

Shedding light into the DM and g-2 puzzle with a muon beam

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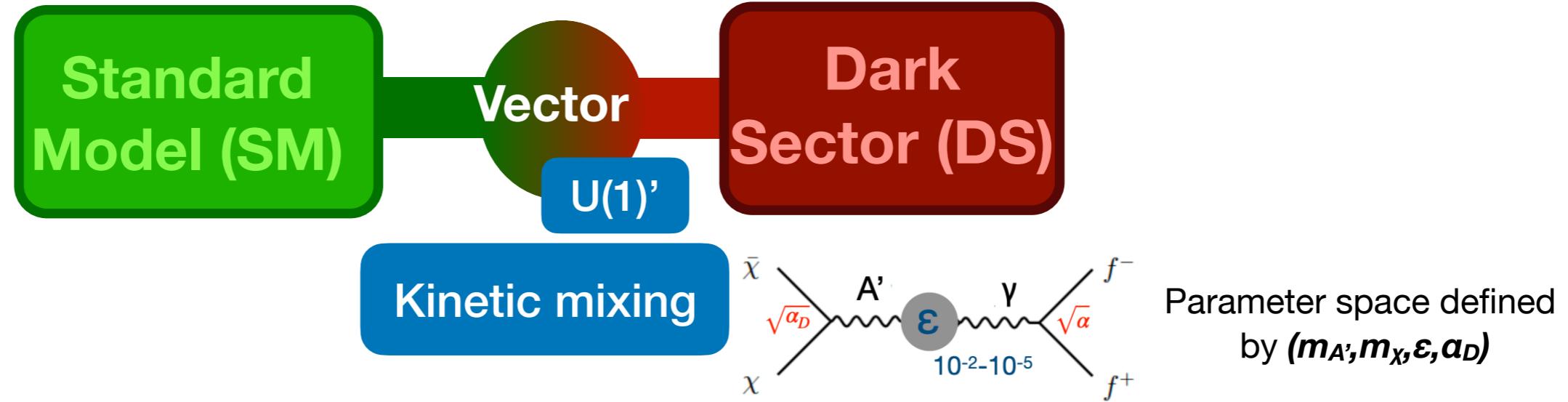


ICHEP 2022
XLI
International Conference
on High Energy Physics
Bologna (Italy)

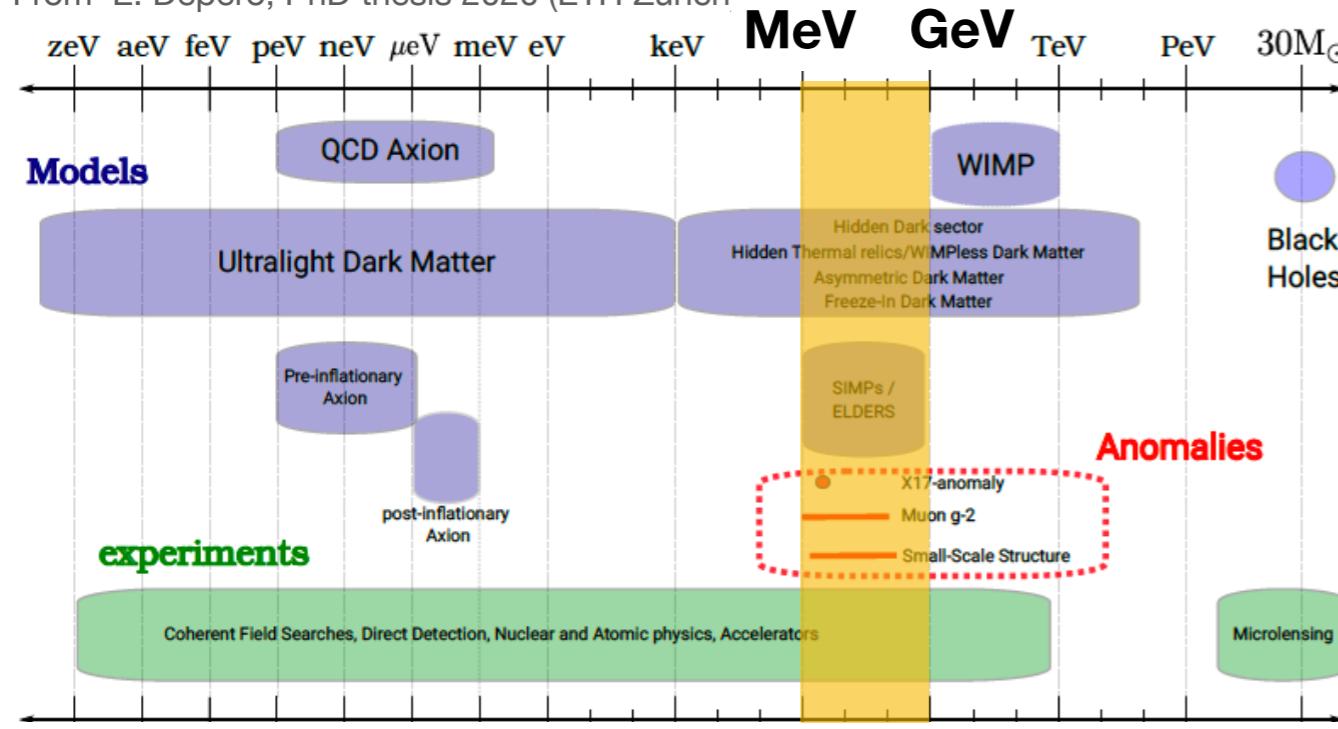
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Motivation: Dark sectors

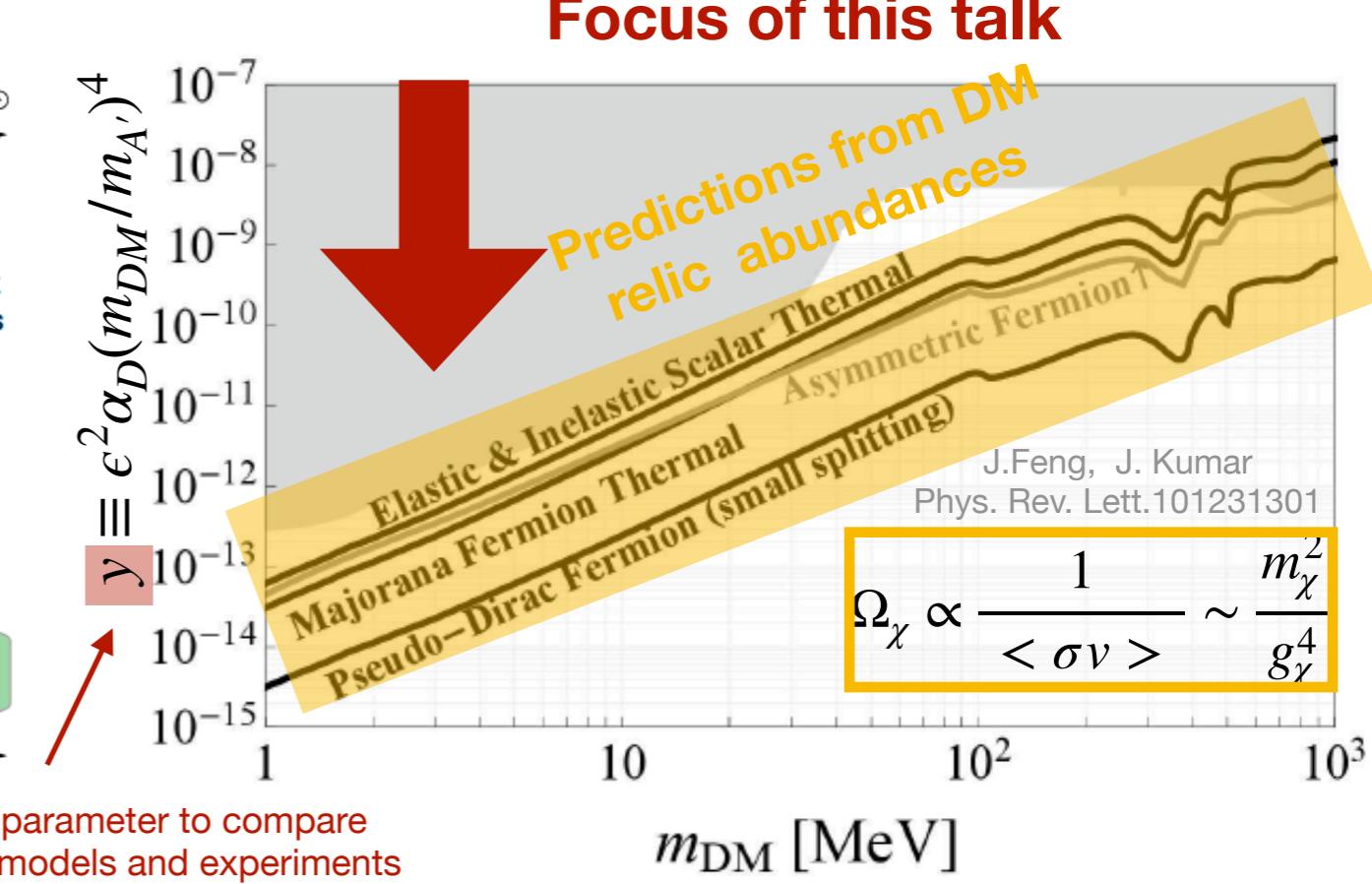
An interesting framework to explain the origin of Dark Matter (DM)



From E. Depero, PhD thesis 2020 (ETH Zürich)



Useful parameter to compare different models and experiments proportional to the DM-SM annihilation cross-section



Review about DS:

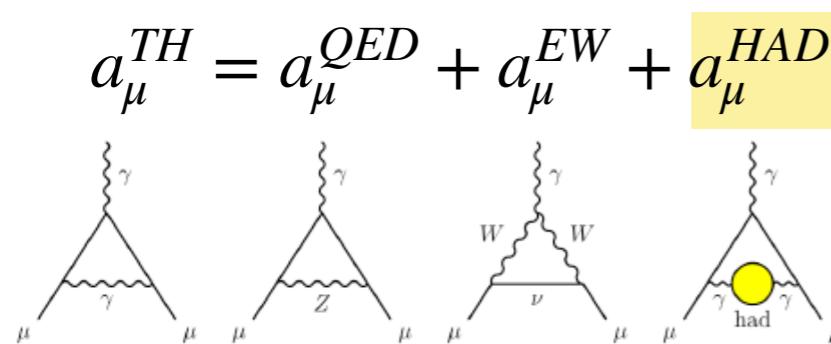
The Search for Feebly Interacting Particles, Gaia Lanfranchi, Maxim Pospelov, Philip Schuster Annual Review of Nuclear and Particle Science 71:1, 279-313 (2021)

From Light Dark Matter experiment arXiv:1808.05219v1

Motivation: The muon $g-2$ anomaly

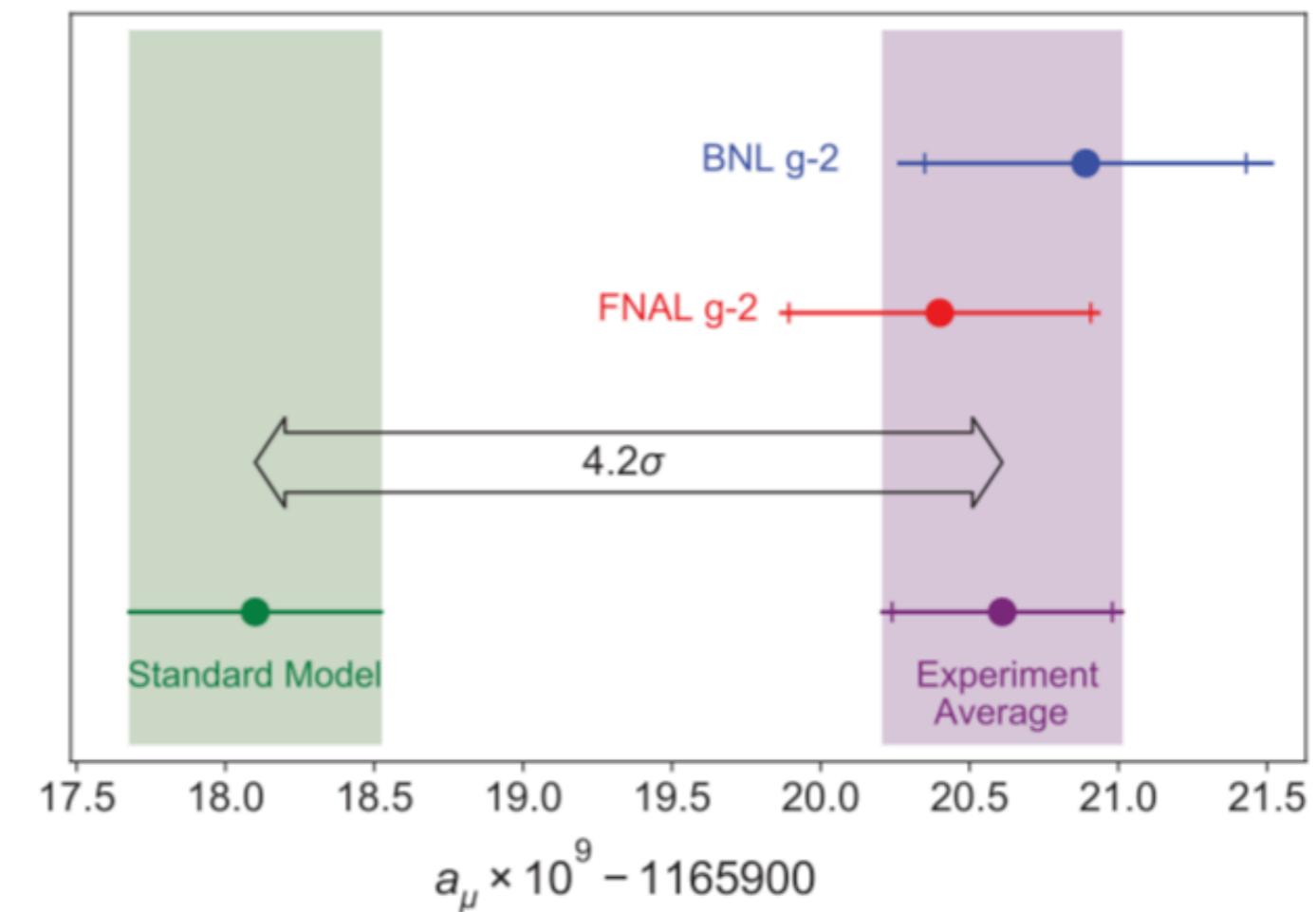
$$a_\mu = \frac{g_\mu - 2}{2}$$

Anomalous muon magnetic moment

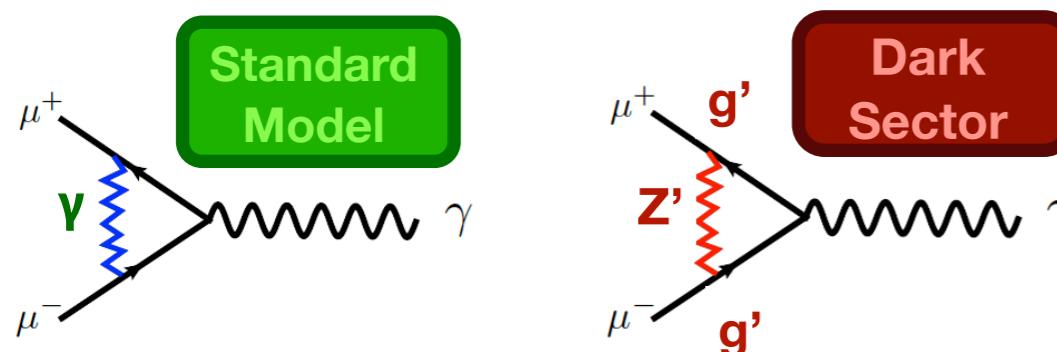


- Including the latest lattice QCD calculations the discrepancy with the experimental value gets reduced below 2σ : S. Borsanyi *et al.*, Nature 593, 51 (2021)
- Main uncertainty in the theoretical calculation coming from the hadronic contributions. Important role of MUONe experiment at CERN to directly measure them: https://indico.cern.ch/event/765096/contributions/3295779/attachments/1785296/2906331/ES_MUonE_document.pdf

$$\Delta a_\mu = a_\mu^{EXP} - a_\mu^{TH} = (251 \pm 59) \cdot 10^{-11}$$



B. Abi *et al.* Muon $g-2$ collaboration Phys. Rev. Lett. 126, 141801 (2021)
T. Aoyama *et al.* Phys. Rept. 887 1 (2020)



Focus of this talk: new physics?
1-loop contributions from dark sector bosons such as Z' or a generic X



