Fermilab

Identification of Dark Matter 2026

Zaragoza, Spain

Searches for millicharged particles at accelerator facilities with skipper-CCD detectors

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U.S. DEPARTMENT of ENERGY

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Millicharged particles: a window to the dark sector

Hypothetical particles with fractional electric charge

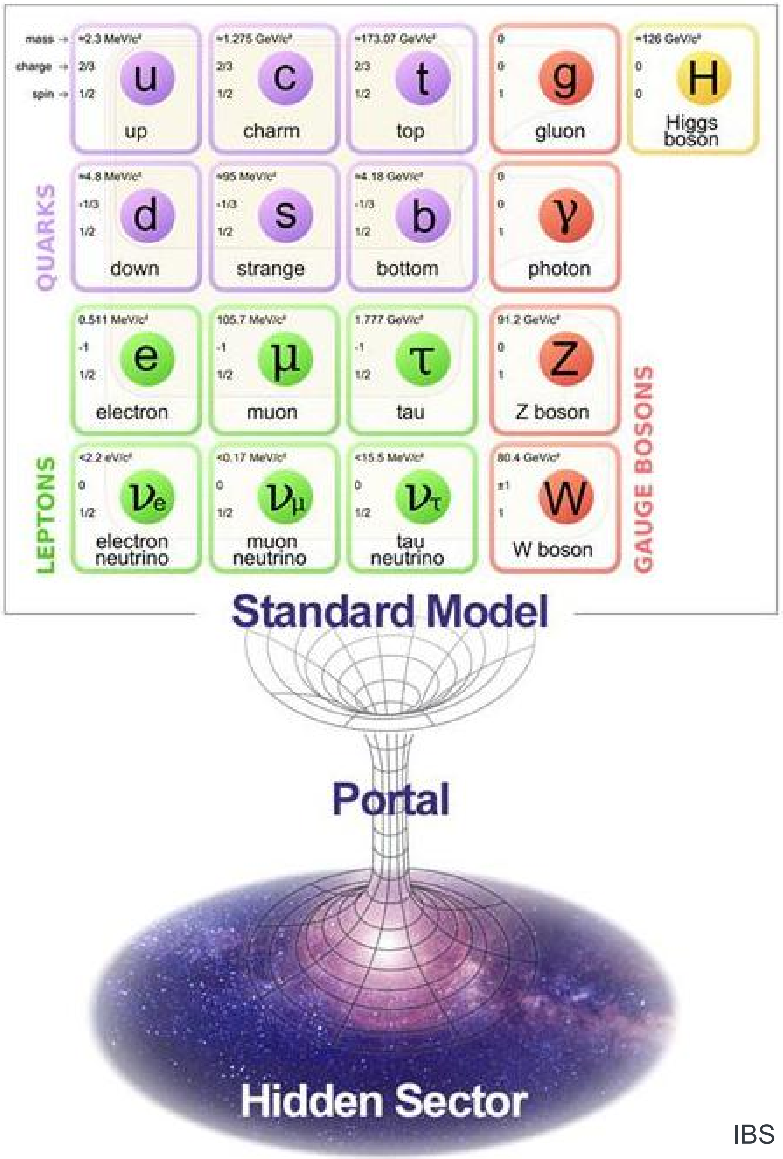
If they exist, they:

- Would **test charge quantization**
- Could be **candidates for a fraction of the dark matter**

mCPs arise naturally in dark sector models, e.g. as a new fermion, charged under a new massless vector boson kinetically mixed with the SM photon.

mCPs interact very feebly with the SM particles

Production: high-intensity sources → **accelerators**
Detection: low-background ultra-sensitive devices → **skipper-CCDs**

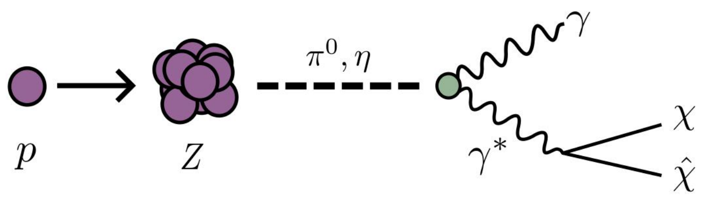


IBS

Millicharged particles: production at p⁺ accelerators

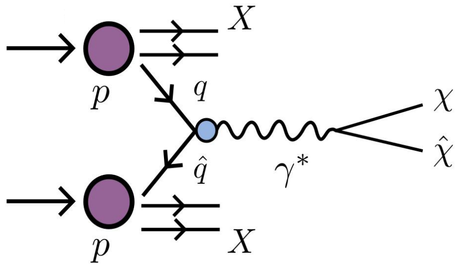
Meson decays

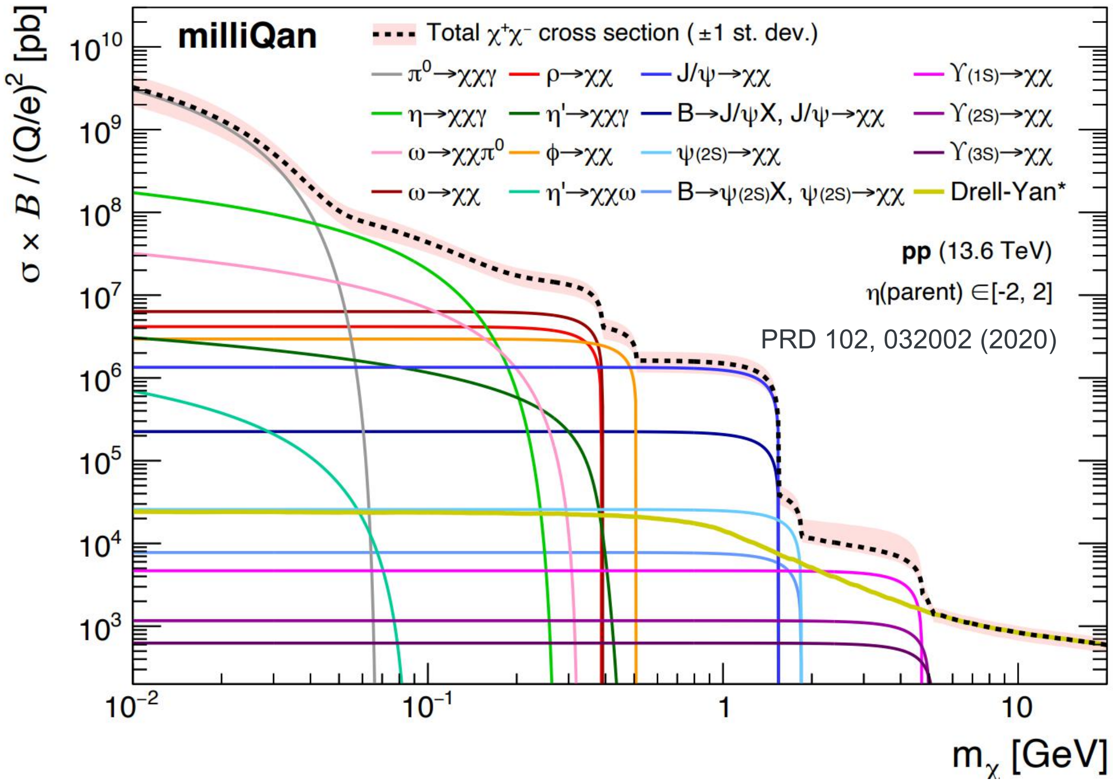
(m_{mCP} ~ MeV)



Drell-Yan processes

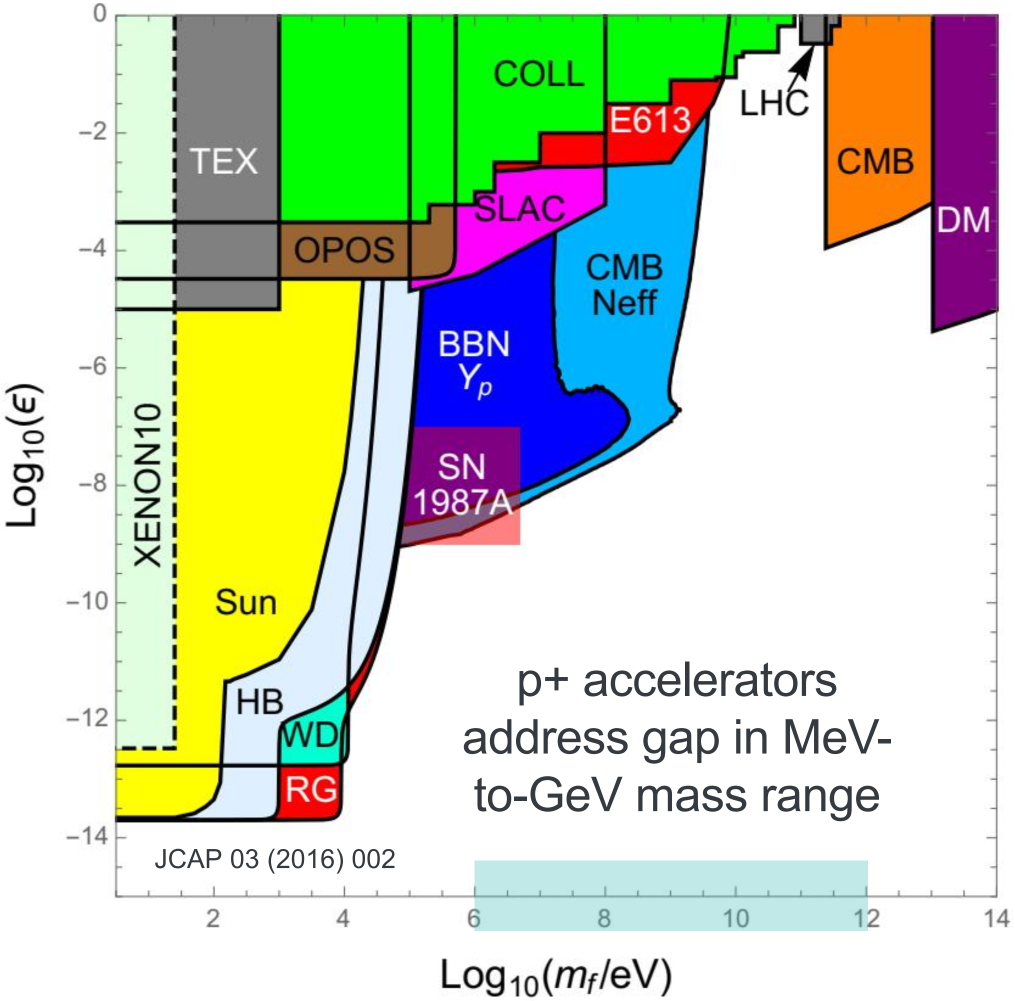
(m_{mCP} ~ GeV)



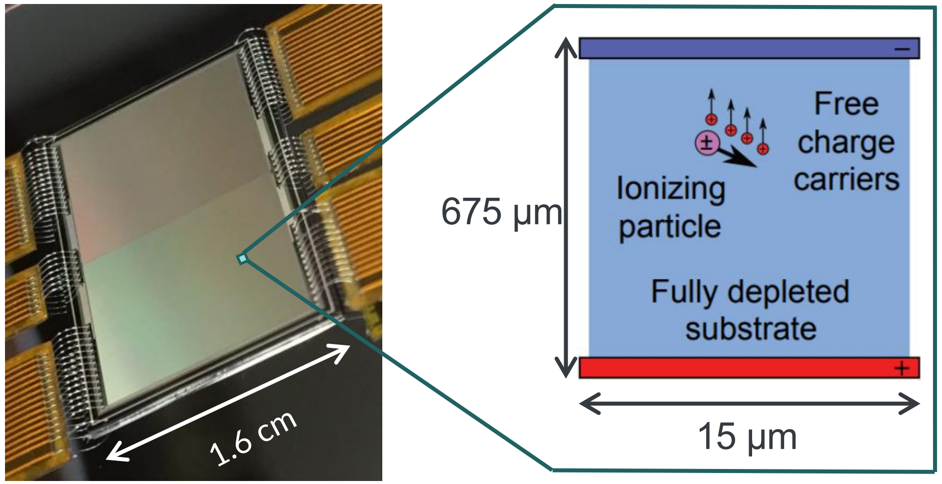


Fixed-target: ~GeV & ~10^{20} POT/year

Colliders: ~TeV & ~10^{16} pp cols/year

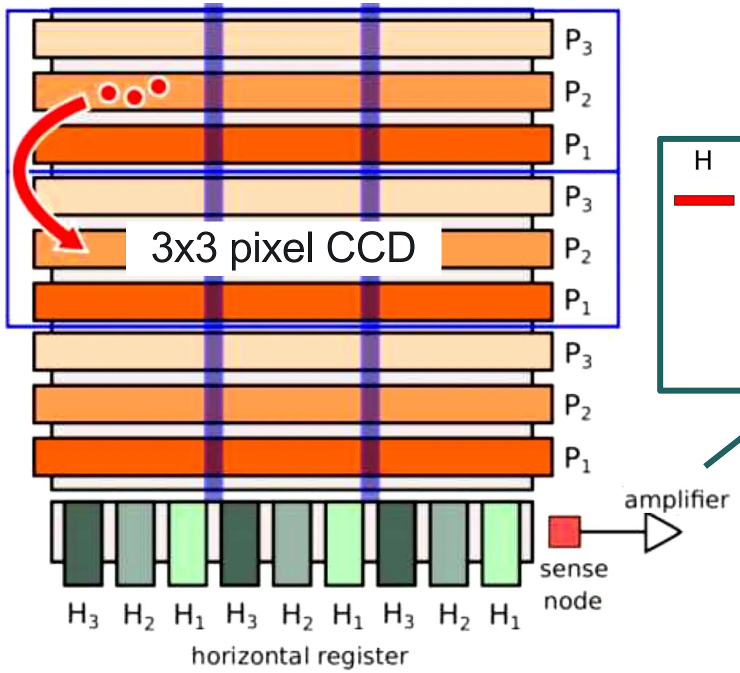


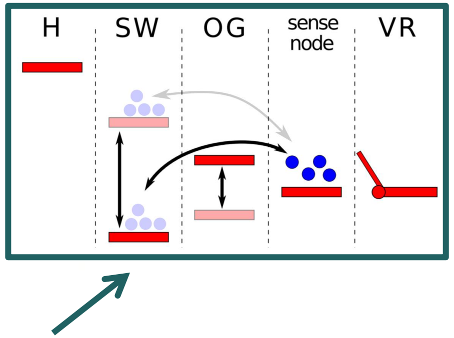
Millicharged particles: detection with skipper-CCDs



