Search for millicharged particles with Skipper-CCDs at particle accelerators

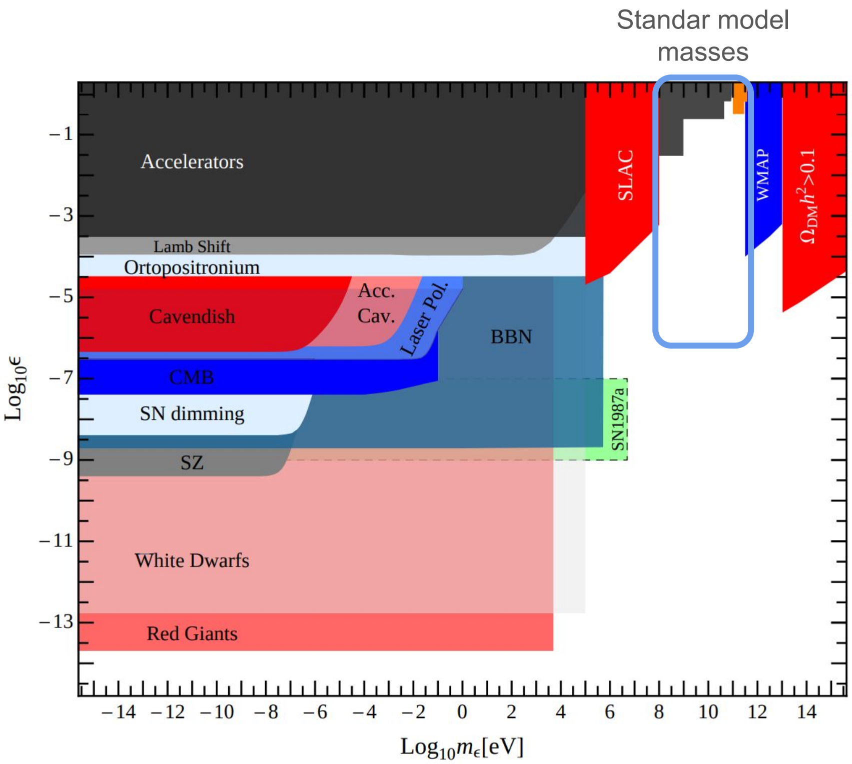
Speaker: Santiago Ezequiel Perez

Astroparticle symposium 2025 Nov 3 – 21, 2025, Institut Pascal, France

mCP model and constraints

$$\mathcal{L}_{mCP} = i\bar{\chi}(\partial\!\!\!/ - i\epsilon e B\!\!\!/ + M_{mCP})\chi$$

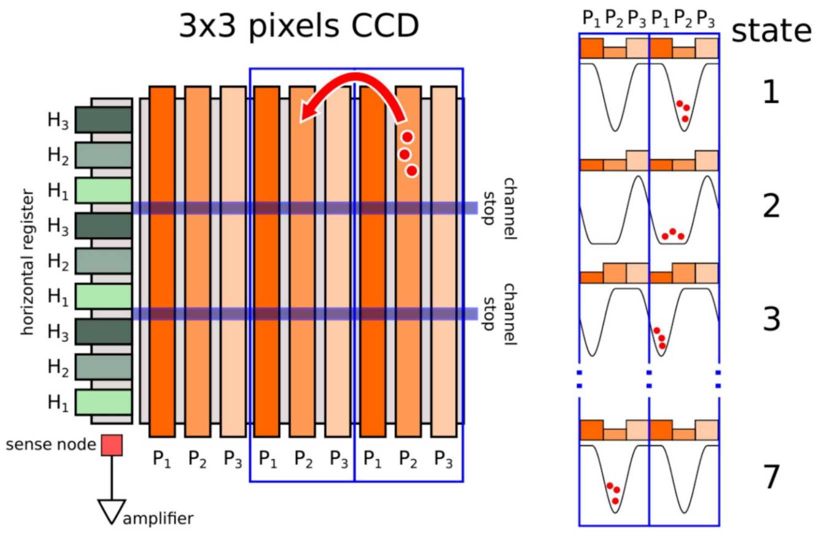
- Simple extension of the SM with deep implications if observed!
- Might be a component of Dark Matter, it can also appear effectively in grand unification theories or string theory.
- Presents itself as a fractionally charged fermion.

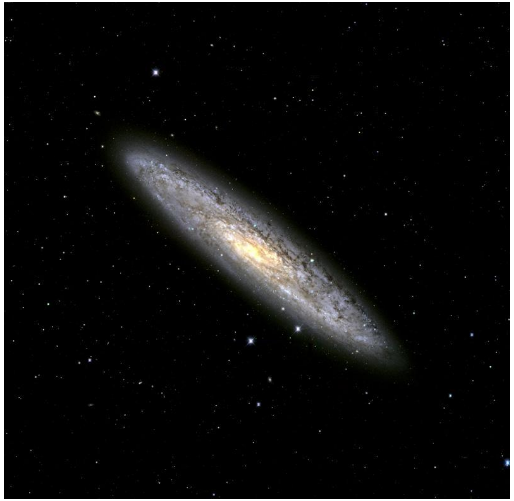


B. Holdom, *Two* U(1)*'s and epsilon charge shifts*, *Phys. Lett.*B 166 (1986) 196.
D.E. Brahm and L.J. Hall, U(1)'*dark matter*, *Phys. Rev.*D 41 (1990) 1067

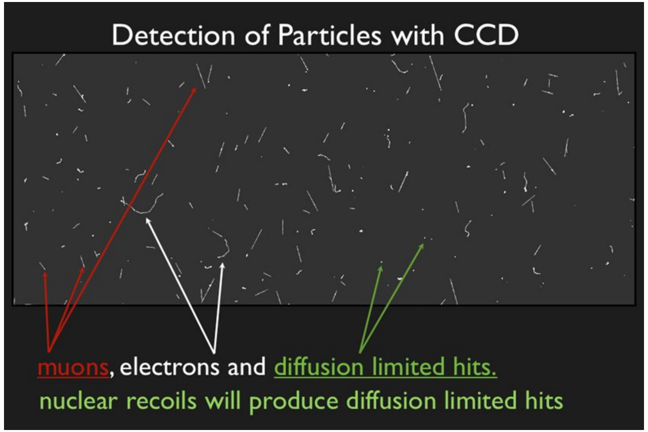
Goodsell, M., Jaeckel, J., Redondo, J., & Ringwald, A. (2009). Naturally light hidden photons in LARGE volume string compactifications. *JHEP*, *2009*(11), 027.

Skipper-CCDs for Dark Matter



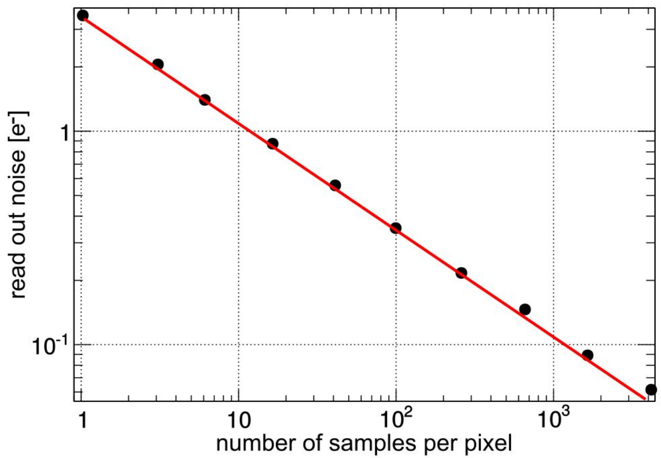


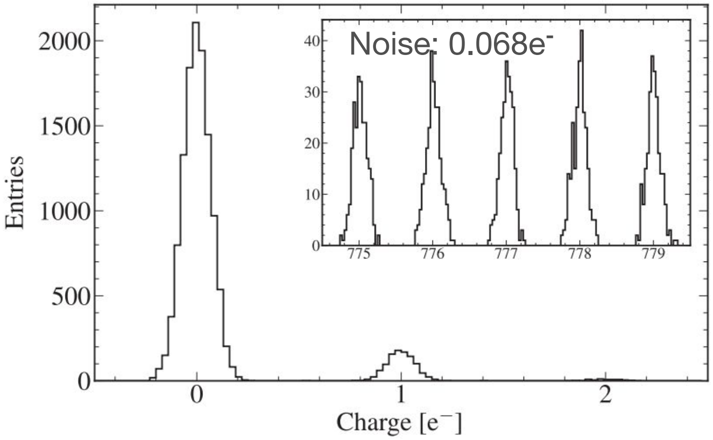
Very nice Dark Energy Camera photo (DECAM)



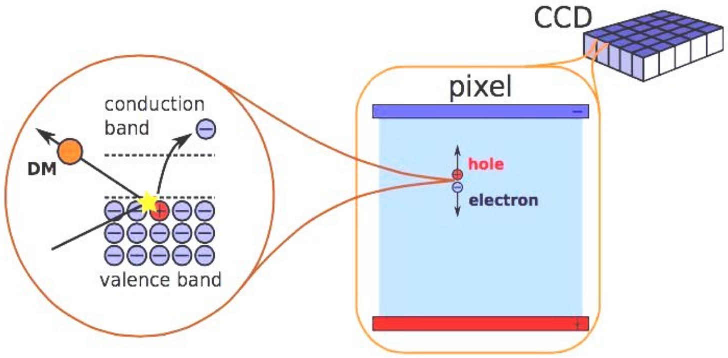
Some particles observed by DAMIC.

Skipper-CCDs for Dark Matter



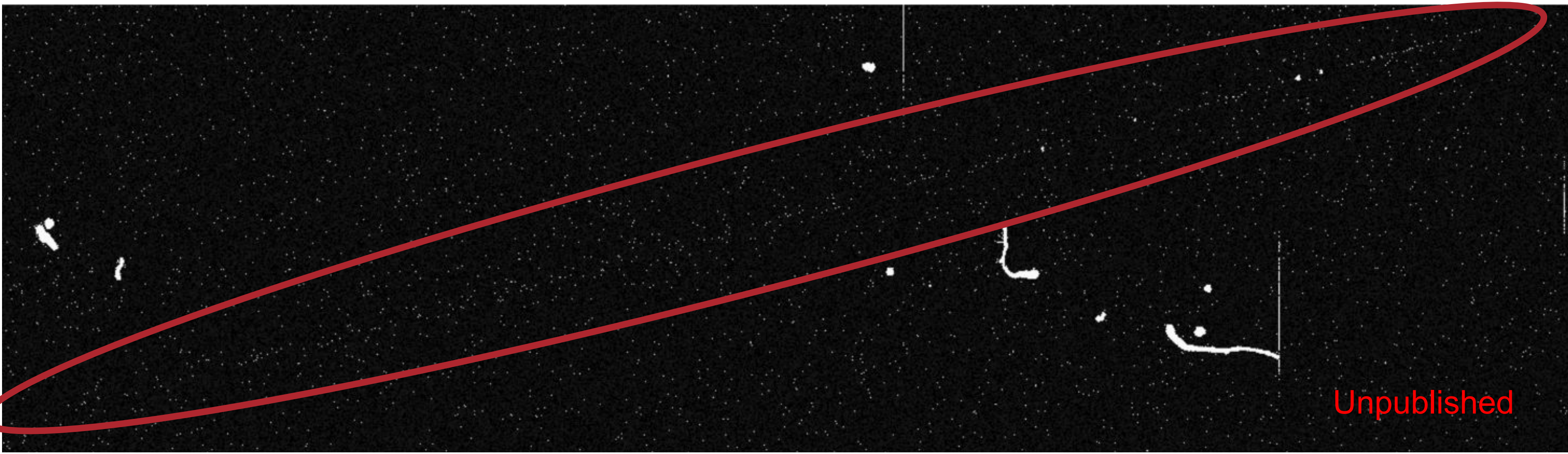


$$\sigma = \frac{\sigma_1}{\sqrt{N}}$$



Janesick et al., New advancements in charge-coupled device technology - sub-electron noise and 4096×4096 pixel CCDs.
Moroni et al., Sub-electron readout noise in a Skipper CCD fabricated on high resistivity silicon.
Tiffenberg et al., Single-Electron and Single-Photon Sensitivity with a Silicon Skipper-CCD.

