Searches for Dark Sectors Weakly Coupled to Muons at the NA64μ Experiment at CERN

Joint Annual Meeting of ÖPG and SPS 2021

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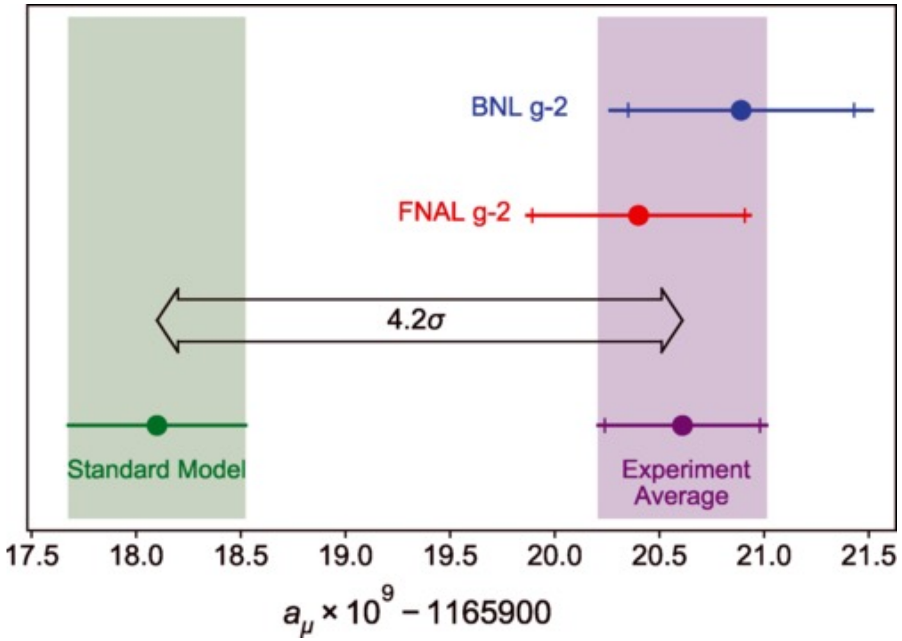
A Standard Model (SM) anomaly: the muon $(g-2)_\mu$ anomalous magnetic moment

Recently published results from Muon (g-2) Experiment @Fermilab indicates:

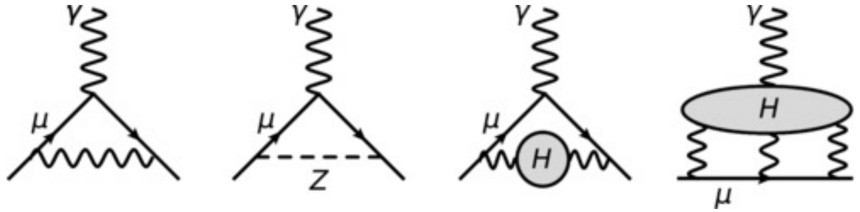
$$a_\mu(\text{Exp}) = 116\ 592\ 061(41) \times 10^{-11}$$



B. Abi et al., PRL 126, 141801 (2021)

Note: recent precise Lattice QCD calculations reduce discrepancy (see S. Borsanyi et al., Nature 593 (2021) 51-55). Hadronic loop contributions to be measured by MUonE @CERN (G. Abbiendi. PoS ICHEP2020, 223 (2021))

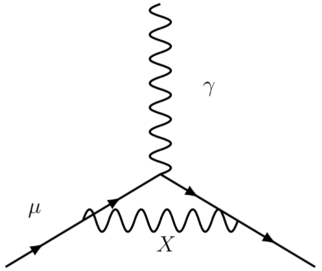
T. Ayoma et al., PR 887, 1-66 (2020)



$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{HVP} + a_\mu^{HLbL} = 116\ 591\ 810(43) \times 10^{-11}$$

$$a_\mu(\text{Exp}) - a_\mu(\text{SM}) = (251 \pm 59) \times 10^{-11}$$

? →

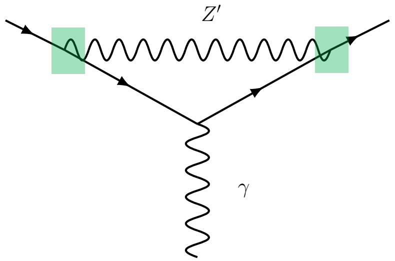


M. Pospelov et al., PLB 662, 53-61 (2008)

As a **New Physics contribution**, generic X boson vertex corrections could serve as possible explanation of $(g-2)_\mu$ discrepancy

→ NA64μ approach !

U(1) L_μ-L_τ model as a solution to the $(g\text{-}2)_\mu$ anomaly



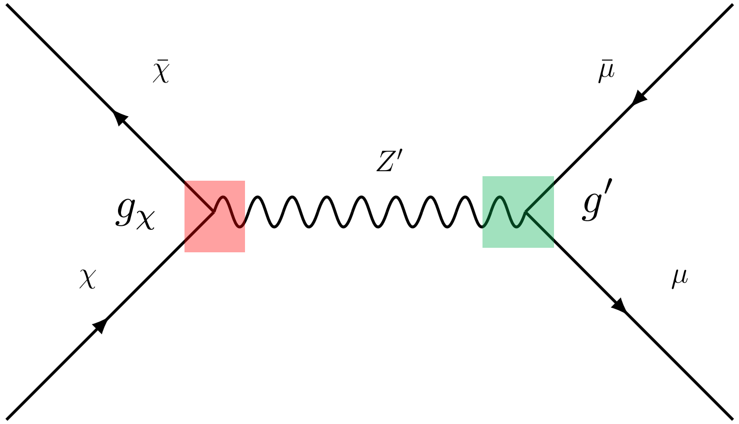
Muon anomaly $(g\text{-}2)_\mu$ can be explained by anomaly-free **U(1)$_{L\mu\text{-}L\tau}$ gauge group** extension of the SM

$$\mathcal{L}_{\mu-\tau} \supset g' \left(\bar{\mu}\gamma_\nu\mu + \bar{\nu}_{\mu L}\gamma_\nu\nu_{\mu L} - \bar{\tau}\gamma_\nu\tau - \bar{\nu}_{\tau L}\gamma_\nu\nu_{\tau L}\right) Z'^\nu$$

$$\Delta a_\mu^{Z'} = \frac{g'^2}{4\pi^2}\int_0^1 dx \frac{x^2(1-x)}{x^2 + (1-x)\, m_{Z'}^2/m_\mu^2}$$

R. Foot, Mod. Phys. Lett. A, 6 (7), 527-529 (1991)
X.G. Hang et al., PRD 44, 2118 (1991)
S. N. Gninenko et al., PRD 91, 095015 (2015)

with broken U(1)'$_{L\mu\text{-}L\tau}$ massive gauge boson Z' typically in the **sub-GeV mass range**.



Note: model also interesting to explain Dark Matter (DM) relic abundance when adding Dark sector current (Light Thermal Dark Matter (LTDM))

$$\mathcal{L}_\chi \supset -Z'_\mu J_\chi^\mu,\quad J_\chi^\mu = g_\chi \begin{cases} i\chi^*\partial_\mu\chi + h.c. & \text{Complex scalar} \\ \bar{\chi}_1\gamma^\mu\chi_2 + h.c. & \text{Pseudo-Dirac Fermion} \\ 1/2\bar{\chi}\gamma^\mu\gamma^5\chi & \text{Majorana Fermion} \\ \bar{\chi}\gamma^\mu\chi & \text{Dirac Fermion} \end{cases}$$

$$<\sigma v> \simeq \frac{3 g_\chi^2 g'^2 m_\chi^2}{\pi^2 m_{Z'}^4}$$

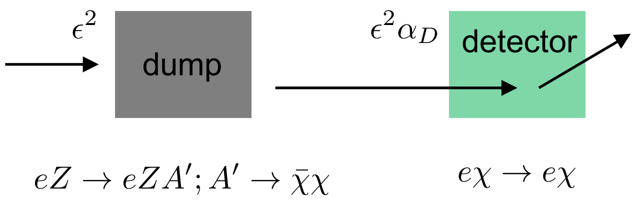
$$Z' \to \begin{cases} \bar{\nu}\nu & , m_{Z'} < 2m_\mu \\ \bar{\mu}\mu,\ \bar{\nu}\nu & , m_Z > 2m_\mu \\ \bar{\chi}\chi & , m_{Z'} > 2m_\chi \end{cases}$$

A fixed-target experiment: missing momentum searches at NA64μ

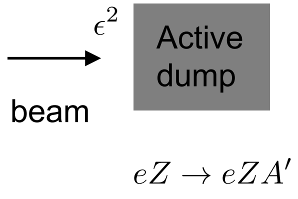
A fixed-target experiment at the CERN Super-Proton Synchrotron (SPS) aiming at probing **Dark Sector physics**

International collaboration with **50 researchers** from **16 institutions**

1) Beam dump (DM scattering off electron) $\sigma \propto \epsilon^4 \alpha_D$



2) Active beam dump (missing energy/momentum) $\sigma \propto \epsilon^2$



NA64e/μ approach !

