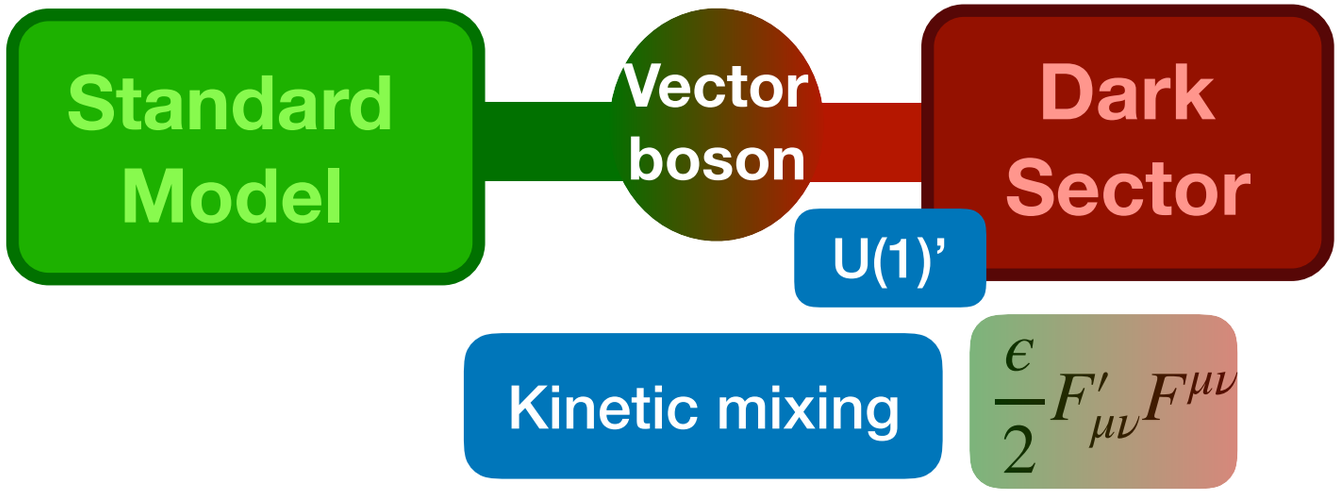
Dark sector searches with NA64 experiment @CERN

Laura Molina Bueno on behalf of NA64 collaboration
laura.molina.bueno@cern.ch

PANIC 2021 conference
5-10th September 2021

ETH Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich
IPA
IFIC Institut de Física Corpuscular
CSIC Consejo Superior de Investigaciones Científicas
Universitat de València

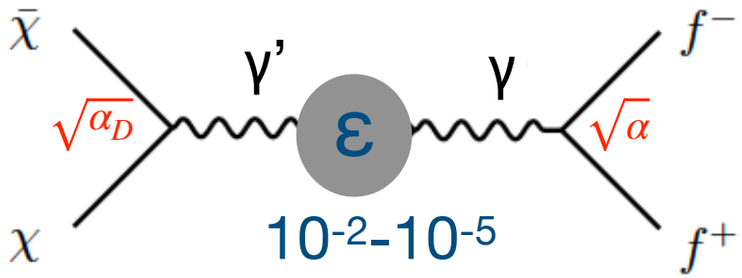
NA64 target: dark sectors →*the vector portal*



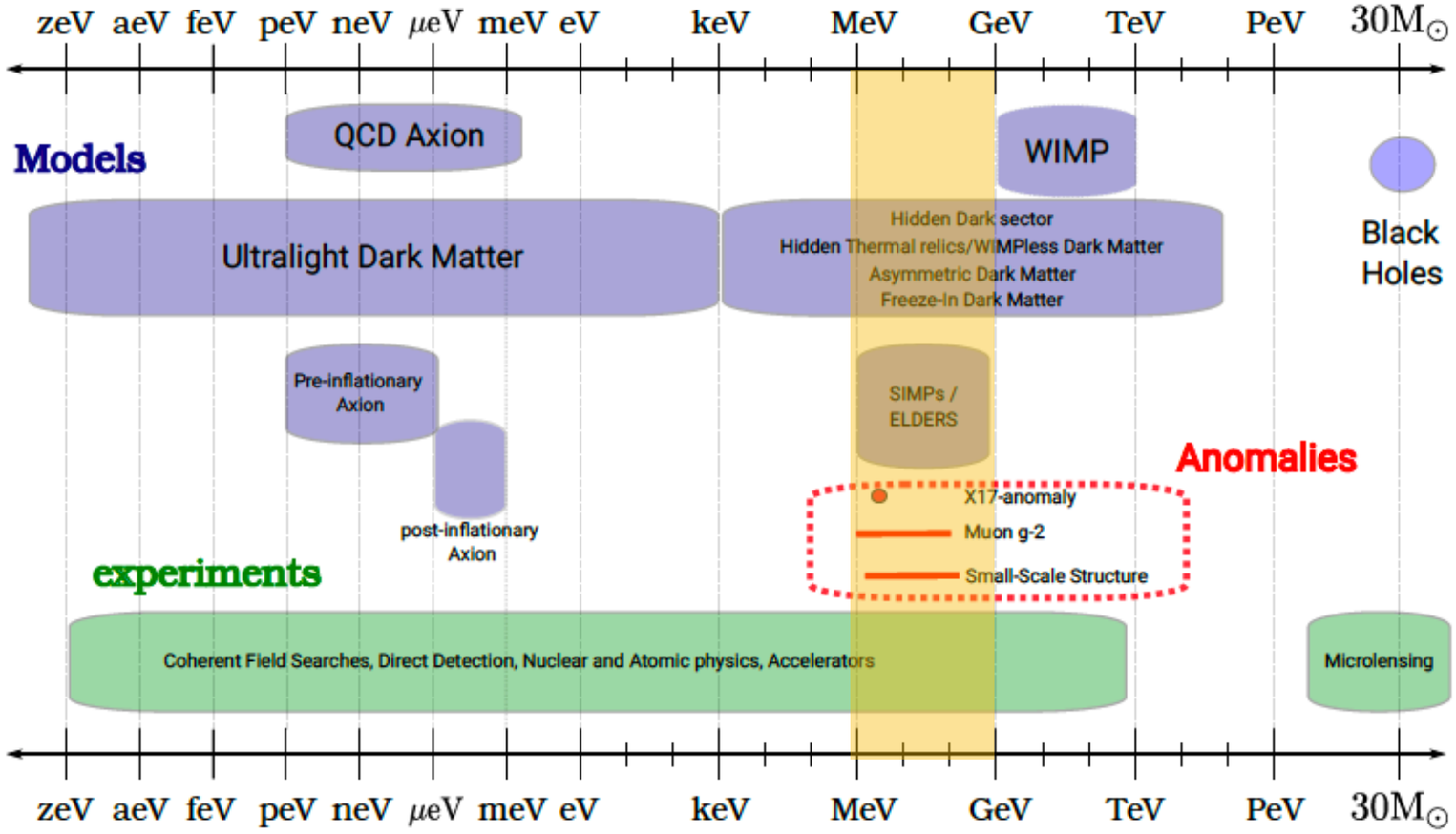
An interesting framework to explain the origin of dark matter

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

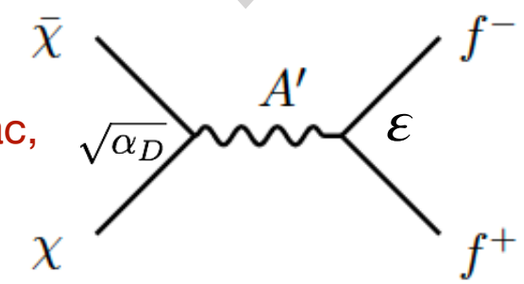
Vector: ***Dark Photon***



From E. Depero, PhD thesis 2020 (ETH Zürich)



For simplicity during the talk



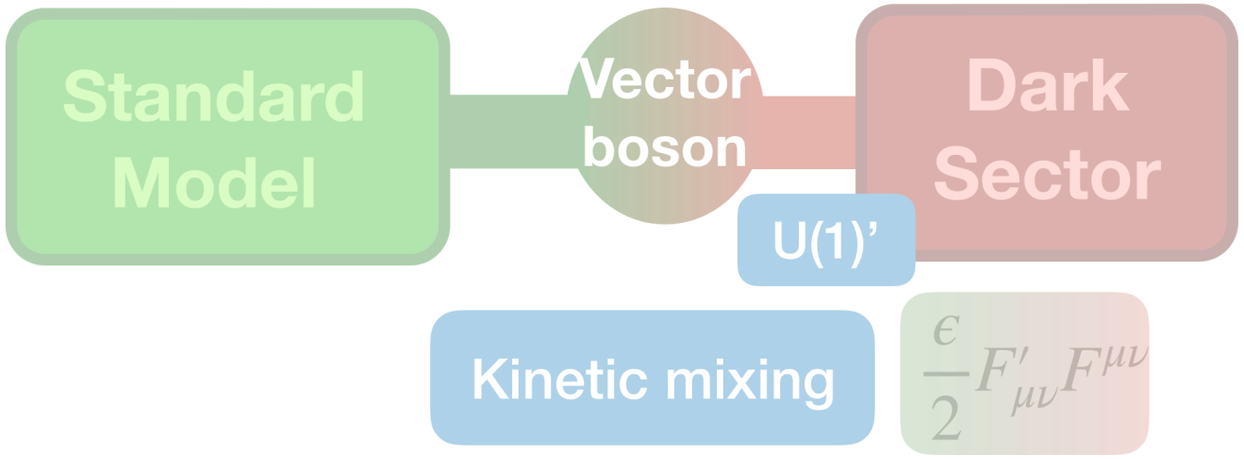
χ : *DM candidate* can be pseudo-Dirac, scalar or Majorana fermion

Parameter space defined by ***(mA',mχ,ε,αD)***

Complementary searches involving different techniques

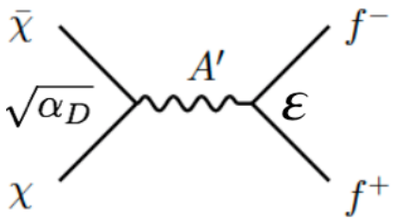
G.Lanfranchi, M.Pospelov and P.Schuster, arxiv:2011.02157
J. Jaeckel et al. Nature Phys. 16 (2020) 393-401

NA64 target: *Light thermal dark matter (LTDM)*



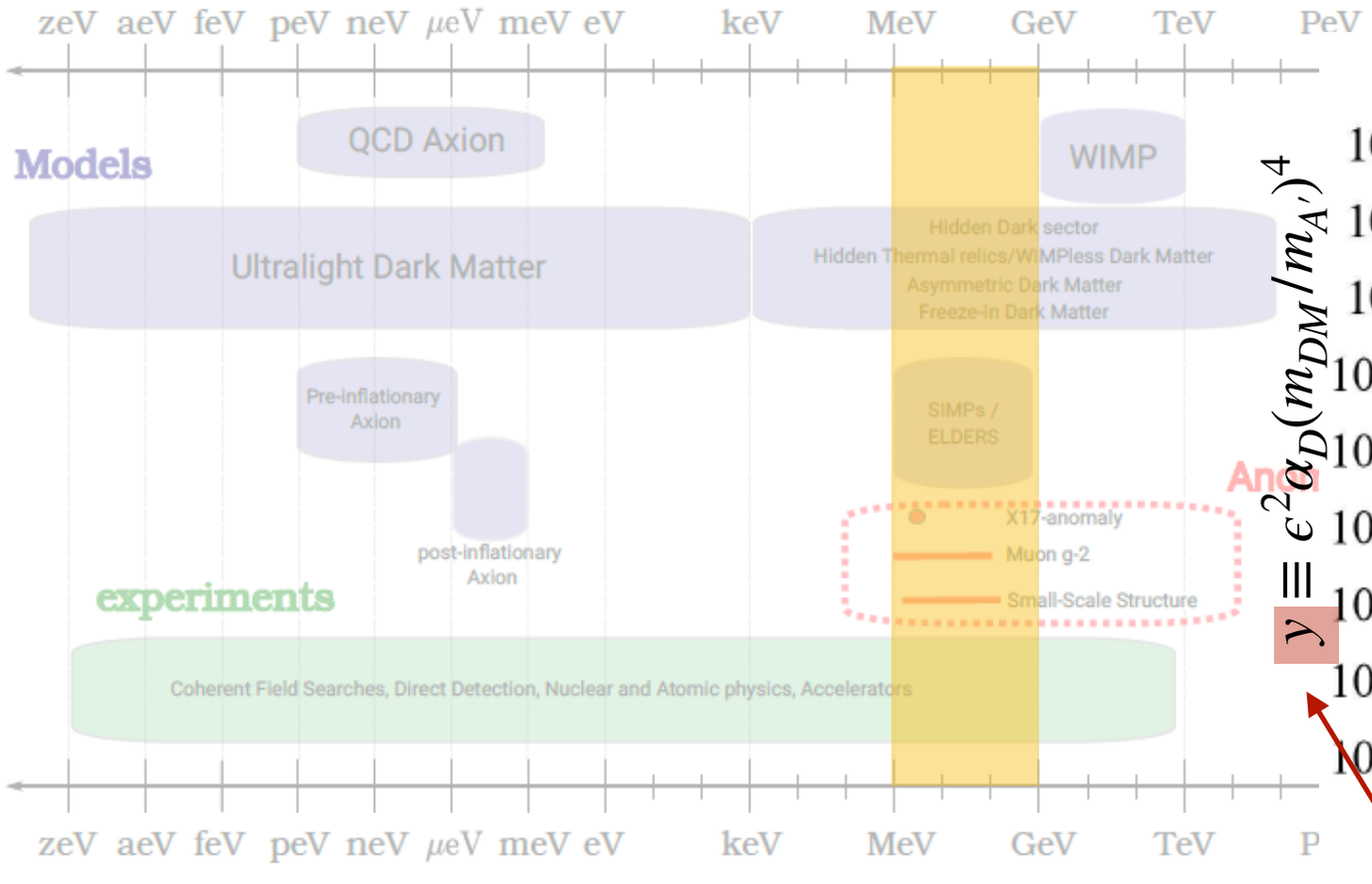
$$\Omega_\chi \propto \frac{1}{<\sigma v>} \sim \frac{m_\chi^2}{g_\chi^4}$$