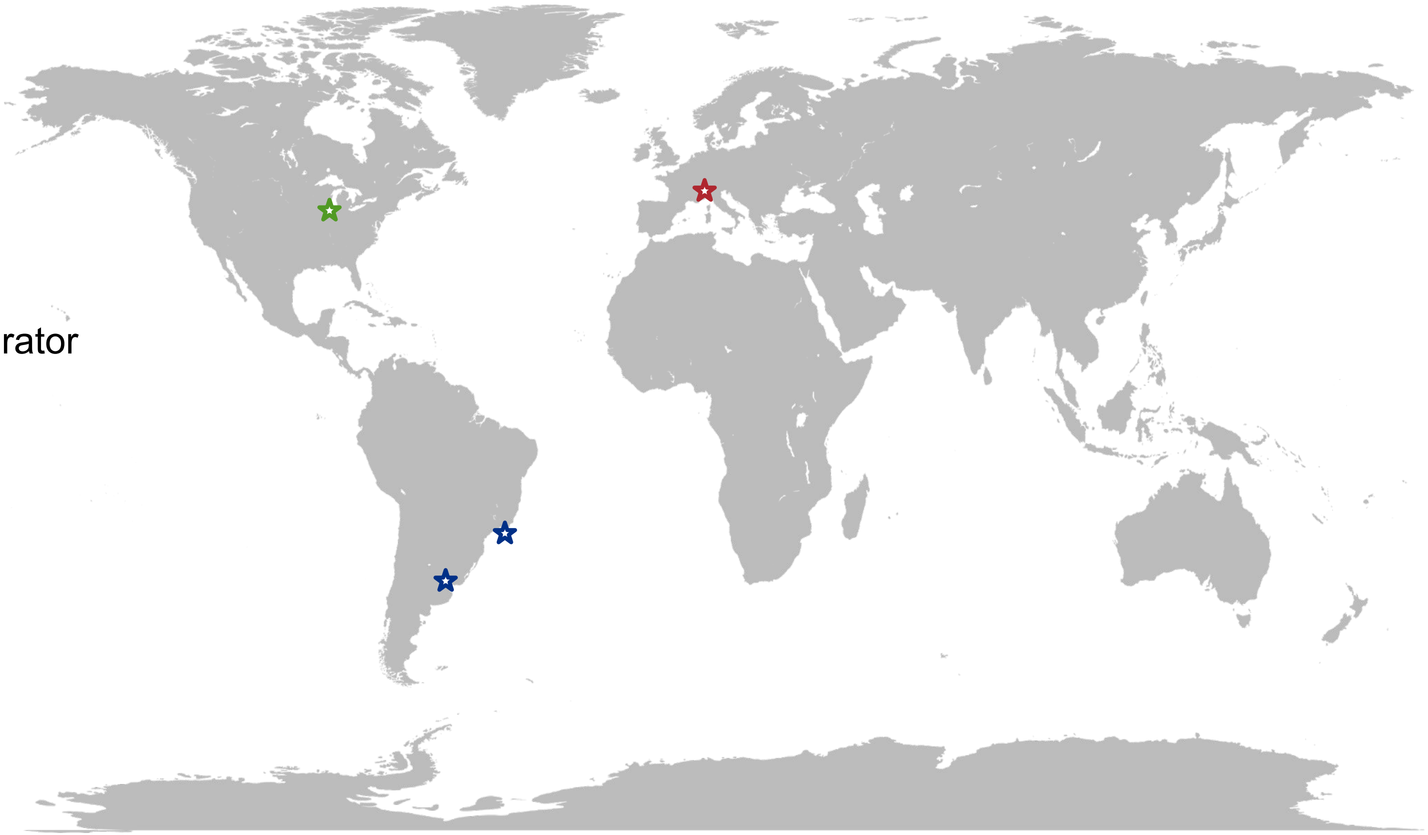
Maybe an mCP?



SENSEI @ MINOS 2020 data

- Low De/Dx track passing through the detector
- Not leaving a continuous track
- Maybe a milicharged particle?? In the end, No! - Muon going through a dead layer

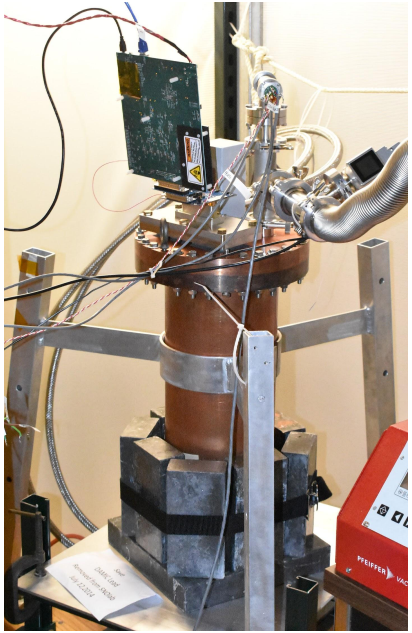
Skipper-CCD millicharged searches

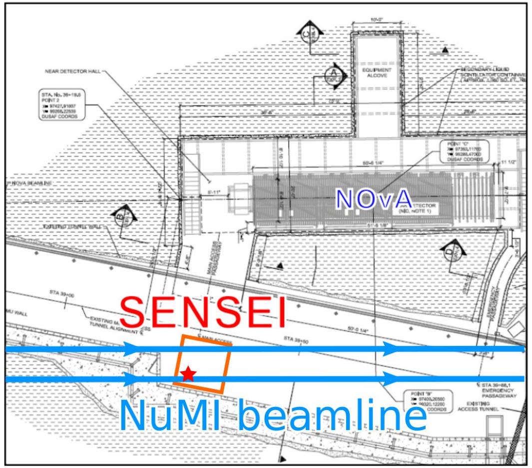


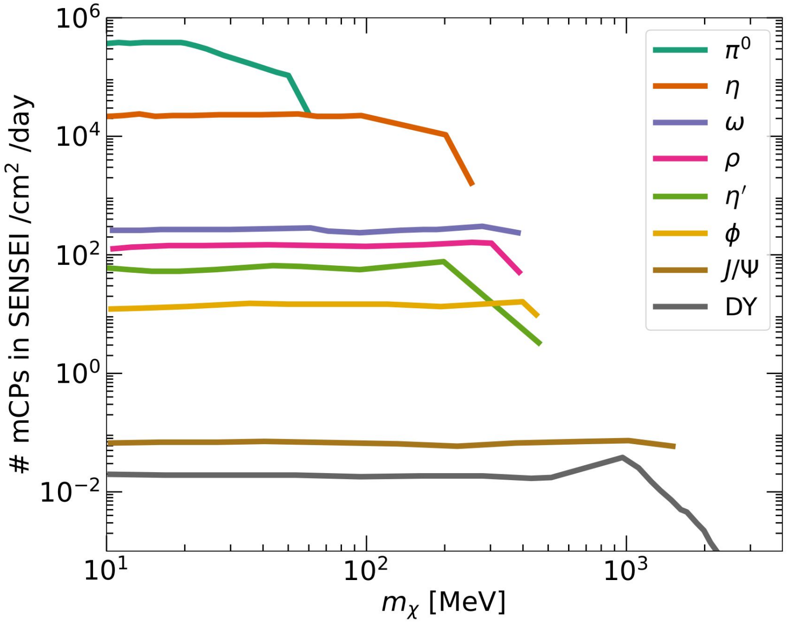
☆ Fixed target accelerator
☆ Reactors
☆ LHC

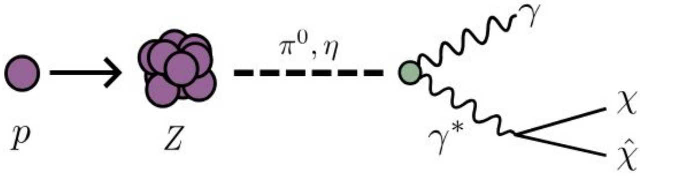
Fixed target: SENSEI@MINOS

Harnik, R., Liu, Z. & Palamara, O. Millicharged particles in liquid argon neutrino experiments. *J. High Energ. Phys.* **2019**, 170 (2019).









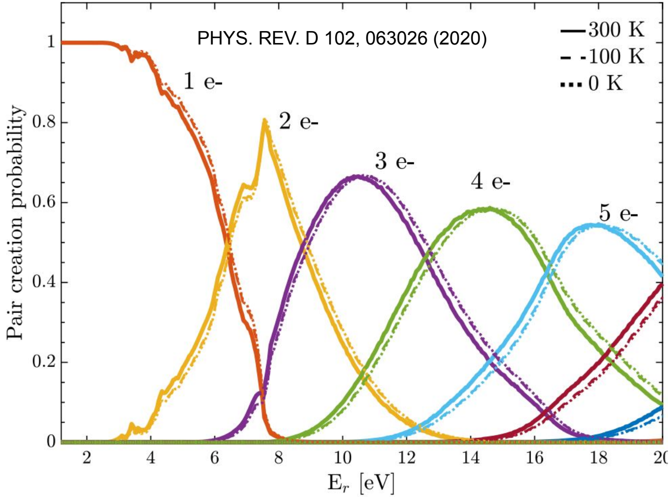
Highly boosted from a 120 GeV proton beam!

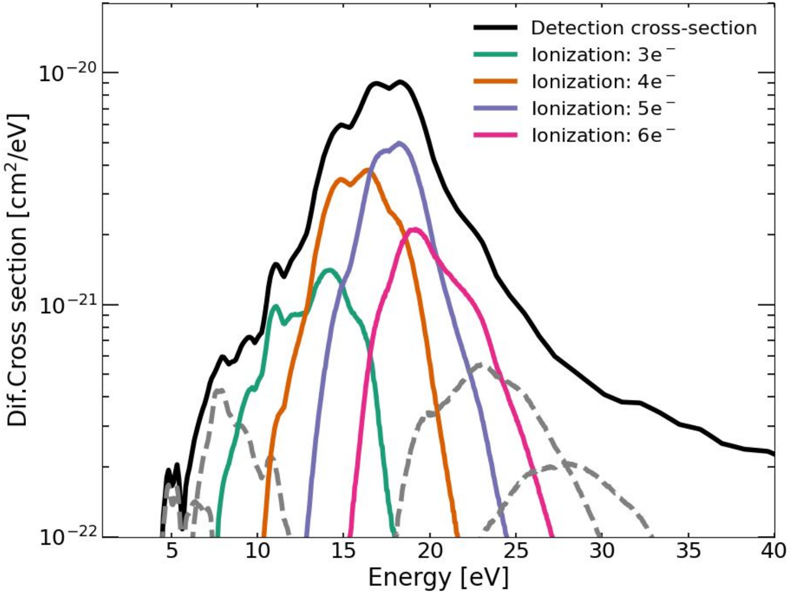
Fixed target: SENSEI@MINOS

From Fermi's energy loss formula, we can model the electron loss function using the DarkELF package

$$\frac{d\sigma}{d\omega} = \frac{8\alpha\varepsilon^2}{n_e\beta^2}\int_0^\infty dk\left\{\frac{1}{k}\mathrm{Im}\left(-\frac{1}{\epsilon(\omega,k)}\right) + k\left(\beta^2 - \frac{\omega^2}{k^2}\right)\mathrm{Im}\left(\frac{1}{-k^2+\epsilon(\omega,k)\omega^2}\right)\right\}$$

Once the mCP interacts we take into account the probability of exciting an electron-hole pair in silicon:



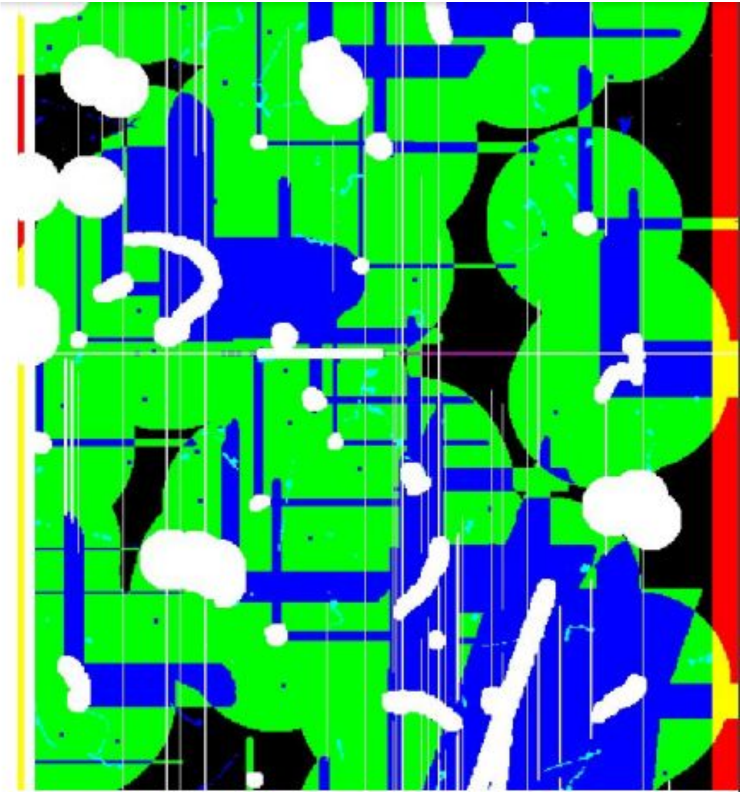


Knapen, Simon, Jonathan Kozaczuk, and Tongyan Lin. "PYTHON package for dark matter scattering in dielectric targets." Physical Review D 105.1 (2022): 015014.

Essig, R., Plestid, R., & Singal, A. (2024). Collective excitations and low-energy ionization signatures of relativistic particles in silicon detectors. *Communications Physics*, *7*(1), 416.

Usual mask in our analyses

- High energy event mask (White)
- Halo mask (Green)
- Bleed mask (Blue)
- Bad pixel/ Column (White)
- Edge mask (Red)
- Crosstalk (cryan)



Only the black pixels are taken into account in data analysis

Fixed target: SENSEI@MINOS

Extended the original 2020 search to 5 and 6 electrons.