Skipper-CCDs: eV threshold, low intrinsic background, µm-scale spatial resolution and **electron-counting capability.**

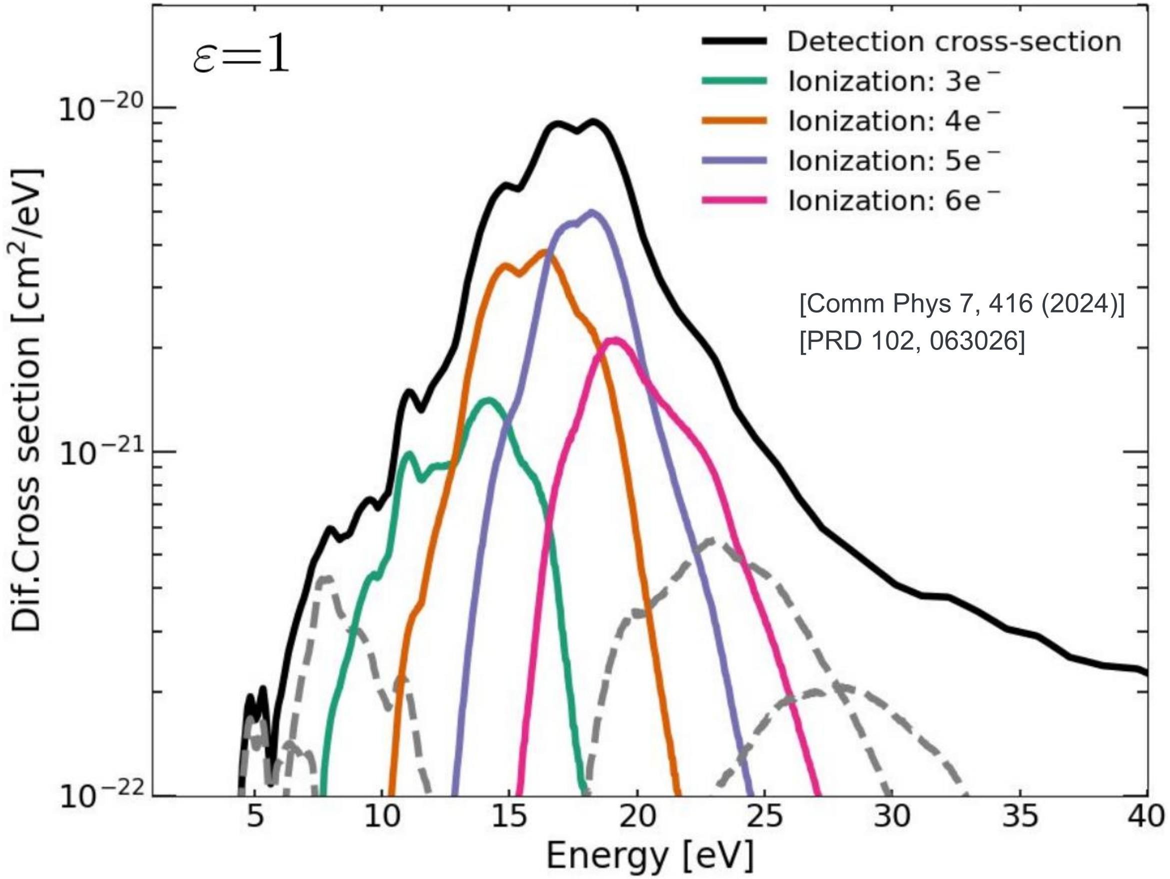
mCPs detection channel: electron scattering





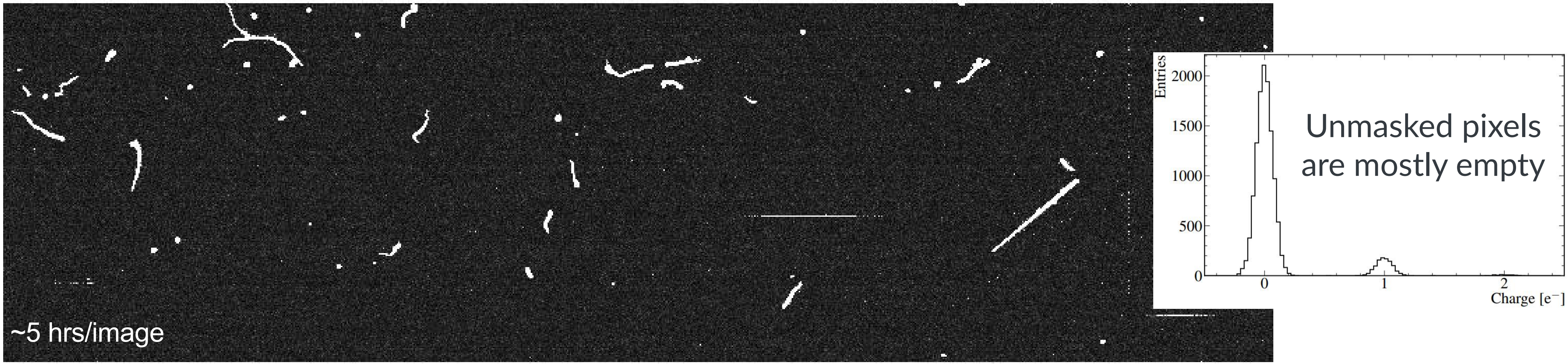
$$Q = \frac{1}{N}\sum_{i=1}^{N} Q_i$$

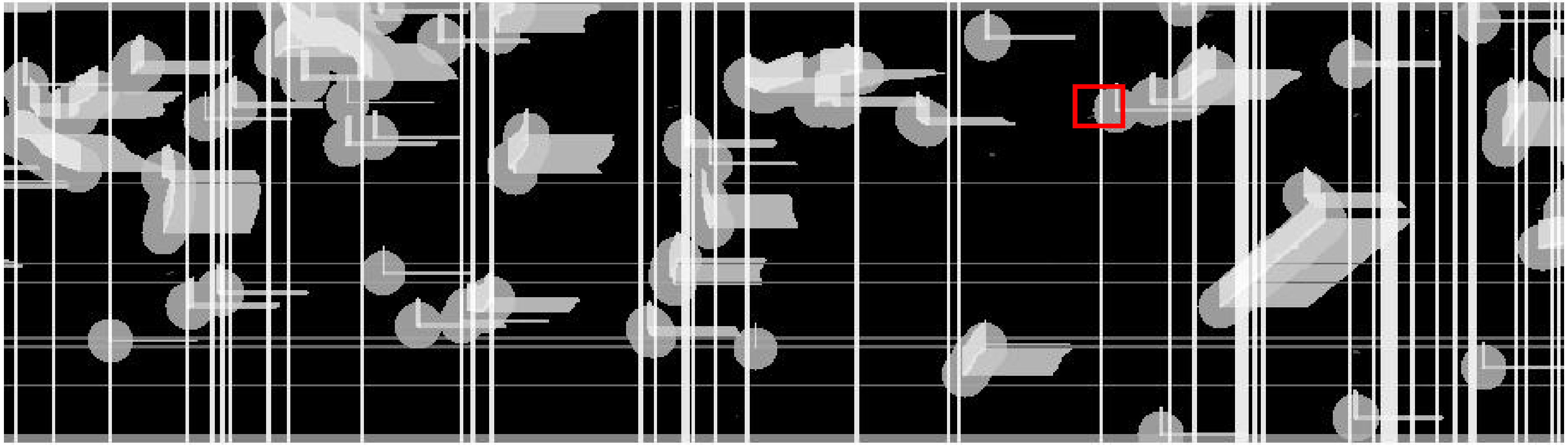
$$\sigma = \sigma_1/\sqrt{N}$$

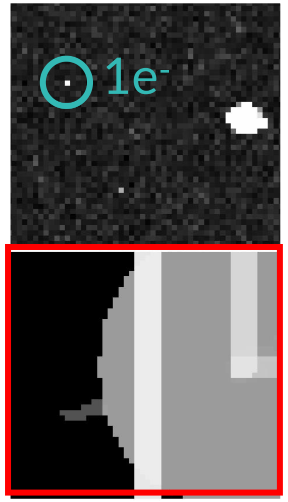


Millicharged particles: detection with skipper-CCDs

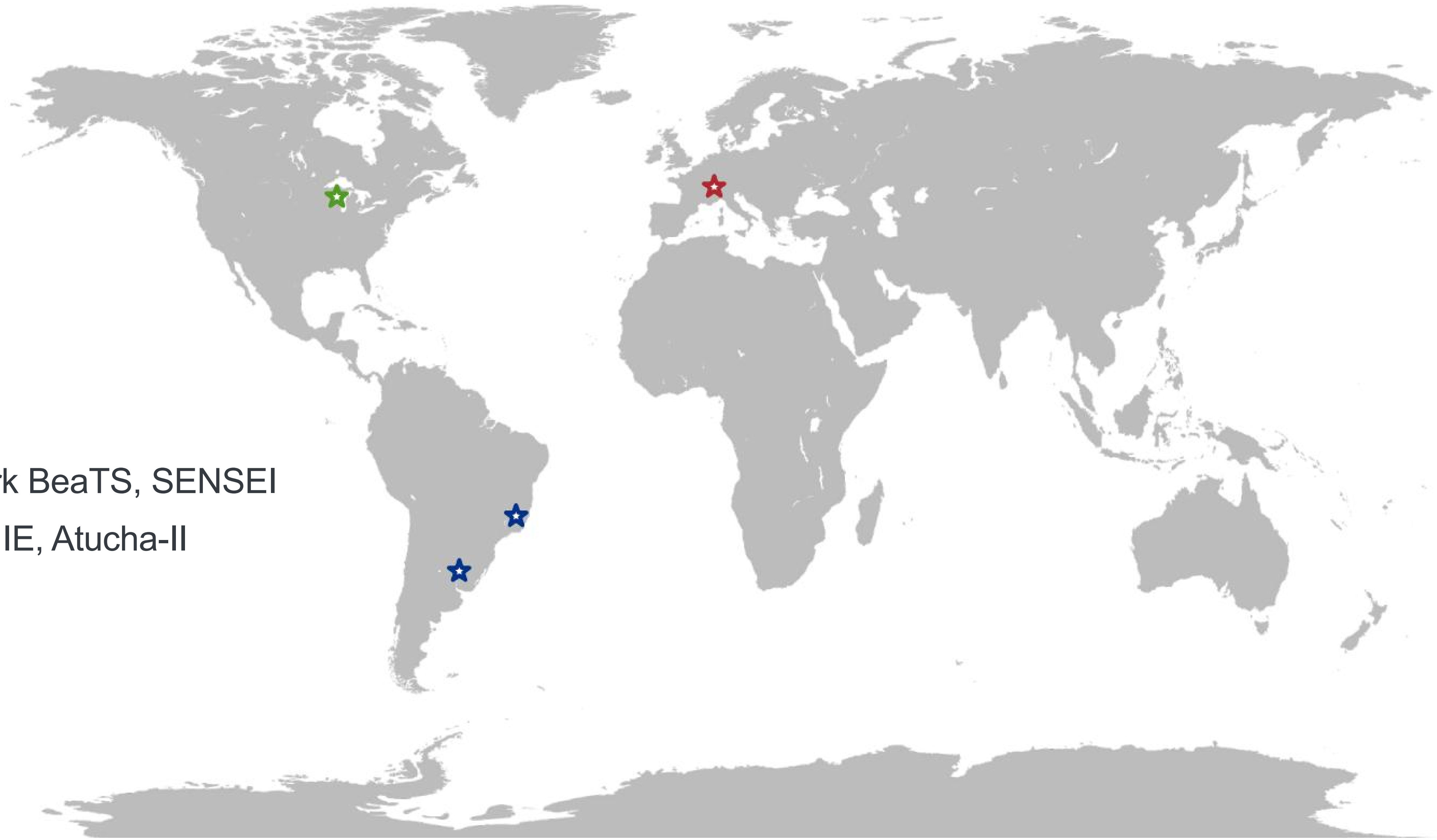
Search for few-e$^-$ depositions in the unmasked region (free of known backgrounds).