J.Feng, J. Kumar
Phys. Rev. Lett.101231301



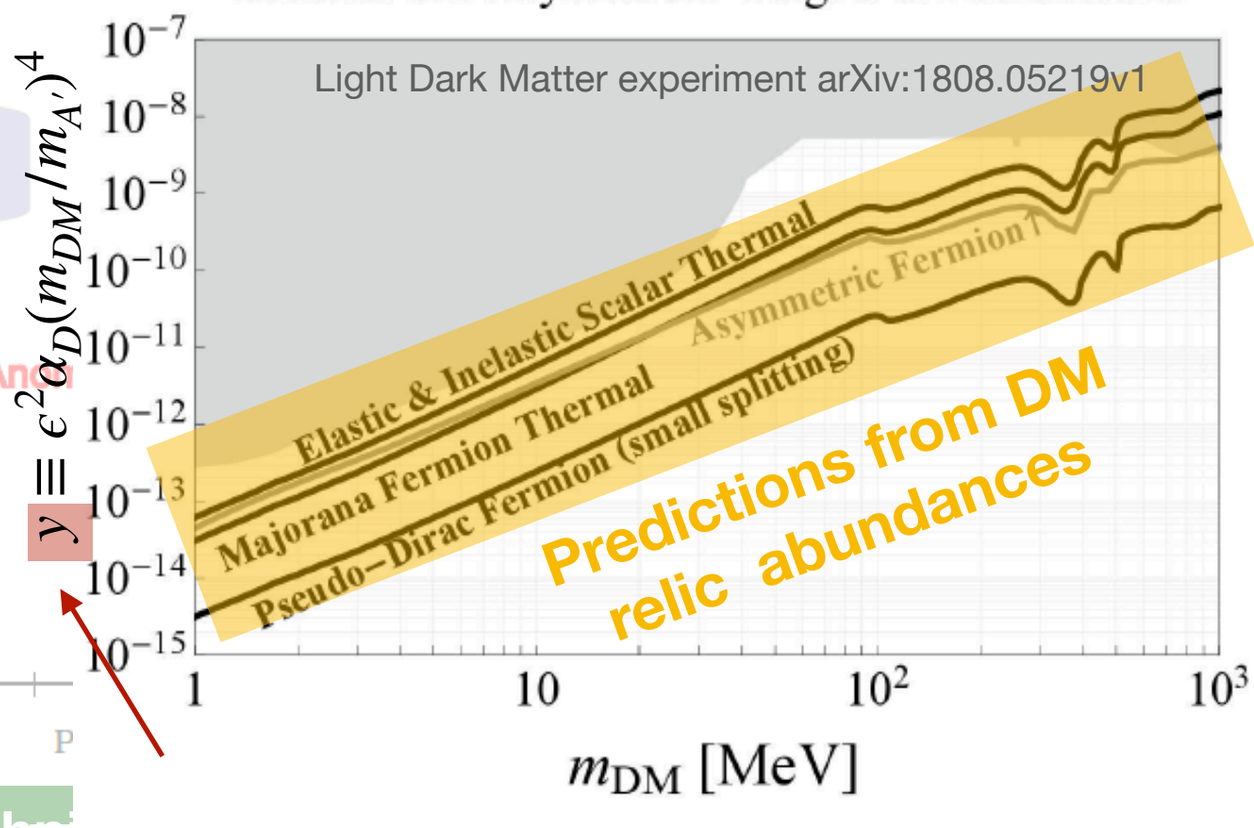
$$\sigma v(\chi\chi \to A'^* \to ff) \propto \epsilon^2 \alpha_D \frac{m_\chi^2}{m_{A'}^4} = \frac{y}{m_\chi^2}$$

From E. Depero, PhD thesis 2020 (ETH Zürich)



Complementary searches involving different tech

Thermal and Asymmetric Targets at Accelerators



Useful parameter to compare different models and experiments proportional to the DM-SM annihilation cross-section

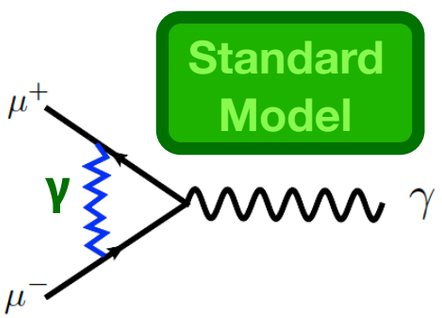
NA64 target: *(g-2)$_\mu$ an additional motivation*

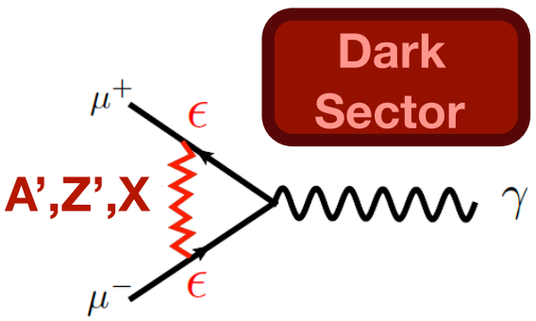
$$a_\mu = \frac{g_\mu - 2}{2}$$

Anomalous muon magnetic moment

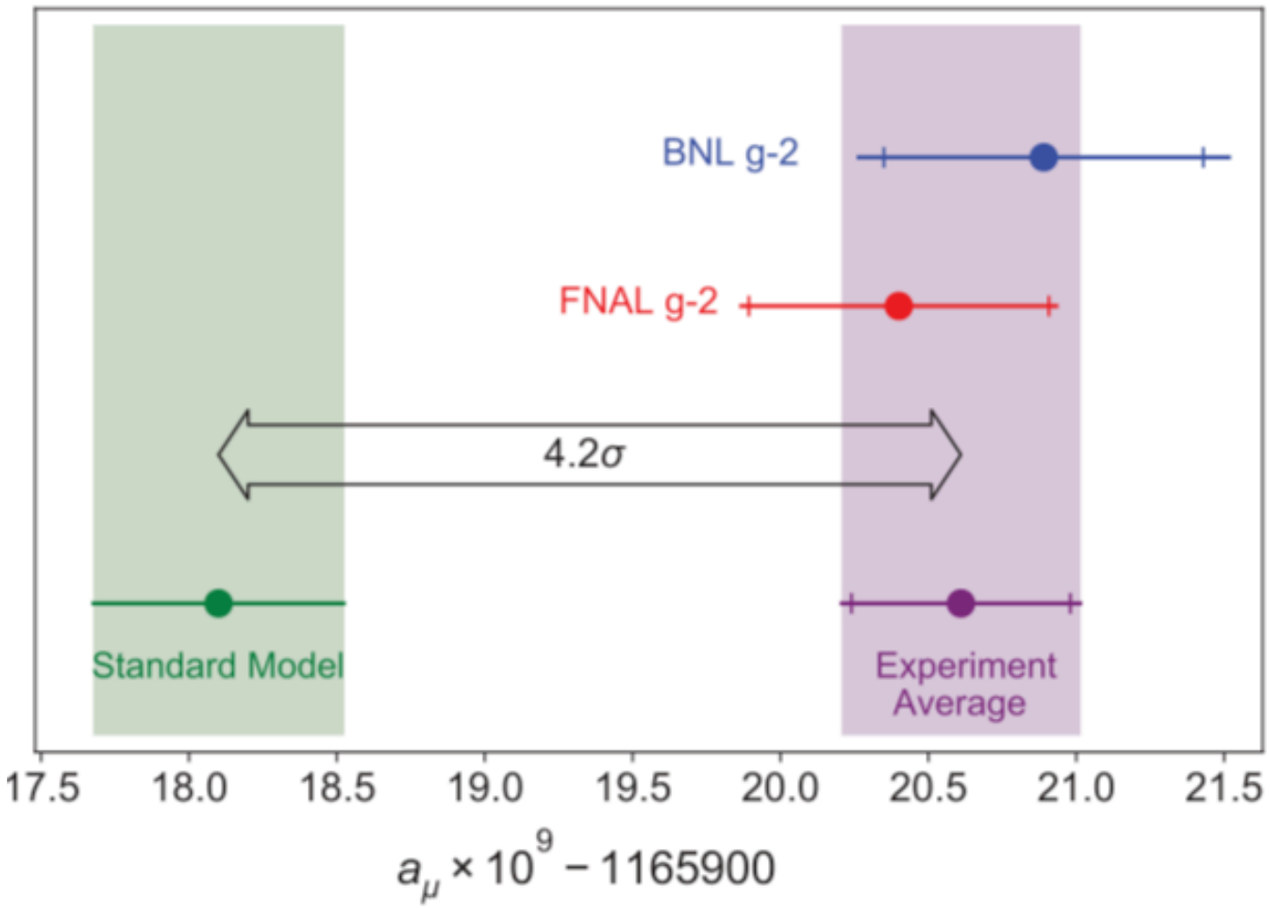
$$\Delta a_\mu = a_\mu^{EXP} - a_\mu^{TH} = (251 \pm 59) \cdot 10^{-11}$$

NA64 approach: **new physics?**
1-loop contributions from dark sector bosons such as A', Z' or a generic X





Specific target for NA64



B. Abi *et al. Muon g-2 collaboration* Phys. Rev. Lett. 126, 141801
T. Aoyama *et al.* Phys. Rept. 887 (2020) 1-166

Including the latest lattice QCD calculations the discrepancy with the experimental value gets reduced below 2σ: Sz. Borsanyi *et al* Nature volume 593, pages 51–55 (2021)

NA64 technique *for A' decays and its signatures*

Fixed target experiment at the CERN SPS designed to probe Dark sector physics

Initial beam → **Active Dump** → **A'**

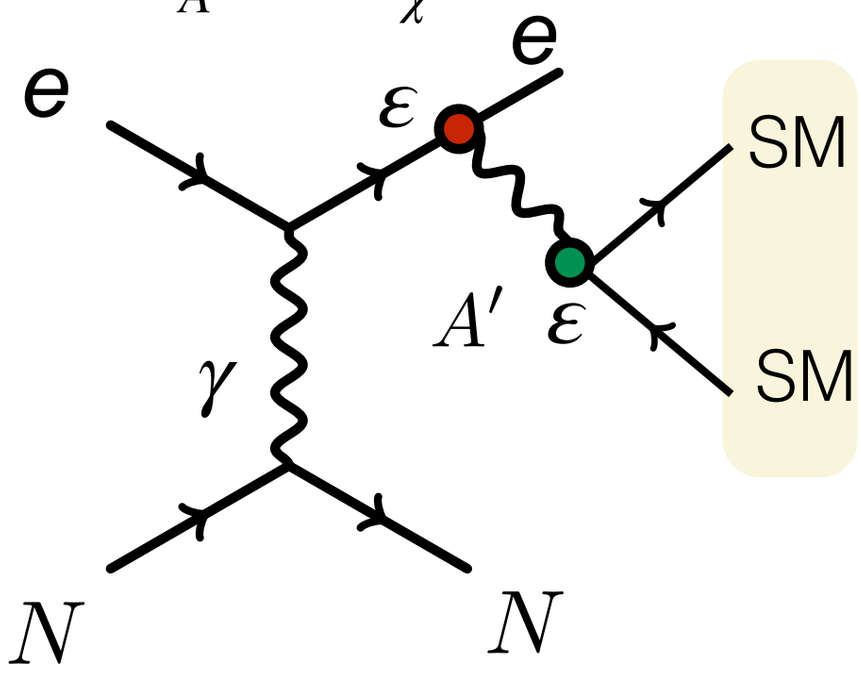
Bremsstrahlung of A'

S. Andreas et al., arXiv:1312.3309 (2013)
S. N. Gninenko, Phys. Rev. D 89, 075008 (2014)

Setup:

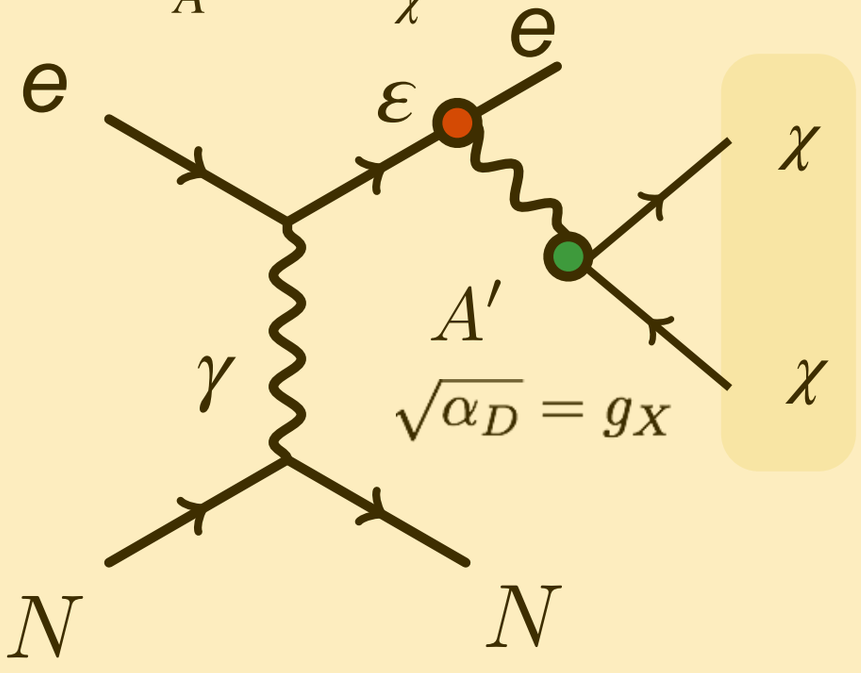
Visible mode

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



Invisible mode

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



Signature:

SM particles pair production

Missing energy

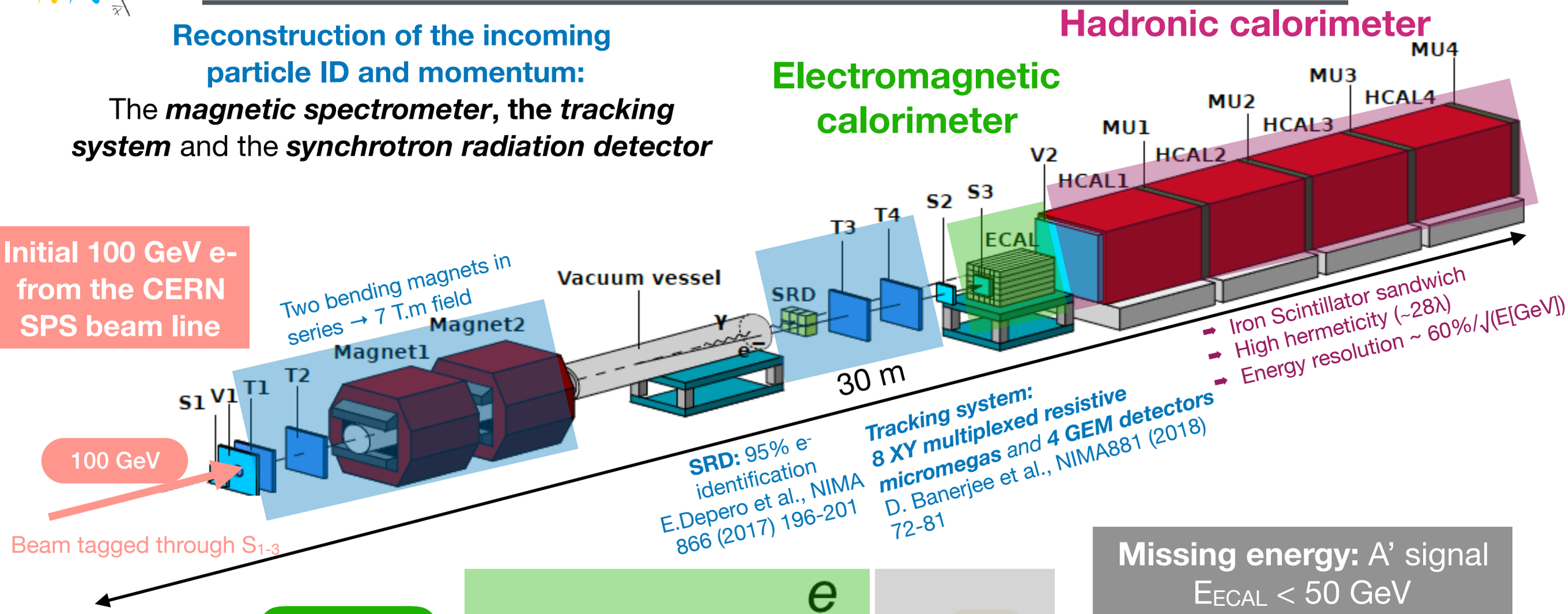
Focus of this talk

NA64 *invisible* mode: *the setup*

Reconstruction of the incoming particle ID and momentum:

