Dark sector searches with NA64 experiment @CERN

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"A rainbow of Dark sectors"

Aspen online winter conference

21st March-1st April 2021

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

IPA

IFIC Institut de Física Corpuscular

CSIC Consejo Superior de Investigaciones Científicas

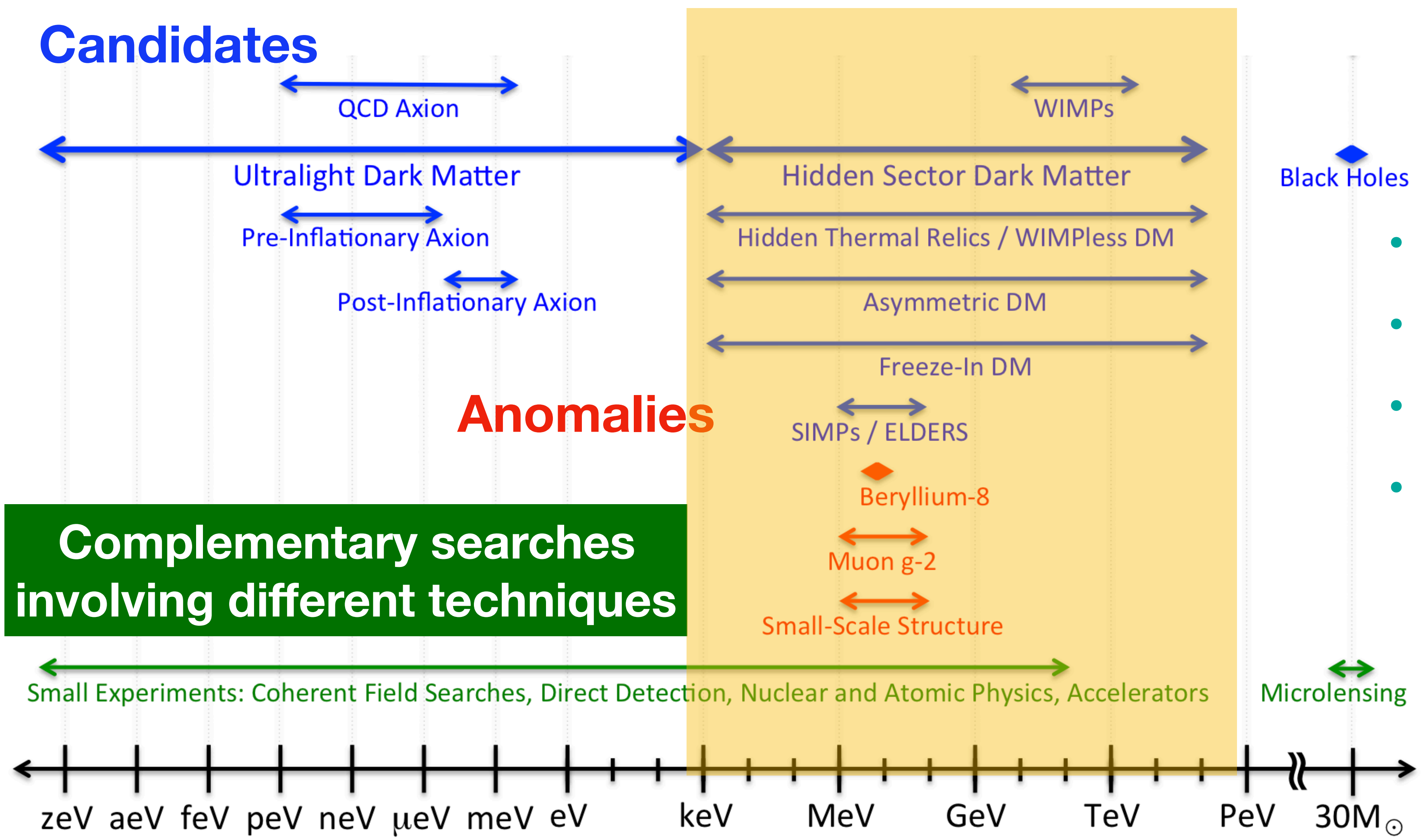
Vniversitat de València

Dark sectors

An interesting framework to explain the origin of dark matter

Existence of ***dark sectors*** which couple weakly with standard model particles and can decay into dark matter candidates.

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



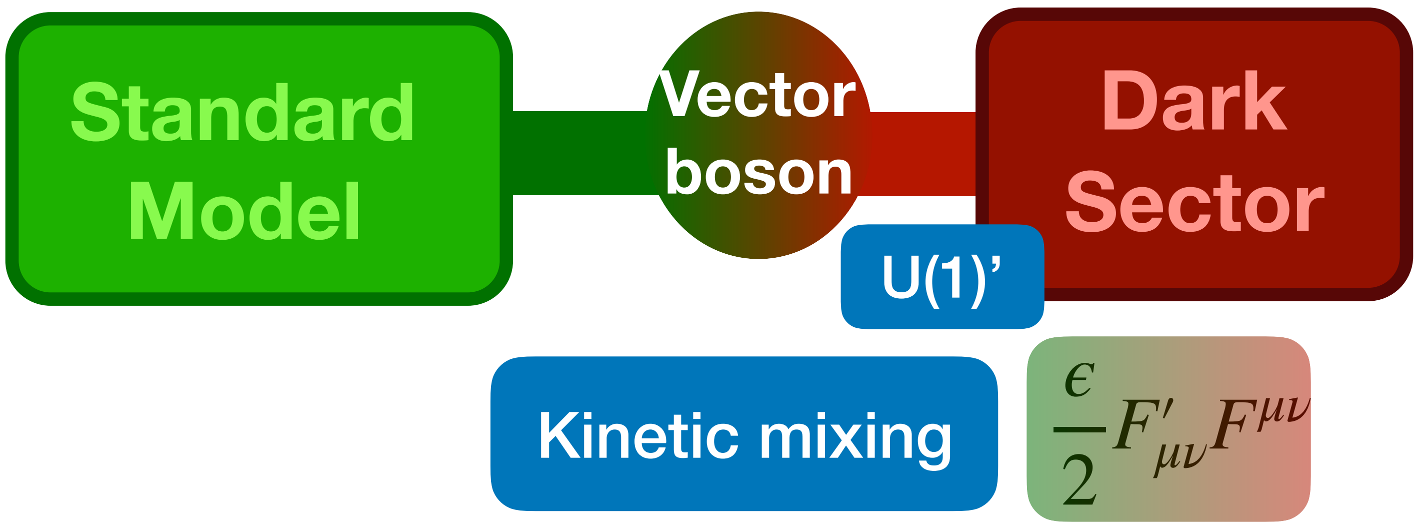
$$L_{Total} = L_{SM} + L_{DS} + L_{Portal}$$

- Vector: ***Dark Photon***
- Scalar: ***Dark Higgs***
- Fermion: ***Heavy neutral lepton***
- Pseudo-scalar: ***Axion***

Recent review:
G.Lanfranchi, M.Pospelov and P.Schuster
arxiv:2011.02157

See N.Toro's talk!

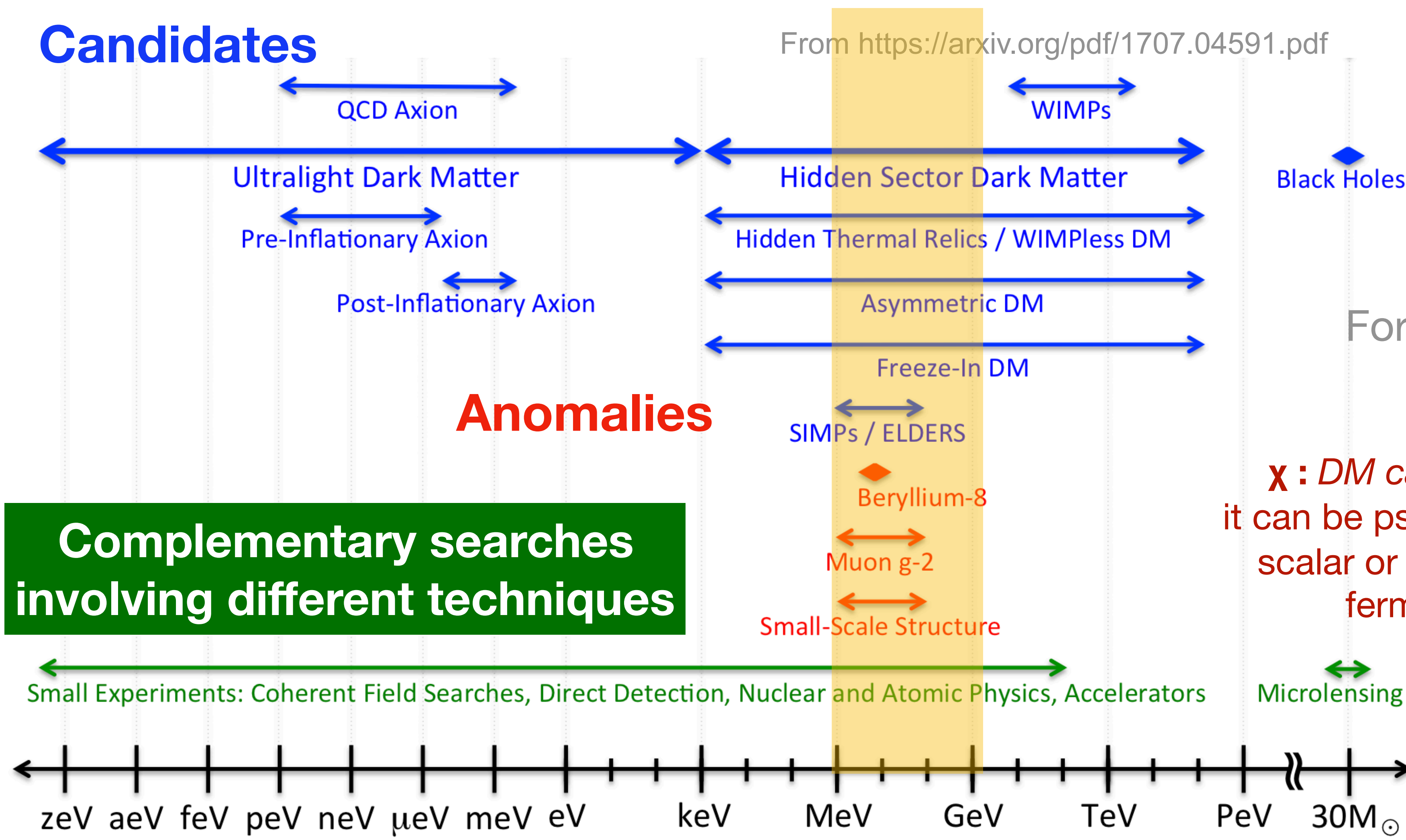
NA64 target: *the vector portal*

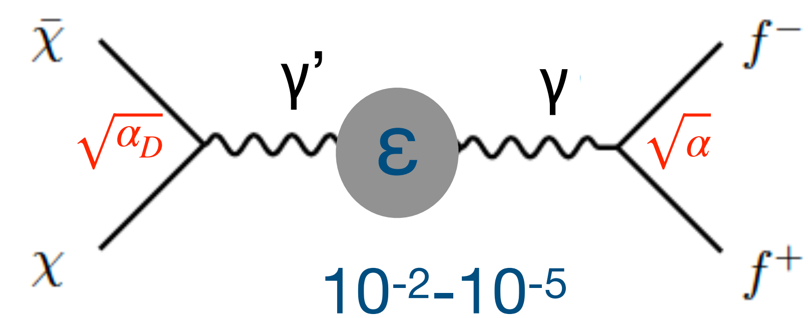


An interesting framework to explain the origin of dark matter

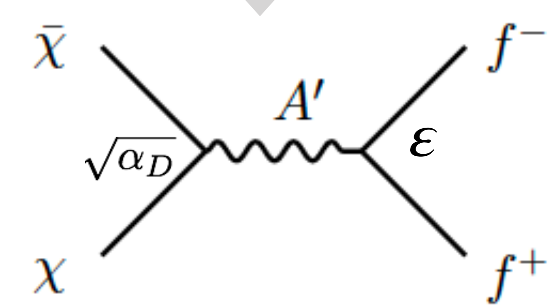
$$L_{Total} = L_{SM} + L_{DS} + L_{Portal}$$

- Vector: ***Dark Photon***





For simplicity during the talk



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

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

See N.Toro's talk!

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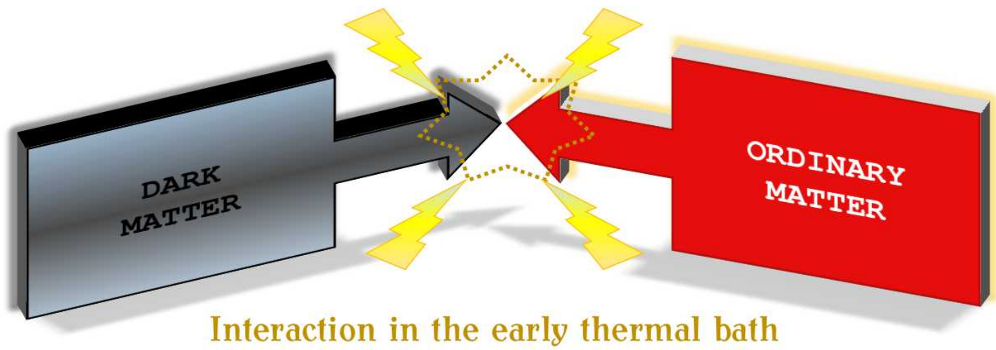
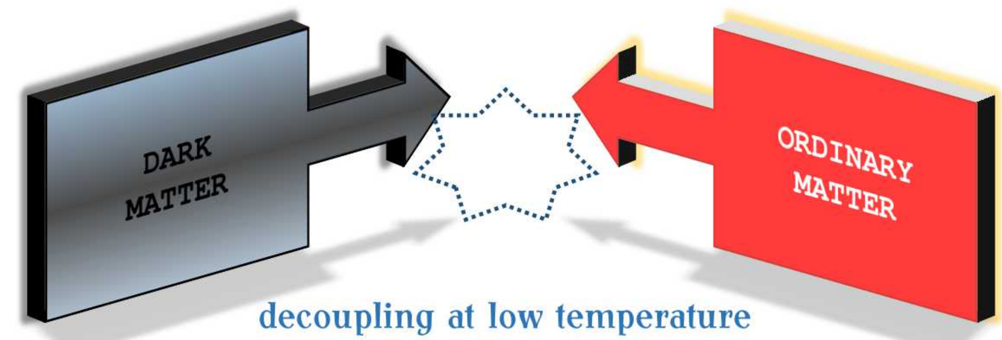
Light thermal dark matter

THE EARLY UNIVERSE

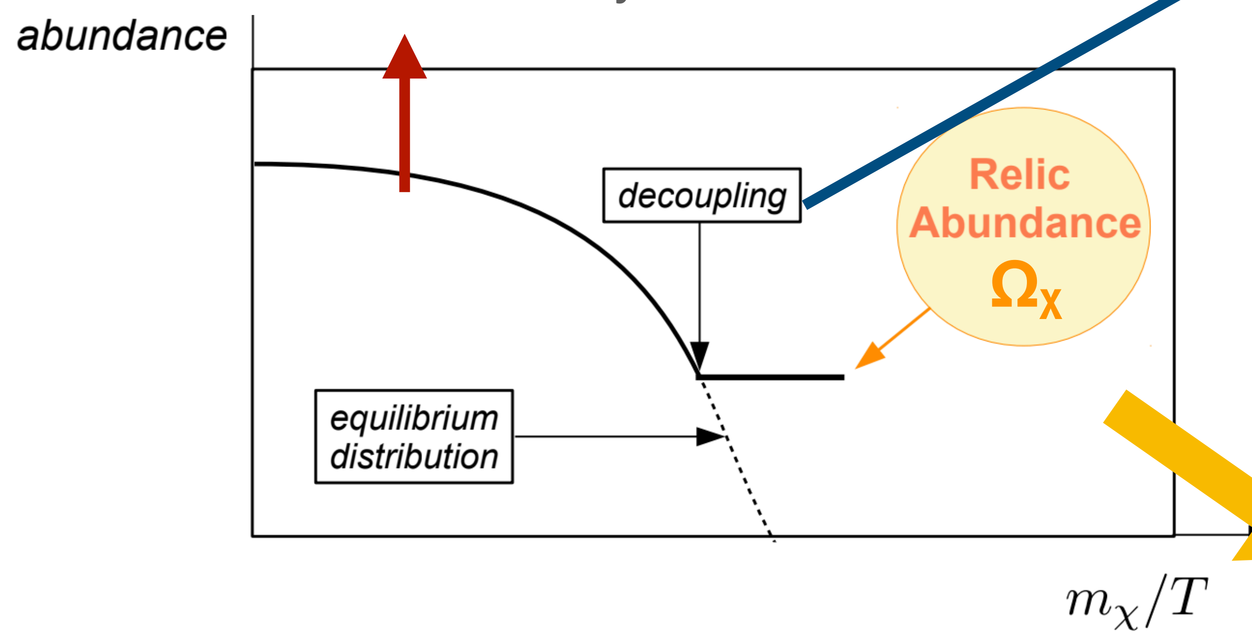


THE LATE UNIVERSE

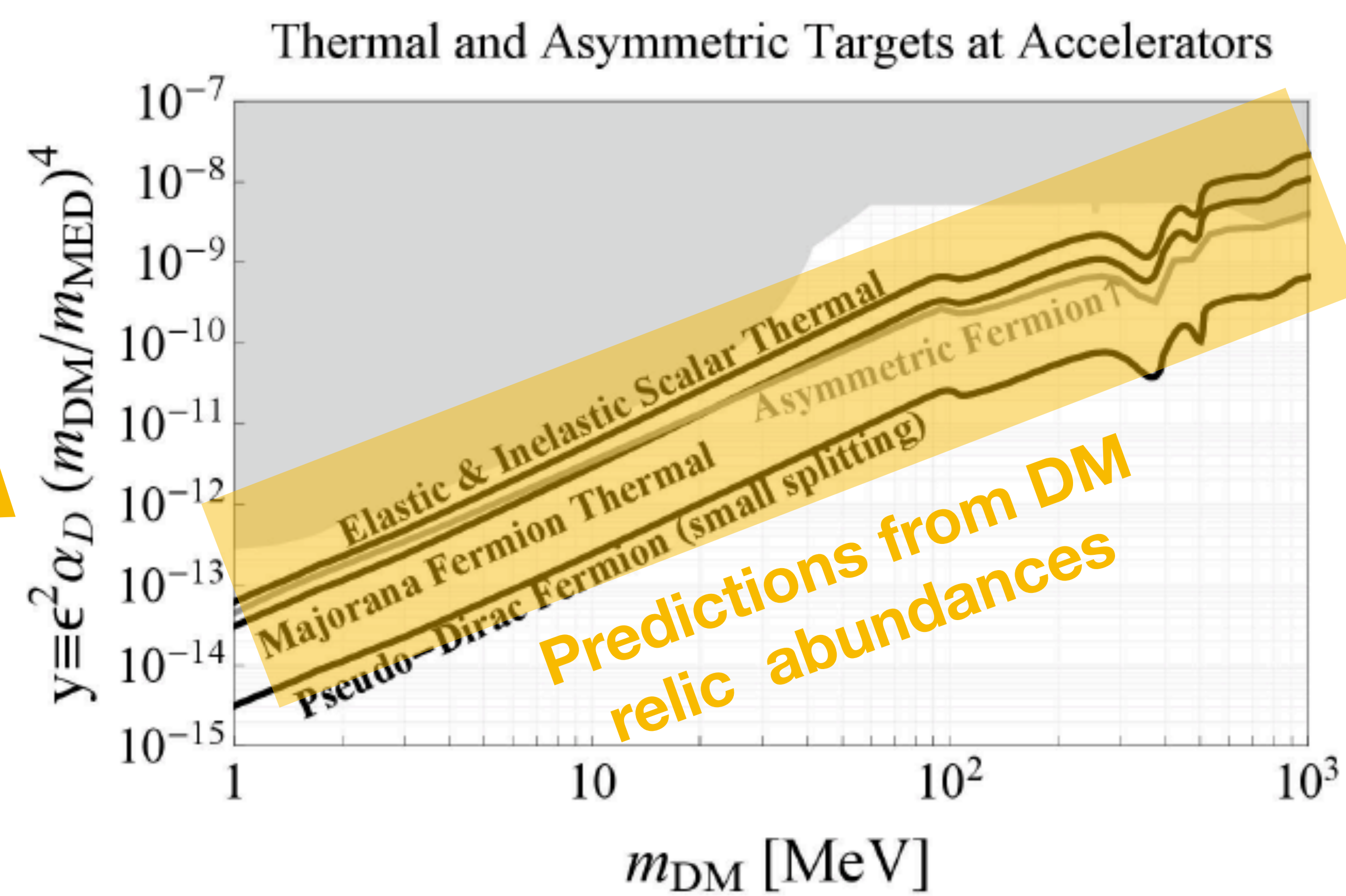


Freeze out

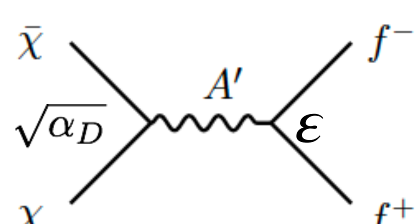
Non-gravitational interactions
in the early thermal bath



This implies a given annihilation rate to predict



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



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

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

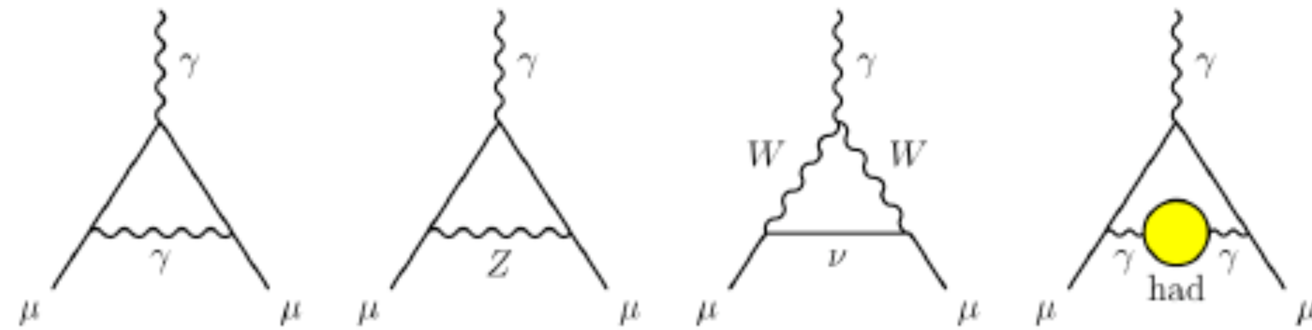
Light Dark Matter experiment arXiv:1808.05219v1

See N. Toro’s and L. Tompkins’s talks!

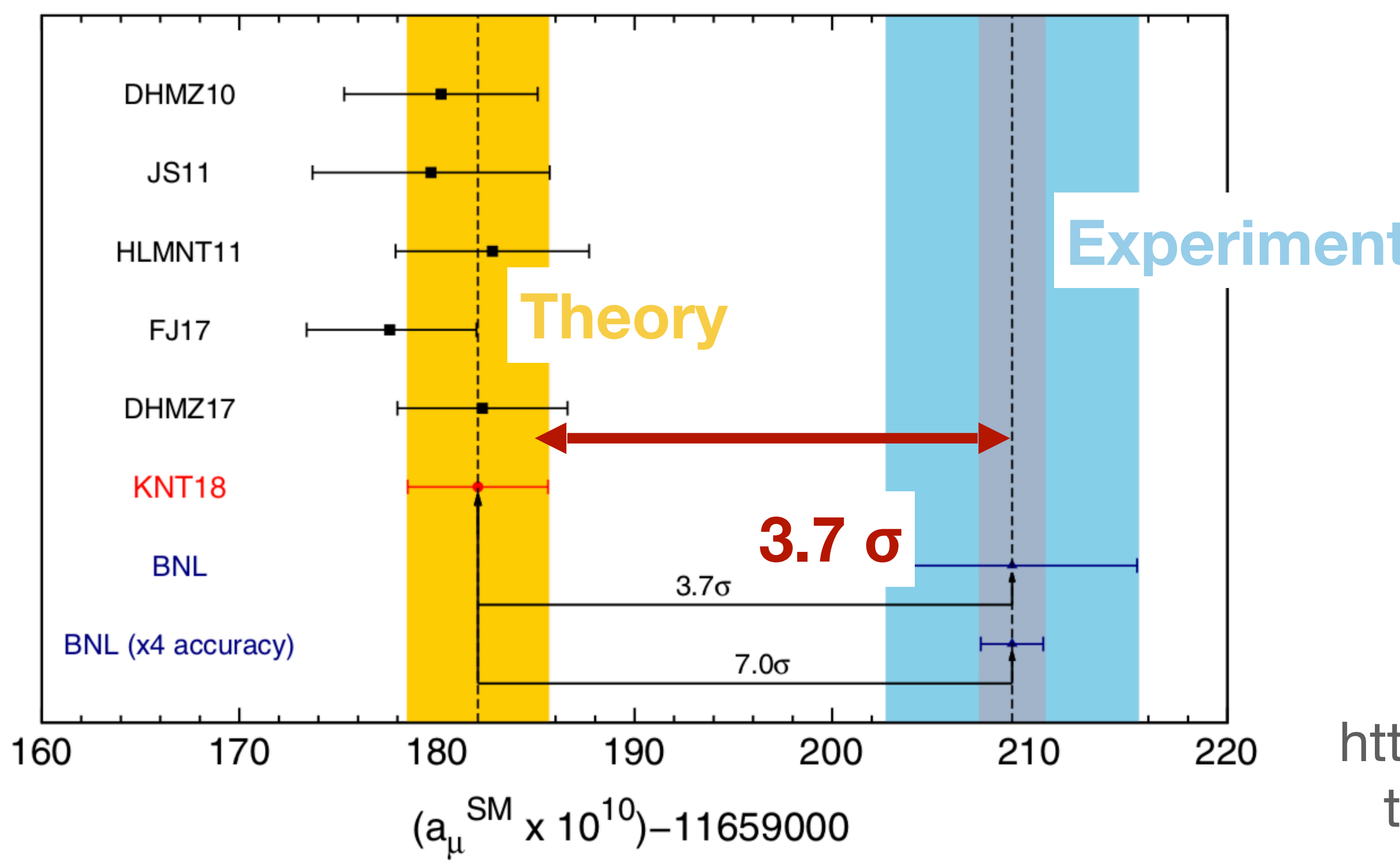
(g-2)$_\mu$ anomaly: *an additional motivation*

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

Anomalous muon magnetic moment



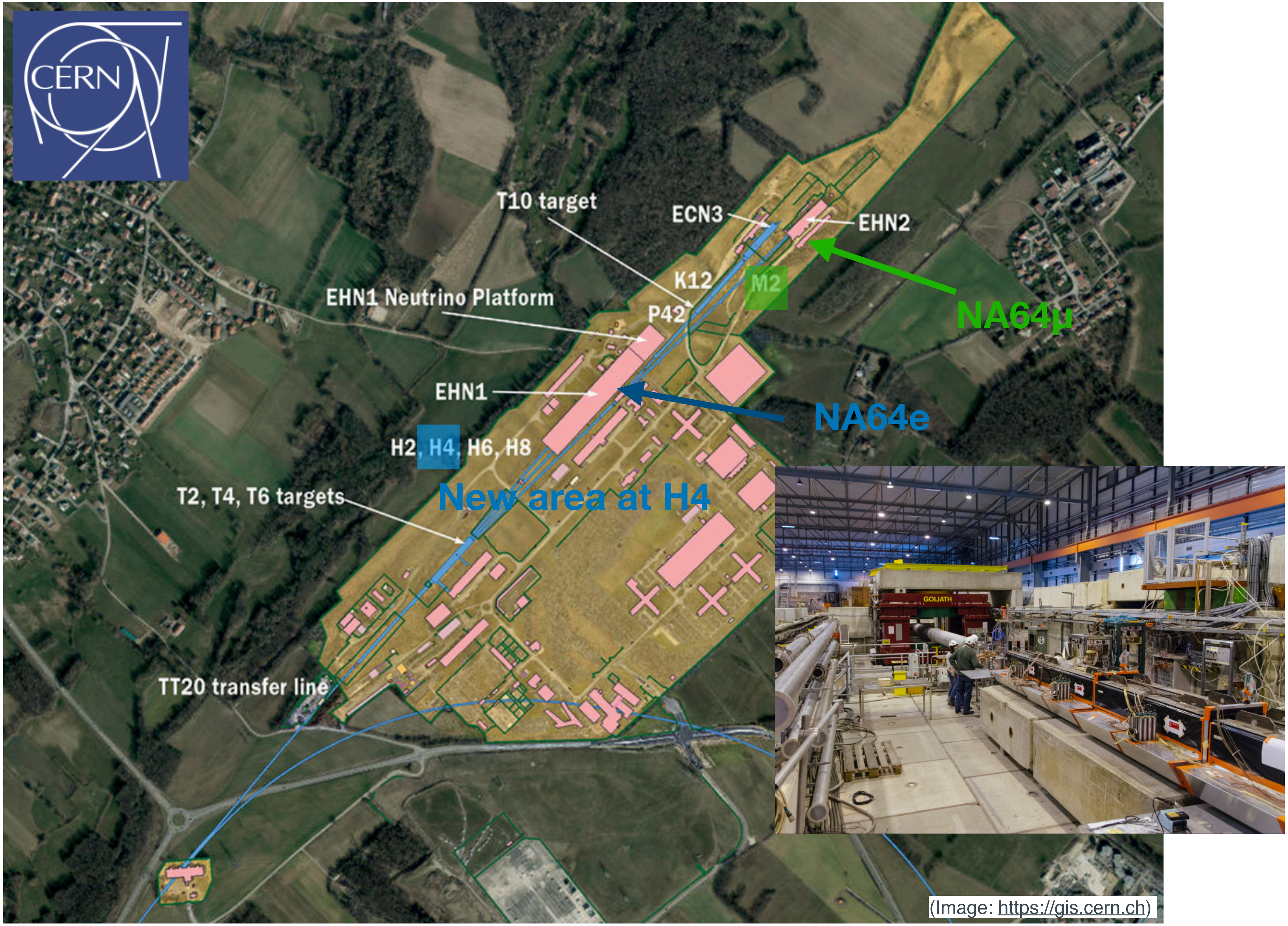
$$a_\mu^{TH} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{HAD}$$



Keshavarzi, A., Nomura, D. & Teubner, T. *Phys. Rev. D* **97**, 114025 (2018).

