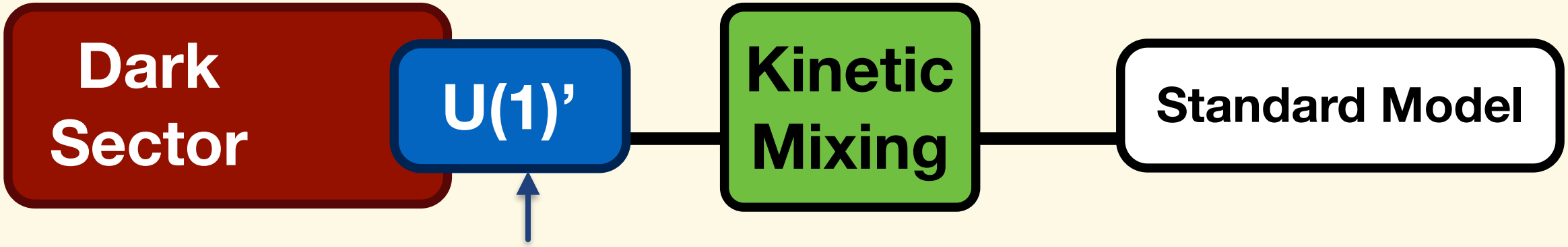
SEARCHING FOR HIDDEN/DARK SECTORS WITH THE NA64 EXPERIMENT AT THE CERN SPS

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

DARK SECTORS - THE VECTOR PORTAL

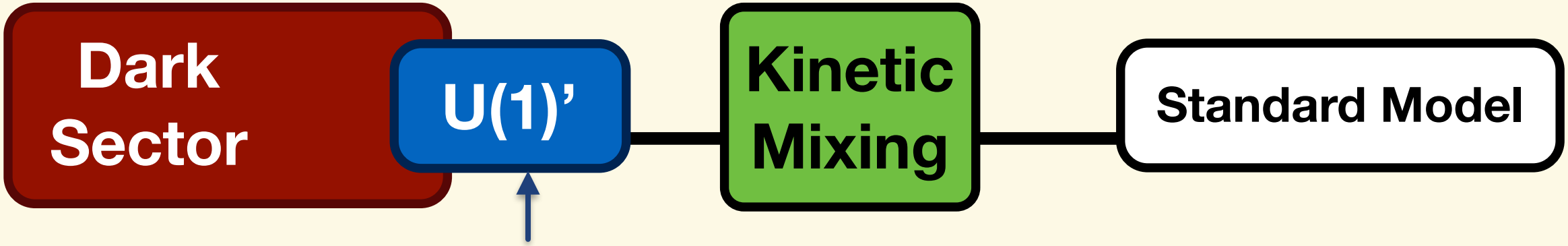


DARK SECTOR (DS) charged under a new U(1)' gauge symmetry and interacts with SM through kinetic mixing (ε) of a MASSIVE VECTOR MEDIATOR (A') with our photon.

Dark matter with mass (m_χ), part of DS. Four parameters: $m_{A'}$, m_χ, α_D ,ε

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + \frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu} + \frac{m^2_{A'}}{2} A'_\mu A'^\mu$$
$$+ i\bar{\chi}\gamma^\mu \partial_\mu \chi - m_\chi \bar{\chi}\chi - \alpha_D \bar{\chi}\gamma^\mu A'_\mu \chi,$$

DARK SECTORS - THE VECTOR PORTAL



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

OBSERVED **AMOUNT OF DARK MATTER** TODAY

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

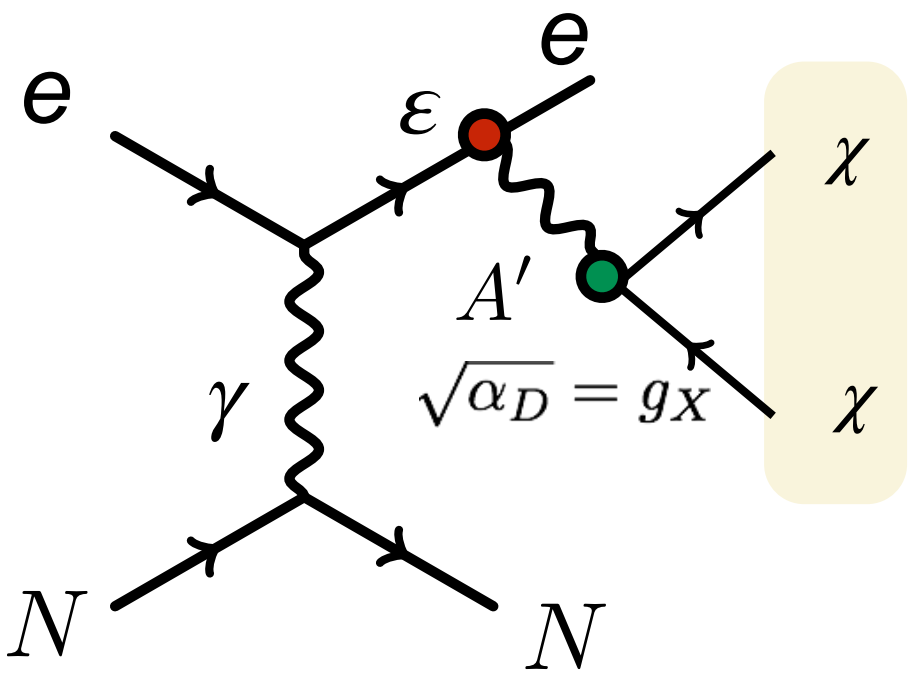
Large range for g_X and m_X

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

SEARCHES FOR DARK SECTORS AT ACCELERATORS

INVISIBLE DECAY MODE $m'_A > 2m_X$

1) BEAM DUMP APPROACH (MiniBooNE, LSND, NA62...)



Flux of X generated by decays of A's produced in the dump.

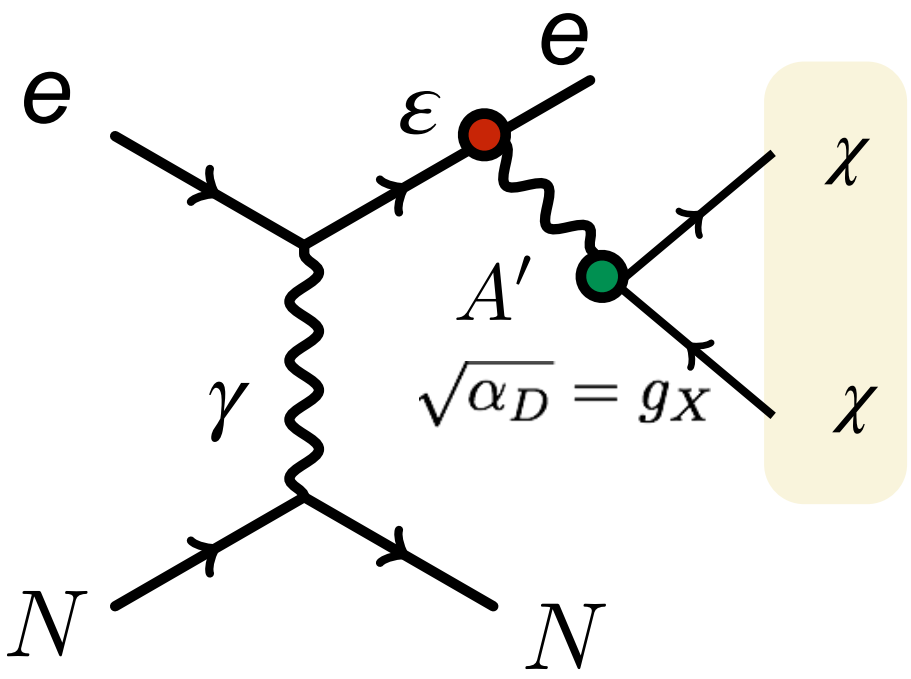
Signal: X scattering in far detector

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

SEARCHES FOR DARK SECTORS AT ACCELERATORS

INVISIBLE DECAY MODE $m'_A > 2m_X$

2) NA64/LDMX APPROACH



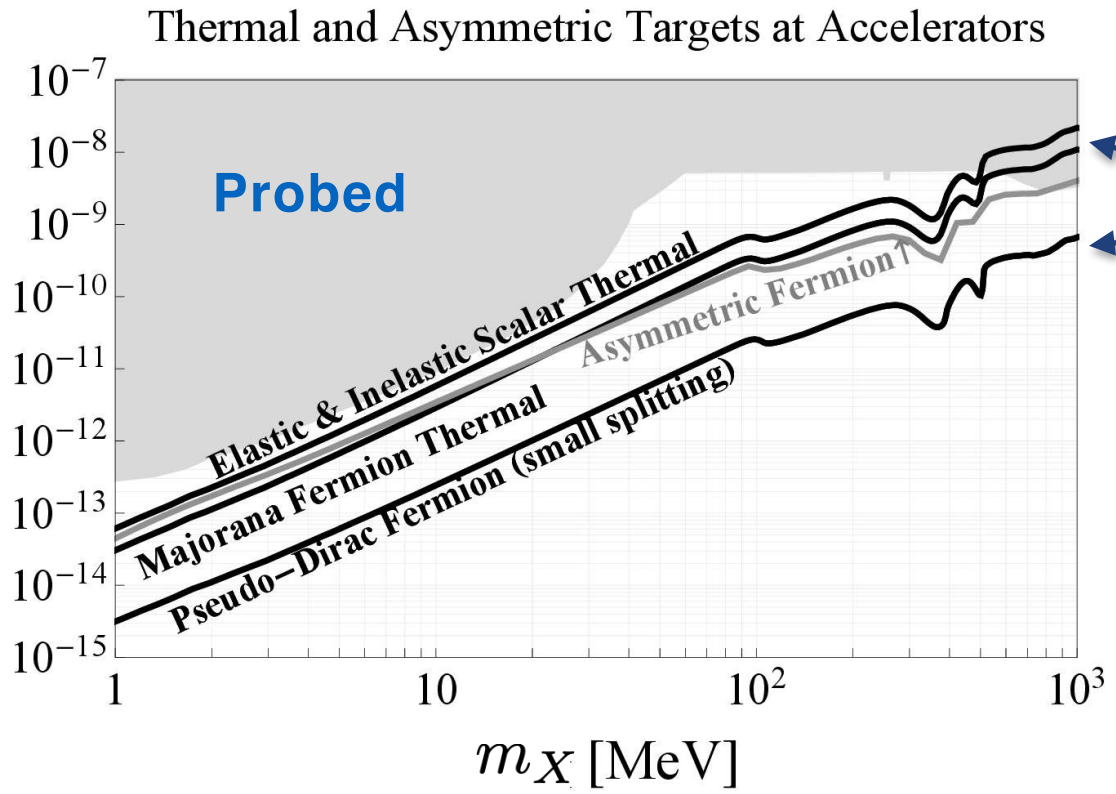
NA64 **missing energy**: produced A's carry away energy form the active dump used to measure recoil e- energy

