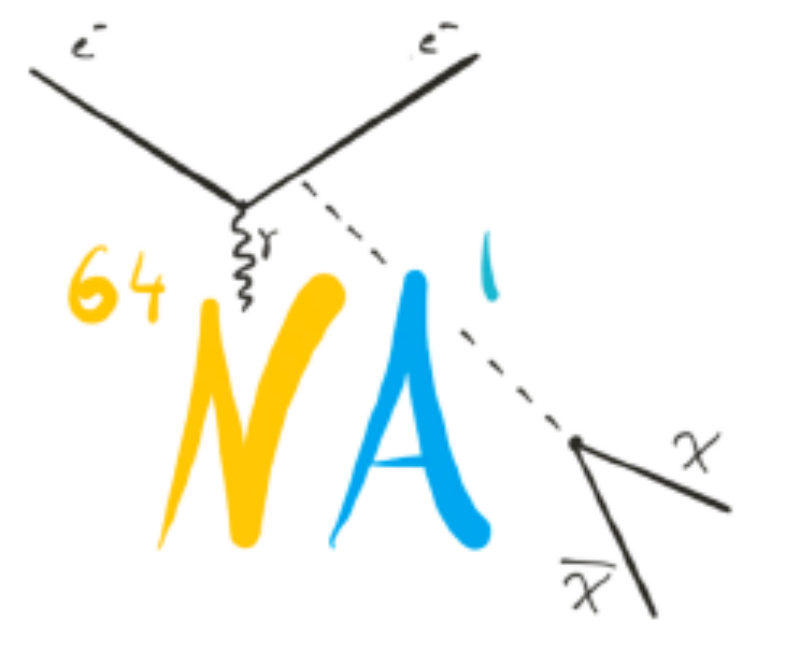




Dark sector searches with the NA64 μ experiment

Mirald Tuzi

IFIC Student Seminar 30th September 2026

Overview

The Dark Matter problem

The NA64 experiment

NA64 μ : muon mode

Technique + reconstruction

Analysis and results

Outlook and summary

Overview

The Dark Matter problem

The NA64 experiment

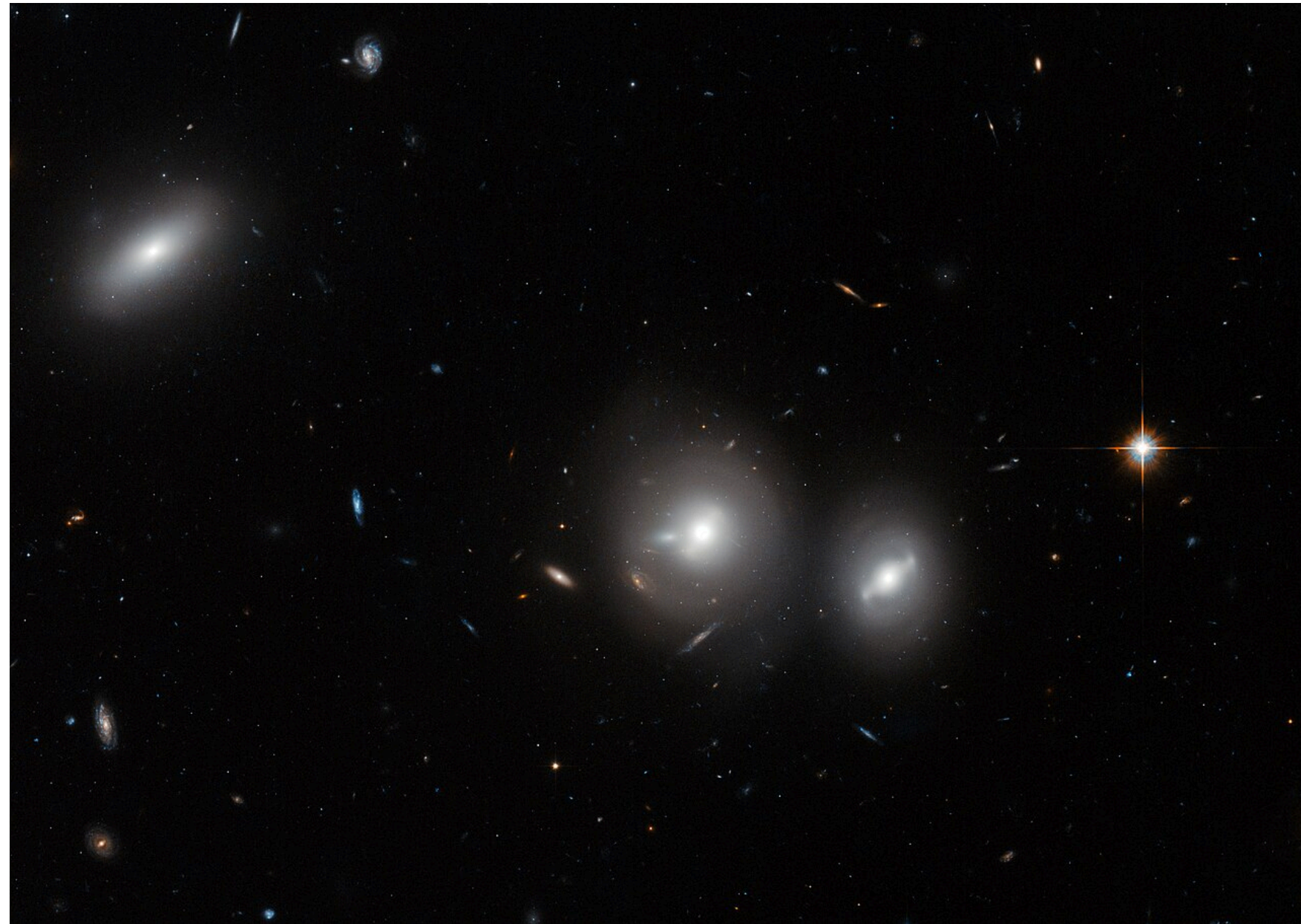
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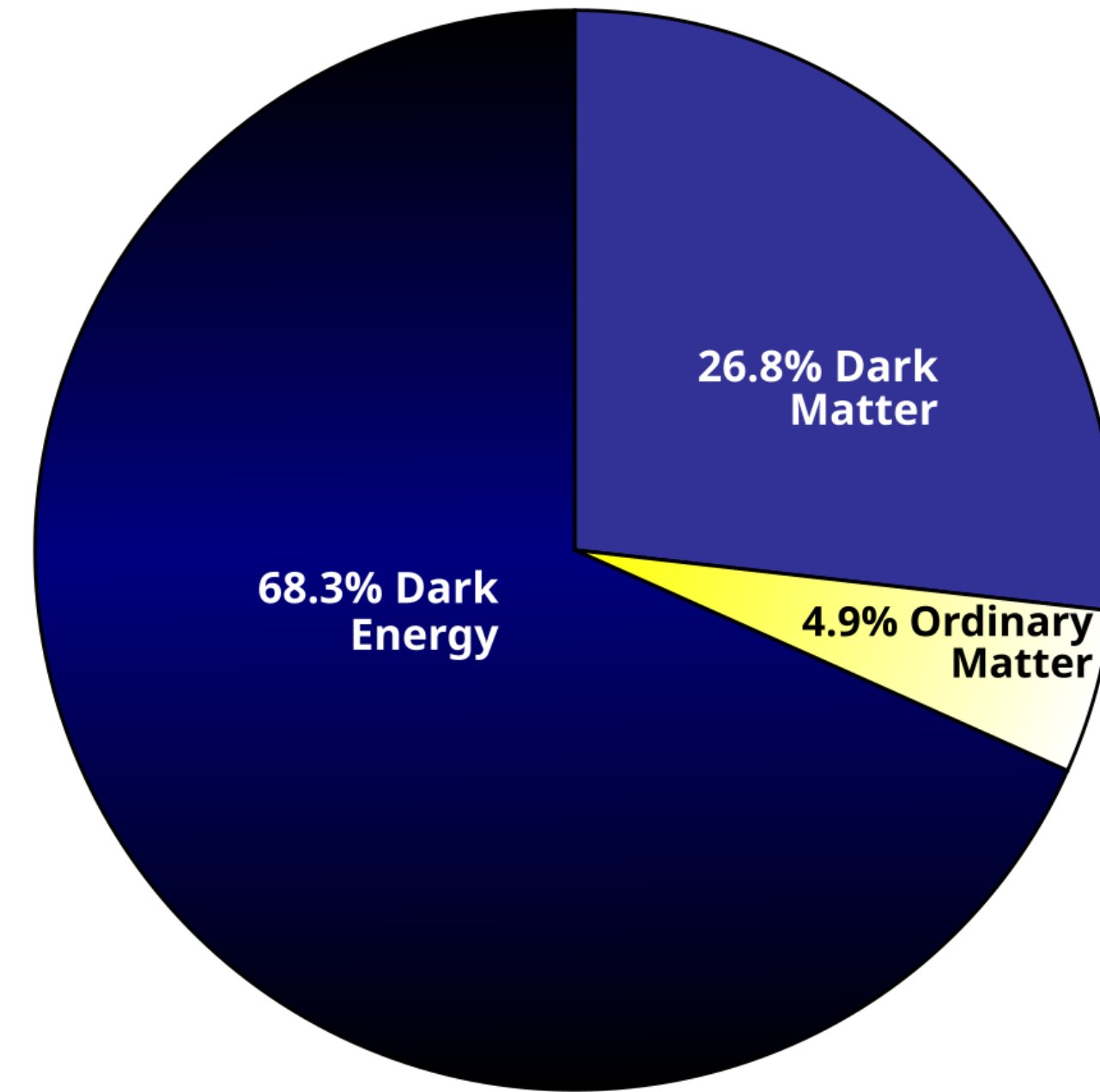
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The problem