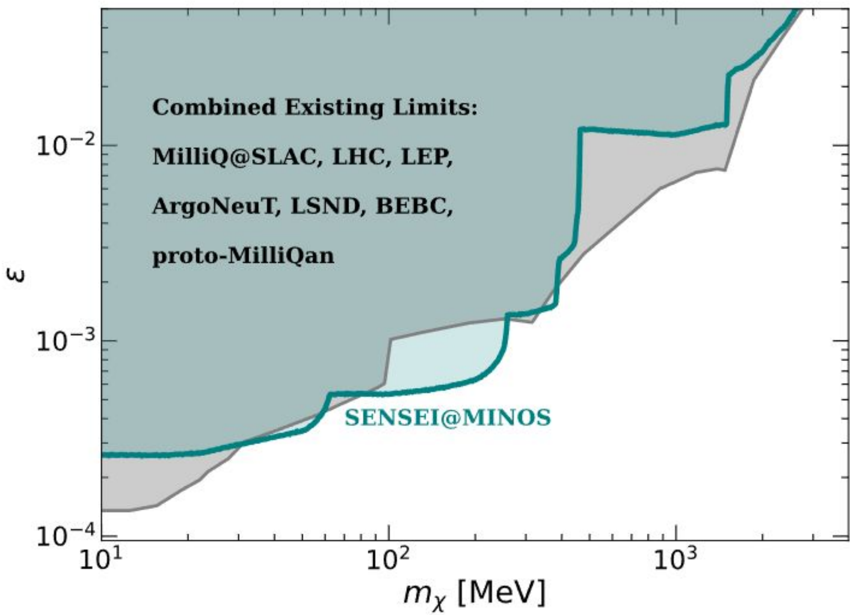
	$1e^-$	$2e^-$	$3e^-$	$4e^-$	$5e^-$	$6e^-$
Eff. Efficiency	0.069	0.105	0.325	0.327	0.331	0.338
Exp. [g-day]	1.38	2.09	9.03	9.10	9.23	9.39
Obs. Events	1311.7	5	0	0	0	0

With only 2 grams of silicon!!

Source	Uncertainty [%]	Error on limit [%]
mCP flux	22	6
σ_{int}	5	2
CCI	$\ll$10	2
POT	2	0.5
	Total:	7

Simulated the systematics to assess impact on limit, error falls in the width of the line.

$$N(\varepsilon, m_\chi) = A\Delta T \int \phi(\varepsilon, E_\chi, m_\chi) P(hits \geq 1) dE_\chi$$

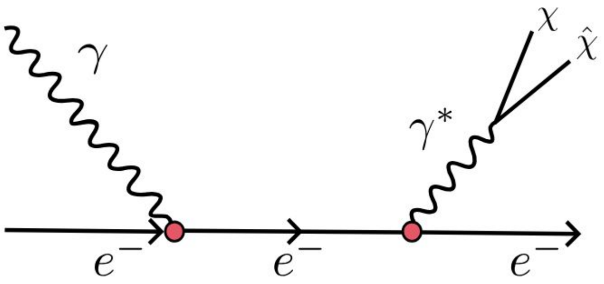


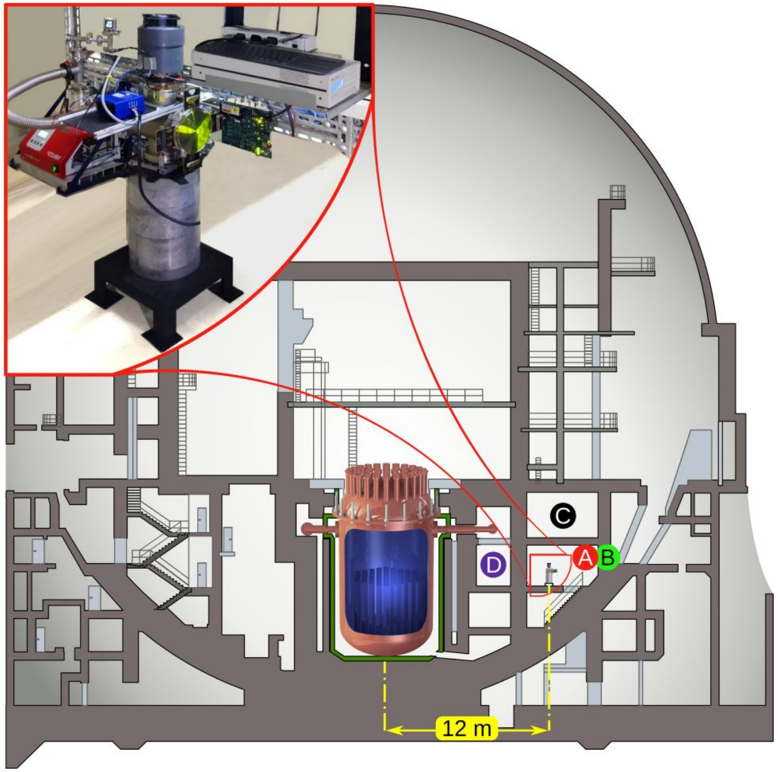
Barak, L., Bloch, I. M., Botti, A. M., Cababie, M., Cancelo, G., Cervantes-Vergara, B. A., ... & Plestid, R. (2024). Search by the SENSEI experiment for millicharged particles produced in the NuMI beam. *Physical review letters*, *133*(7), 071801.

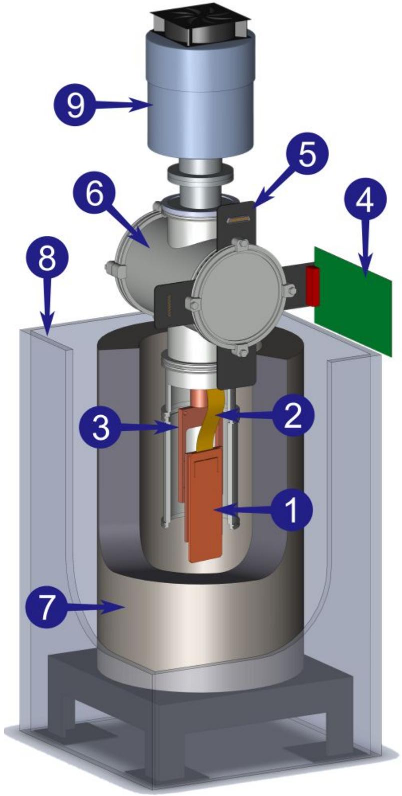
Reactor: ATUCHA-II

- Installed 12 m from the core **inside** the containment dome of the Atucha II 2-GWth reactor.

- Uses skipper-CCD, focus on neutrino physics but ideal to search for BSM physics due to its location.







Reactor: ATUCHA-II & CONNIE

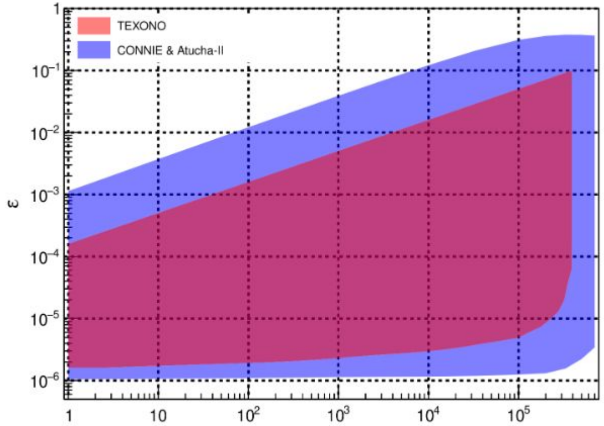
$$\frac{dR}{dT} = \rho_A \int_{E_{\min}}^{E_{\max}} \left[\frac{d\sigma}{dT}\right] \left[\frac{d\phi_{\chi_q}}{dE_{\chi_q}}\right] dE_{\chi_q}$$

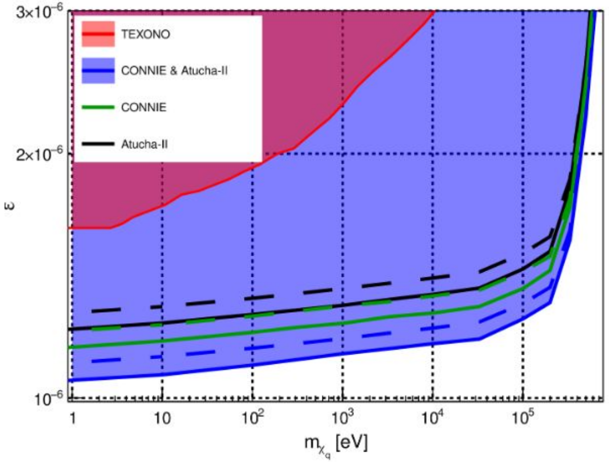
Detection

Production via Compton

Observable	CONNIE	Atucha-II
Reactor ON exposure [g-day]	14.9	59.4
Reactor OFF exposure [g-day]	3.5	22.6
Energy bin [eV]	15–215	40–240
Reactor ON counts	6	168
Reactor OFF counts	2	71
90% C.L. upper limit on events	6.2	30.9

We calculate the 90% C.L for each mass and coupling and combine both reactor experiments

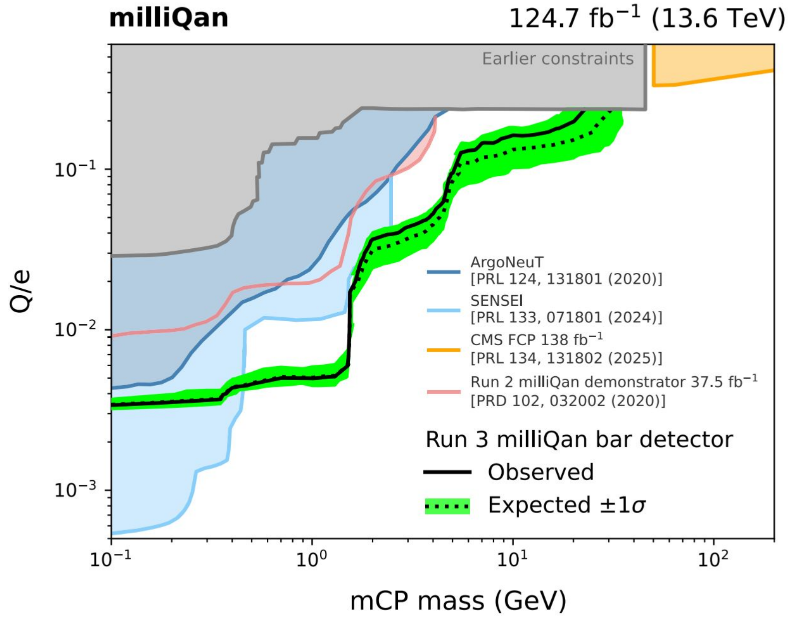


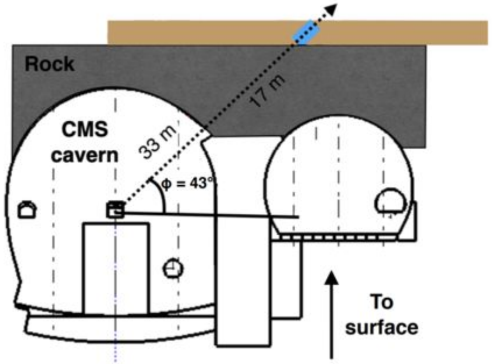


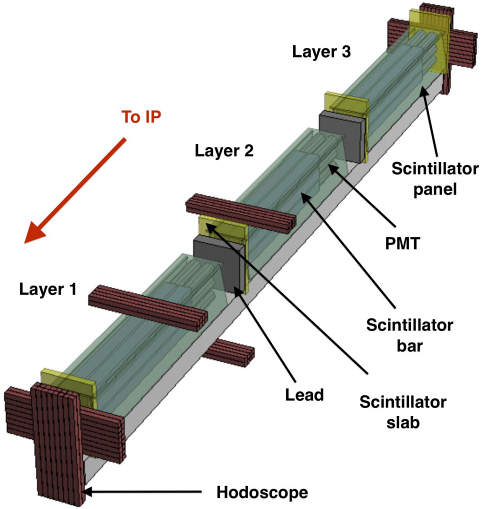
Aguilar-Arevalo, A. A., D'Olivo, J. C., Sarkis, Y., Avalos, N., Bertou, X., Bellino, P., ... & (CONNIE and Atucha-II Collaborations). (2025). Search for reactor-produced millicharged particles with Skipper-CCDs at the CONNIE and Atucha-II experiments. Physical Review Letters, 134(7), 071801.

Accelerator: MOSKITA@LHC

The milliQan collaboration identified the CMS service cavern as a good place to search for mCPs during LHC-RUN 3.