2019	2020	2021	2022	2023	2024	2025

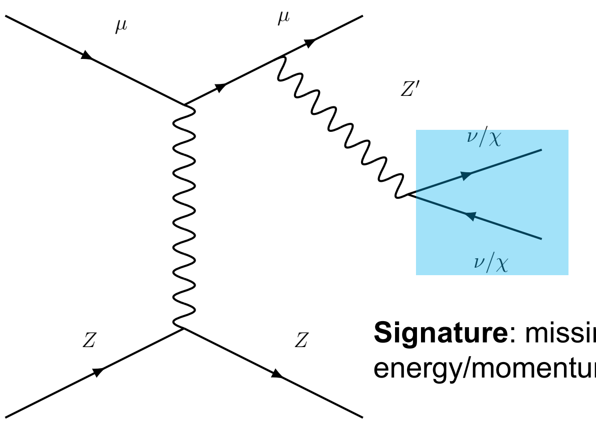
CERN Long Shutdown 2 (LS2)

CERN LS3

Muon test run

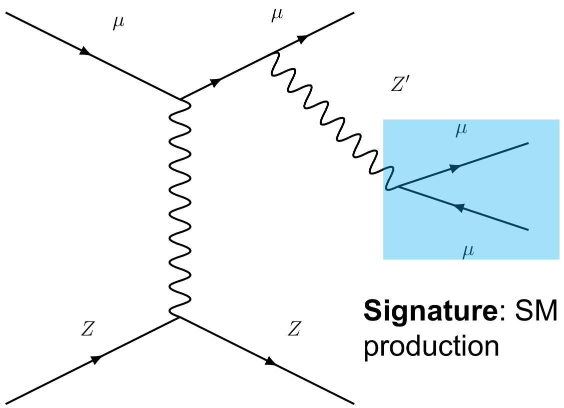
Muon physics run

Invisible



Signature: missing energy/momentum

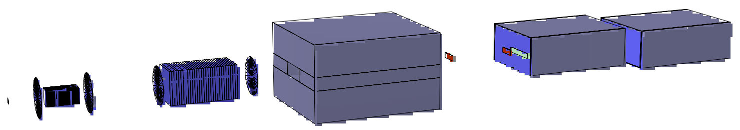
Visible



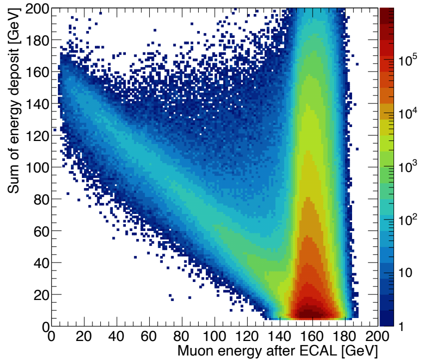
Signature: SM pair production

Monte Carlo (MC) feasibility study: the 2021 pilot run

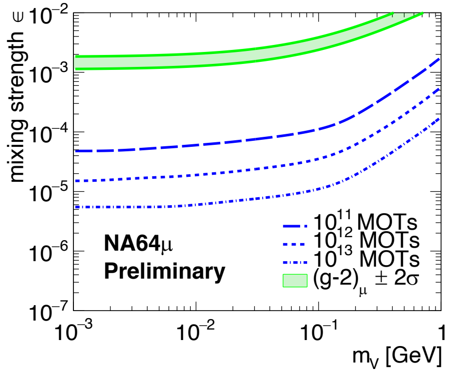
Set-up study: design and optimisation



Signal and background **simulations**



Simulations reconstruction and **analysis**, sensitivity estimation

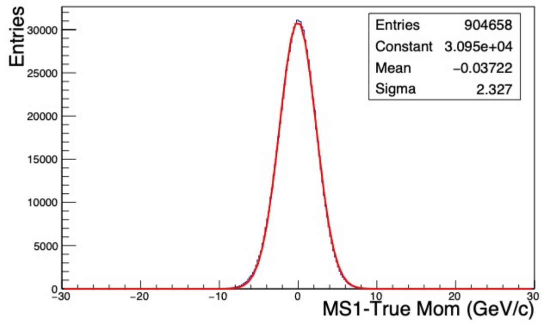


The **2021 pilot run**:

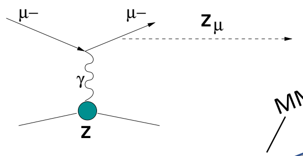
- Validate the MC simulations
- Evaluate the detectors responses
- Accumulate ≤ 10^9 MOTs
- Gather input to optimise set-up and data taking for 2022 physics run

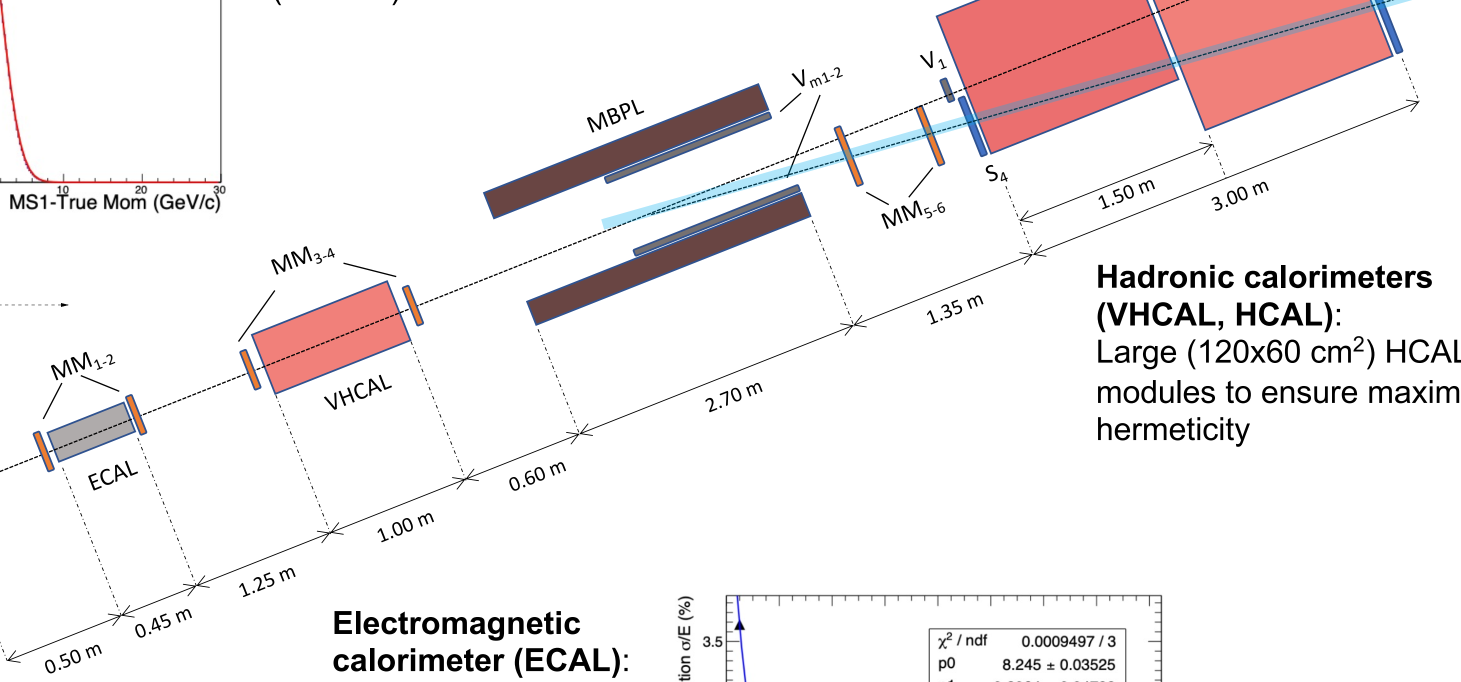
Two weeks **beam-time** in October/November granted by CERN SPSC !

Search for missing momentum events: the 2021 pilot run set-up



Momentum reconstruction:
For both initial and final state muons (1.4 T/m)

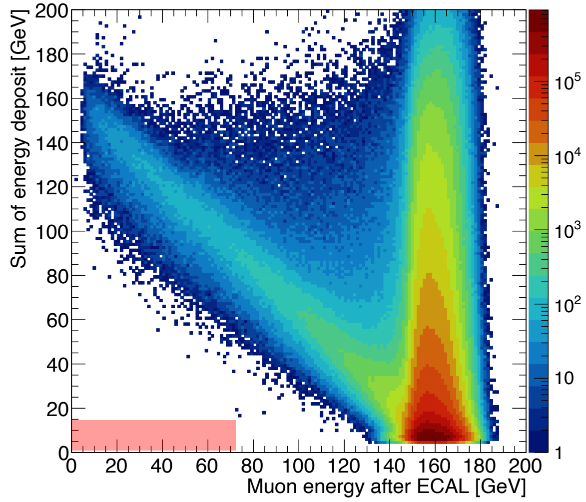




Scintillator counters:
Trigger on the deflected muons

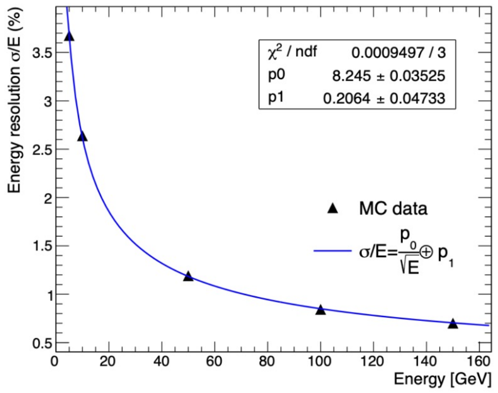
$$TRIGGER = S_0 \times S_1 \times S_\mu \times S_4 \times \overline{V_1} \times \overline{V_{m_1}} \times \overline{V_{m_2}}$$

