Search for Dark Sector Physics at the NA64 experiment in context of Physics Beyond Colliders Project

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Physics Beyond Colliders

PBC Kickoff workshop launched in 2016

Mandate of the "Physics Beyond Colliders" Study Group

CERN Management wishes to launch an exploratory study aimed at exploiting the full scientific potential of its accelerator complex and other scientific infrastructure through projects complementary to the LHC and HL-LHC and to possible future colliders (HE-LHC, CLIC, FCC). These projects would target fundamental physics questions that are similar in spirit to those addressed by high-energy colliders, but that require different types of beams and experiments.

This study should provide input for the future of CERN's scientific diversity programme, which today consists of several facilities and experiments at the Booster, PS and SPS, over the period until ~2040. Complementarity with similar initiatives elsewhere in the world should be sought, so as to optimize the resources of the discipline globally, create synergies with other laboratories and institutions, and attract the international community.

Within the Conventional Beams Working group several projects for the muon beamline (M2) in the CERN North Area were proposed.

- Successor for the COMPASS experiment - (AMBER)
- MuonE - aiming at investigating the hadronic contribution to the vacuum polarisation
- NA64 - Muon Programme for dark sector physics

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- Successor for the COMPASS experiment - (AMBER)
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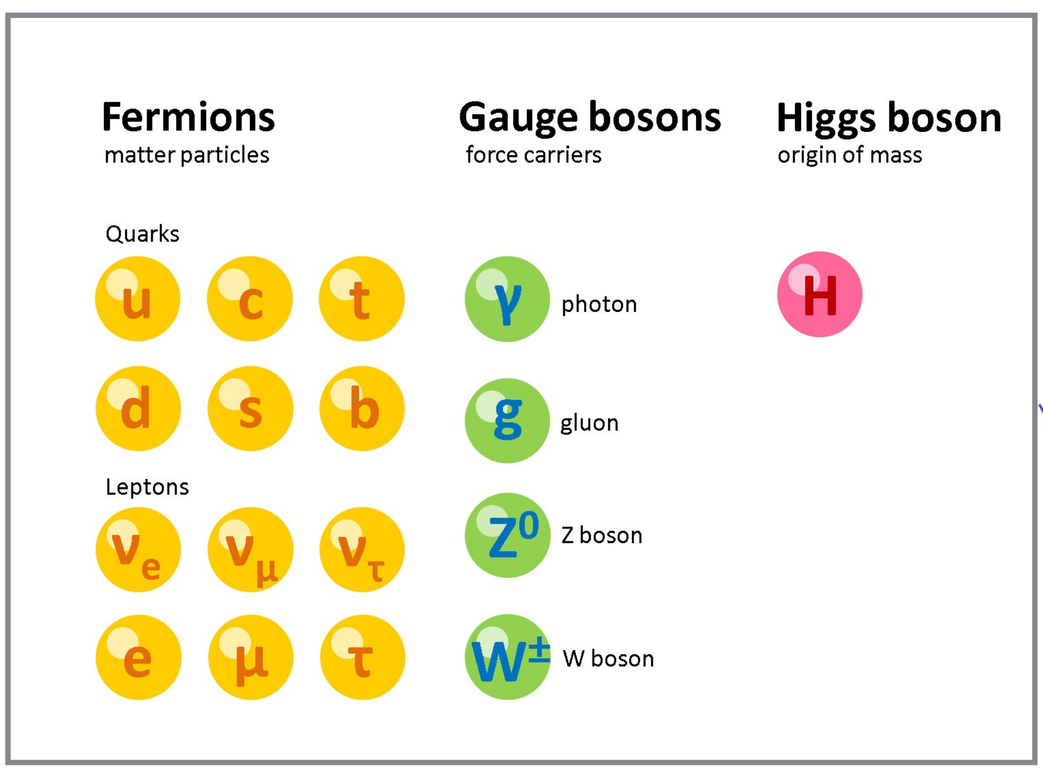
- **NA64 - Muon Programme for dark sector physics**

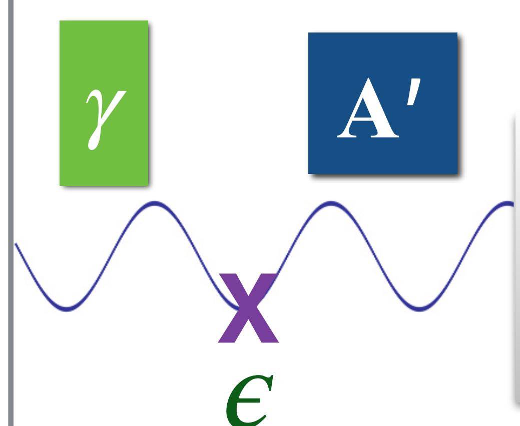
+

NA64 electron beam run/results

NA64 Motivation

- Dark Matter is still a great puzzle despite intensive searches and efforts of the LHC and non-accelerator experiments.
- Several models suggest the existence of dark sectors consisting of $SU(3)_C \times SU(2)_L \times U(1)_Y$.
- Do not interact with ordinary matter but couple to it via gravity.
- Additional very weak interaction mediated by a U′(1) gauge boson, A′, mixing with our photons.
- The gauge boson could be light, having sub-GeV masses and the coupling strength in the experimentally accessible and theoretically interesting region.



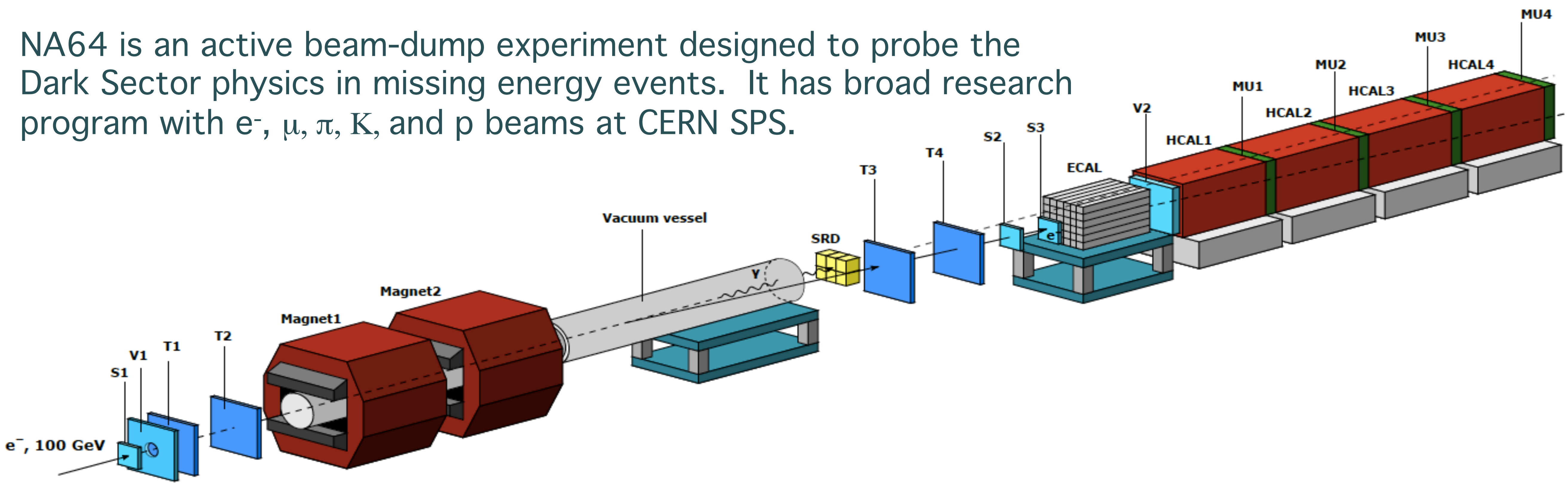


Dark Sector
Particles+Forces
Dark Matter

$$\Delta\mathcal{L} = \frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu}$$

NA64

NA64 is an active beam-dump experiment designed to probe the Dark Sector physics in missing energy events. It has broad research program with e-, μ, π, K, and p beams at CERN SPS.



December 2013 : Proposal to SPSC
April 2014 : Recommended for tests
April 2014-March 2015: Design Production and delivery at CERN.
October 2015: 2 week test run.
February 2016: Proposal approved as a SPS experiment ! P348 become NA64.

2016 - 2018 run:

•Search for vector mediator A′ of LTDM dark matter production in invisible decay mode

•Search for the 17 MeV X-boson from the ^{8}Be excess and dark photon decays A′-> e^+e^-

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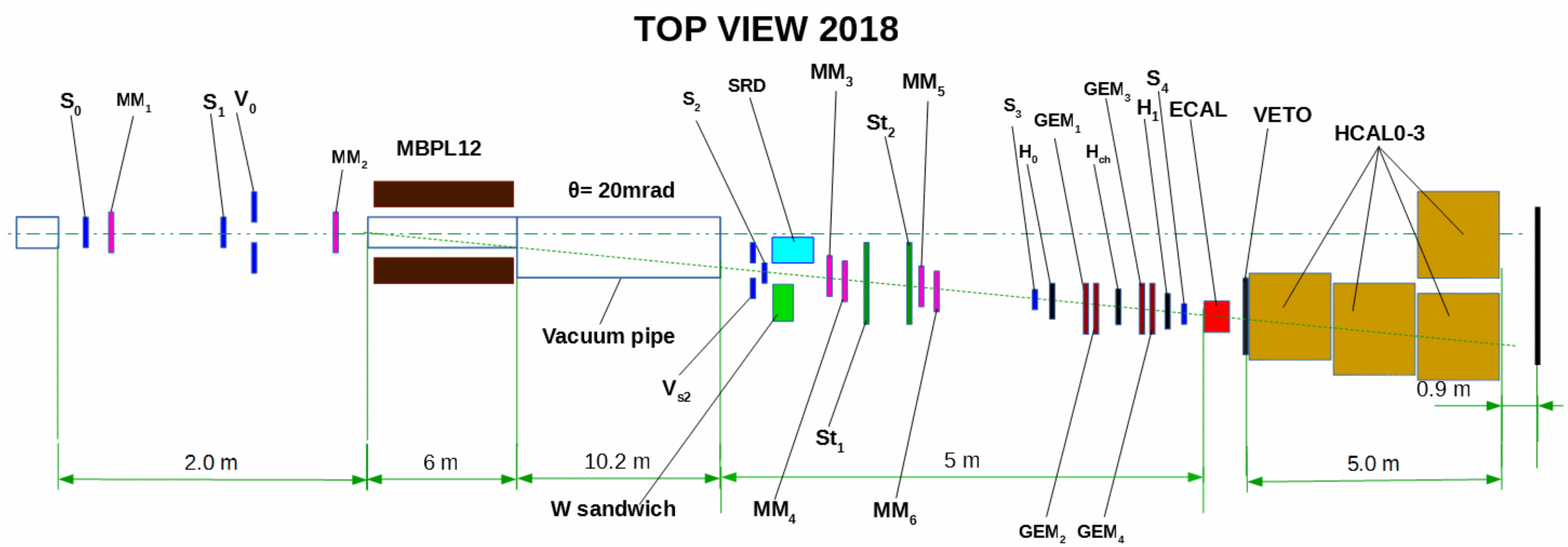

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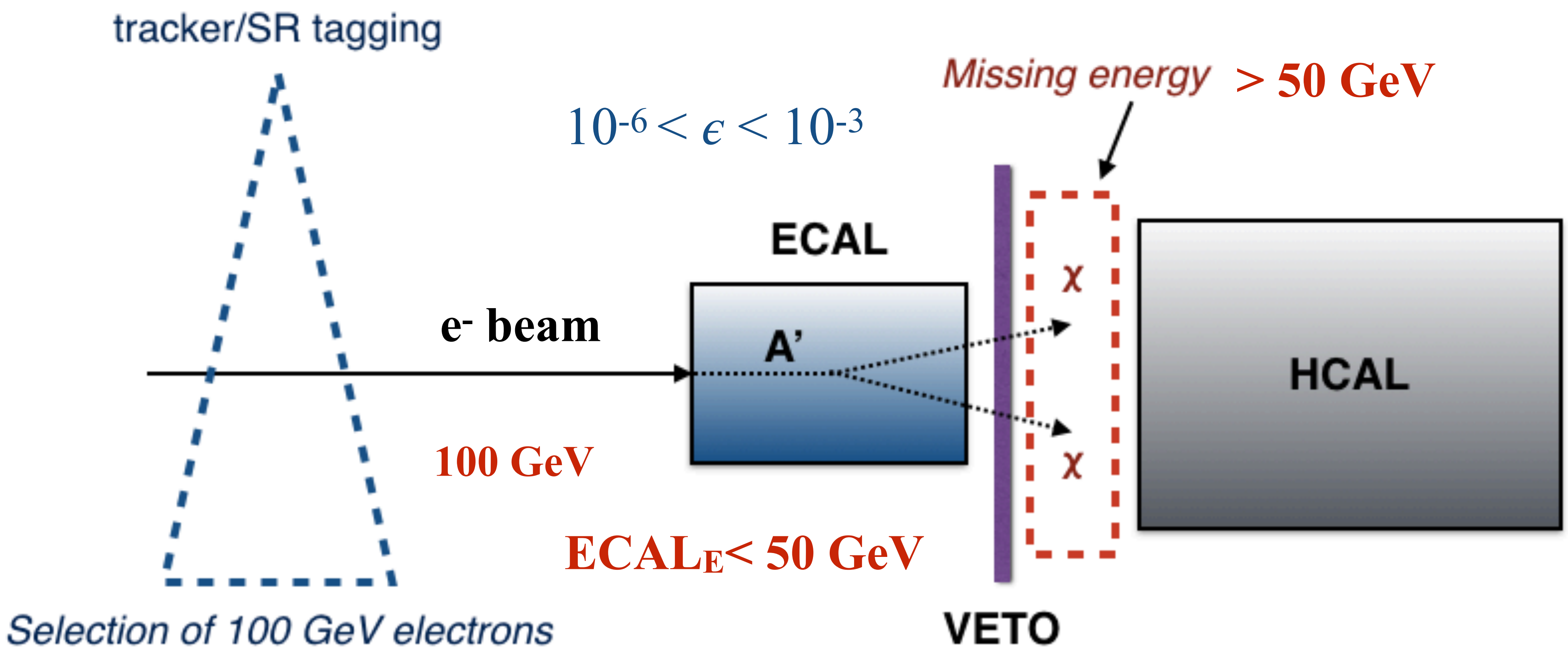
NA64 invisible A′ decay search



