Semi-visible dark photons at the NA64 experiment

SPS - ÖPG Joint Annual Meeting

Martina Mongillo, Group of Prof. Paolo Crivelli
on behalf of the *NA64 Collaboration*

07.09.2023

DARK SECTORS

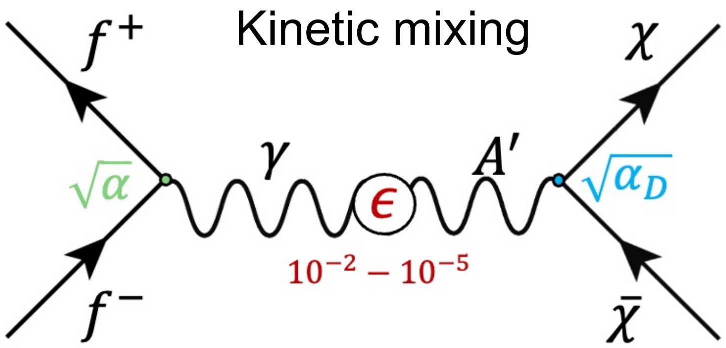
Dark particles could interact via **new feeble interactions**, generating portal connections with the SM

Renormalizable portals:

- **Vector portal → dark photon**
- Scalar portal → dark Higgs
- Fermion portal → heavy neutral leptons

Vector portal: addition of new $U(1)_D$ symmetry to the SM gauge group

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



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Motivations: known gaps in SM + experimental anomalies

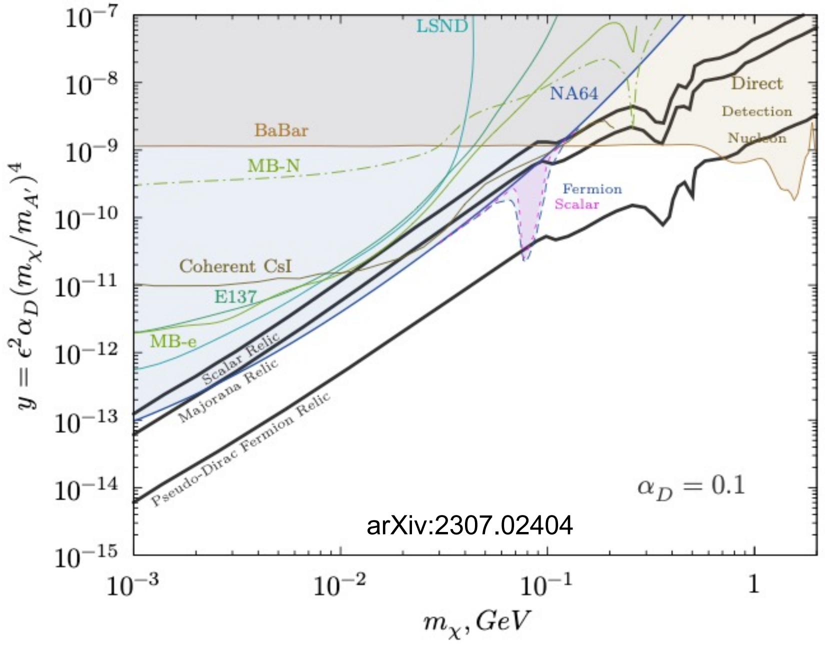
- Sub-GeV thermal dark matter
- Neutrino masses generation
- Muon $(g-2)_\mu$ anomaly

DM abundance

$$\Omega_\chi \propto \frac{1}{<\sigma v>} \approx 0.24$$

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

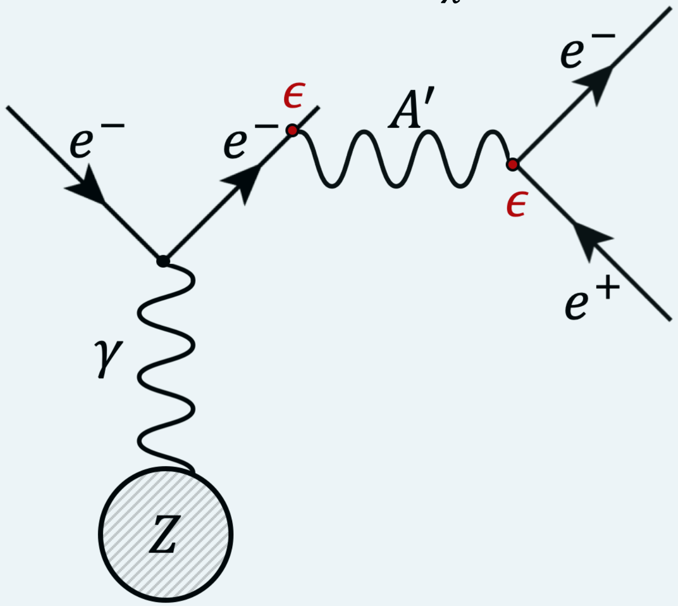
Latest NA64 results



Two main scenarios

Visible decay mode

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



Invisible decay mode

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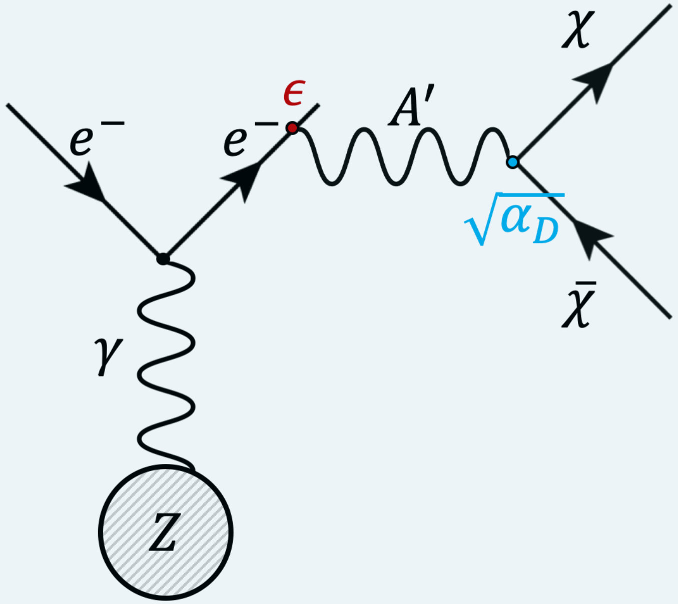

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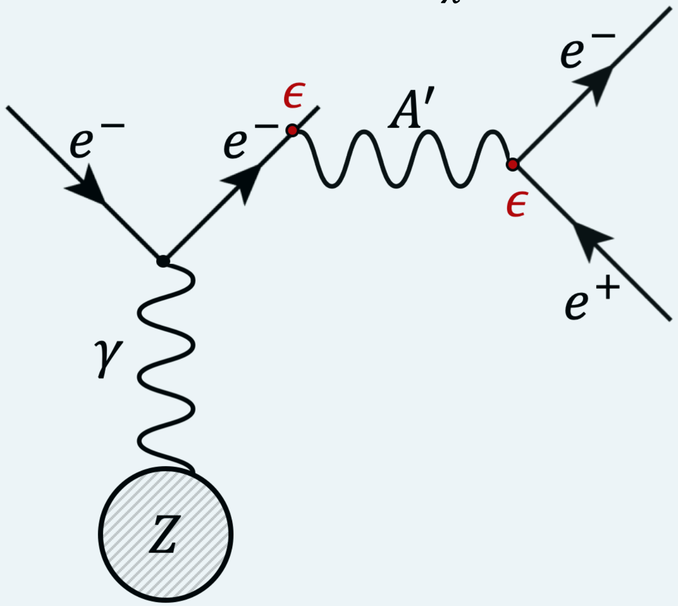

Signature: SM particle pair production

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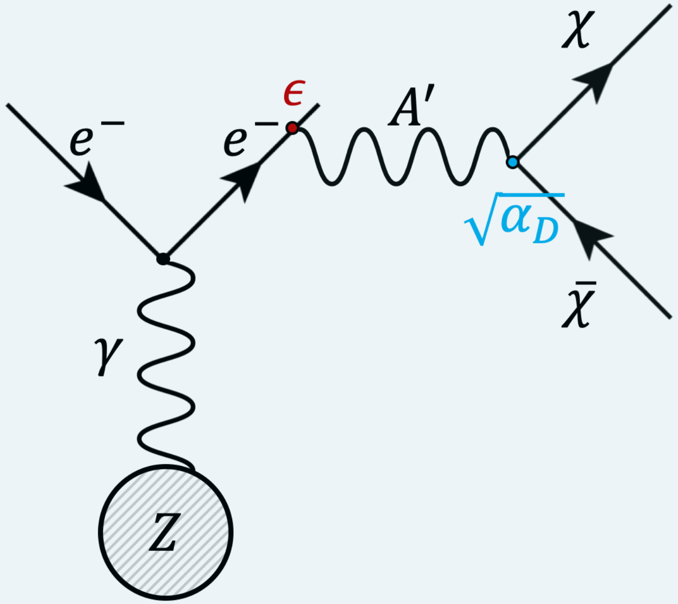
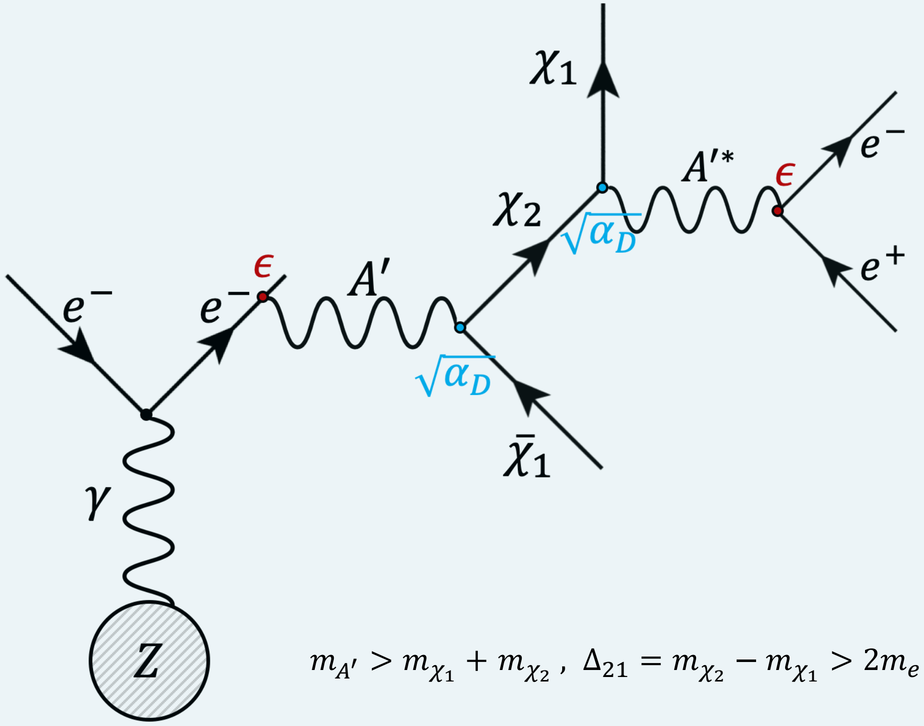


Signature: Missing energy

Next-to-minimal models: semi-visible decay

- Richer dark sectors can be populated by multiple fermions:

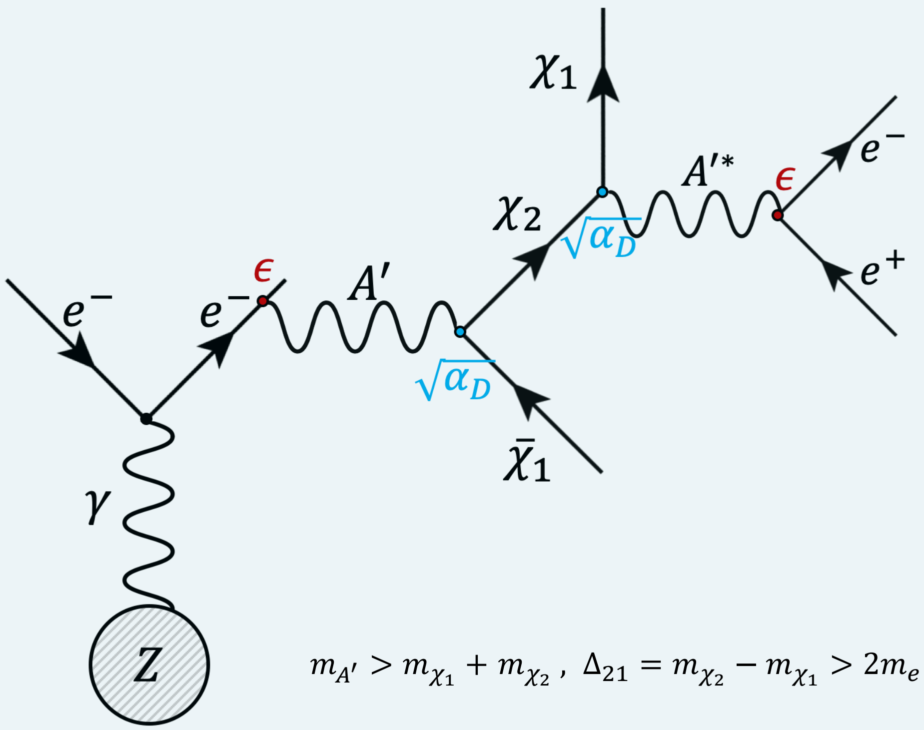


$m_{A'} > m_{\chi_1} + m_{\chi_2}$, $\Delta_{21} = m_{\chi_2} - m_{\chi_1} > 2m_e$

Visible + invisible final states
→ **semi-visible A'**

NEXT-TO-MINIMAL MODELS: SEMI-VISIBLE DECAY

- Richer dark sectors can be populated by multiple fermions:



$m_{A'} > m_{\chi_1} + m_{\chi_2}$, $\Delta_{21} = m_{\chi_2} - m_{\chi_1} > 2m_e$

Signature: SM pair production + missing energy

Visible + invisible final states
→ **semi-visible A'**

NEXT-TO-MINIMAL MODELS: SEMI-VISIBLE DECAY

Inelastic Dark Matter (iDM)

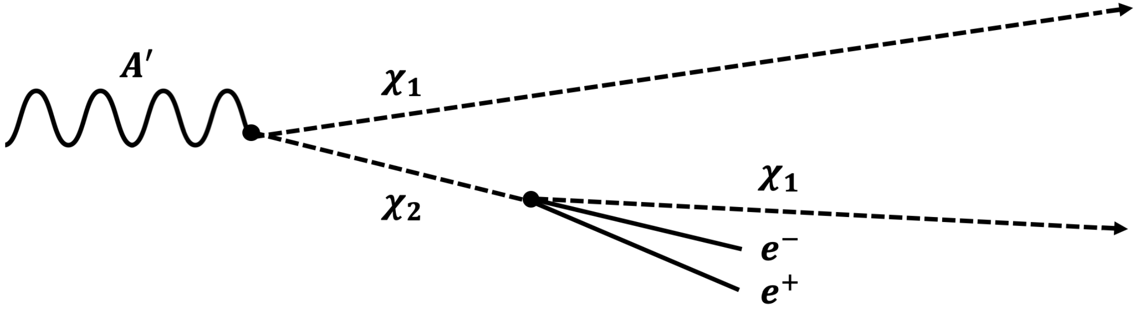
Izaguirre et al.
PRD 96, 055007 (2017)
Mohlabeng
PRD 99, 115001 (2019)
Duerr et al.
JHEP 02 039 (2020)

