
punchthrough γ's, cracks, holes	< 0.01
loss of dimuons	0.024 ± 0.007
$\mu \to e\nu\nu,\ \pi,\ K \to e\nu,\ K_{e3}$ 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

Combined analysis of 2016 and 2017/2018 runs: **2.84x10^{11} EOTs**



D. Banarjee et al., PRL 123, 121801 (2019)



Constraints set by NA64 on LTDM starts to **exceed** the ones set by other beam dump experiment (especially for m < 0.1 GeV)

$$\sigma_{\text{NA64}} \propto \epsilon^2 \qquad \sigma_{\text{dump}} \propto \epsilon^4 \alpha_D$$

Very close **sensitivity** to thermal DM models (see discussion on combined muon searches and 2021 runs prospects)

Invisible decays and the electron $(g\text{-}2)_e$

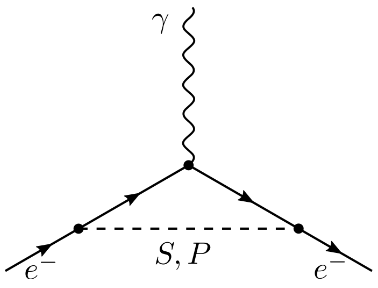
New **precision measurement** at LKB and Berkeley (see L. Morel et al., Nature 588, 61 (2020) and R. H. Parker et al., Science 360, 191 (2018); see also D. Hanneke et al., PRL 100, 120801 (2008))

$$\Delta a_e = a_e^{\mathrm{EXP}} - a_e^{\mathrm{LKB}} = (4.8 \pm 3.0) \times 10^{-13} \ (1.6\sigma)$$

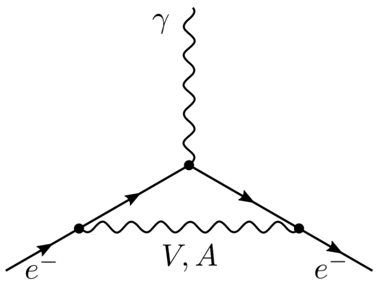
$$\Delta a_e = a_e^{\mathrm{EXP}} - a_e^{\mathrm{B}} = (-8.8 \pm 3.6) \times 10^{-13} \ (-2.4\sigma)$$

Could the bounds be explained a **generic X boson** ?

$$eZ \to eZX; \ X \to invisible$$



scalar, pseudo-scalar



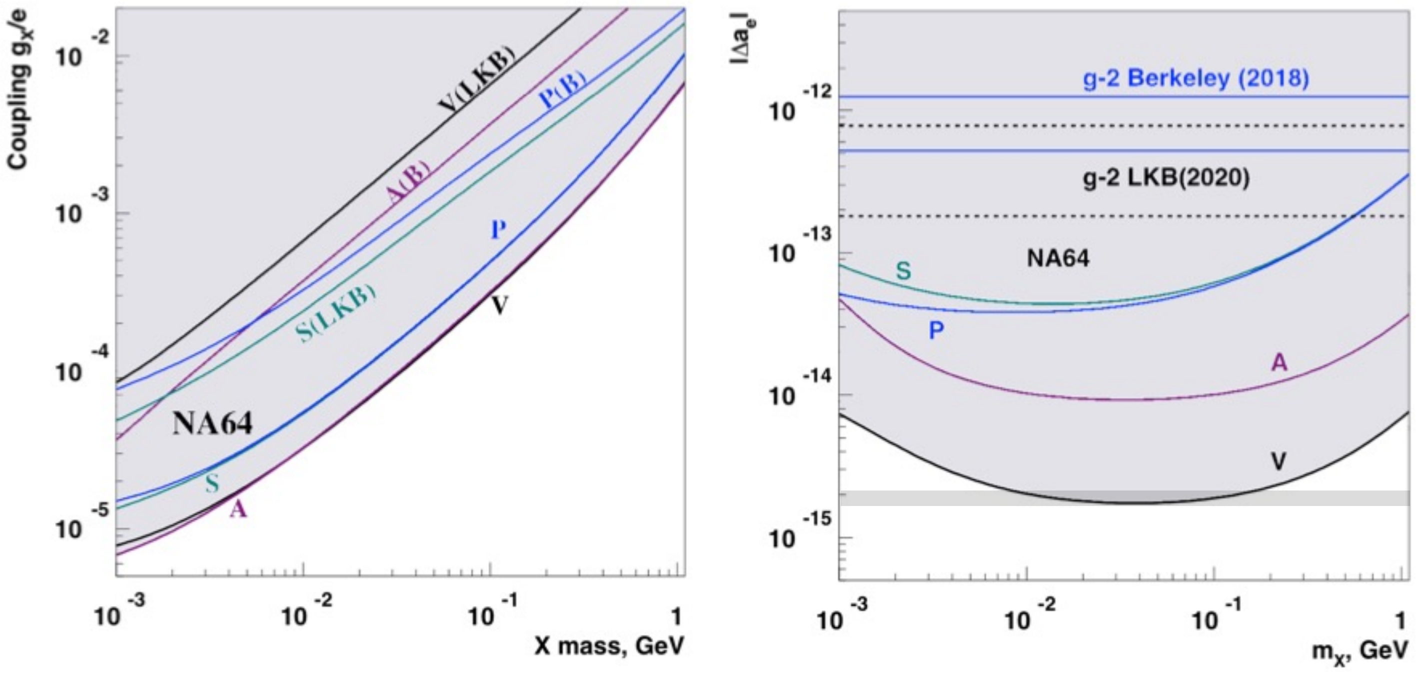
vector, axial

Calculations at **one-loop**:

$$\Delta a_S = \frac{g_S^2}{4\pi^2}\left(\frac{m_e}{m_X}\right)^2\left[\ln\frac{m_X}{m_e} - \frac{7}{12}\right] \qquad \Delta a_V = \frac{g_V^2}{4\pi^2}\left(\frac{m_e}{m_X}\right)^2\frac{1}{3}$$

$$\Delta a_P = \frac{g_P^2}{4\pi^2}\left(\frac{m_e}{m_X}\right)^2\left[-\ln\frac{m_X}{m_e} + \frac{11}{12}\right] \qquad \Delta a_A = \frac{g_A^2}{4\pi^2}\left(\frac{m_e}{m_X}\right)^2\left(-\frac{5}{3}\right)$$

Y. M. Andreev et al., PRL 126, 211802 (2021)



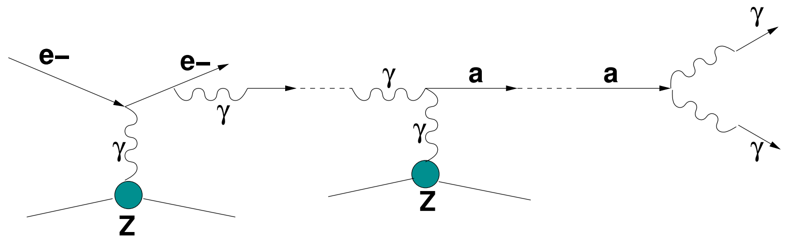
No evidence for such a particle but NA64 results **one order of magnitude** more sensitive on probing NP in $(g\text{-}2)_e$ than current experiments

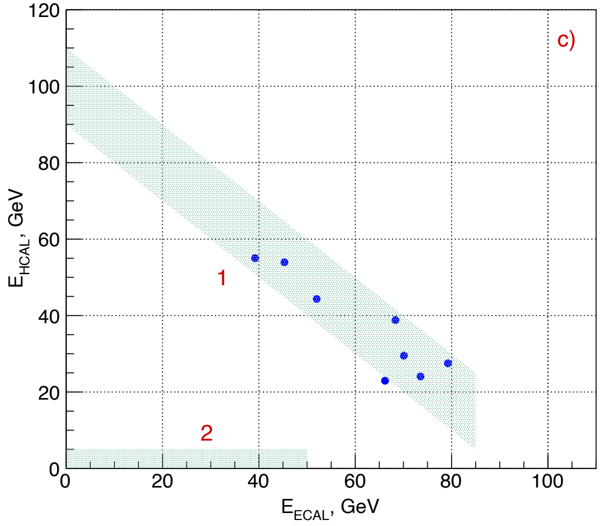
Axion-Like Particles (ALPs) at the NA64 experiment

Complementary searches to Hidden-sector through the **pseudo-scalar portal** with ALPs as mediator

$$\mathcal{L}_a \supset \frac{g_{a\gamma\gamma}}{4} F_{\mu\nu}\tilde{F}^{\mu\nu} a$$

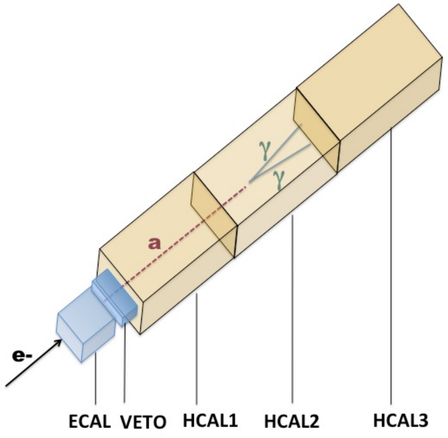
where ALPs are produced through the **Primakoff effect**





No event found in signal box !

