Light dark matter searches at NA64 and NA64++

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on behalf of the NA64 collaboration

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Light Dark Matter Motivation

$$L = L_{SM} - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + m^2_{A'} A'_{\mu} A'^{\mu} + \frac{\epsilon}{2} F_{\mu\nu} F'^{\mu\nu}$$

Standard Model Lagrangian

Additional U(1) symmetry describing the new force carried by a massive vector boson, ***the Dark Photon A'***

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

$\epsilon \sim 10^{-8} - 10^{-2}$

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

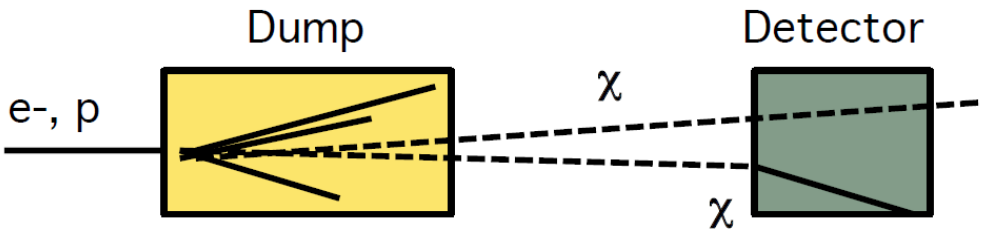
$\epsilon \sim 10^{-8} - 10^{-2}$

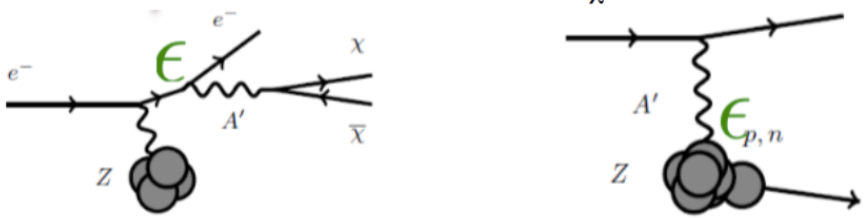
- Can be "mass"-produced in Bremsstrahlung events:
  ➔ Fixed-target experiments with high-intensity charged beams

Fixed-target experiments

Beam dump:

BDX, NA62D, SeaQuest,...

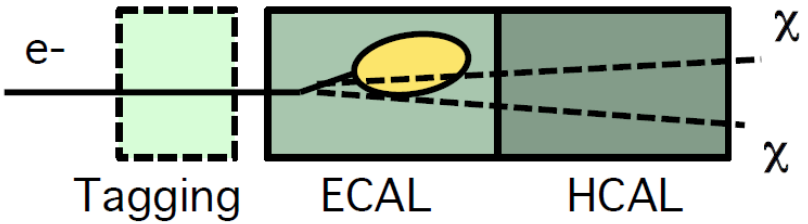


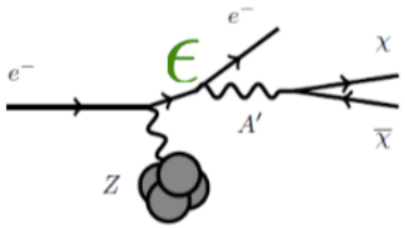


$n_S \sim \alpha_D \varepsilon^4 n_{pot}$

Missing energy:

NA64e (active dump)

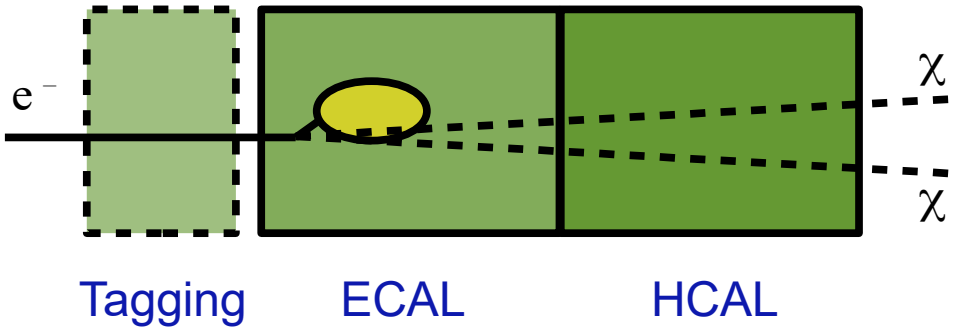


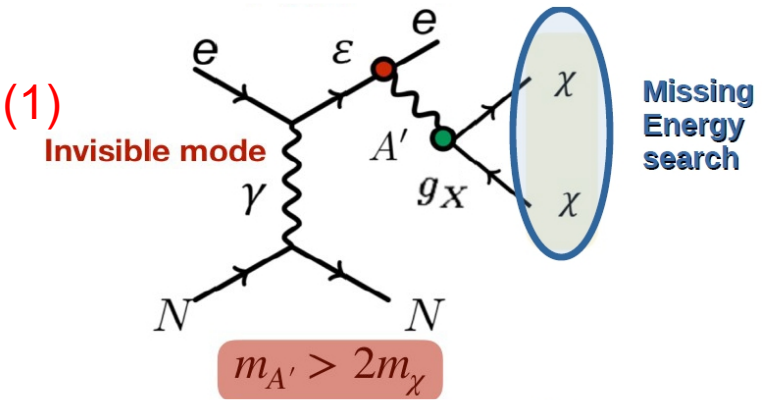


$n_S \sim \varepsilon^2 n_{eot}$

- Active dump/missing energy approach does not rely on "second" DS-SM interaction
- Independent of A'-χ coupling α_D

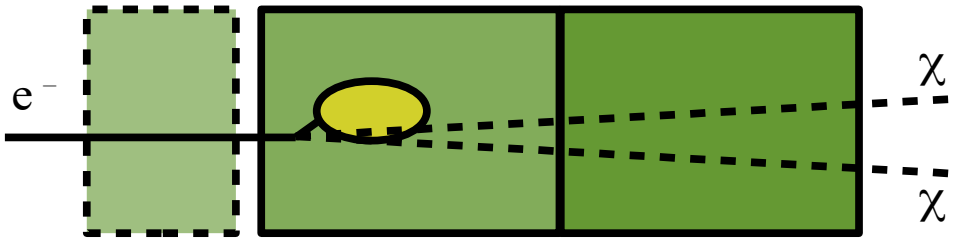
Fixed-target experiments

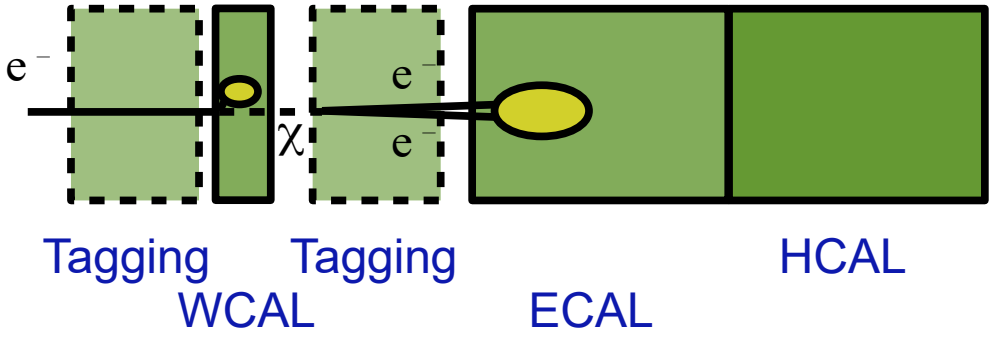


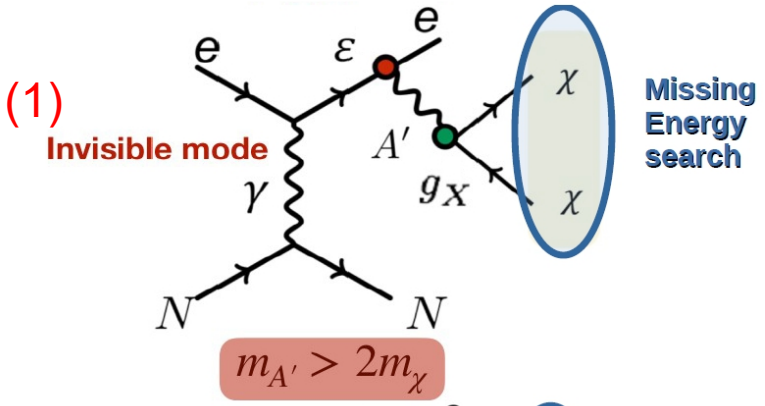


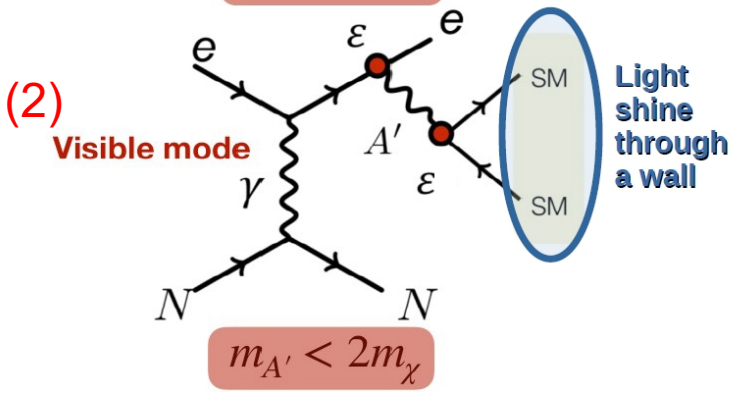
1) NA64 started with the so-called invisible mode
   - ➔ Pure missing energy experiment (2016-2018)
   - ➔ Invisible A' for $(g\text{-}2)_\mu$ or mediator of LDM production

Fixed-target experiments



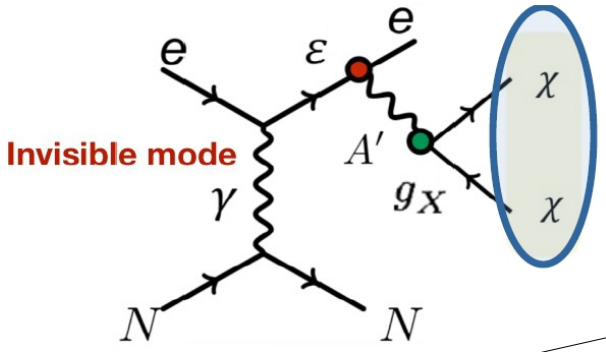






1) NA64 started with the so called invisible mode
   - ➔ Pure missing energy experiment (2016-2018)
   - ➔ Invisible A' for $(g\text{-}2)_\mu$ or mediator of LDM production
2) Shifting the HCAL, adding dump WCAL enabled the visible mode
   - ➔ Allowing general search for DS bosons (2017-2018)
   - ➔ New X(17) boson from Be anomaly, $A' \rightarrow e^+e^-$-decays

The NA64 detector: invisible mode



S.Andreas et al., arXiv: 1312.3309
S.G., PRD(2014)

Signature:

- Incoming 100 GeV e^--track
- <50 GeV shower in ECAL
- No energy in Veto or HCAL