The ***magnetic spectrometer***, **the *tracking system*** and the ***synchrotron radiation detector***

Initial 100 GeV e- from the CERN SPS beam line

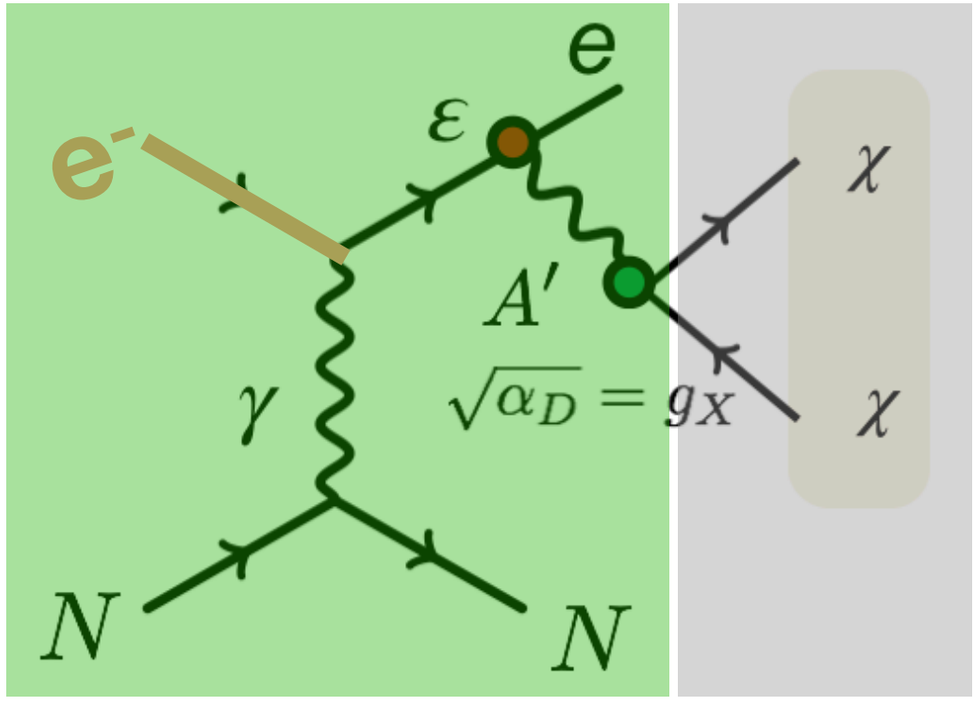


Active target

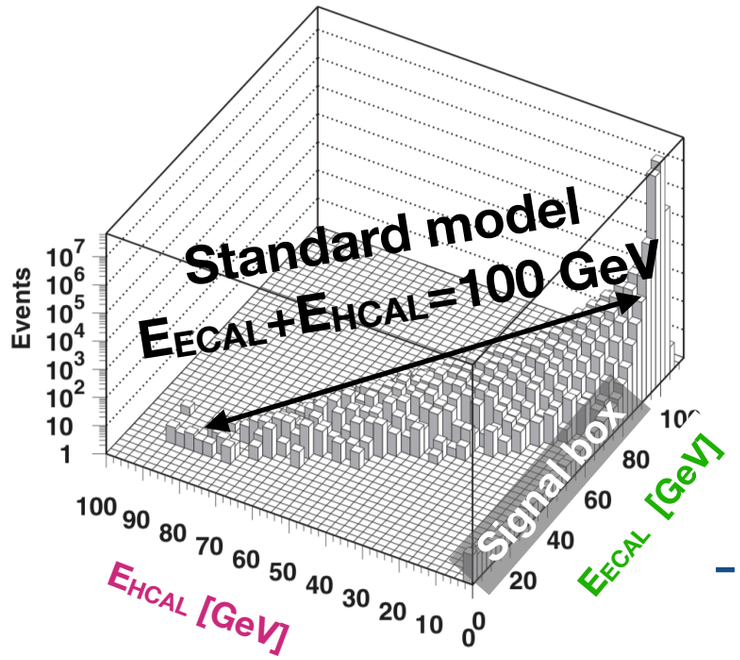
ECAL

- Lead Scintillator sandwich
- High hermeticity (~40 X_0)
- Energy resolution ~ 9%/√(E[GeV])

DMG4 simulation framework
M. Bondi et al. Comput. Phys. Commun. 269, 108129 (2021)



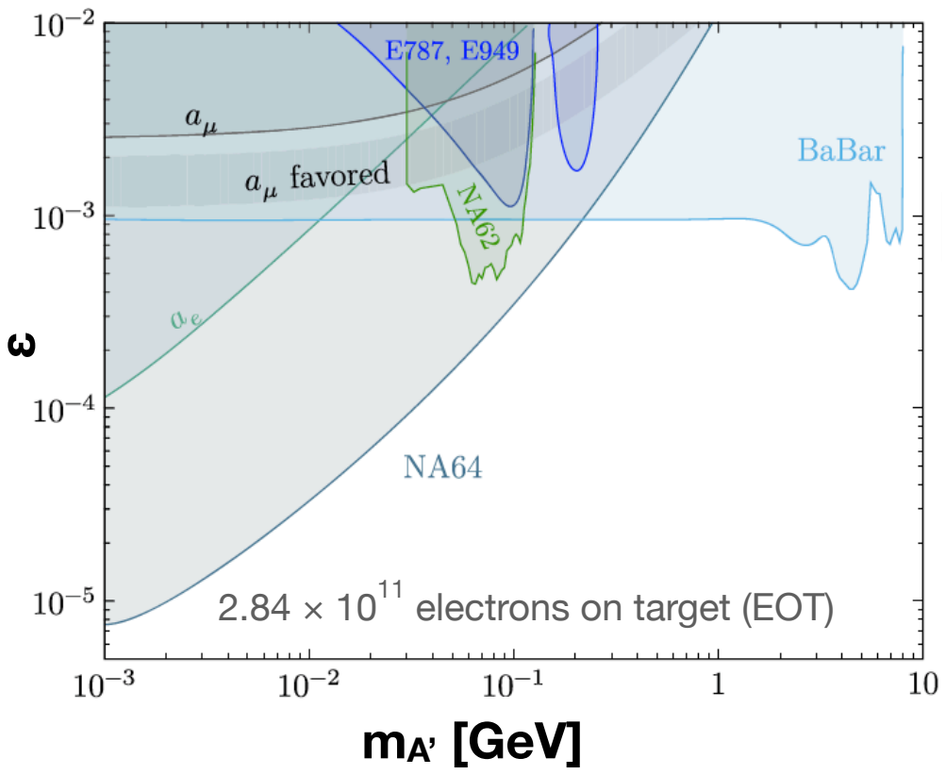
Missing energy: A' signal
$E_{ECAL} < 50$ GeV
E_{HCAL} energy < 2GeV

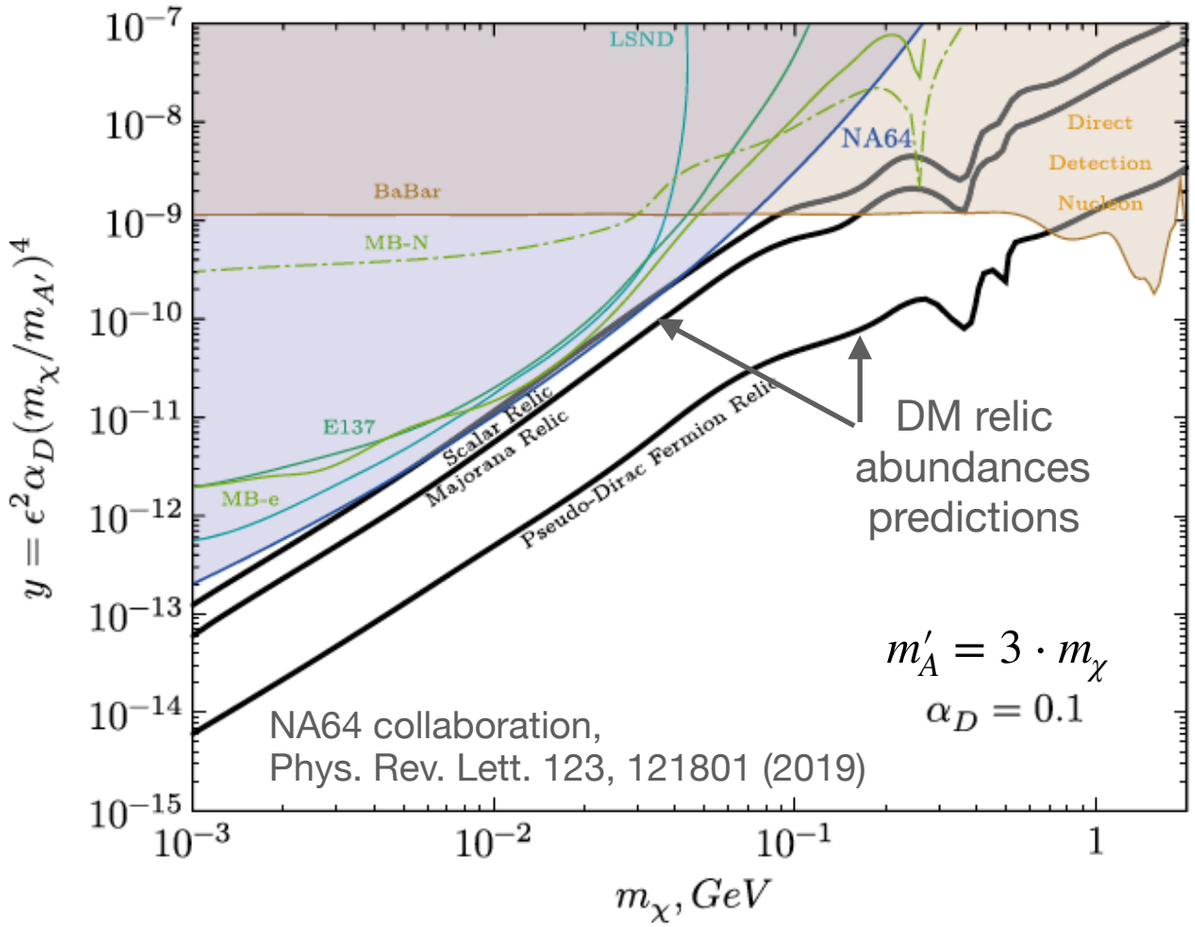


NA64 *invisible* mode: *main physics goal* ***LDM***

2014 | 2015 | 2016 | 2017 | 2018

Beam time





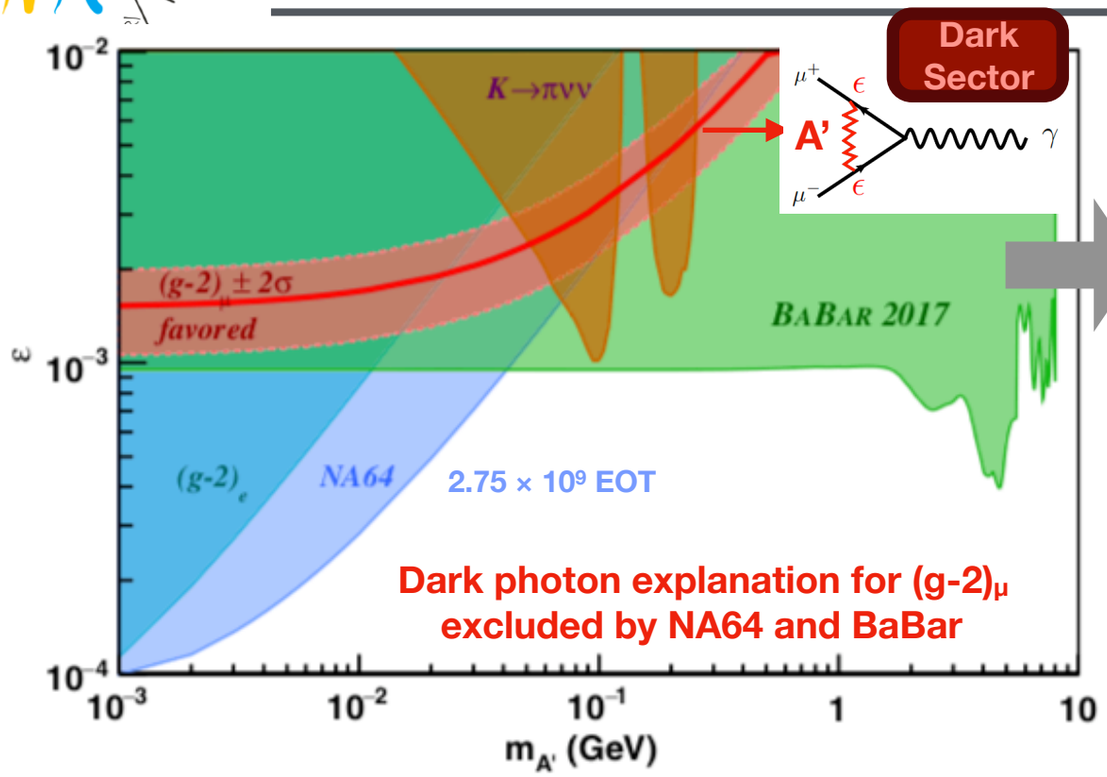
Combined ***invisible analysis*** *data 2016-2018* ***with 2.84 x 10¹¹ EOT***

A' → $\chi\bar{\chi}$: Results exceeded sensitivity of previous experiments to thermal sub-GeV dark matter.

Reminder:

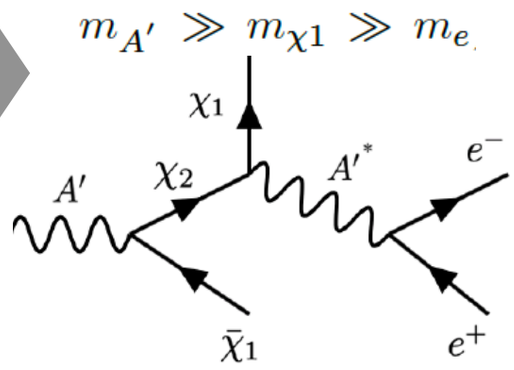
$\sigma_{A'}^{NA64} \propto \epsilon^2$ Vs $\sigma_{A'}^{Beam\ Dump} \propto \epsilon^4 \alpha_D$

NA64 *invisible* mode: *Constraints on new physics in (g-2)μ*



NA64 collaboration, Phys. Rev. Lett. 118, 011802 (2017)
BaBaR collaboration, Phys. Rev. Lett. 119, 131804 (2017)

NEW!