New experiment at Fermilab
http://muon-g-2.fnal.gov/2-the-physics-of-g-2.html

The NA64 experiment and its physics program



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The NA64 experiment and its physics program

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

2014 – Proposed

2015 – 1st test beam

2016 – Invisible; Approved by SPSC as NA64 experiment

2017 – Invisible, *Visible*

2018 – Invisible, *Visible*

LS2

2021 – Already approved to continue running; Invisible

2021 – Muon pilot run

2022 – 1st physics run

LS3

2024 – Proposal to run in muon mode

Beam time (2016–2018)

Broad physics program →

International collaboration: 46 researchers from 14 institutions

CERN-PBC-REPORT-2018-007

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
$\pi^0 \to invisible$	$Br(\pi^0 \to invisible) < 2.7 \times 10^{-7}$
$\eta \to invisible$	$Br(\eta \to invisible) < 1.0 \times 10^{-4}$
$\eta' \to invisible$	$Br(\eta' \to invisible) < 5 \times 10^{-4}$
$K^0_S \to invisible$	no limits
$K^0_L \to invisible$	no limits
e^+ beam	

Resonant A' production

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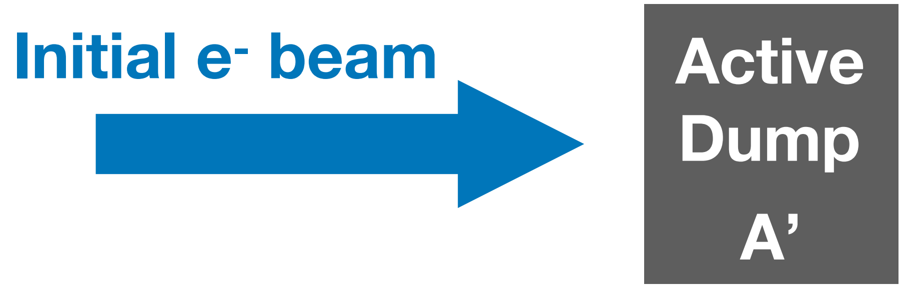
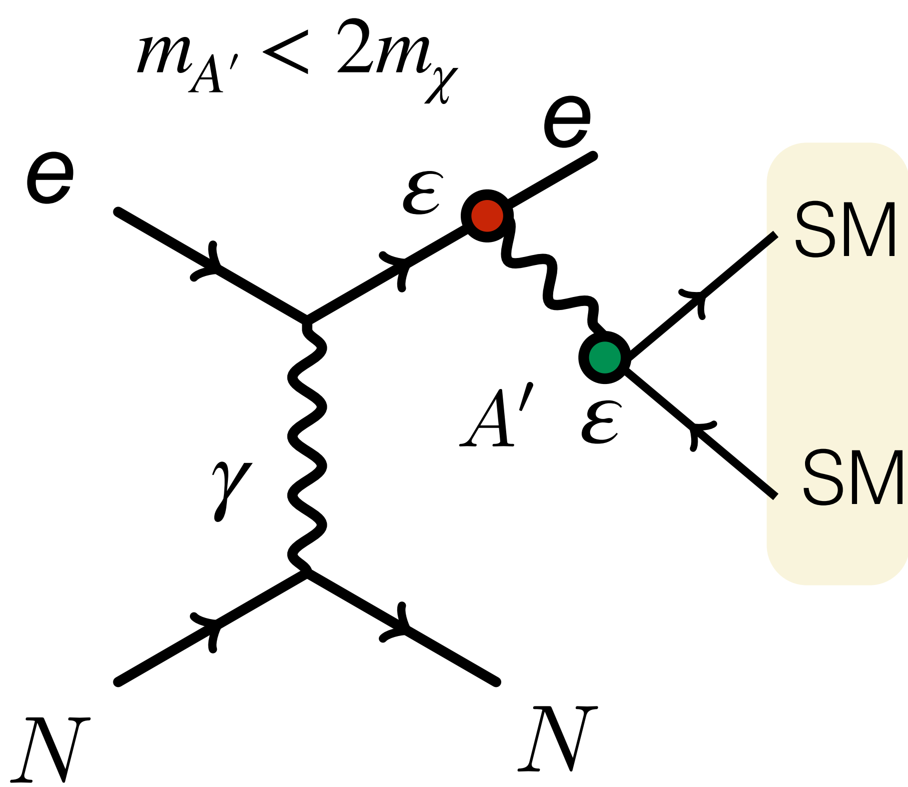


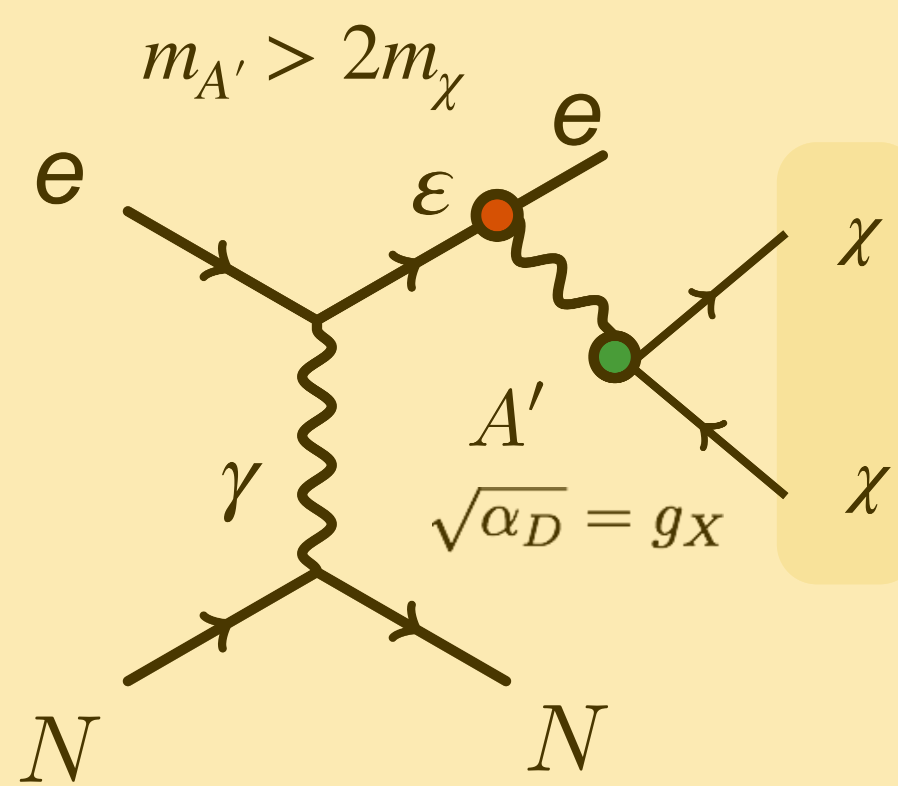
Focus of my talk

Setup:

Visible mode



Invisible mode



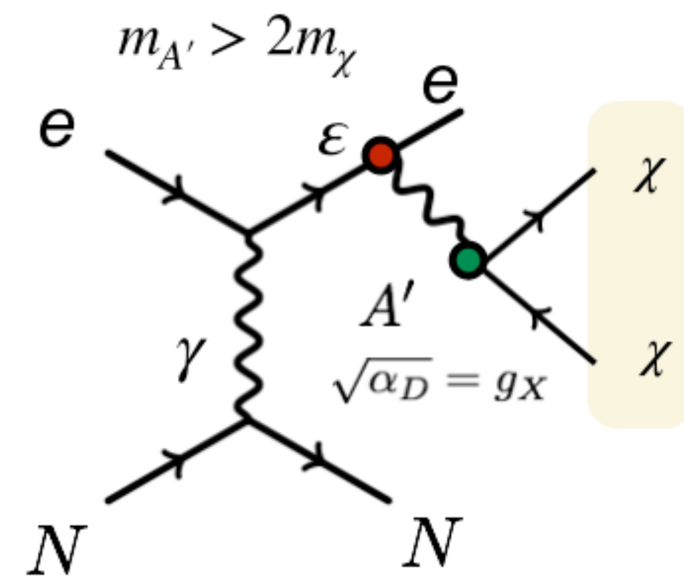
Signature:

SM particles pair production

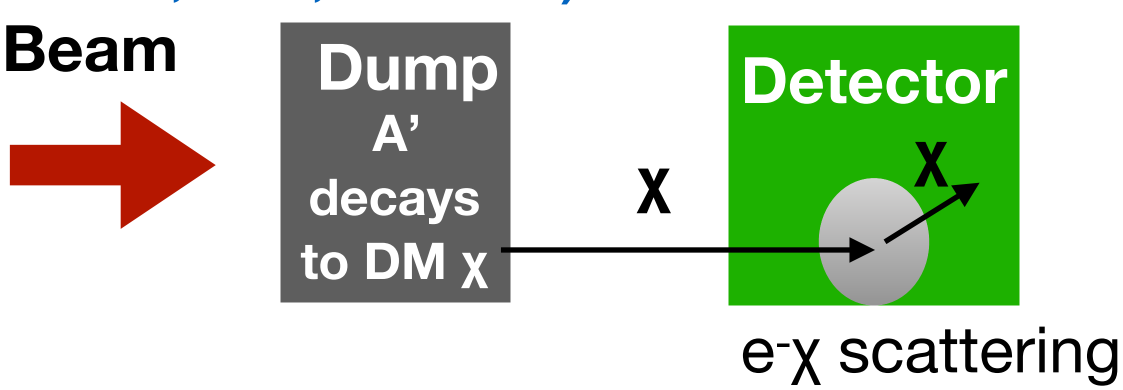
Missing energy

NA64 *invisible* searches

Invisible mode



1) BEAM DUMP APPROACH (MiniBooNE, LSND, NA62, SHIP, T2K, DUNE…)



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

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

2) NA64/LDMX APPROACH

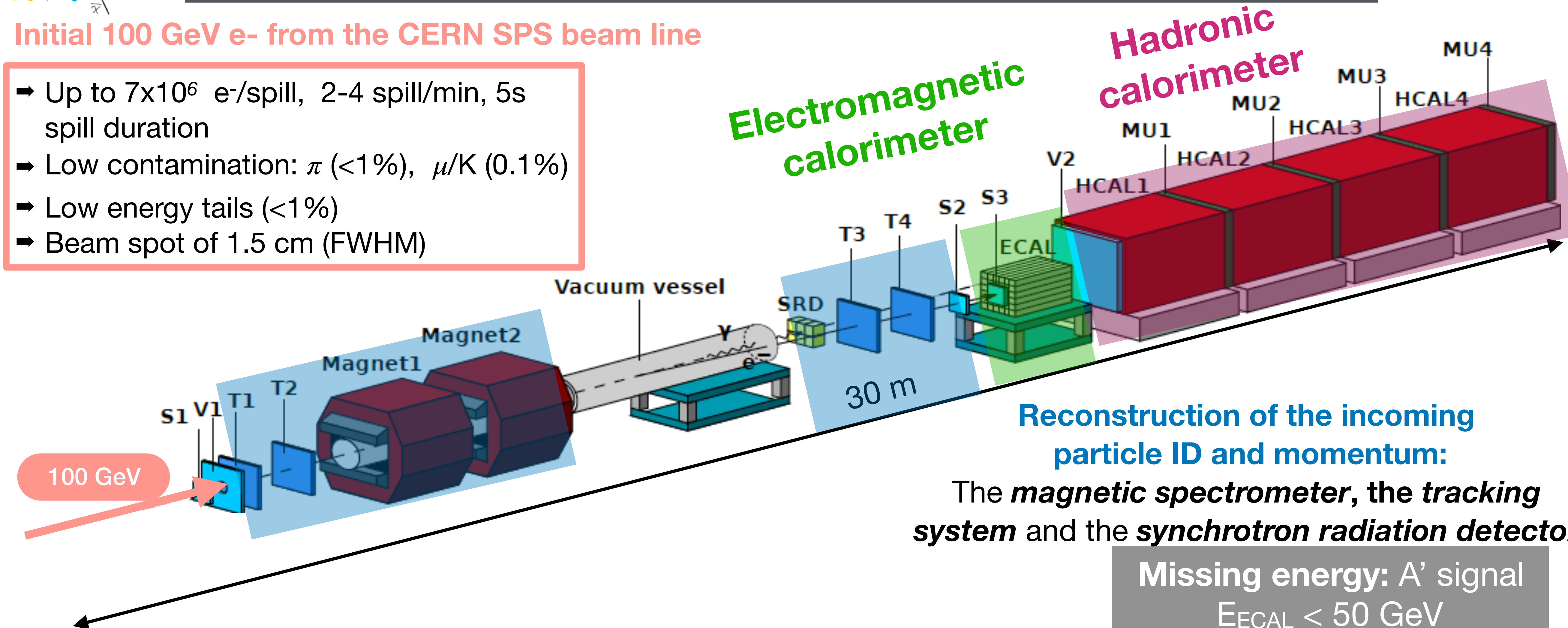
Produced A's carry away energy from the active dump.
Signal: Missing energy/momentum

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

NA64 *invisible* searches: the setup

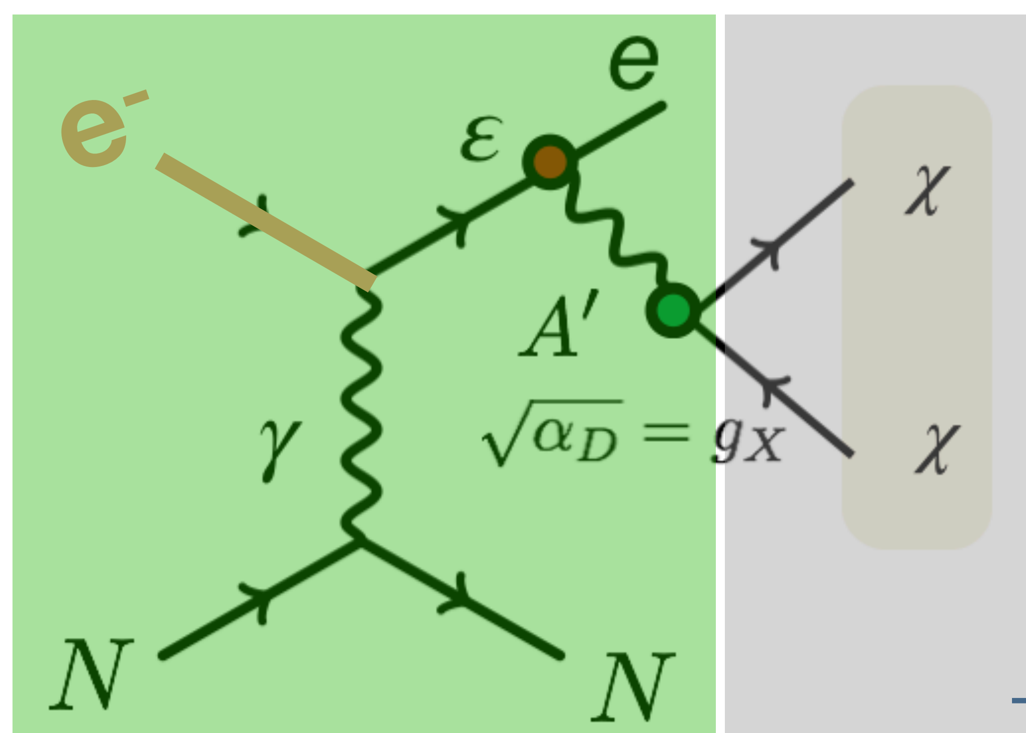
Initial 100 GeV e- from the CERN SPS beam line

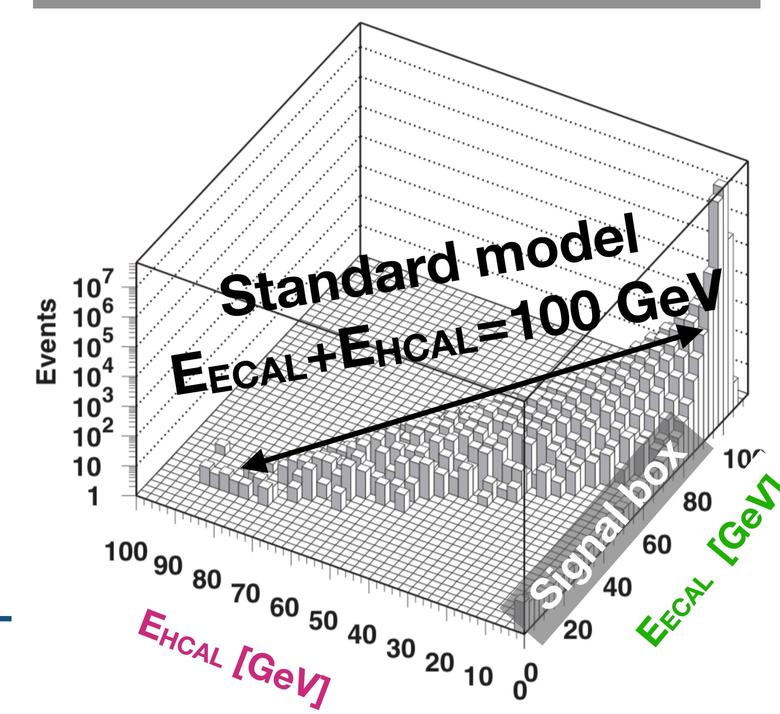
- ➡ Up to 7x10[6] e-/spill, 2-4 spill/min, 5s spill duration
- ➡ Low contamination: π (<1%), μ/K (0.1%)
- ➡ Low energy tails (<1%)
- ➡ Beam spot of 1.5 cm (FWHM)



Reconstruction of the incoming particle ID and momentum:
The ***magnetic spectrometer***, **the** ***tracking system*** and the ***synchrotron radiation detector***

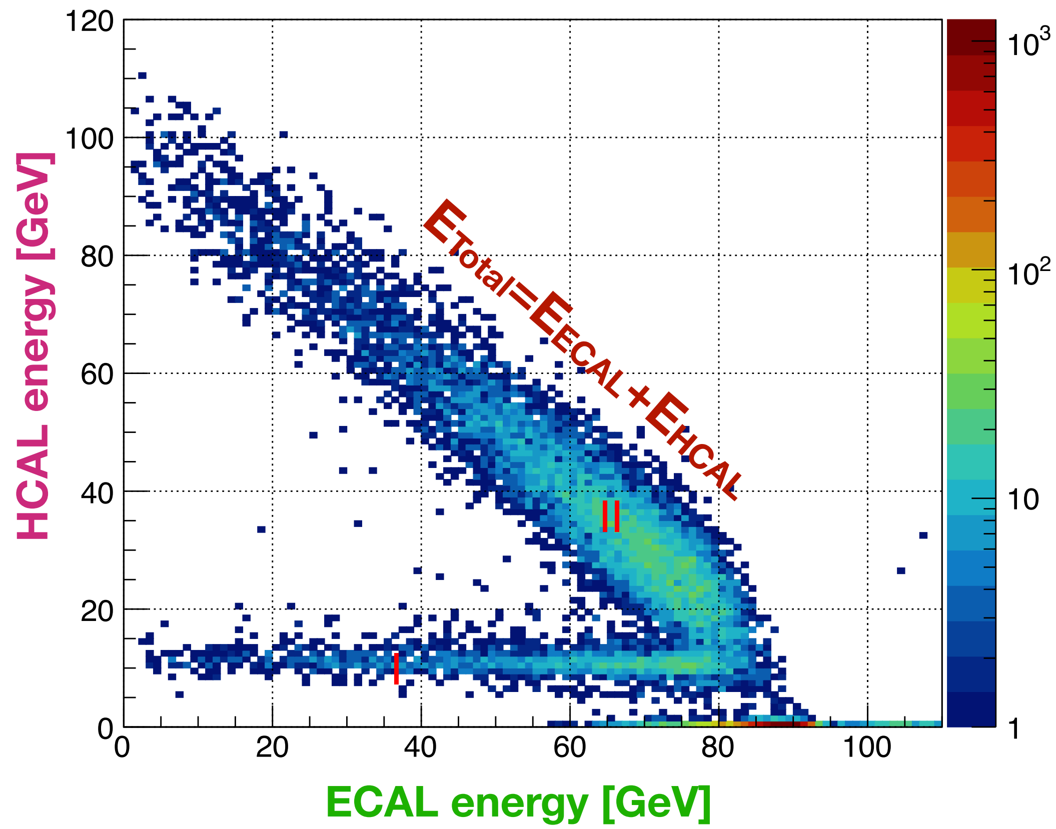
Missing energy: A' signal
E_{ECAL} < 50 GeV
E_{HCAL} energy < 2GeV





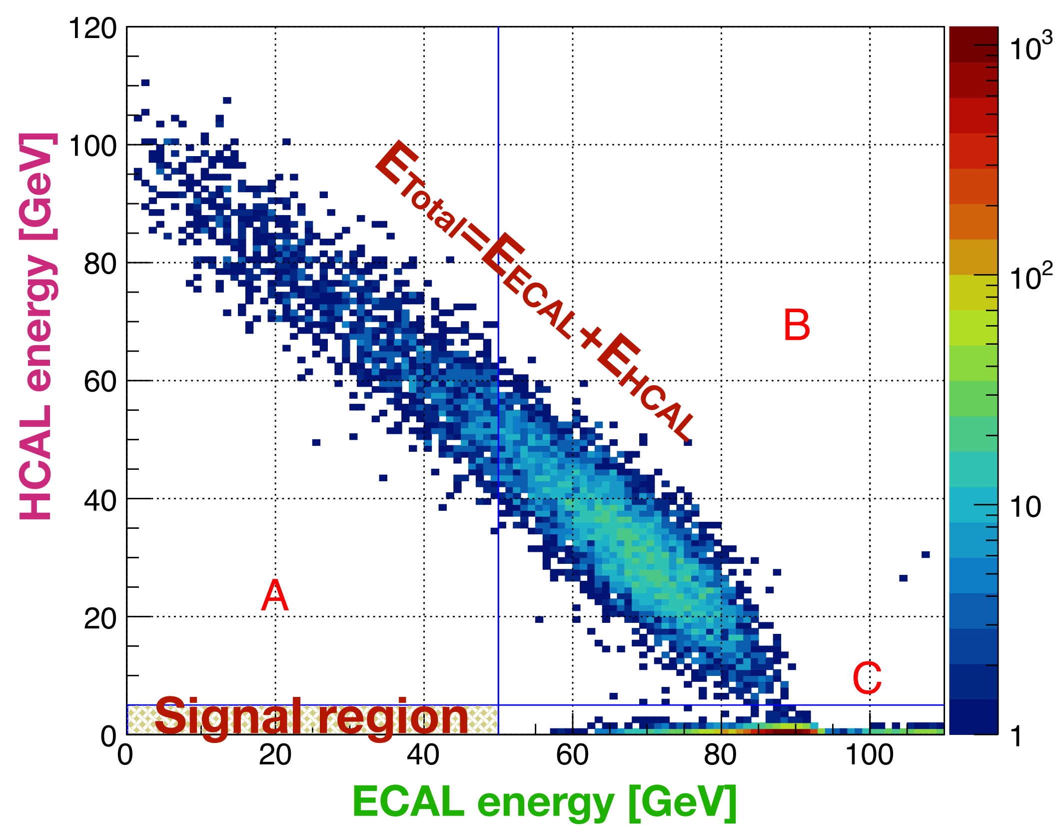
Active target

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

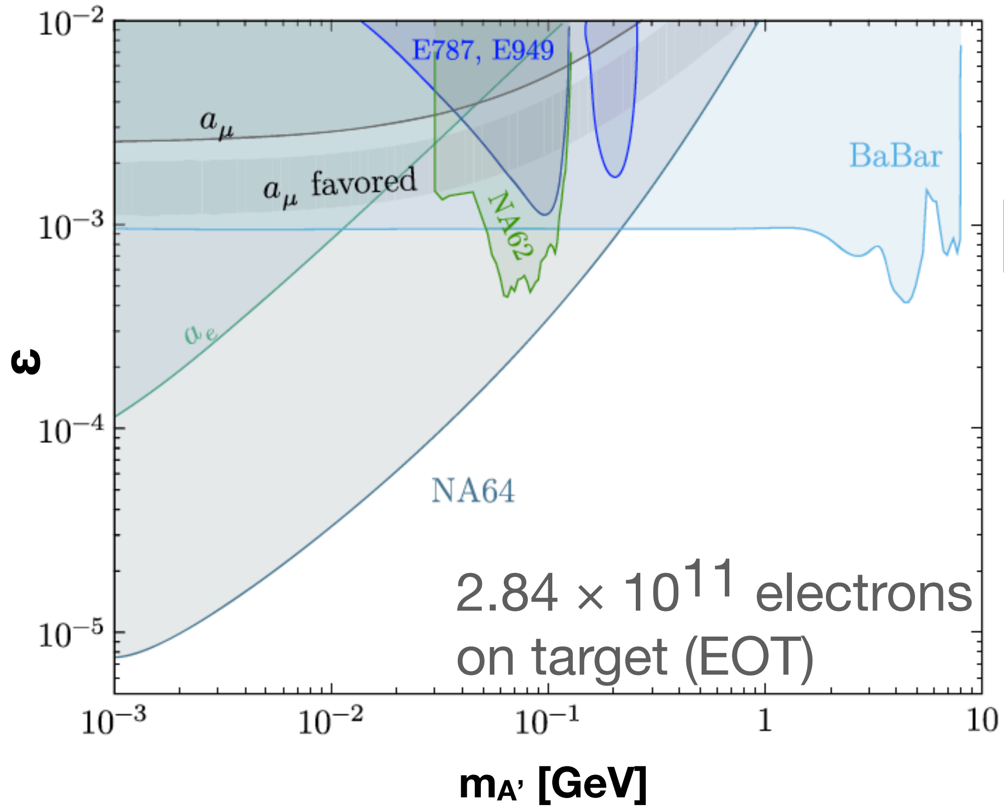


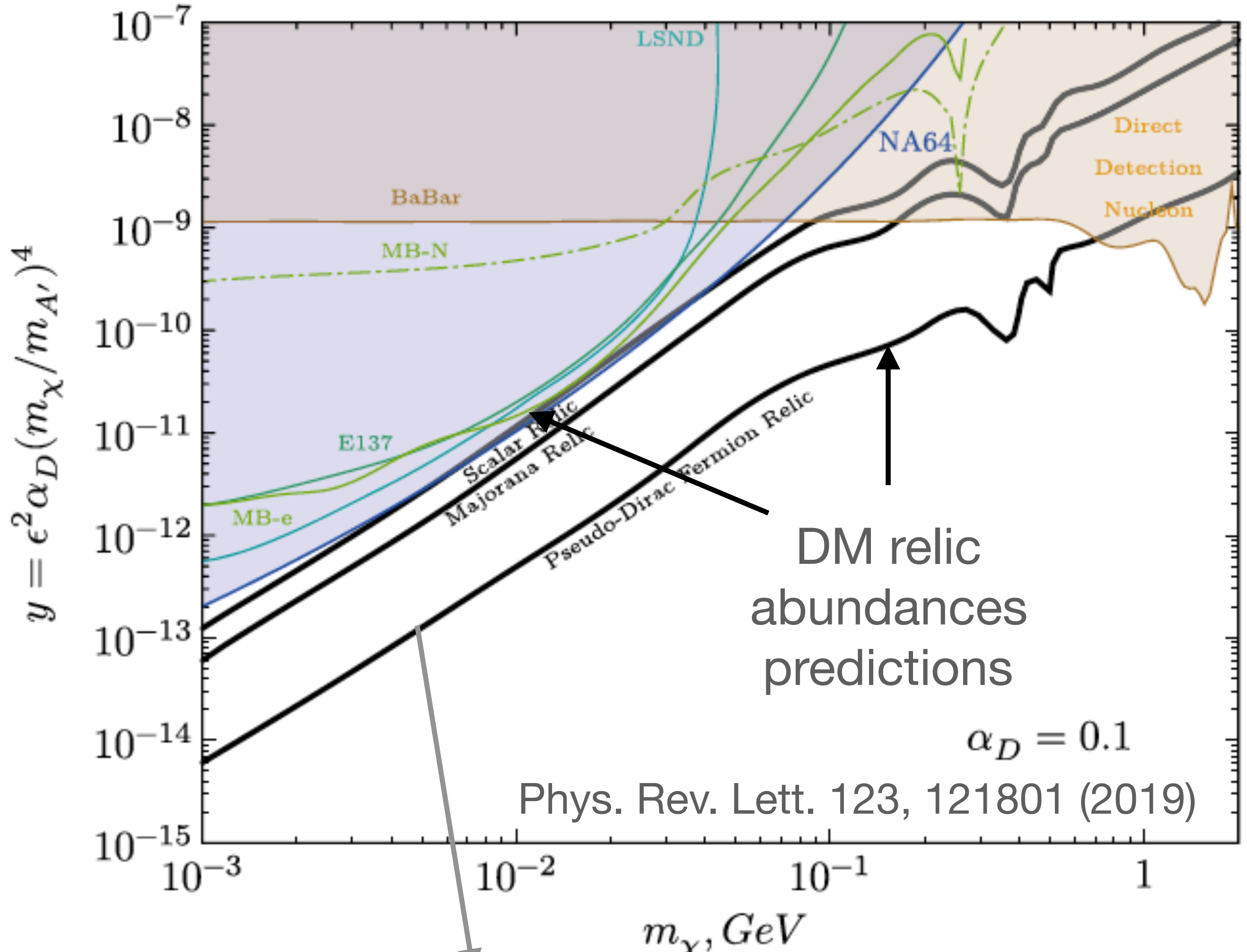
Event Selection Criteria:

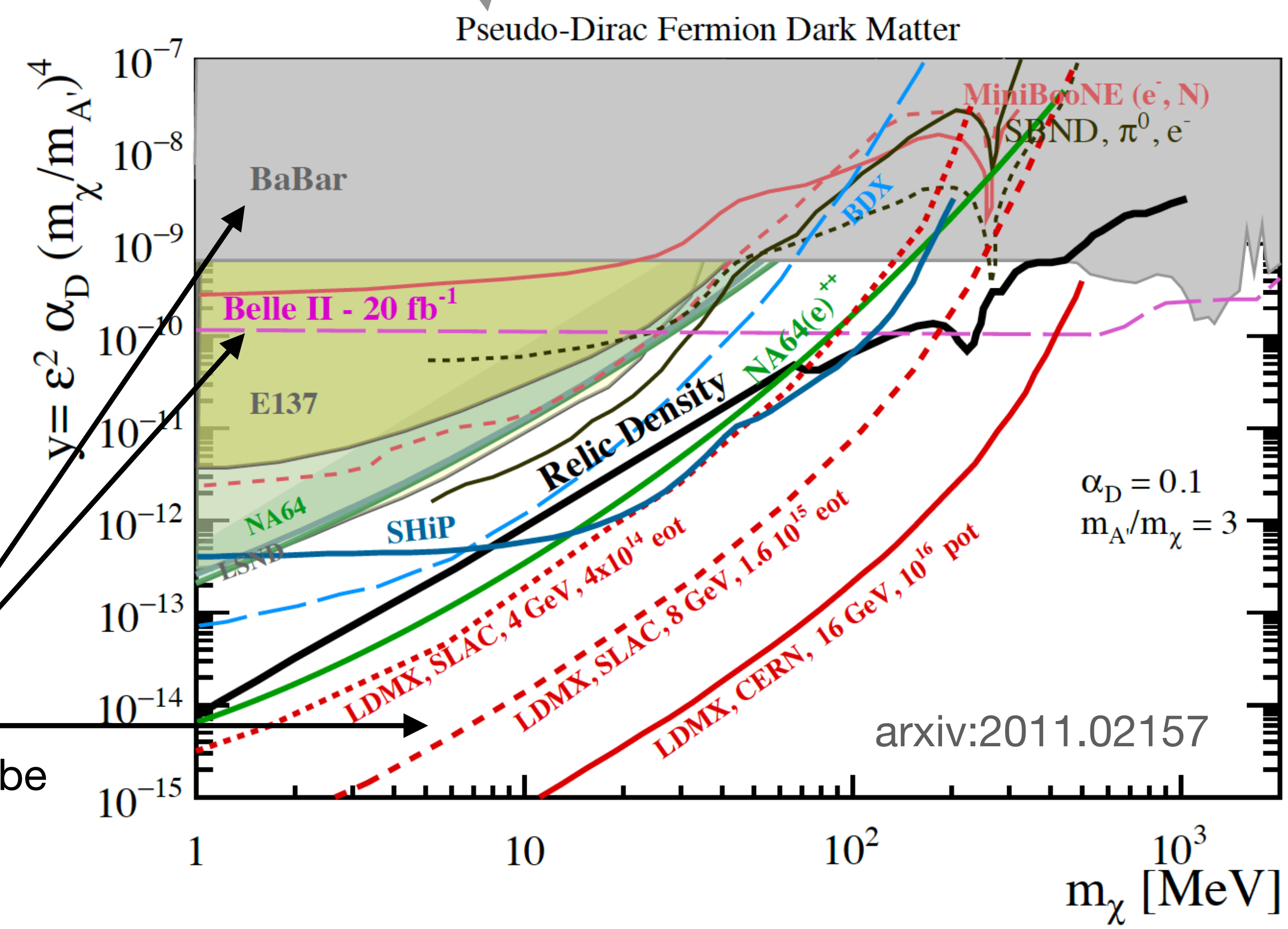
- *Timing information* → Pile up and noise suppression.
- *Clean incoming track:* angle + single hit in all trackers, momentum~100 GeV
- *Electron identification:*
  - Synchrotron radiation
  - Shower profile compatible with e- in ECAL → Hadron suppression
- *No punchthrough:* No activity in Veto and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

Results

Constraints on LTDM models





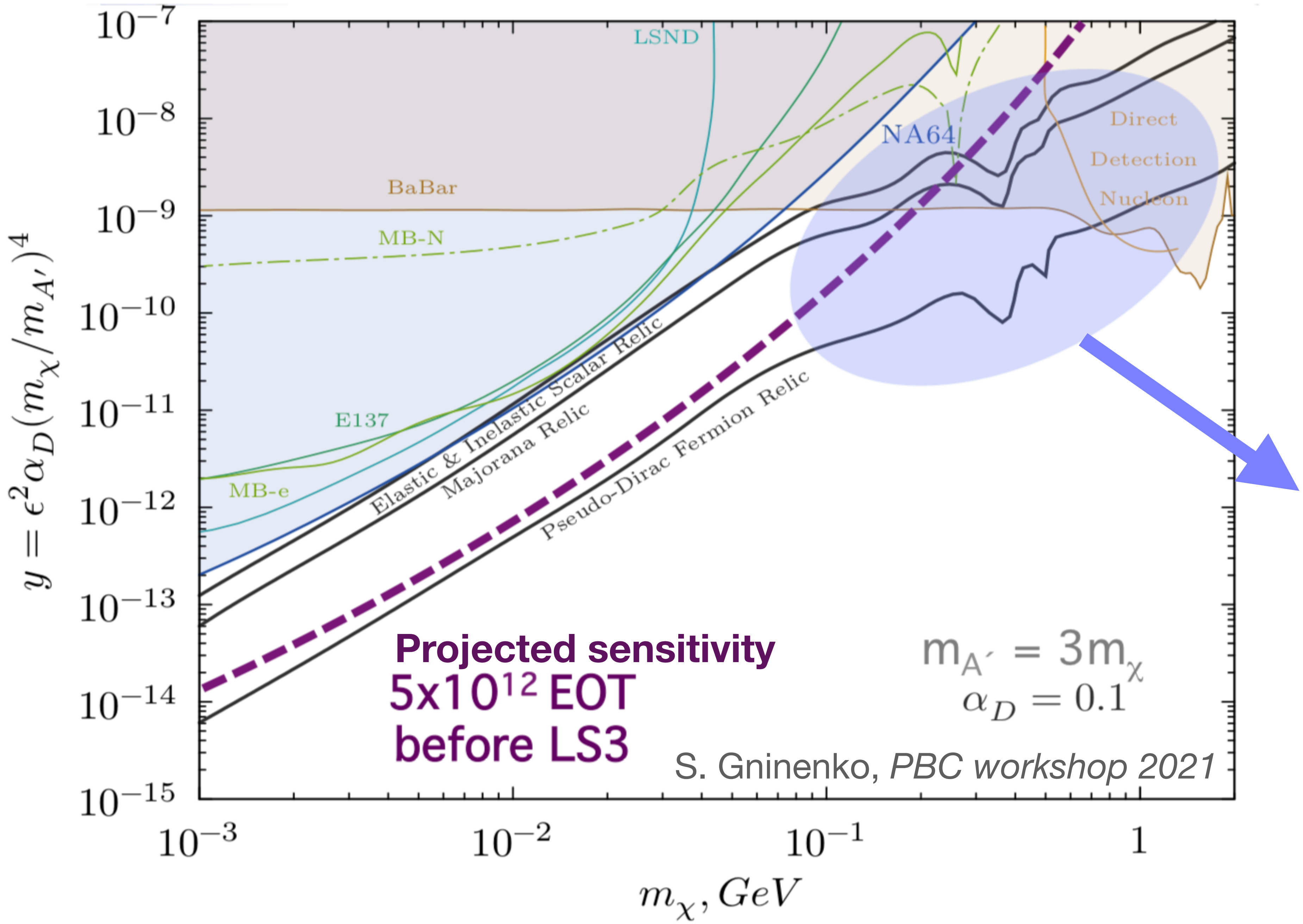


Proportional to **DM<->SM annihilation cross-section**

For the first time NA64 constraints better than in previous experiments and very close to LTDM benchmark models

See talks by B.Shuve, L. Tompkins and J.Strube

Future prospects in 2021



Resume data taking this year

- New fixed location at H4 beam line
- Beam and setup upgrade

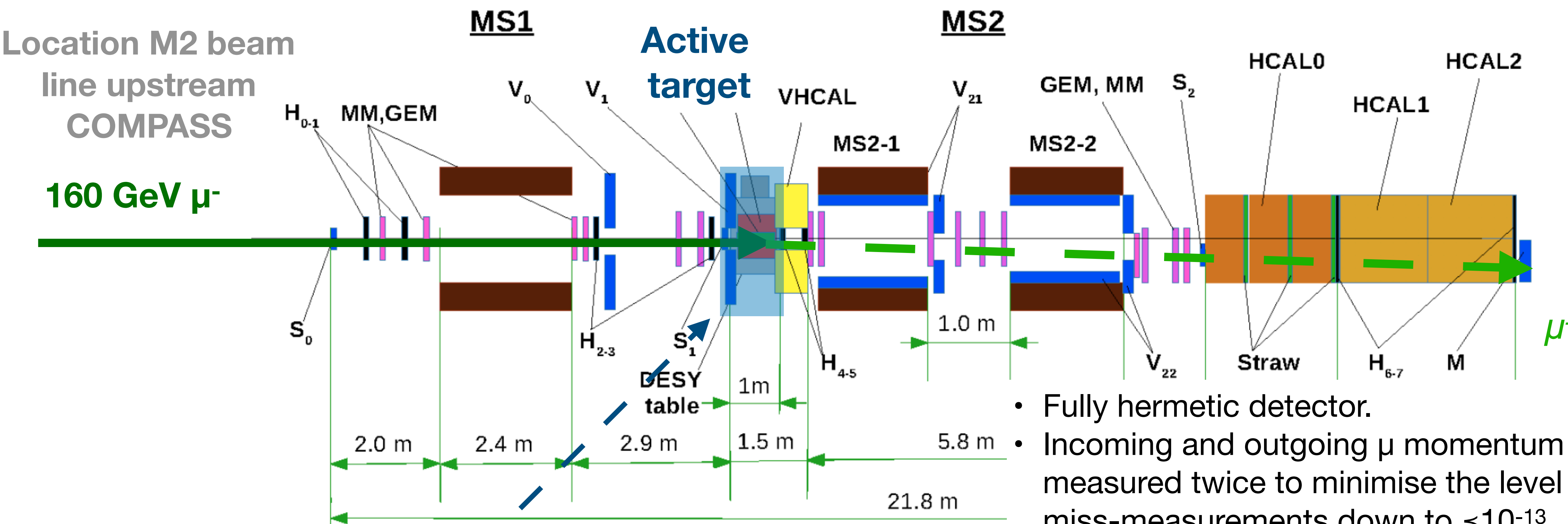
How can we enlarge the sensitivity at higher masses?

New ideas:

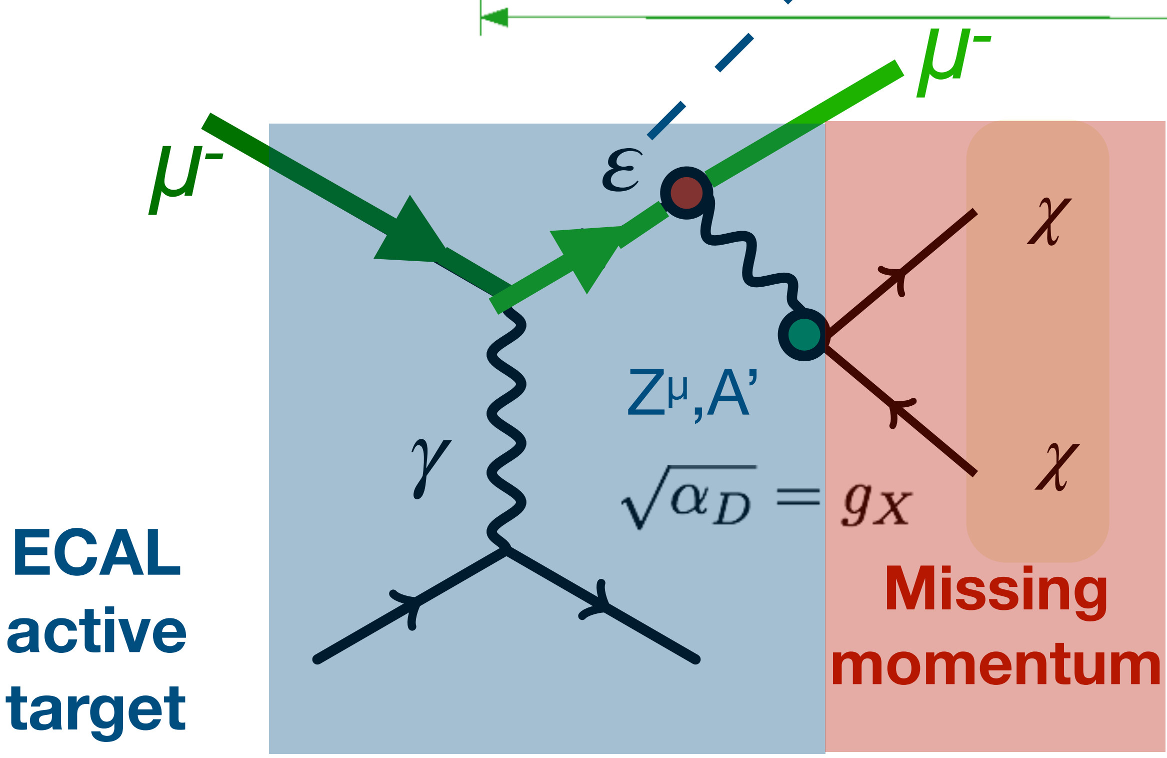
- **A' resonant production**
  L. Marsicano et al. Phys. Rev. Lett. 121, 041802
- **Use a muon beam**
  S.Gninenko et al. PLB796, 117 (2019)

Future prospects: NA64e + NA64$_\mu$

Exploring dark sector physics weakly coupled to muons



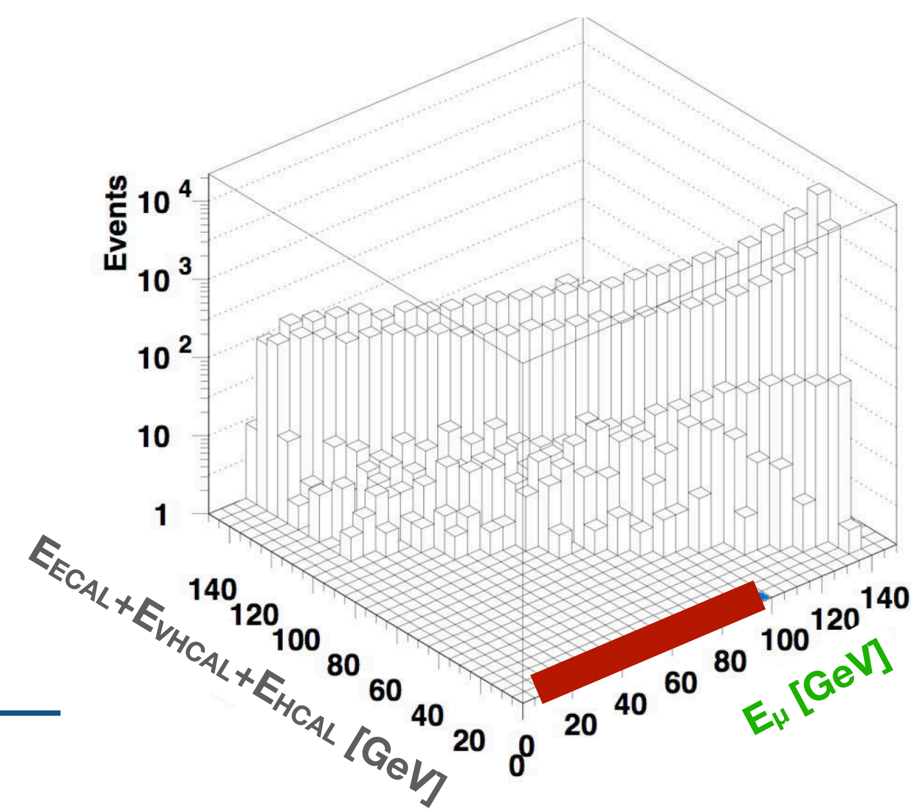
- Fully hermetic detector.
- Incoming and outgoing μ momentum measured twice to minimise the level of its miss-measurements down to ≲10^{-13} .



Z^μ,A' decaying to DM particles

Signature

- Missing momentum (Deflected μ- energy <80 GeV).
- No energy on ECAL, VHCAL and HCAL (meaning compatible with a MIP energy).



Future prospects: NA64$_\mu$ physics goals

1. **Light Z' coupled to the muon**, as a remaining low mass explanation of the $(g-2)_\mu$ (the muon anomaly).
2. **Light Dark Matter** interacting with the Standard Matter via dark photon A' 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.

LS2 | LS3

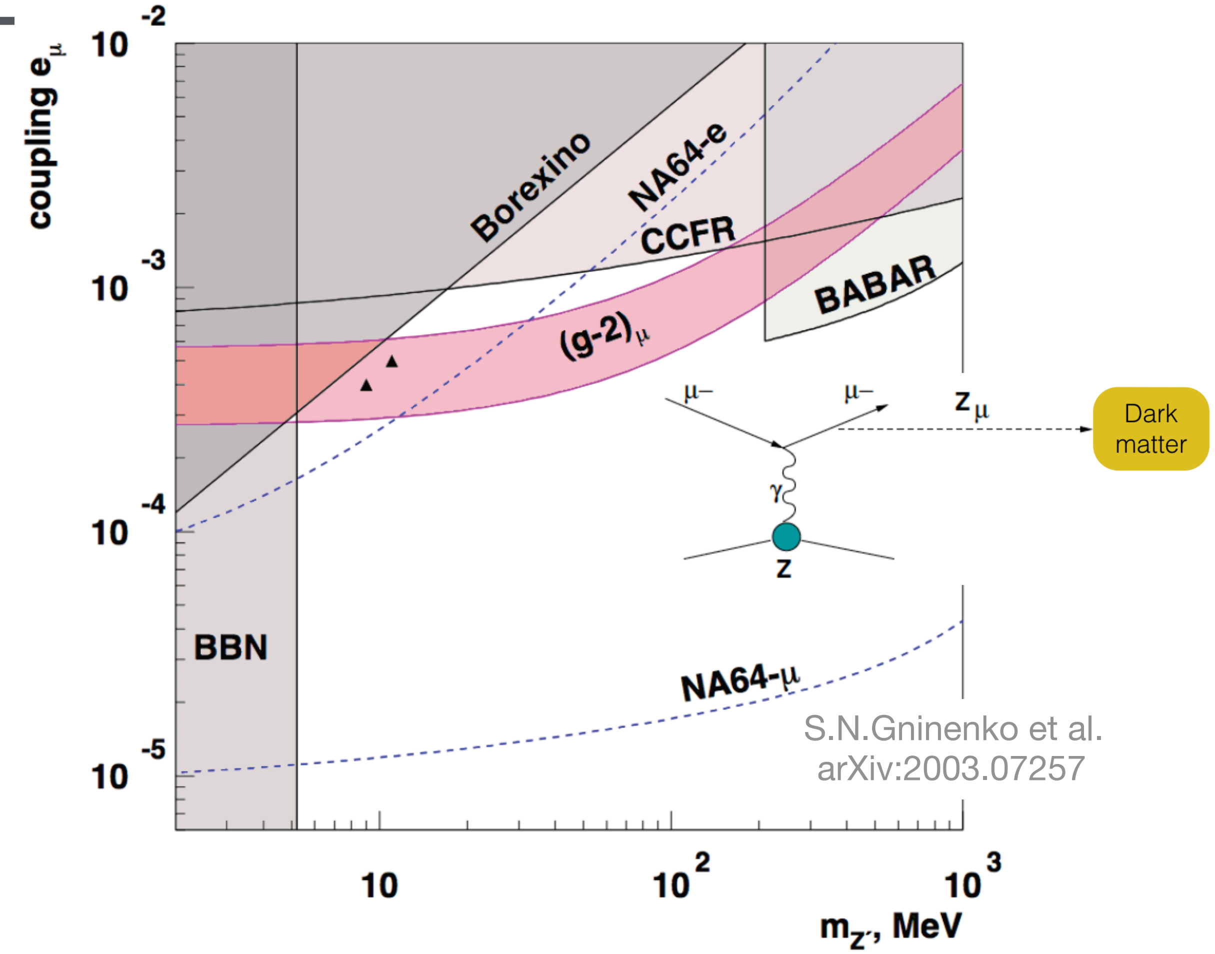
2020 | 2021 | 2022 2023 | 2024

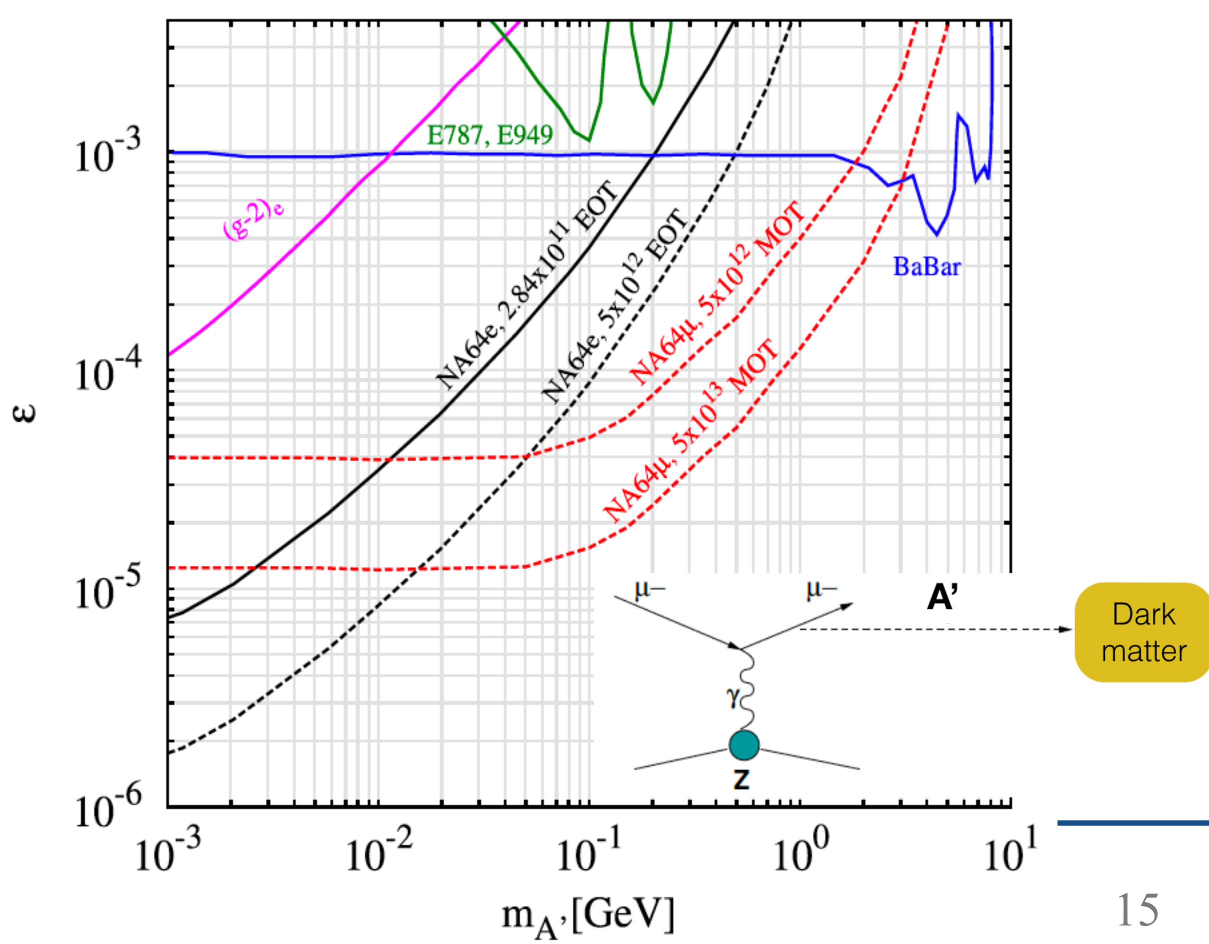
Pilot run | **Phase 1** | **Phase 2**

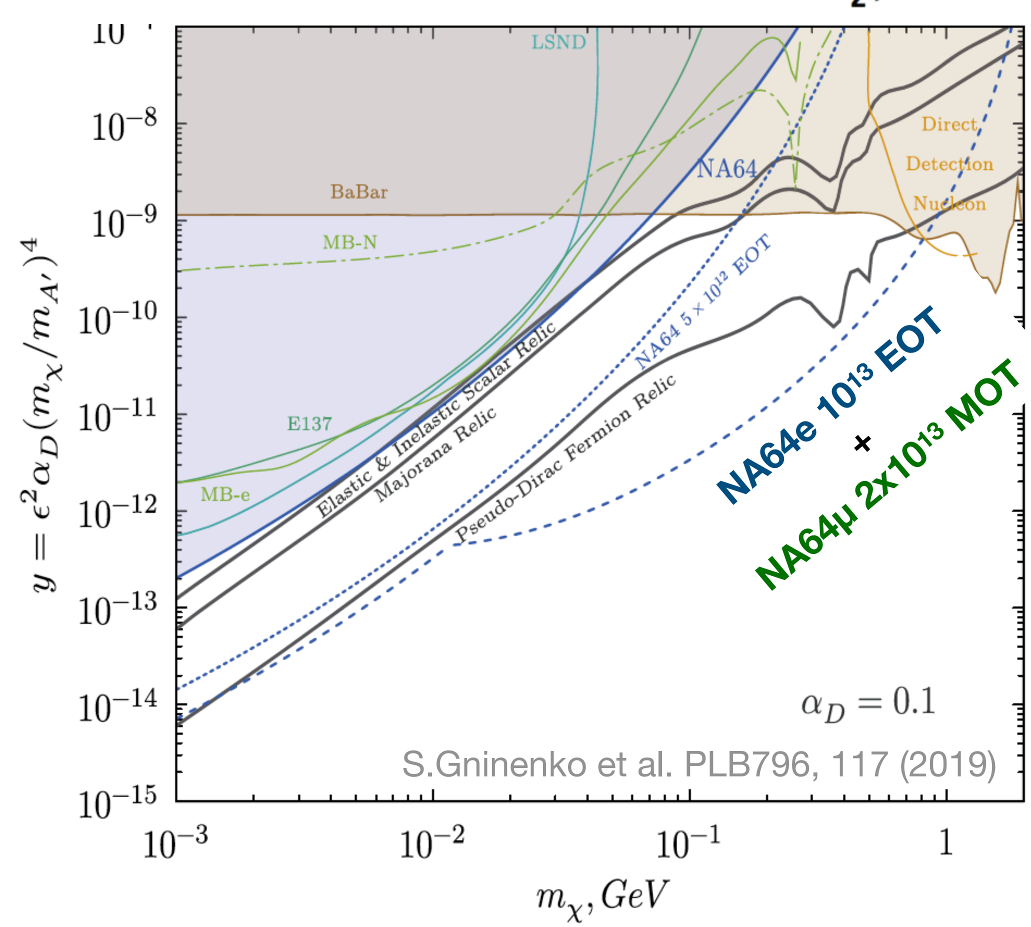
Already approved
Feasibility studies

Phase 1: Expected first physics runs to *probe Z' as $(g-2)_\mu$ explanation*

Phase 2: *cover high A', Z' masses*

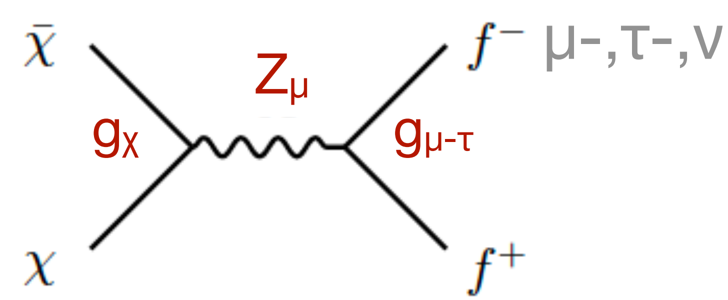






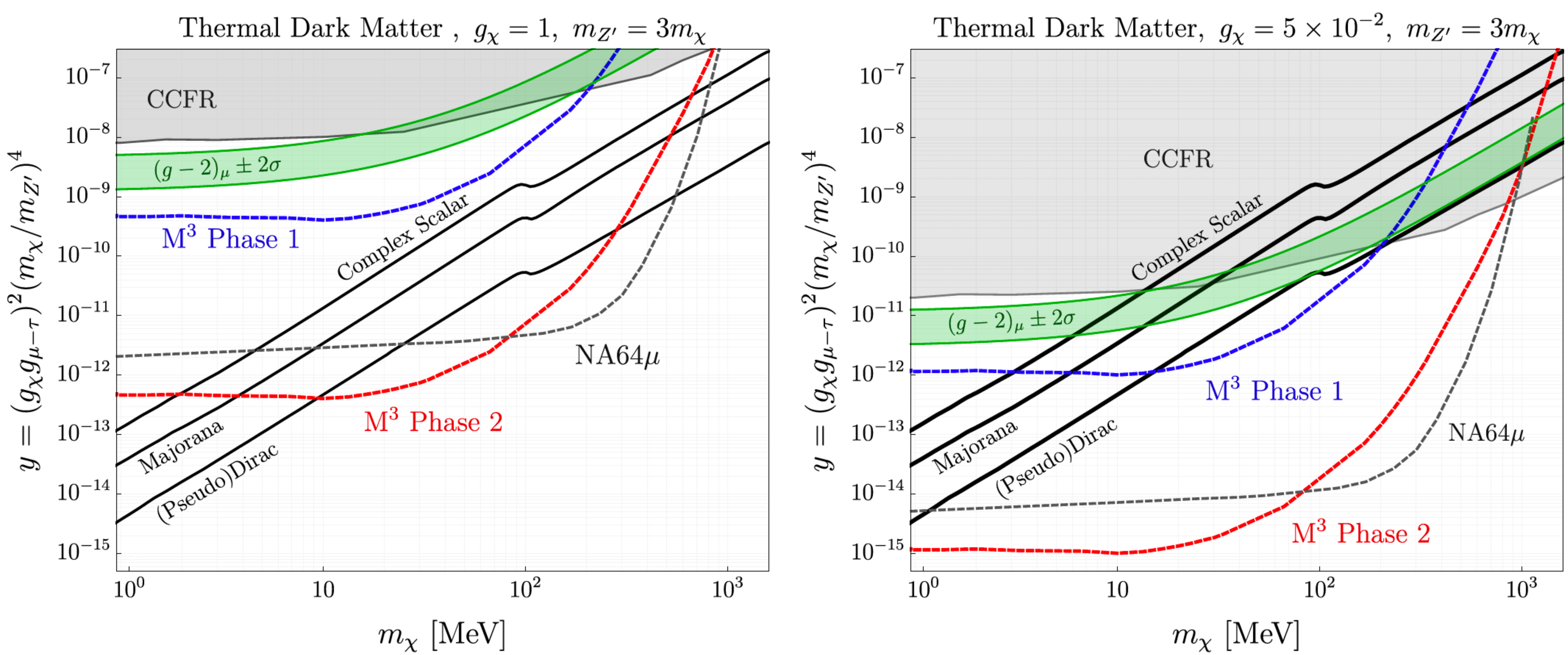
Future prospects: NA64$_\mu$ physics goals

Dark Matter generated via a new massive Z_μ boson from broken $U(1)'_{L\mu-L\tau}$



$$< \sigma v > \propto g_\chi^2 g_{\mu-\tau}^2 \frac{m_\chi^2}{m_{Z'}^4} = \frac{y}{m_\chi^2}$$