The NA64 experiment and its physics program

Located in the North Area at the CERN Super Proton Synchrotron accelerator

1) Light Dark Matter:

→ **Invisible** decays ➔

- 2016-2018 combined analysis
- **2021 and 2022**
- Future prospects:
 - **e⁺ beam 2022**
 - **NA64μ pilot run in 2021 and 2022**

2) Constraints on **New Physics**:

★(g-2)_μ

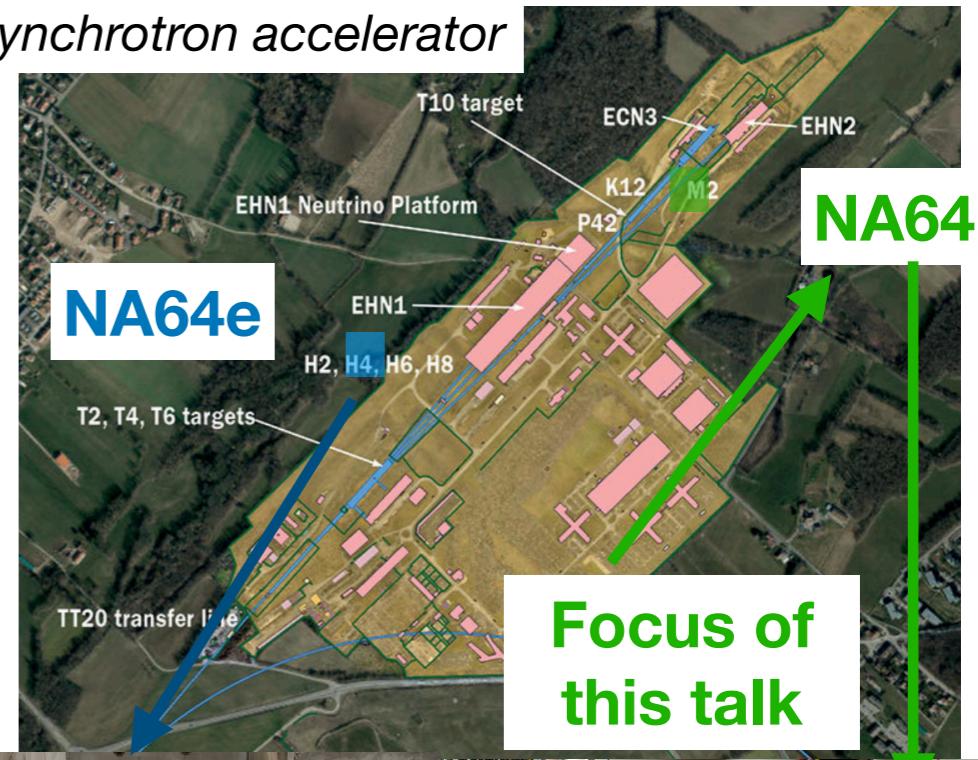
◆ ALPs

◆(g-2)_e

◎ ⁸Be anomaly:

→ **Visible** decays

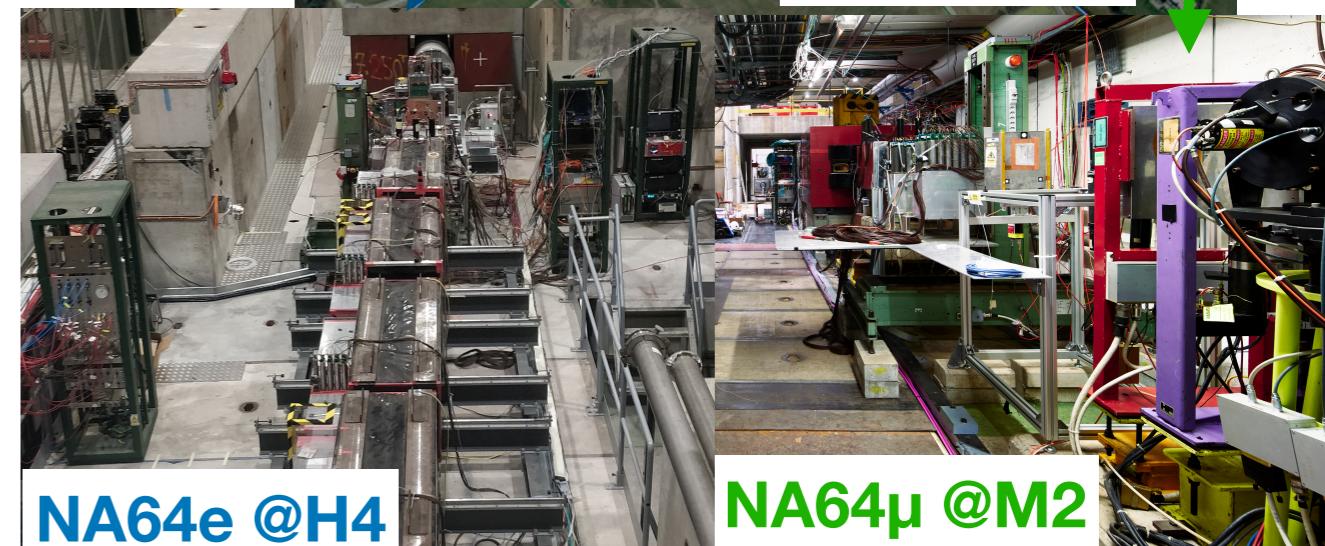
See also L. Marsicano's talk on July, 7th



CERN Council Open Symposium on the Update of
European Strategy for Particle Physics

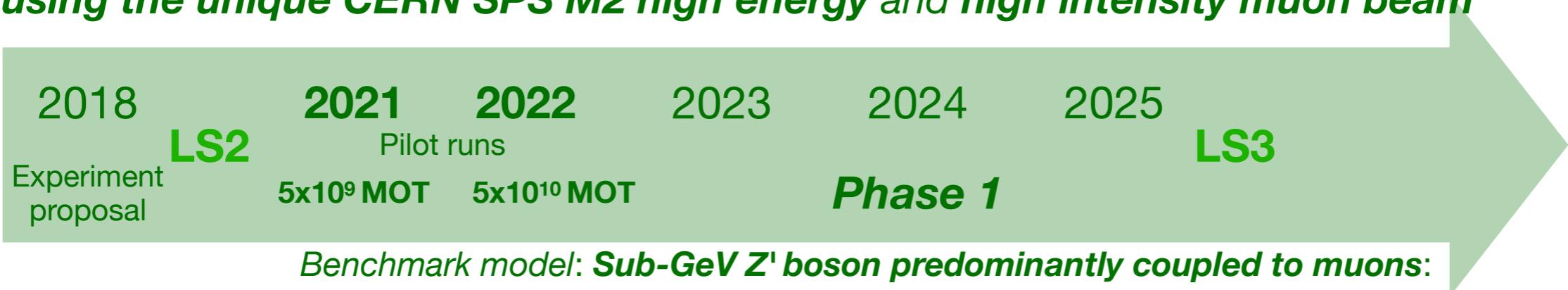
13-16 May 2019 - Granada, Spain

CERN-PBC-REPORT-2018-007



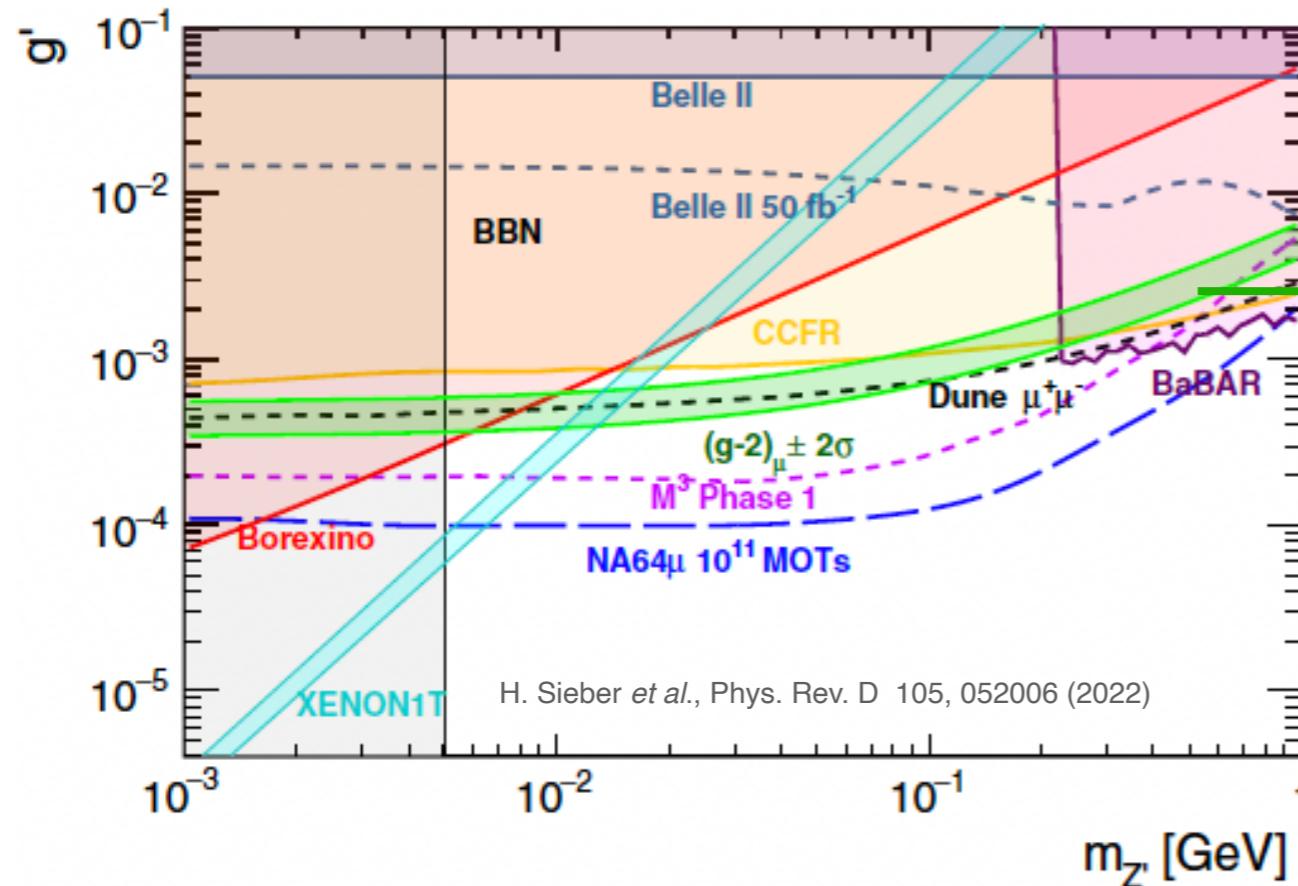
The NA64 μ experiment: physics goals

*Exploring Dark sector physics weakly coupled to muons
using the unique CERN SPS M2 high energy and high intensity muon beam*



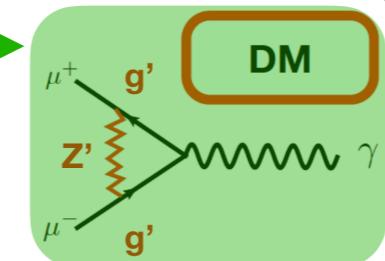
Arising by a U(1)' broken symmetry generated by gauging the difference of the lepton number between the muon and tau flavour, $L_\mu - L_\tau$ models

$$L_{Z'} = g' (\bar{\mu} \gamma_\nu \mu + \bar{\nu}_{\mu L} \gamma_\nu \nu_{\mu L} - \bar{\tau} \gamma_\nu \tau - \bar{\nu}_{\tau L} \gamma_\nu \nu_{\tau L}) Z'^\nu$$



S. N. Glinenko, N. V. Krasnikov, and V. A. Matveev, Phys. Rev. D 91, 095015 (2015)
C. Y. Chen, M. Pospelov, and Y.-M. Zhong, Phys. Rev. D 95, 115005 (2017)
D.W.P. Amaral, D.G. Cerdeño, A. Cheek and P. Foldenauer, Eur. Phys. J. C 81 861 (2021)

It can give via loop effects the required contribution to **explain the (g-2) $_\mu$**