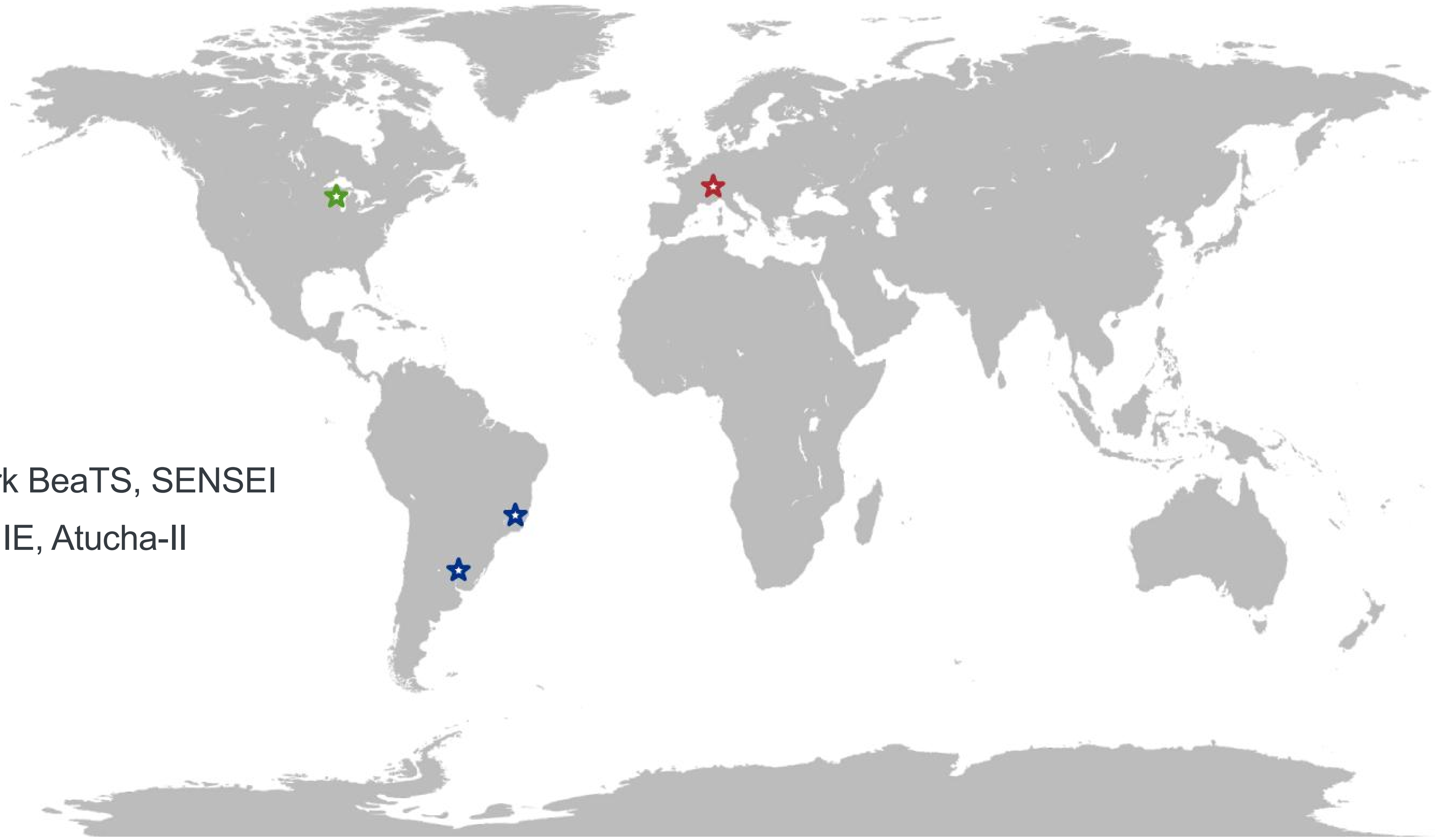


mCPs searches with skipper-CCD detectors



- LHC - Moskita
- Fixed-target - Dark BeaTS, SENSEI
- Reactors - CONNIE, Atucha-II

mCPs searches with skipper-CCD detectors



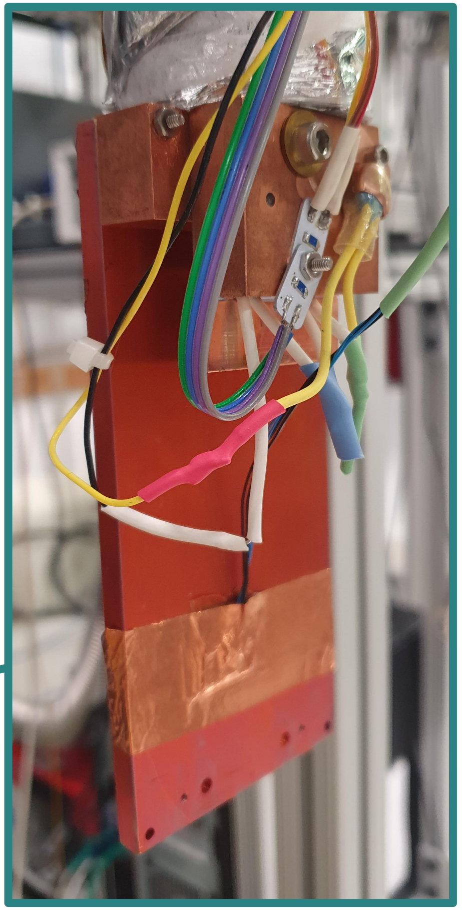
- **LHC - Moskita**
- Fixed-target - Dark BeaTS, SENSEI
- Reactors - CONNIE, Atucha-II

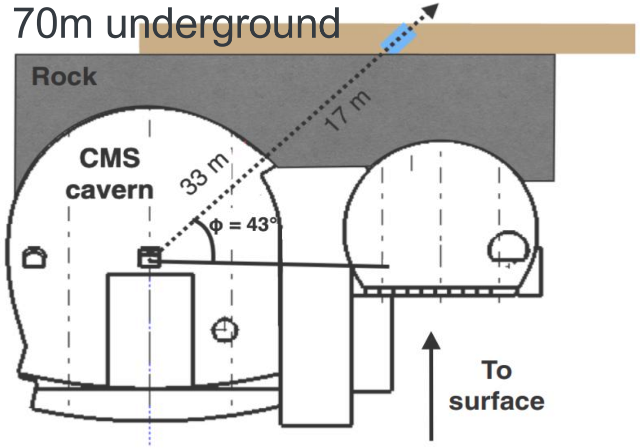
Moskita at the LHC: one module

13.6 TeV p^+p^+ collisions

milliQan identified the **CMS service cavern** as a good place to search for mCPs at the LHC.
Goals: Measure the low-energy background. Assess feasibility and science reach of a larger detector.

03-2024: Deployed Moskita next to milliQan with a 2g SENSEI skipper-CCD (2/4 working quads).





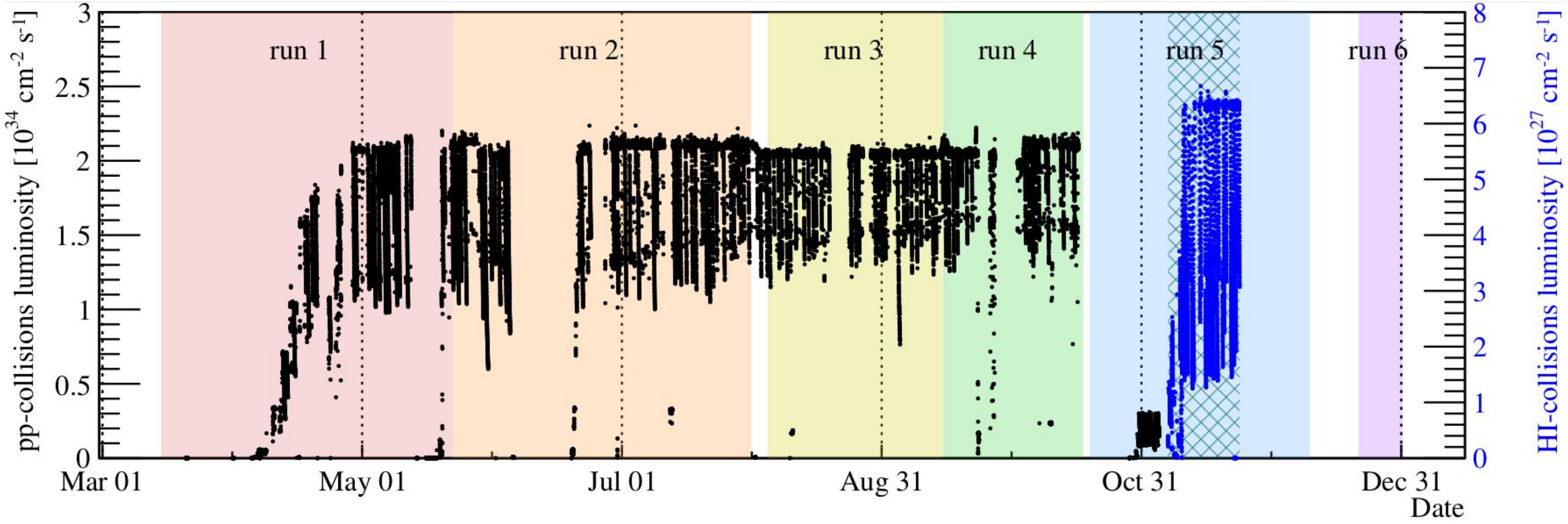
Moskita at the LHC: one module

2024 period

6 DAQ runs

p-p

Pb-Pb



2025 period

6 DAQ runs

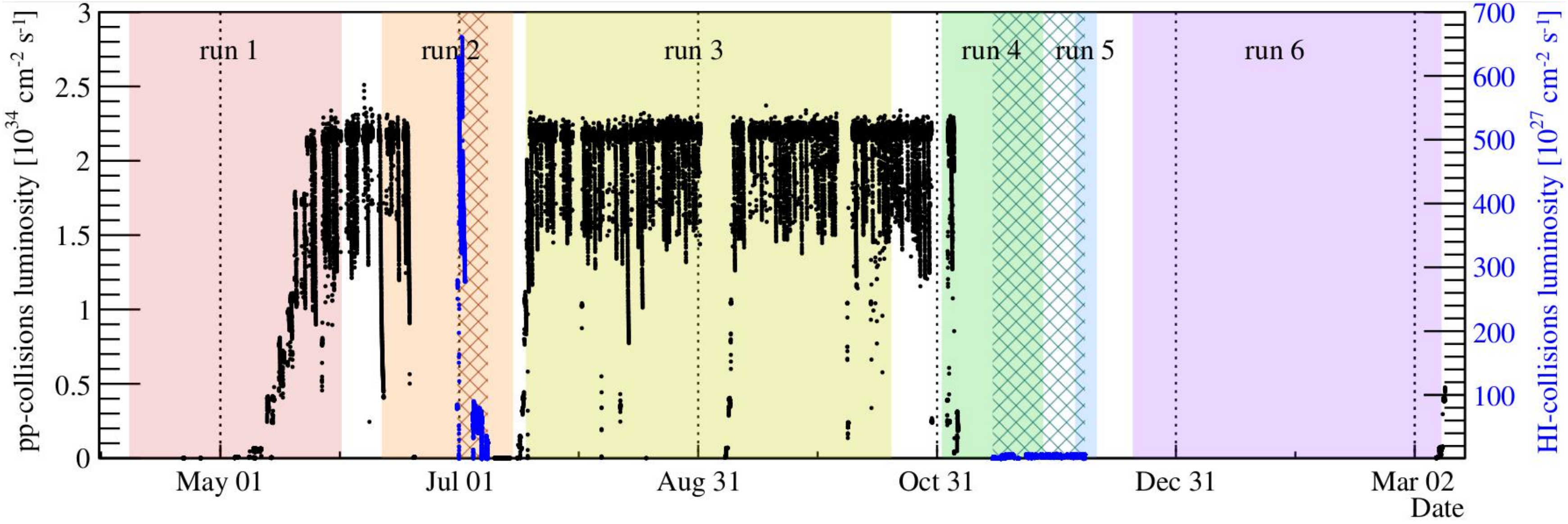
p-p

p-O

O-O

Ne-Ne

Pb-Pb



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Moskita at the LHC: results 2024

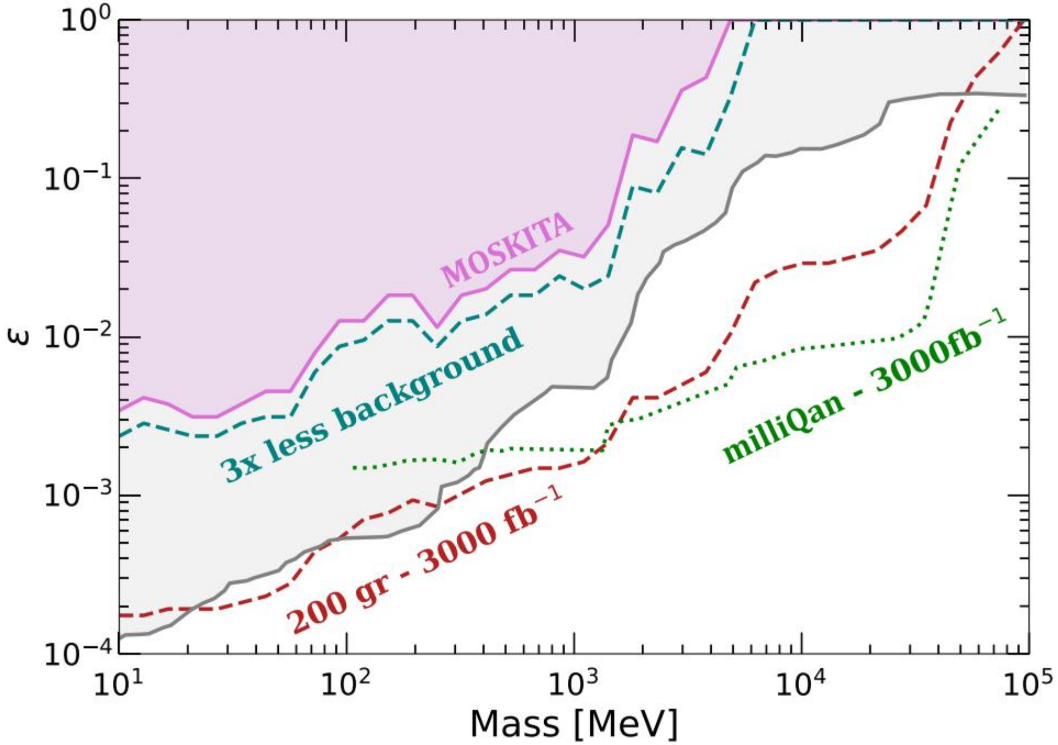
[Phys. Rev. D 113, 032006]

We compare rates with L=0 and L>0 in both, p-p and Pb-Pb collision periods.