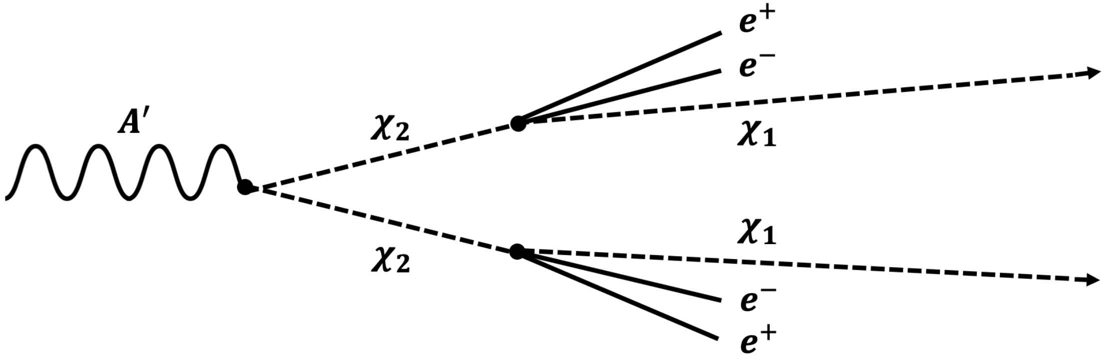
- χ_1 and χ_2 form a **pseudo-Dirac** pair
- Only **off-diagonal** couplings to A':
  $A' \to \chi_1\chi_2$
- Freeze-out through **co-annihilation**
  $\chi_1\chi_2 \to A'^* \to f^+f^-$
  → no CMB bounds

Inelastic Dirac Dark Matter (i2DM)

Filimonova et al.
JHEP 06, 048 (2022)
Abdullahi et al.
arXiv:2302.05410

- χ_1 and χ_2 are **exact Dirac** fermions
- Both **diagonal** and **off-diagonal** interactions:
  $A' \to \chi_i\chi_j,\ i,j \in \{1,2\}$
  → Mixing angle θ determines couplings
- Freeze-out through **co-annihilation**, **co-scattering** and **self-annihilation**
  →Small θ weakens CMB bounds





THE NA64 EXPERIMENT - OVERVIEW

- **Fixed-target** experiment at CERN SPS (intensity frontier)
- High-purity **100 GeV e⁻** beam (H4 beamline)
- Explores **Dark Sectors in the MeV-GeV** scale
- **Active beam-dump** technique + **missing energy** search
  → signal detection relies only on A' *production* $\propto \epsilon^2$

	2016-2018	2021	2022	2023
NA64e	Invisible mode $2.84 \cdot 10^{11}$ EOT	Invisible mode $6 \cdot 10^{10}$ EOT	Invisible mode $6.3 \cdot 10^{11}$ EOT	Invisible mode $5.1 \cdot 10^{11}$ EOT
	Visible mode $8.4 \cdot 10^{10}$ EOT			

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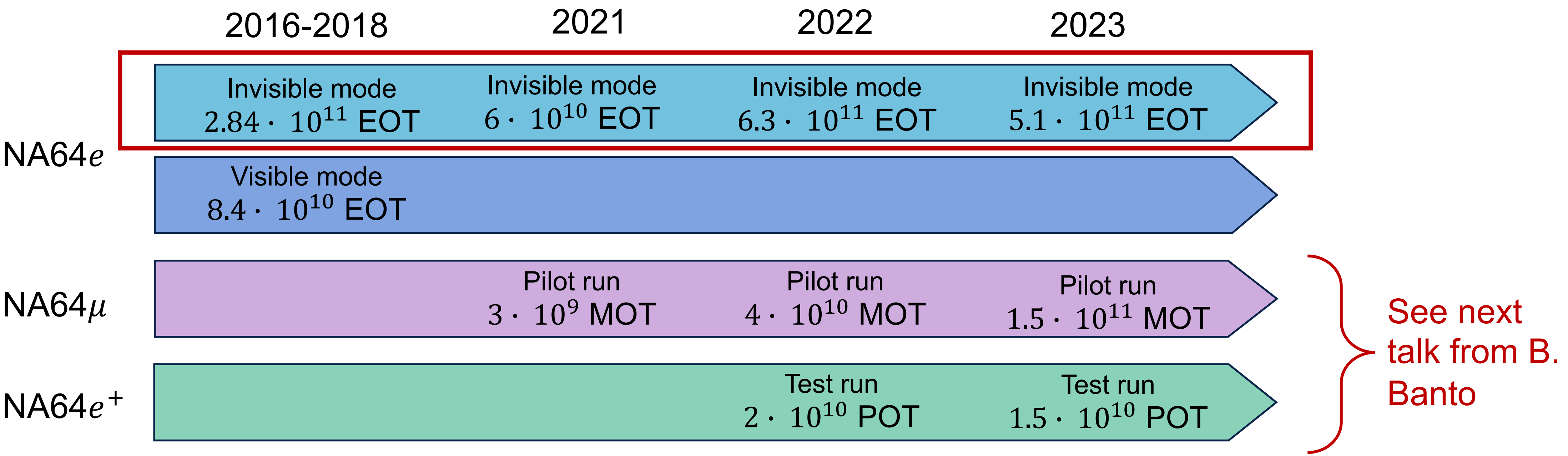
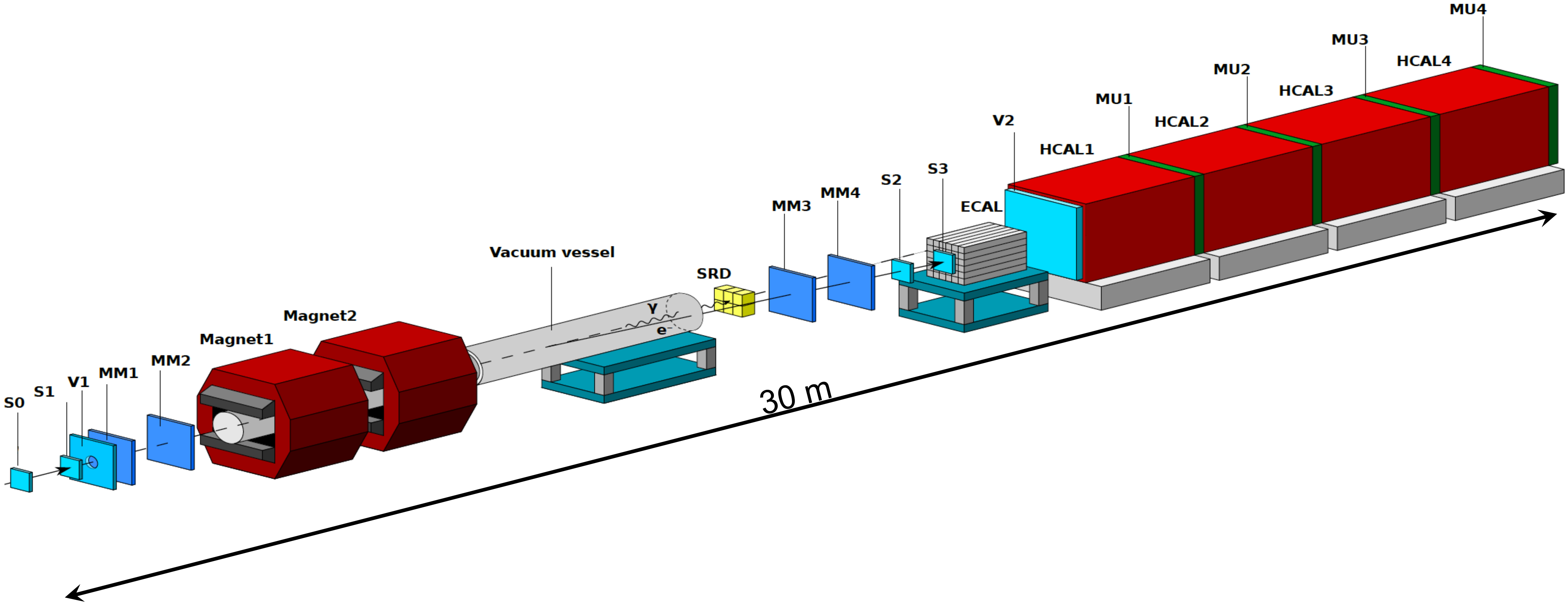
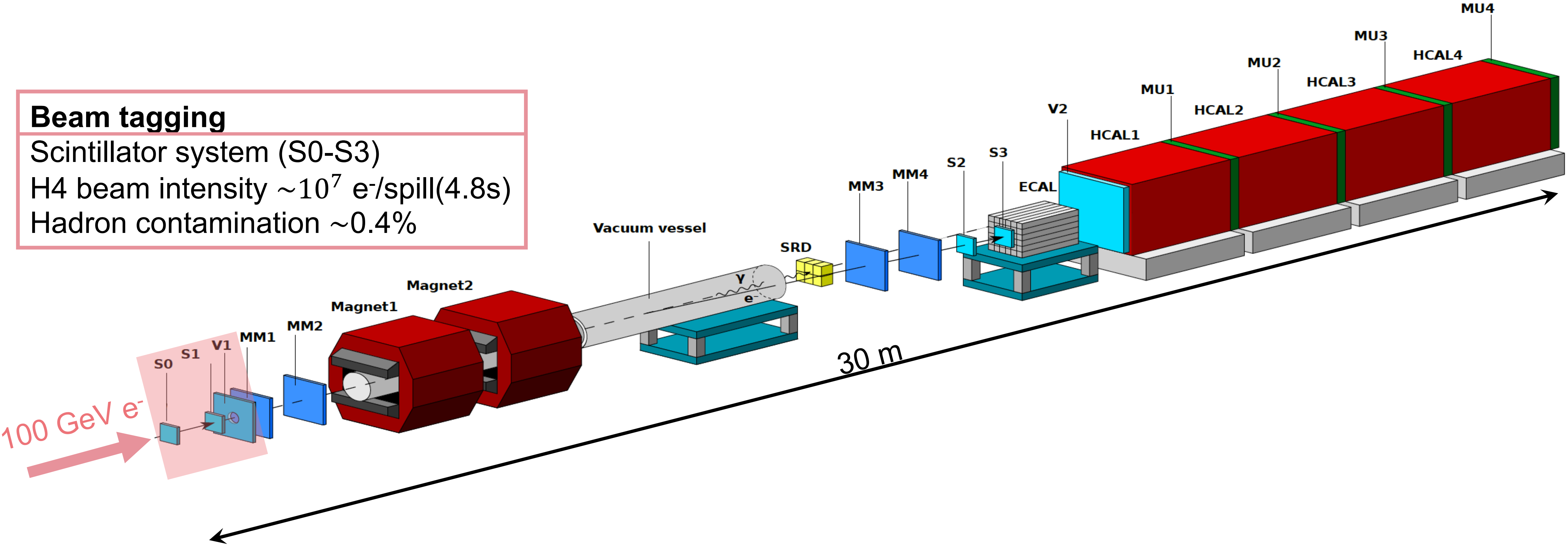


The NA64 setup



THE NA64 SETUP

Beam tagging
Scintillator system (S0-S3) H4 beam intensity ~10^7 e^-/spill(4.8s) Hadron contamination ~0.4%



THE NA64 SETUP

Momentum reconstruction

Tracking system

- 2 bending magnets (7 Tm)
- 4 Micromegas + 2 GEM detectors

Beam tagging

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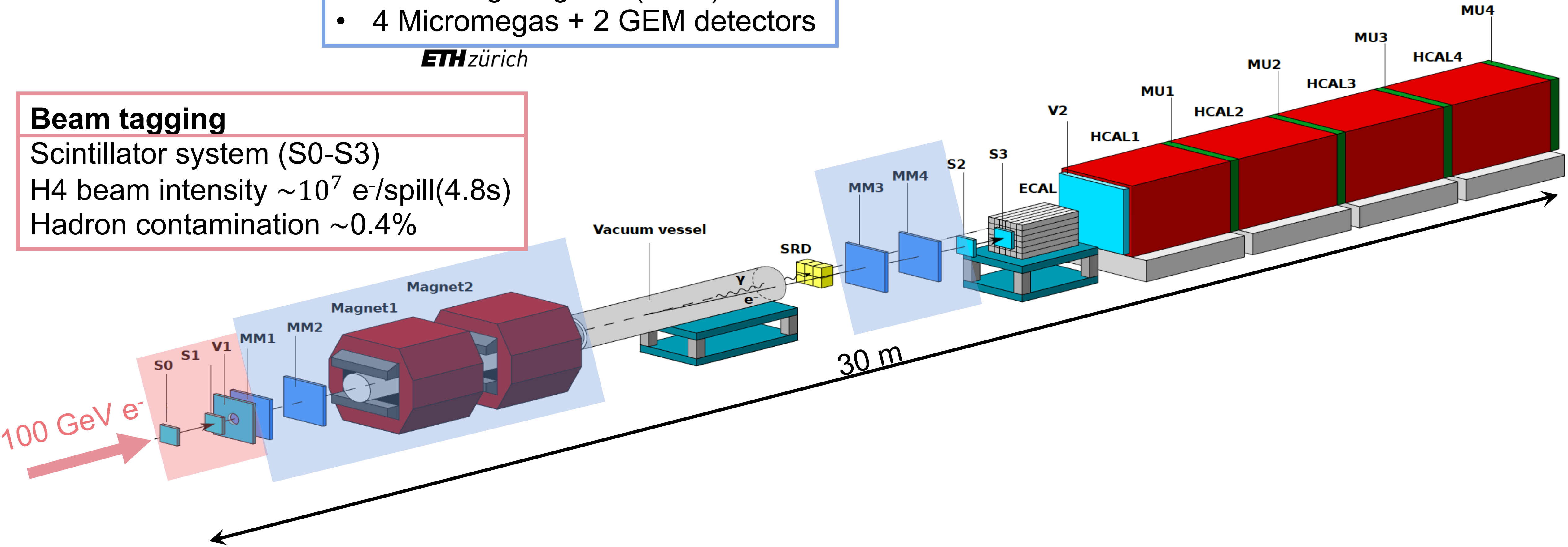