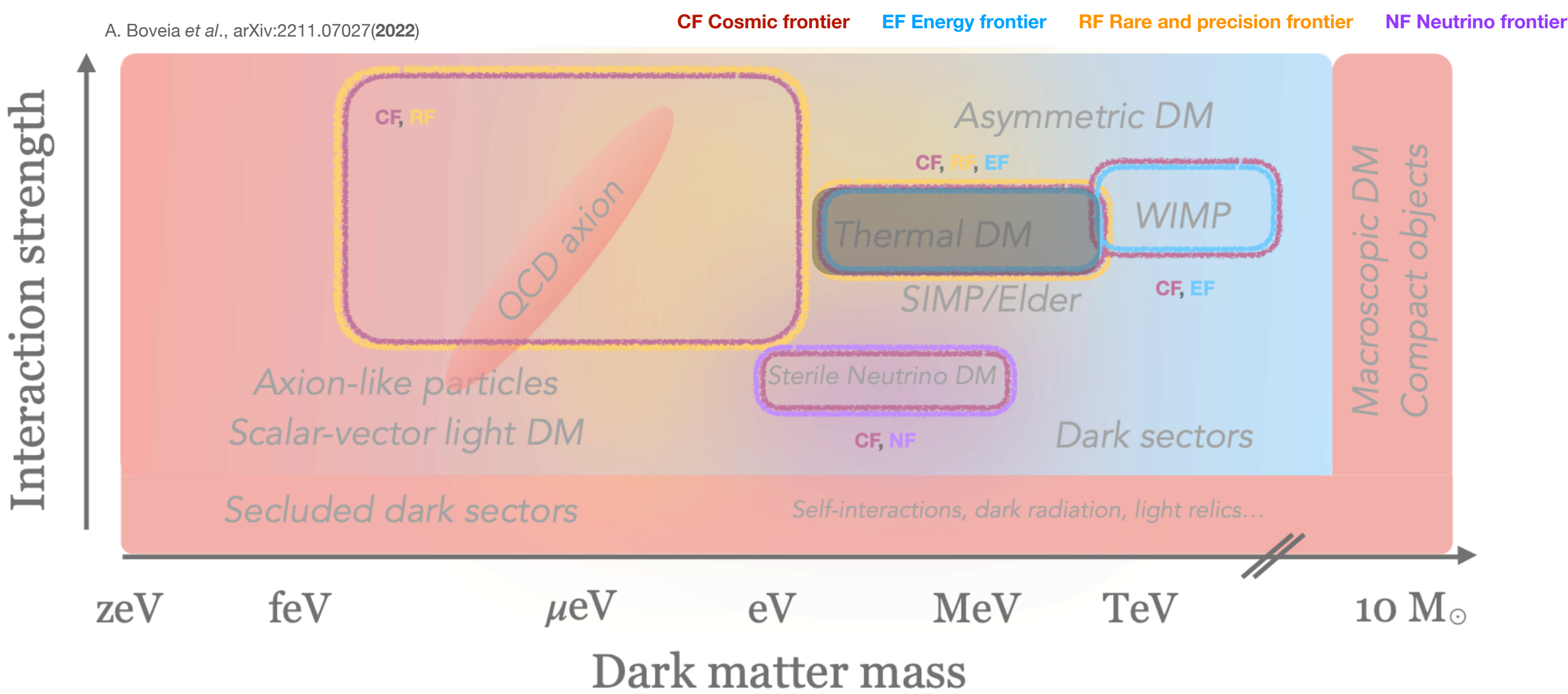
Coma cluster. ESA/Hubble & NASA; D. Carter (LJMU) Acknowledgement: Nick Rose
<https://esahubble.org/images/potw1402a/>



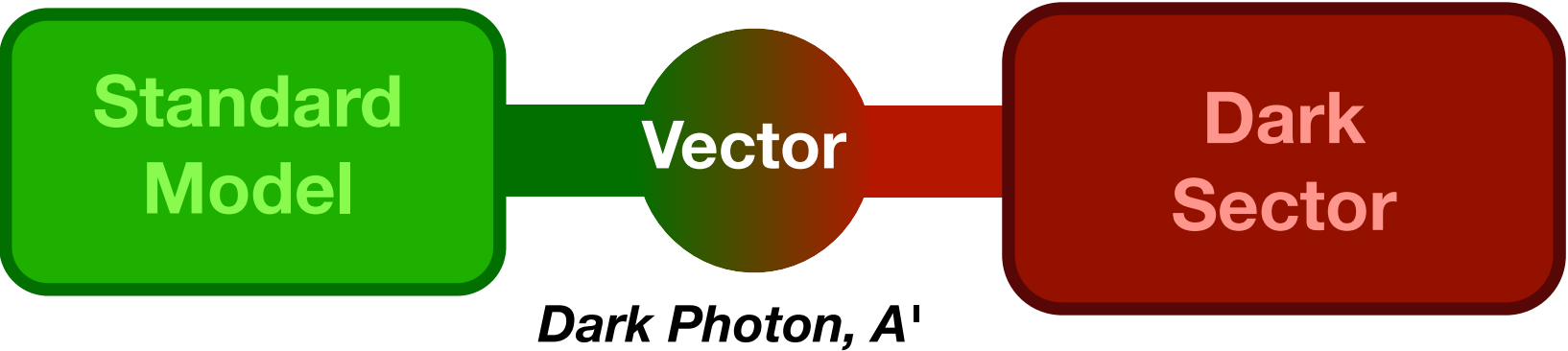
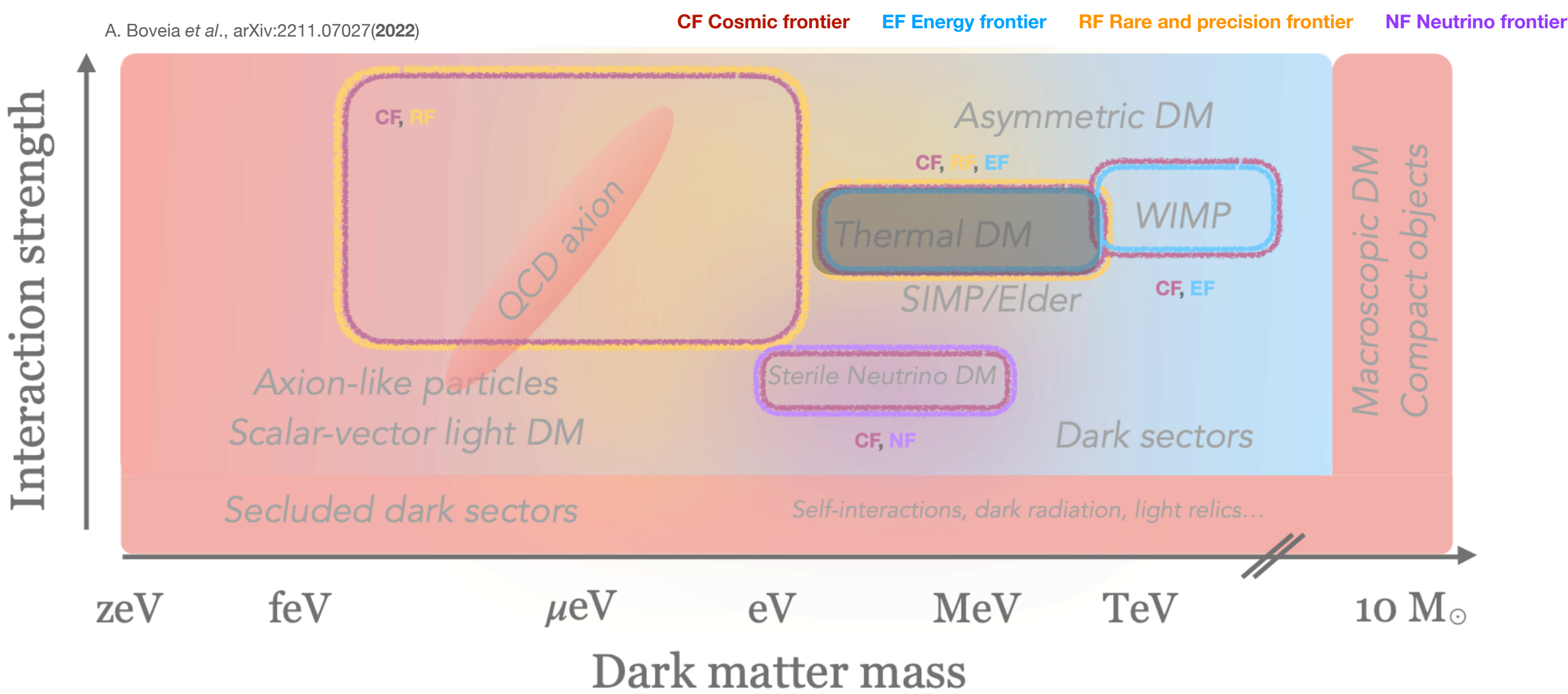
ESA, Planck reveals an almost perfect Universe (2013)
www.esa.int/Our_Activities/Space_Science/Planck/Planck_reveals_an_almost_perfect_Universe