Preliminary



Hadronic calorimeters (VHCAL, HCAL):
Large (120x60 cm^2) HCAL modules to ensure maximal hermeticity

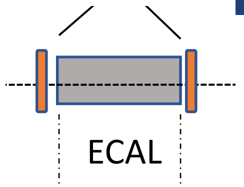
Electromagnetic calorimeter (ECAL):
Lead/Scintillator, 40 X_0



Beam:
- M2 beam line with 160 GeV muons from CERN SPS
- 10^6-10^7 μ/spill, 5s spill duration
- Beam hadron contamination 10^{-6} π/μ and K/π~0.03

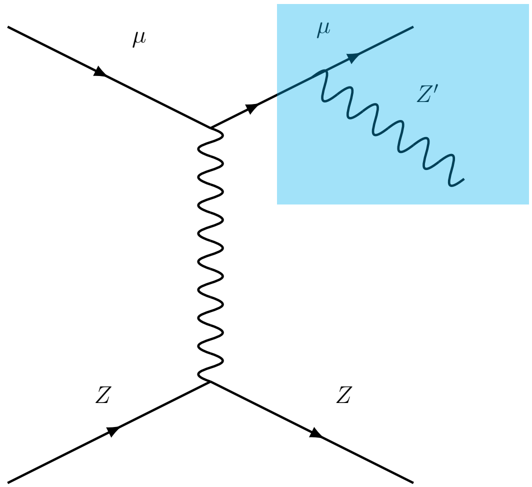
Signature as **missing momentum**:
- Single scattered muon with E < 80 GeV
- No energy deposited in VHCAL and HCAL, ECAL ~ MIP energy

LTDM production: signal simulation



Z’ produced through **muon bremsstrahlung**-like process in active target

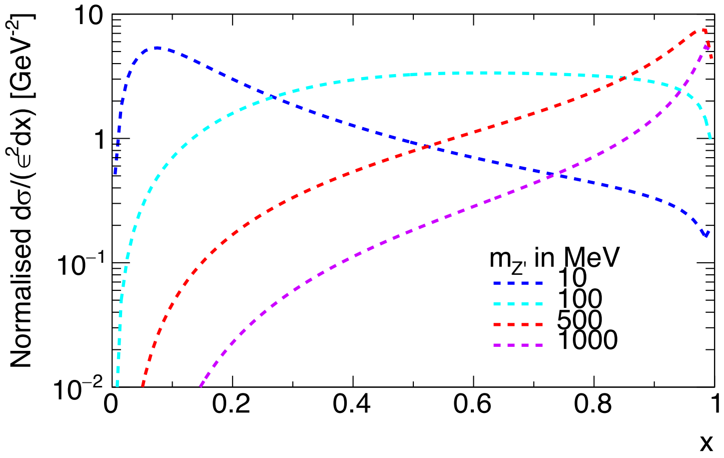
$$N_{Z'} \sim N_{MOT}\sigma_{\mu}^{Z'} L_{\mu},\ L_{\mu} \simeq 40\ X_0$$

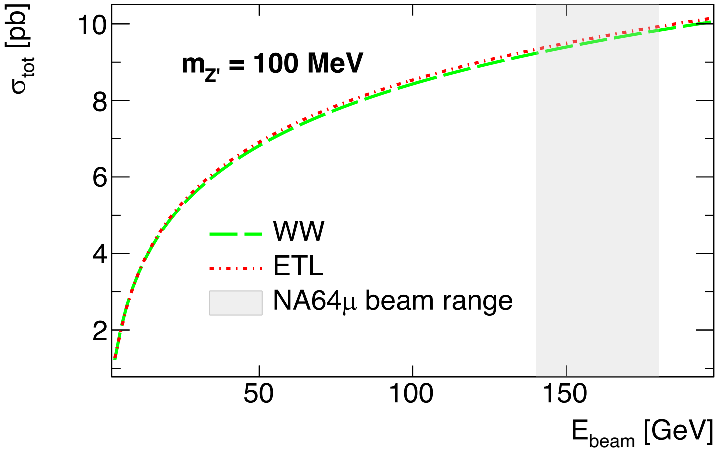


Computations of **ETL cross-section** computationally demanding → significant effort to compute phase-space approximation **WW** and **IWW** cross-sections (see D. Kirpichnikov et al., arXiv:2107.13297 (2021))

Accurate signal simulations developed in a simulations package **DMG4** (see M. Bondi et al., arXiv:2101.12192v2 [hep-ph])
to be fully compatible with the simulation toolkit **GEANT4**

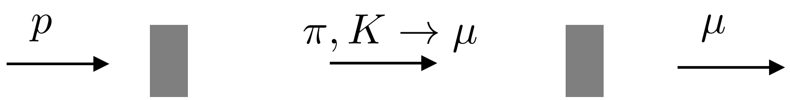
D. Kirpichnikov et al., arXiv:2107.13297 (2021)

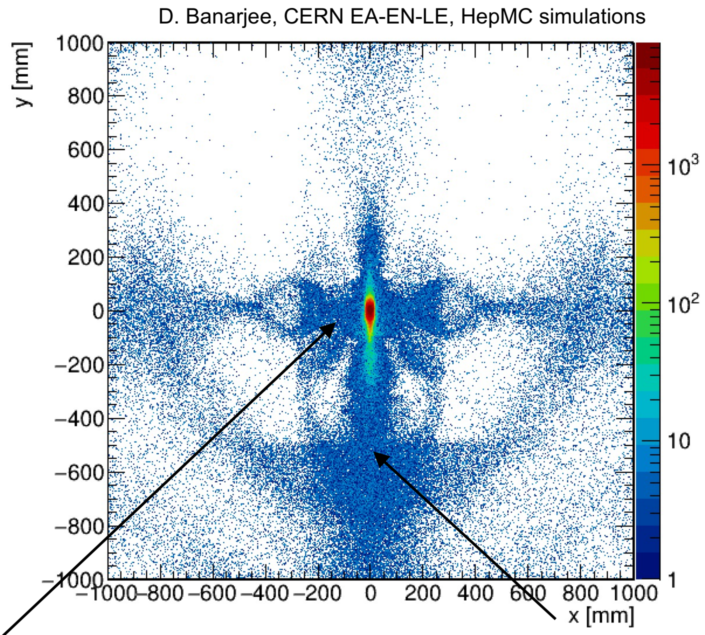




Muons from the M2 beamline: trigger identification

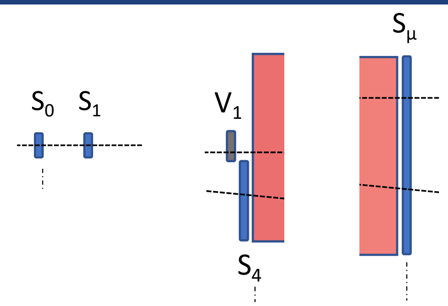
Muons produced from high-energy proton (~400 GeV/c) impinging on a beryllium target (**M2 beamline**), with about 10^6-10^7 μ/spill in the range 100-225 GeV/c