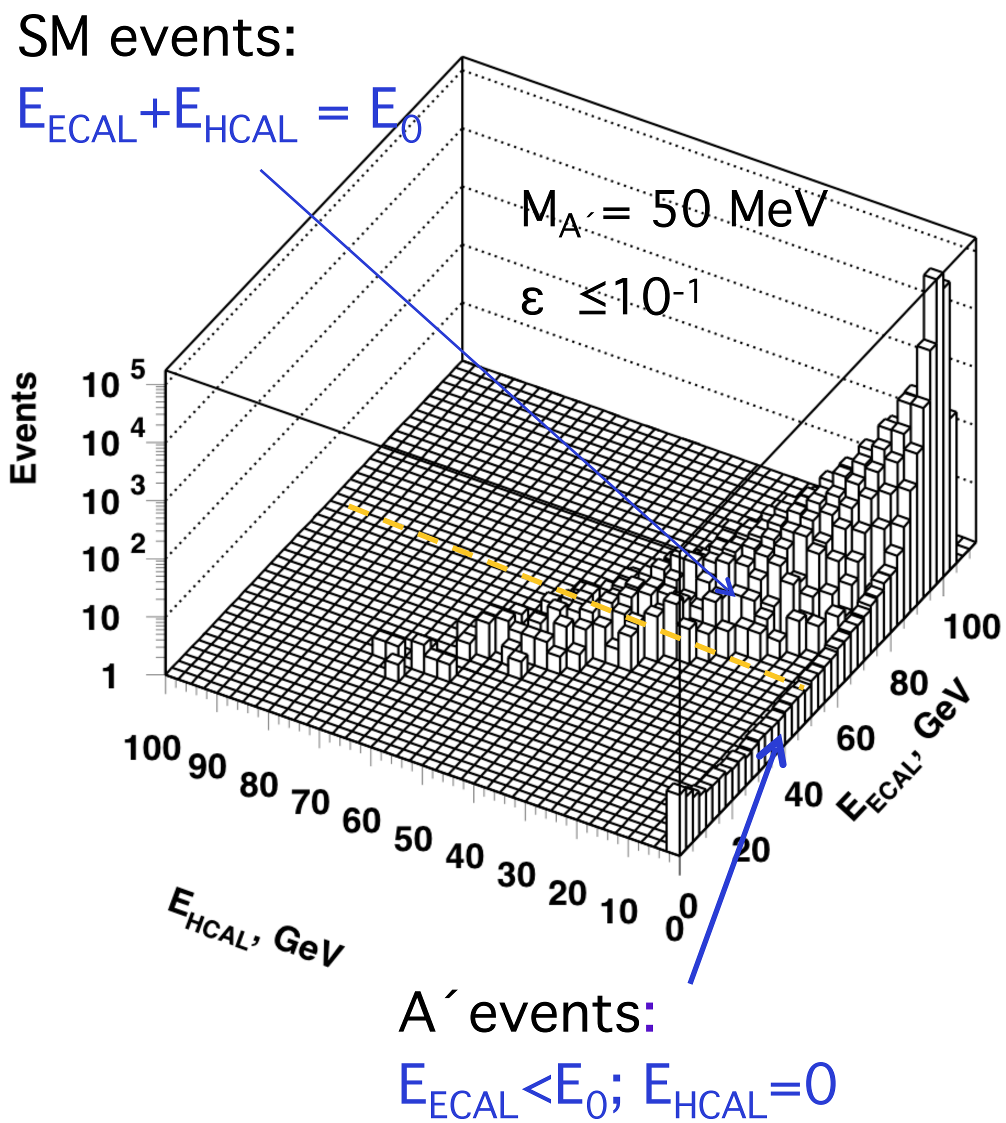
Setup:

- High energy beam to trigger the reaction: 100 GeV e- beam from the CERN SPS H4 secondary beamline.
- High intensity beam > 10^5 $e^-/sec/cm^2$
- Main impurities of H4 beam: π−, low energy e− (~1%) μ− and K− (≤0.2%)
- e- tagging system: trackers +SRD
- 4π fully hermetic detector ECAL+HCAL

Signature:
In:
100 GeV e-
Out:
ECAL < $0.5E_0$
No energy in Veto and HCAL (missing energy)

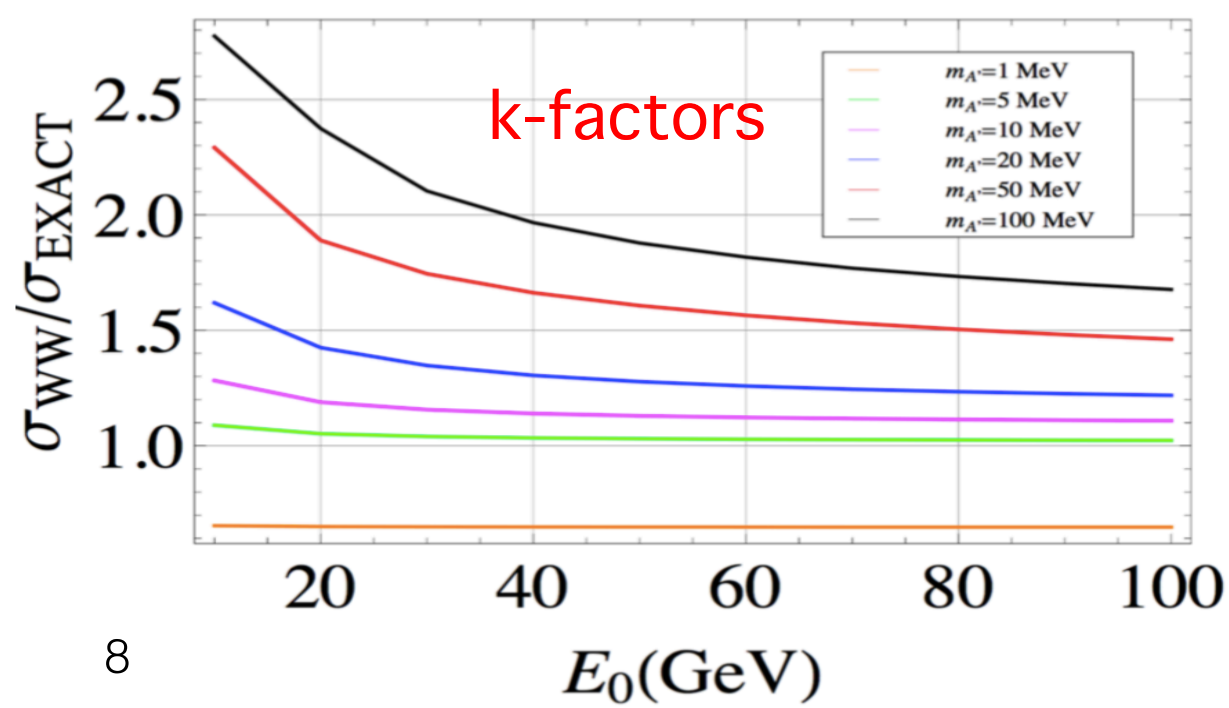
Backgrounds:
Upstream beam interaction with beamline materials.
μ, π, K decays in flight
Beam tail < 50 GeV
Energy leak from ECAL+HCAL

Simulations of e-Z —> e-ZA$'$; A—> invisible

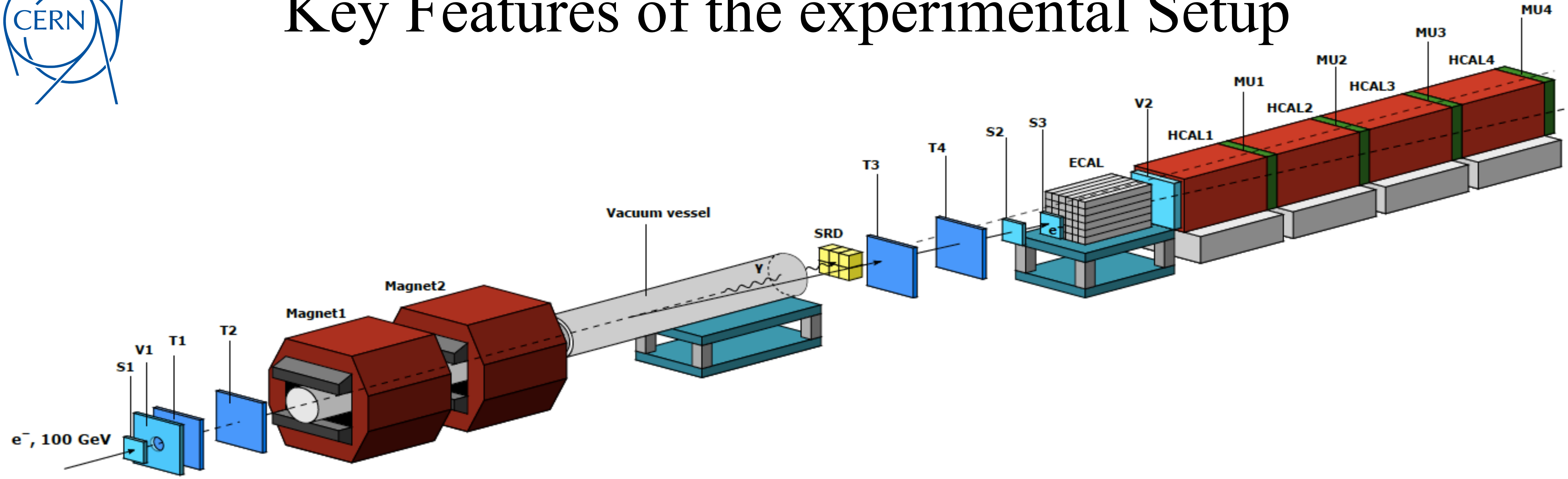


- GEANT4 code for A$'$ emission in the process of e-m shower development
- WW approximation for $\sigma(e^-Z\to e^-ZA')$ (Bjorken et al.'09)
- Corrections (k-factors) to WW from exact tree-level (ETL) calculations: large for higher A$'$ masses
  arXiV:1712.05706, PLB
- The shape of WW and ETL differential cross sections is quite similar: strongly peaked at $x= E_{A'}/E_0 \sim 1$.

SG, Kirsanov,Krasnikov, Kirpichnikov, PRD(2016)

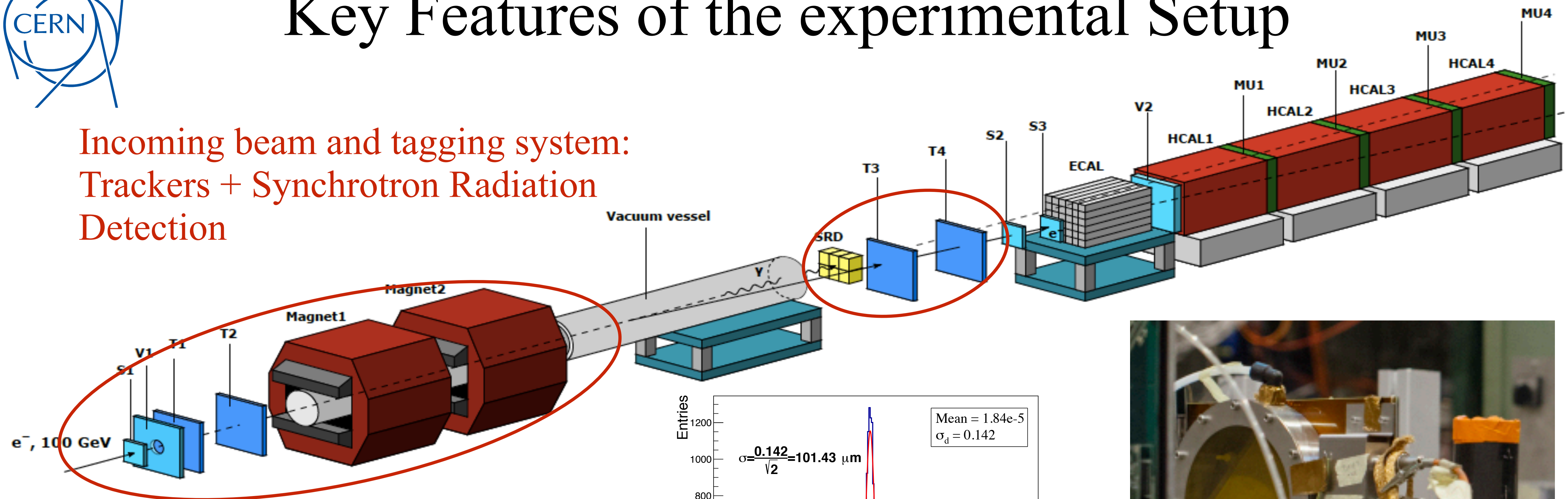


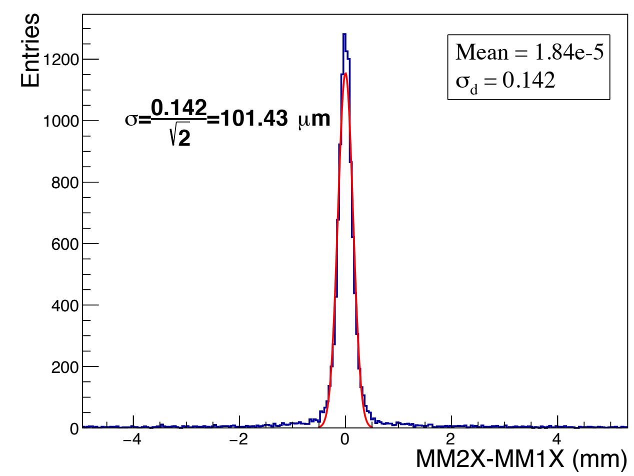
Key Features of the experimental Setup

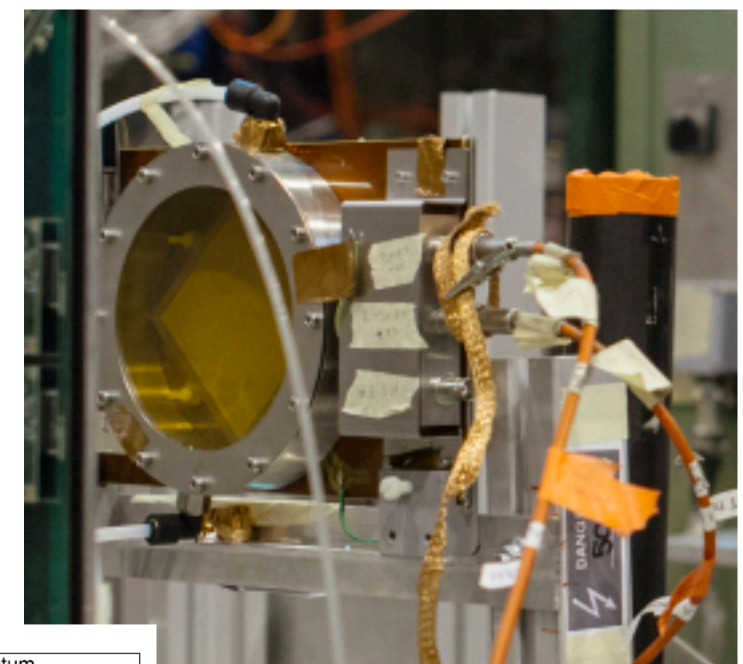


Key Features of the experimental Setup

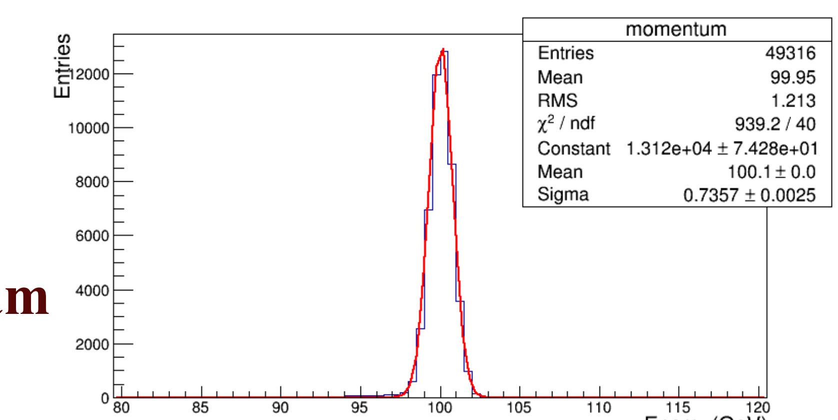
Incoming beam and tagging system:
Trackers + Synchrotron Radiation Detection