Motivation:

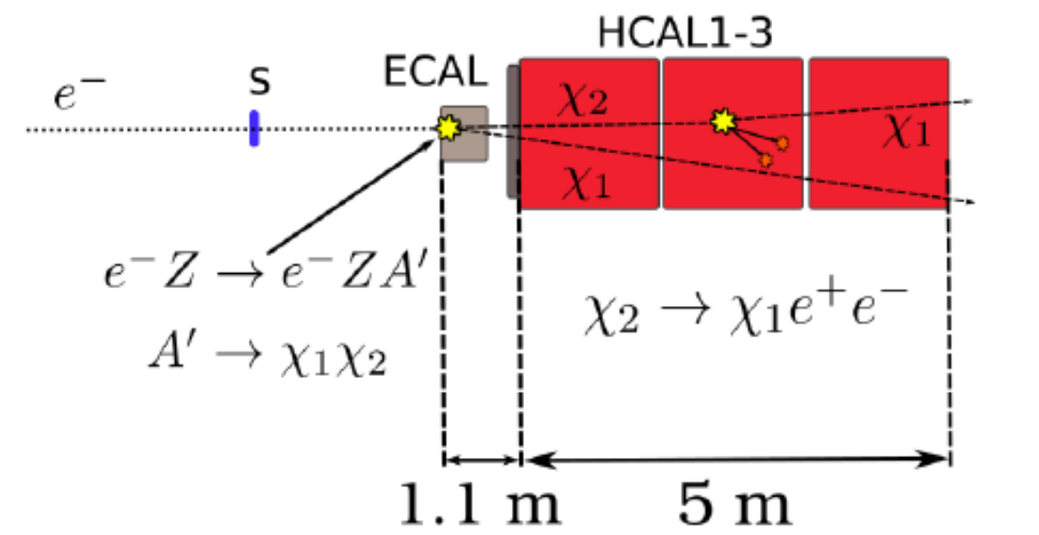
(g-2)μ anomaly+LTDM

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

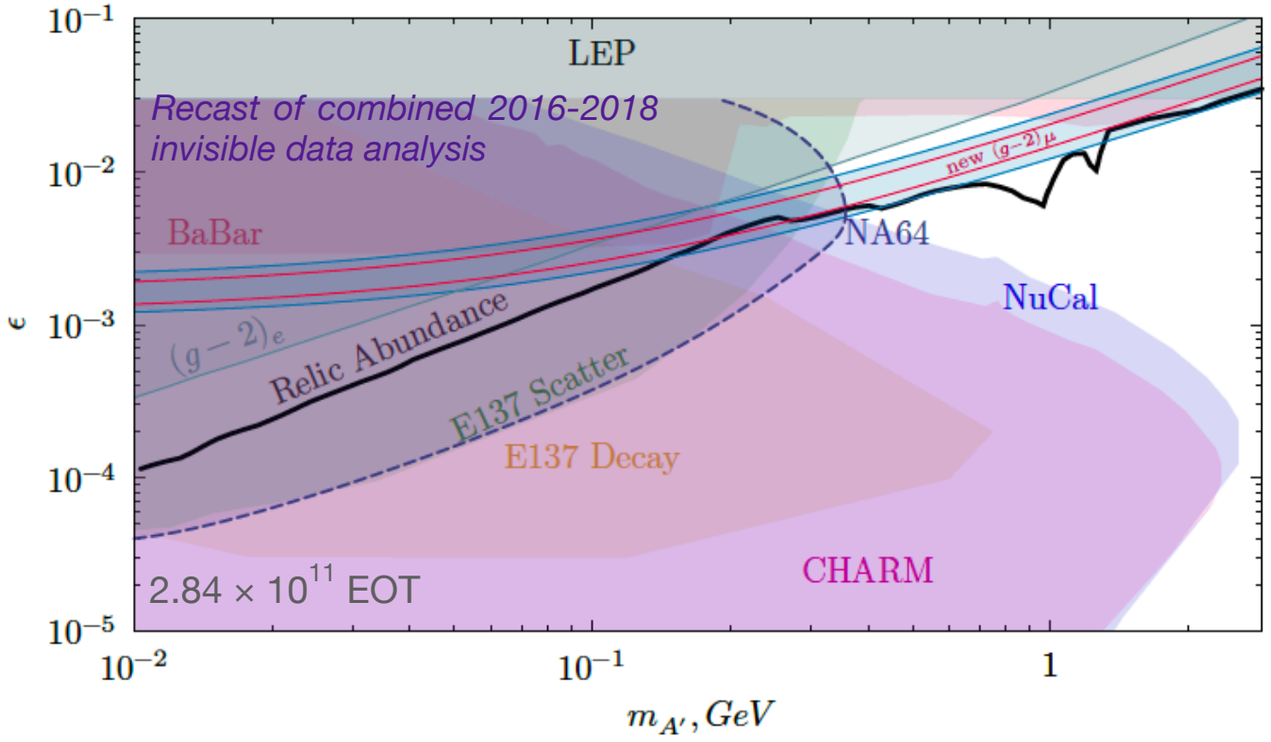
$$\Gamma(\chi_2 \to \chi_1 e^+ e^-) \simeq K \frac{4\epsilon^2 \alpha_{EM} \alpha_D \Delta^5}{15\pi m_{A'}^4}$$

$$\Delta = m_{\chi_2} - m_{\chi_1} \qquad K \simeq 0.640 \pm 0.001$$

Signature: semi-visible decay



$\Delta = 0.4 m_{\chi_1}, m_A = 3 m_{\chi_1}, \alpha_D = 0.1$



NA64 collaboration, arXiv:2107.02021v2

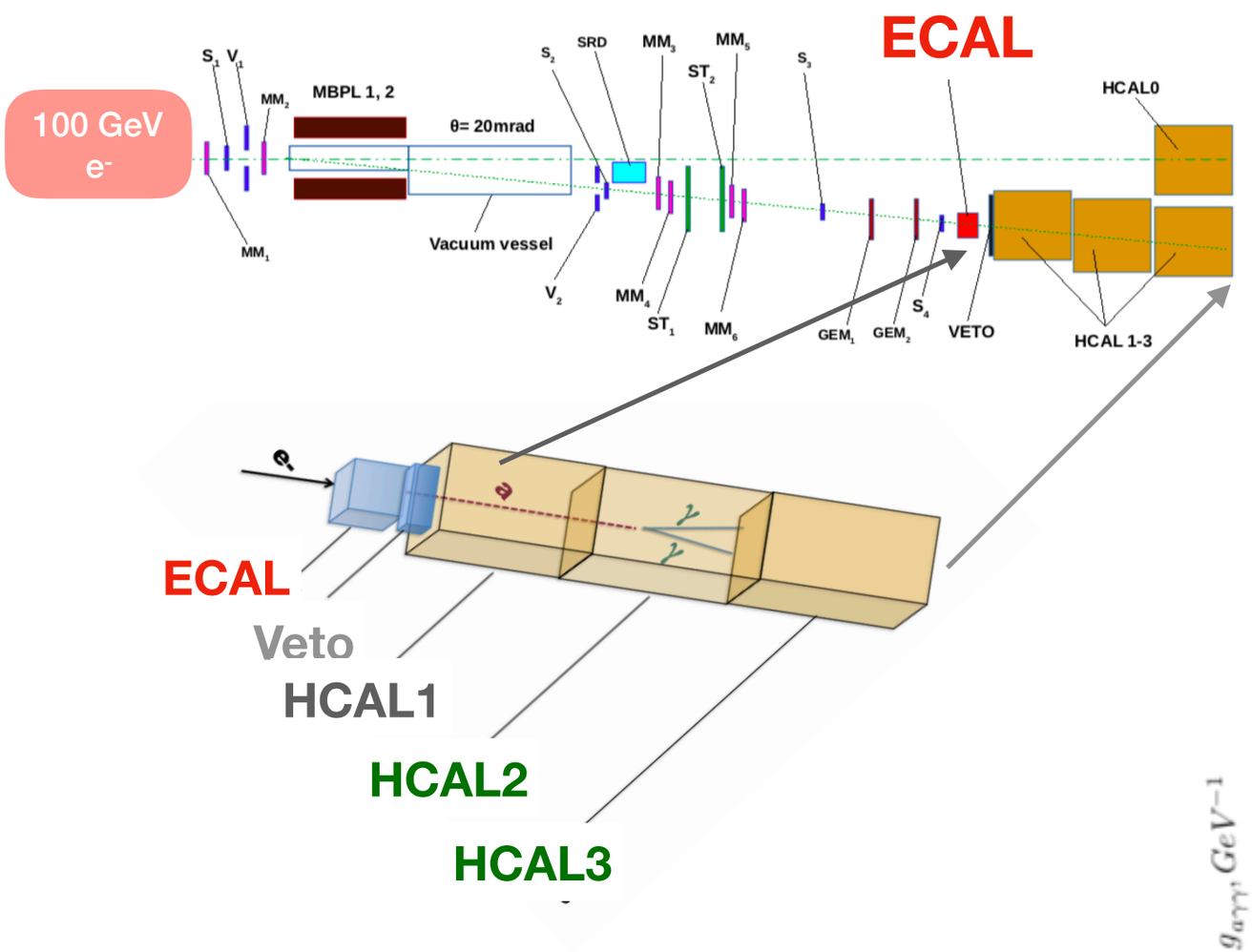
Signature: Missing energy + SM particles pair production

NA64 *invisible* mode: *ALPs*

ALPs predominantly coupled to photons produced via Primakoff effect

$$L_{int} = -\frac{1}{4} g_{a\gamma\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a$$

NA64 invisible setup



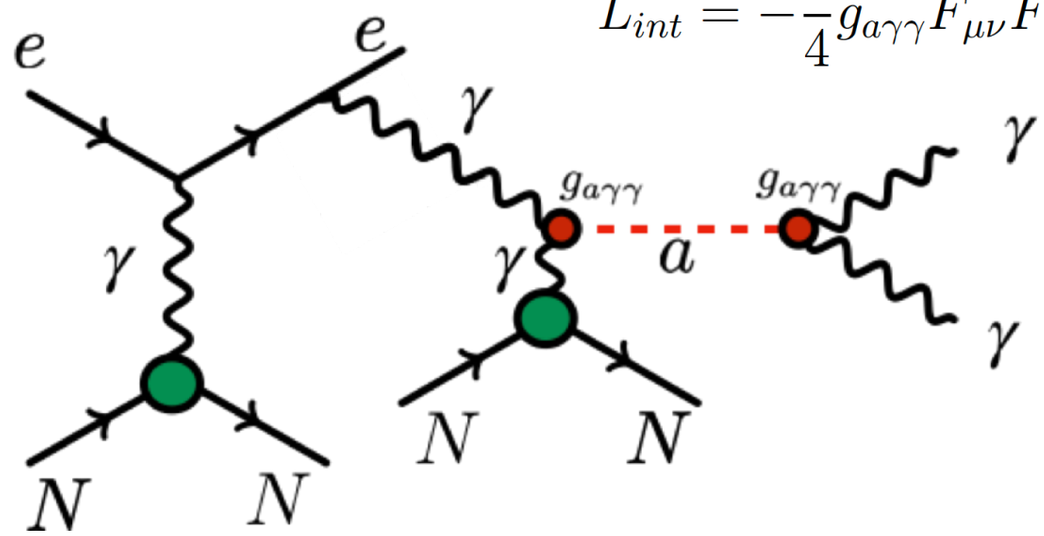
Signature:

No signal on veto and HCAL1

+

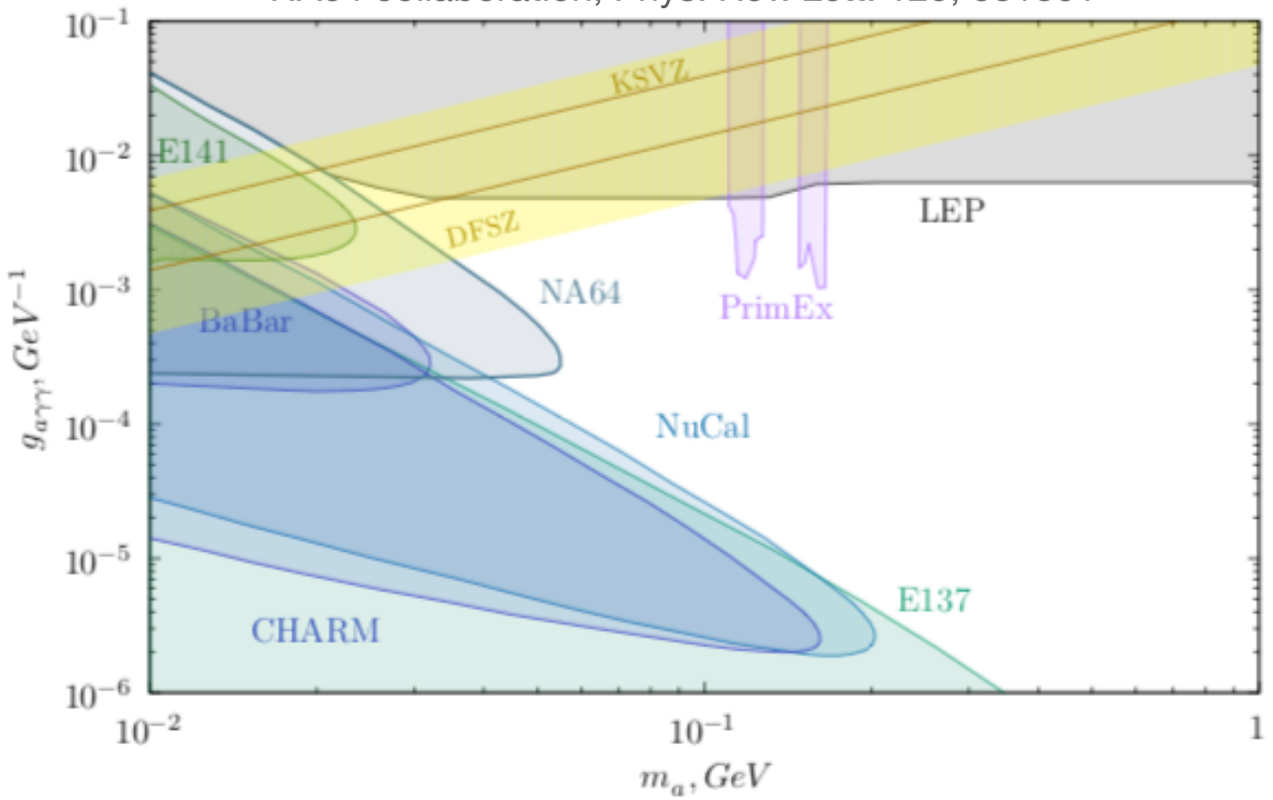
A. ***Visible Decay into γγ*** on HCAL2 || HCAL3