Low-energy (<20e-)

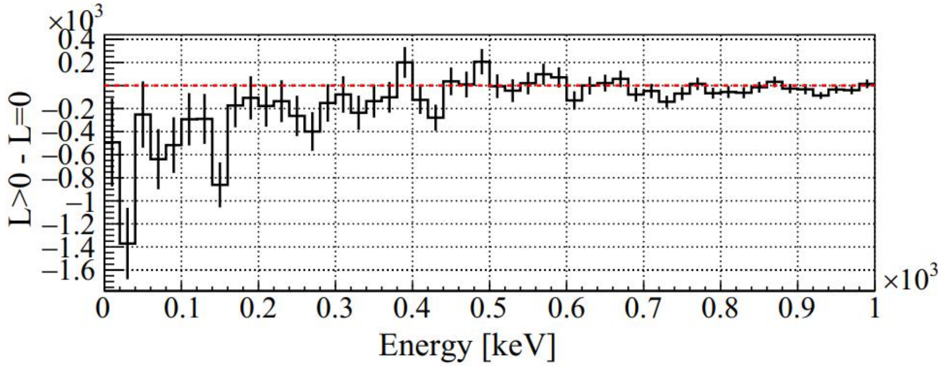
Likelihood analysis: **NO correlation.**

Bin [e^-]	Obs. events	Eff. exposure [g-day]	p-value $\mu = 0$	95% CL limit [events]
2	327	11.40	0.31	5.88
3	17	19.27	0.20	1.41
4	1	23.59	0.12	5.20
5	2	26.74	0.37	3.12
6	0	27.92	1	2.45
7	1	29.10	0.23	4.15

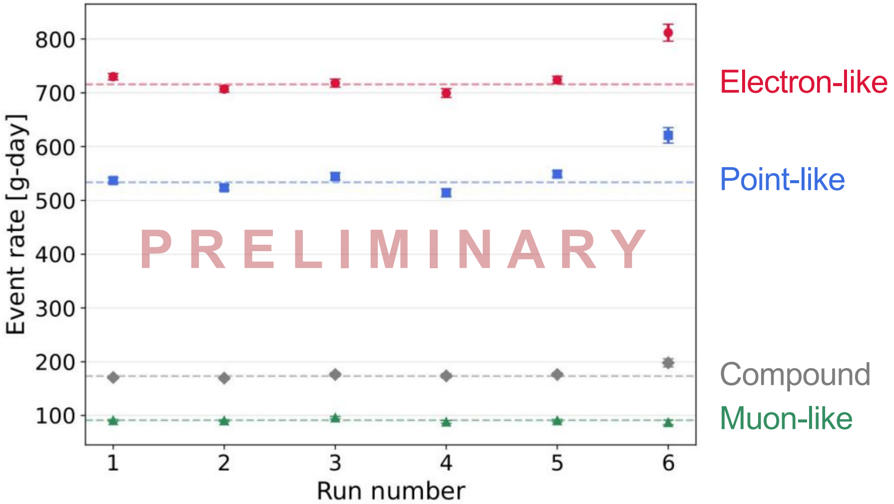


High-energy (80eV to 1MeV)

Slight increase after Pb-Pb collisions.



Preliminary analyses show more point-like & electron-like tracks. 2025 data will allow further understanding.



Stay tuned!

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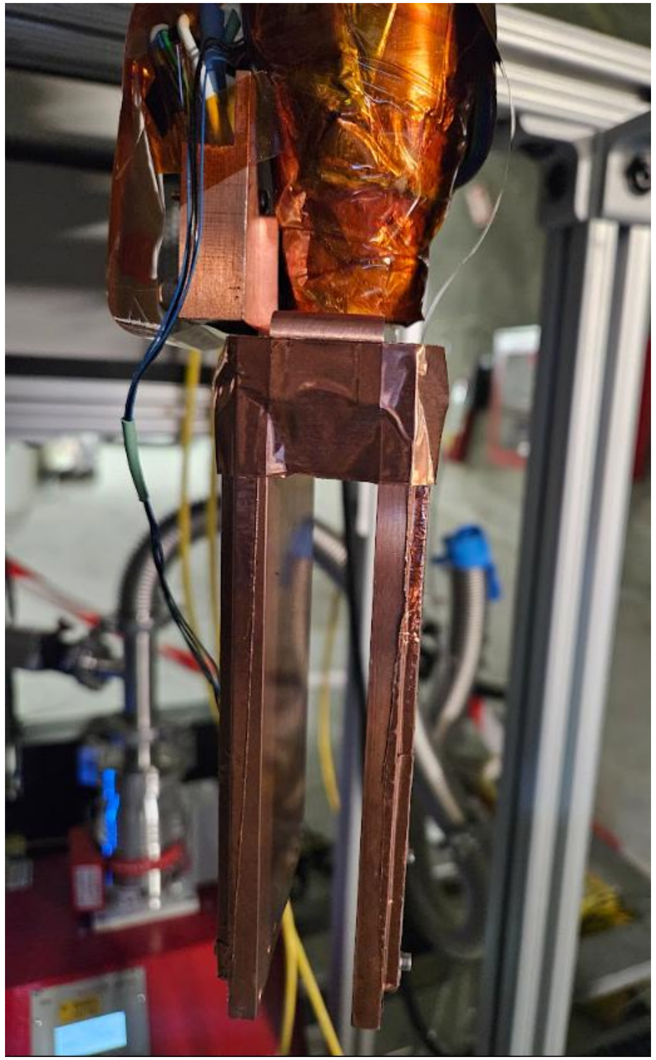
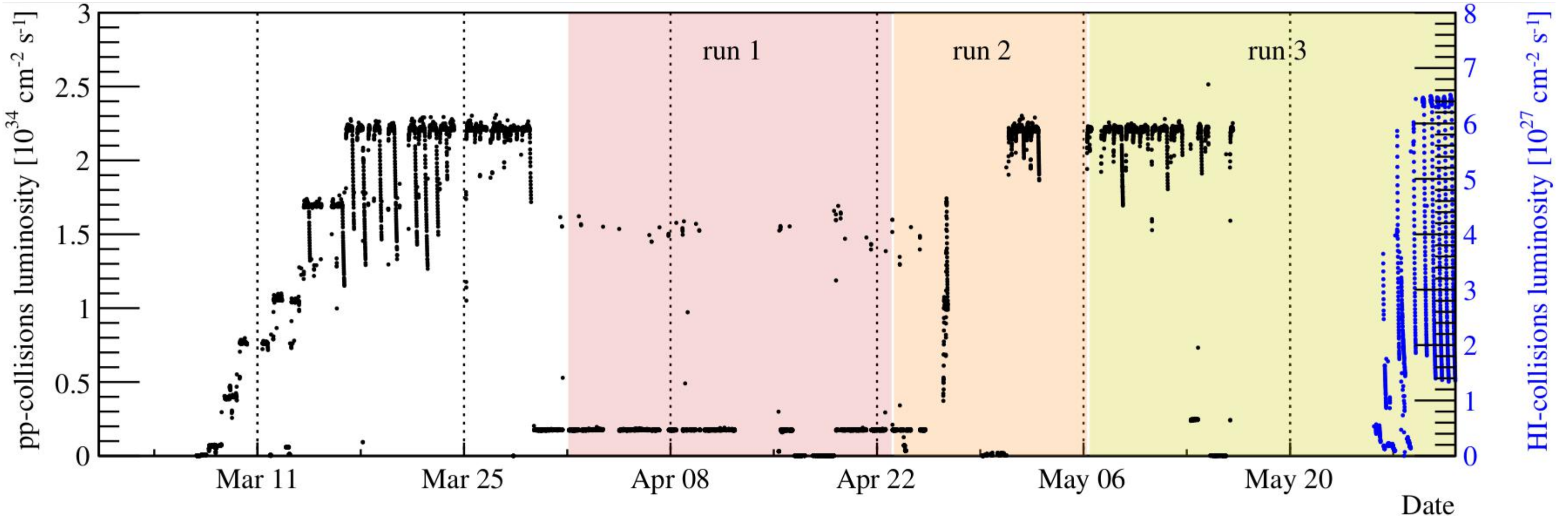
Moskita at the LHC: two modules

04-2026: Detector upgrade to house 2 x 2g SENSEI skipper-CCDs (8/8 working quads).

x4 increase in mass





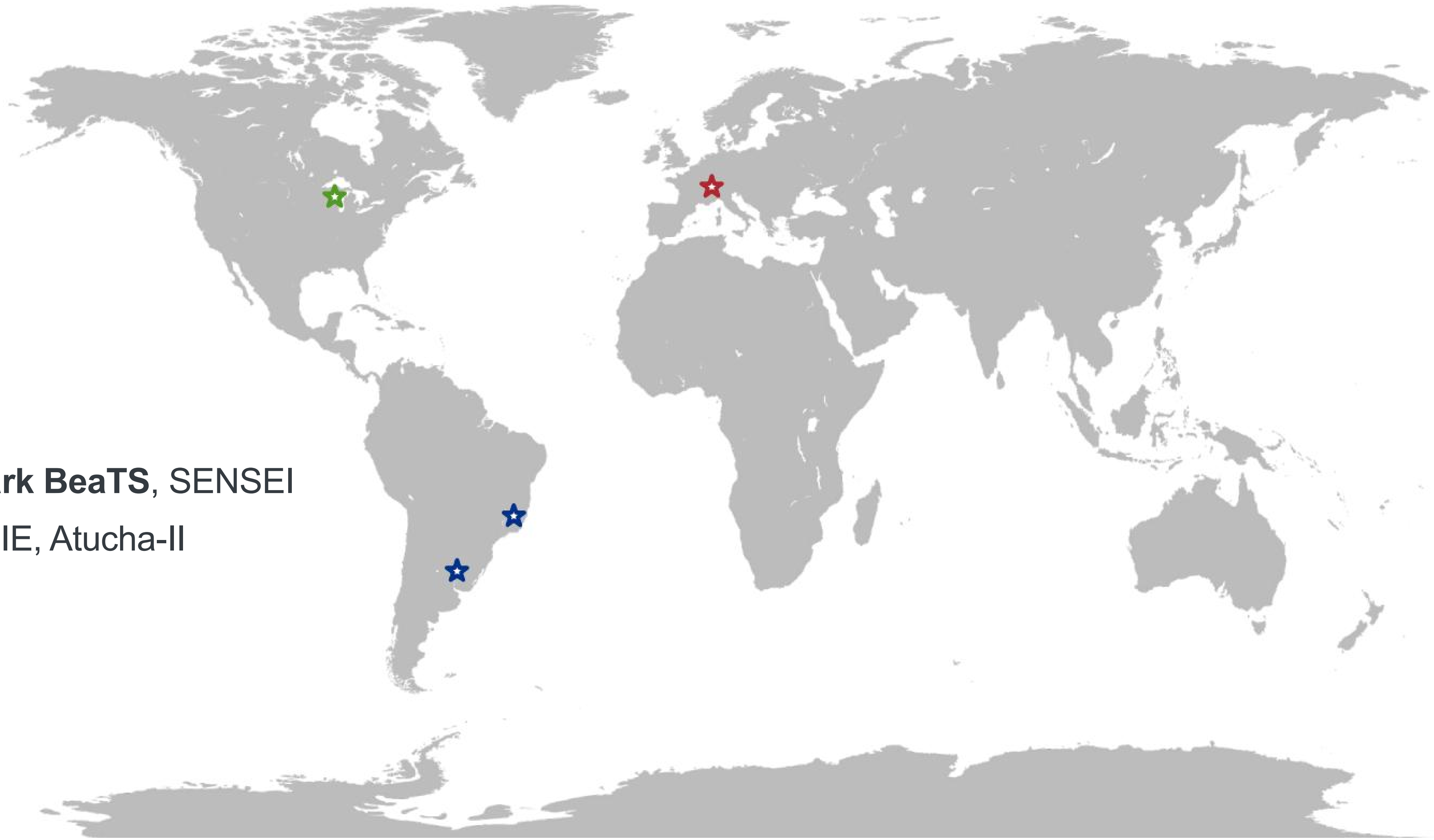
2026 period
DAQ ongoing
p-p
Pb-Pb

2026 data will increase overall statistics and will probe high-energy excess in another "time-of-the-year"

By now, Moskita at LHC has successfully fulfilled its main goals and found something unexpected!
Next step: Towards larger detector for HL-LHC?