- 1933: Fritz Zwicky estimates the mass of the Coma cluster using the virial theorem and finds a mismatch between movement and brightness —> there is matter that we cannot „see“. He calls it **dark matter** (DM).
- Nearly 100 years later, the existence of dark matter has been confirmed countless times, but we still do not know what it is. All we know is that ordinary matter makes up only ~5% of the known Universe

Physics case: Dark matter (DM) – where we are



Physics case: Dark matter (DM) – where we are



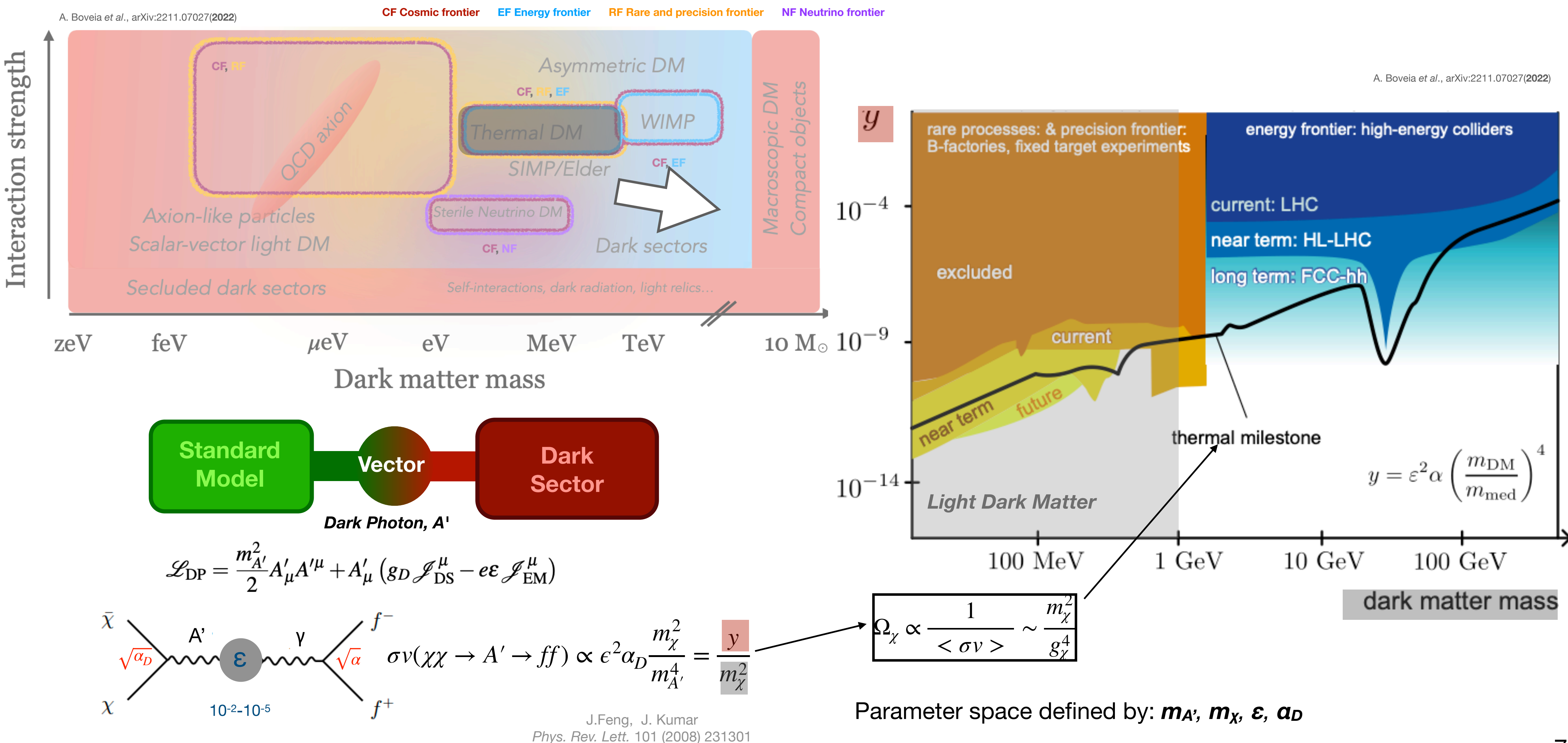
$$\mathcal{L}_{\text{DP}} = \frac{m_{A'}^2}{2} A'_\mu A'^\mu + A'_\mu (g_D \mathcal{J}_{\text{DS}}^\mu - e\epsilon \mathcal{J}_{\text{EM}}^\mu)$$

$\sigma v(\chi\chi \rightarrow A' \rightarrow ff) \propto \epsilon^2 \alpha_D \frac{m_\chi^2}{m_{A'}^4} = \frac{y}{m_\chi^2}$

