
# LATEST RESULTS OF THE N64 EXPERIMENT SEARCHING FOR HIDDEN SECTORS AT THE CERN SPS - EP Seminar 25.05.2021

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

# Light Mediators searches complementary to WIMPs

**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 WIMPless MIRACLE

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

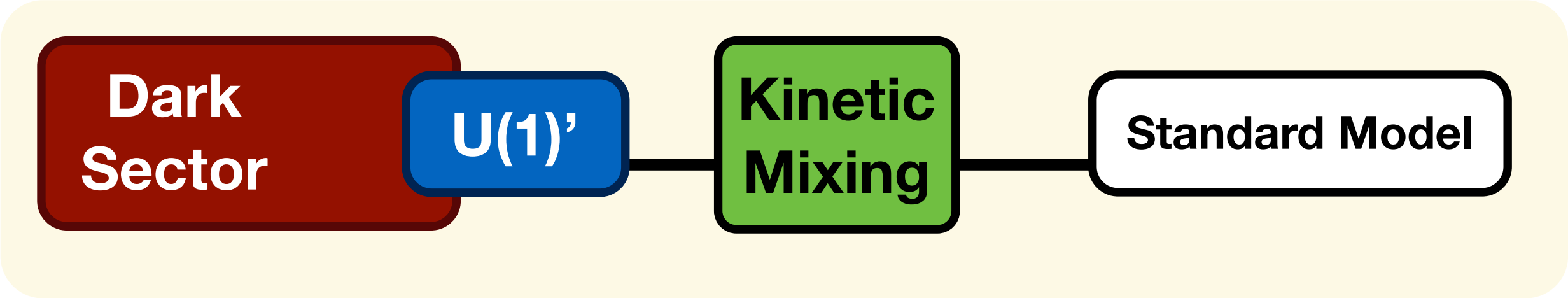
J. Feng and J. Kumar Phys.Rev.Lett.101:231301,2008

The WIMP miracle $(m_X, g_X) \sim (m_{\rm weak}, g_{\rm weak})$

Large range for $g_X$ and $m_X$

For recent reviews see e.g. G. Lanfranchi et al arxiv 2011.02157, J. Jaeckel et al. Nature Phys. 16 (2020) 393-401

# DARK SECTORS - THE VECTOR PORTAL

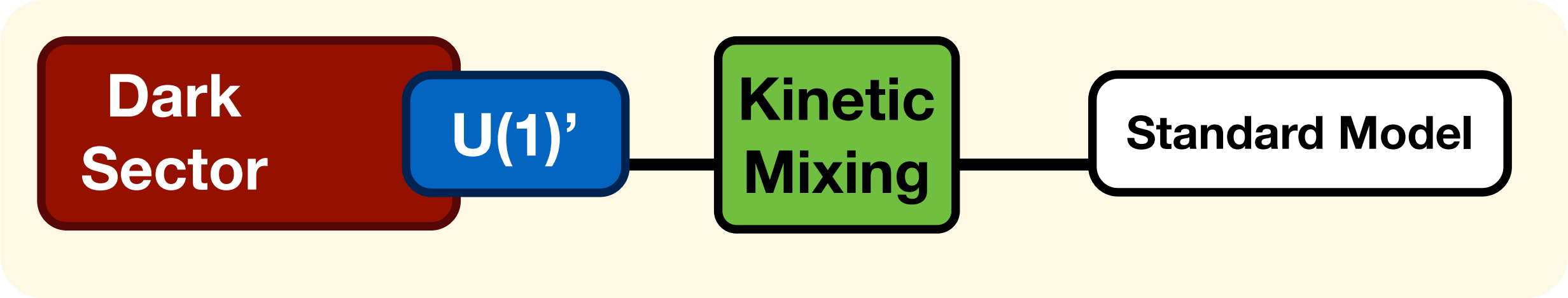



**DARK SECTOR (DS)** charged under a new U(1)' gauge symmetry and interacts with SM through kinetic mixing ($\varepsilon$) of a MASSIVE VECTOR MEDIATOR (A') with our photon.
Dark matter with mass ($m_\chi$), part of DS.

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

**Four parameters:** $m_{A'}$, $m_\chi$, $\alpha_D = e_D^2/4\pi$, $\varepsilon$

# DARK SECTORS - THE VECTOR PORTAL




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

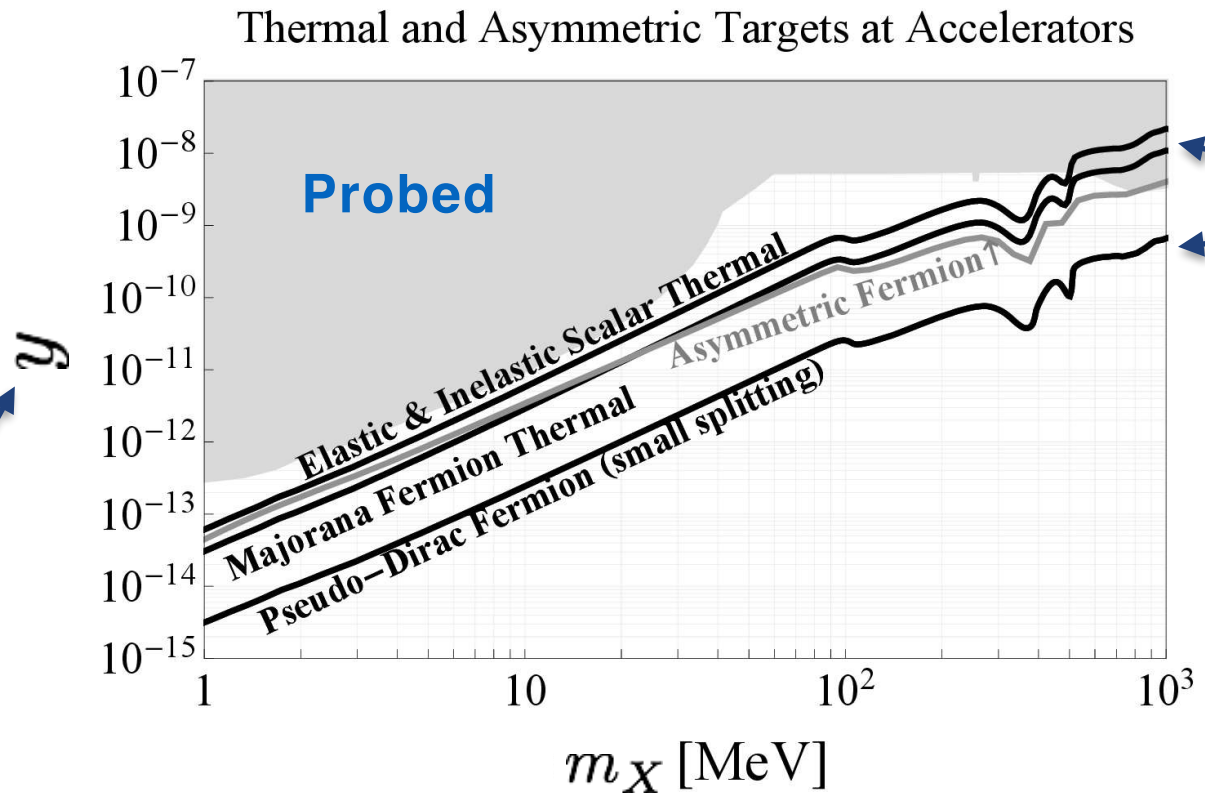
OBSERVED **AMOUNT OF DARK MATTER** TODAY

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

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

# The (y,mX) DM PARAMETER SPACE

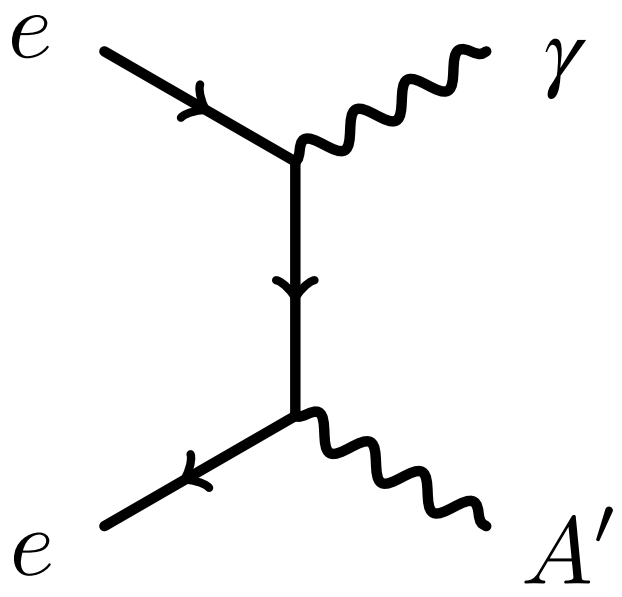
From https://arxiv.org/pdf/1707.04591.pdf



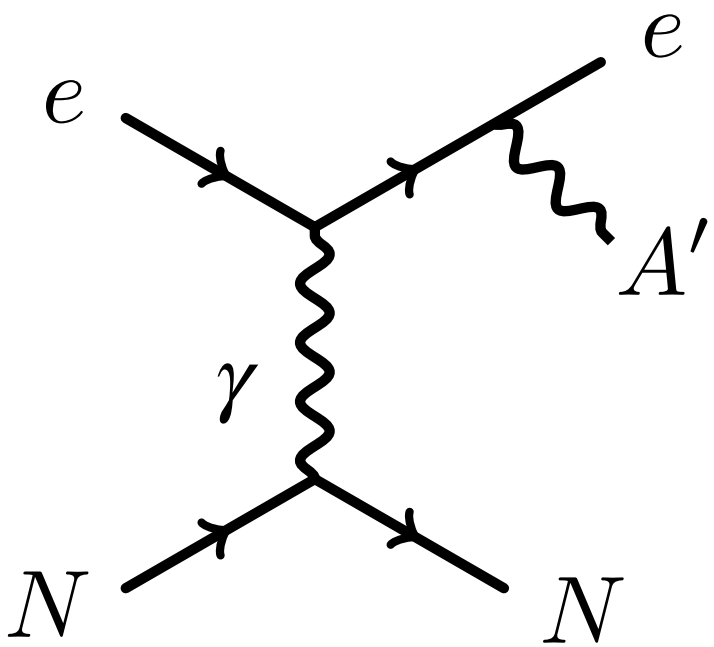

Solid lines predictions from DM relic abundance

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

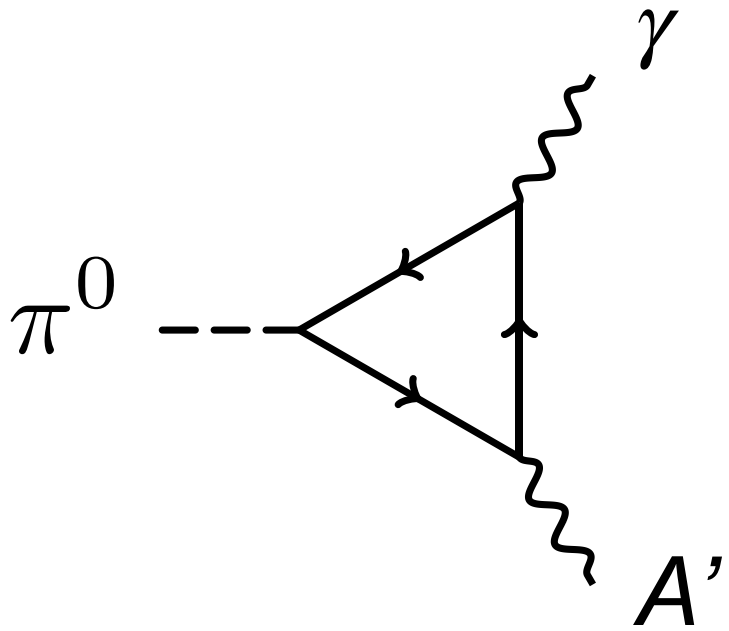
# Some production mechanisms for Dark Photons




annihilation



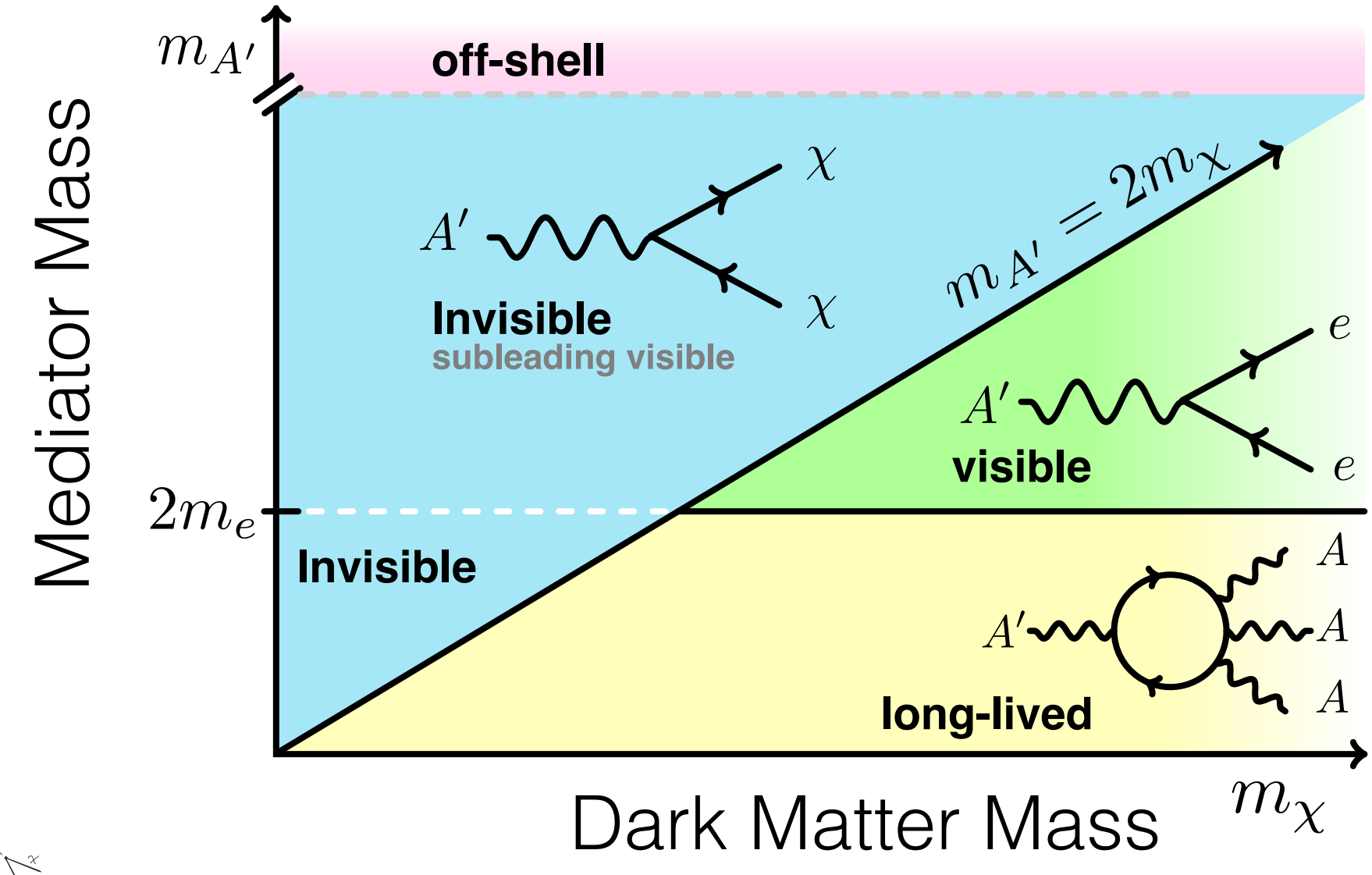

bremsstrahlung




meson decay

# Decays of Dark Photons

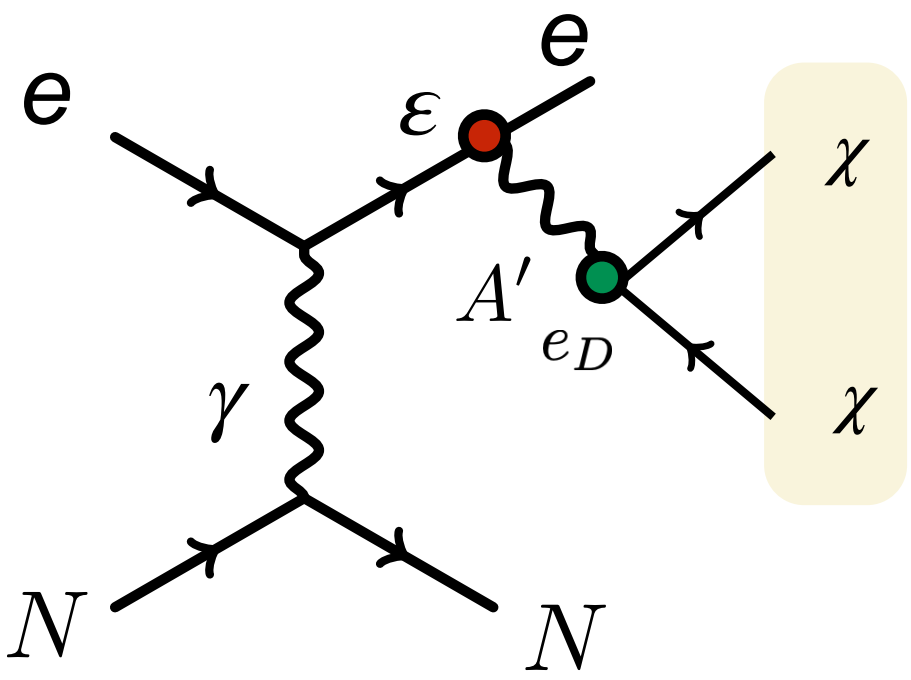
Adapted from Natalia Toro, Dark Sectors 2017 (1608.03591)



# SEARCHES FOR DARK SECTORS AT ACCELERATORS

INVISIBLE DECAY MODE $m'_A > 2m_X$

## 1) BEAM DUMP APPROACH (MiniBooNE, LSND, NA62...)




Flux of X generated by decays of A's produced in the dump.

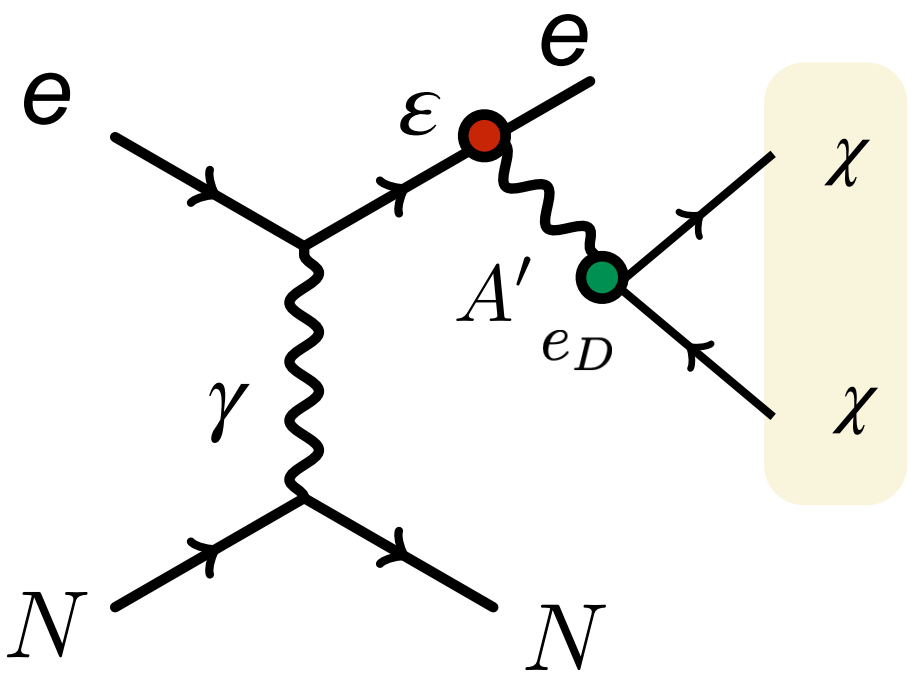
**Signal:** X scattering in far detector

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

# SEARCHES FOR DARK SECTORS AT ACCELERATORS

INVISIBLE DECAY MODE $m'_A > 2m_X$

## 2) NA64/LDMX APPROACH

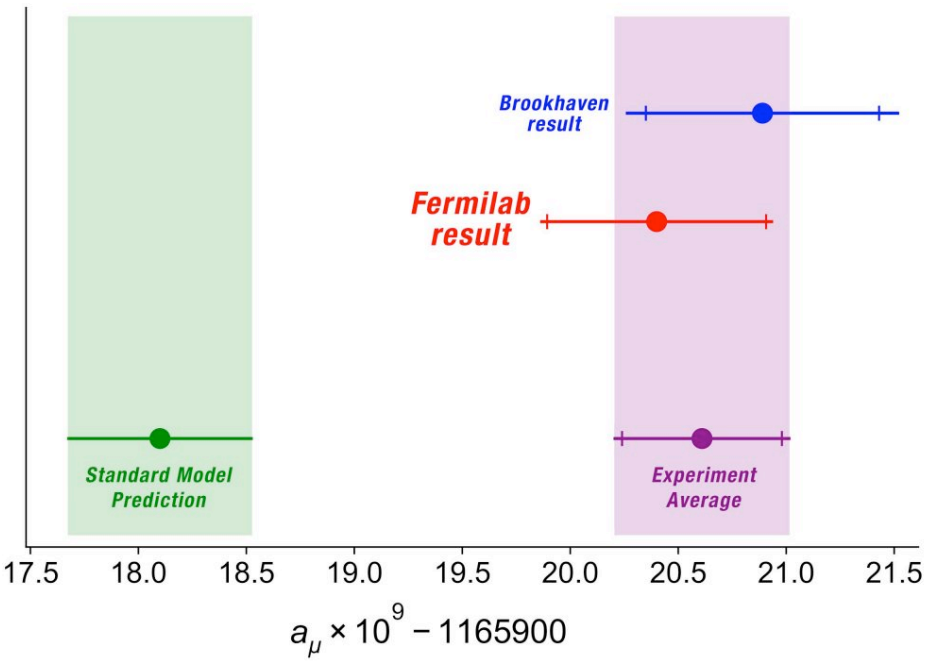



NA64 **missing energy**: produced A's carry away energy form the active dump used to measure recoil e- energy