Stay tuned!

mCPs searches with skipper-CCD detectors



- LHC - Moskita
- **Fixed-target - Dark BeaTS**, SENSEI
- Reactors - CONNIE, Atucha-II

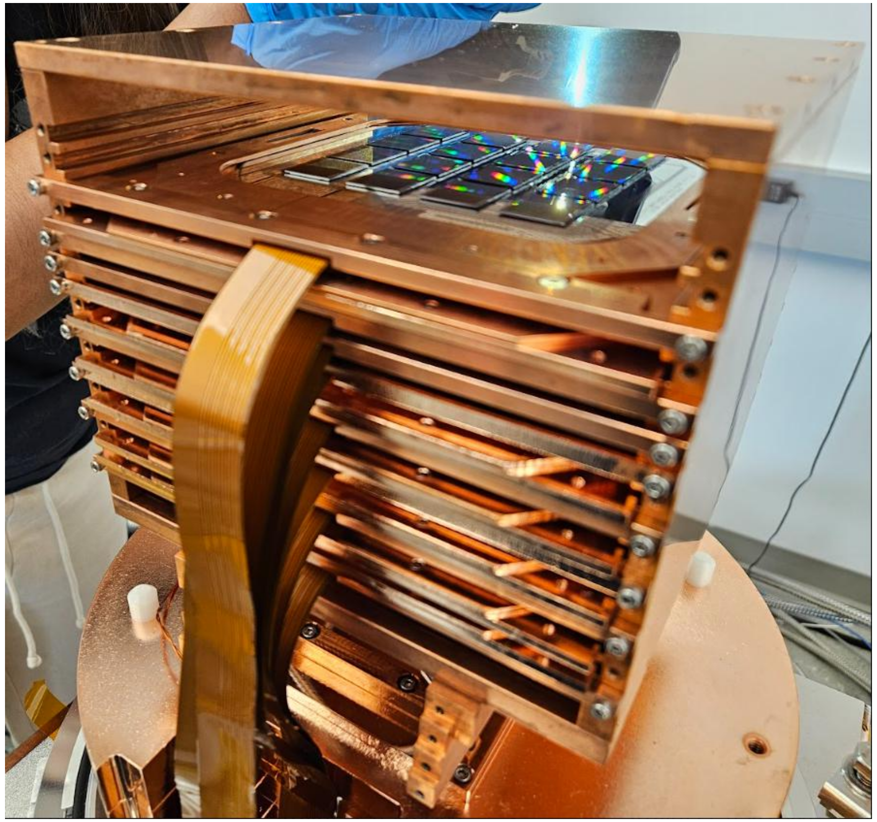
Dark BeaTS at MINOS

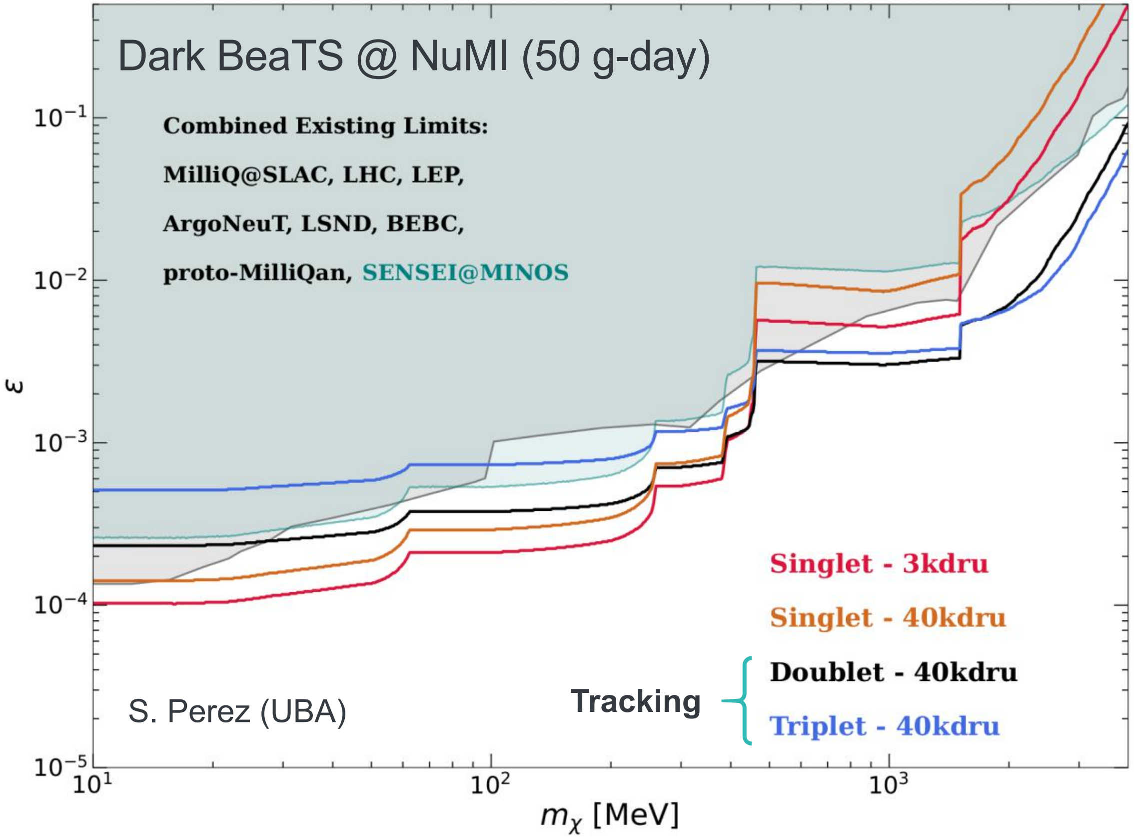
120-GeV p^+ on a graphite target

~100-gram skipper-CCD multi-layer detector to search for mCPs from the NuMI beam.

FNAL-funded project. Motivated by SENSEI mCPs search from NuMI [PRL 133, 071801 (2024)].

Pathfinder to develop the hardware, software and expertise needed for future dark sector searches at accelerators with skipper-CCDs.

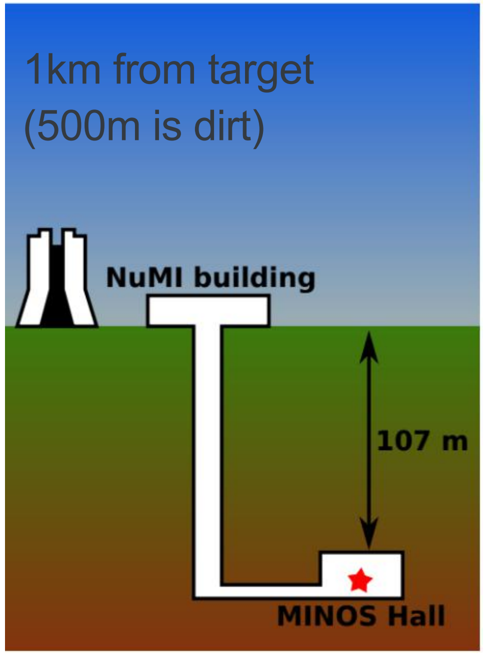


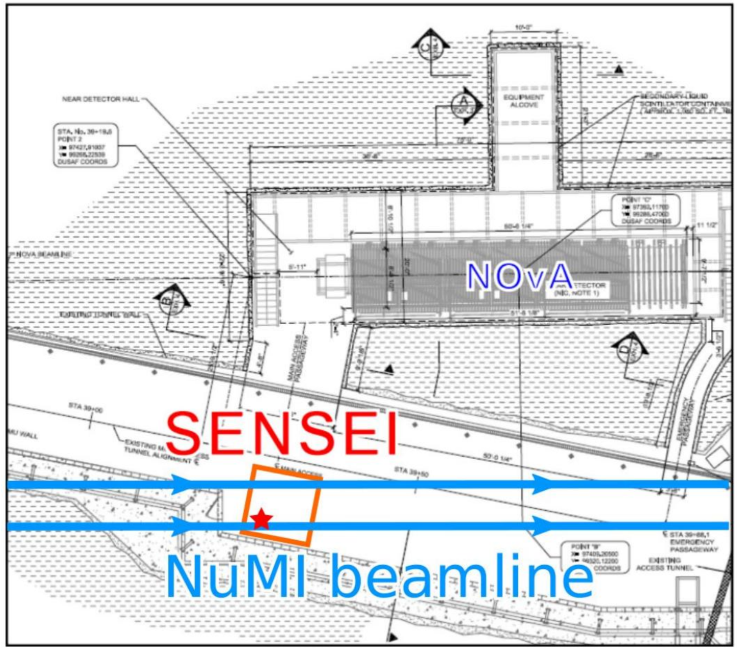


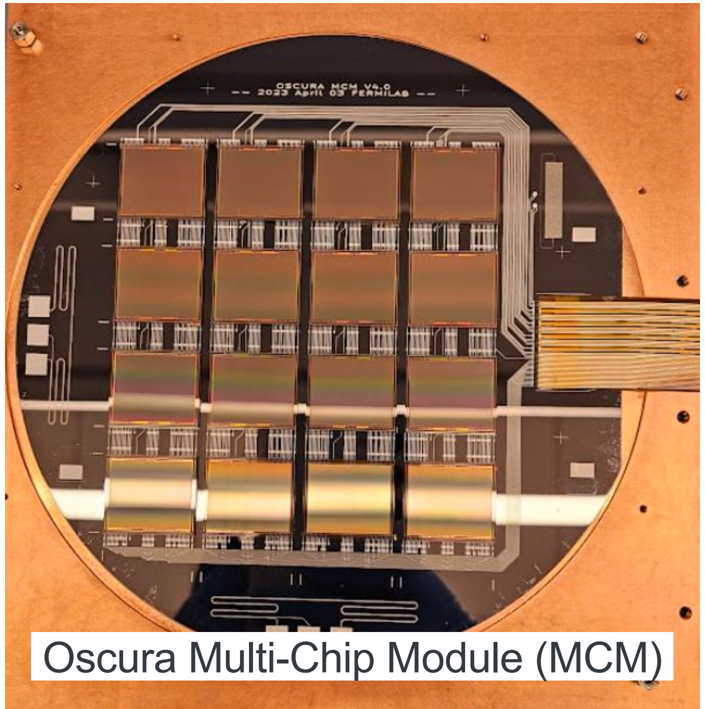
Dark BeaTS at MINOS

Leveraging hardware developed during the R&D phases of SENSEI and Oscura.

SENSEI vessel







Oscura Multi-Chip Module (MCM)

Oscura Multiplexed Electronics

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Dark BeaTS at MINOS: timeline

We are here!

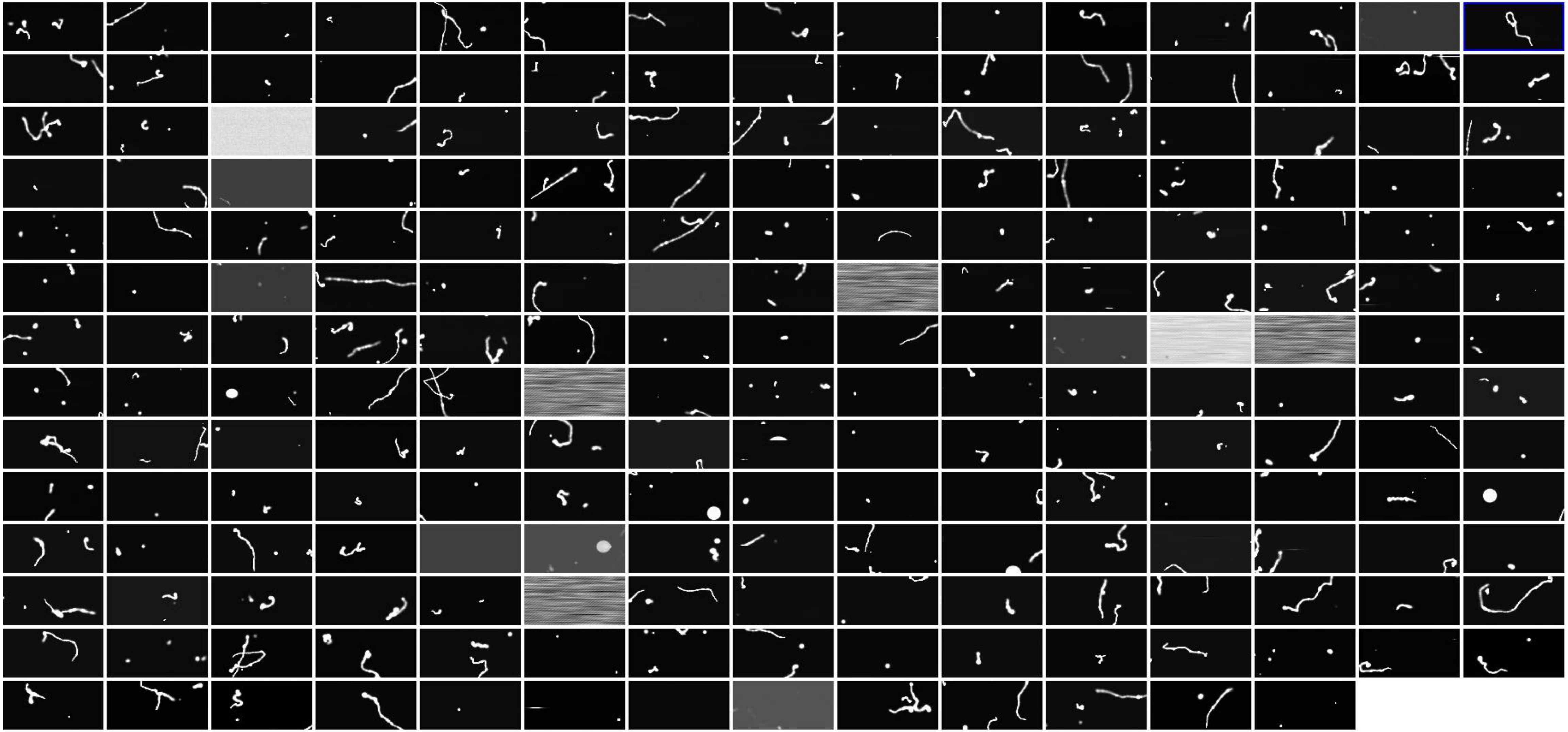
Surface commissioning	Relocation	Underground commissioning	Int. I	Recommissioning	Int. II	Background run	Beam ON run	Background run

24-Q3	24-Q4	25-Q1	25-Q2	25-Q3	25-Q4	26-Q1	26-Q2	26-Q3	26-Q4	27-Q1	27-Q2

and more to come!