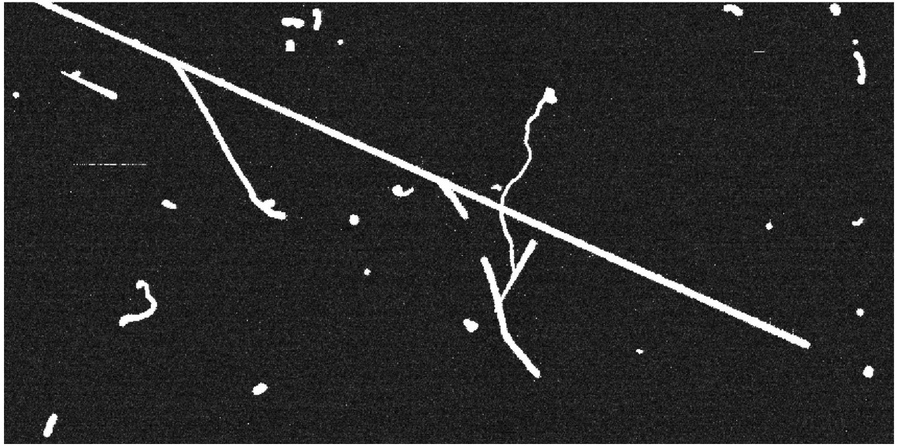


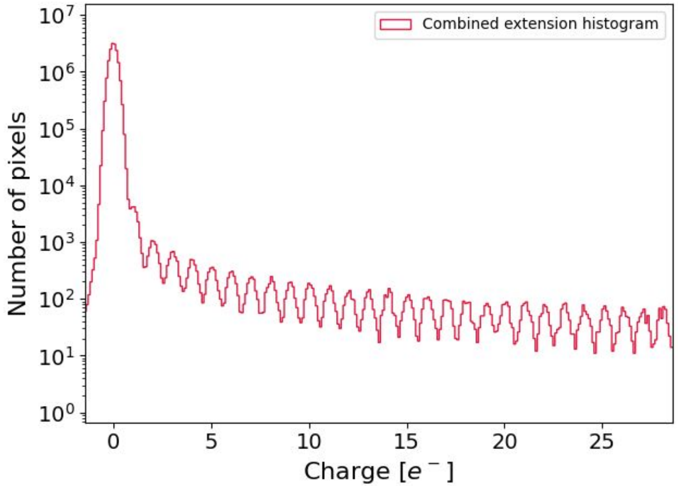




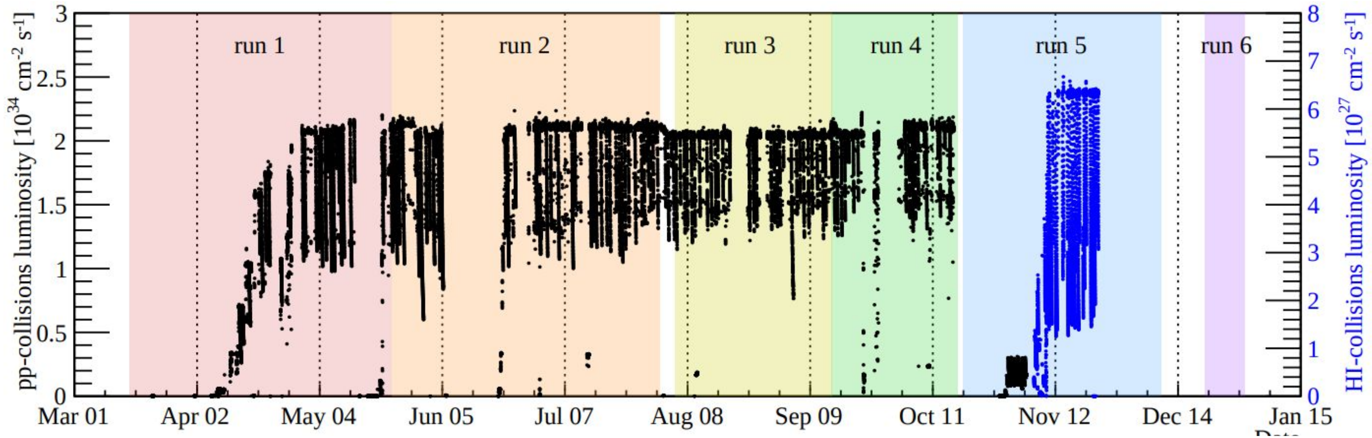
They kindly gave us some space in the cavern.

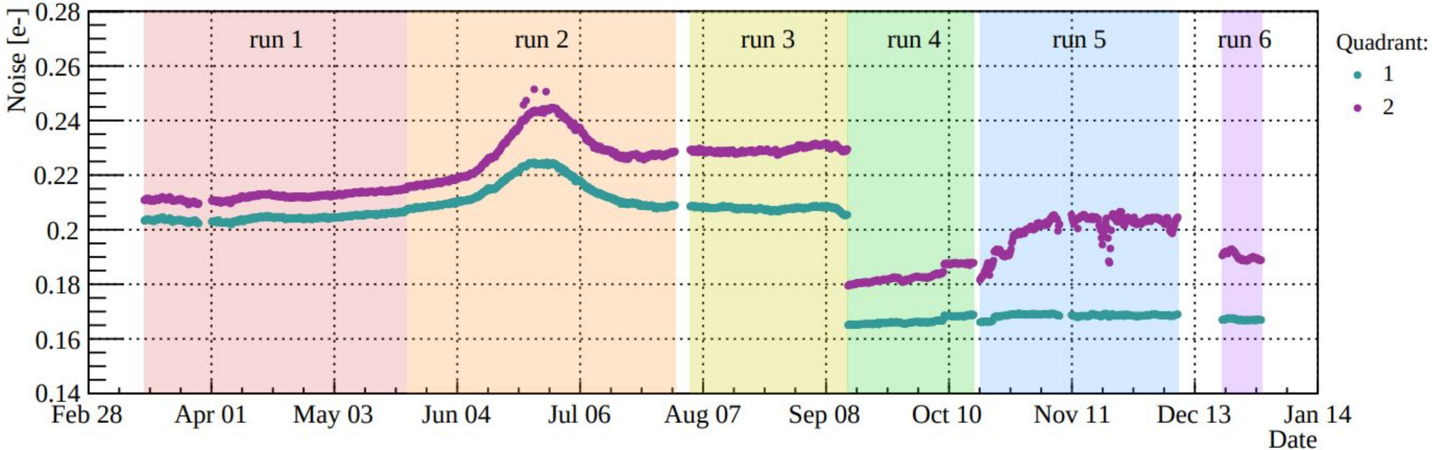
Accelerator: MOSKITA@LHC





Accelerator: MOSKITA@LHC

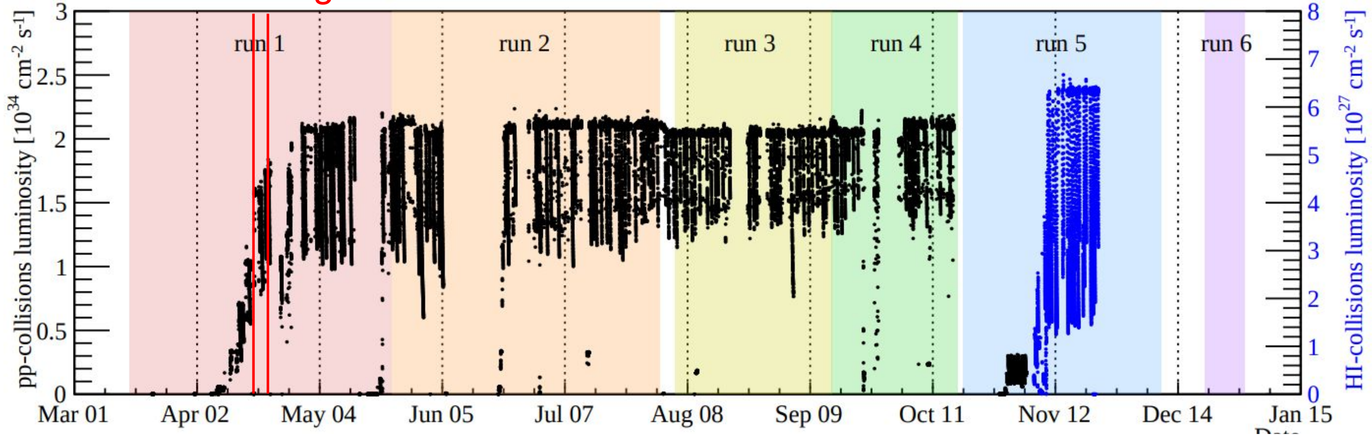


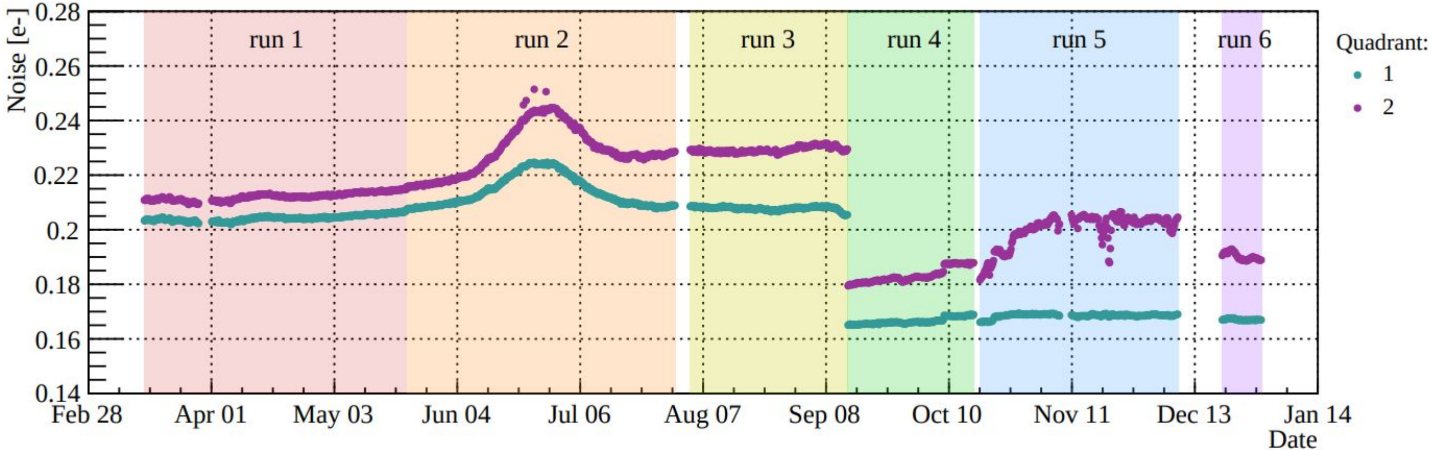


Accelerator: MOSKITA@LHC

Total: 129.50 [fb^-1]
Expo: 44.42 [g-day]

Image duration ~5hrs



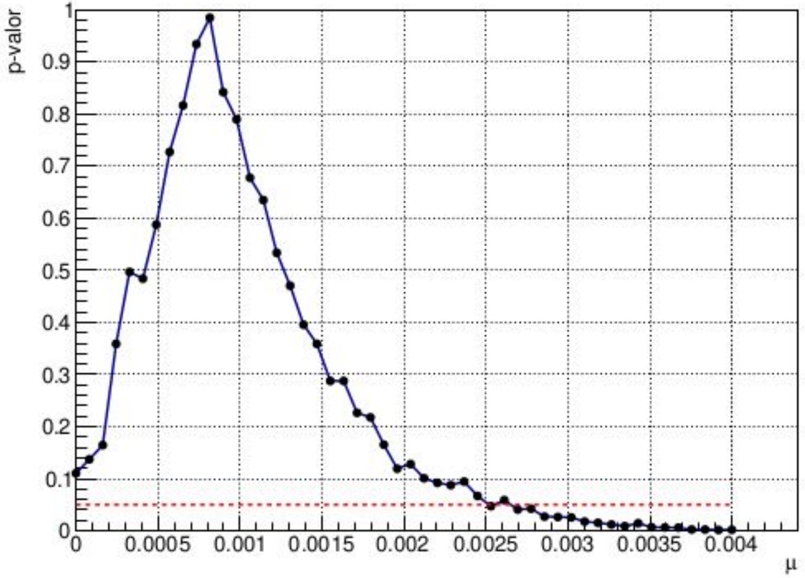


Accelerator: MOSKITA@LHC

Eur. Phys. J. C (2011) 71: 1554

$$\mathcal{L}(\mathbf{n}|\mu, \mathbf{b}) = \prod_{i=1}^{N_{\mathrm{img}}} \frac{e^{-(\mu s_i + b_i)}(\mu s_i + b_i)^{n_i}}{n_i!}$$

$$b_i = \Delta E \times \epsilon_i \times R_b \qquad s_i = \Delta E \times \epsilon_i \times L_i$$



$$\lambda(\mu) = \frac{\mathcal{L}(\mathbf{n}|\mu, \hat{\hat{\mathbf{b}}})}{\mathcal{L}(\mathbf{n}|\hat{\mu}, \hat{\mathbf{b}})}$$

$$t_\mu \equiv -2\ln(\lambda)$$

$$p(\mu) = \int_{t_{obs}}^{\infty} f_\mu(\tilde{t})d\tilde{t}$$

We perform 20000 pseudo experiments to find the f distribution

Accelerator: MOSKITA@LHC - Low Energy results Proton-Proton

Bin [e^-]	Observed events		Eff. exposure [g-day]		Efficiency	P-value	Upper limit 95% C.L.
	ALL	L=0	ALL	L=0		$\mu = 0$	[events]
2	327	161	11.40	5.29	0.29	0.31	5.88
3	17	11	19.27	8.94	0.49	0.20	1.41
4	1	0	23.59	10.94	0.60	0.12	5.20
5	2	0	26.74	12.40	0.68	0.37	3.12
6	0	0	27.92	12.95	0.71	1	2.45
7	1	0	29.10	13.50	0.74	0.23	4.15
8	2	1	29.49	13.68	0.75	0.35	1.41
9	0	0	30.67	14.23	0.78	1	1.81
10	1	0	31.85	14.77	0.81	0.53	3.73
11-20	9	3	33.42	15.50	0.85	0.41	8.17