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

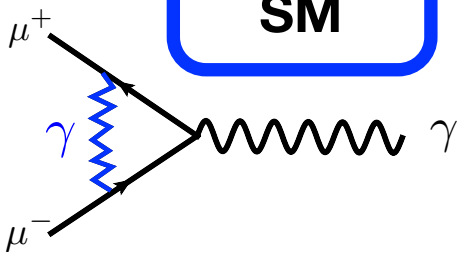
# The muon (g-2): an additional motivation to search for dark photons

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



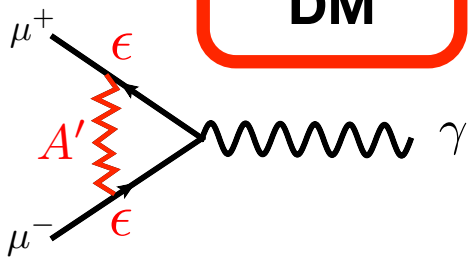

**TO NOTE:** Lattice QCD calculations S. Borsanyi et al. Nature 593 (2021) reduce discrepancy. Hadronic corrections to be directly measured by MUonE EXP @ CERN G. Abbiendi. PoS ICHEP2020, 223 (2021)

**SM**



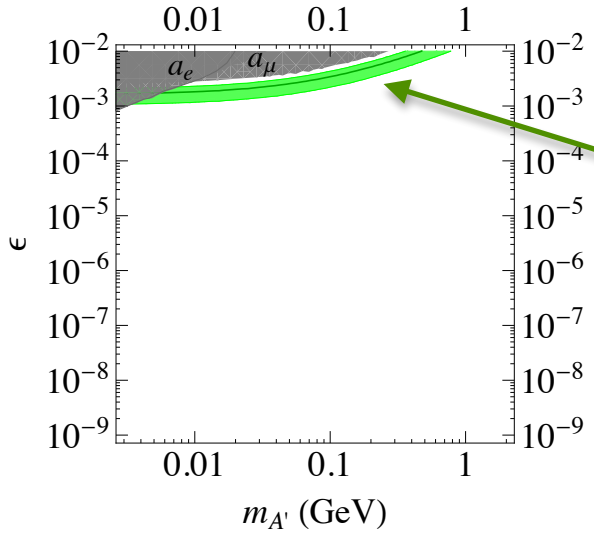

$$(g_s - 2)^{\gamma}_{\mu} \simeq \frac{\alpha}{2\pi}$$
$$\simeq 10^{-3}$$

**DM**




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

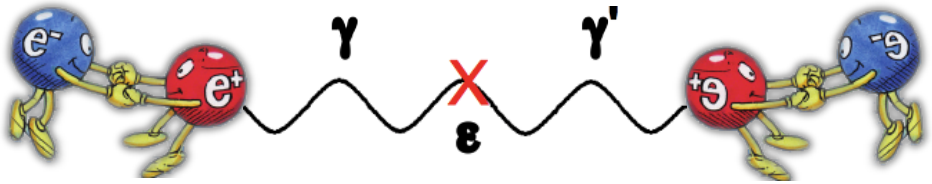
M. Pospelov, A. Ritz and M. B. Voloshin, Phys. Lett. B 662, 53 (2008)

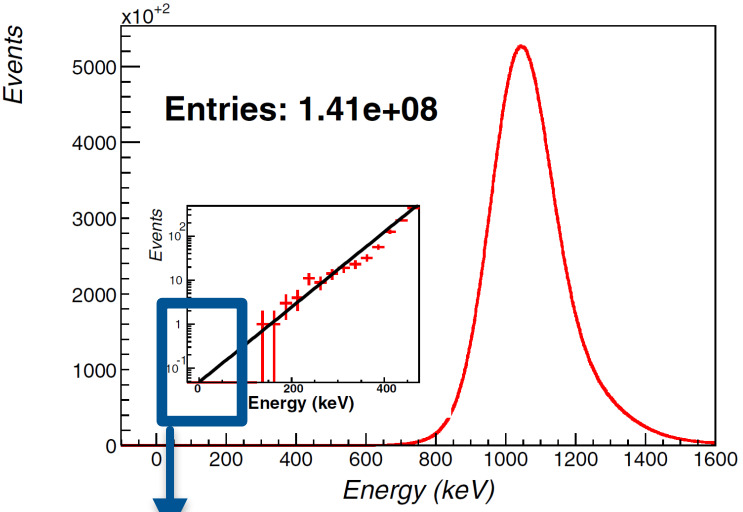


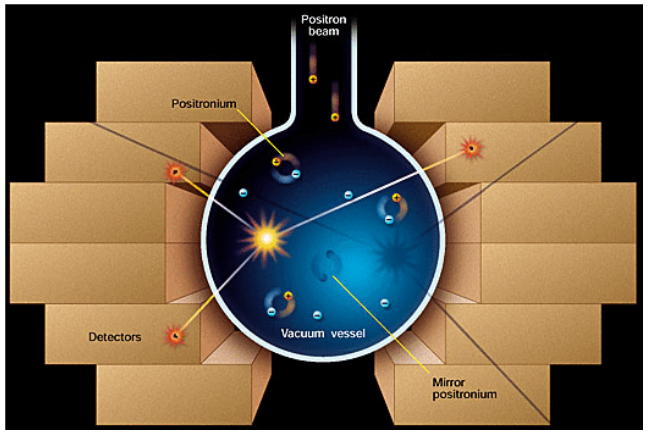

**A' may explain observed anomaly**

# From positronium (search for massless dark photon) → NA64

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




**Signature: disappearance of 1 MeV energy**

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

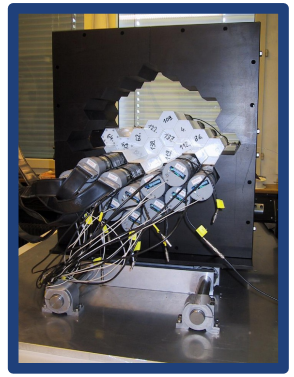


**Table top**

IPA ETH zürich

**At rest → 100 GeV**

# The NA64 collaboration (~50 researchers from 16 Institutes)

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)

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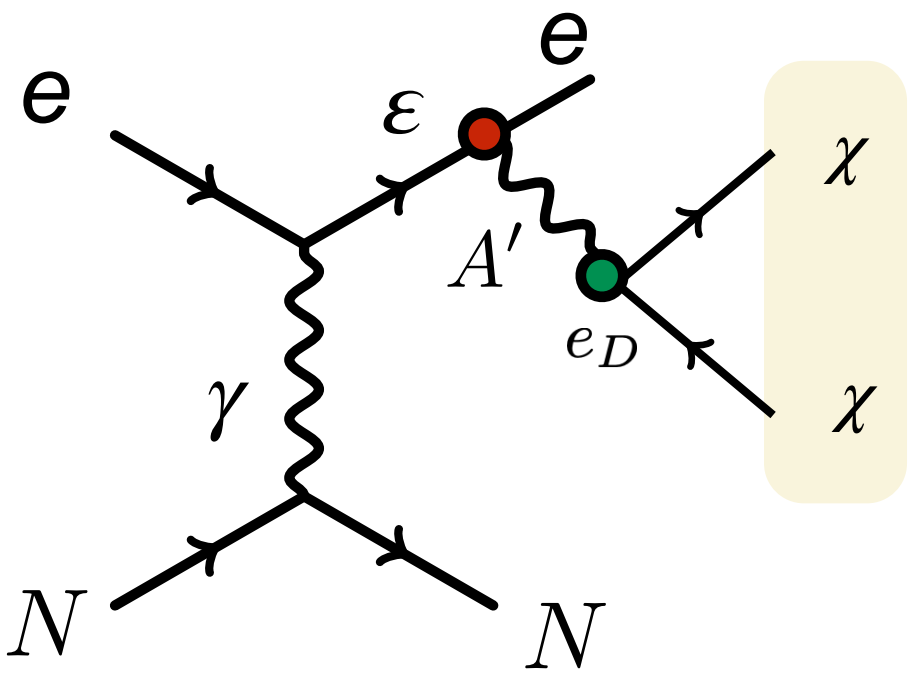
[16] *SAPHIR Millennium Institute of ANID, Chile*

**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.**

# 1) The NA64 search for A' → $\chi\bar{\chi}$

INVISIBLE DECAY MODE $m'_A > 2m_X$




## DS Lagrangian

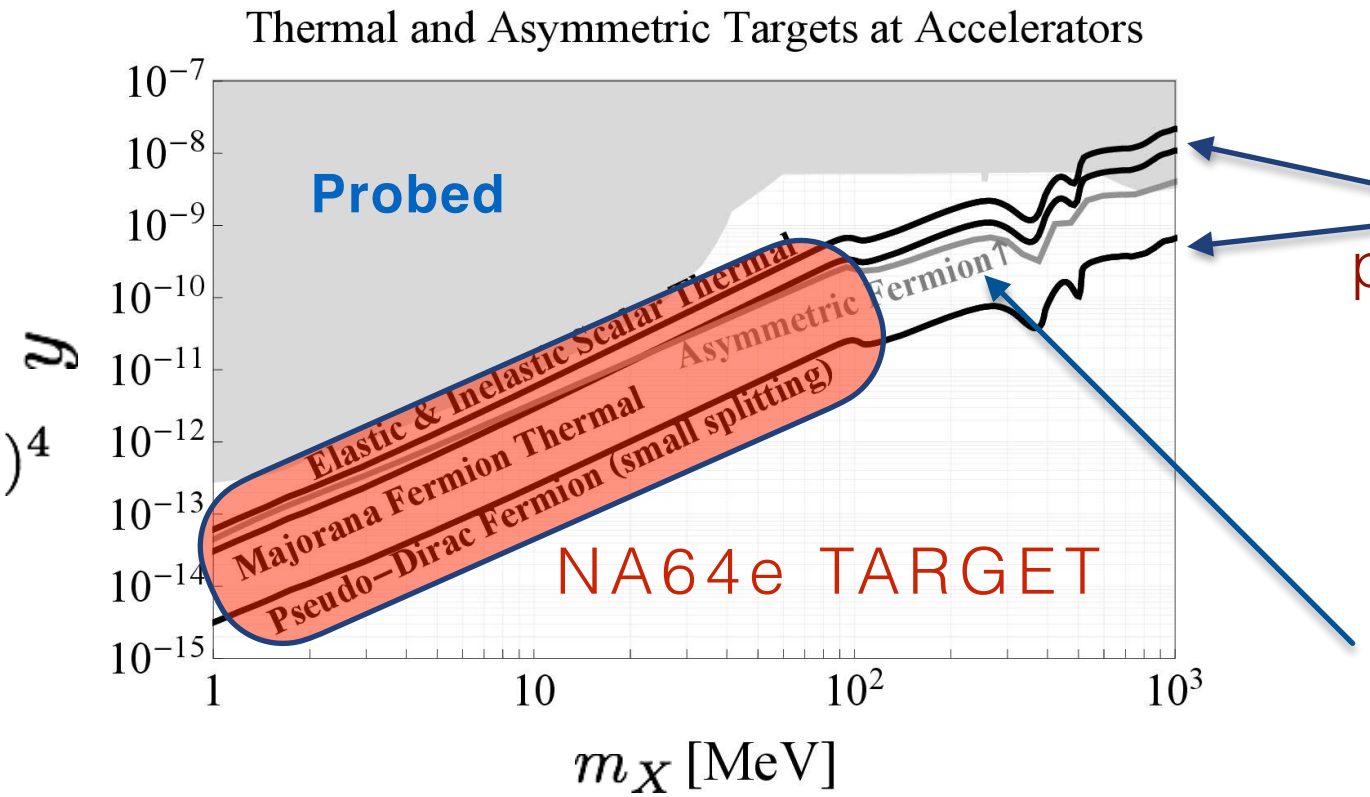
$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu} + \frac{m^2_{A'}}{2}A'_\mu A'^\mu + i\bar{\chi}\gamma^\mu\partial_\mu\chi - m_\chi\bar{\chi}\chi - e_D\bar{\chi}\gamma^\mu A'_\mu\chi,$$

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

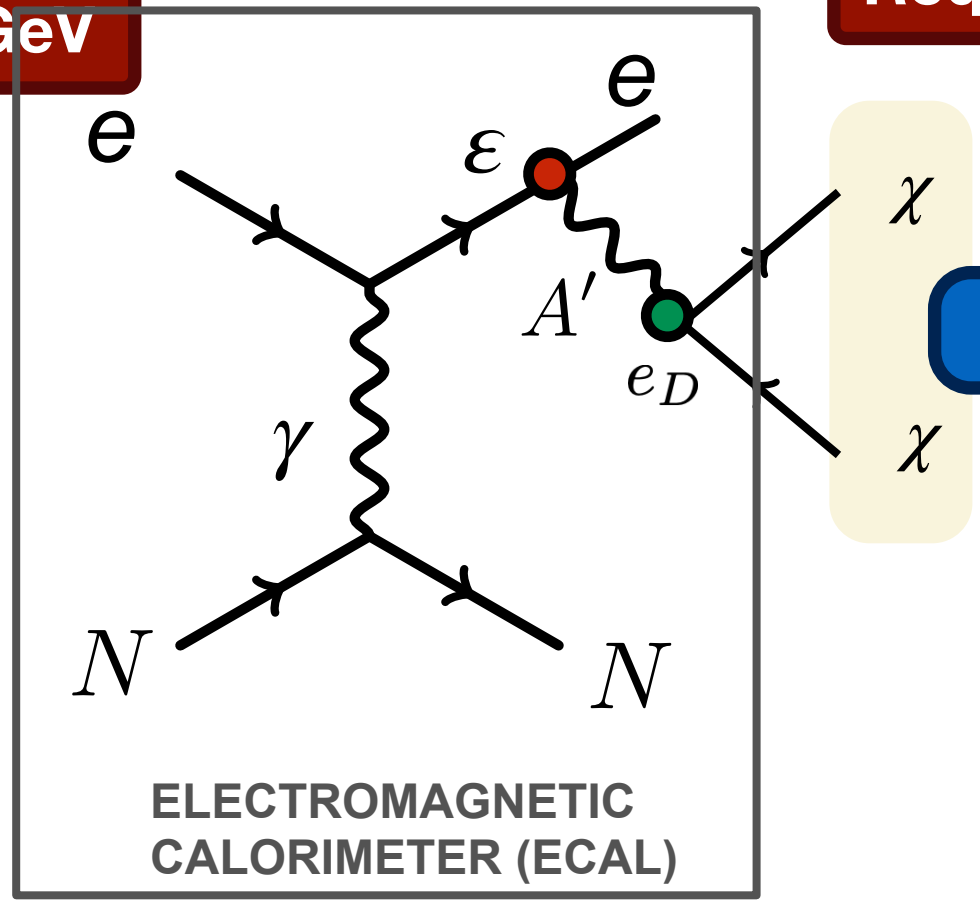
higher mass region could be covered by NA64 in muon/positron mode

PLB796, 117 (2019)

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

TAGGED 100 GeV

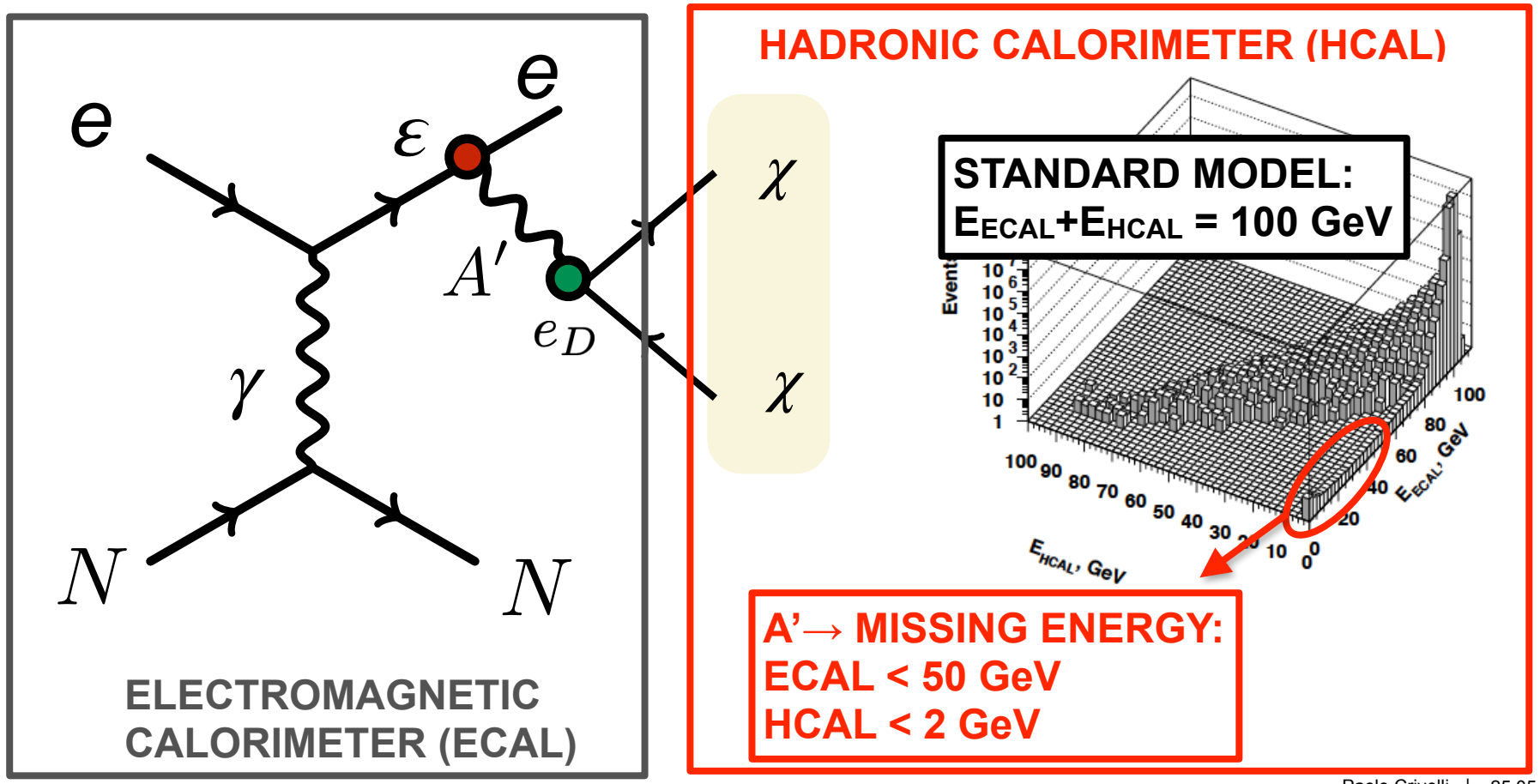
Requested ECAL ENERGY < 50 GeV



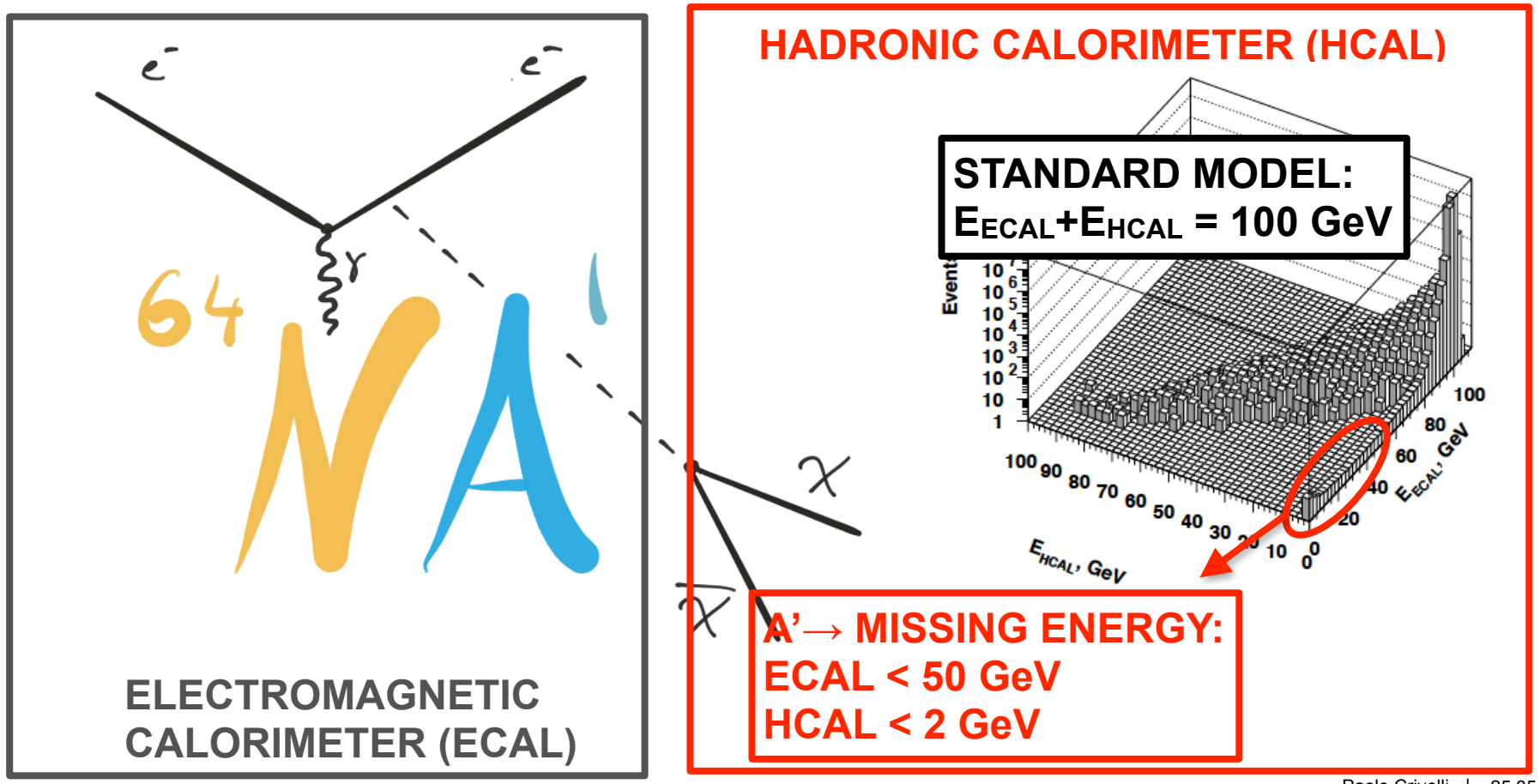

"BREMSSTRAHLUNG" OF A'