$m_{Z\mu} > 2m_\chi$: $Z_\mu \rightarrow \chi\chi$



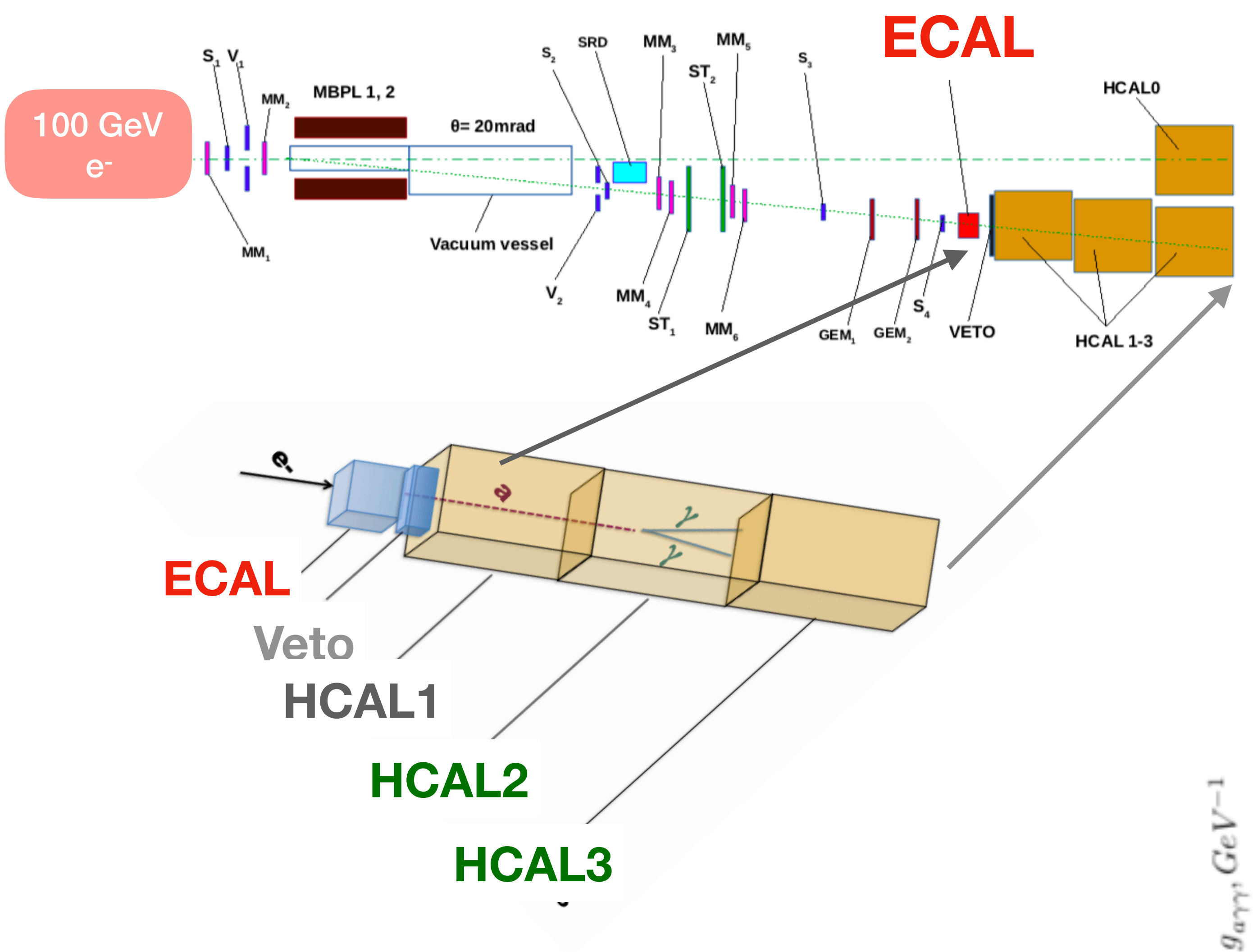
"M³: A New Muon Missing Momentum Experiment to Probe (g−2)μ and Dark Matter at Fermilab", arxiv:1804.03144

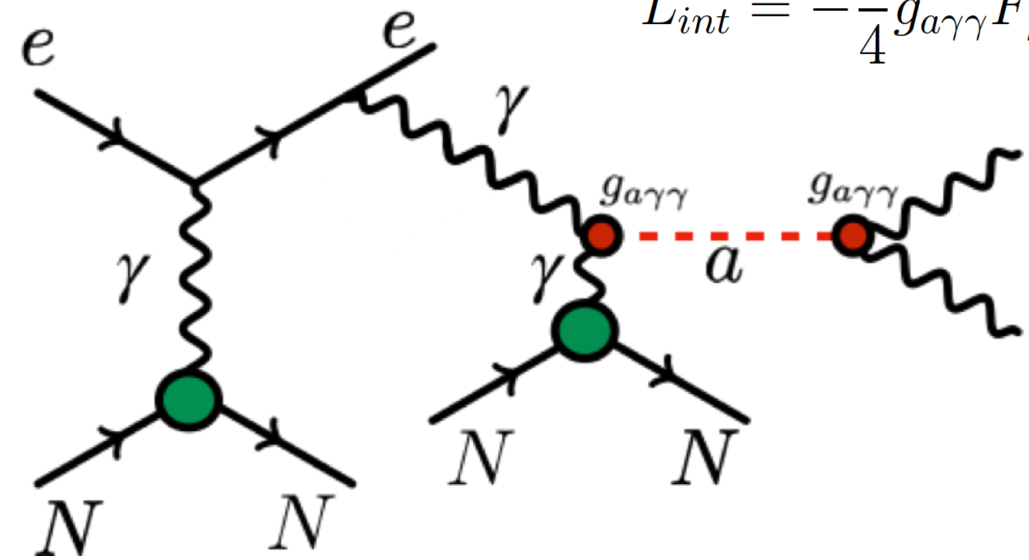
ALPs searches @NA64

ALPs predominantly coupled to photons produced via Primakoff effect

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

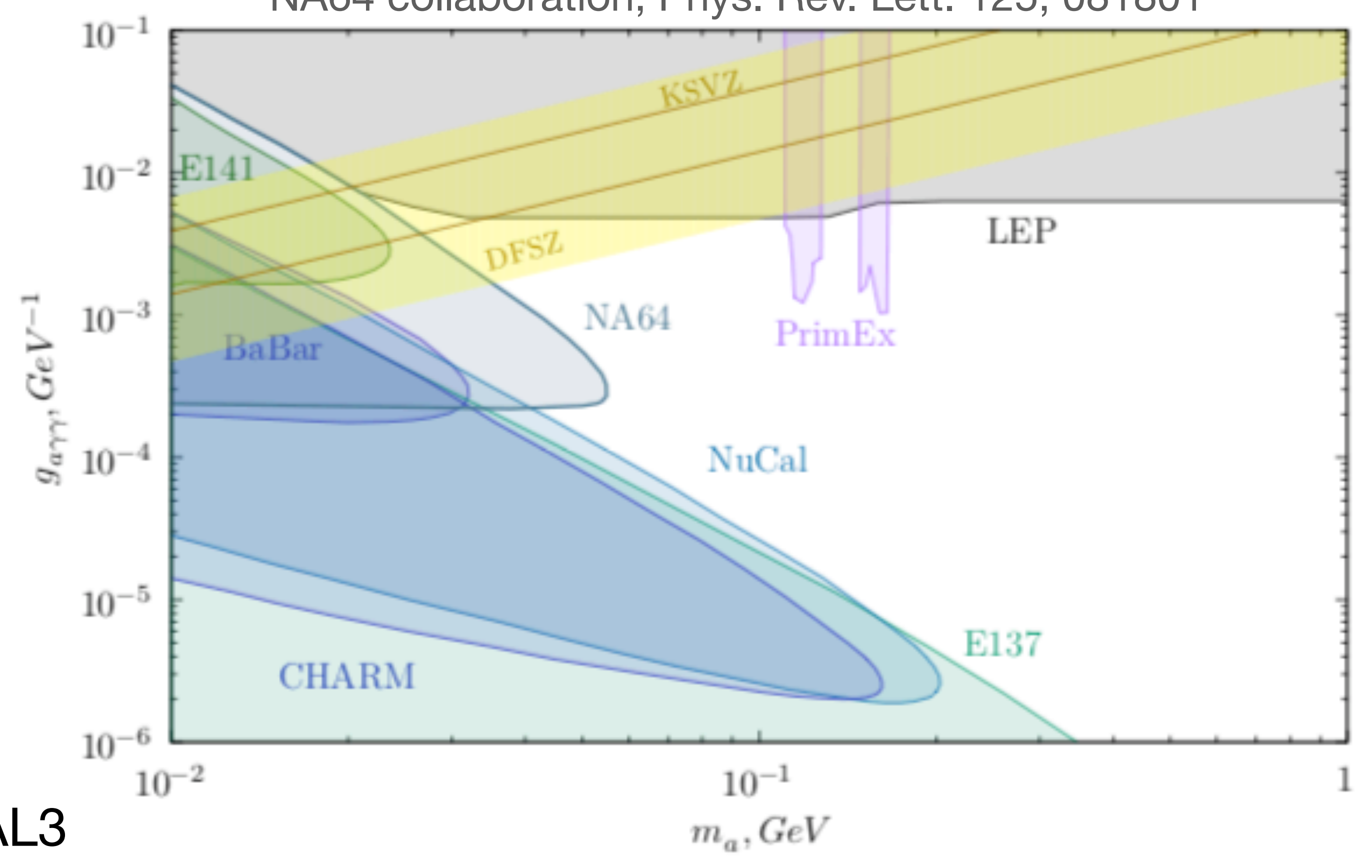
NA64 invisible setup





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

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



Signature:

No signal on veto and HCAL1

+

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

B. ***Decays after HCAL3:*** no activity on HCAL2 & HCAL3

Constraints on new physics in $(g\text{-}2)_e$

$$\Delta a_e = a_e^{exp} - a_e^{LKB} = (4.8 \pm 3.0) \times 10^{-13} \text{ (1.6σ)}$$

$$\Delta a_e = a_e^{exp} - a_e^{B} = (-8.8 \pm 3.6) \times 10^{-13} \text{ (-2.4σ)}$$

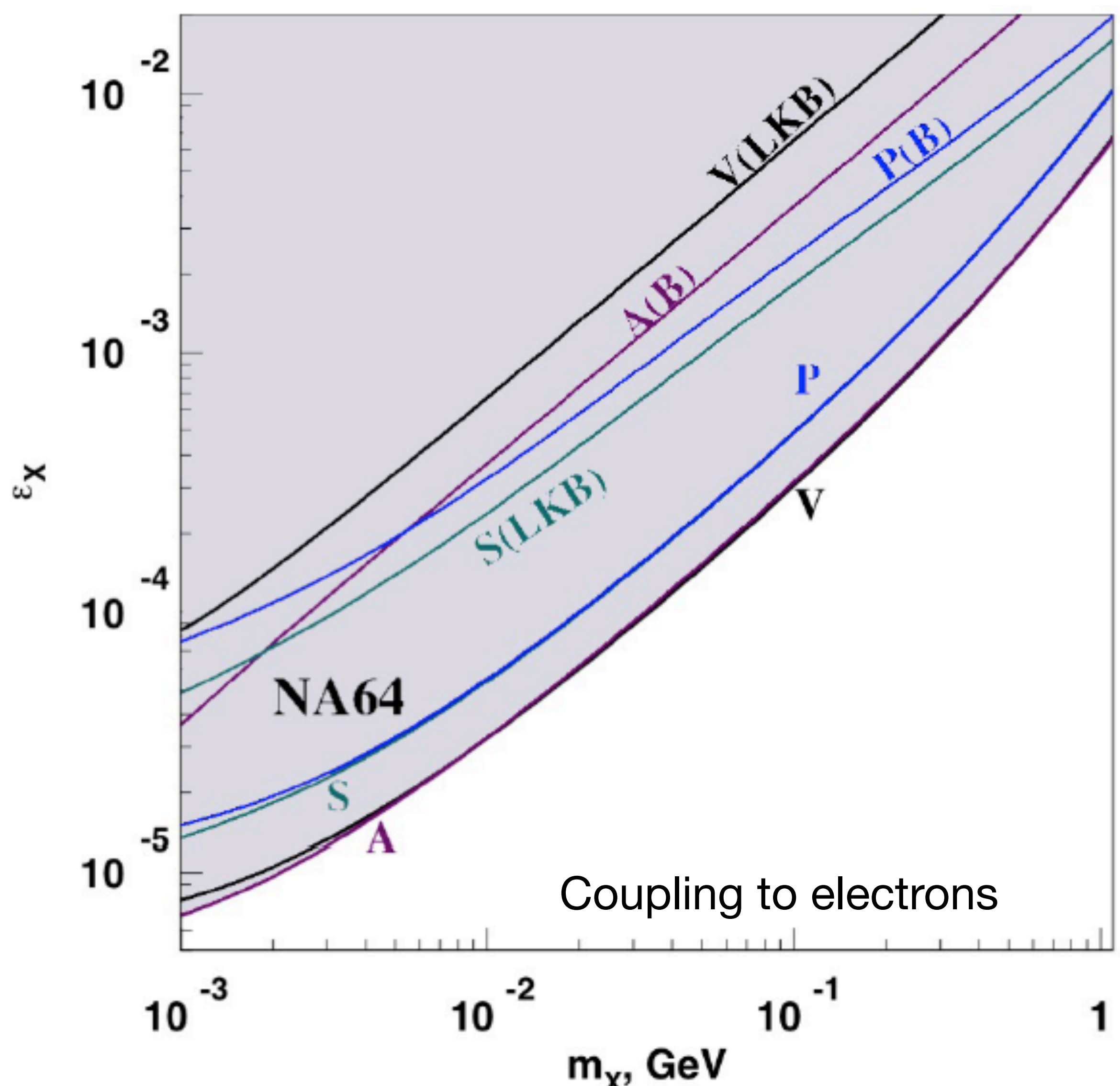
Results from high precision measurements of α at LKB and Berkley

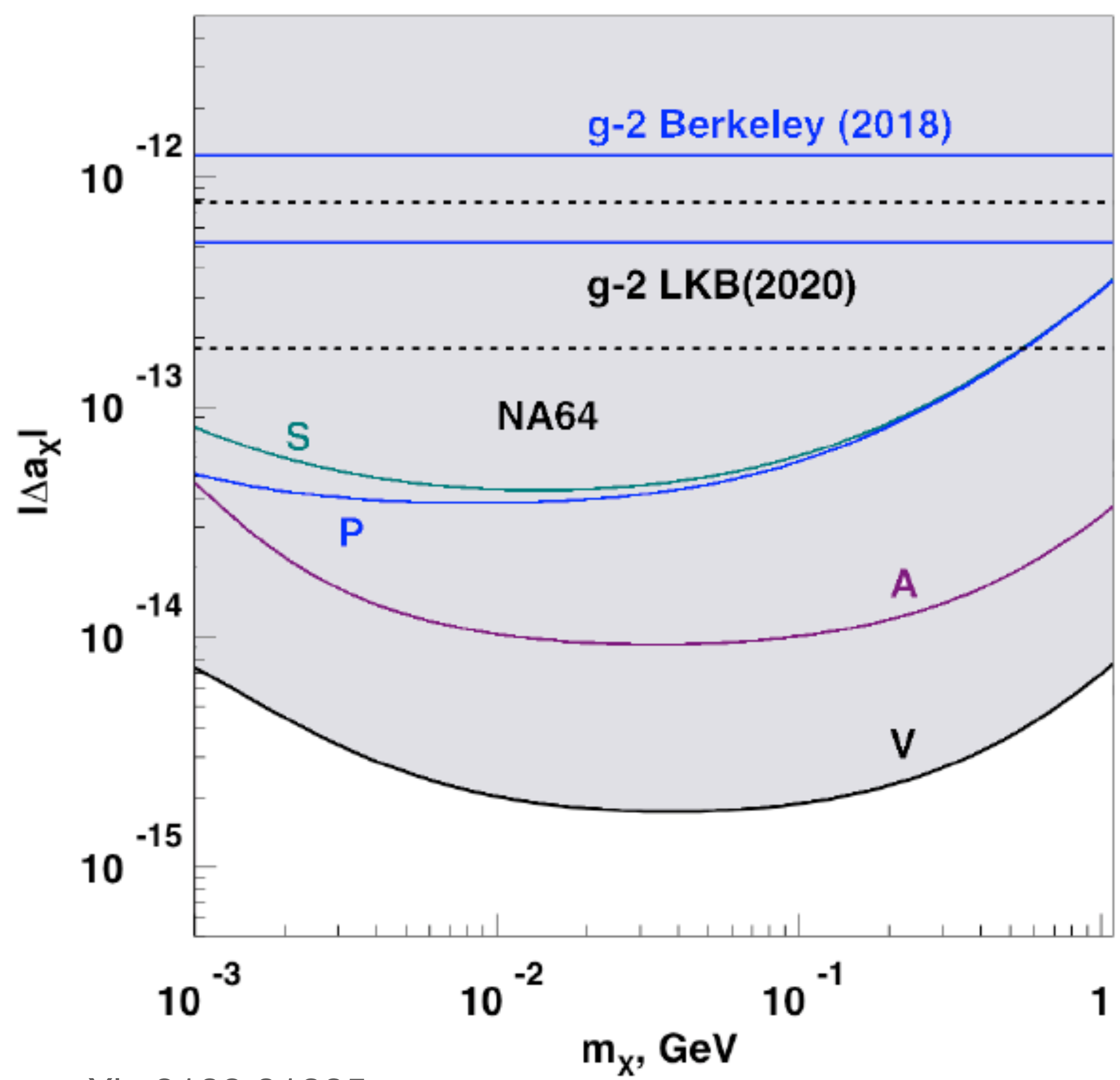
Differences due to unknown experimental error at present or might be an indication of new physics?

Could a new generic boson contribute to $(g\text{-}2)_e$?

$e^- Z \rightarrow e^- Z X; X \rightarrow$ **invisible** *X could be S,P, V or A*

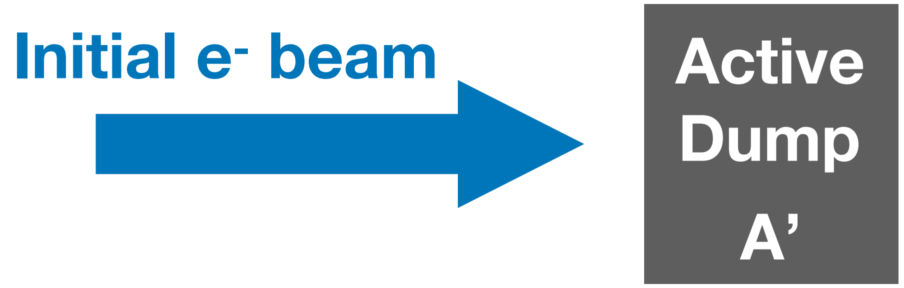
1-loop contributions of S,P,V or A to Δa_e





NA64 collaboration, arXiv:2102.01885

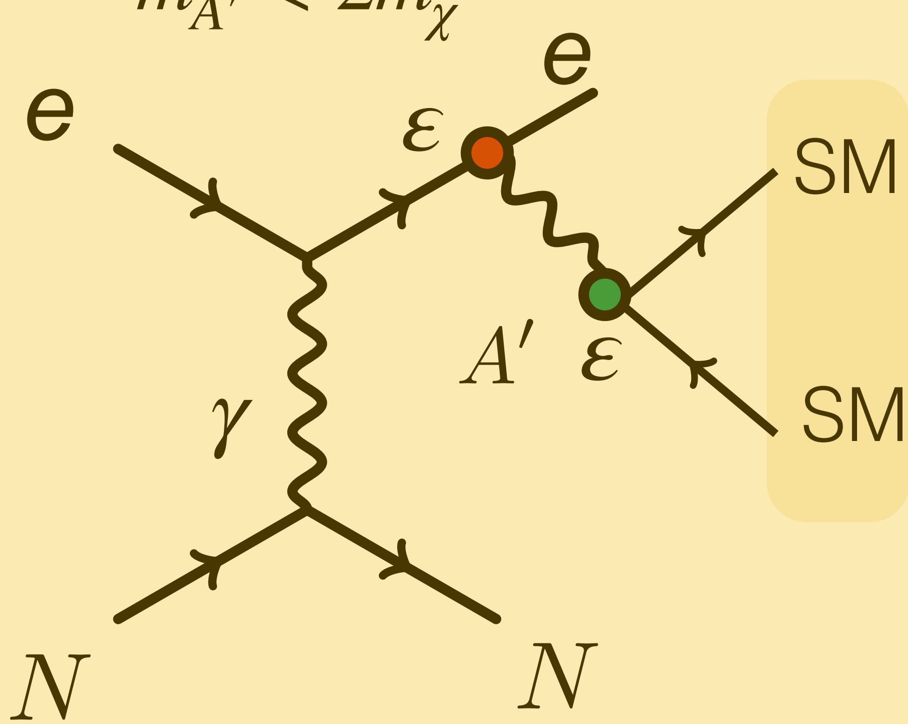
NA64 *visible* searches



Setup:

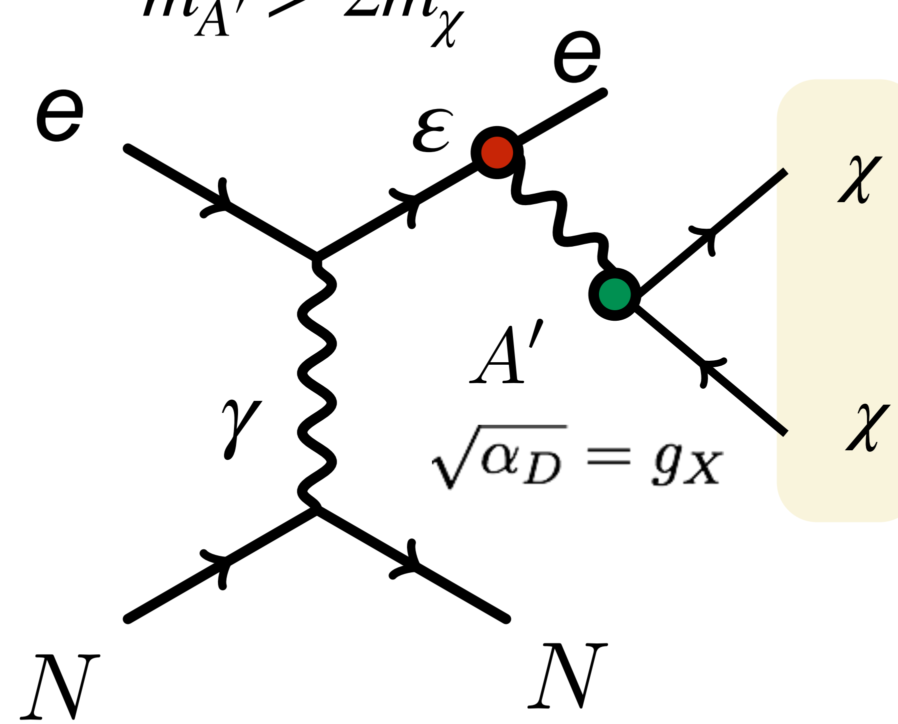
Visible mode

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



Invisible mode

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

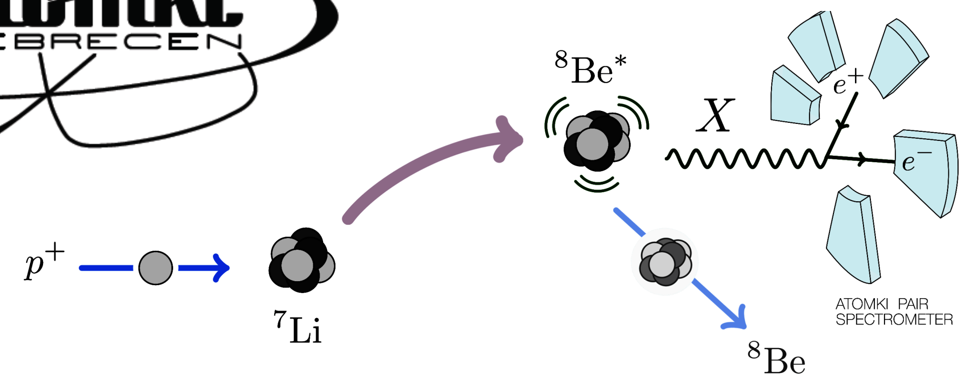


Signature:

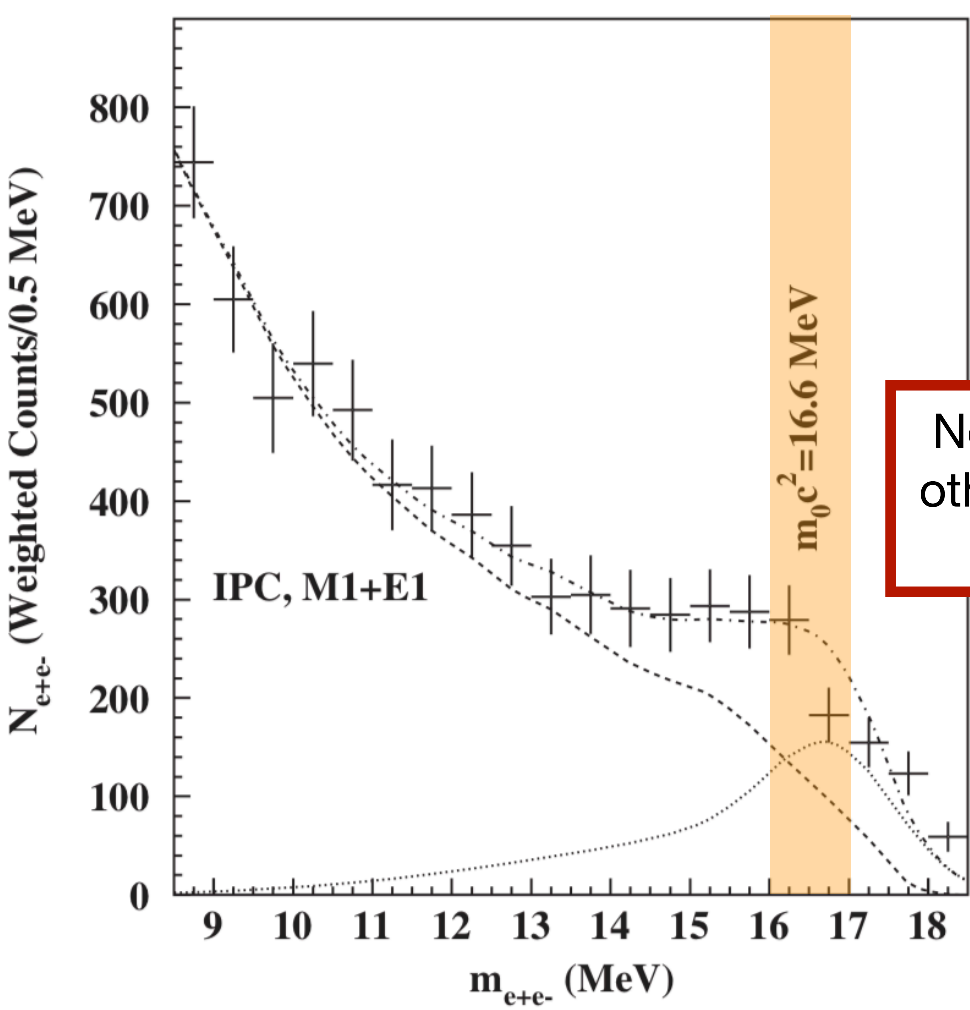
SM particles pair production

Missing energy

Additional motivation: ^{8}Be anomaly



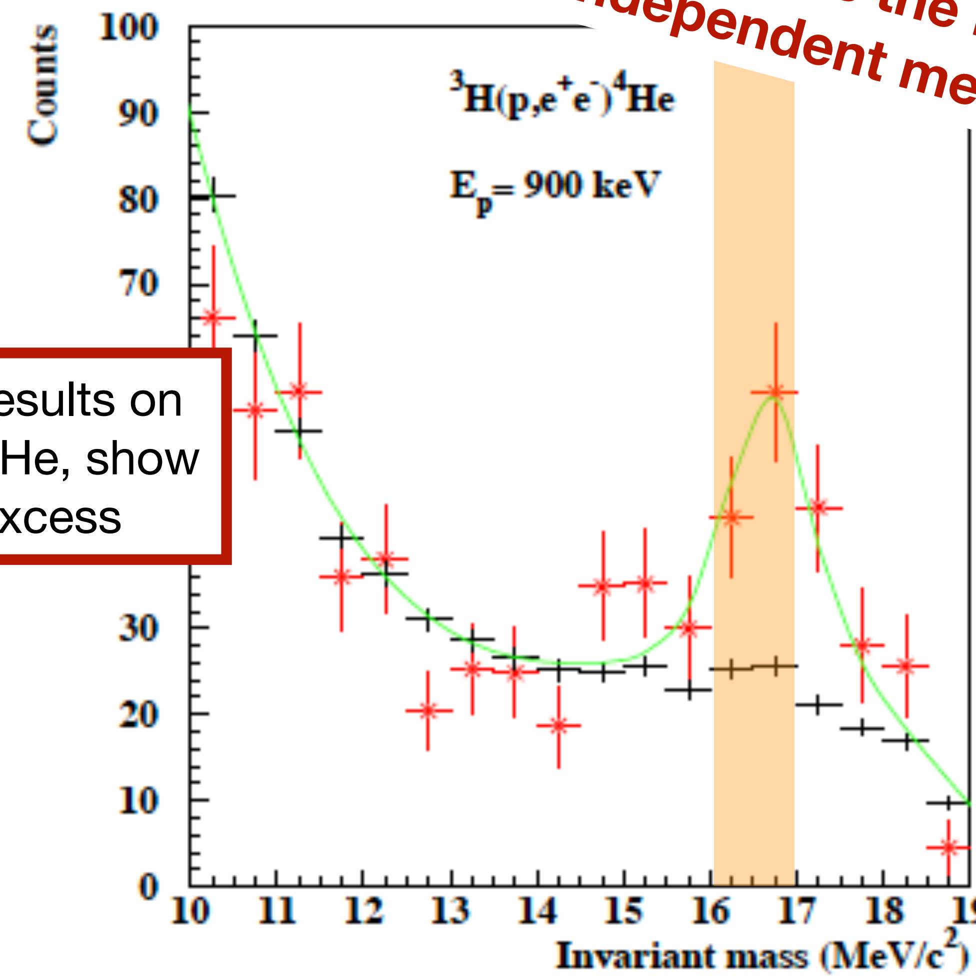
- *Scalar, pseudo-scalar, vector, axial-vector* models could explain the anomaly (large literature)
- NA64 addresses the search for X17 in a model independent way, just assuming its non-zero coupling with electrons.
- Vector model used as benchmark.