B. ***Decays after HCAL3:*** no activity on all HCALs



Main goal: to probe the gap in the parameter space between the beam-dump and LEP searches

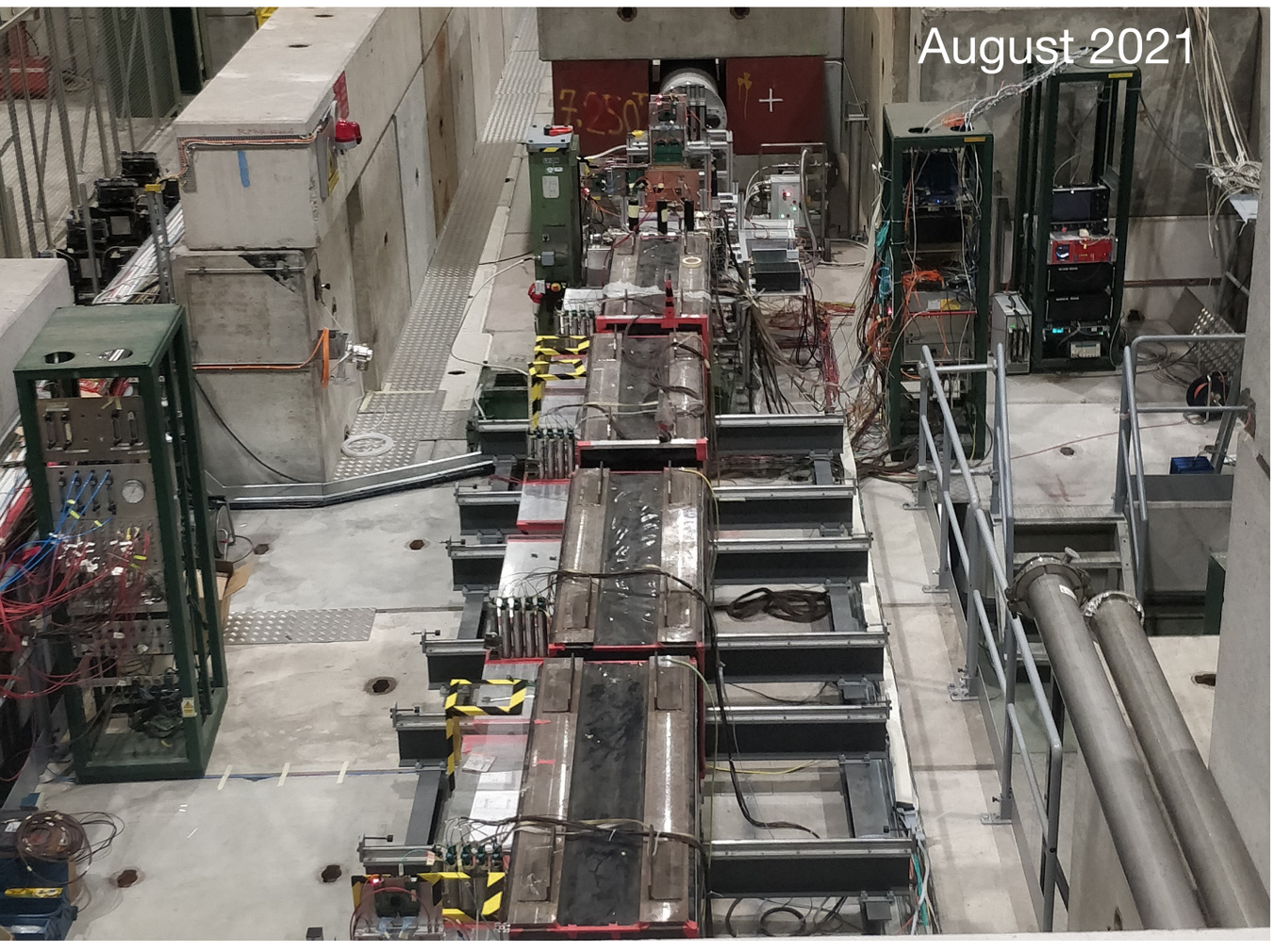
NA64 collaboration, Phys. Rev. Lett. 125, 081801



NA64 *invisible* mode: *LDM future prospects*

2014 | 2015 | 2016 | 2017 | 2018 | LS2 | **2021** | Resume data taking 11th August (5 weeks)

Beam time



- New fixed location at H4 beam line.
- Beam, setup and electronics upgrades:
  - ***Improve performance***
  - **Reduce background from electro nuclear interactions.**

Main source: **electro-nuclear interactions along the beam line**

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

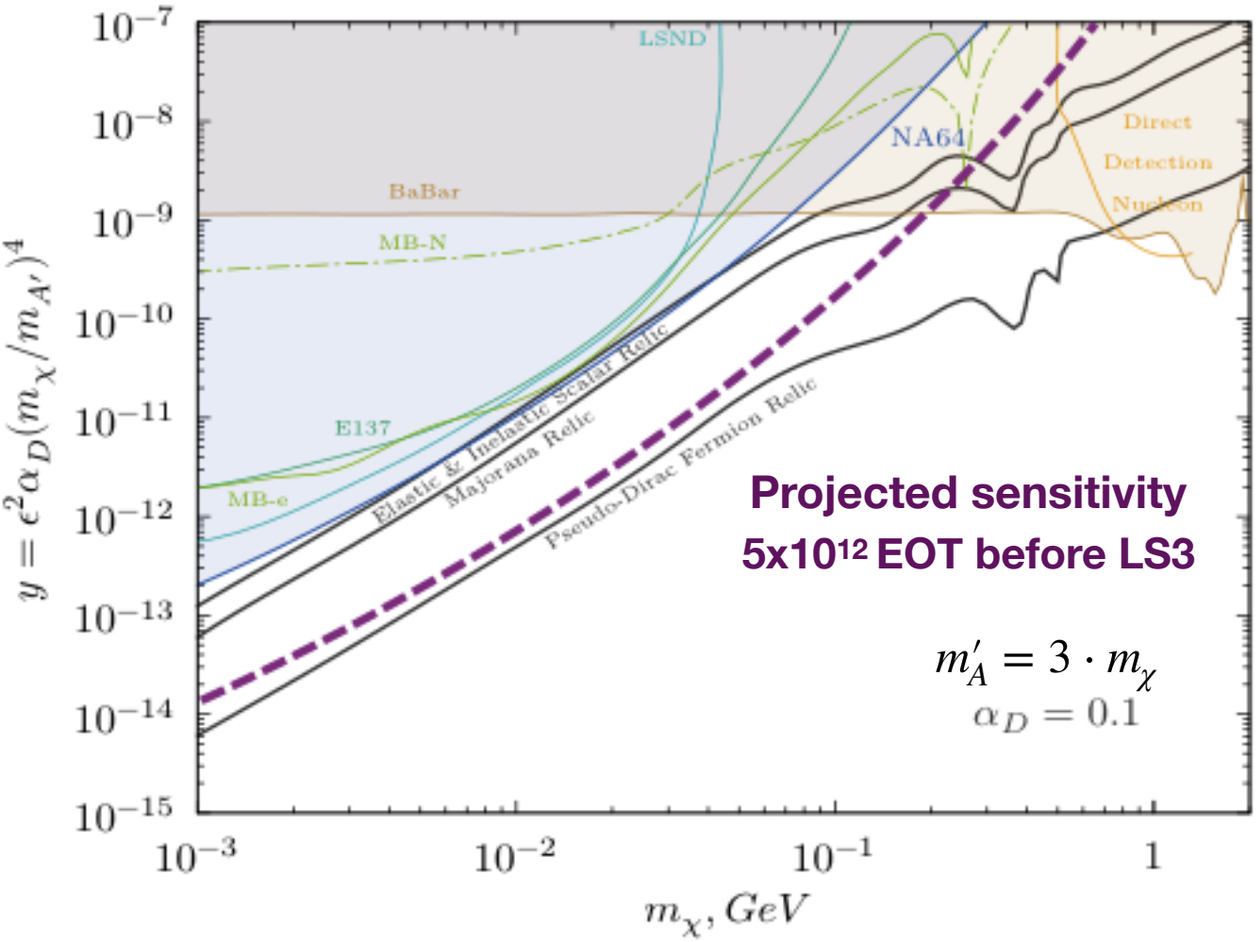
NA64 collaboration,
Phys. Rev. Lett. 123, 121801 (2019)

NA64 *invisible* mode: *LDM future prospects*

2014 | 2015 | 2016 | 2017 | 2018 | LS2 | **2021** | Resume data taking 11th August (5 weeks)

Beam time

S. Gninenko, *PBC workshop 2021*



- New fixed location at H4 beam line.
- Beam, setup and electronics upgrades:
  - ***Improve performance***
  - **Reduce background from electro nuclear interactions.**

Goal: Accumulate 5x10¹² EOT before LS3.

Main source: **electro-nuclear interactions along the beam line**

Background source	Background number, n_b
punchthrough γ's, cracks, holes	< 0.01
loss of dimuons	0.024 ± 0.007
$\mu \to e\nu\nu$, π, $K \to e\nu$, K_{e3} decays	0.02 ± 0.01
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NA64 collaboration,
Phys. Rev. Lett. 123, 121801 (2019)

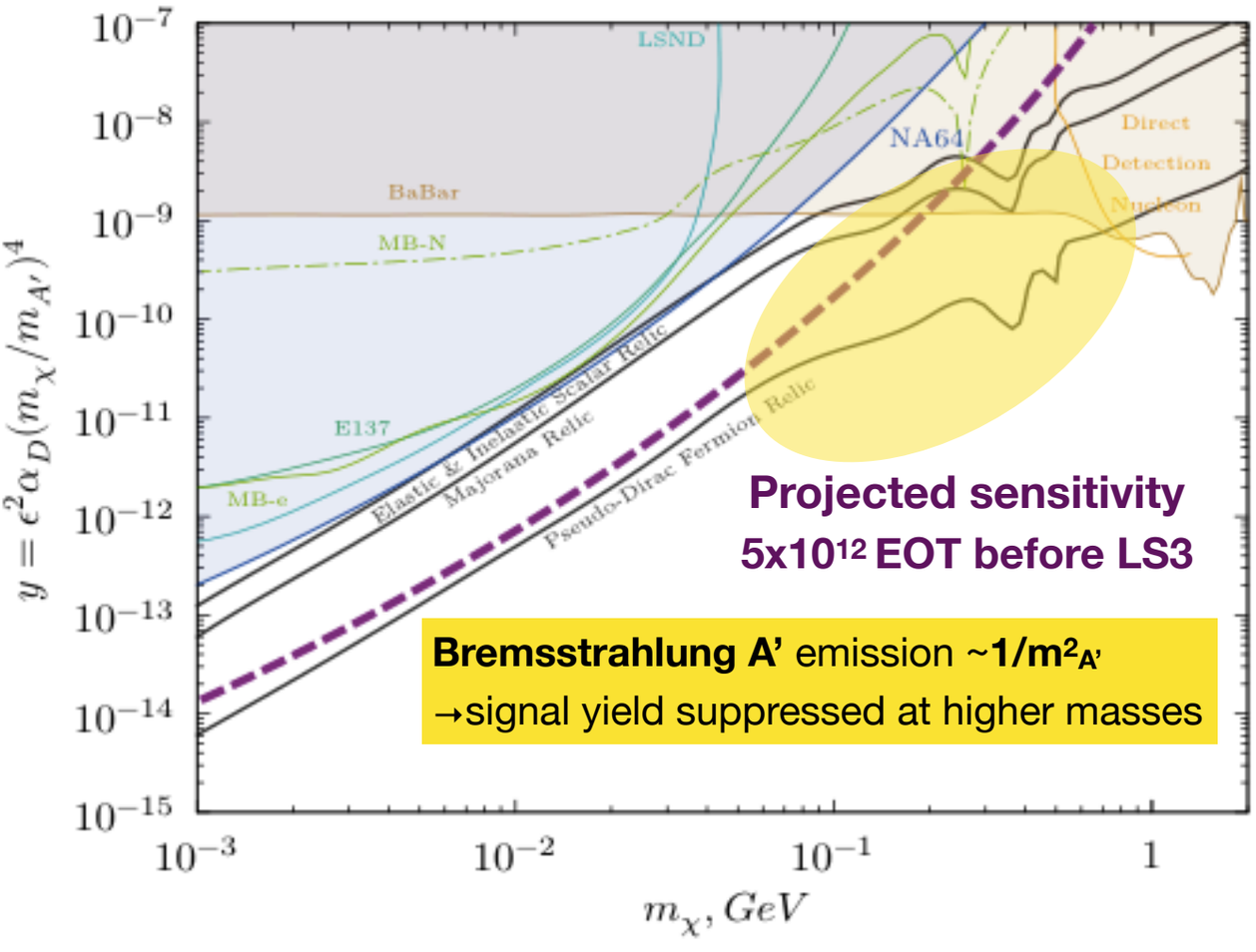
NA64 *invisible* mode: *LDM future prospects*

2014 | 2015 | 2016 | 2017 | 2018 | LS2 | **2021 and beyond**

Beam time

How can we enlarge the sensitivity at higher masses?

S. Gninenko, *PBC workshop 2021*



Projected sensitivity
5x10¹² EOT before LS3

Bremsstrahlung A' emission **~1/m²$_{A'}$**
→signal yield suppressed at higher masses

New ideas:

- **Positron beam and A' resonant production**

  L. Marsicano et al. Phys. Rev. Lett. 121, 041802
  NA64 collaboration, arXiv:2108.04195

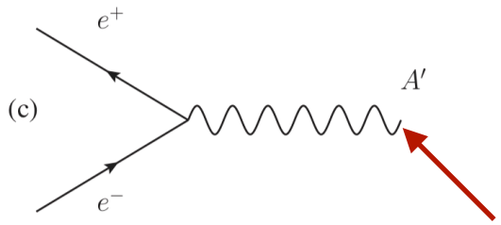
- Use a muon beam: ***NA64μ experiment***

  S.Gninenko et al. PLB796, 117 (2019)

  D. Banerjee et al. [NA64 Collaboration], "Addendum to the proposal P348: Proposal for an experiment to search for dark sector particles weakly coupled to muon at the SPS". CERN-SPSC-2019-002 / SPSC-P-359, January 14, 2019.