Active Dump

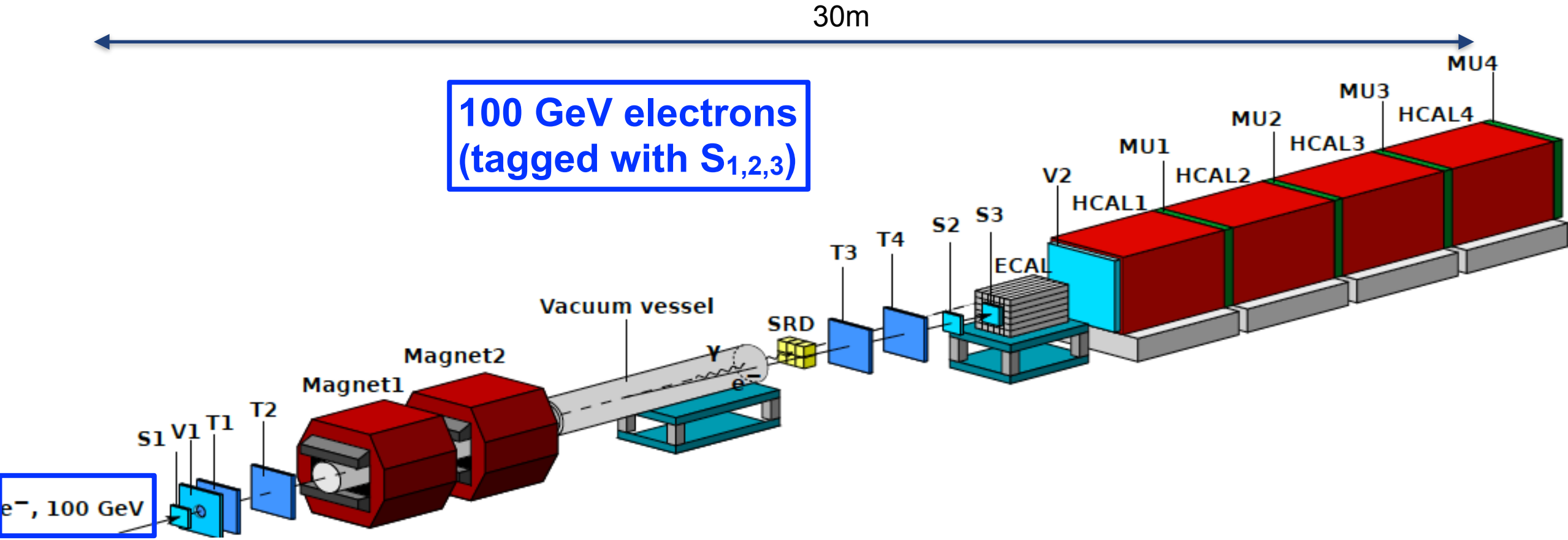
# The NA64 method to search for A' → $\chi\bar{\chi}$



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

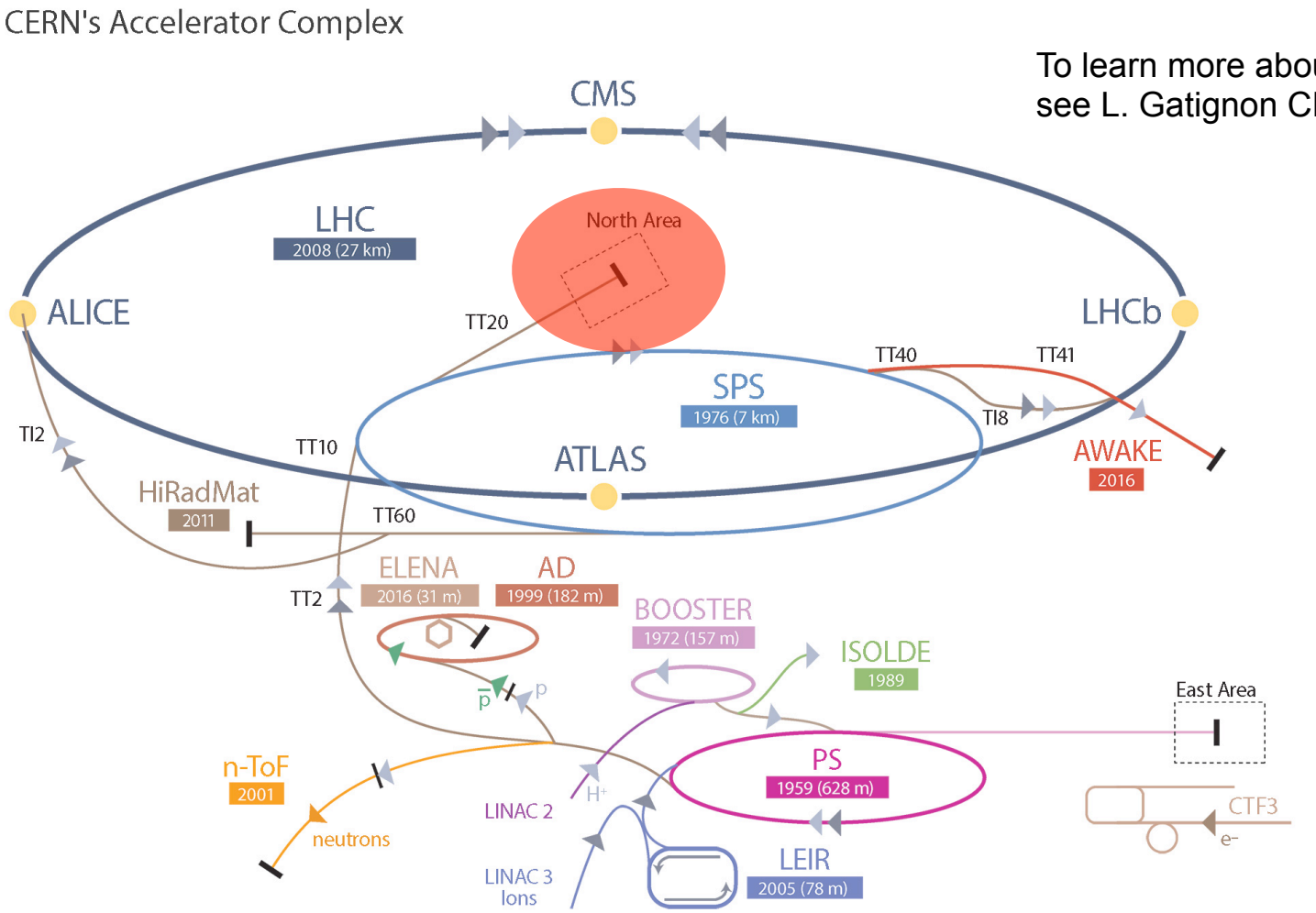


# The CERN SPS H4 electron beam




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

# The CERN SPS H4 electron beam

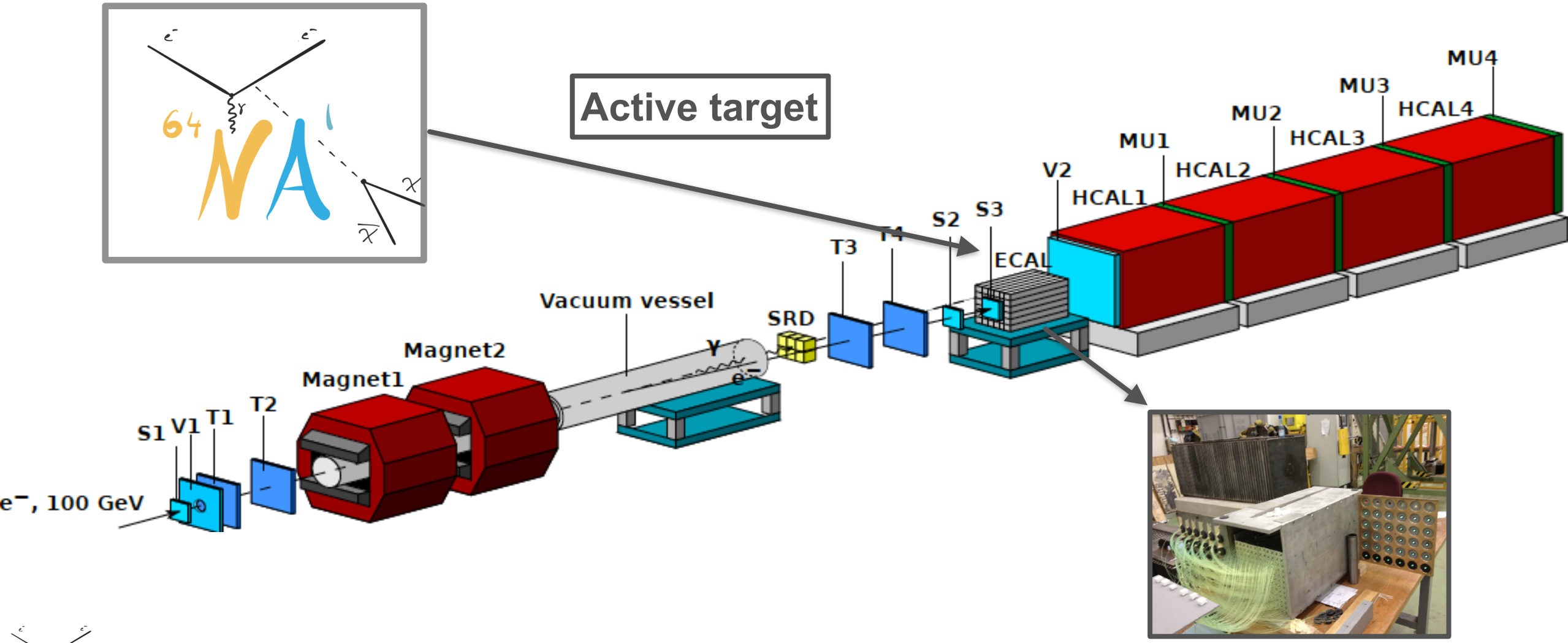



To learn more about SPS secondary beams see L. Gatignon CERN-ACC-NOTE-2020-0043

https://home.cern/science/accelerators

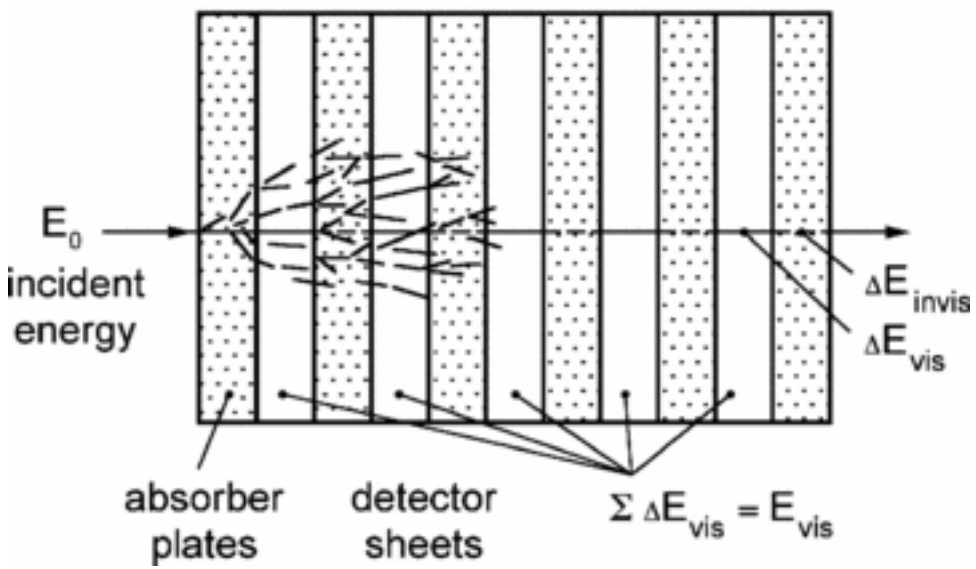
p (proton) | ion | neutrons | p̄ (antiproton) | electron | proton/antiproton conversion

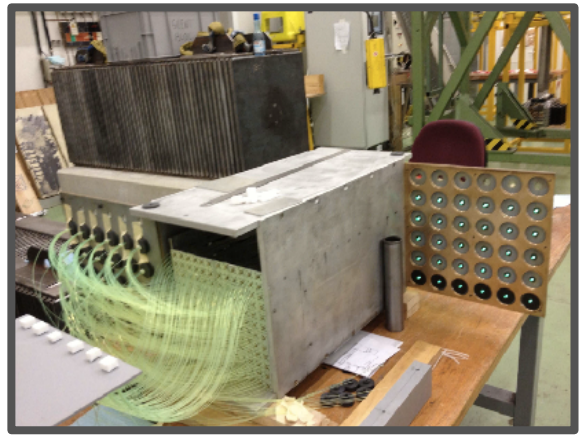
# The Electromagnetic Calorimeter (ECAL)

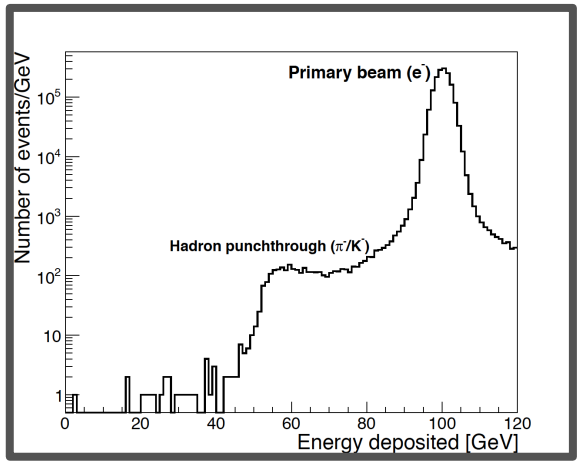


# The Electromagnetic Calorimeter (ECAL)

$$\Sigma \Delta E_{invis} + \Sigma \Delta E_{vis} = E_{invis} + E_{vis} = E_{absorbed}$$





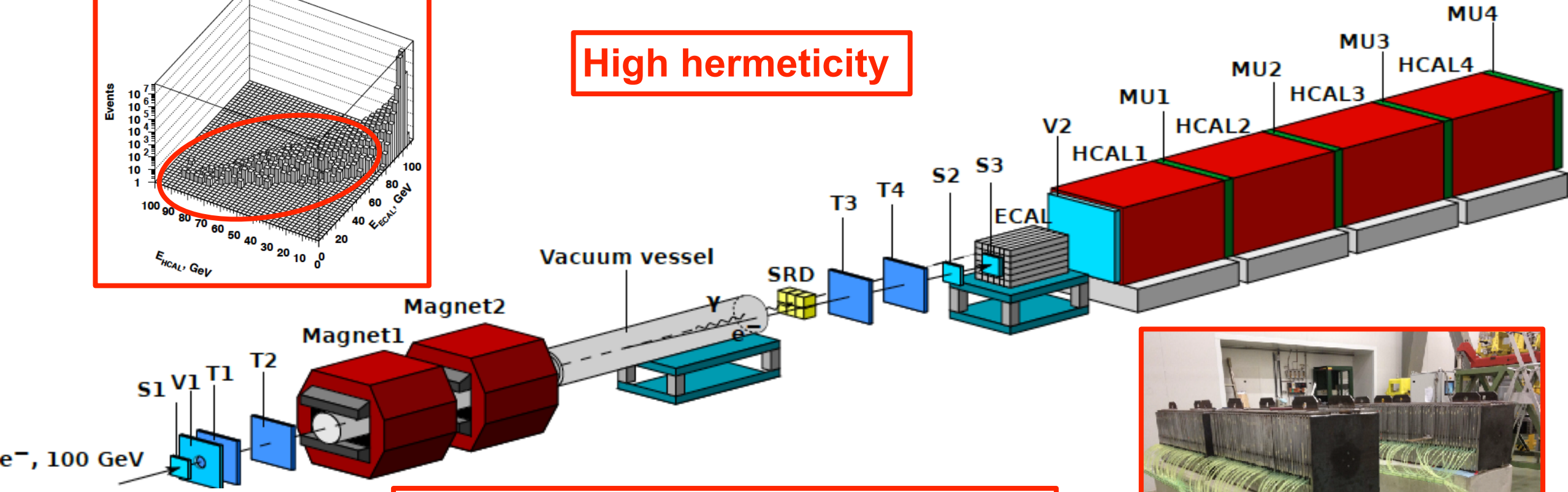

- High hermeticity (~40 $X_0$)
- PbSc sandwich, 6x6 matrix, cells 38x38x490 mm3
- WLS fibers in spiral→ suppress energy leaks
- Energy resolution ~ 9%/√(E[GeV])
- Longitudinal (Pre-shower) and lateral segmentation

→ shower profiles (hadron rejection)

# The Hadronic Calorimeter (HCAL)




**High hermeticity**



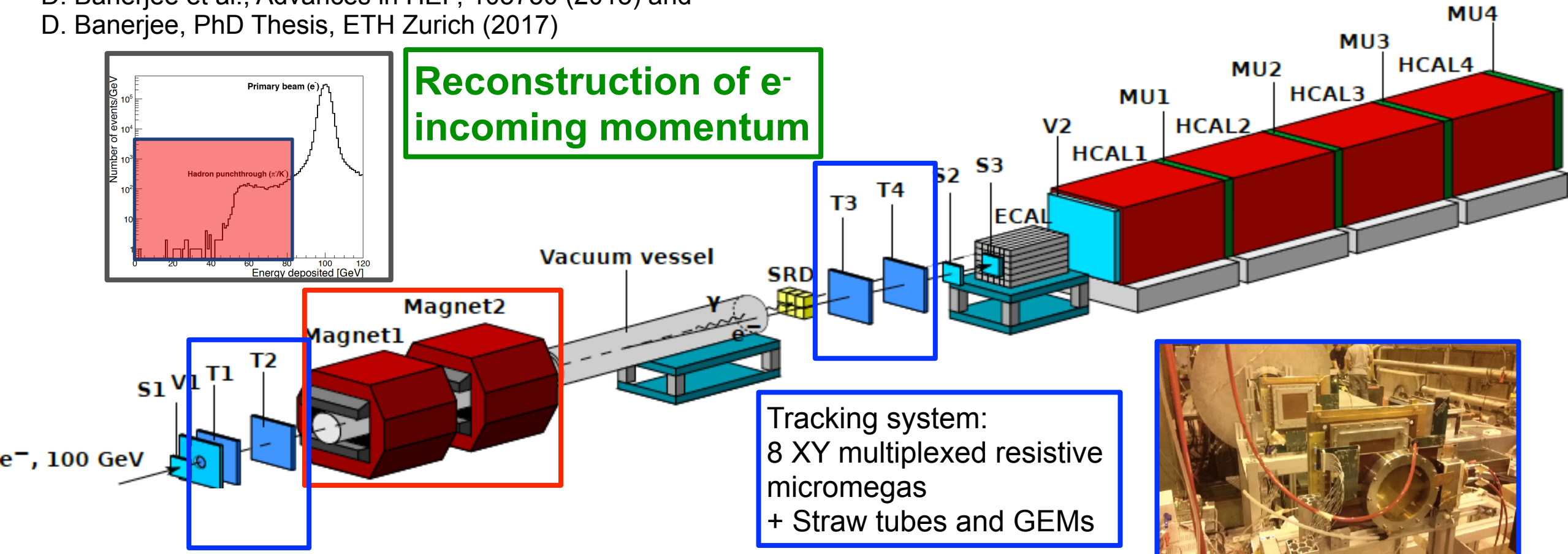

- High hermeticity : 4 HCAL (~7 λ/module)
- FeSc sandwich 3x3 matrix, cells 19.4x19.2x150 $cm^3$
- WLS fibers in spiral→ suppress energy leaks
- Energy resolution ~ 60%/√(E[GeV])