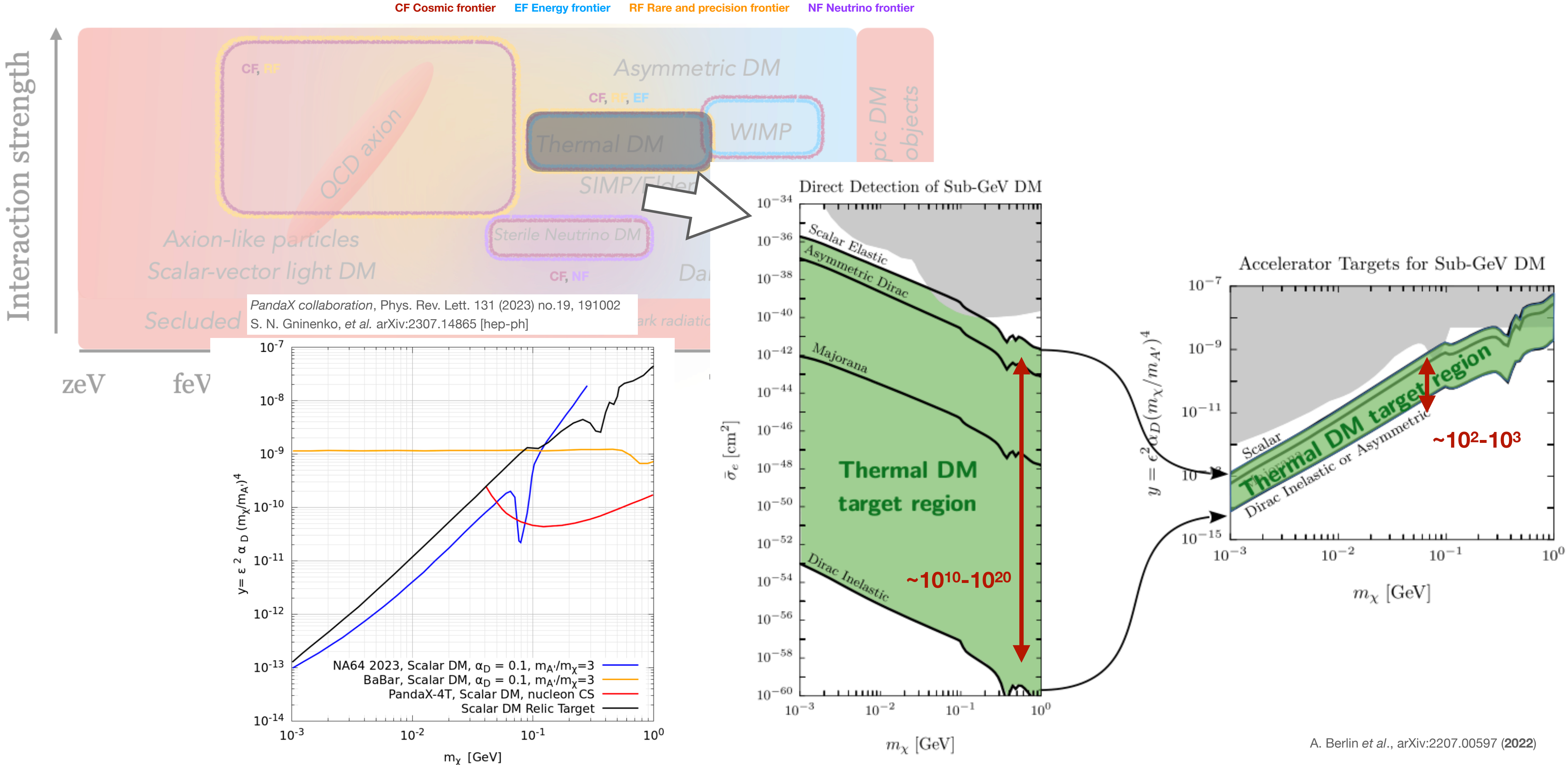
$10^{-2}-10^{-5}$

J.Feng, J. Kumar
Phys. Rev. Lett. 101 (2008) 231301

Physics case: Dark matter (DM) – where we are



Physics target: Light dark matter (LDM) – what and why



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NA64 μ : muon mode

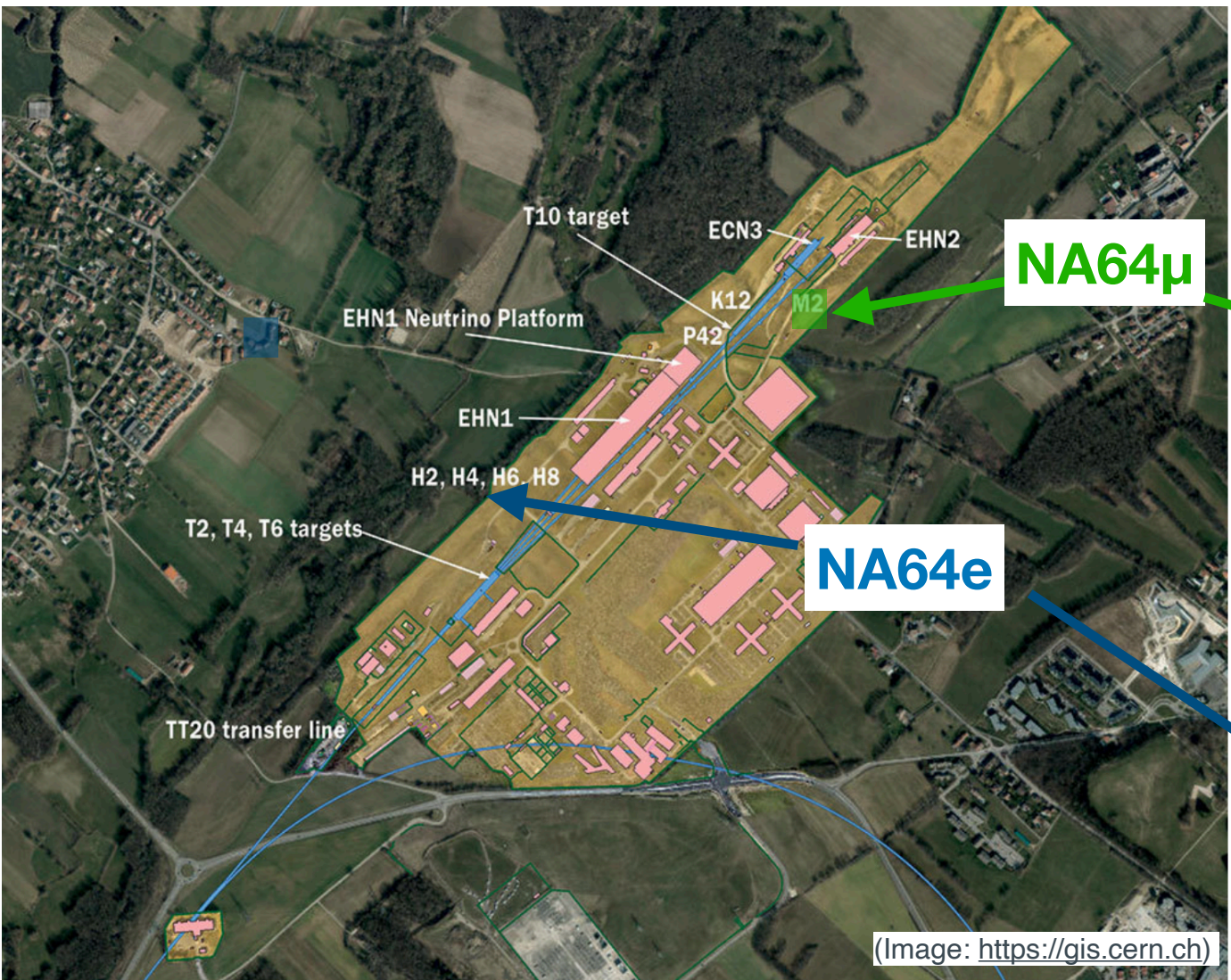
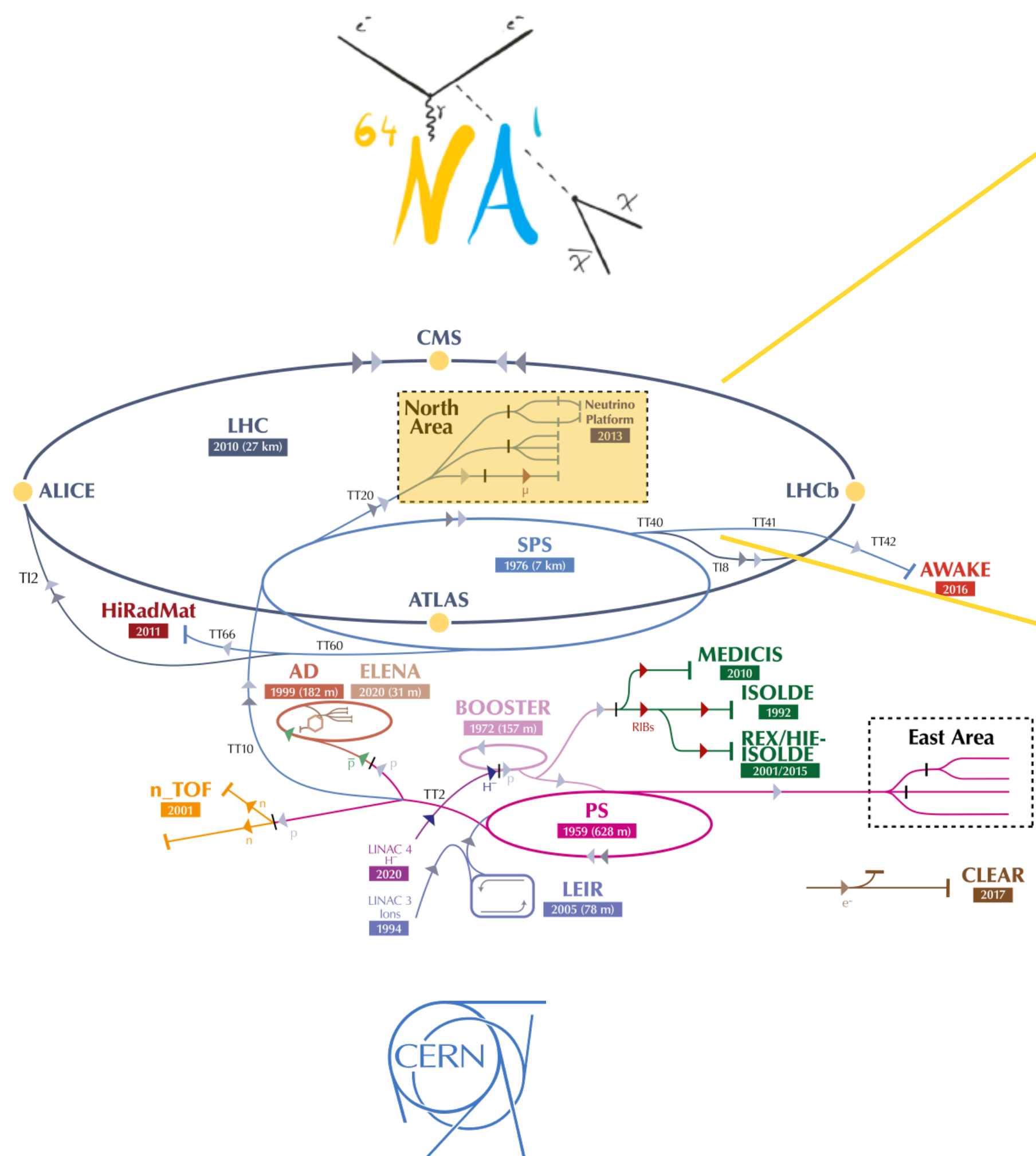
Technique + reconstruction