Background source	Background number, n_b
leading neutrons	0.02 ± 0.008
leading K^0 interactions and decays	0.14 ± 0.025
beam π, K charge-exchange and decays	0.006 ± 0.002
dimuons	< 0.001
Total n_b (conservatively)	0.17 ± 0.026

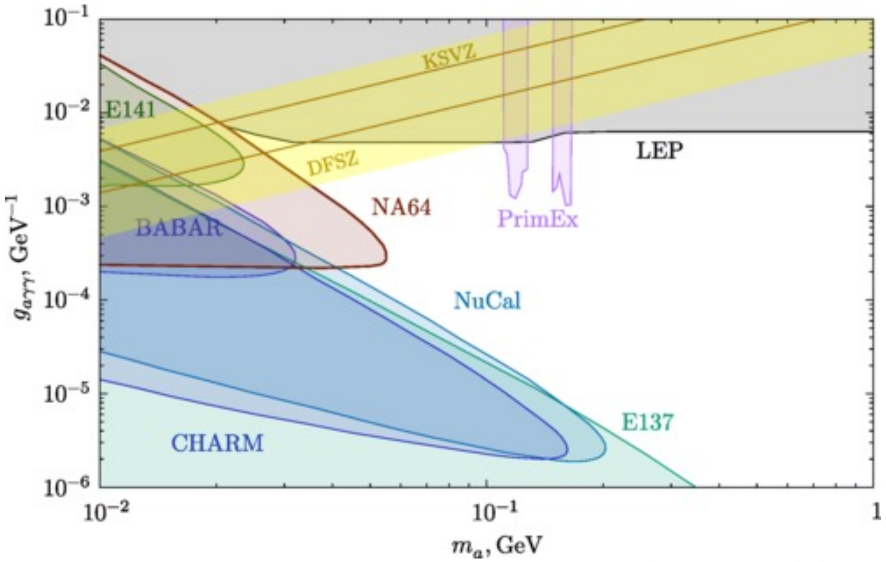


Signal **signatures**:

1. **Visible** decay in HCAL2 or HCAL3 (decay) → EM-like shower in HCAL
2. **Missing energy** in HCAL2 and HCAL3 (no decay)

- **No activity** in HCAL1

D. Banarjee et al., PRL 125, 081801 (2020)

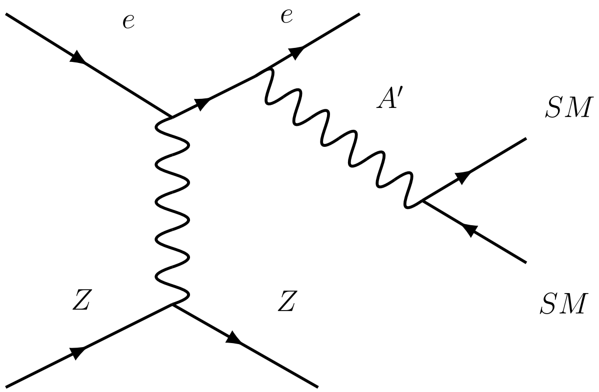


Closing the gap between beam dump and colliders

Visible searches: Decays to SM particles and the ^{8}Be and ^{4}He anomalies

Visible decay to SM particles (**pair creation**)

$$eZ \rightarrow eA'Z;\ A' \rightarrow e^+e^-$$



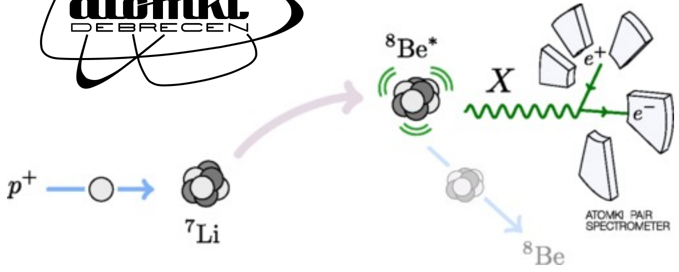
$$m_{A'} < 2m_\chi$$

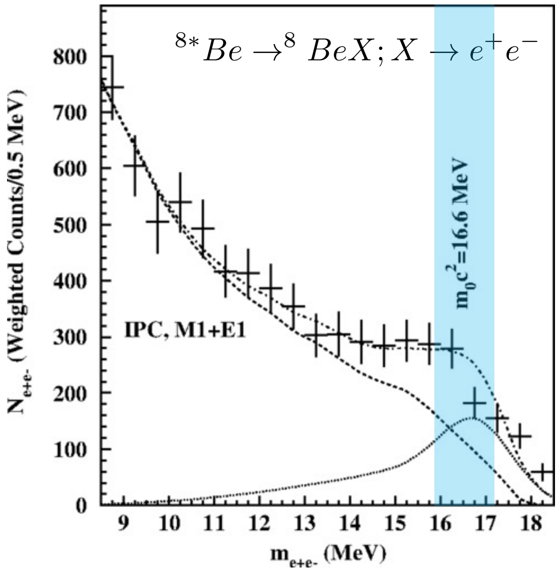
+

Possible models of NP for **protophobic X boson** considered to be of the type pseudo-scalar, axial or vector (see e.g. J. Feng et al., PRD 95, 035017 (2017))

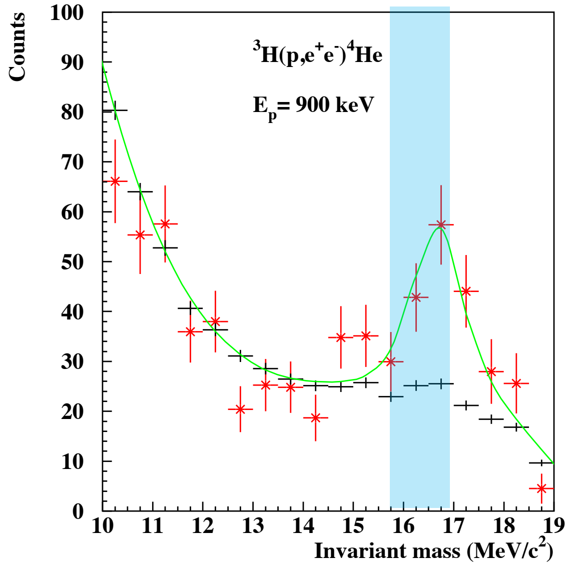
NA64 probes this anomaly in a model-independent way, assuming **non-zero** coupling to electron:

$$eZ \rightarrow eX_{17}Z;\ X_{17} \rightarrow e^+e^-$$



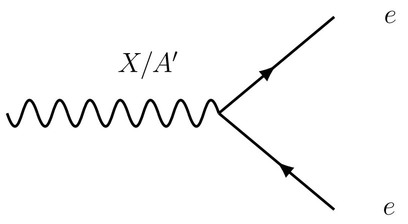


A. Krasznahorkay et al., PRL 116, 042501 (2016)

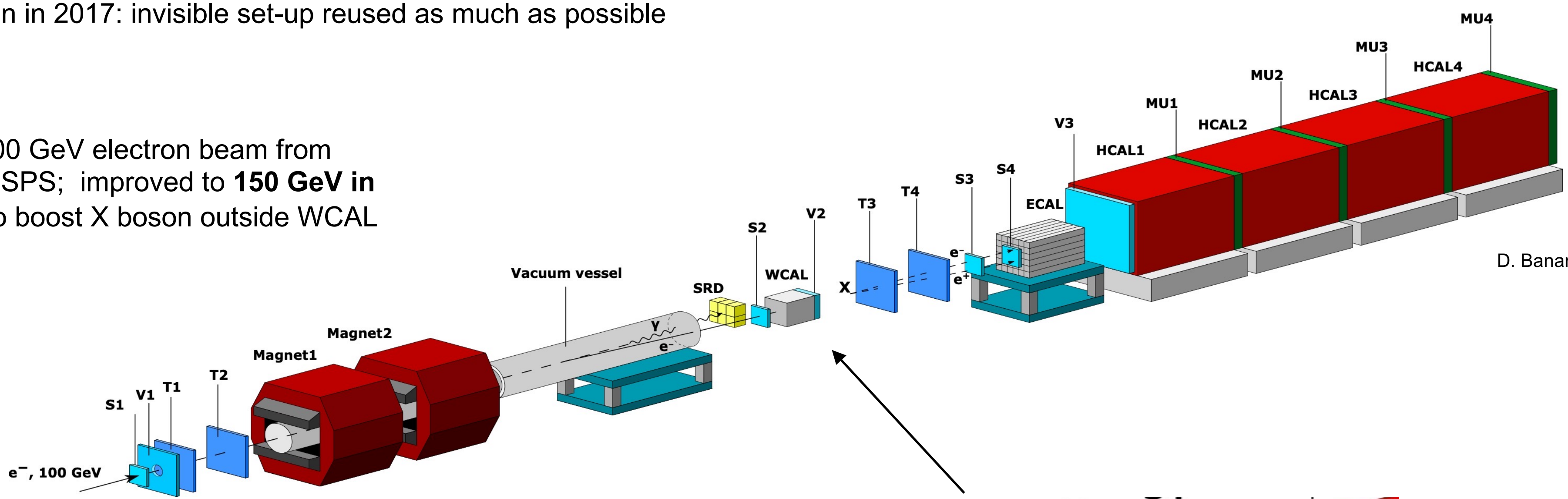


A. Krasznahorkay et al., arXiv:1910.10459 **[nucl-ex]**

Visible decays at the NA64 experiment: set-up



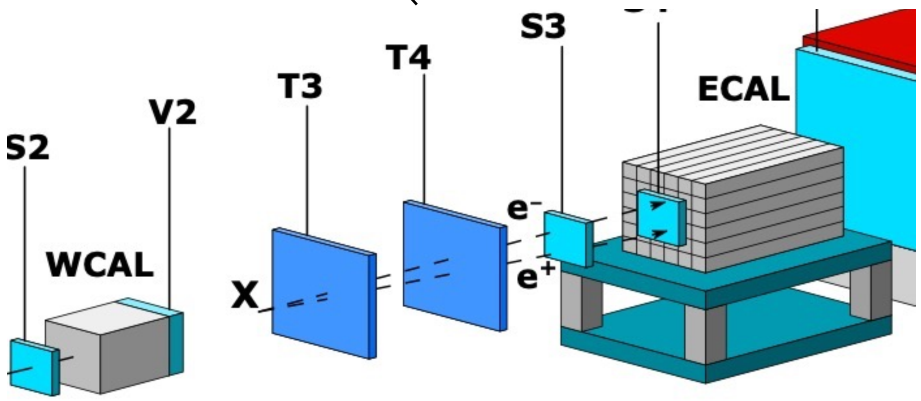
First run in 2017: invisible set-up reused as much as possible



D. Banarjee et al., PRL 120, 231802 (2018)

Beam:
- H4 100 GeV electron beam from CERN SPS; improved to **150 GeV in 2018** to boost X boson outside WCAL

Core of the experiment:
- **Tungsten calorimeter (WCAL)**: short, probe larger mixing strength
- Thin **veto W2**: maximise chance of decaying outside WCAL
- Additional **trackers**: measure decay pairs
- **Electromagnetic calorimeter**: to detect the second shower

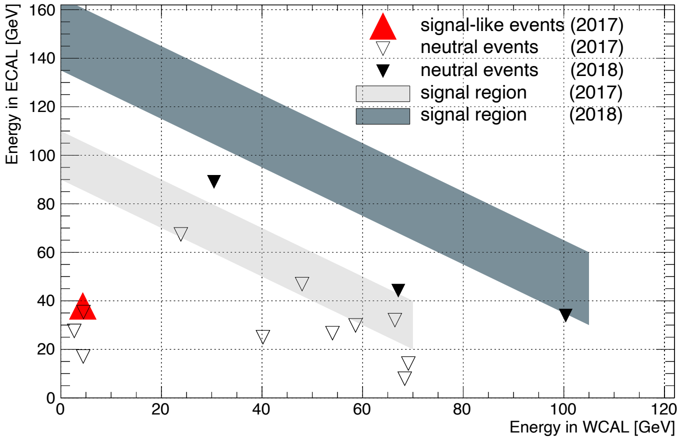


Signature as:
two separated EM showers,
- One in the dump (WCAL)
- One in the ECAL
- $E_{WCAL}+E_{ECAL}=E_{beam}$

2017-2018 combined analysis of the searches for visible decays

2018 set-up upgrade/optimisation allowed a **larger probing** of the ε, and considerable **background reduction**

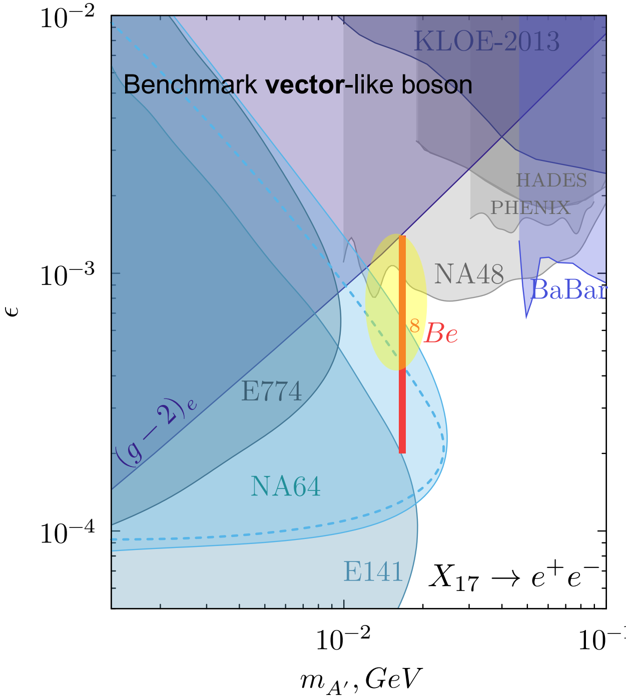
8.4x10^{10} EOTs



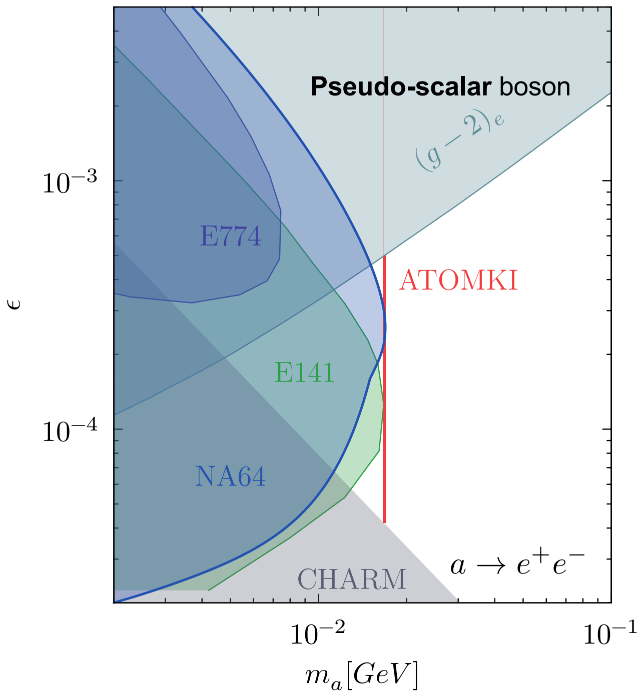
No event found in the signal box !

Background source	2017 data	2018 data
$K_S^0 \to 2\pi^0$	0.06 ± 0.034	0.005 ± 0.003
$\pi N \to (\geq 1)\pi^0 + n + ...$	0.01 ± 0.004	0.001 ± 0.0004
punchthrough π^-	0.0015 ± 0.0008	0.0007 ± 0.0004
punchthrough γ	< 0.001	< 0.0005
$\pi, K \to e\nu$, K_{e4} decays	< 0.001	
$eZ \to eZ\mu^+\mu^-; \mu^\pm \to e^\pm\nu\bar{\nu}$	< 0.001	
Total	0.07 ± 0.035	0.006 ± 0.003

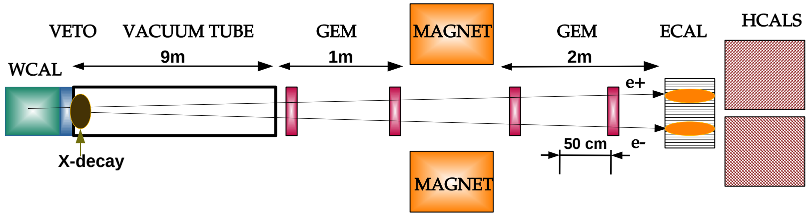
D. Banarjee et al., PRD 101, 071101(R) (2020)