Initial μ beam

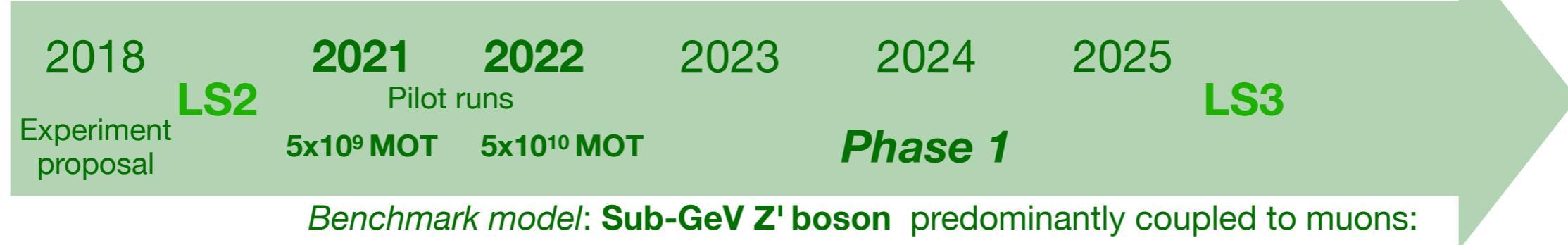
Active Dump

Missing energy/
momentum

$$\mu + Z \rightarrow \mu ZZ'; Z' \rightarrow \nu\bar{\nu}$$

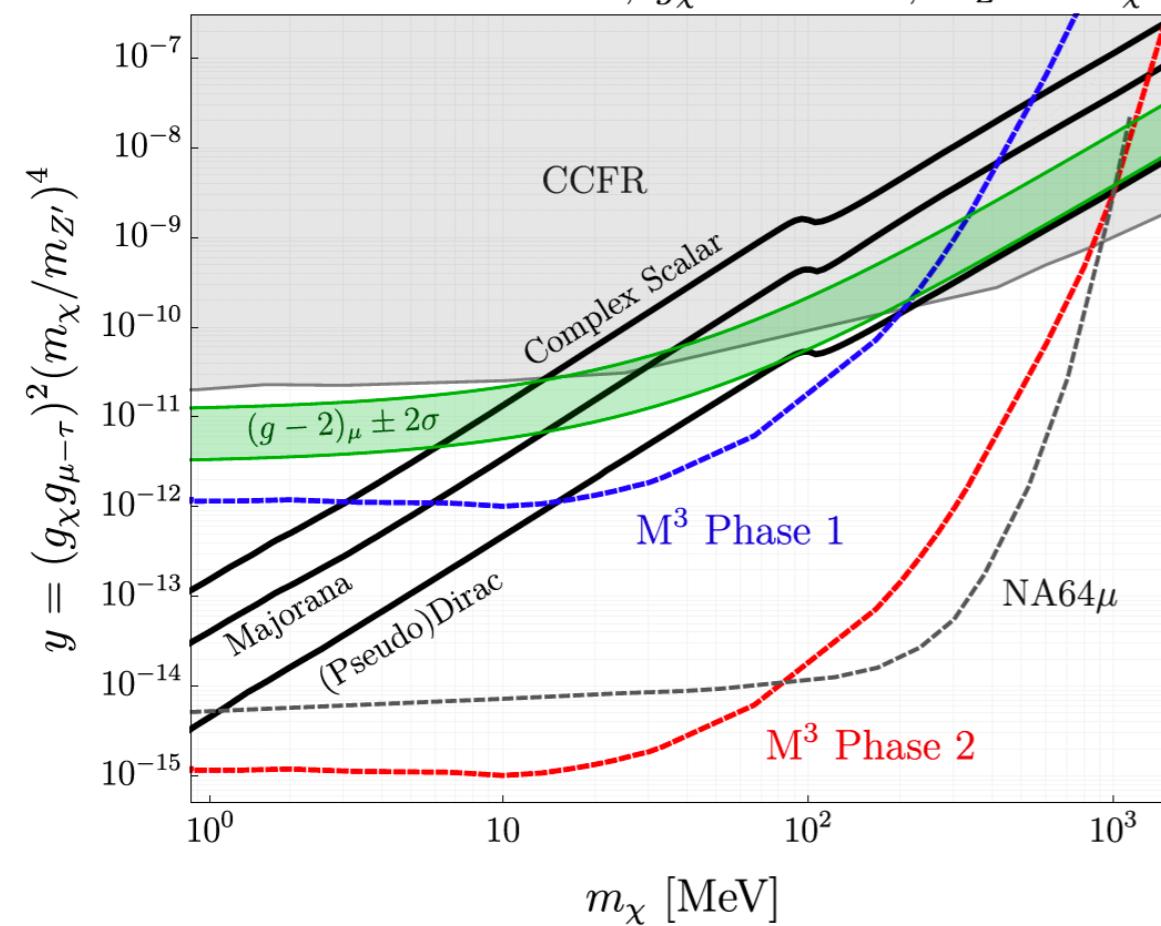
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Y. Kahn, G. Krnjaic, N. Tran, and A. Whitbeck, JHEP 09 153 (2018)

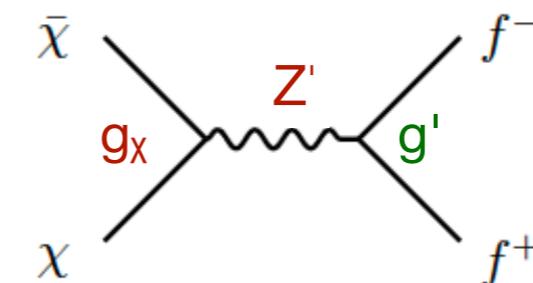
Thermal Dark Matter, $g_\chi = 5 \times 10^{-2}$, $m_{Z'} = 3m_\chi$



In extended models, can also explain DM as a thermal freeze out relic

D. Banerjee et al. [NA64 Collaboration]. CERN-SPSC-2019-002 / SPSC-P-359 (2019)
Y. Kahn, G. Krnjaic, N. Tran, and A. Whitbeck, JHEP 09 153 (2018)

$m_{Z\mu} > 2m_\chi$: $Z' \rightarrow \chi\bar{\chi}$ $\mu + Z \rightarrow \mu ZZ'; Z' \rightarrow \chi\bar{\chi}$



$$\langle \sigma v \rangle \propto g_\chi^2 g'^2 \frac{m_\chi^2}{m_{Z'}^4} = \frac{y}{m_\chi^2}$$

The NA64 μ experiment: physics goals

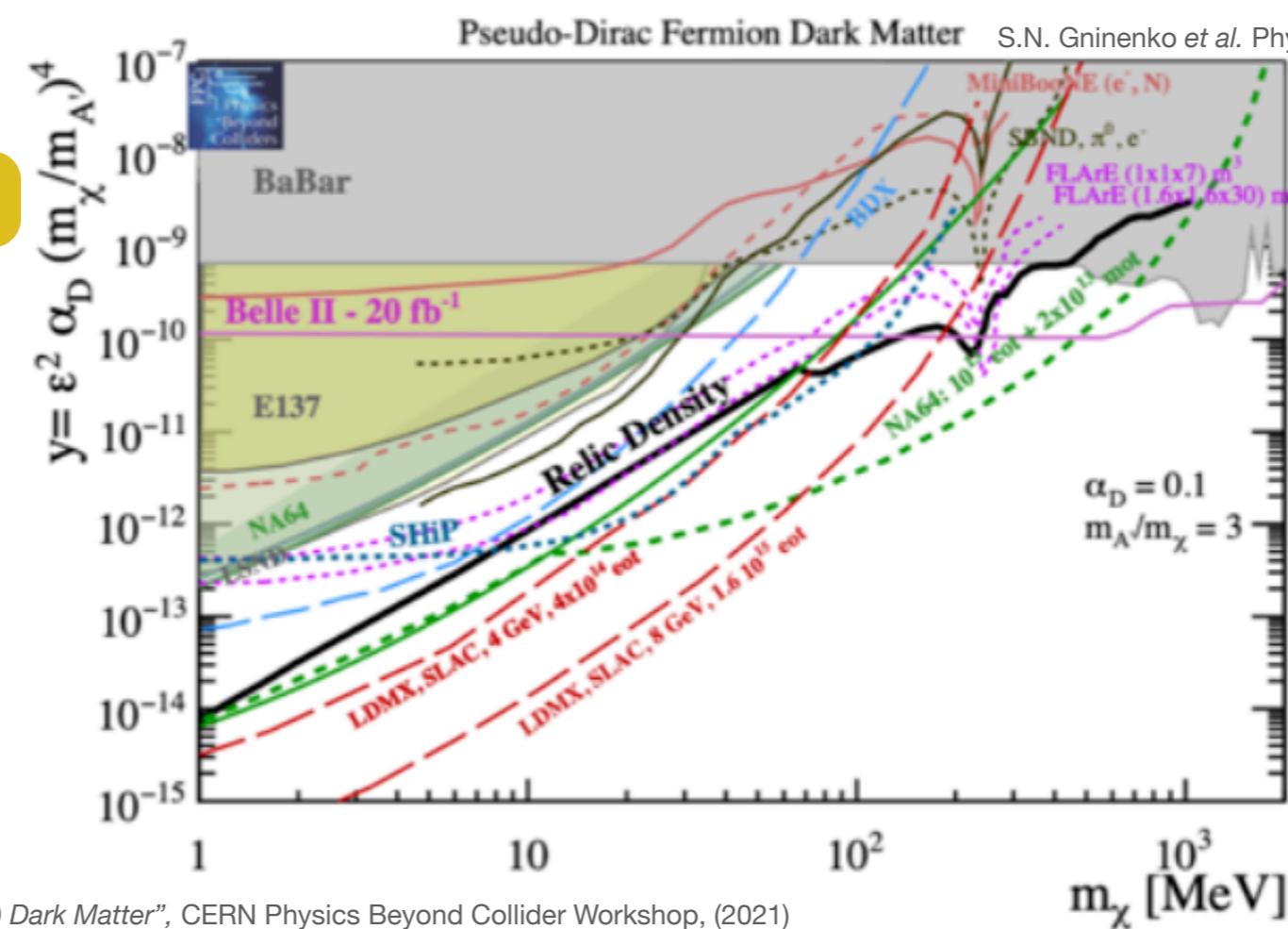
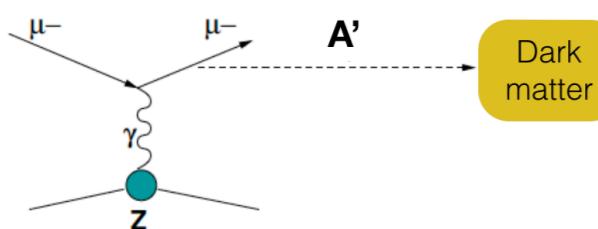
*Exploring Dark sector physics weakly coupled to muons
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Light dark matter in the A' mass region ≥ 0.1 GeV (complementary search to NA64e).

Scalar, ALPs coupled to the muon, **Milli-Charged particles**, **Lepton Flavour Violation** in $\mu Z \rightarrow \tau Z$ conversion in flight.

S. N. Gninenco et al., Phys. Lett. B 796, 117 (2019)
 S.N. Gninenco and N.V. Krasnikov, arXiv:2202.04410 [hep-ph] (2022)
 A.S. Zhevlov et al. arXiv:2204.09978 [hep-ph]
 S.N. Gninenco et al. Phys. Rev. D 98, 015007 (2018)



P. Schuster, "New benchmarks: Light (MeV-GeV) Dark Matter", CERN Physics Beyond Collider Workshop, (2021)

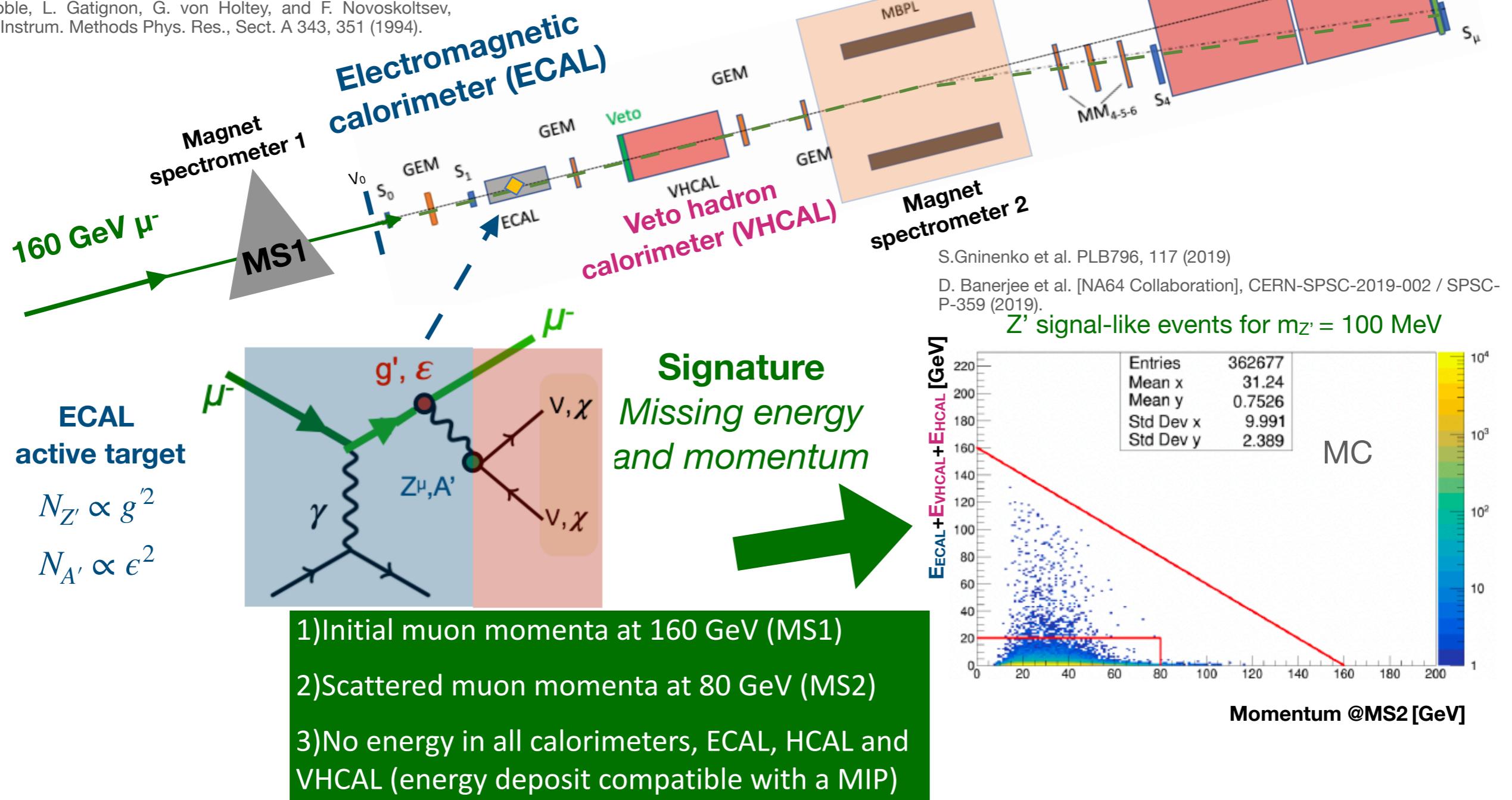
The NA64 μ experiment

Exploring Dark Sector physics weakly coupled to muons

160 GeV muons generated at the high energy (up to 250 GeV) and high intensity (10^5 - 10^7 μ/s) M2 beam-line at the CERN SPS accelerator.

Hadron admixture (typically charged and neutral hadrons such as pions and kaons): $\pi/\mu \sim 10^{-6}$, with $K/\pi \sim 0.03$

