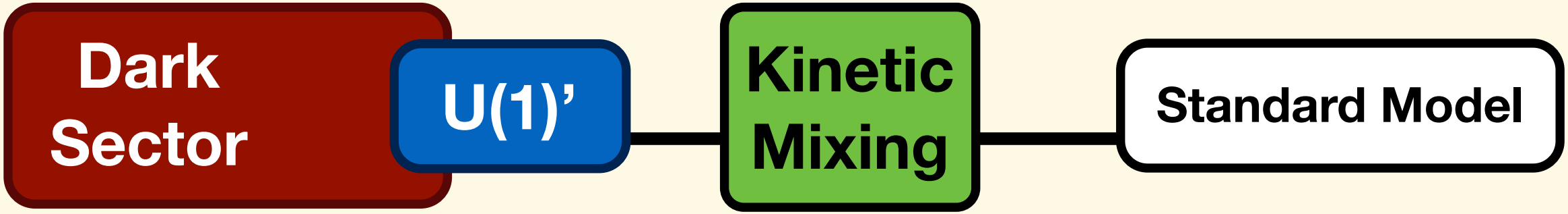
THE NA64 EXPERIMENT SEARCHING FOR HIDDEN SECTORS AT THE CERN SPS - EPS- HEP2021, 30.07.2021

Paolo Crivelli, ETH Zurich, Institute for Particle Physics and Astrophysics on behalf of the NA64 collaboration

DARK SECTORS - THE VECTOR PORTAL

Recent reviews on DS e.g. G. Lanfranchi et al arxiv 2011.02157, J. Jaeckel et al. Nature Phys. 16 (2020) 393-401



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, $\alpha_D = e_D^2/4\pi$, ε

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

DARK SECTORS - THE VECTOR PORTAL

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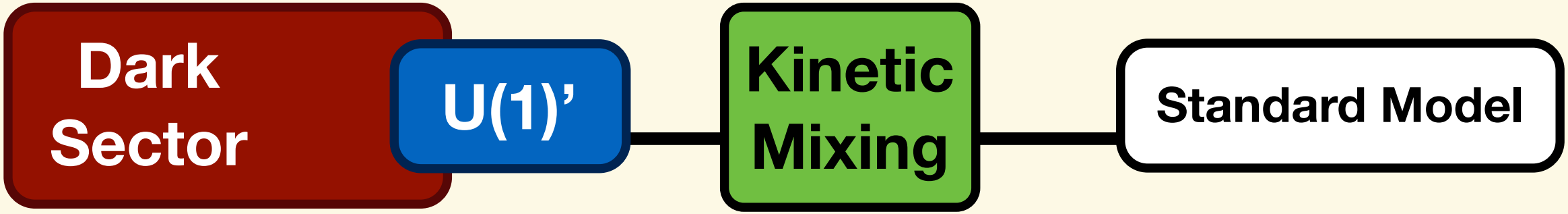


In this framework DM can be produced thermally in the early Universe

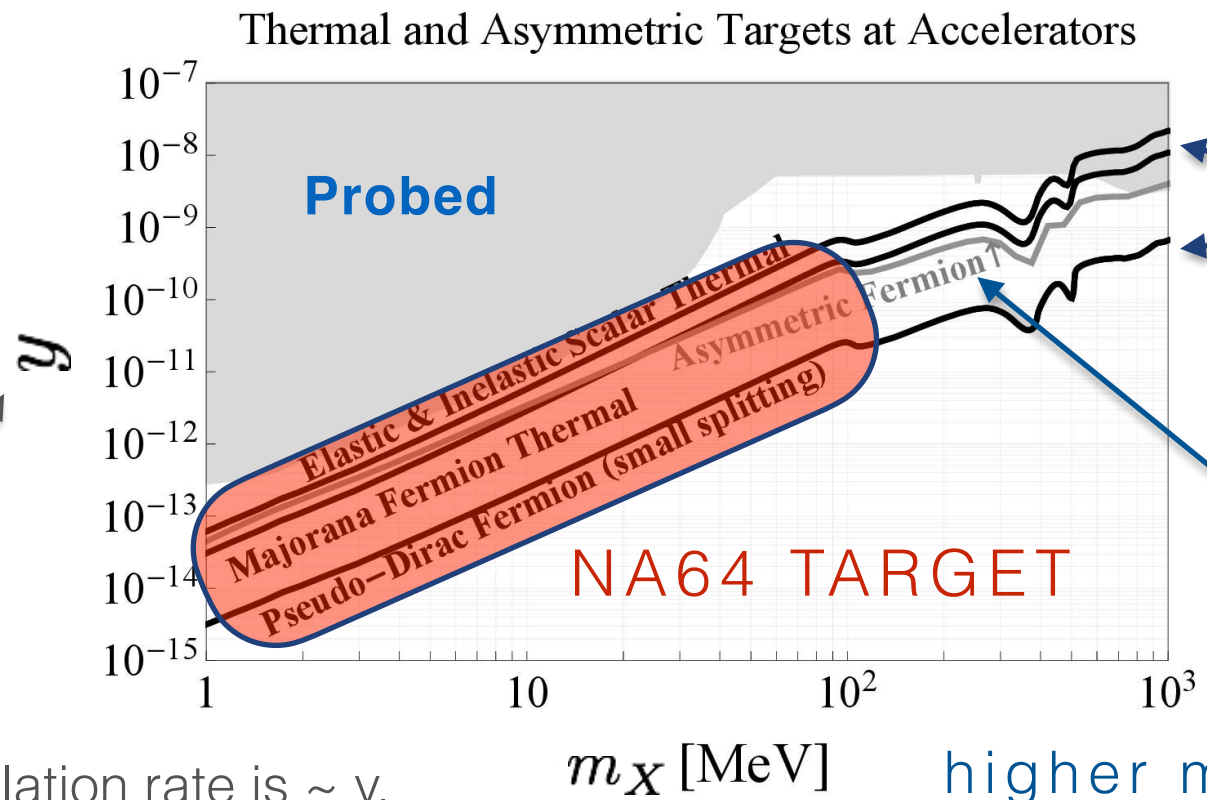
OBSERVED **AMOUNT OF DARK MATTER** TODAY

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

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

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

From https://arxiv.org/pdf/1707.04591.pdf



Solid lines predictions from DM relic abundance

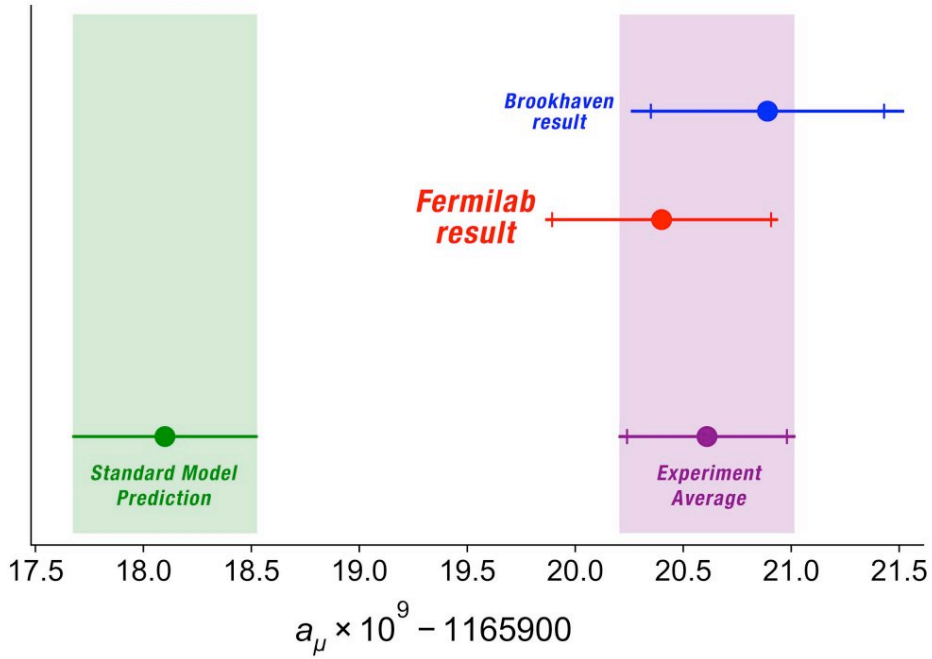
DM -> SM annihilation rate is ~ y, useful variable to compare exp. sensitivities

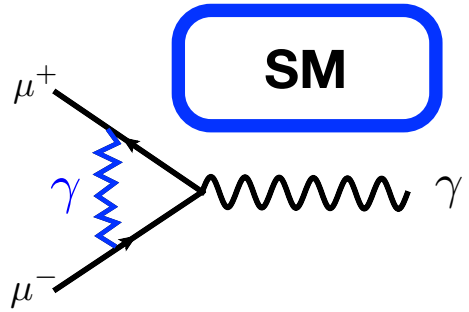
$$y = \epsilon^2 \alpha_D (m_X/m_{A'})^4$$

higher mass region could be covered by NA64 in muon/positron mode PLB796, 117 (2019)

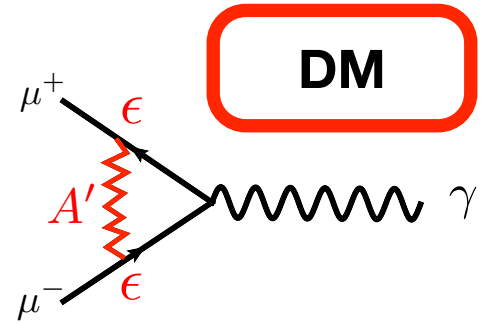
The muon (g-2): an additional motivation to search for dark photons

B. Abi, et al. Phys. Rev. Lett. 126, 141801 (2021)



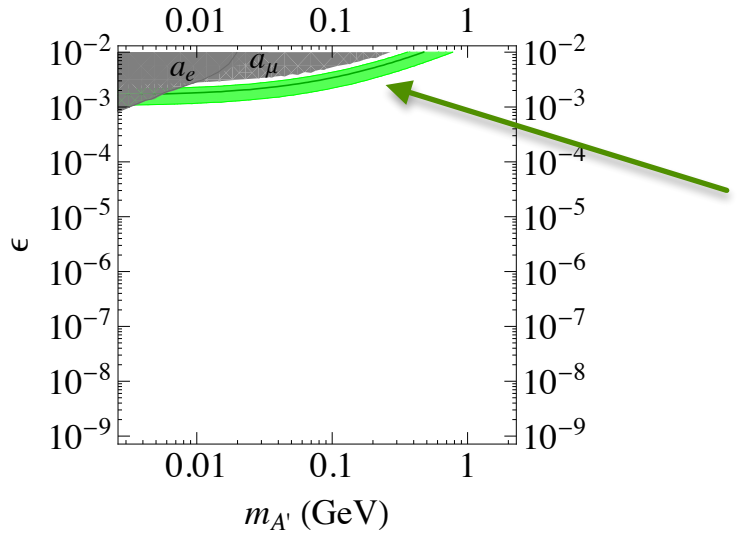


$$(g_s-2)^{\gamma}_{\mu} \simeq \frac{\alpha}{2\pi} \simeq 10^{-3}$$



$$(g_s-2)^{A'}_{\mu} \simeq \frac{\alpha}{2\pi} \times \epsilon^2 \simeq 10^{-3} \times \epsilon^2 \qquad (m_{A'} \ll m_\mu)$$