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

EXPLICIT TARGET FOR NA64 (y,m_X) DM PARAMETER SPACE

recent review https://arxiv.org/pdf/1707.04591.pdf

$$y = \epsilon^2 \alpha_D (m_X/m_{A'})^4$$



Solid lines predictions from DM relic abundance

Cross sections DM -> SM annihilation is ~ Y, useful variable to compare exp. sentivities

EXPLICIT TARGET FOR NA64 (y,m_X) DM PARAMETER SPACE

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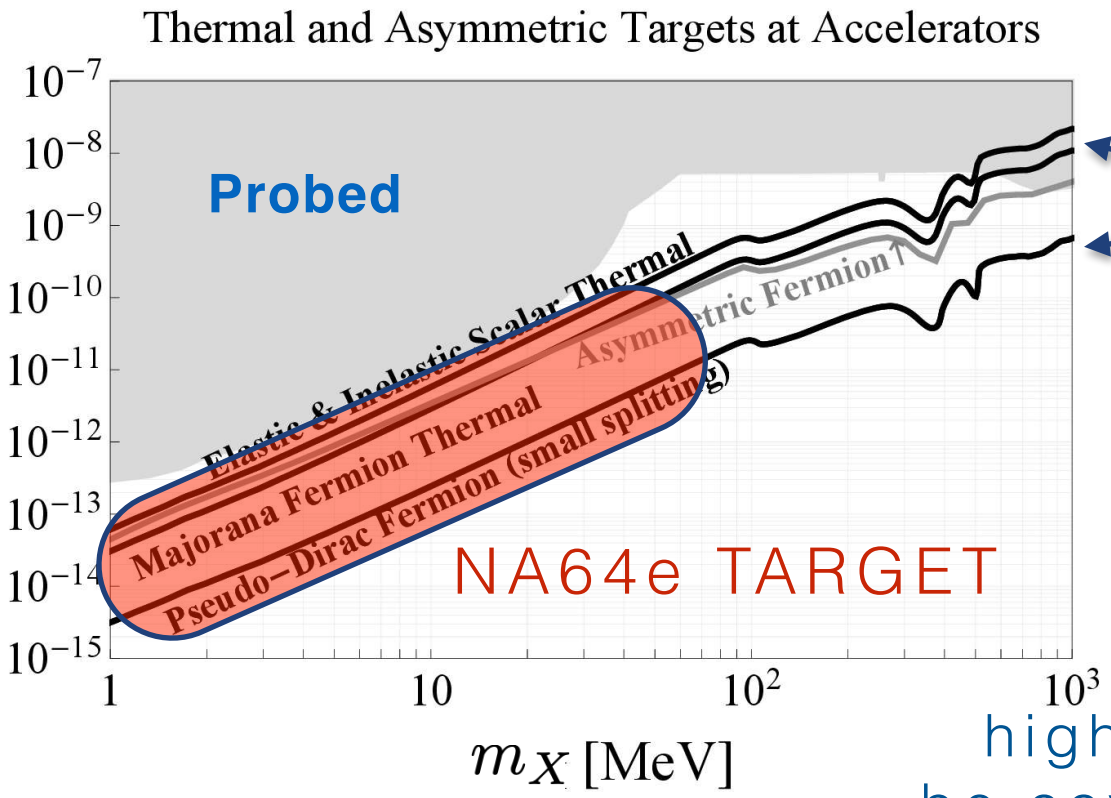


Solid lines predictions from DM relic abundance

$$\alpha_D \simeq 0.02 f \left(\frac{10^{-3}}{\epsilon}\right)^2 \left(\frac{m_{A'}}{100\ \text{MeV}}\right)^4 \left(\frac{10\ \text{MeV}}{m_\chi}\right)^2$$

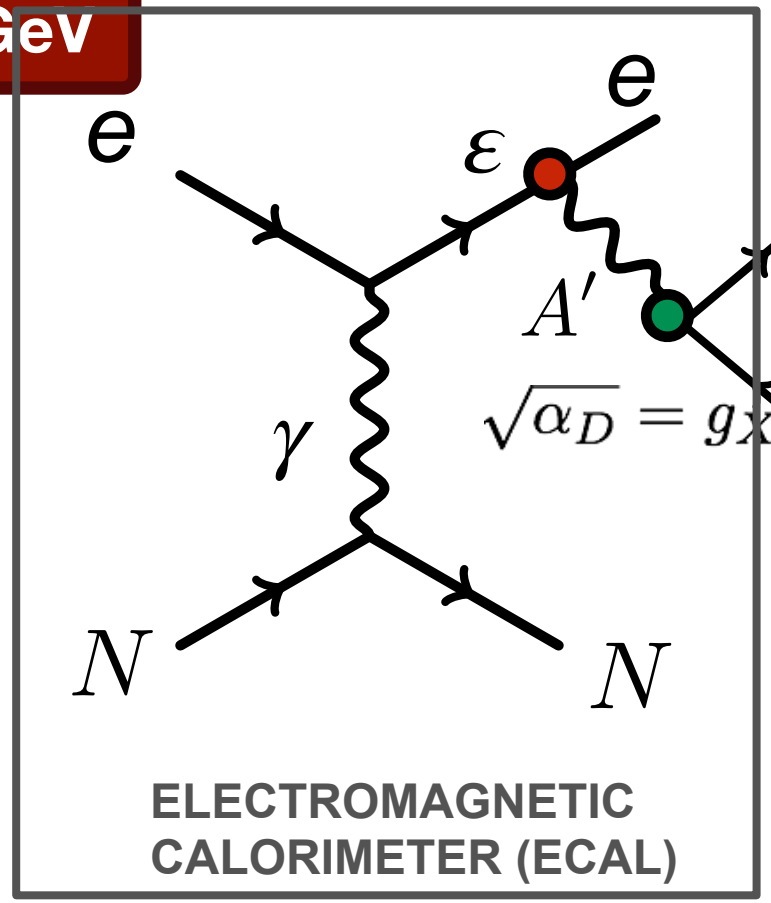
higher mass region could be covered by NA64mu (pilot run in 2021)

PLB796, 117 (2019)

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

TAGGED 100 GeV

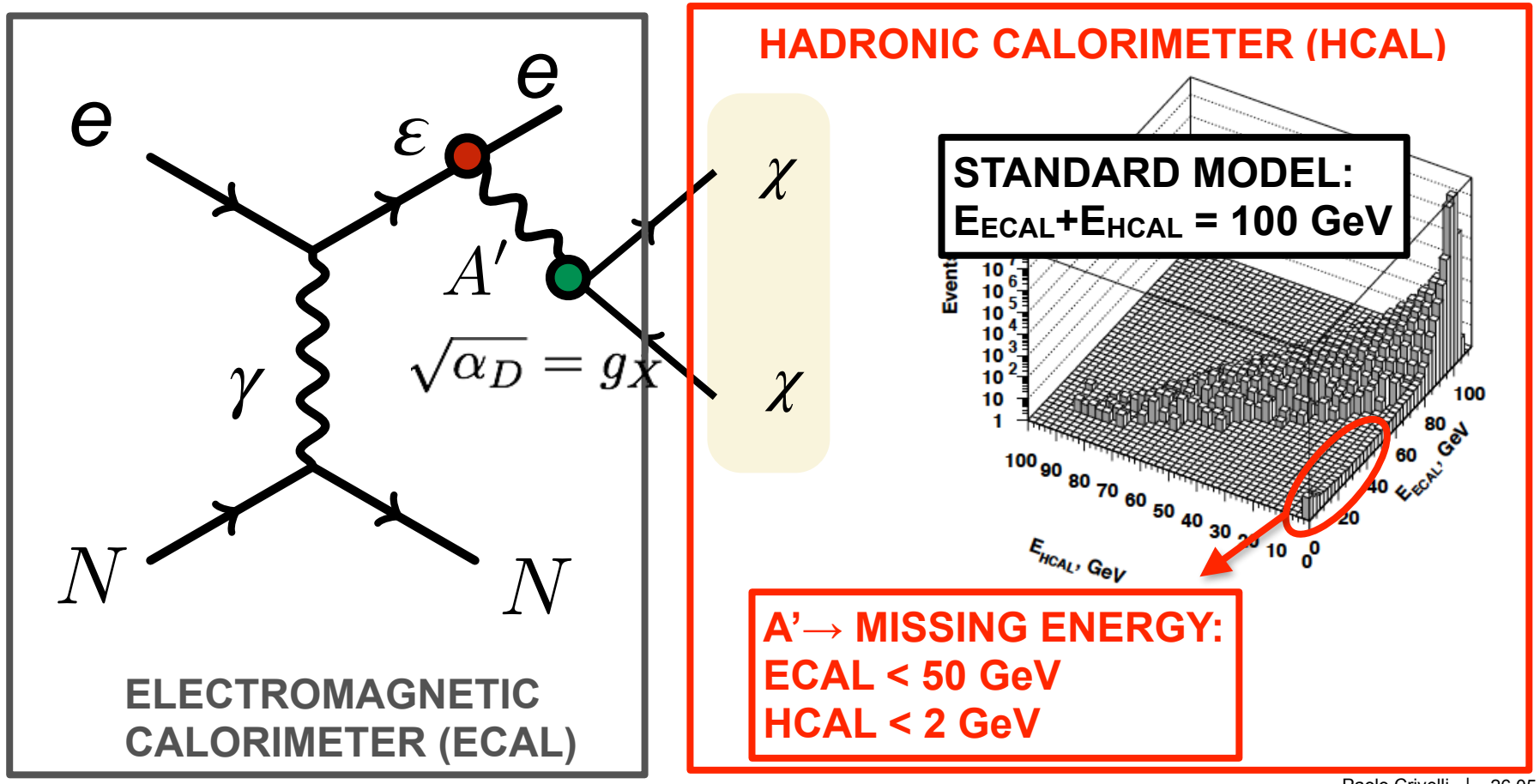
Requested ECAL ENERGY < 50 GeV



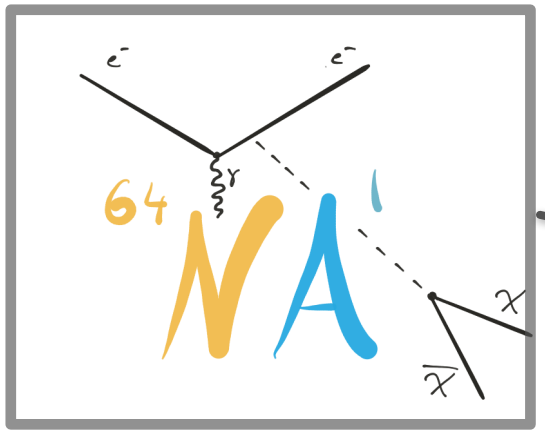
"BREMSSTRAHLUNG" OF A'