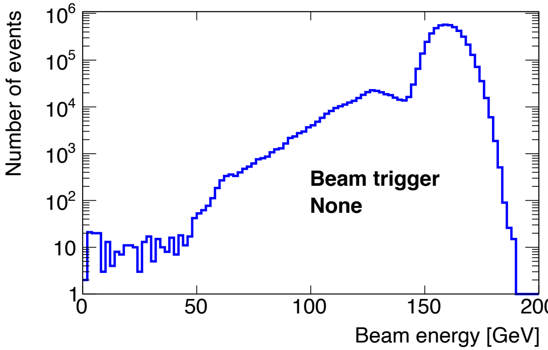




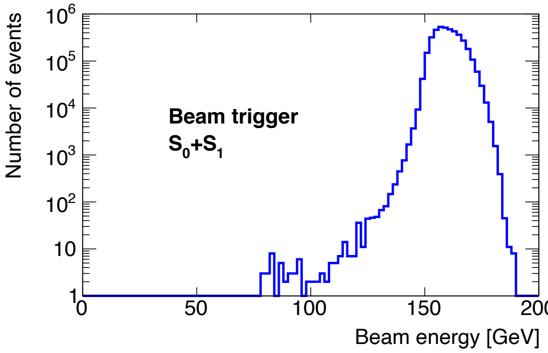
Beam spot σ_x~0.9 cm, σ_y~1.9 cm

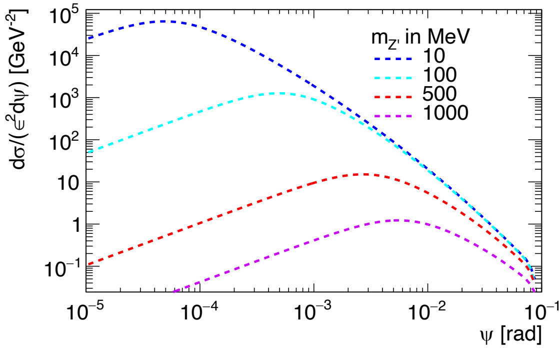
Large contribution from halo muons



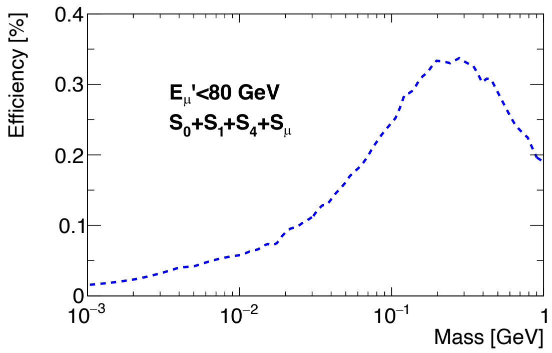


S_0+S_1

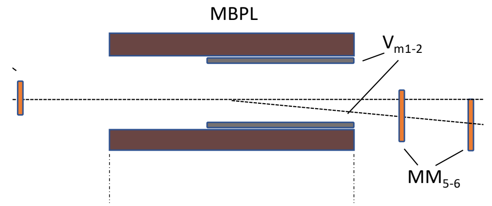




S_4

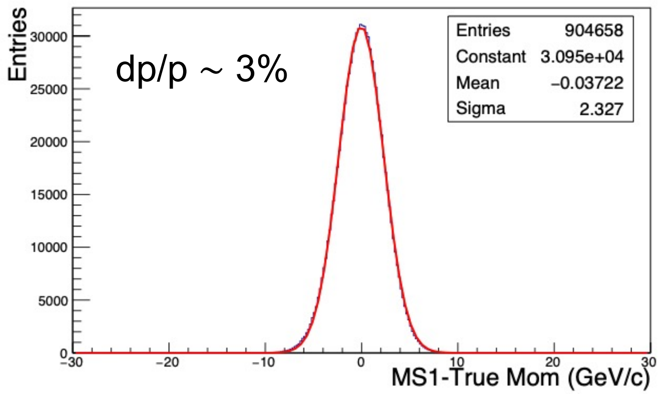


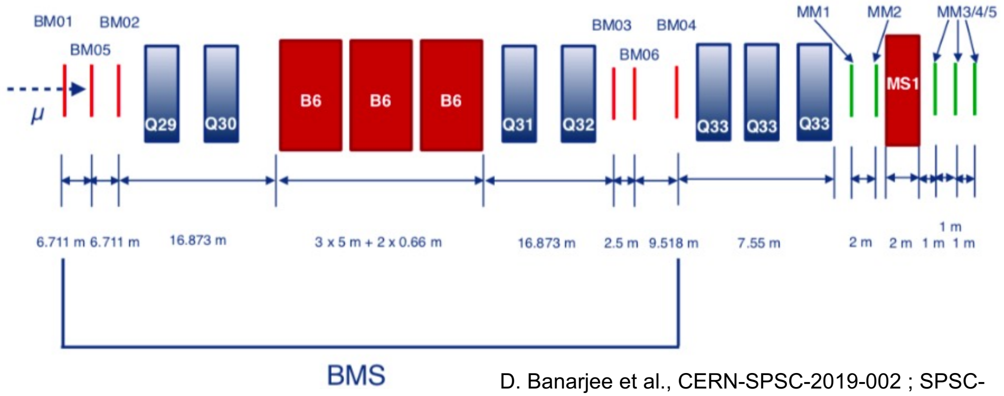
Muons from the M2 beamline: momentum reconstruction



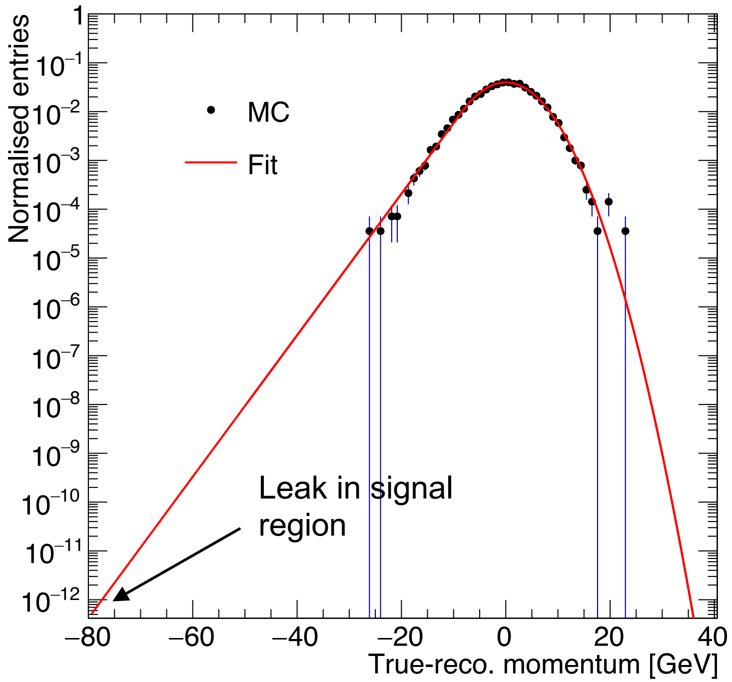
Both **beam and scattered muons** momenta measured to respectively:

- remove low energy muons
- identify the final state deflected muon momentum





D. Banarjee et al., CERN-SPSC-2019-002 ; SPSC-P-359 (2019)

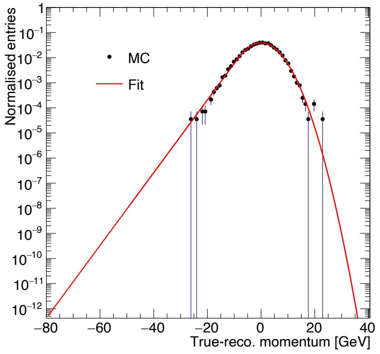


Importance of accurate momentum measurement: avoid **mis-identification** of deflected muon ($E_\mu' \simeq$ 80 GeV), i.e. reconstruct a 160 GeV muon with 80 GeV

→ Background from extrapolation ≤ **10^{-12} per MOT**

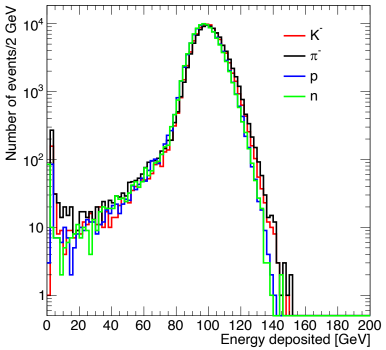
Background study overview

10^4 MOTs with phys. Trigger, single reco. track



+

10^5 hadrons in a single HCAL module



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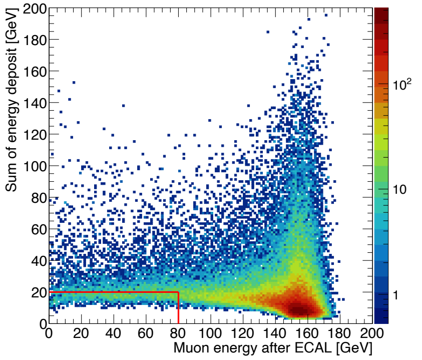
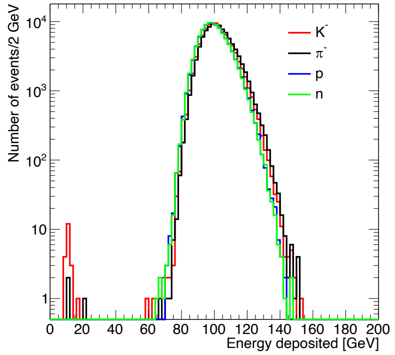
dimuons for 10^{12} MOTs with phys. trigger



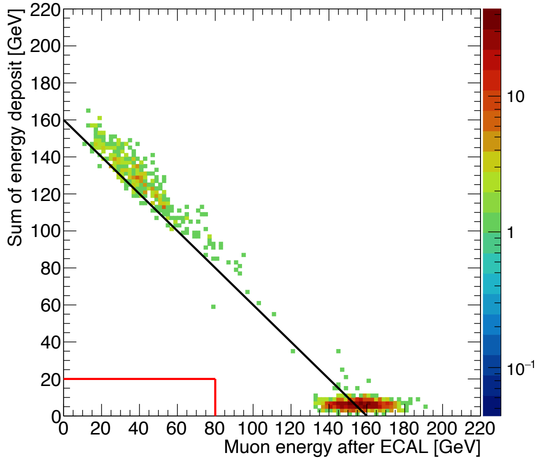
+

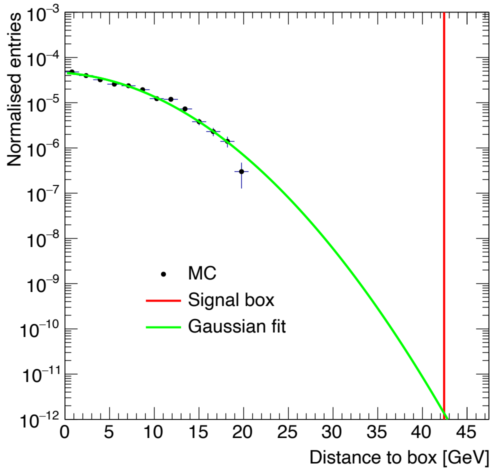
10^5 hadrons in four HCAL modules



Final background estimate obtained through a **cut-flow analysis** and **extrapolation** to the signal box