Y. M. Andreev et al., arXiv:2104.13342 [hep-ex]



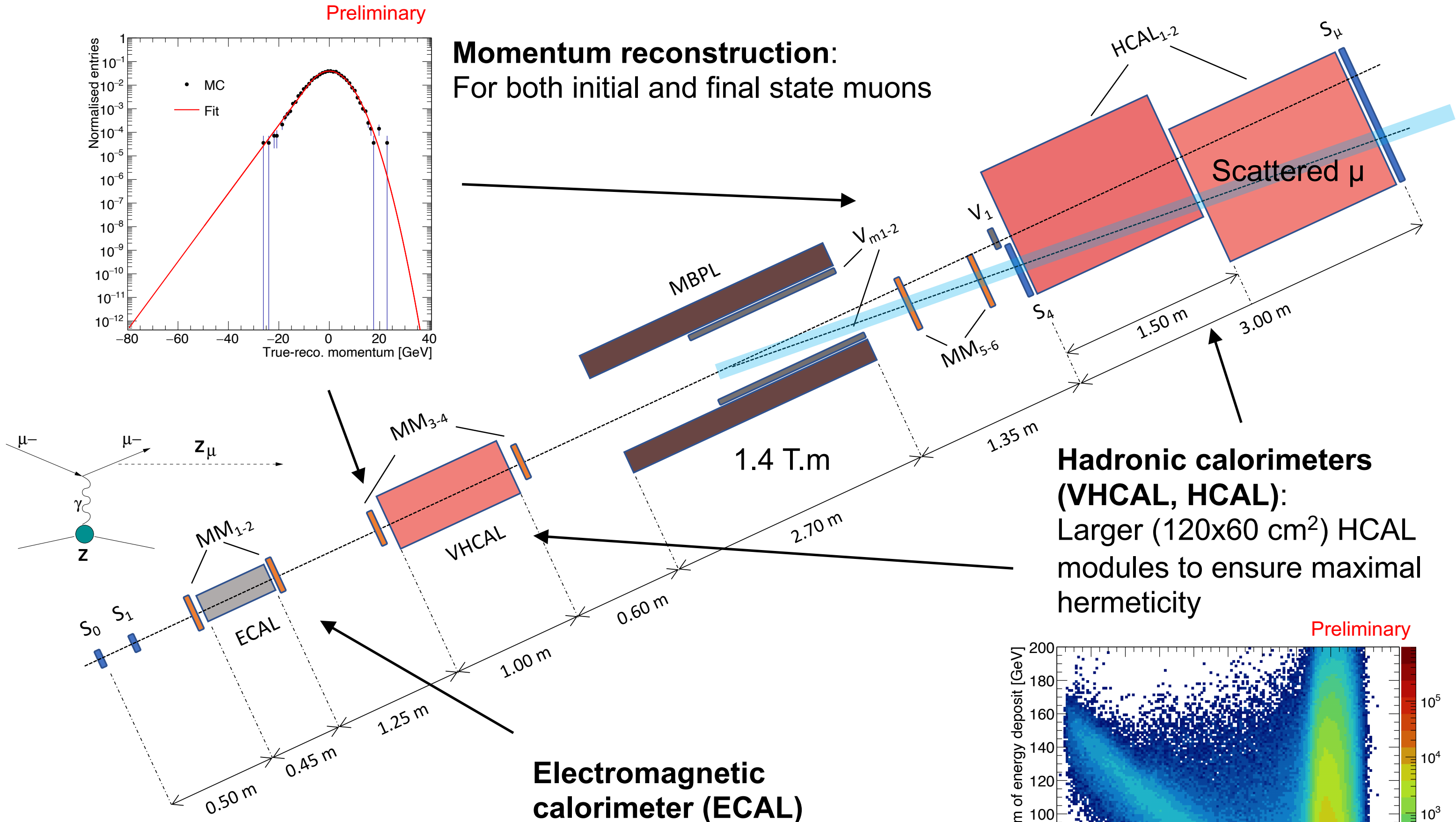
Remaining ε values for vector and pseudo-scalar boson to be probed during the **2022** updated set-up visible run



NA64 Collaboration, EPJ C 80 (2020) 12, 1159

NA64 muon mode 2021 set-up and feasibility study

Momentum reconstruction:
For both initial and final state muons

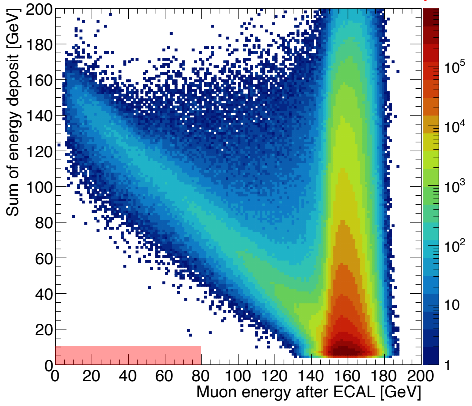


Hadronic calorimeters (VHCAL, HCAL):
Larger (120x60 cm^2) HCAL modules to ensure maximal hermeticity

Electromagnetic calorimeter (ECAL)

Beam:
M2 beam line with 160 GeV muons

Preliminary



Located at the M2 beamline, complementary to NA64e aiming at probing:

- **(g-2)$_\mu$ anomaly** at m < 0.2 GeV through Z' L_μ-L_τ model
- **LTDM** in the mass region > 100 MeV
- Scalar, ALPs, milliQ particles, …

First **test run** to be held in October !

Signature as **missing momentum**:
- Single scattered muon with E < 80 GeV
- No energy deposited in VHCAL and HCAL, ECAL ~ MIP energy

Preliminary

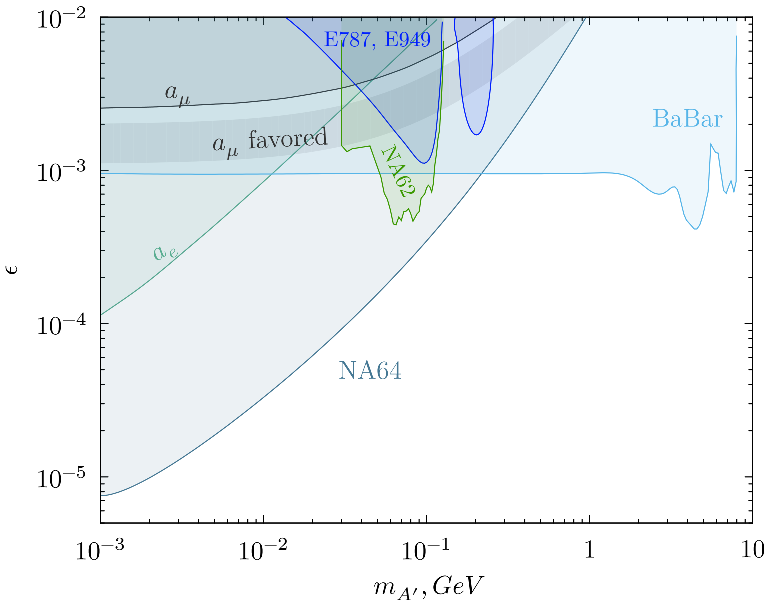
Background source	Level per MOT
momentum reconstruction mismatch	$\lesssim 10^{-13}$
detector non-hermeticity	$\lesssim 10^{-12}$
single-hadron punchthrough	$\lesssim 10^{-12}$
μ, π, K decays	$\lesssim 10^{-13}$
$\mu Z \to \mu Z\gamma; \gamma \to \mu^+\mu^-$, μ trident	$< 10^{-12}$
Total (conservatively)	$\lesssim 10^{-12}$

Complementary searches to the NA64 electron mode: NA64μ

Complementary with mass region ≪ 100 MeV and ≥ 100 MeV due to **production cross-sections behaviour**