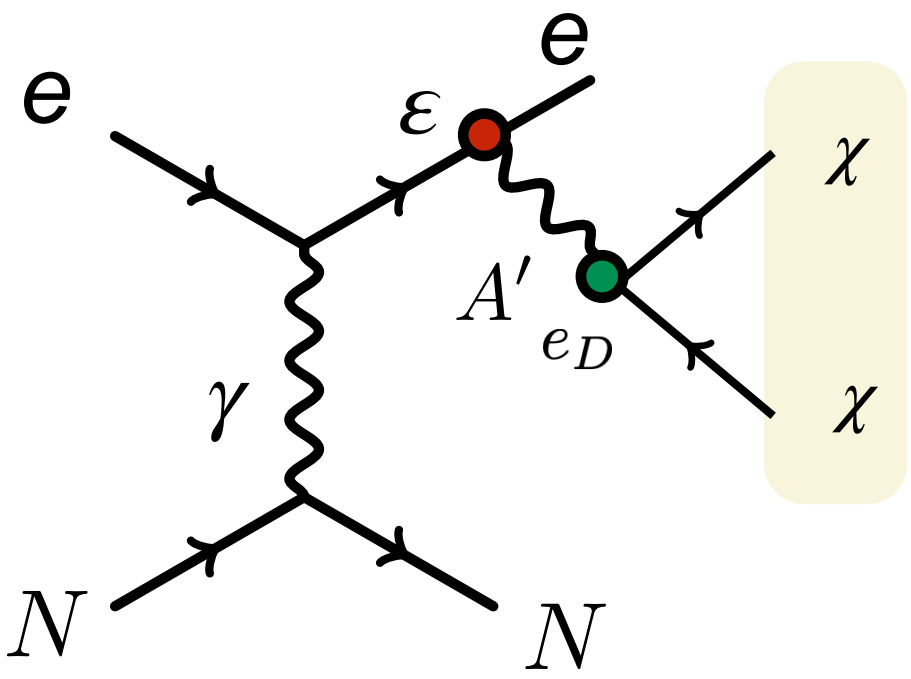
M. Pospelov, A. Ritz and M. B. Voloshin, Phys. Lett. B 662, 53 (2008)



A' may explain observed anomaly

SEARCHES FOR DARK SECTORS AT ACCELERATORS

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



1) BEAM DUMP APPROACH (MiniBooNE, LSND, NA62…) $\sigma \propto \epsilon^4 \alpha_D$

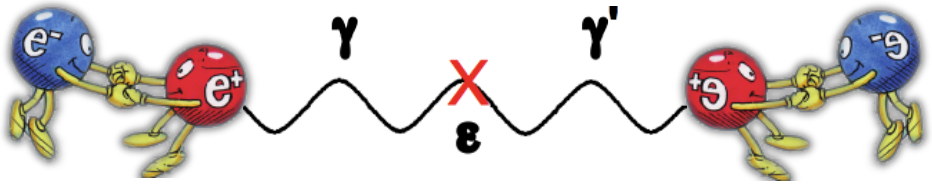
Flux of X generated by decays of A's produced in the dump.
Signal: X scattering in far detector

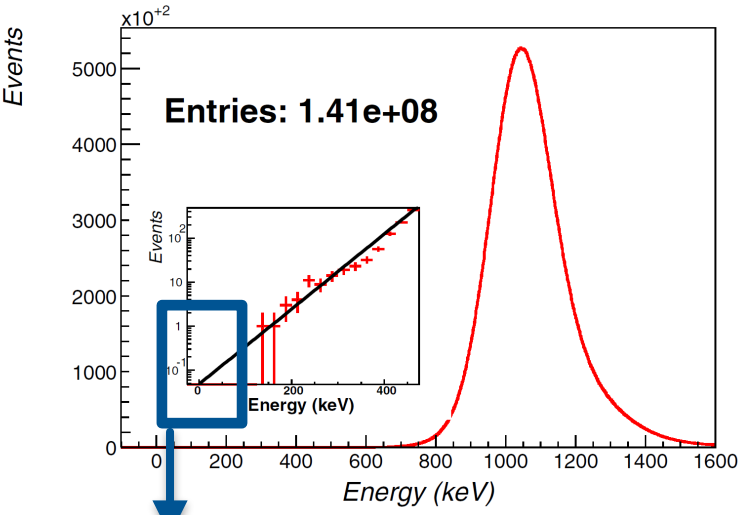
2) NA64/LDMX APPROACH $\sigma \propto \epsilon^2$

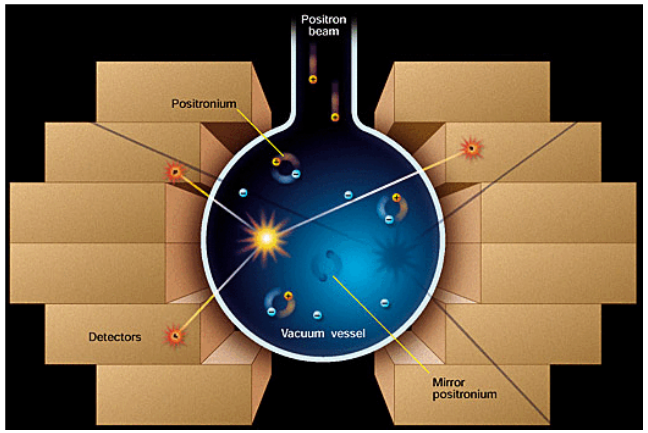
NA64 **missing energy**: produced A's carry away energy form the active dump used to measure recoil e- energy

From positronium (search for massless dark photon) → NA64

S. L. Glashow, Phys. Lett. B167, 35 (1986)







Signature: disappearance of 1 MeV energy

A. Badertscher, et al., Phys. Rev. D. 75, 032004 (2007)
Our latest results 2020 C. Vigo et al. PRL124,101803 (2020)

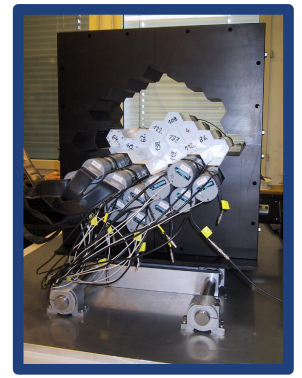


Table top

IPA ETH zürich

At rest → 100 GeV

The NA64 collaboration (~50 researchers from 16 Institutes)

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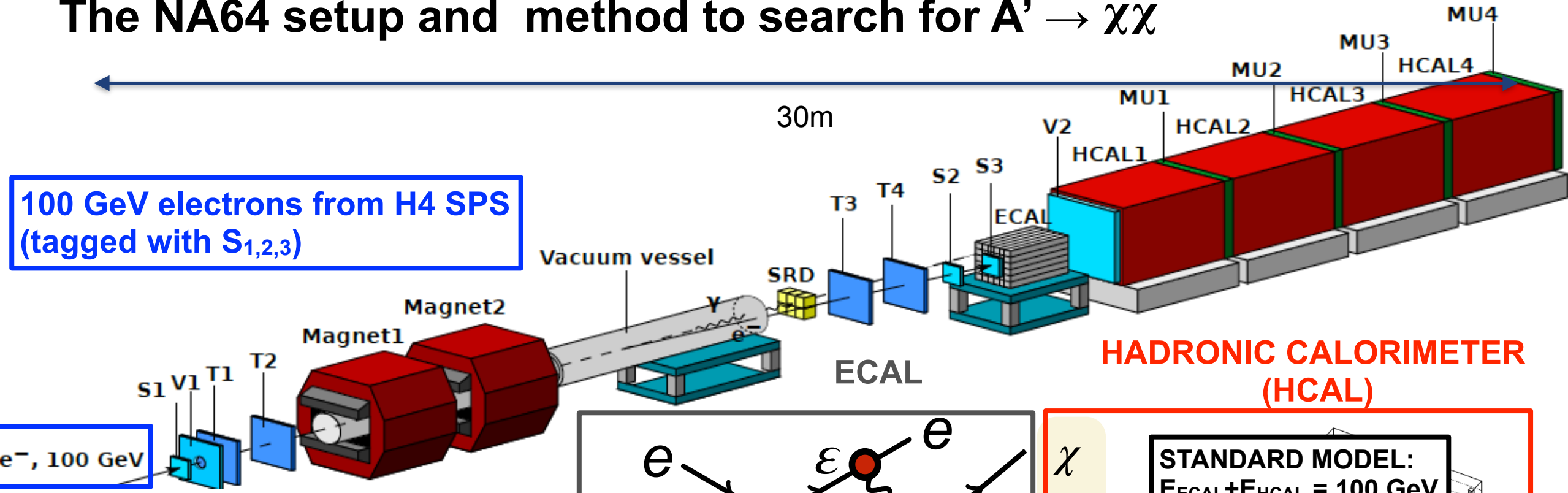
[14] *Universidad Técnica Federico Santa María, 2390123 Valparaíso, Chile*
[15] *ETH Zürich, Institute for Particle Physics and Astrophysics, CH-8093 Zürich, Switzerland*
[16] *SAPHIR Millennium Institute of ANID, Chile*

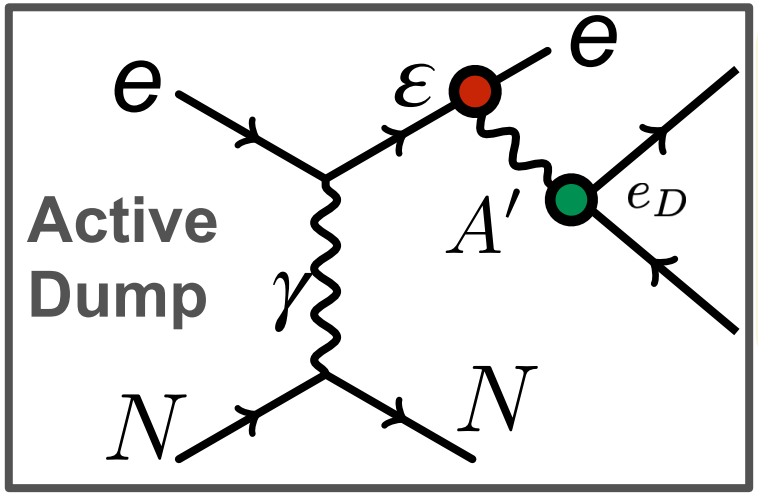
Proposed (P348) in 2014, first test beam in 2015 (2 weeks), Approved by CERN SPSC in March 2016 → NA64.
2016: 5 weeks, 2017: 5 weeks, 2018: 6 weeks.