N. Doble, L. Gatignon, G. von Holtz, and F. Novoskoltsev,
Nucl. Instrum. Methods Phys. Res., Sect. A 343, 351 (1994).

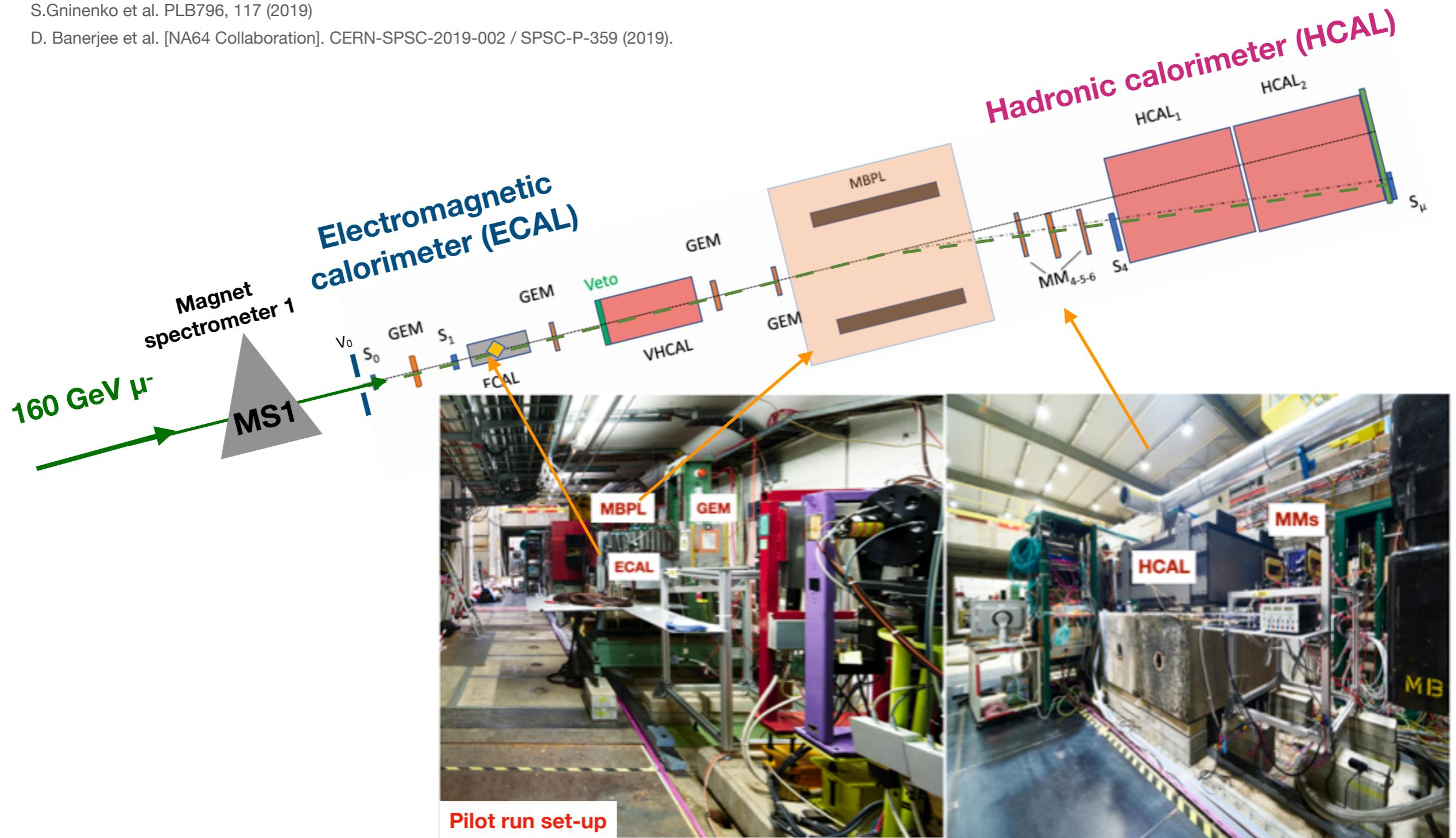


The NA64 μ experiment

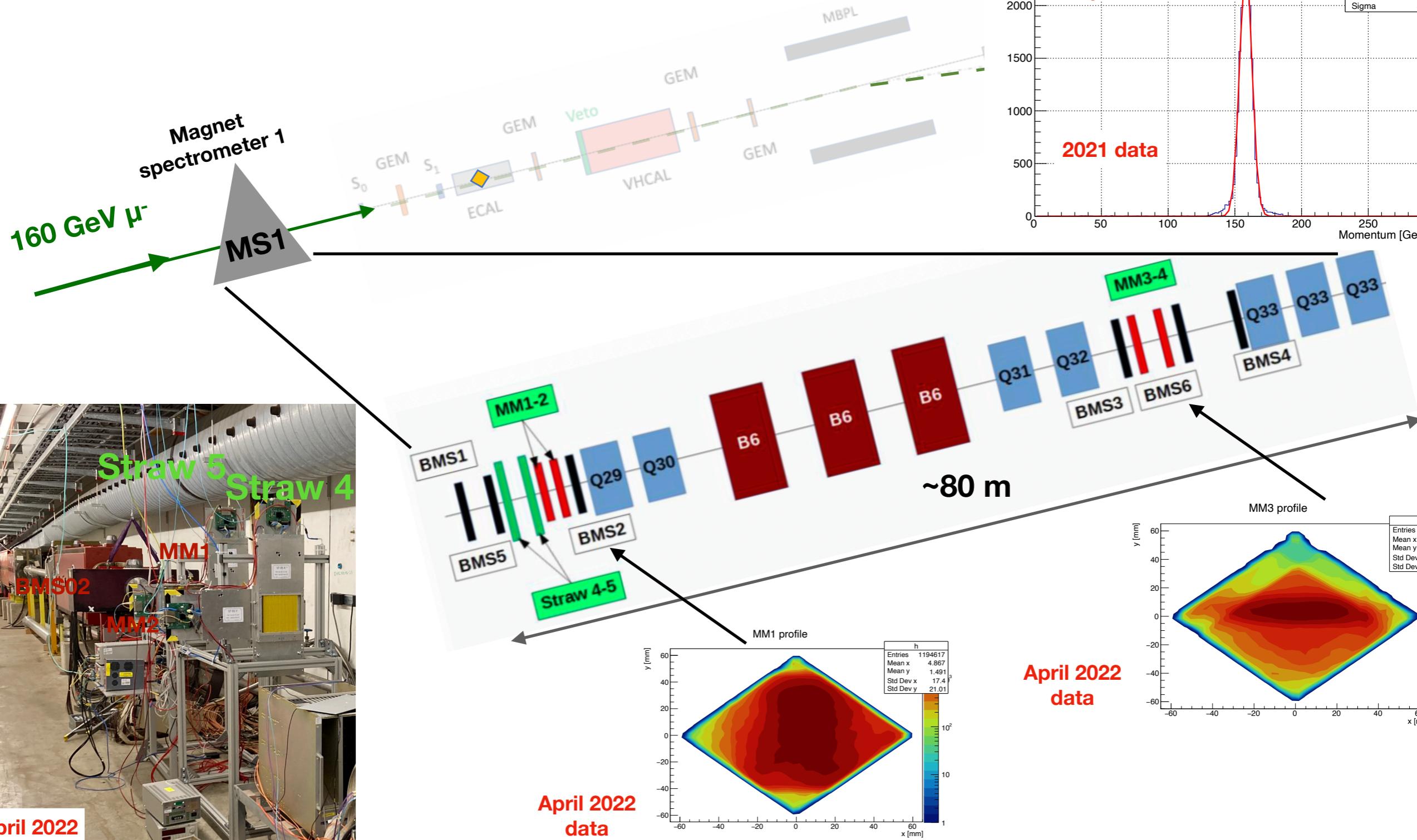
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S.Gninenko et al. PLB796, 117 (2019)

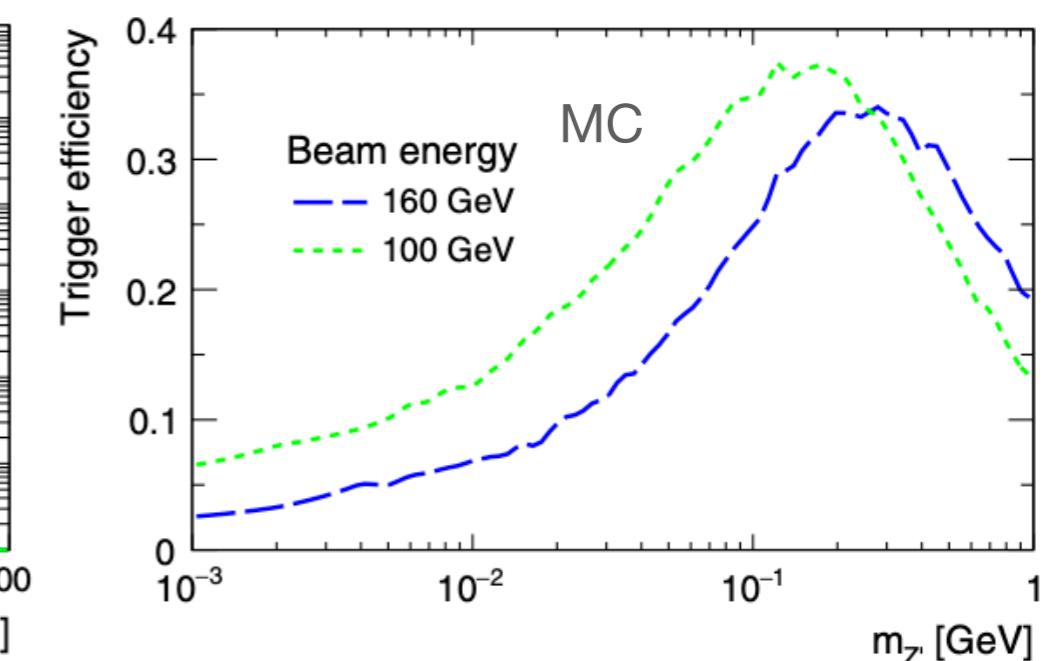
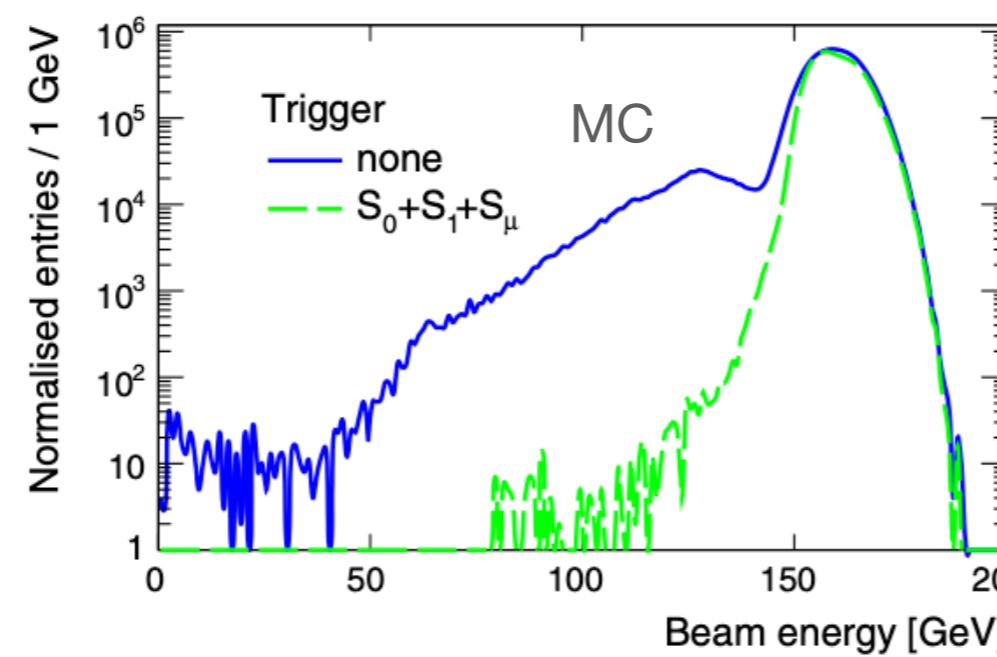
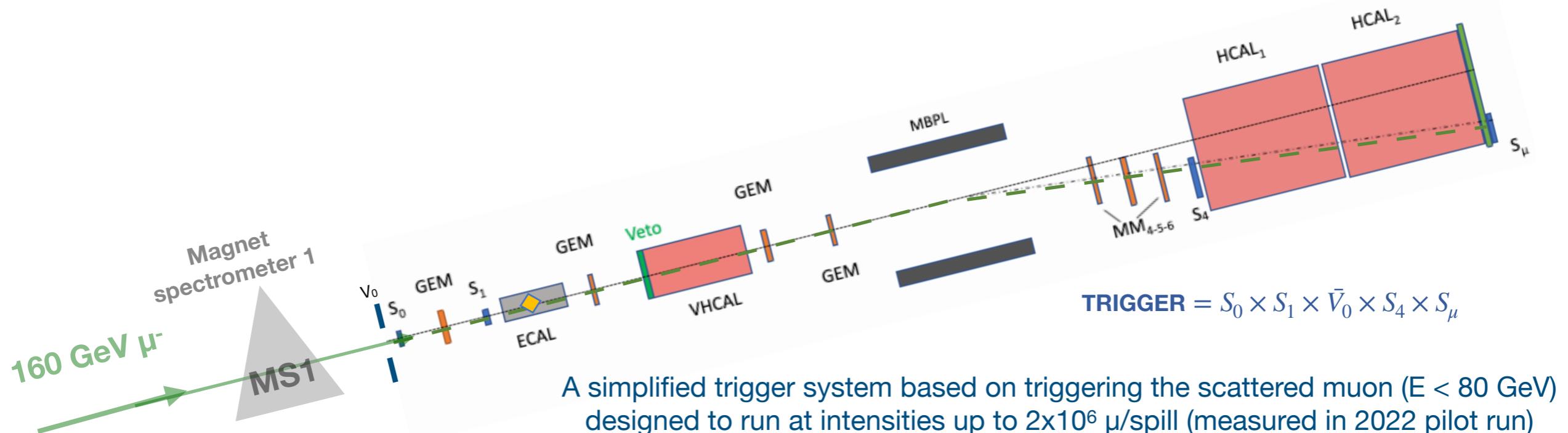
D. Banerjee et al. [NA64 Collaboration]. CERN-SPSC-2019-002 / SPSC-P-359 (2019).



