Searches for dark sectors at the low energy/high intensity frontier - Krakow Seminar on PPP and Exp.- 10.1.2022

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

Outline

- Introduction and motivations to search for Dark sectors (DS)

- Part 1: Searches of DS at the high intensity frontier: the NA64 experiment at CERN

- Part 2: Searches of DS at the high precision frontier: Muonium (M) spectroscopy at PSI (the Mu-MASS experiment)

The shortcomings of the Standard Model (SM)

- Despite its incredible success the SM does not provide a complete description of Nature, e.g. it does not explain the origin of dark matter, dark energy, the baryon asymmetry in the Universe and it does include gravity.

- Moreover, some hints for possible deviations (recent muon g-2 and LHCb results)

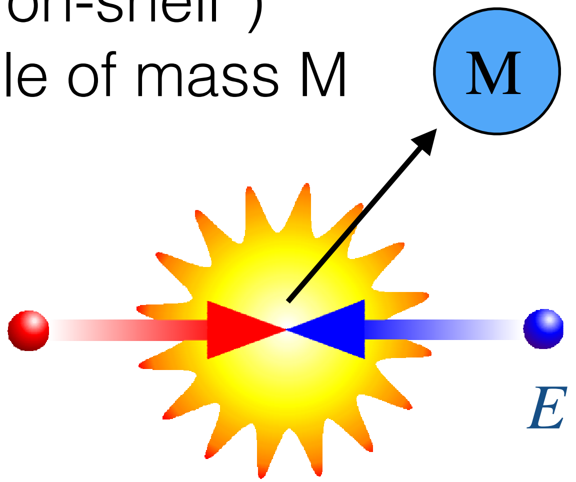
- New Physics (NP) could address some of these problems:
  e.g. supersymmetry, extra dimensions or hidden sectors.

"Collisions" vs "propagator" physics

PART I

High-energy collisions

real ("on-shell") particle of mass M



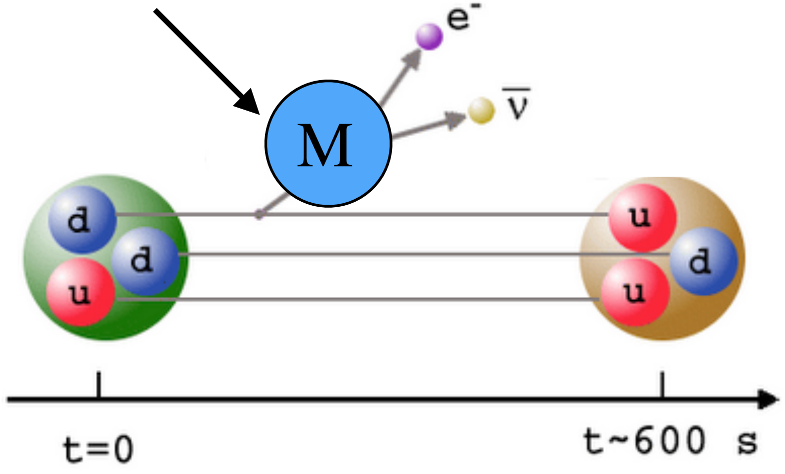
on-shell particles limited by kinematical threshold:

$$(Mc^2) < E_{cms}$$

PART II

Rare processes

virtual ("off-shell") particle of mass M



off-shell particles sensitivity limited by rarity of process:

$$(Mc^2)\Delta t \gtrsim \hbar$$

Light Mediators searches complementary to WIMPs

For a review see e.g. https://arxiv.org/abs/2011.02157

Dark Matter — Mediator — Standard Model

OBSERVED **AMOUNT OF DARK MATTER** TODAY

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

The WIMP miracle

$$(m_X, g_X) \sim (m_{\text{weak}}, g_{\text{weak}})$$

The WIMPless MIRACLE

$$\frac{m_X}{g_X^2} \sim \frac{m_{\text{weak}}}{g_{\text{weak}}^2}$$

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

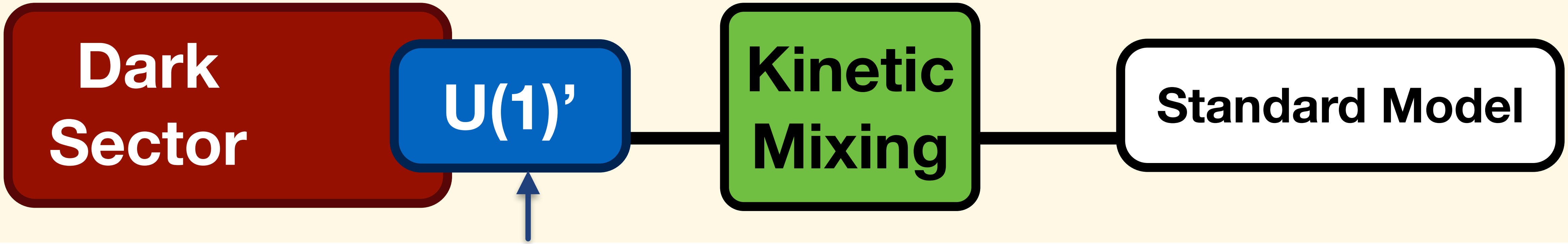
Large range for g_X and m_X

Renormalizable Portals

B. Batell, M. Pospelov and A. Ritz, Phys. Rev. D80 (2009) 095024.

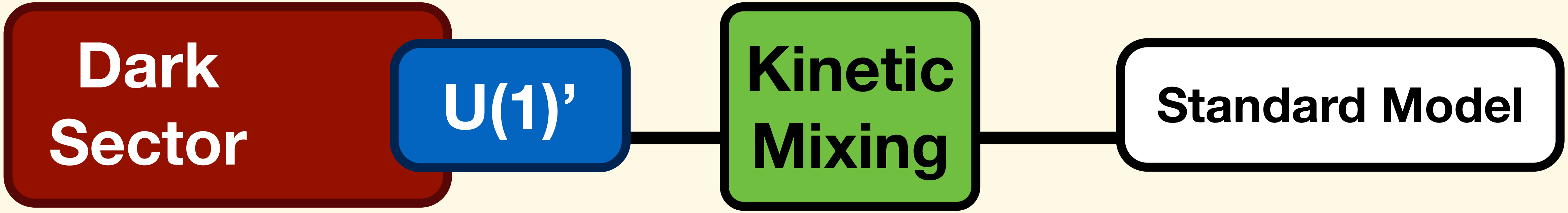
- "Axion" — $\frac{1}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu} a$ — axions & axion-like particles (ALPs)
- "Higgs" — $\lambda H^2 S^2 + \mu H^2 S$ — exotic Higgs decays?
- "Vector" — $\epsilon F^{Y,\mu\nu} F'_{\mu\nu}$ — dark photon A′
- "Neutrino" — $\kappa (HL) N$ — sterile neutrinos?

MAIN FOCUS OF THIS SEMINAR



NEW FORCE CARRIED BY MASSIVE **VECTOR** BOSON: **DARK PHOTON**

DARK SECTORS - THE VECTOR PORTAL



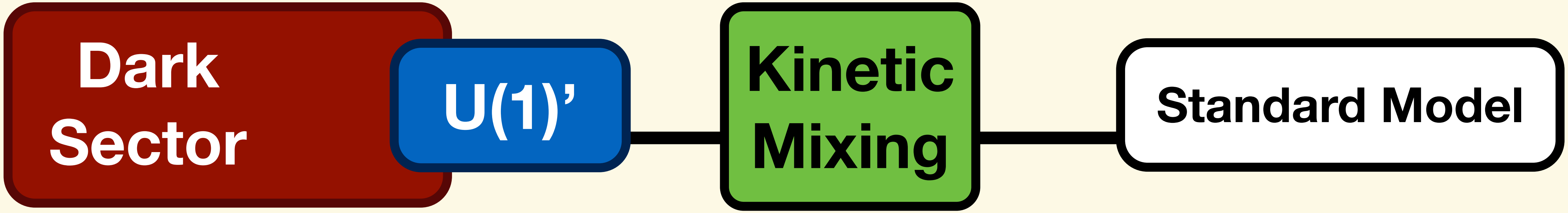
DARK SECTOR (DS) charged under a new U(1)' gauge symmetry and interacts with SM through kinetic mixing (ε) of a MASSIVE VECTOR MEDIATOR (A') with our photon.

Dark matter with mass (m_χ), part of DS.

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

Four parameters: $m_{A'}$, m_χ, $\alpha_D = e_D^2/4\pi$, ε

DARK SECTORS - THE VECTOR PORTAL



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

OBSERVED **AMOUNT OF DARK MATTER** TODAY

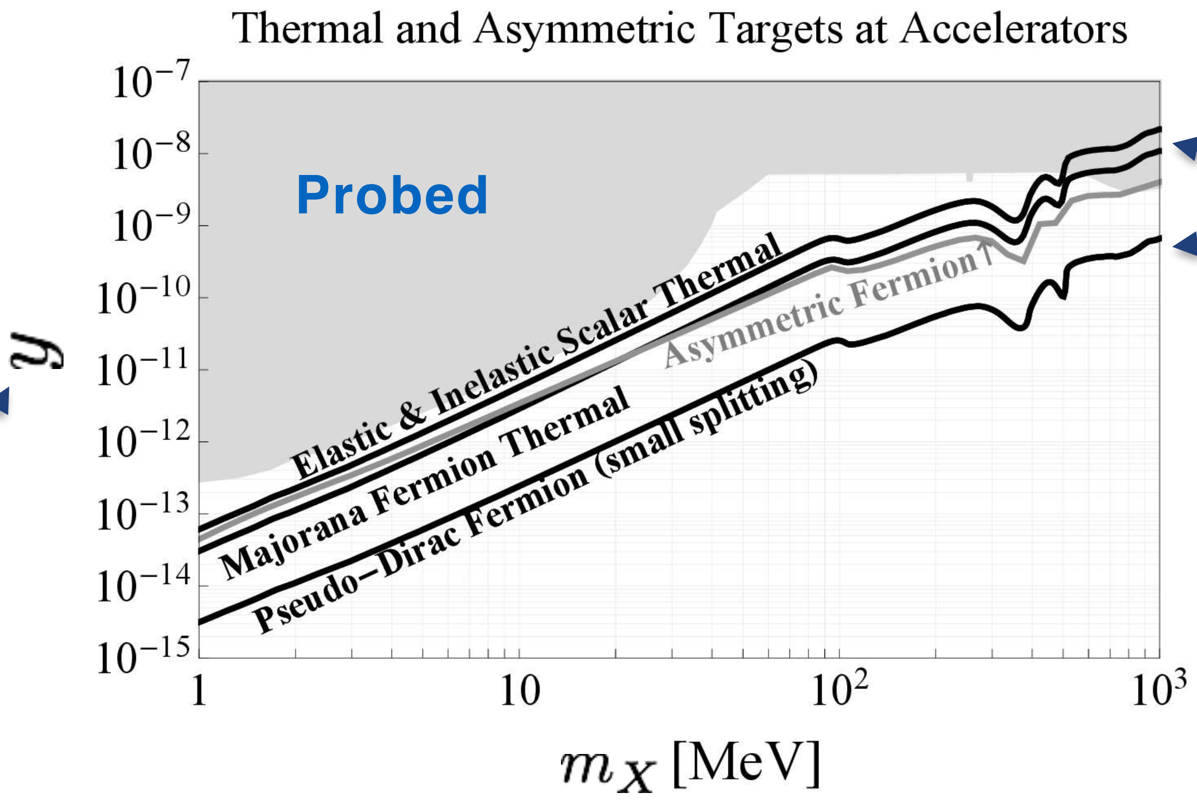
$$\Omega_X \propto \frac{1}{< v\sigma >} \sim \frac{m_X^2}{y}$$

WHERE

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

The (y,mX) DM PARAMETER SPACE

For a review see e.g https://arxiv.org/pdf/1707.04591.pdf

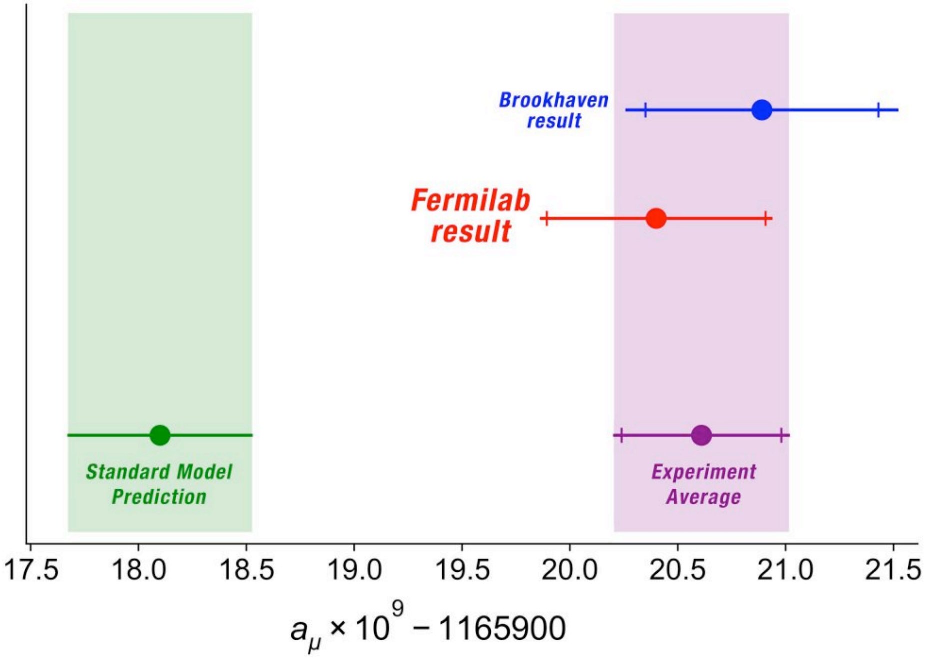


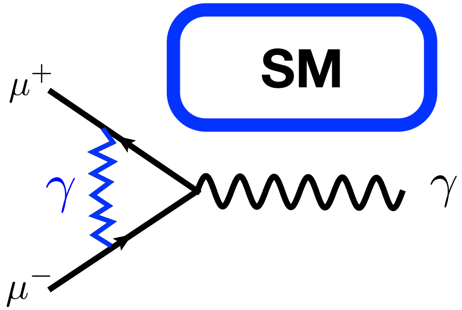
Solid lines predictions from DM relic abundance

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

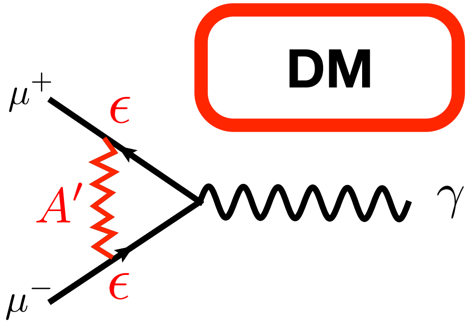
The muon (g-2): an additional motivation to search for dark photons

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



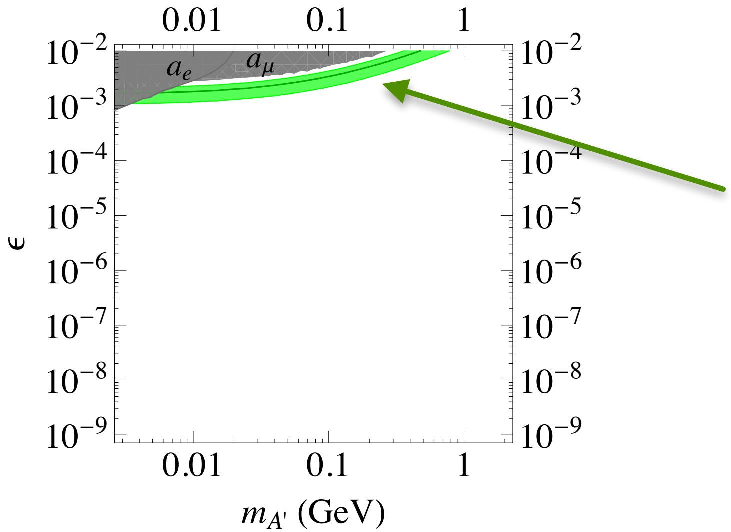


$$(g_s - 2)^{\gamma}_{\mu} \simeq \frac{\alpha}{2\pi} \simeq 10^{-3}$$



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

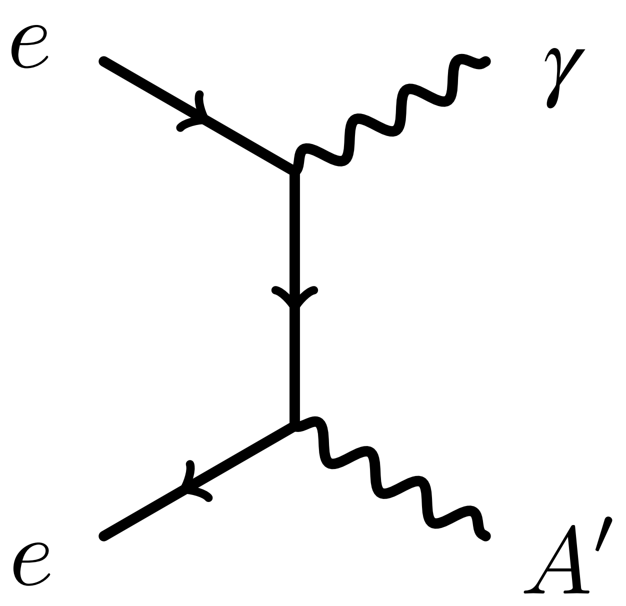
M. Pospelov, A. Ritz and M. B. Voloshin, Phys. Lett. B 662, 53 (2008)



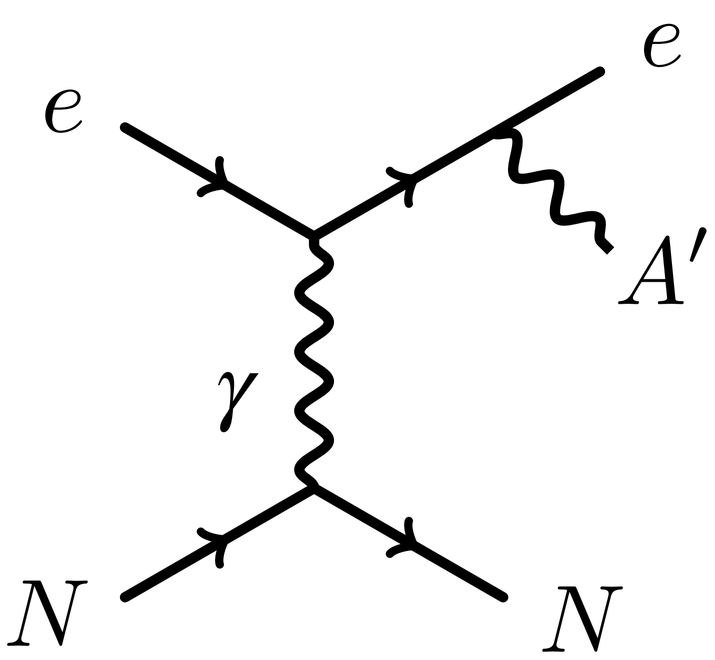
A' may explain observed anomaly

TO NOTE: Lattice QCD calculations S. Borsanyi et al. Nature 593 (2021) reduce discrepancy. Hadronic corrections to be directly measured by MUonE EXP @ CERN G. Abbiendi. PoS ICHEP2020, 223 (2021)