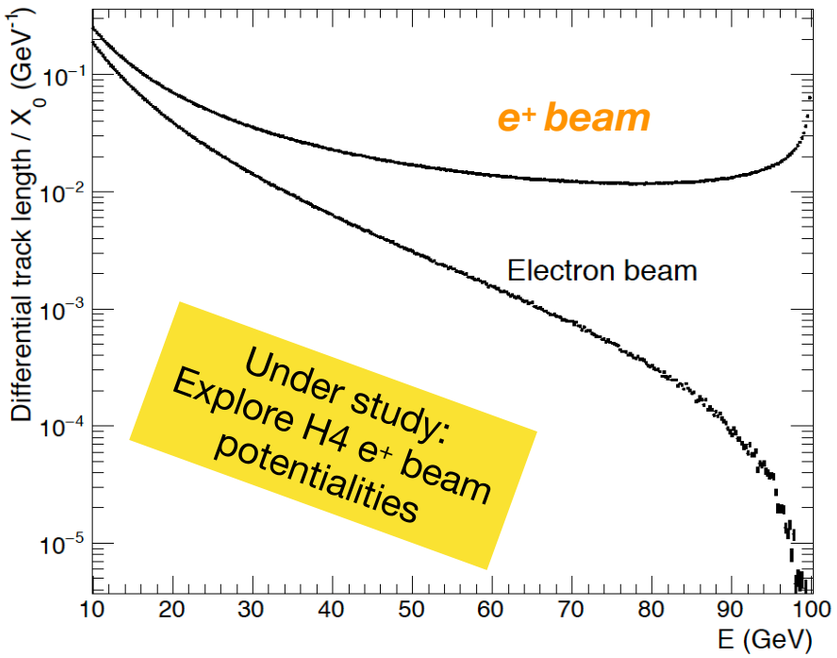
Future prospects: A' resonance

*Explore the **resonance annihilation** channel **using the secondary positrons** present in the electromagnetic (EM) shower in the target **induced by the initial e⁺ beam***



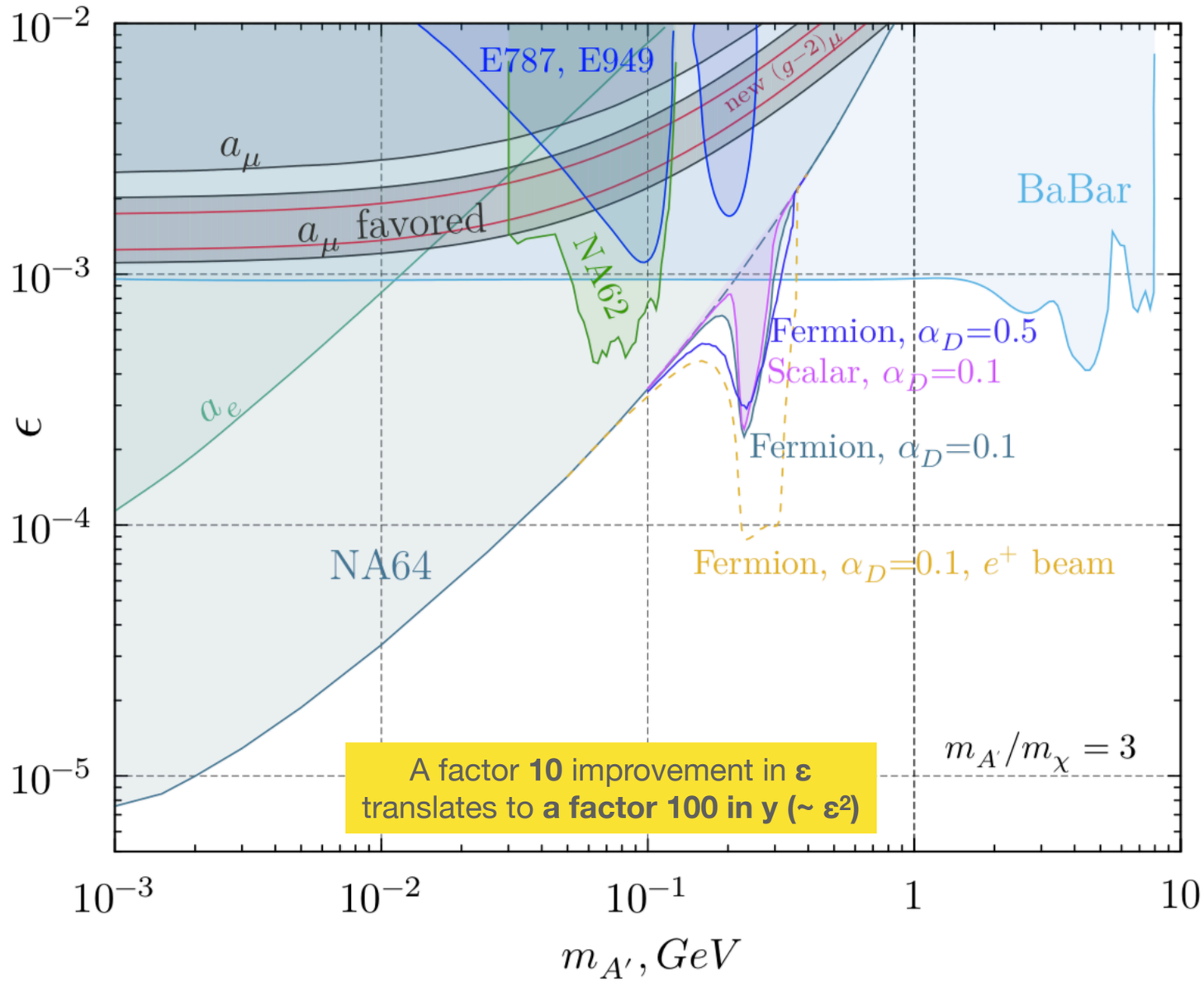
Sensitivity calculated for a generic ***X boson*** (S,P,A,V)

Distribution of secondary e⁺



L. Marsicano et al. Phys. Rev. Lett. 121, 041802

NA64 collaboration, arXiv:2108.04195



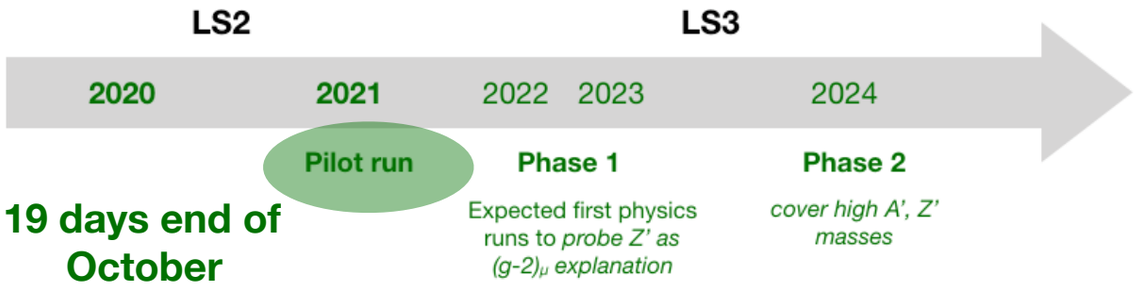
A factor **10** improvement in **ε** translates to **a factor 100 in y (~ ε²)**

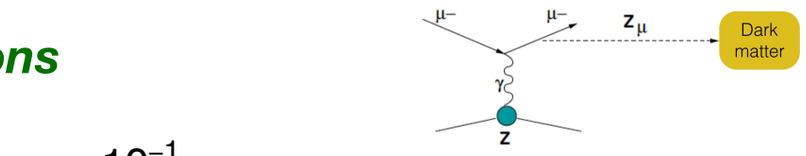
Supported by the ERC Starting Grant 2020 project: POKER "POsitron annihilation into darK mattER" A. Celentano (INFN-Genova)

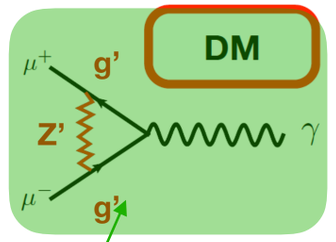
Future prospects: NA64$_\mu$ physics goals

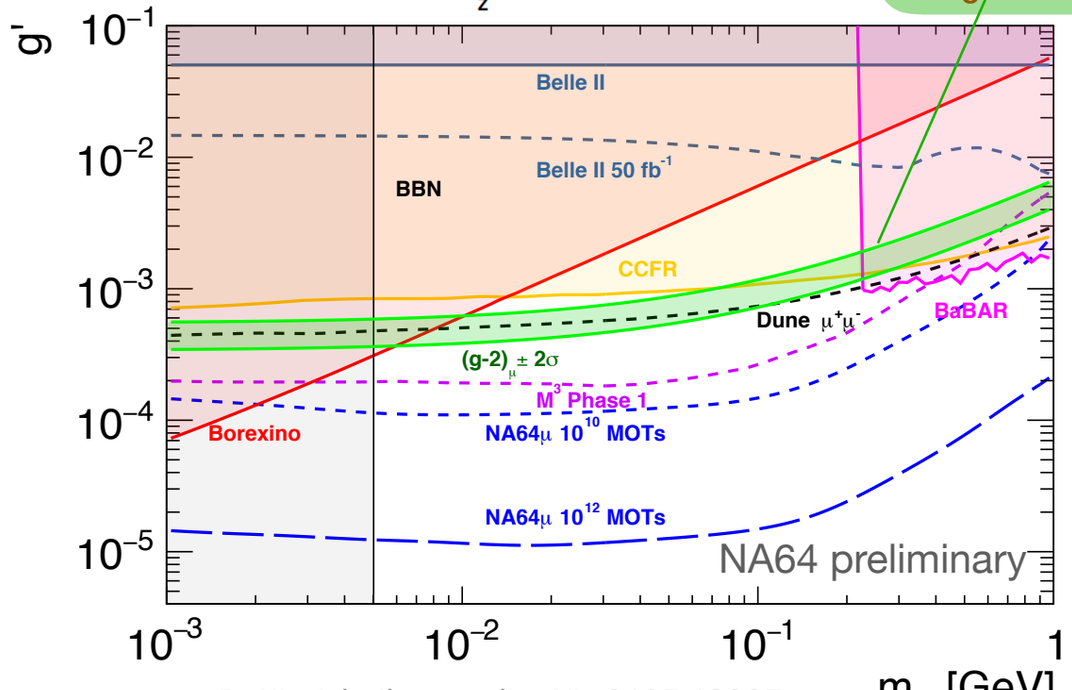
Exploring Dark sector physics weakly coupled to muons

1. **Light Z' coupled to the muon,** as a remaining low mass **explanation of the (g-2)$_\mu$ (the muon anomaly).**
2. **Light thermal dark matter** in the A' mass region ≥ 0.1 GeV (complementary search to NA64e).
3. **Scalar**, **ALPs** coupled to the muon, **millicharged** particles, ...
4. **Lepton Flavour Violation in μZ -> τZ conversion** in flight.