$$N^e_{A'} \sim N_{EOT} L_e \sigma^e_{A'}, \;\; L_e \simeq 1X_0$$

$$\sigma^e_{A'} \sim \frac{\epsilon_e^2}{m^2_{A'}}$$

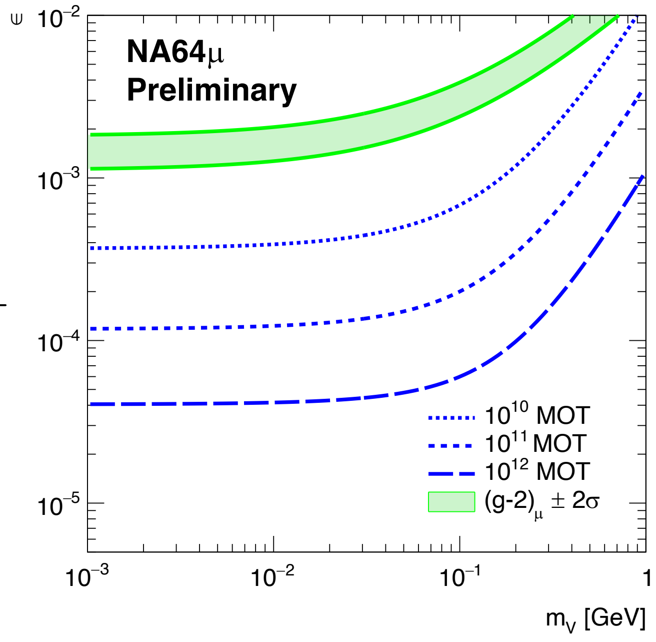


D. Banarjee et al., PRL 123, 121801 (2019)

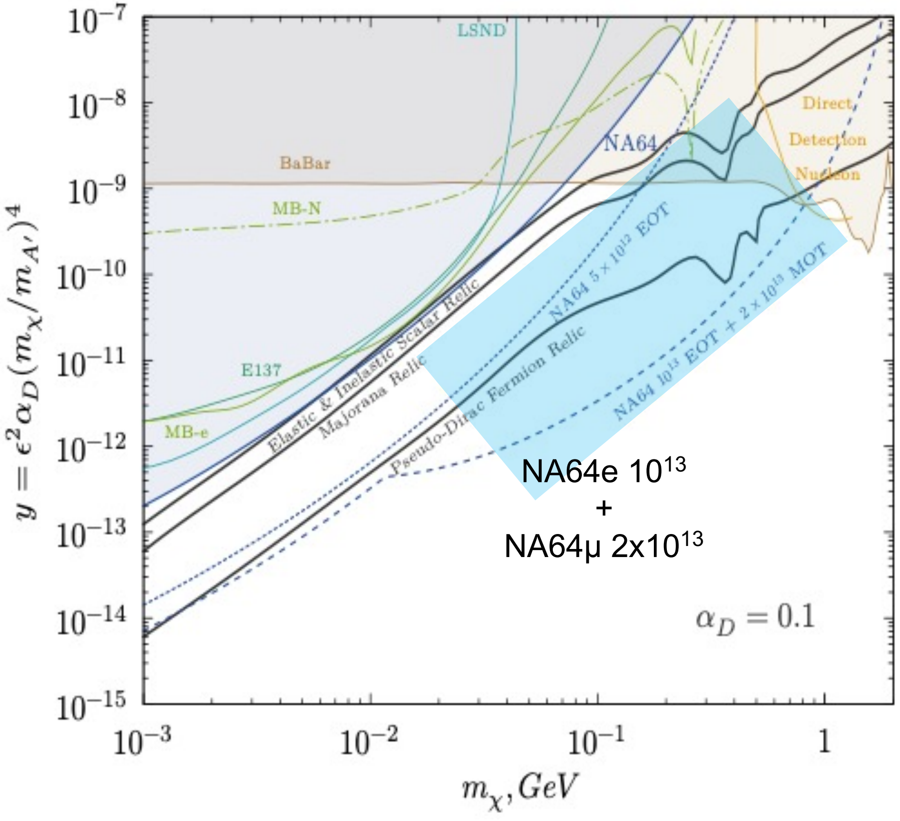
+

$$N^\mu_{A'} \sim N_{MOT} L_\mu \sigma^\mu_{A'}, \;\; L_\mu \simeq 40X_0$$

$$\sigma^\mu_{A'} \sim \frac{\epsilon_\mu^2}{m^2_\mu}$$



S. N. Gninenko et al., PLB 796, 117-122 (2019)



Summary and outlook: the NA64 experiment in the near future

Dark-sector Physics provides an interesting framework to explain the observed relic abundance

NA64 is an active beam-dump experiment combining missing energy and momentum techniques to probe **sub-GeV DM candidates**

Combined analysis for the **2016-2018 invisible** runs with 2.84×10^{11} EOT
- $(g-2)_\mu$ region probed and A' excluded as explanation
- Increased sensitivity on LTDM
- Very close sensitivity to thermal relic abundance
- Sensitivity in probing New Physics in $(g-2)_e$ better than high precision experiments

Combined analysis for the **2017-2018 visible** runs with 8.4×10^{10} EOT
- X_{17} anomalies parameter space largely covered, $\varepsilon < 6.8 \times 10^{-4}$ and m ~ 17 MeV excluded

2021	2022	2023	2024	2025
Invisible run	Invisible + visible runs	Invisible + visible runs	Invisible + visible runs	CERN LS3
Muon test run	Phase 1: first physics run, cover $(g-2)_\mu$		Phase 2: cover high A', Z' masses	

Main prospects until the CERN Long Shutdown 3 (LS3):

- Accumulate ≥ $\mathbf{5 \times 10^{12}}$ **EOT** to fully exploit the experiment potential to reach LTDM relic abundance in $A' \to \chi\chi$
- Explore the unprobed parameter space for $\mathbf{X_{17} \to e^+e^-}$ + invariant mass reconstruction and increase the sensitivity in visible decay $\mathbf{A' \to e^+e^-}$
- Probe the L_μ-L_τ Z' model as an explanation to $\mathbf{(g-2)_\mu}$
- Probe LTDM parameter space for **m > 0.1 GeV**

Acknowledgements

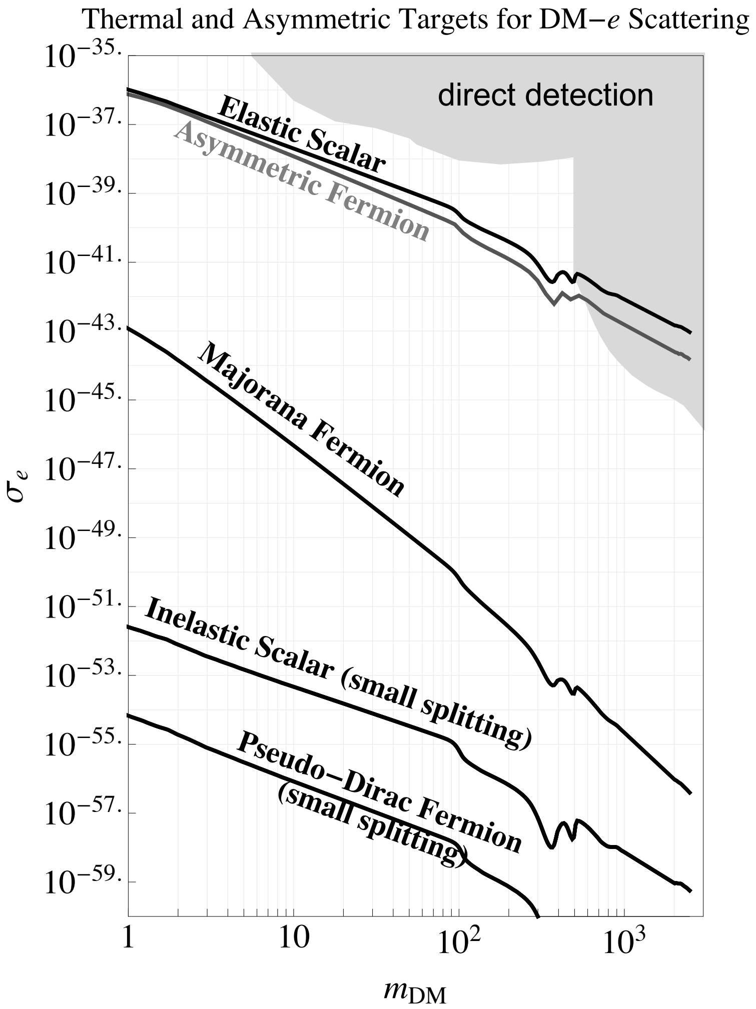
The NA64 Collaboration, in particular **P. Crivelli** and **S. Gninenko**

The ETH Zürich group, in particular **P. Crivelli**, **L. Molina Bueno**, **E. Depero**, **B. Radics** and **B. Banto**

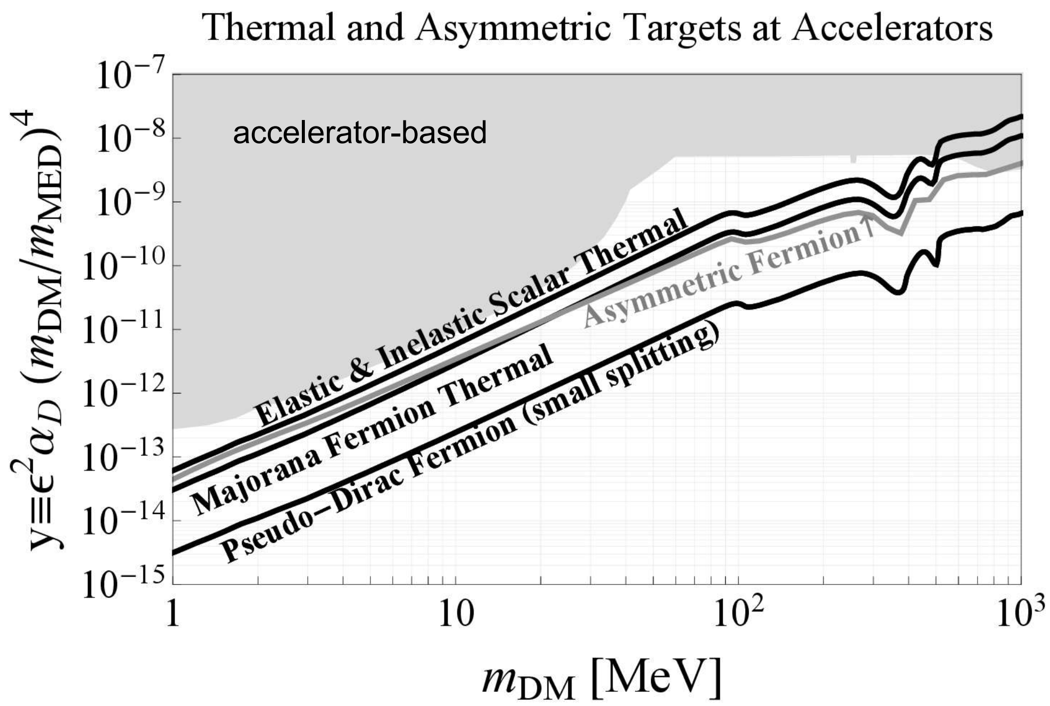
The SNSF Grant No. 16913/186181/197346/186158