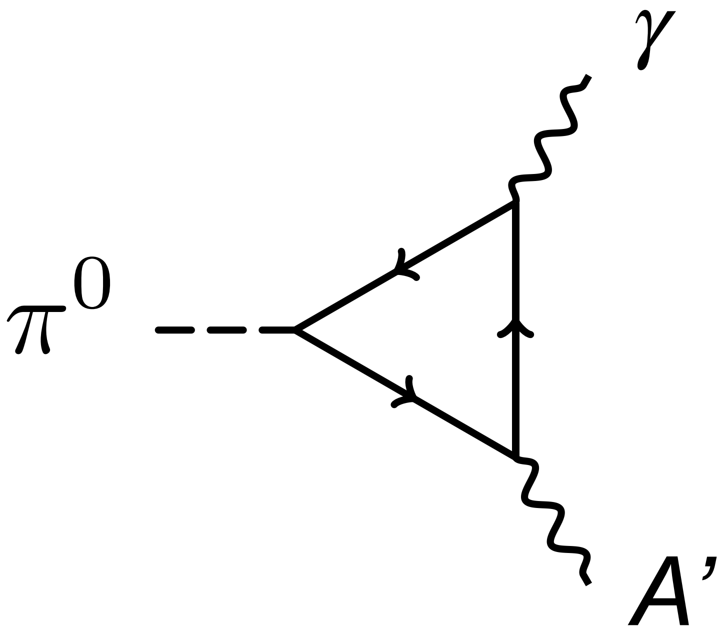
Some production mechanisms for Dark Photons



annihilation



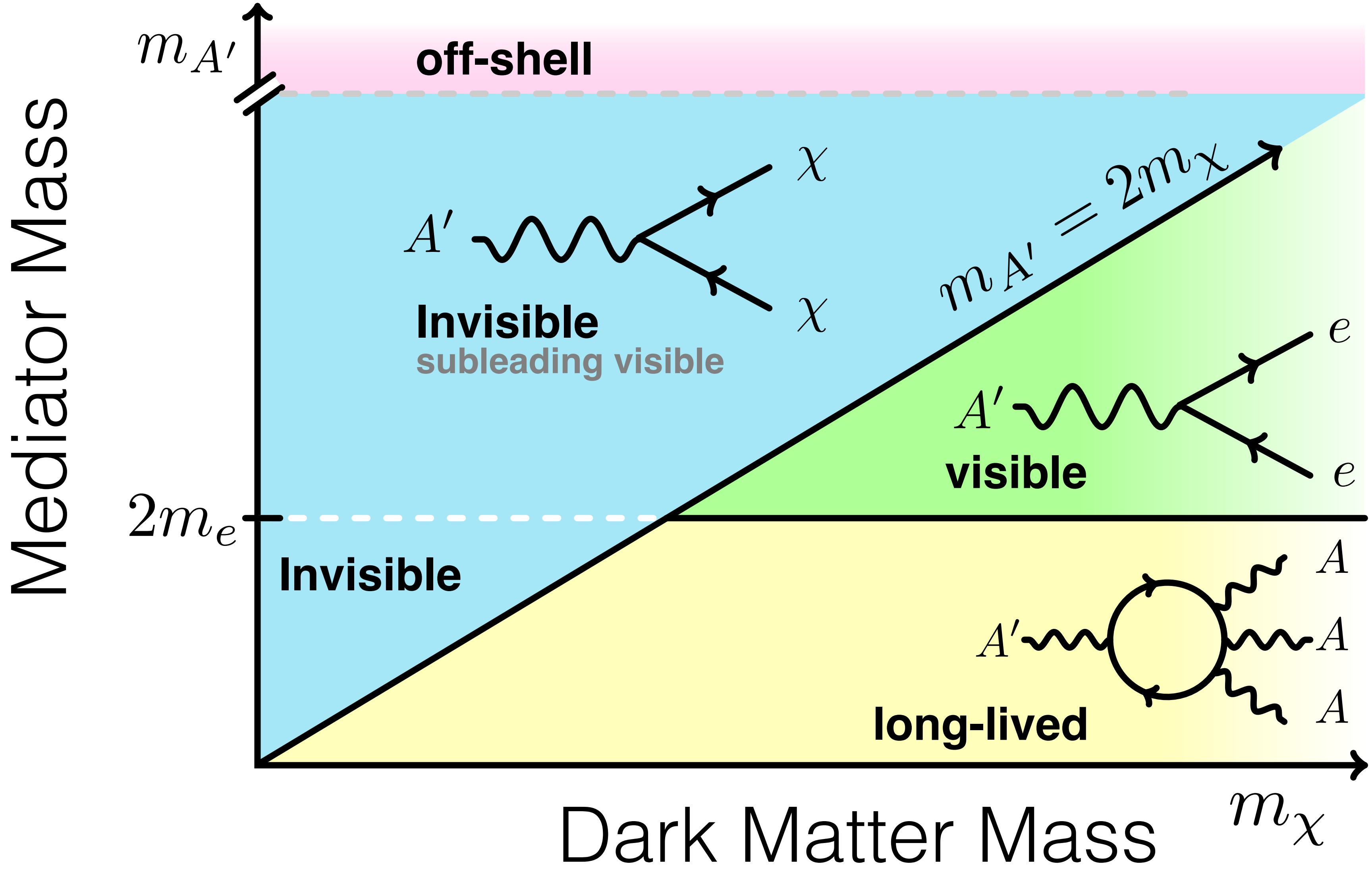
bremsstrahlung



meson decay

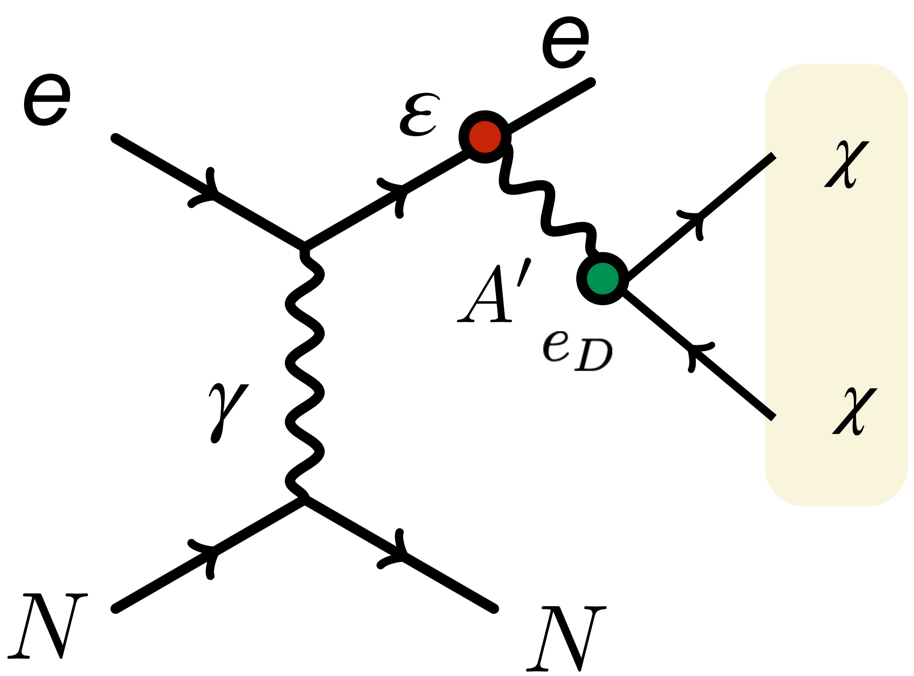
Decays of Dark Photons

Adapted from Natalia Toro, Dark Sectors 2017 (1608.03591)



SEARCHES FOR DARK SECTORS AT FIXED TARGET EXP.

INVISIBLE DECAY MODE $m'_A > 2m_X$



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

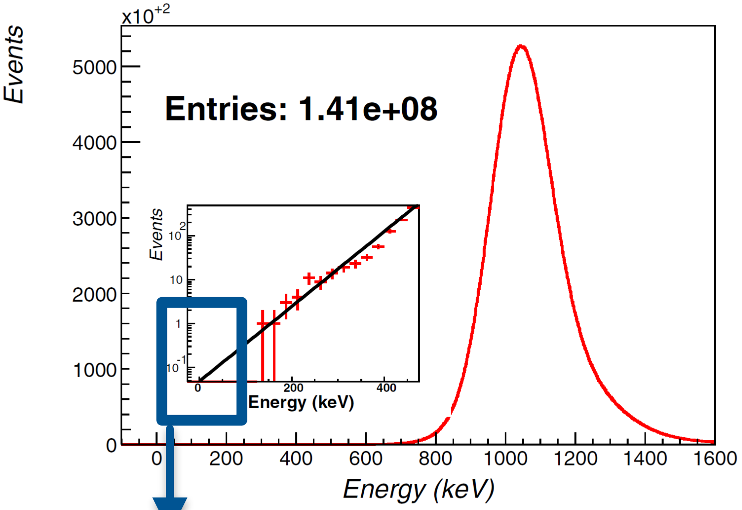
Flux of X generated by decays of A's produced in the dump.
Signal: X scattering in far detector

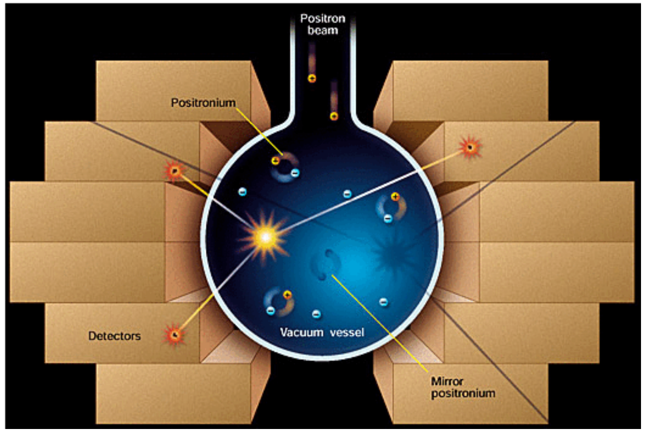
2) NA64/LDMX APPROACH $\sigma \propto \epsilon^2$

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, P. Crivelli et al., Phys. Rev. D. 75, 032004 (2007)
Latest results 2020 C. Vigo, P. Crivelli et al., PRL124,101803

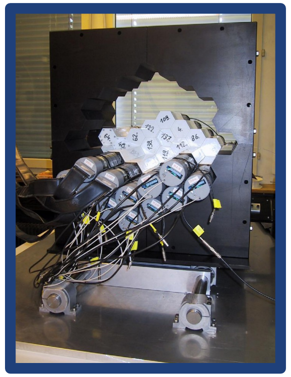


Table top

IPA ETH zürich

At rest → 100 GeV

The NA64 collaboration (~50 researchers from 16 Institutes)

Yu. M. Andreev,[6] D. Banerjee,[4] J. Bernhard,[4] V. E. Burtsev,[2] A. G. Chumakov,[12,13] D. Cooke,[5] P. Crivelli,[15] E. Depero,[15] A. V. Dermenev,[6] S. V. Donskov,[10] R. R. Dusaev,[12] T. Enik,[2] N. Charitonidis,[4] A. Feshchenko,[2] V. N. Frolov,[2] A. Gardikiotis,[9] S. G. Gerassimov,[3,7] S. N. Gninenko*,[6] M. Hösgen,[1] V. A. Kachanov,[10] A. E. Karneyeu,[6] G. Kekelidze,[2] B. Ketzer,[1] D. V. Kirpichnikov,[6] M. M. Kirsanov,[6] V. N. Kolosov,[10] I. V. Konorov,[3,7] S. G. Kovalenko,[11] V. A. Kramarenko,[2,8] L. V. Kravchuk,[6] N. V. Krasnikov,[2,6] S. V. Kuleshov,[11,16] V. E. Lyubovitskij,[12,13,14] V. Lysan,[2] V. A. Matveev,[2] Yu. V. Mikhailov,[10] L. Molina Bueno,[15] D. V. Peshekhonov,[2] V. A. Polyakov,[10] B. Radics,[15] R. Rojas,[14] A. Rubbia,[15] V. D. Samoylenko,[10] H. Sieber,[15] D. Shchukin,[7] V. O. Tikhomirov,[7] I. Tlisova,[6] A. N. Toropin,[6] A. Yu. Trifonov,[12,13] B. I. Vasilishin,[12] P. V. Volkov,[2,8] and V. Yu. Volkov[8]

(The NA64 Collaboration)

[1] *Universität Bonn, Helmholtz-Institut für Strahlen-und Kernphysik, 53115 Bonn, Germany*
[2] *Joint Institute for Nuclear Research, 141980 Dubna, Russia*
[3] *Technische Universität München, Physik Department, 85748 Garching, Germany*
[4] *CERN, European Organization for Nuclear Research, CH-1211 Geneva 23, Switzerland*
[5] *UCL Departement of Physics and Astronomy, University College London, Gower St. London WC1E 6BT, United Kingdom*
[6] *Institute for Nuclear Research, 117312 Moscow, Russia*
[7] *P.N. Lebedev Physical Institute, Moscow, Russia, 119 991 Moscow, Russia*
[8] *Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, 119991 Moscow, Russia*
[9] *Physics Department, University of Patras, 265 04 Patras, Greece*
[10] *State Scientific Center of the Russian Federation Institute for High Energy Physics of National Research Center 'Kurchatov Institute' (IHEP), 142281 Protvino, Russia*
[11] *Departamento de Ciencias Físicas, Universidad Andres Bello, Sazié 2212, Piso 7, Santiago, Chile*
[12] *Tomsk Polytechnic University, 634050 Tomsk, Russia*
[13] *Tomsk State Pedagogical University, 634061 Tomsk, Russia*
[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*

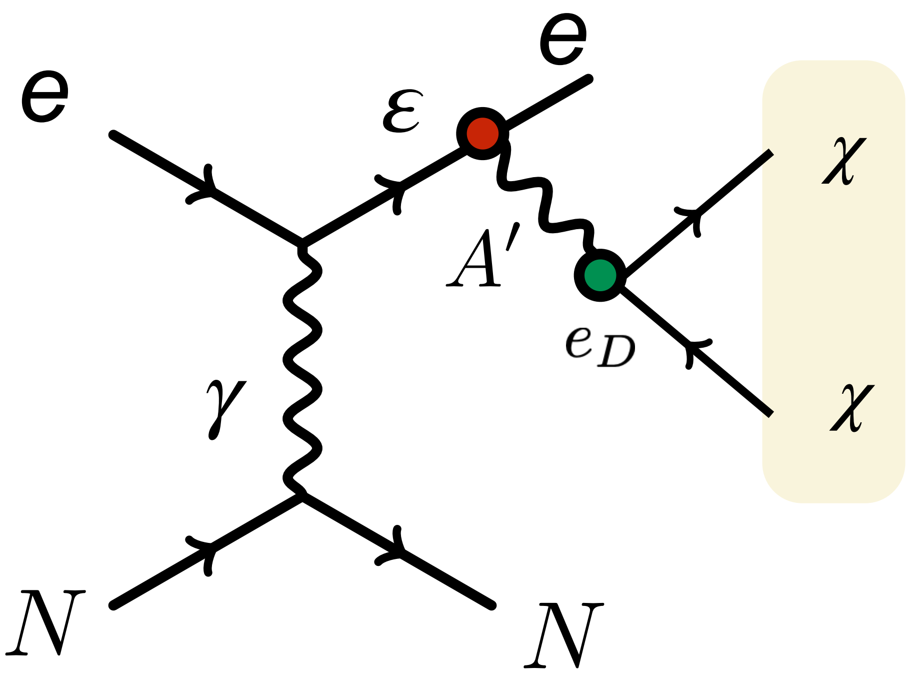
Proposed (P348) in 2014, first test beam in 2015 (2 weeks), Approved by CERN SPSC in March 2016 → NA64. 2016: 5 weeks, 2017: 5 weeks, 2018: 6 weeks.

August 2021: 5 weeks in H4

October 2021: 3 weeks in M2

The NA64 search for A’ → $\chi\bar{\chi}$

INVISIBLE DECAY MODE $m'_A > 2m_X$



DS Lagrangian

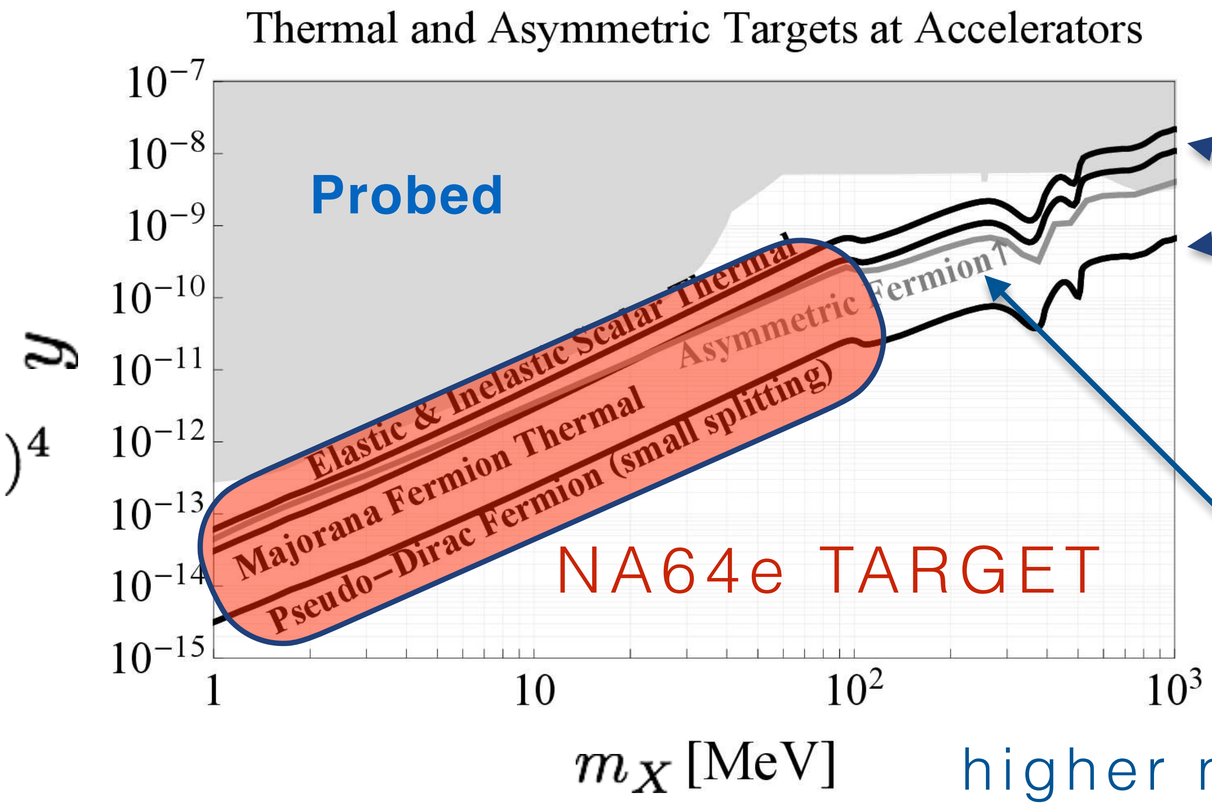
$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu} + \frac{m^2_{A'}}{2}A'_\mu A'^\mu$$
$$+ i\bar{\chi}\gamma^\mu\partial_\mu\chi - m_\chi\bar{\chi}\chi - e_D\bar{\chi}\gamma^\mu A'_\mu\chi,$$

Missing Energy/momentum

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

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

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

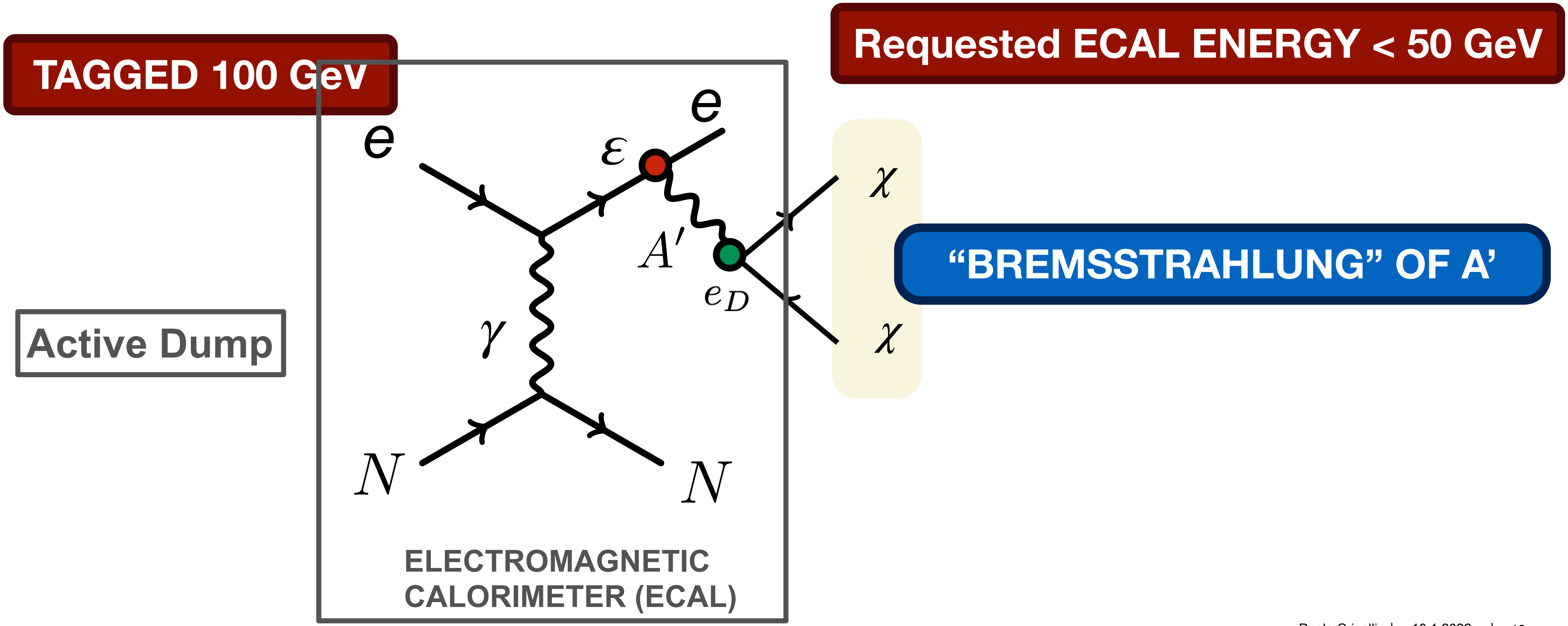


Solid lines predictions from DM relic abundance

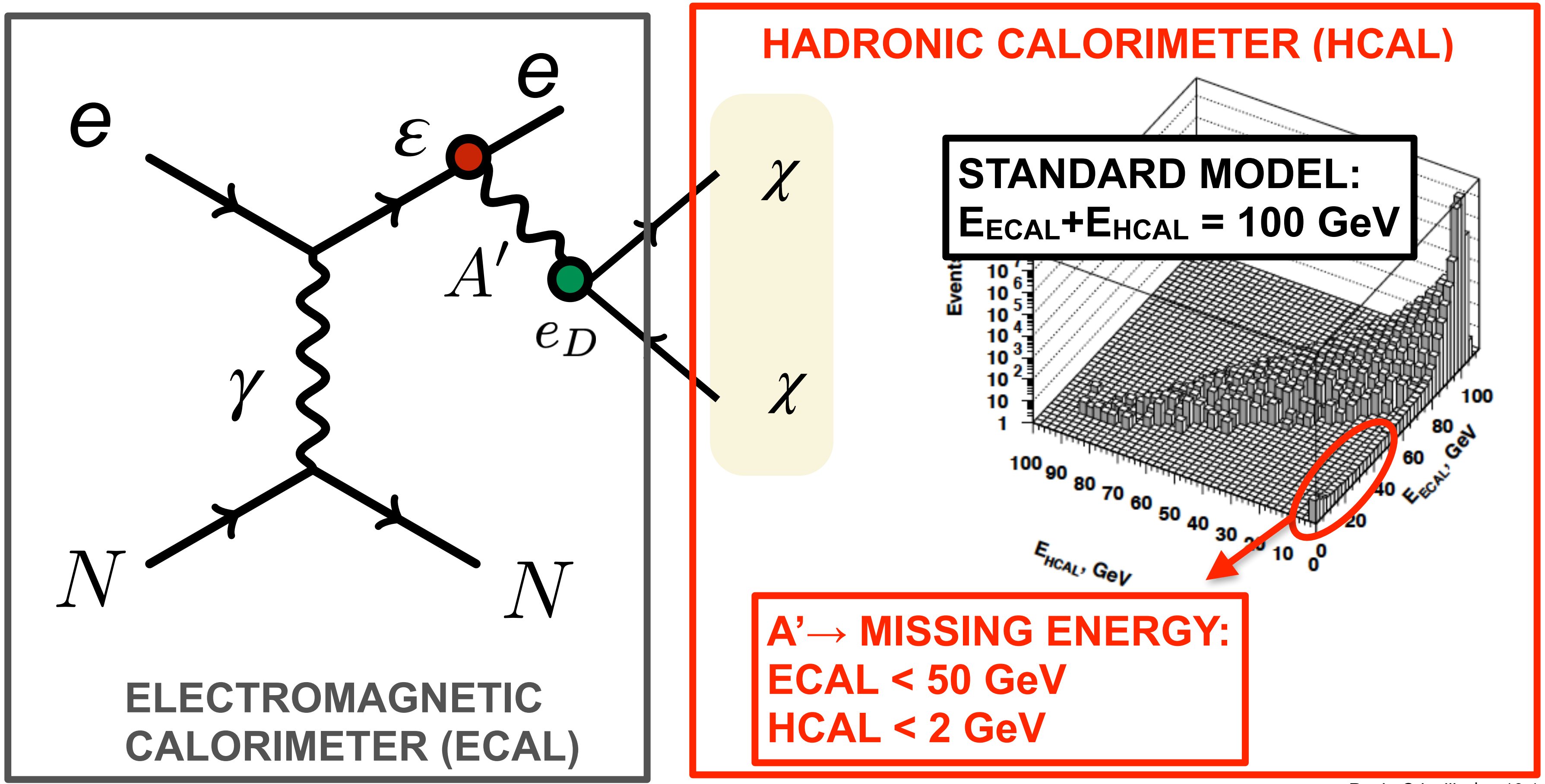
higher mass region could be covered by NA64 in muon mode