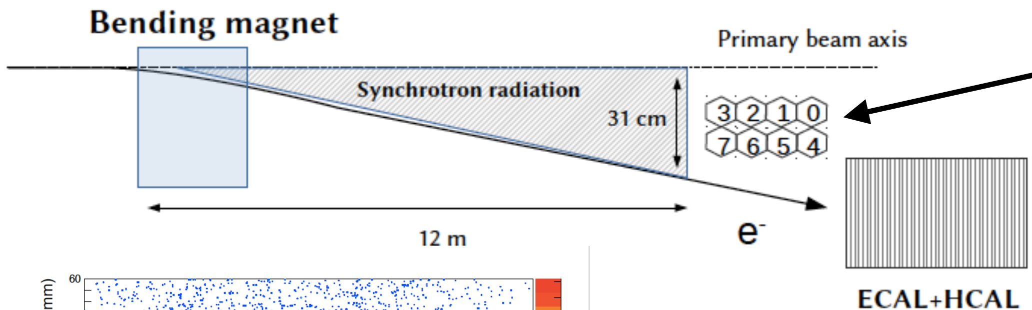
- 250 μm pitch Resistive Multiplexed Micromegas Trackers.
- 8 cm x 8 cm, Multiplexed by a factor 5.
- 2 MBPL magnets 7 T.m strength and 4.8 m long in total.
- Detectors resolution ~ 100 μm.

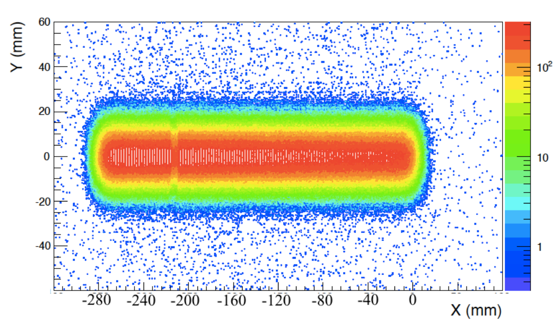


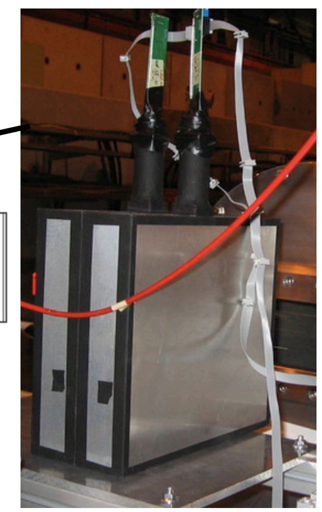
Momentum resolution ~ 1 % for a 100 GeV/c beam

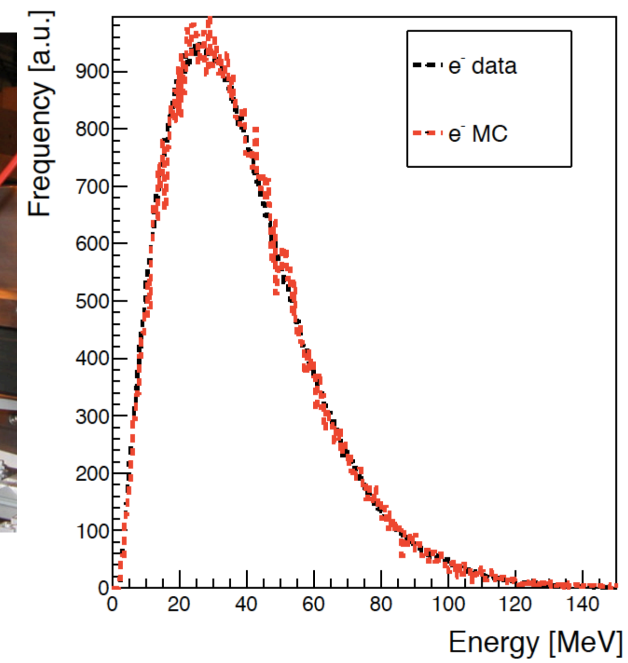
D. Banerjee et. al NIM A881 (2018) 72-81

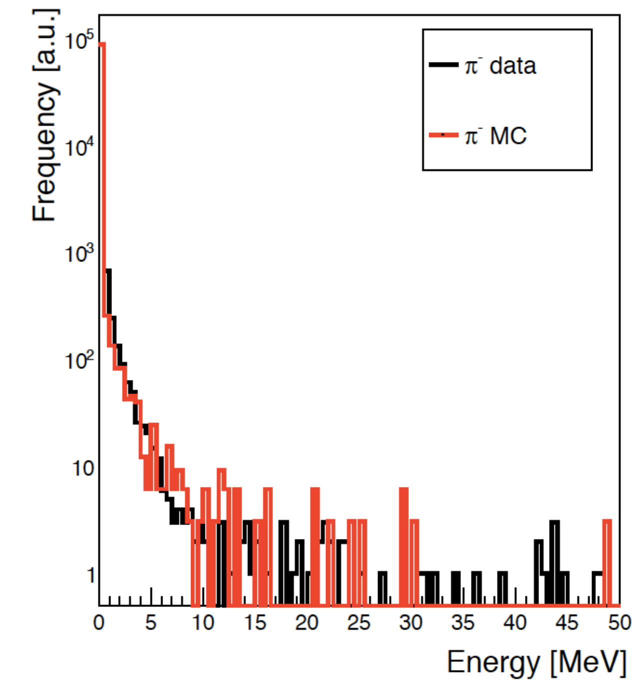
Electron Tagging with Synchrotron Radiation



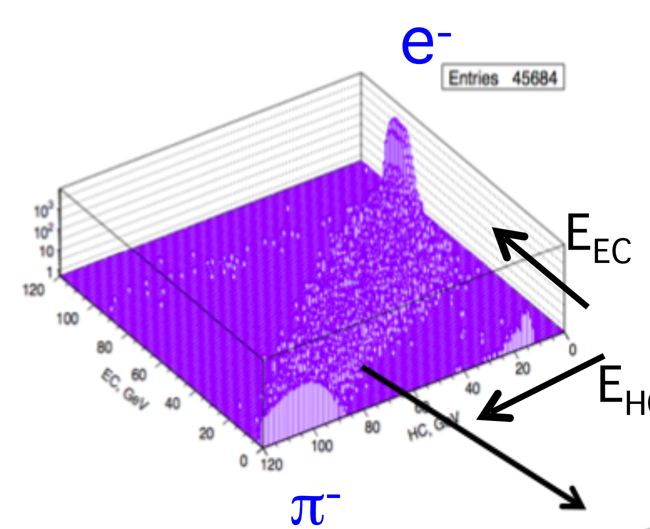


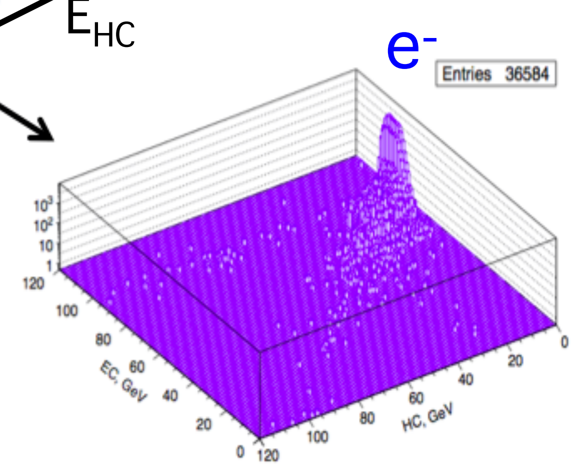






- Detected synchrotron radiation energy ~ $1/M^4$
  - Synchrotron radiation detector — Fast fine granularity sandwich Pb-Sc SRD.
  - 18 cm x 8 cm including 250 layers of 0.1 mm/0.2 mm (120/130) Pb + 1.1 mm scintillators
- SRD selection cuts:
  - $1 < SRD_i < 80$ MeV
  - All SRD_i in time within ±2 ns
  - **$\varepsilon_{SRD} > 0.95$, $\pi/e \sim 10^{-6}$**