# 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**



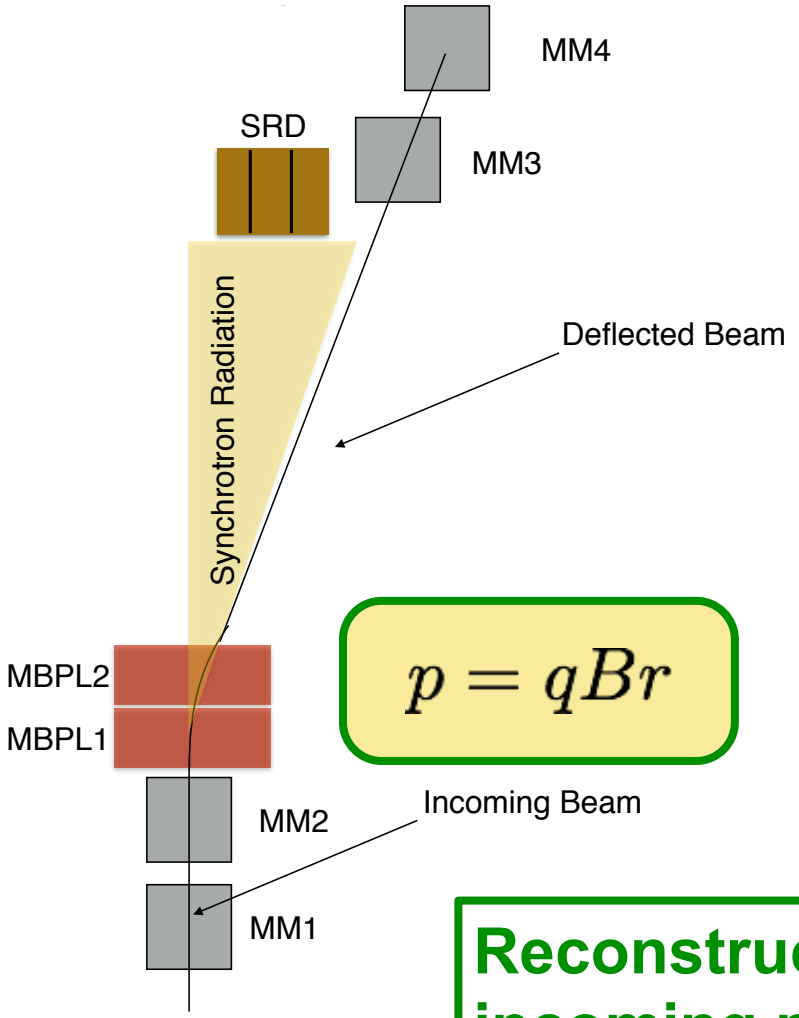

Tracking system:
8 XY multiplexed resistive micromegas
+ Straw tubes and GEMs



Two bending magnets in series → 7 T.m field

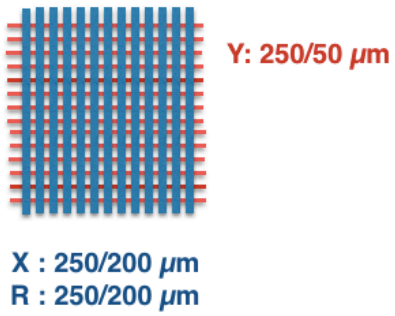
# The magnetic spectrometer

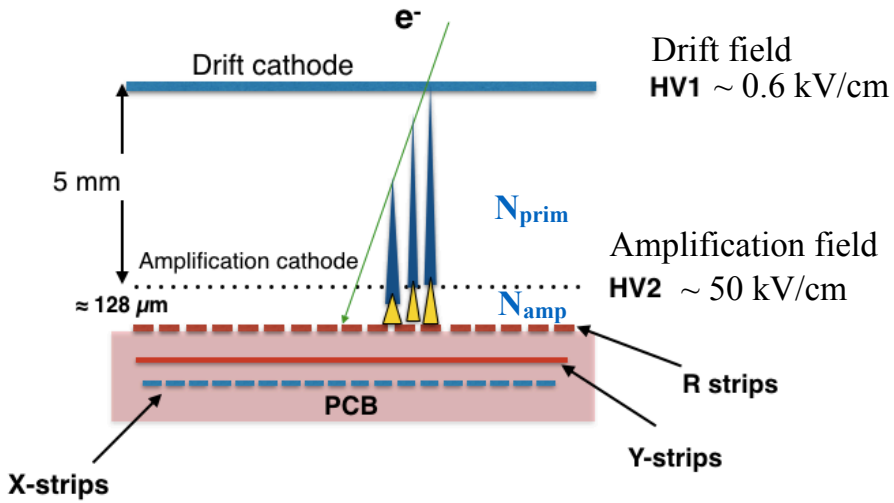
D. Banerjee et al., NIMA881 (2018) 72-81 and
D. Banerjee, PhD Thesis, ETH Zurich (2017)

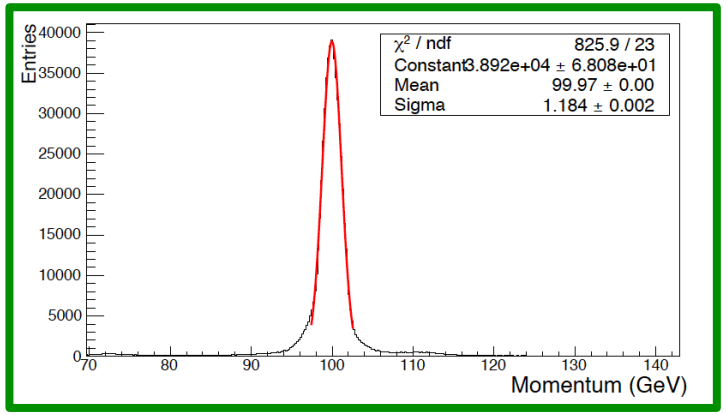



$$p = qBr$$

Tracking system MM1-MM4: multiplexed resistive micromegas

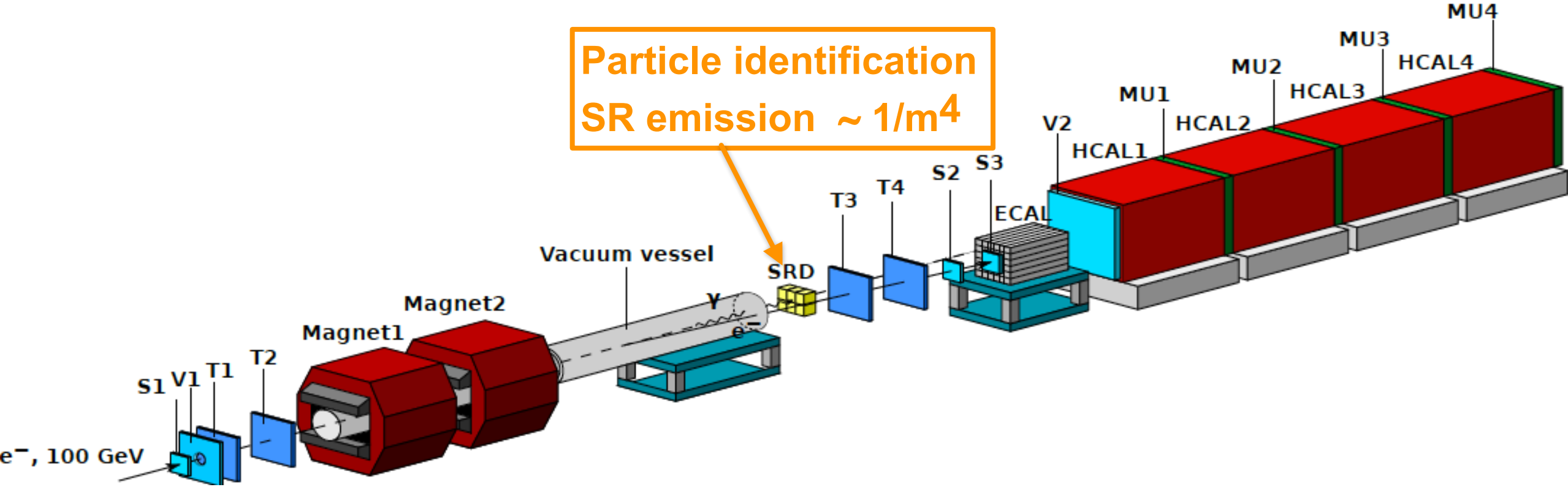


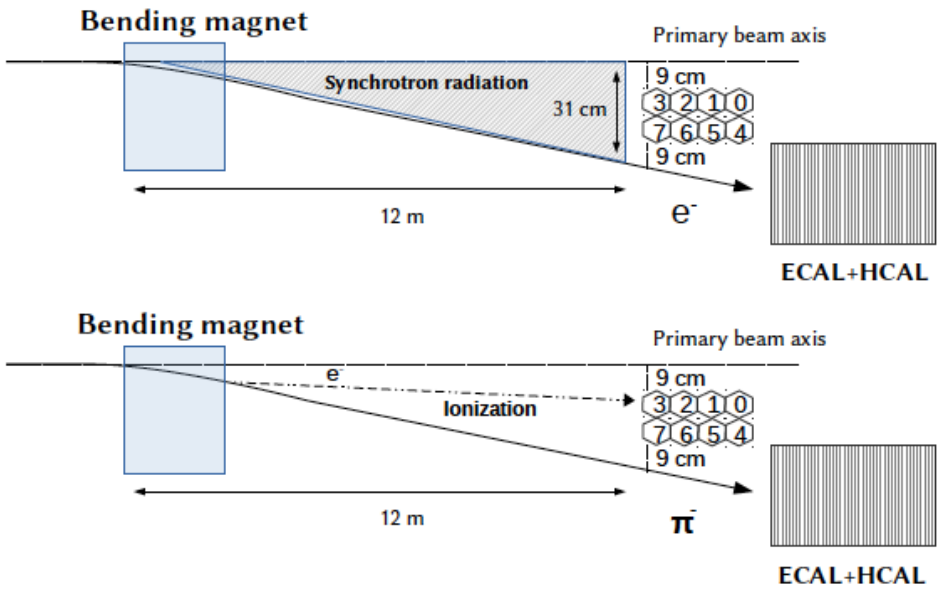

**Reconstruction of e- incoming momentum**

# The Synchrotron Radiation (SR) detector

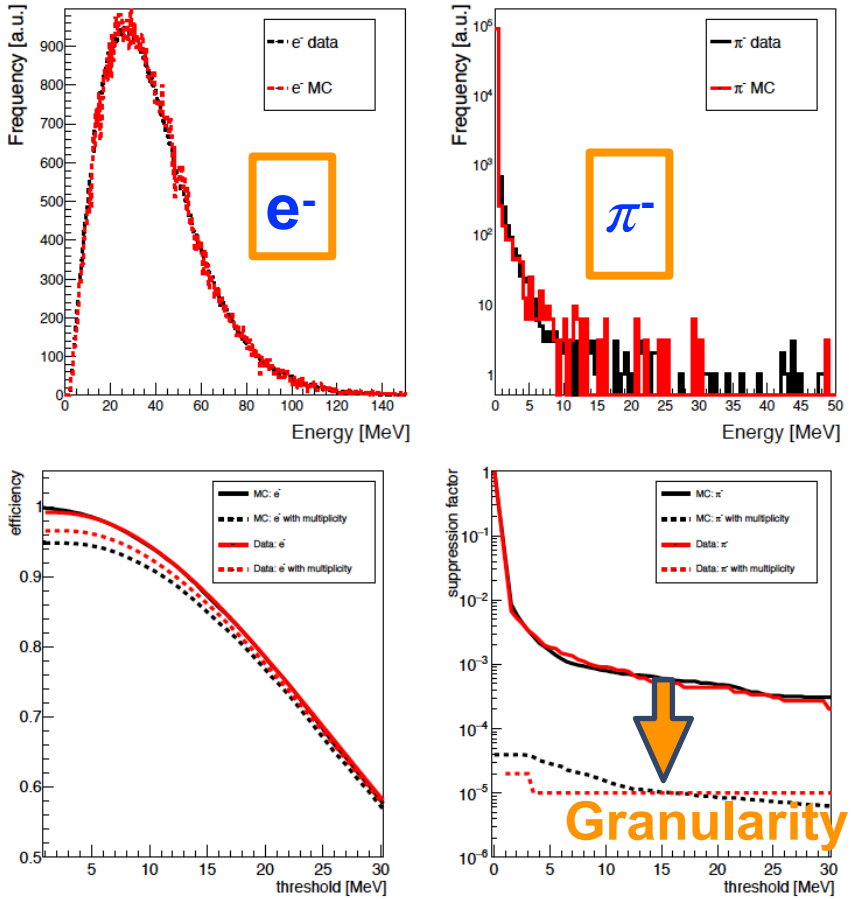


# The Synchrotron Radiation (SR) detector

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

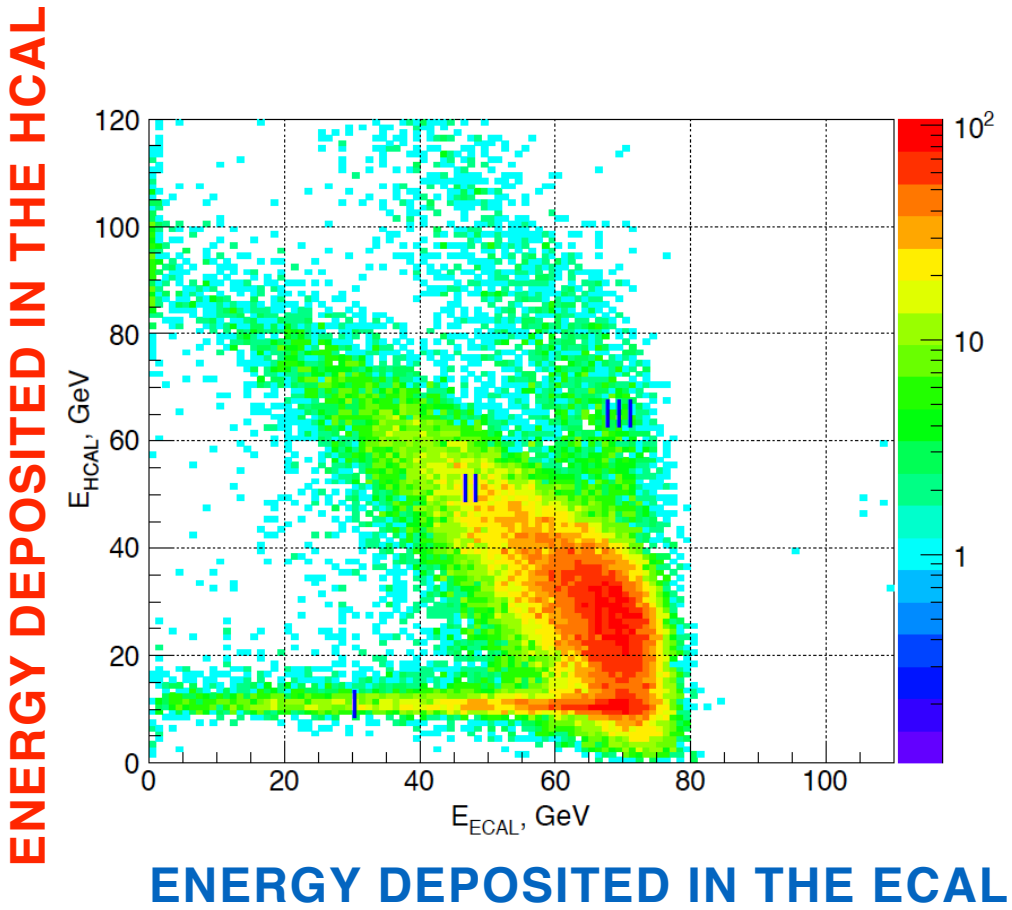



**Efficiency > 95%**
**Suppression >$10^{-5}$**




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

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

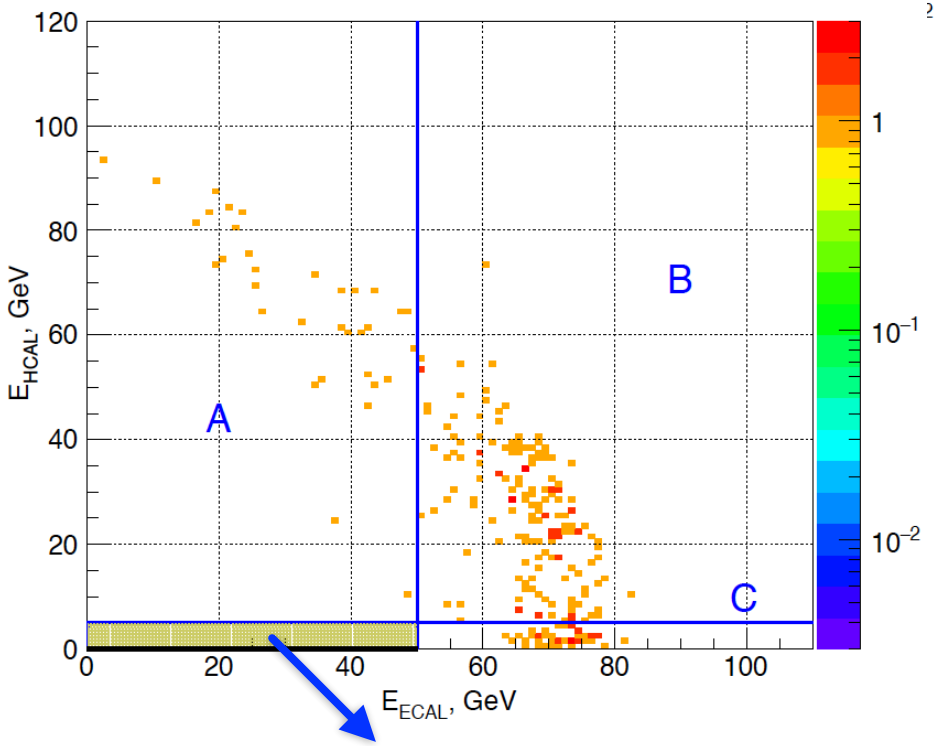



★ **Region I:** e- Z → e-Zγ; γ → μ+μ- → benchmark for MC

★ **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)



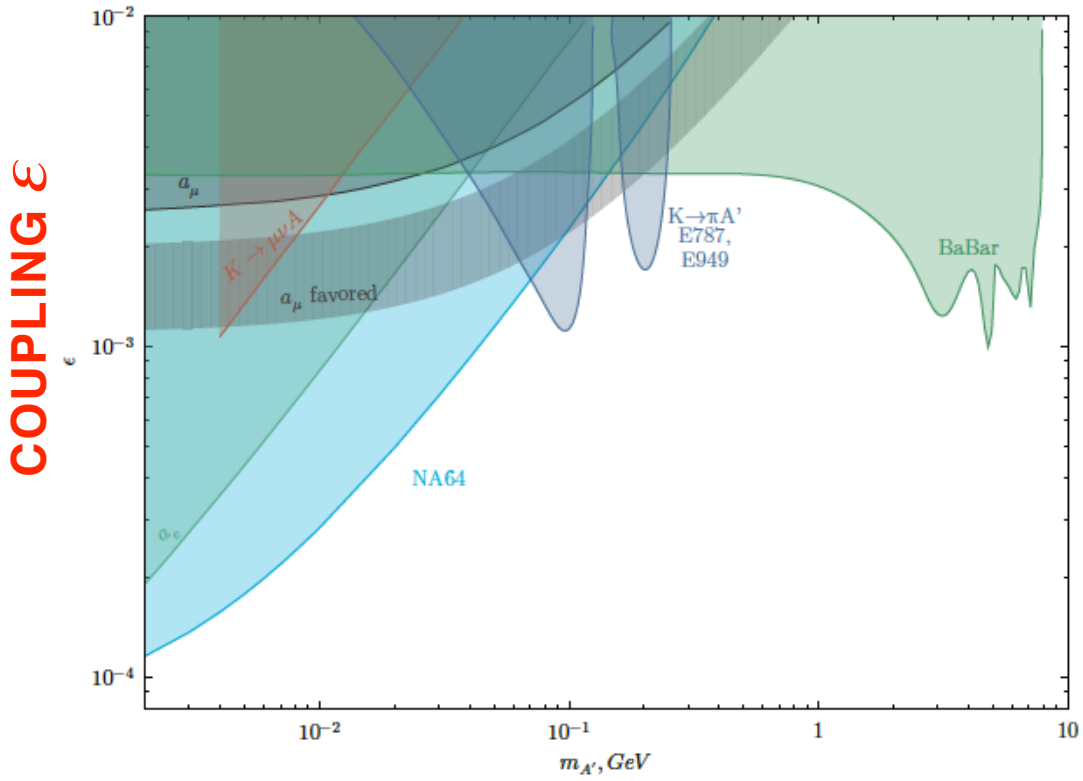

**Event Selection Criteria:**

- 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




MASS OF THE DARK PHOTON

→ exclusion of most of g-2 muon favored region

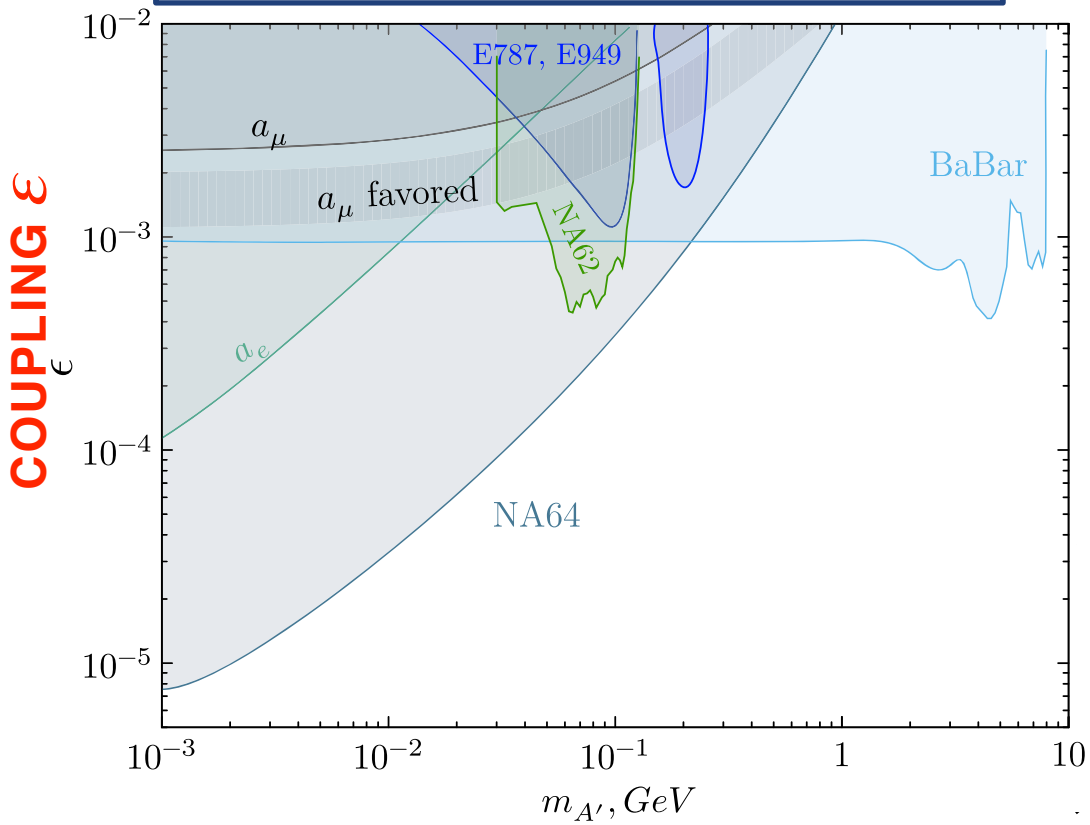
NA64 collaboration, Phys. Rev. Lett. 118, 011802 (2017)

g-2 closed completely by BABAR results

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

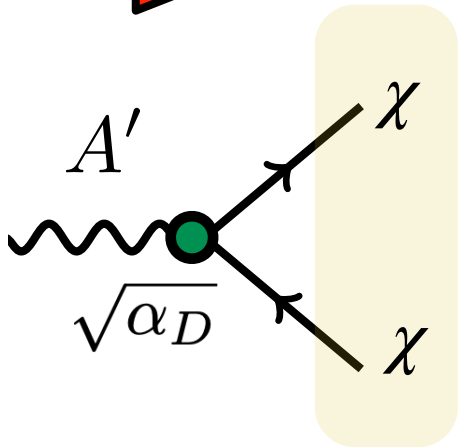
# The NA64 search for A' → $\chi\bar{\chi}$ - *results combined analysis 2016-2018*