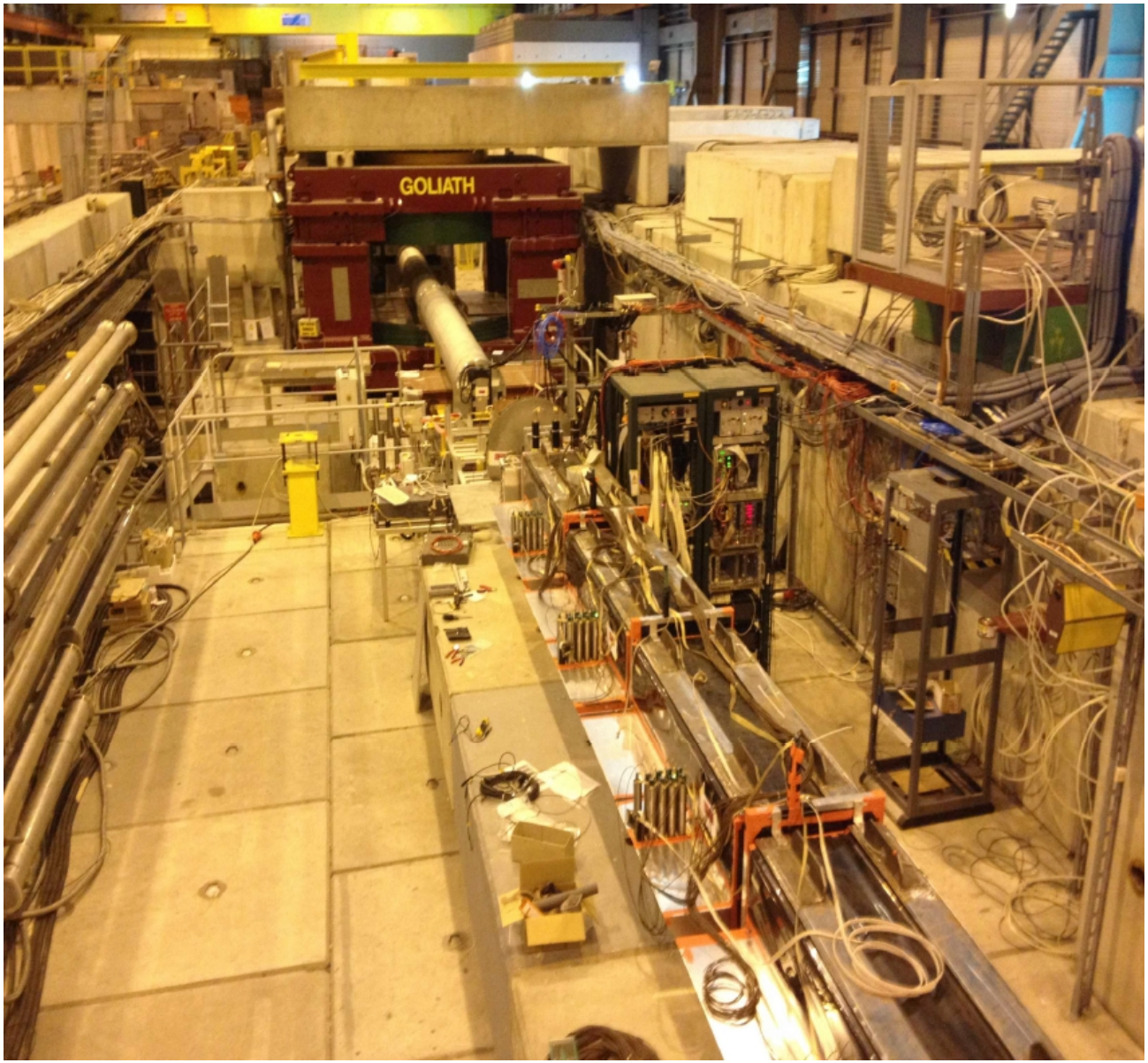
Main components:

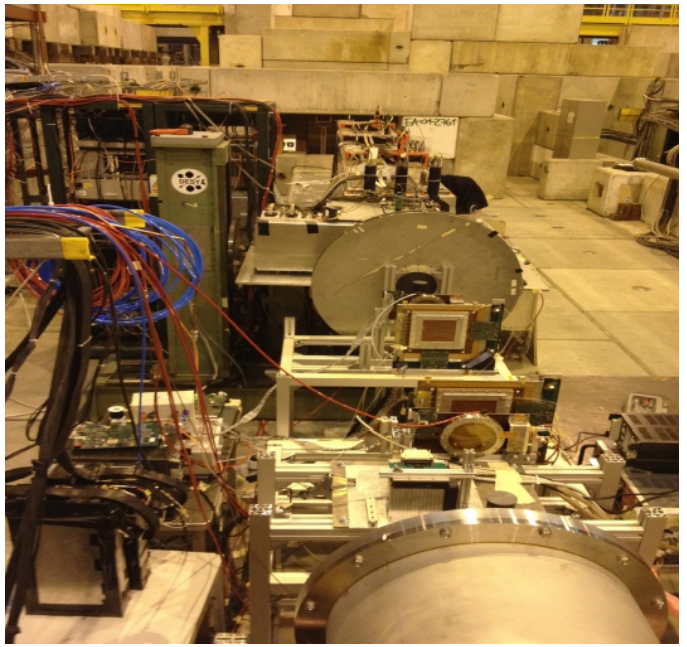
- Clean 100 GeV e^--beam
- e^- tagging system: tracker + SRD
- Fully hermetic ECAL+HCAL

Background:

- e^- from in-flight decays (μ, π, K)
- e^- from beamline interactions
- Energy leak from calorimeters

The NA64 detector at CERN SPS (H4 EHN1)





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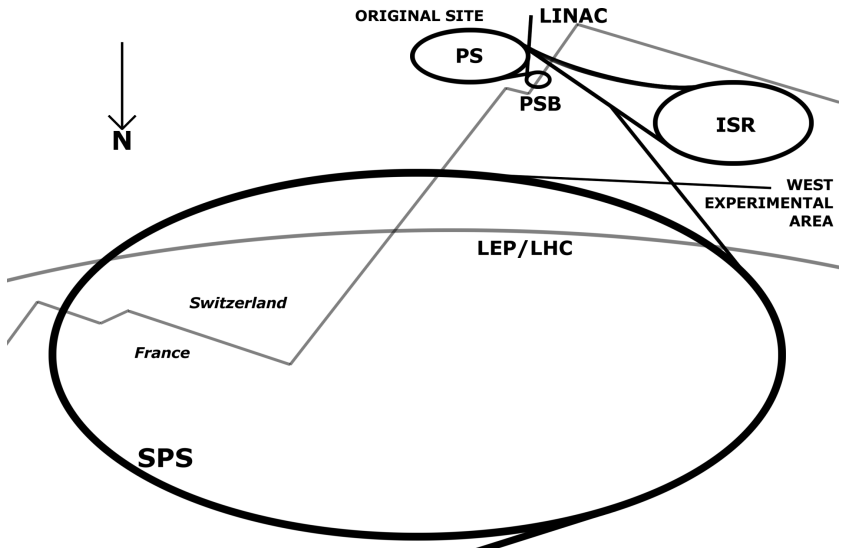
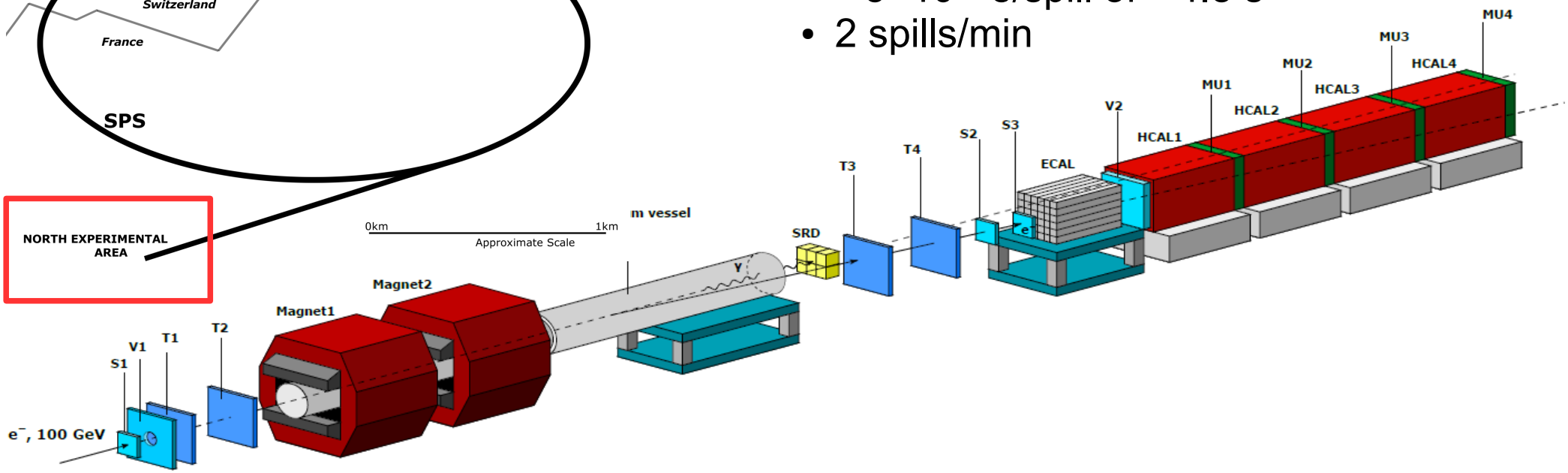


- CERN SPS H4 Beam in NA
- 450 GeV proton + beryllium target
- 100 GeV electron beam
- ~5×10⁶ e/spill of ~4.8 s
- 2 spills/min



Characteristics of the beam delivered by SPS:

- Momentum spread of ~1%
- Low energy tail of <1%
- Hadron contamination of ~1% π, <0.1% K, μ

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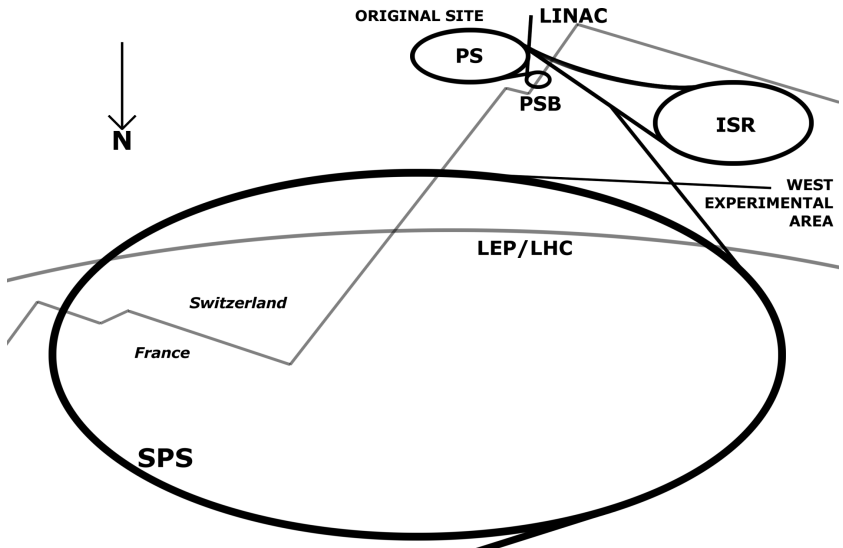

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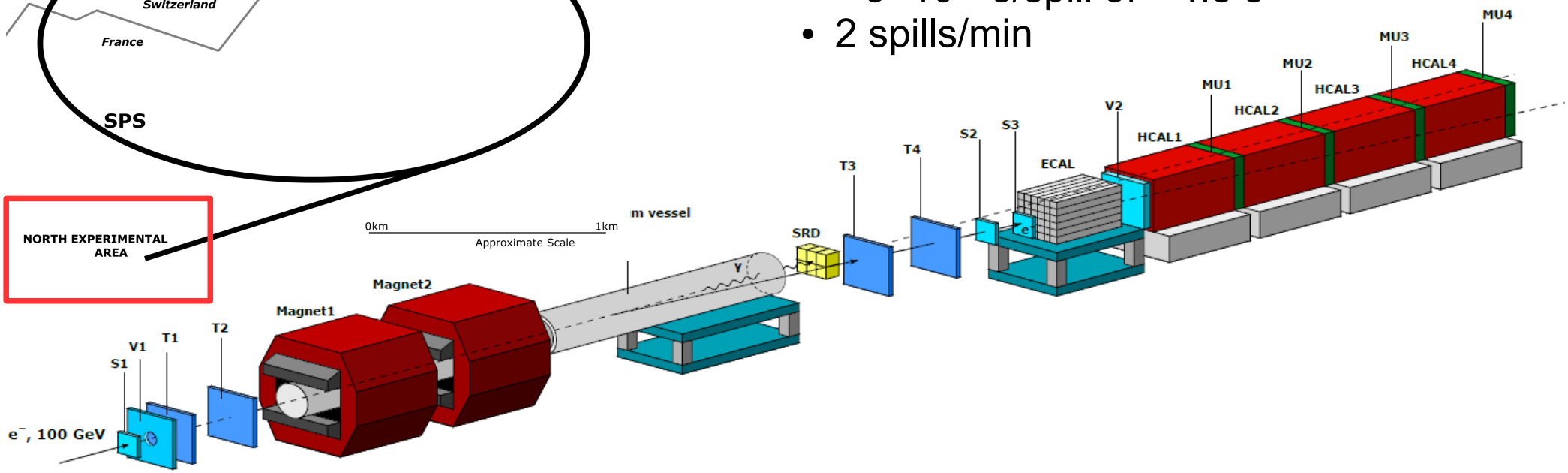

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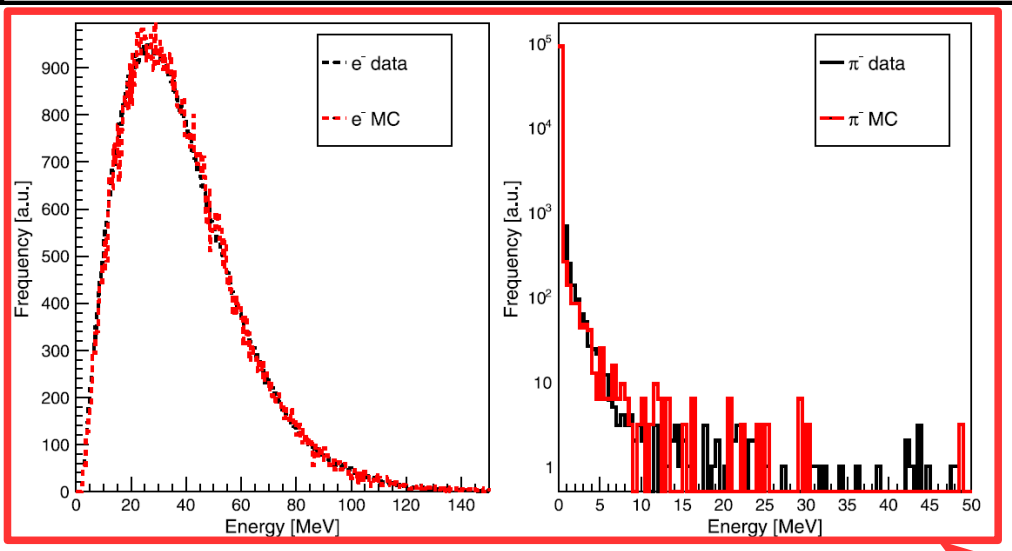
→ Sophisticated system for 100 GeV electron tagging