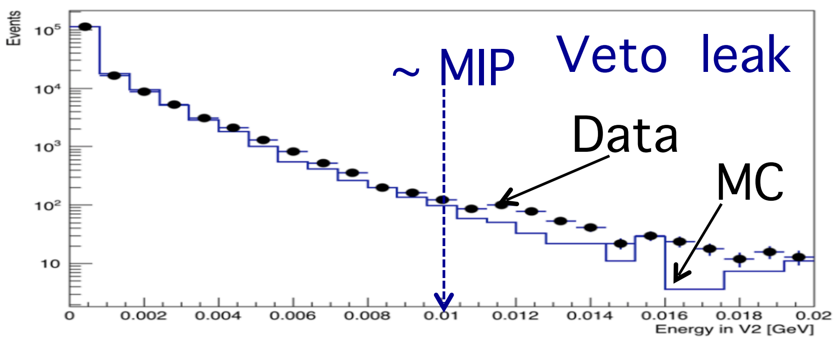


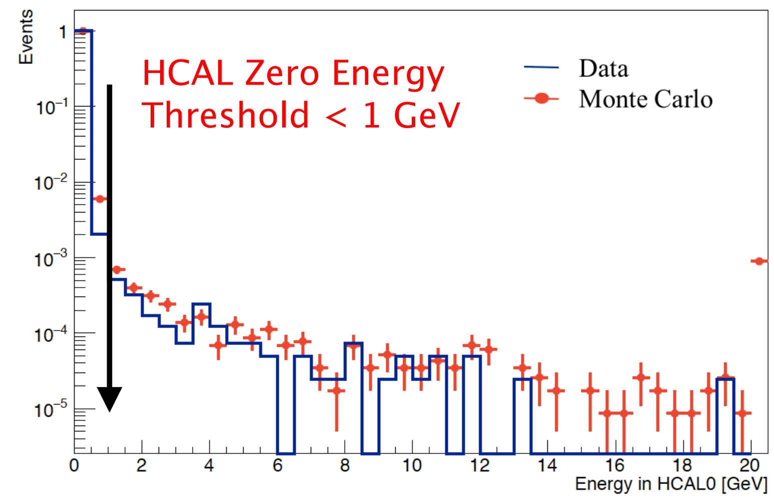


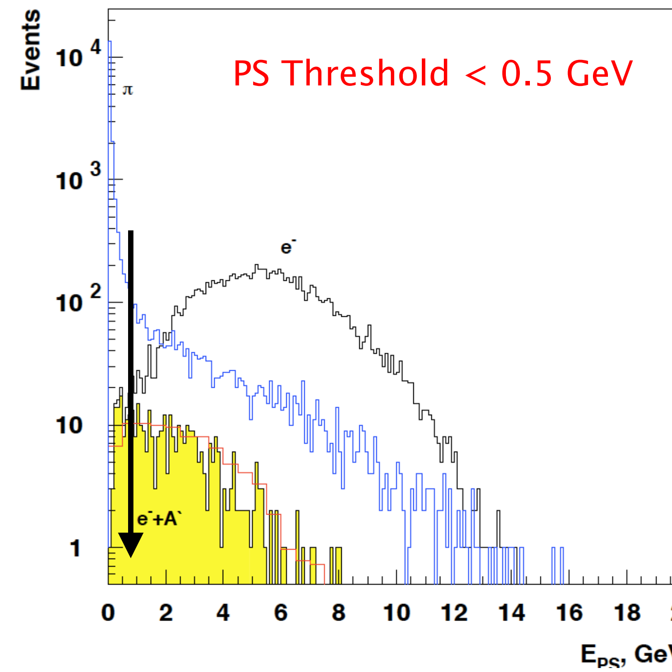
NA64 Collaboration arXiV:1703.05993

Signal Selection and cuts

Veto Zero Energy Threshold < 10 MeV

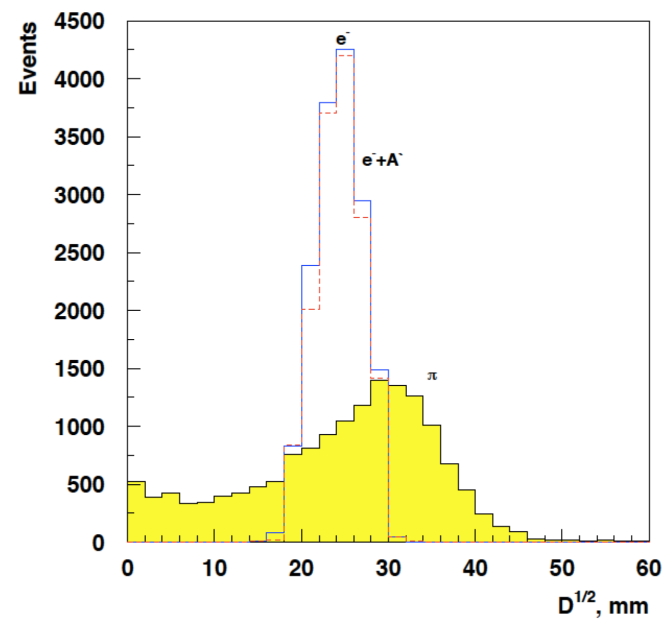


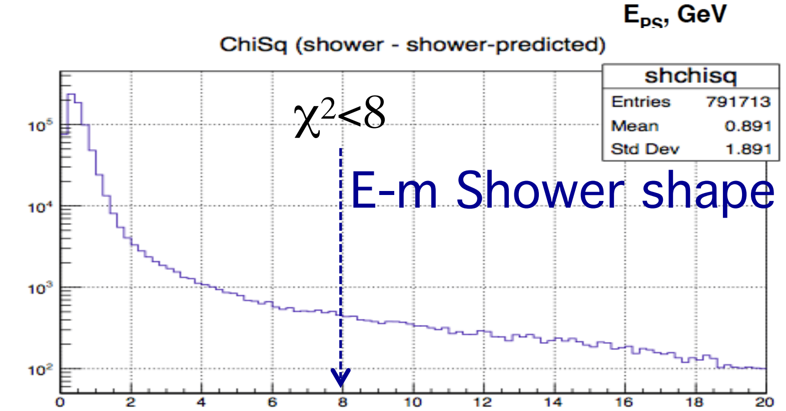


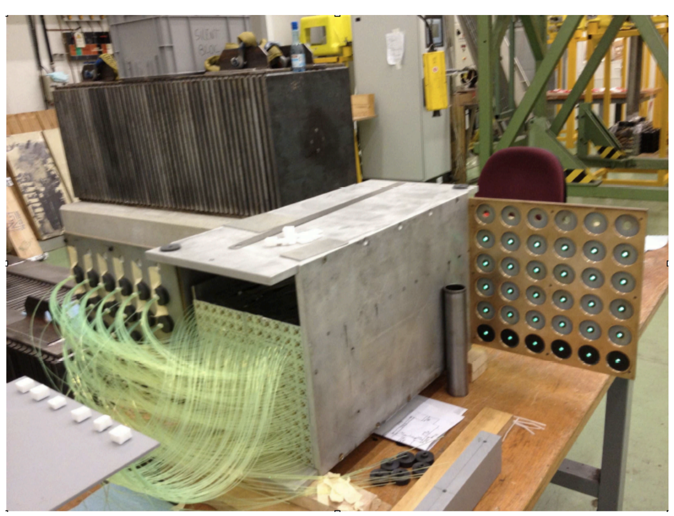


- Incoming beam tagging
- Lateral and Longitudinal shower shape consistent with that expected from a signal shower.
- No activity in Veto and HCAL above set threshold.

$D = \Sigma_i E_i[(X_i - X_e)^2 + (Y_i - Y_e)^2]^{1/2}/\Sigma_i E_i$

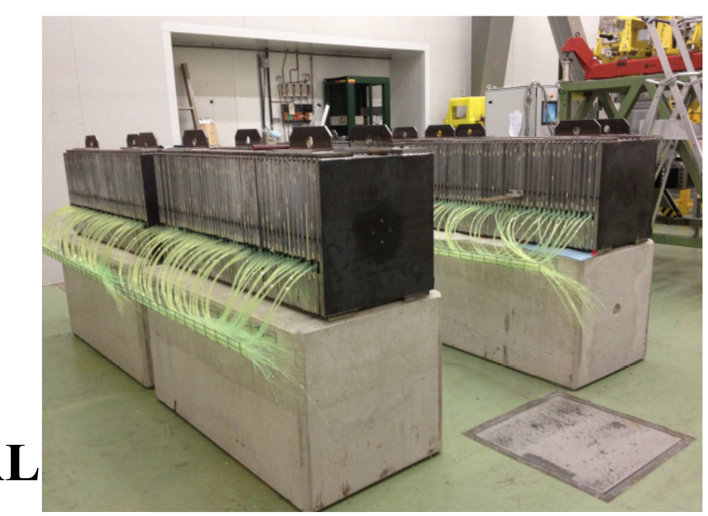






ECAL —> 40X_0

HCAL



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A′ Selection

- Cut Selection Criteria
  - Maximal A′ efficiency.
  - Minimal background
- Selection efficiencies cross-checked with data from e- beams and MC.
- Overall detection efficiency ~ 0.5-0.6 depending on $m_{A'}$.

- Systematic errors dominated by uncertainties in A′ yield ~ 10%
- **Cross-checked with dimuon production.**

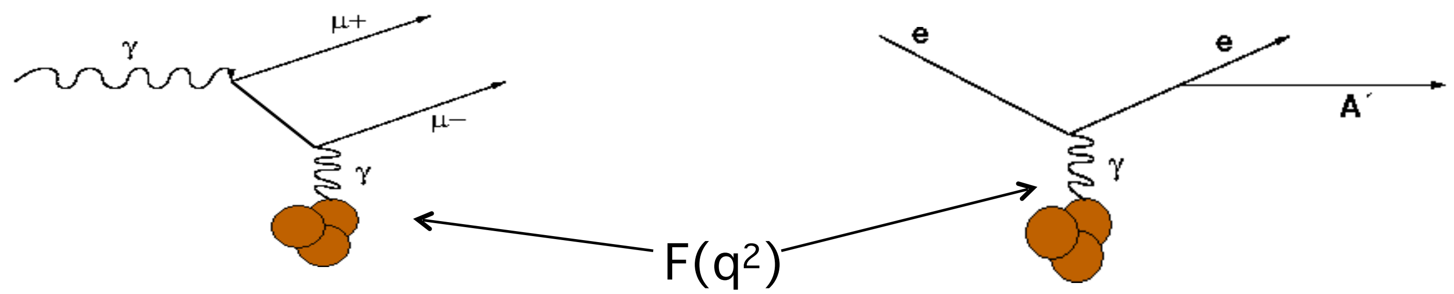
TABLE II. Summary of efficiencies for the signal event selection for the mass $m_{A'} = 10(100)$ MeV in the data sample obtained for the high intensity run III. For discussion of corresponding uncertainties, see Sec. VII.

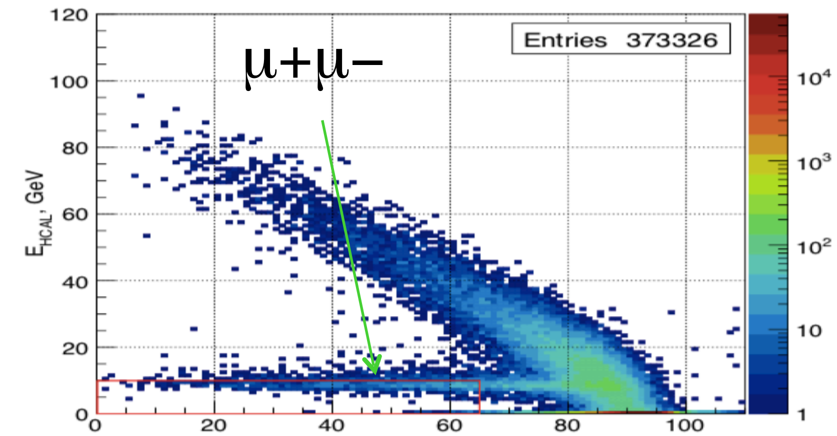
item	Efficiency	sample
primary e^-, ϵ_e	0.58	Data, Dimuons
ECAL, $\epsilon_{\rm ECAL}$	0.93(0.90)	Data, Dimuons
V_2, ϵ_V	0.94	Data, MC
HCAL, $\epsilon_{\rm HCAL}$	0.98	Data, MC
Total	0.50(0.48)	

TABLE III. Summary of systematic uncertainties for the mass $m_{A'} = 10(100)$ MeV in the high intensity run III.

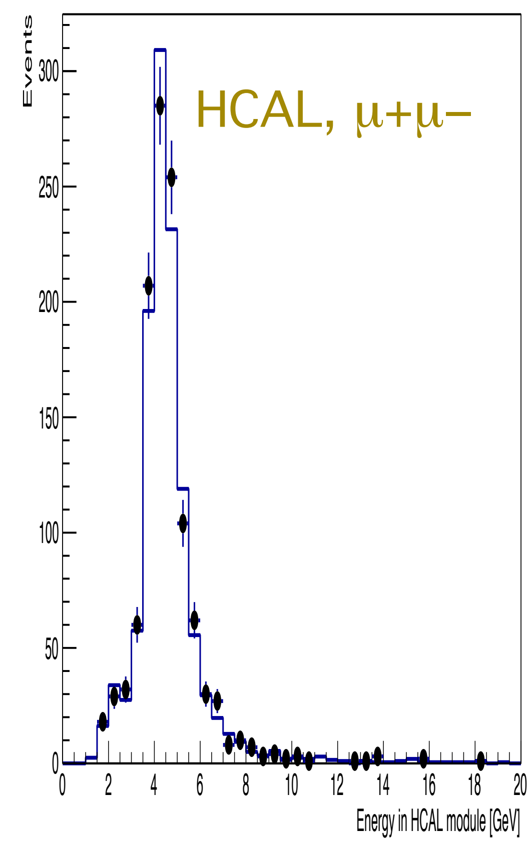
Source of the error	Estimated error
Normalization	
number of collected EOT, $n_{\rm EOT}$	2%
A' Yield	
signal cross section	10%
A' efficiency	
primary e^- selection	4%
ECAL selection	2% (3.5%)
ECAL spectrum reweighting	7% (5%)
V_2 cut threshold	3%
HCAL cut threshold	2%
Total	9%(8%)

Dimuon Production

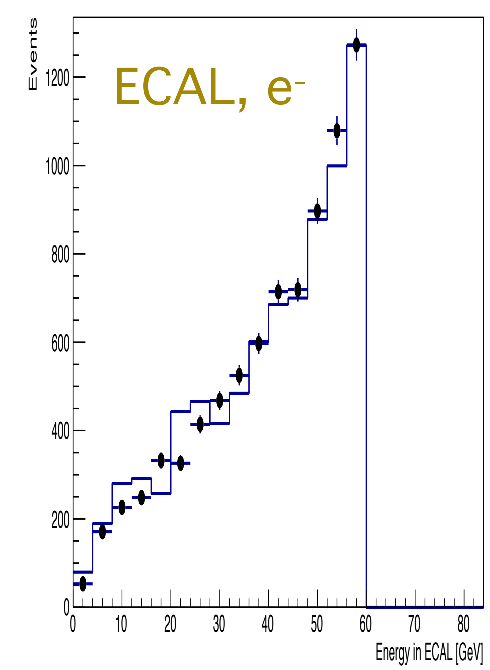




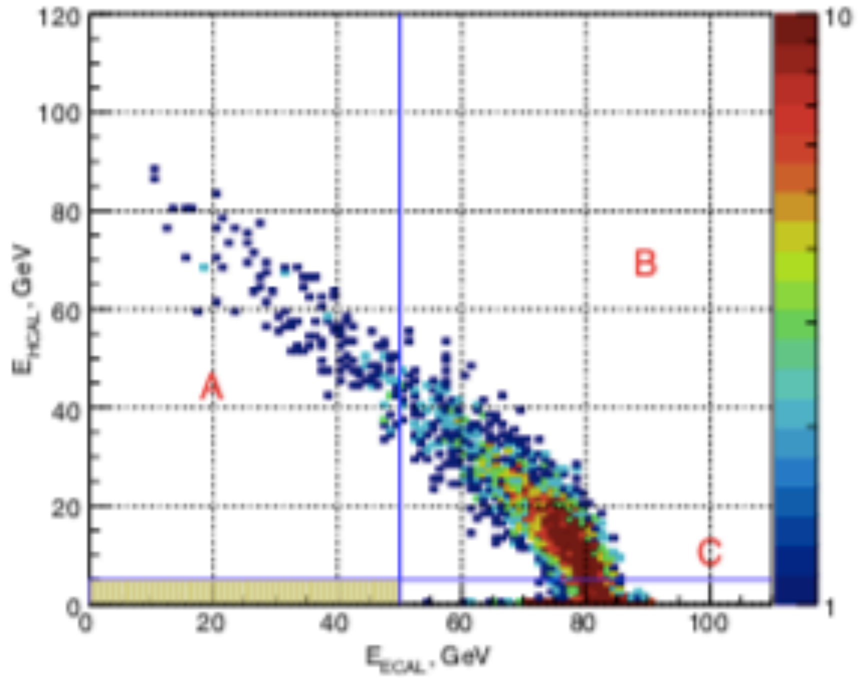
- Rare QED reference process ~ 10^{-5} /EOT

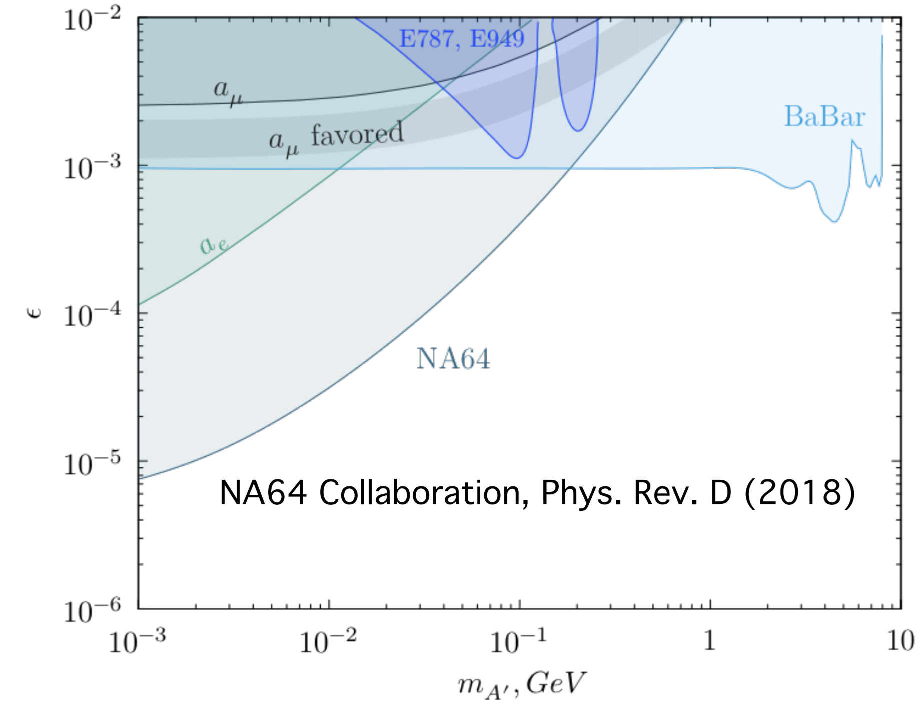


- Similar to A′ production
- Same region of $q^2 \sim m_{A'}^2/E \sim m^2_{\mu\mu}/E$
- Cross-check of A′ yield, systematic errors.
- Background prediction from data
- Cross-check of overall efficiency



Sensitivity from combined data





No signal observed in 2016–17 data sample of ~10^{11} EOT (Preliminary 2017) with combined background ~ 0.2 events.