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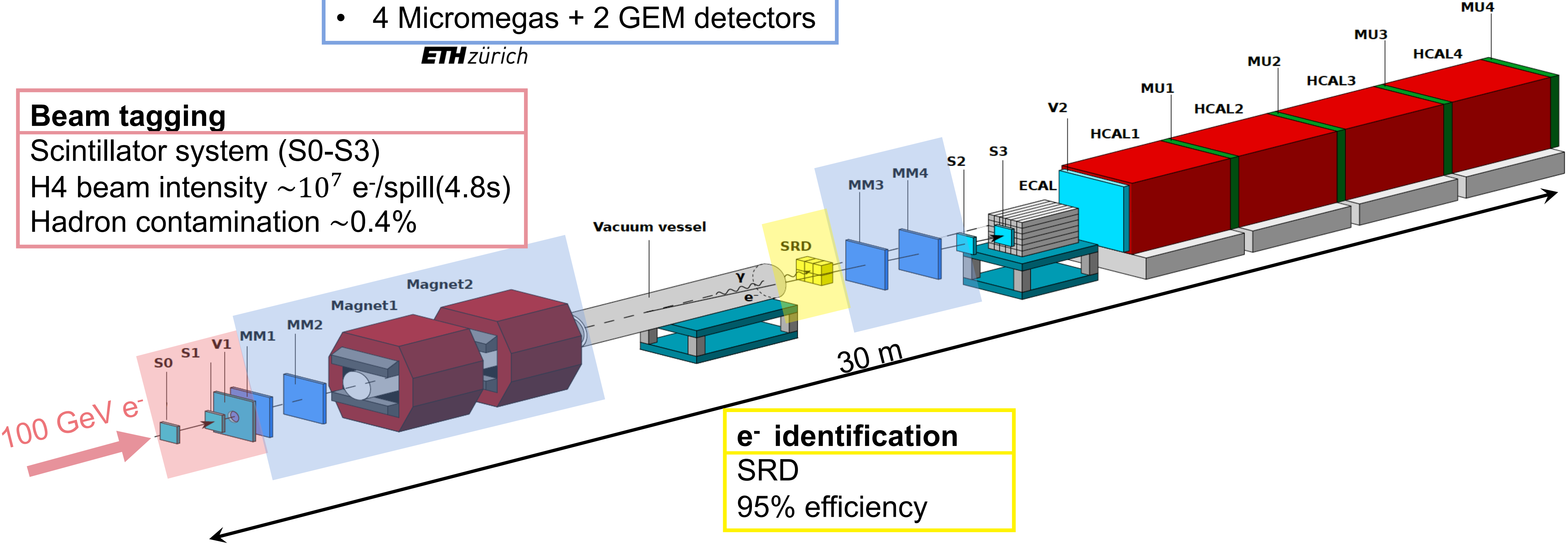

e⁻ identification

SRD
95% efficiency

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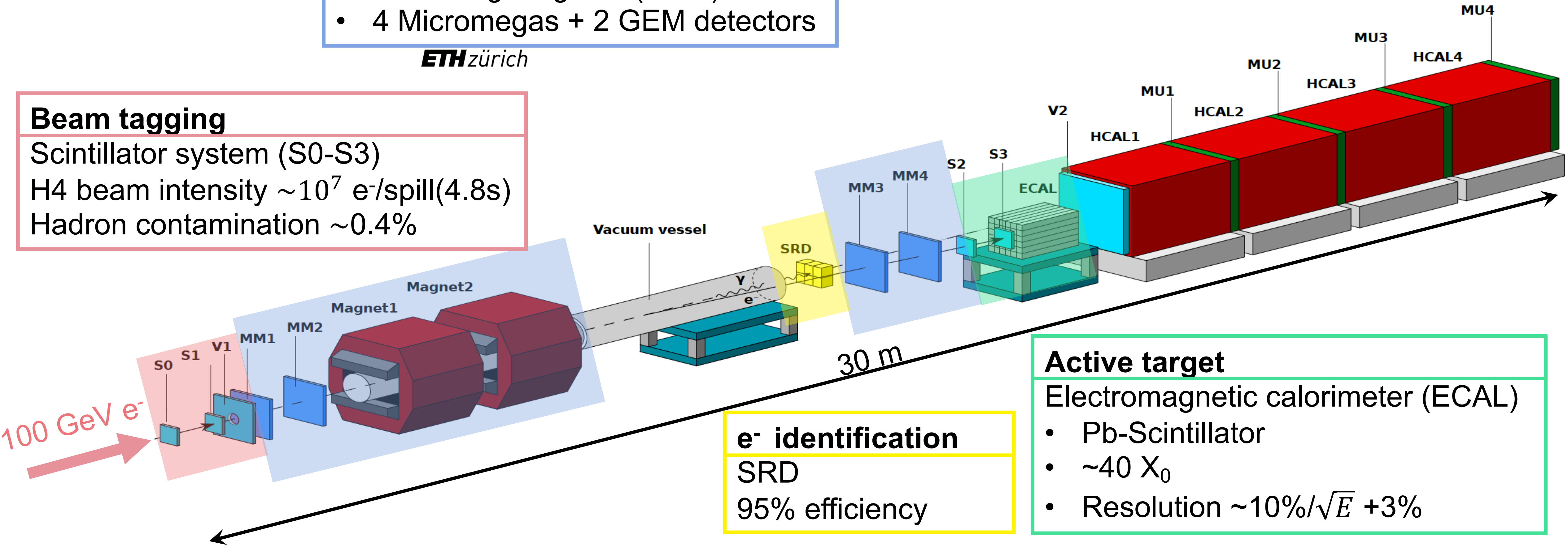

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Active target

Electromagnetic calorimeter (ECAL)
- Pb-Scintillator
- ~40 X_0
- Resolution ~10%/$\sqrt{E}$ +3%

The NA64 setup

Momentum reconstruction

Tracking system
- 2 bending magnets (7 Tm)
- 4 Micromegas + 2 GEM detectors

Hermeticity

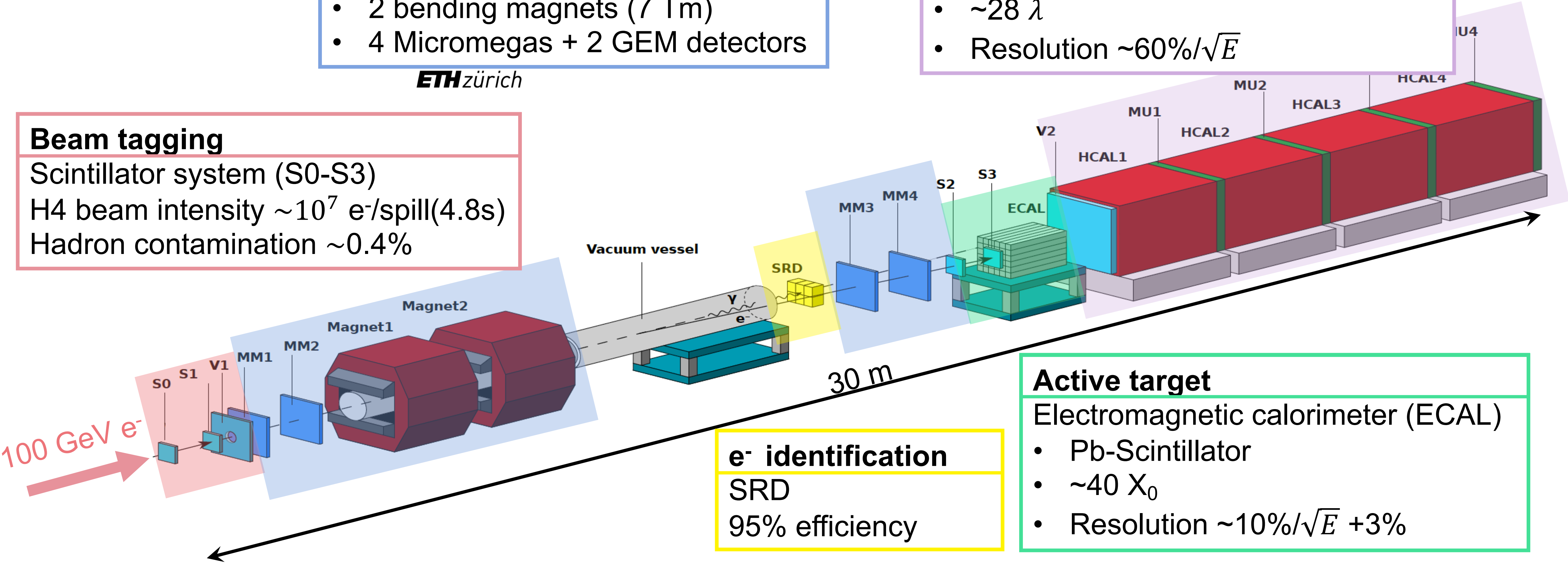
Veto + Hadronic calorimeter (HCAL)
- Fe-Scintillator
- ~28 λ
- Resolution ~60%/$\sqrt{E}$

Beam tagging

Scintillator system (S0-S3)

H4 beam intensity $\sim 10^7$ e^-/spill(4.8s)

Hadron contamination ~0.4%



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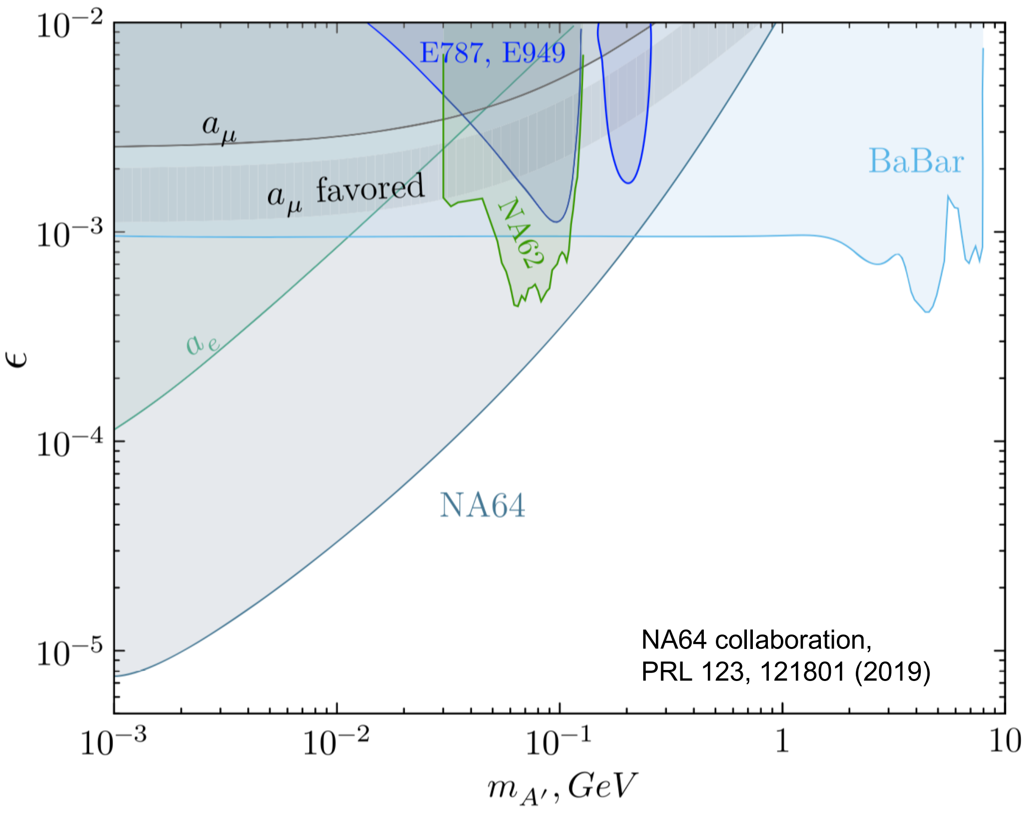
SEMI-VISIBLE RECAST ANALYSIS

- Event selection:
  - Well-defined 100 GeV e⁻
  - Missing energy
  - No activity in VETO and HCALs

Signal region: $ECAL < 50$ GeV, $HCAL < 1$ GeV

- Signal MC: Bremsstrahlung A' production, grid simulations using Geant4 and DMG4 M. Bondi et al. CPC 269, 108129 (2021)
- Constraints: 90% C.L. exclusion limits, background-free hypothesis (~0.5 expected bkg)

Data collected in 2016-2018 (2.84$\cdot 10^{11}$ EOT)



Recasted on iDM and i2DM

SEMI-VISIBLE RECAST ANALYSIS

Difference w.r.t. invisible scenario: e^-e^+ **visible energy deposit**

$$\Gamma(\chi_2 \to \chi_1 f\bar{f}) \sim \frac{4\epsilon^2 \alpha \alpha_D \Delta^5}{15\pi m_{A'}^4} \qquad \tau_{\chi_2} \propto \frac{1}{\varepsilon^2 m_{A'}}$$

→ Depending on the parameter settings, **3 main regimes** can be distinguished:

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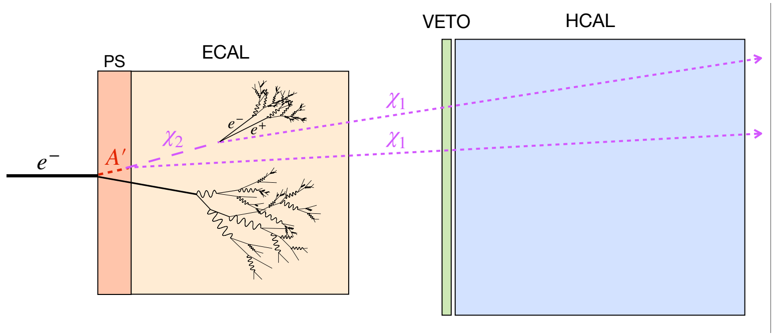
χ_2 decay point

Within ECAL

Reduced missing E



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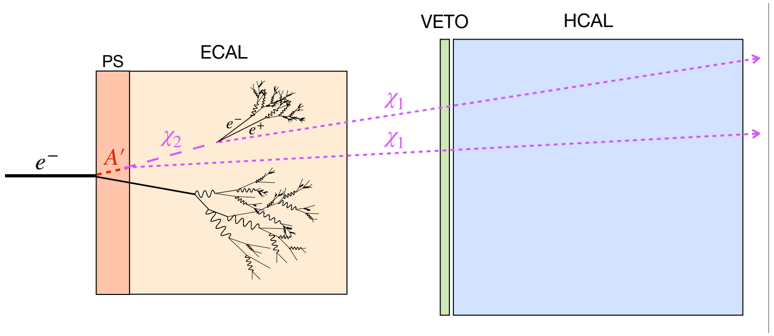
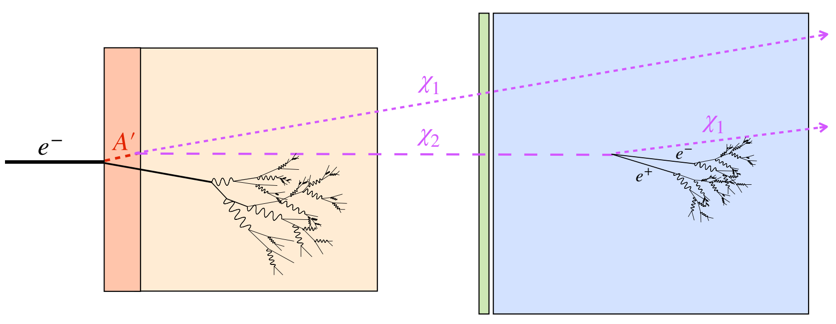
- Within ECAL → Reduced missing E
- ECAL end – setup end → Vetoed event