A.J. Krasznahorkay et al. Phys. Rev. Lett.116, 042501 (2015)

New recent results on other nuclei, ^{4}He, show a similar excess

Motivates the need of an independent measurement

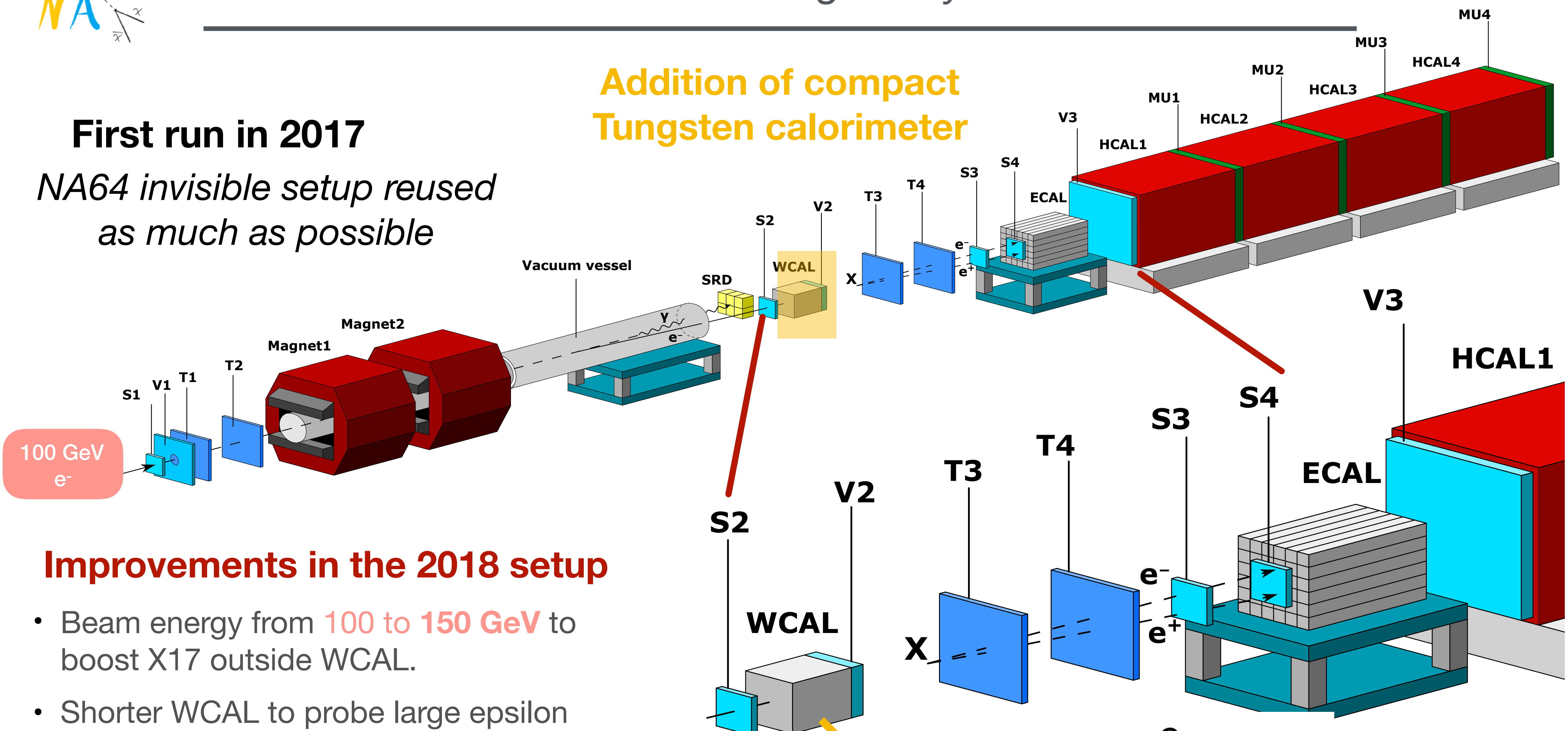


A. J. Krasznahaorkay et. Al Arxiv:1910.10459 (2019)

NA64 *visible* searches. *Challenge: very short-lived X17*

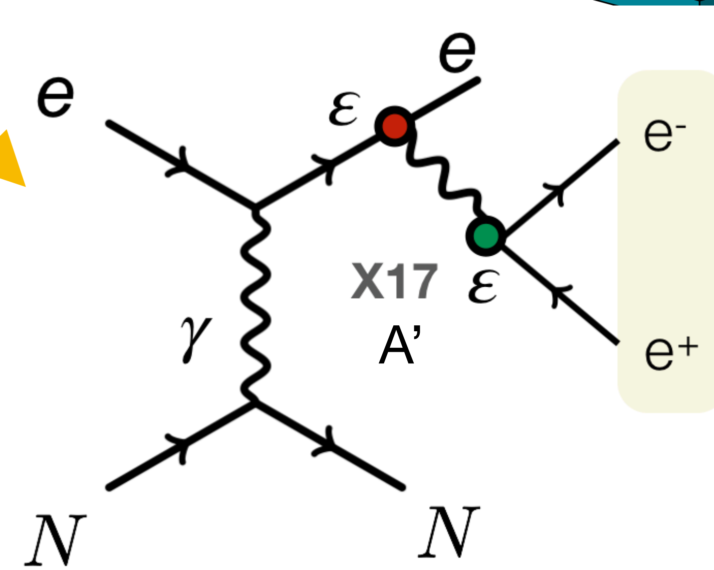
First run in 2017

NA64 invisible setup reused as much as possible



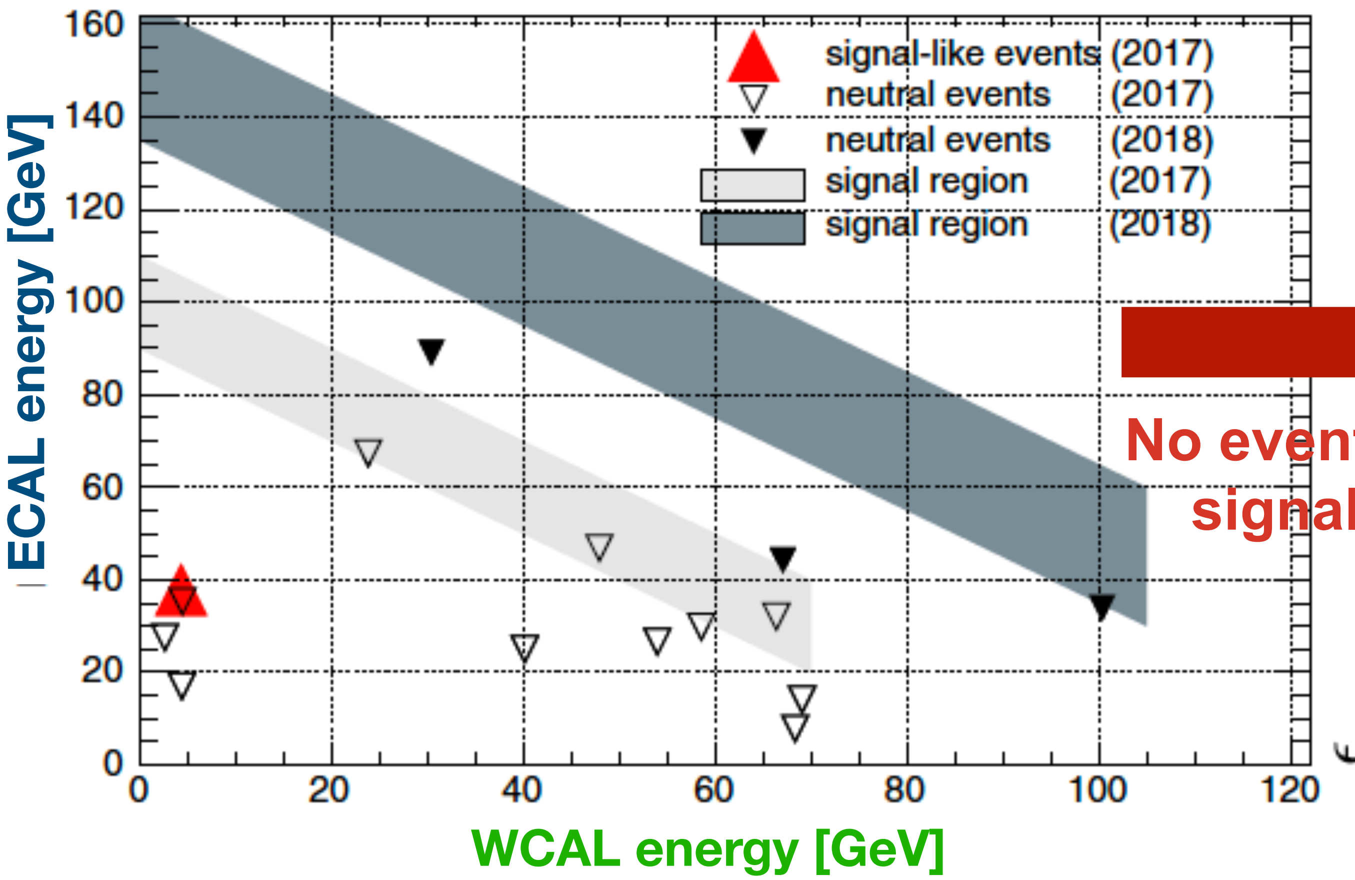
Improvements in the 2018 setup

- Beam energy from 100 to **150 GeV** to boost X17 outside WCAL.
- Shorter WCAL to probe large epsilon
- Thinner veto (W2) after WCAL to minimise the probability that X17 decays in it.
- For Background suppression: vacuum pipe installed+increased WCAL-ECAL distance
- Additional trackers



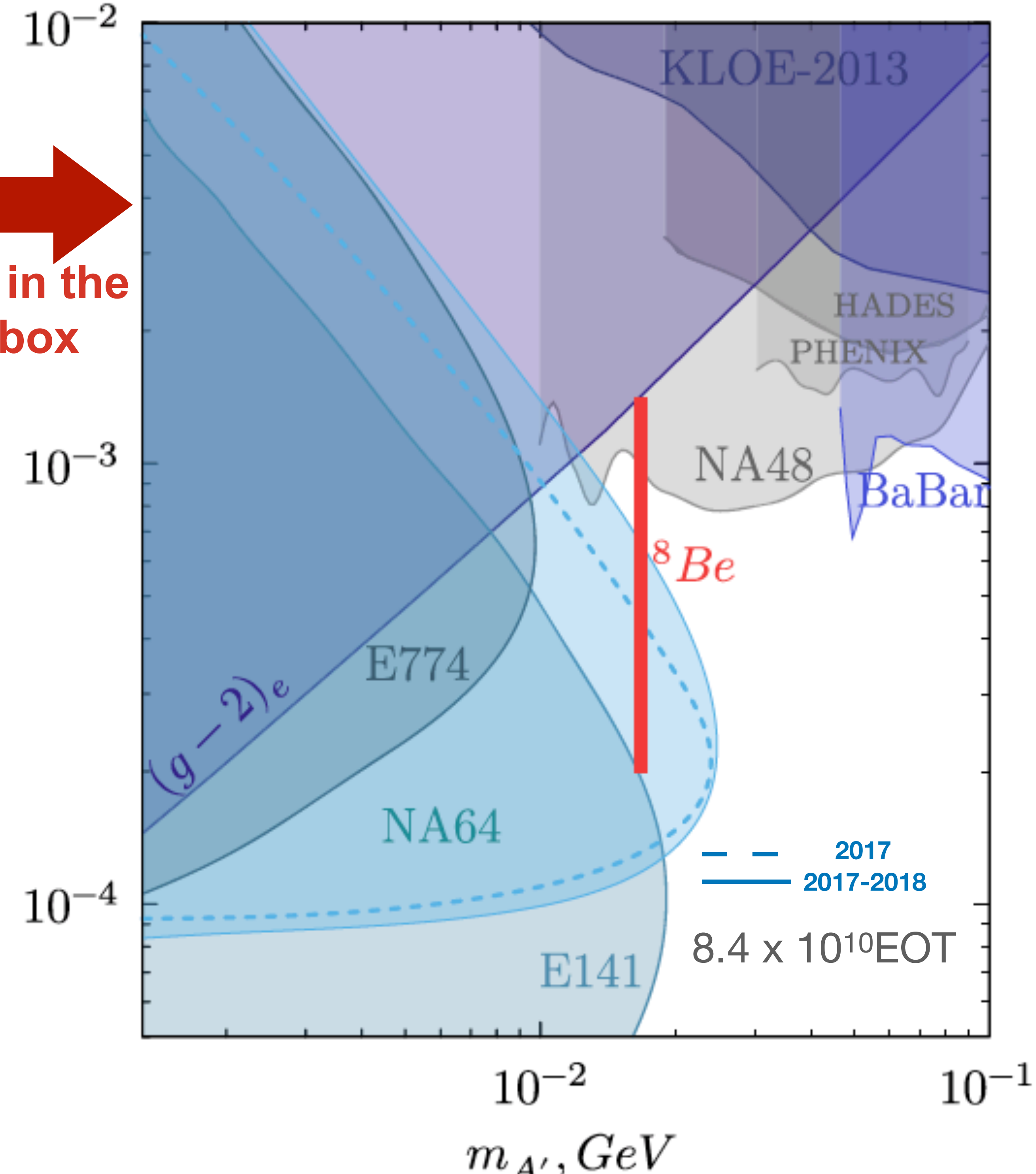
L.Molina Bueno

Combined results for 2017 and 2018



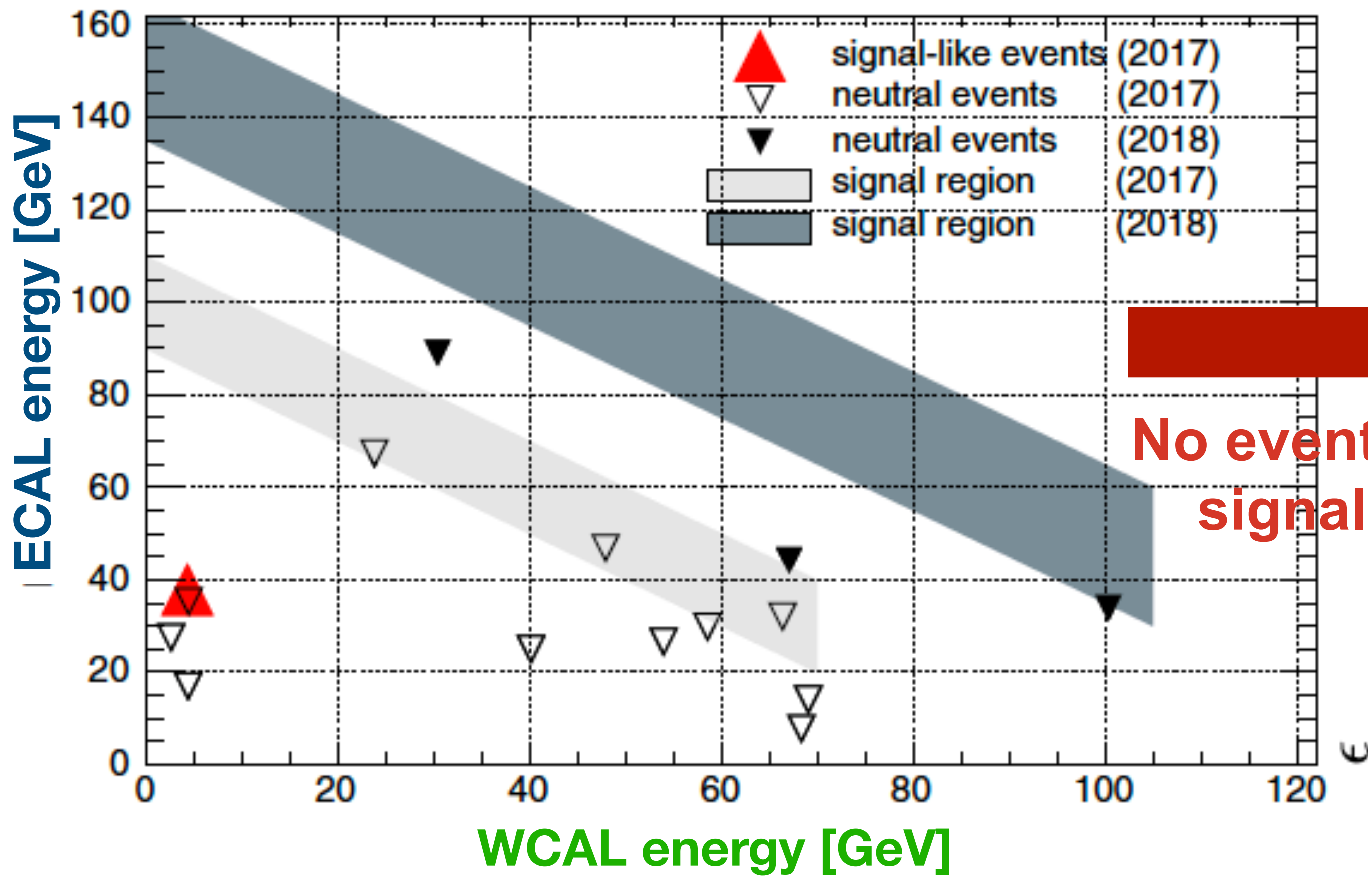
No event in the signal box

Without the 2018 setup optimisation ε would have only increased logarithmically with the number of EOTs.



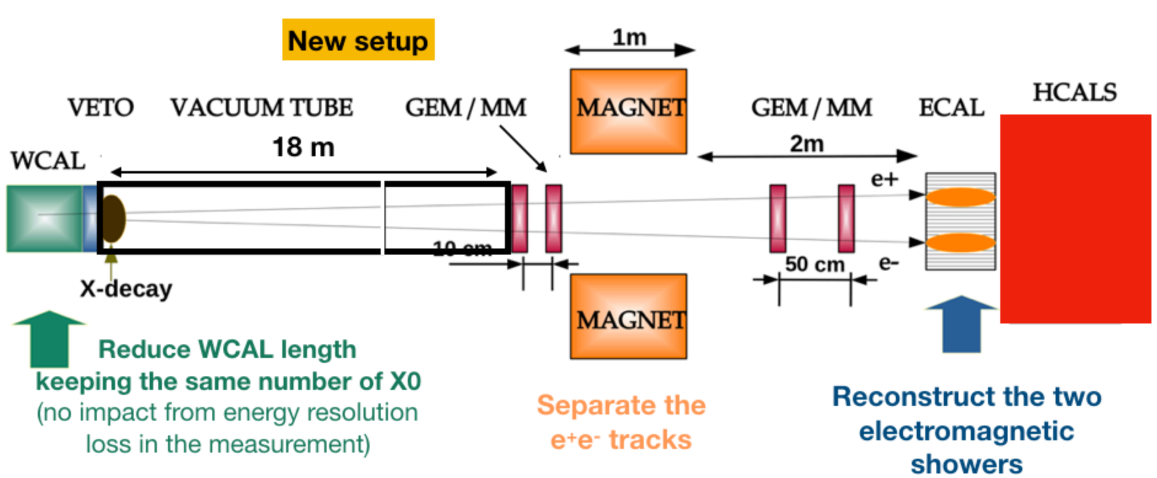
NA64 collaboration,
PRL 120, 231802 (2018), PRD 107, 071101 (R) 2020

Future prospects for 2022



No event in the signal box

Full parameter space
Invariant mass reconstruction



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

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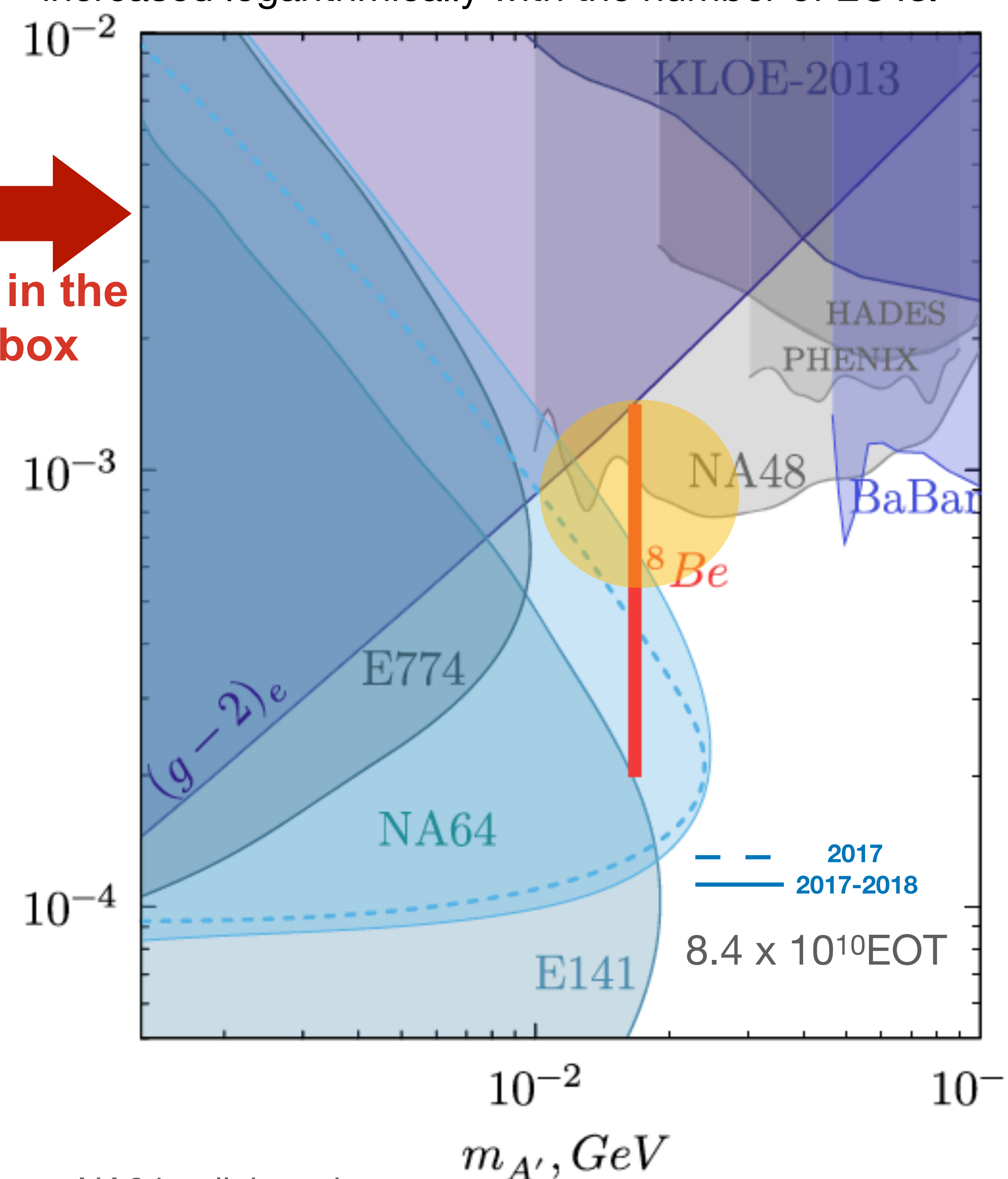


NA64 collaboration,
PRL 120, 231802 (2018), PRD 107, 071101 (R) 2020

Summary

Dark sector physics **interesting framework to explain dark matter**

The European Strategy Group recommended to support searches for dark sector candidates.

NA64 **is an ideal experiment for testing benchmark scalar, Majorana and pseudo-Dirac thermal sub-GeV dark matter models**

Combined ***invisible analysis*** *data 2016-2018* ***with 2.84 x 10^{11} EOT***

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

Combined ***visible*** *data 2017-2018* ***with 8.4 x 10^{10} EOT***

X17 **→e^+e^-:** Vector coupling with electrons at ε < 6.8 x 10^{-4} and a mass of 16.7 excluded

Future prospects after LHC long shutdown 2 for 2021-2024

- NA64 setup upgrade to run at high intensity
- Main goal to explore the parameter space of benchmark light dark matter with > **goal 5x10^{12} EOT**
- Substantially increase sensitivity to A' → *e^+e^-* decays and explore remaining parameter space for *X17→ e^+e^-*
  - *In case of X17 signal-like events reconstruct the invariant mass with precision at few percent level.*
- **Start searches of dark sectors weakly coupled to muons with NA64μ:**
  - *$(g-2)_\mu$ and L_μ-L_τ Z'*: pilot run in 2021 at M2 beamline at CERN SPS (160 GeV/c muon)
  - Probing light dark matter parameter space for mA'> 100 MeV

-Improve sensitivity for ALPs (a) and scalars (s) to probe the challenging region of mass $m_{a,s}$~$m_{\pi 0}$

L.Molina Bueno

THANKS!

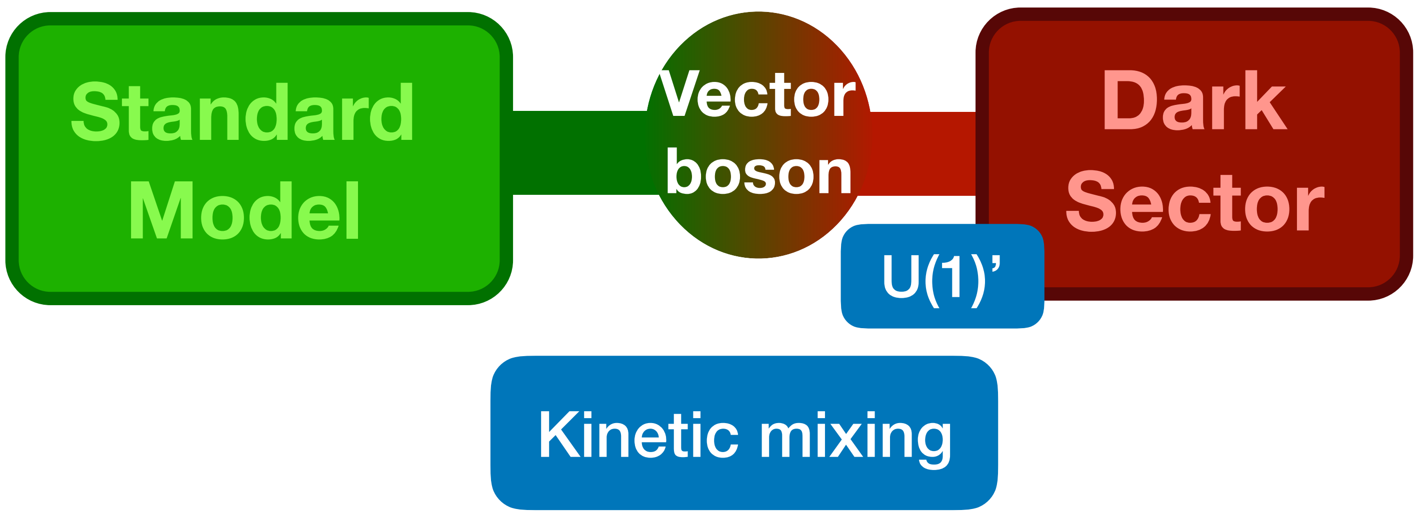
Acknowledgements

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

FNSNF
SWISS NATIONAL SCIENCE FOUNDATION

SNSF Ambizione grant: PZ00P2_186158

NA64 target: *the vector portal*



An interesting framework to explain the origin of dark matter

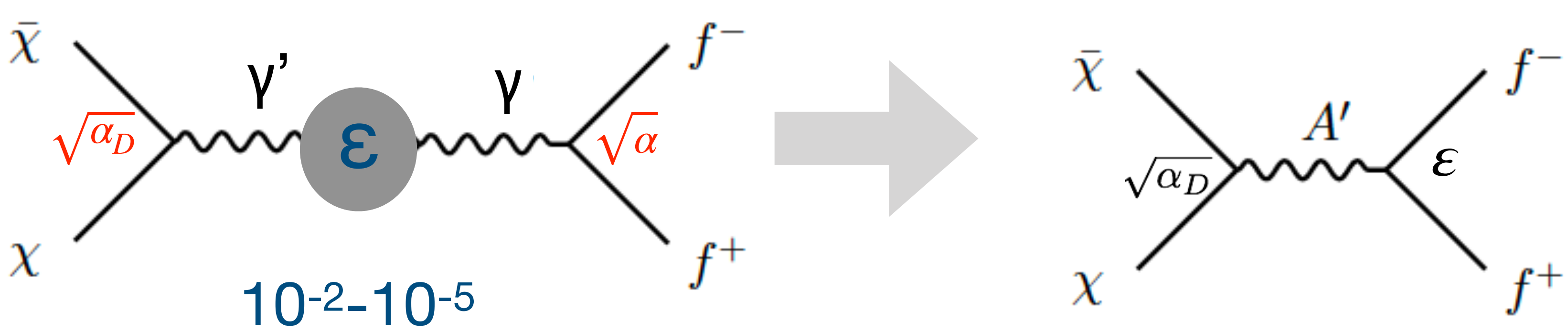
$$L = L_{SM} - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + \frac{m^2_{A'}}{2} A'_\mu A'^\mu + \frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu} + i\bar{\chi}\gamma^\mu \partial_\mu \chi - m_\chi \bar{\chi}\chi - e_D \bar{\chi}\gamma^\mu A'_\mu \chi$$