1.9 x 10^{11} EOT collected for 2018 at 100 GeV/c.

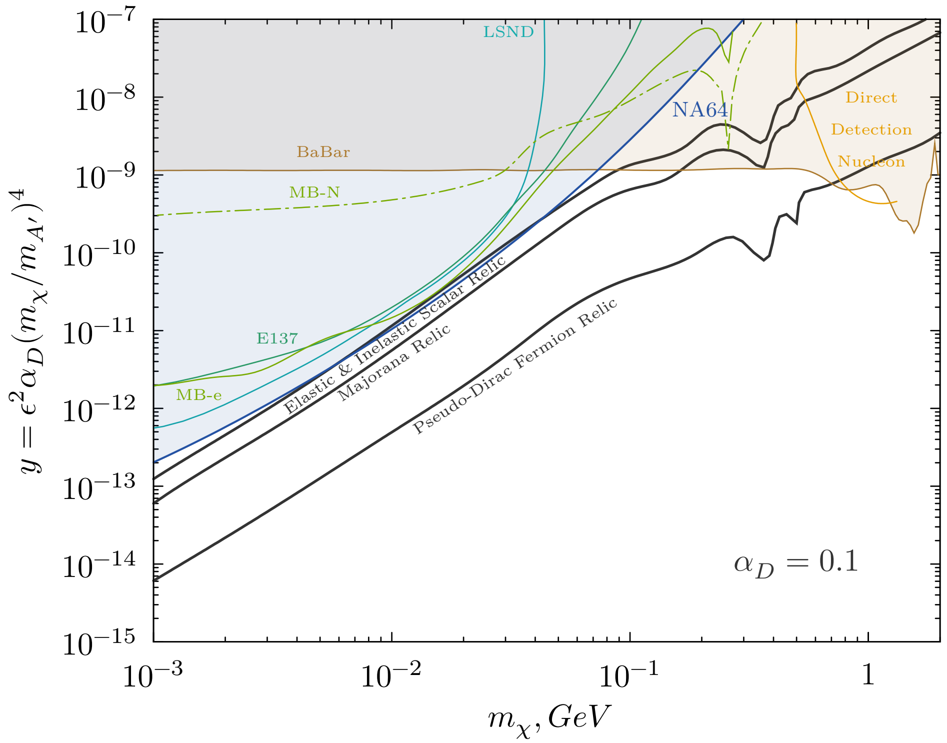
Data analysis ongoing for 2018 run.

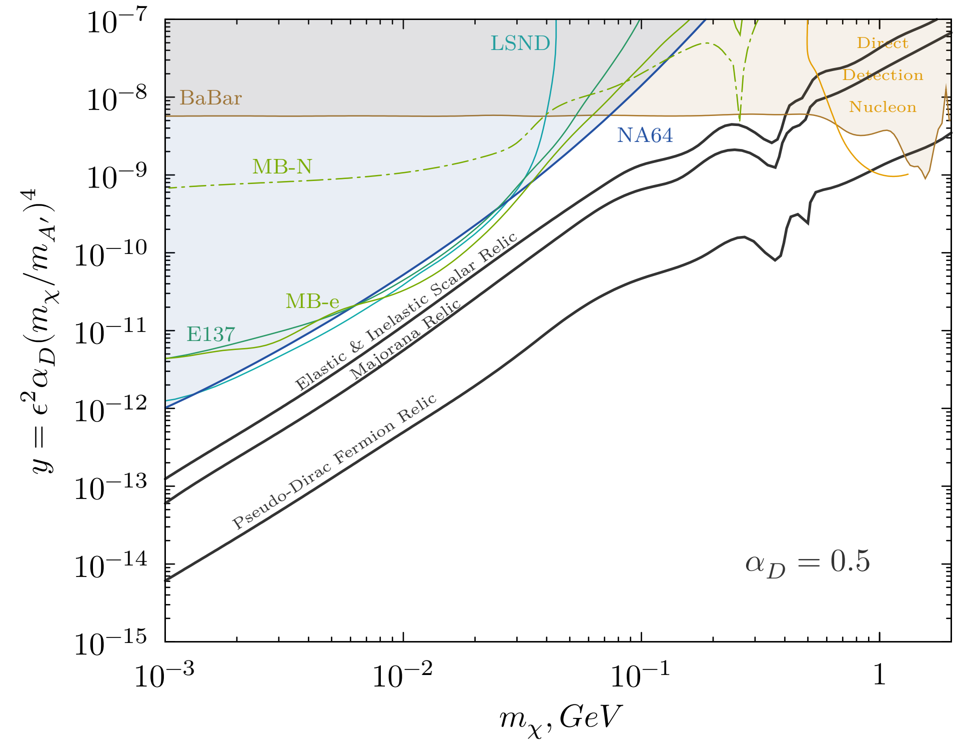
Combined sensitivity on the total 3 x 10^{11} EOT calculated.

Recent results of the NA64 experiment at the CERN SPS
https://www.epj-conferences.org/articles/epjconf/pdf/2019/17/epjconf_phi...

Invited talk at APS Meeting, April 14–17, 2018; Columbus, Ohio (P. Crivelli, ETH)
Invited talk at Light Dark World 2018, Dec 18, 2018; Daejeon, South Korea (D. Banerjee, CERN)

Results from 2016 and beyond: Light TDM





With ~ 3×10^{11} EOT for $\alpha_D = 0.1$ first beam dump experiment to touch the scalar relic sensitivity. Aim to further probe new areas of the mixing and parameters of the sub-GeV (Majorana, Pseudo-Dirac models).

Advantage of NA64 – its sensitivity ~ ε^2, while for beam-dump exp. ~ $\varepsilon^2 \times \alpha_D \varepsilon^2$

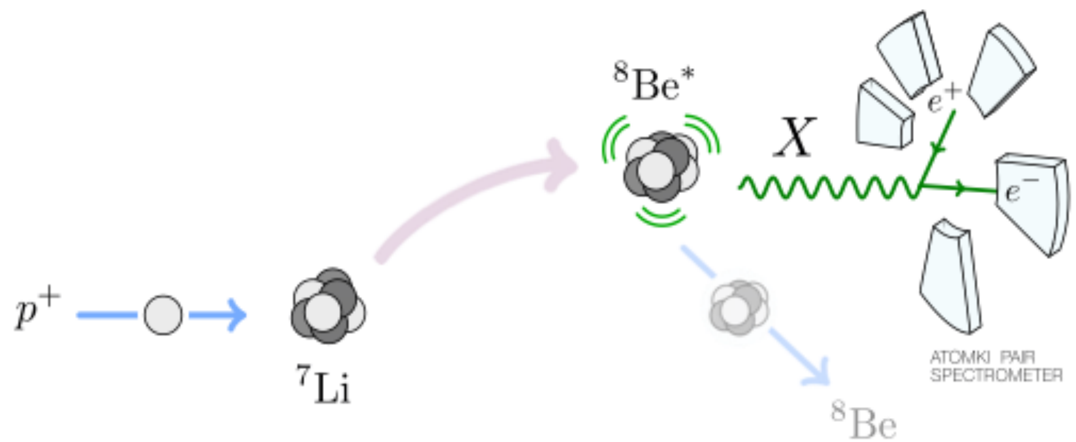
A′ —> e+e- Visible Channel

- Feasibility study in Oct 2016
- Data taking in Sept 2017

Additional Motivation: X boson explanation of ^{8}Be* anomaly ?

^{7}Li(p,γ)^{8}Be, M_X =17 MeV

ATOMKI ^{8}Be* anomaly: a new 17 MeV gauge boson ?



Feng et al, 2016

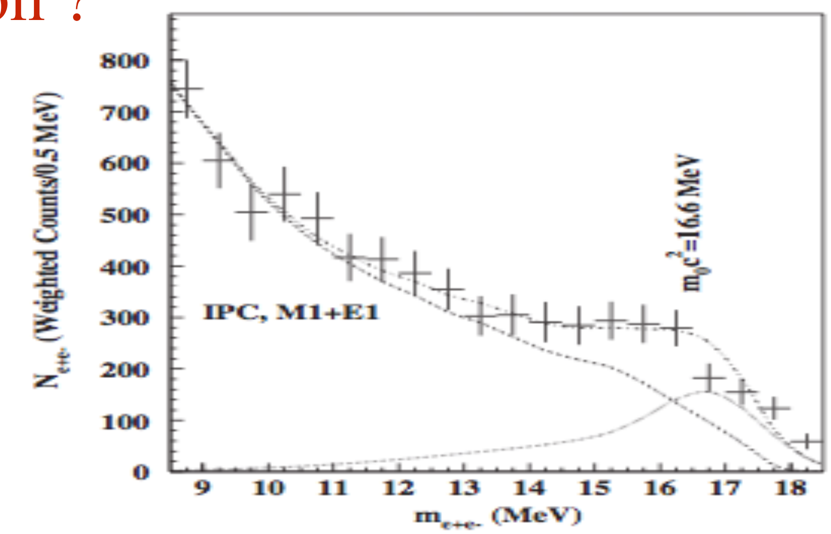
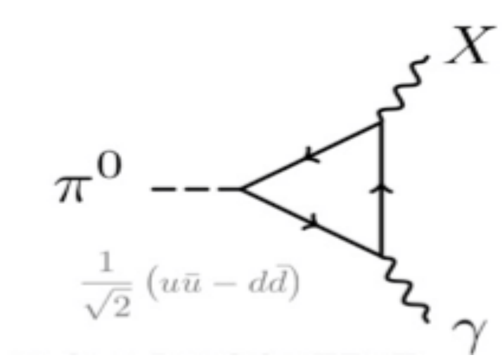


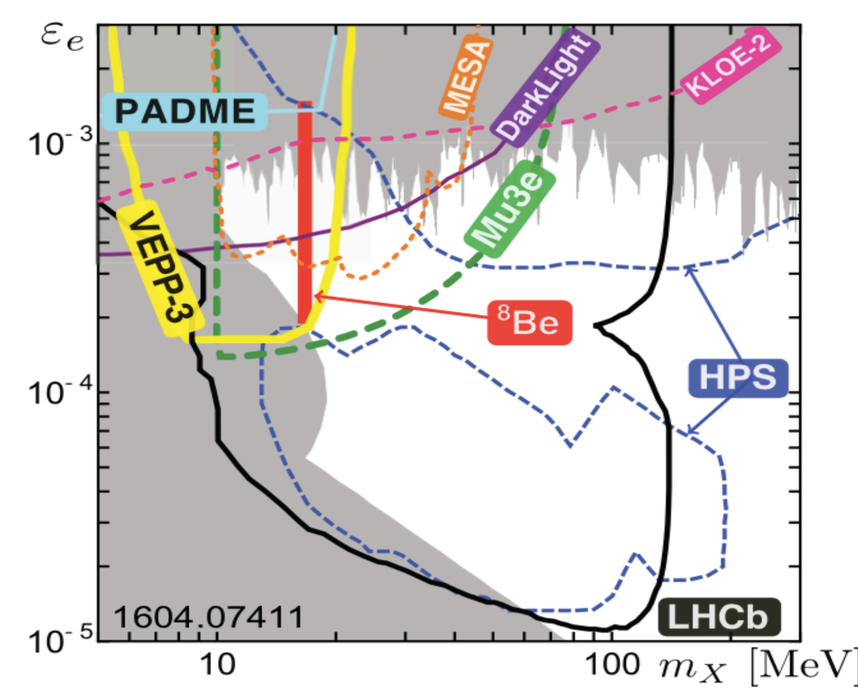
FIG. 5. Invariant mass distribution derived for the 18.15 MeV transition in ^{8}Be.