Active Dump

Signature for the invisible decay A' → $\chi\bar{\chi}$ - large missing energy



The Electromagnetic Calorimeter (ECAL)

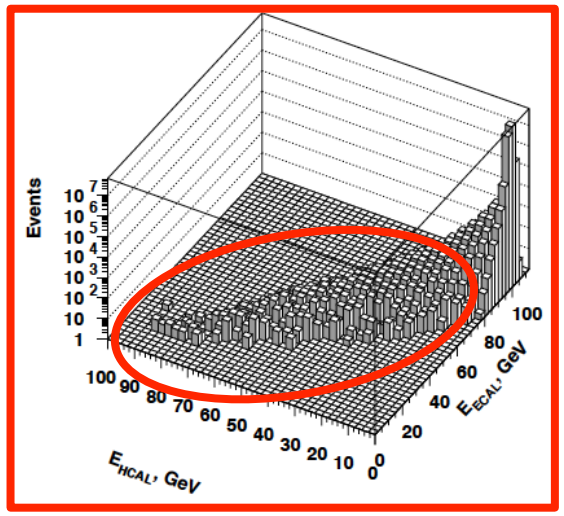


- High hermeticity (~40 X_0)
- PbSc sandwich, 6x6 matrix, cells 38x38x490 mm3
- WLS fibers in spiral→ suppress energy leaks
- Energy resolution ~ 9%/√(E[GeV])
- Longitudinal (Pre-shower) and lateral segmentation

→ shower profiles (hadron rejection)

100 GeV electrons (tagged with $S_{1,2,3}$)

The Hadronic Calorimeter (HCAL)



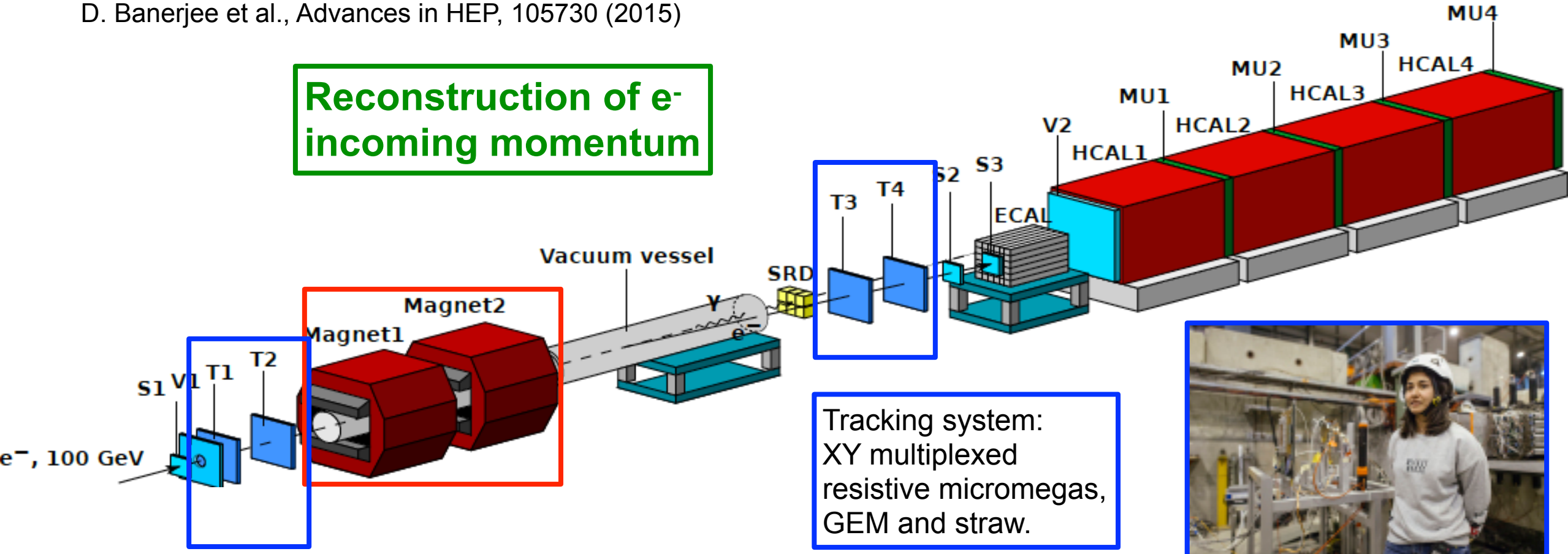
High hermeticity due to Lorentz boost

- High hermeticity : 4 HCAL (~7 λ/module)
- FeSc sandwich 3x3 matrix, cells 19.4x19.2x150 cm^3
- WLS fibers in spiral→ suppress energy leaks
- Energy resolution ~ 60%/√(E[GeV])

The magnetic spectrometer

D. Banerjee et al., Advances in HEP, 105730 (2015)

Reconstruction of e⁻ incoming momentum

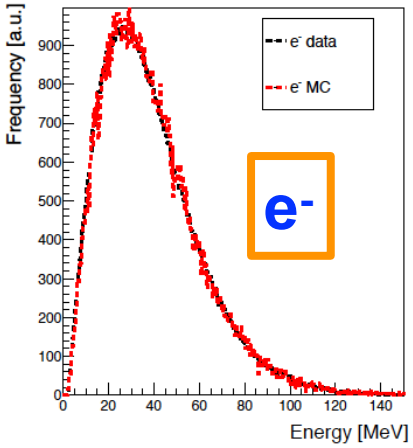


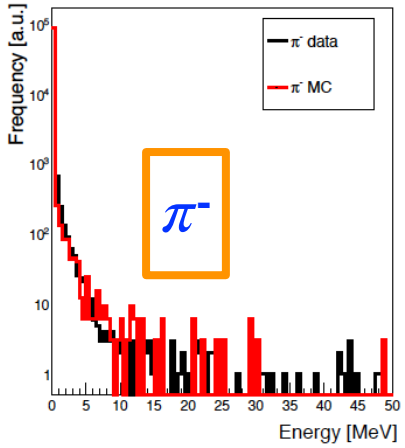
Tracking system:
XY multiplexed resistive micromegas, GEM and straw.

Two bending magnets in series → 7 T.m field

D. Banerjee et al., NIMA881 (2018) 72-81

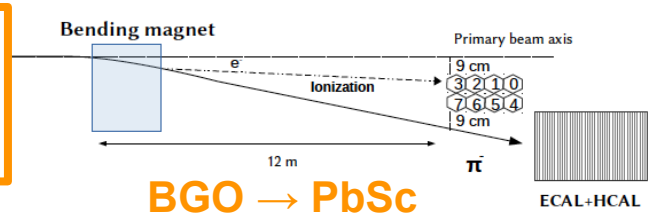
The Synchrotron radiation detector (e- tagging)





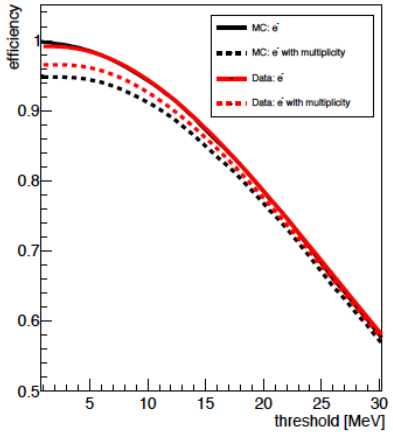
Particle identification
SR emission ~ $1/m^4$

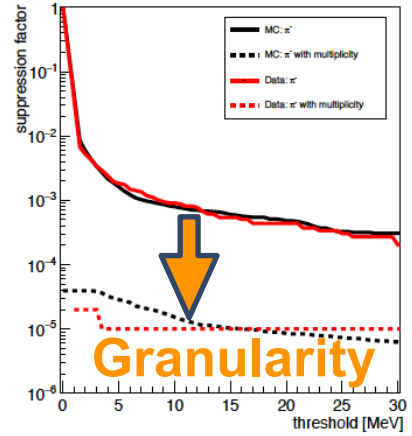
E. Depero et al., NIMA 866 (2017) 196-201.