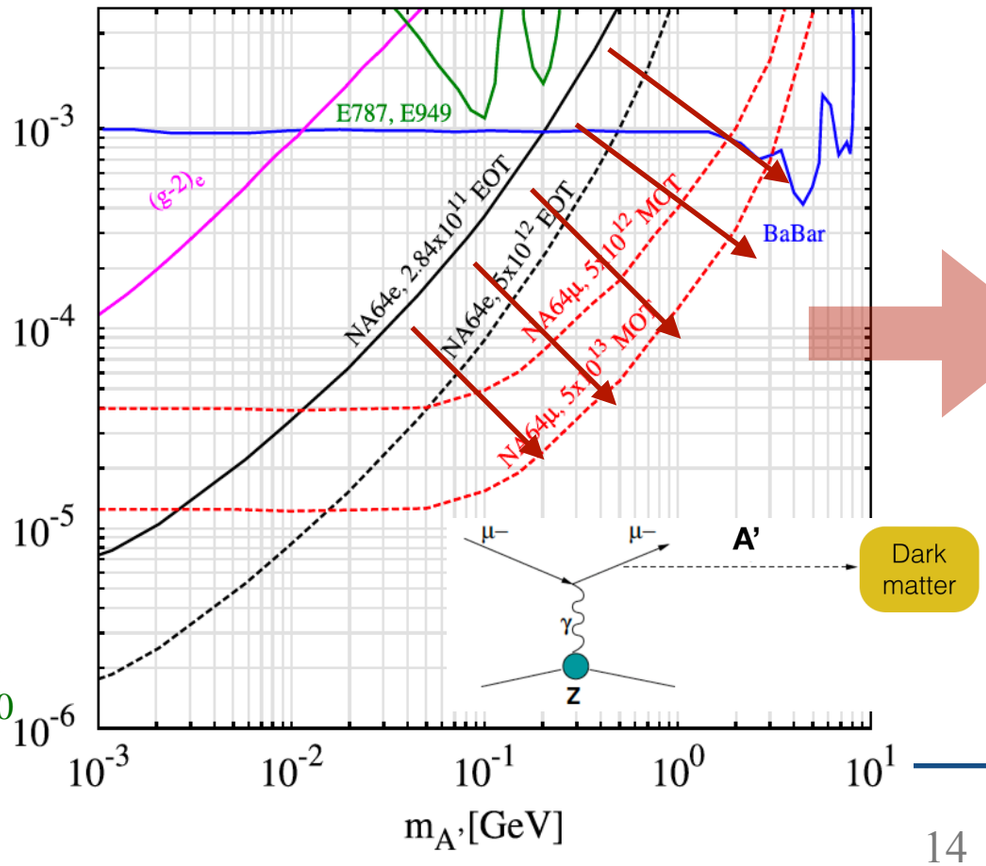


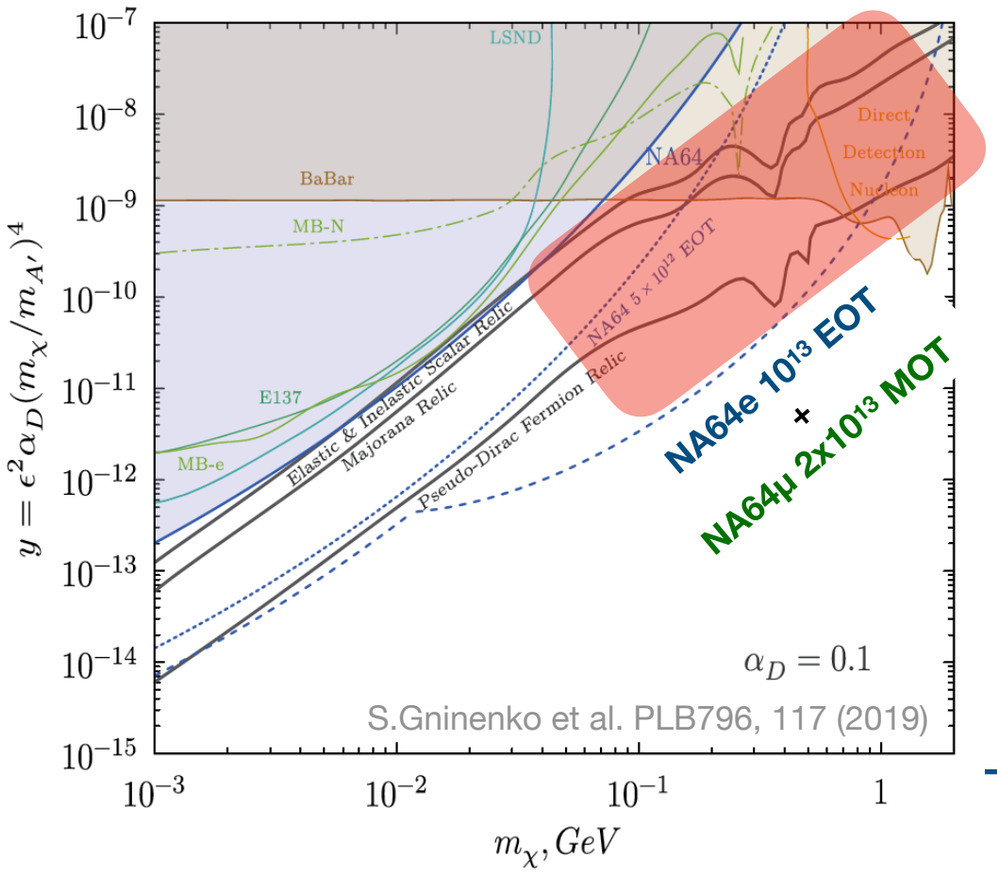
D. Kirpichnikov et al. arXiv:2107.13297

$$N'_A \sim L\sigma'_A \sim L\frac{\epsilon^2}{m^2_{A'}}$$

e- $L^e = X_0$

μ- $L^\mu = 40X_0$



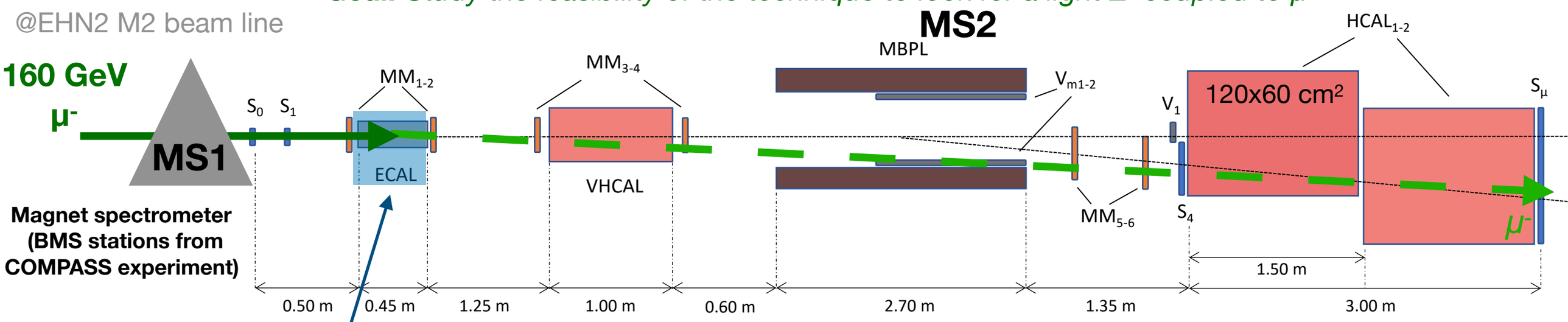


S.Gninenko et al. PLB796, 117 (2019)

Future prospects: NA64$_\mu$ pilot run in 2021

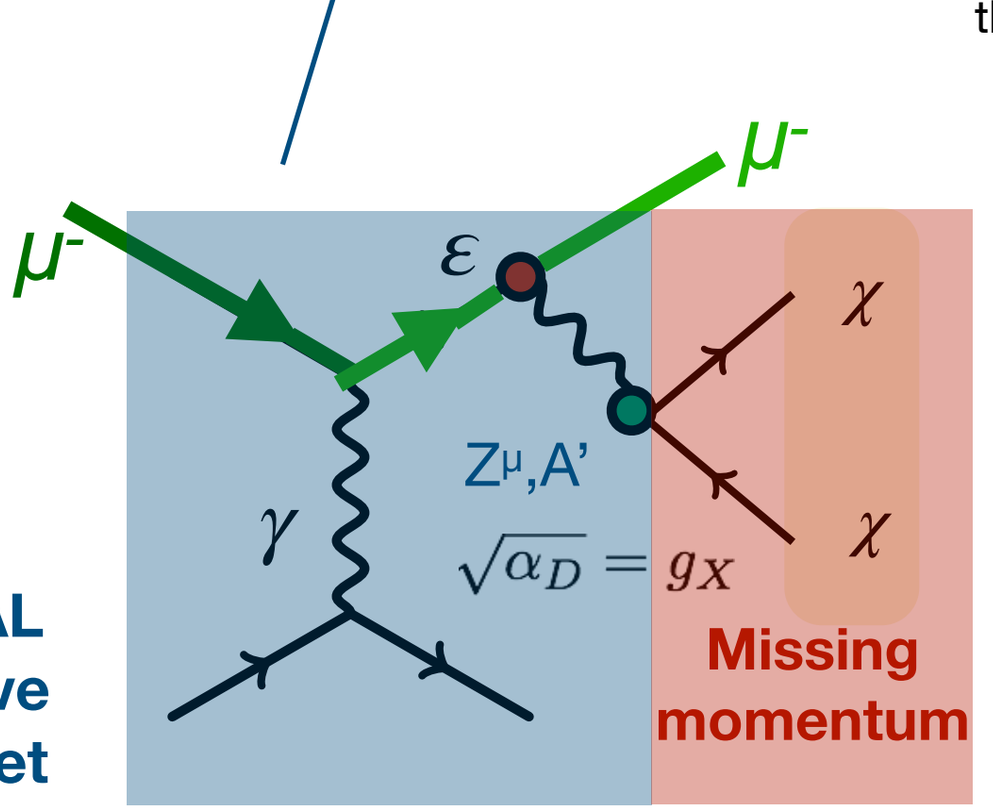
Location
@EHN2 M2 beam line

Goal: *Study the feasibility of the technique to look for a light Z' coupled to μ⁻*



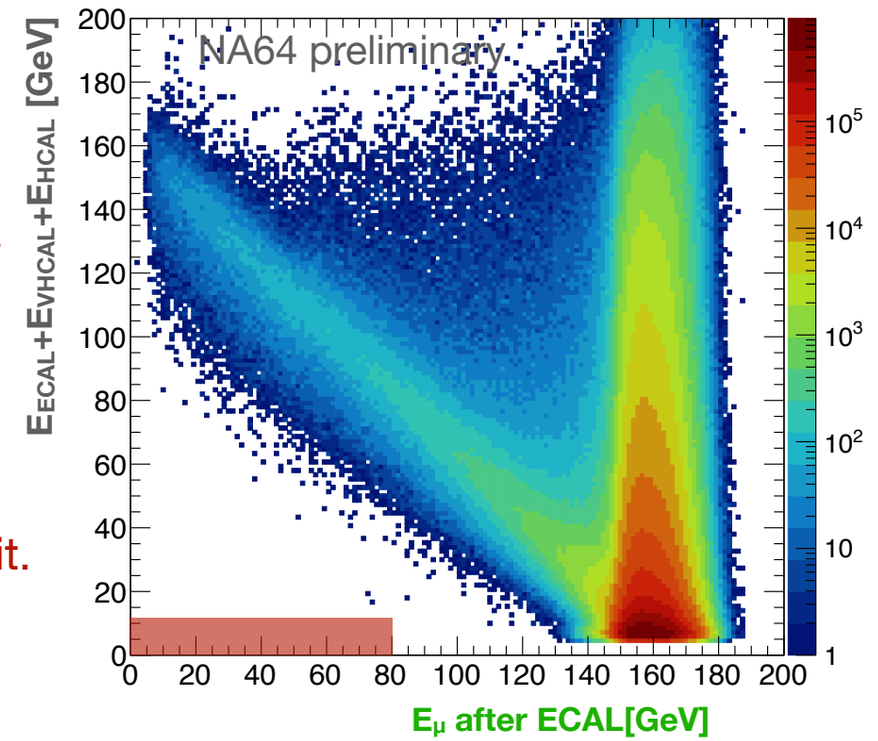
Magnet spectrometer (BMS stations from COMPASS experiment)

- Trigger based on scattered muon deflection.
- Incoming and outgoing μ momentum measured twice to minimise the level of its mis-measurements down to ≲10^{-12} .



Signature

- Missing momentum (Deflected μ- energy <80 GeV).
- Energy on ECAL, VHCAL and HCAL compatible with a muon energy deposit.



Zμ,A' decaying to DM particles

Summary and outlook

Dark sector physics interesting framework to explain dark matter

_NA64_ is an ideal experiment for testing benchmark scalar, Majorana and pseudo-Dirac thermal sub-GeV dark matter models

Future prospects for LDM searches before LHC long shutdown 3

- New area at H4 beamline and setup upgrade to run at high intensity
- **Main goal** to explore **LDM parameter space** with > **5x10^{12} EOT**
  - Start **searches of dark sectors weakly coupled to muons** with **NA64μ**:
    - $(g\text{-}2)_\mu$ *and* L_μ-L_τ *Z'*: **pilot run in 2021** at M2
    - Probing light dark matter parameter space for mA'> 100 MeV

Exploration of LDM with NA64 has just began.

Full physics potential to be exploited in the coming years!

THANKS!

Acknowledgements

NA64 collaboration in particular ***P.Crivelli*** and ***S.Gninenko***
ETH Zürich group in particular ***P. Crivelli, B.Banto, E. Depero, H.Sieber***

Swiss National Science Foundation

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The NA64 experiment and its physics program

	2021	2022	2023	2024	LS3
NA64e	*Invisible mode* 5 weeks 11th August	*Invisible mode* *Visible mode*	*Invisible mode* *Visible mode*	*Invisible mode* *Visible mode*	
NA64μ	Pilot run 19 days October	1st physics run			

Broad physics program →

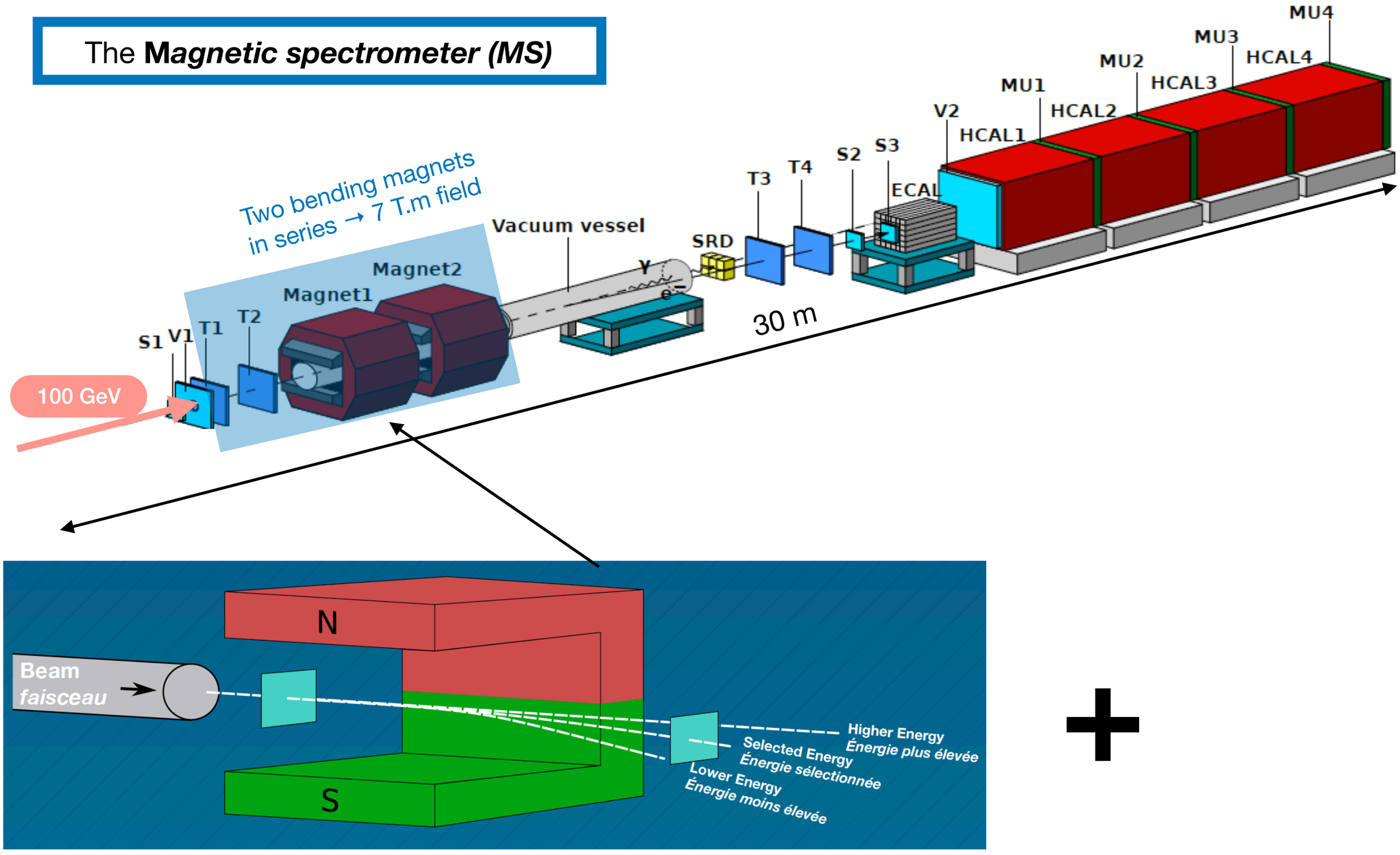
Process	New Physics
e^- **beam**	
$A' \to e^+e^-$, and $A' \to invisible$	Dark photon
$A' \to \chi\overline{\chi}$	sub-GeV Dark Matter (χ)
$X \to e^+e^-$	new gauge X- boson
milliQ particles	Dark Sector, charge quantisation
$a \to \gamma\gamma, invisible$	Axion-like particles
μ^- **beam**	
$Z_\mu \to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