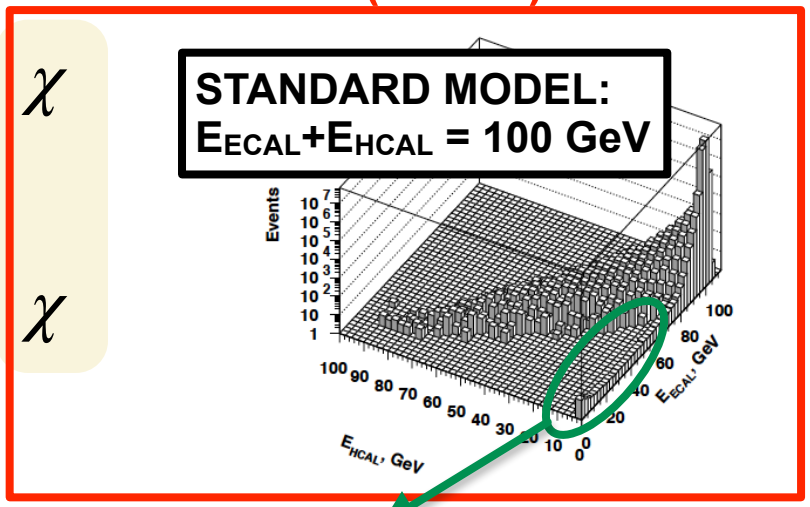
The NA64 setup and method to search for A' → $\chi\bar{\chi}$



100 GeV electrons from H4 SPS (tagged with $S_{1,2,3}$)

HADRONIC CALORIMETER (HCAL)

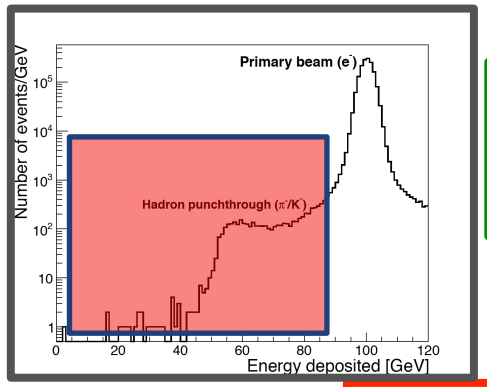




A'→ MISSING ENERGY (ECAL < 50 GeV, HCAL < 2 GeV)

The magnetic spectrometer

D. Banerjee et al., Advances in HEP, 105730 (2015) and
D. Banerjee, PhD Thesis, ETH Zurich (2017)
D. Banerjee et al., NIMA881, 72-81 (2018)

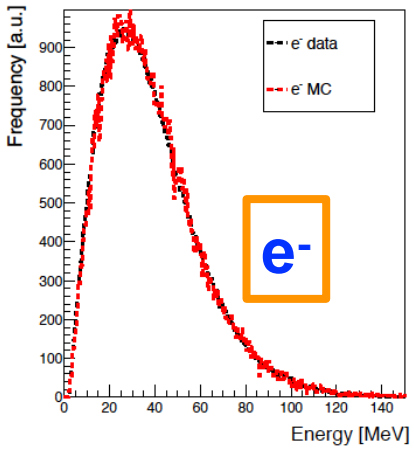


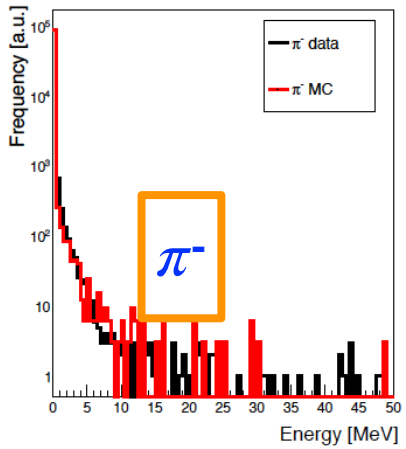
Reconstruction of e⁻ incoming momentum

Tracking system:
8 XY multiplexed resistive micromegas
+ Straw tubes and GEMs

Two bending magnets in series → 7 T.m field

The Synchrotron Radiation (SR) detector



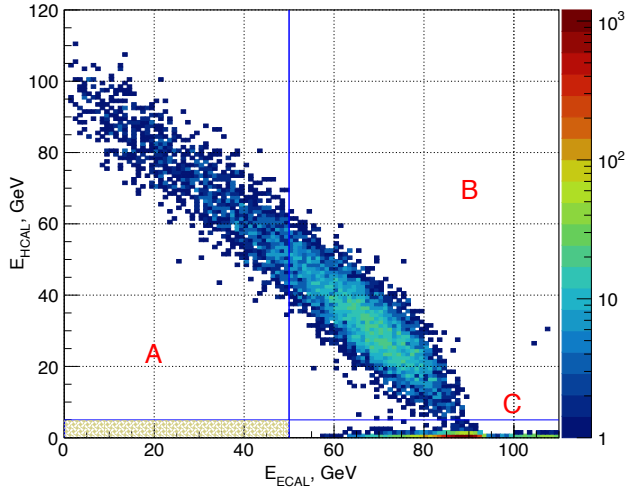


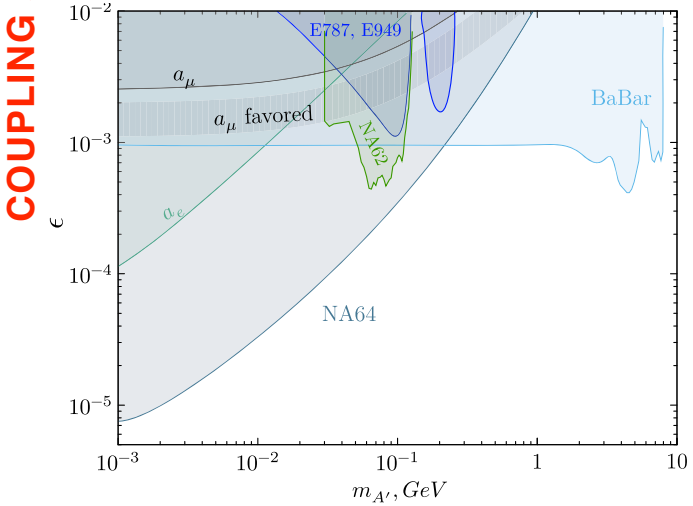
Particle identification
SR emission ~ $1/m^4$

Efficiency > 95%
Suppression $>10^{-5}$

E. Depero et al., NIMA 866 (2017) 196-201 and
E. Depero, PhD thesis, ETH Zurich (2020).

1) The NA64 search for A' → $\chi\bar{\chi}$ - *results combined analysis 2016-2018*