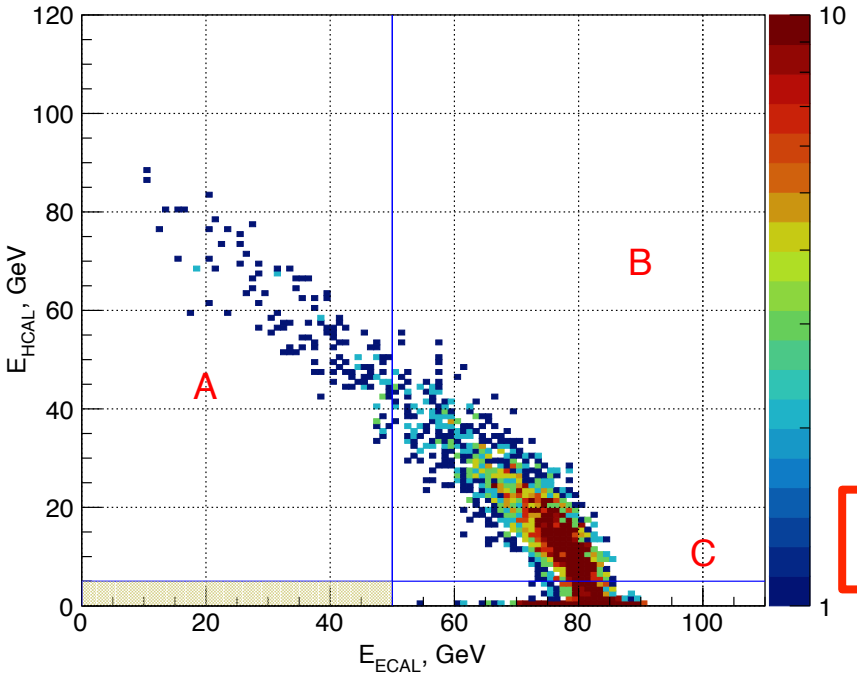
e-efficiency > 95%
Suppression π, K>10^{-5}

BGO → PbSc



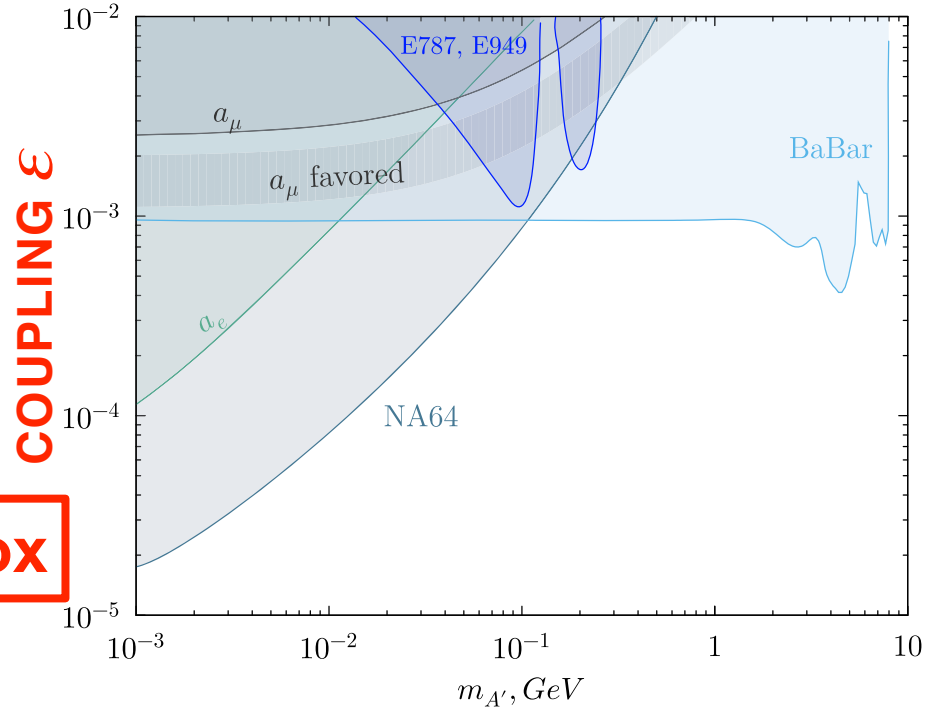


The NA64 search for A' → $\chi\bar{\chi}$ - results (July + October 2016, 5 weeks)



4 x 10^{10} electrons on target

No event in signal box



MASS OF THE DARK PHOTON

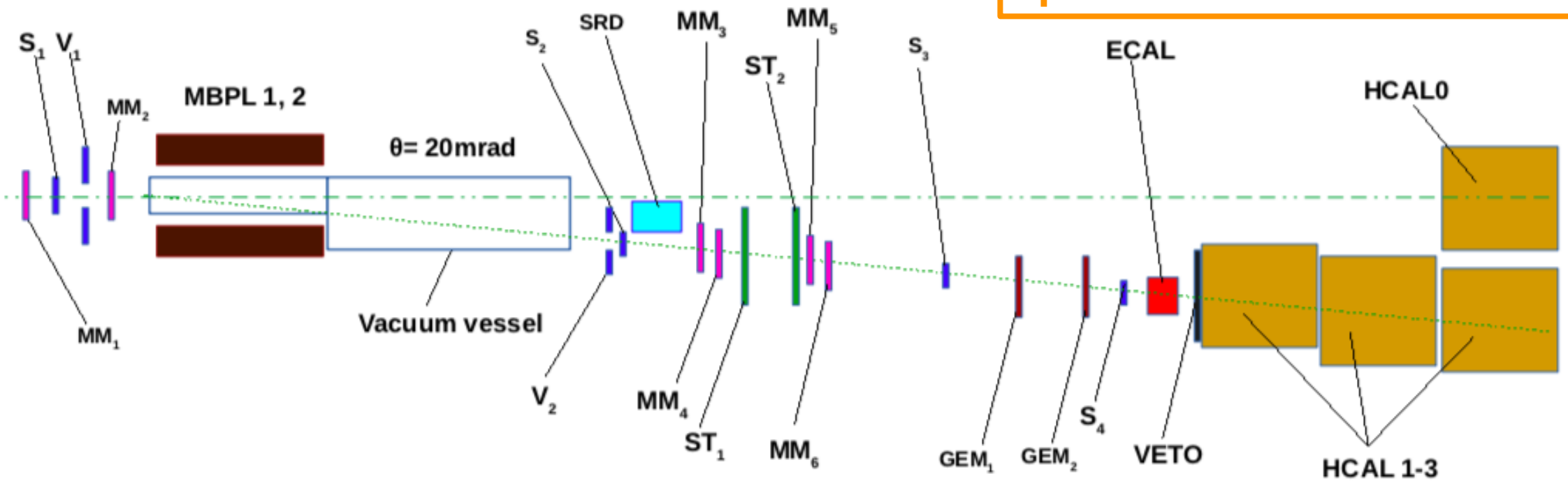
→ exclusion of most of g-2 muon favored region

g-2 closed completely by BABAR results

NA64 collaboration, Phys. Rev. Lett. 118, 011802 (2017) and Phys. Rev. D 97, 072002 (2018)

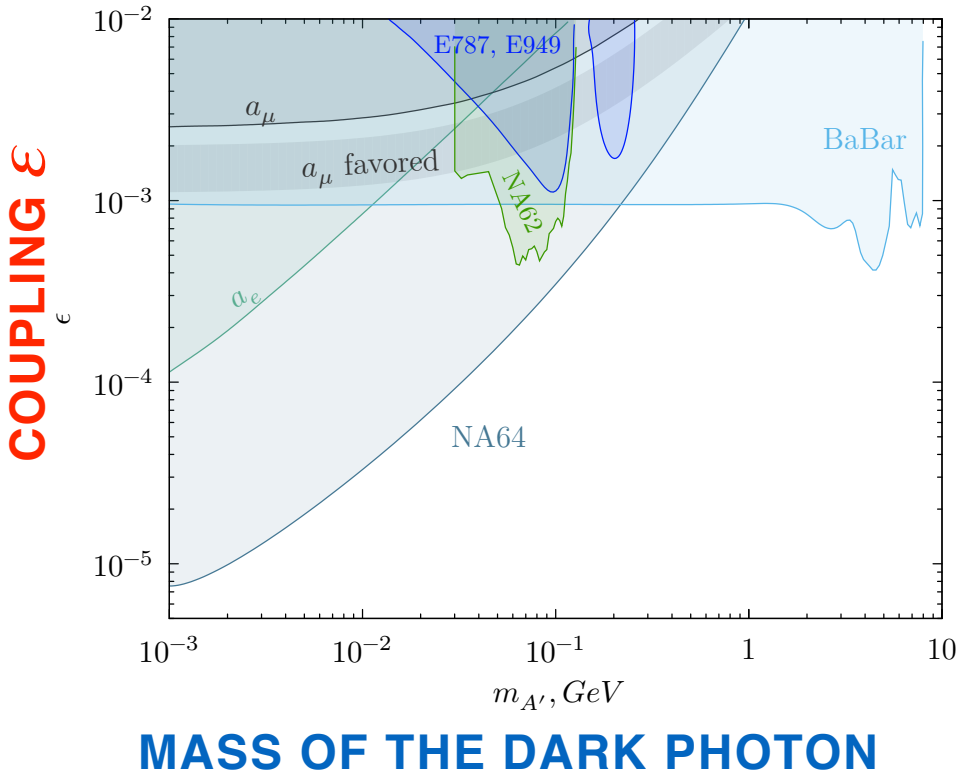
Improvement of setup for 2018 run

HCAL0: Rejection of events with hard neutral from upstream e- interactions



ST1,2: New straw-tube trackers: VETO against hadron electro-production in the beam material upstream the ECAL.

Combined results (2016-2018)



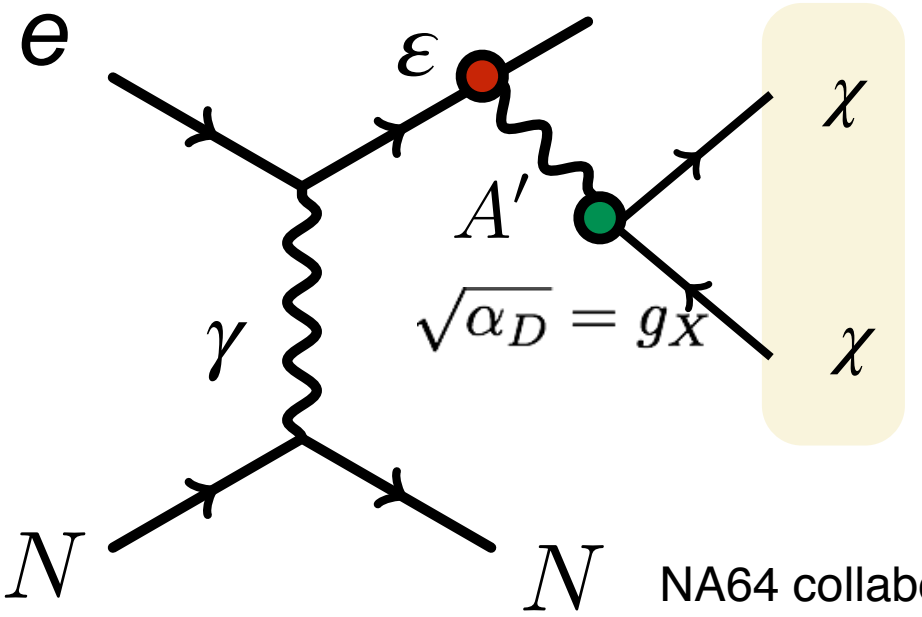
TOT: 2.84 x 10^{11} electrons on target

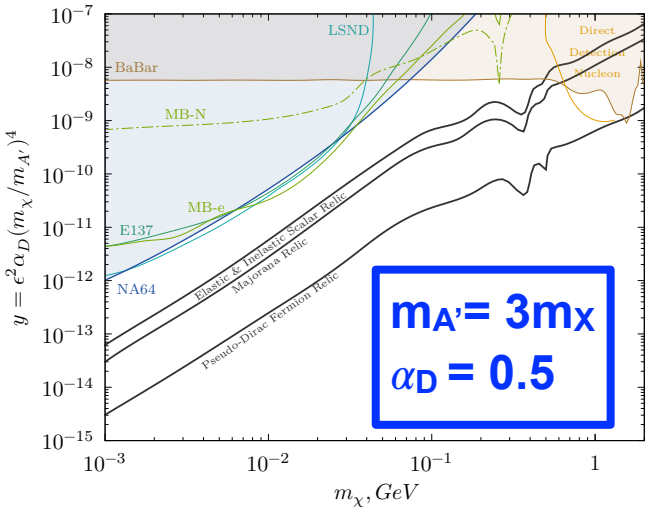
Signal efficiency: ~50% slightly mass dependent.