10^7 MOTs with all cuts



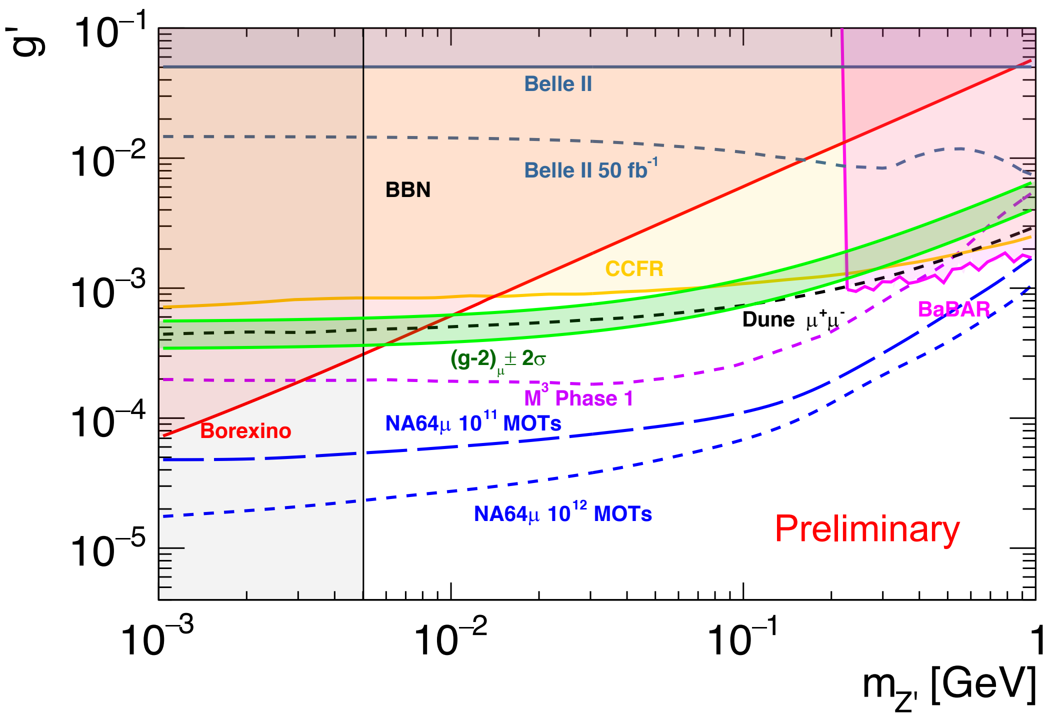


Source of background	Level per MOT
Scattered muon momentum reconstruction mismatch	$\sim 5 \times 10^{-13}$
Detector non-hermeticity	$\lesssim 10^{-12}$
Single-hadron punch-through	$\sim 5 \times 10^{-12}$
Hadron in-flight decay	$\sim 5 \times 10^{-13}$
Dimuon production	$< 10^{-12}$
Total	$\lesssim \mathbf{10^{-12}}$

NA64μ sensitivity to $(g\text{-}2)_\mu$

Sensitivity estimated through full GEANT4 simulations of the set-up and Z' physics, given the number of produced Z' > 2.3 events

$$N_{Z'}^{(\bar{\nu}\nu)} = N_{MOT} \cdot \frac{\rho \mathcal{N}_A}{A} \cdot \sum_i \Delta L_i \cdot \sigma_{tot}^{Z'}(E_\mu^i) \cdot Br(Z' \to \bar{\nu}\nu)$$



→ **At 90% C.L.**, region for $(g\text{-}2)_\mu$ fully covered with 10^{11} MOTs

D. Kirpichnikov et al., arXiv:2107.13297 (2021)

Summary and outlook: NA64μ before LS3

NA64μ is an active beam-dump experiment combining missing energy and momentum techniques to probe **$(g\text{-}2)_\mu$** and **sub-GeV DM candidates**

NA64μ will collect its first data in the **2021 pilot run** in October/November

Main prospects until the CERN LS3:

Phase I:
- Accumulate 10^{11} MOTs
- Cover the $(g\text{-}2)_\mu$ anomaly through broken $U(1)'_{L\mu\text{-}L\tau}$ light massive gauge boson Z' (sub-GeV mass region)

Phase II:
- Accumulate 10^{13} MOTs
- Explore light thermal dark matter (LTDM) Z' parameter
- Complement NA64e in dark photon A' searches in mass region ≥ 0.1 GeV

2021 | 2022 | 2023 | 2024 | 2025

CERN LS3

Muon test run

Phase 1: first physics run, cover $(g\text{-}2)_\mu$

Phase 2: cover high A', Z' masses

Acknowledgements

The NA64 Collaboration, in particular **L. Molina Bueno**, **P. Crivelli**, **S. Gninenko**, **D. Kirpichnikov** and **M. Kirsanov**

The ETH Zürich P. Crivelli group, in particular **P. Crivelli**, **E. Depero** and **B. Banto**

The SNSF Grant No. 16913/186181/197346/186158

Back-up

Light Thermal Dark Matter (LTDM): Hidden-sectors and the portal formalism

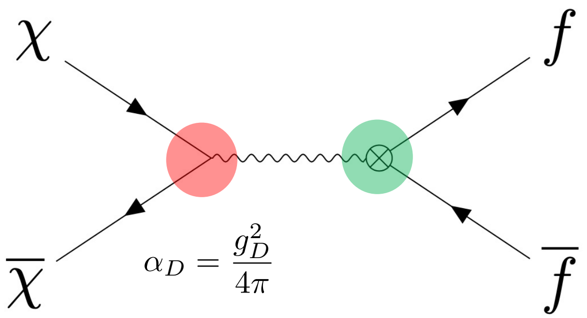
Particle model: interaction of DM with SM through a **new force** carried by a light mediator

$$\mathcal{L}_{\text{total}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DS}} + \mathcal{L}_{\text{Portal}}$$

Vector portal (Dark photon, A')
Scalar portal (Dark Higgs, S)
Fermion portal (Heavy Neutral Lepton, N)
Pseudo-scalar portal (ALPs, a) (generic case)

The **vector** portal: a massive U(1)' vector mediator, A', interacts with SM particles through kinetic mixing ε with SM photons

$$\mathcal{L}_V \supset g_D A'_\mu \bar{\chi}\gamma_\mu\chi + m_\chi\bar{\chi}\chi + \frac{1}{2}m^2_{A'}(A'_\mu)^2 + \frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu}$$

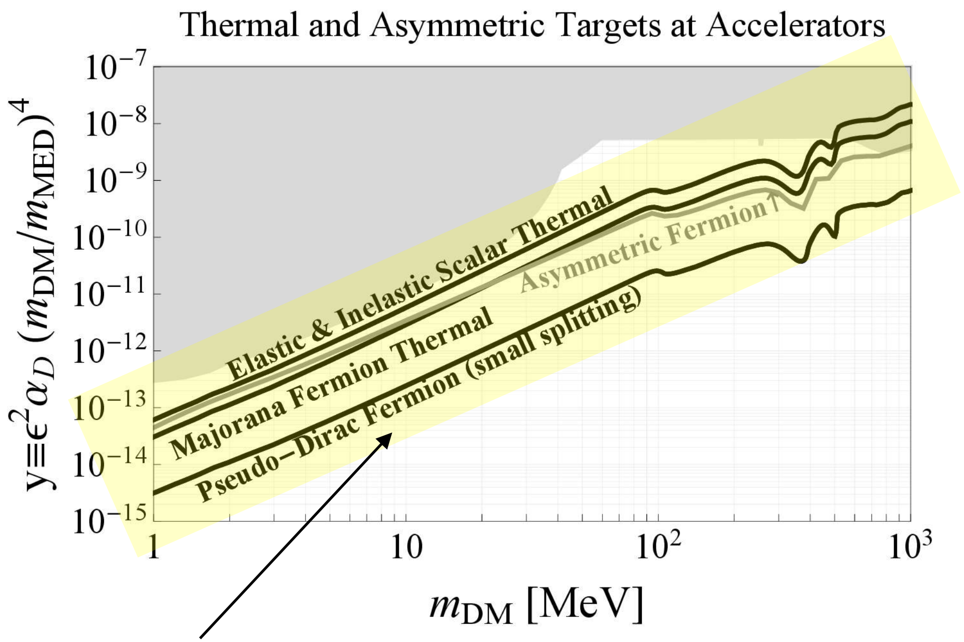


The relic abundance can be expressed in terms of the model **4 parameters**

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

$$\Rightarrow \Omega_\chi \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_\chi^2}{y}$$

for which the correct abundance is obtained through fine –tuning of the **y parameter**.



"thermal target" in {m, y} plane

M. Battaglieri et al., arXiv:1707.04591 **[hep-ph]**

J. L. Feng and J. Kumar, PRL 101, 231301 (2008)

Complementary searches: NA64e and NA64μ combined results

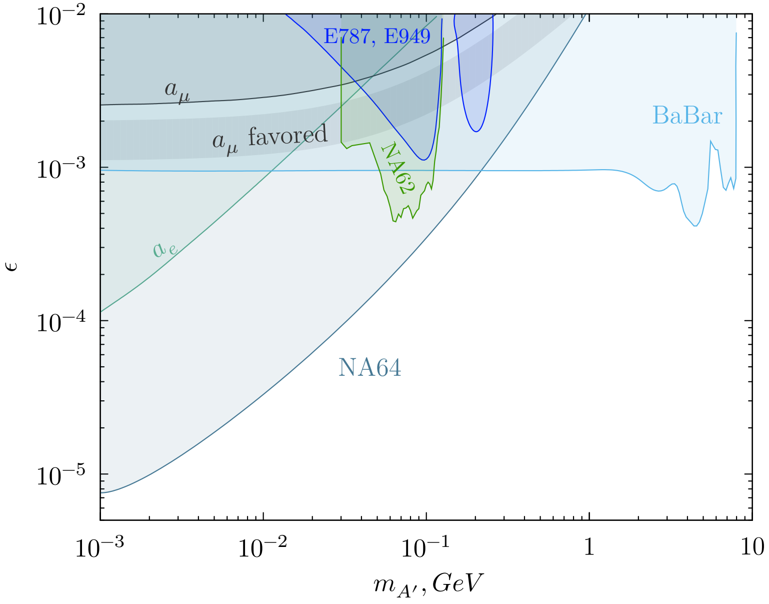
Complementary with mass region ≪ 100 MeV and ≥ 100 MeV due to **production cross-sections behaviour**