The NA64 _{μ} experiment: the initial momenta

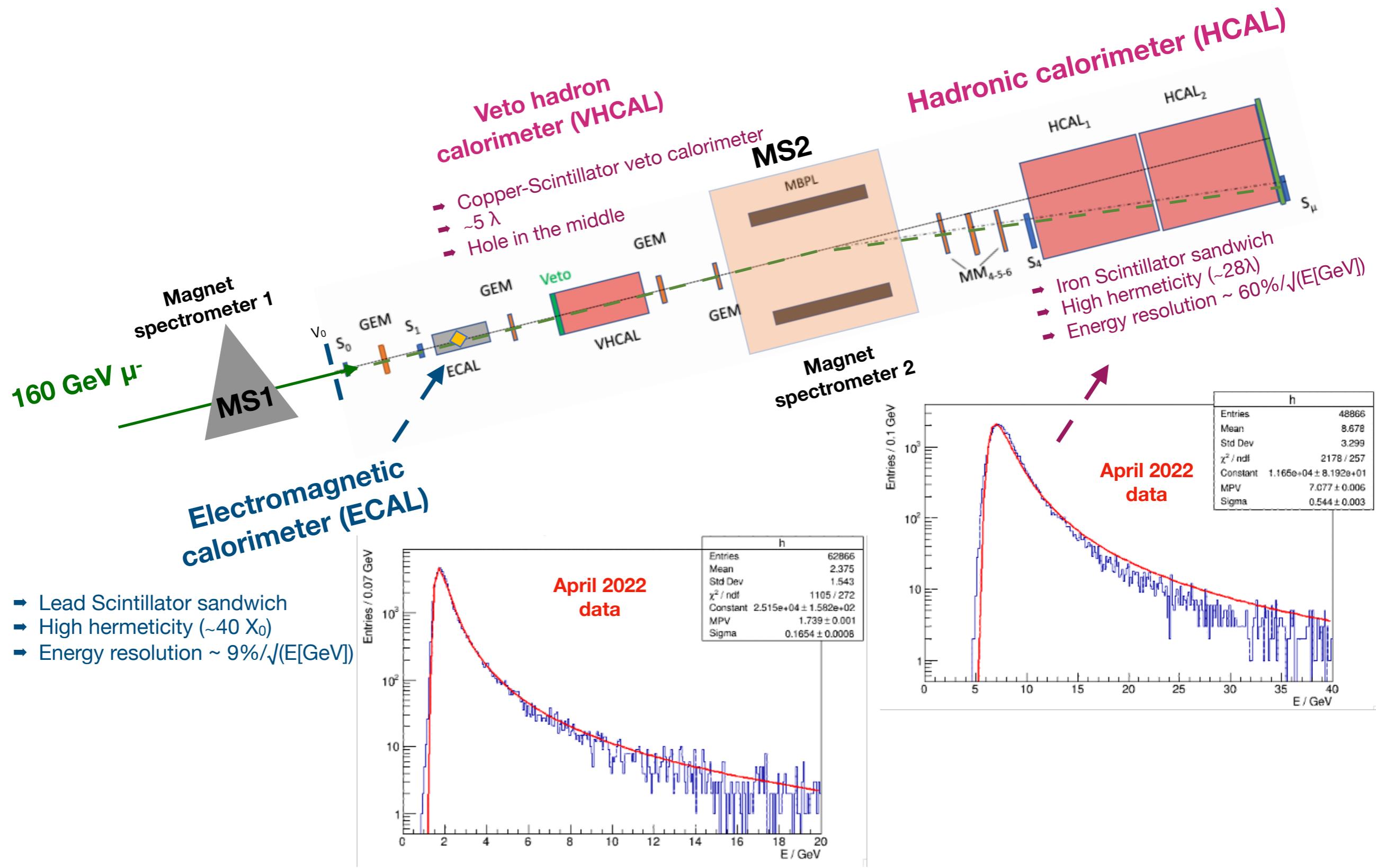


The NA64 μ experiment: the trigger system

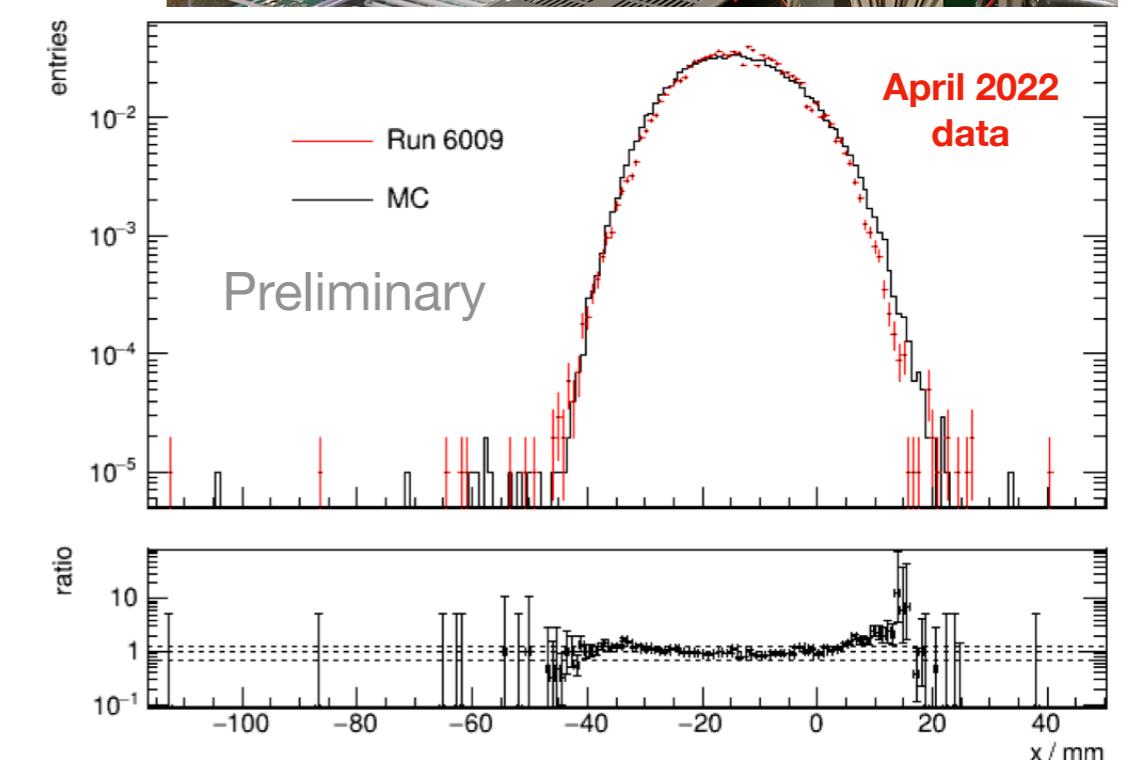
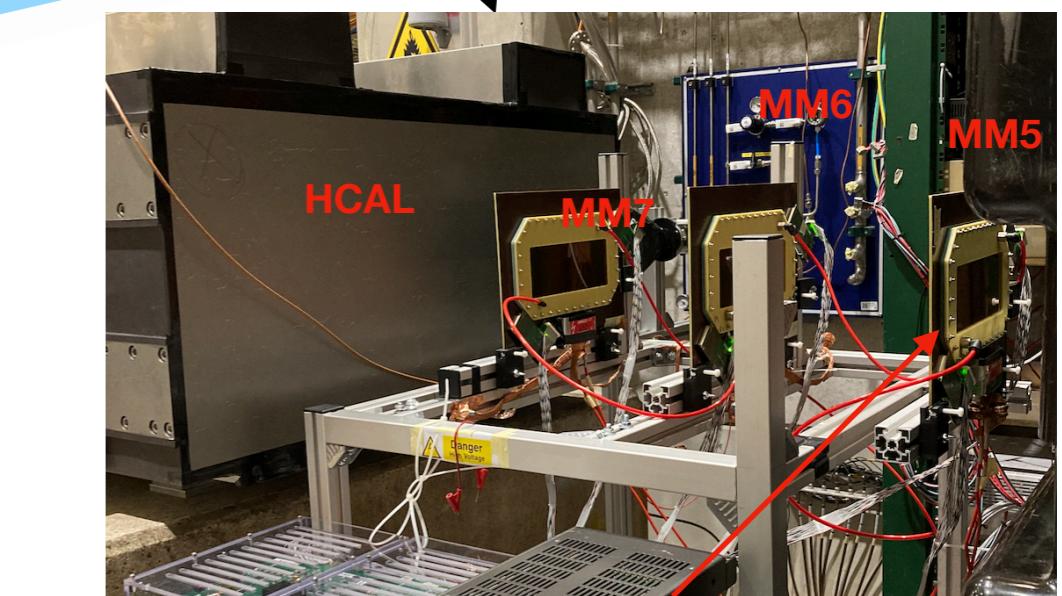
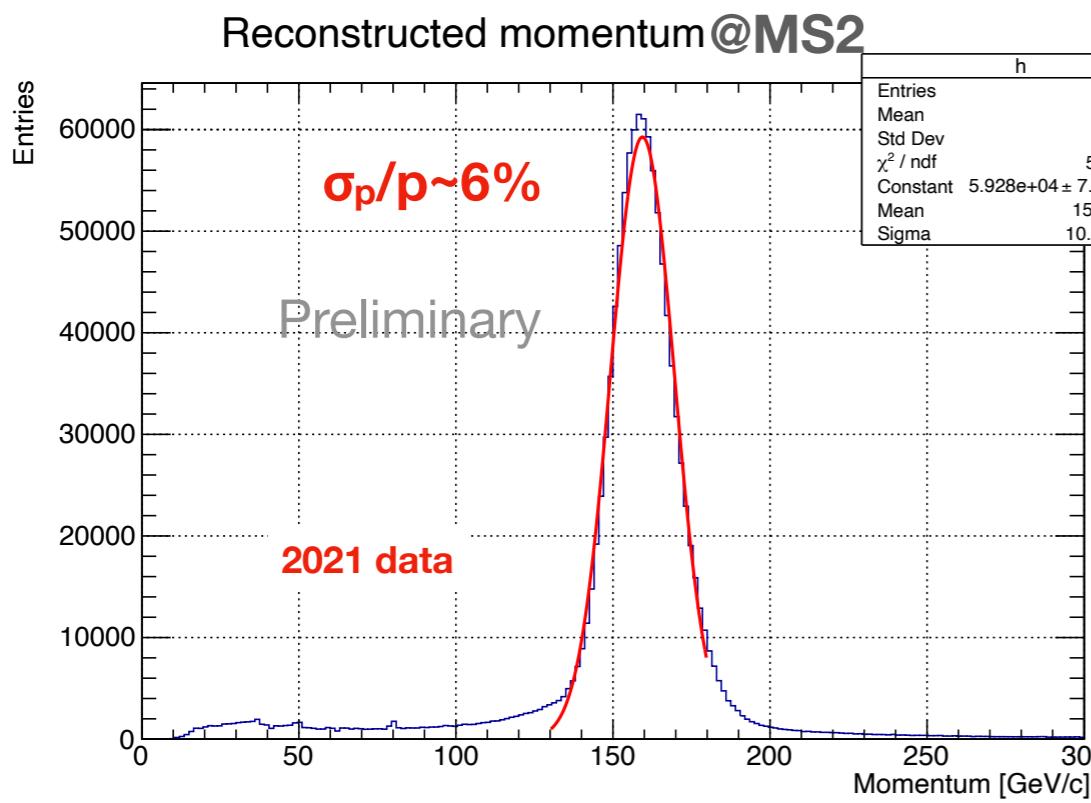
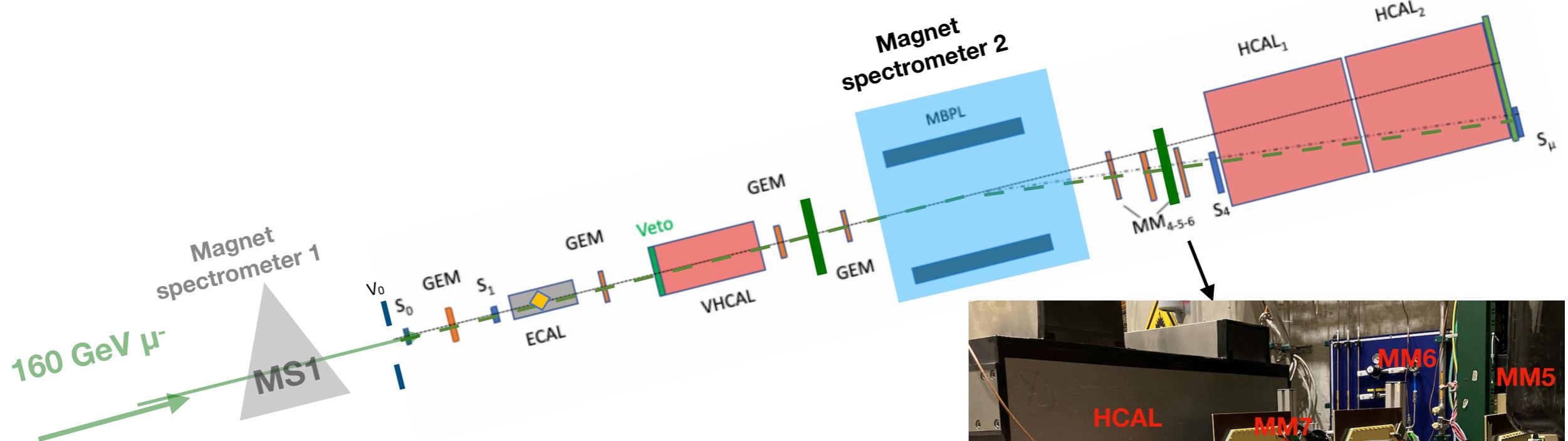


H. Sieber *et al.*, Phys. Rev. D 105, 052006 (2022)

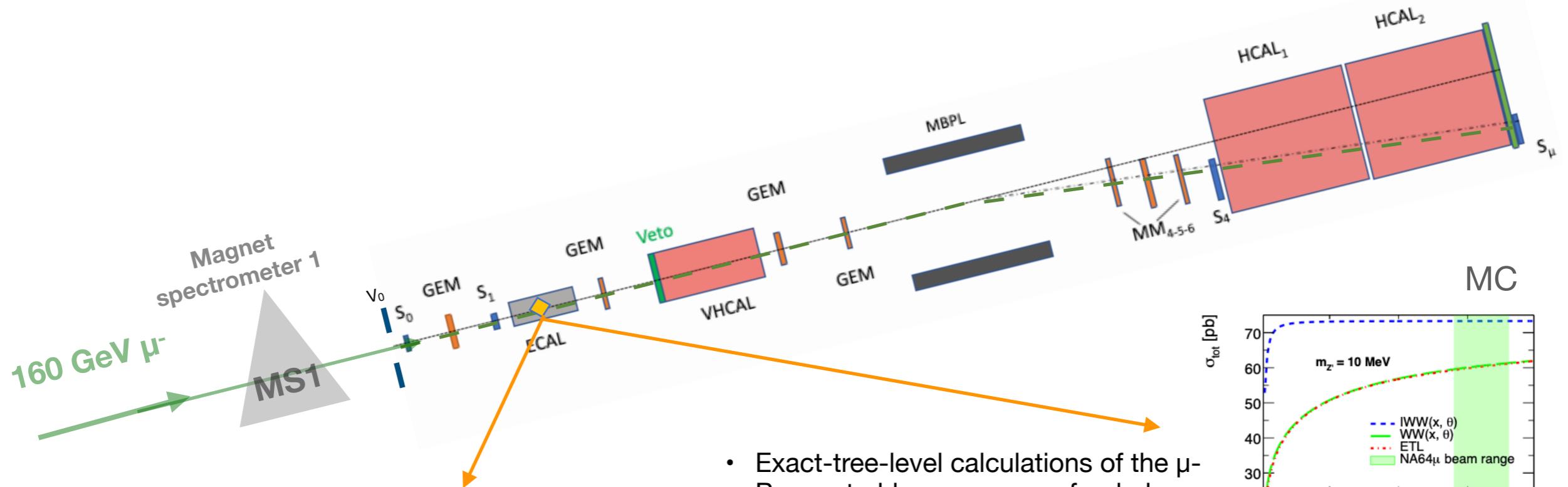
The NA64 $_{\mu}$ experiment: the calorimeters



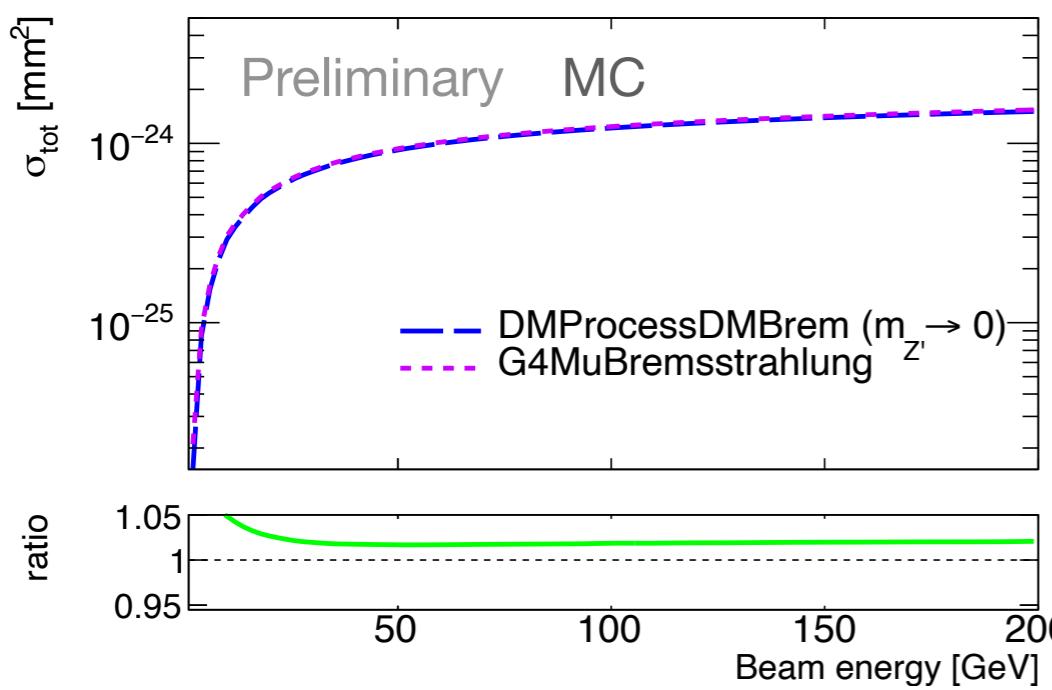
The NA64 μ experiment: the final momenta