Accelerator: MOSKITA@LHC - Low Energy results Proton-Proton

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9	0	0	30.67	14.23	0.78	1	1.81
10	1	0	31.85	14.77	0.81	0.53	3.73
11-20	9	3	33.42	15.50	0.85	0.41	8.17

From masks and simulations

Accelerator: MOSKITA@LHC - Low Energy results Proton-Proton

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9	0	0	30.67	14.23	0.78	1	1.81
10	1	0	31.85	14.77	0.81	0.53	3.73
11-20	9	3	33.42	15.50	0.85	0.41	8.17

From likelihood analysis and MonteCarlo Simulations

Accelerator: MOSKITA@LHC - Low Energy results - Heavy ions

Bin [e^-]	Observed events ALL	Observed events L=0	Eff. exposure [g-day] ALL	Eff. exposure [g-day] L=0	Efficiency	P-value $\mu = 0$	Upper limit 95% C.L. [events]
2	85	72	2.74	2.22	0.29	0.52	5.80
3	6	5	4.63	3.75	0.49	0.43	2.05
4	0	0	5.67	4.59	0.60	1	1.14
5	2	2	6.43	5.20	0.68	0.57	2.02
6	0	0	6.71	5.43	0.71	1	1.50
7	2	0	6.99	5.66	0.74	0.017	5.74
8	0	0	7.09	5.74	0.75	1	1.74
9	0	0	7.37	5.97	0.78	1	1.46
10	0	0	7.65	6.20	0.81	1	2.30
11-20	6	4	8.03	6.50	0.85	0.71	4.87

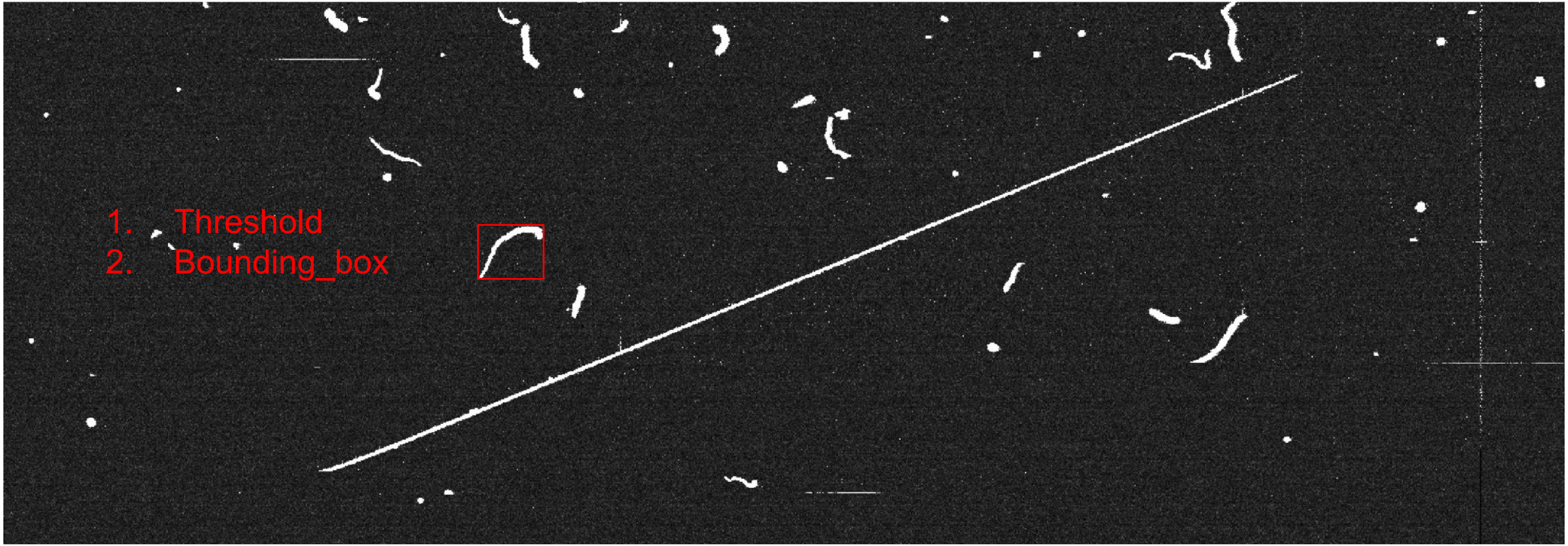
Accelerator: MOSKITA@LHC - Low Energy results - Heavy ions

Bin [e^-]	Observed events		Eff. exposure [g-day]		Efficiency	P-value	Upper limit 95% C.L.
	ALL	L=0	ALL	L=0		$\mu = 0$	[events]
2	85	72	2.74	2.22	0.29	0.52	5.80
3	6	5	4.63	3.75	0.49	0.43	2.05
4	0	0	5.67	4.59	0.60	1	1.14
5	2	2	6.43	5.20	0.68	0.57	2.02
6	0	0	6.71	5.43	0.71	1	1.50
7	2	0	6.99	5.66	0.74	0.017	5.74
8	0	0	7.09	5.74	0.75	1	1.74
9	0	0	7.37	5.97	0.78	1	1.46
10	0	0	7.65	6.20	0.81	1	2.30
11-20	6	4	8.03	6.50	0.85	0.71	4.87

Slightly unlikely result in the 7e bin! It washes away a little bit when considering the look-elsewhere effect.
More data coming this year!

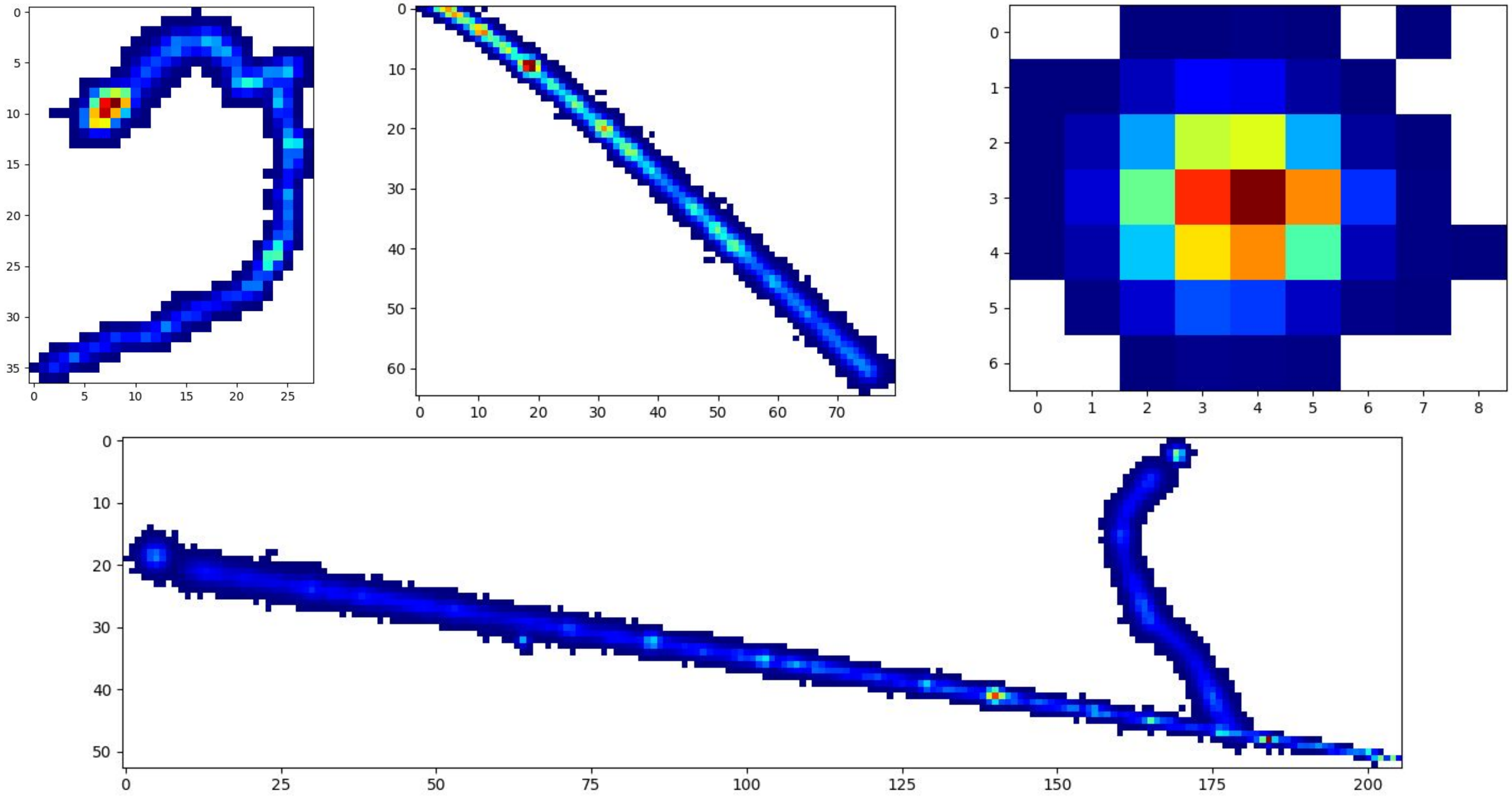
Accelerator: MOSKITA@LHC - High energy events

That analysis was until 20 electrons, lets see what happens to events larger than that…



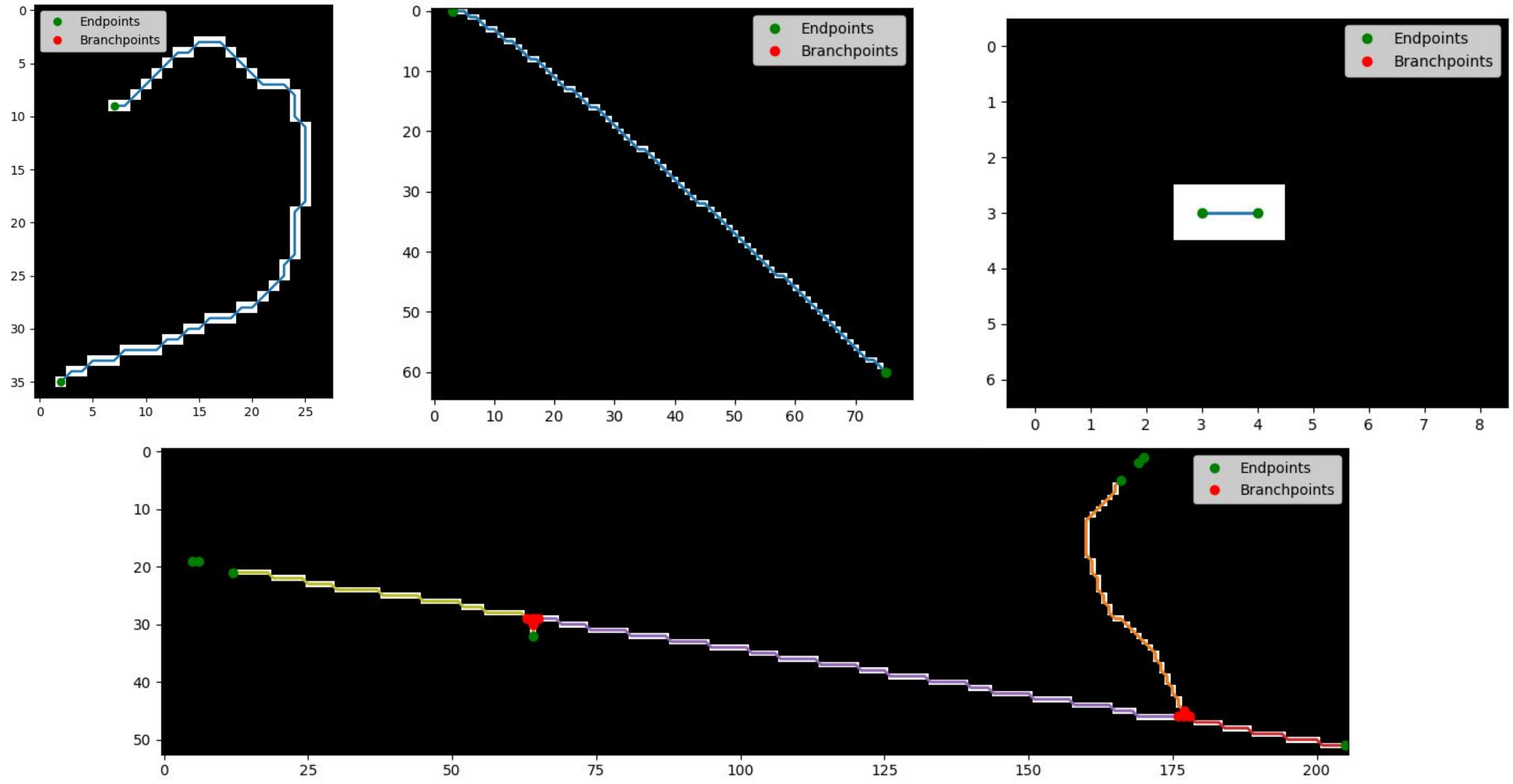
Accelerator: MOSKITA@LHC - High energy events