$$N^{e}_{A'} \sim N_{EOT} L_e \sigma^{e}_{A'}, \;\; L_e \simeq 1X_0$$

$$\sigma^{e}_{A'} \sim \frac{\epsilon_e^2}{m_{A'}^2}$$

$$N^{\mu}_{A'} \sim N_{MOT} L_\mu \sigma^{\mu}_{A'}, \;\; L_\mu \simeq 40X_0$$

$$\sigma^{\mu}_{A'} \sim \frac{\epsilon_\mu^2}{m_\mu^2}$$



D. Banarjee et al., PRL 123, 121801 (2019)

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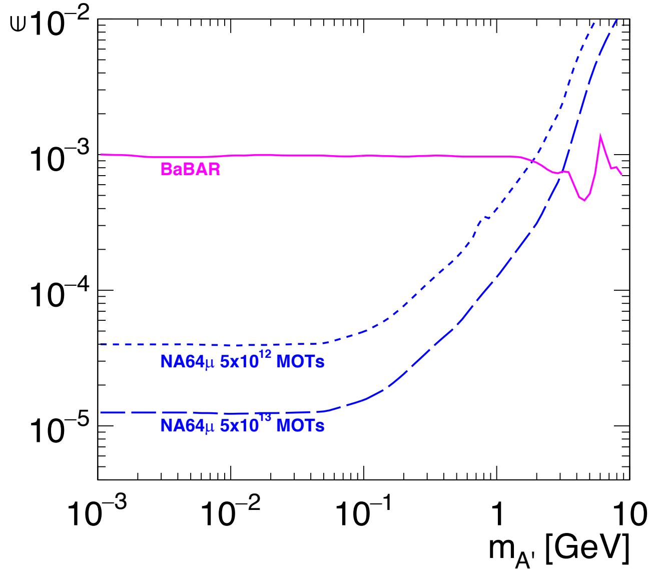
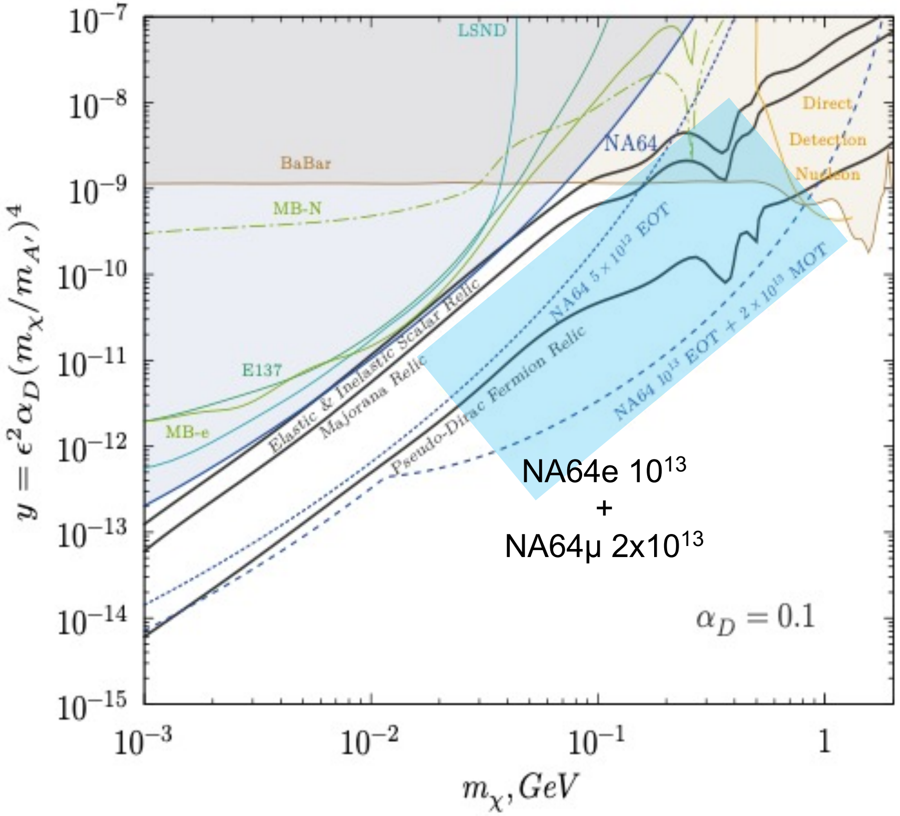
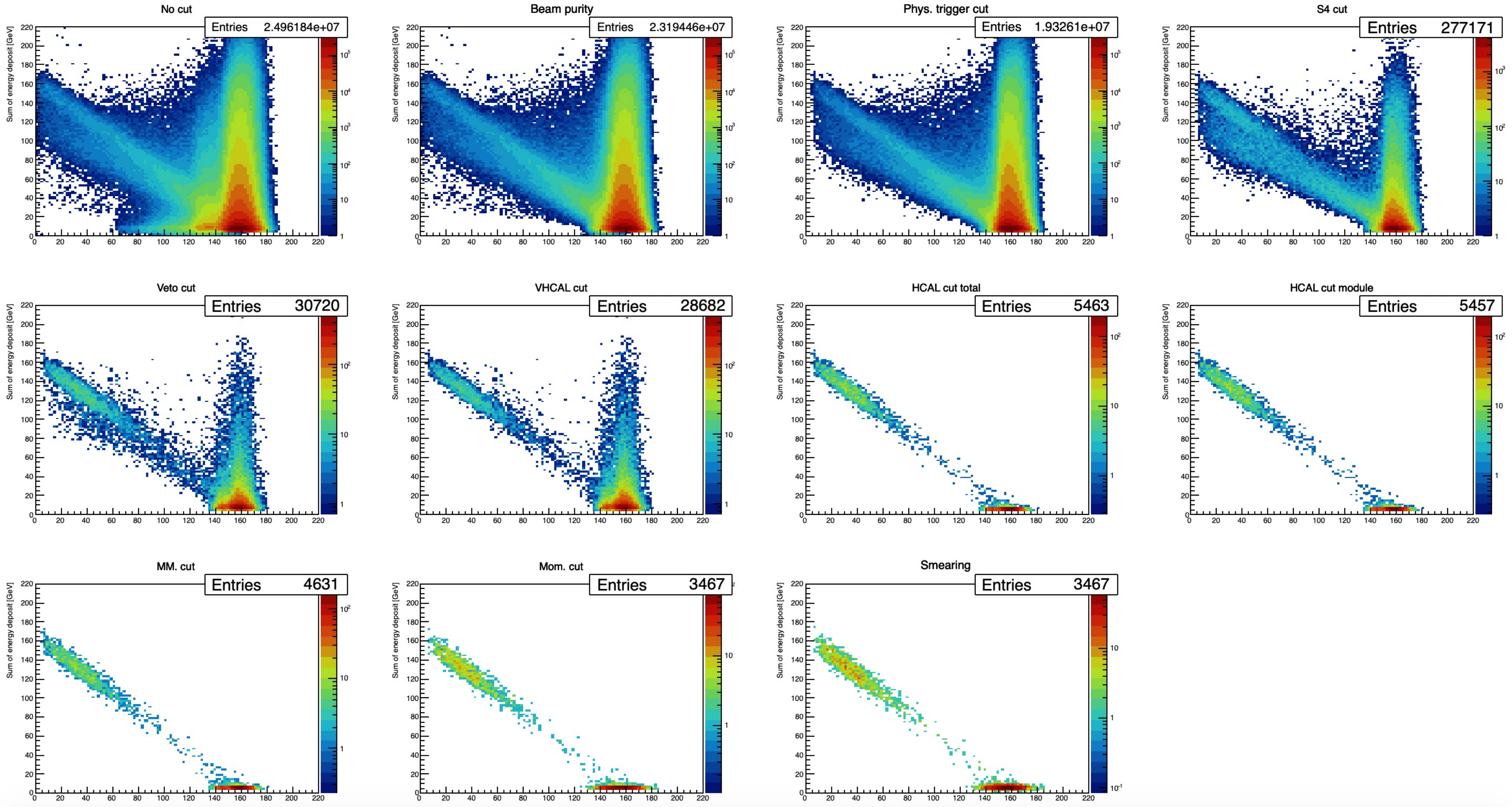


D. Banarjee et al., CERN-SPSC-2019-002 ; SPSC-P-359 (2019)

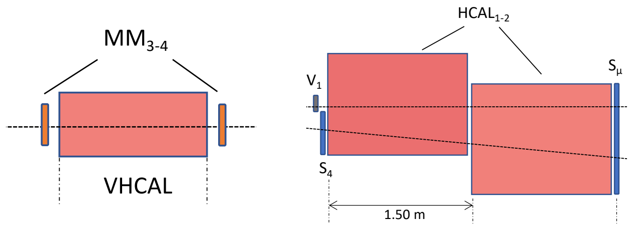
S. N. Gninenko et al., PLB 796, 117-122 (2019)