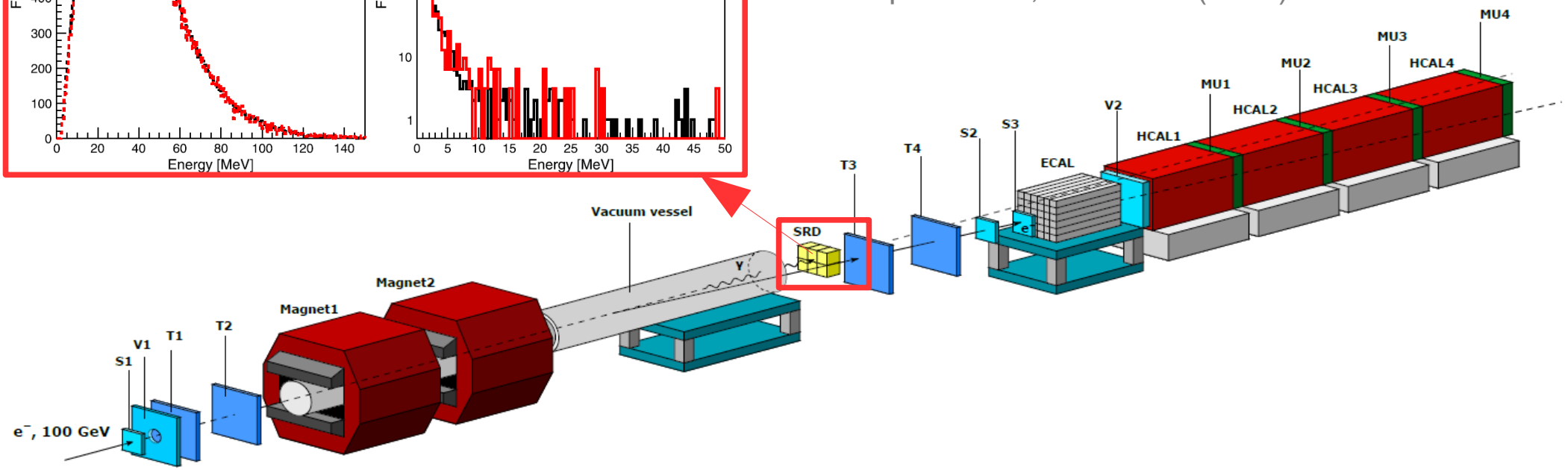
Electron tagging and hadron rejection



SRD: Synchrotron radiation detector

- ~ factor 10^5 hadron suppression

arXiV:1703.05993
E. Depero et al., NIMA 866 (2017) 196-201



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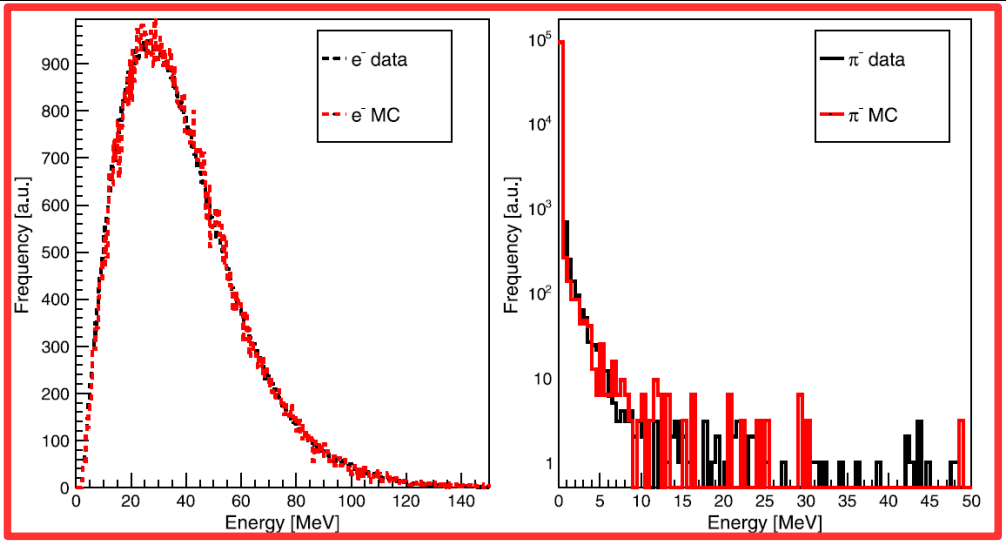

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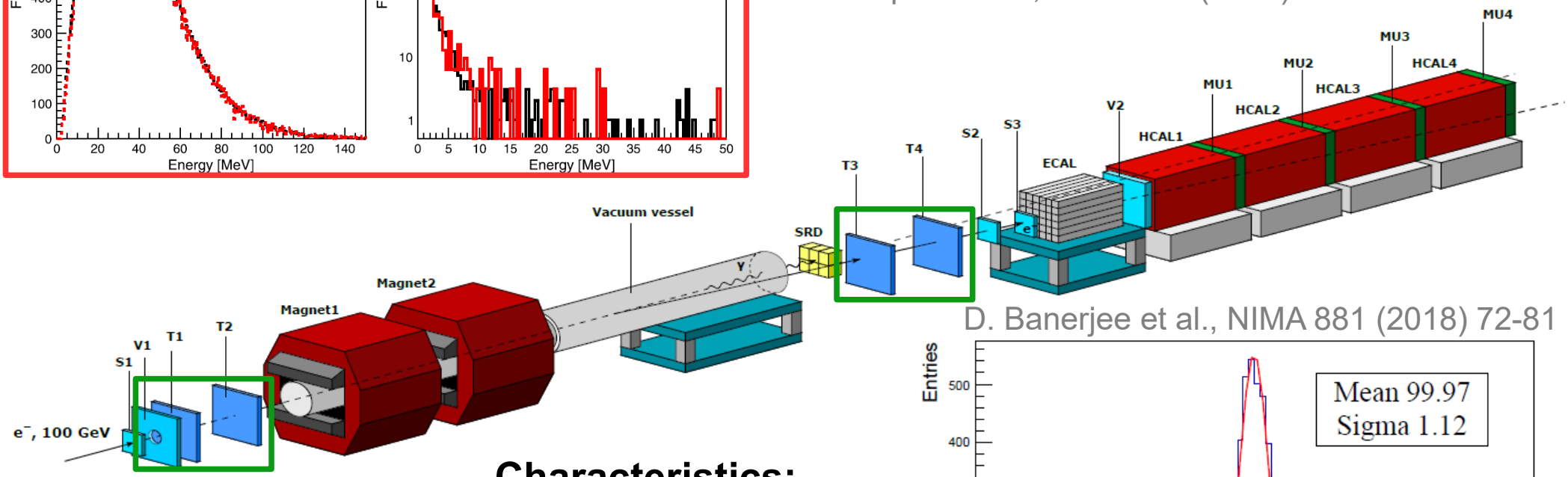
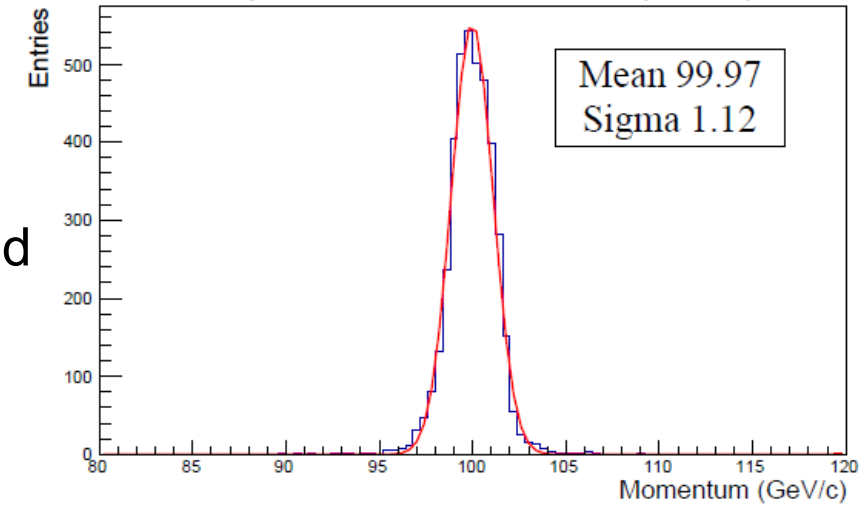


D. Banerjee et al., NIMA 881 (2018) 72-81



Tracking detectors:

- 8 UV multiplexed Micromegas
- 4 XY GEM stations

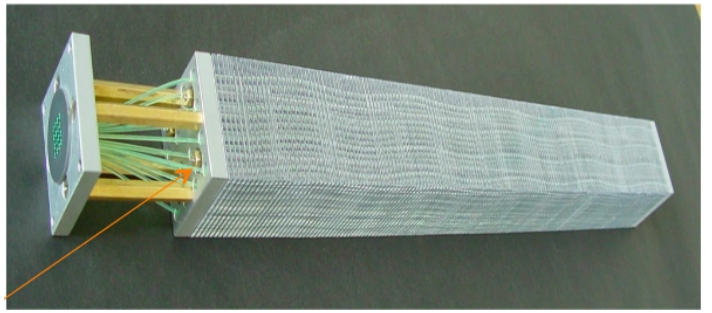
Characteristics:

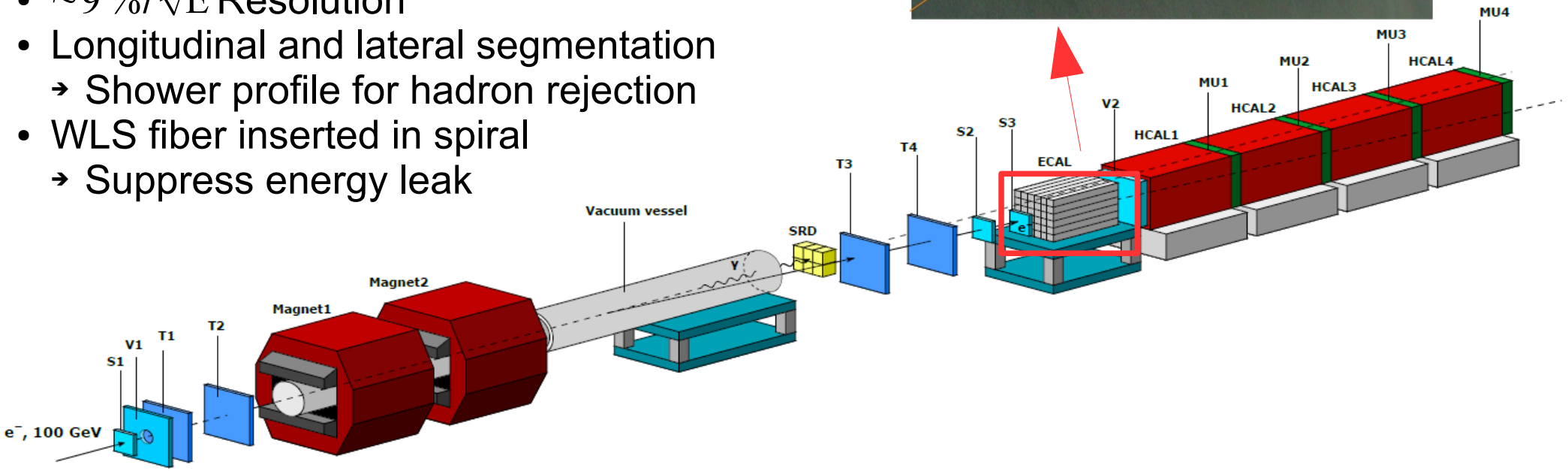
- 7.2 Tm integrated field
- Capable of coping with high intensity
- 1% momentum resolution

ECAL active dump

ECAL: Lead scintillator sandwich calorimeter

- High hermeticity ($40X_0$)
  - ➔ 314 layers (1.5+1.5mm)
- $\sim 9\,\%/\sqrt{E}$ Resolution
- Longitudinal and lateral segmentation
  - ➔ Shower profile for hadron rejection
- WLS fiber inserted in spiral
  - ➔ Suppress energy leak