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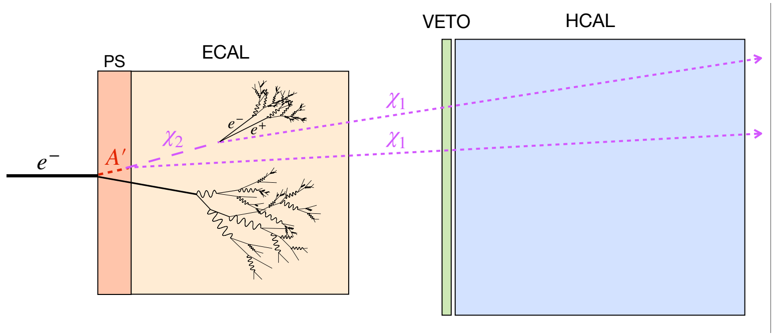
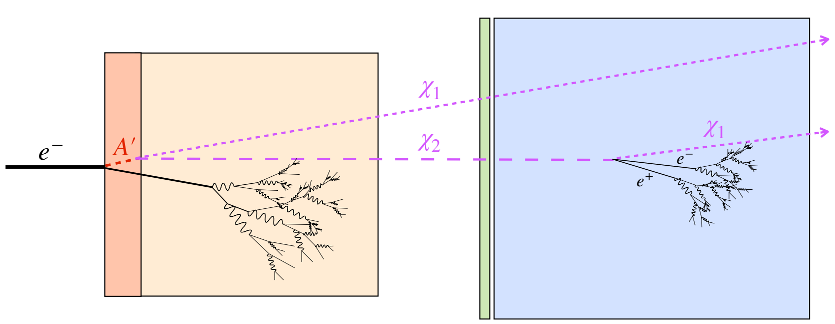
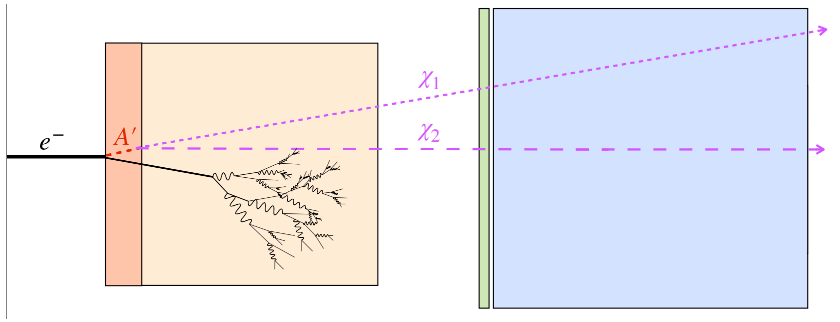
→ Depending on the parameter settings, **3 main regimes** can be distinguished:

χ_2 decay point

- Within ECAL → Reduced missing E
- ECAL end – setup end → Vetoed event
- Beyond setup → Mimics invisible event

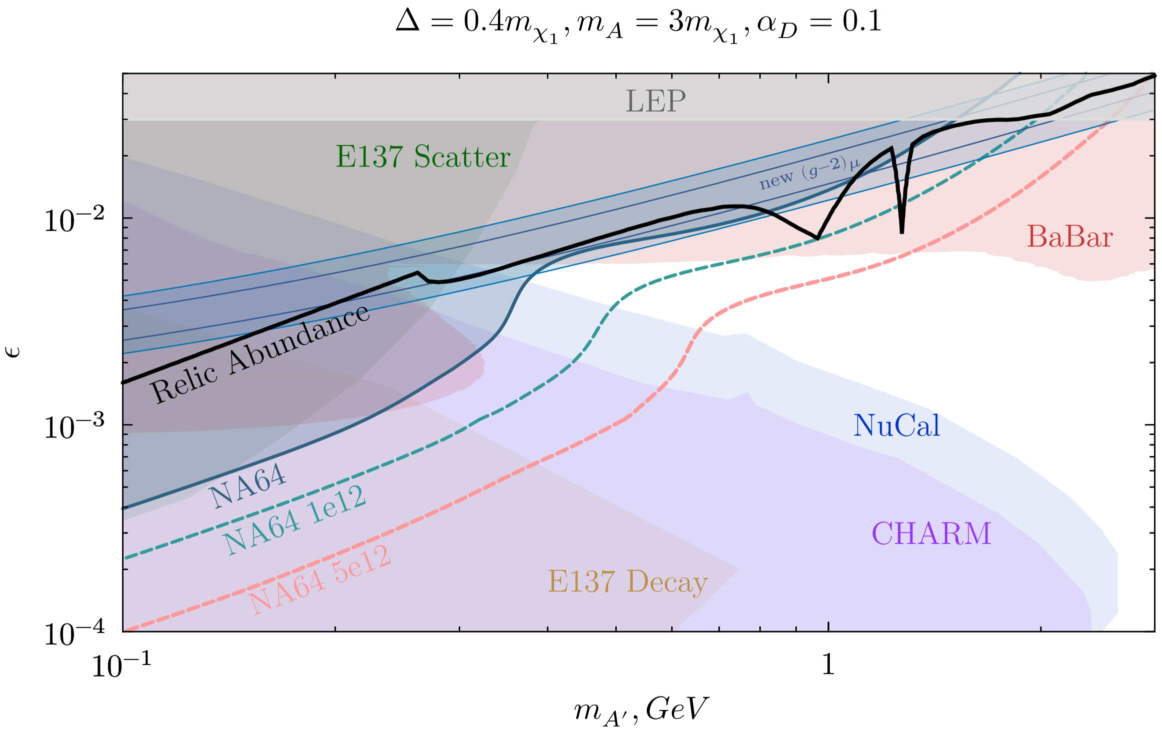




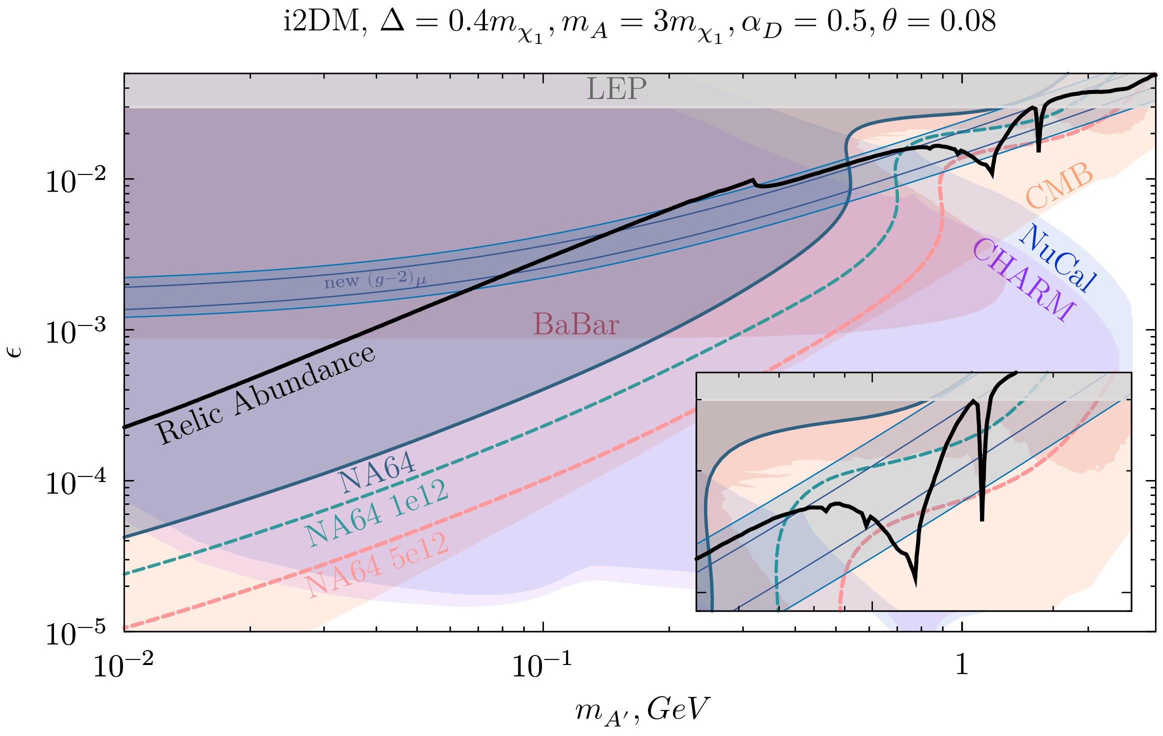


Results - focus on $(g-2)_\mu$

iDM



i2DM

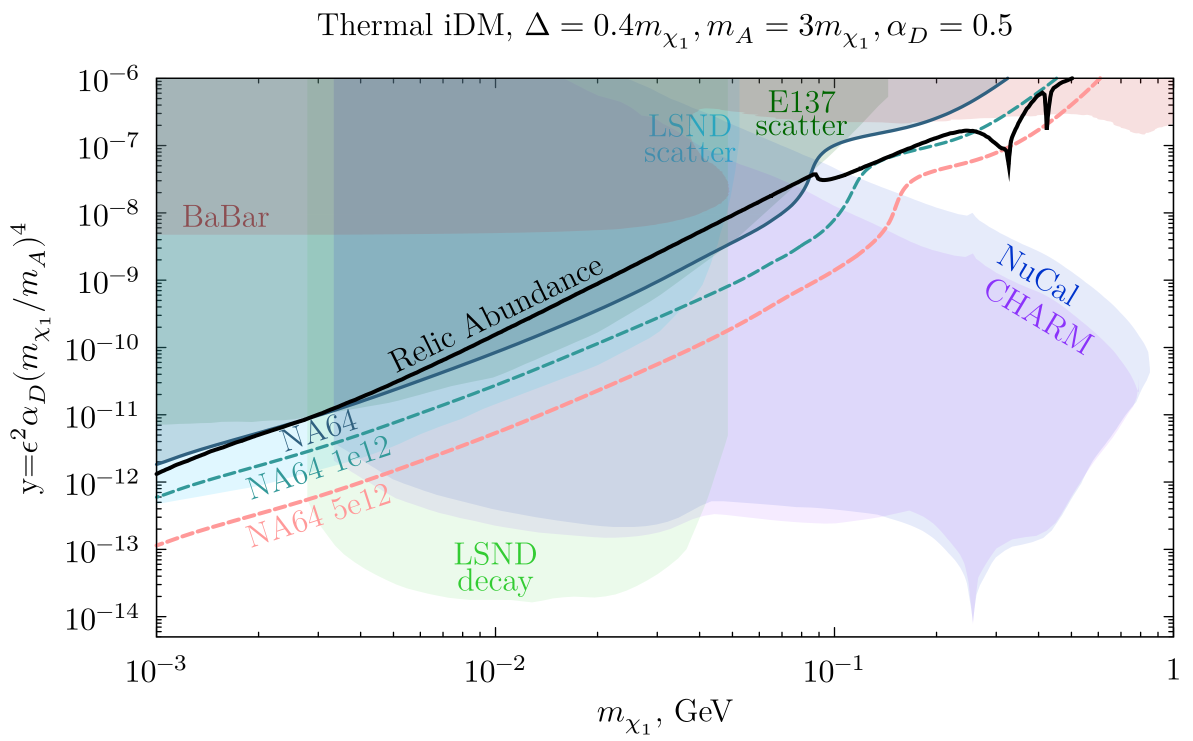


Both iDM and i2DM **are excluded** as viable explanation of the $(g-2)_\mu$ anomaly

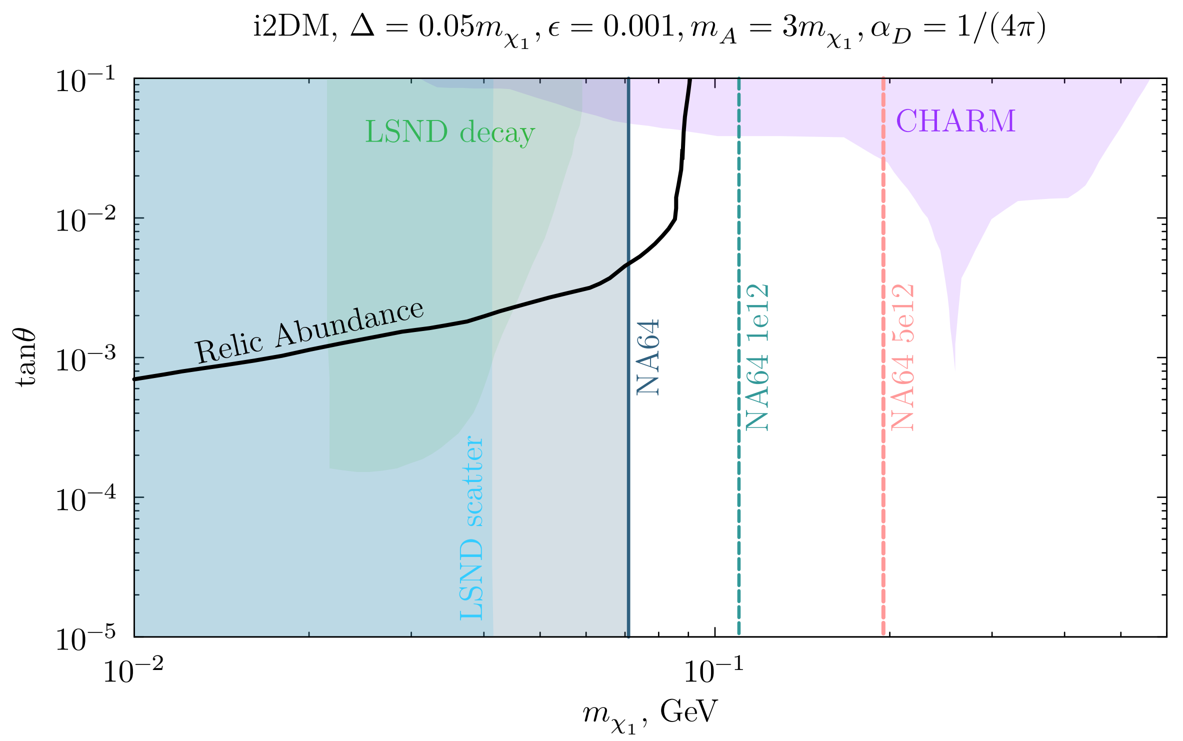
M. Mongillo et al.,
EPJ C 83, 391 (2023)

RESULTS

iDM



i2DM



Some relic target region remains to be probed for both models

→ With increased statistics NA64 can reach wide coverage of the DM targets

M. Mongillo et al.,
EPJ C 83, 391 (2023)

ETH zürich IPA Swiss National Science Foundation

CONCLUSIONS AND OUTLOOK

- NA64 is a **powerful probe** of semi-visible dark photons
- **New limits** were obtained on regions of parameter space characterized by prompt χ_2 decays
- Most of the parameter space favoured for $(\boldsymbol{g-2})_{\boldsymbol{\mu}}$ **discrepancy has been excluded** for both the iDM and i2DM
- With the statistics expected before LS3, **NA64 can test the thermal targets** for iDM and i2DM in MeV-GeV range

Conclusions and outlook

- NA64 is a **powerful probe** of semi-visible dark photons
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What is next?

- Analysis of the 2022 data (6.3 $\cdot 10^{11}$ EOT) combining invisible and displaced vertex search → ongoing
- Analysis of the 2023 data (5.1 $\cdot 10^{11}$ EOT) → ongoing
- Inclusion of the A' resonant annihilation production
- Extension to other semi-visible models (e.g. HNL models Abdullahi et al. arXiv:2302.05410)

Thank you!