PLB796, 117 (2019)

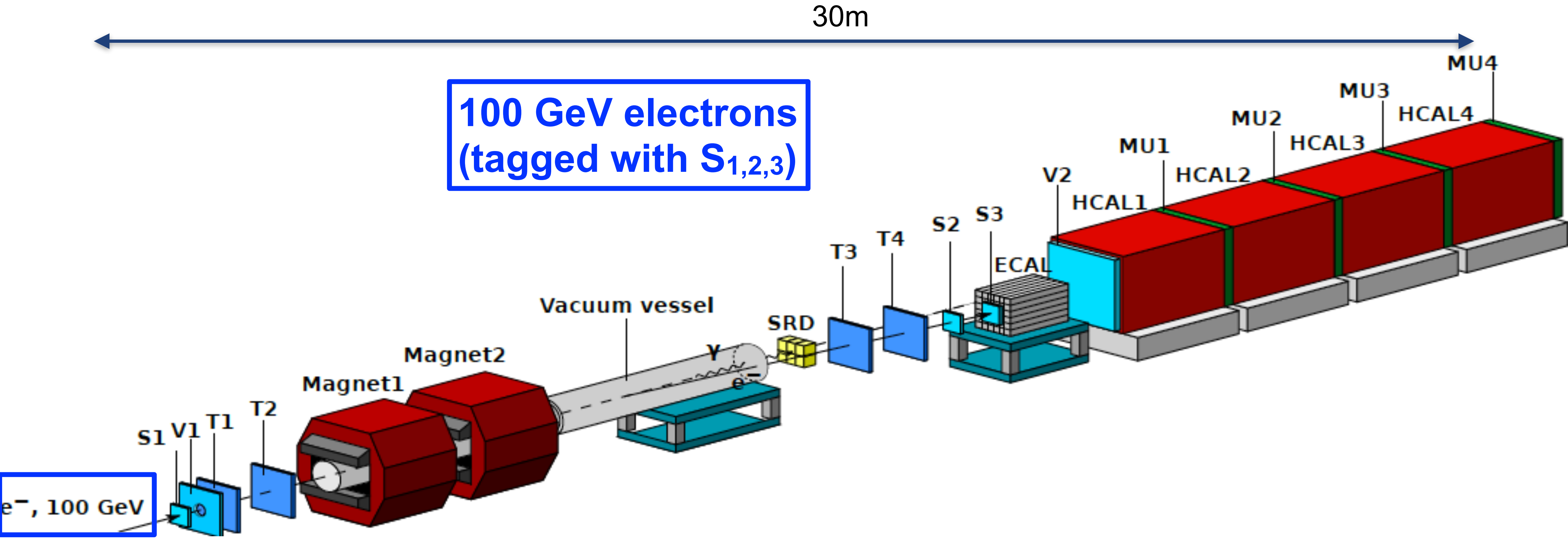
The NA64 method to search for A’ $\rightarrow \chi\bar{\chi}$



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



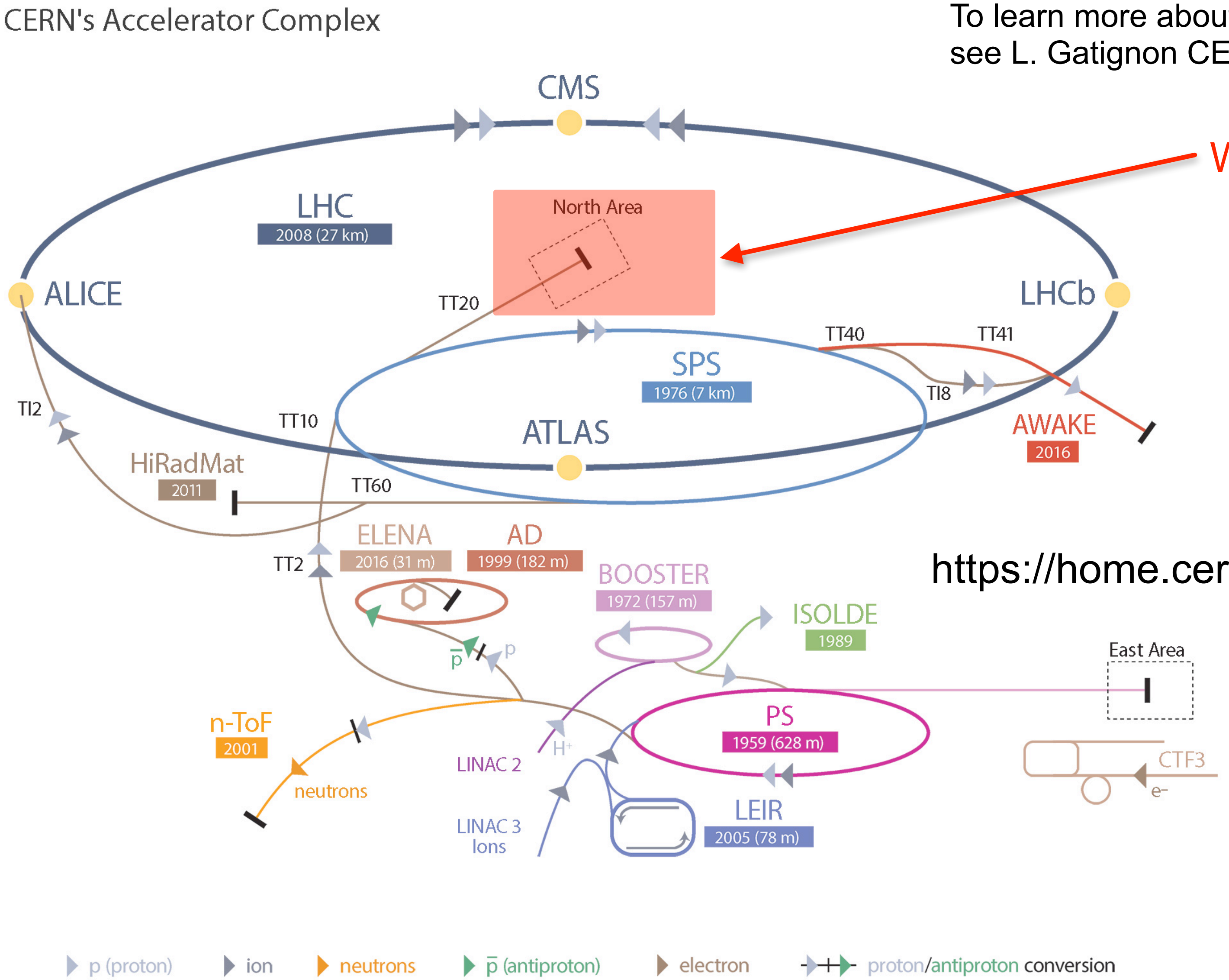
The CERN SPS H4 electron beam



- Up to 7×10^6 e^-/spill, 2-4 spill/min, spill duration 5s
- Low contamination: π (<1%), μ/K (0.1%)
- Low energy tails (<1%)
- Beam spot of 1.5 cm (FWHM)

The CERN SPS H4 electron beam

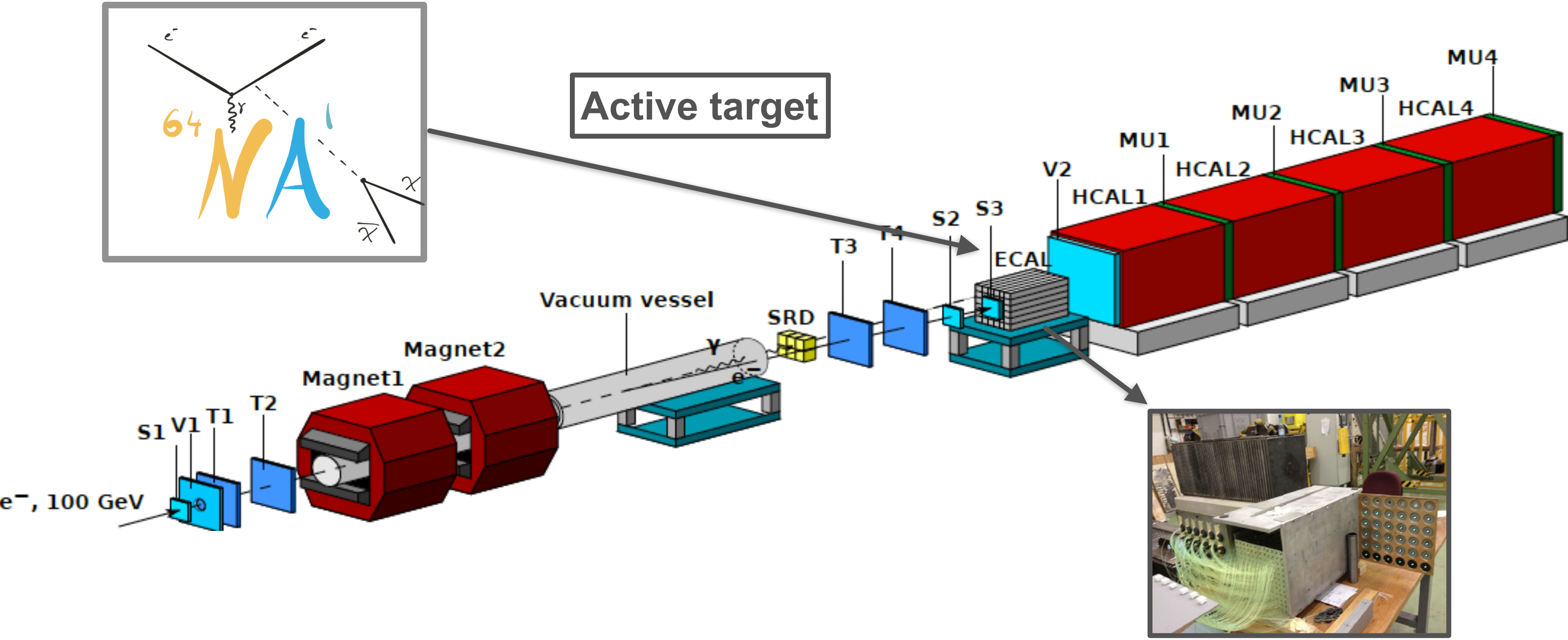
To learn more about SPS secondary beams see L. Gatignon CERN-ACC-NOTE-2020-0043



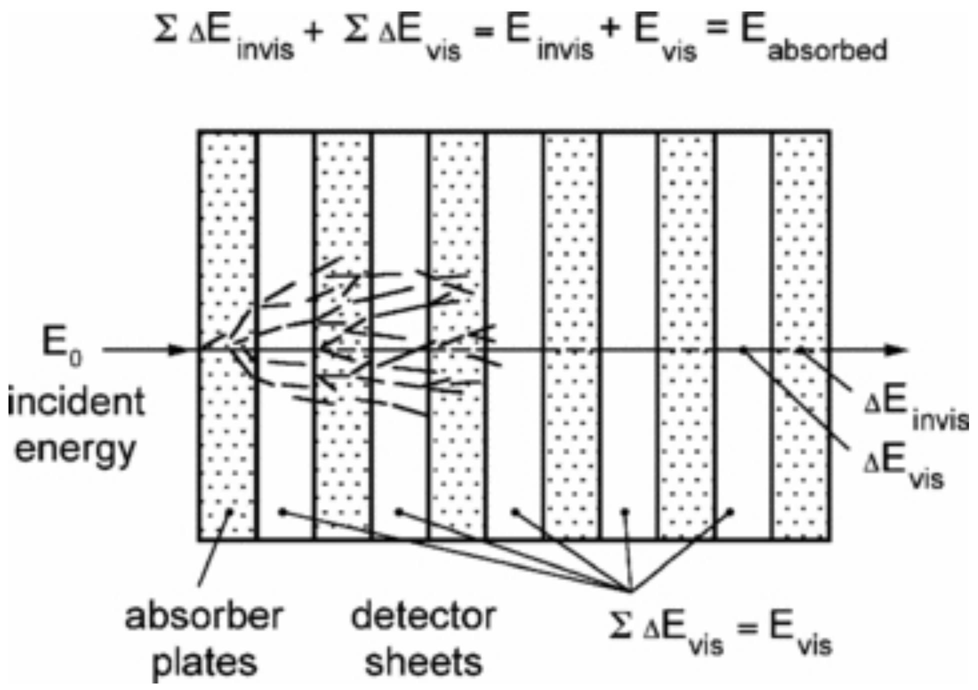
WE ARE HERE

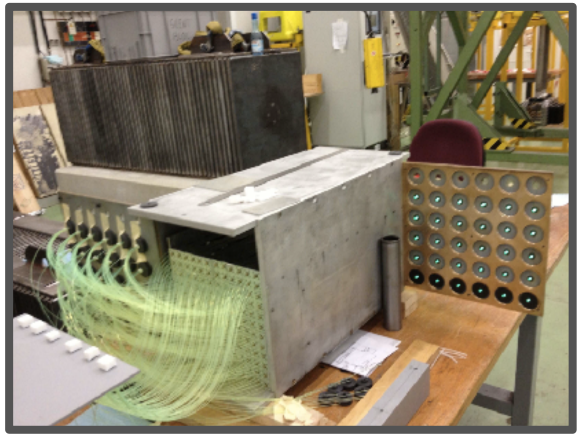
https://home.cern/science/accelerators

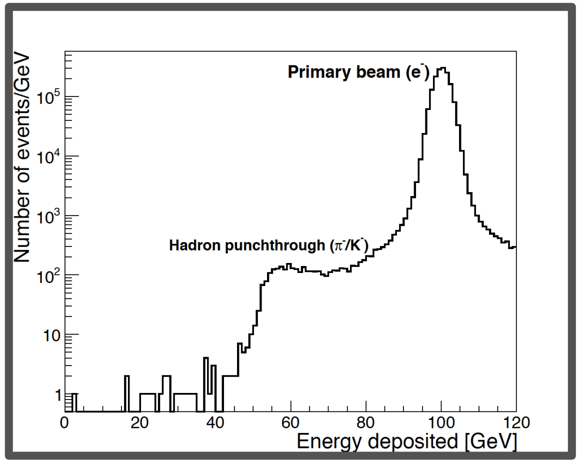
The Electromagnetic Calorimeter (ECAL)



The Electromagnetic Calorimeter (ECAL)

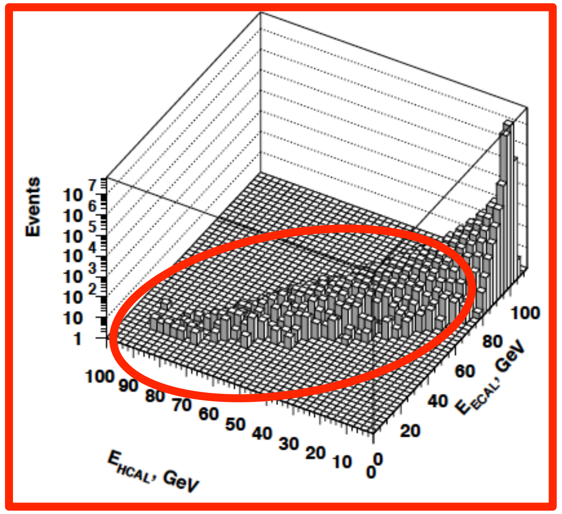




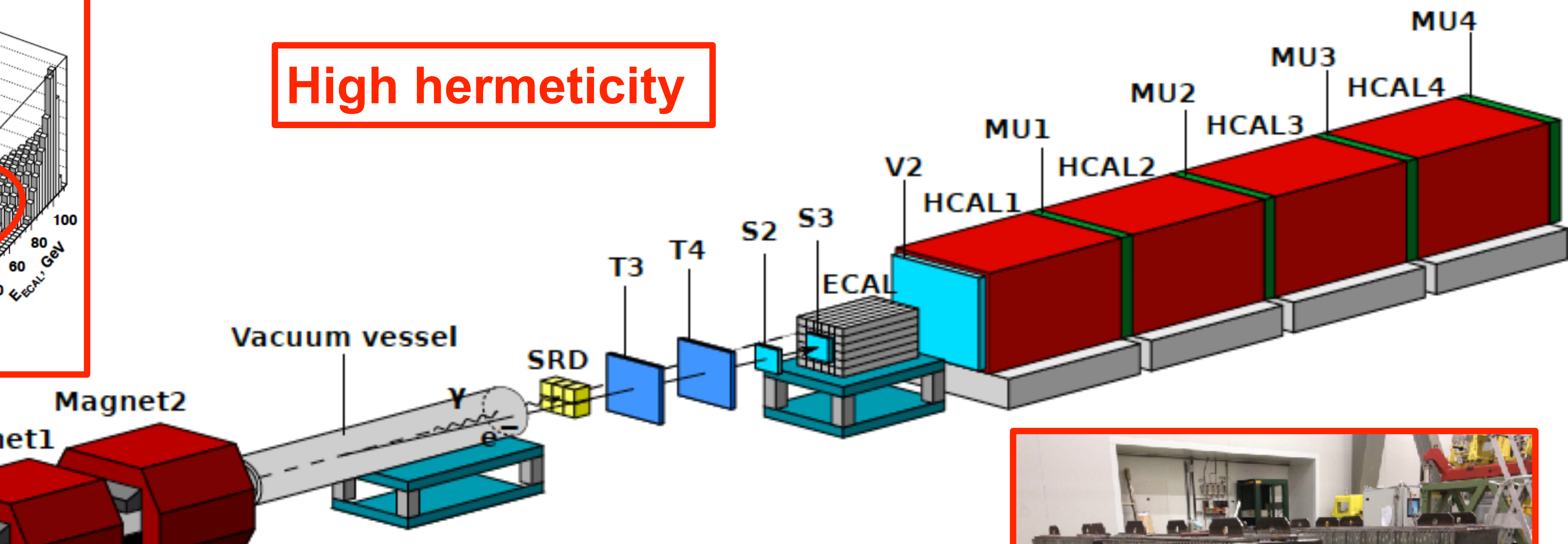


- High hermeticity (~40 X_0)
- PbSc sandwich, 6x6 matrix, cells 38x38x490 mm3
- WLS fibers in spiral→ suppress energy leaks
- Energy resolution ~ 9%/√(E[GeV])
- Longitudinal (Pre-shower) and lateral segmentation → shower profiles (hadron rejection)

The Hadronic Calorimeter (HCAL)



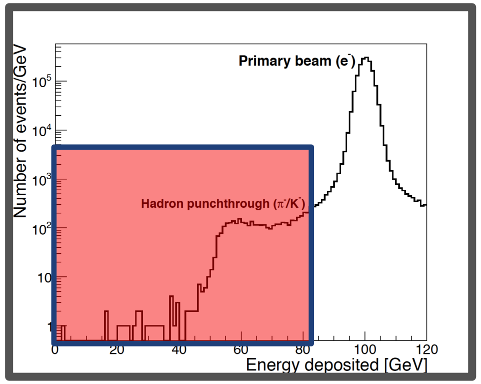
High hermeticity



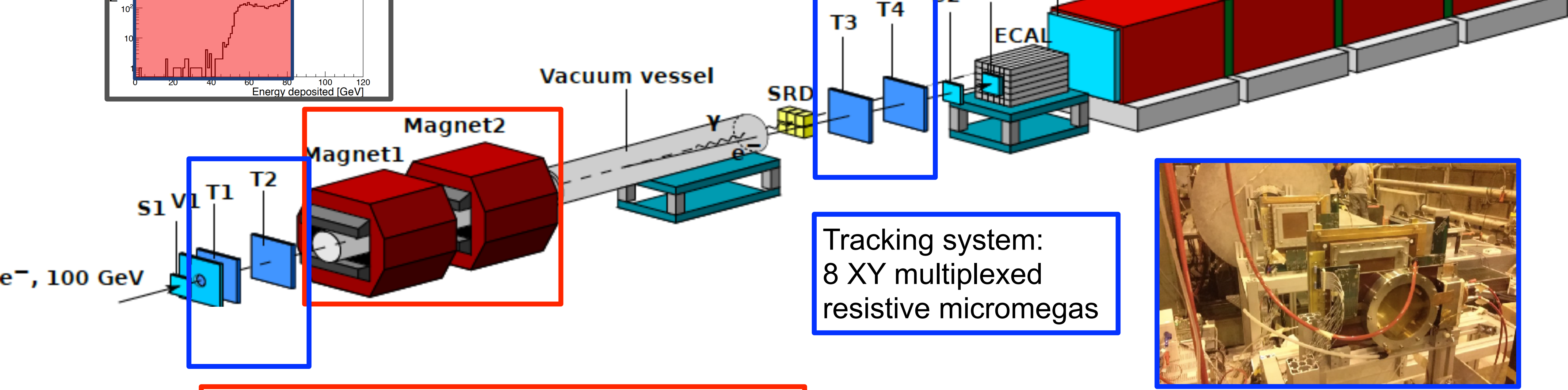
- High hermeticity : 4 HCAL (~7 λ/module)
- FeSc sandwich 3x3 matrix, cells 19.4x19.2x150 cm^3
- WLS fibers in spiral→ suppress energy leaks
- Energy resolution ~ 60%/√(E[GeV])