Standard Model Lagrangian

A' massive vector field associated with the U'(1) broken symmetry

Kinetic mixing term with the ***standard photon γ***

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

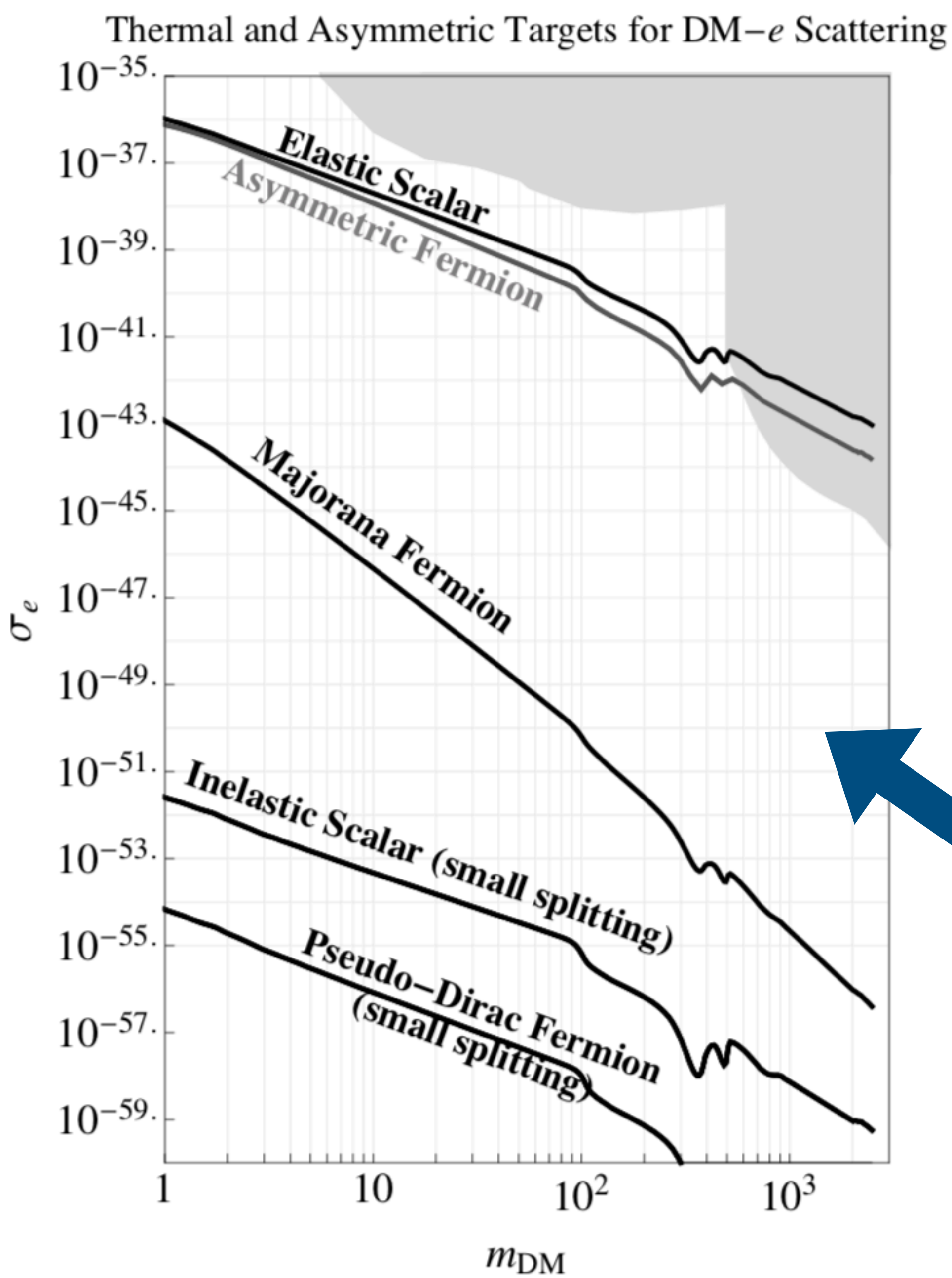


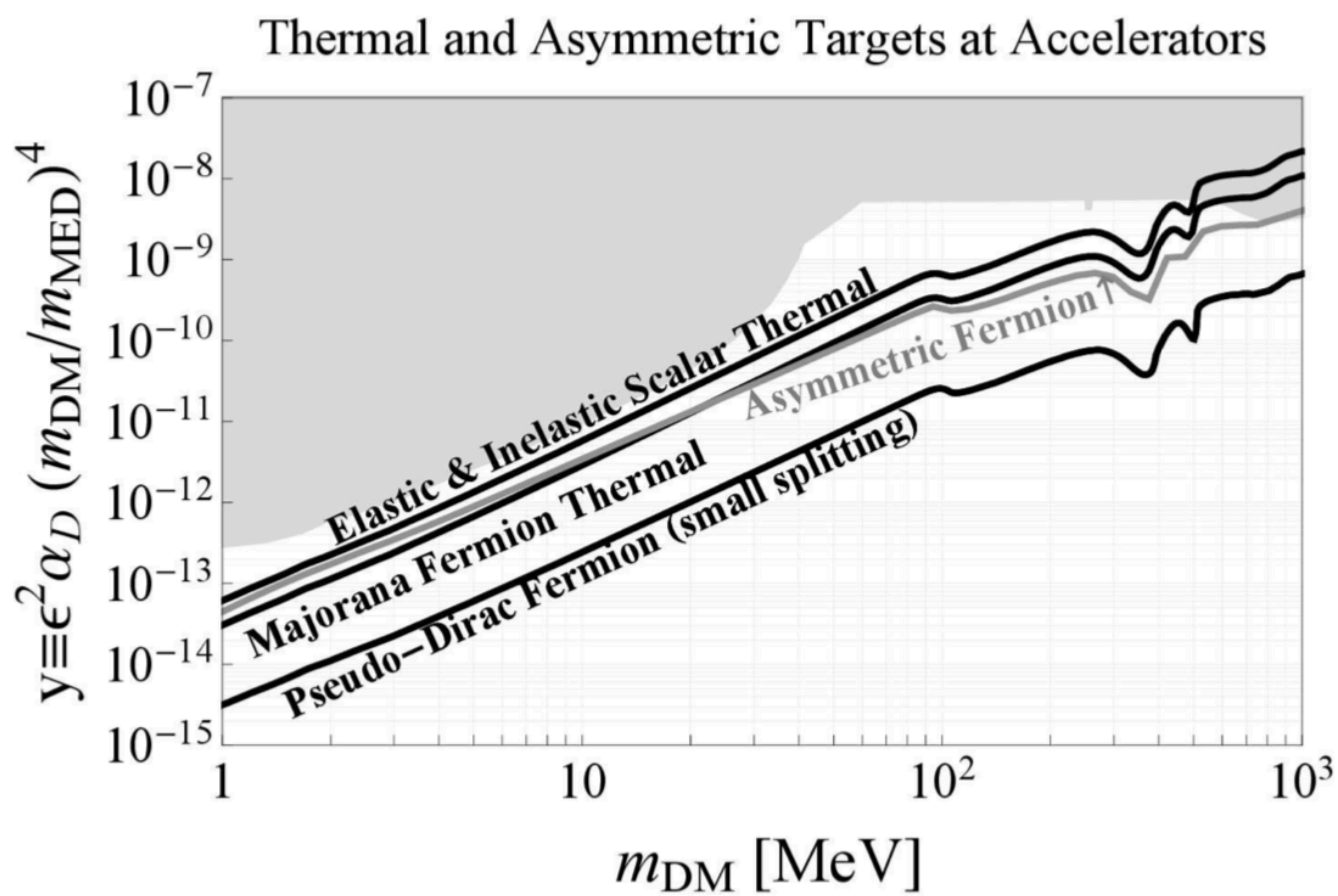
For simplicity during the talk

Parameter space defined by ***(mA',mχ,ε,α$_D$)***

Light thermal dark matter

Equivalent parameter space for e⁻DM scattering probed by direct-detection experiments

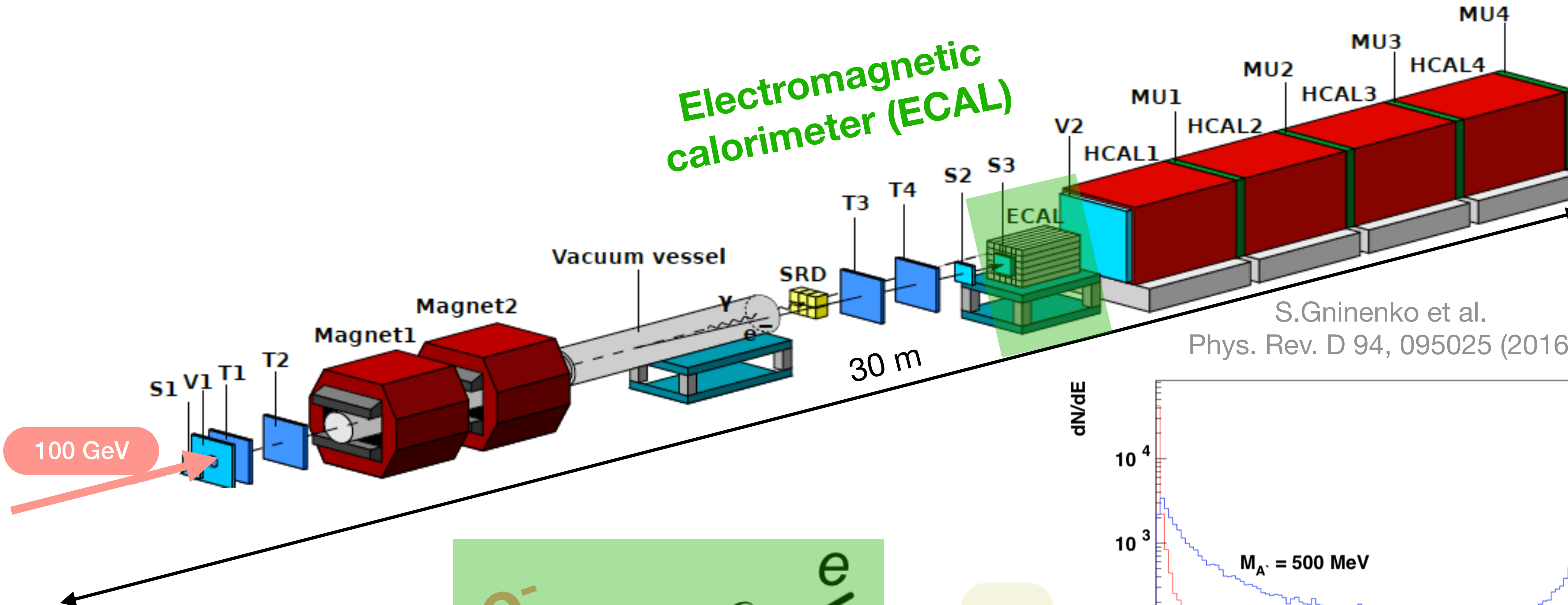




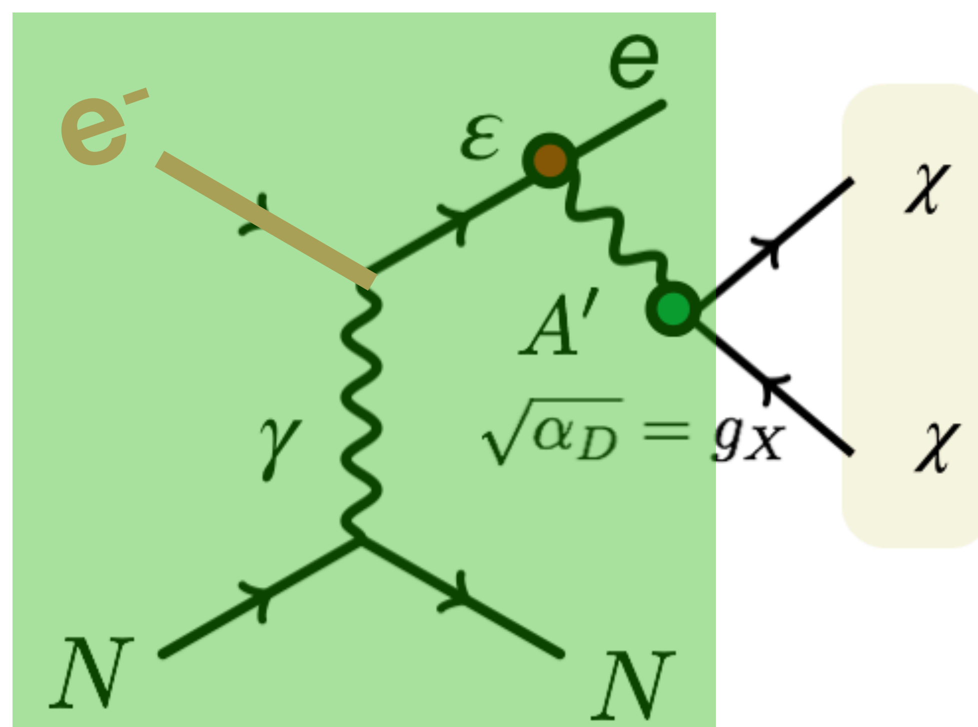
Light Dark Matter experiment arXiv:1808.05219v1

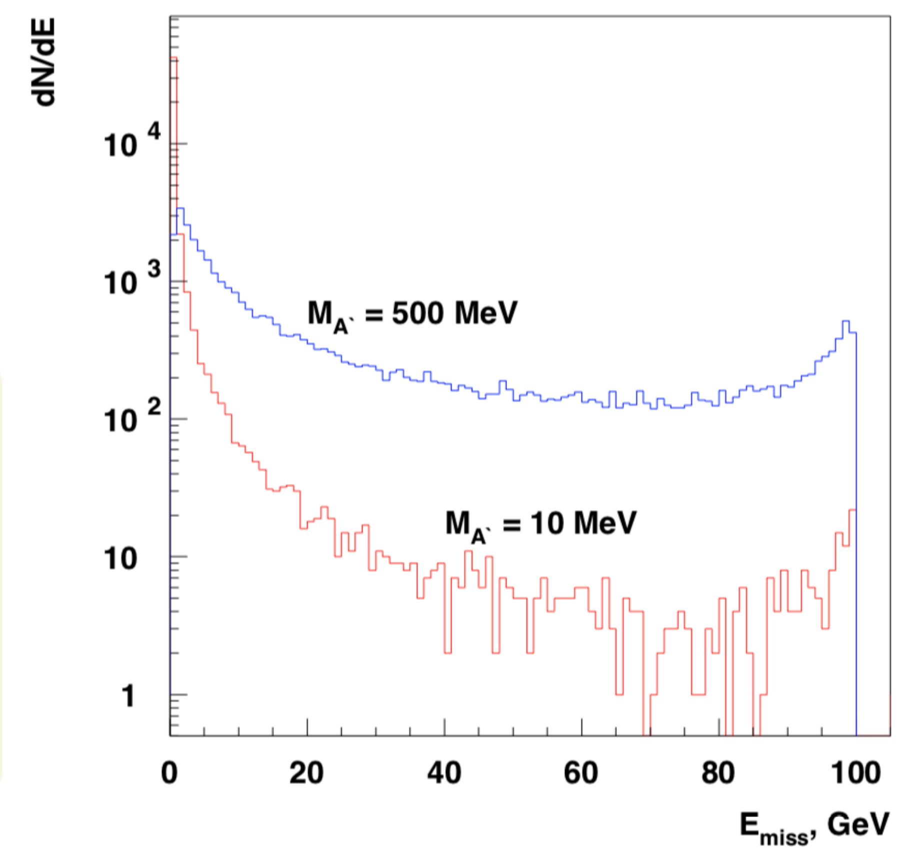
L.Molina Bueno

NA64 *invisible* searches: the setup



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

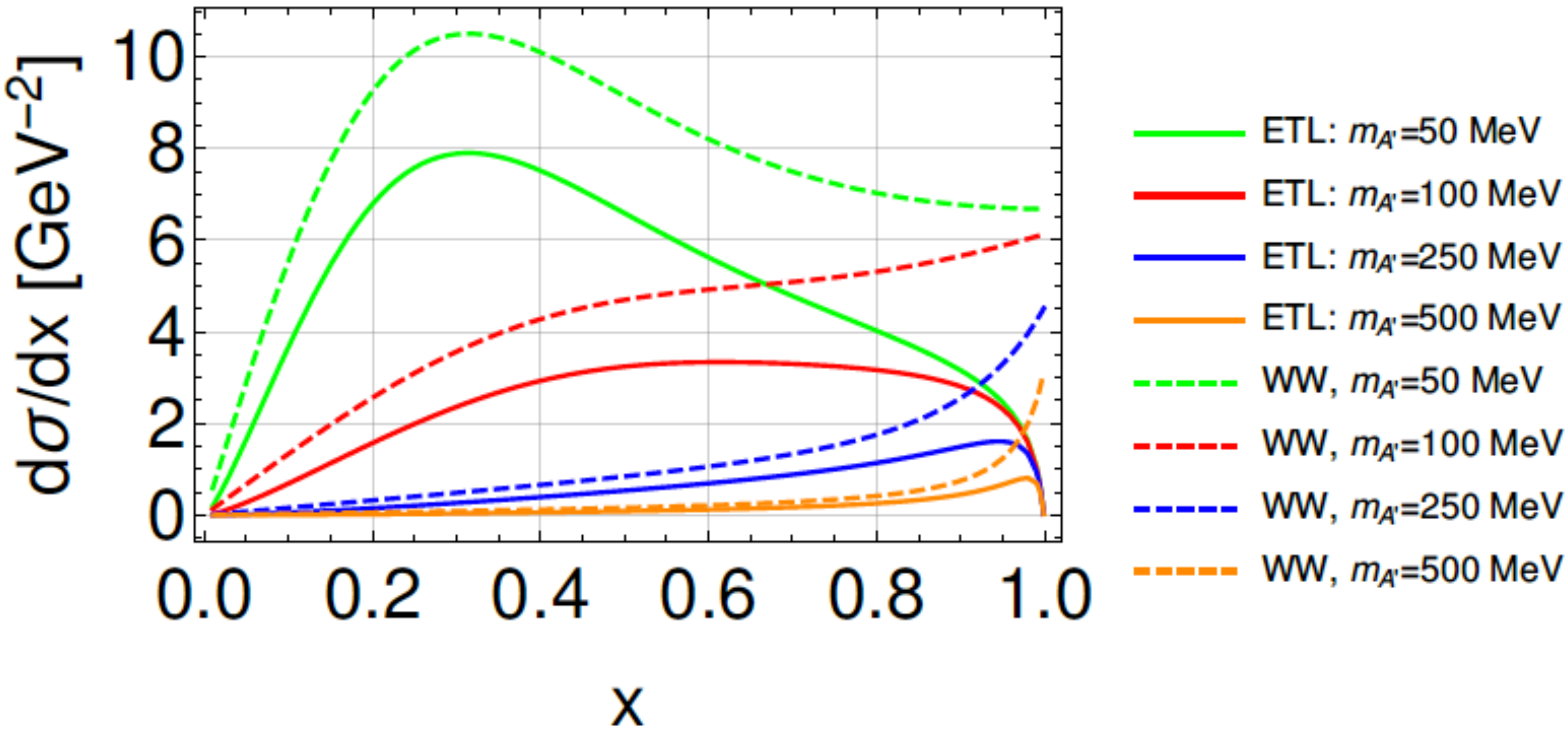




Active target

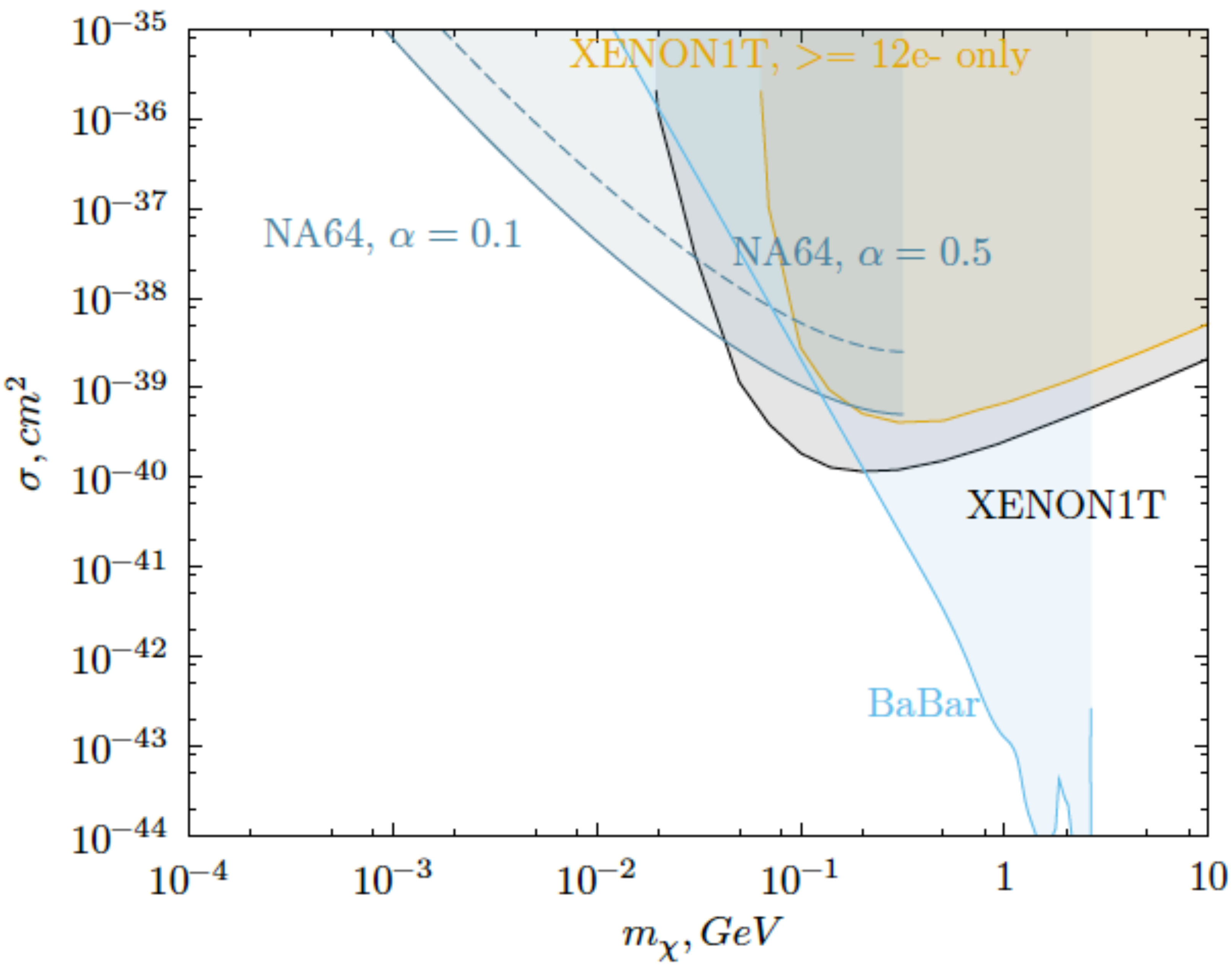
Bremsstrahlung of A’

Exact tree level cross-section calculation



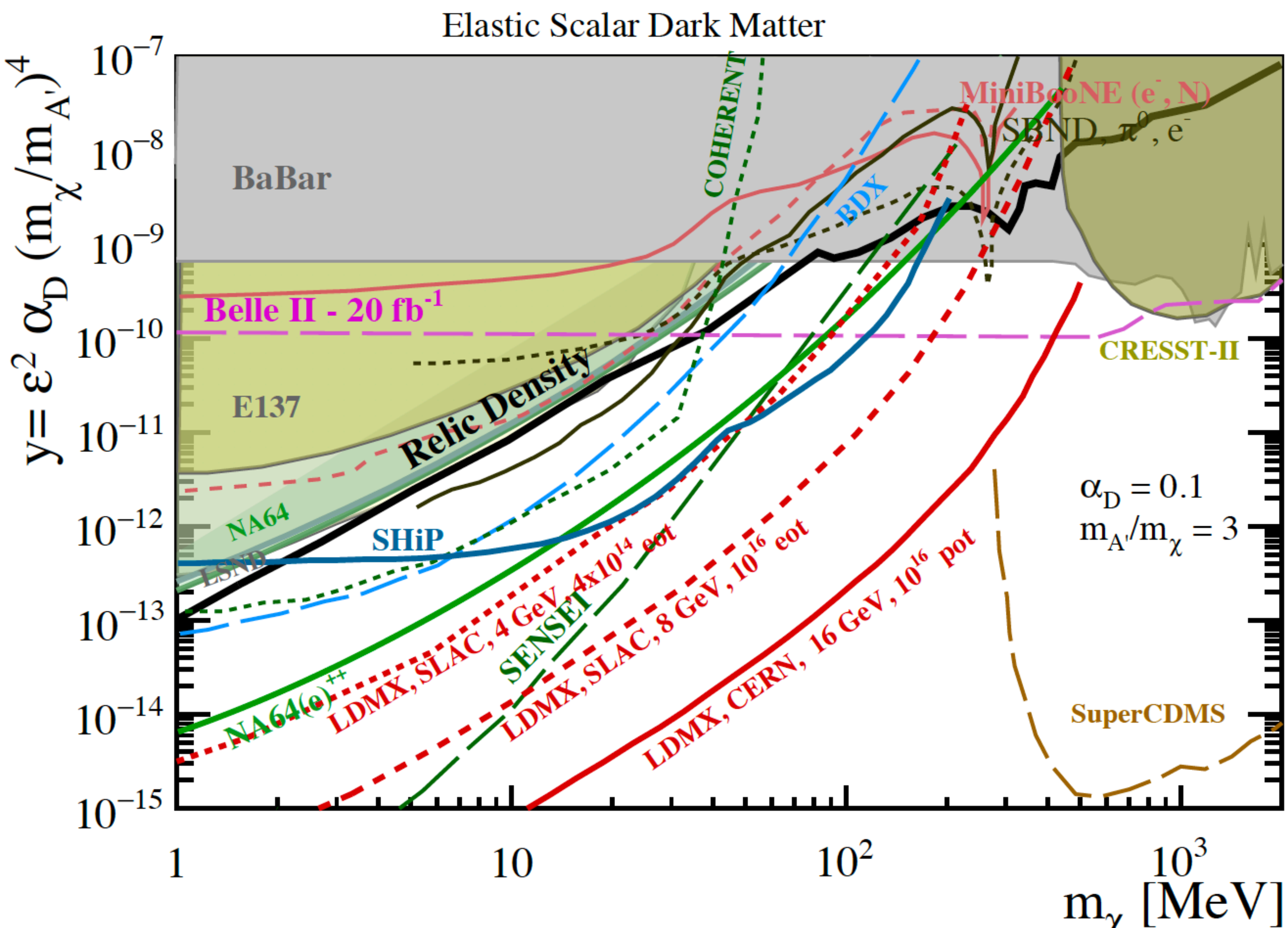
NA64 *invisible* searches: results

Complementarity with direct DM searches



XENON Collaboration. arXiv:1907.11485
S.N.Gninenko, N.V. Krasnikov and V.A.Matveev, arXiv:2003.07257

Invisible searches



G.Lanfranchi, M.Pospelov and P.Schuster
arxiv:2011.02157

Invisible **searches**

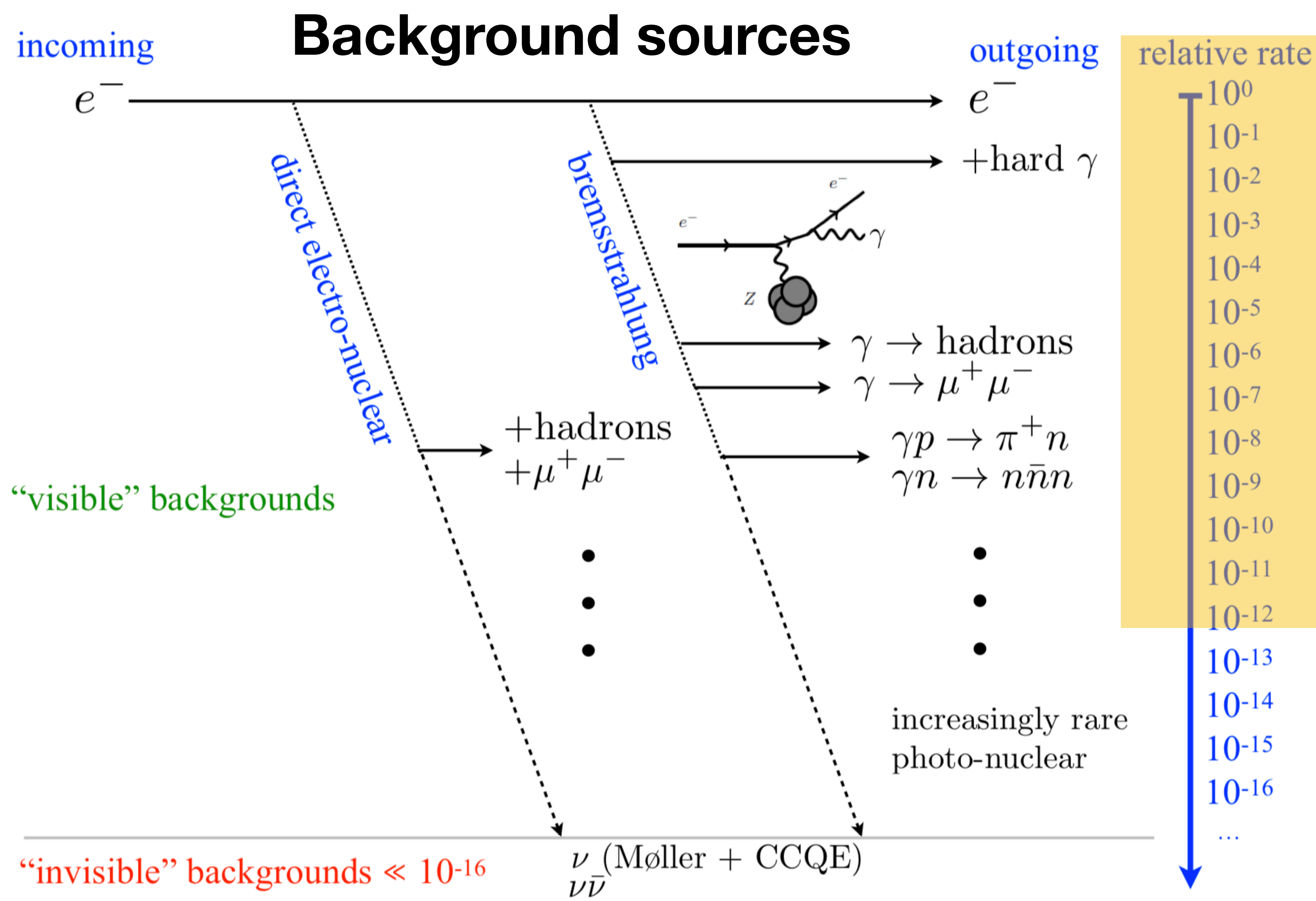
The observed abundance of DM relic density, with the requirement of the thermal freeze-out of DM annihilation into visible matter through γ – A′ mixing allows one to derive a relation between the parameters:

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

mA'/mχ=3 f<=10 for scalar and f<=1 for fermion

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

NA64 *invisible* searches: **results**



Light Dark Matter experiment arXiv:1808.05219v1

Extrapolated from data

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

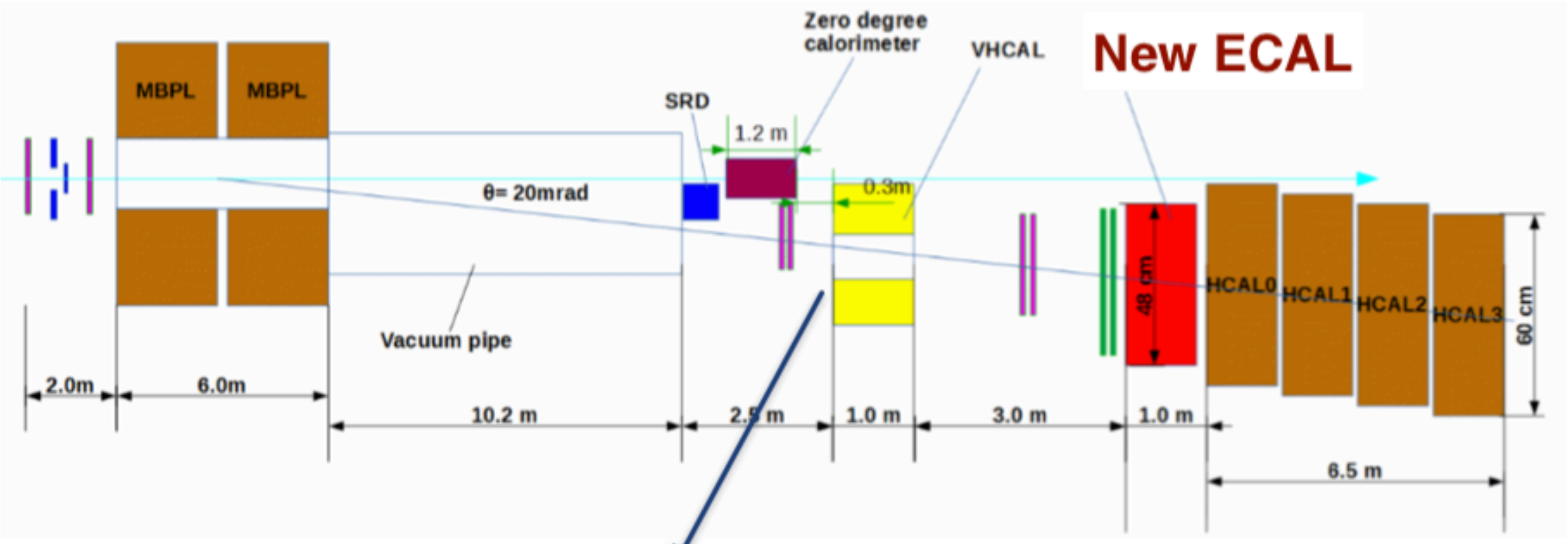
NA64 collaboration, Phys. Rev. Lett. 123, 121801 (2019) Editor's suggestion

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

2.84×10^{11} electrons on target (EOT)

Setup upgrade

GOAL: increase the overall performance and improve background rejection

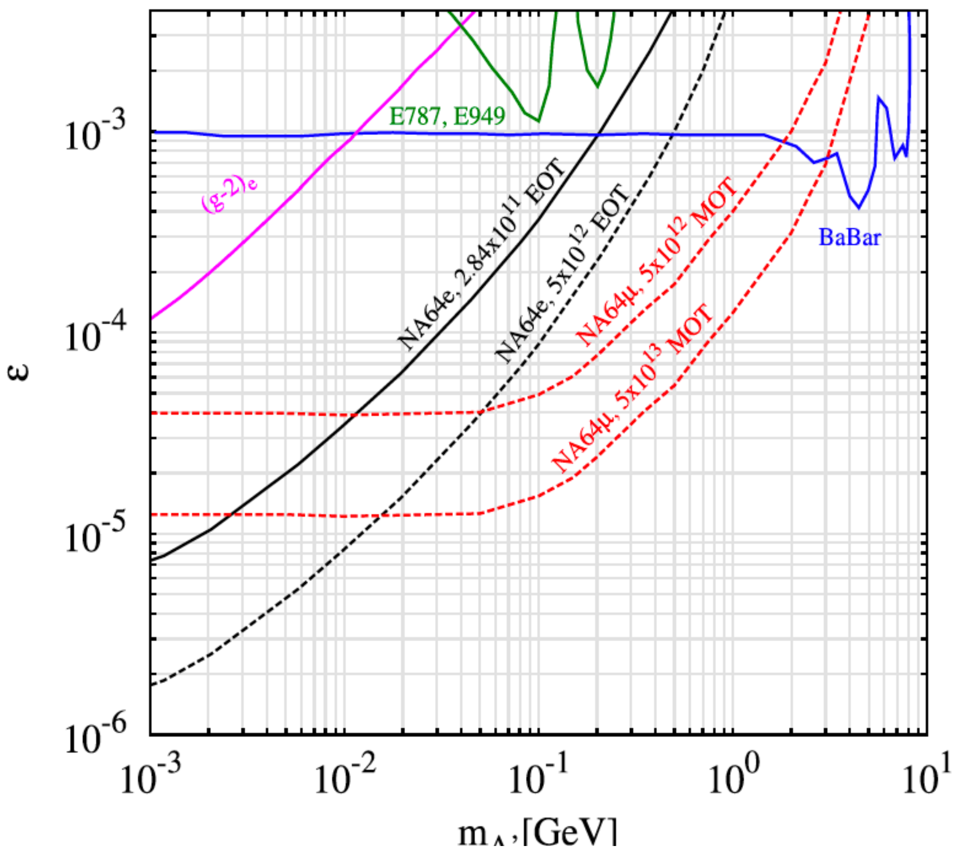


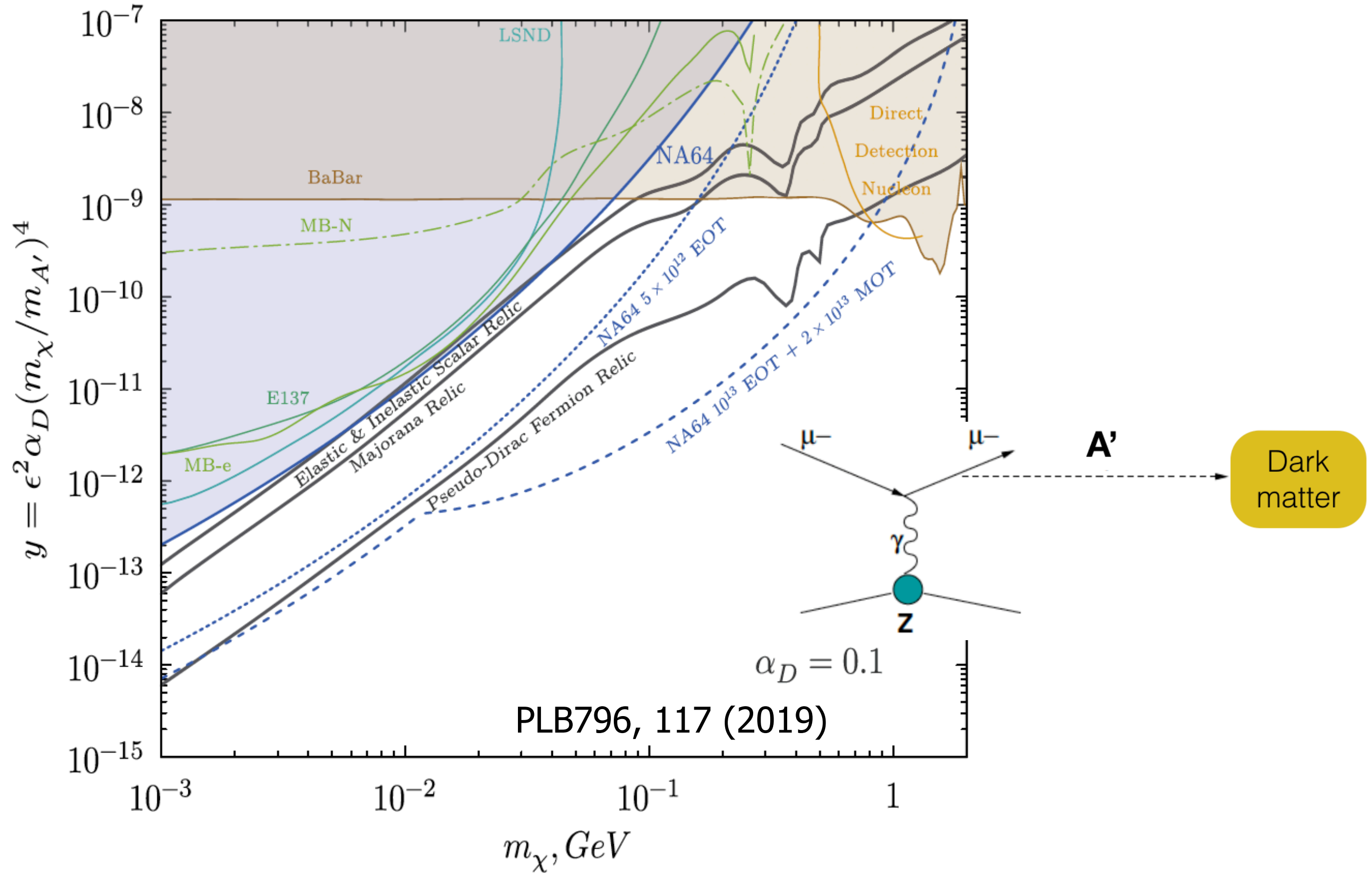
New VHCAL: to improve detector hermiticity and reject high-p_t hadronic secondaries from beam interactions stream the ECAL dump. Search expected to be BKG free up to ~ 10^{13} EOT

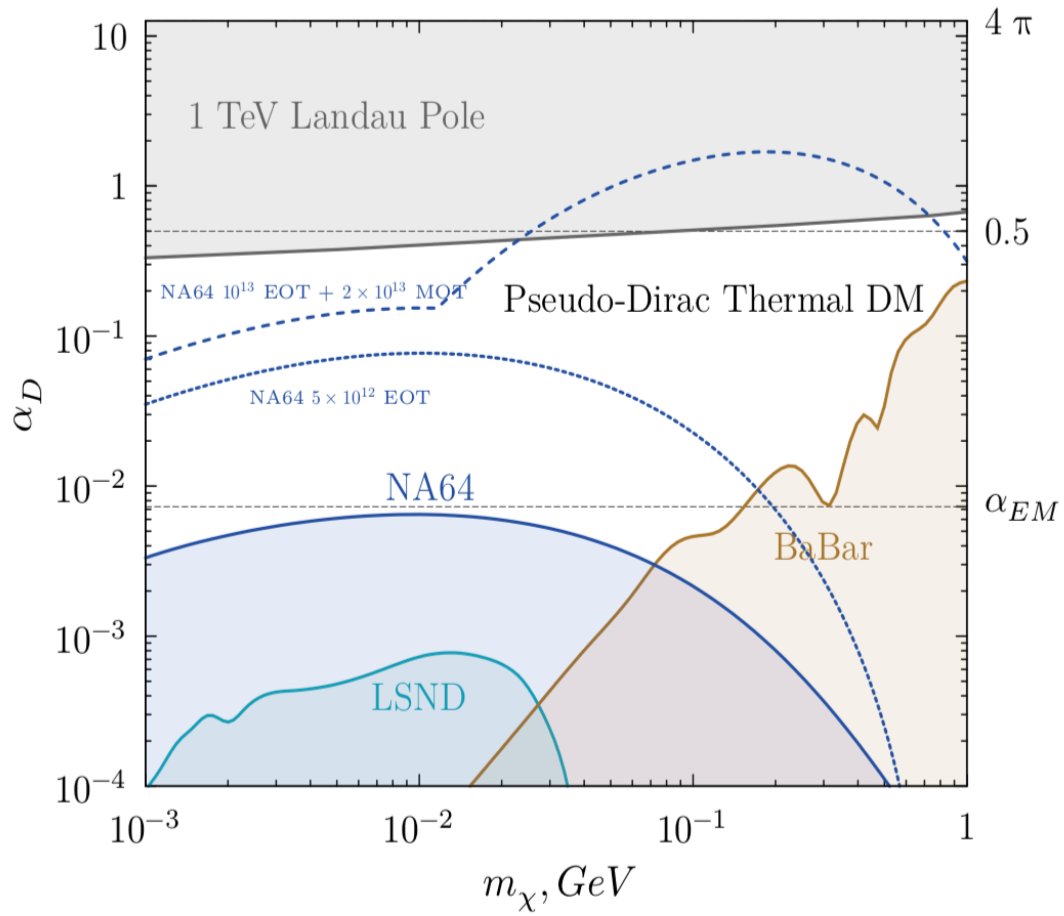
- Dimensions ~ 50 × 50 cm^2 , 16 cells, matrix 4x4 cells
- Central hole size 12 × 6 cm^2
- Cell size 12×12 cm^2
- Length ~100 cm, 5 λ
- 30 layers, 25 mm copper + 2 mm scintillator
- Read out WLS fiber, 12 fibers per scintillator
- Light yield ~15 photoelectrons per MIP

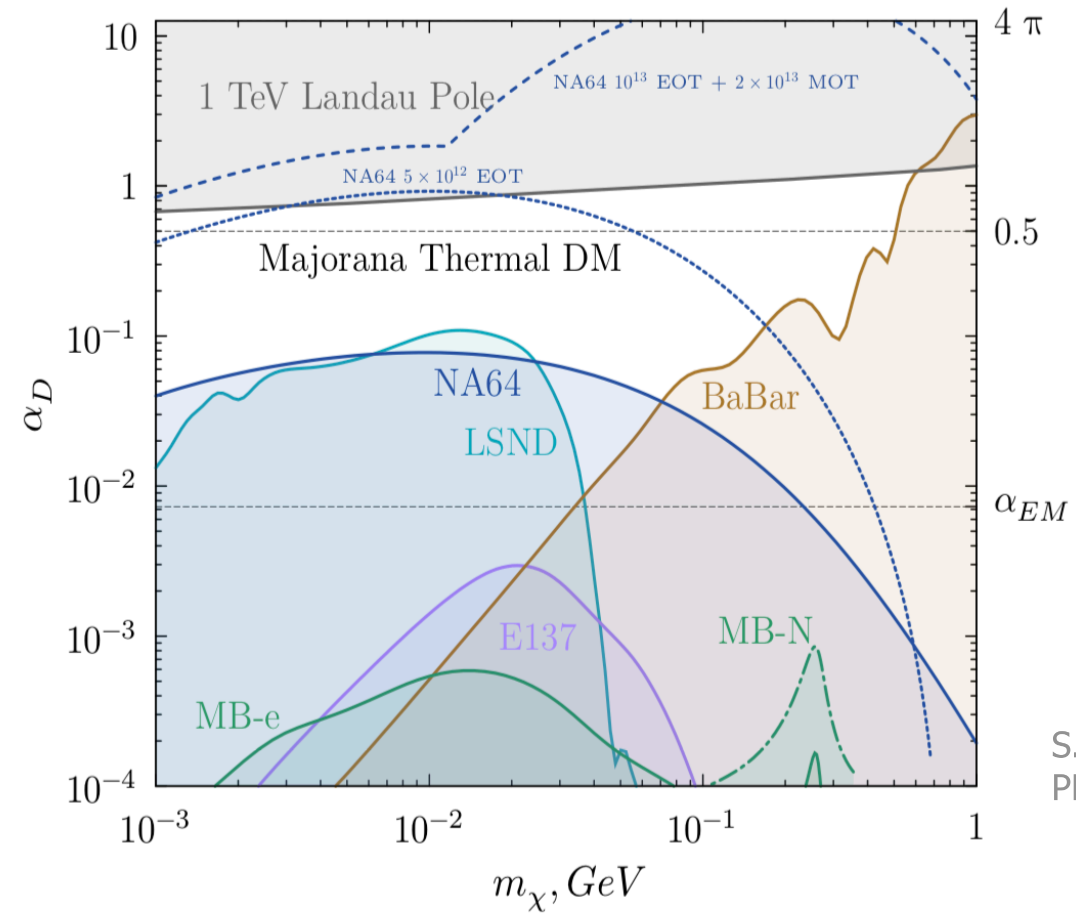
From P.Crivelli, 138th SPSC meeting June 2020

NA64e + NA64$_\mu$









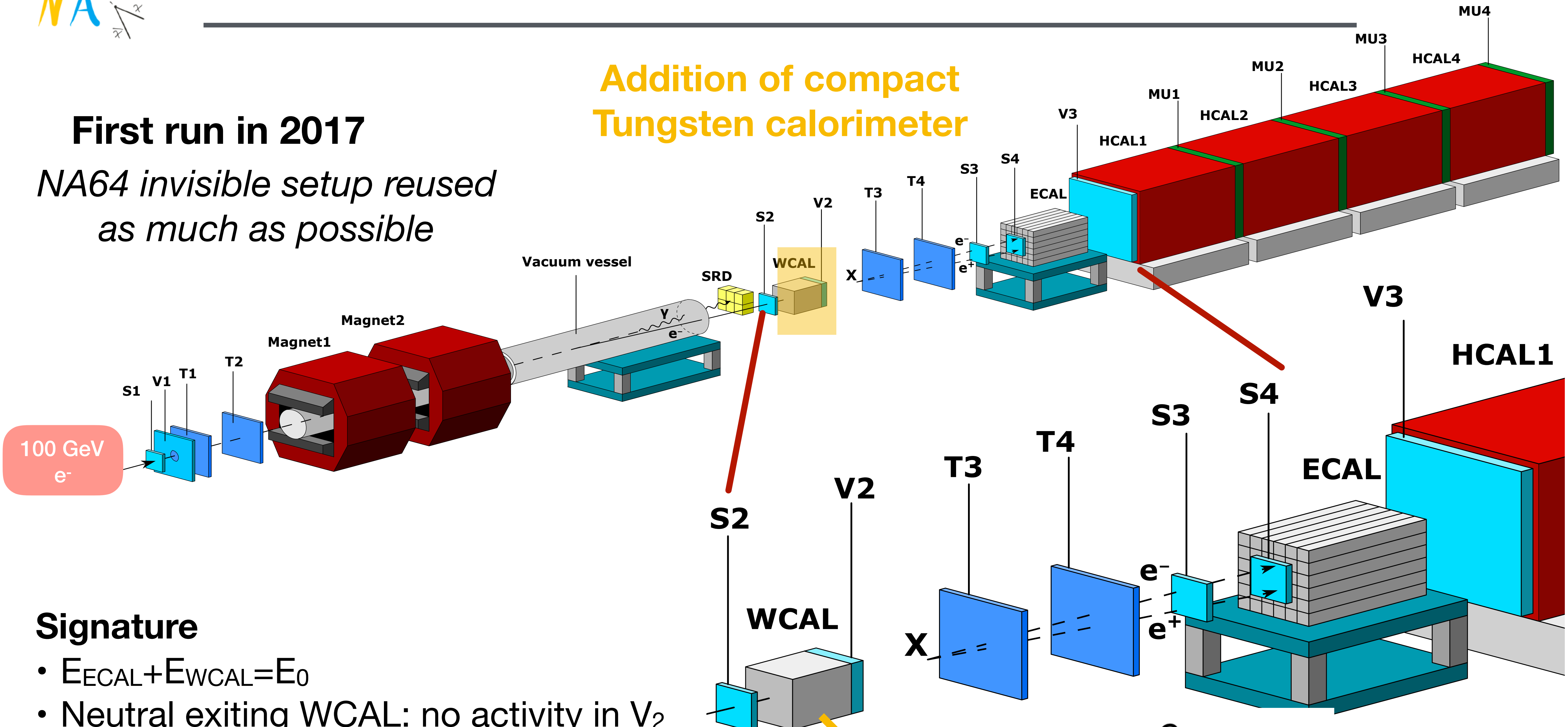
S.Gninenko et al.
PLB796, 117 (2019)

NA64 *visible* searches

First run in 2017

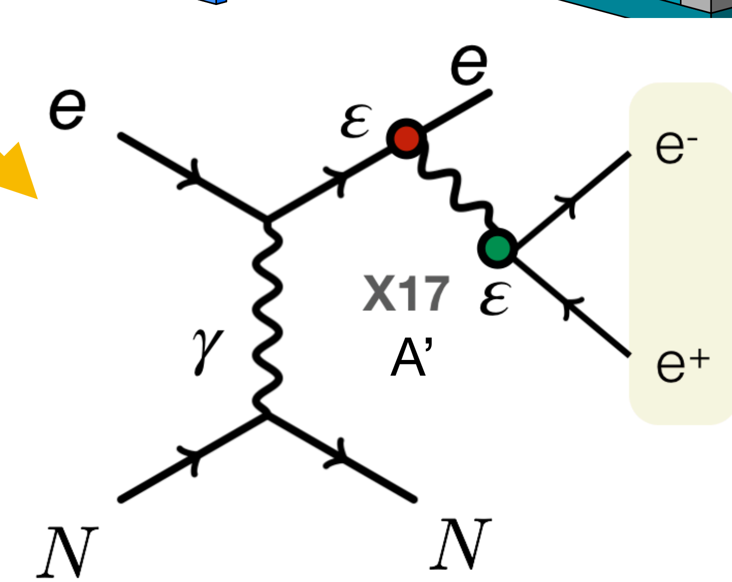
NA64 invisible setup reused as much as possible

Addition of compact Tungsten calorimeter



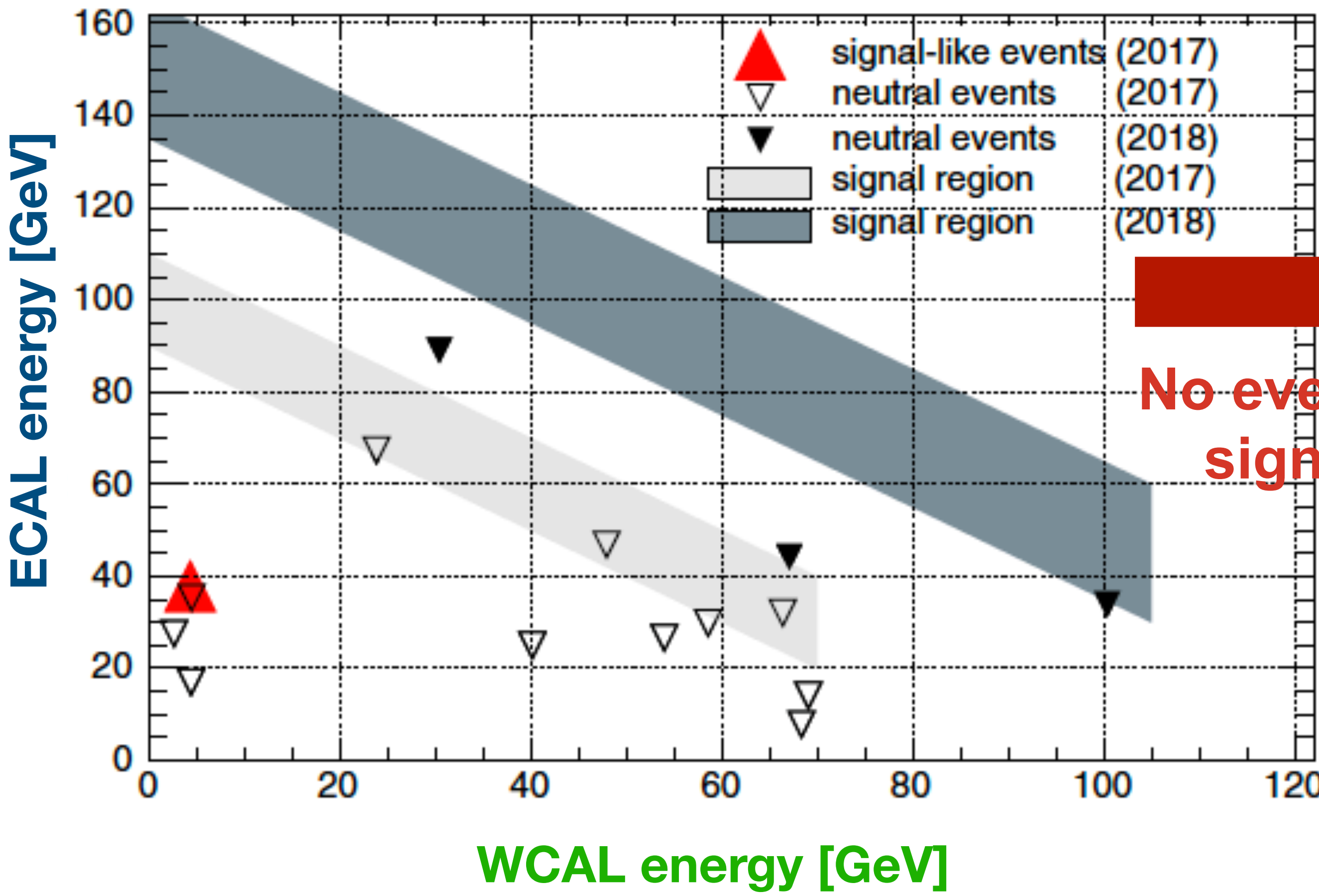
Signature

- $E_{ECAL}+E_{WCAL}=E_0$
- Neutral exiting WCAL: no activity in V_2
- Leaking in decay volume: single electromagnetic shower
- Charged particle in decay volume: signal on $S_{3,4}$
- No hadron large scattering: no activity in HCAL/V_3



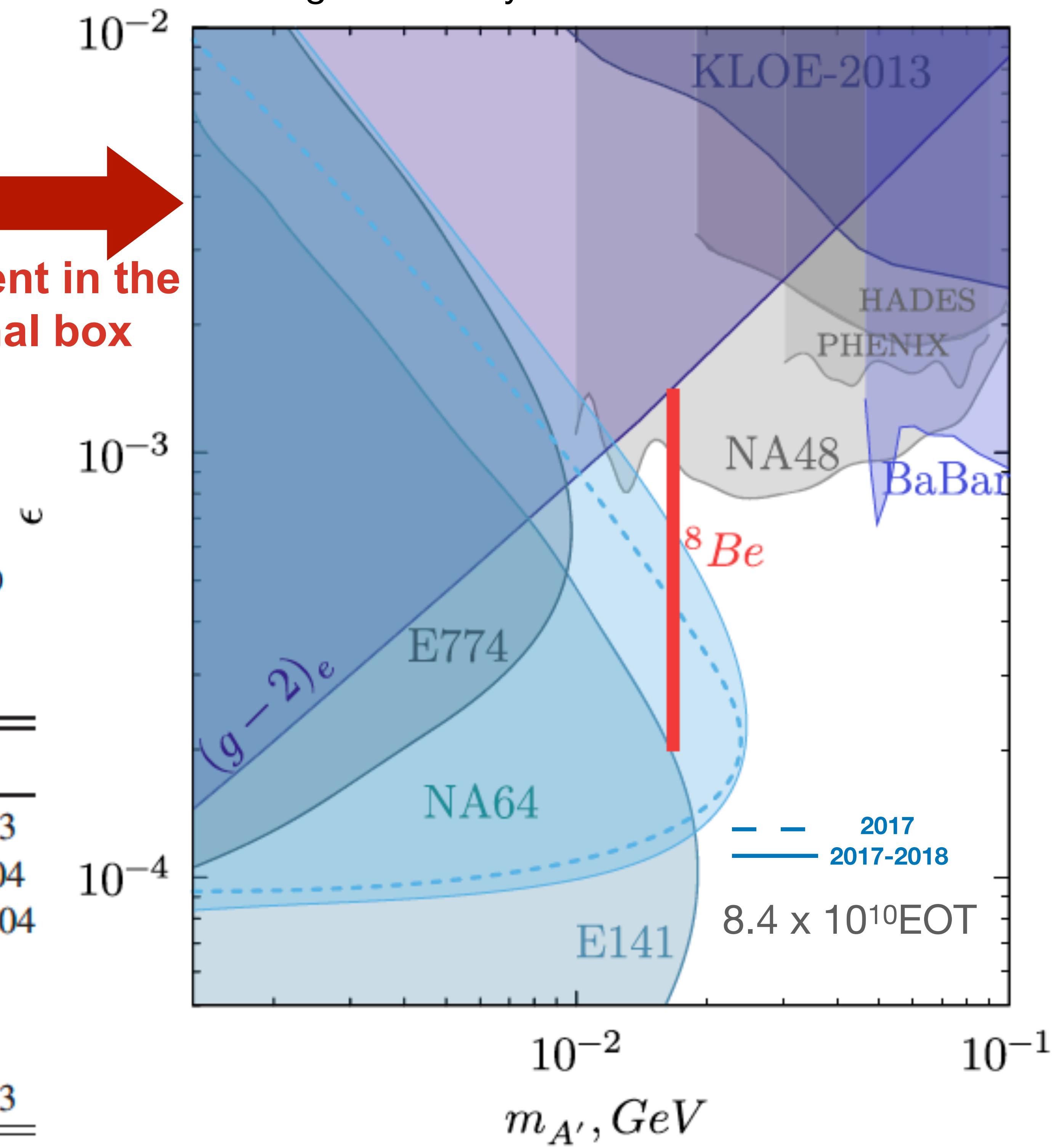
L.Molina Bueno

Combined results for 2017 and 2018



No event in the signal box

Without the 2018 setup optimisation ε would have only increased logarithmically with the number of EOTs.