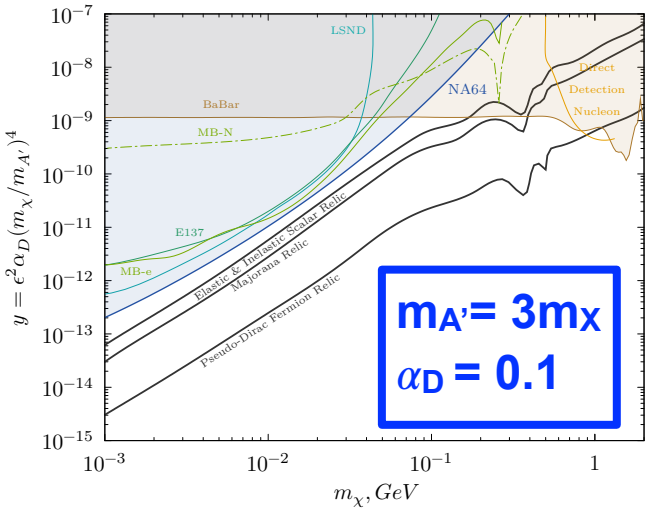
NA64 collaboration, Phys. Rev. Lett. 123, 121801 (2019)

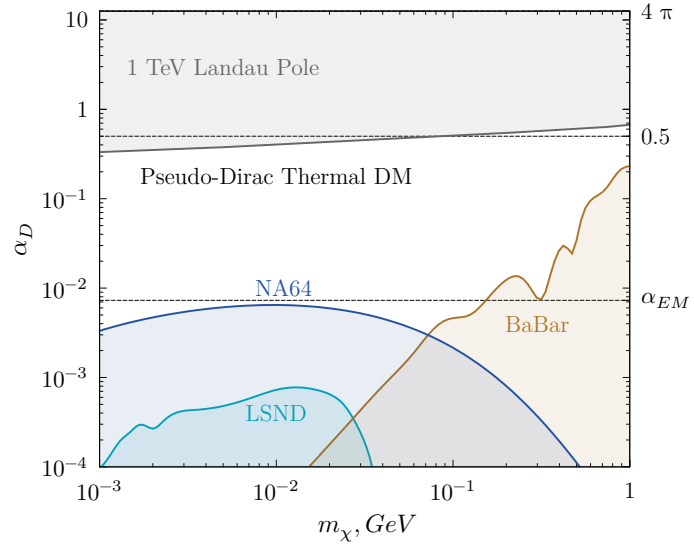
NEW constraints on sub-GeV DM parameter space (2016-2018)

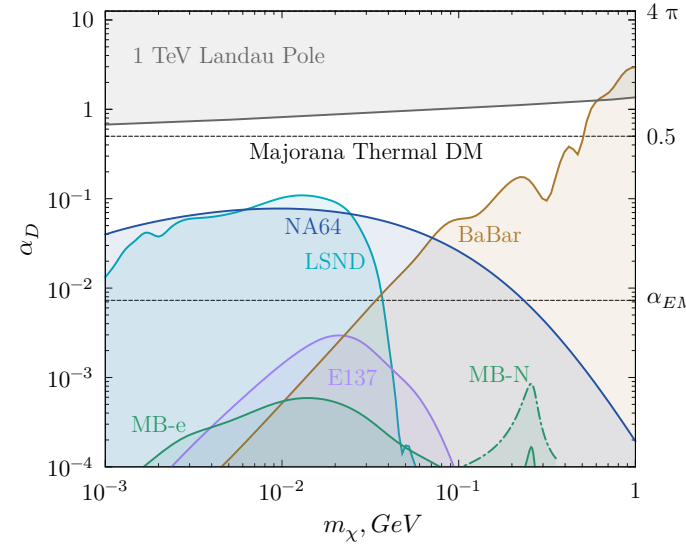
First time NA64 constraints on light thermal DM exceeding sensitivity of beam dump exp. (suppressed by $\epsilon^2\alpha_D$)





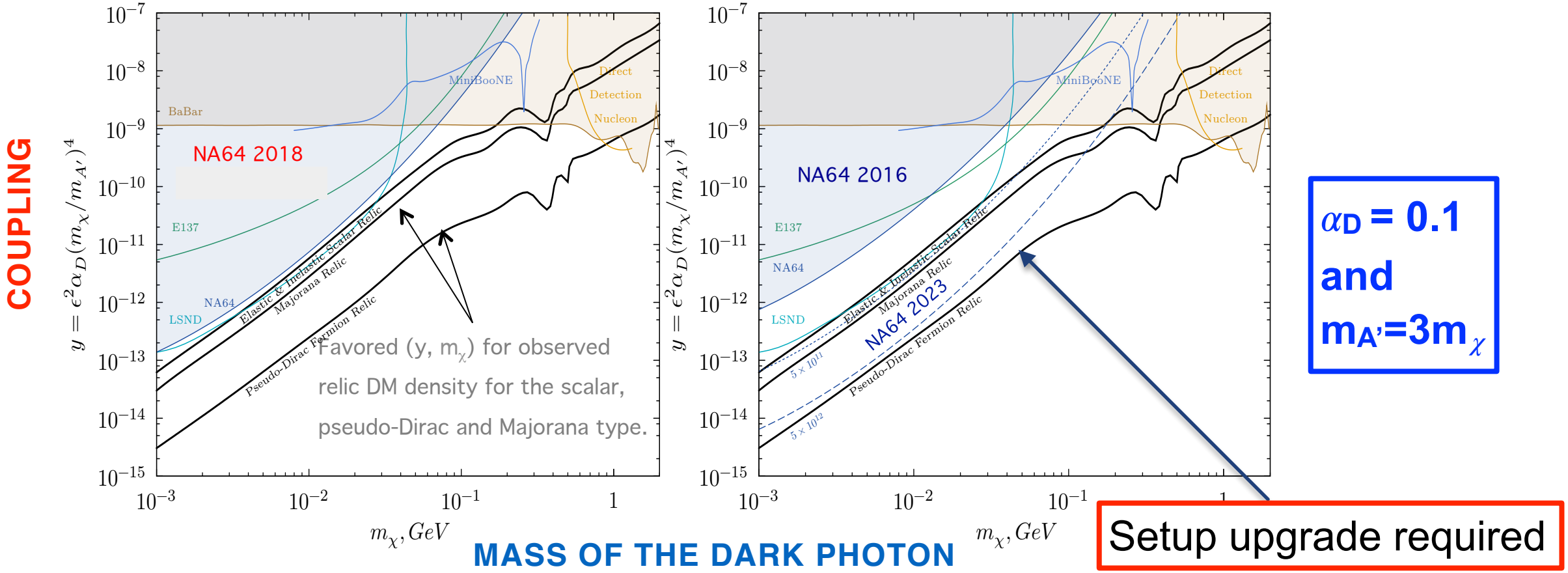






NA64 collaboration, Phys. Rev. Lett. 123, 121801 (2019)

Current bounds on thermal relic DM & projected NA64 sensitivity



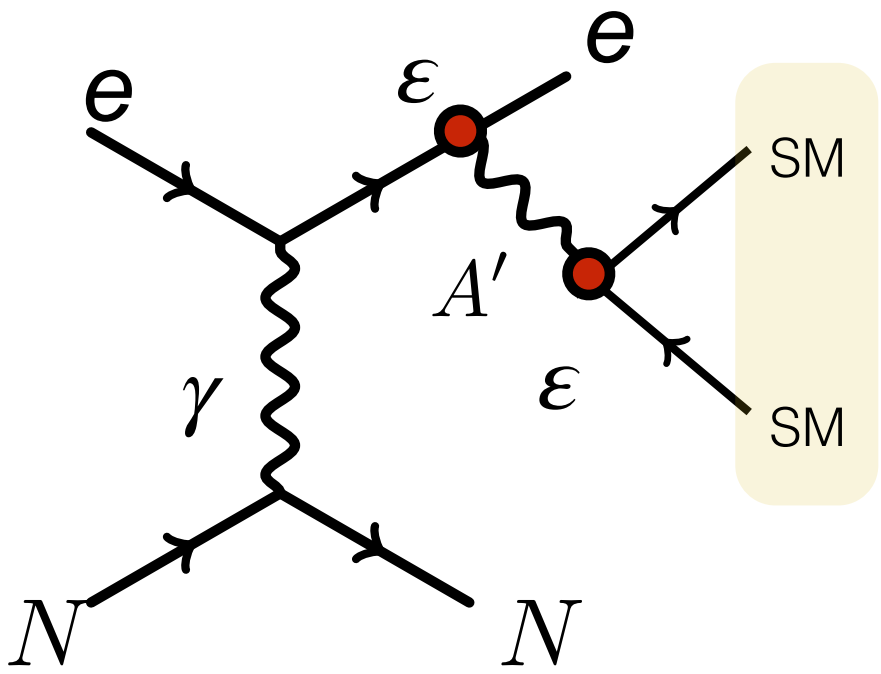
$\alpha_D = 0.1$ and $m_{A'} = 3m_\chi$

Setup upgrade required

New VHCAL: to improve detector hermiticity and reject high-p_t hadronic secondaries from beam interactions upstream the ECAL dump. Search expected to be BKG free up to ~ 10^{13} EOT