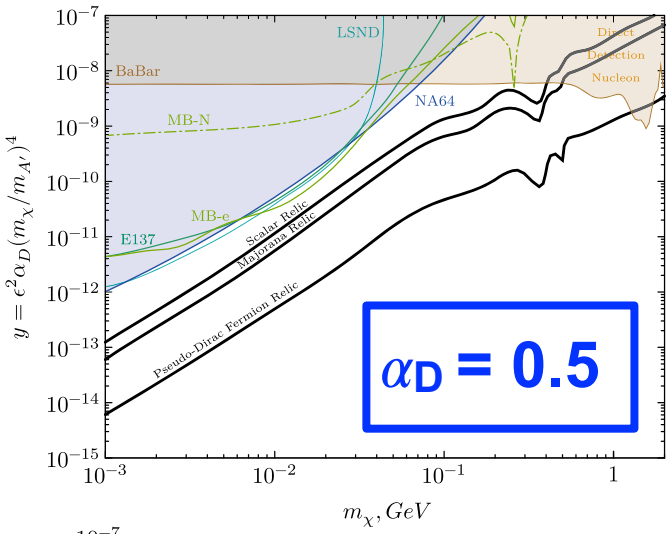
2.8 x $10^{11}$ electrons on target

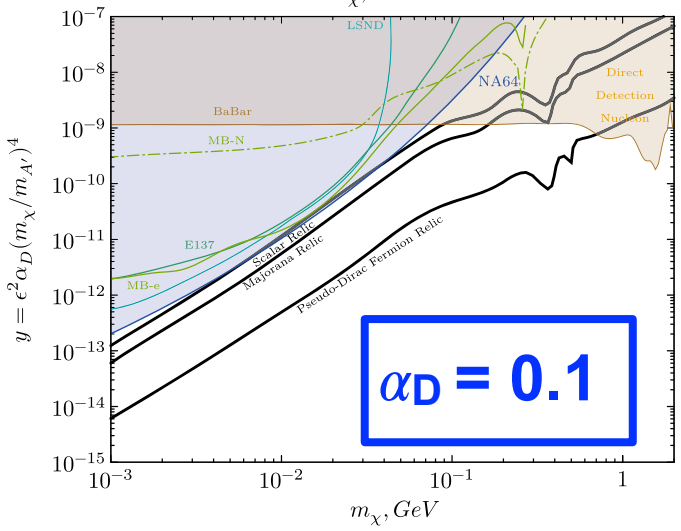



MASS OF THE DARK PHOTON

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

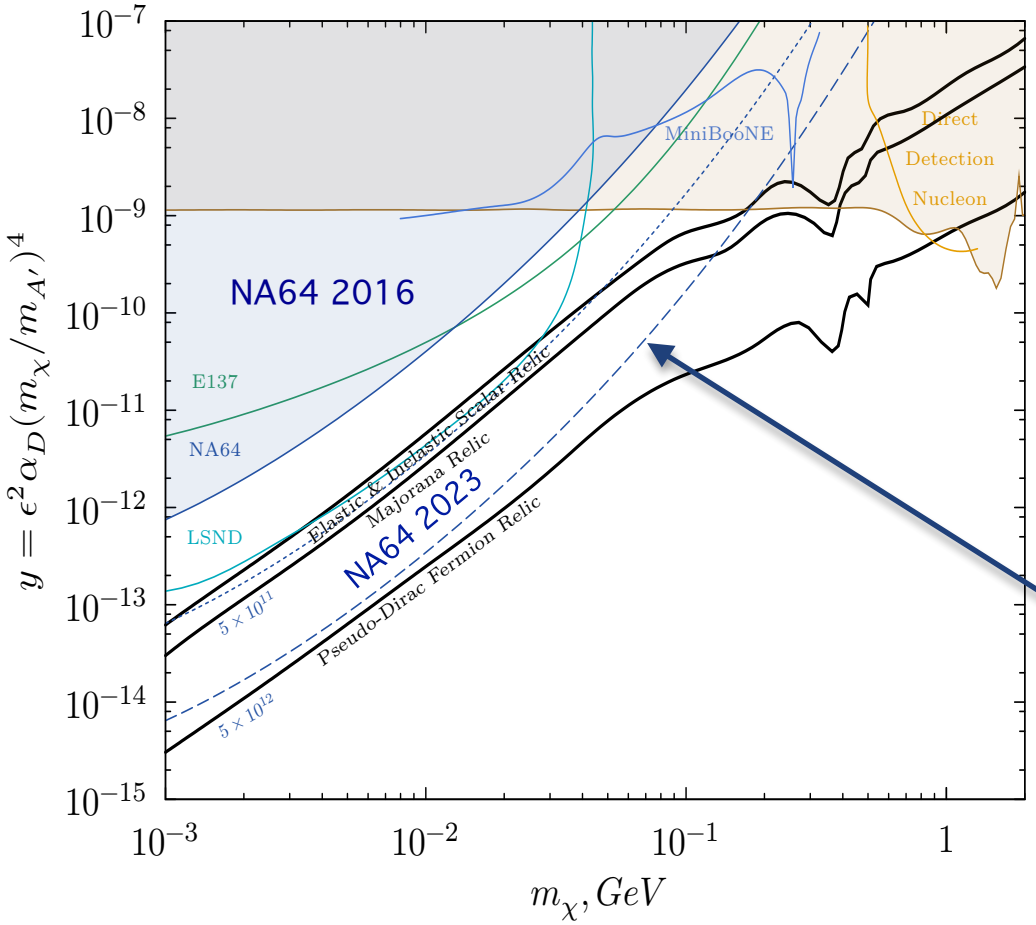



NA64 collaboration, Phys. Rev. Lett. 123, 121801 (2019)

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




**MASS OF THE DARK PHOTON**

$\alpha_D = 0.1$

$m_{A'} = 3m_\chi$

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

Setup upgrade/ optimisation required (ongoing)

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

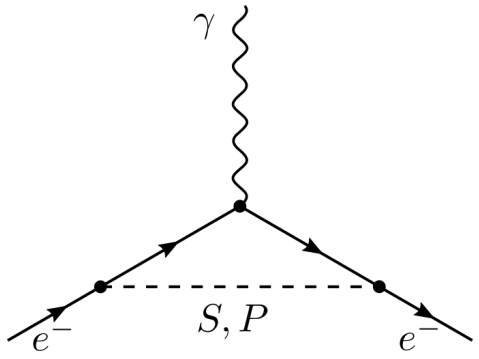
$$e^- Z \rightarrow e^- Z X; \; X \rightarrow invisible.$$

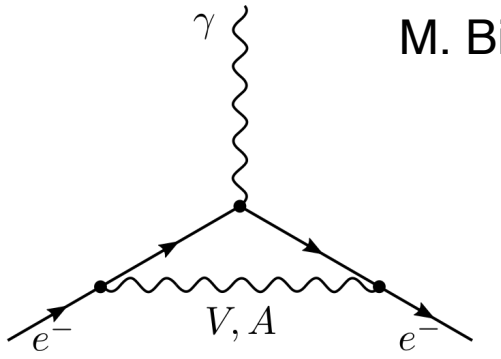
**X: scalar (S), pseudoscalar (P), vector (V) or an axial vector (A)**

e-X: interaction with the coupling strength: $g_X = \varepsilon_X e$

$$\mathcal{L}_S = g_S \bar{e} e S$$
$$\mathcal{L}_P = i g_P \bar{e} \gamma_5 e P$$
$$\mathcal{L}_V = g_V \bar{e} \gamma_\mu e V_\mu$$
$$\mathcal{L}_A = g_A \bar{e} \gamma_\mu \gamma_5 e A_\mu$$

DMG4 package
M. Biondi et al. arXiv:2101.12192




$m_X \gg m_e.$

$$\Delta a_S = \frac{g_S^2}{4\pi^2}\left(\frac{m_e}{m_X}\right)^2\left[\ln\frac{m_X}{m_e} - \frac{7}{12}\right]$$
$$\Delta a_P = \frac{g_P^2}{4\pi^2}\left(\frac{m_e}{m_X}\right)^2\left[-\ln\frac{m_X}{m_e} + \frac{11}{12}\right]$$
$$\Delta a_V = \frac{g_V^2}{4\pi^2}\left(\frac{m_e}{m_X}\right)^2\frac{1}{3}$$
$$\Delta a_A = \frac{g_A^2}{4\pi^2}\left(\frac{m_e}{m_X}\right)^2\left(-\frac{5}{3}\right)$$

Latest experimental determination of

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

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

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

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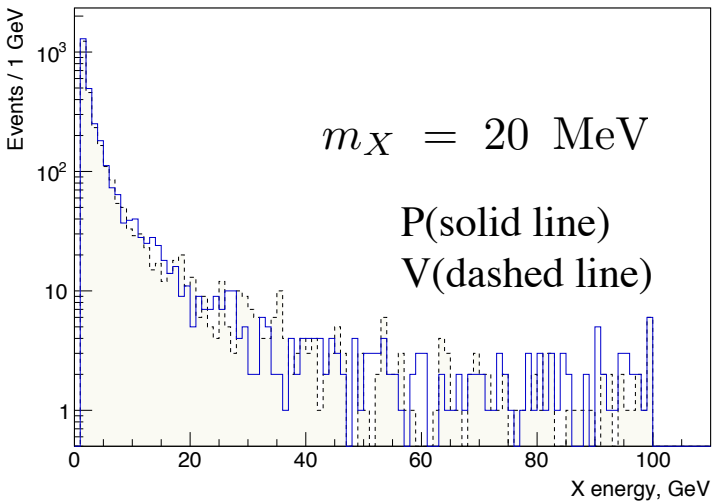
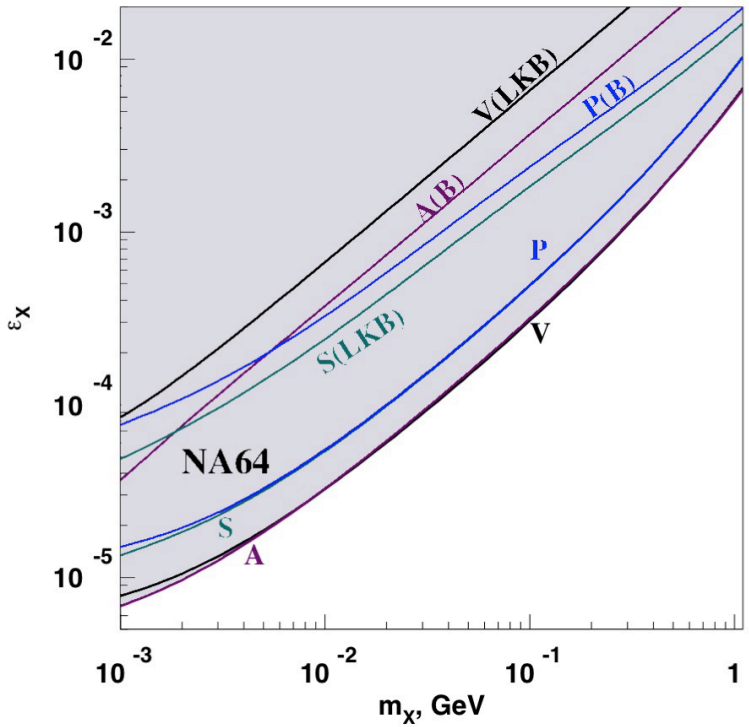
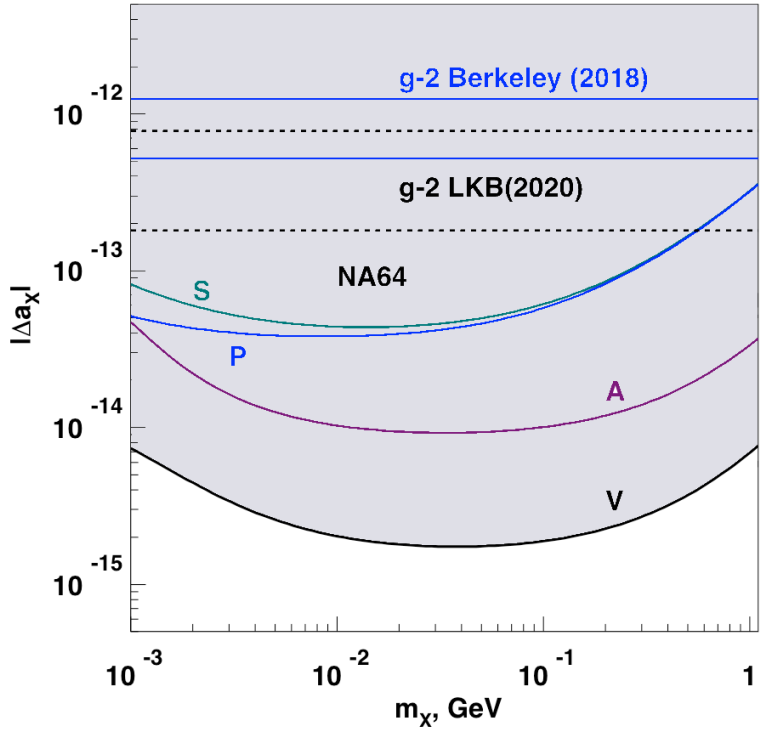
**X: scalar (S), pseudoscalar (P), vector (V) or an axial vector (A)**

e-X: interaction with the coupling strength: $g_X = \varepsilon_X e$

G4 + ETL calculations

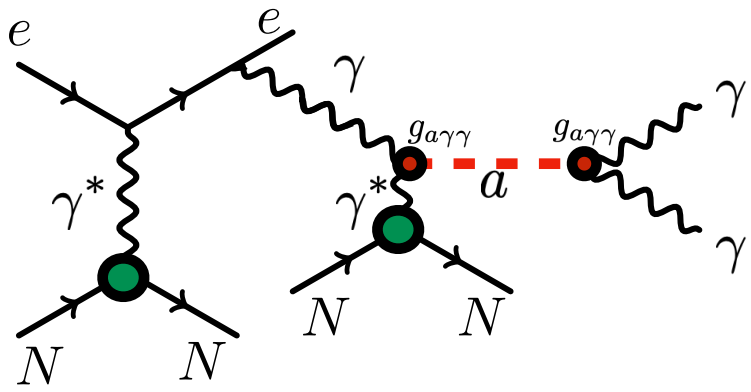


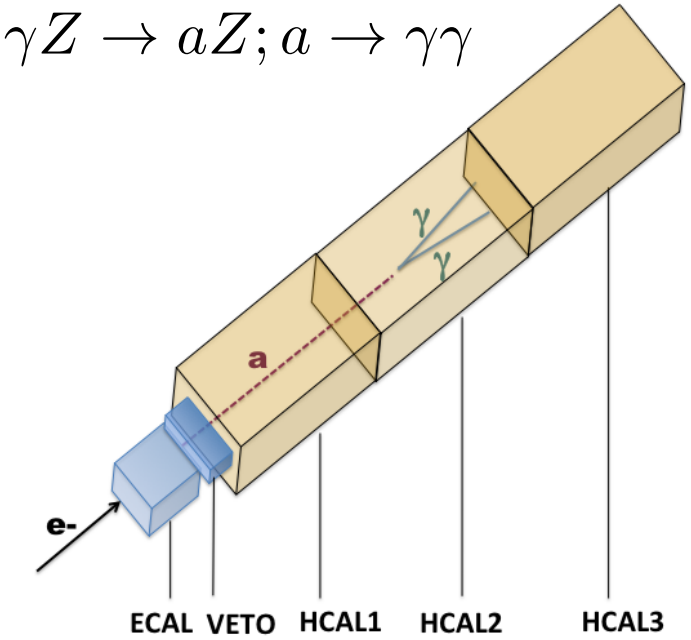

NA64 collaboration, arXiv:2102.01885 (to appear in PRL)

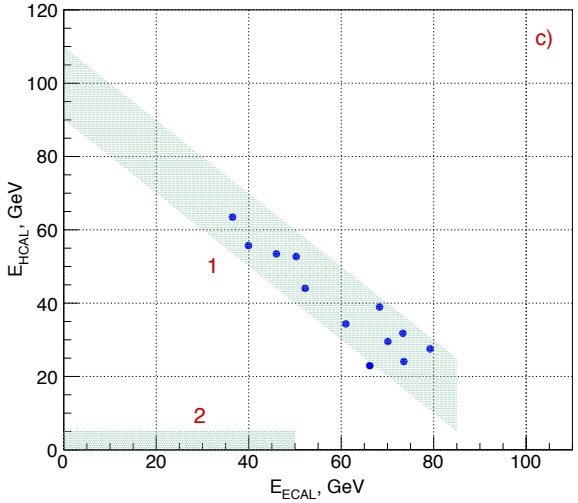
# 2) The NA64 ALP search

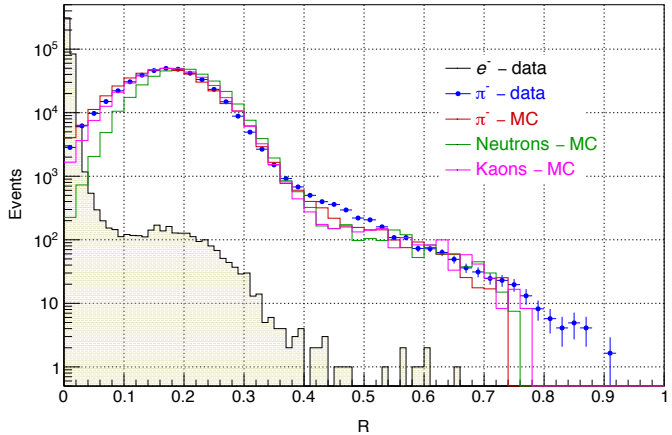



## Production via Primakoff effect

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



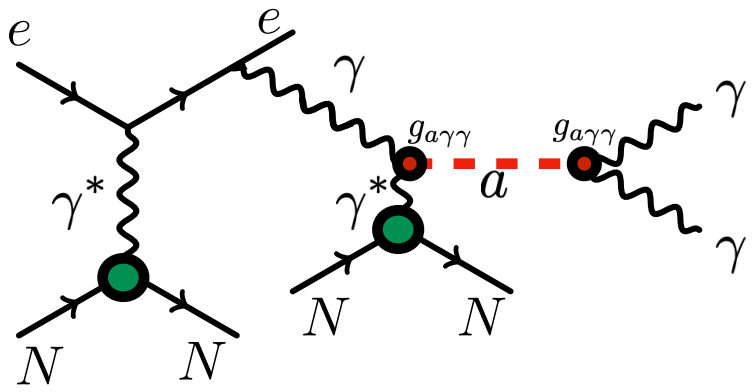




blue dots represent 12 events in the control region R > 0.06 from lea

| Background source | Background, $n_b$ |
|---|---|
| leading neutrons | $0.02 \pm 0.008$ |
| leading $K^0$ interactions and decays | $0.14 \pm 0.045$ |
| beam $\pi$, $K$ charge exchange and decays | $0.006 \pm 0.002$ |
| dimuons | $< 0.001$ |
| Total $n_b$ | $0.17 \pm 0.046$ |

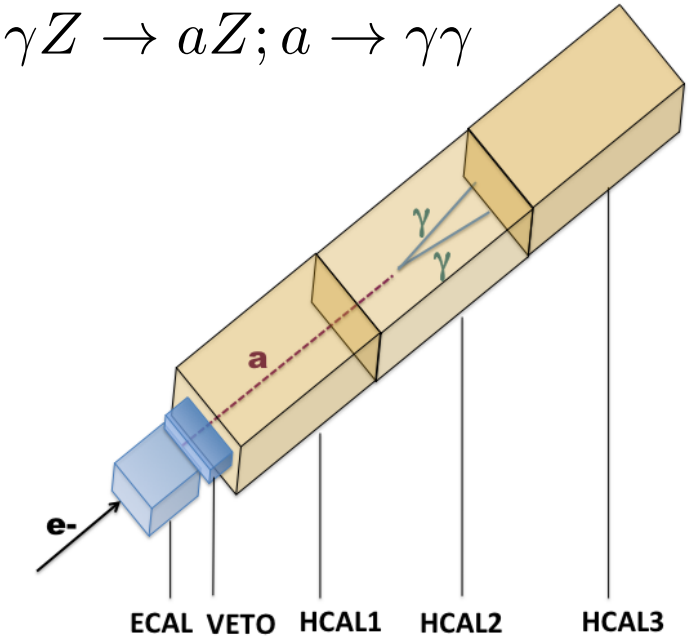
NA64 collaboration PRL 125, 081801 (2020)