The method of search: cut-flow analysis



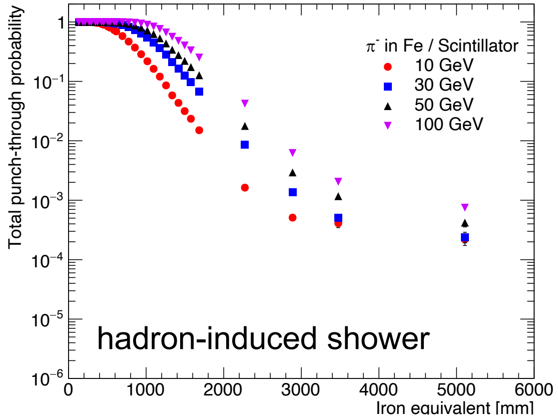
Hadrons in the set-up: detector non-hemerticity and punch-through



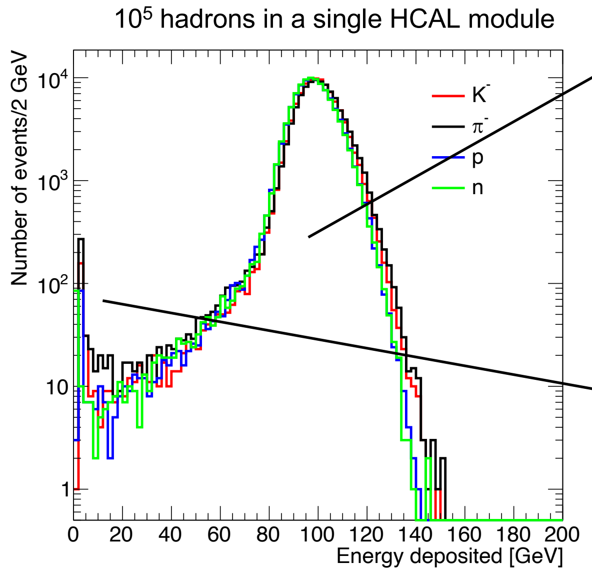
Detector non-hermeticity: can lead to **large missing energy events** than can mimick low energy scattered muon from Z' bremsstrahlung

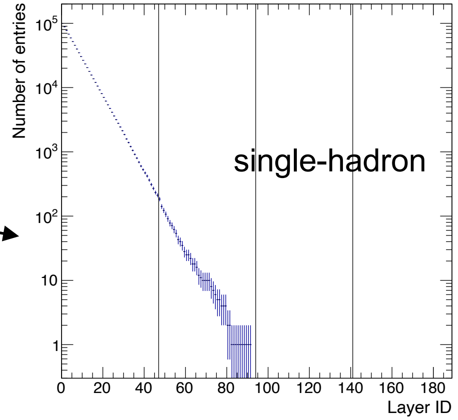
$$\pi \rightarrow \mu\nu \qquad\qquad \mu + X \rightarrow \mu + Y + h$$

Hadrons in the set-up originate from
- **Admixture** in the M2 beam line (~10^{-6} π/μ and K/π~0.03)
- **Leading hadrons** production in the active target (P(μ+N→μ+X+h)~10^{-6} from MC)



Punch-through hadrons: **single hadron** mimicking energy deposit of a muon (~2.5 GeV and ~0.1 GeV for charged and neutral hadrons)





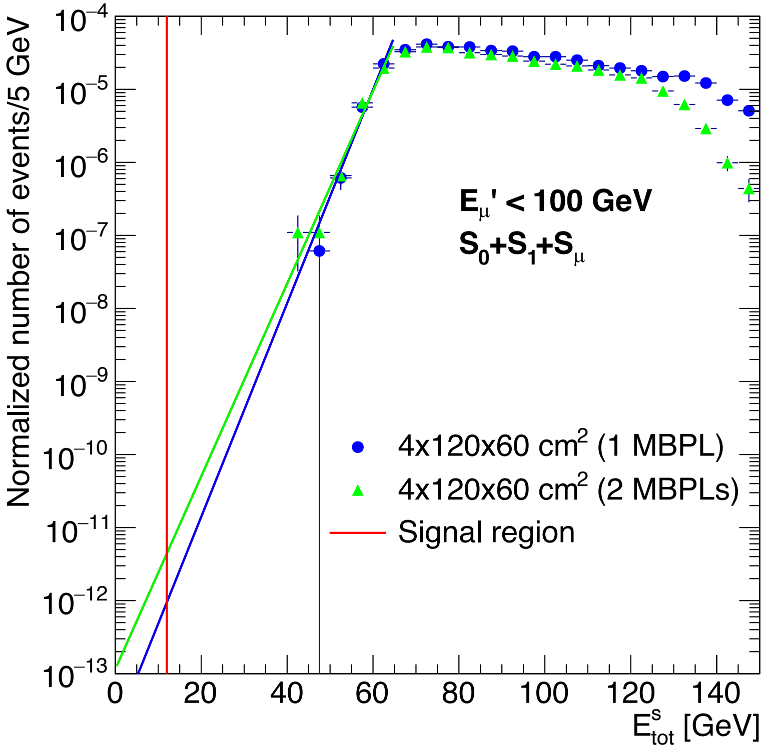
From MC simulations

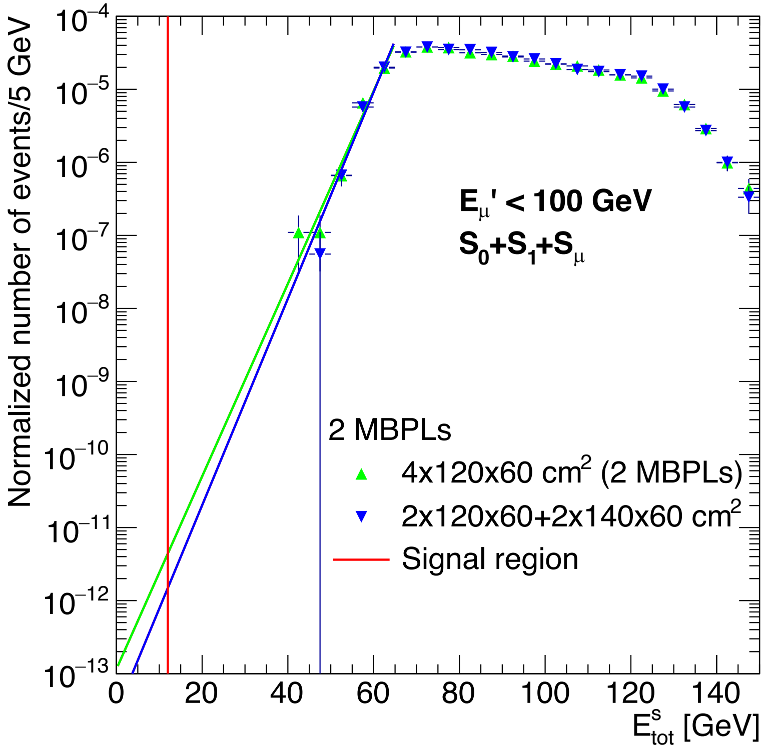
Particle (100 GeV)	1 HCAL	2 HCAL	4 HCAL
π^-	2×10^{-3}	$\mathbf{5 \times 10^{-6}}$	3×10^{-11}
p	4×10^{-4}	$\mathbf{4 \times 10^{-7}}$	2×10^{-13}
n	4×10^{-4}	$\mathbf{3 \times 10^{-7}}$	8×10^{-14}