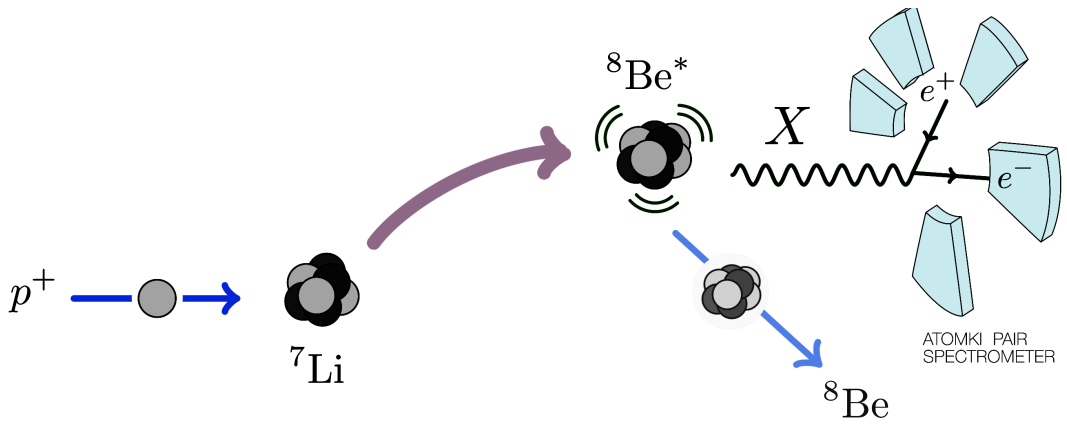
2) The NA64 search for X/A' → e^+e^-

VISIBLE DECAY MODE $m'_A < 2m_X$

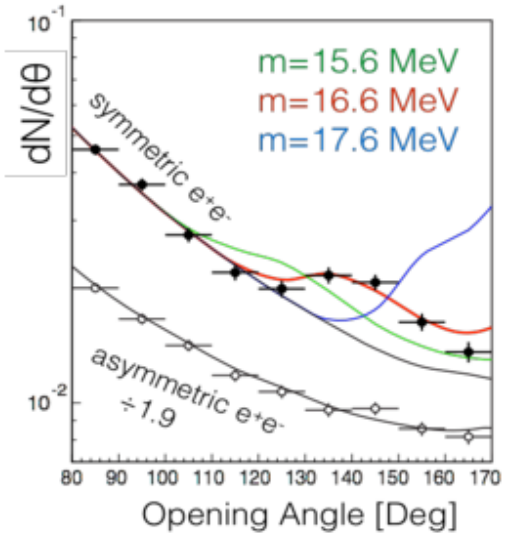


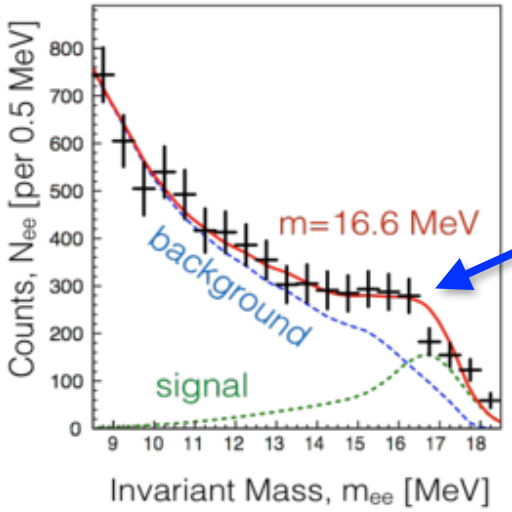
Pair production of SM particles

^{8}Be anomaly and X boson



A. J. Krasznahorkay et al. Phys. Rev. Lett.116, 042501 (2015)
and new results for 4He arXiv:1910.10459

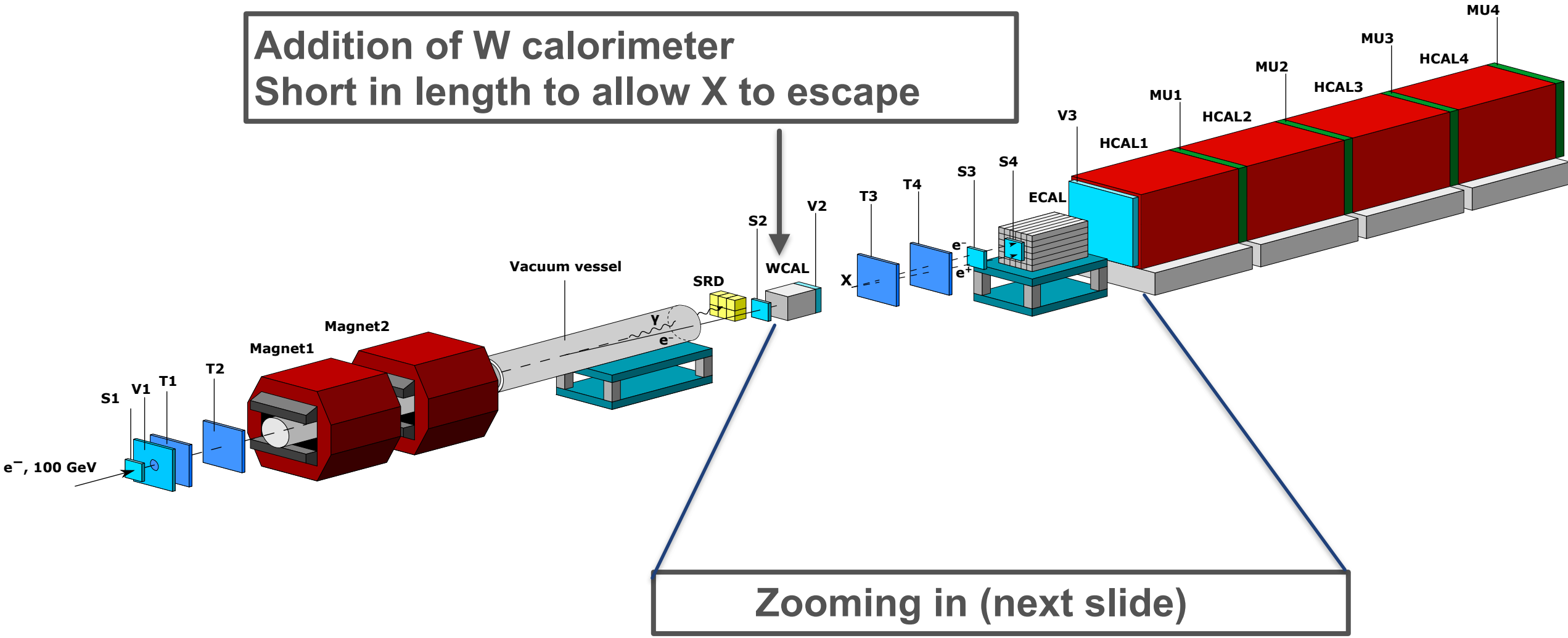




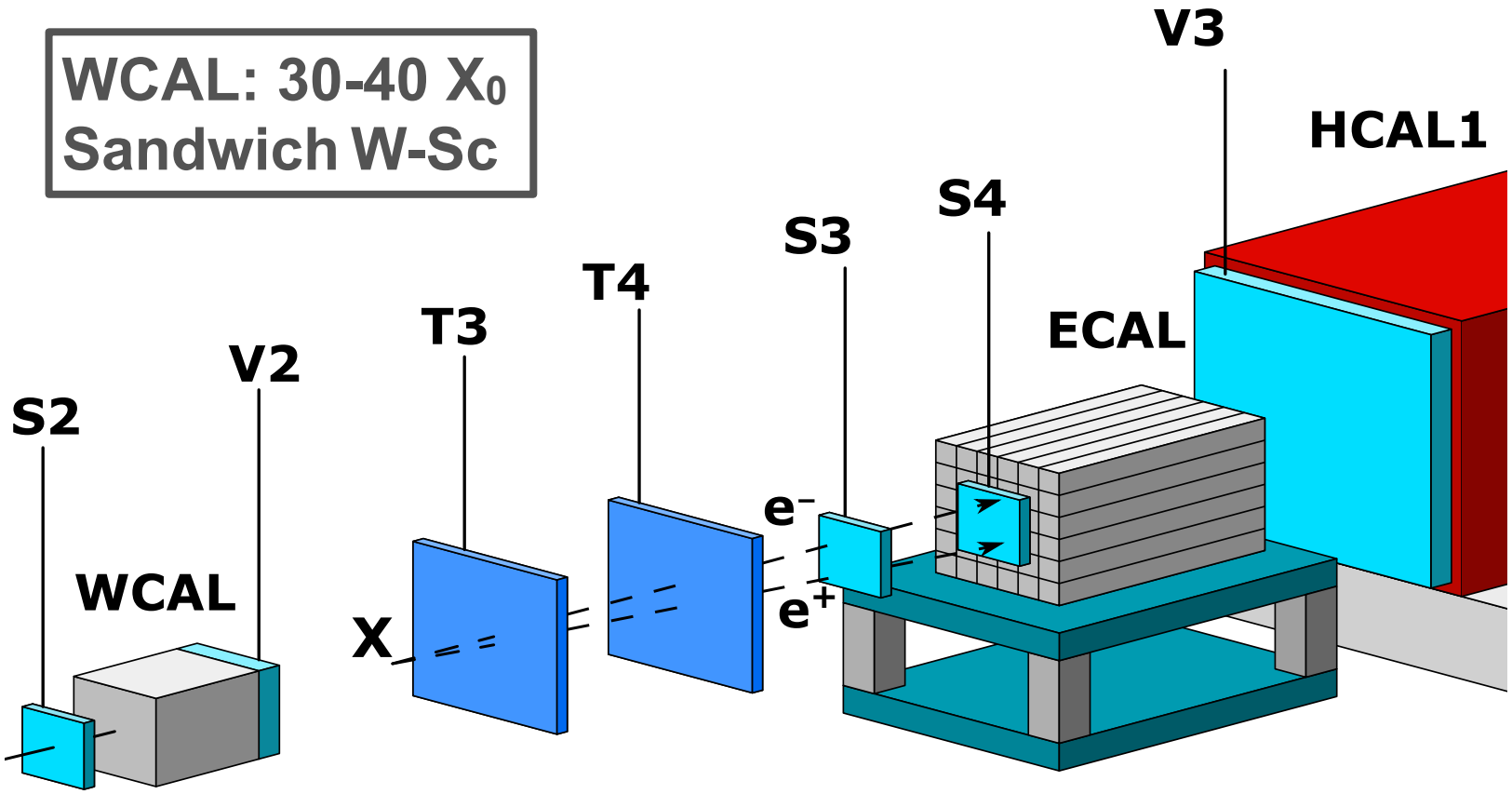
Could be explained by new 'protophobic' gauge boson X with mass around 17 MeV