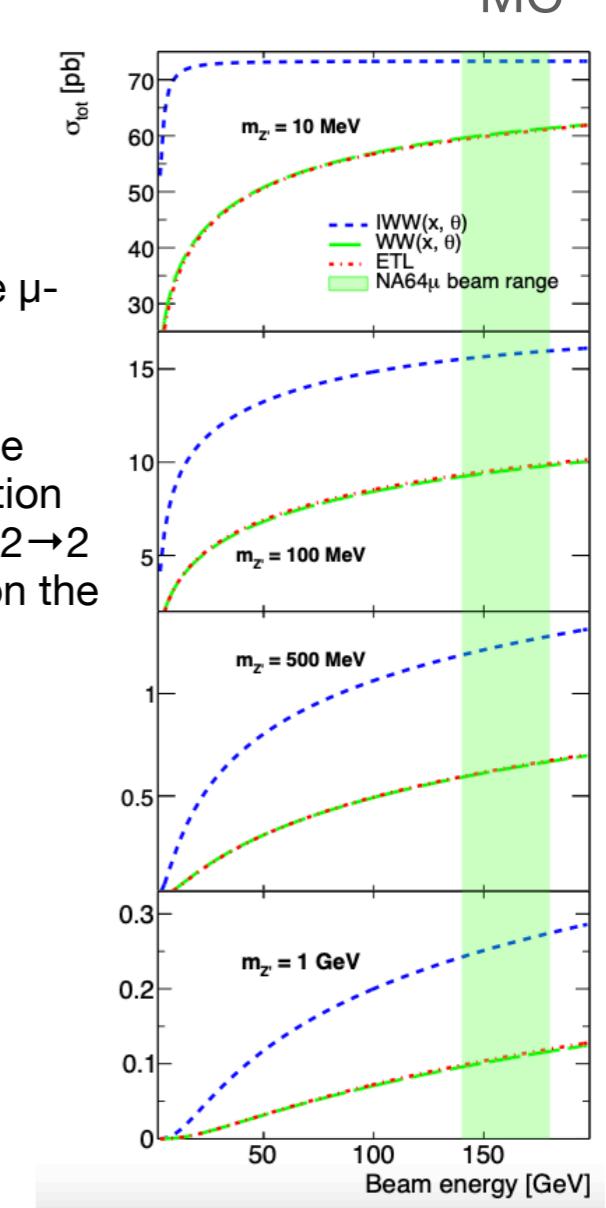
The NA64 μ experiment: the signal simulation



- Simulations performed in a Geant4-based Dark Matter simulation framework **DMG4**
(M. Bondi et al., Comput. Phys. Commun. 26, 108129 (2021))

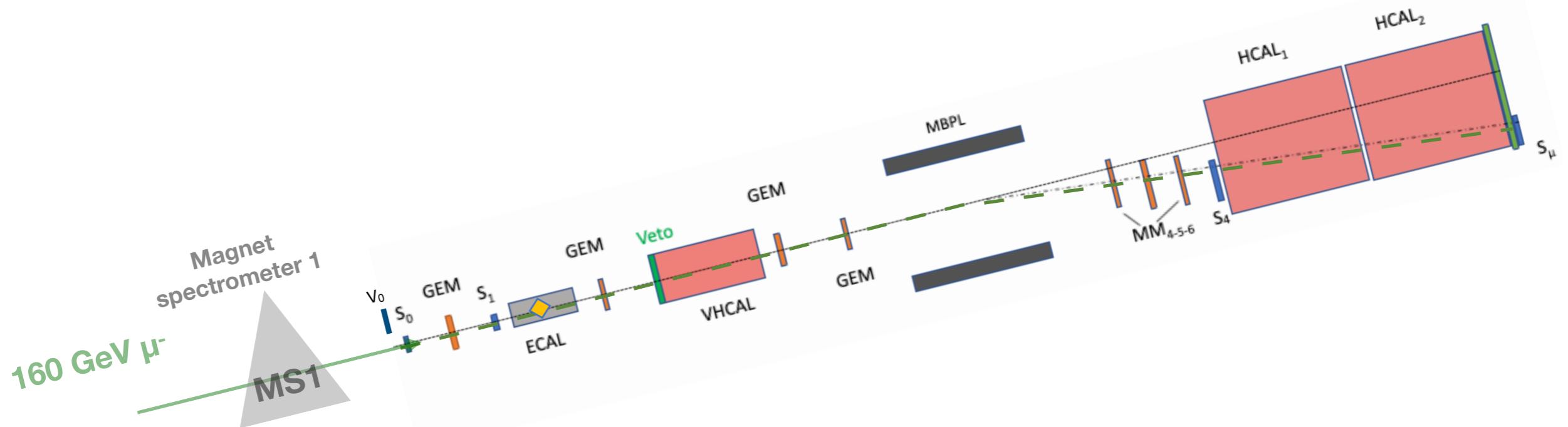


- Exact-tree-level calculations of the μ -Bremsstrahlung process of a dark vector boson used.
- Impact of the different phase space approximations used in cross-section calculations to reduce a $2 \rightarrow 3$ to a $2 \rightarrow 2$ body decay (Weizacker-Williams) on the **signal yield studied**.



D. V. Kirpichnikov et al., Phys. Rev. D 104, 076012 (2021)

The NA64 μ experiment: expected background



Main sources of background studied through simulations

Source of background	Level per MOT
Hadron in-flight decay	$\lesssim 10^{-11}$
Momentum mismatch	$\lesssim 10^{-12}$
Detector non-hermeticity	$\lesssim 10^{-12}$
Single-hadron punch-through	$\lesssim 10^{-12}$
Dimuon production	$< 10^{-12}$
Total (conservatively)	$\lesssim 10^{-11}$

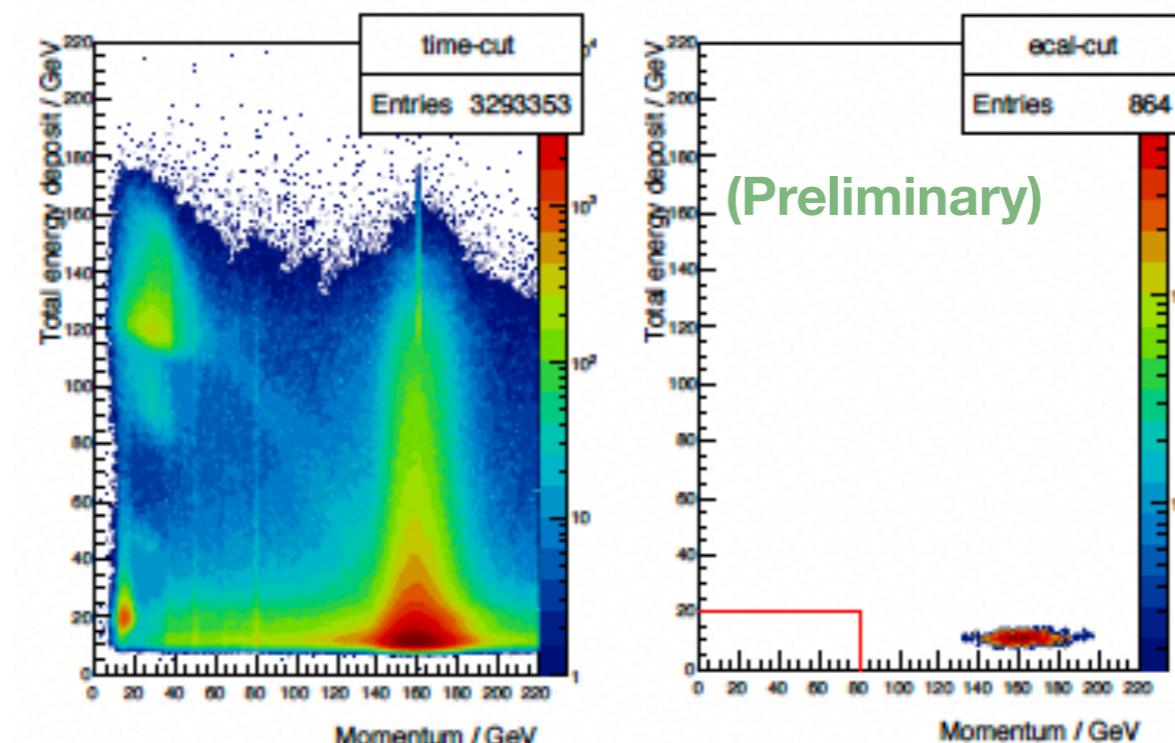
H. Sieber *et al.*, Phys. Rev. D 105, 052006 (2022)

The NA64 μ experiment: preliminary results

Cut-flow analysis for the $\sim 5 \times 10^9$ MOT collected in 2021 (in 2022 statistics increased a factor 10)

Event Selection Criteria:

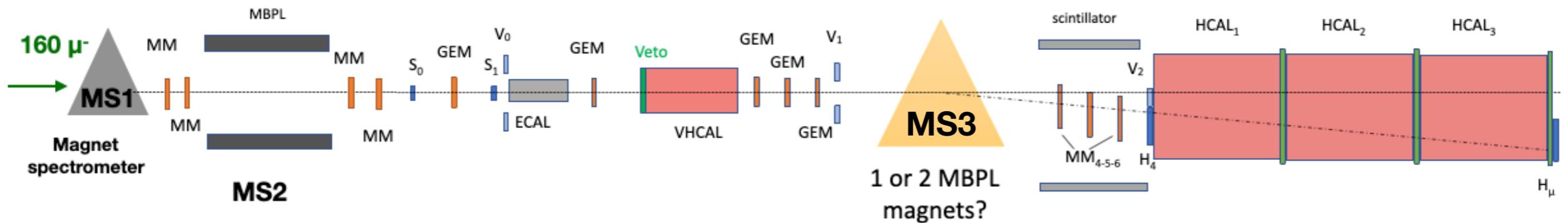
- I) In-time events
- II) Single-hit per tracker
- III) Reconstructed momenta in MS1 [135, 185 GeV].
- IV) Quality cut on downstream momenta in MS2 based on χ^2 .
- V) Energy compatible with MIP energy in calorimeters and veto



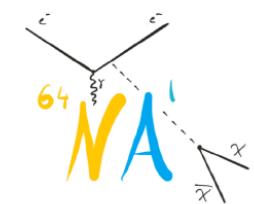
No background observed at this level

Data analysis: work in progress

The NA64 μ experiment: future physics run



- Setup for the first physics run foreseen at the end of 2023 or beginning of 2024 under study.
- **Main goals:**
 - Fully hermetic detector.
 - Initial and final μ momenta measured twice to minimise the level of its mis-measurements down to $\lesssim 10^{-13}$.
 - MS1 and MS2 will measure the initial momenta
 - Under study to have 2 MBPLs magnet in the spectrometer downstream, MS3, to further reduce mis-reconstructions in the final momenta.
 - New trigger system to run at higher intensities $> 10^7 \mu/\text{spill}$.



Summary and outlook

- **NA64 μ experiment** started searching for dark sectors weakly coupled to muons at M2 beam-line complementing **NA64e** efforts.
- A pilot run in 2021 and 2022 devoted to study the feasibility of the technique:
 - ▶ 4×10^{10} MOT collected.
 - ▶ Preliminary encouraging results about beam quality, trigger rate and hermeticity.
 - ▶ No events in the signal region for the 5×10^9 MOT collected in 2021. A factor 10 higher statistics collected in 2022 (data analysis is ongoing)

- NA64 μ can discover or disprove very interesting predictive thermal LDM models and greatly explore DS weakly coupled to muons in the coming years.
- It is an ideal experiment to decisively probe many New Physics scenarios such as the existence of a light Z' boson as explanation of the muon g-2 anomaly, scalar, ALPs and lepton flavour conversion in $\mu \rightarrow \tau$.



THANKS!

Acknowledgements

NA64 collaboration in particular **P.Crivelli** and **S.Gninenko**

ETH Zürich group in particular P. Crivelli, B.Banto, E. Depero, M. Mongillo, H.Sieber and M. Tuzi (PhD student at IFIC)