Dark BeaTS at MINOS: commissioning

95% of sensors working with single-electron resolution!
and with a stable performance over time

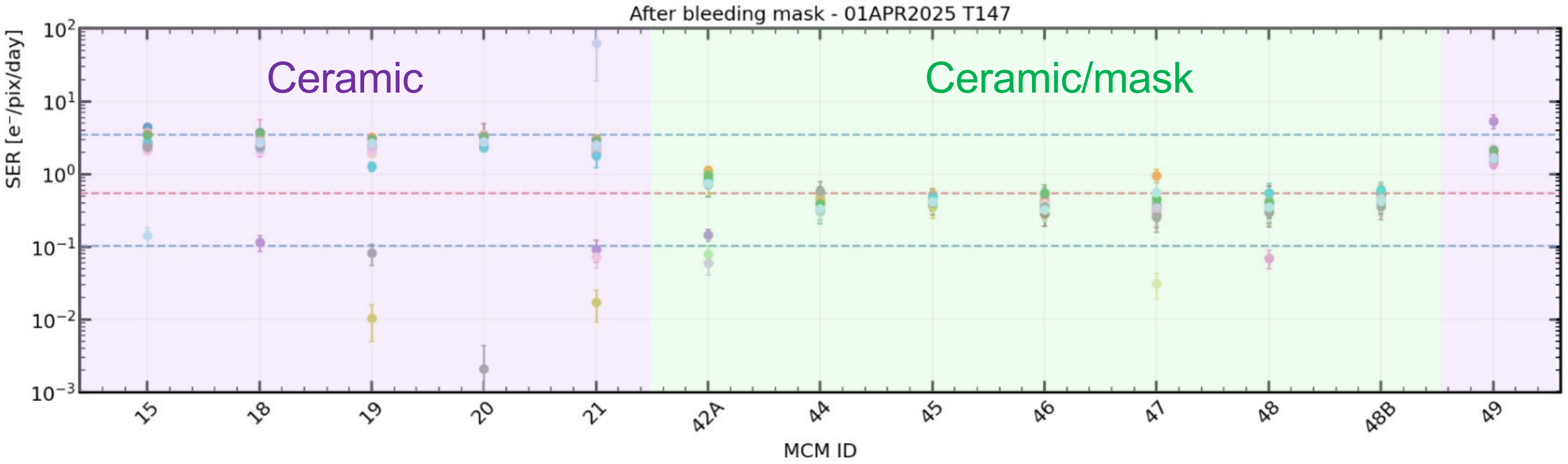


Dark BeaTS at MINOS: commissioning

Important findings on MCMs performance, backgrounds and instrumental effects.
Feedback for optimal operational parameters, pipeline analysis and future instrumentation.

Single-electron rate

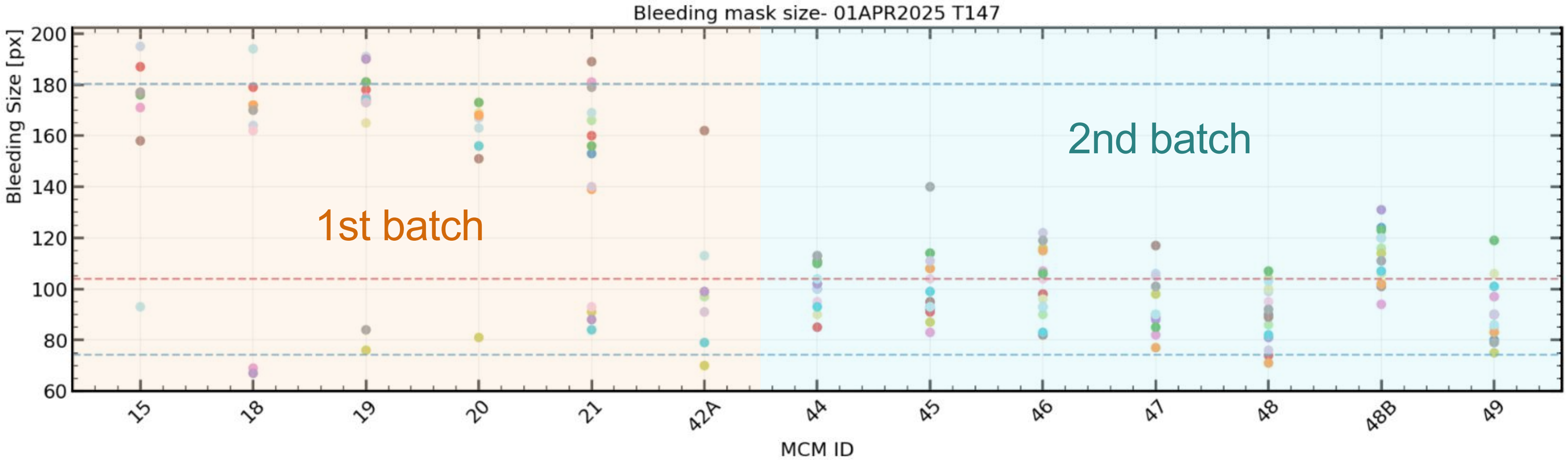
Dependent on MCM substrate material.



Charge from traps

Dependent on CCD fabrication batch.

Confirmed work in J. Appl. Phys. 136, 204502 (2024)



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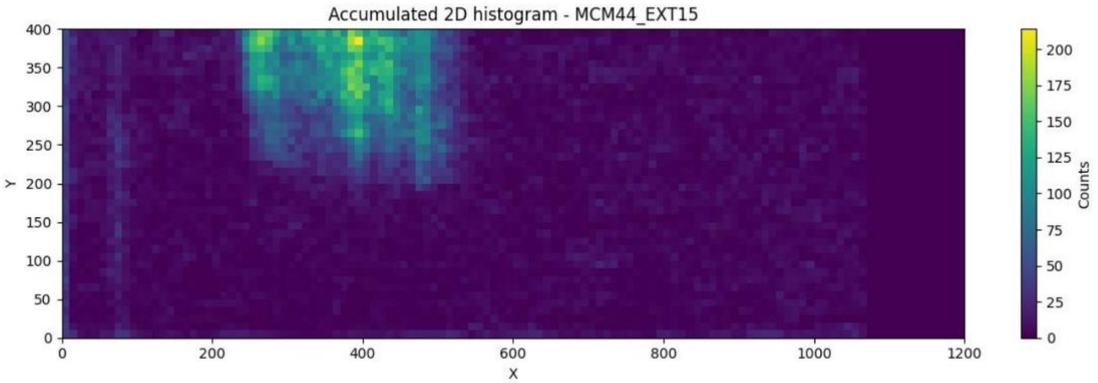
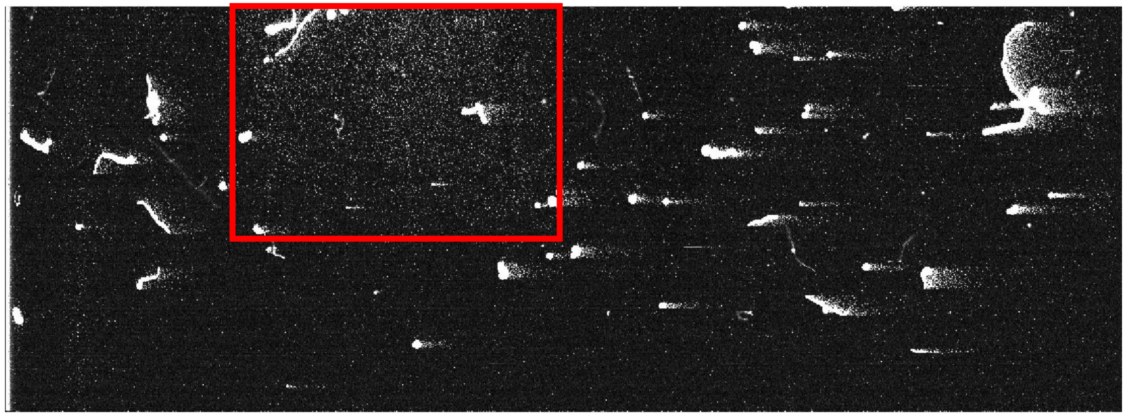
Dark BeaTS at MINOS: commissioning

Clouds of 1-3e$^-$ depositions

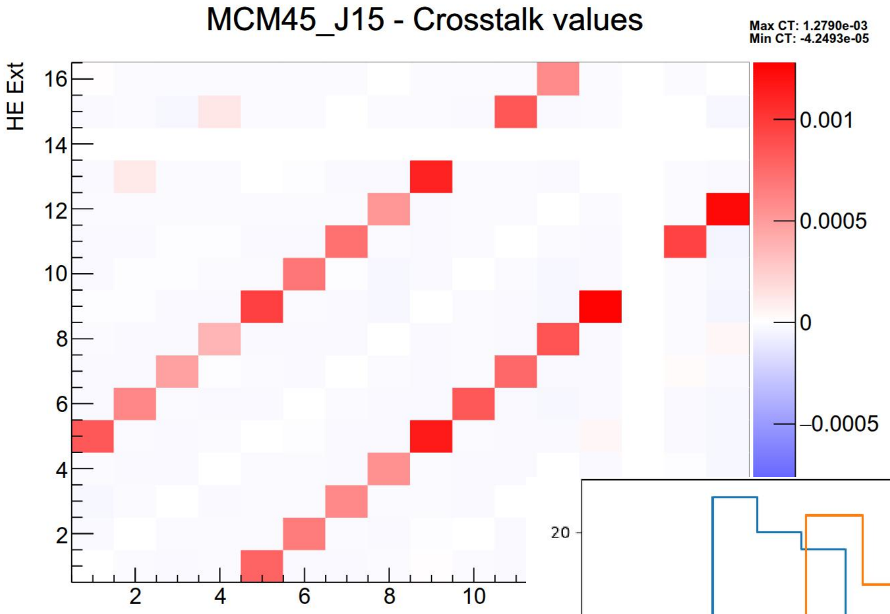
Fixed zones in some CCDs with higher counts.
Same time dependence in non-cloud and cloud regions but different density.
Originated from mechanical stress?

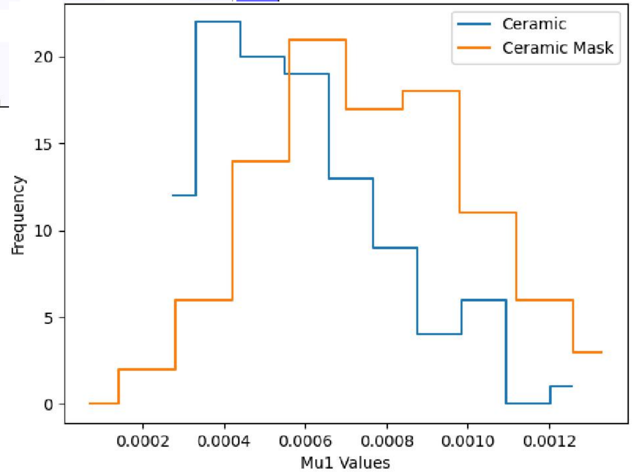




IntraMCM crosstalk

Correlation with electronic lines.
Magnitude dependent on MCM substrate material.





Stay tuned!

Conclusions

- Electron-counting skipper-CCDs are a promising technology to search for feebly interacting particles, e.g. mCPs.
- High-intensity accelerators enable the production of light dark sector particles, providing a powerful laboratory probe of dark sector physics.
- Accelerator-based skipper-CCD experiments enable access to a largely unexplored low-energy regime in those environments.
- For beam-produced mCPs, skipper-CCDs are competitive probing the MeV-to-GeV mass range.
- Dark BeaTS and Moskita are paving the way for future dark sector searches at accelerators with skipper-CCD detectors.

Thank you!