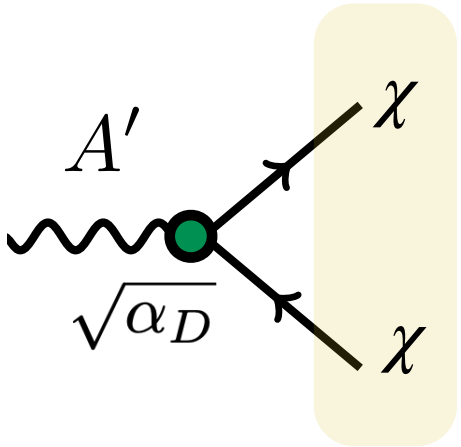


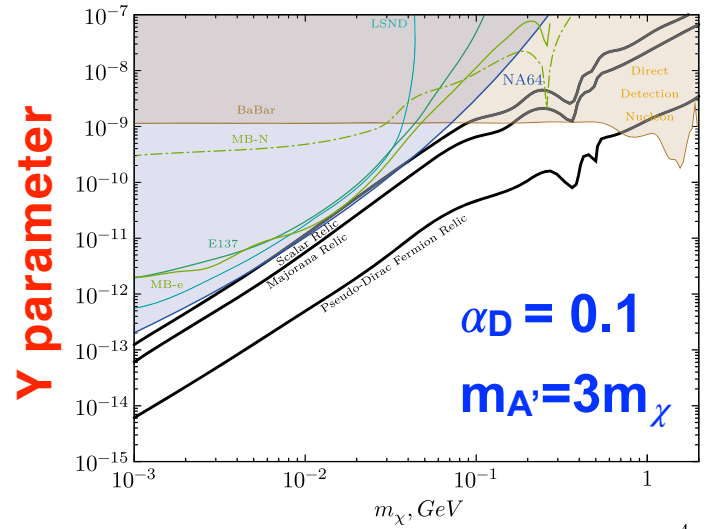


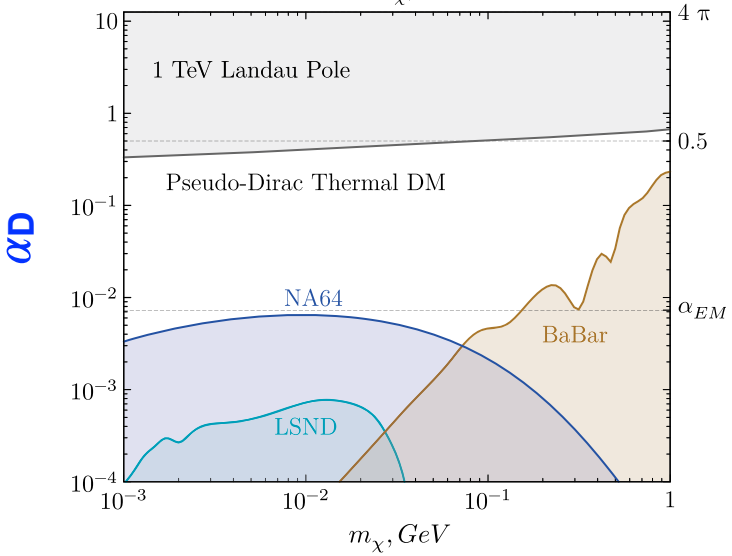
MASS OF THE DARK PHOTON

2.8 x 10^{11} electrons on target

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

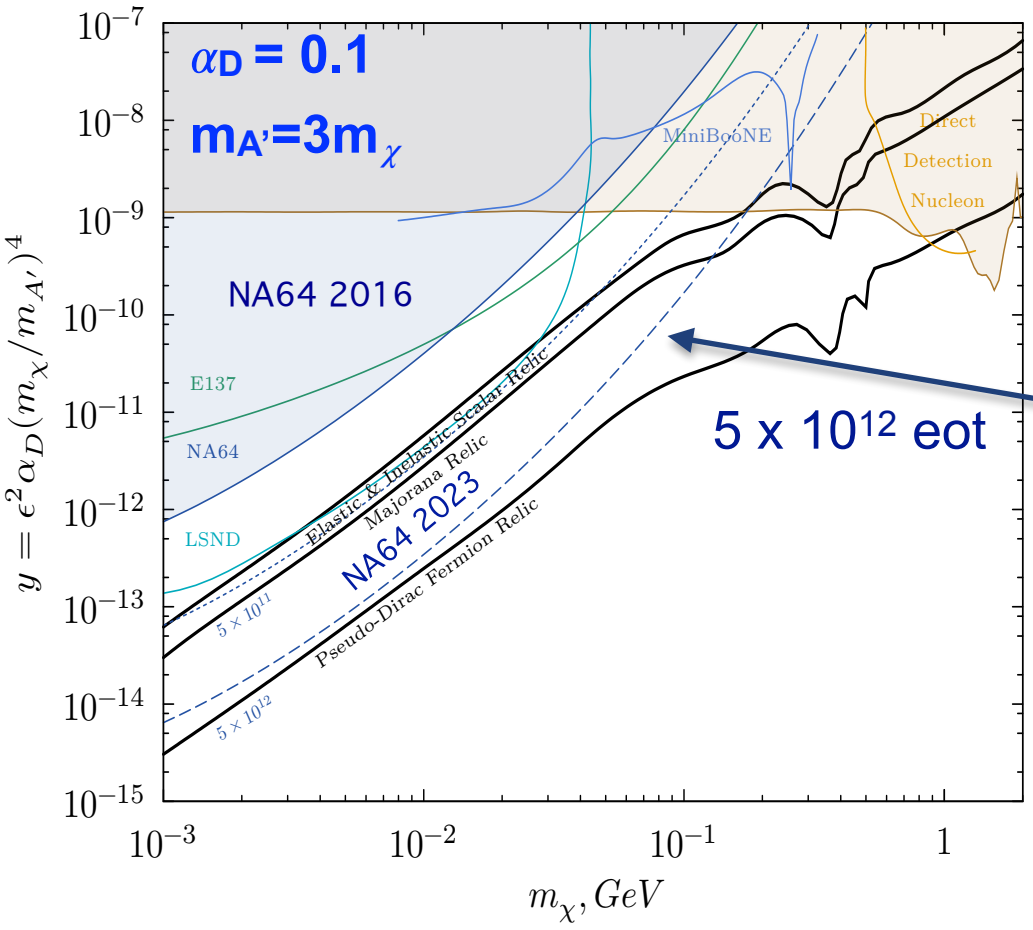






NA64 collaboration, Phys. Rev. Lett. 118, 011802 (2017)
NA64 collaboration, Phys. Rev. Lett. 123, 121801 (2019)

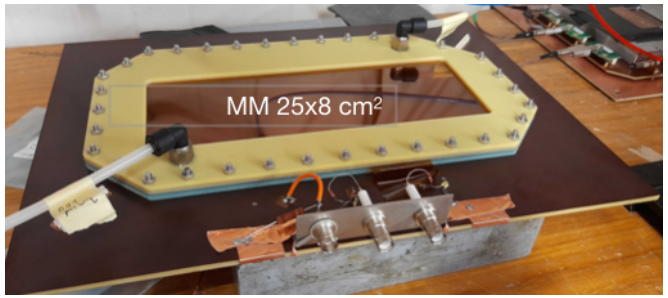
The NA64 search for A' → $\chi\bar{\chi}$ - *Future prospects 2021-2023*



Background source	Background, n_b
(i) dimuons	0.024 ± 0.007
(ii) π, $K \to e\nu$, K_{e3} decays	0.02 ± 0.01
(iii) e^- hadron interactions in the beam line	0.43 ± 0.16
(iv) e^- hadron interactions in the target	< 0.044
(v) Punch-through γ's, cracks, holes	< 0.01
Total n_b (conservatively)	0.53 ± 0.17

5 x 10^{12} eot

Setup upgrade (ongoing)



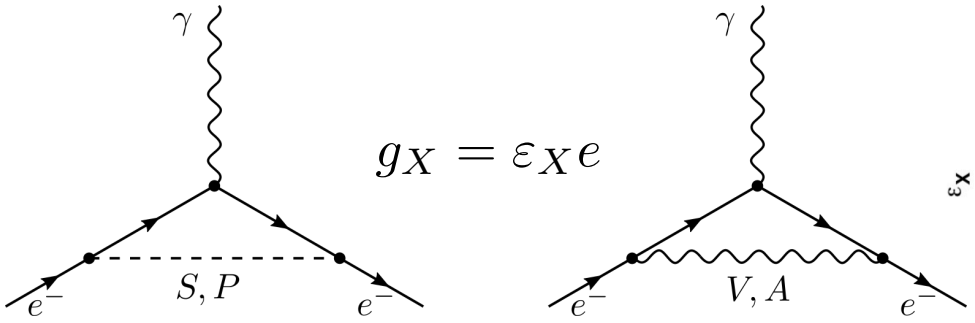
2) NA64 search for a new generic X boson and implications for $(g-2)_e$

Latest experimental determination of $(g-2)_e$

$$\Delta a_e = a_e^{exp} - a_e^{LKB} = (4.8 \pm 3.0) \times 10^{-13}$$
$$\Delta a_e = a_e^{exp} - a_e^{B} = (-8.8 \pm 3.6) \times 10^{-13}$$

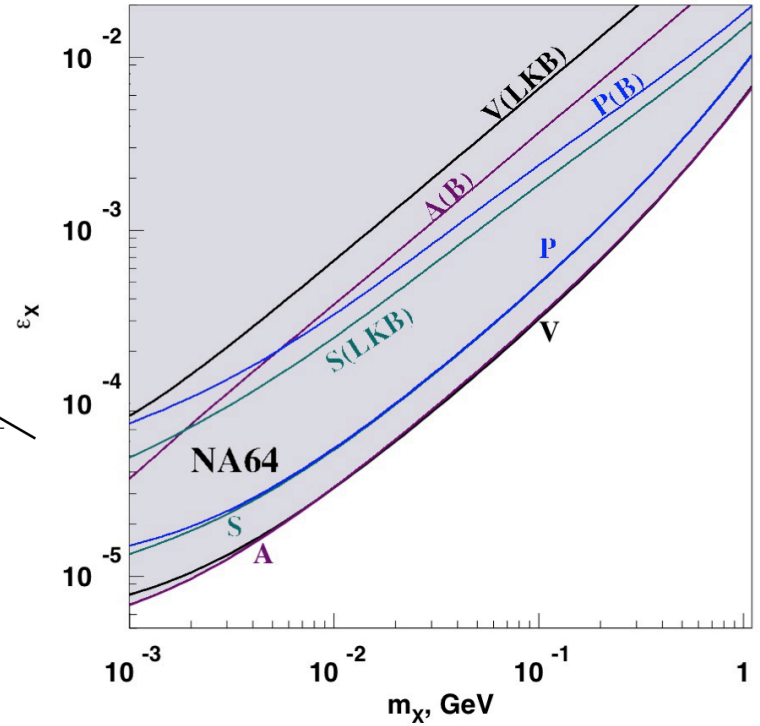
L. Morel et al, Nature 588, 61 (2020),
R. H. Parker et al., Science 360, 191 (2018).
D. Hanneke, S. Fogwell, and G. Gabrielse PRL 100, 120801 (2008)

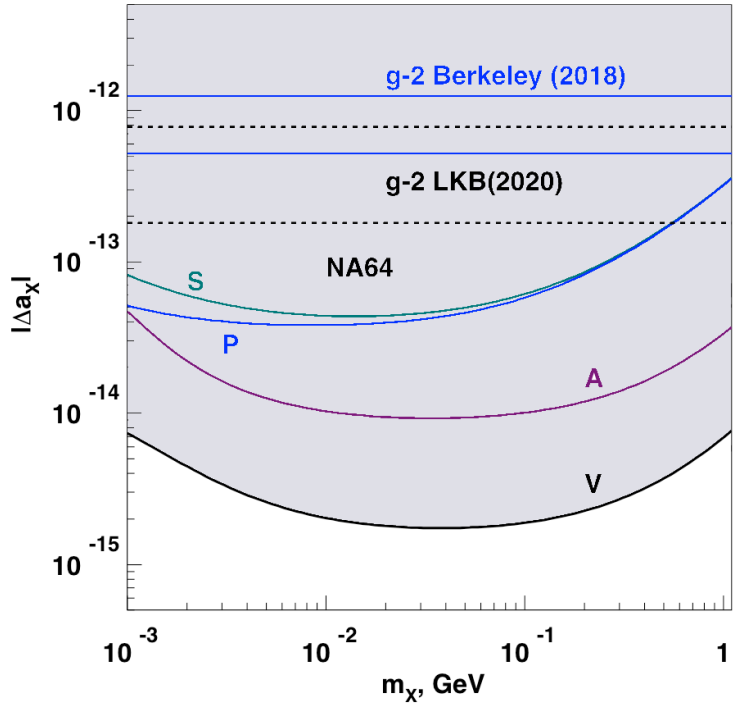
Possible NP contributions



$$g_X = \varepsilon_X e$$

$$e^- Z \rightarrow e^- Z X; \; X \rightarrow invisible.$$

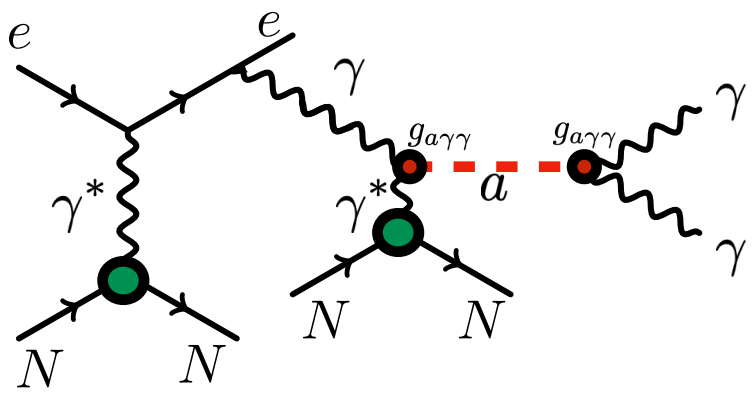




NA64 collaboration, Phys. Rev. Lett. 126, 211802 (2021)