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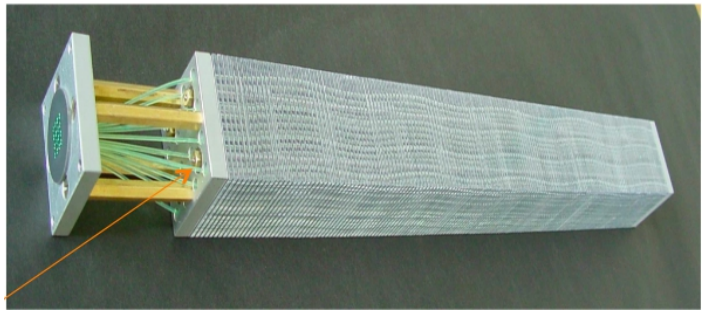

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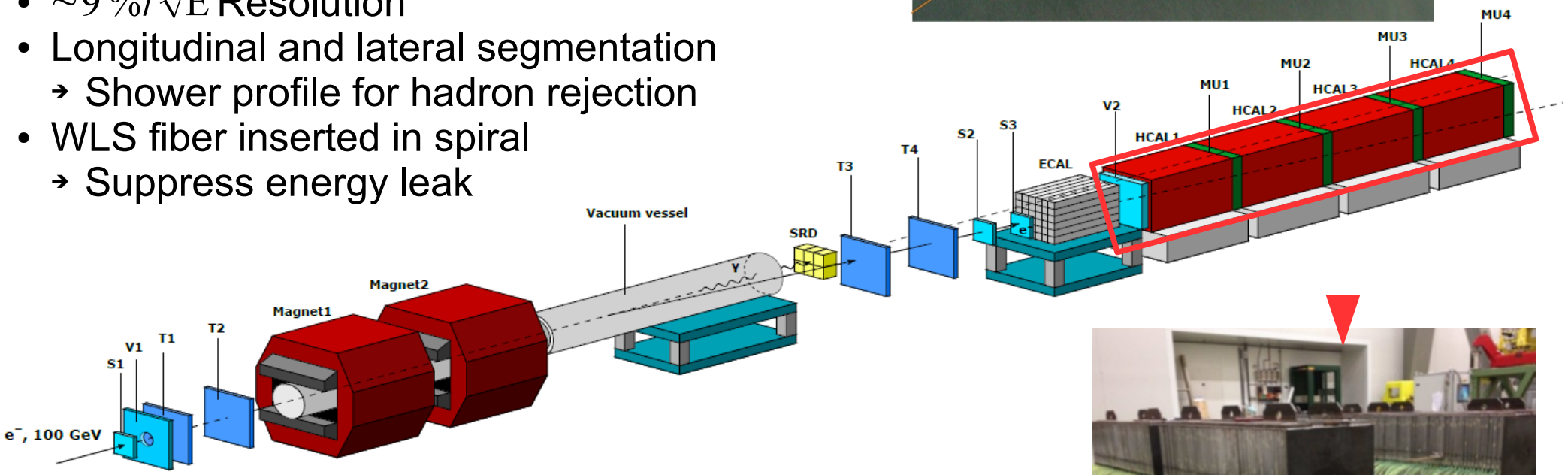
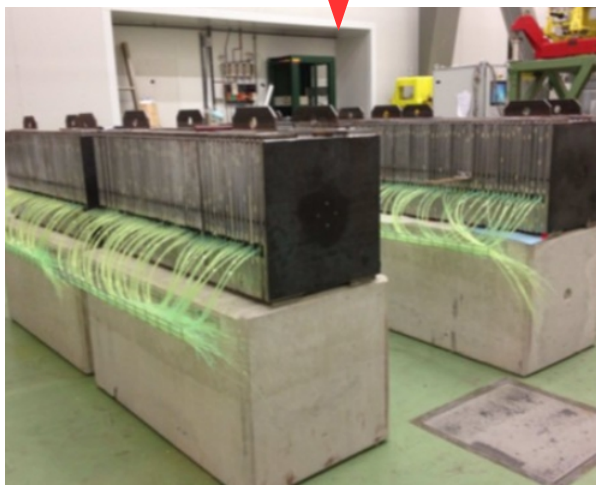
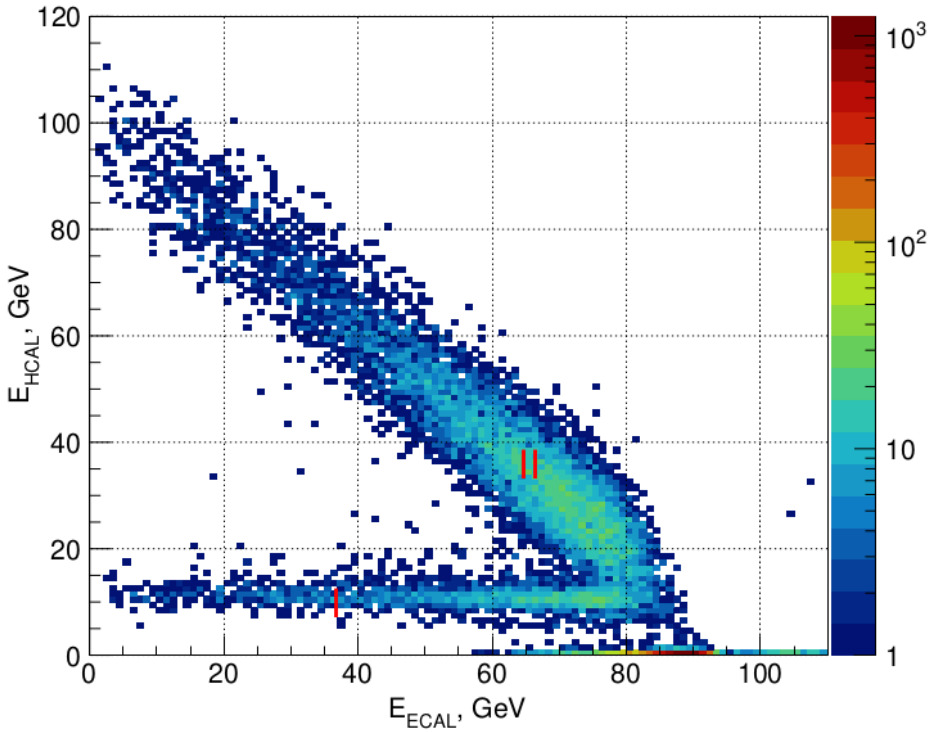


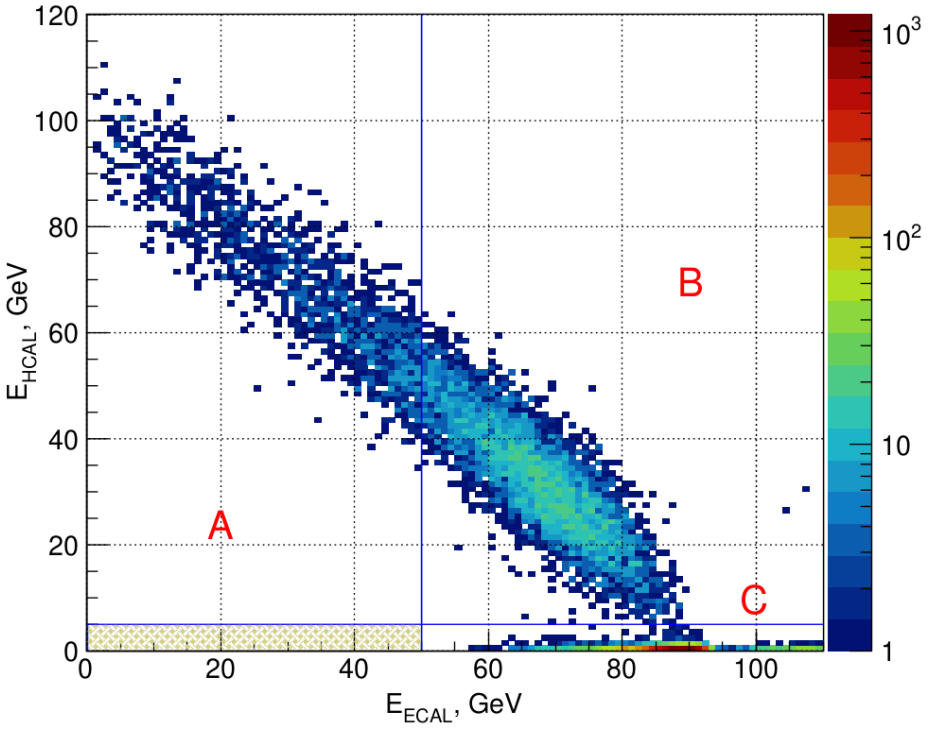


HCAL: Iron scintillator sandwich calorimeter

- High hermeticity (4λ/module)
- $\sim 50\,\%/\sqrt{E}$ Resolution
- Lateral segmentation: 3x3 matrix, $19.4 \times 19.2 \times 150\,\mathrm{cm}^3$