Overall background ≤ **10^{-12} per MOT**

Detectors hermeticity: hadronic calorimeters

Background estimated from **extrapolation** towards signal region

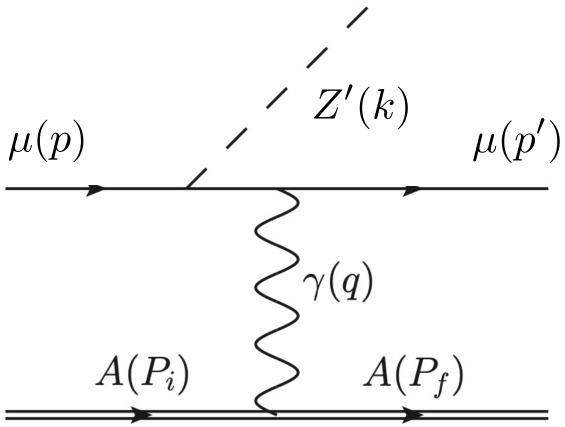


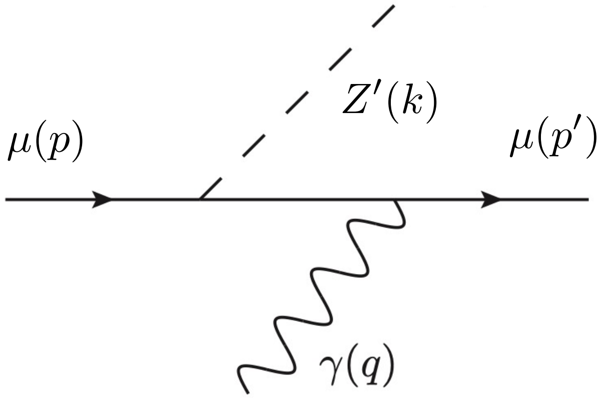


Vector boson production with a muon beam: phase space approximations

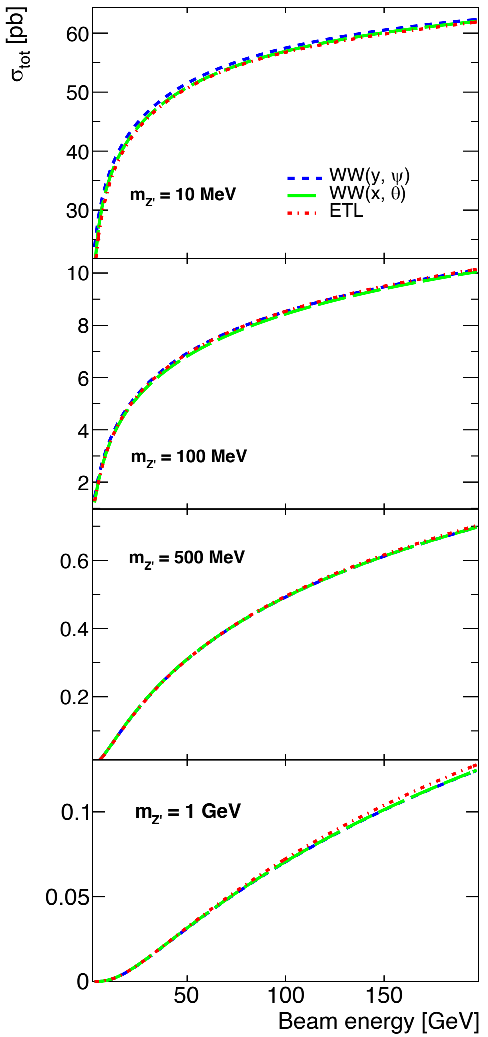
Approximation of a **2 → 3 process** with a **2 → 2 process** through **William-Weiszäcker** approximation

$$\mu^-(p) + N(P_i) \to \mu^-(p') + N(P_f) + Z'(k)$$



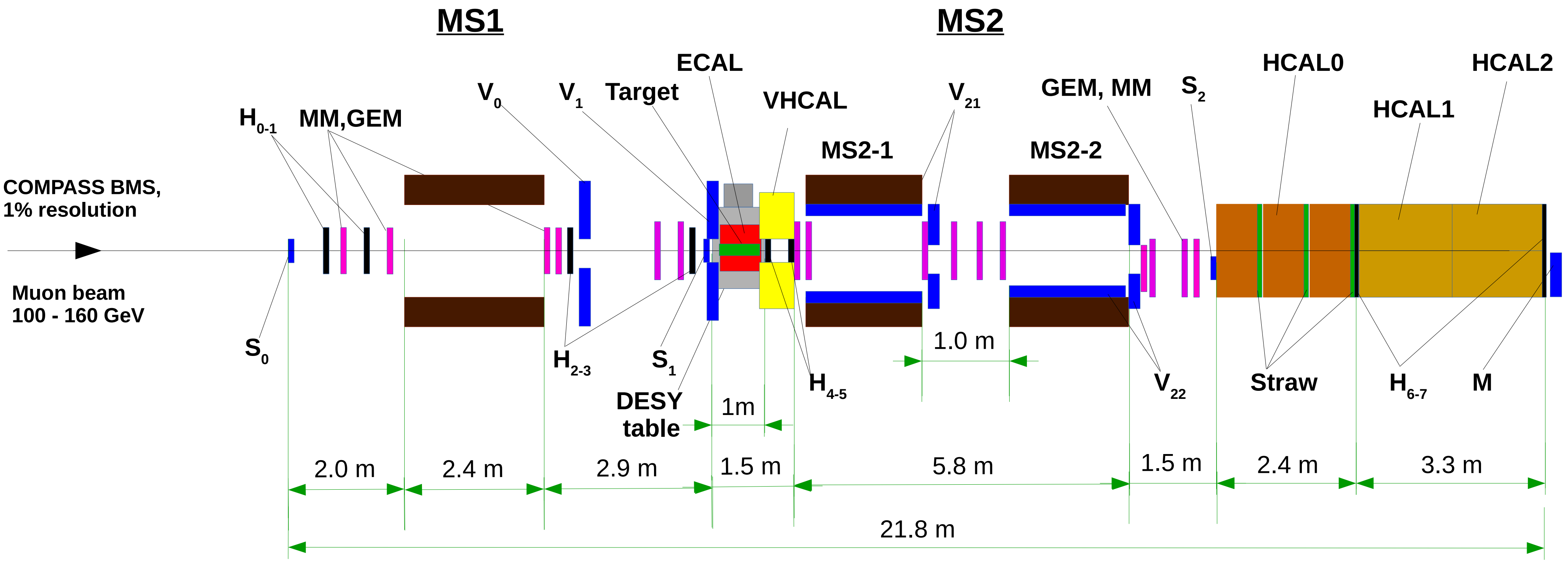


$$\chi^{WW} = \int_{t_{min}}^{t_{max}} dt \frac{t - t_{min}}{t^2} F^2(t)$$

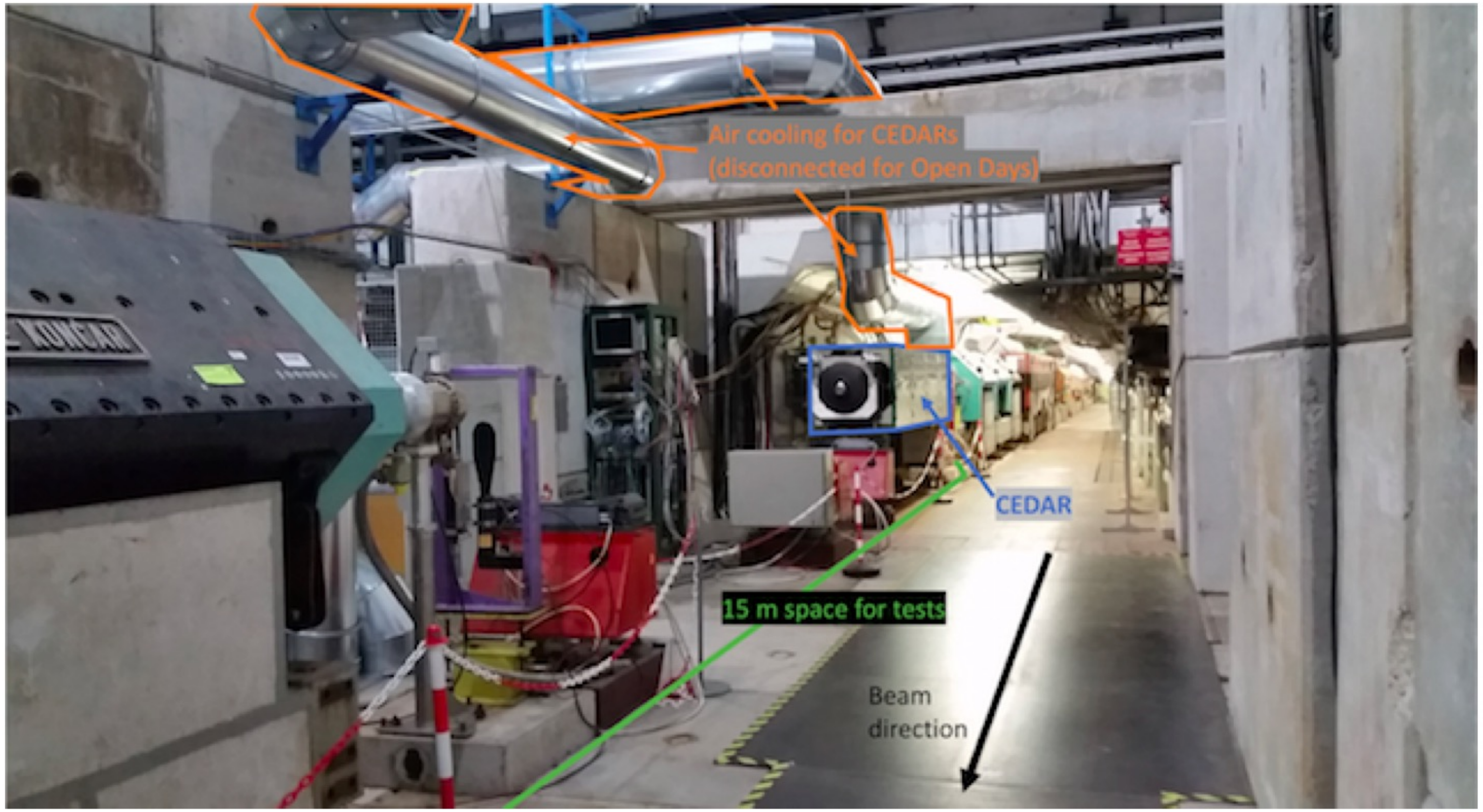


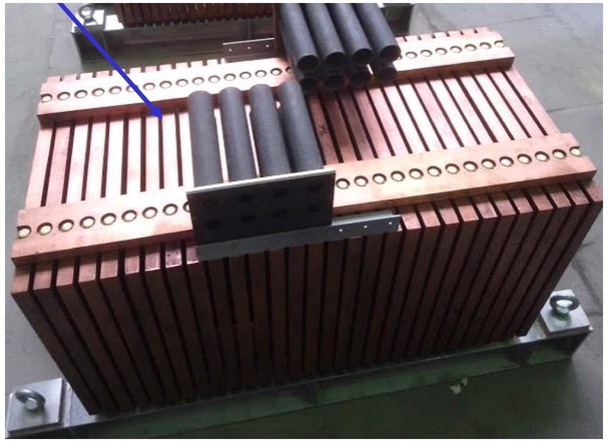
D. Kirpichnikov et al., arXiv:2107.13297 (2021)

The 2022 physics run (RUN 1)



NA64μ: preparation of the 2021 pilot run





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