J. L. Feng et al. Phys. Rev. D95, 035017 (2017)

The NA64 search for $X \rightarrow e^+e^-$ - *experimental setup*



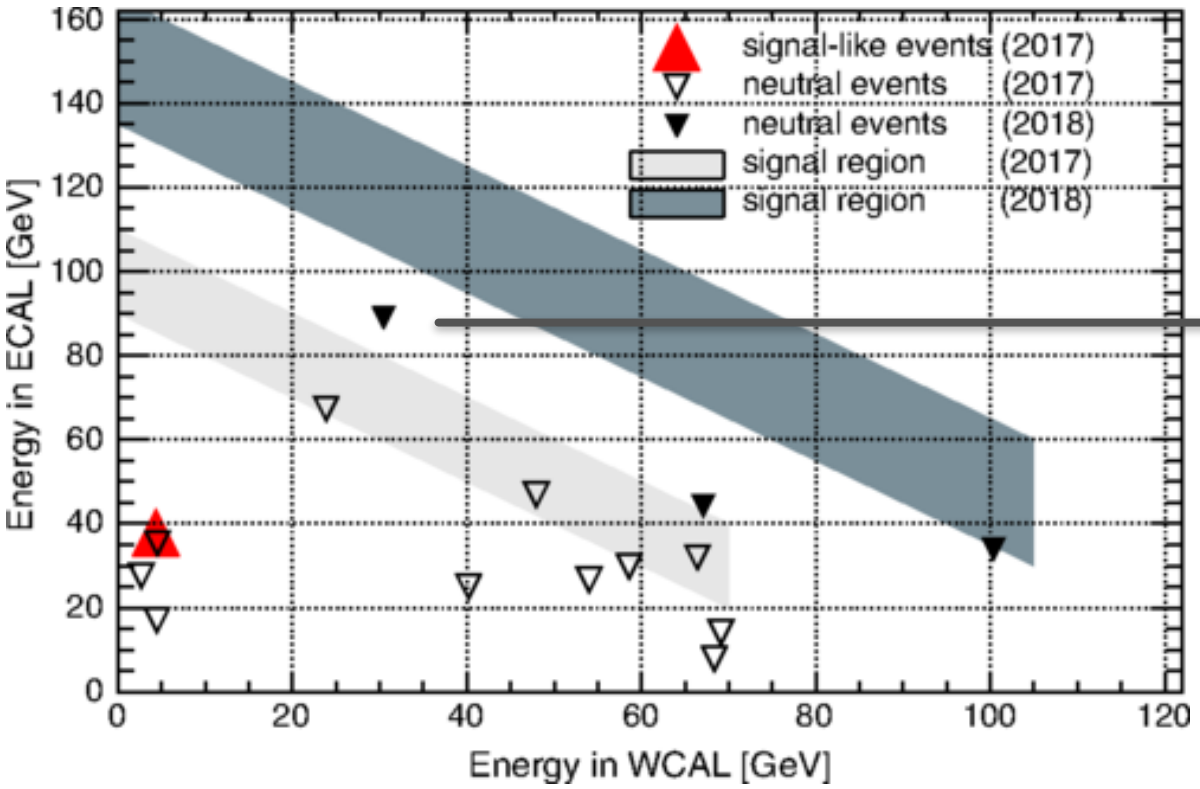
The NA64 search for $X \rightarrow e^+e^-$ - *experimental signature*



Signature:

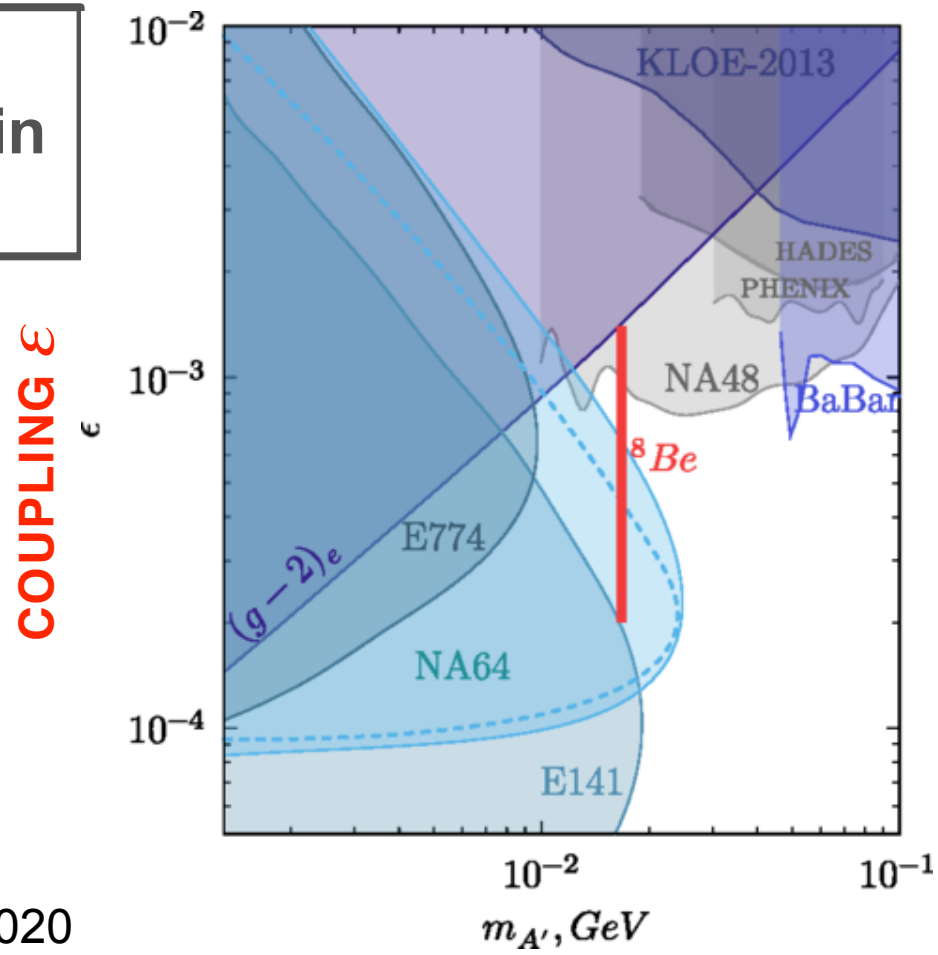
1) $E_{WCAL}+E_{ECAL}$ = 100 GeV
2) No activity in $V_{2,3}$ and HCAL
3) Signal in S3, S4
4) e-m shower in ECAL