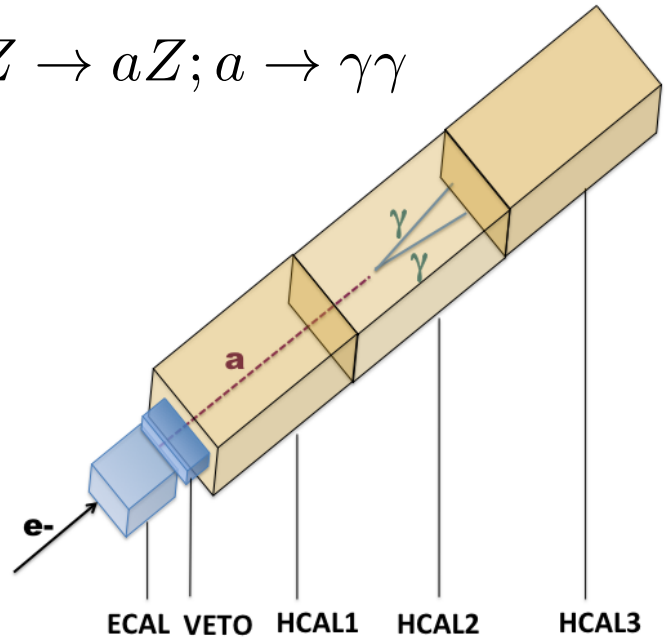
NA64 one order of magnitude more sensitive than precision exp.!

3) The NA64 ALP search

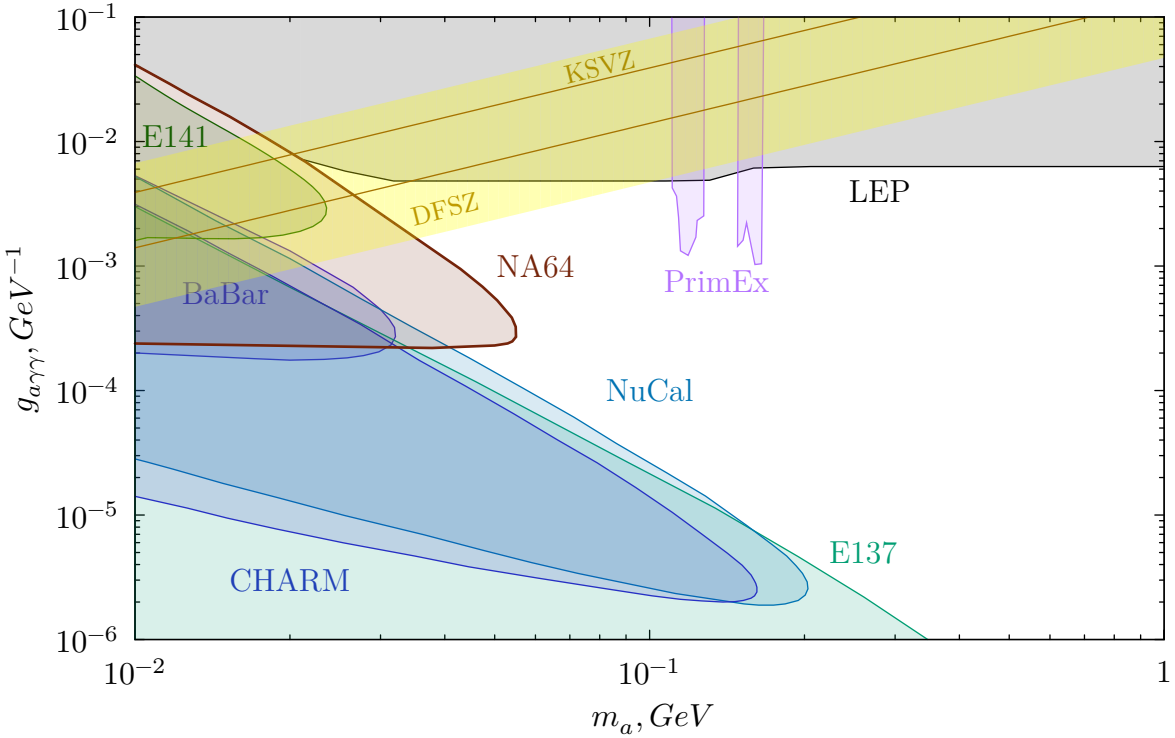


Production via Primakoff effect

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



Closing the gap between beam dump and colliders



NA64 collaboration PRL 125, 081801 (2020)

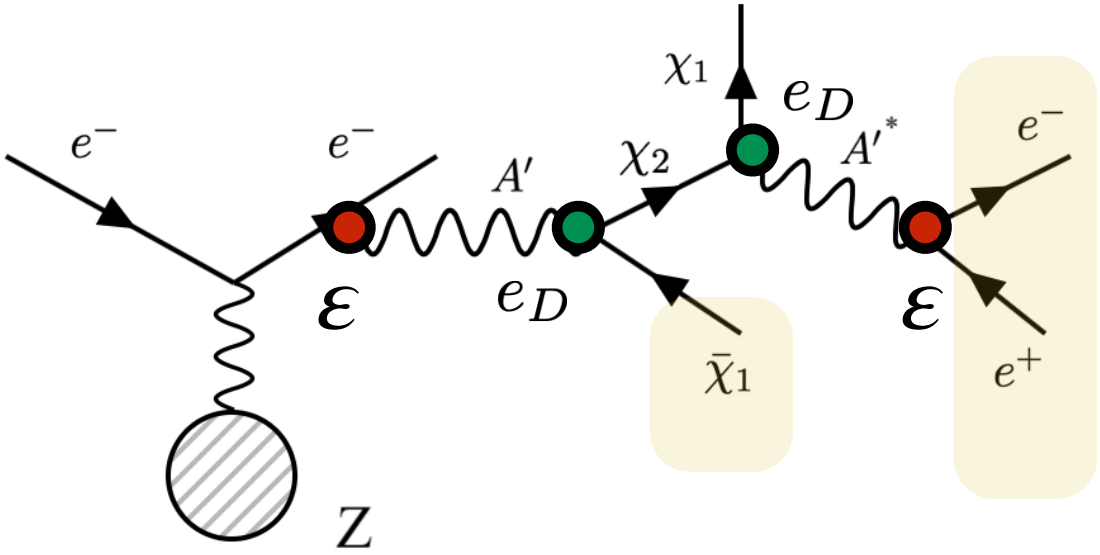
4) The NA64 search for A' → $\chi_1\chi_2$, $\chi_2 \to \chi_1$A', A' → e^+e^-