CERN BE-EA group in particular D. Banerjee



**Swiss National
Science Foundation**

SNSF Ambizione grant: PZ00P2_186158

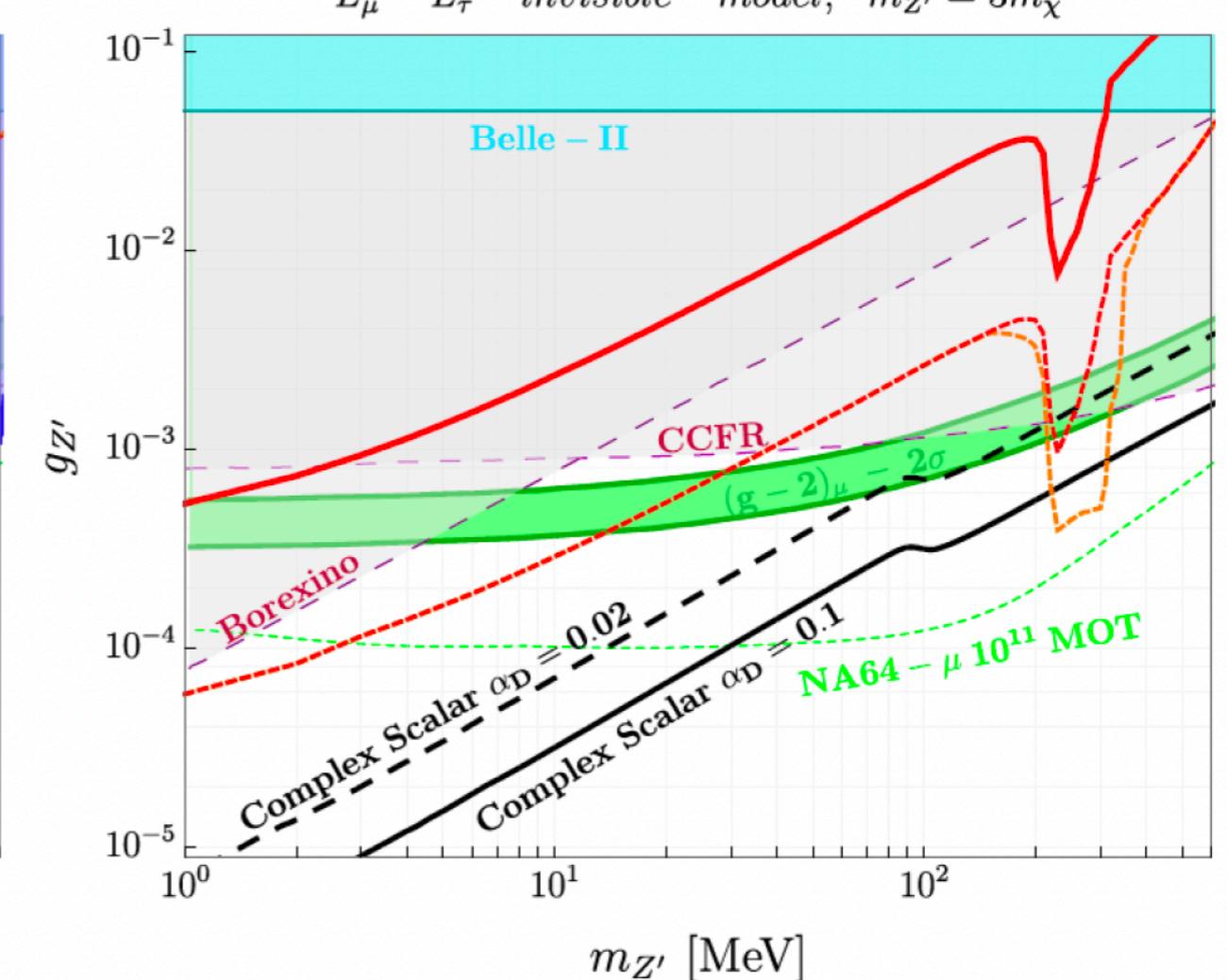
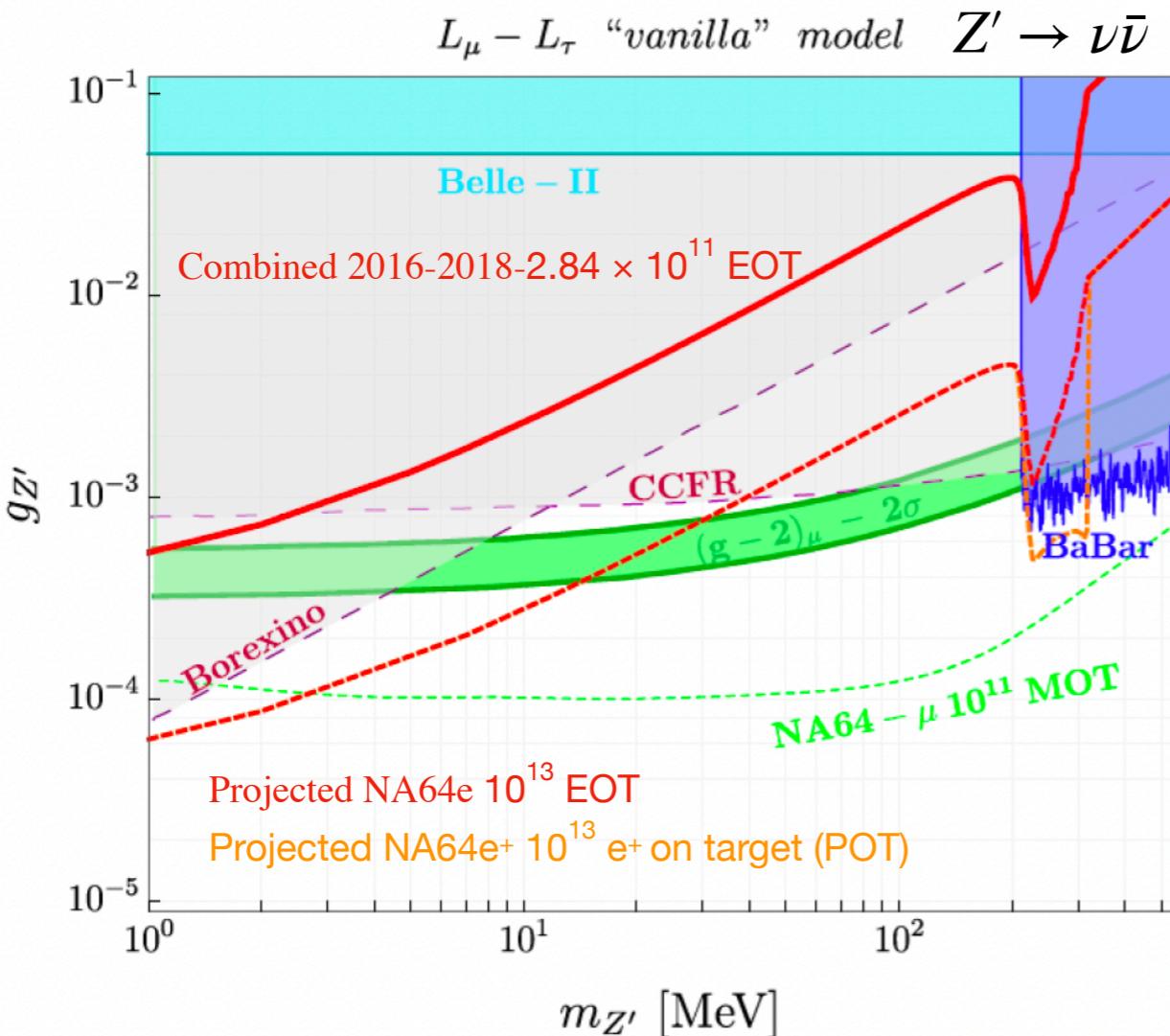
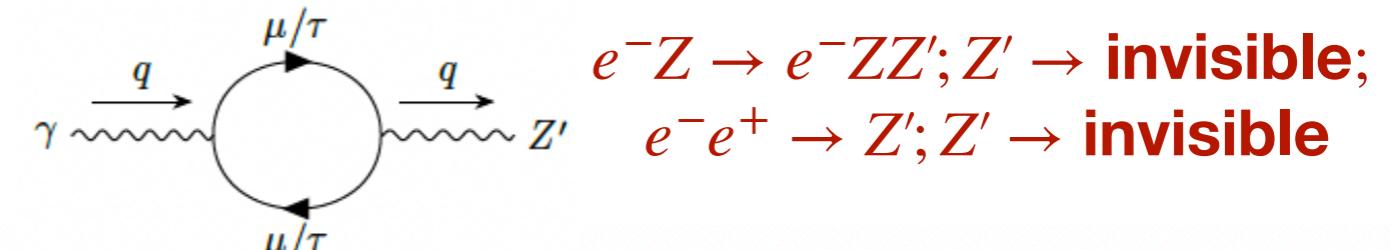


NA64 invisible searches: $L_\mu - L_\tau Z'$

A well-motivated SM extension:

- A **light Z'** arising by gauging the difference of the lepton number between the muon and tau flavour, $L_\mu - L_\tau$.
- It can accommodate the **muon g-2 anomaly** and the **DM freeze-out relic origin**.

First result using the *NA64e* collected data in 2016-2018

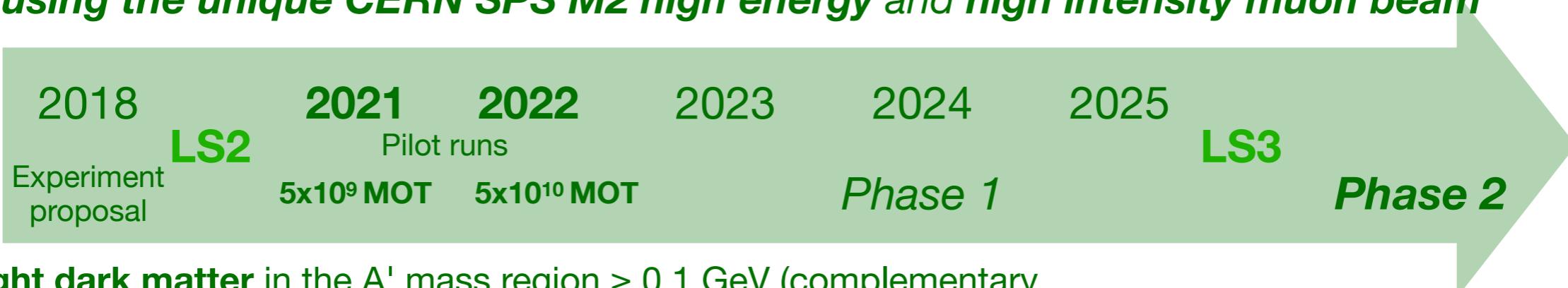


NA64 collaboration, <https://arxiv.org/abs/2206.03101> (June, 8th 2022)

Complementarities between electron, muon and positron programs to unequivocally probe these models.

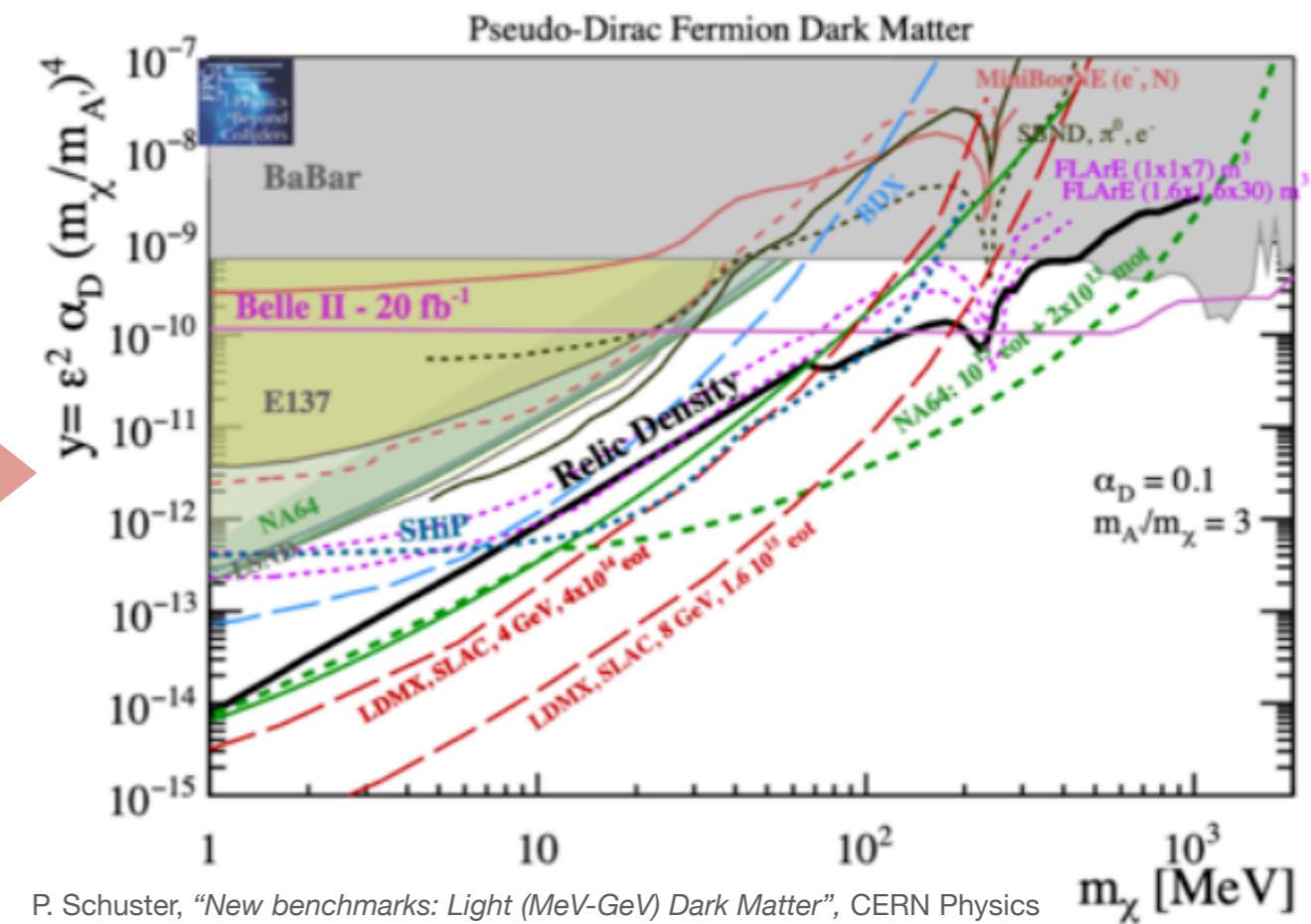
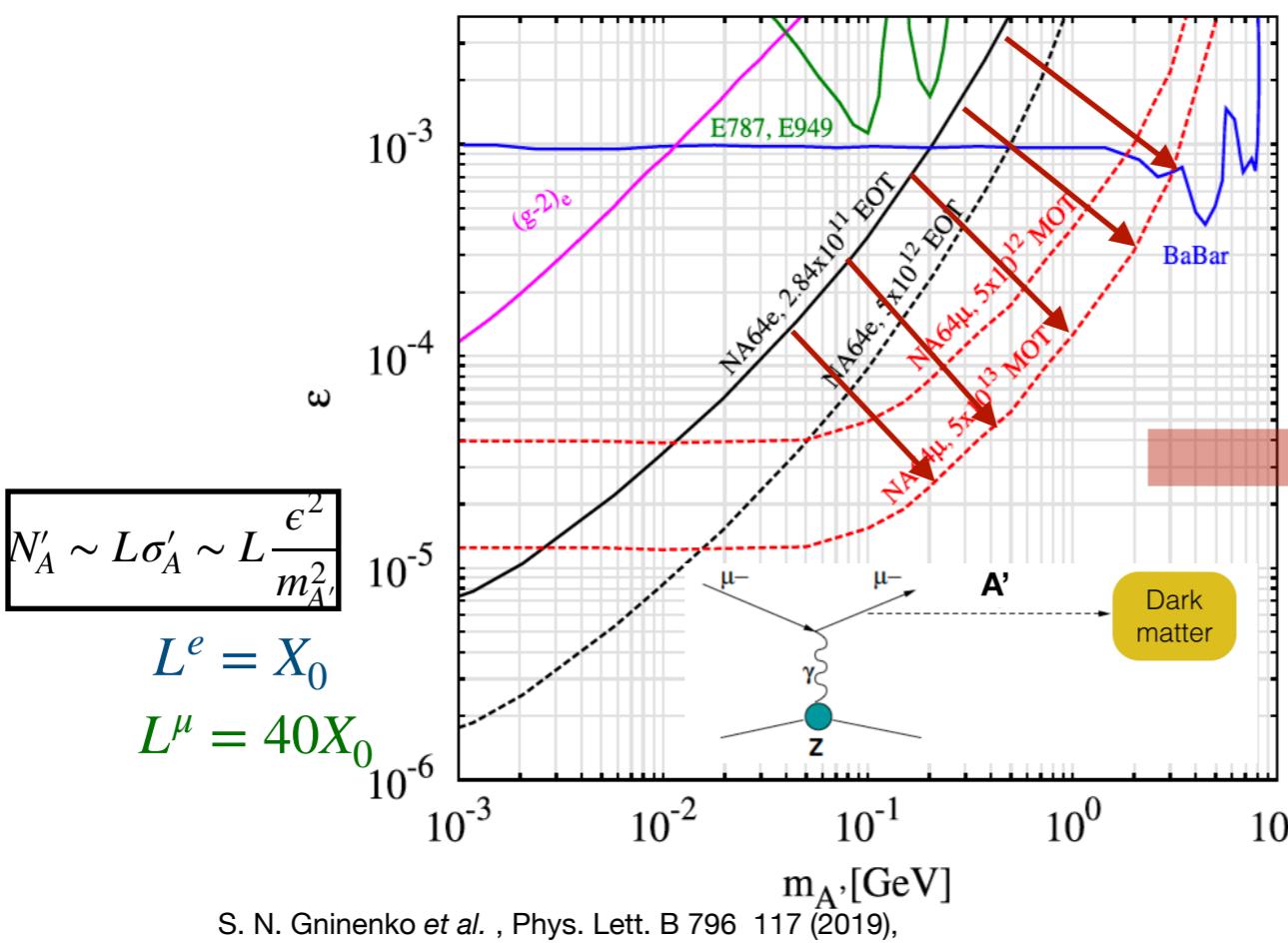
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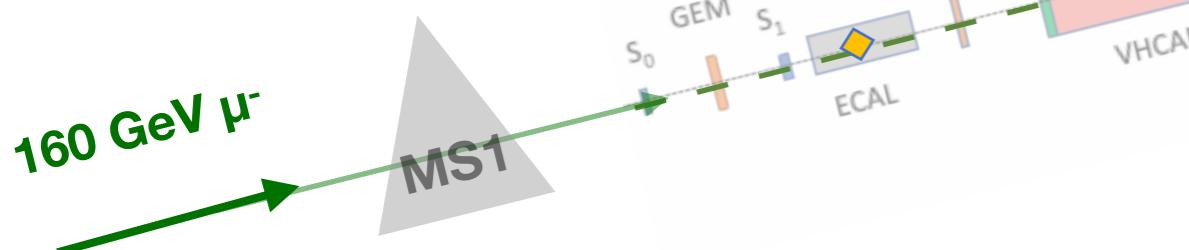


The NA64 μ experiment: the beam

160 GeV muons generated at the **high energy** (up to 250 GeV) and **high intensity** (10^5 - 10^7 μ/s) **M2 beam-line** at the **CERN SPS accelerator**.