We can isolate each event type to create a ground truth for classification…

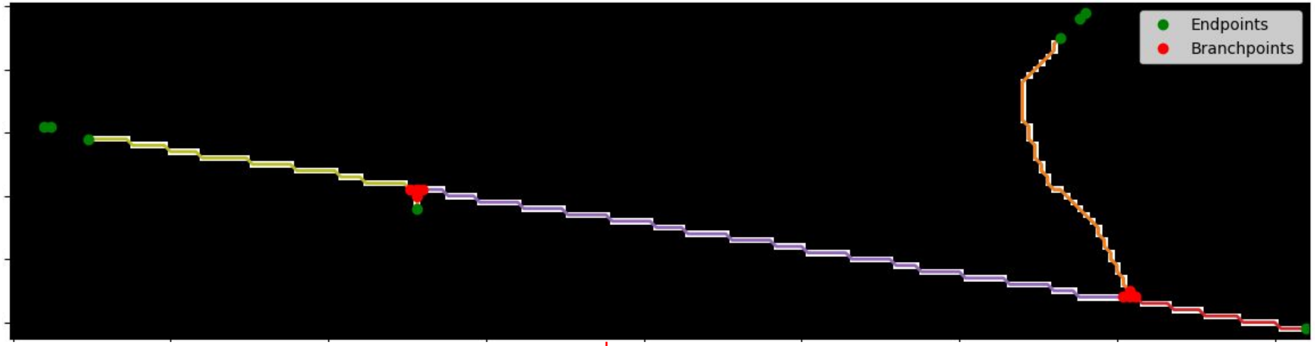


Accelerator: MOSKITA@LHC - High energy events

A skeletonization algorithm helps us measure if the event branches or crosses into others



Accelerator: MOSKITA@LHC - High energy events



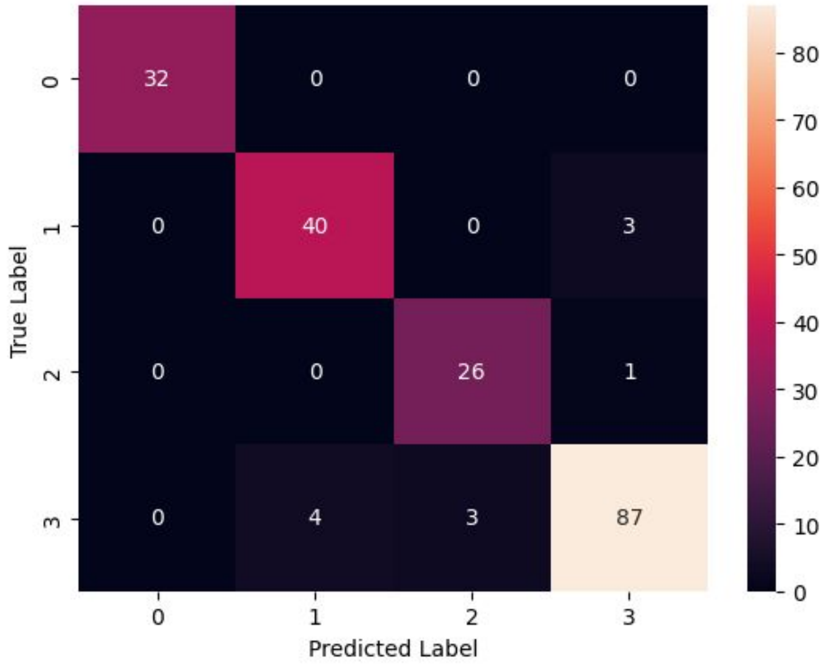
Measure each segment properties

	segment_id	start	end	segment_type	length_pixels	path_length_px	length_um	angle_deg	curvature	intensity_sum	intensity_mean	intensity_std	intensity_min	intensity_max	charge_per_um	angle_change_deg
0	0	(5, 166)	(45, 177)	endpoint_to_branch	42	50.112698	751.690476	74.623749	1.207973	22006.617188	523.967102	171.056488	257.697754	906.859131	29.276169	78.690068
1	1	(5, 166)	(46, 178)	endpoint_to_branch	43	51.526912	772.903679	73.686148	1.206154	22497.876953	523.206421	169.127609	257.697754	906.859131	29.108254	63.434949
2	2	(45, 177)	(46, 178)	branch_to_branch	3	2.000000	30.000000	45.000000	1.414214	1760.810791	586.936951	98.252129	491.258392	722.036926	58.693693	0.000000
3	3	(45, 177)	(29, 65)	branch_to_branch	113	119.455844	1791.837662	-171.869898	1.055850	77837.812500	688.830200	401.224152	315.540558	3445.897217	43.440215	18.434949
4	4	(45, 177)	(46, 177)	branch_to_branch	3	2.414214	36.213203	90.000000	2.414214	2154.870361	718.290100	137.932709	547.515503	885.317932	59.505102	0.000000
5	5	(46, 178)	(51, 205)	endpoint_to_branch	28	29.071068	436.066017	10.491477	1.058706	28532.761719	1019.027222	720.354919	341.968445	4060.973877	65.432207	18.434949
6	6	(29, 65)	(29, 63)	branch_to_branch	3	2.828427	42.426407	180.000000	1.414214	1117.832764	372.610931	103.168243	248.450729	501.051514	26.347571	0.000000
7	7	(29, 63)	(21, 12)	endpoint_to_branch	52	54.313708	814.705627	-171.085073	1.052109	20762.029297	399.269806	107.885086	225.636414	703.387024	25.484087	0.000000
8	8	(29, 63)	(29, 64)	branch_to_branch	3	2.414214	36.213203	0.000000	2.414214	1044.939087	348.313019	74.718079	248.450729	428.157867	28.855196	0.000000
9	9	(19, 6)	(19, 5)	endpoint_to_endpoint	2	1.000000	15.000000	180.000000	1.000000	1744.286133	872.143066	168.877930	703.265137	1041.020996	116.285742	0.000000
10	10	(30, 64)	(32, 64)	endpoint_to_branch	3	2.000000	30.000000	90.000000	1.000000	1677.389526	559.129822	440.201080	247.270966	1181.667847	55.912984	0.000000
11	11	(1, 170)	(2, 169)	endpoint_to_endpoint	2	1.414214	21.213203	135.000000	1.000000	2269.693115	1134.846558	887.104187	247.742371	2021.950806	106.994360	0.000000

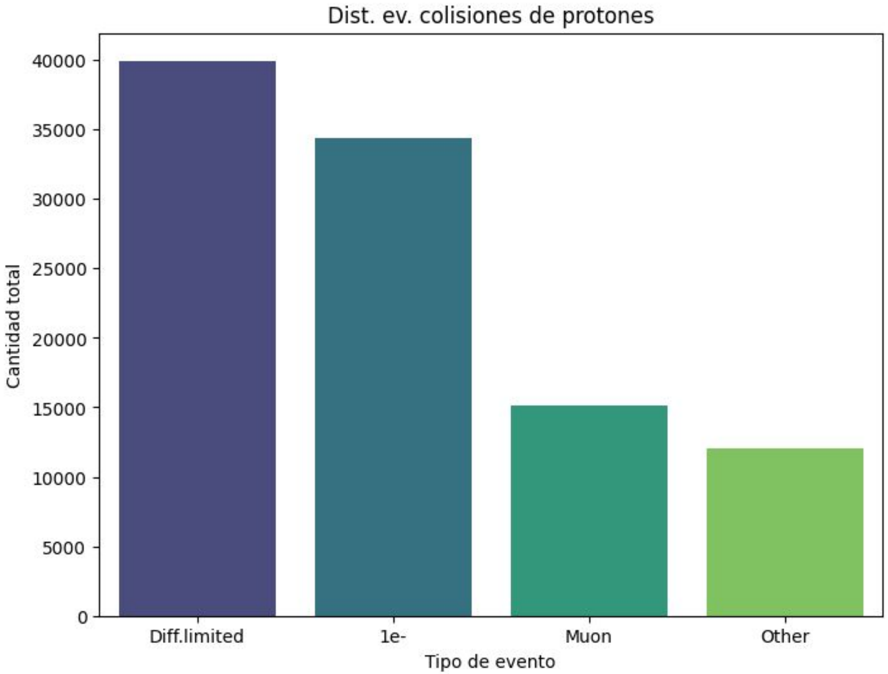
=====

With this we train a supervised classifier on a labeled dataset

Accelerator: MOSKITA@LHC - High energy events



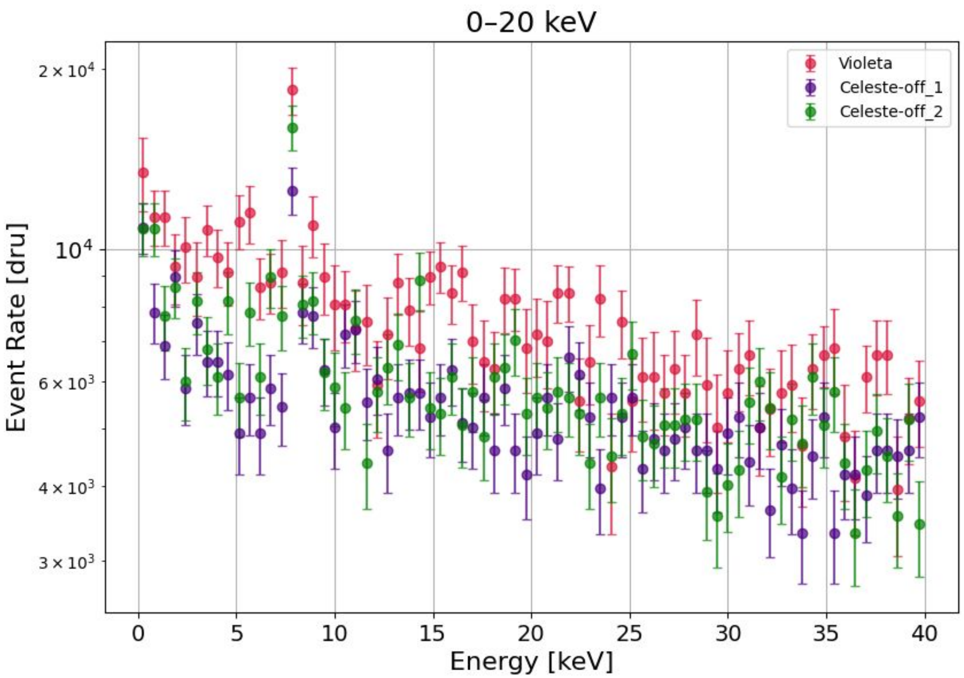
Performance of around 0.94 for the testing dataset

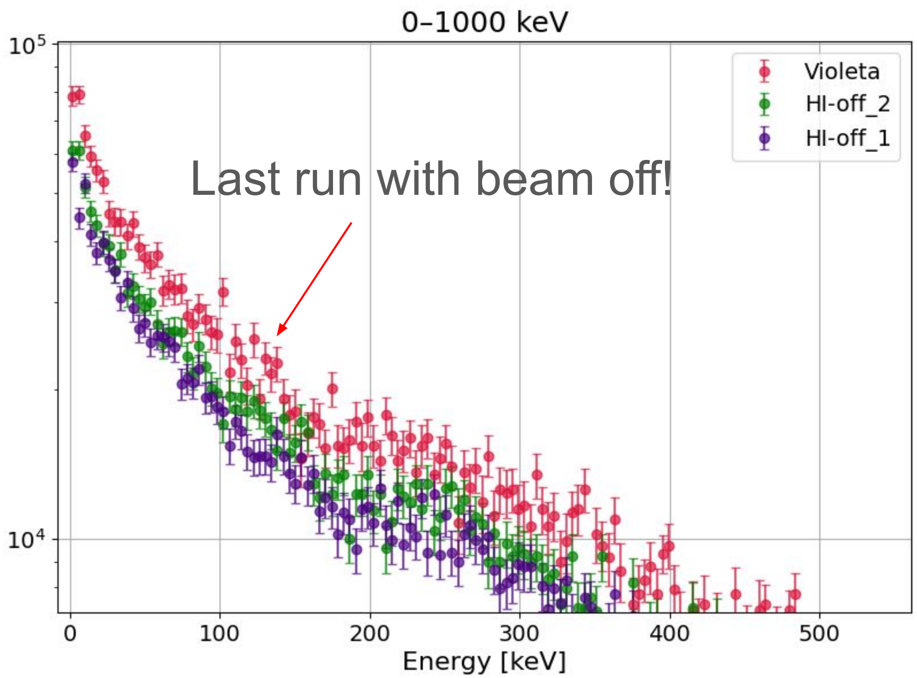


Distribution during the ppcol run

Accelerator: MOSKITA@LHC - High energy events

Doing a likelihood analysis for each particle type we find a very low p-value for electrons ~0.0003
dru=[events/(day x kg x keV)]