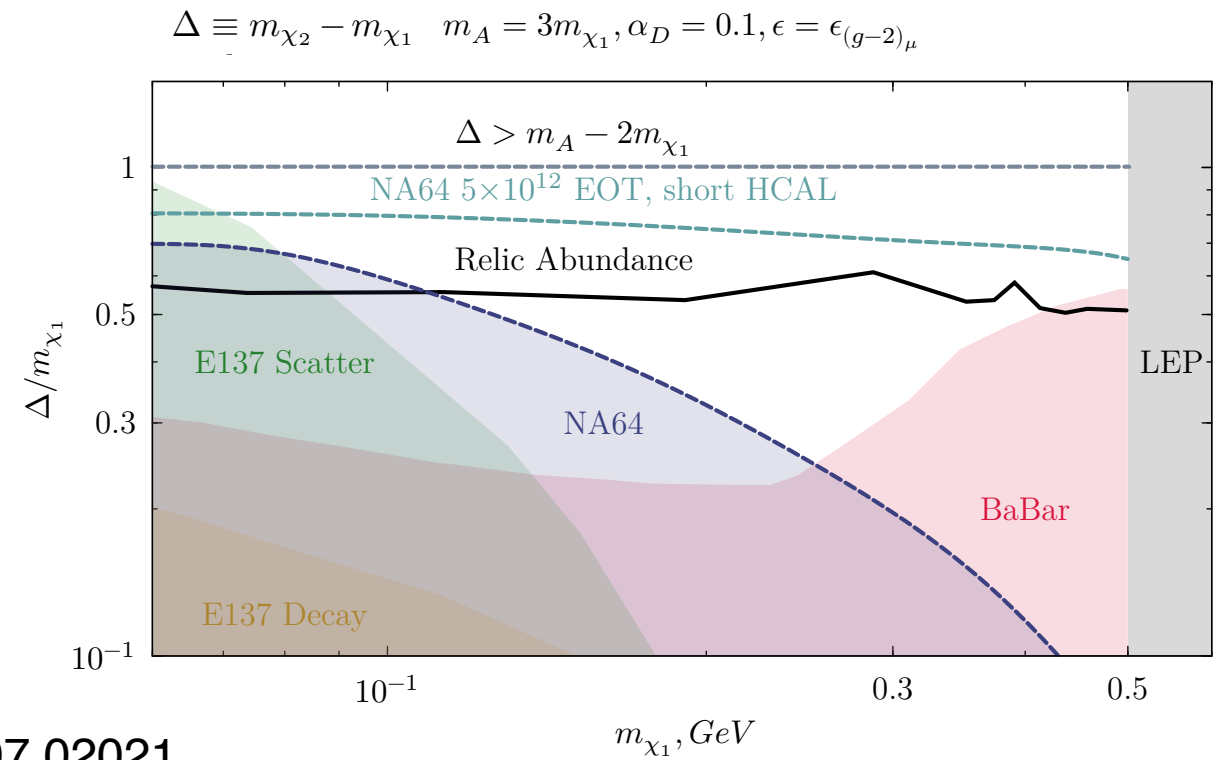
SEMIVISIBLE DECAY MODE

E. Izaguirre, et al. PRD 96, 055007 (2017), G. Mohlabeng. PRD 99, 115001 (2019) ,Y. Tsai, et al., PRL126, 181801 (2021)

Pair production of
SM particles + Missing energy

Possible explanation of $(g-2)_\mu$ anomaly+LTDM

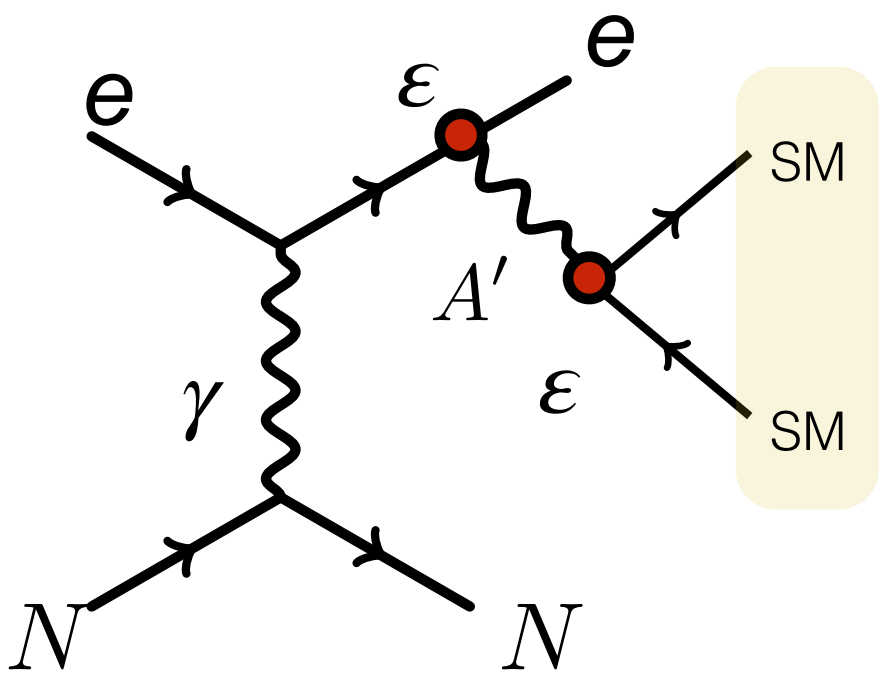




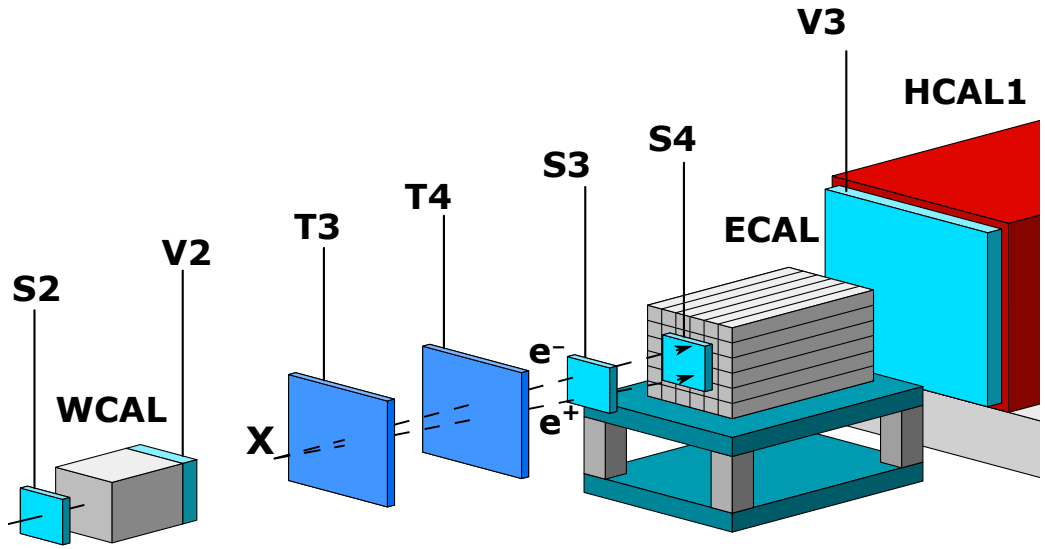
NA64 collaboration, arXiv:2107.02021

5) The NA64 search for A' → e⁺e⁻

VISIBLE DECAY MODE $m'_A < 2m_X$



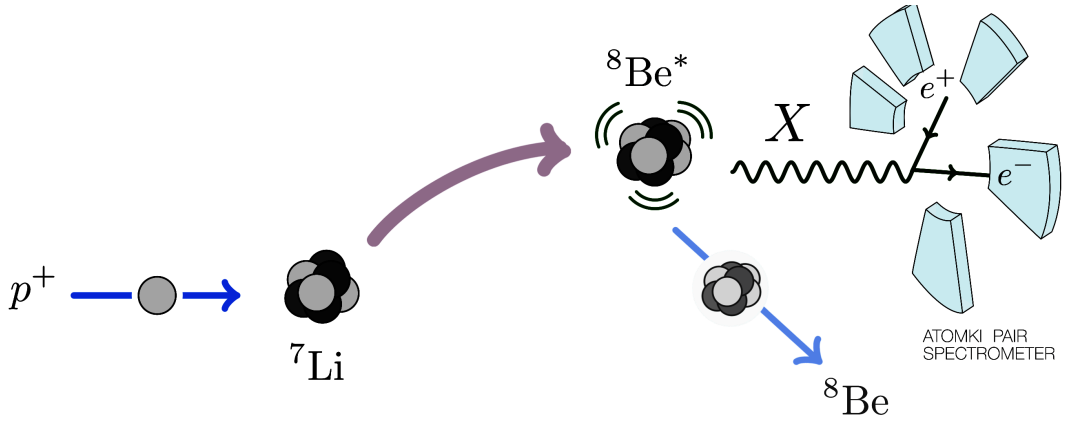
Pair production of SM particles



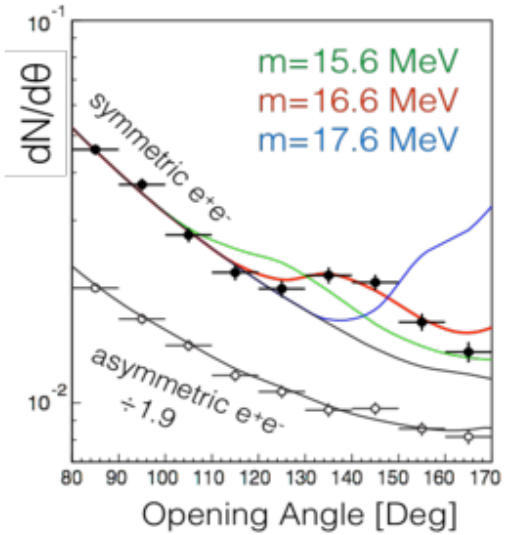
WCAL: 30-40 X_0
Sandwich W-Sc

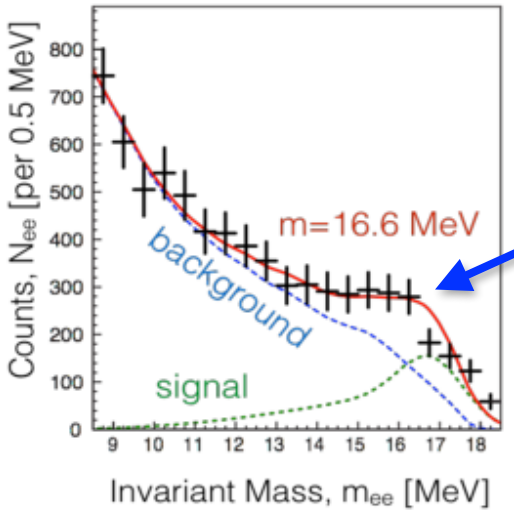
Signature:
1) $E_{WCAL}+E_{ECAL}$ = 100 GeV
2) No activity in $V_{2,3}$ and HCAL
3) Signal in S3, S4
4) e-m shower in ECAL

^{8}Be anomaly and X boson



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

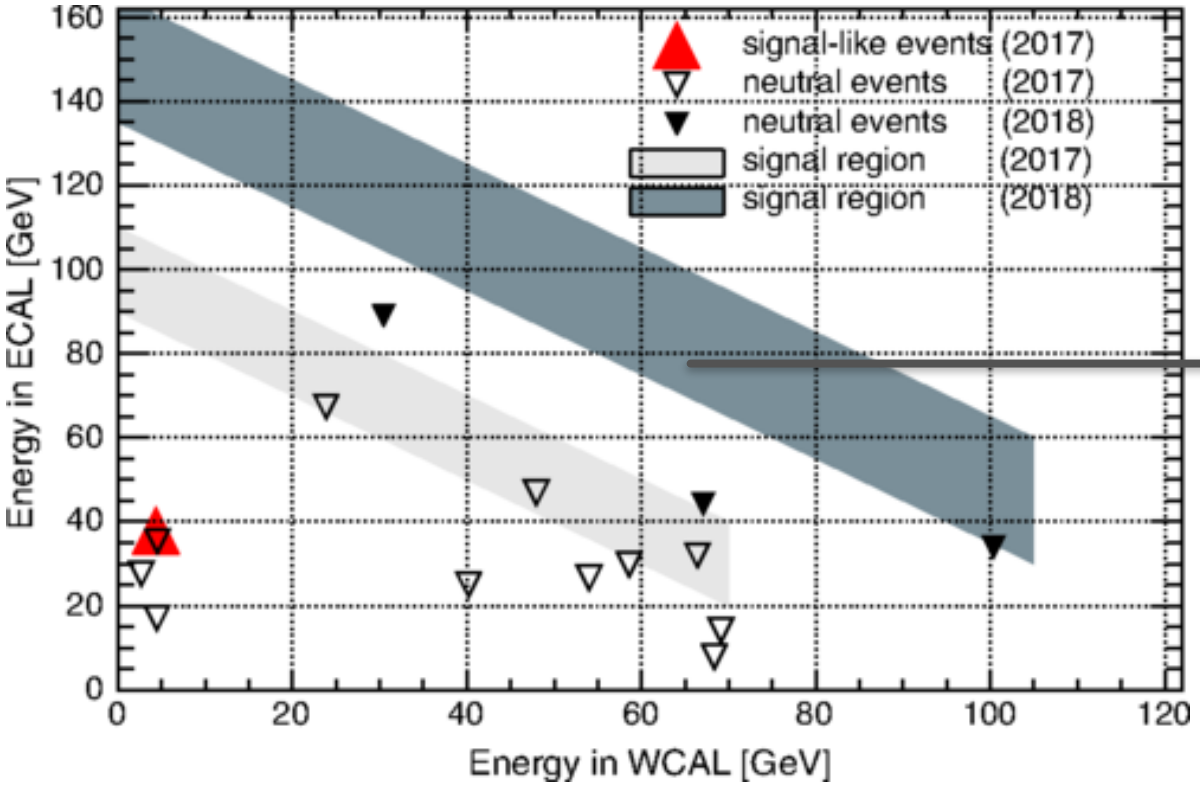




Could be explained e.g by new 'protophobic' gauge boson X with mass around 17 MeV