# 2) The NA64 ALP search

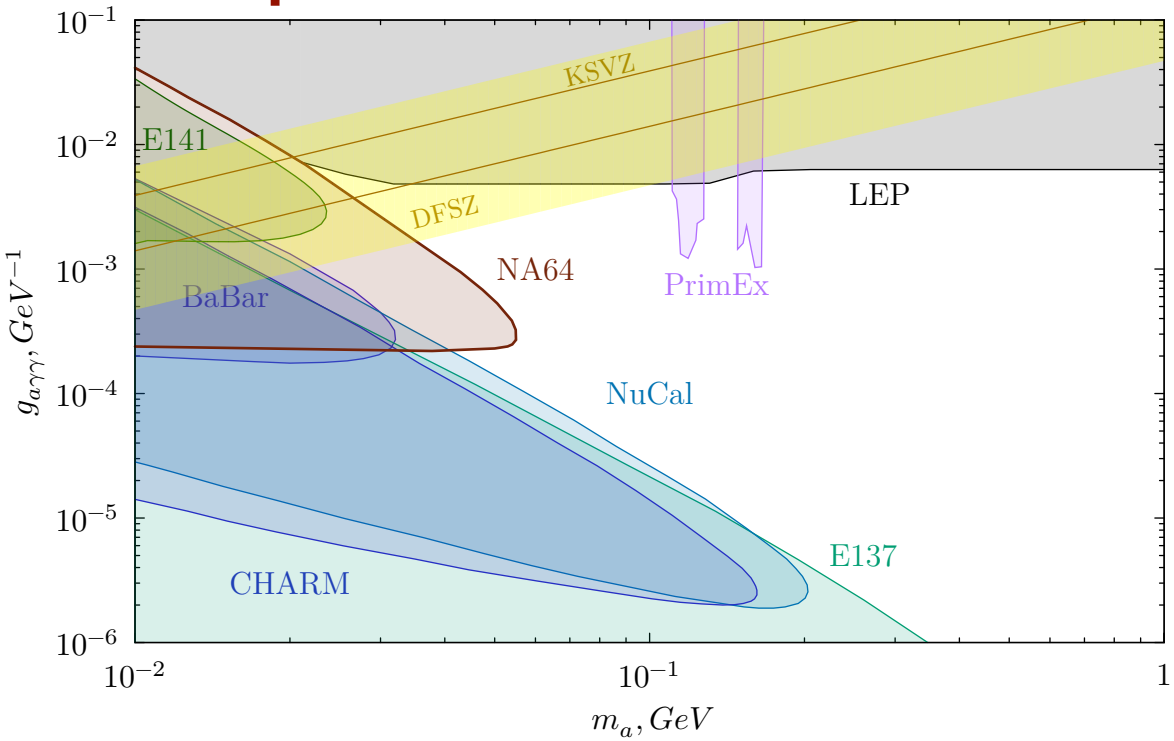



## Production via Primakoff effect

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




## Closing the gap between beam dump and colliders

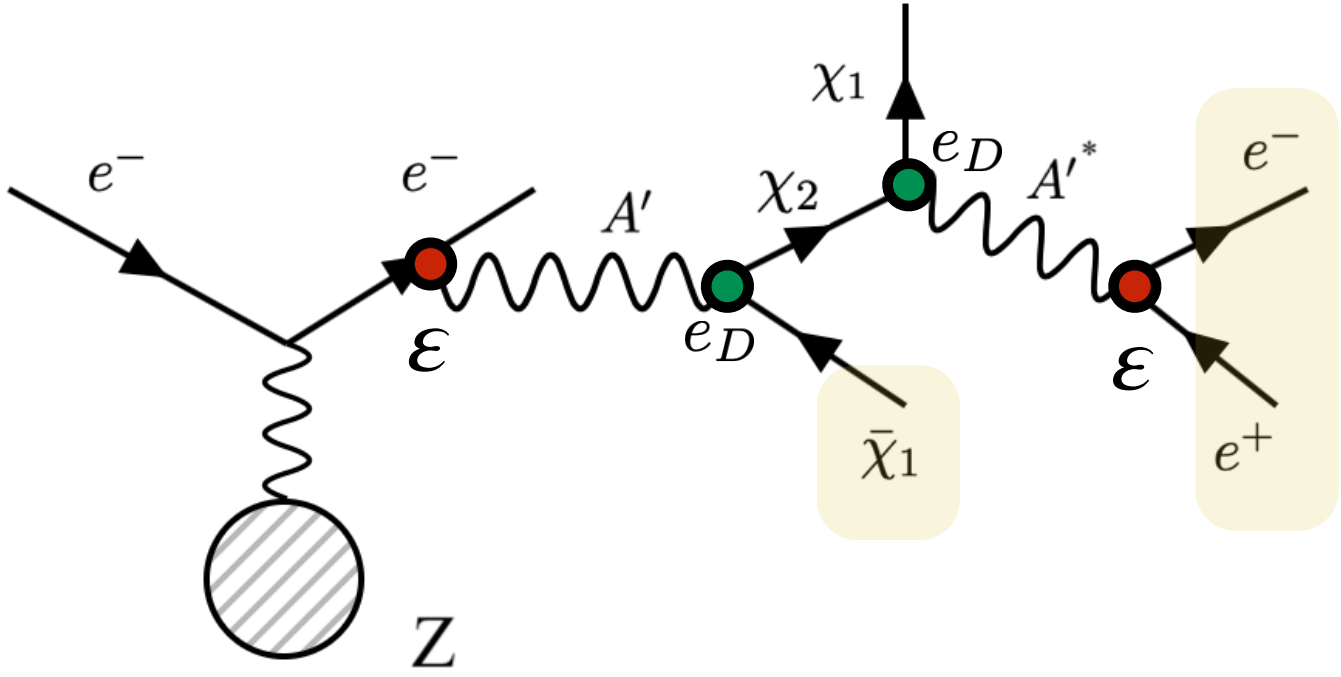



NA64 collaboration PRL 125, 081801 (2020)

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

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

SEMIVISIBLE DECAY MODE




$$m_{A'} \gg m_{\chi 1} \gg m_e$$

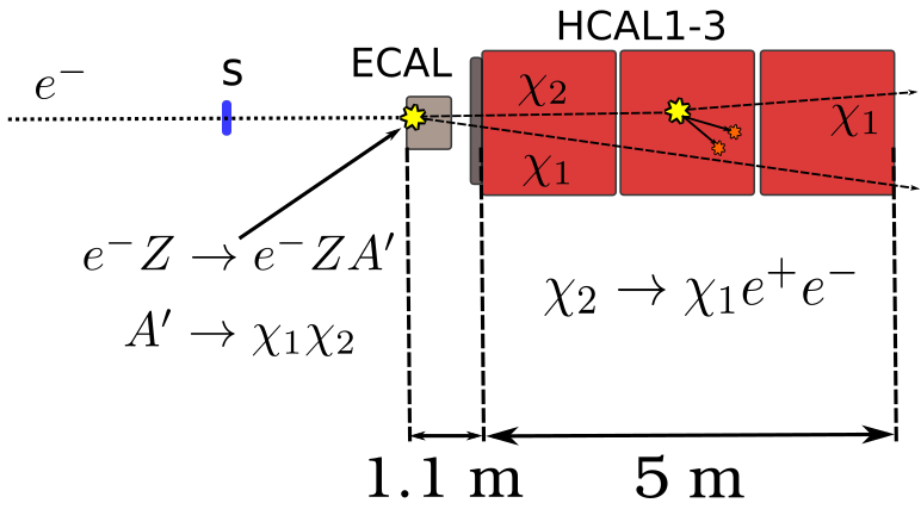
$$\Gamma(\chi_2 \to \chi_1 e^+ e^-) \simeq K \frac{4\epsilon^2 \alpha_{EM} \alpha_D \Delta^5}{15\pi m_{A'}^4}$$

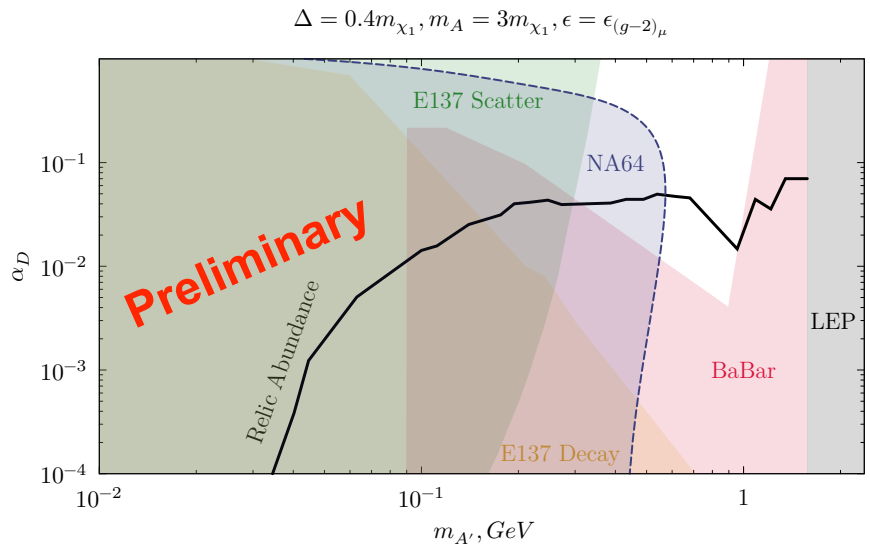
$$\Delta \equiv m_{\chi_2} - m_{\chi_1}$$

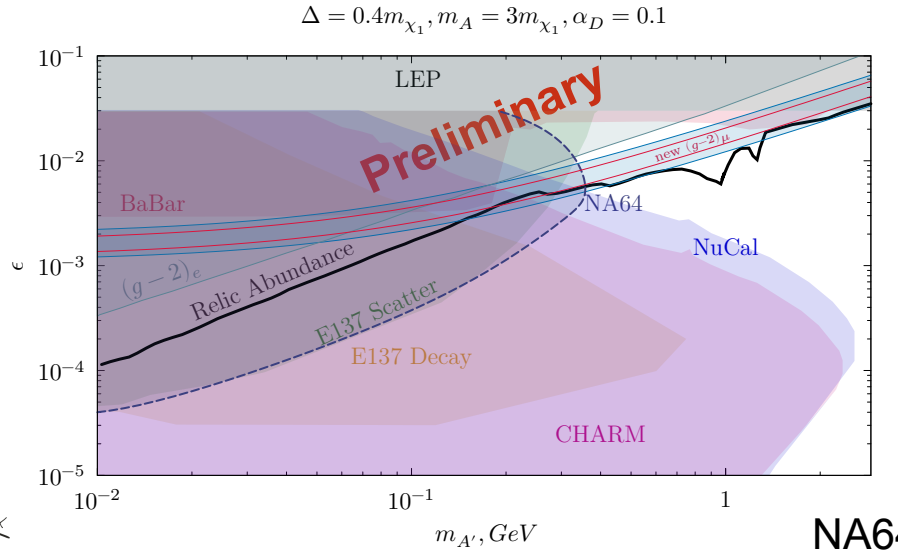
$$K \simeq 0.640 \pm 0.001$$

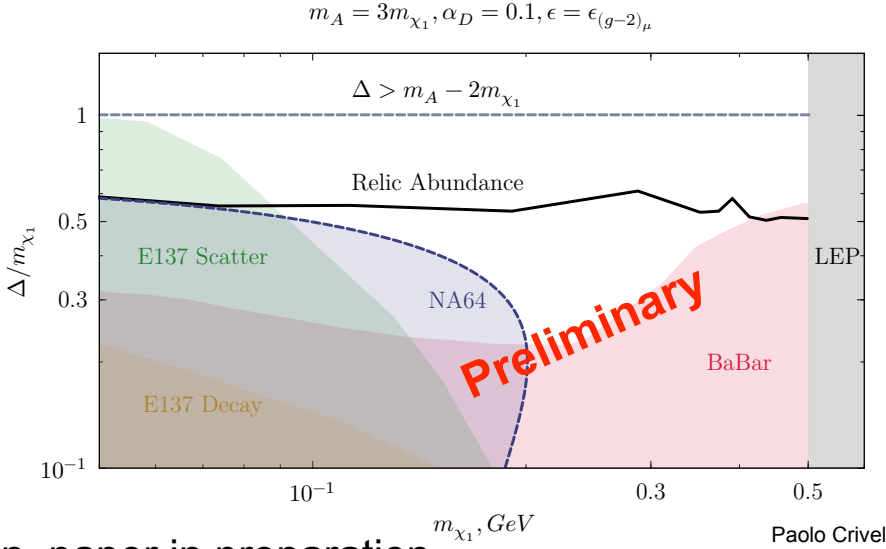
Pair production of
SM particles + Missing energy

# 2) The NA64 search for A' → $\chi_1\chi_2$ , $\chi_2 \rightarrow \chi_1$A', A' → $e^+e^-$



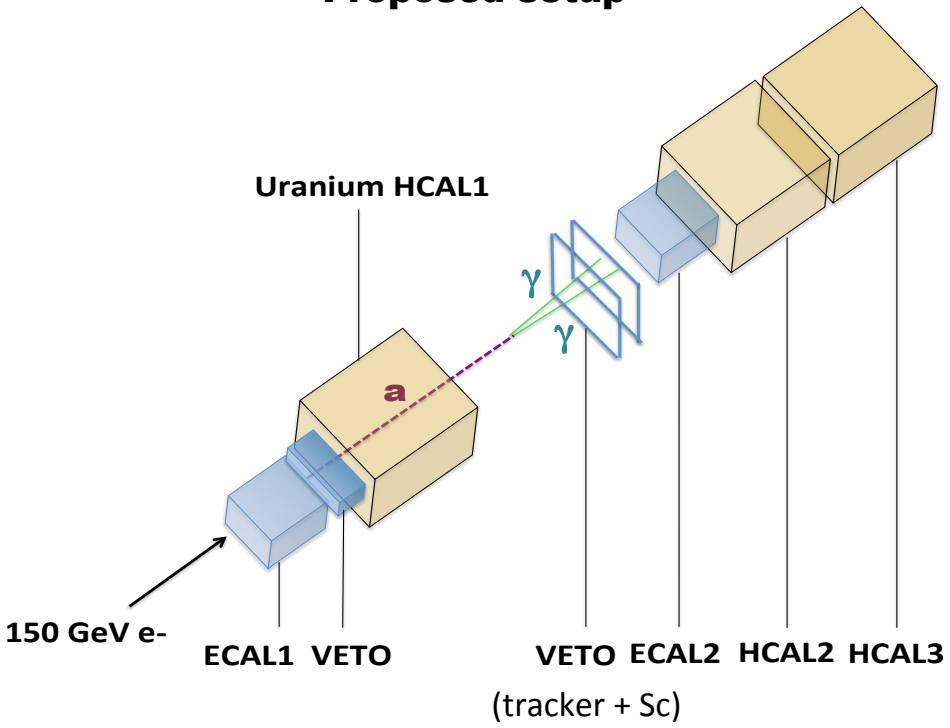




NA64 collaboration, paper in preparation

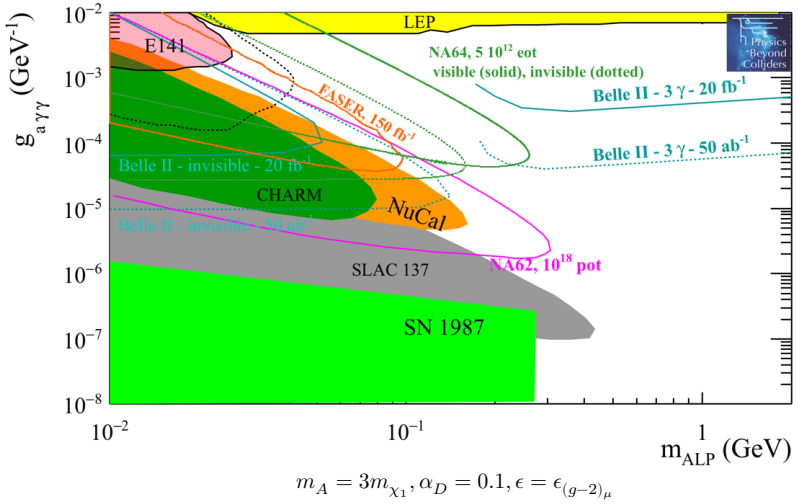
# The NA64 ALP @ semi-visible searches - *future prospects*

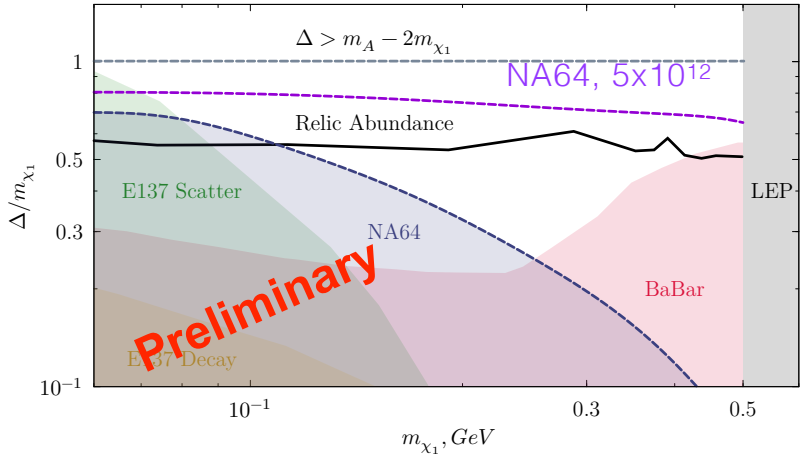
## Feasibility for combining ALPs/semi-visible with A' → invisible searches under study