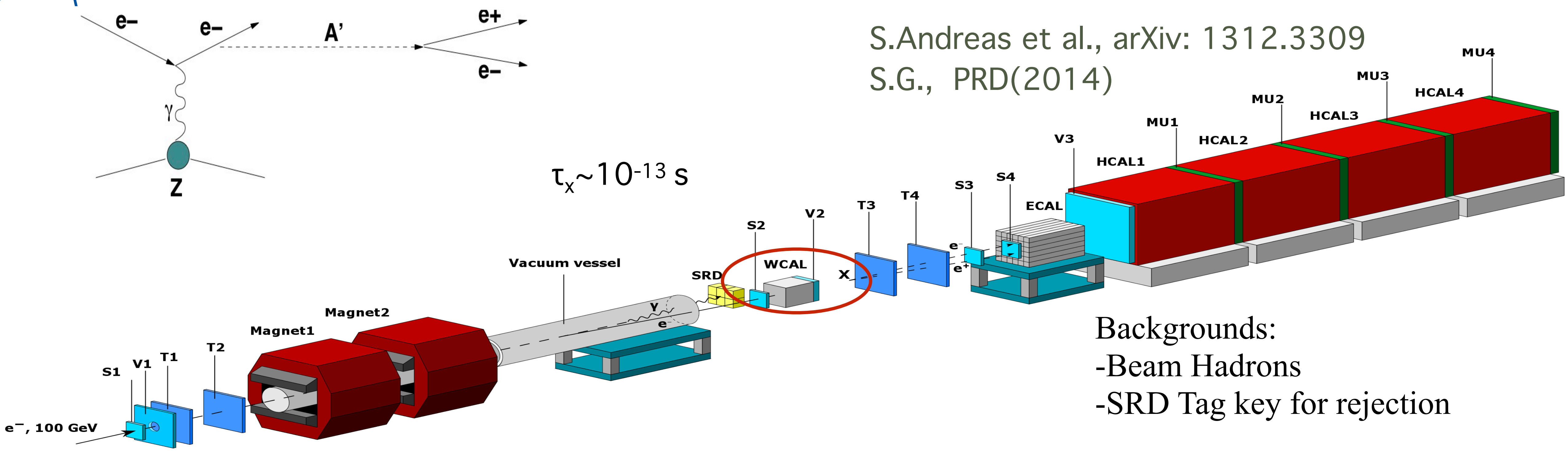
X cannot be A′ due to constraints from $\pi^0 \to X\gamma$ decay:

$\Gamma(\pi^0 \to X\gamma) \sim (\varepsilon_u q_u - \varepsilon_d q_d)^2 \sim 0$

if $2\varepsilon_u = -\varepsilon_d$ -> protophobic X



Search for X(A') —> e+e- decays



τ_X~10^{-13} s

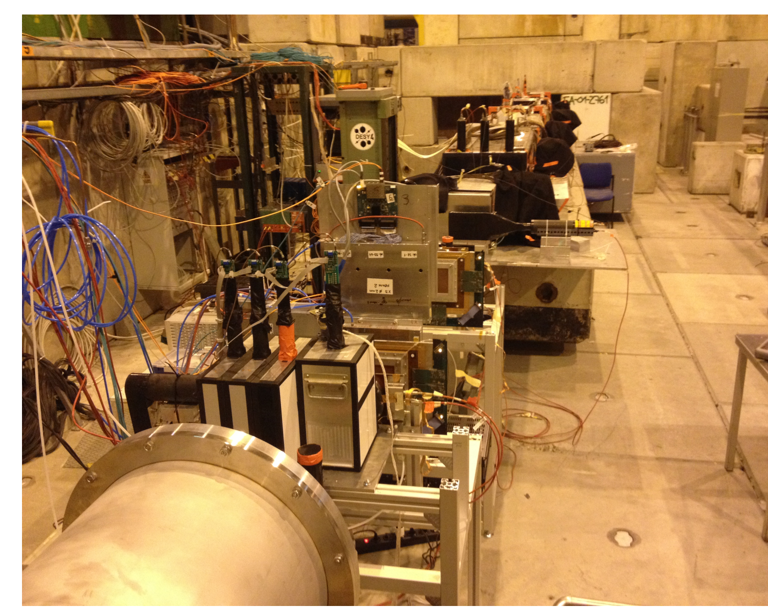
S.Andreas et al., arXiv: 1312.3309
S.G., PRD(2014)

Backgrounds:
-Beam Hadrons
-SRD Tag key for rejection

Setup:

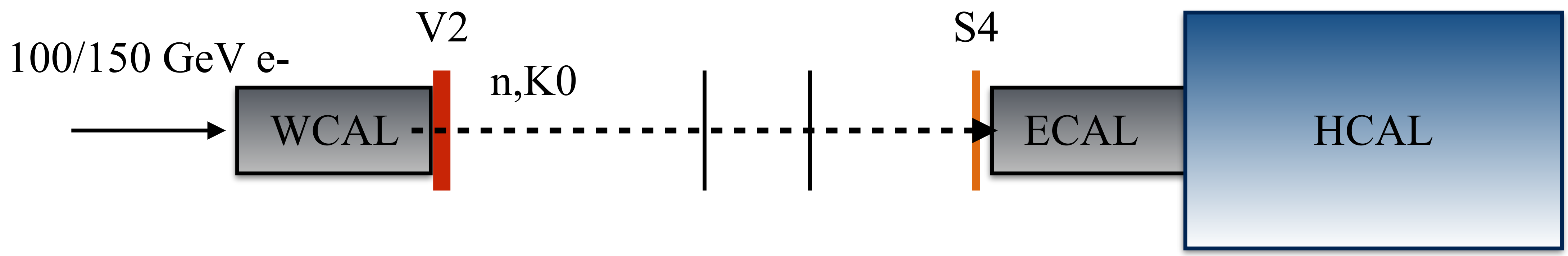
- High energy beam to trigger the reaction: 100/150 GeV e- beam from the CERN SPS H4 beamline.
- High intensity beam > 10^5 e-/sec/cm^2
- Main impurities of H4 beam: π−, low energy e− (~1%) μ− and K− (≤0.1%)
- e- tagging system: trackers +SRD
- 4π fully hermetic detector ECAL+HCAL

Signature:
In:
Single 100/150 GeV e-
Out:
No signal in V2.
Two MIP signal in S4.
$E_{WCAL} < E0$, and
$E0 = E_{WCAL} + E_{ECAL}$
θ_{e+e-} too small to be resolved
ECAL showers consistent with a single e-m one.
No interaction downstream.



2017 run e⁻, 100 GeV

Main background from $K^0_S \longrightarrow \pi^0\pi^0 \longrightarrow \gamma$'s $\longrightarrow e^+e^-$ decay chain



Estimate of K^0_S flux: $|K^0\rangle \sim |K^0_S\rangle + |K^0_L\rangle$

Method 1 -> Measured ECAL+HCAL energy of long-lived neutral hadrons.
No signal in V2 and S4.
No signal in ECAL, absorbed in HCAL.
1000 events observed; $n:K^0 \sim 10:1$; $nK^0 \sim 10^2$
Estimate K^0_L and hence K^0_S

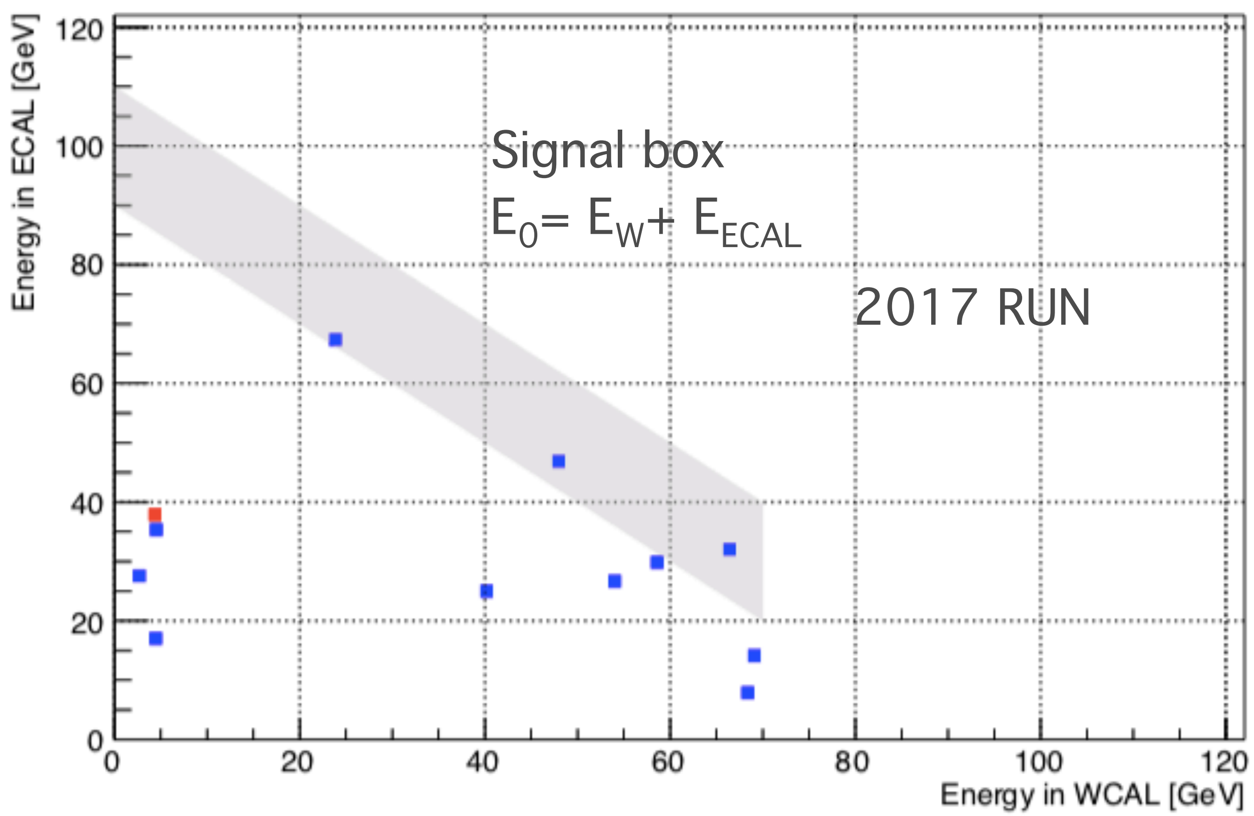
Method 2 -> True neutral e-m events (γ's) selected.
No signal in V2 and S4+single e-m shower in ECAL.
Assume all γ's from K^0 chain;
Simulate no. of required K^0: $nK^0 \sim 1.5\times10^2$

TABLE I. Expected numbers of background events in the signal box estimated for 5.4×10^{10} EOT.

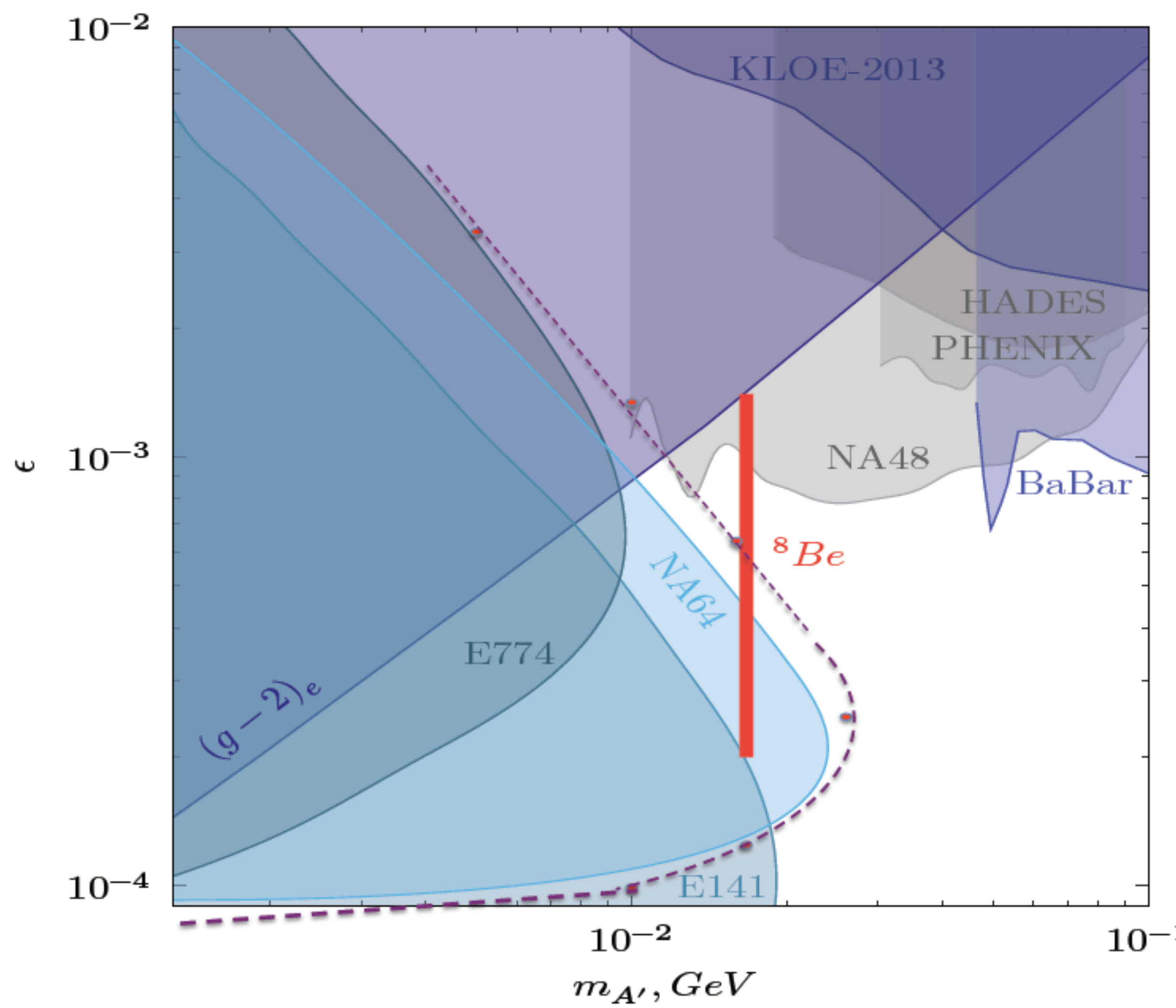
Source of background	Events
e^+e^- pair production by punchthrough γ	< 0.001
$K^0_S \to 2\pi^0; \pi^0 \to \gamma e^+e^-; \gamma \to e^+e^-$; $K^0_S \to \pi^+\pi^-$	0.06 ± 0.034
$\pi N \to (\geq 1)\pi^0 + n + ...; \pi^0 \to \gamma e^+e^-; \gamma \to e^+e^-$	0.01 ± 0.004
π^- bremsstrahlung in the WCAL , $\gamma \to e^+e^-$	< 0.0001
$\pi, K \to e\nu$, K_{e4} decays	< 0.001
$eZ \to eZ\mu^+\mu^-; \mu^\pm \to e^\pm\nu\nu$	< 0.001
punchthrough π	< 0.003
Total	0.07 ± 0.035

Results from 2017+2018 run, 8x10^10 EOT

In 2018: i) Beam Energy increased to 150 GeV/c to increase sensitivity to short lived X bosons (higher ϵ) ;
ii) Thinner V2 placed immediately after the WCAL ; iii) Distance between ECAL and WCAL increased.



Br(X → e^+e^-)=1, $\varepsilon^2 \sim 10^{-7}$



$10^{-5} < \varepsilon < 10^{-3}$

Event selection :

- Neutral track;
- No V2 and S4 signal.
- No HCAL.
- Single e-m shower

Three events observed in 2017 and 1 event in 2018 within signal box. Identified as photons (no track).