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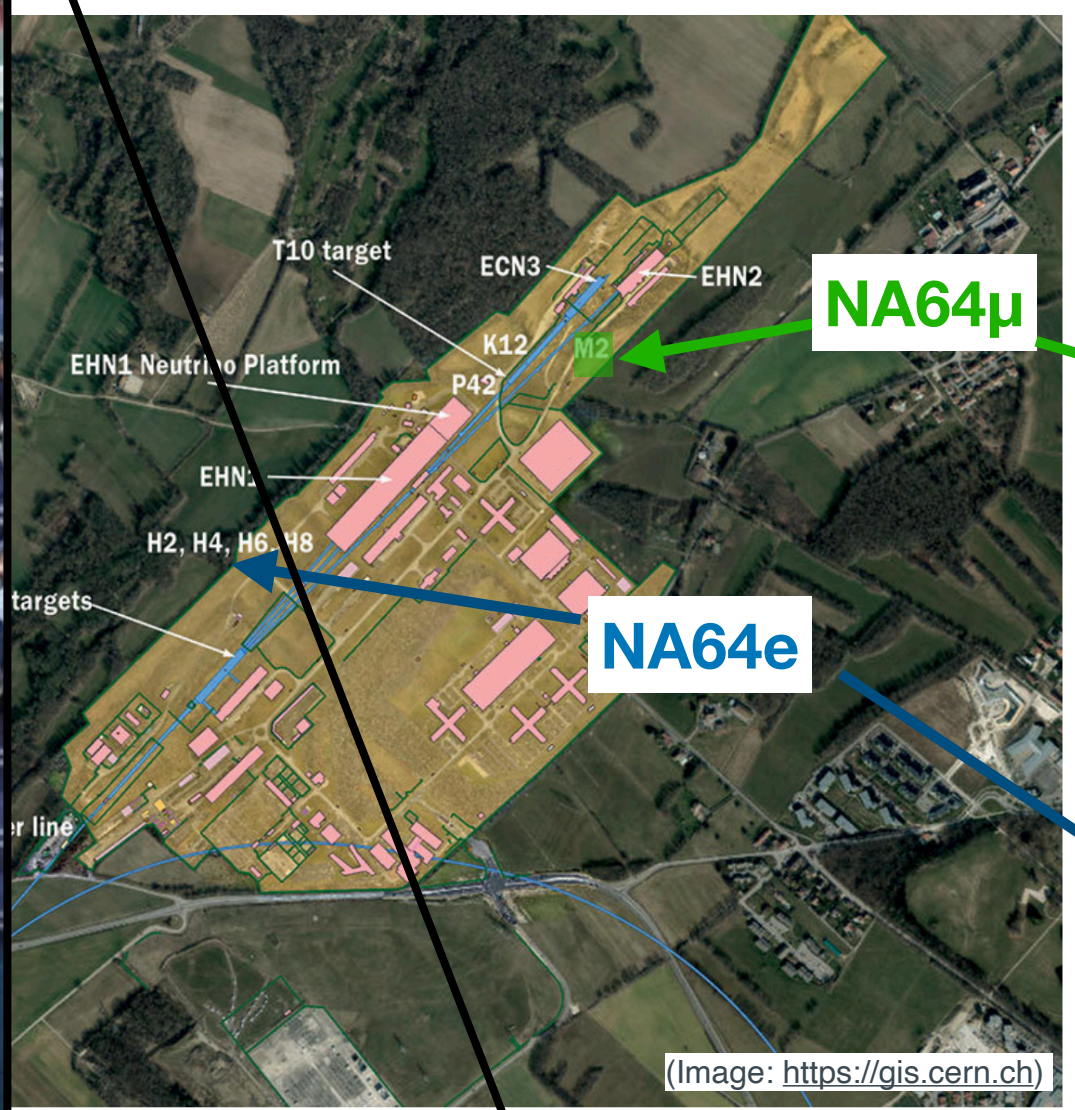
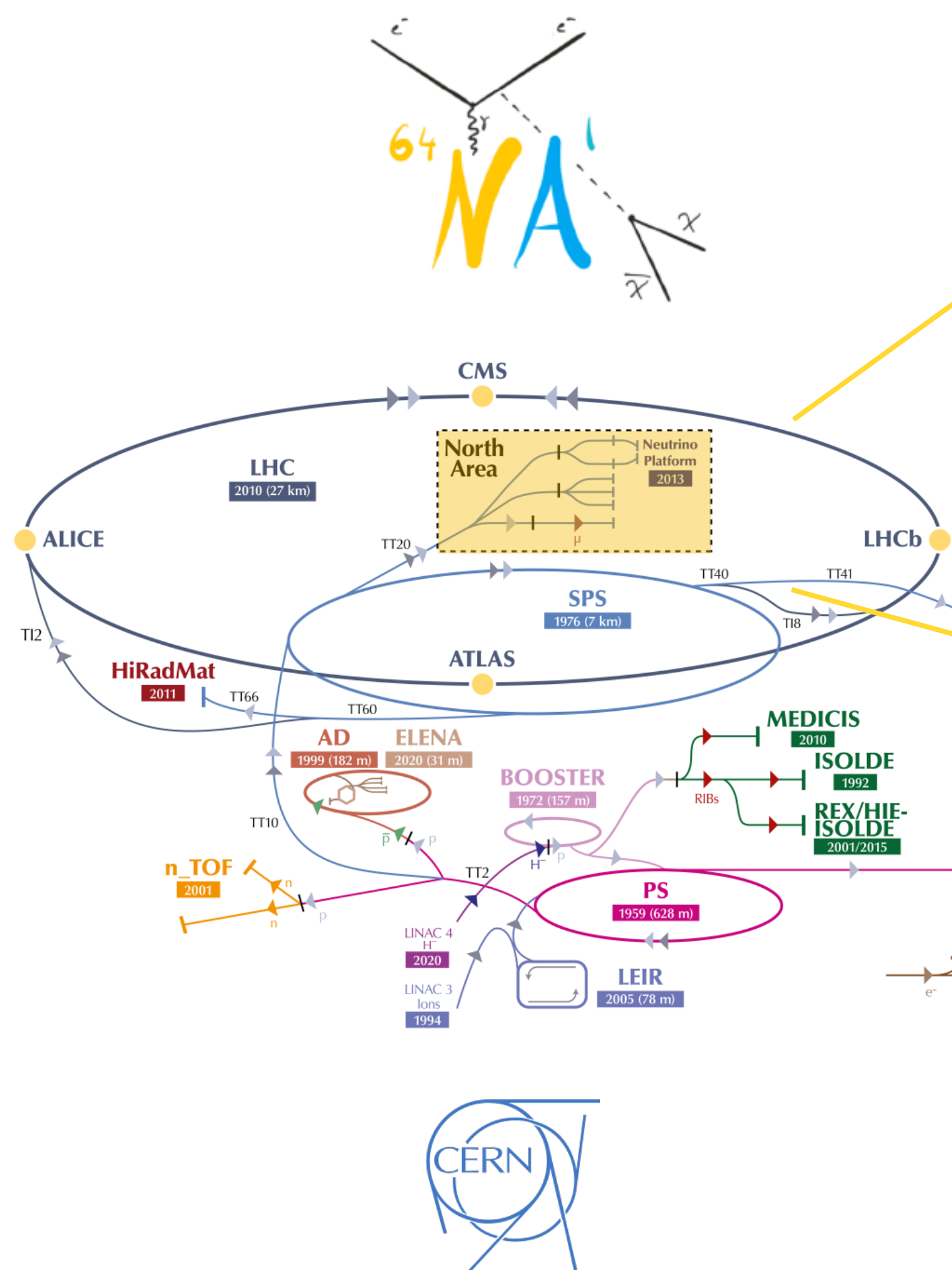
NA64: a fixed-target experiment probing LDM models

Fixed-target experiment devoted to exploit unequivocally Dark Sector physics combining *complementary* and *different* beams from the CERN SPS (e^- , e^+ , μ and hadron)



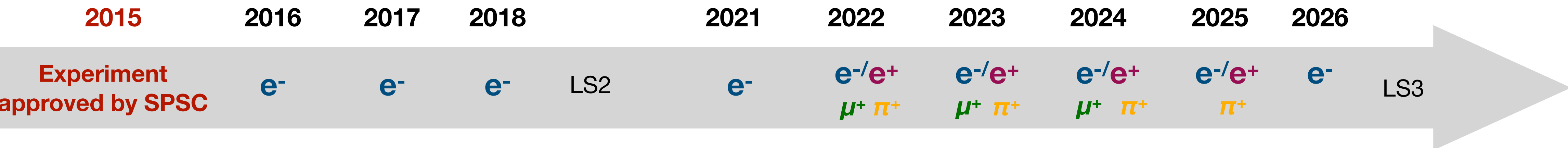
NA64: a fixed-target experiment probing LDM models

Fixed-target experiment devoted to exploit unequivocally Dark Sector physics combining **complementary** and **complementary** CERN SPS (e^- , e^+ , μ and hadron)