Acknowledgments

NA64 collaboration
ETH Zürich group: P. Crivelli, B. Banto Oberhauser, E. Depero, H.Sieber
IFIC group: L. Molina Bueno, M. Tuzi
A. Abdullahi, M. Hostert, D. Massaro, S. Pascoli

Funded by ETH Zürich Grant 22-2 ETH-031 and SNSF Grants No. 169133, 186181, 186158, 197346

BACKUP SLIDES

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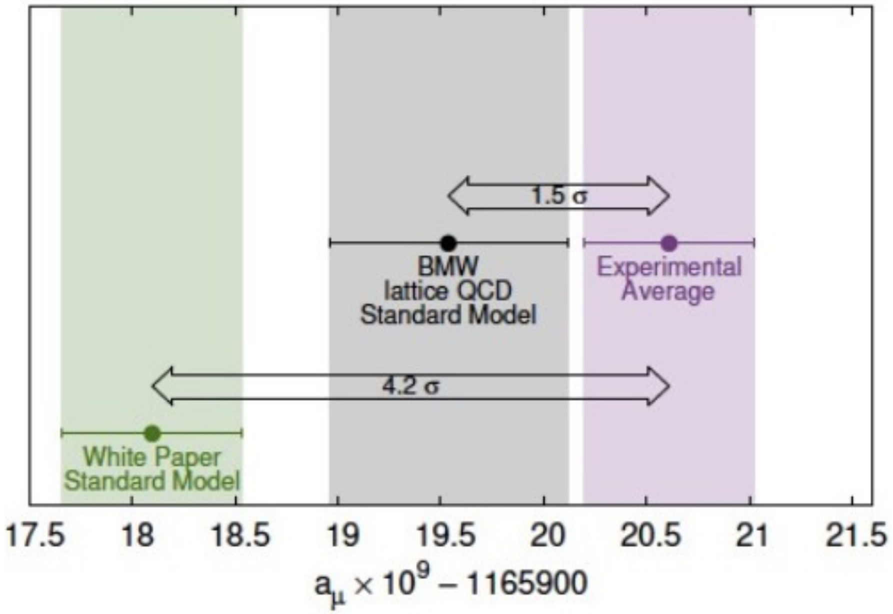
$\mathcal{L}_{A'}$ $\mathcal{L}_{kin}$ $\mathcal{L}_{\chi\chi}$

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

2002: E821 experiment at BNL → 3.7σ discrepancy
2021: E989 experiment at FNAL → increased discrepancy to 4.2σ
Next: experiment at J-PARC

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

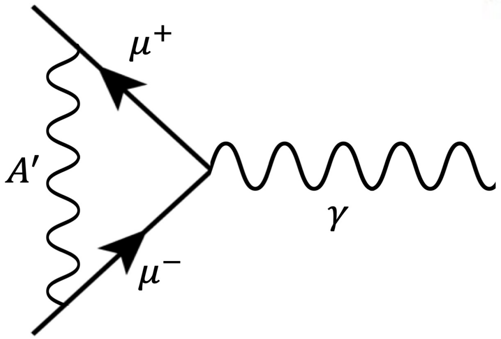


SM prediction: $a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{Had}$
→ data-driven traditional method
→ lattice QCD

2.1σ

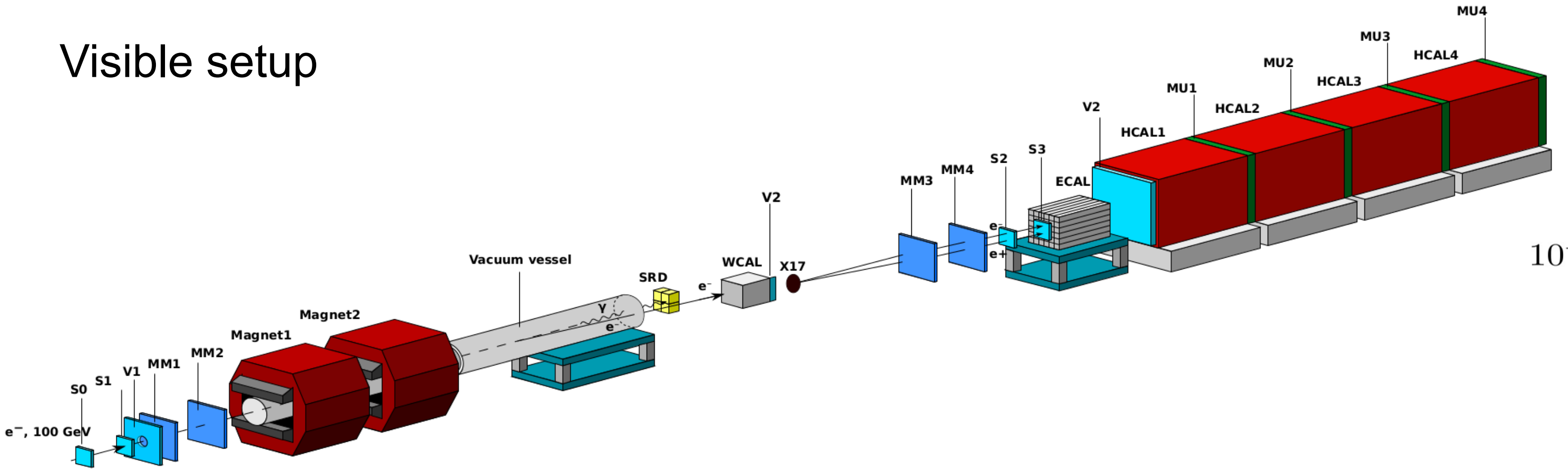
Dark photon contribution:

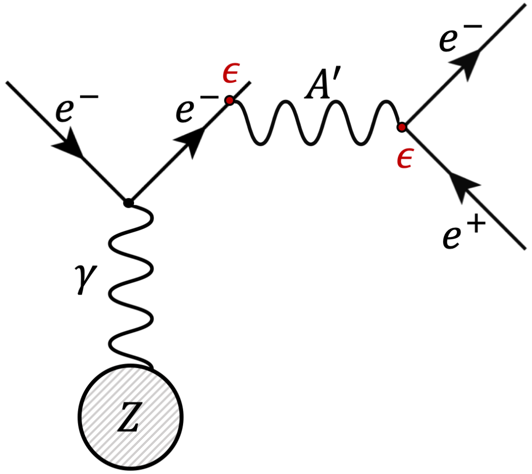
$$a_\mu^{A'} = \frac{\alpha}{2\pi}\varepsilon^2 F\left({m_{A'}}/{m_\mu}\right)$$

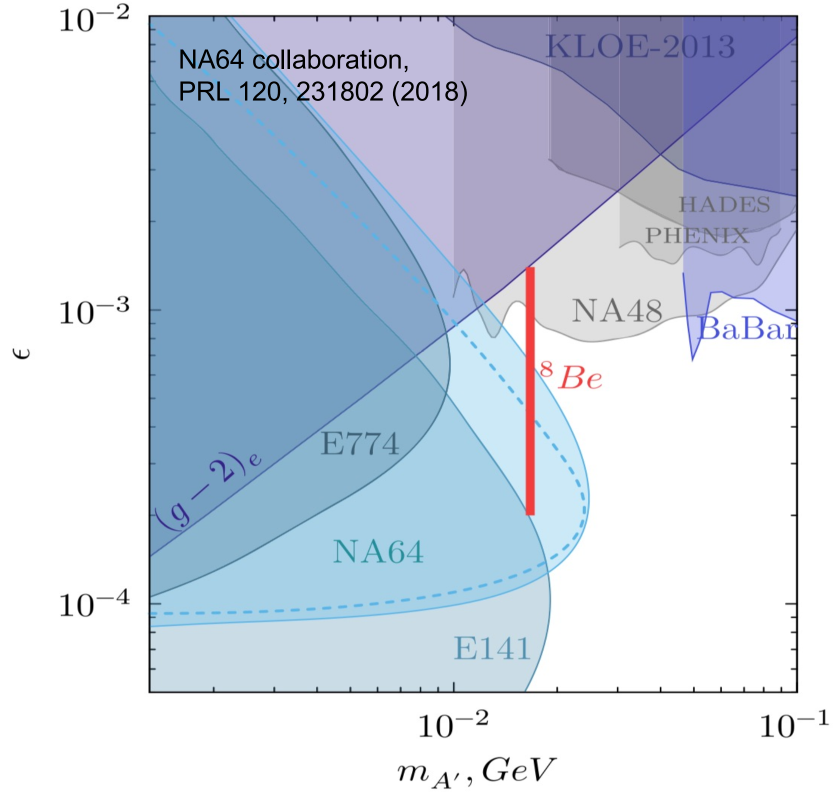


NA64 – VISIBLE MODE

Visible setup

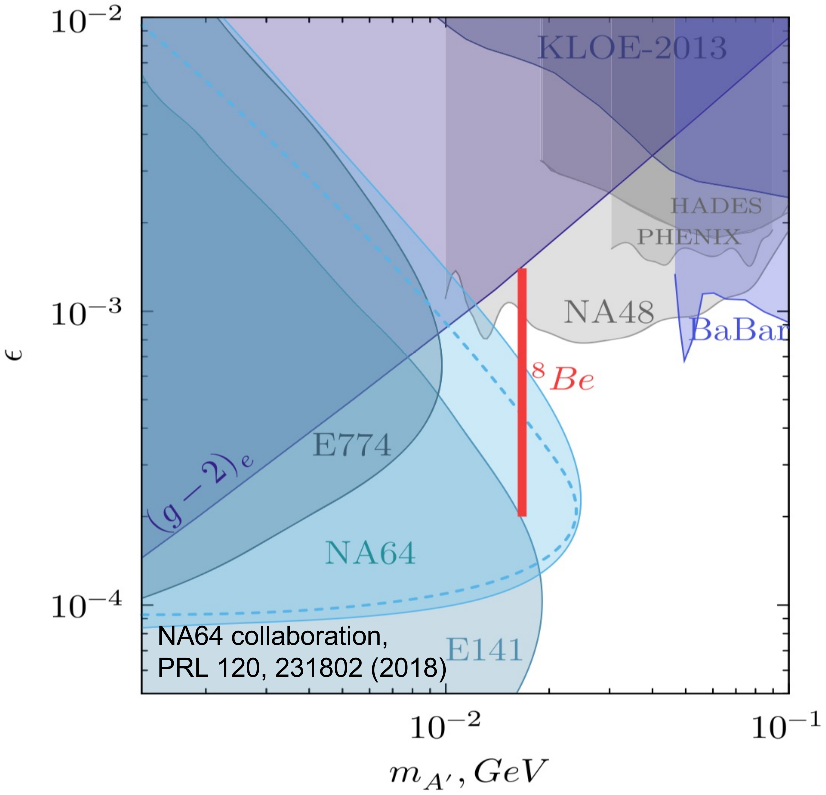






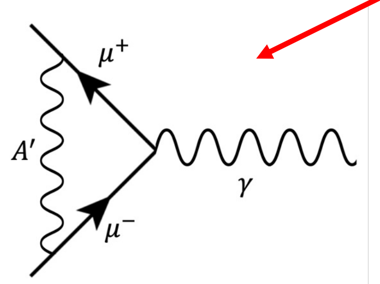
VISIBLE AND INVISIBLE DARK PHOTON DECAYS

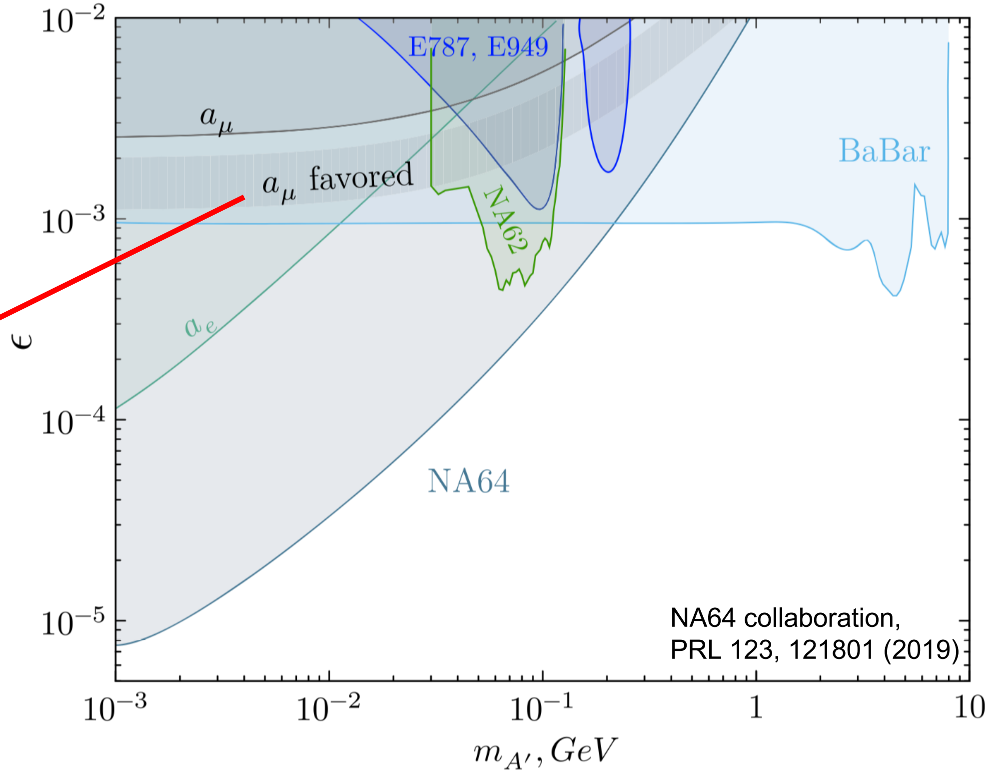
Visible decay mode



NA64 collaboration,
PRL 120, 231802 (2018)

Invisible decay mode





NA64 collaboration,
PRL 123, 121801 (2019)

→ Both decay modes had been excluded experimentally as explanations of the $(g-2)_\mu$ discrepancy

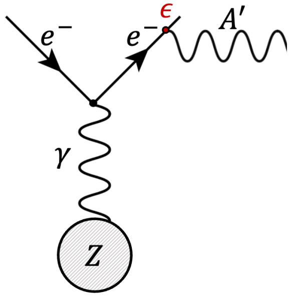
THE NA64 TECHNIQUE

Well-defined beam

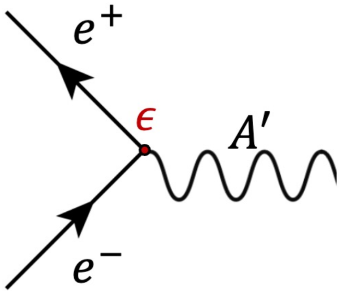
ACTIVE DUMP

Production

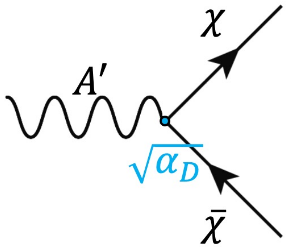
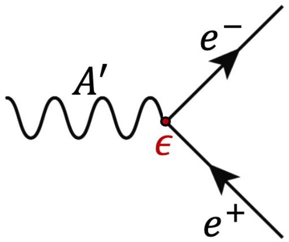
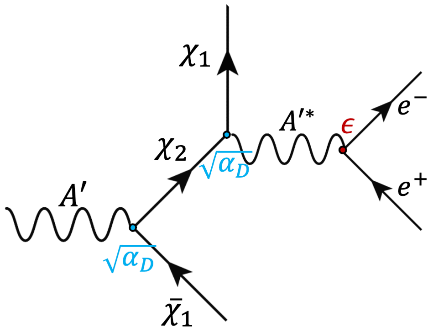
- A'-bremsstrahlung