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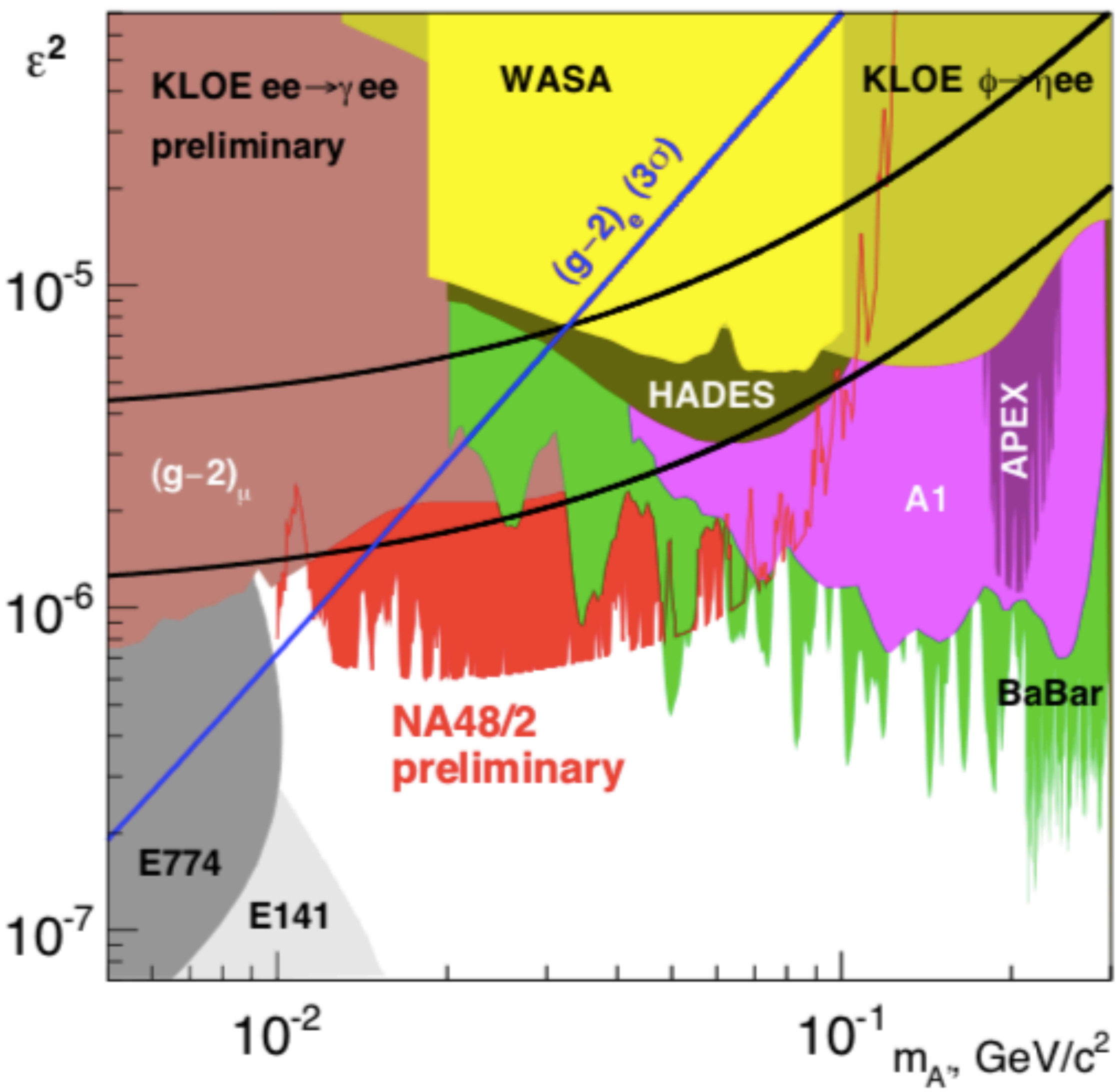
NA64 Collaboration, Phys.Rev.Lett. (2018)

NA64μ - Plan of searches at the CERN M2 muon beam

April 2019 : Proposal to SPSC
Currently: Pilot run in 2021-2022 currently under approval by SPSC

A′ explanation for $(g-2)_\mu$ ruled out

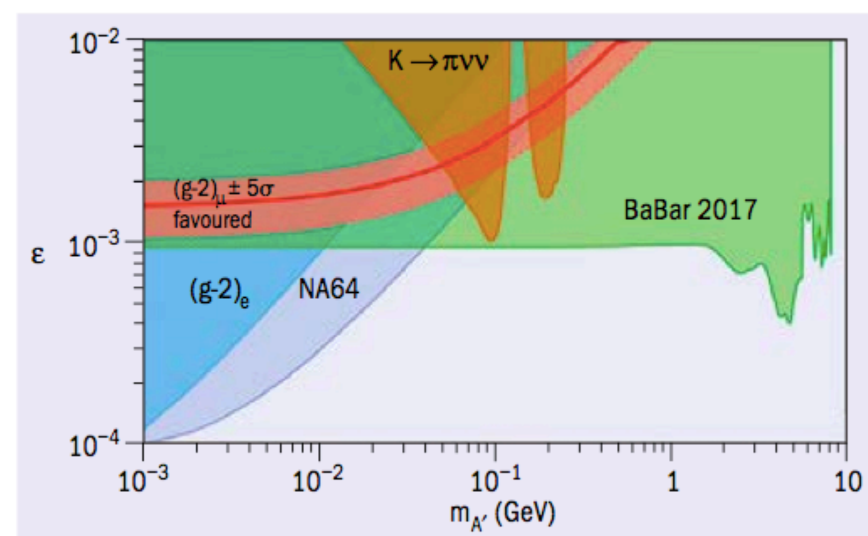
A′ —> e+e- (visible)



A′ —> invisible

CERN Courier April 2017

News



Regions of the dark-photon parameter space (mixing strength versus mass) excluded by BaBar (green) compared with the previous constraints. The new analysis rules out dark-photon coupling as the explanation for the muon (g-2) anomaly and places stringent constraints on dark-sector models.

of Caltech, who has worked on dark-photon models. "In contrast to massless dark photons, which are analogous to ordinary photons, this experiment constrains a slightly different idea of dark force-carrying particles that are associated with a broken symmetry, which therefore get a mass and then can decay. They are more like 'dark Z bosons' than dark photons."

● **Further reading**

BaBar Collaboration 2017 arXiv:1702.03327.

NA64 Collaboration 2017 *Phys. Rev. Lett.* **118** 011802.

BaBar: e+e- —> γA′, A′ —> e+e-

APEX: e-Z —> e-ZA′, A′ —> e+e-

NA48: π0 —> γA′, A′ —> e+e-

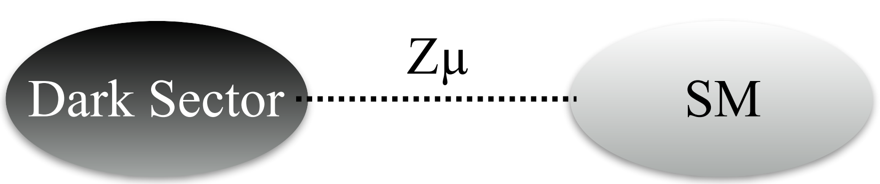
BaBar: e+e- —> γA′, A′ —> invisible

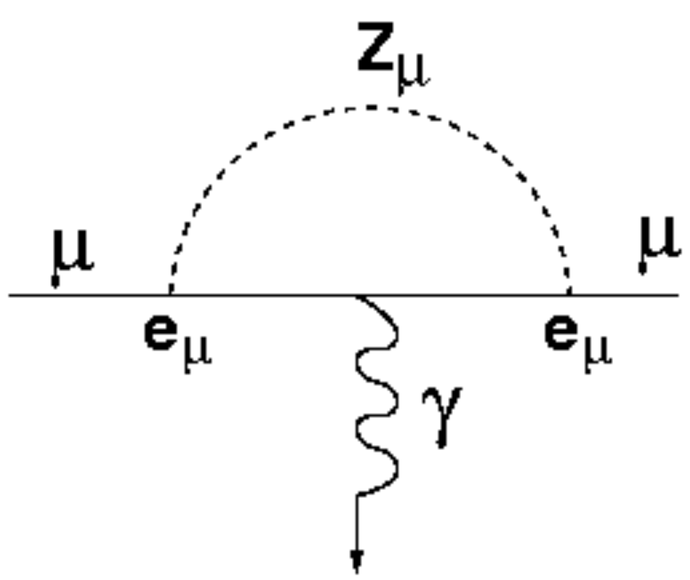
NA64: e-Z —> e-ZA′, A′ —> invisible

Zμ as explanation for the (g-2) anomaly

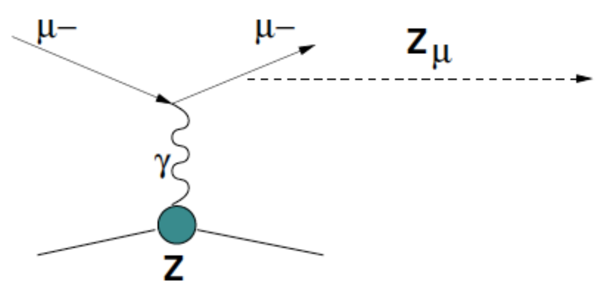
- Particles coupling predominantly to muons or tau.
- Standard Model extension with the $U(1)_{L\mu - L\tau}$ gauge symmetry.
- Doesn't require addition of fermions beyond the three SM generations.
- Predict the existence of a new massive gauge Zμ boson coupled predominantly to the second and third lepton generations through the $L\mu$-$L\tau$ current.
- $M_{Z\mu}$ in sub-GeV range.
- Zμ decays : Zμ —> μμ, ττ, ν ν ; if $M_{Z\mu} < 2m_\chi$

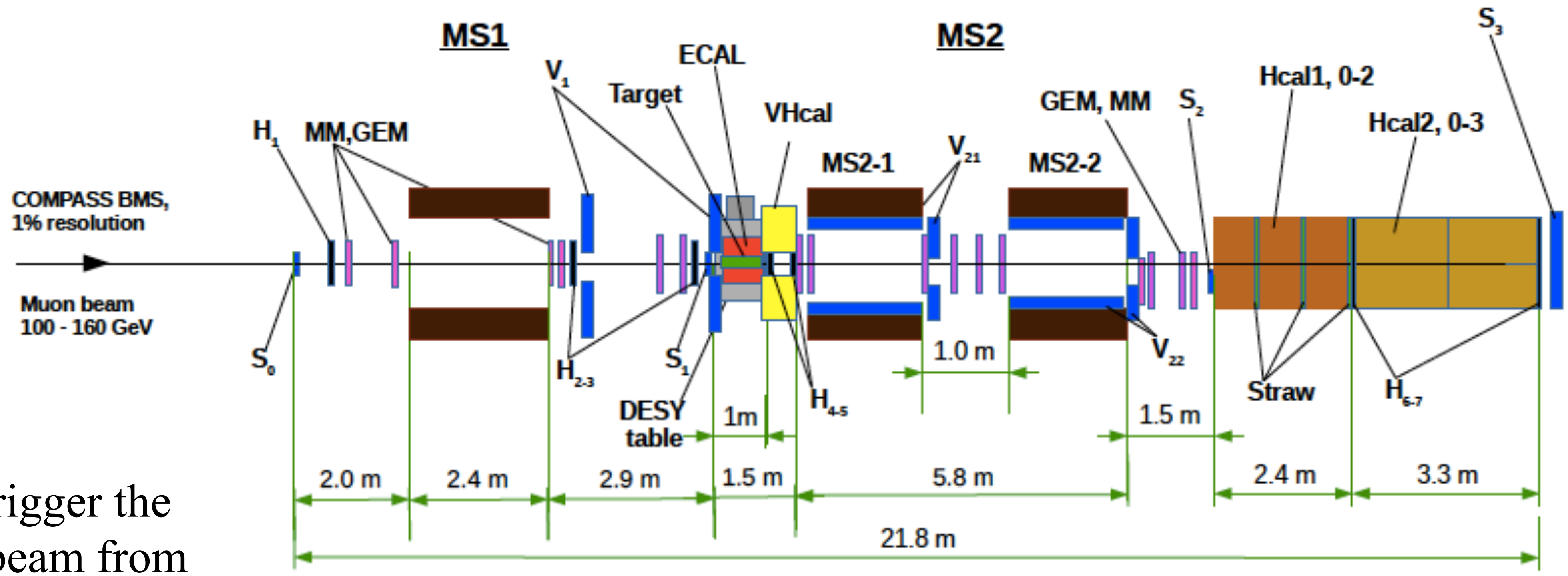
  Zμ —> χχ ; if $M_{Z\mu} > 2m_\chi$





Future Prospects of NA64 for dark sector searches- μ beam





Setup:

- High energy beam to trigger the reaction: 160 GeV μ- beam from the CERN SPS M2 beamline.
- High intensity beam > 10^7 μ^-/spill
- In μ- tagging system: BMS +MS1 (Magnet+Trackers)
- Out μ tagging system: MS2 (2 Magnets + Trackers)
- 4π fully hermetic detector ECAL+HCAL+Veto

Signature:

In:

Single 160 GeV μ-

Out:

< 80-100 GeV μ-

No energy in ECAL, VETO, HCAL.