Back-up

LTDM equivalence from direct detection to accelerator-based searches



M. Battaglieri et al., arXiv:1707.04591 **[hep-ph]**

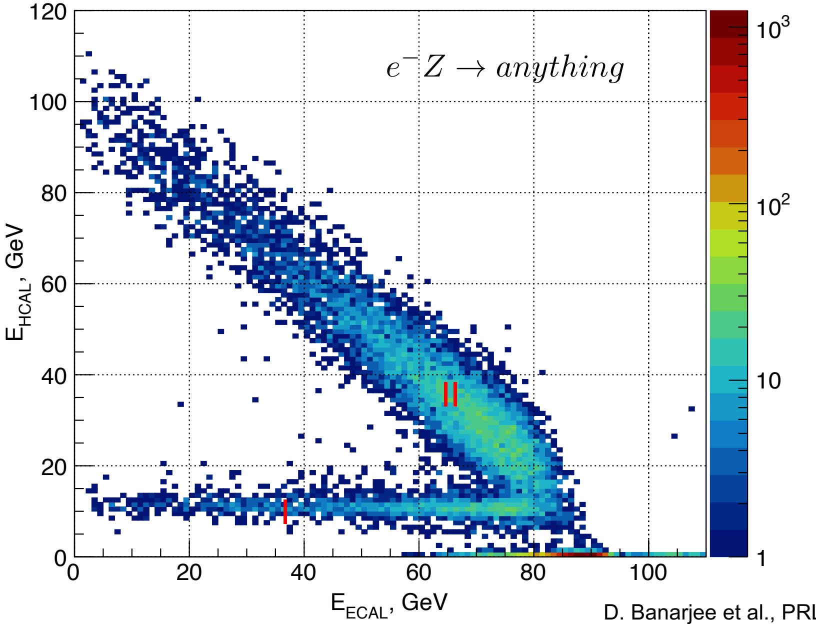


weakly dependent on DM velectiy

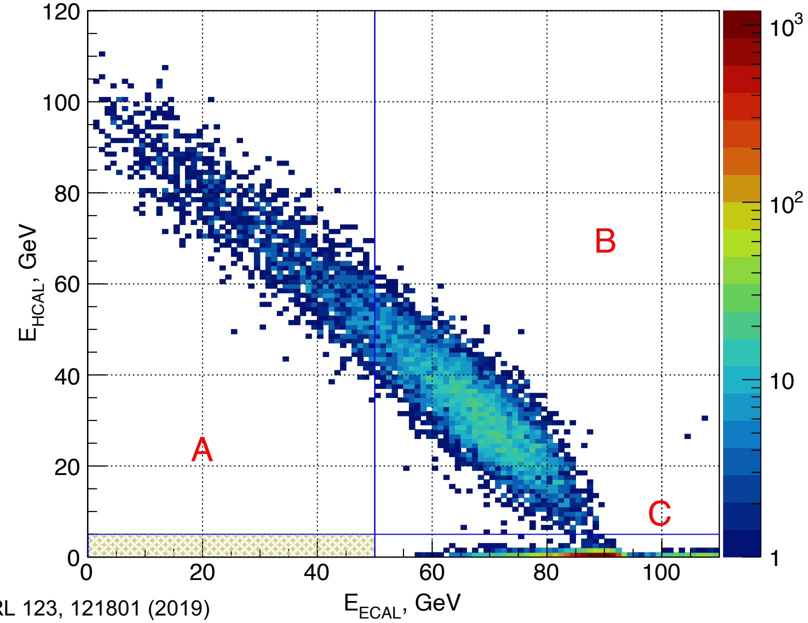
2016-2018 invisible runs analysis: event candidate selections

Selection **criteria**:
1. **Single track** with momentum 100±3 GeV (clean track)
2. **In time** trigger and energy deposit in **SRD** compatible with an e^- (timing information and electron identification)
3. Longitudinal and lateral shape of **EM shower** in ECAL consistent with an e
4. No activity in the **VETO** and **HCAL** (no punch-through)

3x10^4 events



1.6x10^4 events



D. Banarjee et al., PRL 123, 121801 (2019)

Regions:

I. Dimuon production through

$$e^- Z \rightarrow e^- Z\gamma;\ \gamma \rightarrow \mu^+\mu^-$$

II. SM events with hadron electroproduction in ECAL satisfying (within detector resolutions)

$$E_{\mathrm{ECAL}} + E_{\mathrm{HCAL}} = 100\ \mathrm{GeV}$$

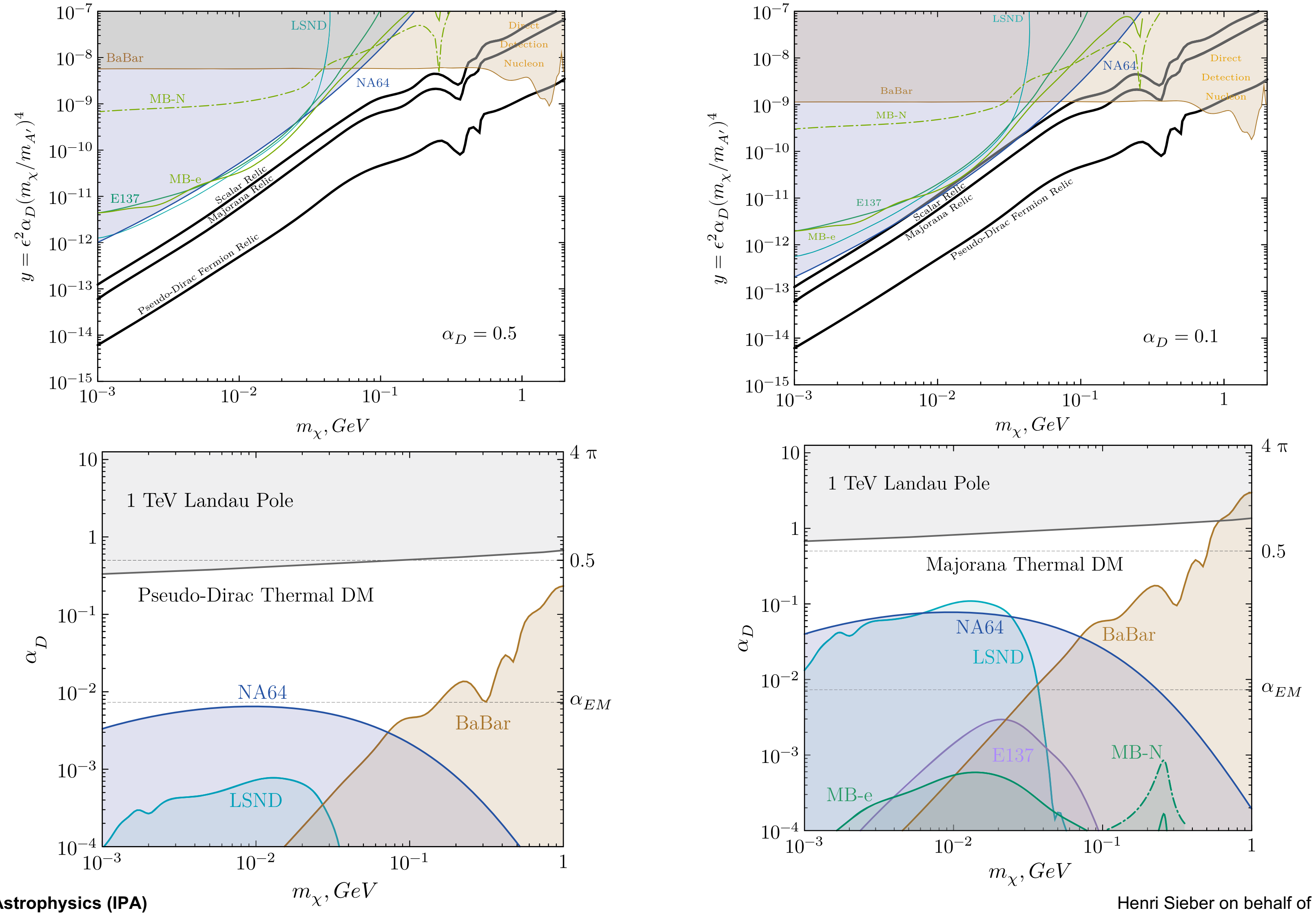
Regions:

A. Pure **neutral hadronic secondaries** produced in ECAL

B. e- hadronic interaction in the target

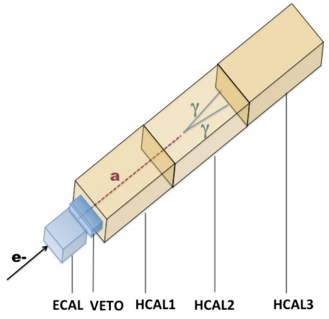
C. e- hadronic interactions **downstream the beam line** (SRD) with large transverse fluctuations in hadronic secondaries

2016-2018 invisible runs analysis: exclusion limits



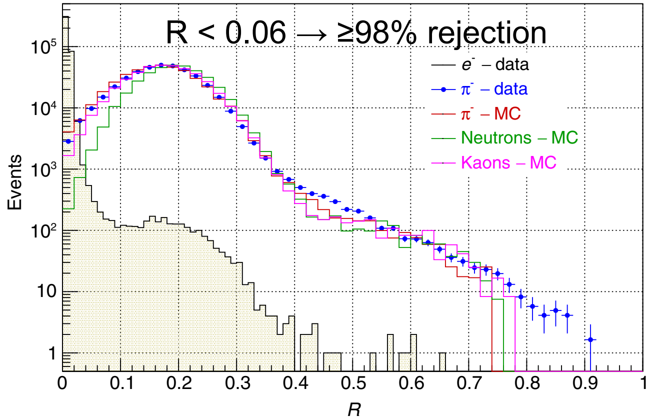
2016-2018 invisible runs analysis: ALPs event candidate selections

Selection **criteria**:
1. **Single track** with momentum 100±3 GeV (clean track)
2. **In time** trigger and energy deposit in **SRD** compatible with an e^- (timing information and electron identification)
3. Longitudinal and lateral shape of **EM shower** in ECAL consistent with an e
4. No activity in the **VETO**
5. No activity in **HCAL** (signature 2)
6. No activity in HCAL1 and **EM-like shower** in HCAL2,3 (R-cut)

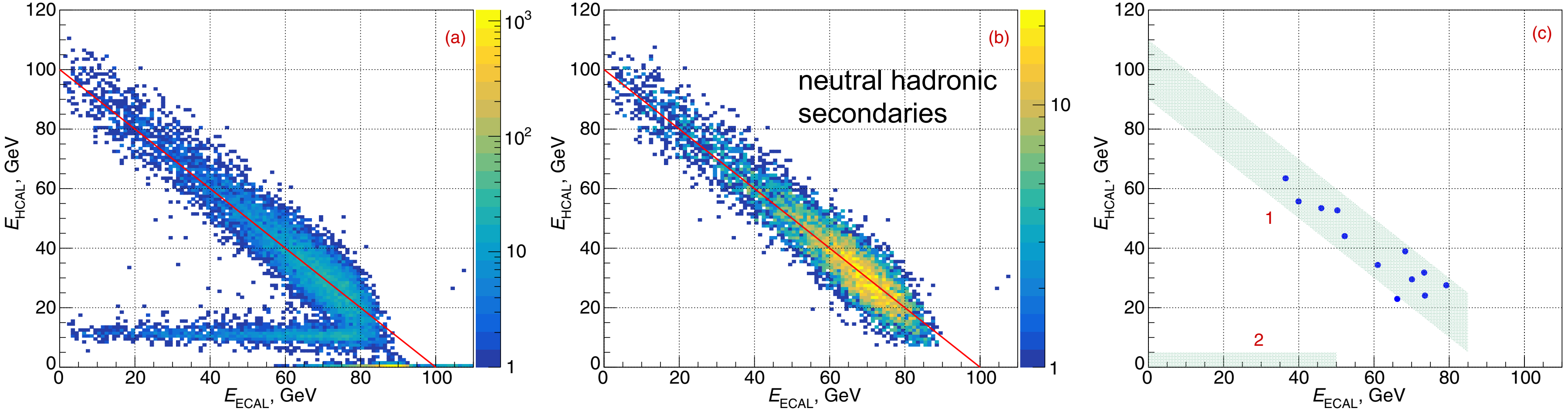


R-cut: using shower lateral shape in HCAL to discriminate e- induced shower from hadron's

$$R = \frac{E_{\mathrm{HCAL}} - E^{\mathrm{c}}_{\mathrm{HCAL}}}{E_{\mathrm{HCAL}}}$$



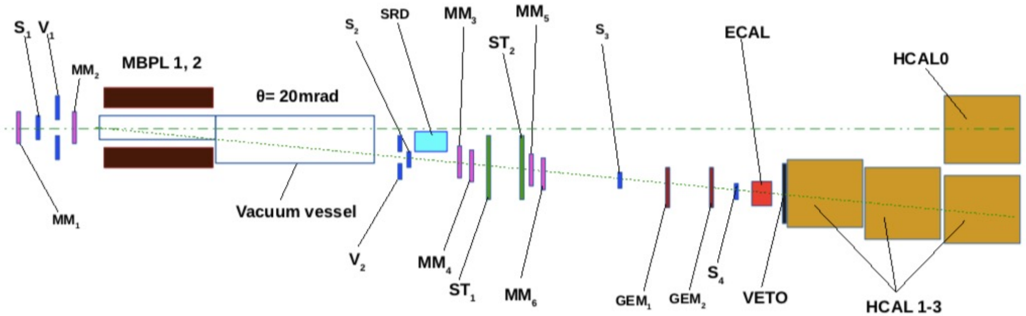
3x10⁴ events | **7x10³ events** | **12 events**



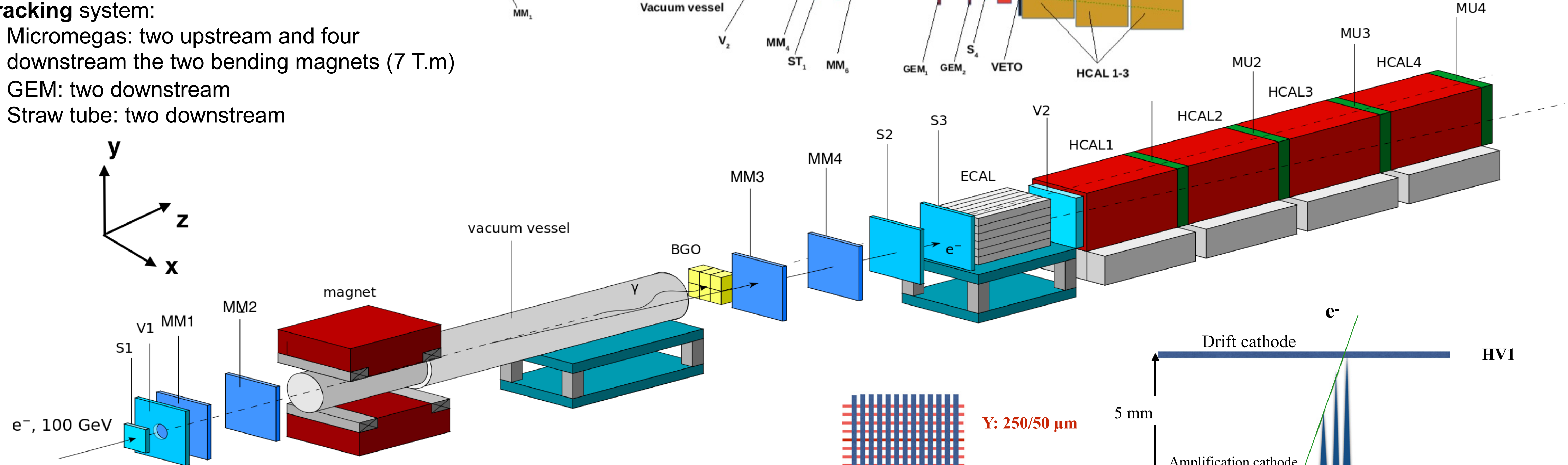
D. Banarjee et al., PRL 125, 081801 (2020)

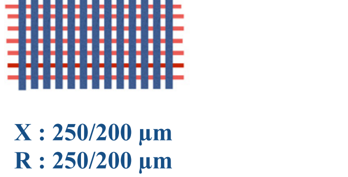
SRD electron identification → No activity in VETO → All selection criteria (+R > 0.06)

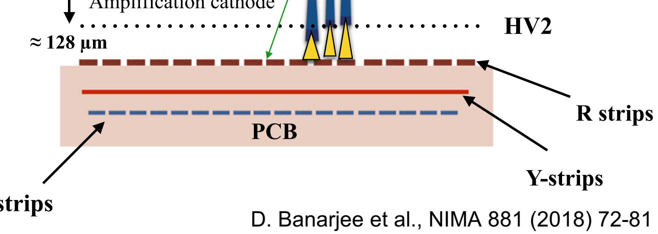
2016-2018 invisible runs: tracking



Tracking system:
- Micromegas: two upstream and four downstream the two bending magnets (7 T.m)
- GEM: two downstream
- Straw tube: two downstream