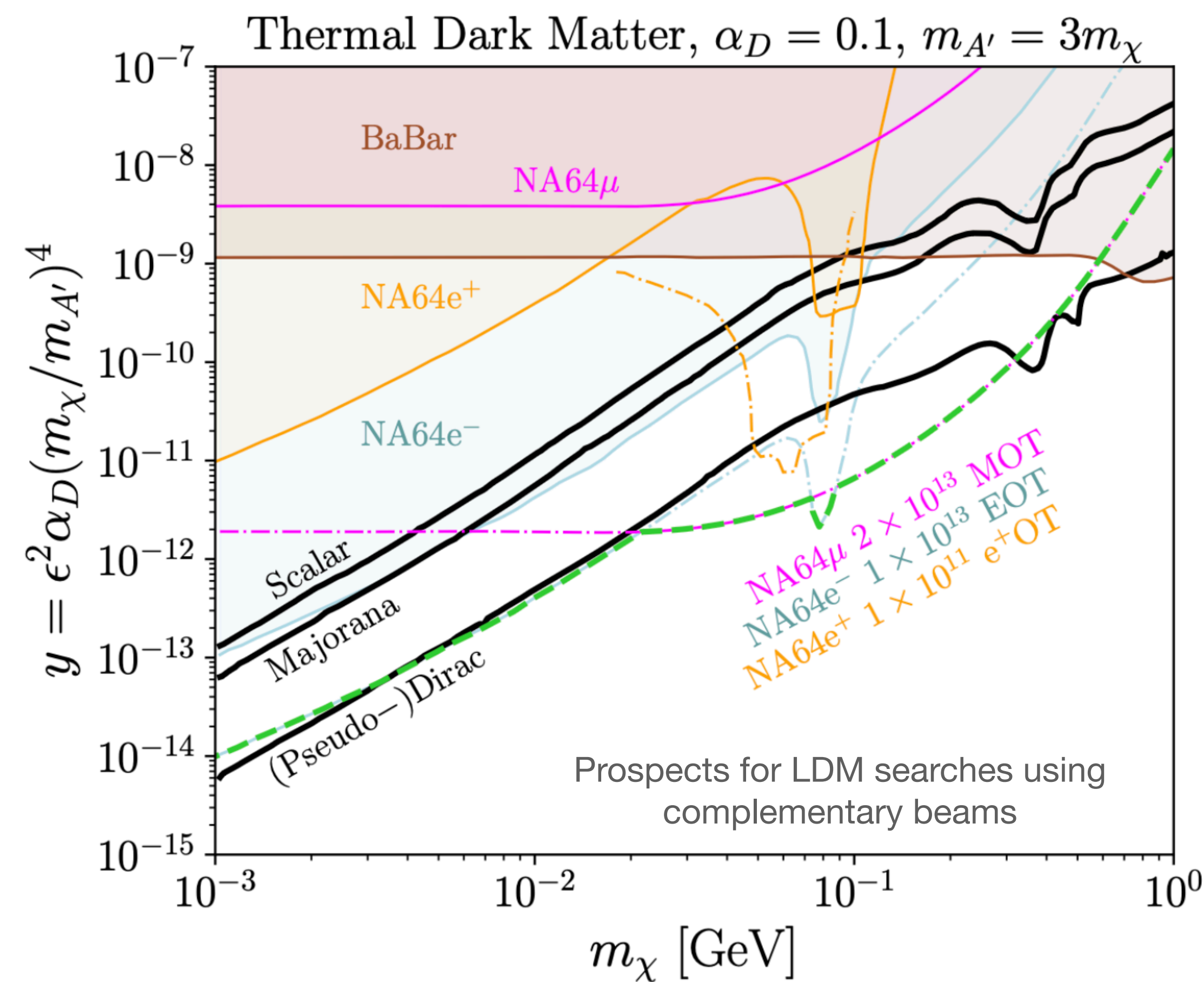
International collaboration: 53 researchers from 9 institutions

The NA64 programme

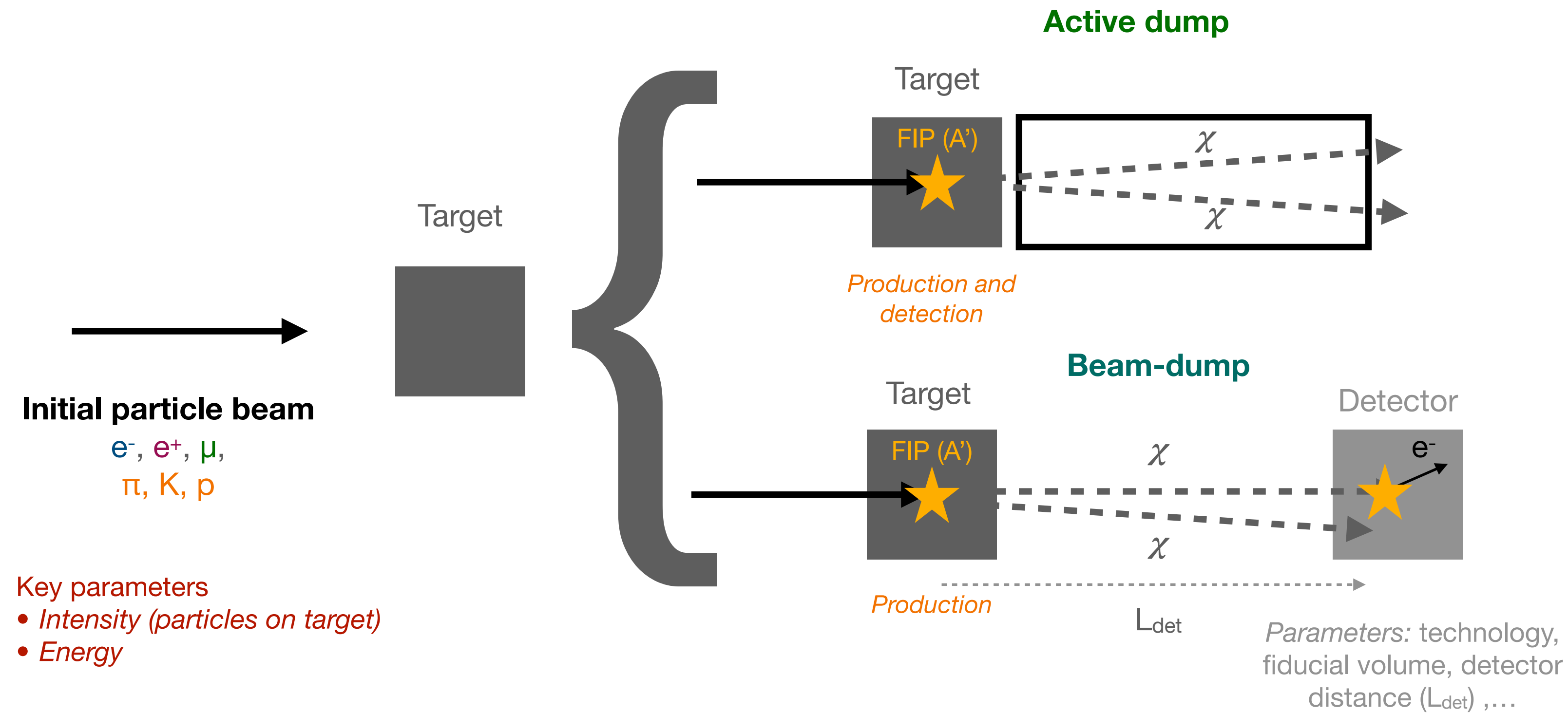


Well-defined beam + Active dump + Fully hermetic detector

- **NA64 e^- , NA64 e^+**
 - Search for vector-mediated (A') LDM, inelastic DM, ALPs, scalar, millicharge...
- **NA64 μ :**
 - Leptophilic DS coupled to μ
 - Phase 1: L_μ - L_τ Z' as a solution to the (g-2) μ anomaly and LDM
 - Phase 2: Complementary A' LDM searches, ALPs, scalar, inelasticDM, millicharge, ...
- **NA64 h :**
 - Use lower energy hadron charge-exchange scattering on heavy target as a source of neutral mesons ($\eta, \eta', \dots$) followed by their invisible decays, or transitions to DS state.



The active dump technique



Example: *Dark Photon A' (applicable for other mediators)*

Experimental signature

Missing energy/momentum

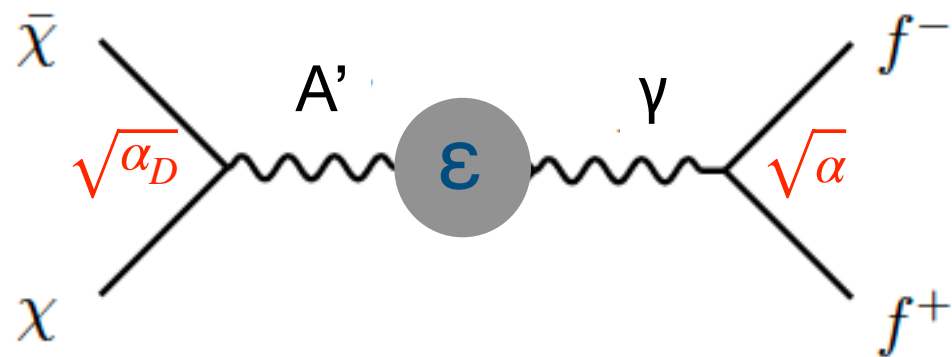
$$N_{A'} \propto \epsilon^2$$

Examples: **NA64**, *DarkSHINE*, *LDMX*, *M3*...

Scattering or decay of the new particle in the detector

$$N_{A'} \propto \epsilon^4 \alpha_D$$

Examples: **MicroBoone**, **SBND**, **T2K**, **ICARUS**, **DUNE**, **HyperK**, **NA62**, **FASER**, **SHIP**, **FPF**,...