The magnetic spectrometer

D. Banerjee et al., Advances in HEP, 105730 (2015) and
D. Banerjee, PhD Thesis, ETH Zurich (2017)



Reconstruction of e- incoming momentum

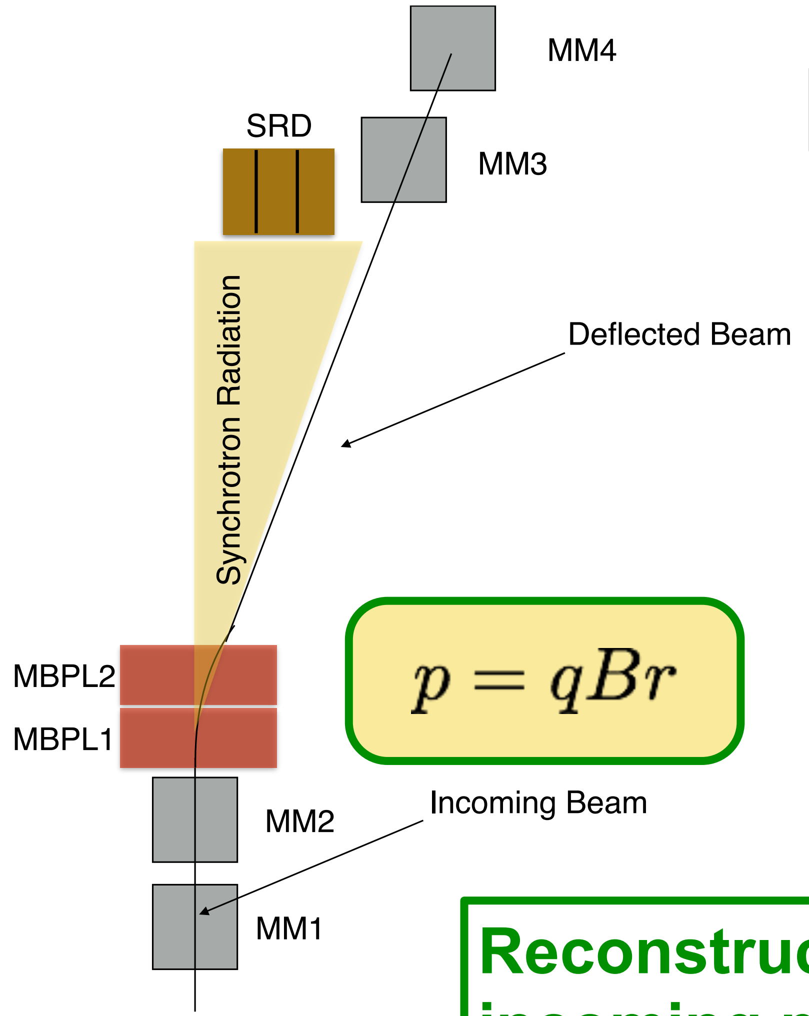


Tracking system:
8 XY multiplexed resistive micromegas

Two bending magnets in series → 7 T.m field

The magnetic spectrometer

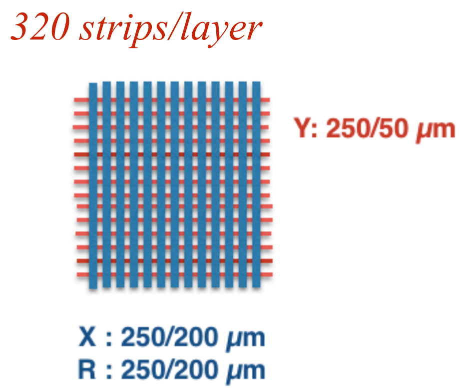
D. Banerjee et al., NIMA881 (2018) 72-81 and
D. Banerjee, PhD Thesis, ETH Zurich (2017)

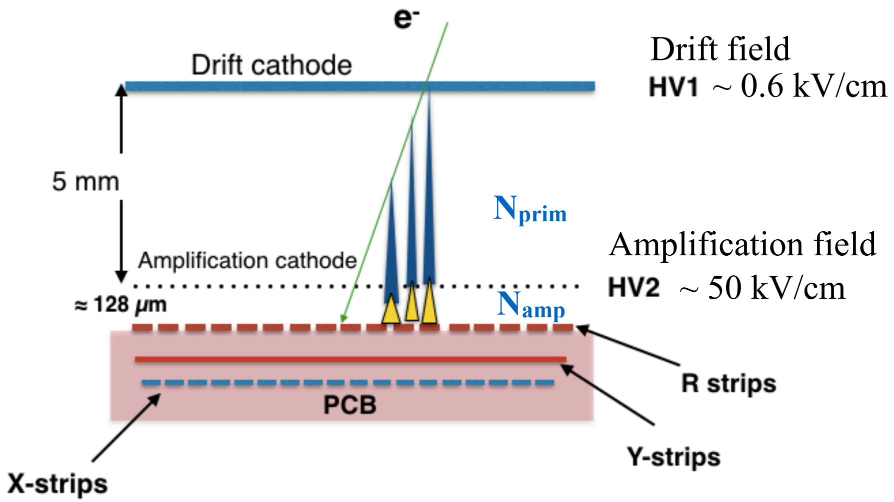


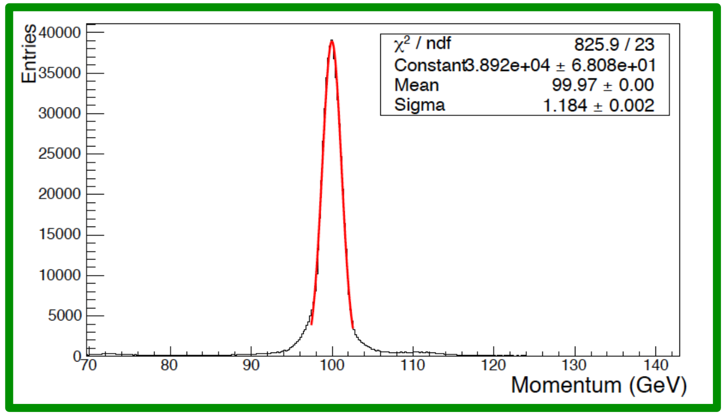
$$p = qBr$$

Reconstruction of e- incoming momentum

Tracking system MM1-MM4: multiplexed resistive micromegas



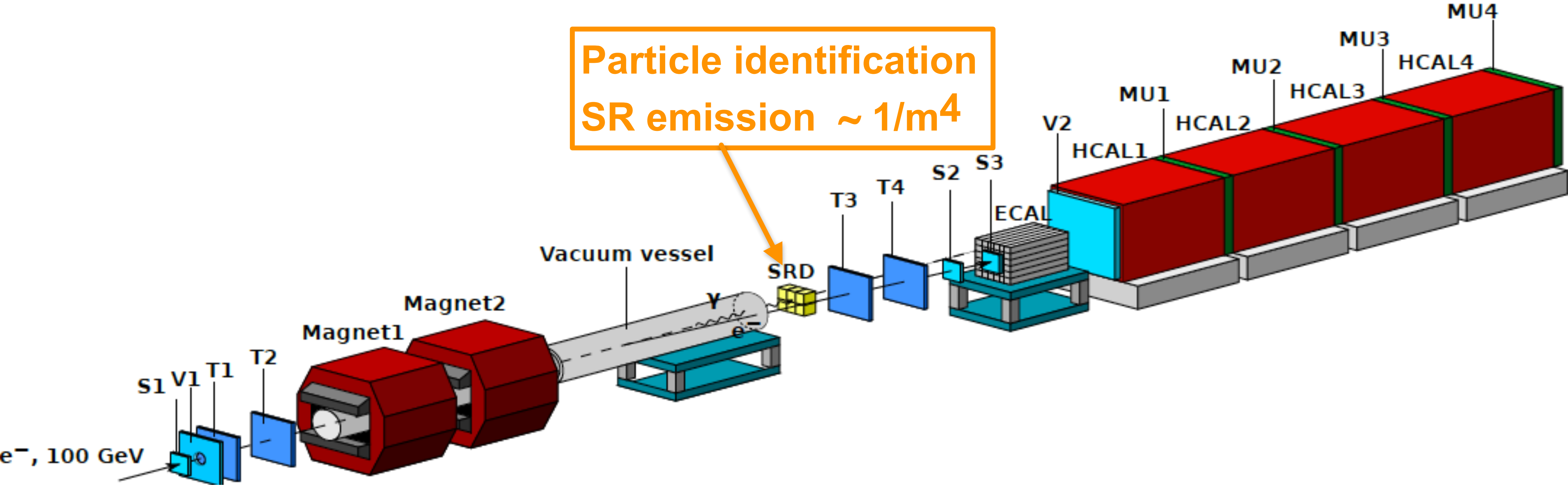




The Synchrotron Radiation (SR) detector

Particle identification

SR emission ~ $1/m^4$



The Synchrotron Radiation (SR) detector

Particle identification

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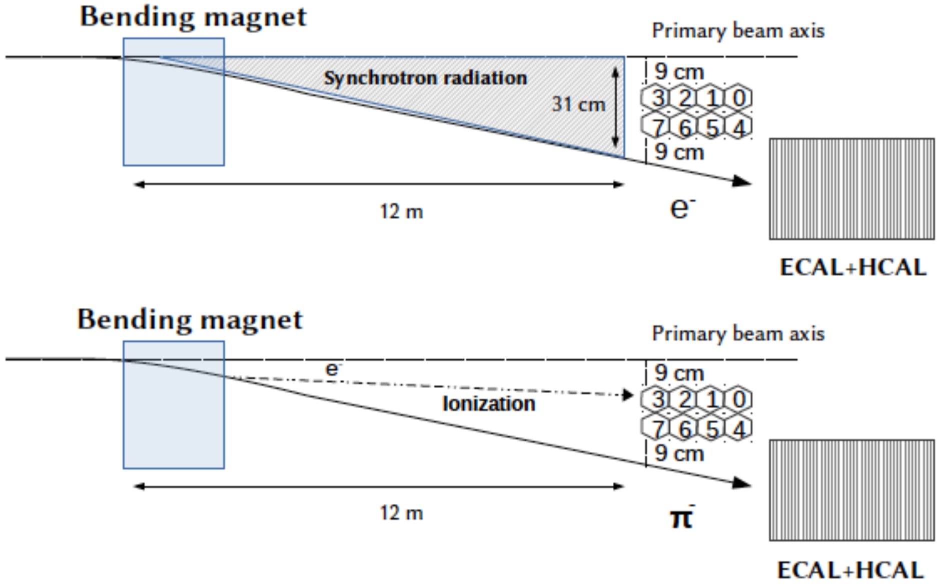
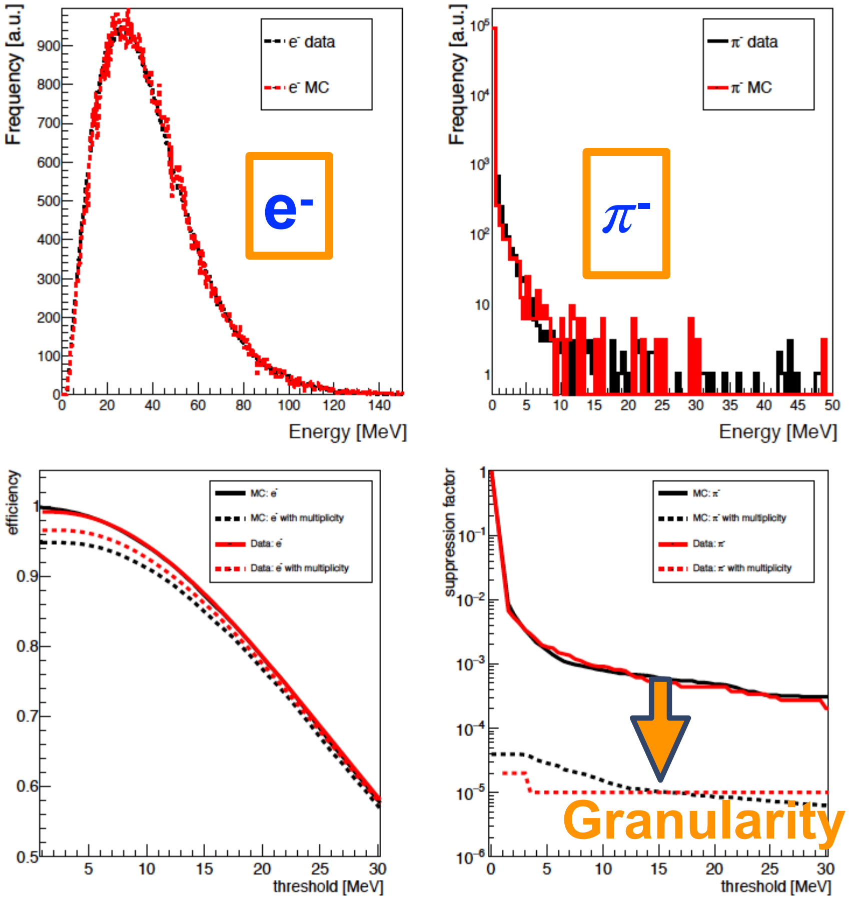


Efficiency > 95%

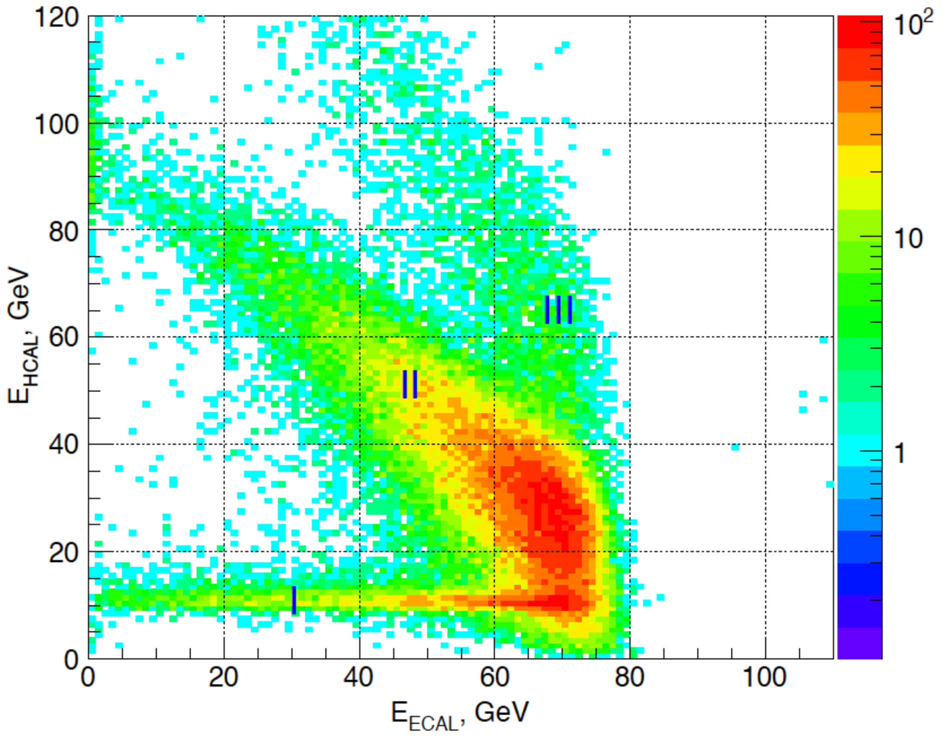
Suppression $>10^{-5}$



E. Depero et al., NIMA 866 (2017) 196-201 and
E. Depero, PhD thesis (defence 27.11.2020)

The NA64 search for A’ → $\chi\bar{\chi}$ - results (July 2016, 2 weeks)

ENERGY DEPOSITED IN THE HCAL



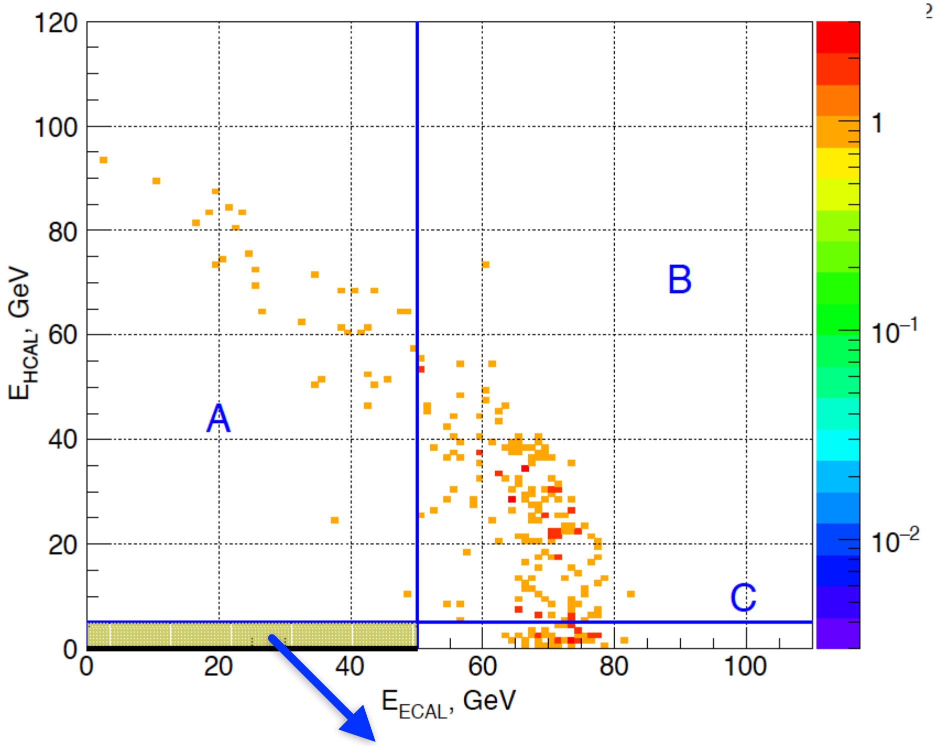
ENERGY DEPOSITED IN THE ECAL

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

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

★**Region III** —> pile-up events

The NA64 search for A’ → $\chi\bar{\chi}$ - results (July 2016, 2 weeks)



Event Selection Criteria:

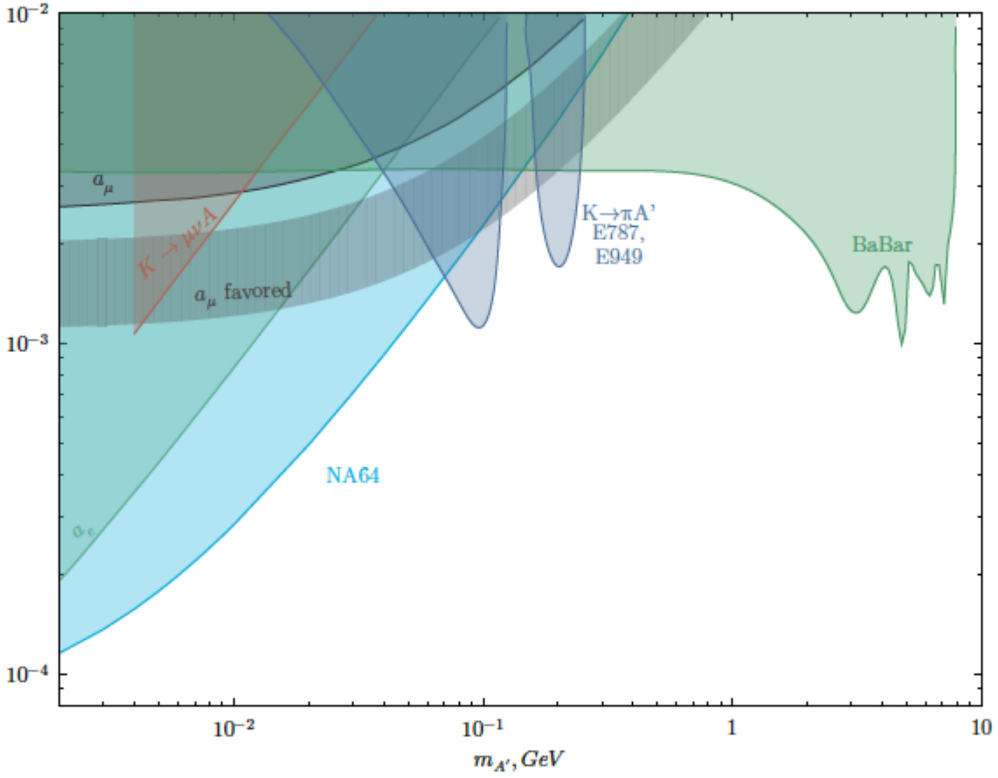
- ✦ Timing information → Pile up suppression.
- ✦ Clean incoming track: angle + single hit in all trackers, correct momentum.
- ✦ Synchrotron radiation → Hadron suppression
- ✦ Shower profile compatible with e^-
- ✦ No activity in Veto counters.