Sensitivity ~ g_μ^2

Background:

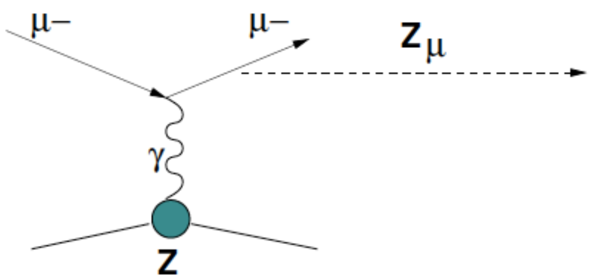
Π, K —> μν decays

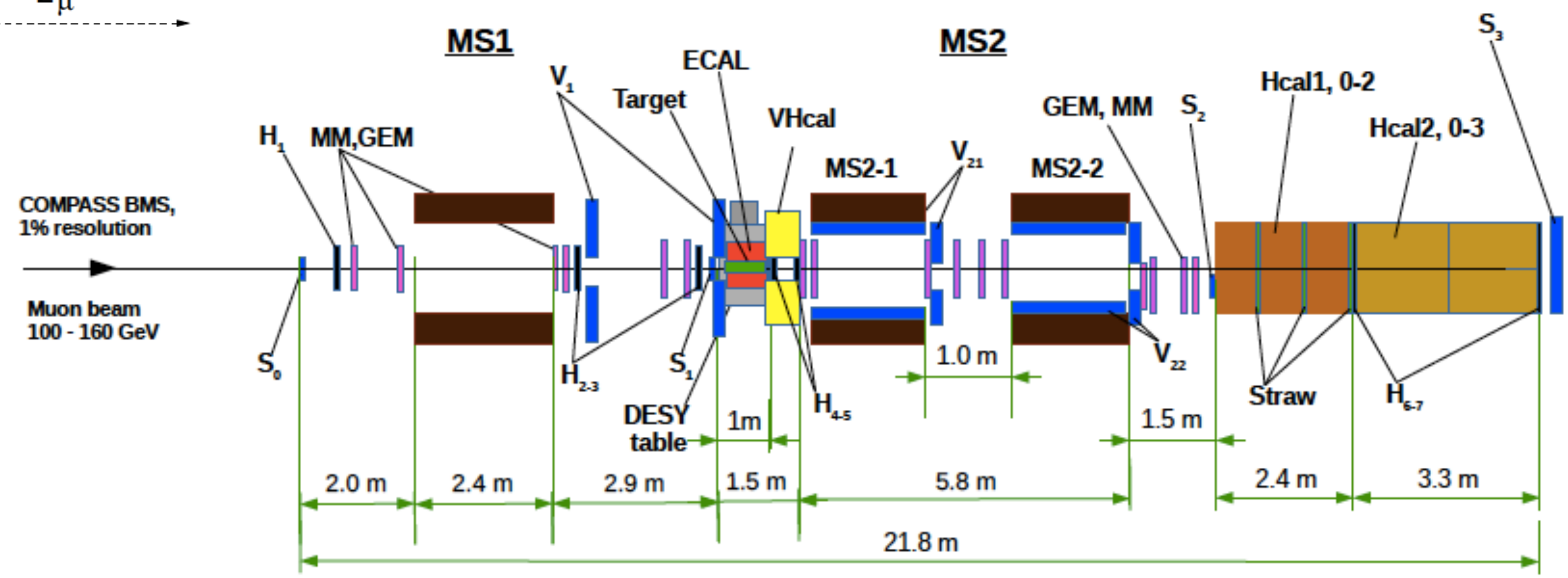
Energy Leak / Non Hermetic detector

Low energy incoming muons

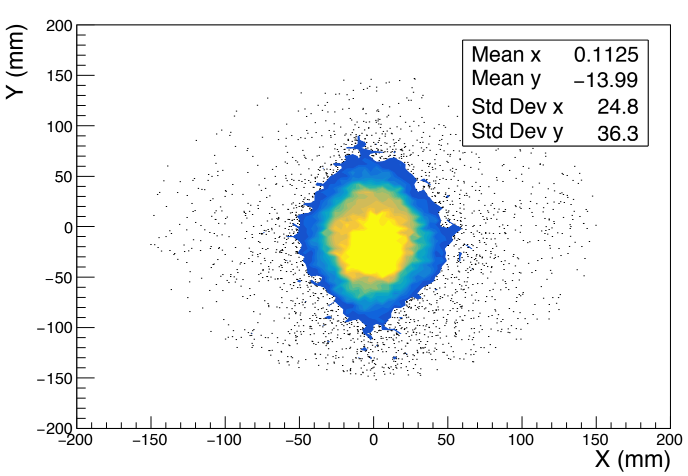
Physical background (trident, EW processes, …)

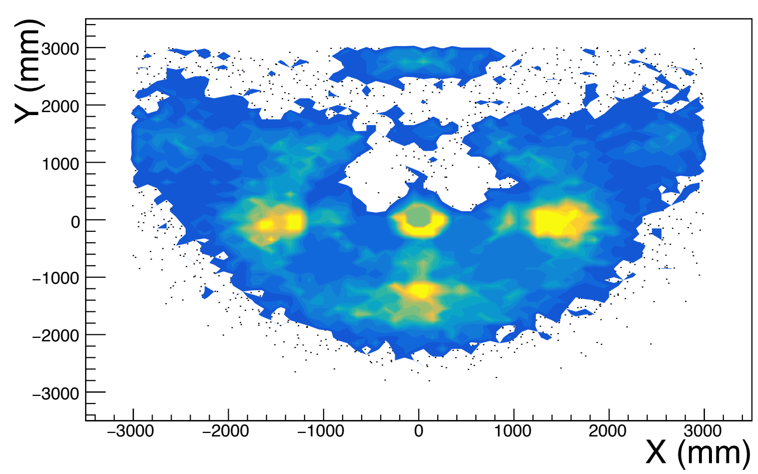
Future Prospects of NA64 for dark sector searches- μ beam





- Incoming beam from the CERN SPS EHN2 Muon Beamline
  - 160 GeV/c beam at 10^7/sec.
  - $\sigma x \sim \sigma y \sim 20$ mm
  - $\sigma x' \sim \sigma y' \sim 0.2$ mrad
  - Large Halo component.

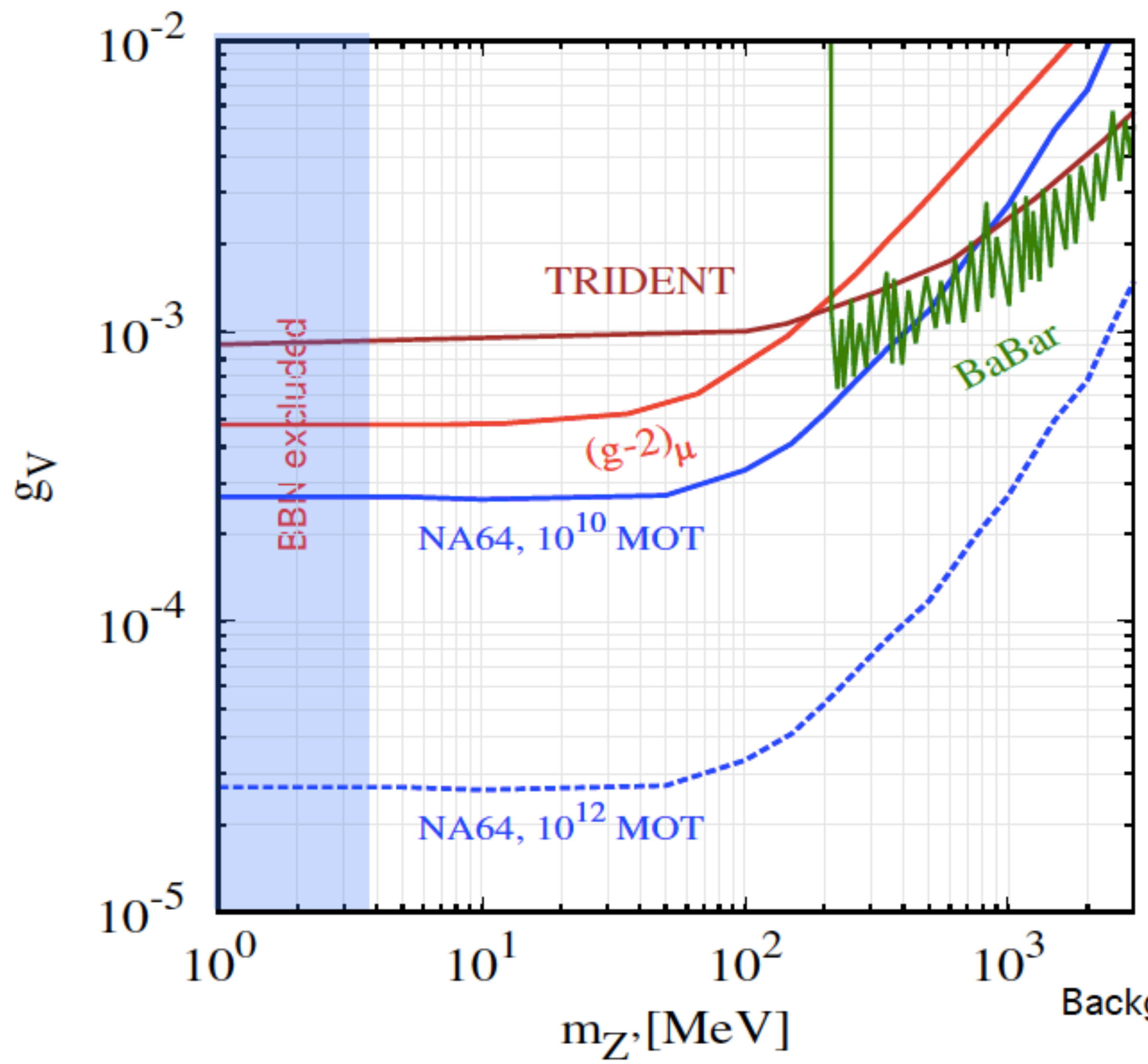




Different scales

- Requires detailed simulation for trigger selection; beam tagging; background estimation.
- Preliminary simulation and estimation of detector performance done
- Proposal submitted in 2019
- Subject to approval first run to be taken beginning of 2022 after CERN LS2

Expected sensitivity



Background-free case.

160 GeV μ
10^{12} MOT

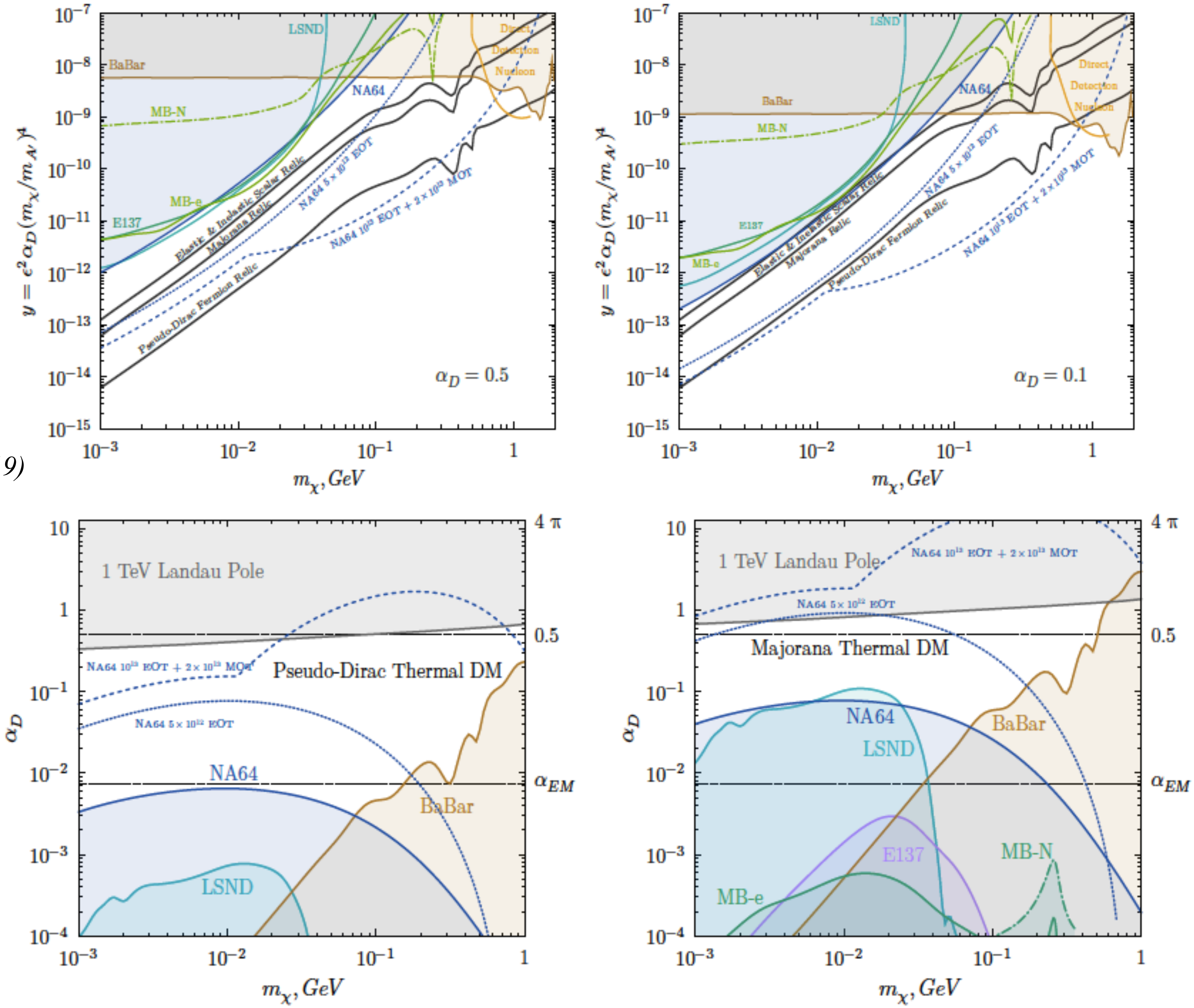
$a_\mu > 10^{-11}$

Possible to cover $(g\text{-}2)_\mu$ favored parameter space with ~ 10^{10} MOT

With the high intensity μ beam at CERN: Possible in a month running time.

Preliminary feasibility study:
SG, Krasnikov, Matveev PRD(2015)
Background-free case.

Dark Matter sensitivities



S. N. Gninenko et al., Phys. Let. B 796 (2019) 117-122

Plans for 2021

A´-> invisible

• 2021: 100 GeV e^-, ~10^7 e^- /spill, >10^{12} EOT

•Goal with ~$5x10^{12}$ EOT to exceed the sensitivity of beam-dump experiments (Majorana TDM) and to probe new areas of the mixing and parameters of the sub-GeV TDM models.

Strategy for the Be-anomaly and A´-> e^+e^-

•Fully exploit the H4 beam potential for energy 150 GeV

-2021: 150 GeV e^-, ~3–$4x10^6$ e^- /spill, > 5 $x10^{11}$ EOT

-Search with the ~$5X_0$ WCAL and Si pixel in B-field

•Goal: with ~10^{12} EOT to rule out the region $1.3x10^{-4}<\varepsilon_e<$ ~$7–8x10^{-3}$

Strategy for the Zμ search if approved

• 2022 – Setup the experiment at the EHN2 Beamline.

• ~ 2 weeks of detector testing, calibrations, initial beam tests.

• ~ 2 week of physics – collect ~ 10^{10} MOT —> significant improvement of existing constraints for Zμ —> invisible decay mode

•Possibly constrain part of the muon g-2 parameter space

Summary

- Dark sector physics can effectively be probed with the NA64 techniques in the medium term future.
- Two complementary approaches to search for sub-GeV dark matter: beam dump and missing energy/momentum.
- Look for visible and invisible decays of dark sector mediators.
- The experiment can discover or rule-out nearly all predictive models of sub-GeV thermal DM
- Clarify the origin of the Be-anomaly.
- The new results promise to be rich.

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Thank You !!