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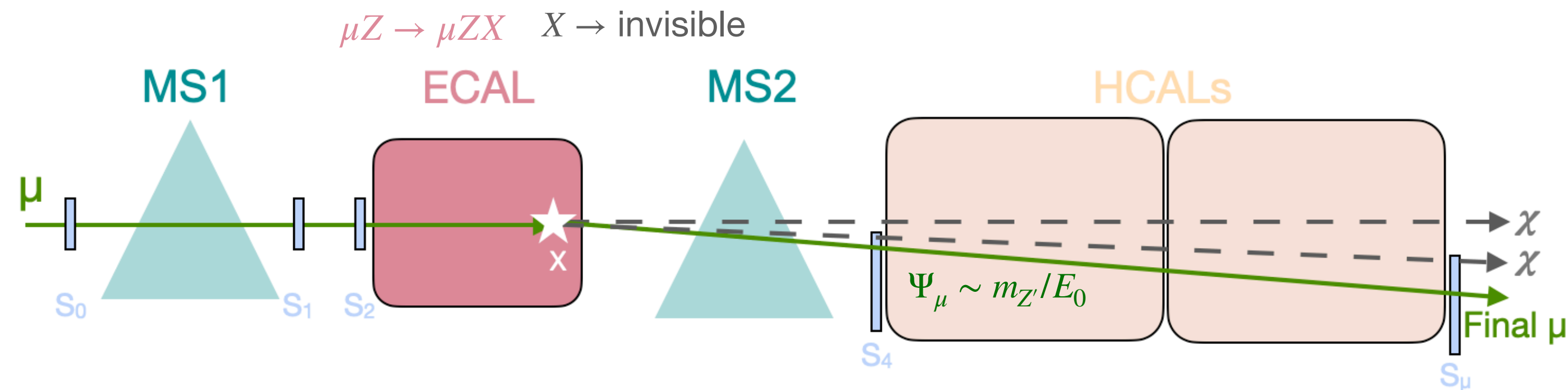
NA64 μ : muon mode

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Focus: NA64μ



1) **M2: unique** high energy (up to 250 GeV) and high intensity (up to 10^7 μ /s) muon beam

2) Measure p_{in} (~ 160 GeV)

3) Full target length contributes to the signal yield, compensating for the suppressed muon bremsstrahlung cross section

4) Measure p_{out} (< 80 GeV)

5) Tag muons and catch secondaries

We search for: **missing energy** + **missing momentum**

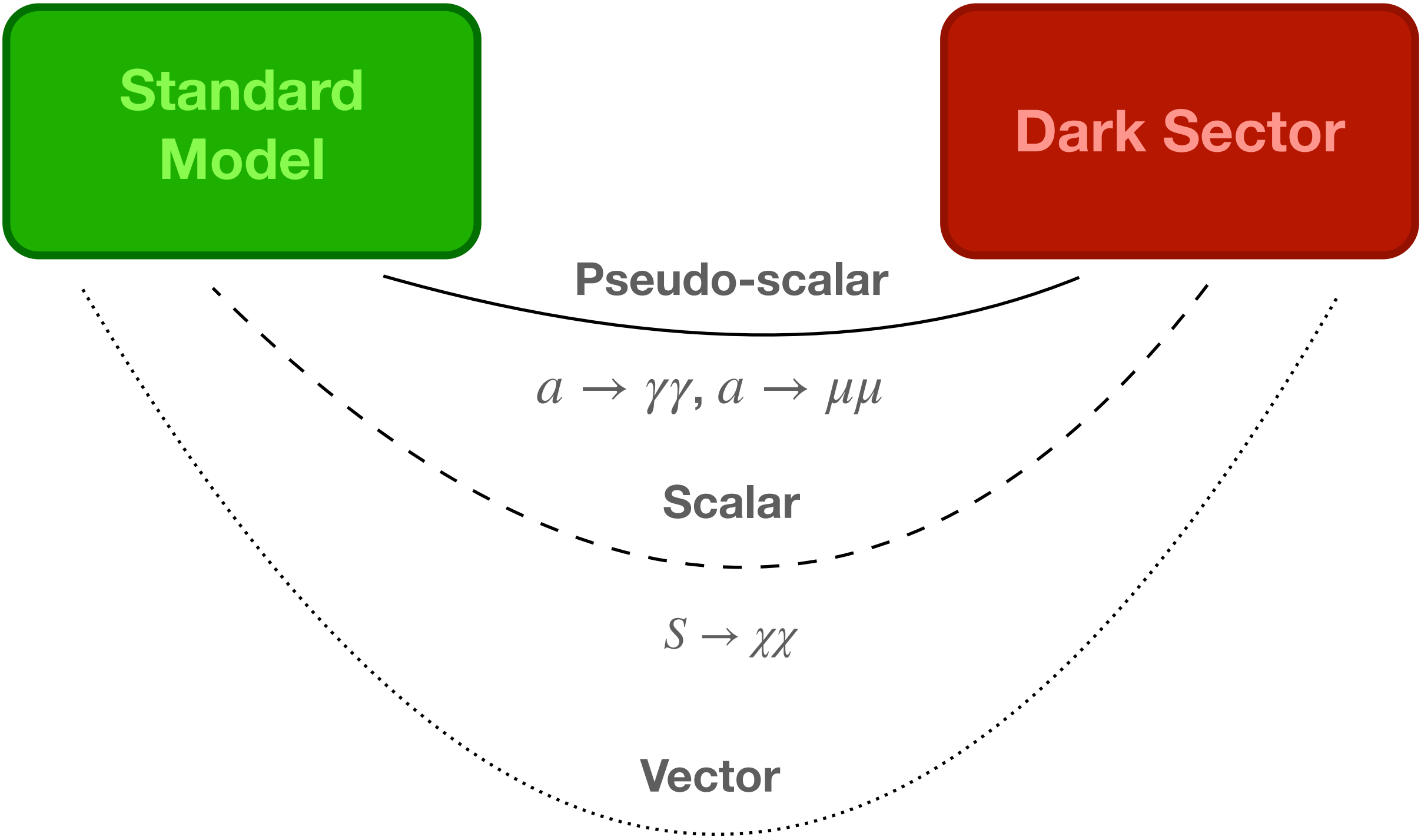
$\sigma \sim g'^2 Z^2 \alpha^2 / m^2$

$X = A', Z', \dots$

Generic boson X



What can NA64μ probe?

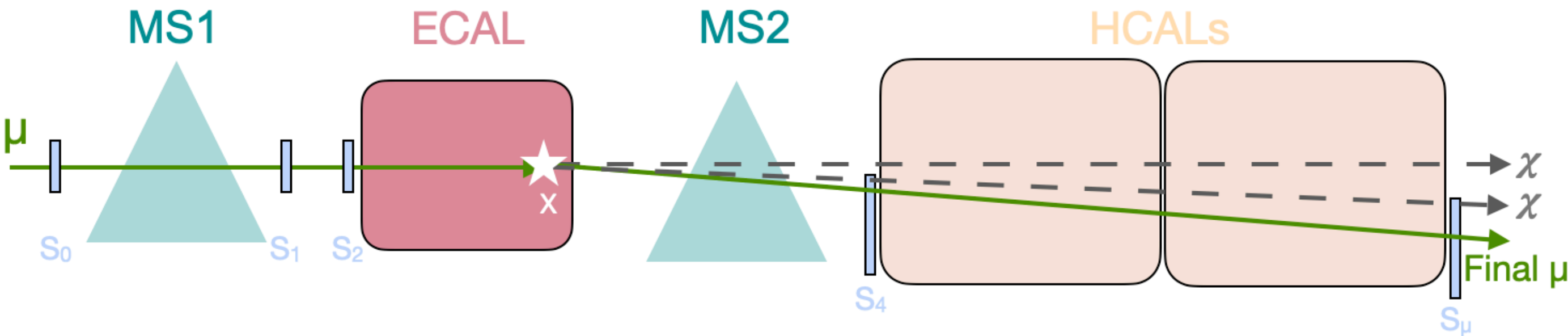


$$A' \rightarrow \chi\chi, A' \rightarrow \chi_1\chi_2, Z'_{L_\mu-L_\tau} \rightarrow \chi\chi$$

And many more...

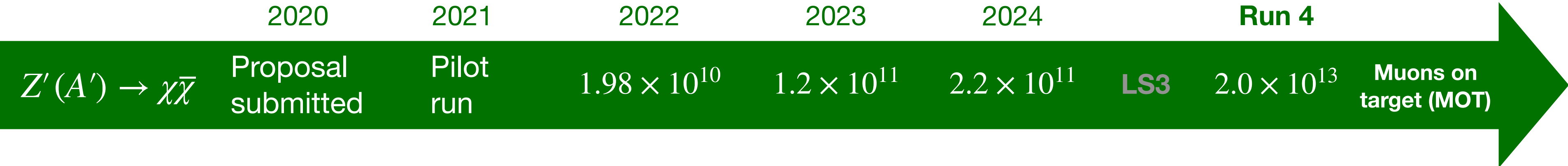
Key Aspects:

- *Beam intensity*
- *Reconstruction of initial/final muon momenta*
- *Hadron contamination*
- *Hermeticity (energy conservation)*