The NA64 search for $X \rightarrow e^+e^-$ - *results (2017-2018)*



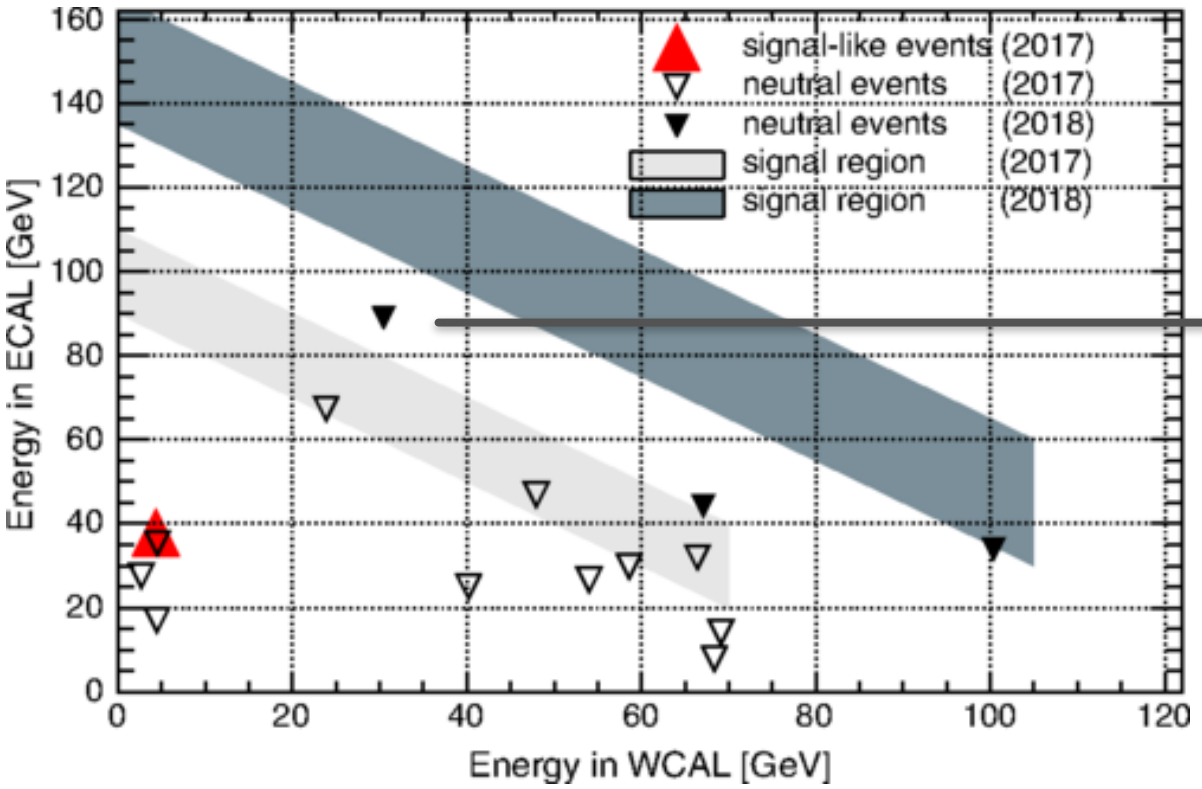
No signal-like event in signal box

~ 8×10^{10} EOT

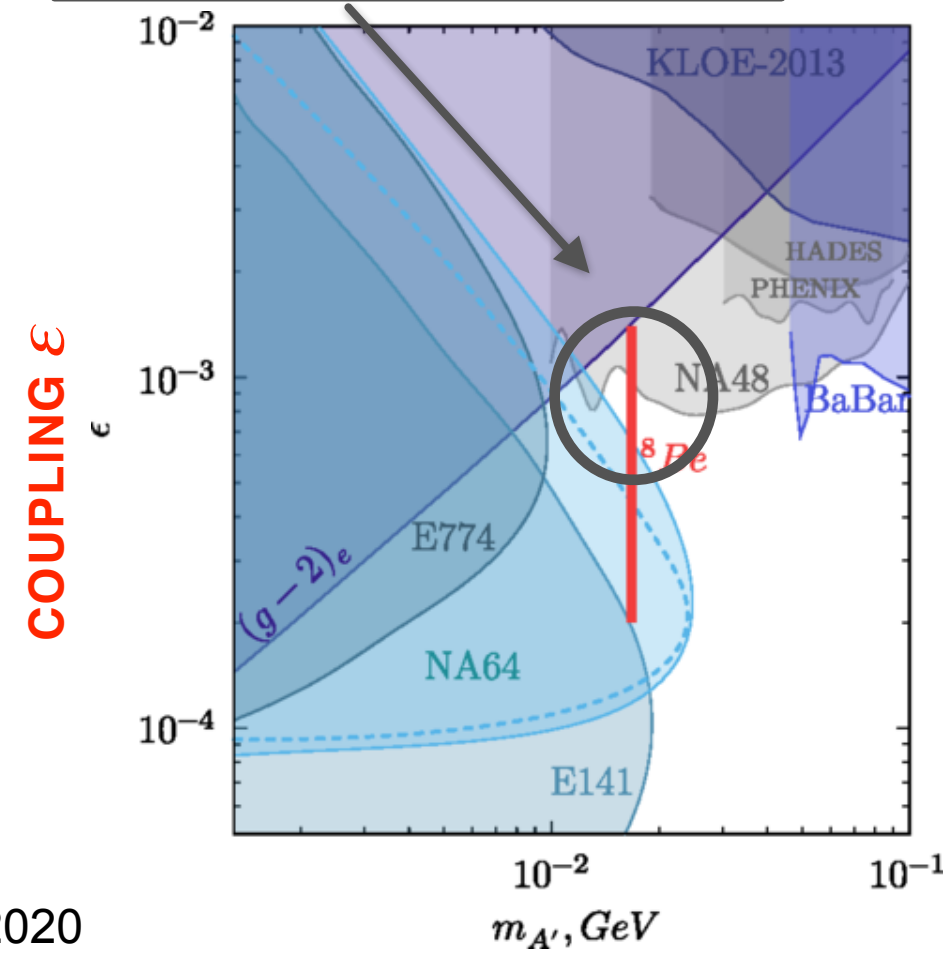


NA64 collaboration, PRL 120, 231802 (2018), PRD 107, 071101 (R) 2020

The NA64 search for $X \rightarrow e^+e^-$ - *prospects (2021)*



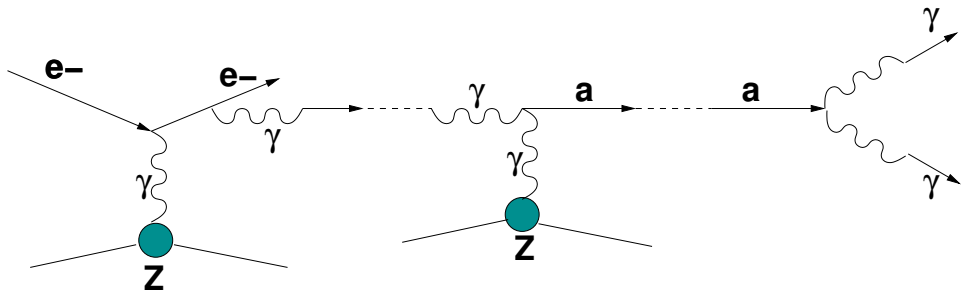
Feasibility under study



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

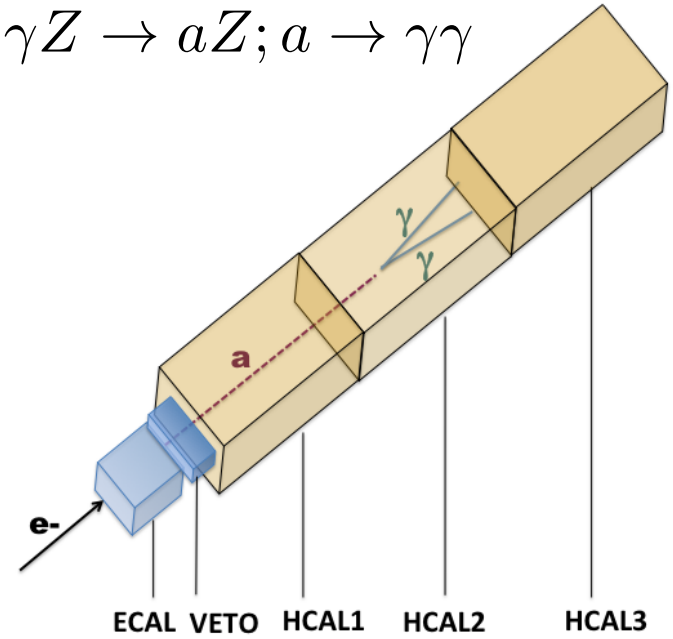
The NA64 search for ALP

NA64 collaboration, CERN-EP-2020-068 arXiv:2005.02710

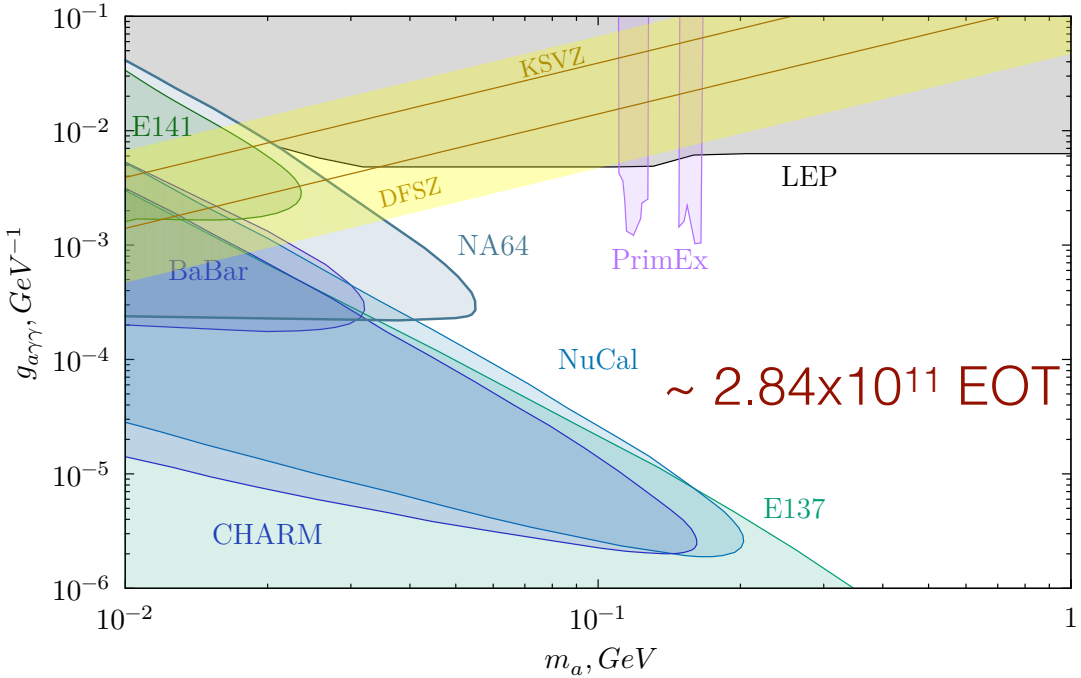


Production via Primakoff effect

$$e^- Z \to e^- Z\gamma; \gamma Z \to aZ; a \to \gamma\gamma$$



Closing the gap between beam dump and colliders



Search expected to be BKG free up to ~ 5 x10¹² EOT

The NA64 physics prospects

Process	New Physics
e^- **beam**	
$A' \to e^+e^-$, and	Dark photon
$A' \to invisible$	
$A' \to \chi\overline{\chi}$	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 particles
μ^- **beam**	
$Z_\mu \to \nu\nu$	gauge Z_μ-boson of $L_\mu - L_\tau$, $< 2m_\mu$
$Z_\mu \to \chi\overline{\chi}$	$L_\mu - L_\tau$ charged Dark Matter (χ)
milliQ	Dark Sector, charge quantisation
$a_\mu \to invisible$	non-universal ALP coupling
$\mu - \tau$ conversion	Lepton Flavour Violation
π^-, K^- **beams**	Current limits, PDG'2018
$\pi^0 \to invisible$	$Br(\pi^0 \to invisible) < 2.7 \times 10^{-7}$
$\eta \to invisible$	$Br(\eta \to invisible) < 1.0 \times 10^{-4}$
$\eta' \to invisible$	$Br(\eta' \to invisible) < 5 \times 10^{-4}$
$K_S^0 \to invisible$	no limits
$K_L^0 \to invisible$	no limits

NA64 program: submitted as input to the European Strategy Group in the context of the PBC

CERN-PBC-REPORT-2018-007

Could provide an explanation of $(g\text{-}2)_\mu$ anomaly

Summary and Outlook

- **NA64: Active beam dump + missing-energy approach is very powerful probe for Dark Sector physics.**
- **Experiment exceeded sensitivity of previous beam dump exps. to thermal light dark matter.**
- **To fully exploit NA64 potential probing most of the remaining parameter space predicted by the DM relic density accumulate 5×10^{12} EOT for $A' \rightarrow \chi\bar{\chi}$ after LS2**
- **Exploration of the remaining parameter space $X \rightarrow e^+e^-$**
- **New permanent location being prepared with active participation of NA64.**
- **Proposed searches in NA64 with leptonic and hadronic beams: unique sensitivities highly competitive/complementary to similar projects.**