- A' resonant annihilation



FULLY HERMETIC DETECTOR

Decay		Signature
• Invisible $m_{A'} > 2m_\chi$		Missing energy
• Visible $m_{A'} < 2m_\chi$		SM particle pair
• Semi-visible $m_{A'} > m_{\chi_1} + m_{\chi_2}$ $\Delta_{21} > 2m_e$		Missing energy + SM particle pair

Recast invisible analysis results

- Projections show that these semi-visible models are within the reach of the experiment even without dedicated modifications in the analysis techniques → reinterpret the invisible analysis bounds obtained with the 2016-2018 statistics

Procedure:

1. Simulate many parameter space points $(m_{A'}, \epsilon)$ for each model (grid of 80x80 points)
2. Apply relevant cuts for semi-visible signals on MC simulations (all the cuts effective from the point where A' could potentially be produced) → cut values taken from invisible analysis
3. Correct accumulated EOT with total efficiency obtained from the entire list of cuts applied in the invisible analysis (these efficiency were estimated on electron calibration runs)
4. Given that the calculated boundaries were basically unaltered when considering the expected background, the limits were calculated with a background-free hypothesis, excluding a specific parameter if: $N_{A'}/EOT \cdot EOT \geq 2.3$

	2016 I	2016 II	2016 III	2017	2018
EOT 10^{10}	2.3	1.1	0.9	5.4	19
Efficiency	0.7	0.841	0.786	0.55	0.5
Effective EOT 10^{10}	1.61	0.92	0.71	3	9.5
BKG	0.0097	0.0088	0.002	0.237	0.215

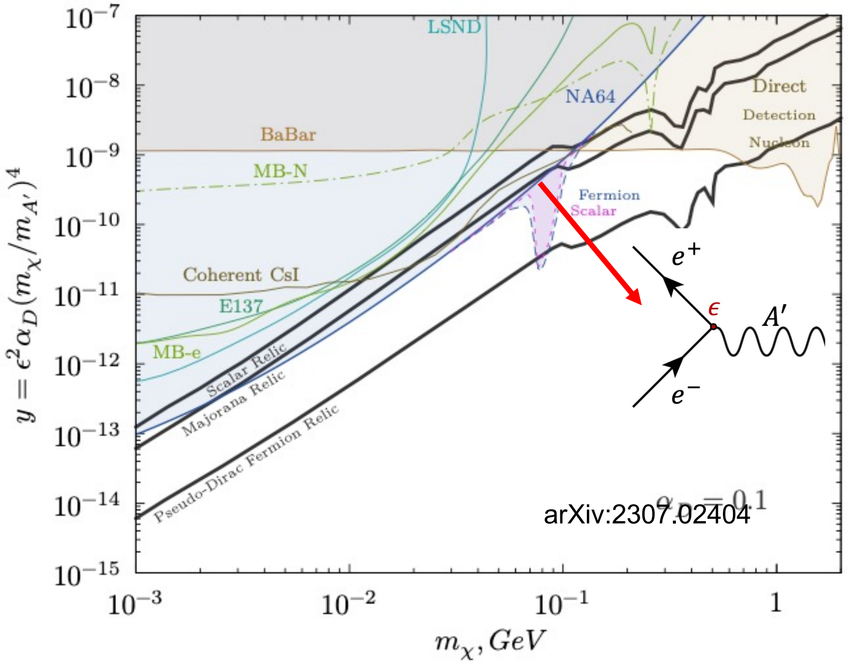
Background source	Background, n_b
(i) Dimuons	0.024 ± 0.007
(ii) π, $K \to e\nu$, K_{e3} decays	0.02 ± 0.01
(iii) e^- hadron interactions in the beam line	0.43 ± 0.16
(iv) e^- hadron interactions in the target	<0.044
(v) Punch-through γ's, cracks, holes	<0.01
Total n_b (conservatively)	0.53 ± 0.17

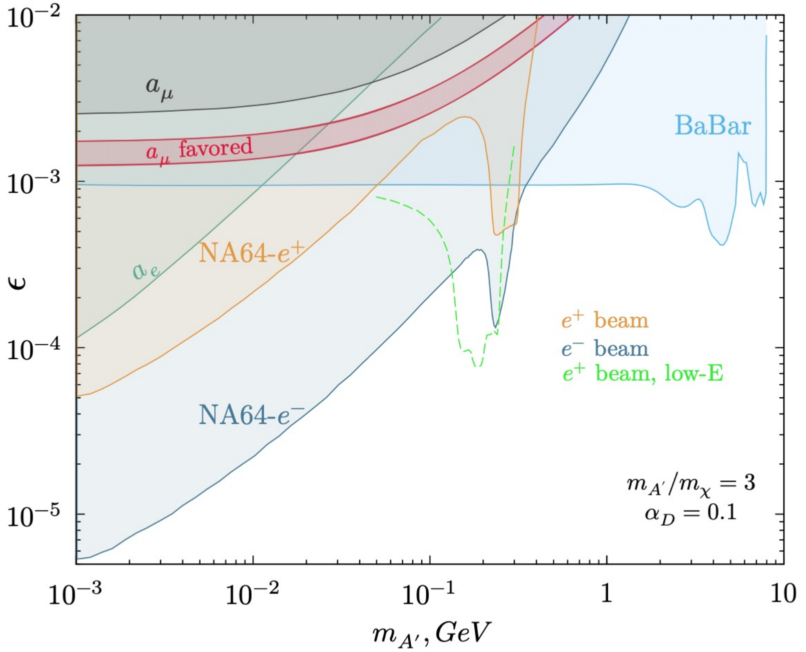
A' RESONANT ANNIHILATION PRODUCTION

- A' strahlung production $\propto {}^{1}/_{m_{A'}^{2}}$

- A' e^+ e^- - ahhinilation production → Breit-Wigner like cross-section peaked at $m_{A'}^2$=$2m_eE_{e^+}$

→ enhancement $\sqrt{2m_eE_{thr}} < m_{A'} < \sqrt{2m_eE_0}$





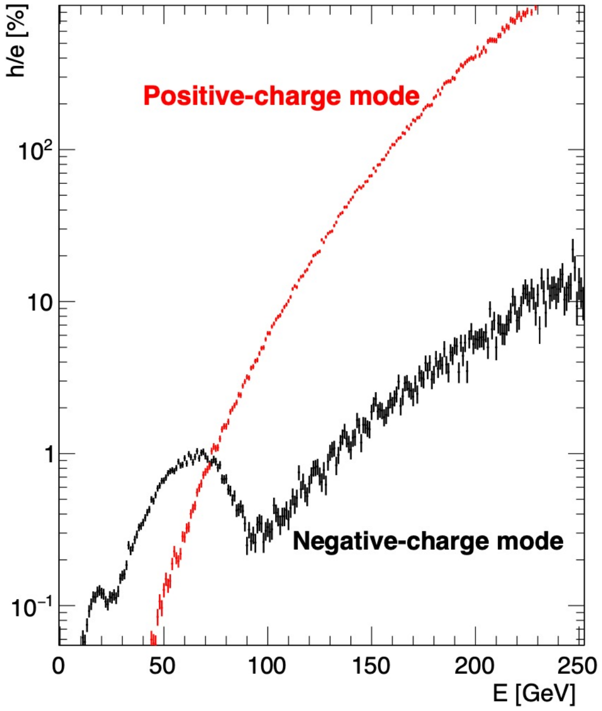
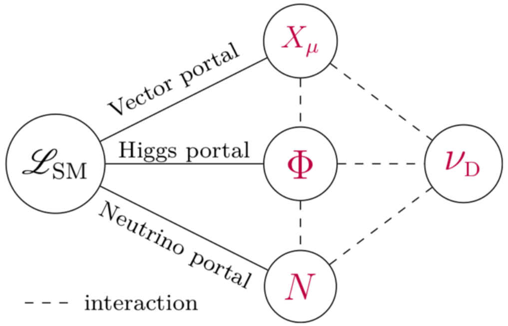


Figure 4: The FLUKA calculated ratio between hadrons and electrons / positrons at the H4 lead converter. The angular and momentum acceptance of H4 beamline have been applied both for the negative-charge (black) and positive-charge (red) mode. The structure at $E \simeq 50$ GeV for the negative charge mode is a result of the convolution between the energy spectrum of the produced Λ baryons and the maximum energy allowed in the $\Lambda \to p\pi^-$ decay.

HNL MODEL

- Exploits a 3 portal connection: vector portal, Higgs portal, neutrino portal



- Based on addition of $U(1)_D$ symmetry but with a richer DS: dark boson A', dark scalar ϕ, dark neutrino ν_D (charged under $U(1)_D$) and sterile neutrino ν_N (neutral w.r.t. all symmetries)

→ After SSB and mass matrix diagonalization two types of mass ES: ν (SM neutrino) and N (HNL)

$$\mathcal{L}_{HNL} = \mathcal{L}_{SM} + \mathcal{L}'_A + \mathcal{L}_{kin.mix} + \underbrace{(D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi)}_{\mathcal{L}_\Phi} - \underbrace{\lambda_{\Phi H} |H|^2 |\Phi|^2}_{\mathcal{L}_{H-\Phi mix}}$$
$$+ \underbrace{\overline{\nu_D} i\gamma^\mu D_\mu \nu_D}_{\mathcal{L}_{\nu_D}} + \underbrace{\overline{\nu_N} i\gamma^\mu \partial_\mu \nu_N - \left(\frac{\mu'}{2}\overline{\nu_N}\nu_N^c + h.c.\right)}_{\mathcal{L}_{\nu_N}}$$
$$- \left[\underbrace{y_\nu^\alpha \overline{L}_\alpha \tilde{H} \nu_N^c + y_{\nu_N} \overline{\nu_N} \nu_D^c \Phi + h.c.}_{\mathcal{L}_{\nu-mix}}\right]$$

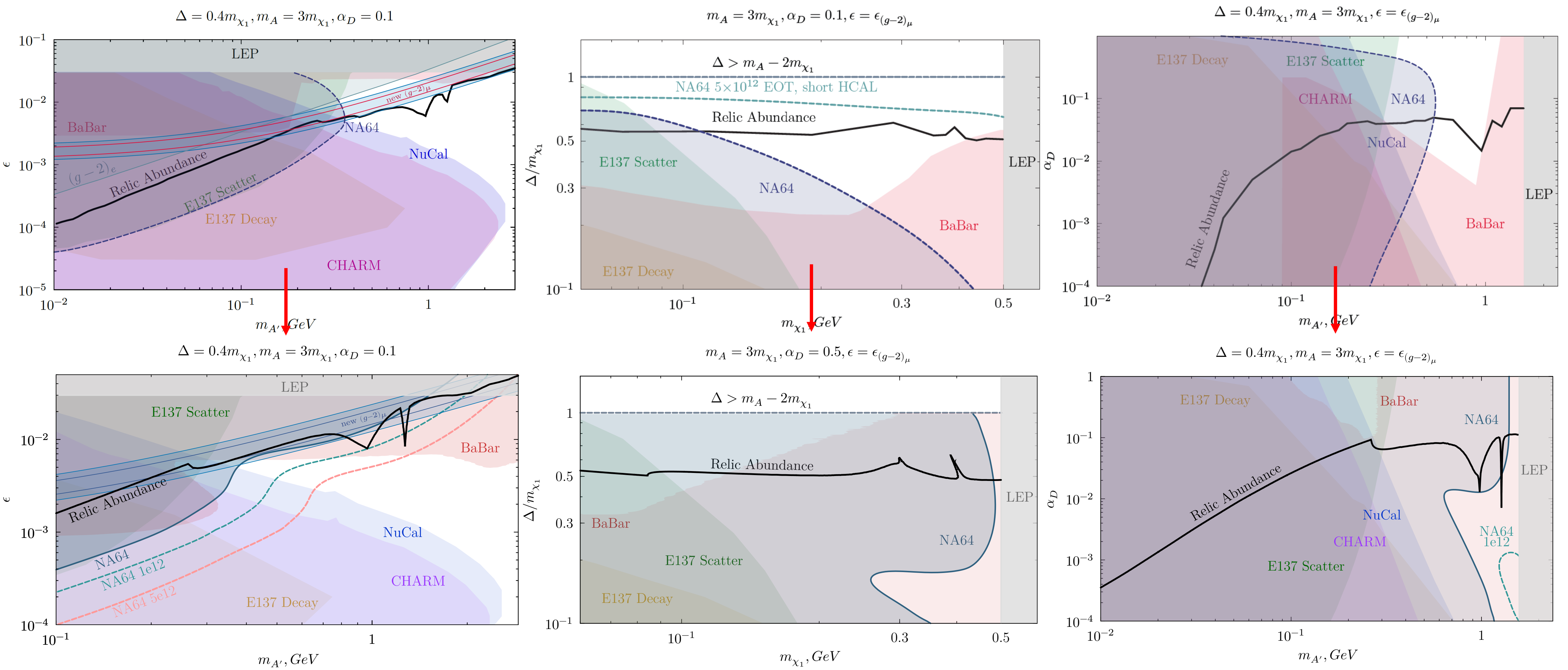
$$\Gamma(Z' \to N_i N_j) = |V_{ij}|^2 \frac{g_D^2 m_{Z'}}{12\pi} \left(1 + \frac{\Delta r}{2}\right) (1-R)^{3/2} \sqrt{1 - \Delta r}$$

$$R = (m_i + m_j)^2 / m_{Z'}^2, \quad \Delta r = (m_i - m_j)^2 / m_{Z'}^2$$

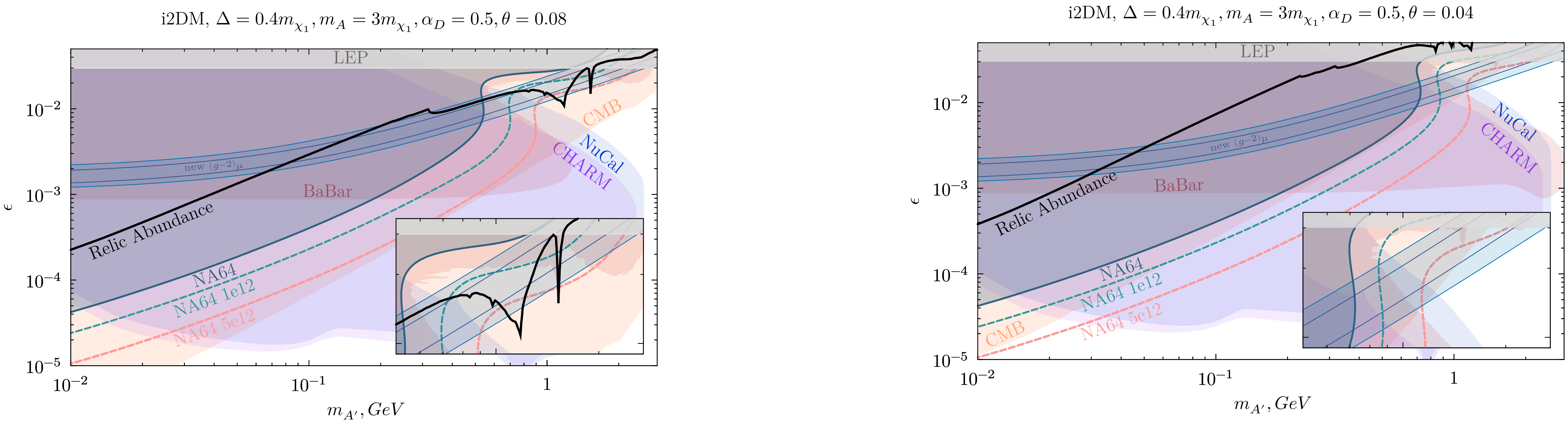
$$\Gamma(N_l \to N_m e^+ e^-) \simeq |V_{lm}|^2 F(x_{ml}) \frac{(e g_D \epsilon)^2}{384\pi^3} \frac{m_l^5}{m_{Z'}^4} \qquad x_{ml} = \frac{m_m}{m_l}$$

$$F(x) = 1 + 2x - 8x^2 + 18x^3 - 18x^5 + 8x^6$$
$$-2x^7 - x^8 + 24x^3(1 - x + x^2) \ln x.$$