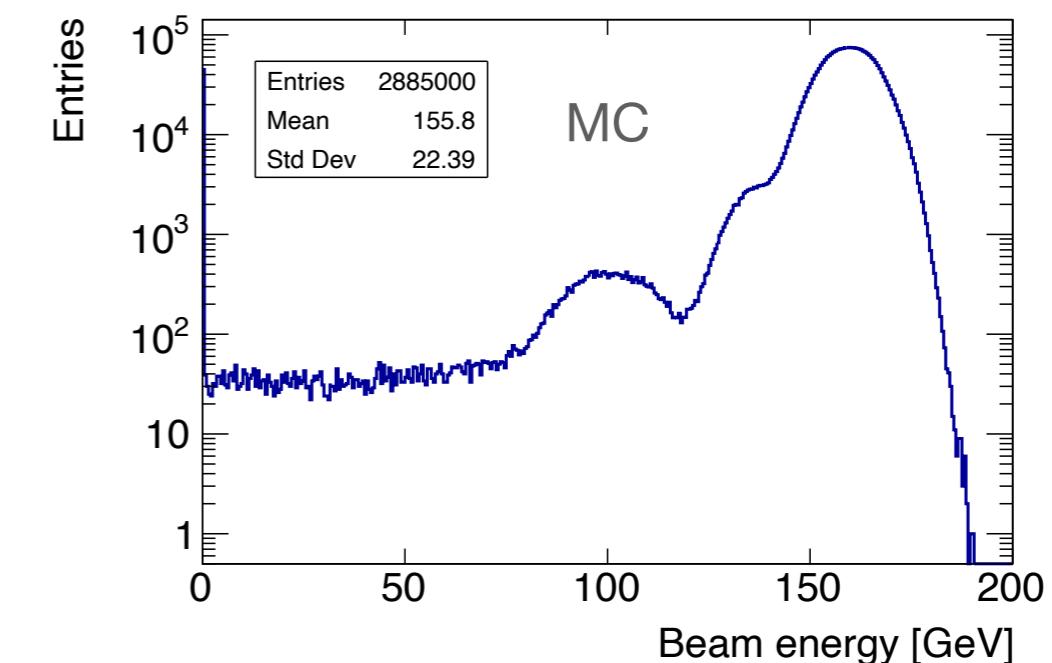
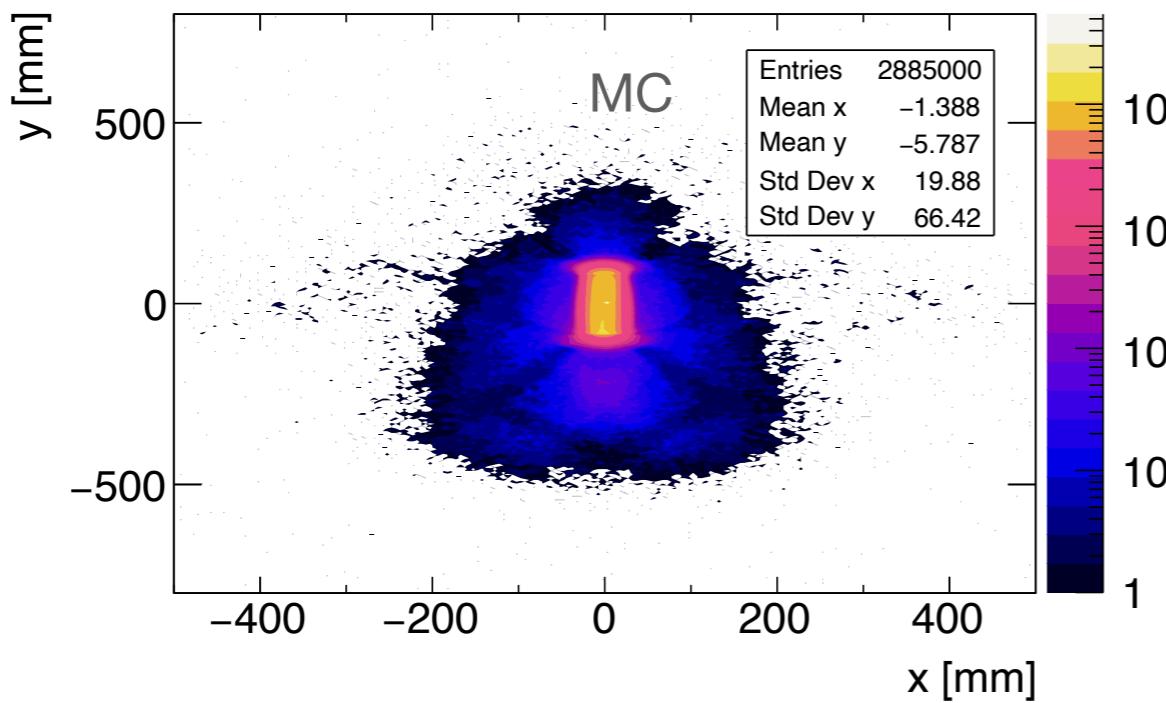
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N. Doble, L. Gatignon, G. von Holtey, and F. Novoskoltsev,
Nucl. Instrum. Methods Phys. Res., Sect. A 343, 351 (1994).



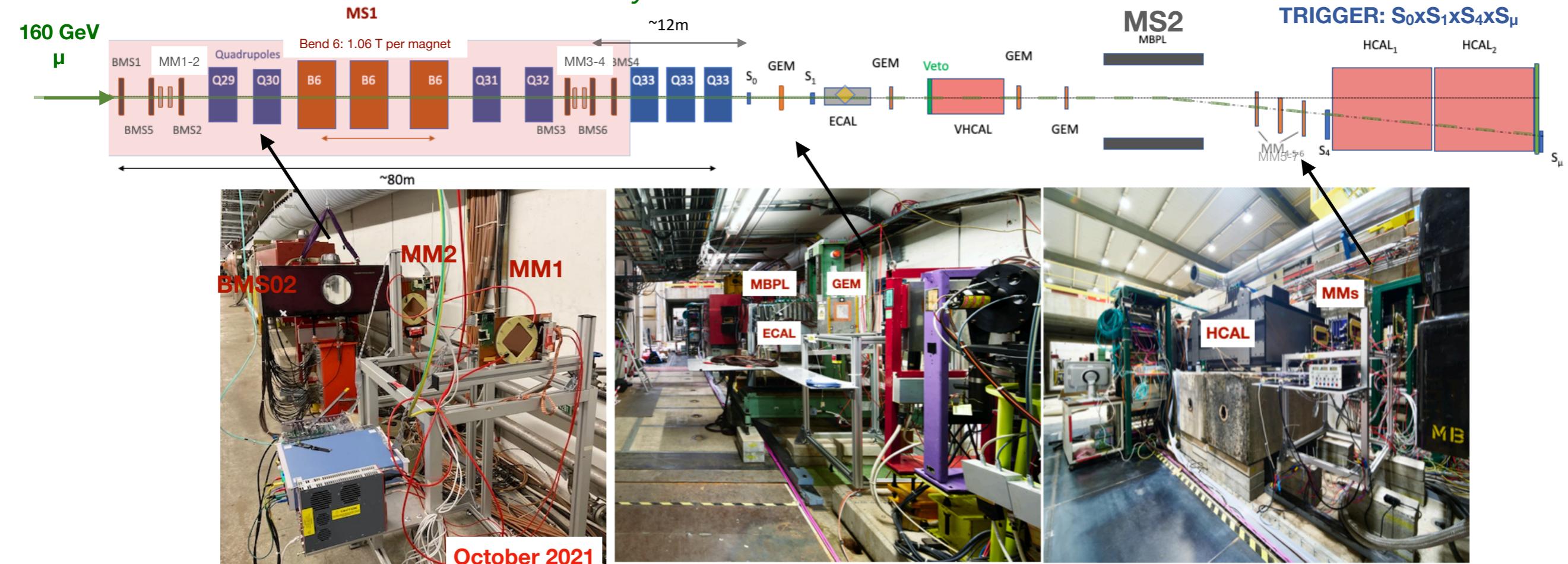
Realistic simulation framework developed using the M2 beam-optics simulation @NA64 μ location obtained through HALO program by the CERN beam department.

J. Bernhard et al., AIP Conf. Proc. 2249, 030035 (2020)

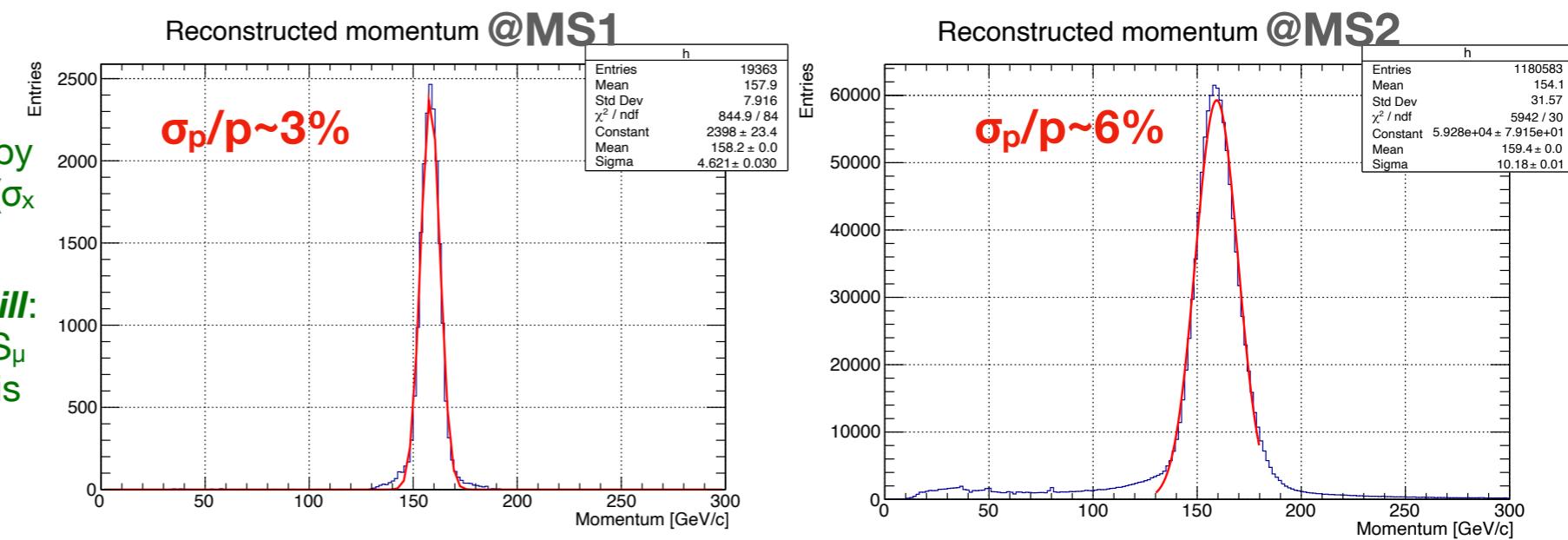


NA64 μ 2021 pilot run

19 days of beam time @M2 beam-line



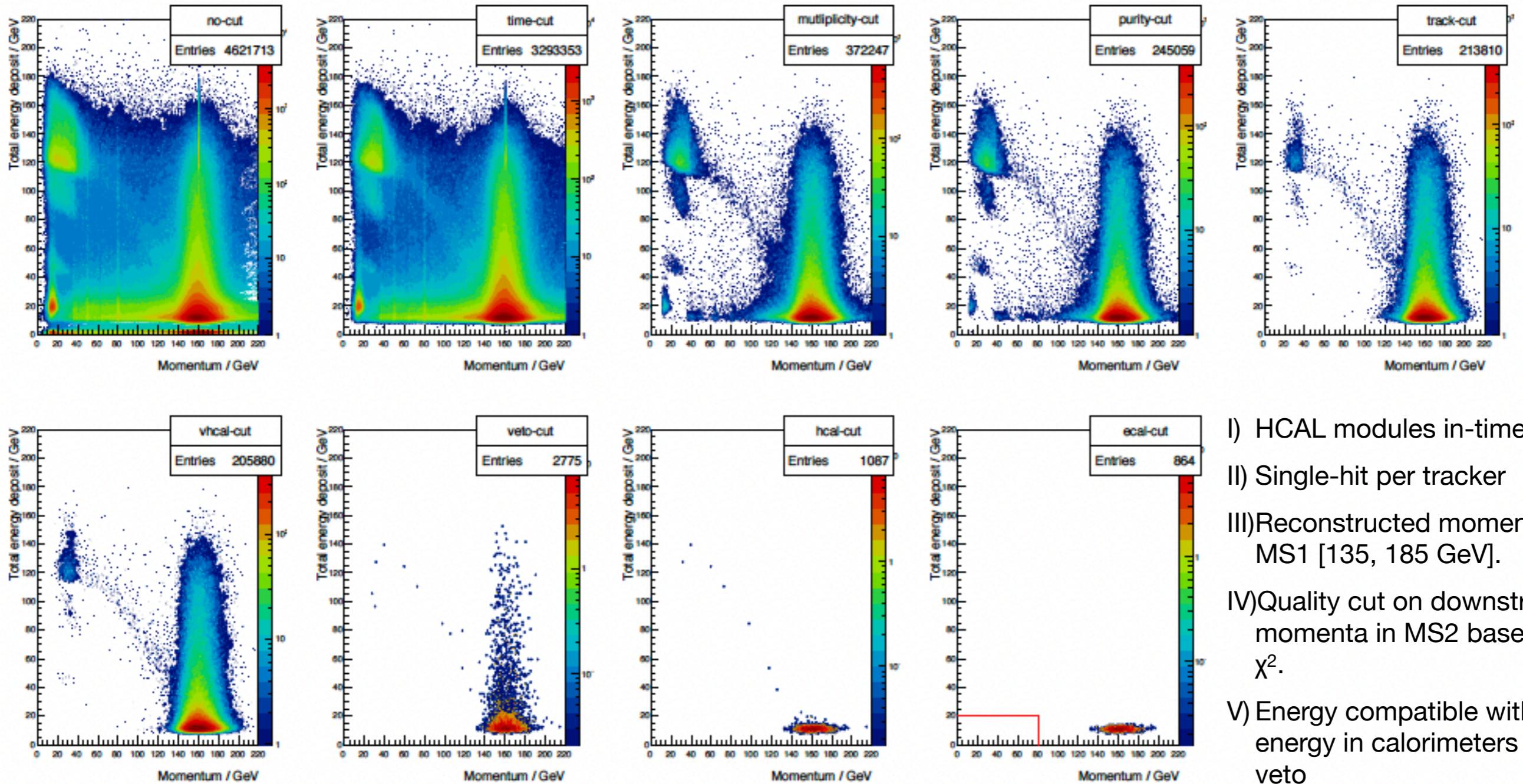
- The beam profile was measured for the first time.** A narrower beam can be obtained with S_0+S_1 trigger with a divergence compatible with the beam-optics simulation estimations performed by D. Banerjee from the BE-EA department ($\sigma_x \sim 0.9\text{ cm}$ and $\sigma_y \sim 1.9\text{ cm}$).
- Trigger rate reduced by 500 at $10^6 \mu/\text{spill}$:** coincidence in the 4 counters $S_0 \times S_1 \times S_4 \times S_\mu$ after shifting S_4 and S_μ from the beam axis required.
- Accidental rate of ~1%** measured after delaying S_4 signal by 200 ns.



NA64 μ 2021 pilot run

Cut-flow analysis for the $\sim 5 \times 10^9$ MOT collected

(Preliminary)



- I) HCAL modules in-time
- II) Single-hit per tracker
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Data analysis: work in progress