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

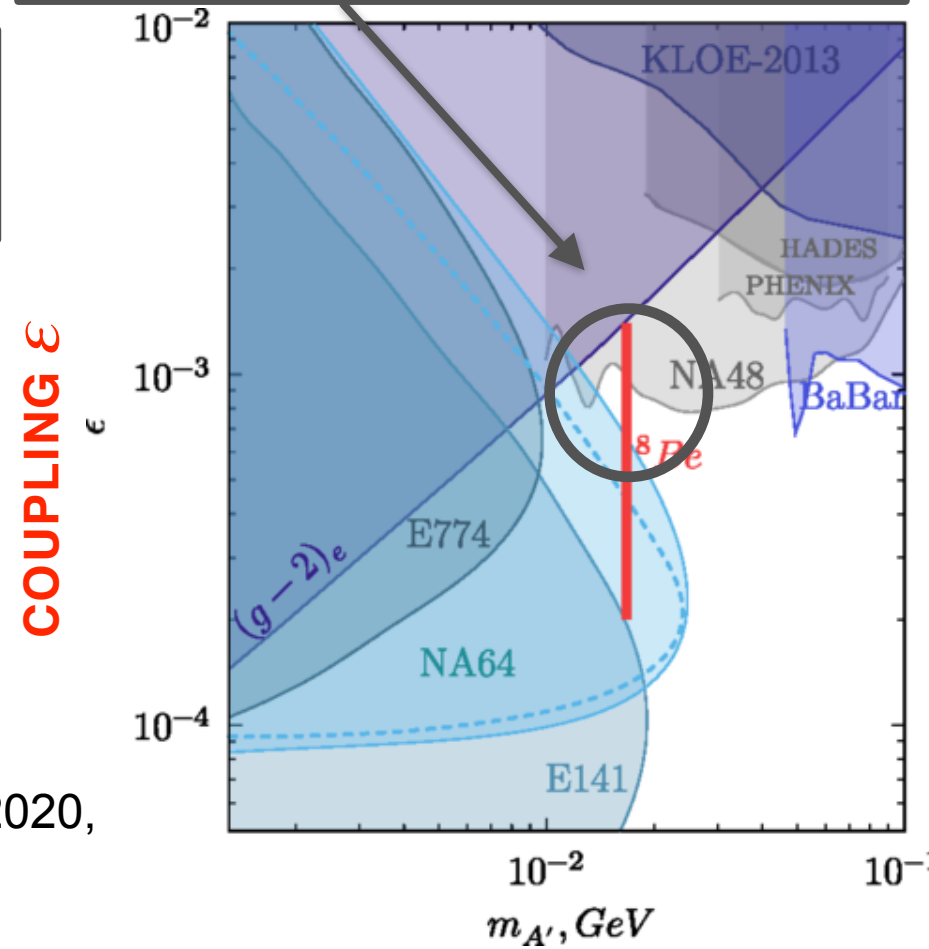
The NA64 search for A'/*X17*→ e^+e^- - *results (2017-2018) & prospects*



No signal-like event in signal box

~ 8×10^{10} EOT

X17 very short lived <10^{-13} s

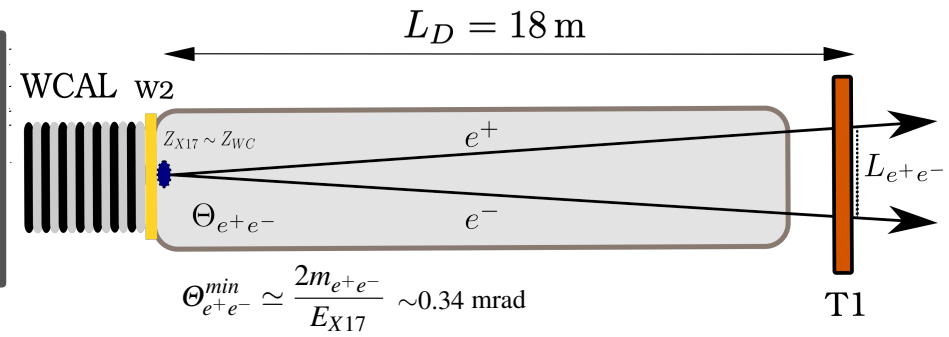


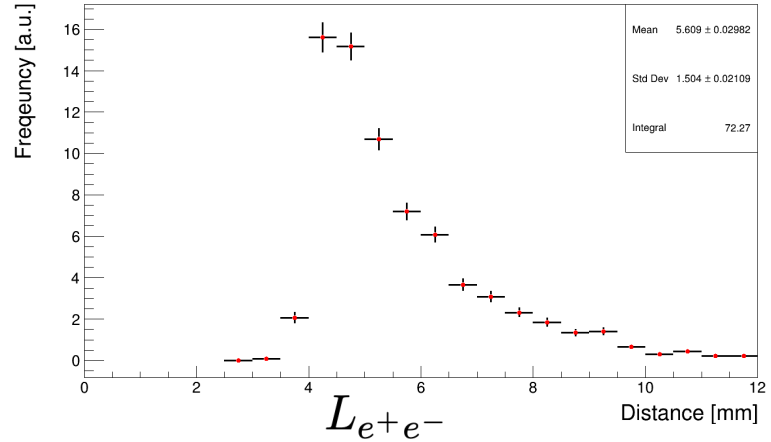
NA64 collaboration, PRL 120, 231802 (2018), PRD 107, 071101 (R) 2020, arXiv:2104.13342 (pseudoscalar case)

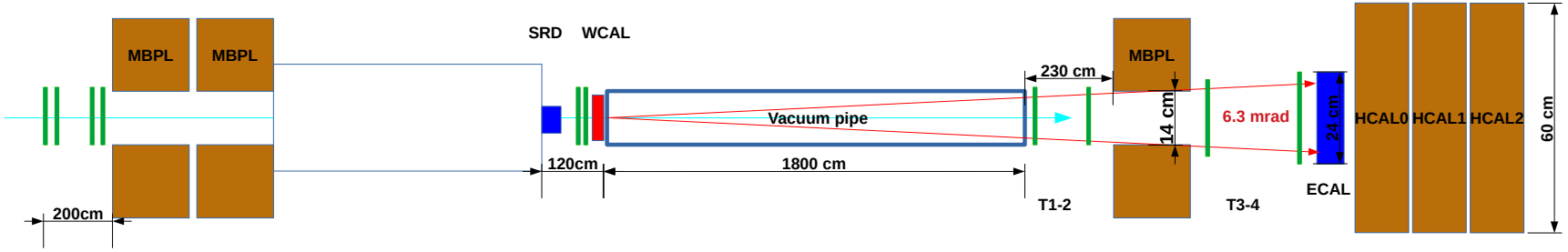
The NA64 search for *X17*→ e^+e^- - *prospects (2021-2023)*

NA64 collaboration. EPJC 80, 1159 (2020)

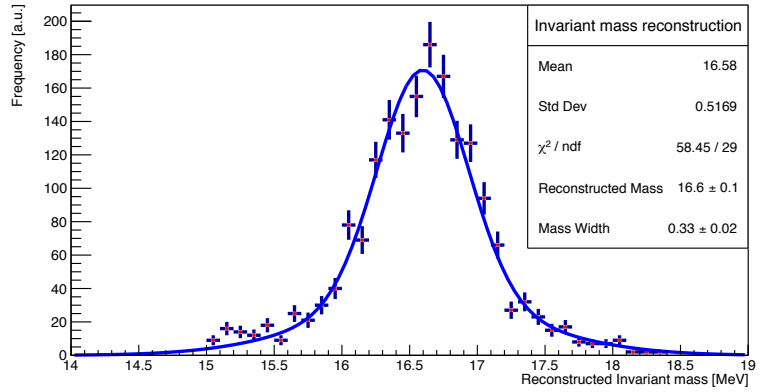
Optimization of WCAL: 20% shorter keeping 30X_0







$$m_{X17} = [E_{e^+}E_{e^-}]^{1/2}\Theta_{e^+e^-}$$

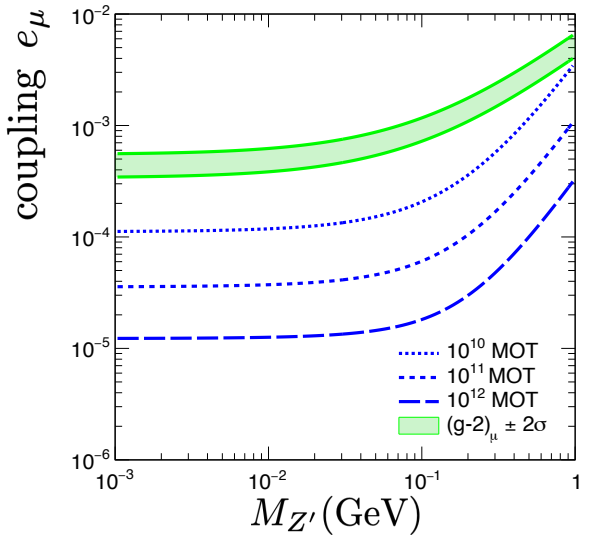


Invariant mass reconstruction: Spectrometer + angle measurement

~ 10^{11} EOT (20 days) required to cover remaining X17 phase space

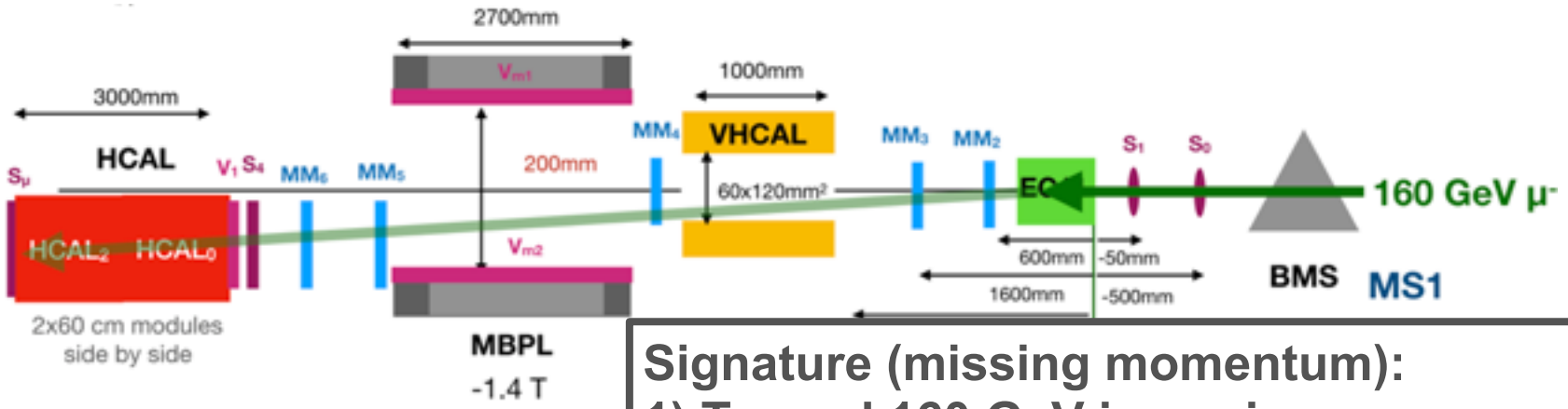
6) NA64 in muon mode- NA64μ

CERN SPS **M2 160 GeV muon beam:** unique opportunities
For **searches for DS** of particles predominantly weakly-coupled to 2nd second and possibly 3rd generations of the SM.