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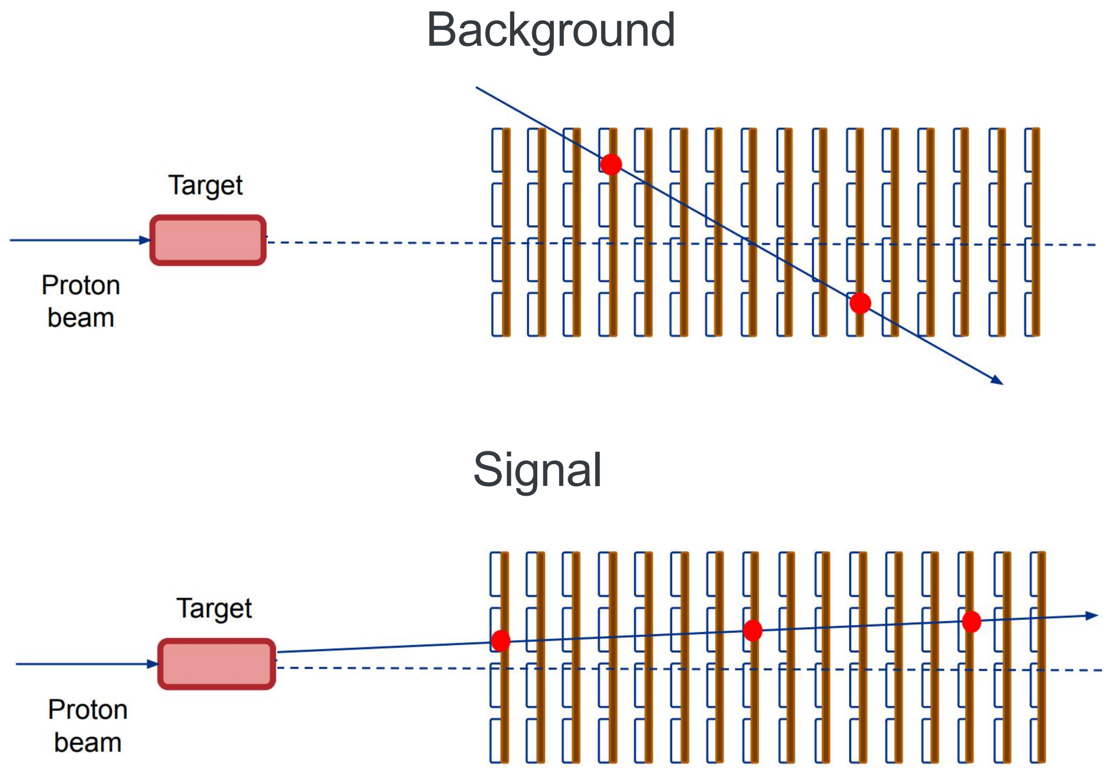
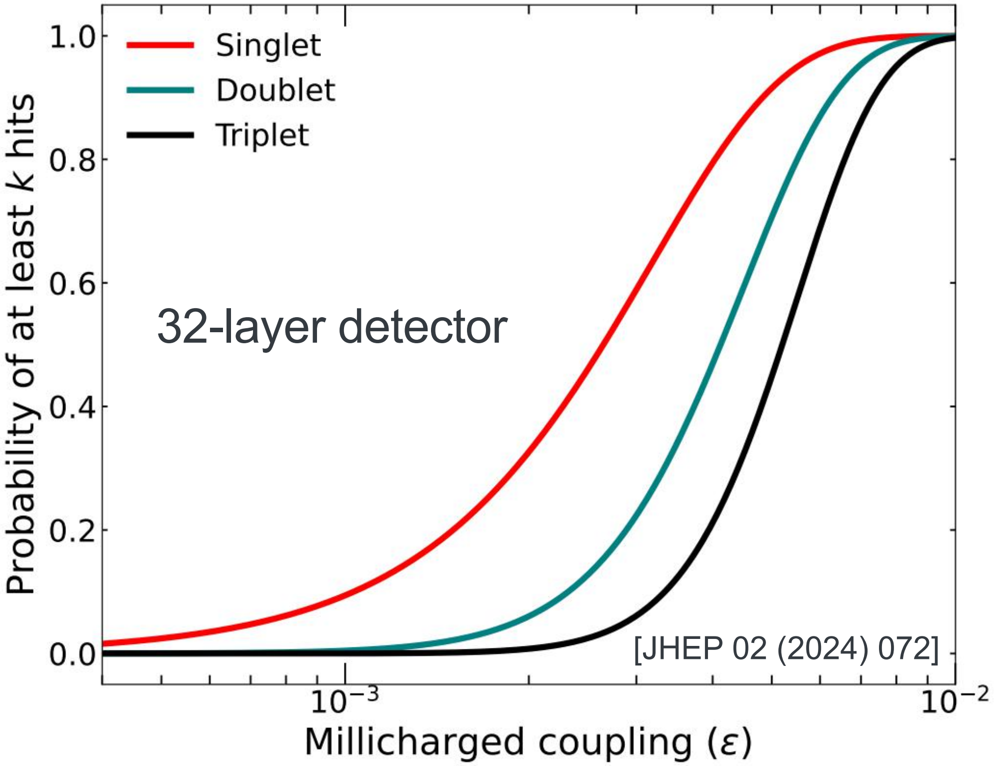
Tracking: a way to reduce backgrounds

Skipper-CCDs lack time resolution to reduce beam-unrelated backgrounds.

Multi-layer detectors could enable background-free mCP searches by tracking multiple interactions, despite low occurrence probability.





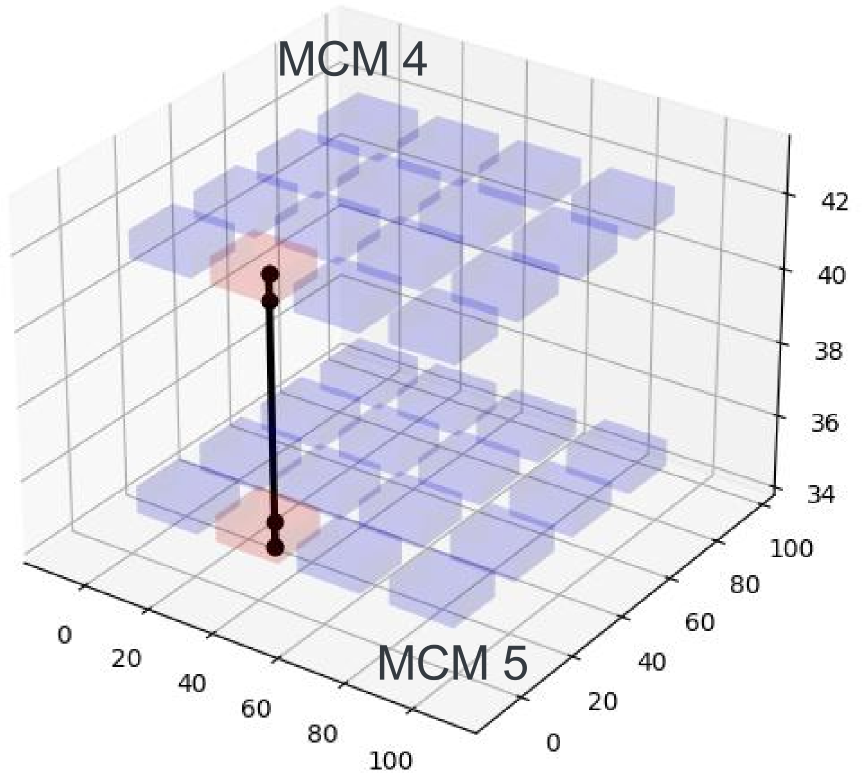
R. Harnik et al.. Millicharged particles in liquid argon neutrino experiments. [10.1007/JHEP07(2019)170]
S. Perez et al.. Searching for millicharged particles with 1 kg of Skipper-CCDs using the NuMI beam at Fermilab. [10.1007/JHEP02(2024)072]

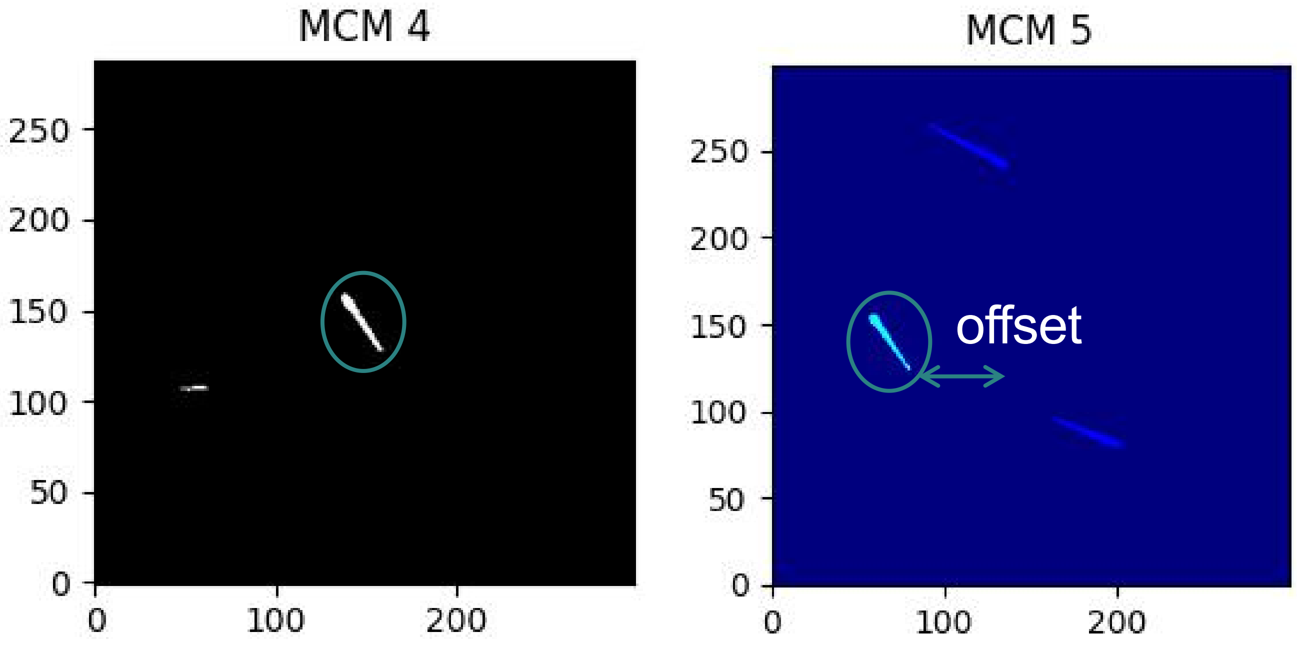
Dark BeaTS: challenges with tracking

Tracking is challenging with current hardware. **New packaging and precise module assembly are needed to reduce degrees of freedom.**

Other ideas: Optical measurements to determine sensor misalignment during module assembly.
In-situ alignment to correct for disalignment during thermal cycles.

Demonstrated muon tracking with surface data. Effort needed to track low-energy depositions.