Event selection

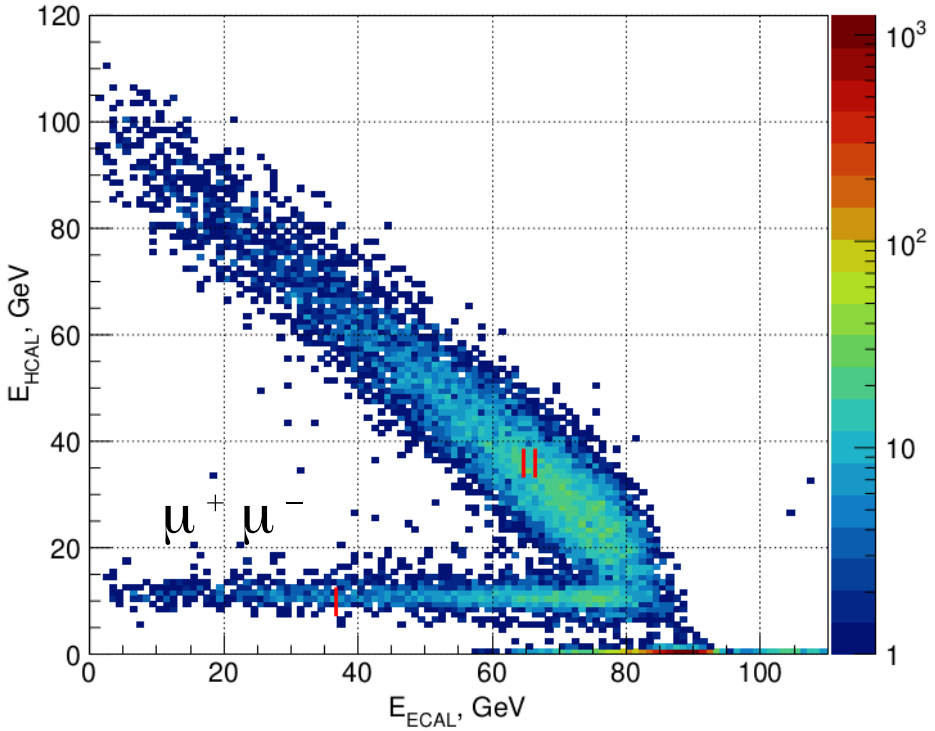


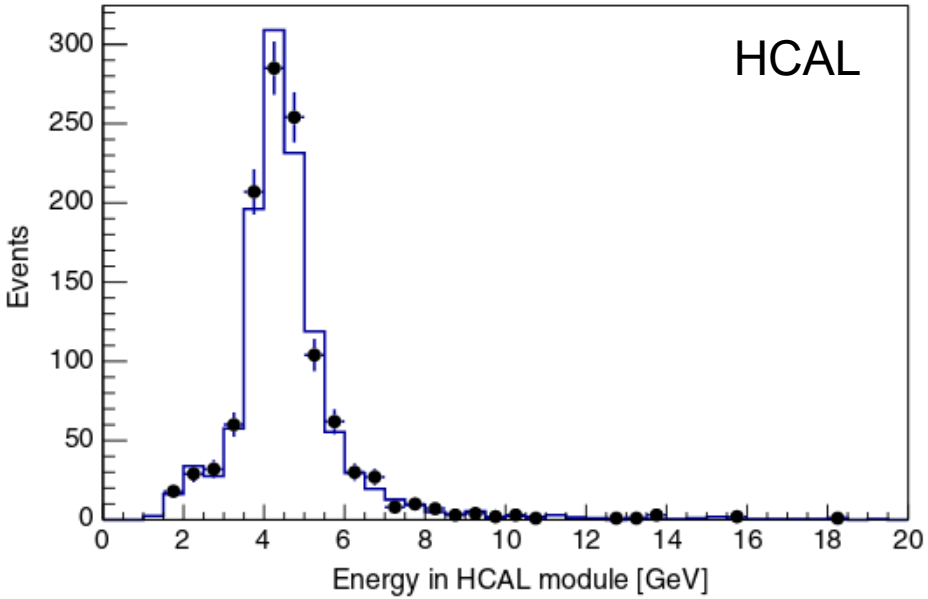


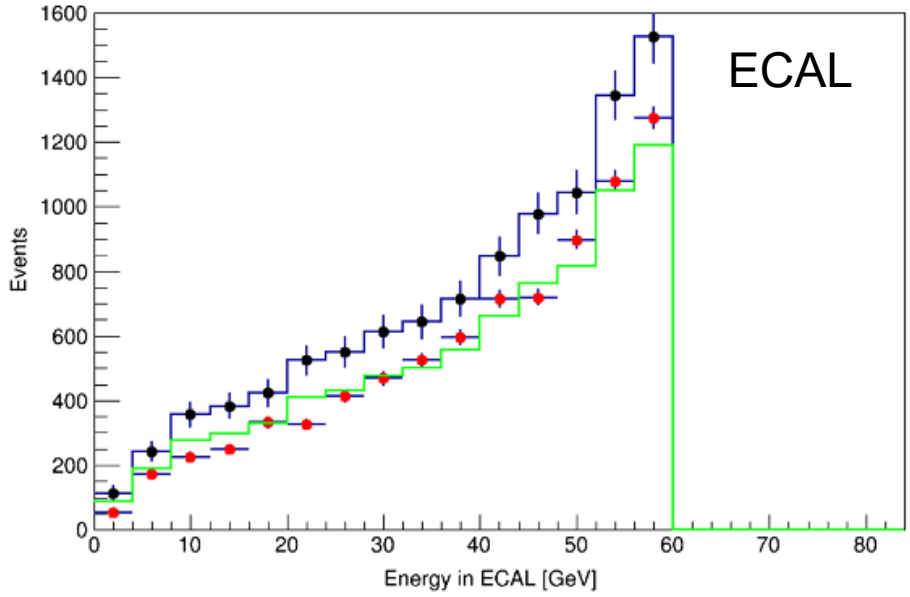
selection criteria	efficiency
incoming e- selection	2016(18)
S_i ,tracker hits in time	0.98(0.95)
SRD_i in-time, SR range	0.98(0.95)
no large Θ_{in}angle tracks	0.95(-)
p momentum in range	0.80(0.83)

A´ signal, $m_{A'}$~ 20 MeV	
Yield ε_{EC}, ECAL<50 GeV	$m_{A'}$ dep.
ε_{PS} , PS > 0.3 GeV	0.94(0.91)
ε_{SH}, ECAL in time	
+ shower shape	0.96(0.92)
ε_V ,Veto < MIP	0.97(0.93)
ε_{HC}, HCAL<1 GeV	0.96(0.94)

Gauge: dimuon production







Region I: Rare QED process $\sim 10^{-5}$/ EOT

$$e^- Z \to e^- Z \gamma, \gamma \to \mu^+ \mu^-$$

- Similar to A' production
- Cross check of A' yield, systematic error
- Background prediction from data
- Cross check for overall efficiency

Background estimation

Background source	Background, n_b
(i) dimuons	0.024 ± 0.007
(ii) $\pi, K \to e\nu, K_{e3}$ 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

- (i),(ii) estimated with full statistics simulation
- (iii) extrapolation of events from region C
- (iv) extrapolation of events from region A
  → Pure neutral hadronic secondaries
- Based on data itself and longitudinal shower shape in HCAL

→ Can still be treated as background free

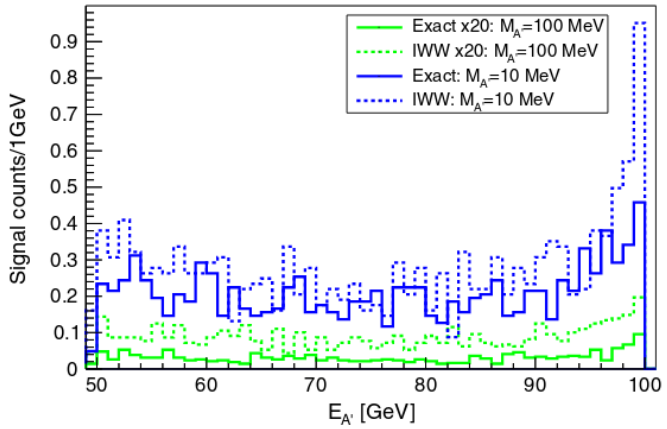
→ After background estimation the analysis is unblinded

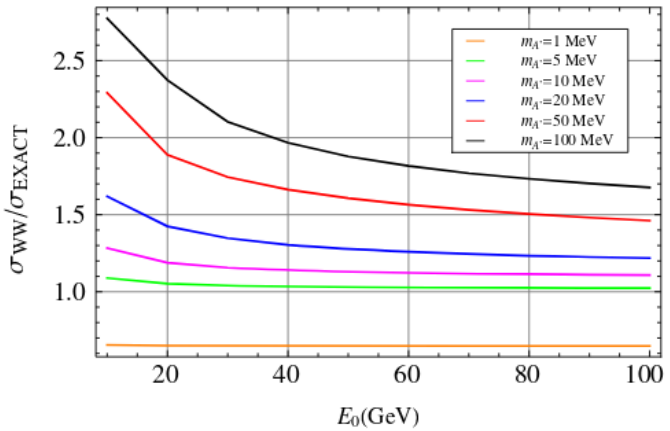
Calculating exclusion power

Average number of A' from Poisson distribution:

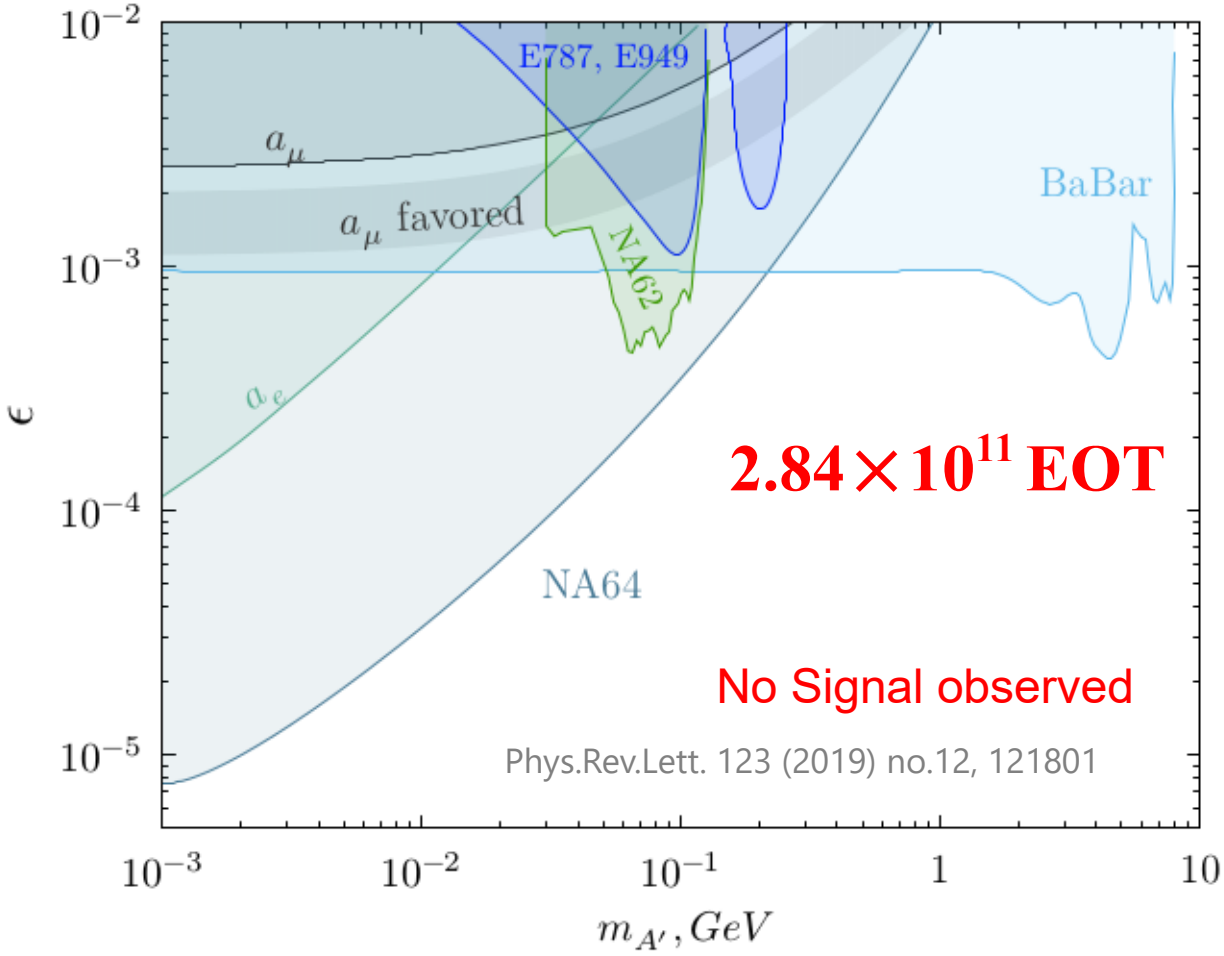
$$N_{A'} = n_{eot} \cdot n_{A'}(\epsilon, m_{A'}, \Delta E_{A'}) \cdot \varepsilon_{A'}(m_{A'}, \Delta E_{A'})$$

Signal yield simulated with exact tree level integration of cross section via k-factor





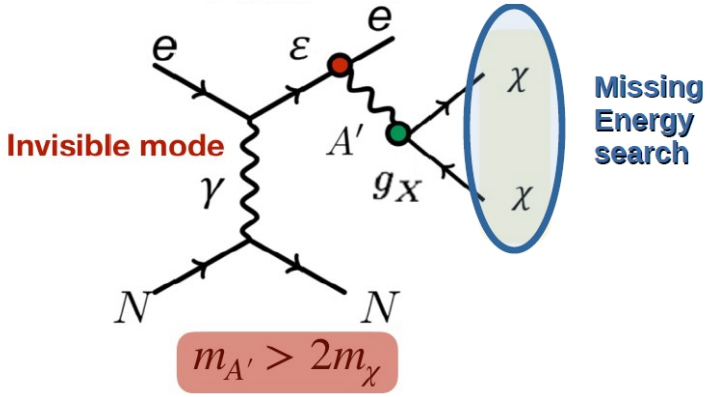
S. Gninenko et al. Phys.Lett. B782 (2018) 406-411