Comparison of the two semi-visible searches



i2DM – FOCUS ON $(g-2)_\mu$

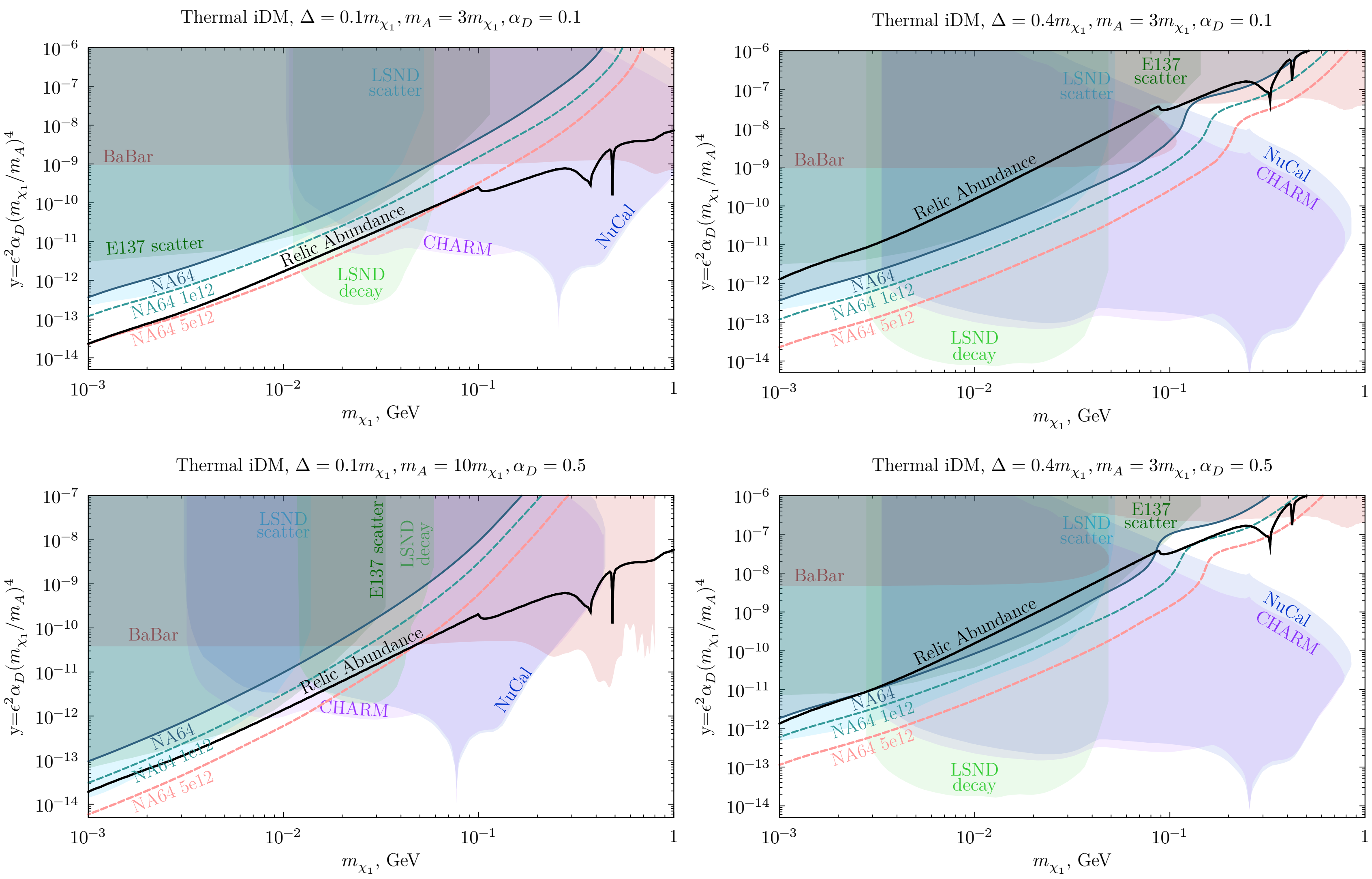


- Smaller mixing (parametrized by θ)→ suppressed χ_1 self-annihilation → loosen CMB bounds BUT
- Smaller mixing → suppressed coscattering and annihilations → overabundant scenario

→Both iDM and i2DM are excluded as viable explanation of the $(g-2)_\mu$ anomaly

$$Br(A' \to \chi_1\chi_1) \propto \sin^4\theta,$$
$$Br(A' \to \chi_1\chi_2) \propto \sin^2\theta\cos^2\theta,$$
$$Br(A' \to \chi_2\chi_2) \propto \cos^4\theta,$$

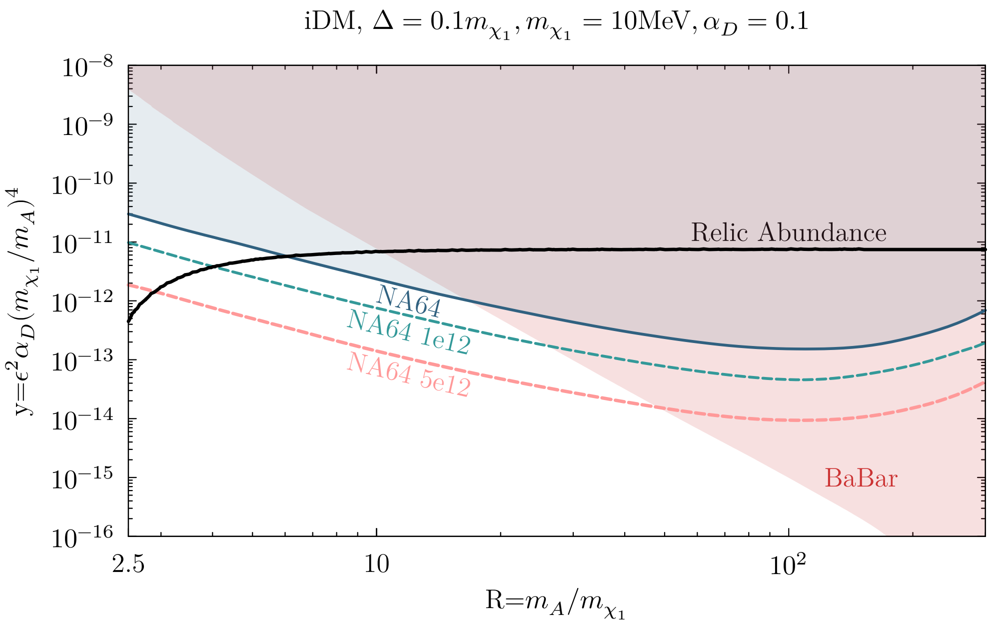
THERMAL RELIC TARGET – IDM

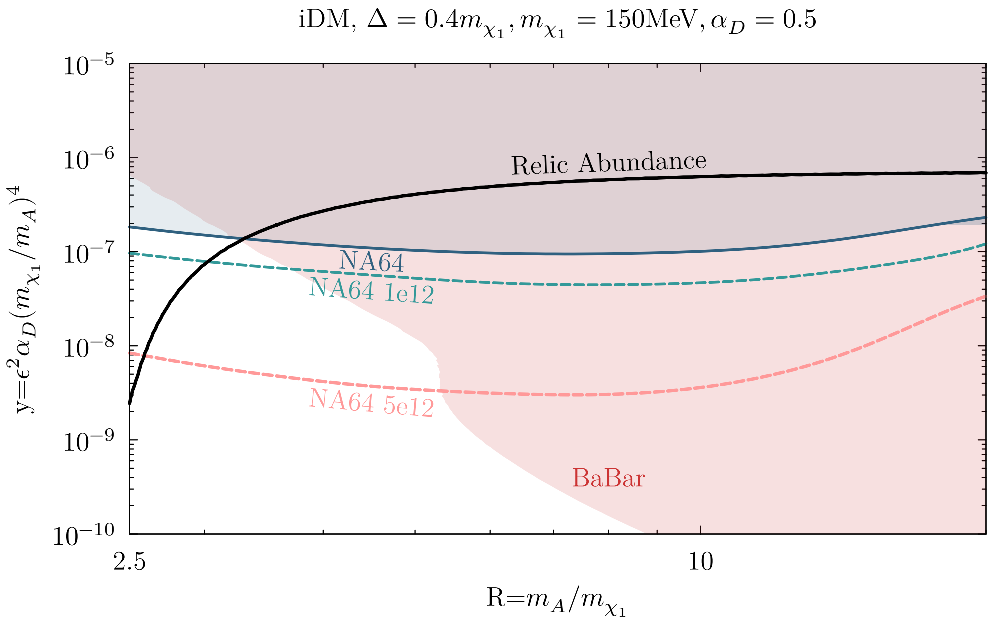


Projections in $m_{\chi_1} - y$ plane:

- With 10^{12} EOT: the relic target for $\Delta = 0.4m_{\chi_1}, m_{A'} = 3m_{\chi_1}$, $\alpha_D = 0.5$ can be further explored
- With $5 \cdot 10^{12}$ EOT: large coverage of the relic targets for different parametrizations

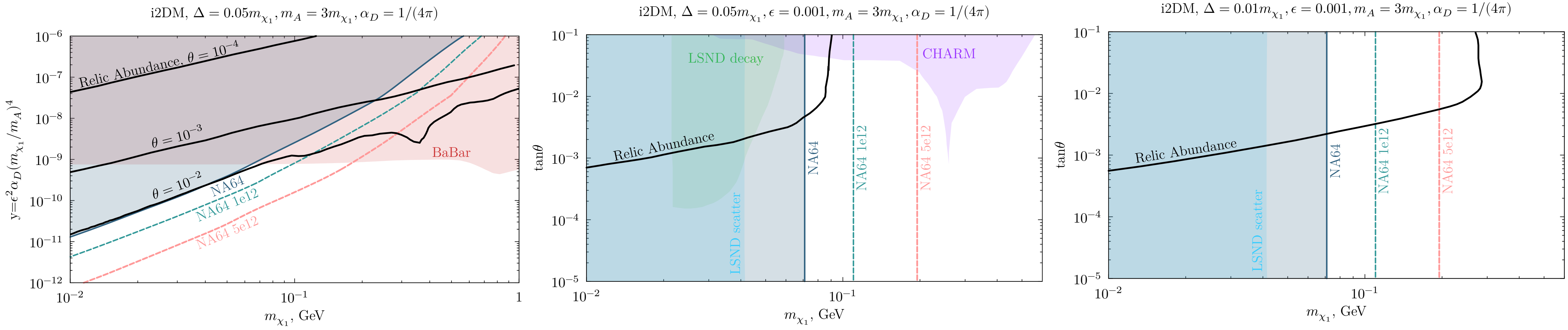
PARAMETER SPACE R VS y – IDM





- Interplay between the experimental sensitivities and the DM relic density as a function of the $R = m_{A'}/m_{\chi_1}$ is often neglected
  → For BP1 (left) the range $R \sim 2.5 - 6$ of the relic line remains unprobed by current searches
  → For BP2 (right) a smaller range within $R \sim 2.5 - 3.3$ is still untested
- With $5 \cdot 10^{12}$ EOT the NA64 sensitivity extends below the standard $R = 3$ point

Thermal relic target – i2DM



Small mass splitting → χ_2 is long-lived → invisible bounds & reduced sensitivity in displaced vertex searches

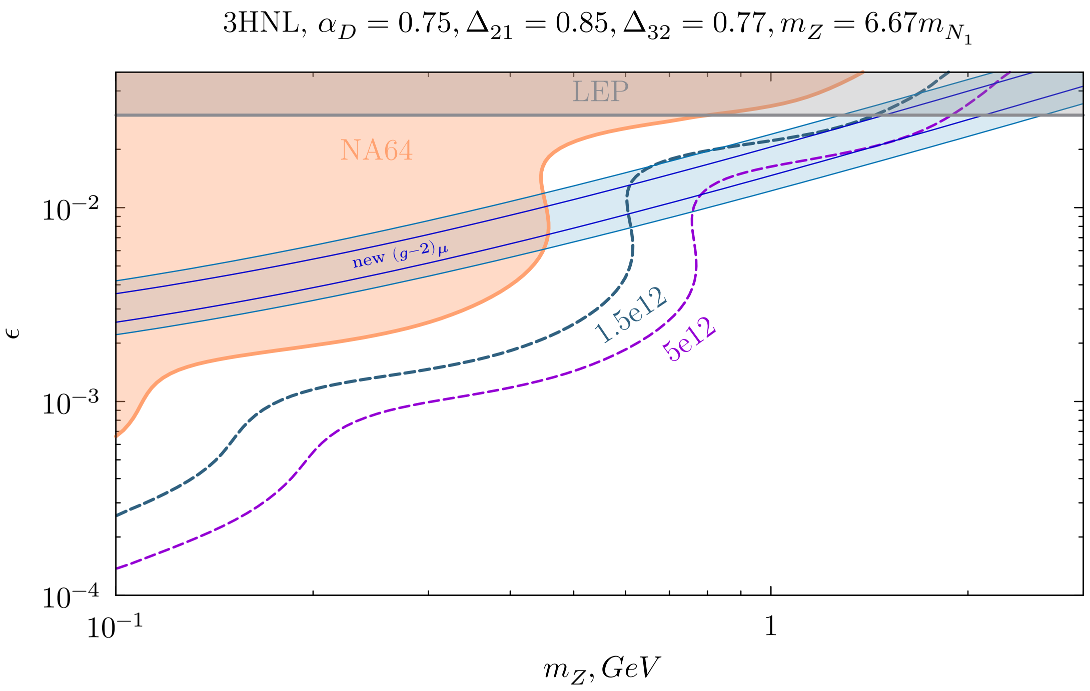
$m_{\chi_1} - y$ plane:

- NA64 bound matches closely the DM relic curve for $\theta = 10^{-2}$ in range $m_{\chi_1} \sim 10 - 50$ MeV
- With 10^{12} EOT: the relic targets for $\theta < 10^{-2}$ can be fully explored