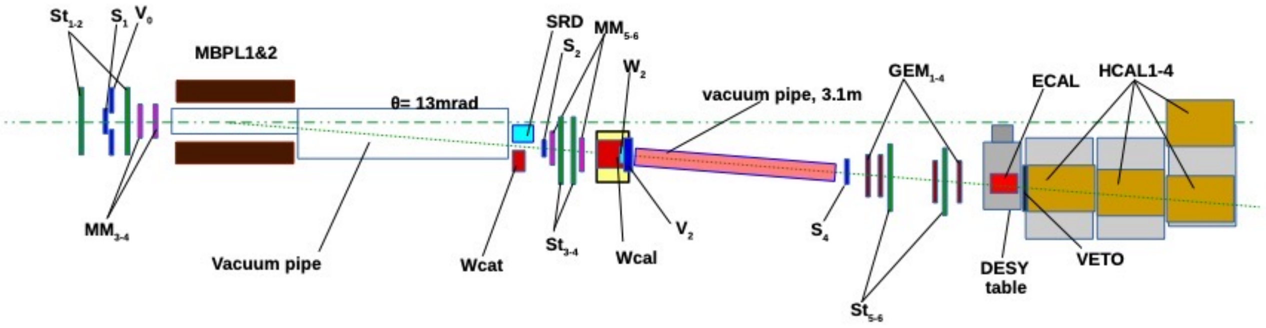






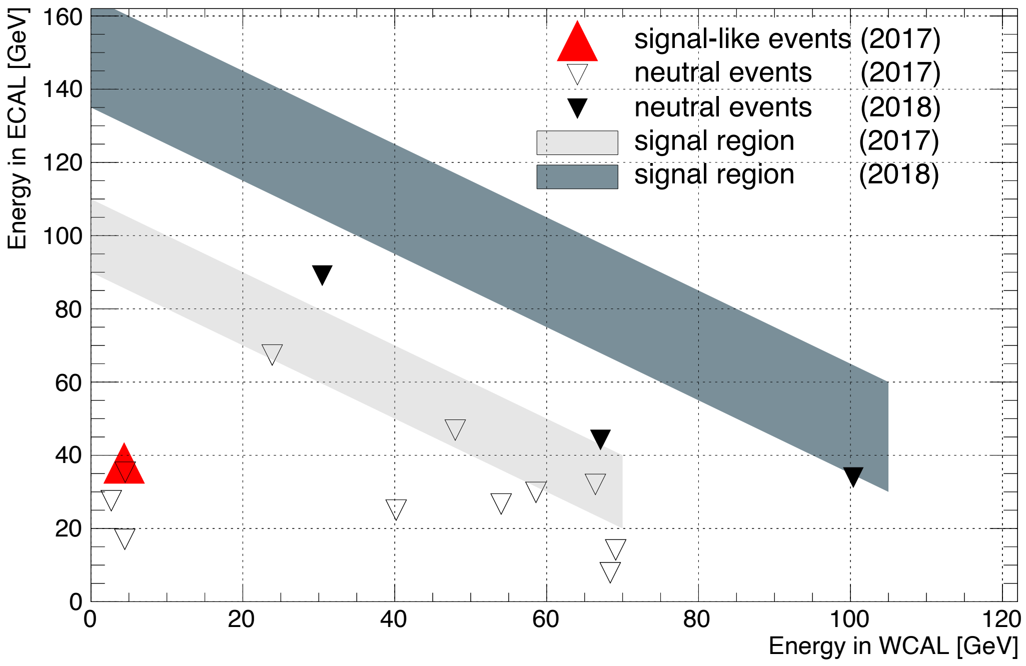
D. Banarjee et al., NIMA 881 (2018) 72-81

2017-2018 visible runs analysis: event candidate selections



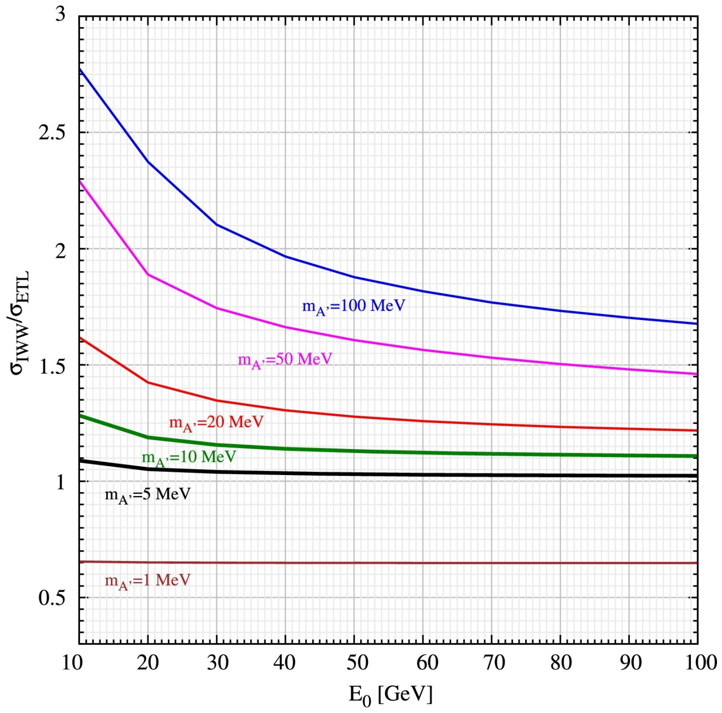
Selection **criteria**:
1. **Single track** entering the dump
2. **In time** trigger and energy deposit in **SRD** compatible with an e^- (timing information and electron identification)
3. No energy in **V2** (0.5 MIP)
4. Signal in $\mathbf{S_4}$ **counter** compatible with 2 MIPs
5. Two EM-like showers in **WCAL** and **ECAL** with $E_{beam} = E_{WCAL} + E_{ECAL}$
6. No energy deposit on **VETO** and **HCAL**

D. Banarjee et al., PRD 101, 071101(R) (2020)



Signal simulations: compatibility with Monte Carlo simulations toolkit

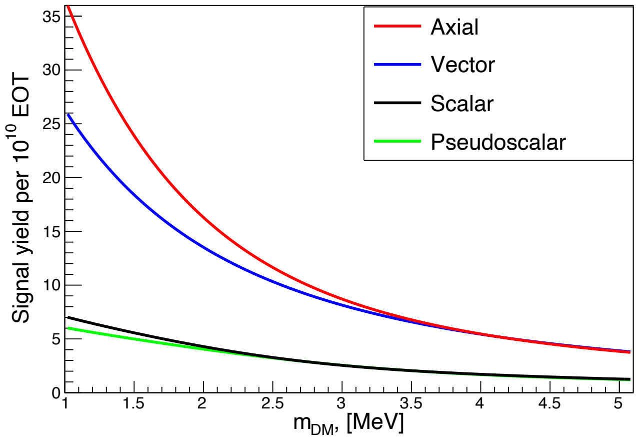
Significant effort driven towards **computation of A' production** through bremsstrahlung at **ETL** and with **WW** and **IWW** approximation (see e.g. S. N. Gninenko et al., PLB 789 (2018) 406-411), as well as **Z' production** (paper in preparation) and others

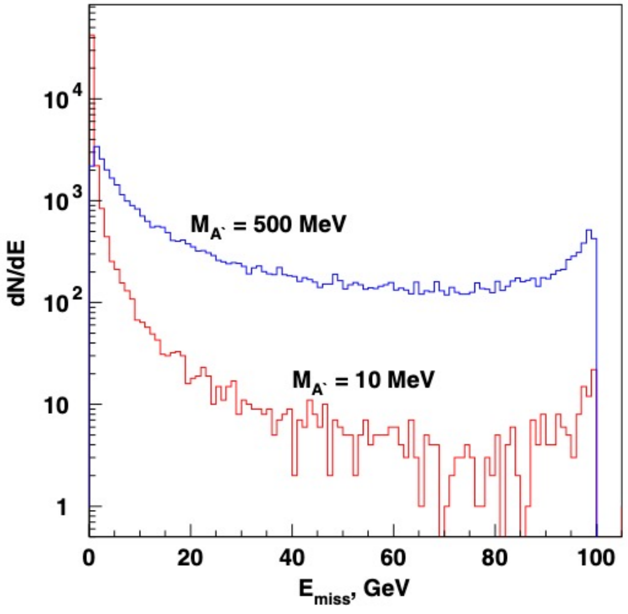


Accurate signal simulations developed in a simulations package **DMG4** (see M. Bondi et al., arXiv:2101.12192v2 [hep-ph]) to be fully compatible with the simulation toolkit **GEANT4**

S. N. Gninenko et al., PRD 94, 095025 (2016)

M. Bondi et al., arXiv:2101.12192v2 [hep-ph]





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