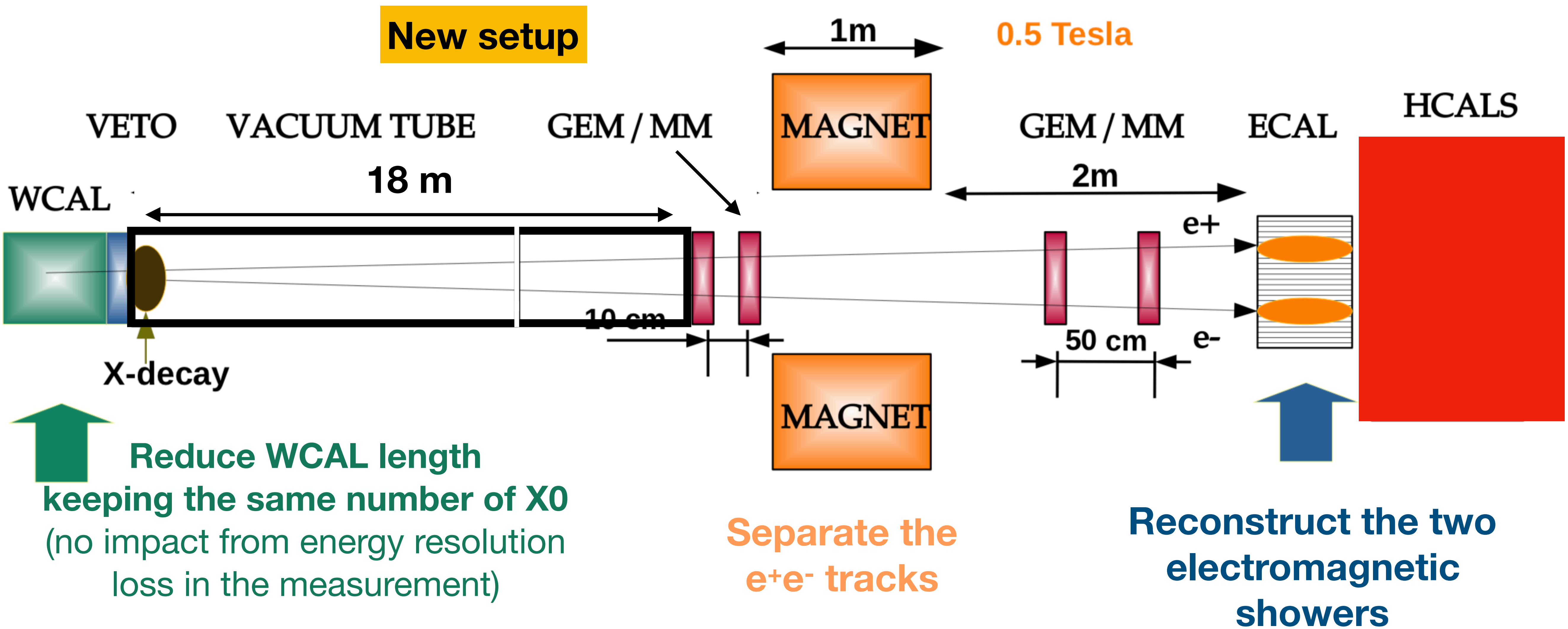


Source of background	2017 data	2018 data
$K^0_S \to 2\pi^0$	0.06 ± 0.034	0.005 ± 0.003
$\pi N \to (\geq 1)\pi^0 + n + \cdots$	0.01 ± 0.004	0.001 ± 0.0004
Punchthrough π^-	0.0015 ± 0.0008	0.0007 ± 0.0004
Punchthrough γ	<0.001	<0.0005
$\pi, K \to e\nu$, K_{e4} decays	<0.001	
$eZ \to eZ\mu^+\mu^-; \mu^\pm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

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

Future prospects for 2022 run

Explore the **full X17 allowed parameter space** to explain the ^{8}Be anomaly
Invariant mass reconstruction in case signal-like events are founded



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

Future prospects for 2022 run

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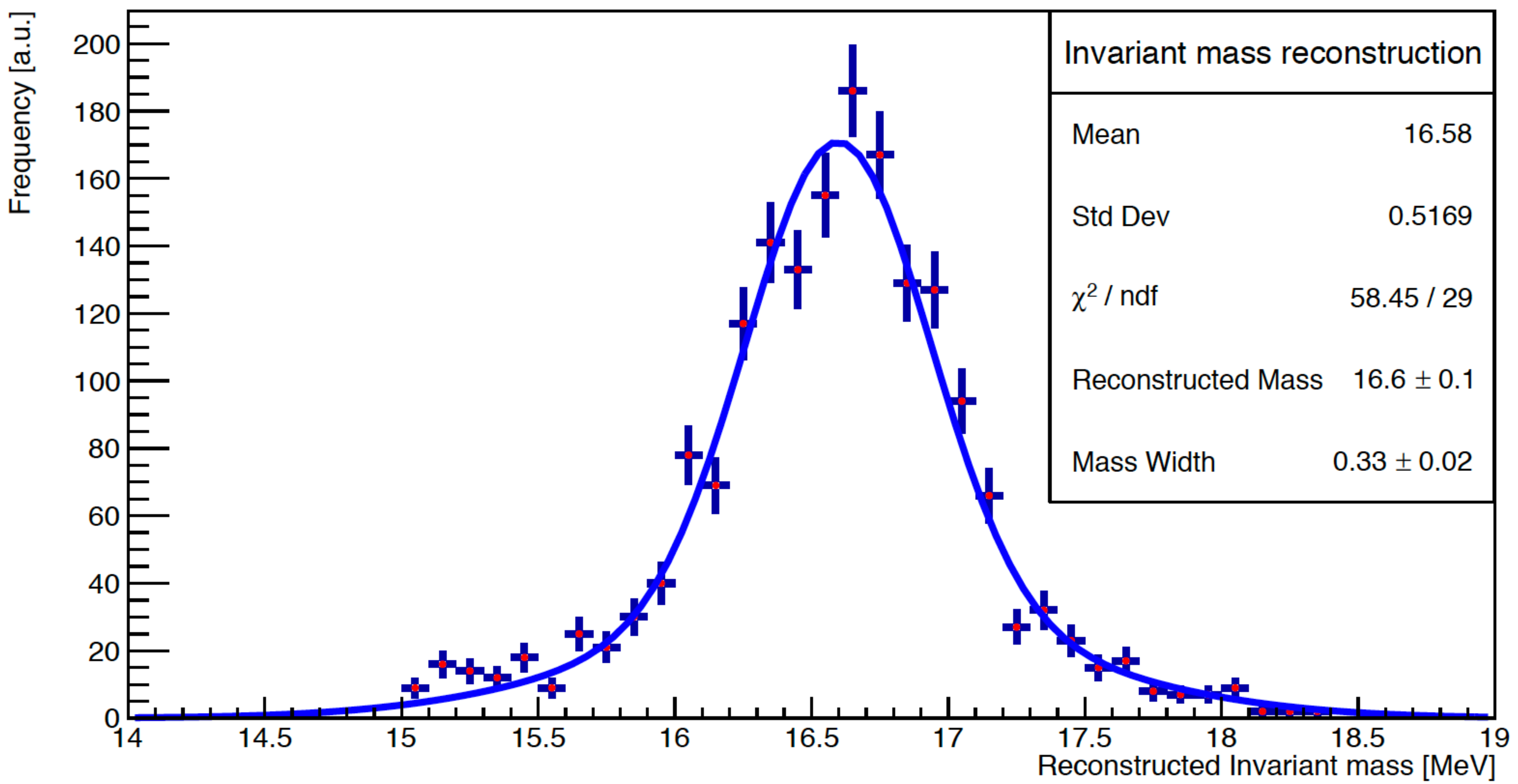
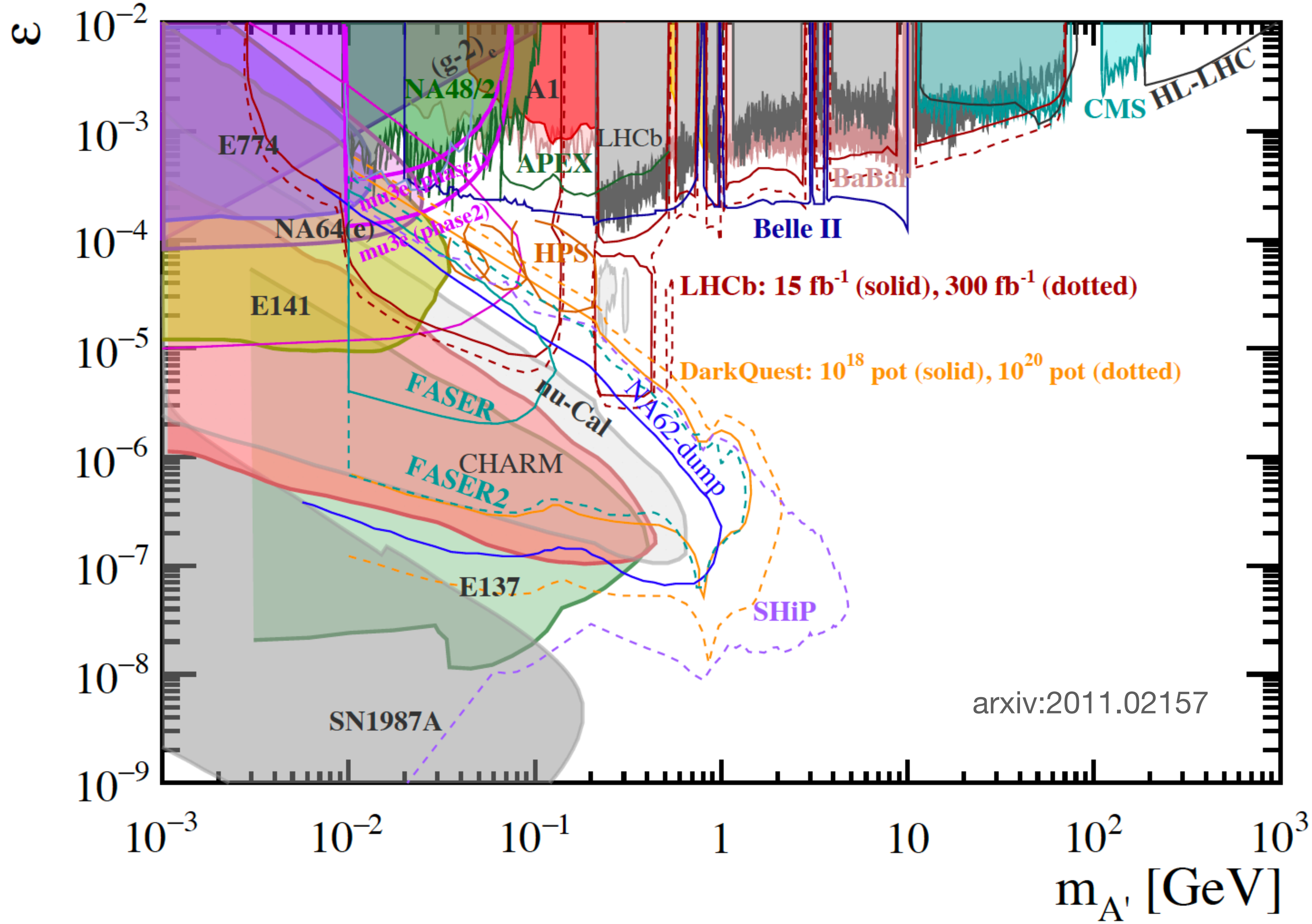


Invariant mass reconstruction precision at the level of 2%

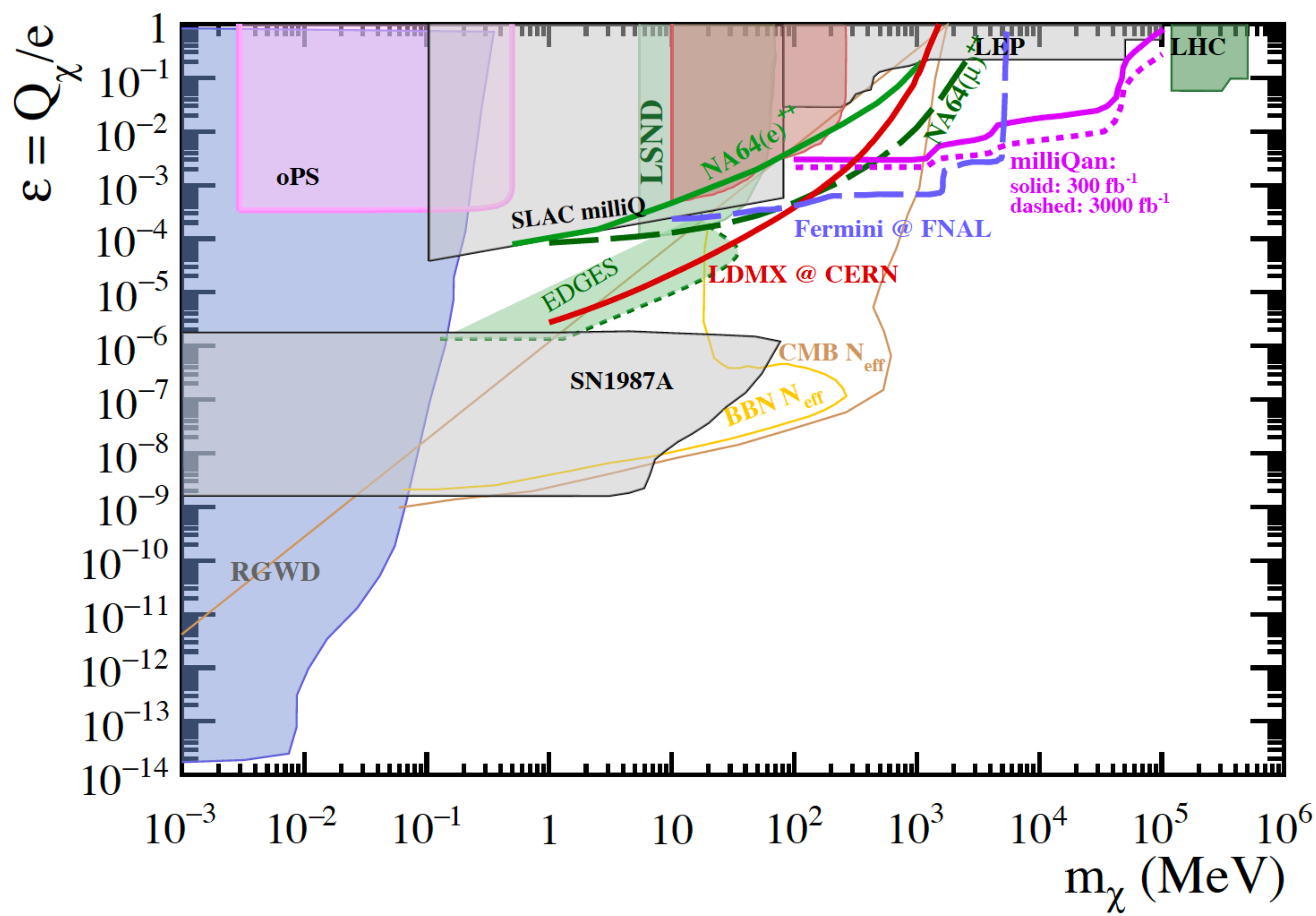
NA64 collaboration, EPJ C 80 (2020) 12, 1159

Dark photon visible searches



G.Lanfranchi, M.Pospelov and P.Schuster
arxiv:2011.02157

Millicharged particles



G.Lanfranchi, M.Pospelov and P.Schuster
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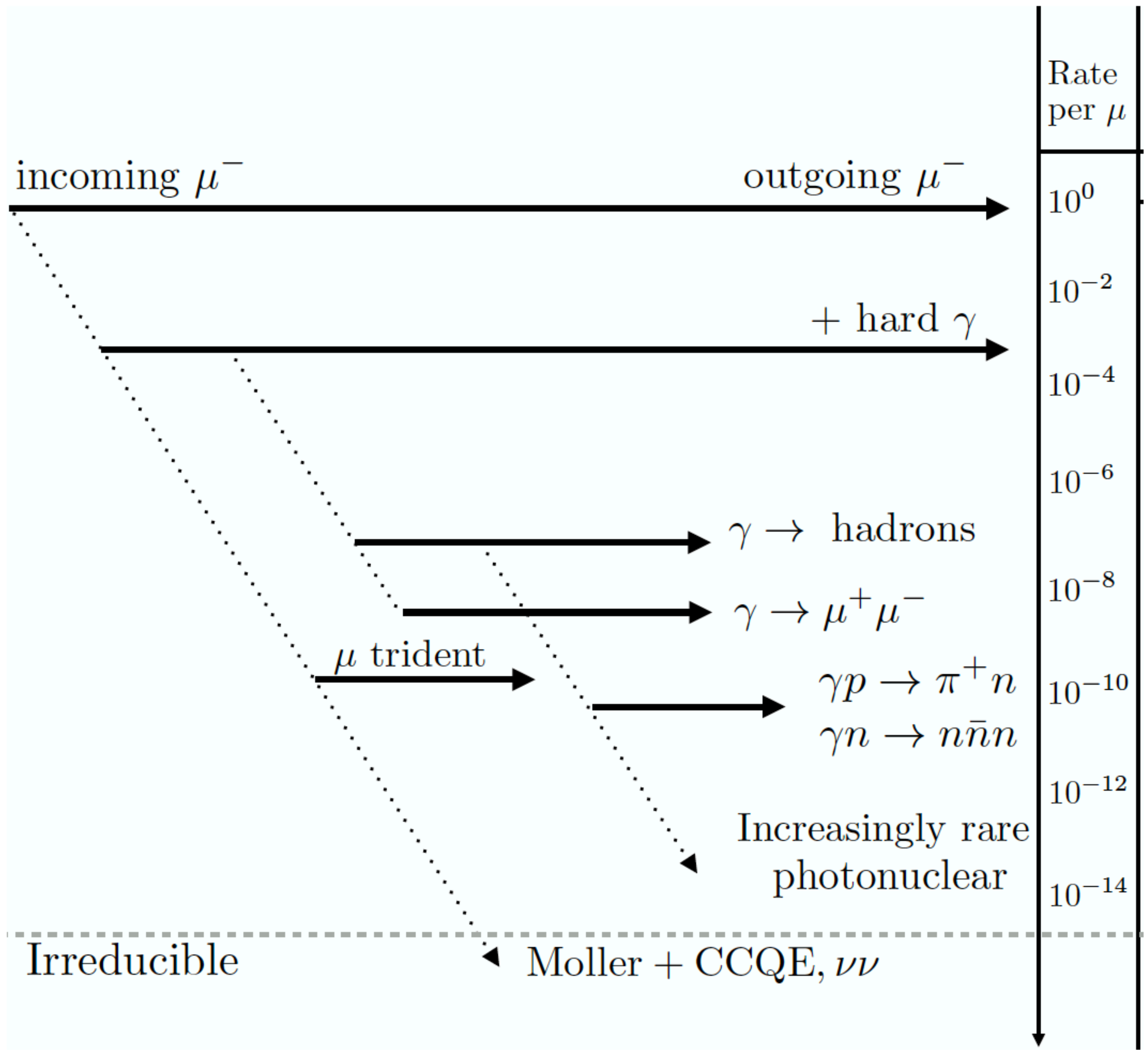
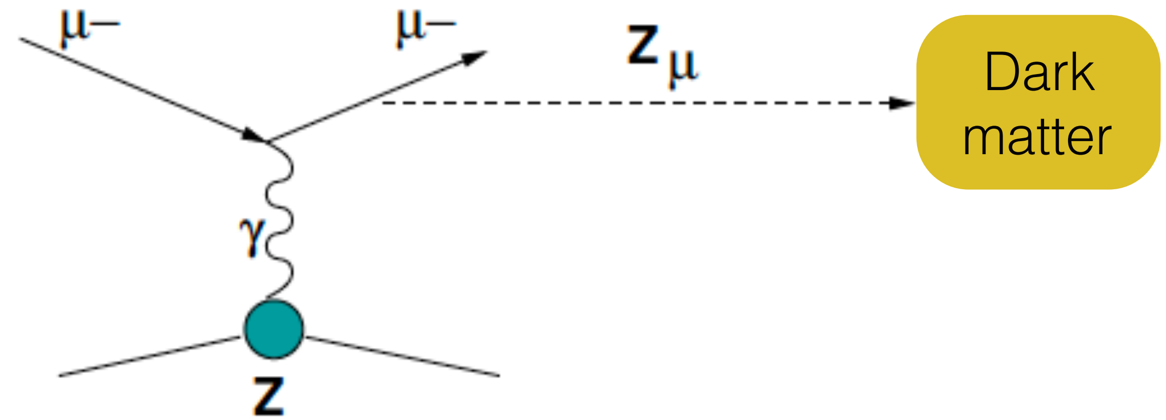
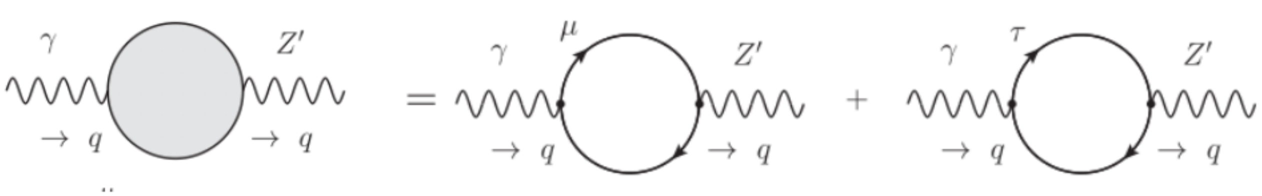
Background sources



"M³: A New Muon Missing Momentum Experiment to Probe (g−2)μ and Dark Matter at Fermilab", arxiv:1804.03144

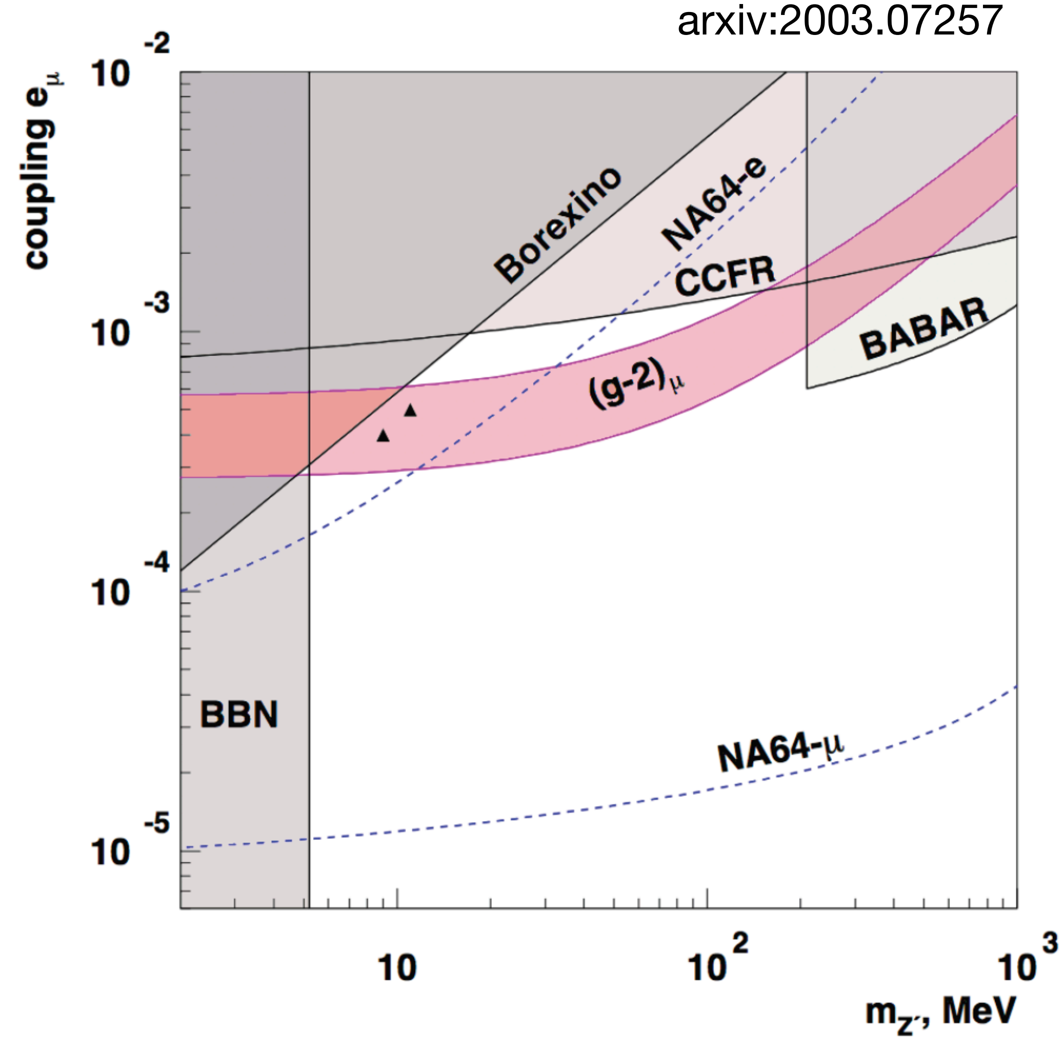
Future prospects: NA64$_\mu$ physics goals





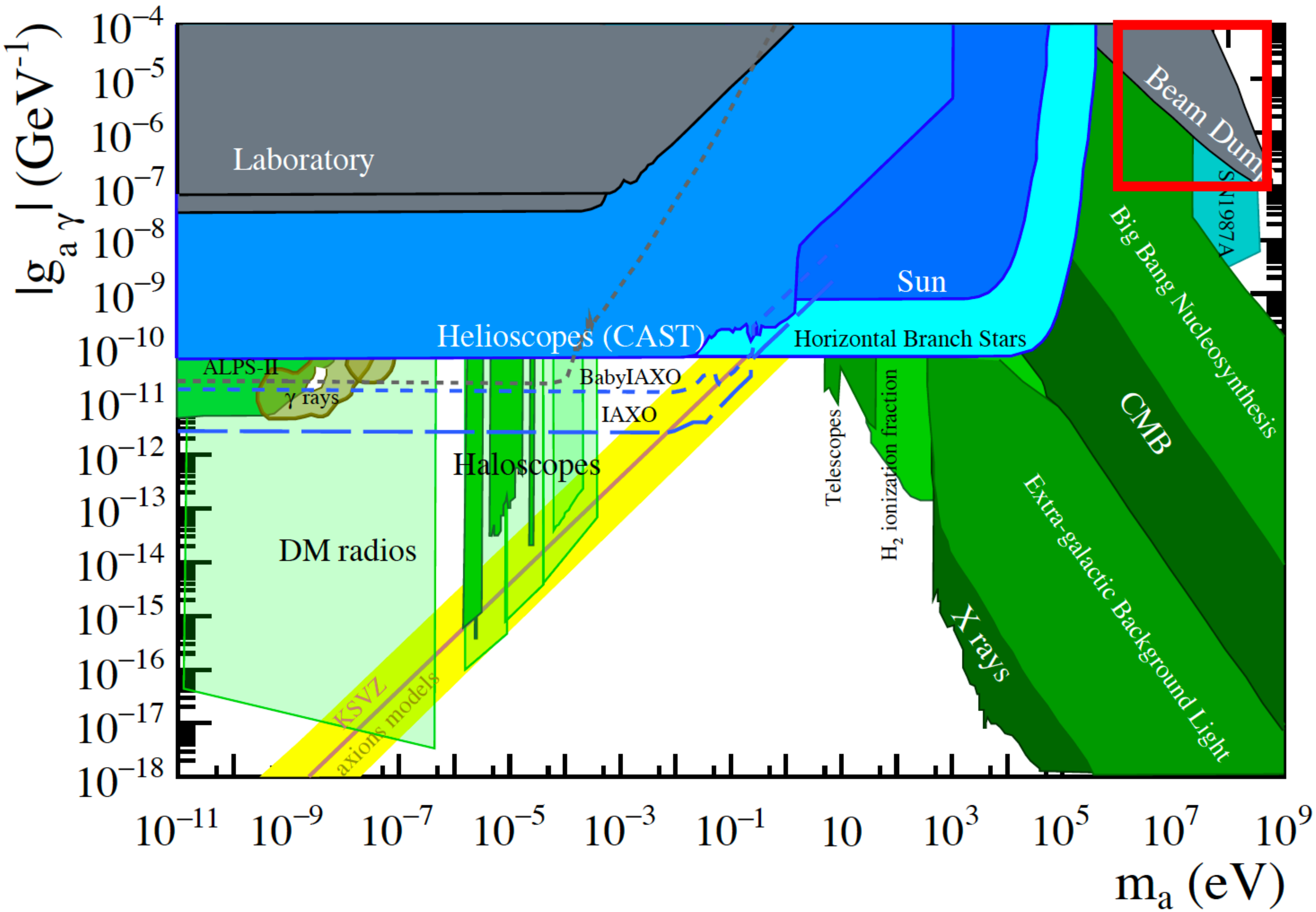
- γ-Z' mixing via loop
- **Complementarity between muon and electron mode:** If Z' is observed in muon mode should also be observed in e$^-$ mode

arxiv:2003.07257



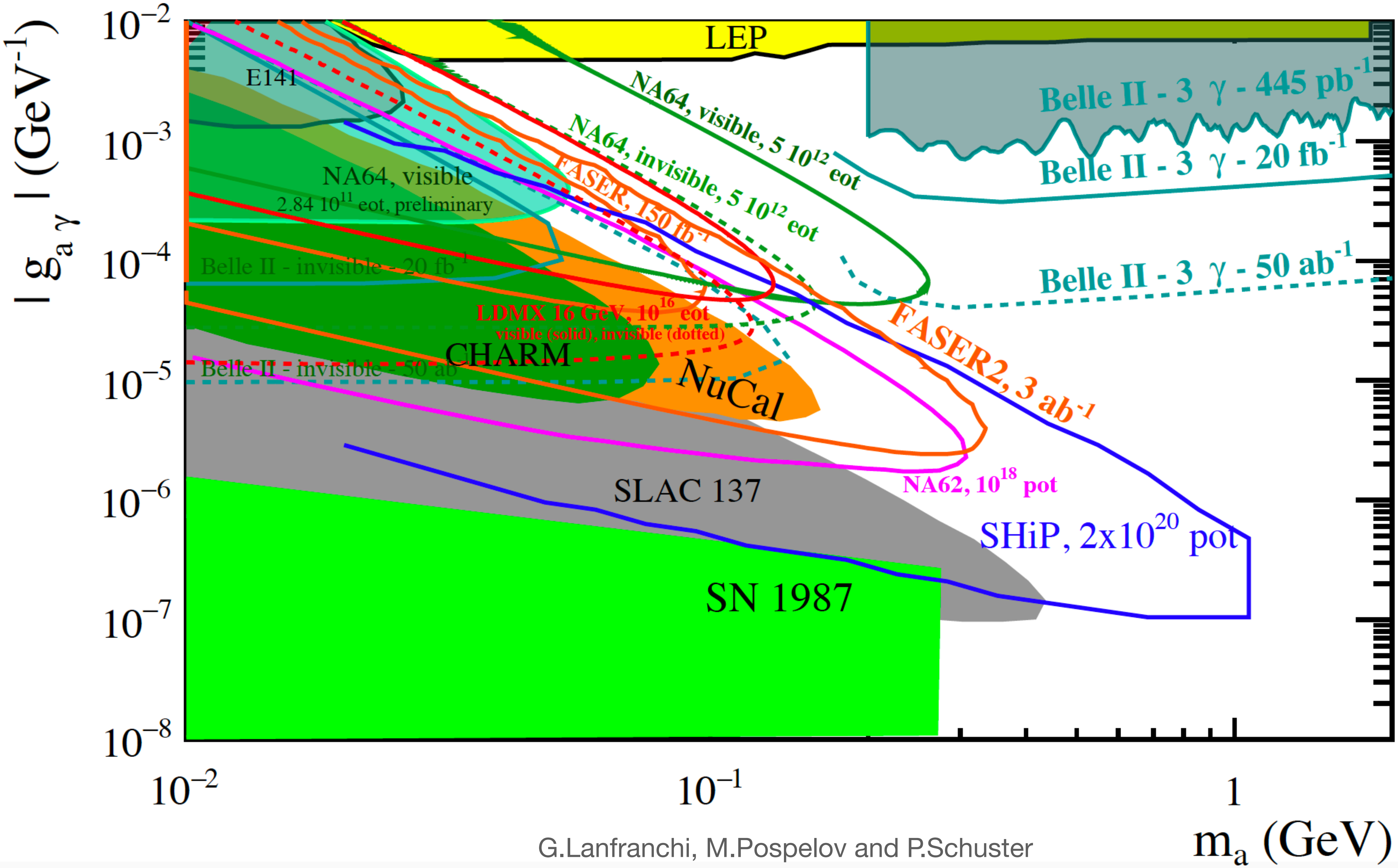
L.Molina Bueno

ALPs searches



G.Lanfranchi, M.Pospelov and P.Schuster
arxiv:2011.02157

Projections for *ALPs*



G.Lanfranchi, M.Pospelov and P.Schuster
arxiv:2011.02157