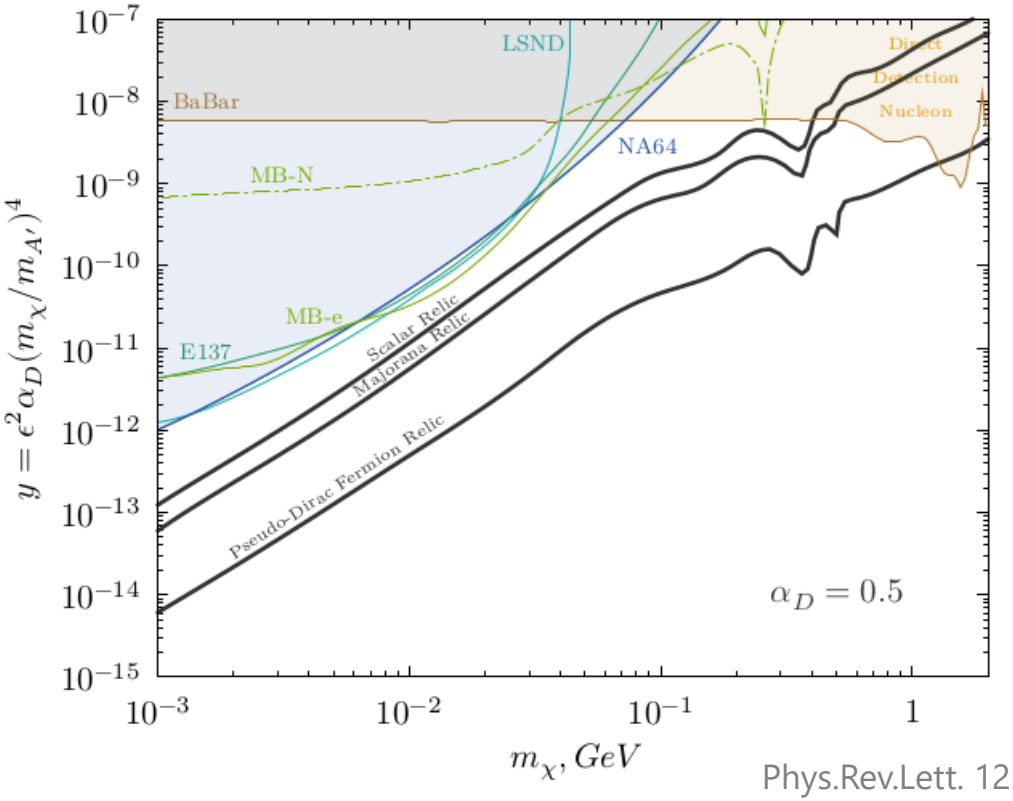


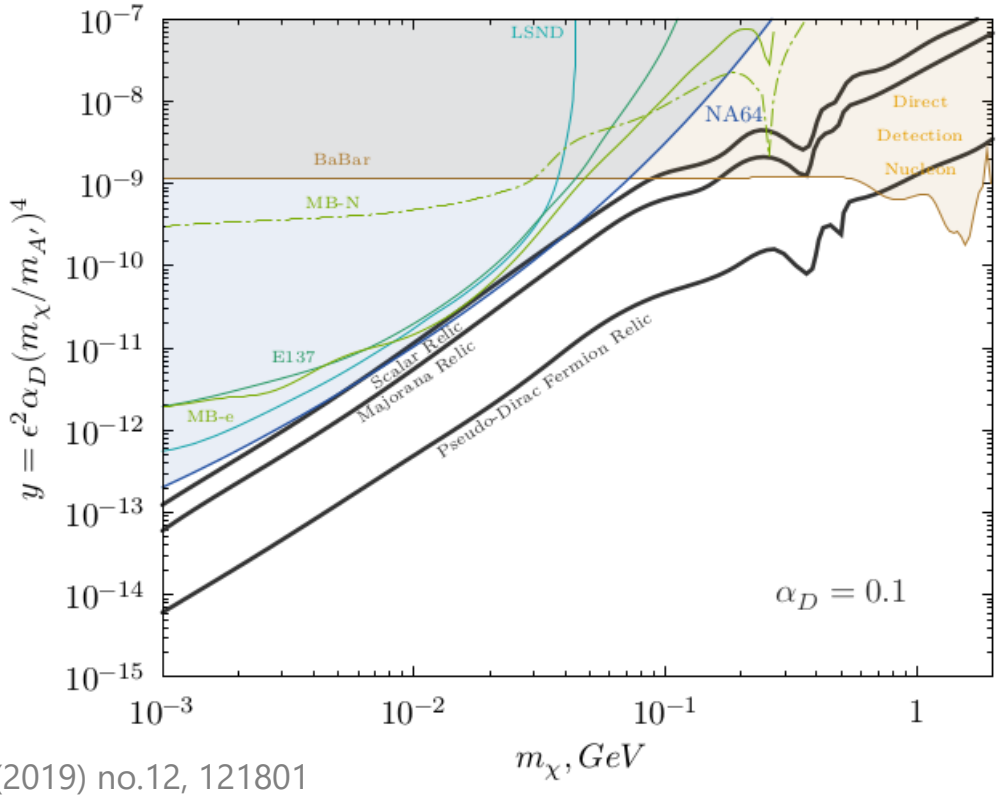
Constraints on light dark matter

$m_{A'} = 3\, m_{\chi}$, for selected $\alpha_D = g_{\chi}$

For the first time better results than previous beam dump experiments!

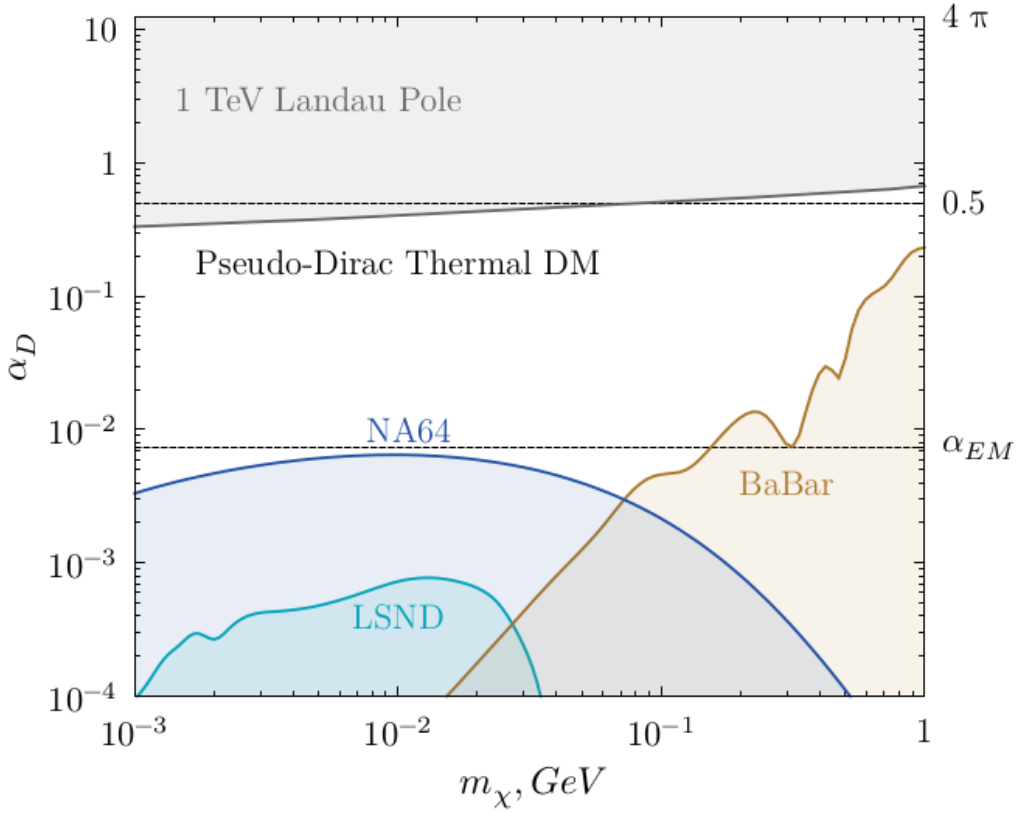


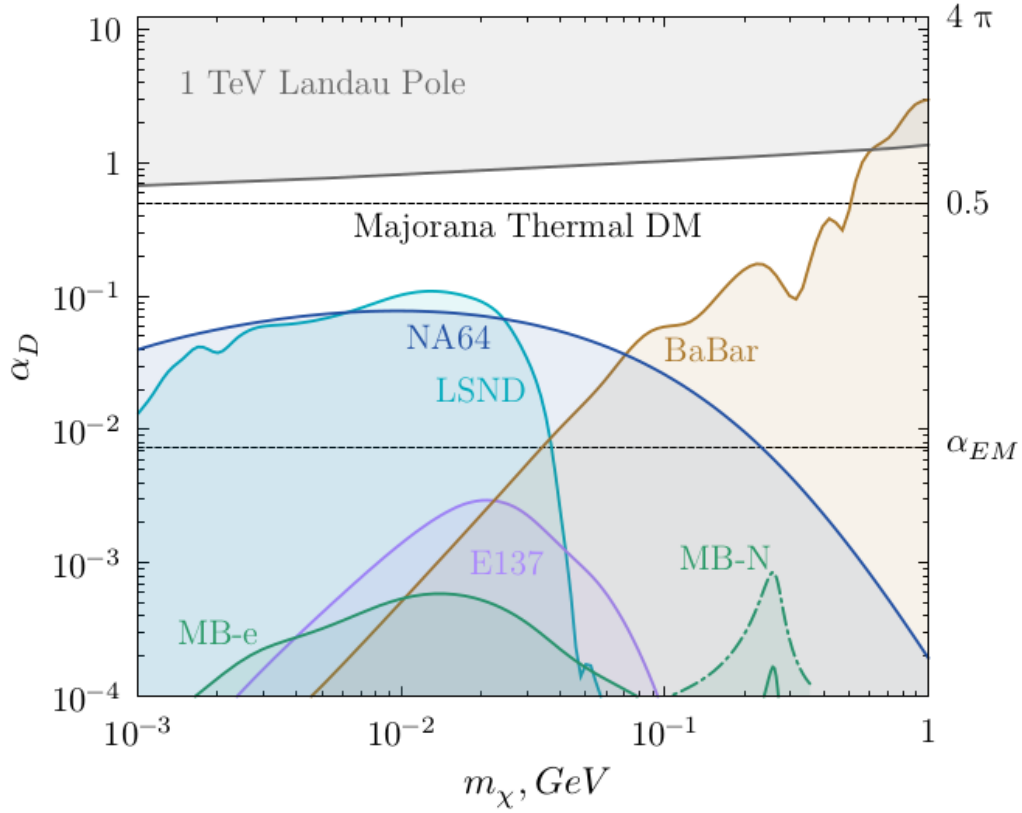




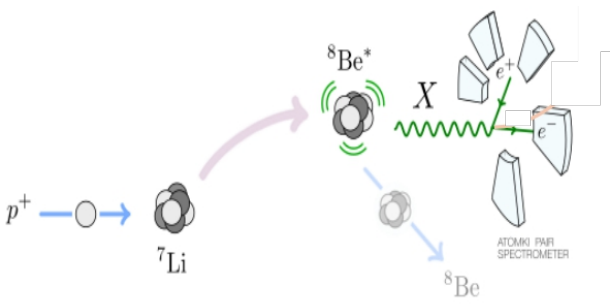
Phys.Rev.Lett. 123 (2019) no.12, 121801

Pseudo-Dirac and Majorana Thermal Dark Matter



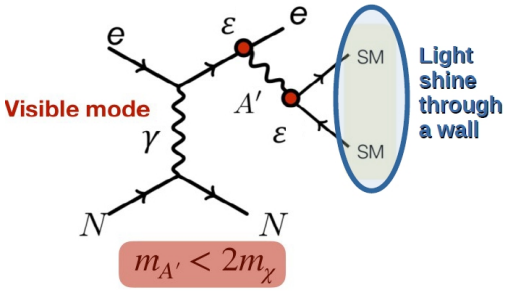


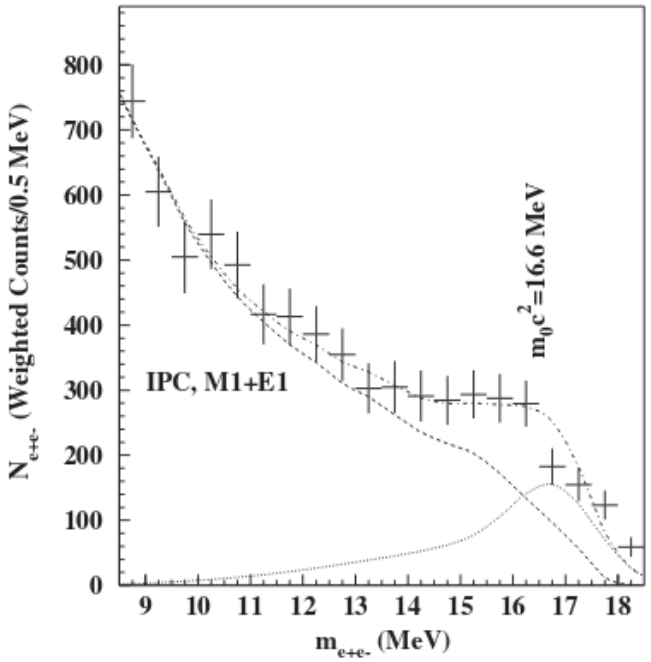
The NA64 detector: invisible mode



^{8}Be anomaly: a new 17 MeV X boson

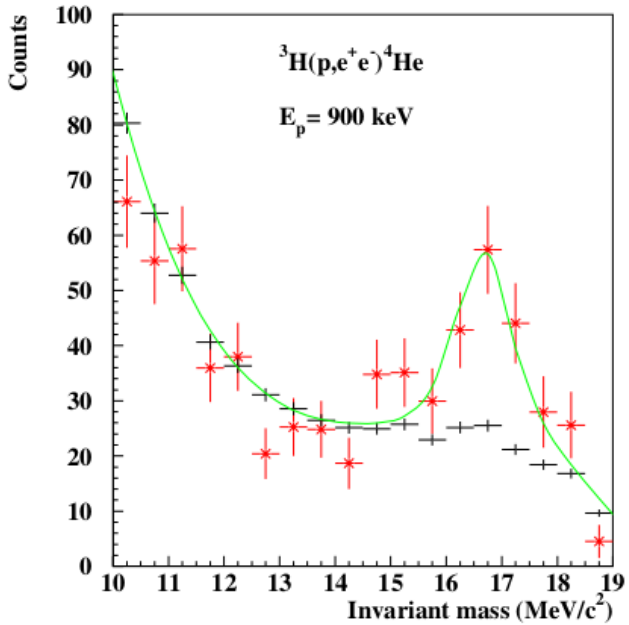
- NA64 invisible mode setup has sensitivity over the anomaly





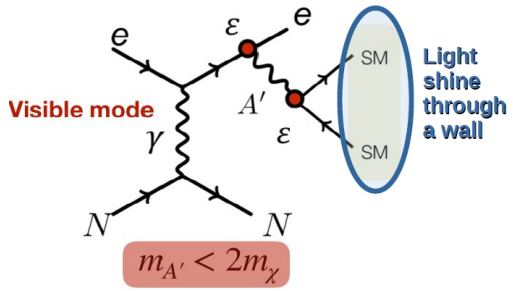
A.J. Krasznahorkay et al., PRL 116, 042501 (2016)

confirmed?