All selection cuts applied → no event in signal region

The NA64 search for A’ → $\chi\bar{\chi}$ - results (July 2016, 2 weeks)

2.75 x 10^9 electrons on target

COUPLING ε



MASS OF THE DARK PHOTON

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

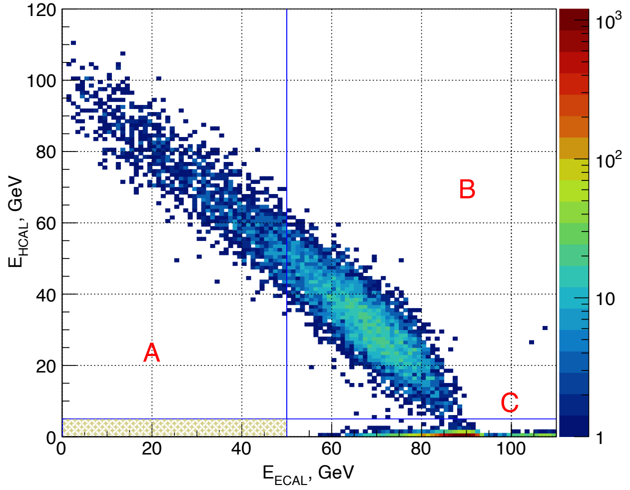
→ exclusion of most of g-2 muon favored region

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

g-2 closed completely by BABAR results

BABAR collaboration, Phys. Rev. Lett. 119, 131804 (2017)

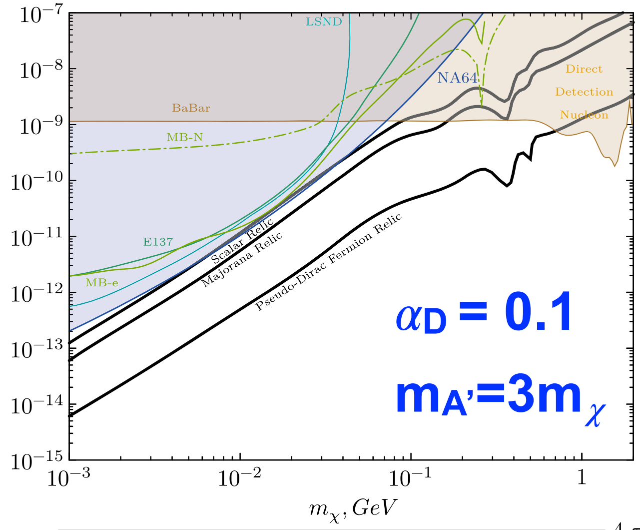
1) The NA64 search for A’ → $\chi\bar{\chi}$ - *results combined analysis 2016-2018*



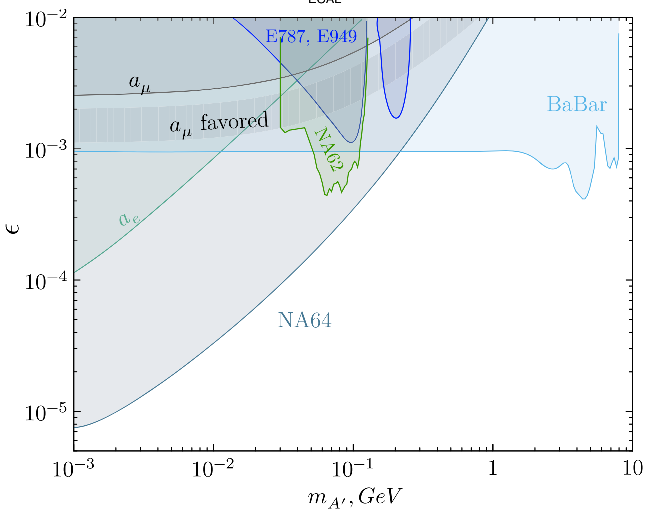
2.8 x 10^{11} electrons on target

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

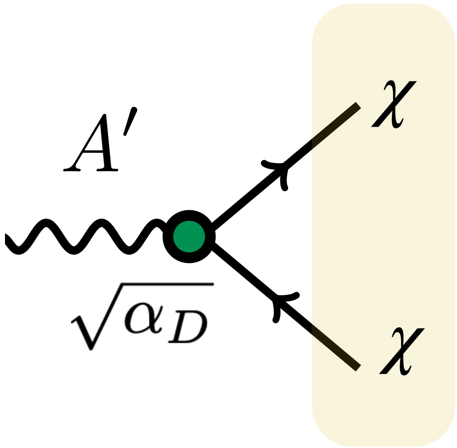
Y parameter



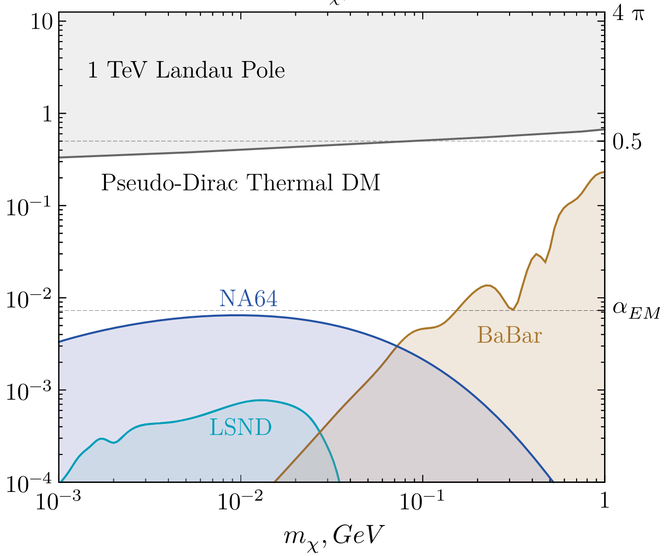
COUPLING ϵ



MASS OF THE DARK PHOTON



α_D

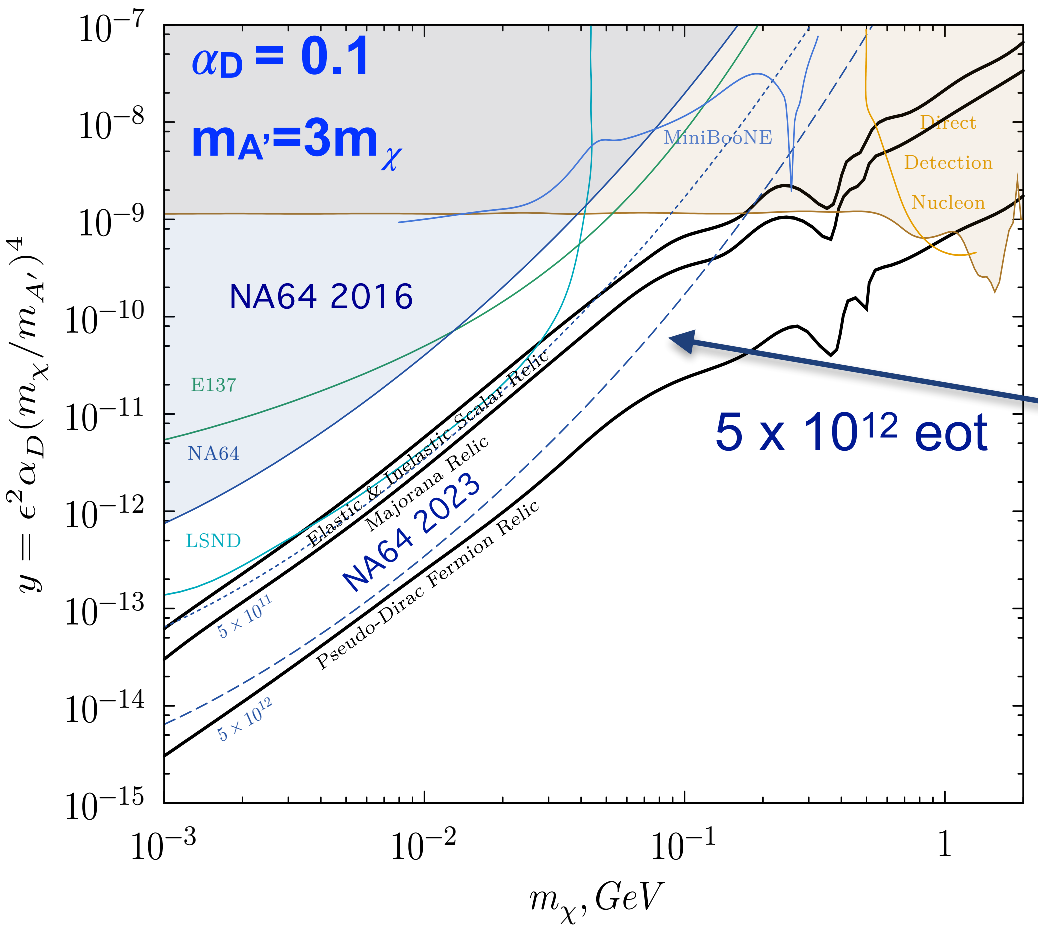


NA64 collaboration, Phys. Rev. Lett. 118, 011802 (2017)
NA64 collaboration, Phys. Rev. Lett. 123, 121801 (2019)

The NA64 search for A’ $\rightarrow \chi\bar{\chi}$ - *Future prospects 2021-2024*

Data taking resumed last August:
5 weeks in invisible mode

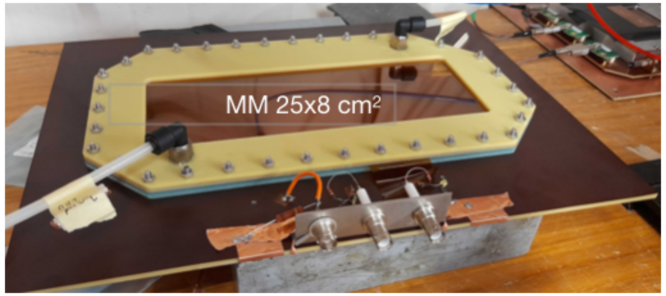
The NA64 search for A' → $\chi\bar{\chi}$ - *Future prospects 2021-2024*



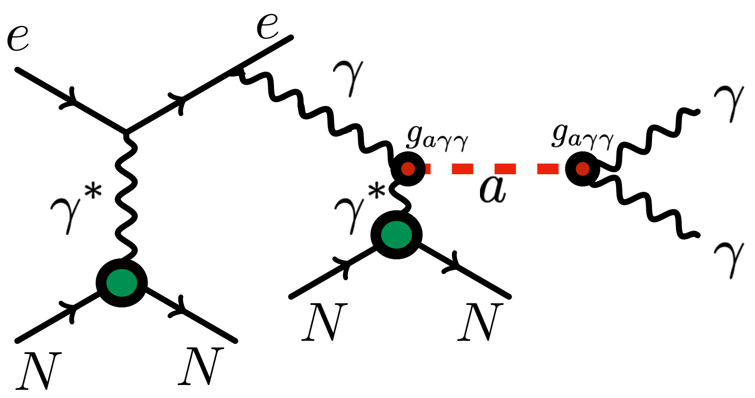
MASS OF THE DARK PHOTON

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

Setup upgrade (ongoing)

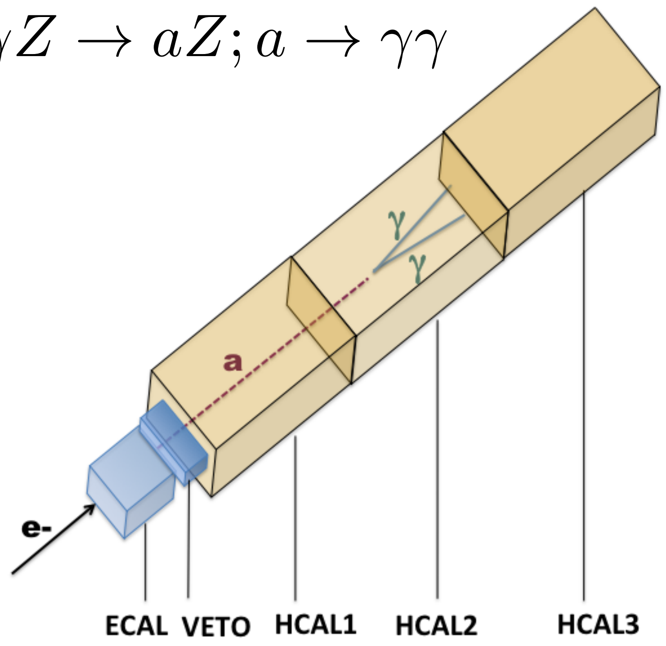


Other results: NA64 Axion Like Particles (ALPs) search

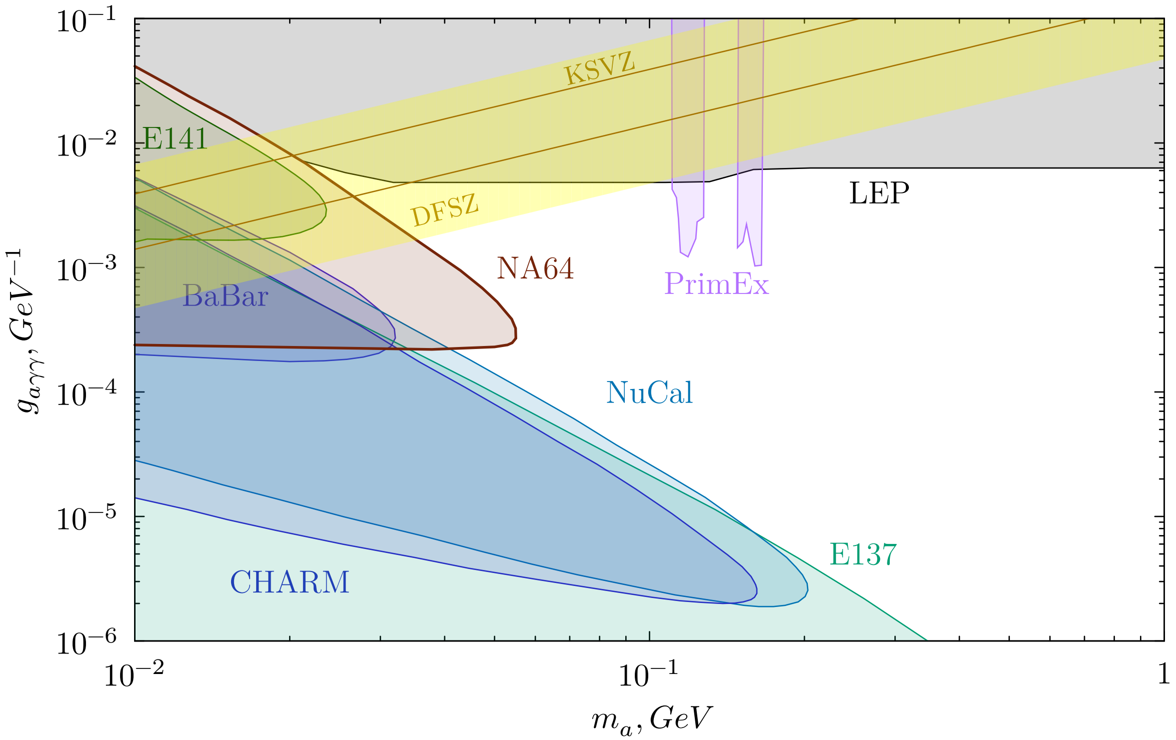


Production via Primakoff effect

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



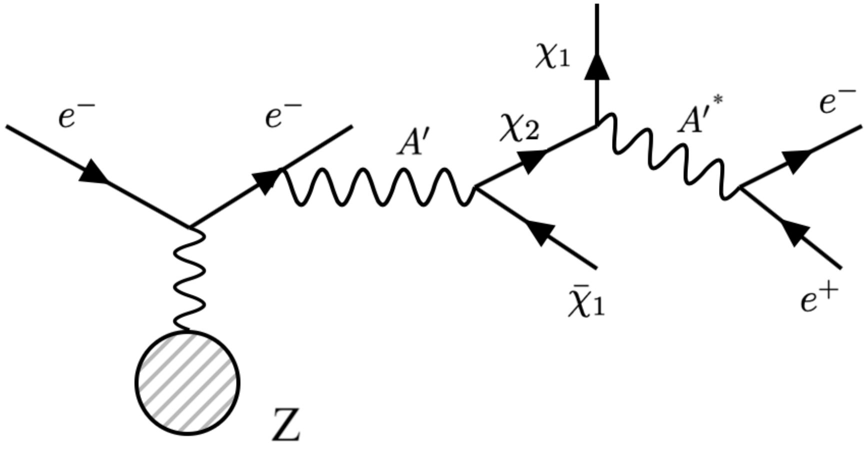
Closing the gap between beam dump and colliders



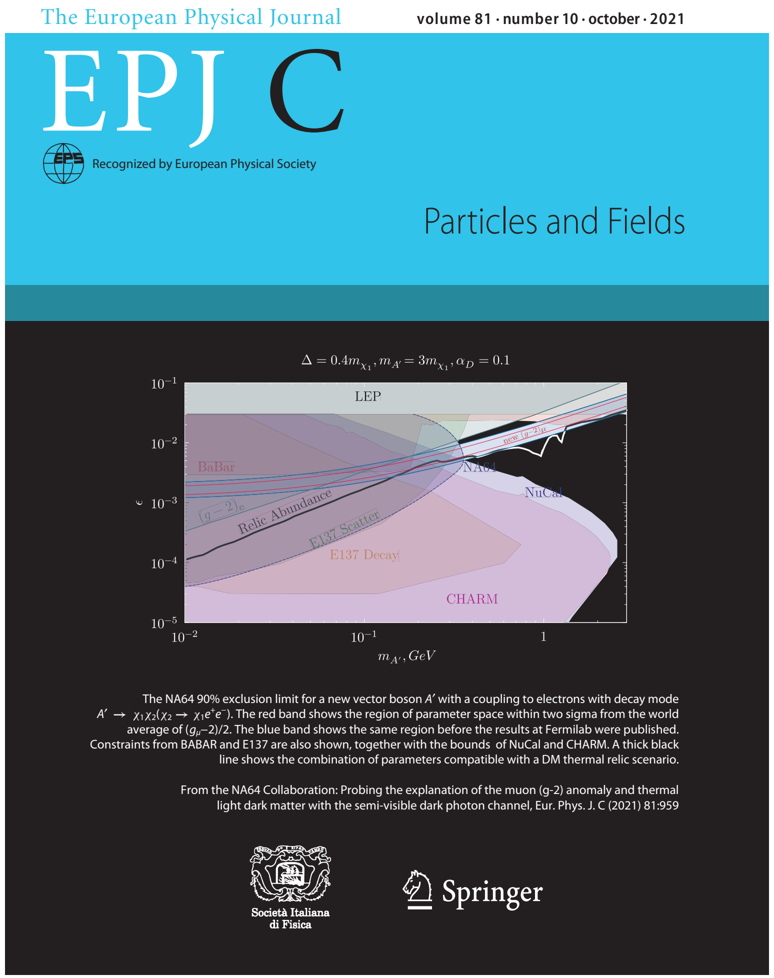
NA64 collaboration PRL 125, 081801 (2020)

Other results: searches for inelastic Dark Matter

SEMIVISIBLE DECAY MODE



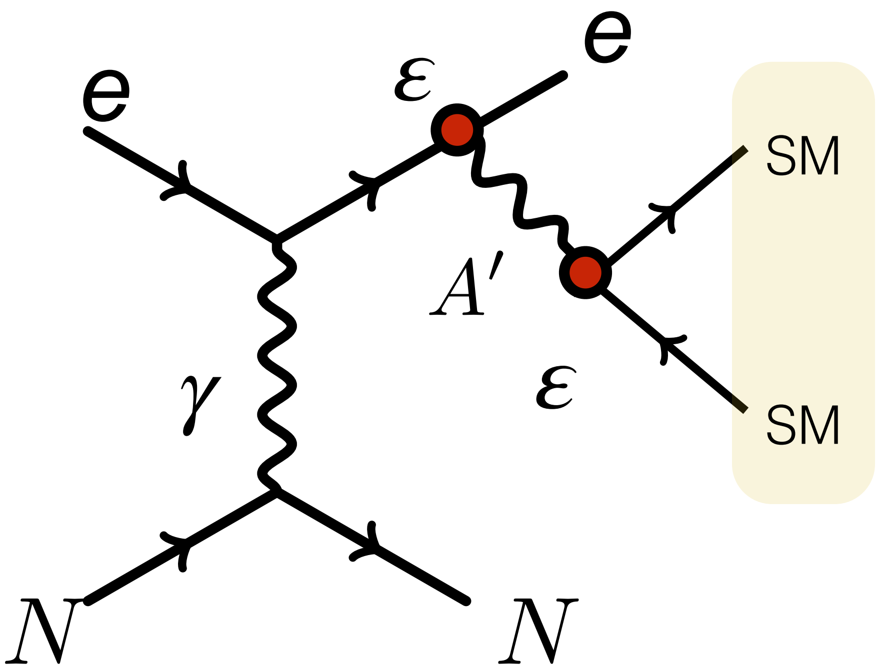
E. Izaguirre, et al. PRD 96, 055007 (2017)
G. Mohlabeng. PRD 99, 115001 (2019)
Y. Tsai, et al., PRL126, 181801 (2021)



Possible explanation of (g-2)μ anomaly +light thermal dark matter

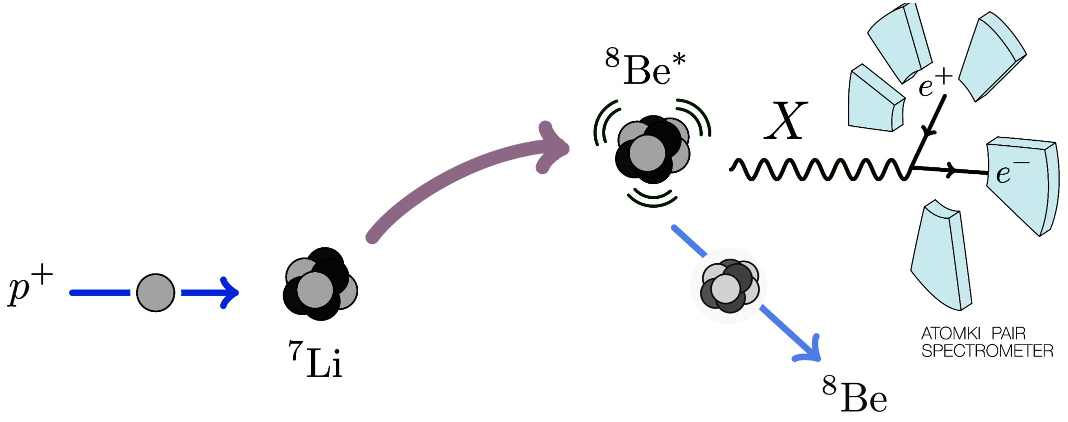
The NA64 search for A’ → e⁺e⁻

VISIBLE DECAY MODE $m'_A < 2m_X$

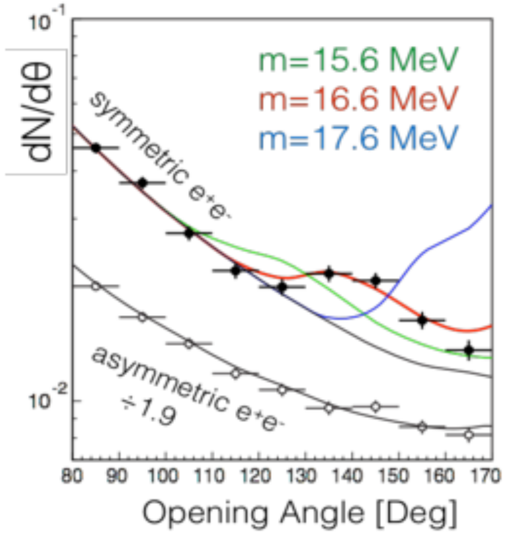


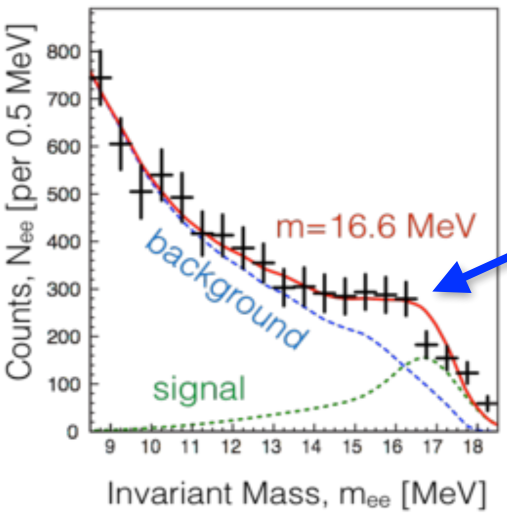
Pair production of SM particles

^{8}Be anomaly and X boson



Krasznahorkay et al. Phys. Rev. Lett.116, 042501 (2015)
and recently for 4He,
Krasznahorkay et al. Phys. Rev. C 104, 044003 (2021)