**Proposed setup**



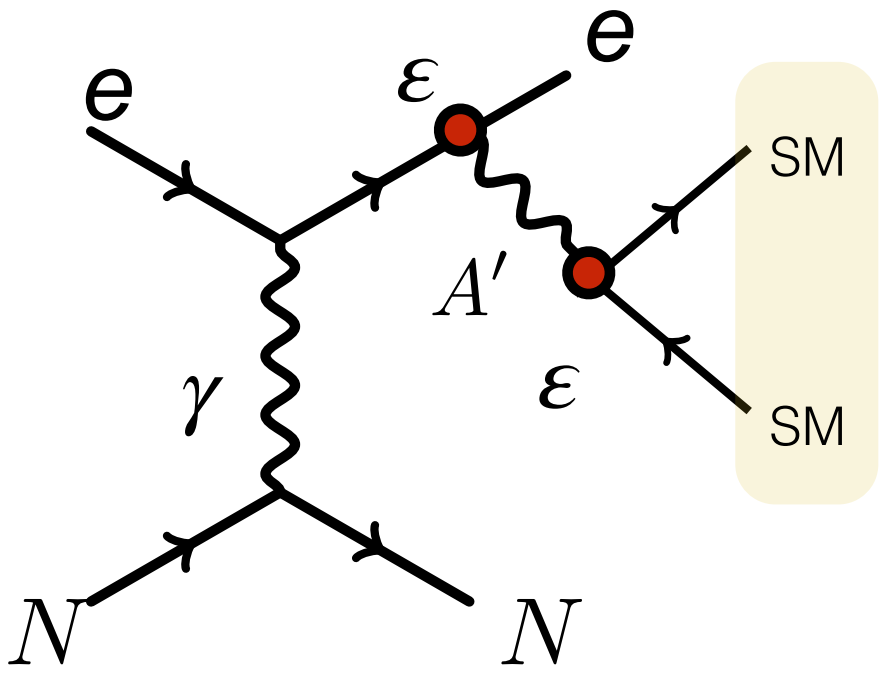

J. Beacham et al., J.Phys. G 47, 010501 (2020).



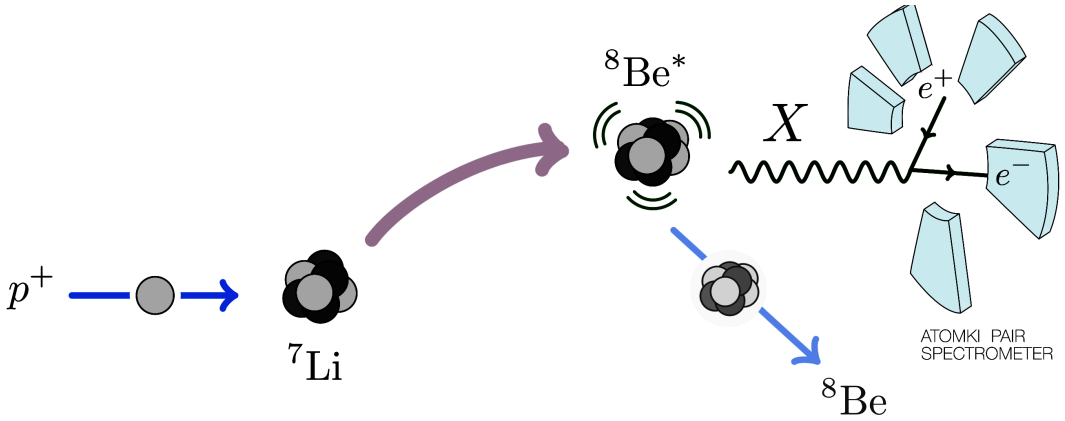
# 4) The NA64 search for A' → e⁺e⁻

VISIBLE DECAY MODE $m'_A < 2m_X$

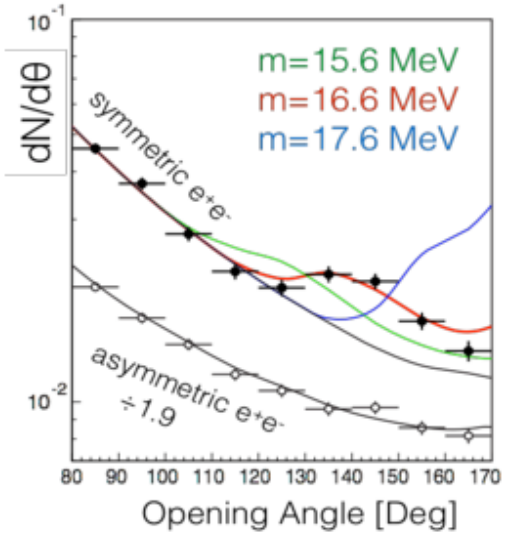


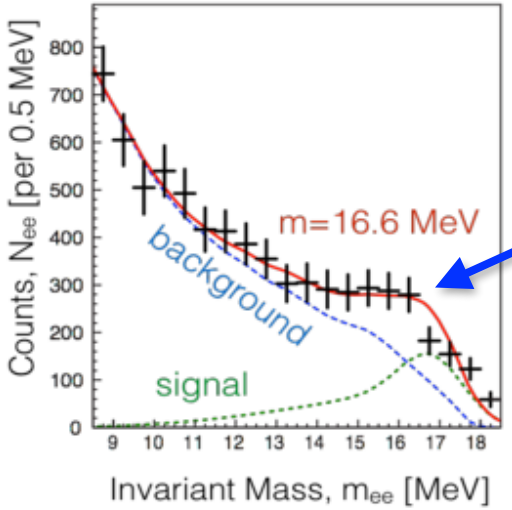

Pair production of SM particles

# $^8$Be anomaly and X boson




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

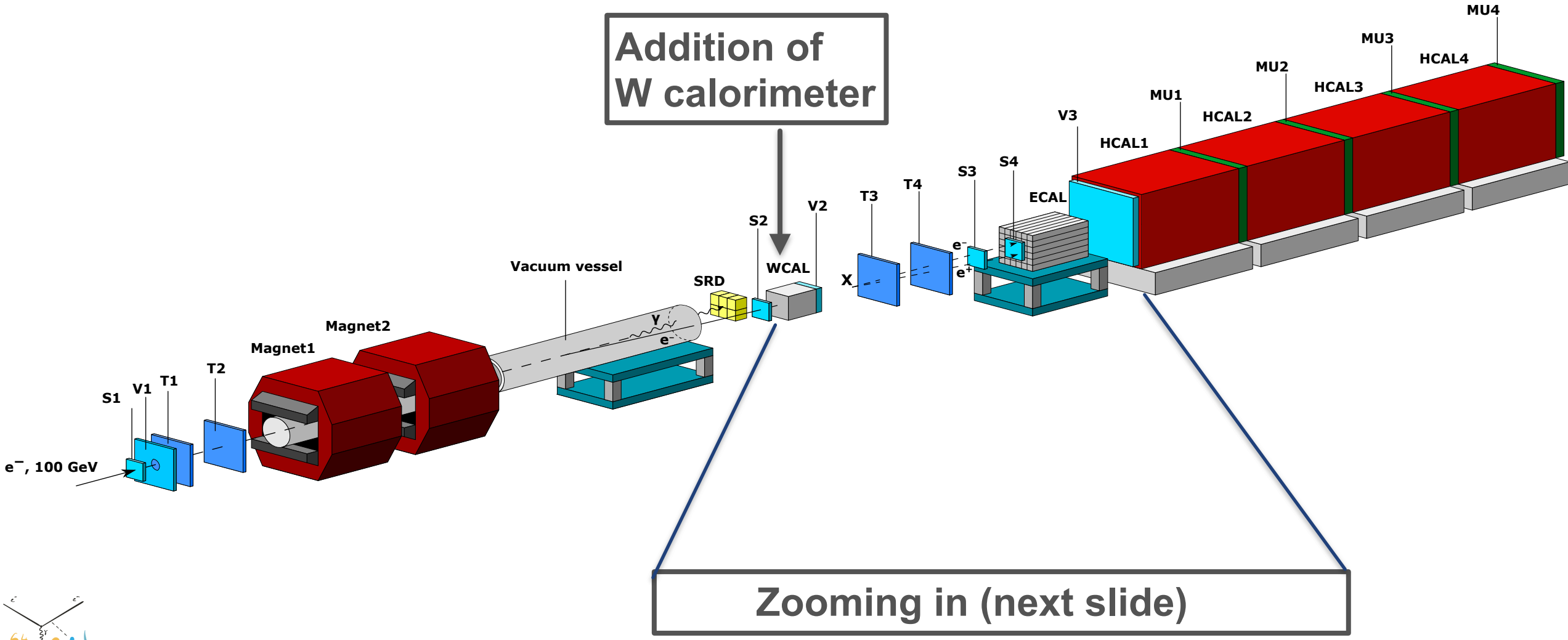



Could be explained by new 'protophobic' gauge boson X with mass around 17 MeV

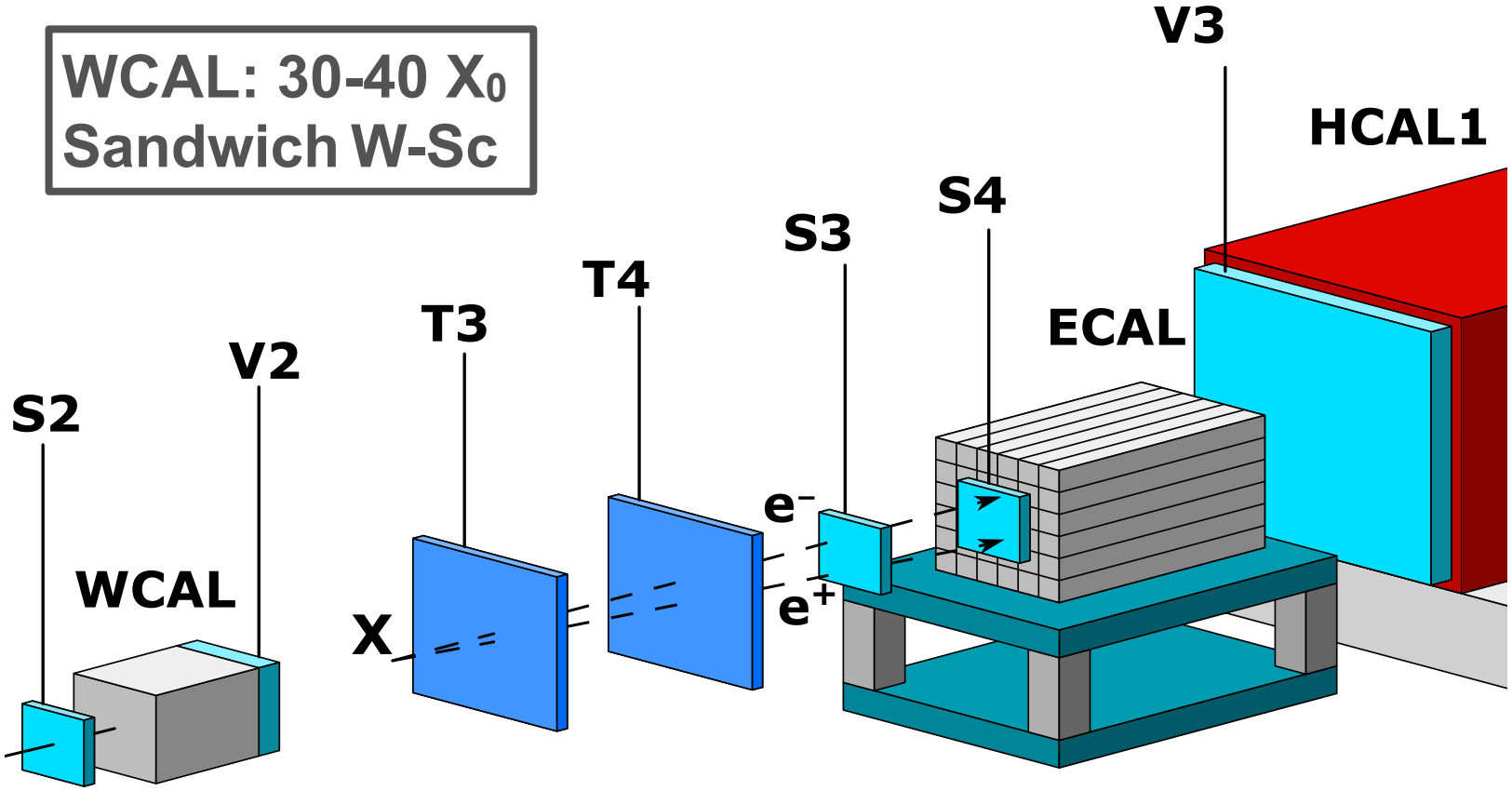
J. L. Feng et al. Phys. Rev. D95, 035017 (2017)

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



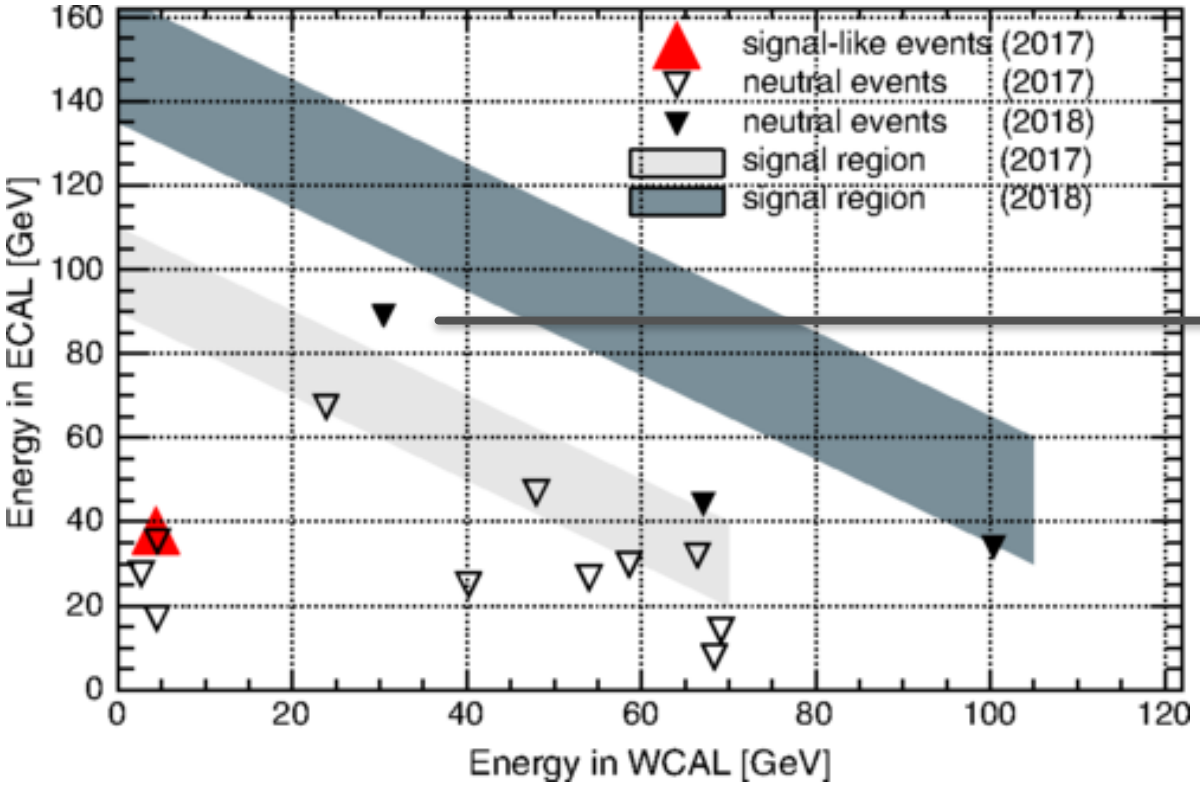
# The NA64 search for A'/*X17*→ $e^+e^-$ - *experimental signature*

WCAL: 30-40 $X_0$
Sandwich W-Sc



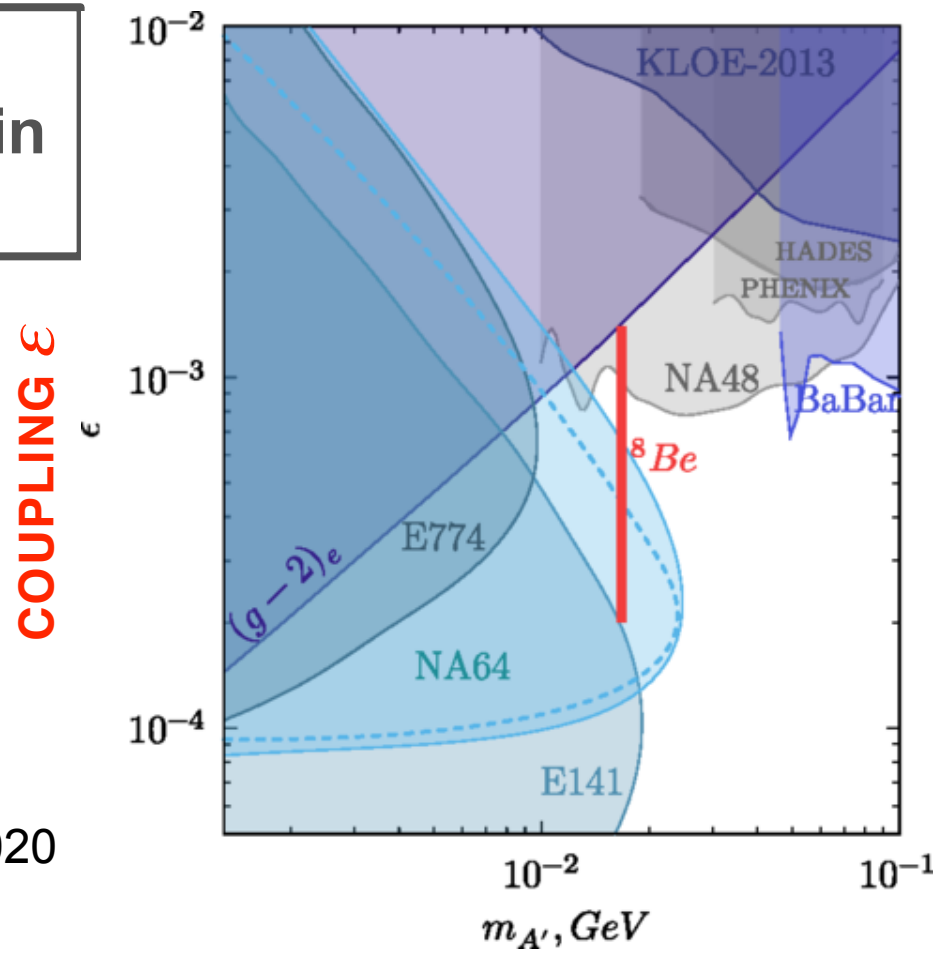

Signature:
1) $E_{WCAL}+E_{ECAL}$ = 100 GeV
2) No activity in $V_{2,3}$ and HCAL
3) Signal in S3, S4
4) e-m shower in ECAL

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




**No signal-like event in signal box**

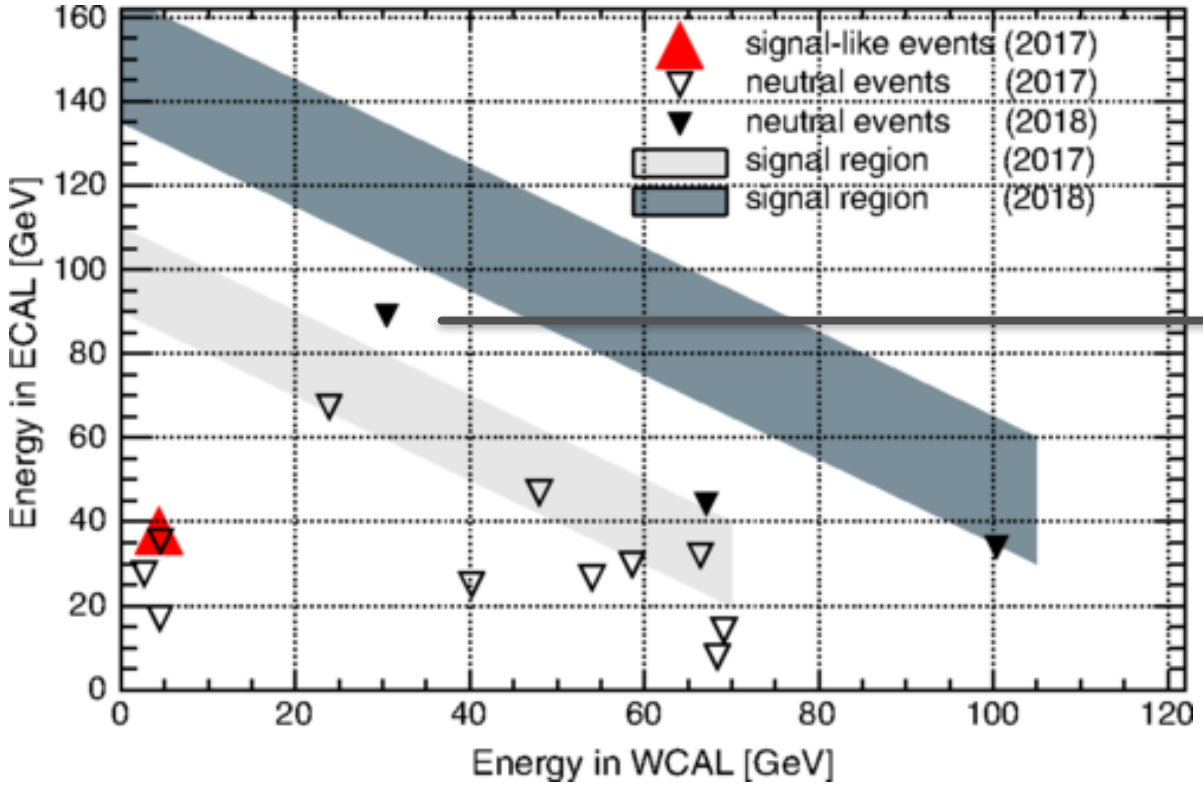
~ $8 \times 10^{10}$ EOT

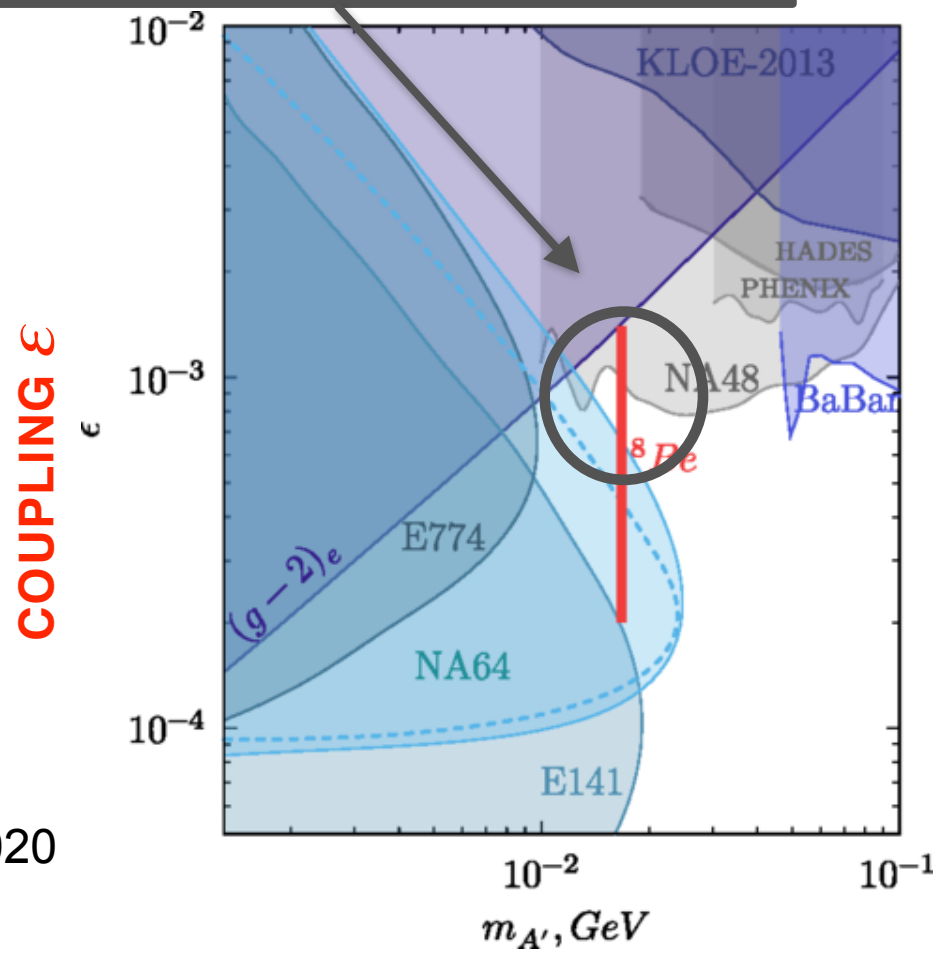



NA64 collaboration, PRL 120, 231802 (2018), PRD 107, 071101 (R) 2020

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

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



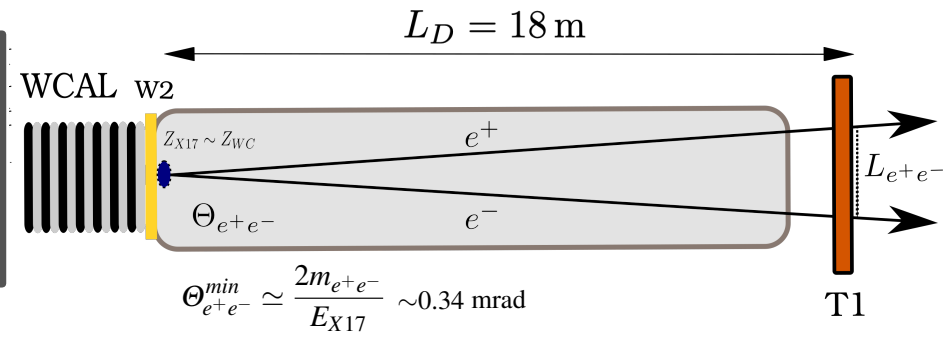



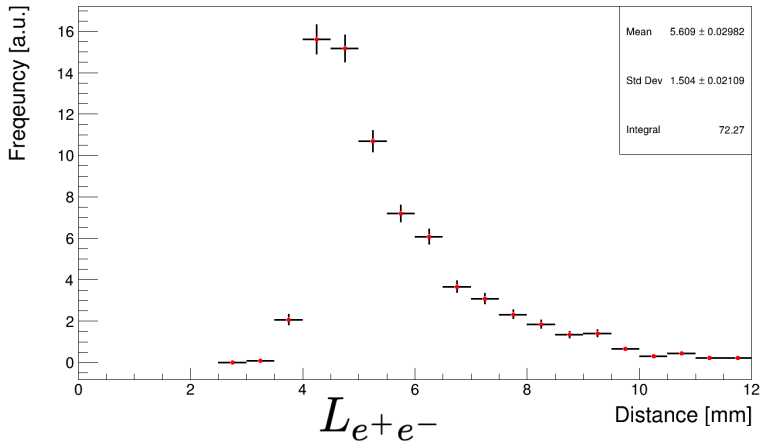

NA64 collaboration, PRL 120, 231802 (2018), PRD 107, 071101 (R) 2020

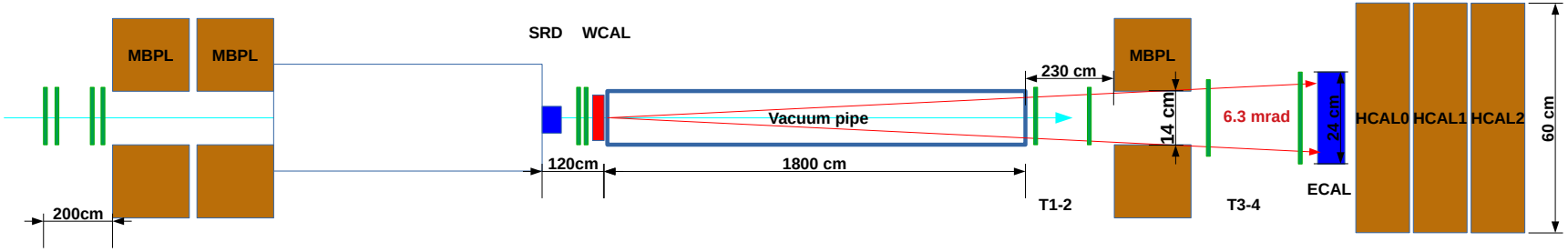
**NEW: pseudoscalar case see NA64 collaboration, arXiv:2104.13342**