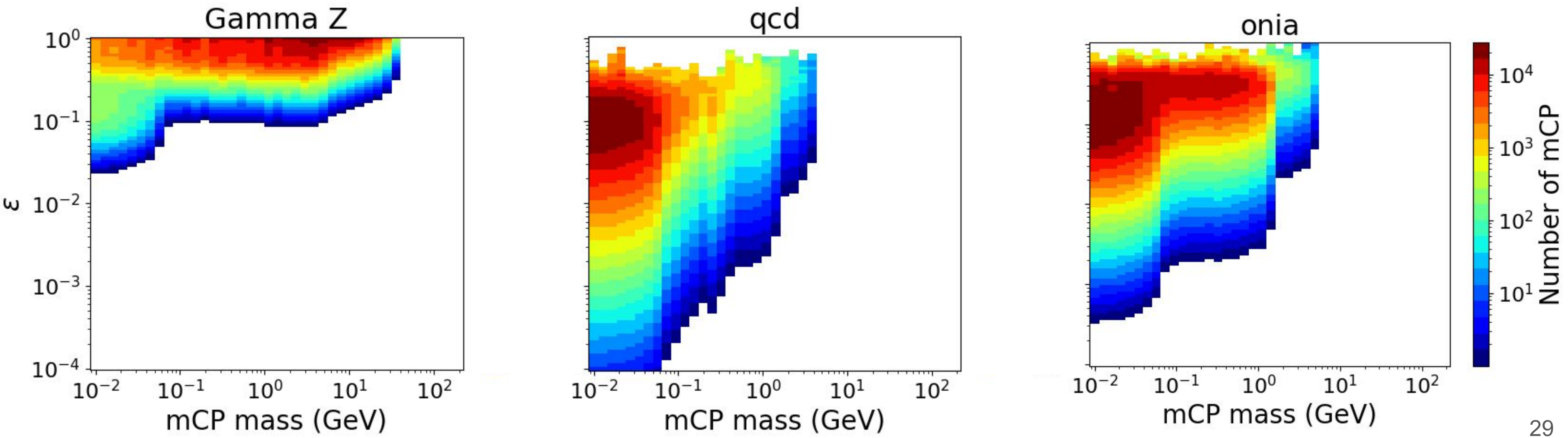
Increased event counts after heavy ion collisions, odd!

Accelerator: MOSKITA@LHC - mCP limit

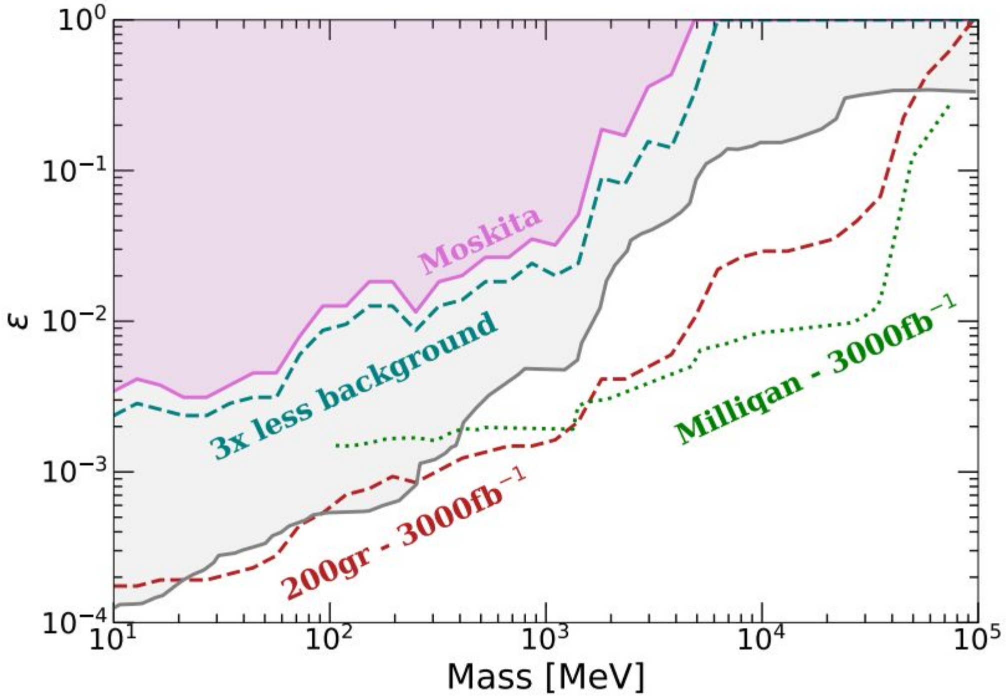
Basically the pythia simulation takes into account all process that can generate a pair $\mu^+\mu^-$ along with other particles and reescales the probability (branching ratios) by ε^2 and the "muon" mass in pythia by that of the mCP. This simulation was developed by the Milliqan Team

The pythia modes used are HardQCD:all, Onia:all, and WeakSingleBoson:ffbar2gmZ.

When doing this the contribution of each process to the total number of mCPs observed is:

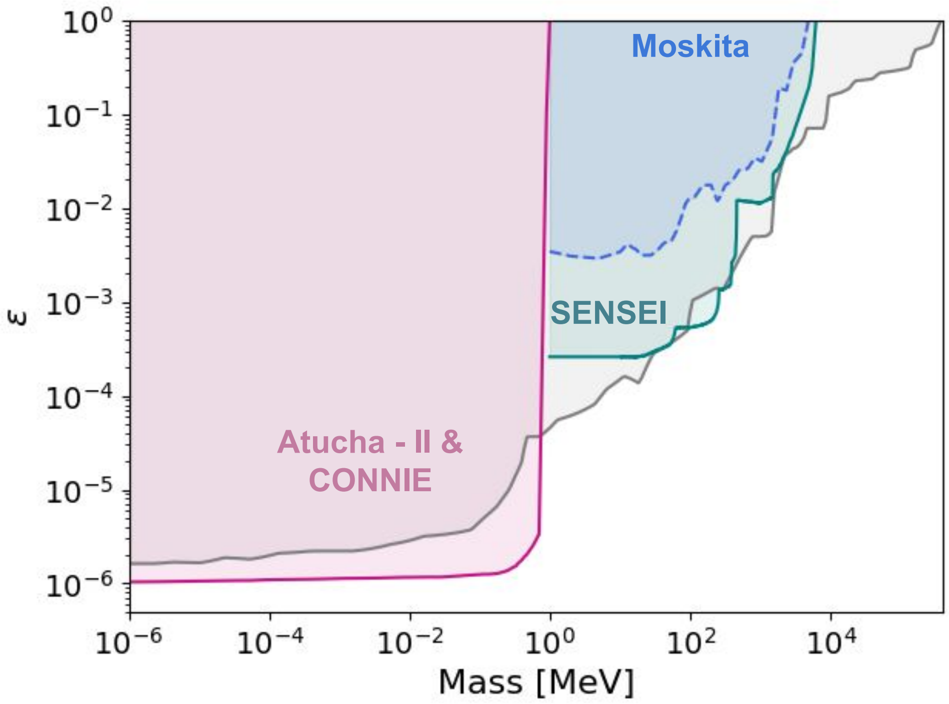


Accelerator: MOSKITA@LHC - mCP results



Cervantes-Vergara, B. A., Perez, S. E., Bacchetta, N., Castelló-Mor, N., Estrada, J., Garcia, M. F., ... & Cortabitarte, R. V. (2025). Investigation of Low-Energy Particle Remnants in High-Energy Collisions at the LHC with a Skipper-CCD detector. *arXiv preprint arXiv:2508.06749*.

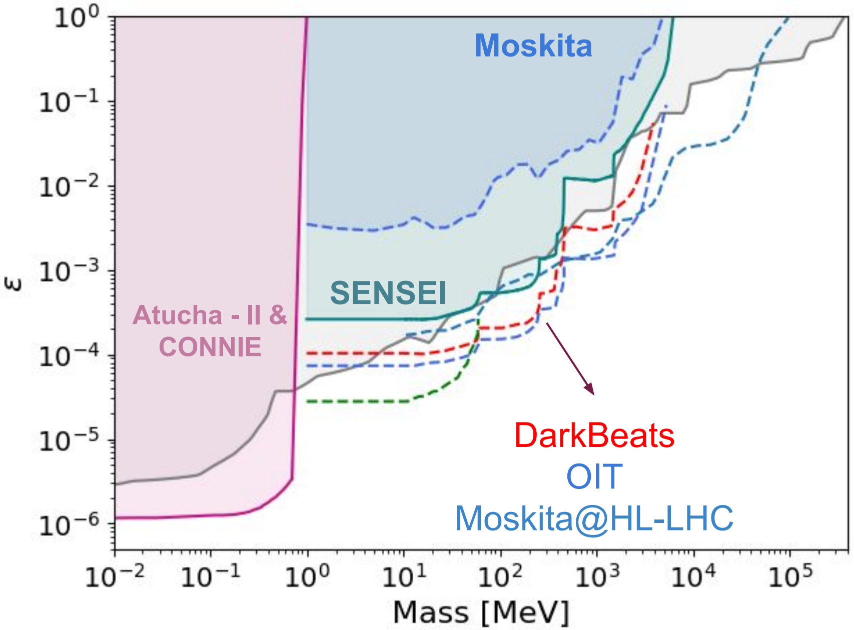
mCP limits - Whole Skipper program



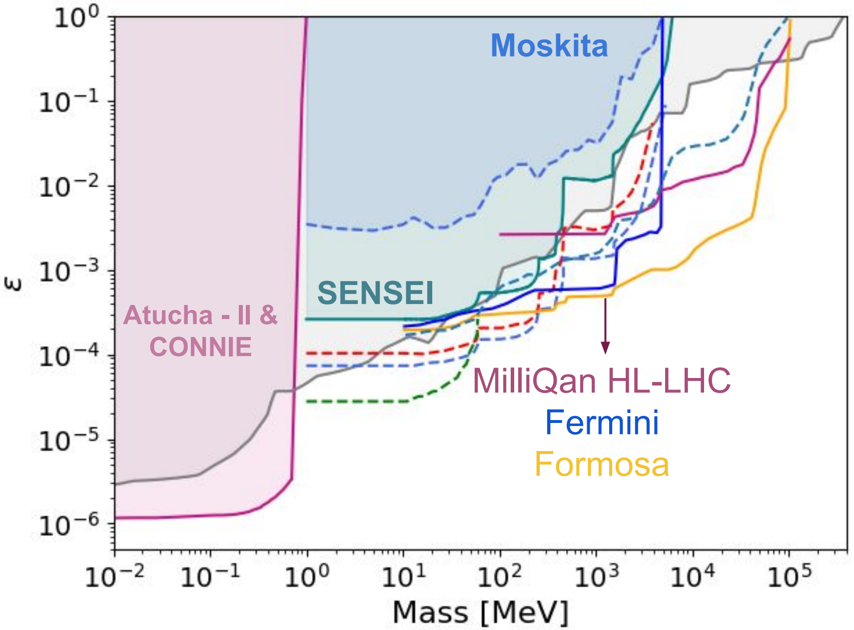
We covered 9 orders of magnitude with this sensor!