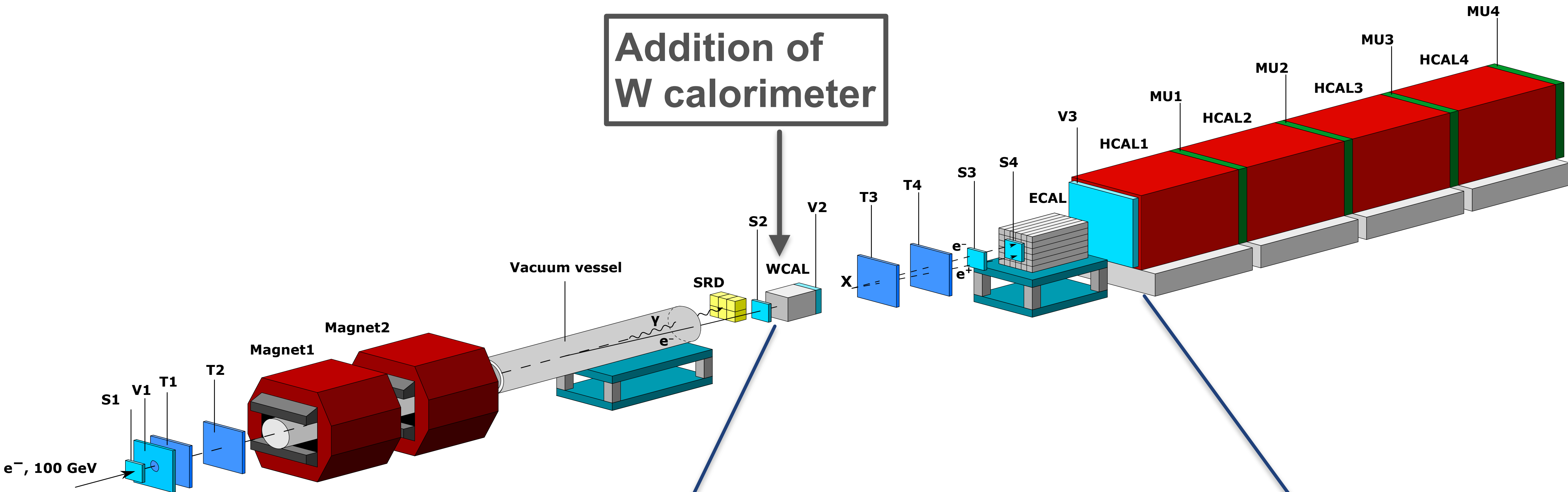


Could be explained by new ‘protophobic’ gauge boson X with mass around 17 MeV

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

The NA64 search for A'/*X17*→ e^+e^- - *experimental setup*

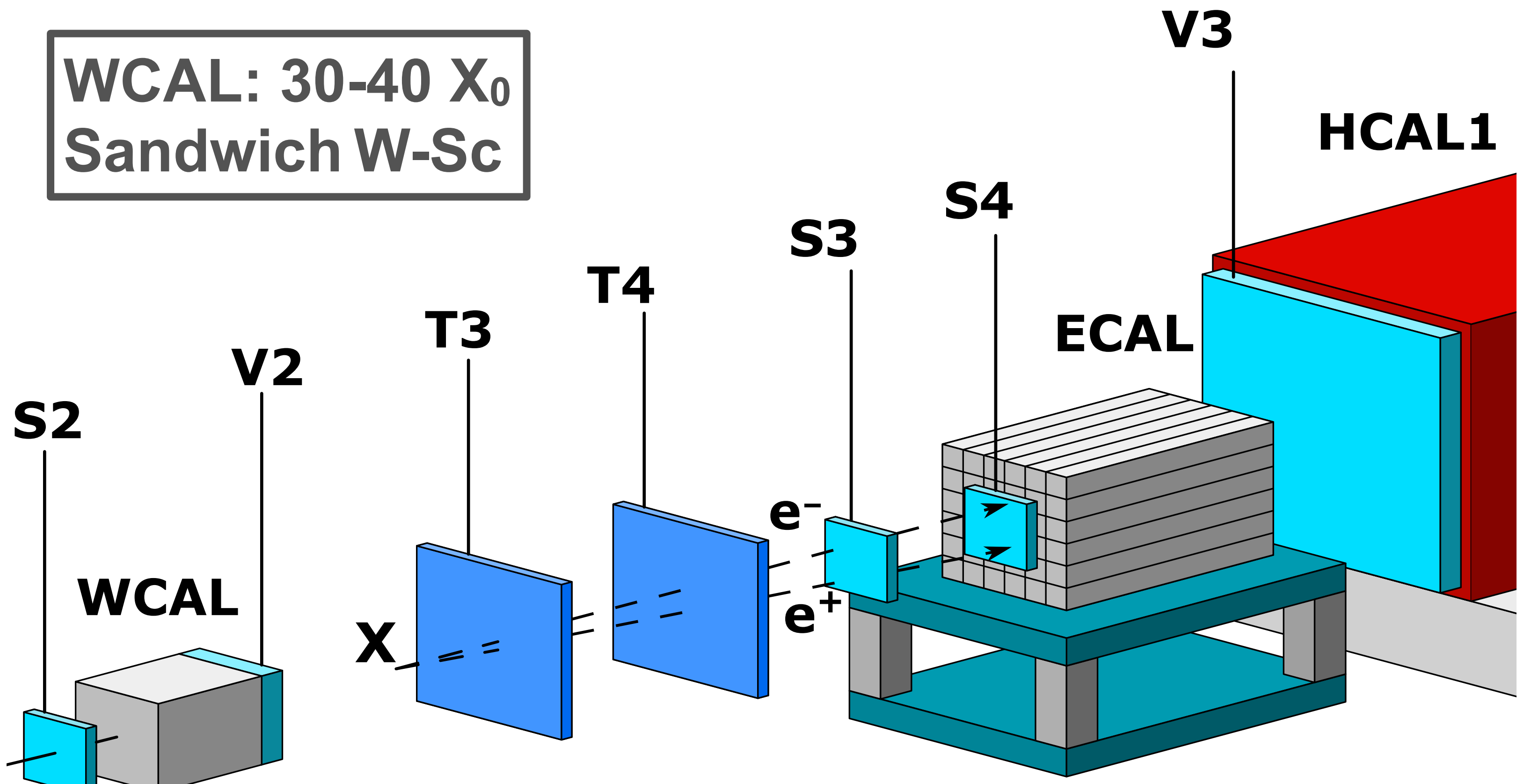
Addition of W calorimeter



Zooming in (next slide)

The NA64 search for A'/X17→ e^+e^- - experimental signature

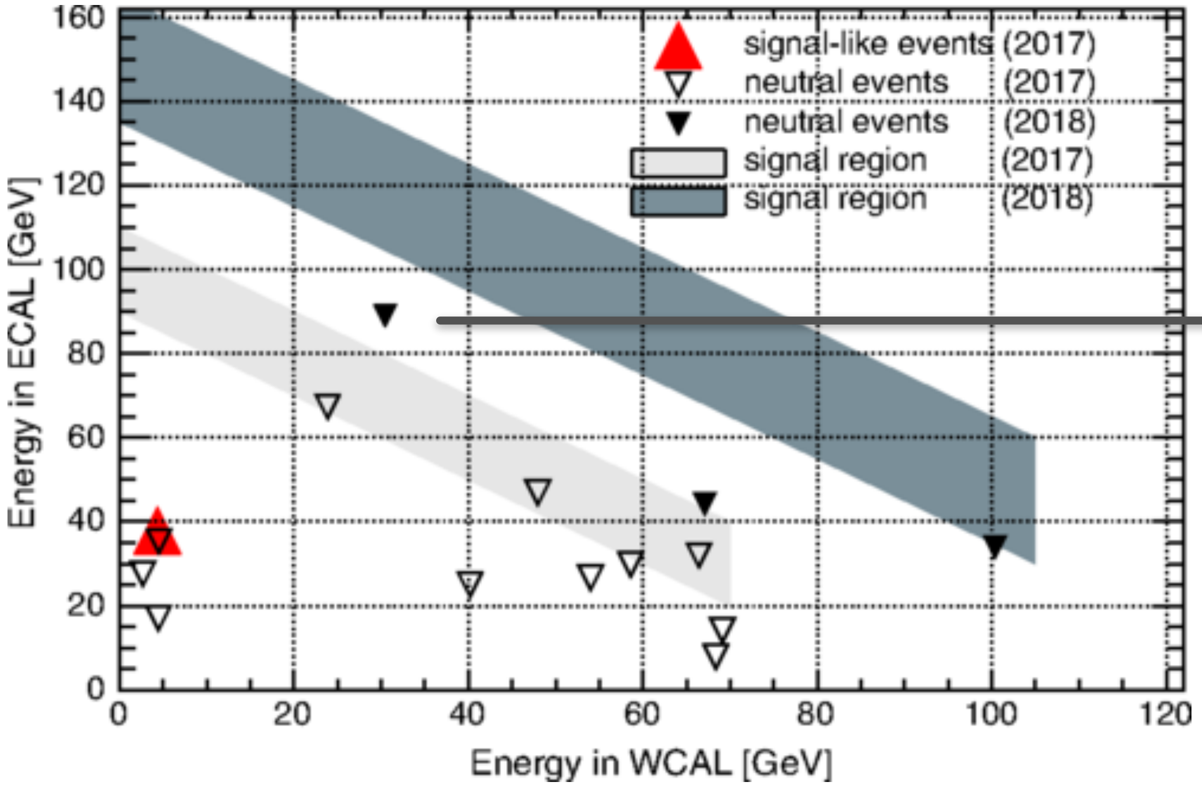
WCAL: 30-40 X_0
Sandwich W-Sc



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

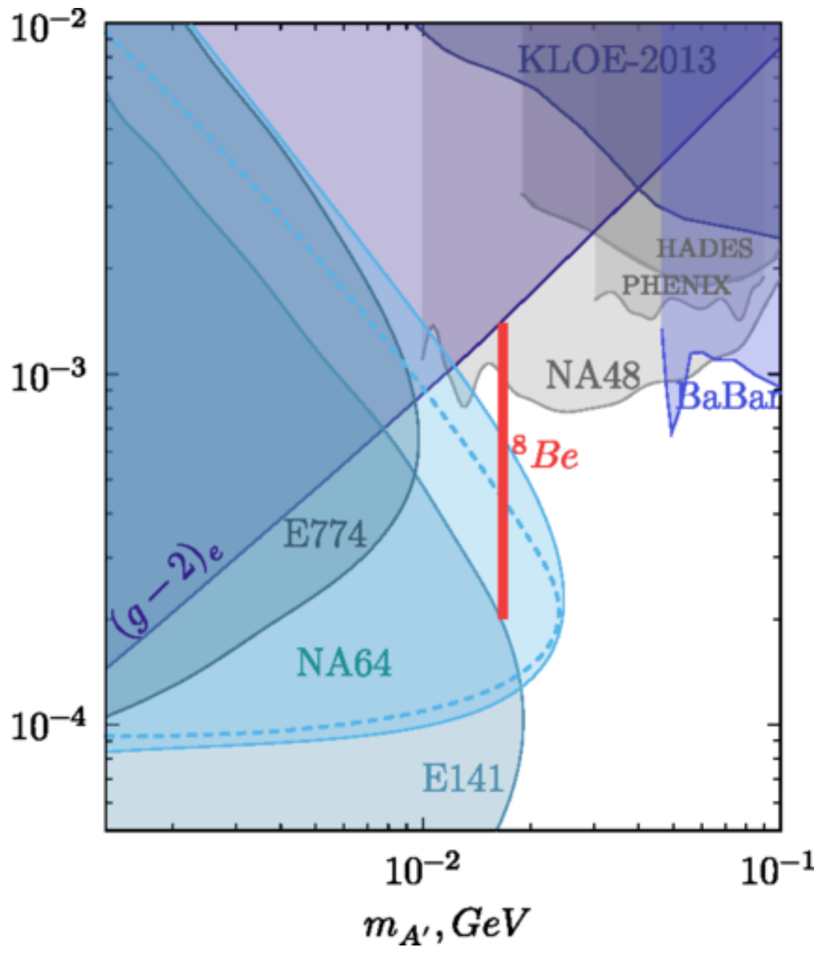
The NA64 search for A'/*X17*→ e^+e^- - *results (2017-2018)*



No signal-like event in signal box

~ 8×10^{10} EOT

COUPLING ε

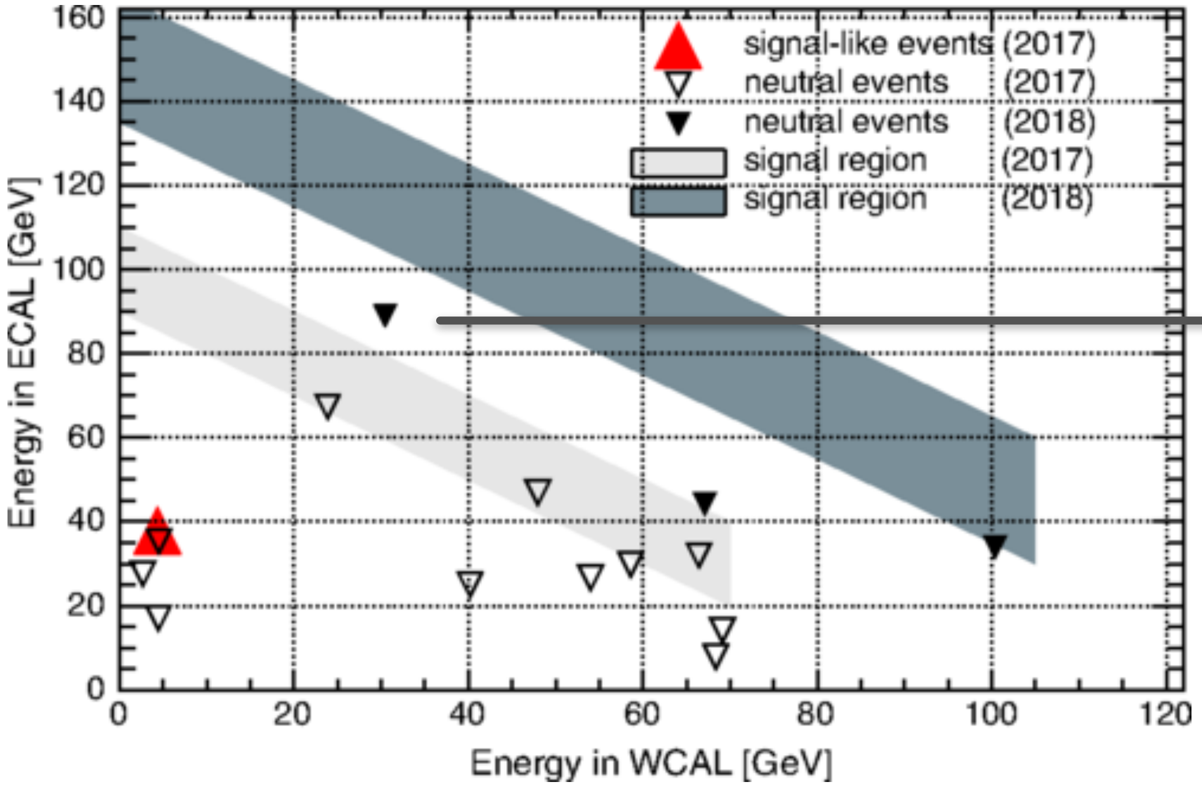


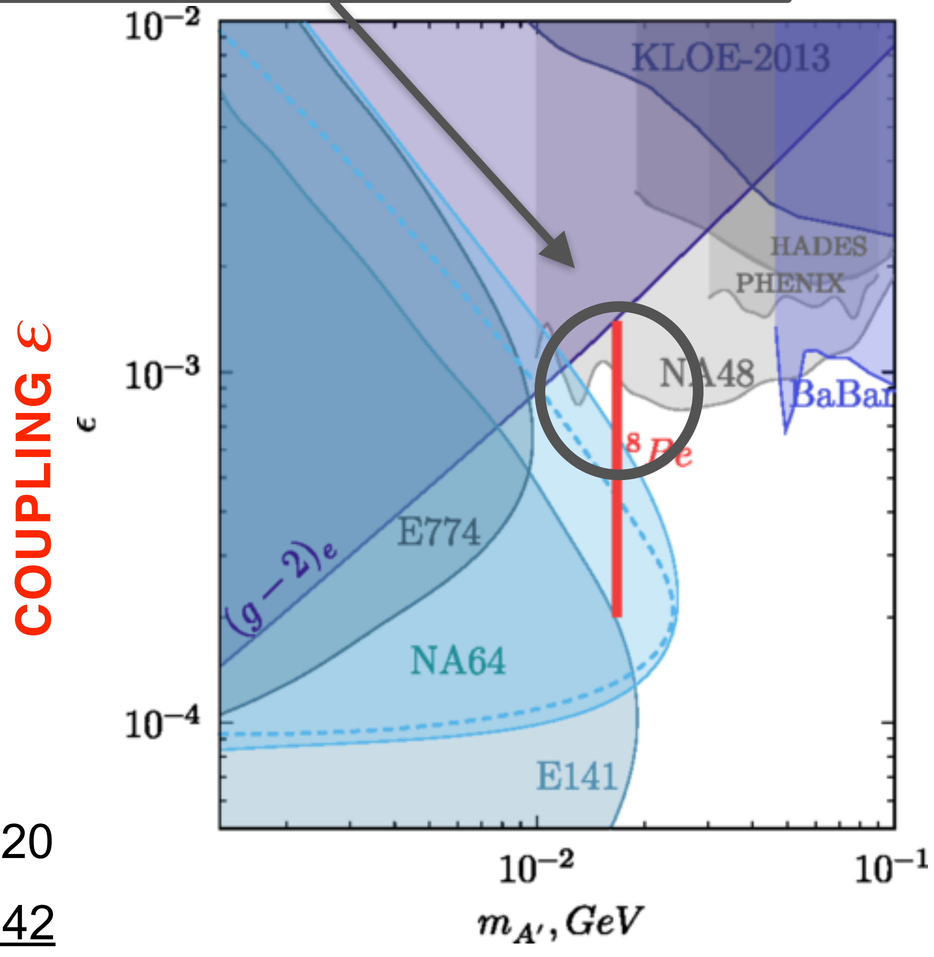
NA64 collaboration, PRL 120, 231802 (2018), PRD 107, 071101 (R) 2020

For pseudoscalar case see NA64 collaboration, arXiv:2104.13342

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

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





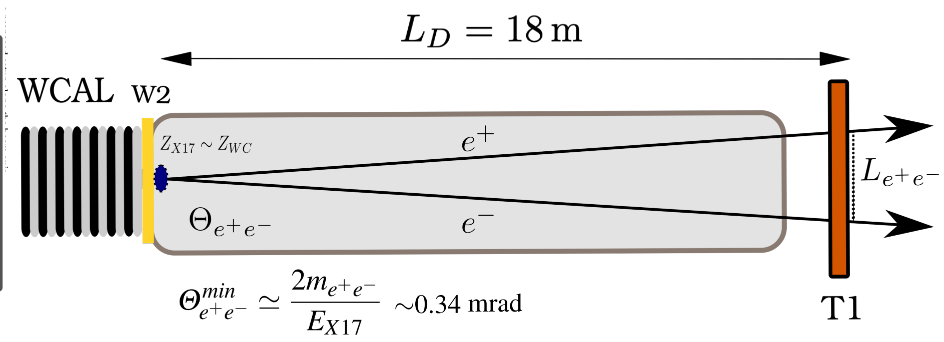
NA64 collaboration, PRL 120, 231802 (2018), PRD 107, 071101 (R) 2020

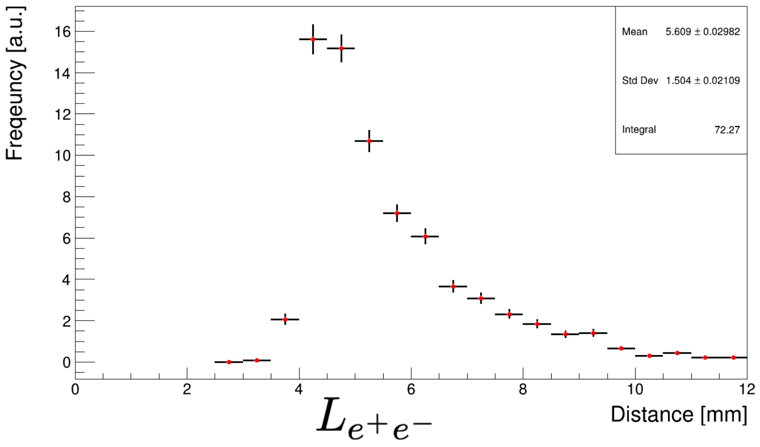
For pseudoscalar case see NA64 collaboration, arXiv:2104.13342

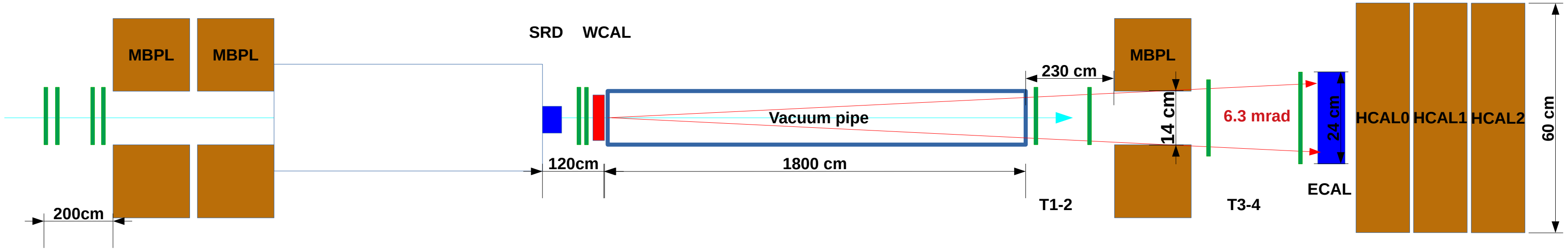
The NA64 search for *X17→ e⁺e⁻ - prospects (2021-2023)*