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

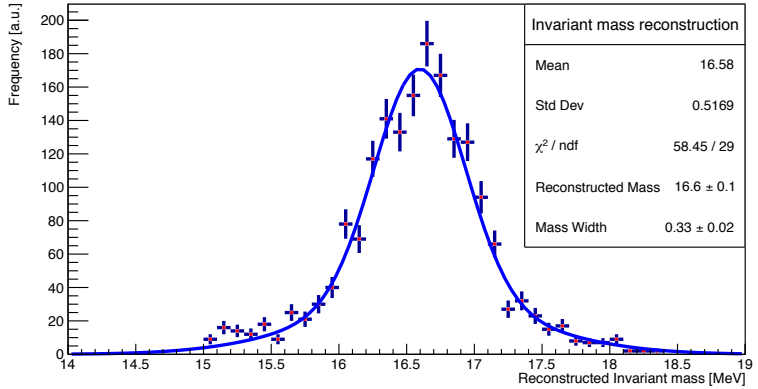
**Optimization of WCAL: 20% shorter keeping 30$X_0$**




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




**Invariant mass reconstruction: Spectrometer + angle measurement**

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

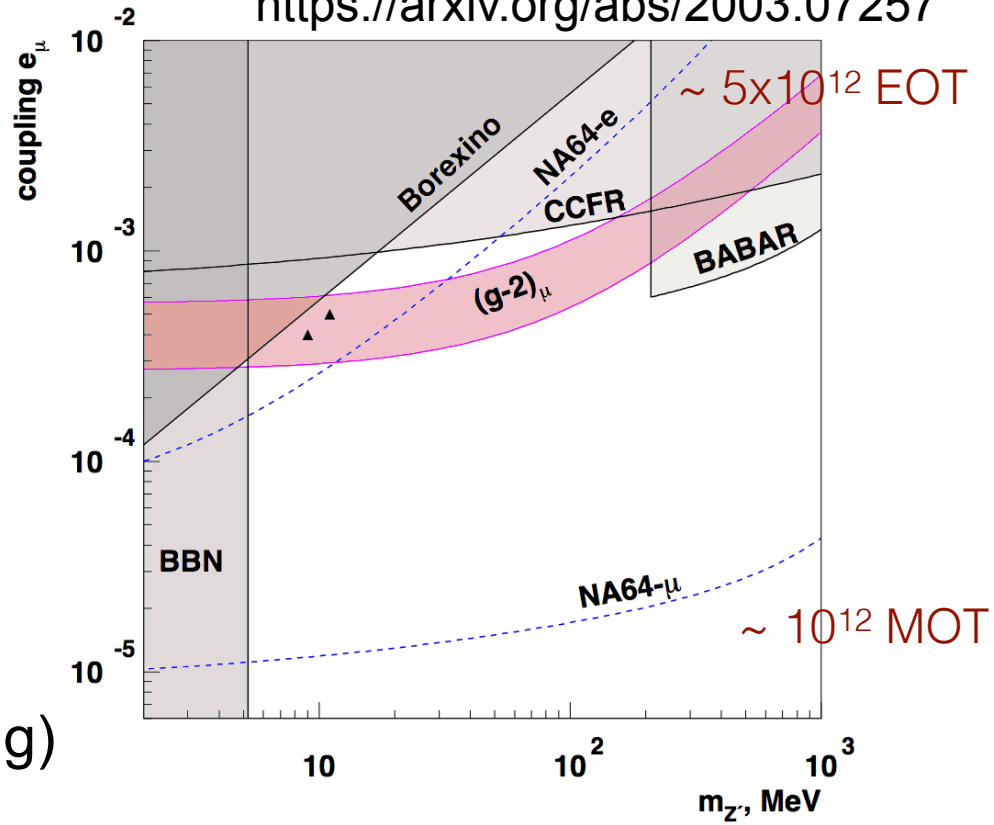
# 5) NA64 in muon mode- NA64$_\mu$

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.

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

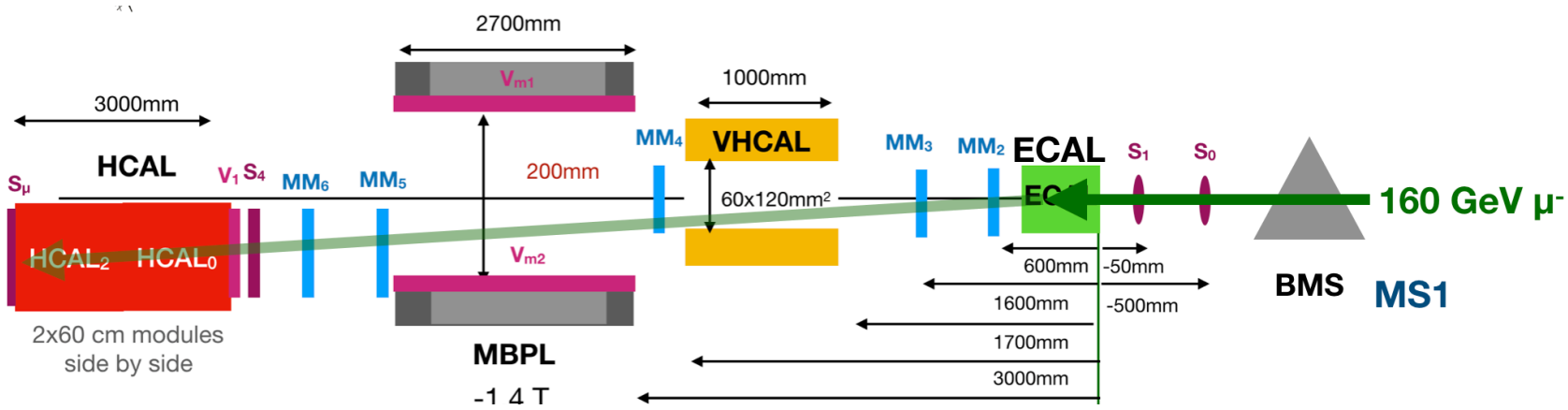
**$L_\mu$-$L_\tau$ models $Z_\mu$ could explain (g-2)$_\mu$**

https://arxiv.org/abs/2003.07257

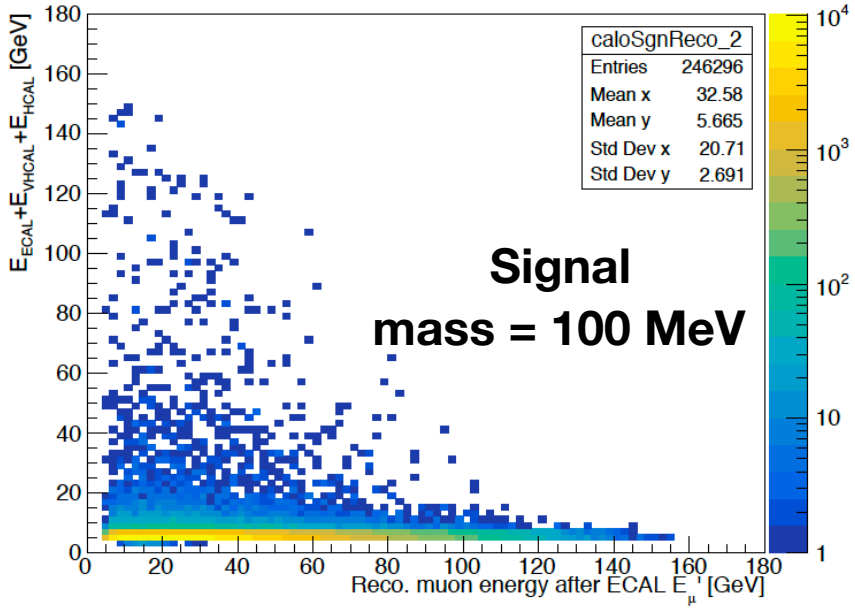


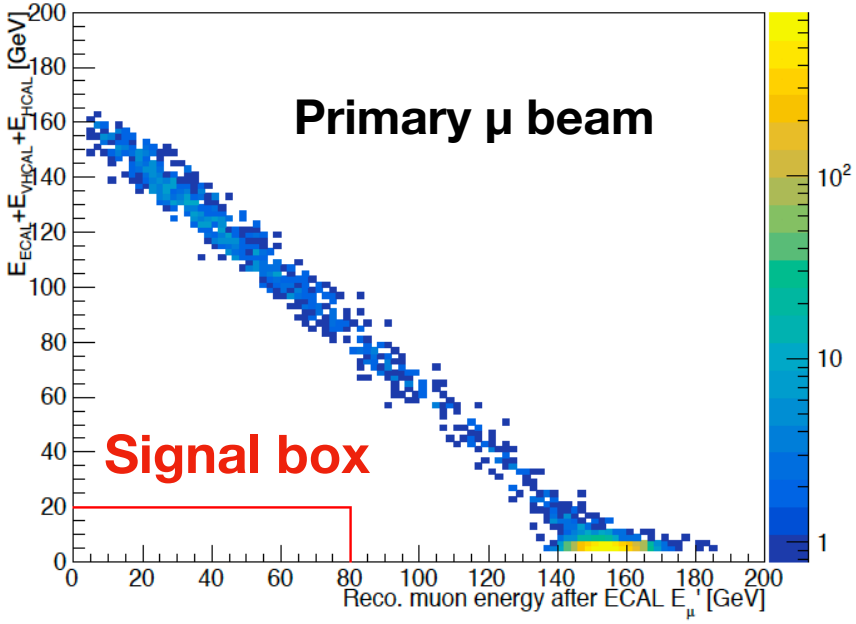

Sensitivity to be update with exact tree level calculations (ongoing)

# NA64 in muon mode- experimental setup (pilot run 2021, 2 weeks)




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

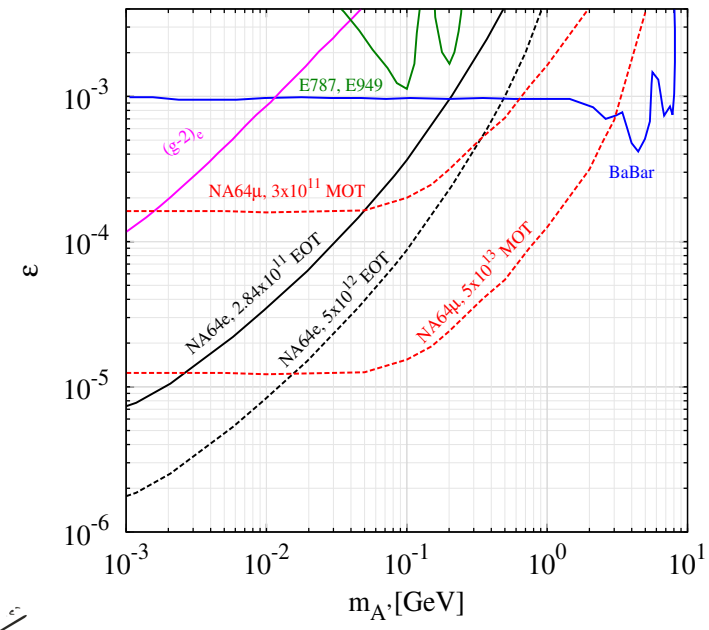


# NA64 in muon mode - Search for LDM

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

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



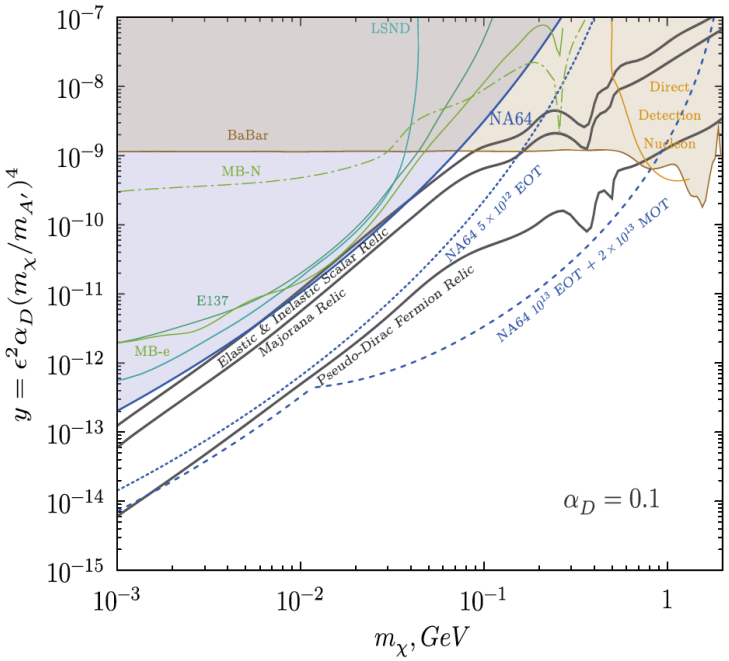

**NA64$_e$**

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

**NA64$_\mu$**

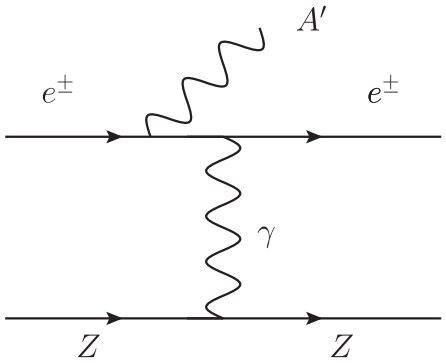
$$N^\mu_{A'} \sim L^\mu \sigma^\mu_{A'}$$
$$L^\mu \simeq 40 X_0$$
$$\sigma^\mu_{A'} \sim \epsilon_\mu^2/m^2_\mu \qquad m_{A'} \lesssim m_\mu$$

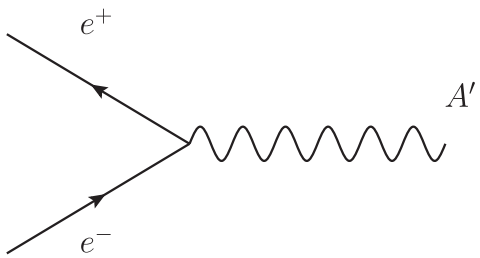
**Combined LDM sensitivity of NA64$_e$ -NA64$_\mu$**

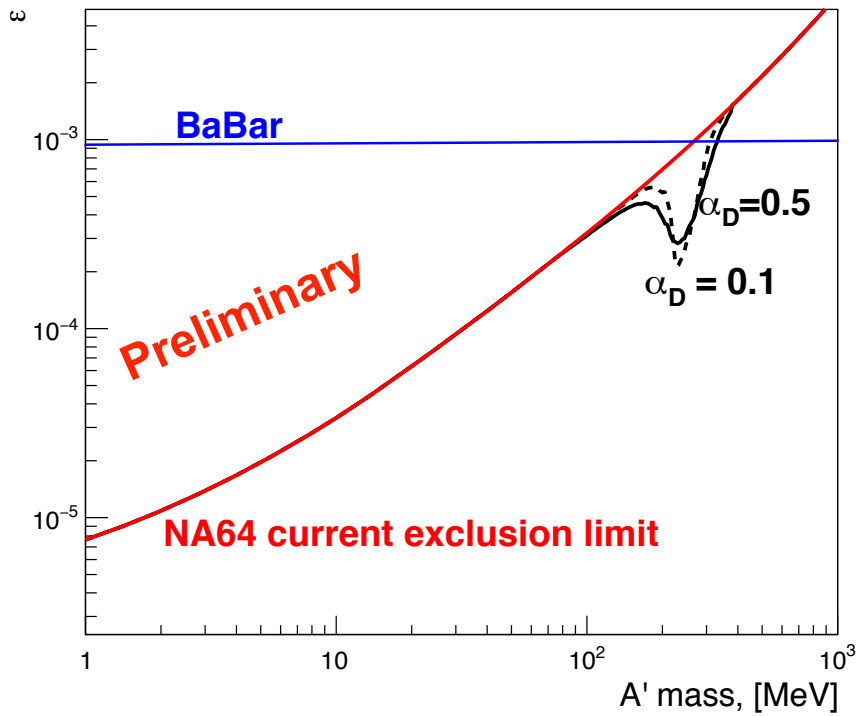


# 6) NA64 electron mode- A' resonant production

A' Bremsstrahlung vs **resonant production**



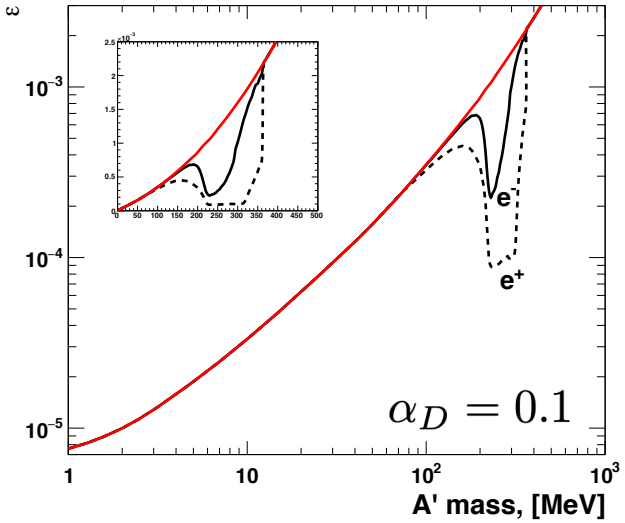

**IDEA:** Exploit secondary positrons in the EM shower induced by the primary impinging electron

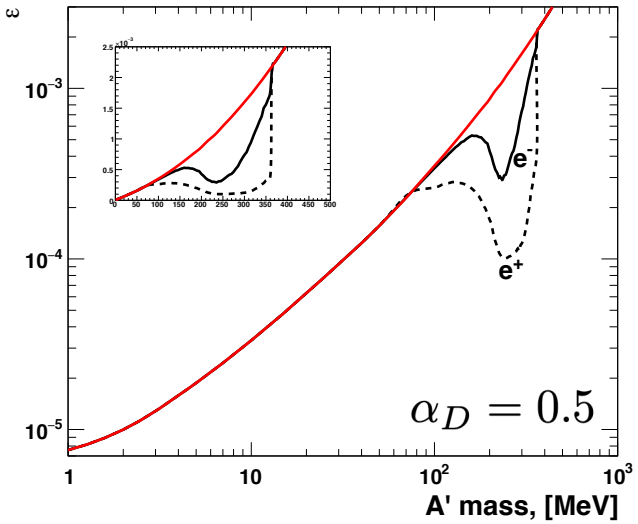
L. Marsicano et al., Phys. Rev. Lett. 121, 041802 (2018)

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

# NA64 in positron mode - A' resonant production

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




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

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

# The NA64 physics prospects

| Process | New Physics |
|---|---|
| $e^-$ **beam** | |
| $A' \to e^+e^-$, and | Dark photon |
| $A' \to invisible$ | |
| $A' \to \chi\overline{\chi}$ | sub-GeV Dark Matter ($\chi$) |
| $X \to e^+e^-$ | new gauge $X$- boson |
| milliQ particles | Dark Sector, charge quantisation |
| $a \to \gamma\gamma, invisible$ | Axion-like particles |
| $\mu^-$ **beam** | |
| $Z_\mu \to \nu\nu$ | gauge $Z_\mu$-boson of $L_\mu - L_\tau$, $< 2m_\mu$ |
| $Z_\mu \to \chi\overline{\chi}$ | $L_\mu - L_\tau$ charged Dark Matter ($\chi$) |
| milliQ | Dark Sector, charge quantisation |
| $a_\mu \to invisible$ | non-universal ALP coupling |
| $\mu - \tau$ conversion | Lepton Flavour Violation |
| $\pi^-$, $K^-$ **beams** | Current limits, PDG'2018 |
| $\pi^0 \to invisible$ | $Br(\pi^0 \to invisible) < 2.7 \times 10^{-7}$ |
| $\eta \to invisible$ | $Br(\eta \to invisible) < 1.0 \times 10^{-4}$ |
| $\eta' \to invisible$ | $Br(\eta' \to invisible) < 5 \times 10^{-4}$ |
| $K_S^0 \to invisible$ | no limits |
| $K_L^0 \to invisible$ | no limits |

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

CERN-PBC-REPORT-2018-007


+ PROGRAM WITH POSITRONS
- Resonant production
- True muonium (see presentation P. Crivelli @ PBC 2021 workshop)

# Summary and Outlook

**DARK SECTORS: very interesting candidate for DM**

**NA64: Active beam dump + missing-energy approach is very powerful**

**2016: A' → $\chi\bar{\chi}$**

- July run: 2.75x$10^9$ EOT: no signal → most of g-2 muon favored region excluded (PRL118, 011802 (2017)) .
- October run : 4x$10^{10}$ EOT: no signal → new constraints on TLDM (PRD97, 072002 (2018)).

**2017-2018:** - **A' → $\chi\bar{\chi}$:** 3x$10^{11}$ EOT collected PRL 123, 121801 (2019)

**- *X*→ $e^+e^-$** : 5x$10^{10}$EOT@100 GeV PRL120, 231802 (2018), 3x$10^{10}$ EOT@150 GeV PRD (2020)

**This August NA64 will resume data taking**

**GOAL to fully exploit potential to reach LTDM (>5x$10^{12}$ EOT for *A'* → $\chi\bar{\chi}$ and explore remaining parameter space *X*→ $e^+e^-$), Pilot run in 2021 at M2 (muon mode)**

**→ Proposed searches in NA64 with leptonic and hadronic beams: unique sensitivities highly complementary to similar projects.**