A.J. Krasznahorkay et al., arXiv: 1910.10459

The NA64 detector: visible mode



S.Andreas et al., arXiv: 1803.07748

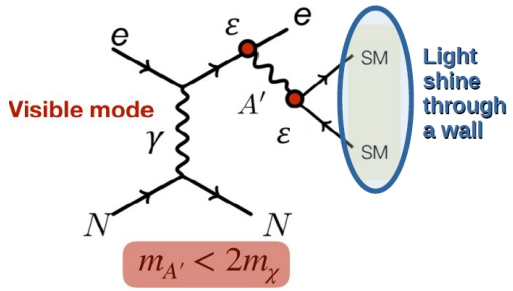
Main components:

- Clean 100 GeV e-beam
- e^- tagging system: tracker + SRD
- Active dump WCAL
- Fully hermetic ECAL+HCAL

Signature:

- Incoming 100(150) GeV e^--track
- <100(150) GeV shower in WCAL
- Double or single shower in ECAL
- No energy in Veto or HCAL
- $E_{WCAL} + E_{ECAL} = E_0$

The NA64 detector: visible mode



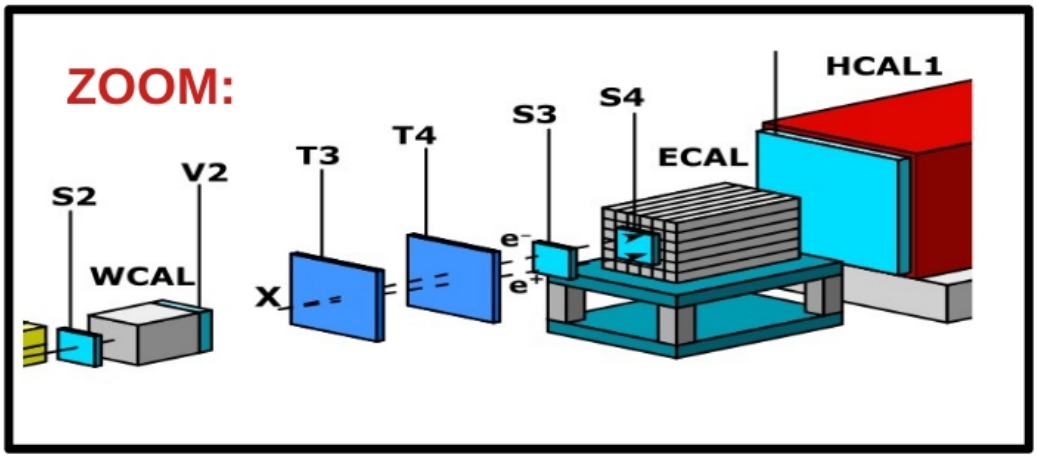
Setup as used in 2017

WCAL: Tungsten scintillator sandwich calorimeter for X production

- 4 GEM stations for vertex reconstruction
- Compact WCAL to allow short-lived X boson detection ($30\,X_0$ in $17\,\mathrm{cm}$)

In 2018 the setup was improved

- Beam energy to 150 GeV
- Added V2 to veto punchthrough
- Vacuum pipe to reduce background
- Additional Micromegas before WCAL

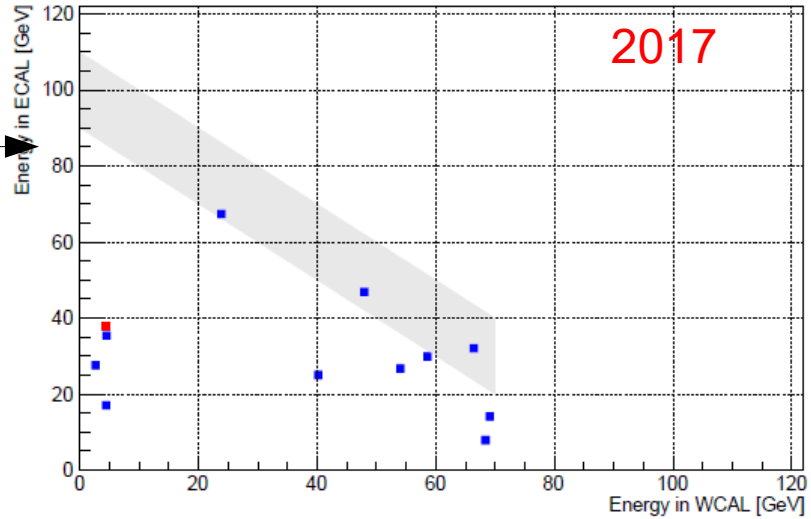


Background estimation

Background source	2017	2018
(i) $K_S^0 \to 2\pi^0$	0.06 ± 0.034	0.005 ± 0.003
(ii) $\pi N \to (\geq 1)\pi^0 + n + \ldots$	0.01 ± 0.004	0.001 ± 0.0004
(iii) punchthrough π^-	0.0015 ± 0.0008	0.0007 ± 0.0004
(iv) punchtrhough γ	<0.001	<0.0005
(v) $\pi, K \to e\nu, K_{e4}$ *decays*	<0.01	<0.01
(vi) $eZ \to eZ\mu^+\mu^-; \mu^\pm \to e^+ - \nu\bar{\nu}$	<0.001	<0.001
Total n_b (conservatively)	0.07 ± 0.035	0.006 ± 0.003

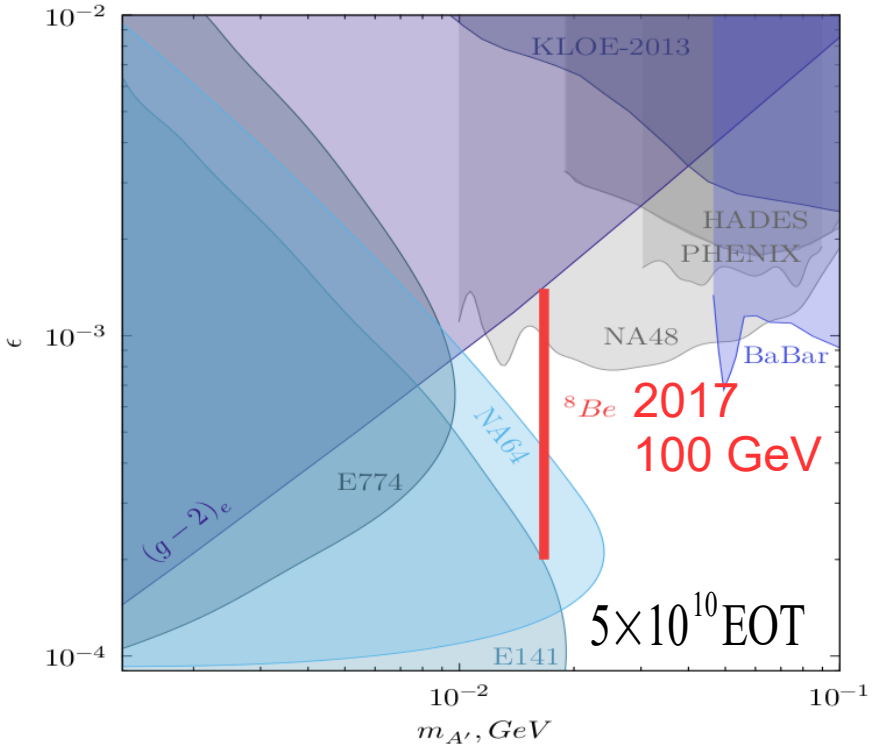
(i) estimated with simulation and data
  1) Selected true neutral e-m events (photon)
    - No signal in V2, S4 + single e-m in ECAL
    - Simulate K to match that → ~150
  2) Select long lived neutrals
    - No signal in V2, S4, ECAL. Absorbed in HCAL
    - In 2017 ~1000 events→~100 K

(ii) extrapolation of other charge-exchange studies

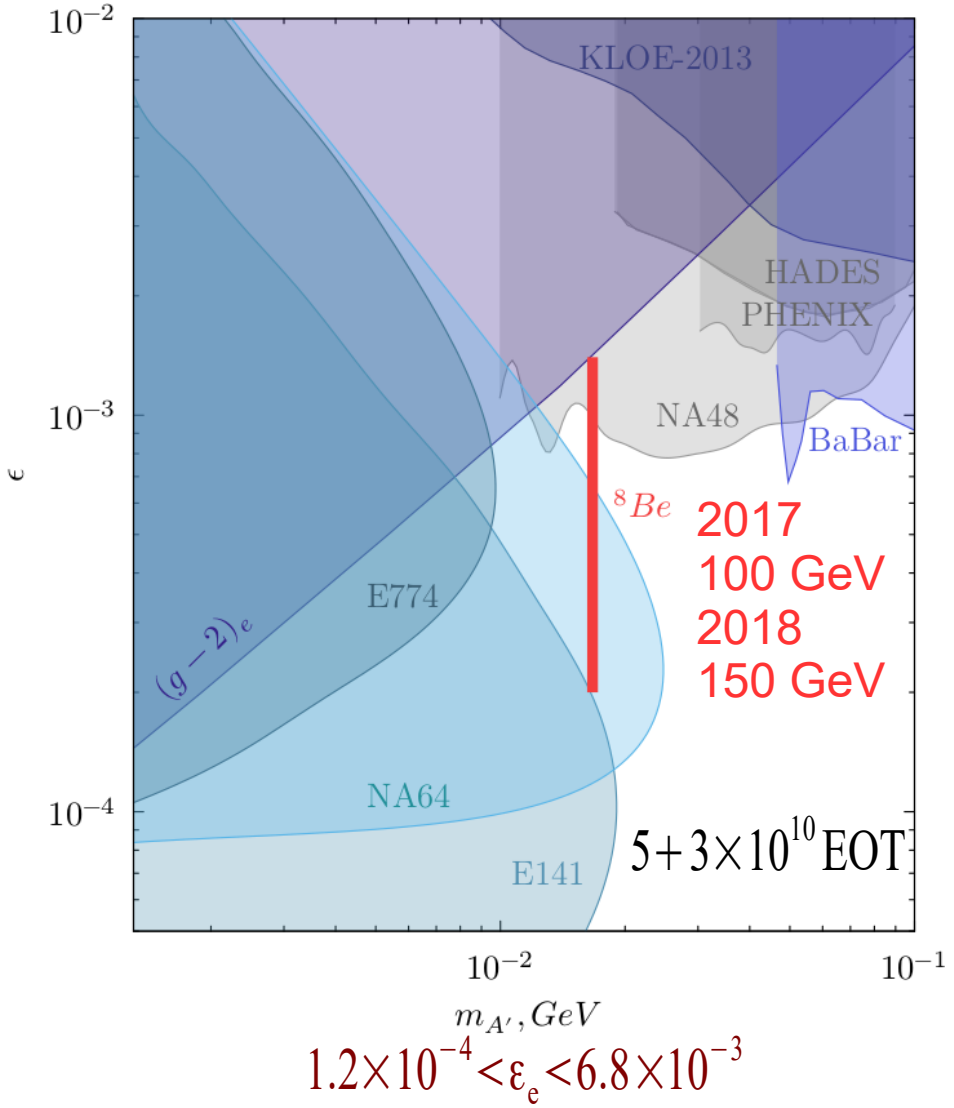


Constraints on X boson

No events survived the cuts in 2017 + 2018:



$1.3\times10^{-4}<\varepsilon_e<4.2\times10^{-3}$



$1.2\times10^{-4}<\varepsilon_e<6.8\times10^{-3}$

- sensitivity for smaller ϵ defined by WCAL dump length
  - ➔ Might be limiting factor for future searches

S. Gninenko et al. Phys.Lett. B782 (2018) 406-411

Summary and Plans

NA64e invisible mode:

- Recorded 2.84×10^{11} EOT
  → Set new constraints on A', LDM
- Detailed study of dimuon production

NA64e visible mode:

- Recorded 8.4×10^{10} EOT
  → Set new constraints on X(17)
- Detailed study of WCAL width ongoing

NA64e was approved for a permanent setup in EHN1-H4 at CERN SPS

- Detector upgrade during LS2 → Invisible A', LDM, Be anomaly, ALP
- In 2021-24 record 5×10^{12} EOT (invisible)
- In 2021-24 record 1×10^{12} EOT (visible) → $1.2\times10^{-4}<\varepsilon_e<7-8\times10^{-3}$

NA64μ currently under discussion for M2 beamline

- April 2019: Proposal to SPSC, CERN-SPSC-2019-002/SPSC-P-359
- Competition from COMPASS++/Amber, MUonE
- Decision expected in 2020

Thank you for your attantion!