NA64 collaboration. EPJC 80, 1159 (2020)

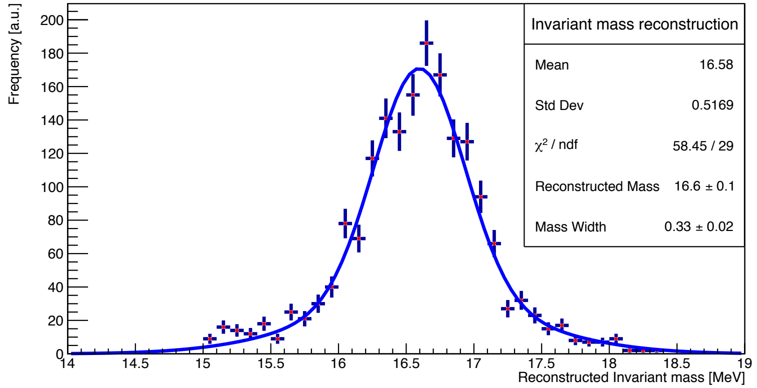
Optimization of WCAL: 20% shorter keeping 30X$_0$







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



Invariant mass reconstruction: Spectrometer + angle measurement

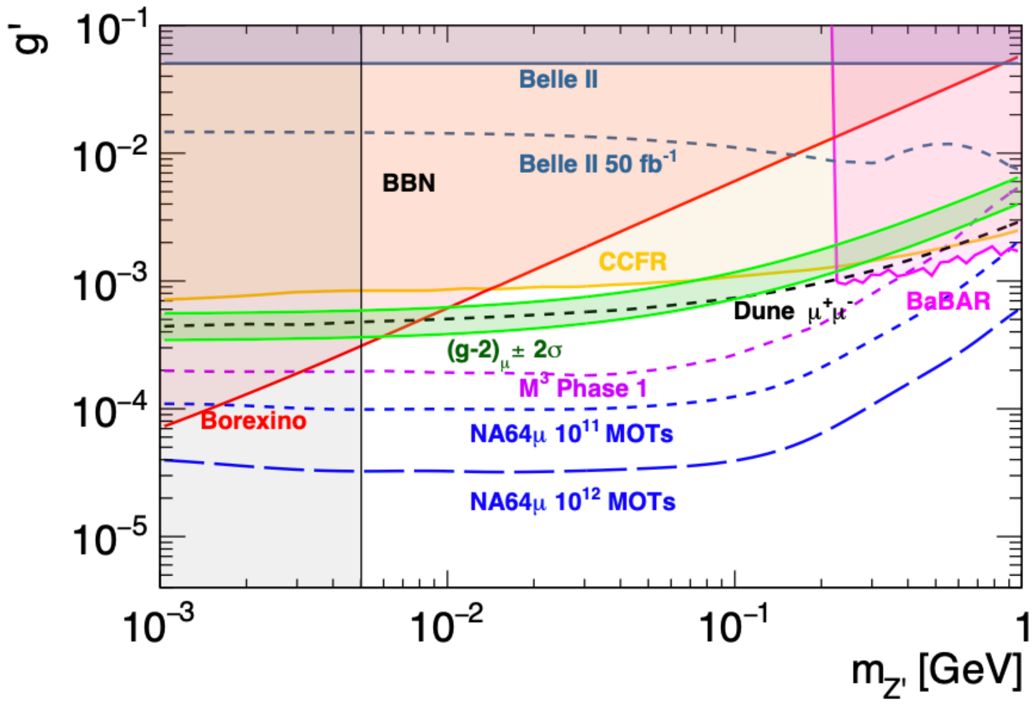
~ 10^{11} EOT (20 days) required to cover remaining X17 phase space

NA64 in muon mode- NA64$_\mu$

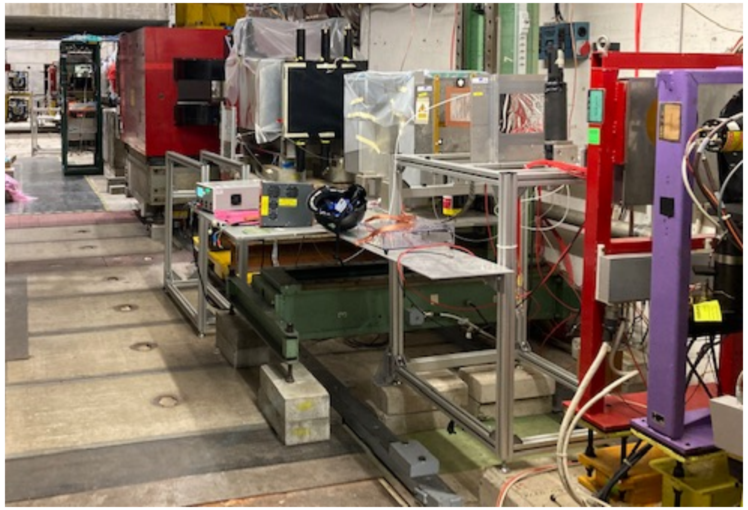
CERN SPS **M2 160 GeV muon beam** offers unique opportunities to further **searches for DS** of particles predominantly weakly-coupled to 2nd second and possibly 3rd generations of the SM.

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

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

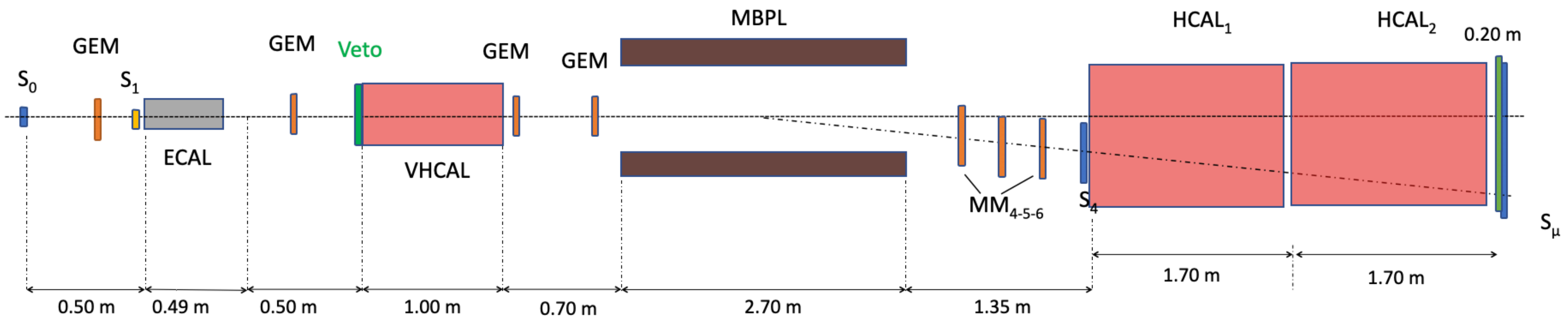


D. V. Kirpichnikov, Phys. Rev. D 104, 076012 (2021), H. Sieber et al. , arXiv 2110.15111



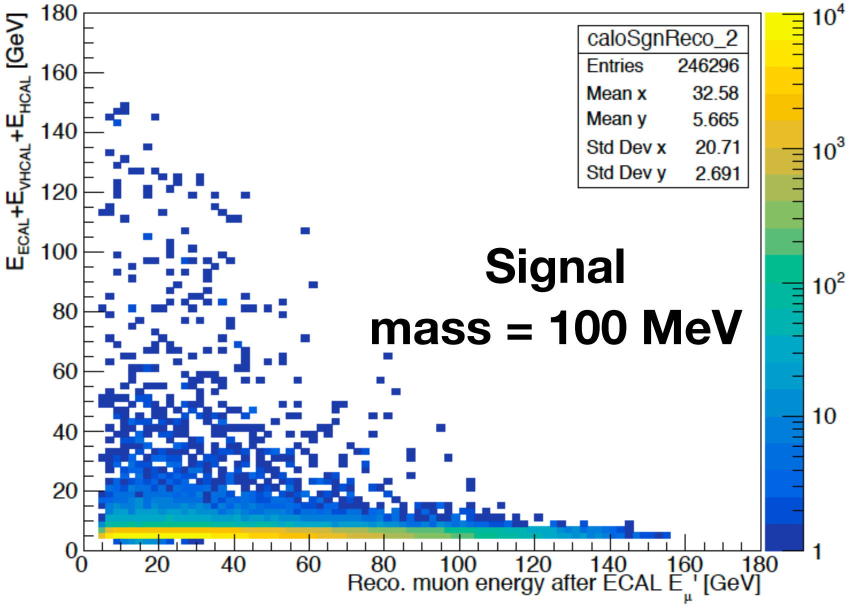
Pilot run 2021: 19 days (27.10-14.11)
Physics run (2022-2024)

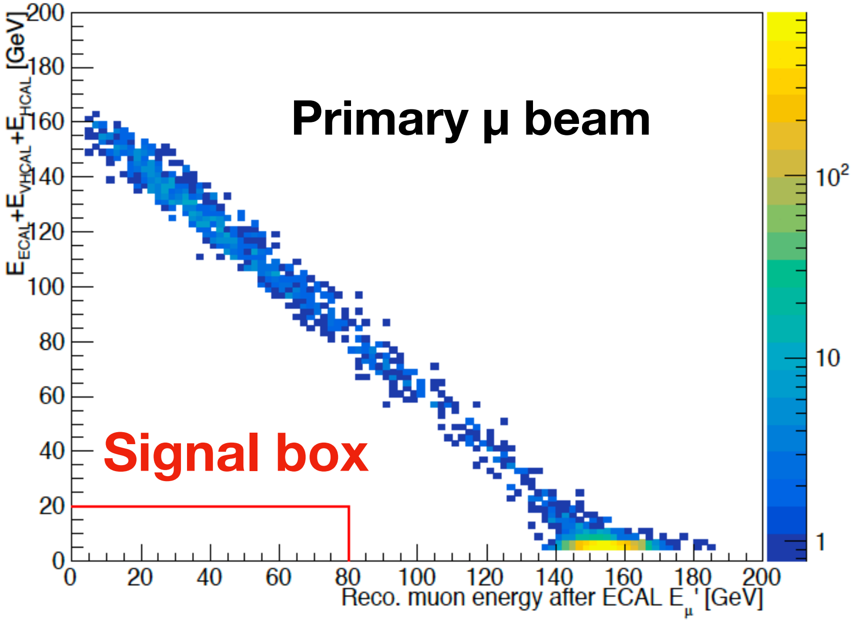
NA64 in muon mode- experimental setup (pilot run 2021)



$$\mu + Z \rightarrow \mu + Z + Z_\mu, \; Z_\mu \rightarrow \nu\bar{\nu}$$

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

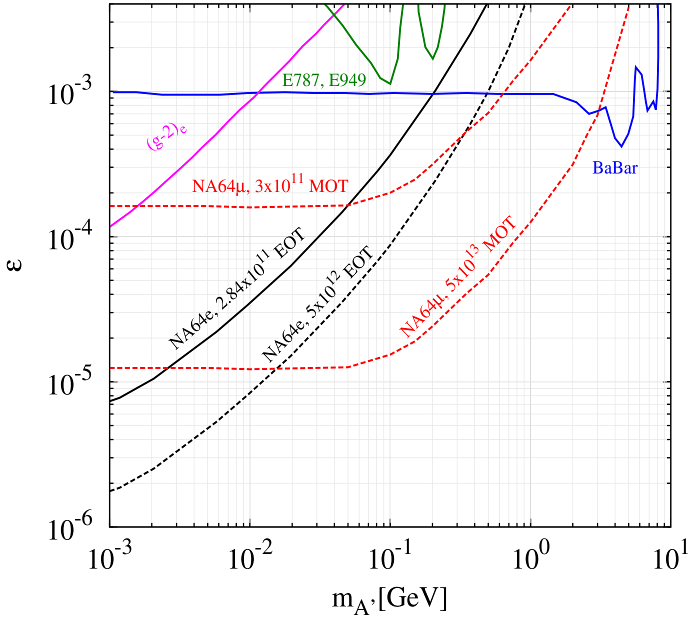




NA64 in muon mode - Search for LDM

Search for **Dark photons** complementary to NA64e in mass region $m_{A'} > 0.1$ GeV

$$\mu + Z \to \mu + Z + A', A' \to \chi\bar{\chi}$$



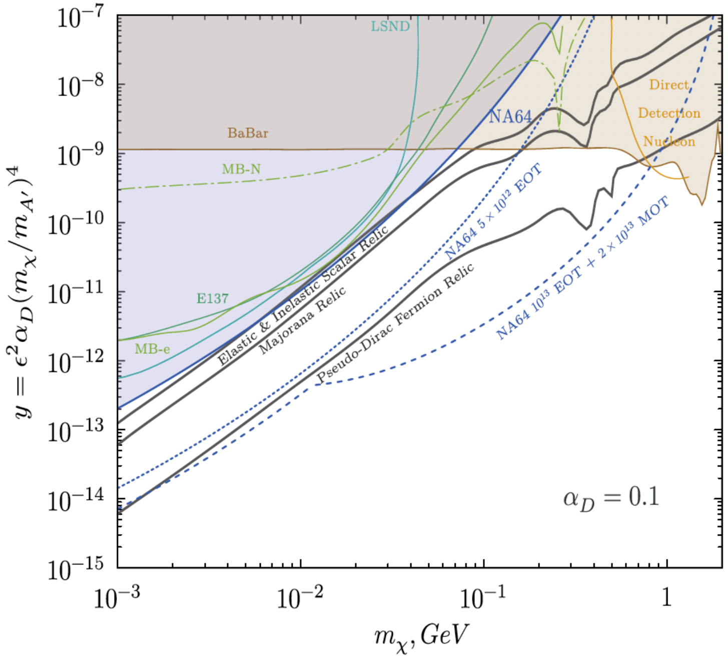
NA64$_e$

$$N^e_{A'} \sim L^e \sigma^e_{A'}$$
$$L^e \simeq X_0$$
$$\sigma^e_{A'} \sim \epsilon_e^2 / m^2_{A'}$$

NA64$_\mu$

$$N^\mu_{A'} \sim L^\mu \sigma^\mu_{A'}$$
$$L^\mu \simeq 40 X_0$$
$$\sigma^\mu_{A'} \sim \epsilon_\mu^2 / m^2_\mu \qquad m_{A'} \lesssim m_\mu$$

Combined LDM sensitivity of NA64$_e$ -NA64$_\mu$



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

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

CERN-PBC-REPORT-2018-007

Summary and outlook for NA64

- Low energy antihydrogen formation
- Interaction of anti-hydrogen with radiation
- Antihydrogen spectroscopy

- **CURRENT STATUS**
  - NA64: Active beam dump + missing-energy approach is very powerful to search for DARK SECTORS/Light (MeV-GeV) Thermal Dark Matter
  - This August 2021 we resumed data taking (4 weeks), goal until LS3 >5x10^{12} EOT for $A' \rightarrow \chi\bar{\chi}$, explore remaining parameter space $X \rightarrow e^+e^-$, improve sensitivity to ALPs and Inelastic dark matter. Pilot run in 2021 at M2 (muon mode) completed, 1st physics run (2022)

FUTURE PROSPECTS:

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

CERN & PBC

Special thanks to: E. Depero, H. Sieber, B. Banto-Oberhauser, M. Mongillo, L. Molina-Bueno C. Cazzaniga, P. Odagiu

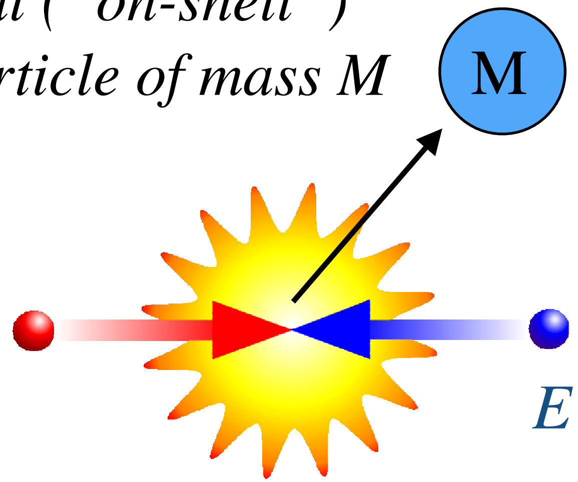
Funding: ETH Zurich and SNSF Grant No. 169133 and 186158 (Switzerland)

“Collisions" vs “propagator” physics

PART I

High-energy collisions

real (“on-shell”) particle of mass M



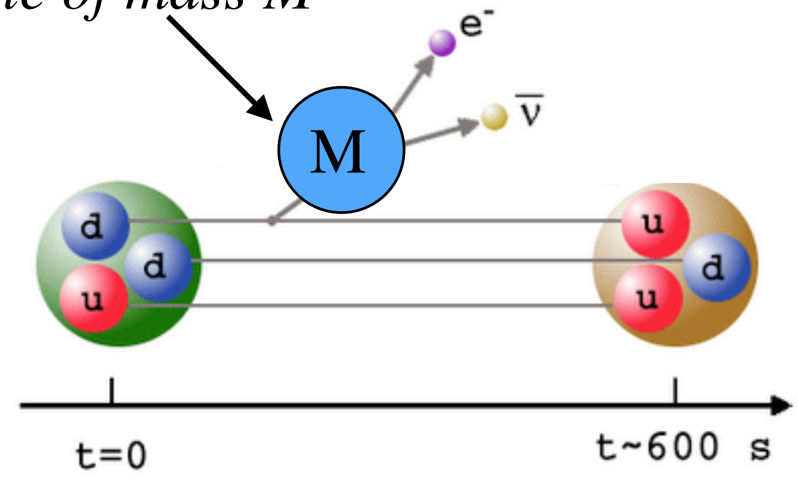
on-shell particles limited by kinematical threshold:

$$(Mc^2) < E_{cms}$$

PART II

Rare processes

virtual (“off-shell”) particle of mass M

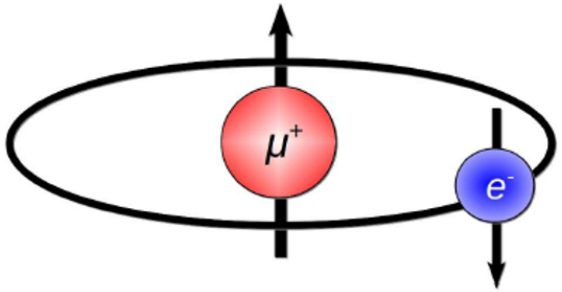


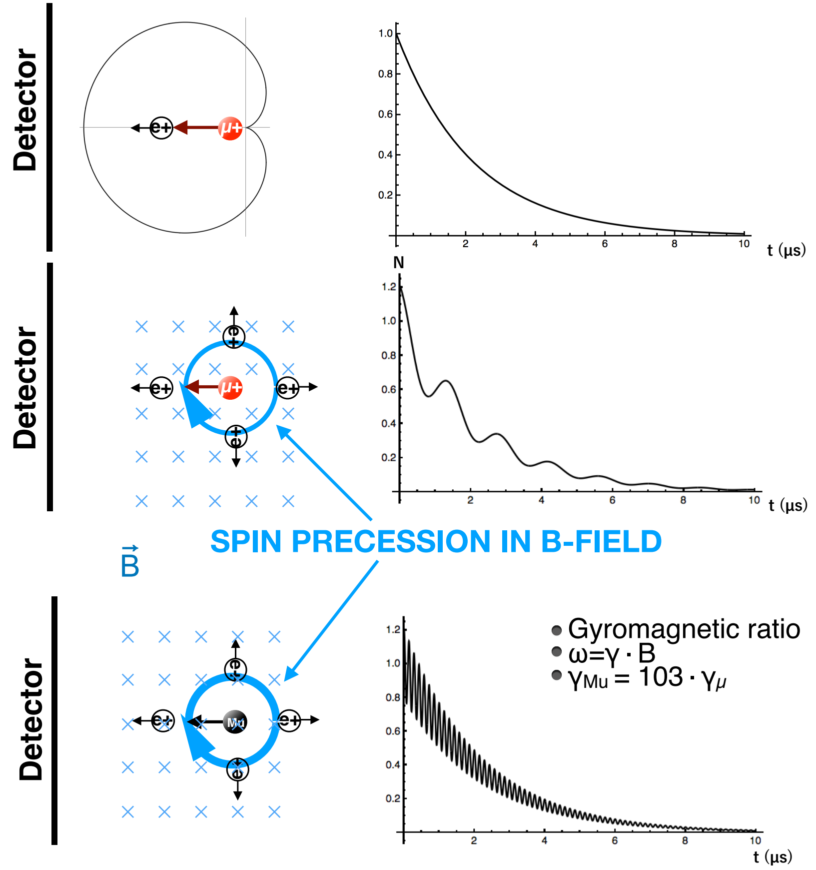
off-shell particles sensitivity limited by rarity of process:

$$(Mc^2)\Delta t \gtrsim \hbar$$

The muonium (M) atom

M (positive muon-electron bound state)
Predicted in 1957 (Friedmann, Telegdi, Hughes)
Unstable with lifetime of 2.2 μs.
Main decay channel: $\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$





Discovered in 1960 (Hughes) by detecting muonium spin (Larmor) precession in an external magnetic field perpendicular to the spin direction.