mCP limits - Whole Skipper program

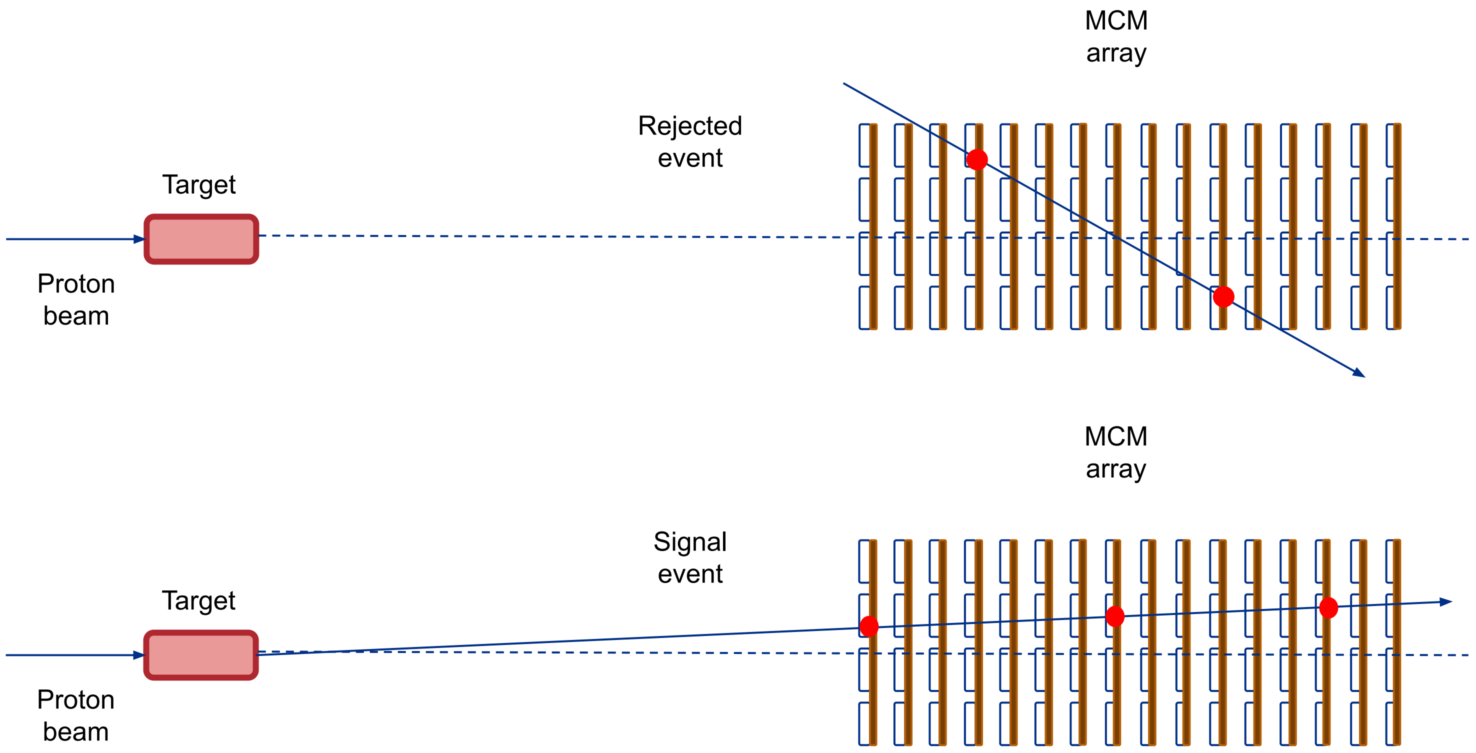
Current limits and future Skipper-CCD projects



Current limits and future - all detectors

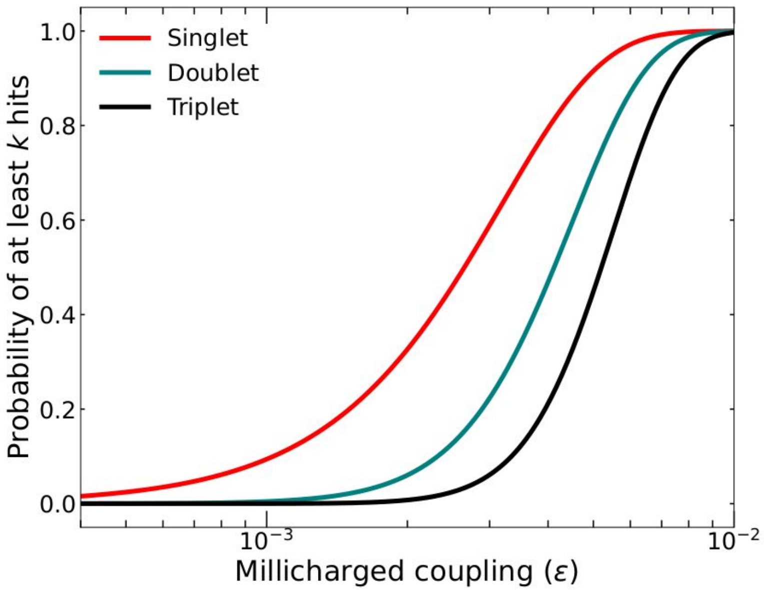


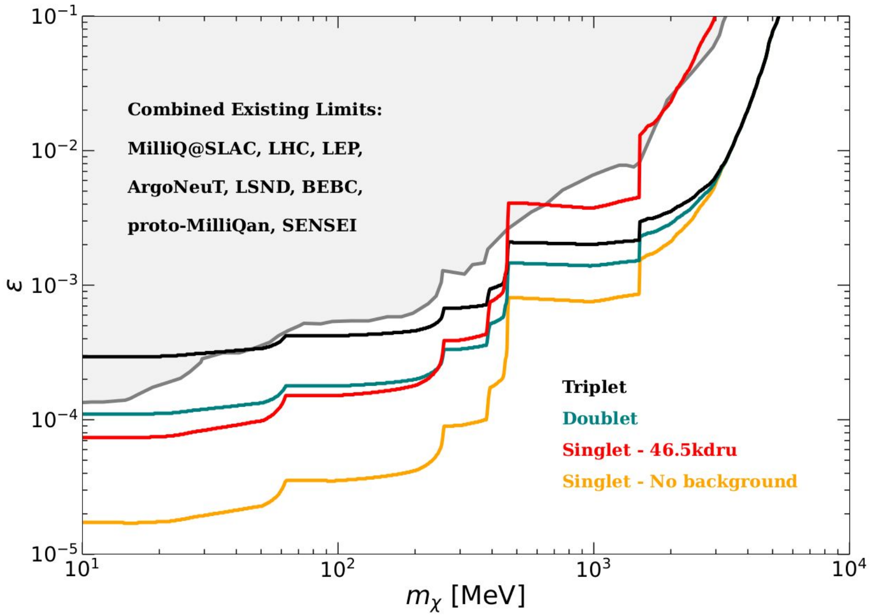
DarkbeaTs and OIT - background reduction with particle tracking



Perez, S., Rodrigues, D., Estrada, J. *et al.* Searching for millicharged particles with 1 kg of Skipper-CCDs using the NuMI beam at Fermilab. *J. High Energ. Phys.* **2024**, 72 (2024).

DarkbeaTs and OIT - background reduction with particle tracking





Lower probability to have doublet events but more robust to background - can help for higher masses

Perez, S., Rodrigues, D., Estrada, J. *et al.* Searching for millicharged particles with 1 kg of Skipper-CCDs using the NuMI beam at Fermilab. *J. High Energ. Phys.* **2024**, 72 (2024).

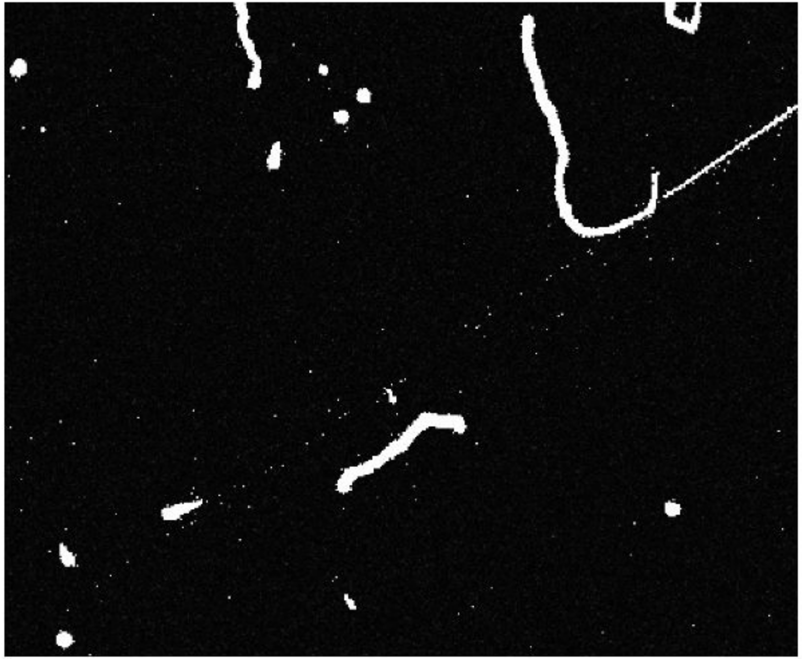
Conclusions

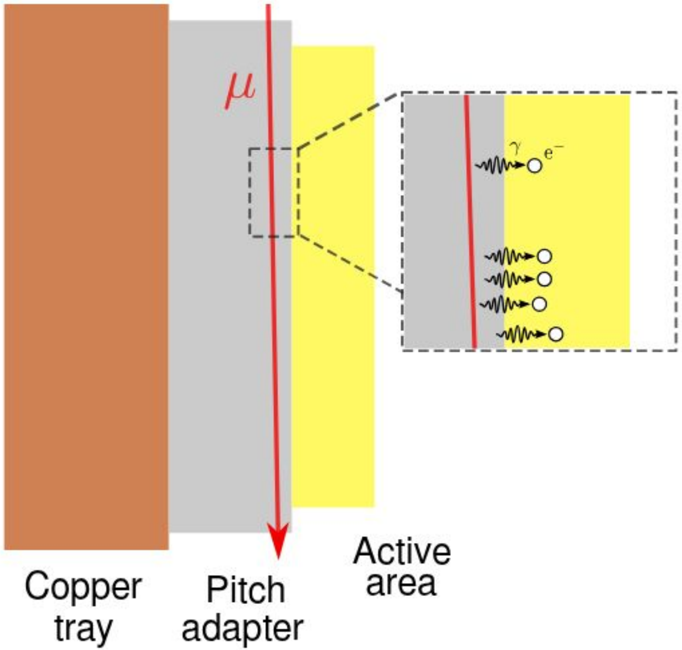
- Skipper-CCDs continue to be very promising for detecting low-energy processes.
- The mCP's mass and charge parameter space can be greatly constrained by Skipper-CCD based experiments to investigate the mystery of charge quantization.
- Accelerators experiments (LHC) can extend the search to the GeV mass mCP and also take advantage of tracking.
- Low energy likelihood analysis presented some interesting features which will be resolved this year with more statistic.
- Event ID with Machine Learning can help search for excesses or other quirks in data.
- Very active area of BSM physics right now! A lot of proposed experiments.

Thanks!

Maybe mCP? No!

Searching the whole dataset we found a muon that gives rise to a collinear event (the muon goes through a dead layer of silicon and sends Cherenkov photons to the CCD active area)





High energy was also higher for the ppcol run

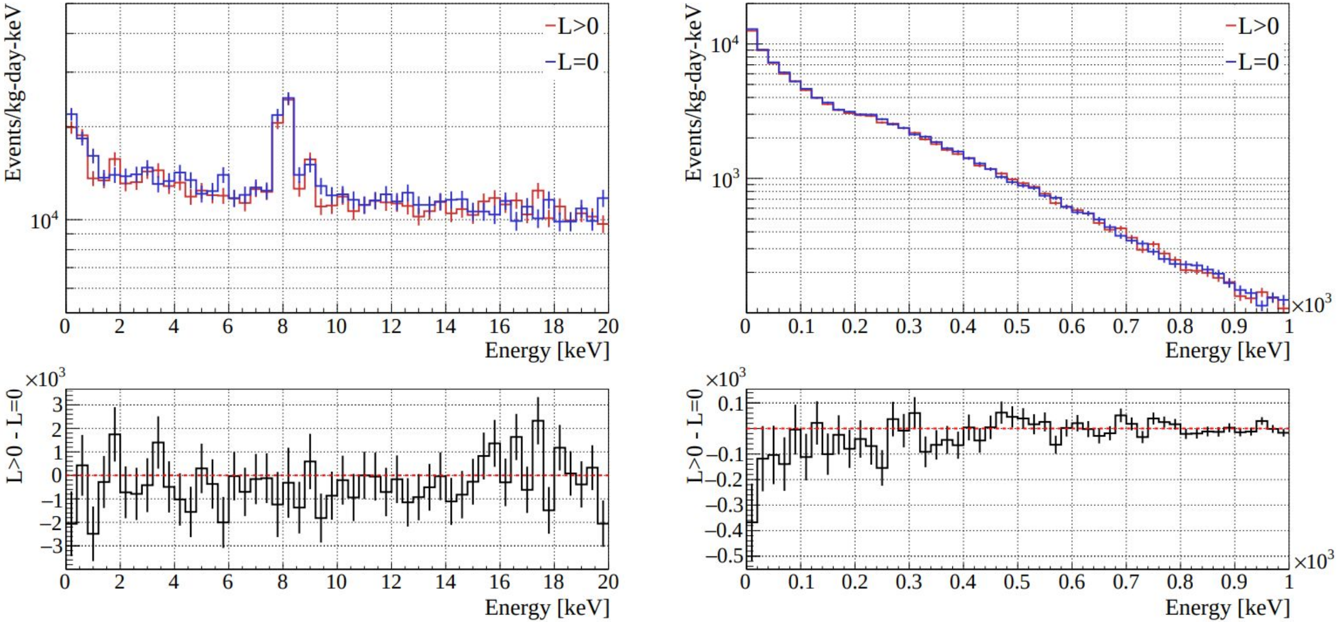


Figure 16: Top: High-energy event rates for the proton-proton collision period, for images with L=0 (blue) and L>0 (red), shown from 0 to 20 keV (left) and from 0 to 1000 keV (right). Bottom: Difference in event rates between images with and without luminosity (black), i.e. L>0 - L=0, for the same energy ranges. A higher event rate below ∼450 keV for L=0 is observed.