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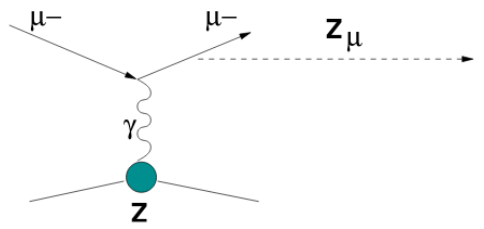
Thank you for your attantion!

BACKUP!

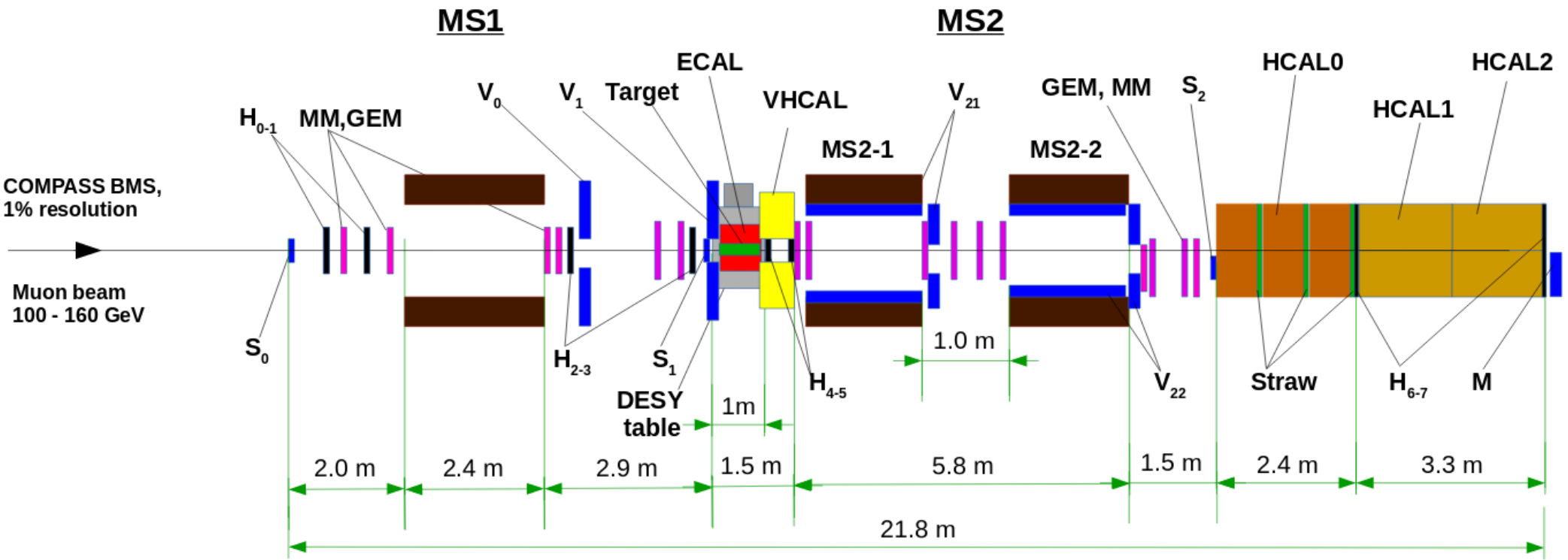
Remaining low mass solution to $(g-2)_\mu$: Z_μ of $L_\mu - L_\tau$



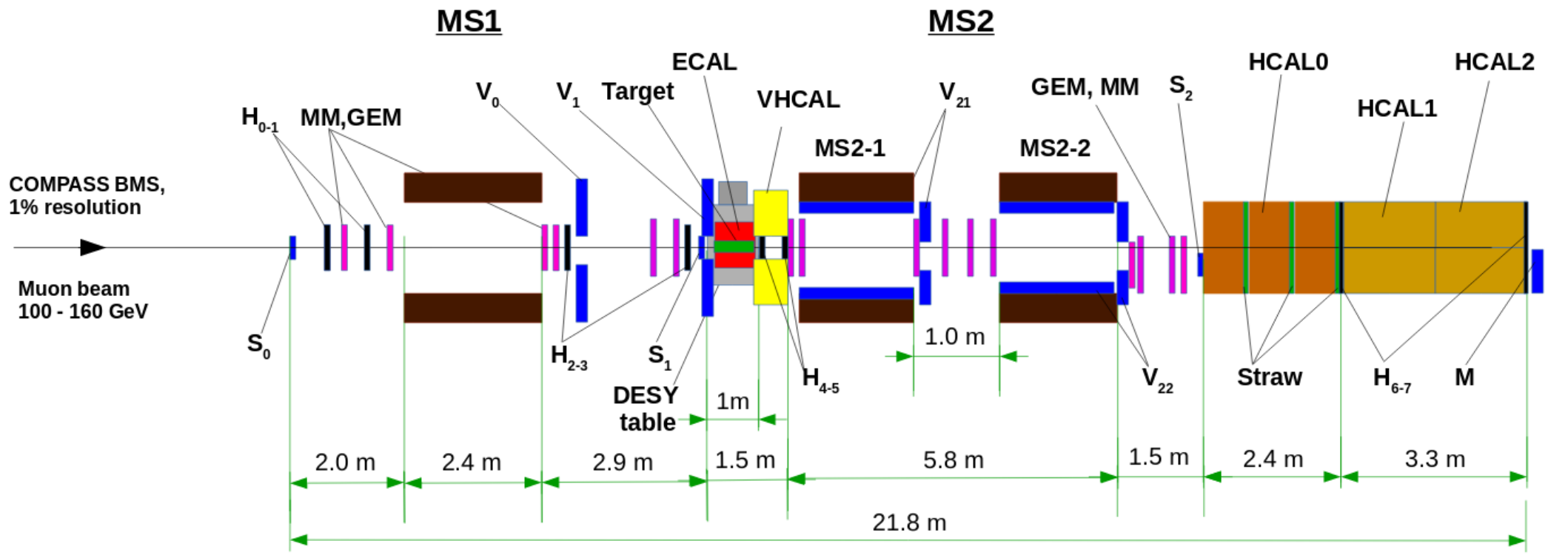
- New massive boson Z_μ, coupled predominantly to μ, τ

$$Z_\mu \rightarrow \mu^+ \mu^- \quad \text{or} \quad Z_\mu \rightarrow \nu\ \nu$$

- Z_μ can be produced in Bremstrahlung events



NA64μ



Main components:

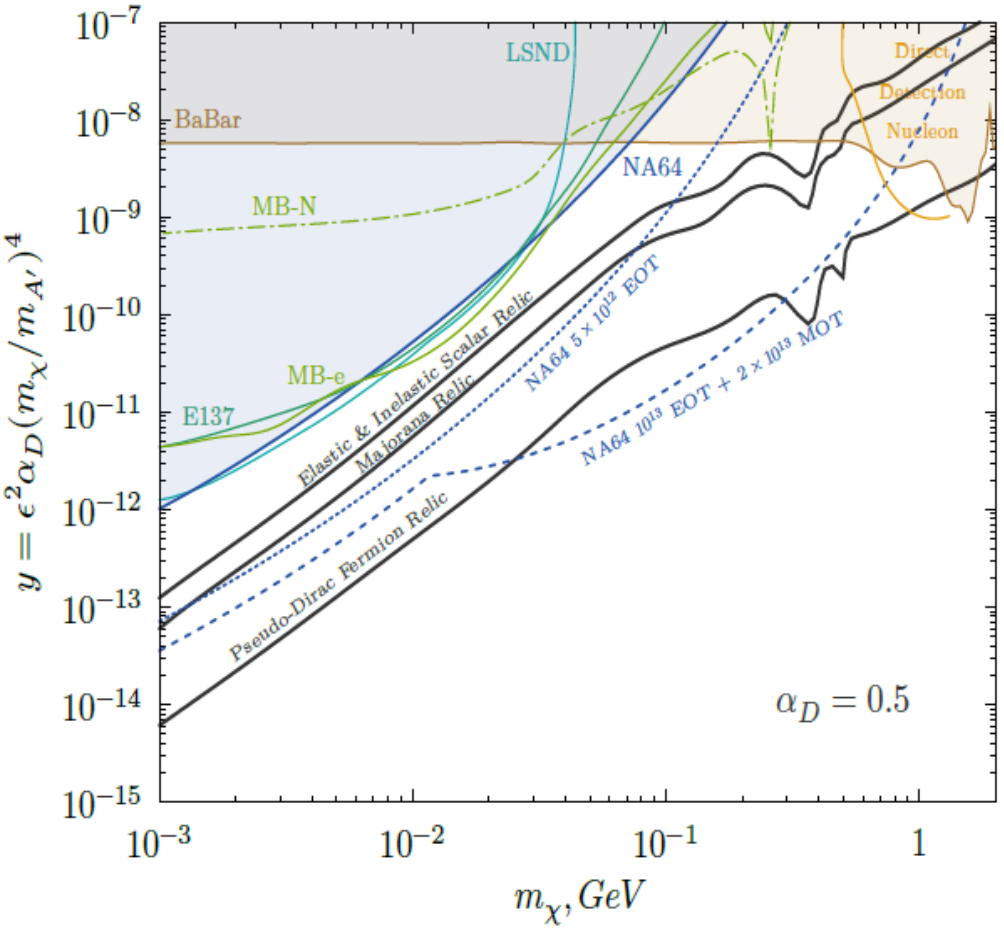
- Clean 160 GeV μ-beam
- μ tagging in: BMS + MS1
- μ tagging out: MS2
- Fully hermetic system: ECAL+HCAL+VHCAL

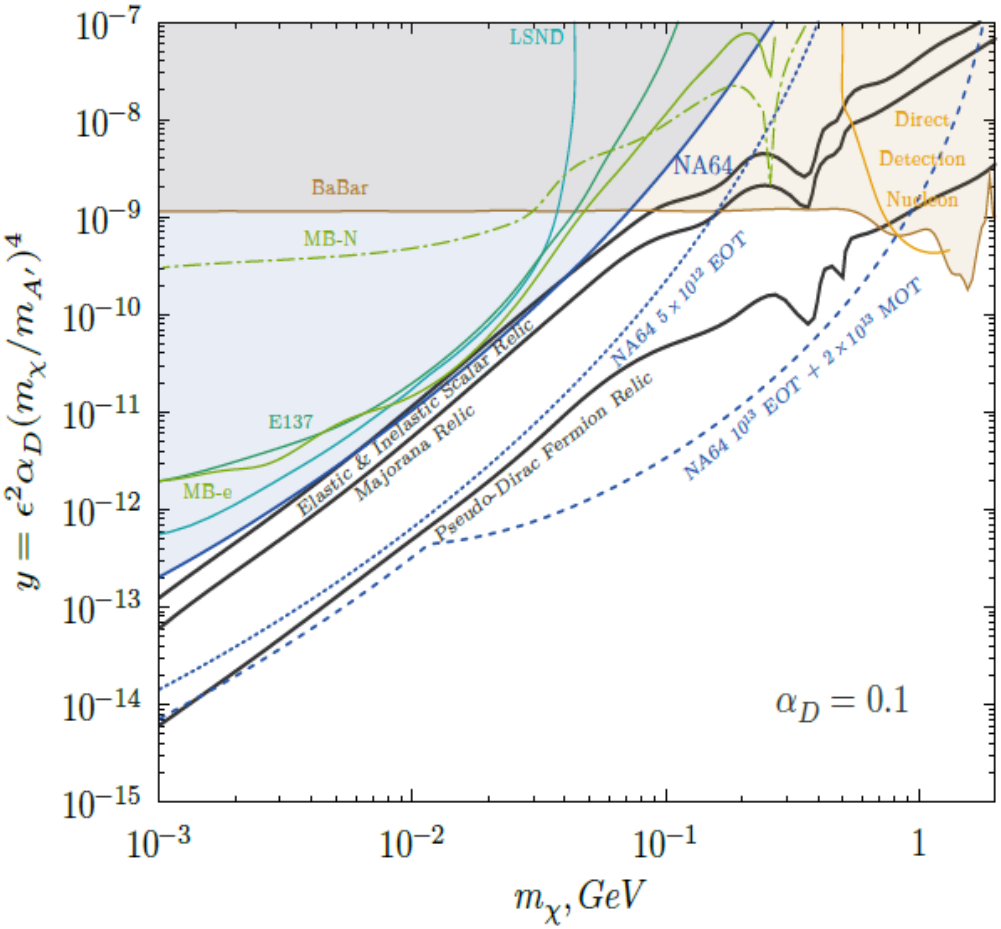
Signature/Background:

- μ beam: 160 GeV in → 80-100 GeV out
- No energy in ECAL, HCAL, VHCAL, Veto
- Detector hermiticity
- π, K → μν

Complementary to NA64e: $\gamma - Z_\mu$ mixing

- Search for Z_μ with e-Beam over lepton loops ($M_{Z_\mu} < 100$ MeV)





NA64μ

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