The Mu-MASS experiment at PSI

P. Crivelli, Hyp. Int. 239, 49 (2018)

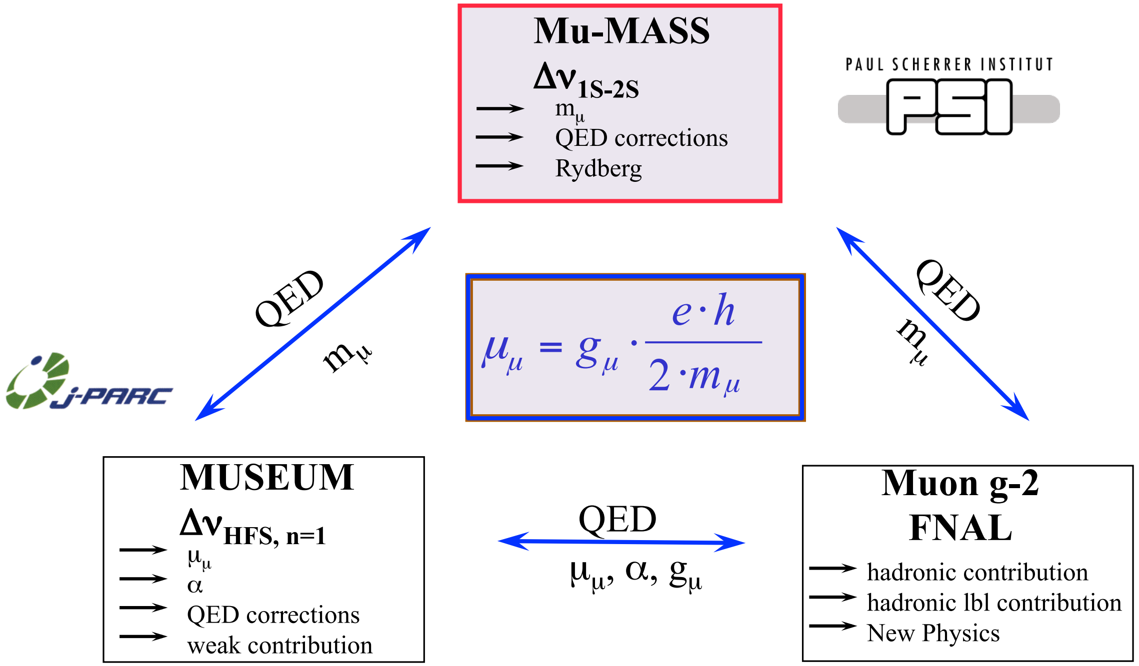
MU-MASS

High precision laser and microwave Muonium spectroscopy experiment

FINAL GOAL : improve 1S-2S transition with Doppler free laser spectroscopy by 3 orders of magnitude (10 kHz, 4 ppt)

OUTPUT

- → Muon mass @ 1 ppb
- → Ratio of q_e/q_μ @ 1 ppt
- → Test of bound state QED (1×10^{-9})
- → Input to muon g-2 theory
- → Rydberg constant @ ppt level
- → New determination of α @ 1 ppb
- → Search for New Physics



Project funded through the ERC consolidator grant (818053 -Mu-MASS) and by the Swiss National Foundation under the grant 197346.

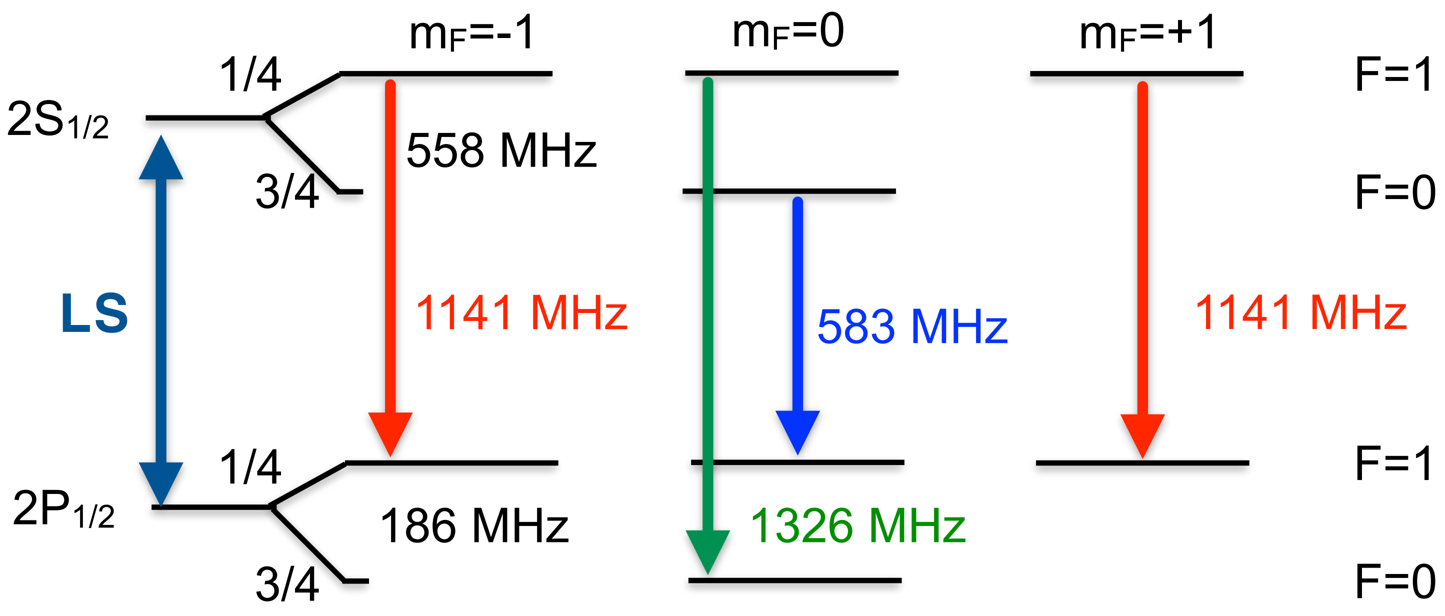
European Research Council
Established by the European Commission

Fermilab

Swiss National Science Foundation

https://www.psi.ch/en/ltp/mu-mass

Muonium Lamb shift



THEORY $(E(2S_{1/2}) - E(2P_{1/2}))^{th}_{Mu} = 1047.498(1)\ \mathrm{MHz}.$

G. Janka, B. Ohayon and P. Crivelli, arXiv:2111.13951 (2021)
V. Yerokhin et al. ,Annalen der Physik 531, 1800324 (2019)
M. I. Eides, H. Grotch, and V. A. Shelyuto, Phys. Rep. 342, 63 (2001).
W. Liu, M. Boshier, S. Dhawan et al., Phys. Rev. Lett. 82, 711 (1999).

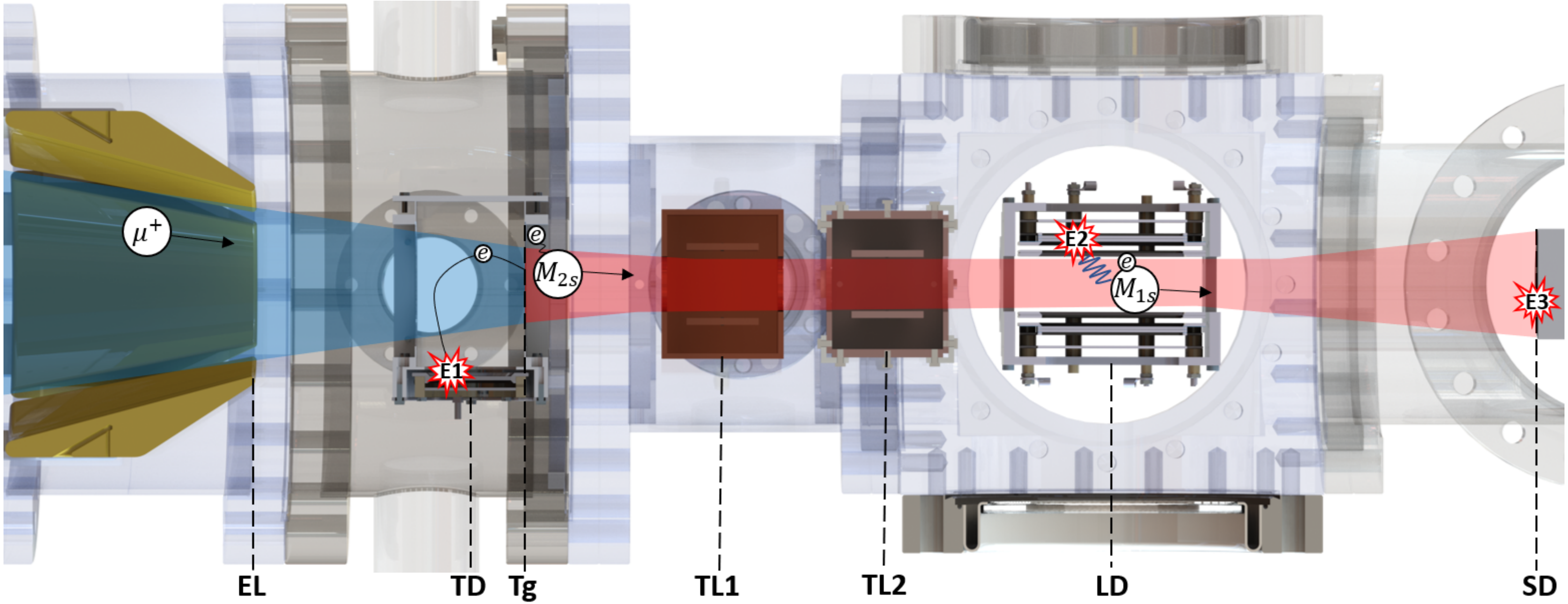
EXPERIMENT $(E(2S_{1/2}) - E(2P_{1/2}))^{exp}_{Mu} = 1042(22)\ \mathrm{MHz}.$

C .J. Oram et al. Phys. Rev. Lett. 52, 910 (1984). DOI 10.1103/PhysRevLett.52.910. @ TRIUMF
K. Woodle, et al., Phys. Rev. A 41, 93 (1990). DOI 10.1103/ PhysRevA.41.93 @ LAMPF

Measurement of the Lamb shift (beamtime Dec 2020/June 2021)

LEM beamline T. Prokscha et al., NIMA 595, 317 (2008)

LYMAN-ALPHA DETECTOR



TAGGING+M(2S) FORMATION

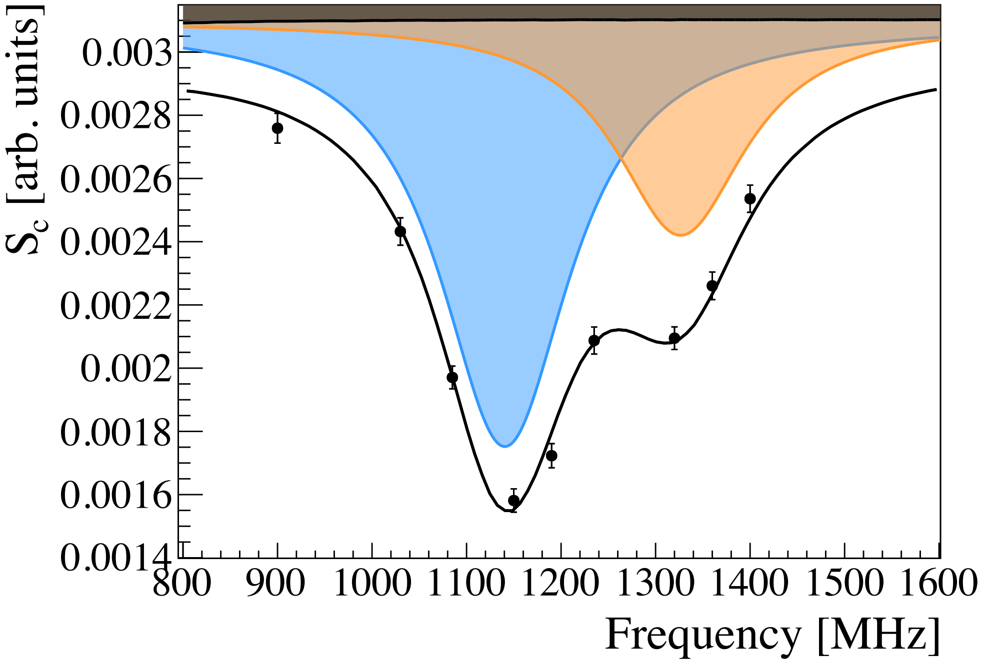
MW REGION (HFS SELECTOR + MW TRANSITION)

STOP DETECTOR

Results of the M Lamb shift

B. Ohayon, P. Crivelli et al., PRL 128, 011802 (2022)

48 HOURS DATA TAKING (100x statistics compared to previous measurements)



	Central Value	Uncertainty
Fitting	1139.9	2.3
4S contribution		< 1.0
MW-Beam alignment		< 0.32
MW field intensity		< 0.04
M velocity distribution		< 0.01
AC Stark $2P_{3/2}$	+0.26	< 0.02
2^{nd}-order Doppler	+0.06	< 0.01
Earth's Field		< 0.05
Quantum Interference		< 0.04
$2S_{F=1}-2P_{1/2,F=1}$	1140.2	2.5
Hyperfine	−93.0	0.0
Lamb Shift	1047.2	2.5
Theoretical value	1047.47	0.02

Results in **agreement with theoretical calculations**. Precision not enough to test b-QED but can be used to constraint new physics.

Searches for new bosons via positronium/muonium spectroscopy

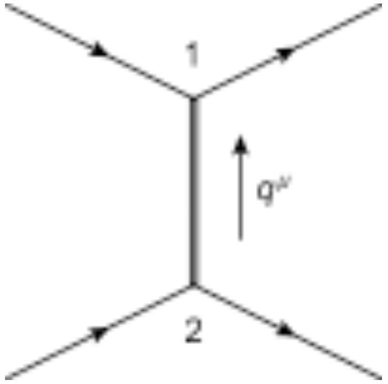
- New bosons could mediate new forces resulting in shifts of Ps and M energy levels.

C Frugiuele et al., Phys. Rev. D100, 015010 (2019)

- Scattering between two fermions described by different potentials (scalar-scalar, vector-vector…)
We focus on the scalar-scalar potential:

P.Fadeev et al.,Phys. Rev. A 99, 022113 (2019)

$$V_{ss}(\vec{r}) = -g_1^s g_2^s \frac{e^{-Mr}}{4\pi r}$$



- Leading order corrections: $\langle V_{ss}\rangle = -\frac{g_1^s g_2^s}{4\pi} F^1_{n,l}(M)$

$$F^k_{n,l}(M) = \langle\frac{e^{-Mr}}{r}\rangle_{n,l}, \; k = 1$$

	$l = 0$	$l = 1$	$l = 2$
$n = 1$	$\frac{4}{a_0(Ma_0+2)^2}$	X	X
$n = 2$	$\frac{2M^2a_0^2+1}{4a_0(Ma_0+1)^4}$	$\frac{1}{4a_0(Ma_0+1)^4}$	X
$n = 3$	$\frac{4(243M^4a_0^4+216M^2a_0^2+16)}{9a_0(3Ma_0+2)^6}$	$\frac{64(9M^2a_0^2+1)}{9a_0(3Ma_0+2)^6}$	$\frac{64}{9a_0(3Ma_0+2)^6}$

Searches for new bosons via positronium/muonium spectroscopy

- Perturbations

$$\Delta E_{ss}(2S^0 \to 1S^0) = \frac{g_1^s g_2^s}{4\pi}\left(\frac{4}{a_0(Ma_0+2)^2} - \frac{2M^2 a_0^2+1}{4a_0(Ma_0+1)^4}\right)$$

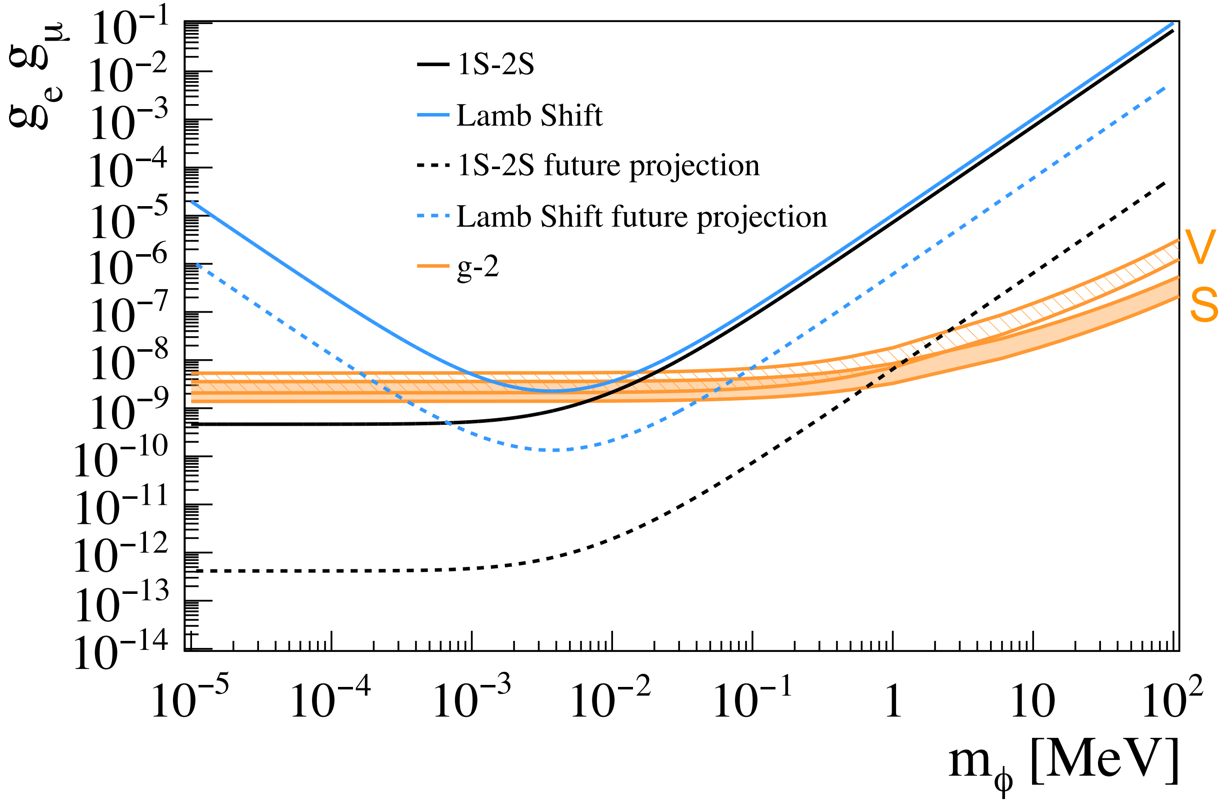
$$\Delta E_{ss}(2S^0 \to 2P^0) = \frac{g_1^s g_2^s}{4\pi}\left(\frac{1}{4a_0(Ma_0+1)^4} - \frac{2M^2 a_0^2+1}{4a_0(Ma_0+1)^4}\right)$$

- To set a bound calculate the minimal value for a given M to exceed 2σ of theoretical result

$$g_\zeta^1 g_\zeta^2 > \frac{h \max_{\pm}\left|(\nu_{exp}-\nu_{the})\pm 2\rho_{the,exp}\right|}{C_{transition}(M)}$$

where $\rho_{the,exp} = \sqrt{\rho_{the}^2 + \rho_{exp}^2}$ and $C_{transition}(M) = \frac{\Delta E_{\zeta\zeta}(transition)}{g_\zeta^1 g_\zeta^2}$

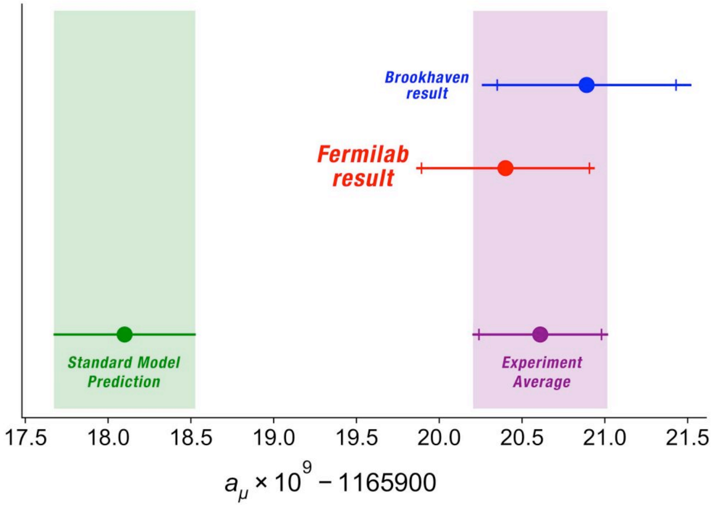
Muonium spectroscopy as a probe for new muonic forces

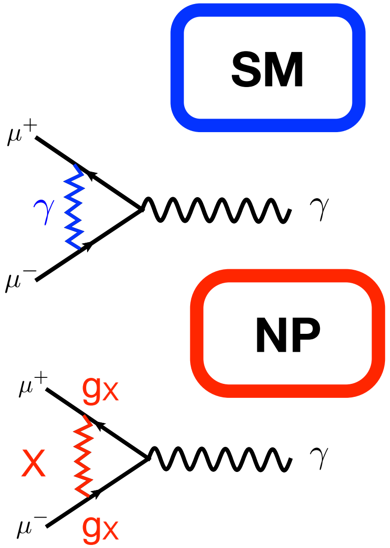


B. Ohayon, P. Crivelli et al., PRL 128, 011802 (2022)

Bands: region suggested by **$(g-2)_\mu$**

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

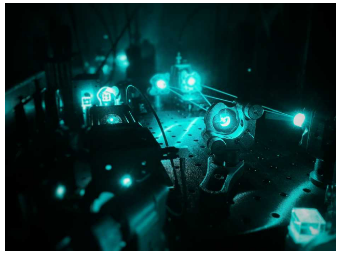




combined with bound from **$(g-2)_e$**

L. Morel et al, Nature 588, 61 (2020),
R. H. Parker et al., Science 360, 191 (2018).
D. Hanneke et al. e Phys. Rev. Lett. 100, 120801 (2008)

Summary and outlook for Mu-MASS



CURRENT STATUS:
- New measurement of the M LS
- Detection of 2S states achieved but S/N to be improved
- Laser system, CW 20W @ 244 nm circulating power achieved
- Frequency reference for the experiment is ready.

Z. Burkley, P. Crivelli et al. Opt. Express 29, 27450 (2021)

FUTURE PLANS:

2022 combine CW laser system + experiment at PSI, first attempts to excite 1S-2S transition using a CW laser + pulsed laser for photoionisation (PI) detecting the PI muons + decaying positron

2023-2024 Data taking at the low energy muon beam line

MuCool Beamline and **HiMB** UPGRADES @ PSI (2 orders of magnitude larger muon flux)
WOULD GREATLY EXPAND THE PHYSICS REACH OF Mu-MASS

arXiv 2111.05788

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