$m_{\chi_1} - \tan\theta$ plane:

- No constraints from BaBar for $\varepsilon < 10^{-3}$
- NA64 can set new limits on the minimum allowed DM candidate mass
- With 10^{12} EOT area below $m_{\chi_1} < 110$ MeV can be tested while $5 \cdot 10^{12}$ EOT would increase this value to $m_{\chi_1} < 195$ MeV

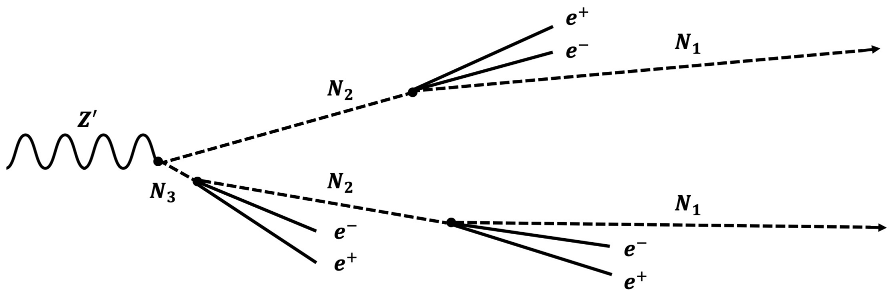
SENSITIVITY TO HNL MODEL TARGETING $(g-2)_\mu$



Heavy neutral leptons HNL

Ballett et al.
PRD 101, 115025 (2020)
Abdullahi et al.
PLB 820 (2021) 136531
Abdullahi et al.
arXiv:2302.05410

- Motivations:
  - $(g-2)_\mu$
  - ν mass problem
  - other low E experimental anomalies
- Benchmark model:
  $\alpha_D = 0.75$
  $\Delta_{21} = 0.85 m_{N_1}$, $\Delta_{32} = 0.77 m_{N_2}$
  $m_{Z'}/m_{N_1} = 6.67$
  $|V_{12}|^2 = 0.01$, $|V_{23}|^2 = 0.99$

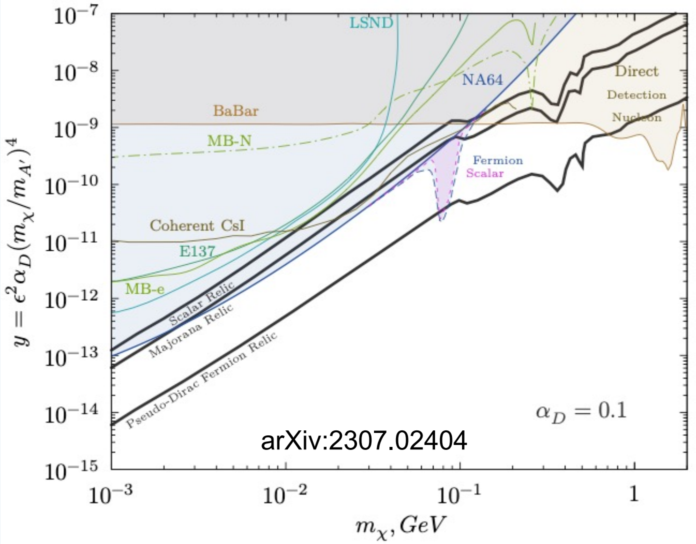


ONGOING SEMI-VISIBLE ANALYSIS ON 2022 DATASET

New data collected in 2022: $6.3 \cdot 10^{11}$ EOT (more than double the 2016-2018 statistics)

Invisible signature

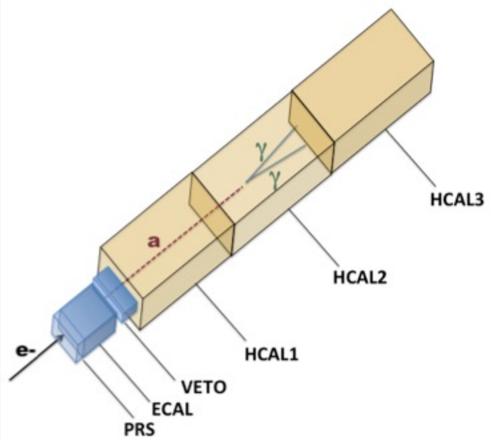
Data has been unblinded and results are on arXiv:



→ Bounds will be recasted on semi-visible parameter spaces

Displaced vertex signature

Ongoing analysis in parallel with ALP analysis:



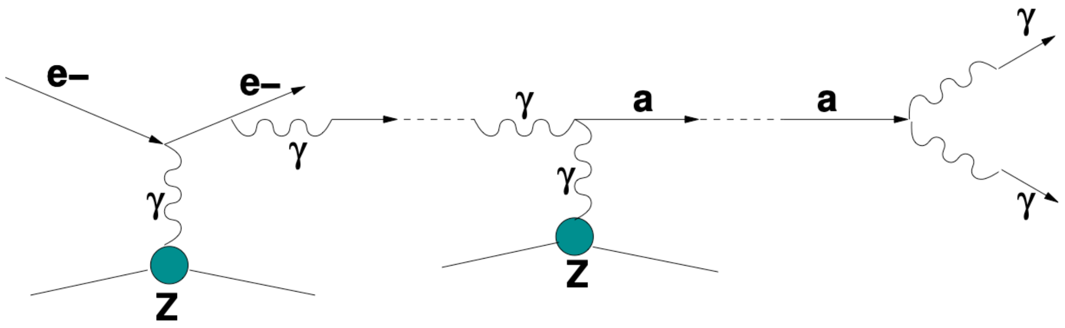
Similar signature → signal region: missing energy in ECAL + energy deposit in HCAL

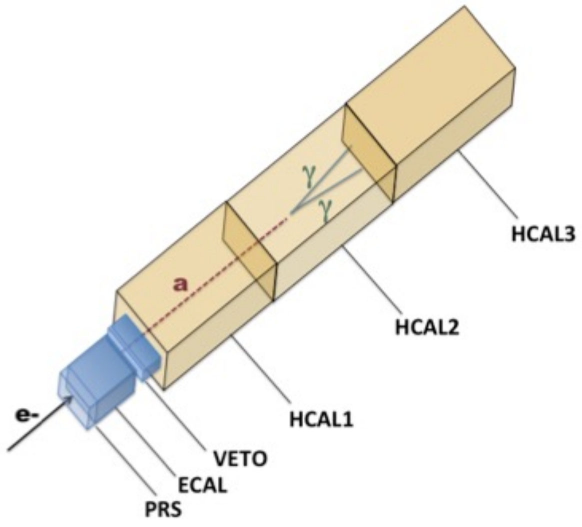
ALP = axionlike particle (a)

→ Pseudoscalar particle coupling to photons

Motivation: strong CP problem
→*Peccei-Quinn mechanism*: addition of a new U(1) broken symmetry generating a pseudo-Goldstone boson = a

ALP production: Primakoff effect in γ interactions





ALP signatures:

- $a \to \gamma\gamma$ decay beyond setup → missing energy

SR: $ECAL < 50$ GeV, $HCAL < 1$ GeV

- $a \to \gamma\gamma$ decay in HCALs → displaced vertex

SR: $ECAL < 85$ GeV, $HCAL > 15$ GeV
$ECAL + HCAL \sim 100$ GeV

ALP SEARCHES

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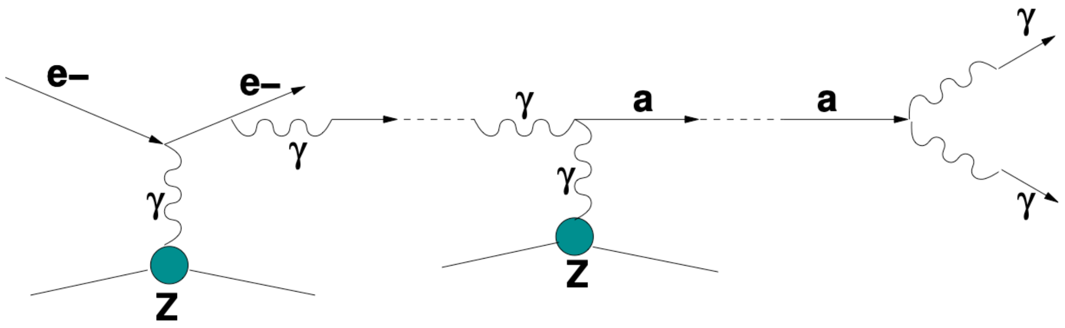

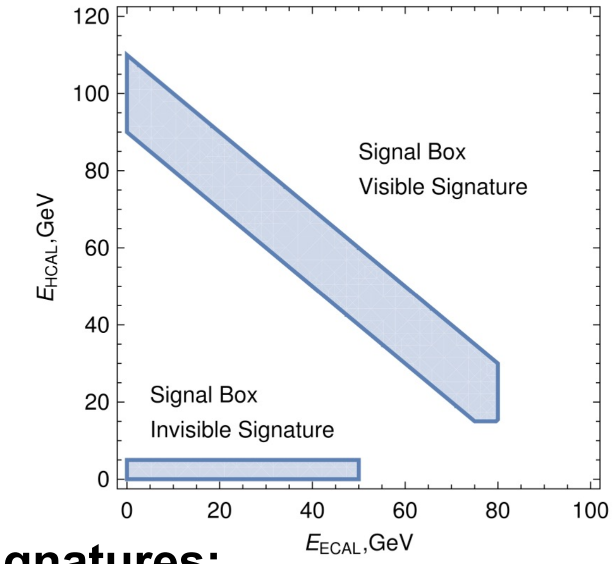

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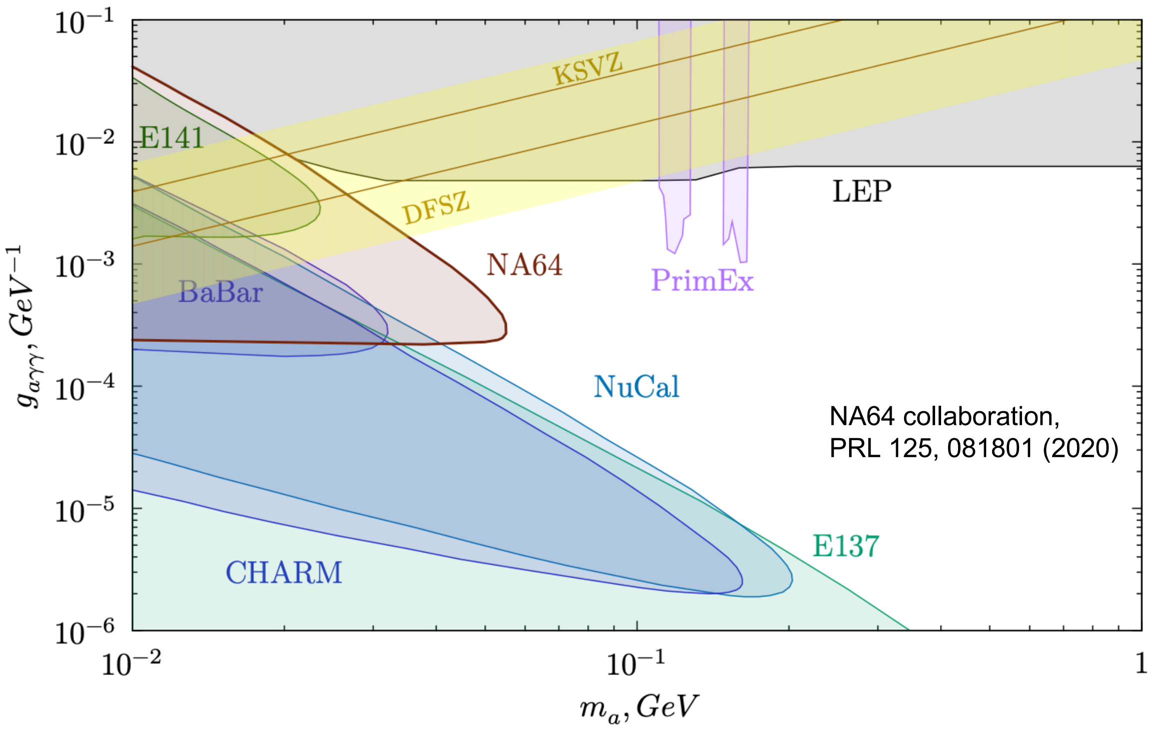
Background source	Background, n_b
leading neutrons	0.02 ± 0.008
leading K^0 interactions and decays	0.14 ± 0.045
beam π, K charge exchange and decays	0.006 ± 0.002
dimuons	< 0.001
Total n_b	0.17 ± 0.046

Data collected in 2016-2018 (2.84· 10^{11} EOT)



NA64 collaboration,
PRL 125, 081801 (2020)

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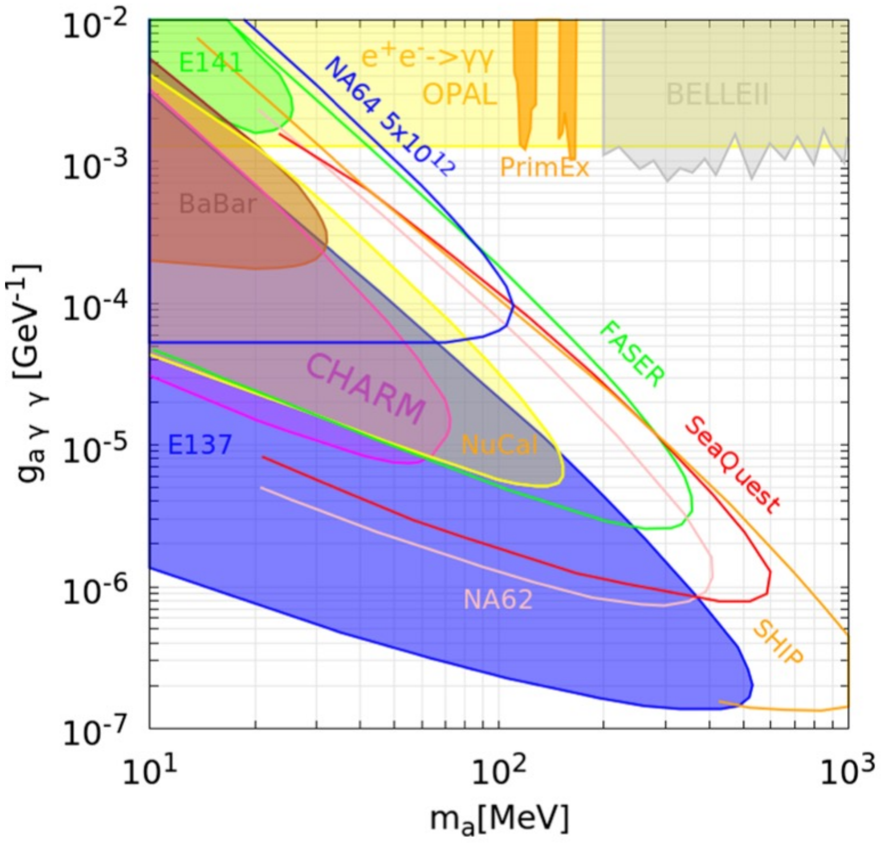
Future sensitivity:



NA64 collaboration,
PRD 102, 055018 (2020)