International collaboration: 50 researchers from 16 institutions

CERN-PBC-REPORT-2018-007

NA64 *invisible* searches: the setup

The ***Magnetic spectrometer (MS)***



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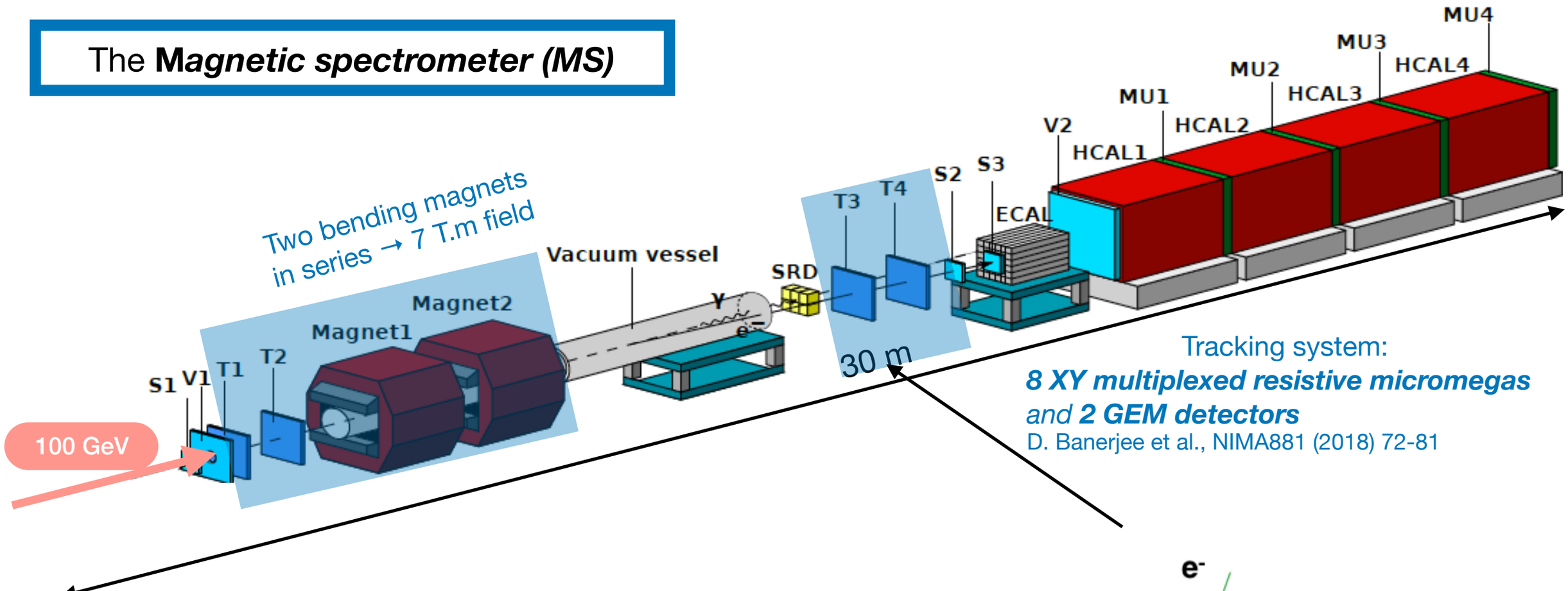
NA64 *invisible* searches: the setup

The **Magnetic spectrometer (MS)**



Tracking system:

8 XY multiplexed resistive micromegas
and ***2 GEM detectors***

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

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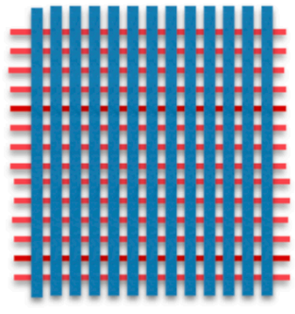
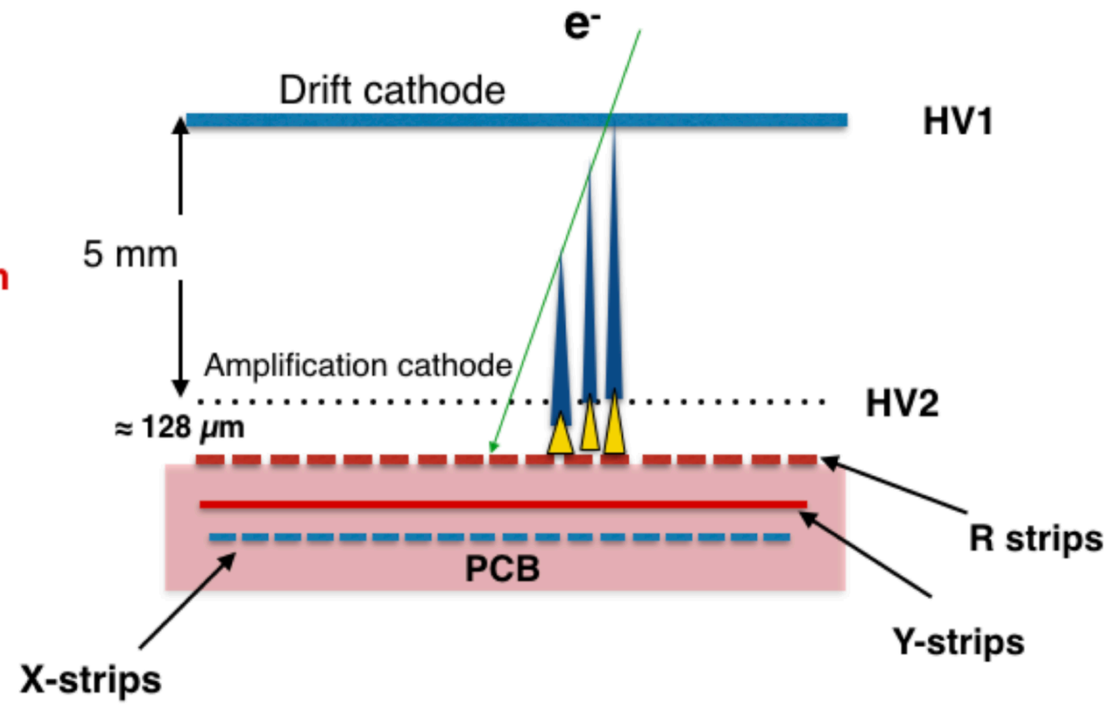
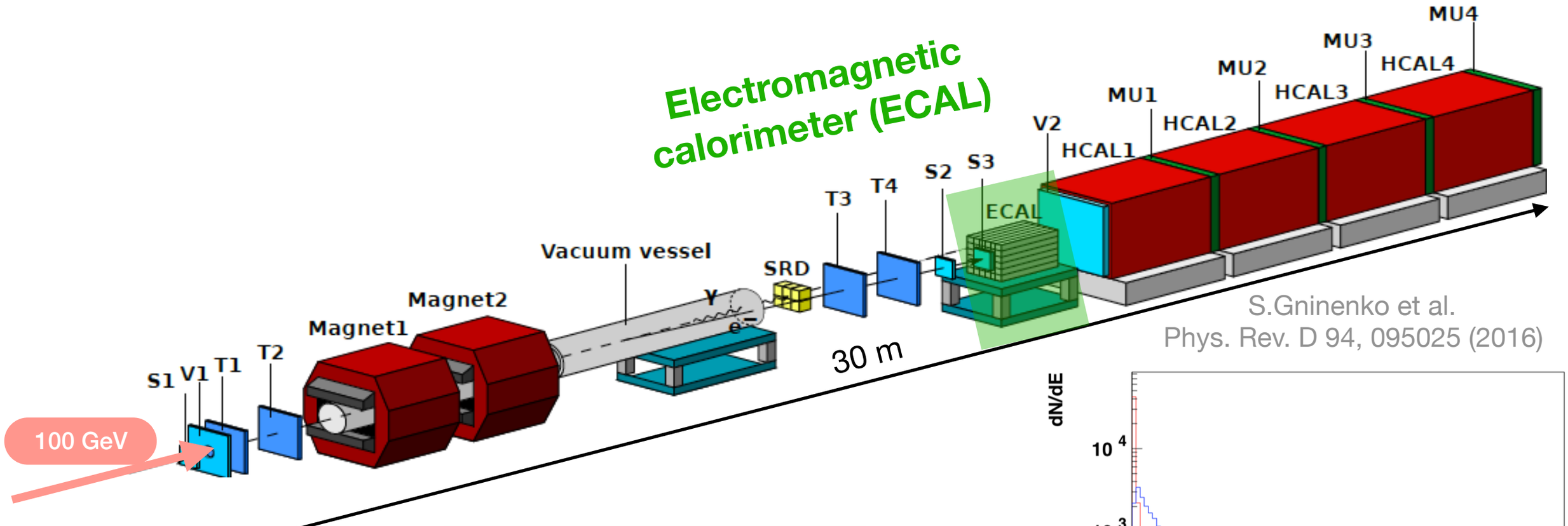


Y: 250/50 μm

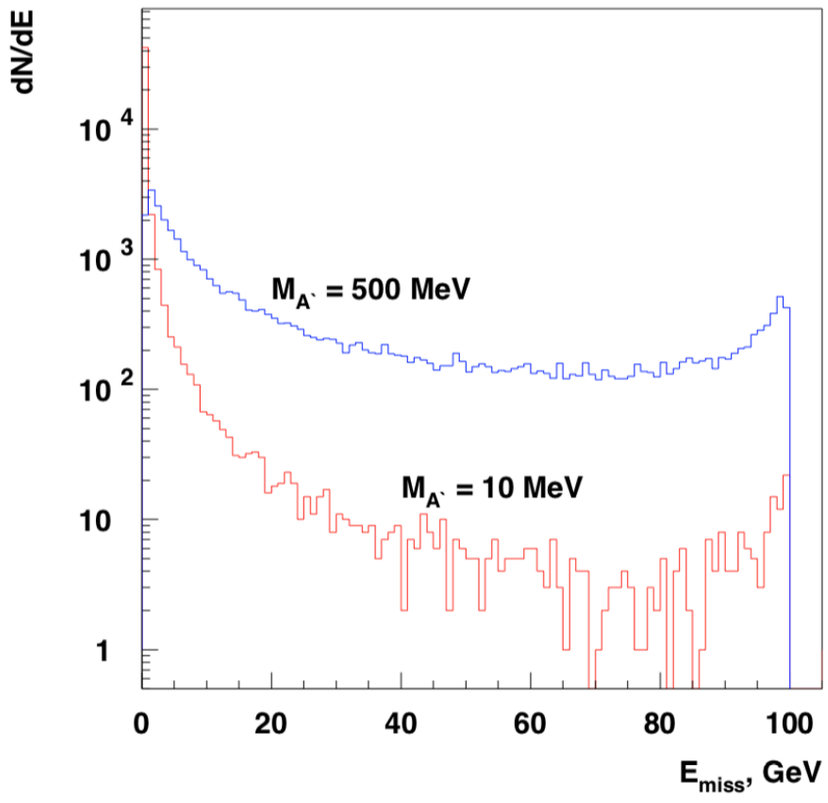
X : 250/200 μm
R : 250/200 μm



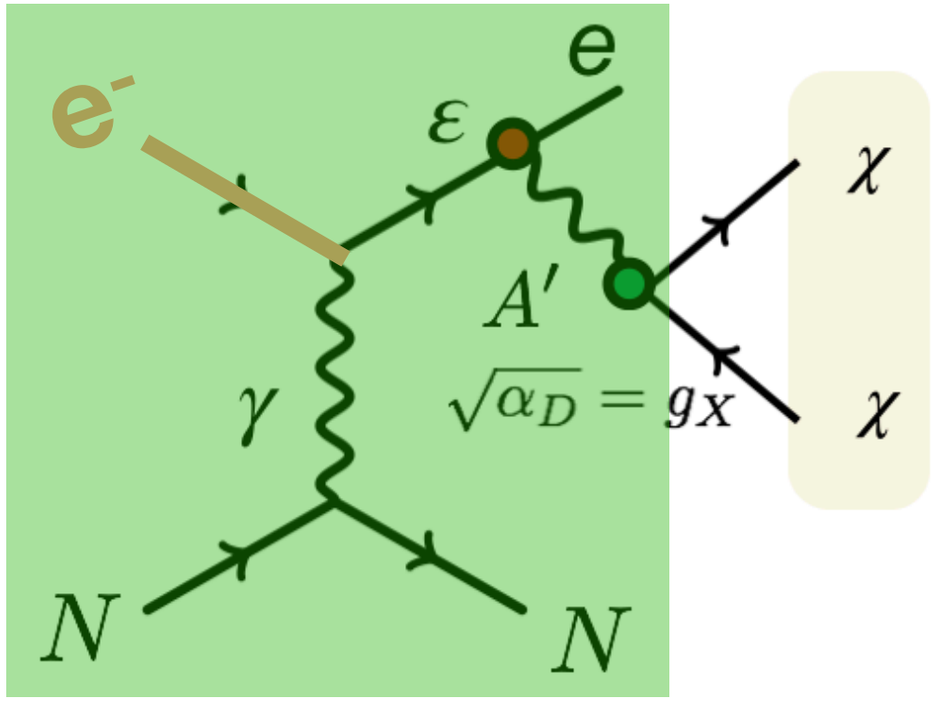
NA64 *invisible* searches: the setup



S.Gninenko et al.
Phys. Rev. D 94, 095025 (2016)

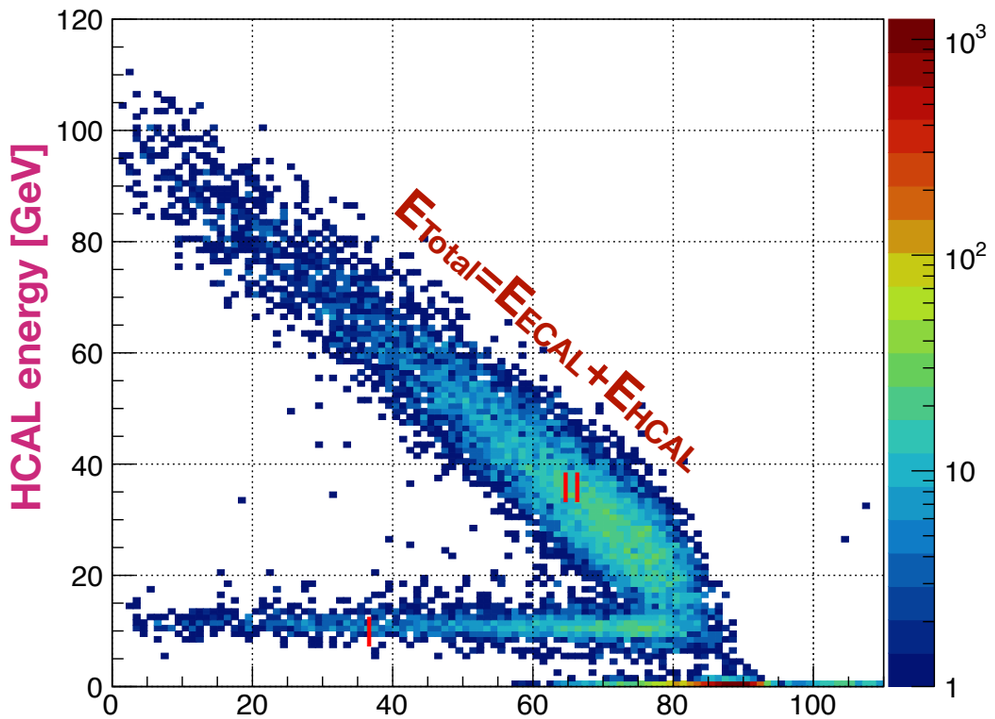


Active target



Bremsstrahlung of A'

NA64 *invisible* searches: results



Full 2016-2018 data:
2.84×10^{11} EOT

➡ **Region I:** e- Z → e-Zγ; γ → μ+μ-
→ benchmark for MC

➡ **Region II:** SM events
$E_{ECAL} + E_{HCAL} \simeq 100$ GeV

Event Selection Criteria:

- *Timing information* → Pile up and noise suppression.
- *Clean incoming track:* angle + single hit in all trackers, momentum~100 GeV
- *Electron identification:*
  - Synchrotron radiation
  - Shower profile compatible with e^- in ECAL → Hadron suppression
- *No punchthrough:* No activity in Veto and in HCAL