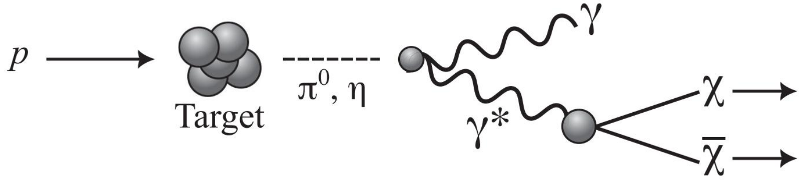


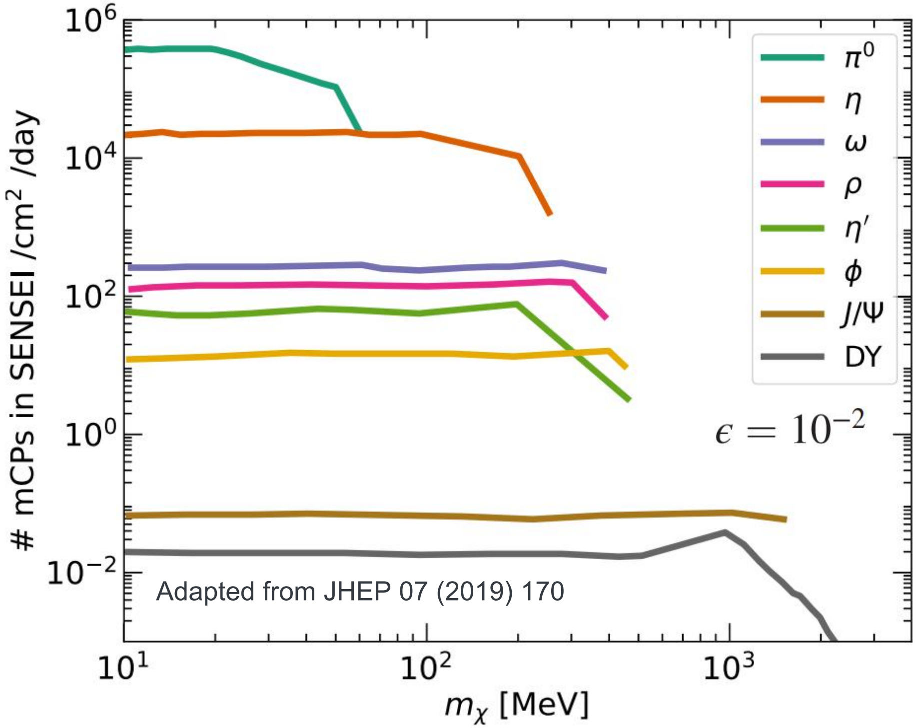


SENSEI at MINOS: mCP search

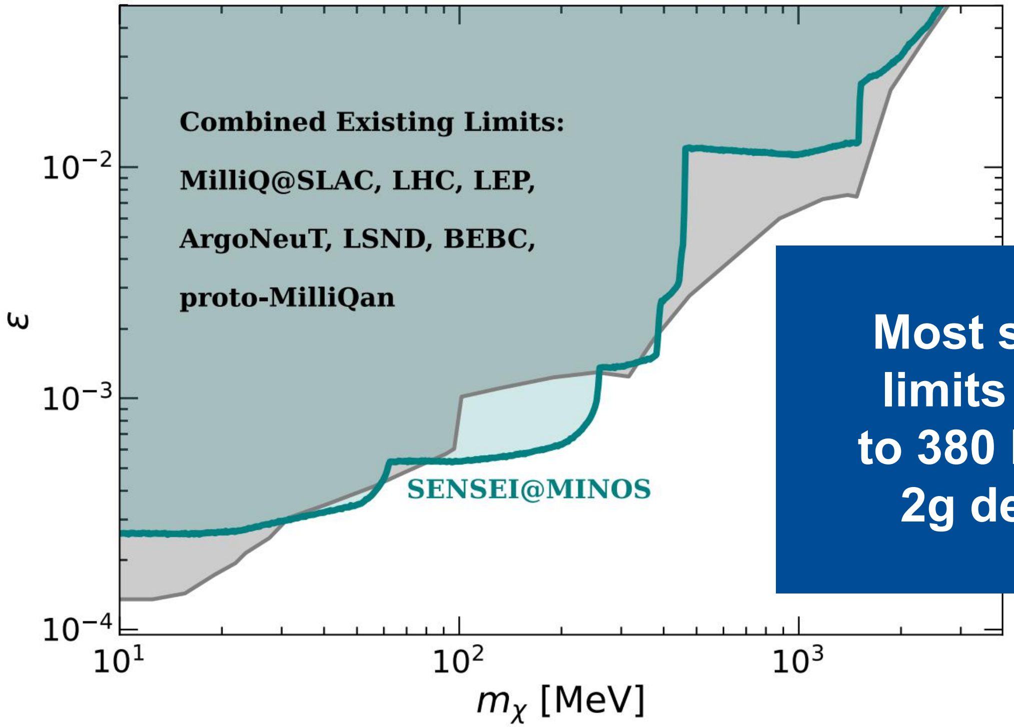
PRL 133, 071801 (2024)

NuMI beam: 120-GeV proton beam striking a graphite target.
mCPs could be produced collinearly with the beam primarily in meson decays.
Included collective excitation effects [Comm Phys 7, 416 (2024)] and pair-creation probabilities [PRD 102, 063026], 063026] in detection cross-section.



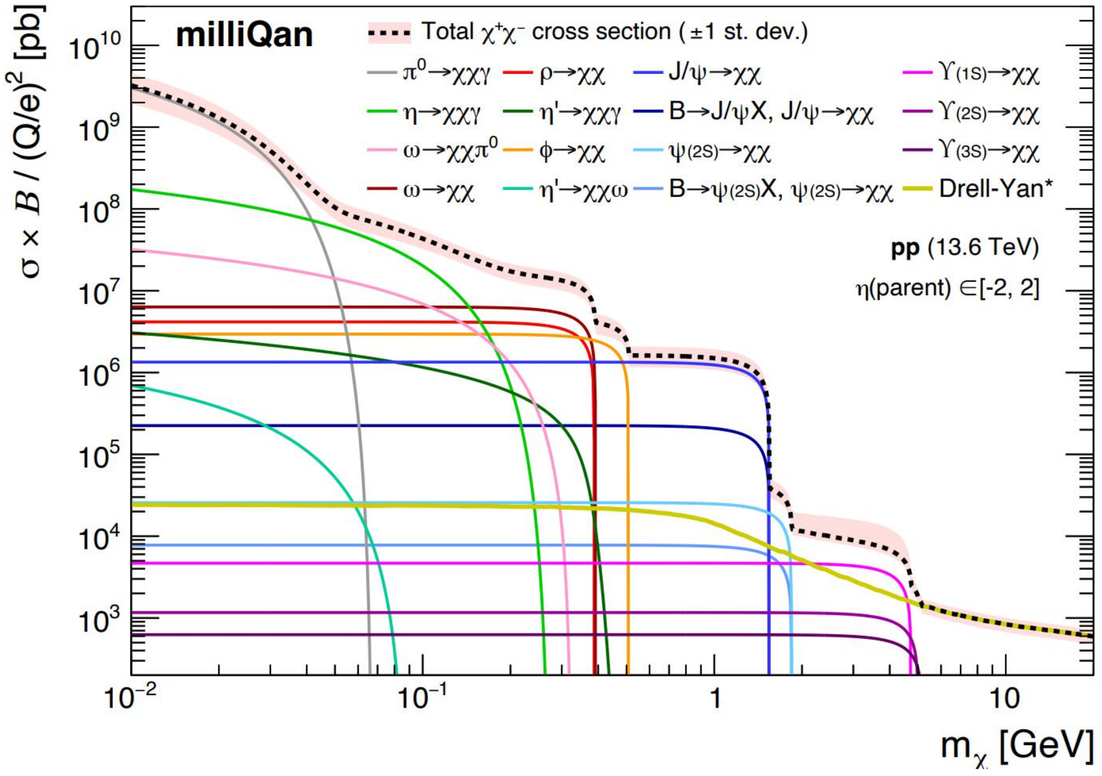


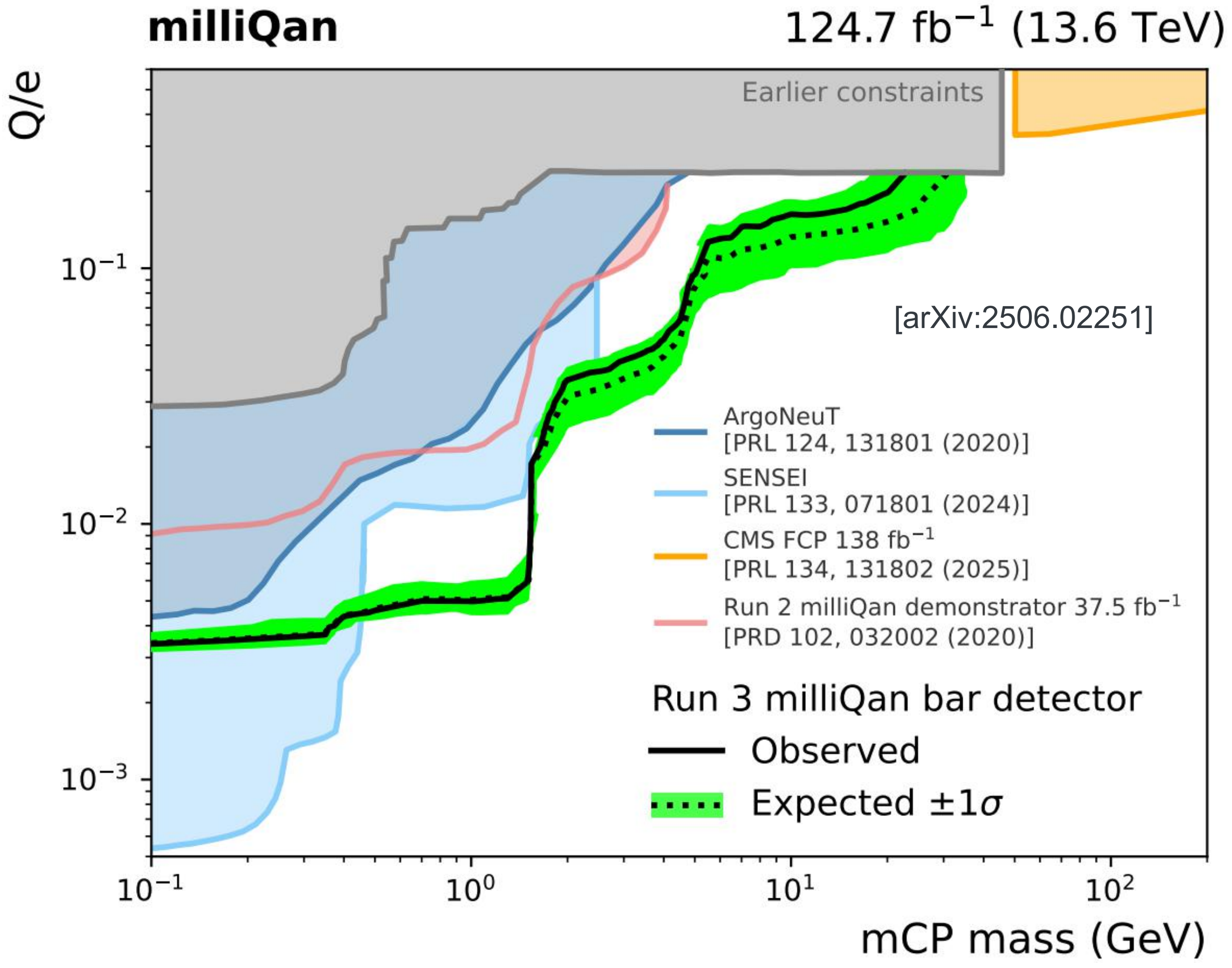
	$1e^-$	$2e^-$	$3e^-$	$4e^-$	$5e^-$	$6e^-$
Effective Efficiency	0.069	0.105	0.325	0.327	0.331	0.338
Exposure [g-day]	1.38	2.09	9.03	9.10	9.23	9.39
Observed Events	1311.7	5	0	0	0	0



Most stringent limits from 30 to 380 MeV with 2g detector!

milliQAN latest results





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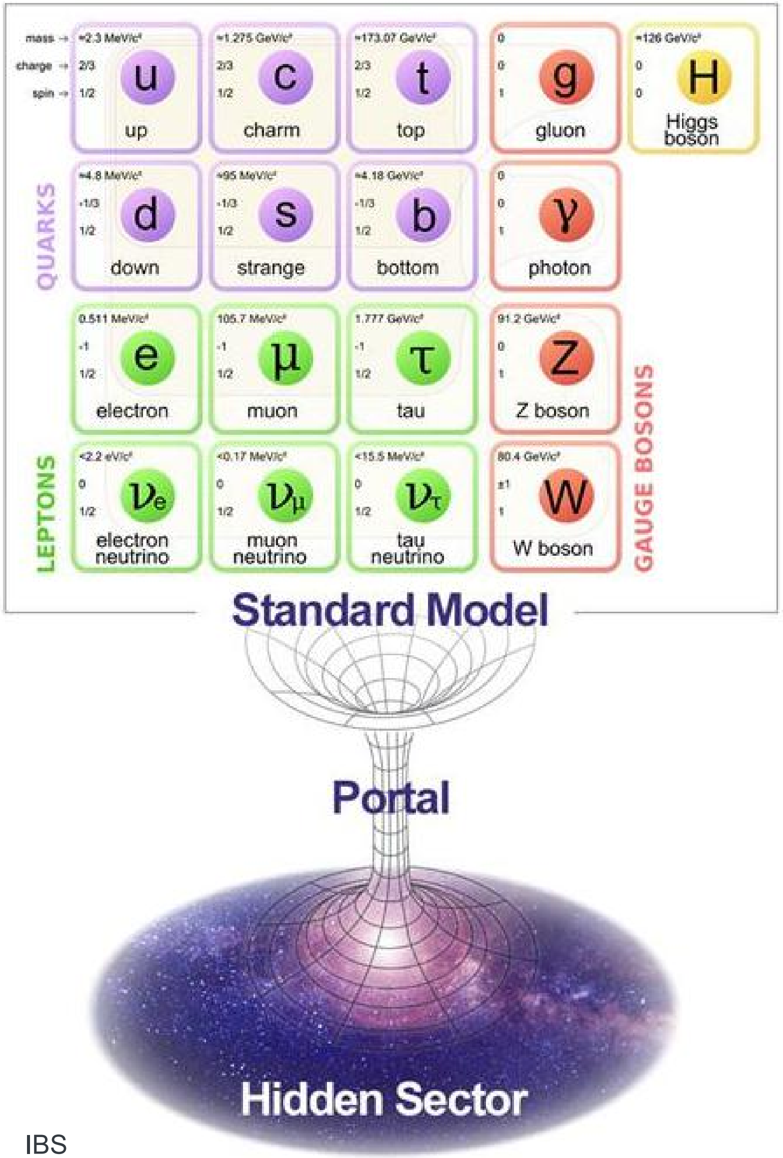
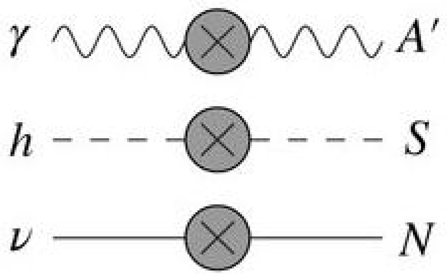
Dark sector models



IBS

Set of new particles and forces, interacting very feebly with the SM through "portals" associated to specific mediators

$$\mathcal{L}_{\text{portal}} = \sum O_{\text{SM}} \times O_{\text{DS}}$$



Dark photon (vector)

Dark Higgs (scalar)

Dark neutrino (fermion)

Appealing framework to address key puzzles (e.g. Dark Matter), as experiments continue to rule out other explanations.

Due to their extremelly small couplings, the production and detection of dark sector particles is challenging.

J. Beacham et al.. Physics Beyond Colliders at CERN: BSM working group report. [10.1088/1361-6471/ab4cd2]
N. Bozorgnia et al.. Dark matter candidates and searches. [10.1139/cjp-2024-0128]