L_μ-L_τ models Z_μ could explain $(g-2)_\mu$

$$\mu + Z \to \mu + Z + Z_\mu,\ Z_\mu \to \nu\bar{\nu}$$



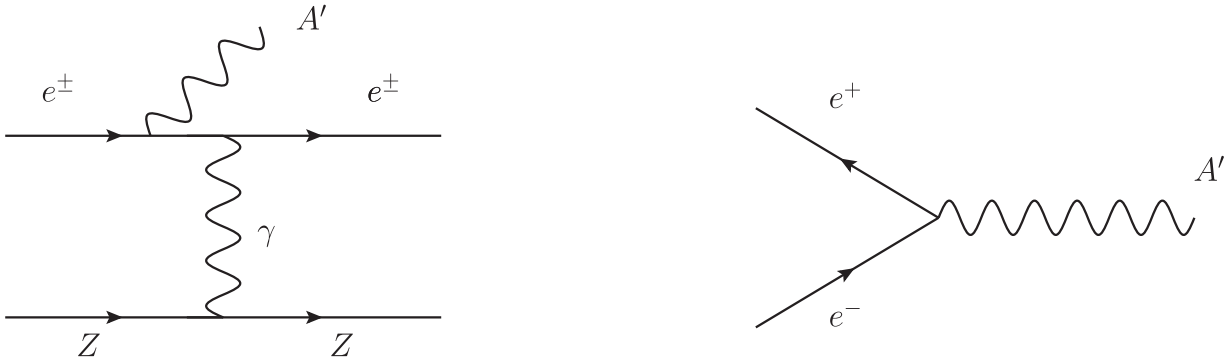
Background source	Level per MOT
momentum reconstruction mismatch	$\lesssim 10^{-13}$
detector non-hermeticity	$\lesssim 10^{-12}$
single-hadron punchthrough	$\lesssim 10^{-12}$
μ, π, K decays	$\lesssim 10^{-13}$
$\mu Z \to \mu Z\gamma; \gamma \to \mu^+\mu^-$, μ trident	$< 10^{-12}$
Total (conservatively)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

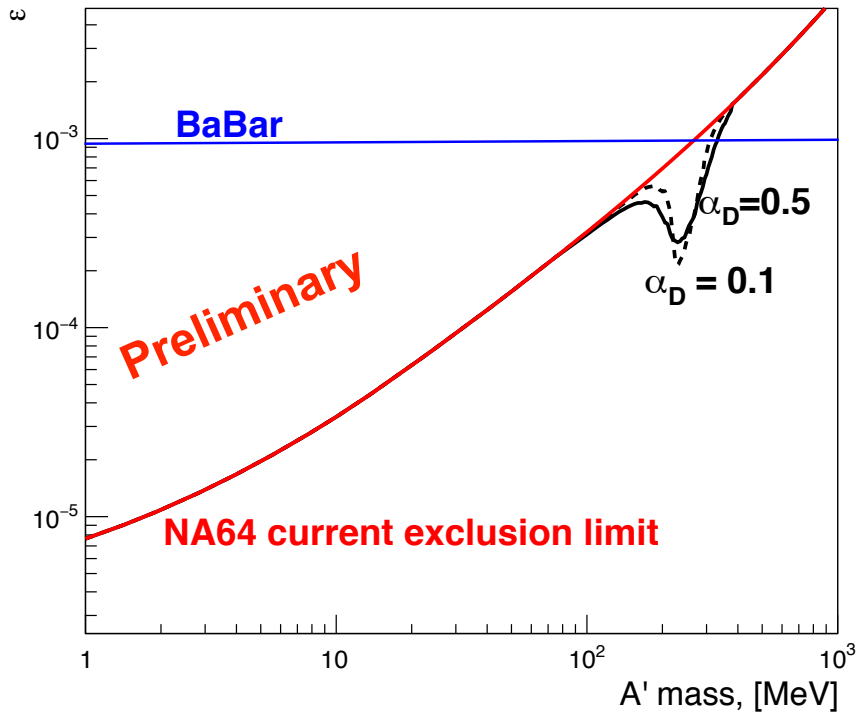
Signature (missing momentum):
1) Tagged 160 GeV incoming muon
2) Scattered muon with <80 GeV
3) No activity in HCAL

Pilot run in 2021 (2 weeks)
Physics runs (2022-2024)

7) NA64 electron mode- A' resonant production

A' Bremsstrahlung vs **resonant production**





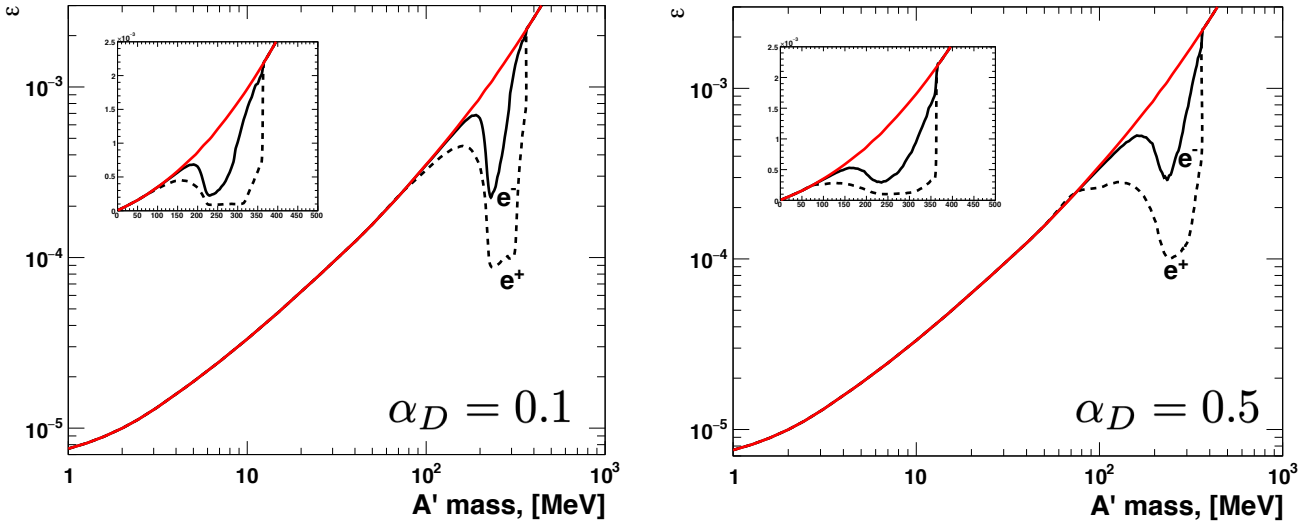
IDEA: Exploit secondary positrons in the EM shower induced by the primary impinging electron

L. Marsicano et al., Phys. Rev. Lett. 121, 041802 (2018)

Improvement of NA64 exclusion limits from current invisible-mode dataset by up to a **factor 5 in mass range 200-300 MeV.** Increased sensitivity to a generic X (S,P,A,V), (M. Biondi, A. Celentano and L. Marsicano, NA64 Note).

NA64 in positron mode - A' resonant production

Search for Dark photons using **100 GeV positrons**



For masses $m_{A'}$ ~ 220–320 MeV
A factor **~10** improvement for ε
Enhancement **~10^2 for y~ε^2**

The e+ measurements are supported by an ERC Starting Grant 2020, Project "POKER", "POsitron annihilation into darK mattER", A. Celentano (INFN-Genova)

The NA64 physics prospects

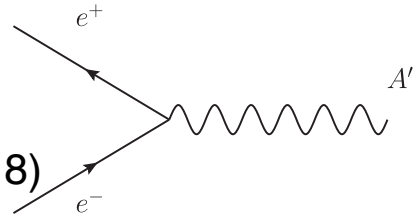
Process	New Physics
e^- **beam**	
$A' \to e^+e^-$, and	Dark photon
$A' \to invisible$	
$A' \to \chi\overline{\chi}$	sub-GeV Dark Matter (χ)
$X \to e^+e^-$	new gauge X- boson
milliQ particles	Dark Sector, charge quantisation
$a \to \gamma\gamma, invisible$	Axion-like particles
μ^- **beam**	
$Z_\mu \to \nu\nu$	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

+ PROGRAM WITH POSITRONS

- Resonant production
  L. Marsicano et al., PRL. 121, 041802 (2018)



- True muonium
  (see presentation P. Crivelli @ PBC 2021 workshop)

Summary and Outlook

NA64: Active beam dump + missing-energy approach is very powerful to search for DARK SECTORS/LDM

This August NA64 will resume data taking (4 weeks), goal until LS3 >5x10^{12} EOT for $A' \rightarrow \chi\bar{\chi}$, explore remaining parameter space $X \rightarrow e^+e^-$, Pilot run in 2021 at M2 (muon mode), 1st physics run (2022)

The exploration of the NA64 physics potential has just begun. Proposed searches in NA64 with leptonic and hadronic beams: unique sensitivities highly complementary to similar projects.

Acknowledgments

NA64 collaboration and in particular S: Gninenko

Beam department: D. Banerjee, J. Bernhard, N. Charitonidis, L. Gattignon, M. Brugger

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