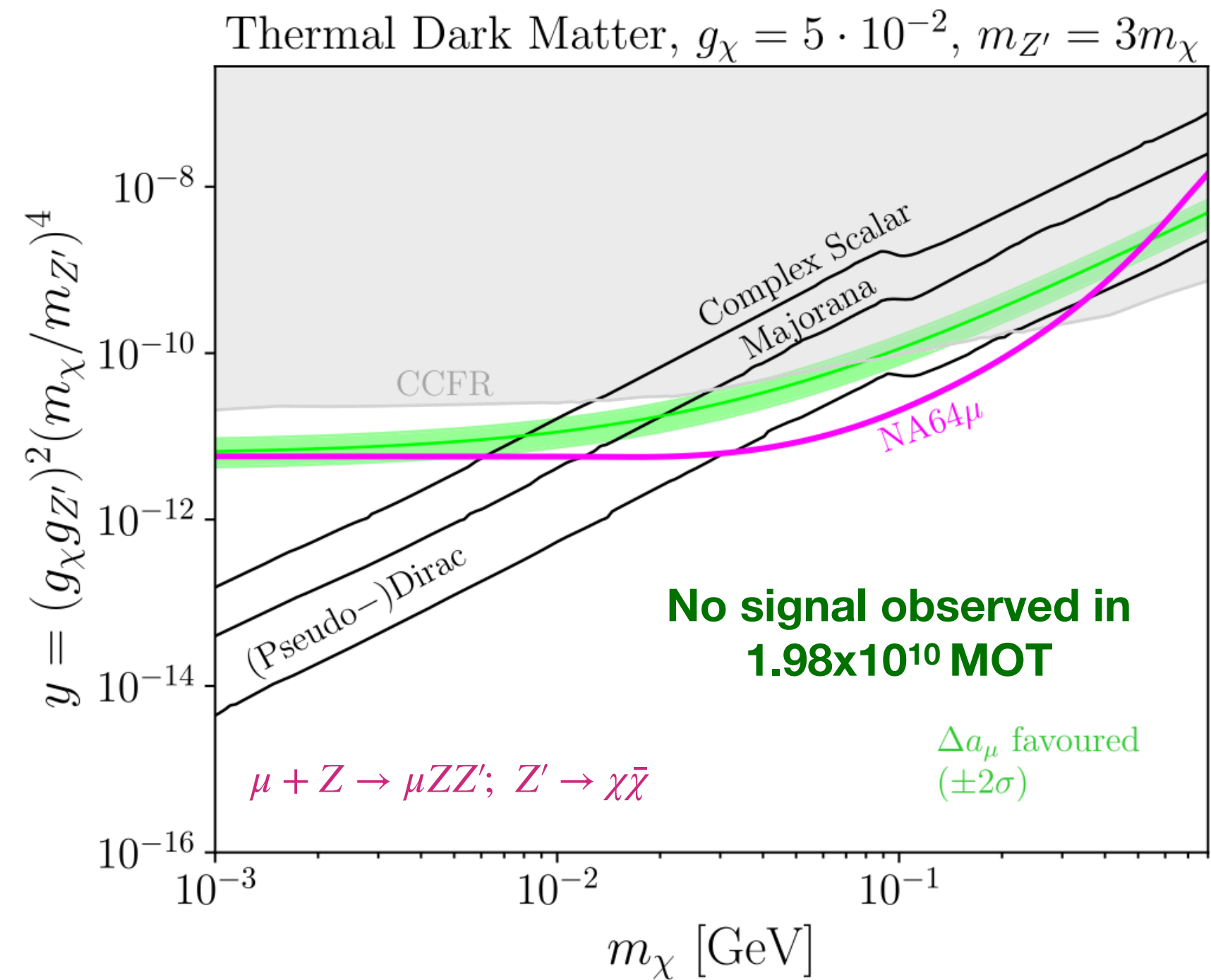


S.Gninenko et al. PLB796, 117 (2019)
D. Banerjee et al. [NA64 Collaboration]. CERN-SPSC-2019-002 / SPSC-P-359, January 14, 2019.

NA64μ results so far and what we learned



Strategy: two analyses of the 2023 and 2024 datasets



Featured in Physics

Open Access

First Results in the Search for Dark Sectors at NA64 with the CERN SPS High Energy Muon Beam

Yu. M. Andreev *et al.*

Phys. Rev. Lett. **132**, 211803 – Published 21 May 2024

PhysiCS

See synopsis: [Careful Accounting Could Reveal the Dark Sector](#)

Background source	Background, n_{bkg}
(i) Single-hadron punch-through	$\ll 0.01$
(ii) Dimuon production	$\ll 0.01$
(iii) Detector nonhermeticity	< 0.01
(iv) Hadron in-flight decays	0.010 ± 0.001
(v) Momentum misreconstruction	0.045 ± 0.039
Total (conservatively) n_{bkg}	0.07 ± 0.04

NA64 collaboration, *Phys. Rev. Lett.* 132 (2024) 211803

NA64 collaboration, *Phys. Rev. D* **110** (2024) 112015

—> **Goal in 2023/2024:** optimise the setup to further suppress background and increase intensity

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NA64 μ : muon mode

Technique + reconstruction

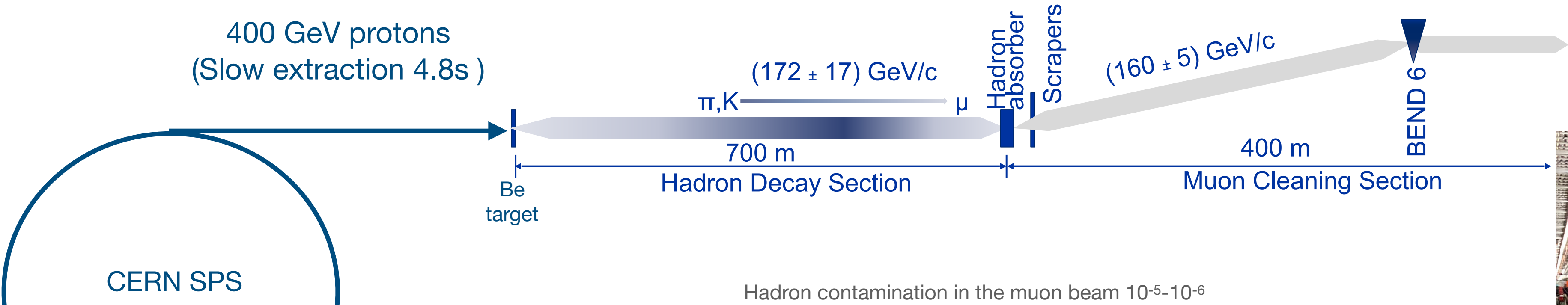
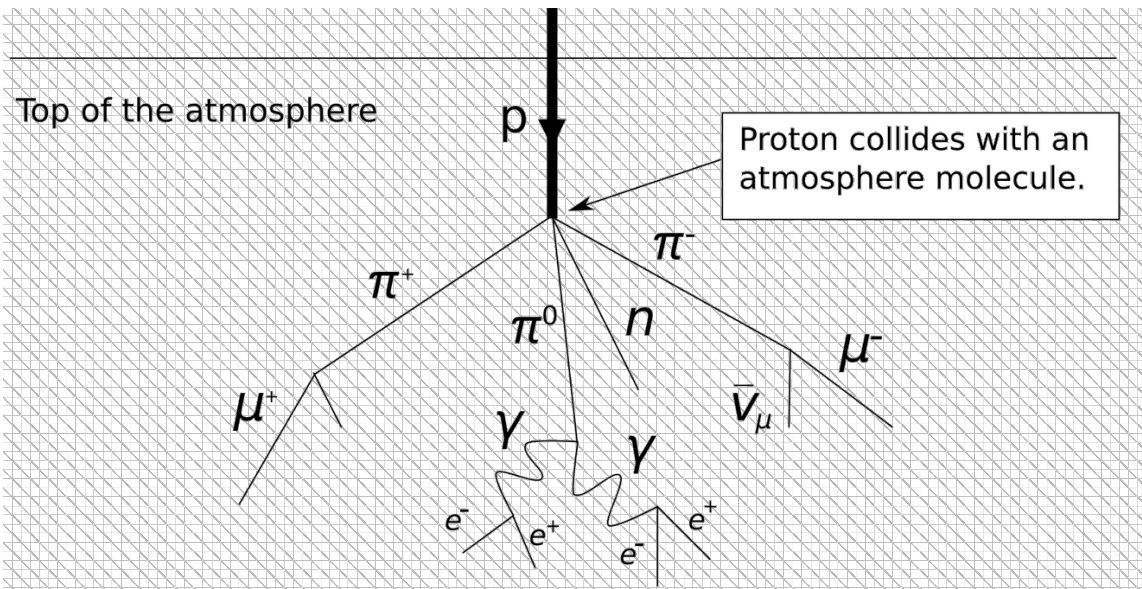
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Key aspects: High-intensity muon beam

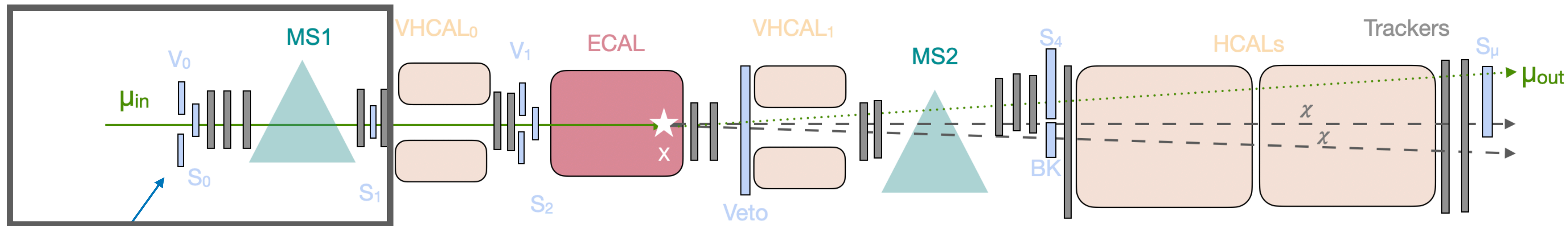
Generation of secondary beams

Principle inspired by cosmic-rays interactions: **Protons from the SPS accelerator hit a beryllium (Be) target, producing a shower of secondary particles**

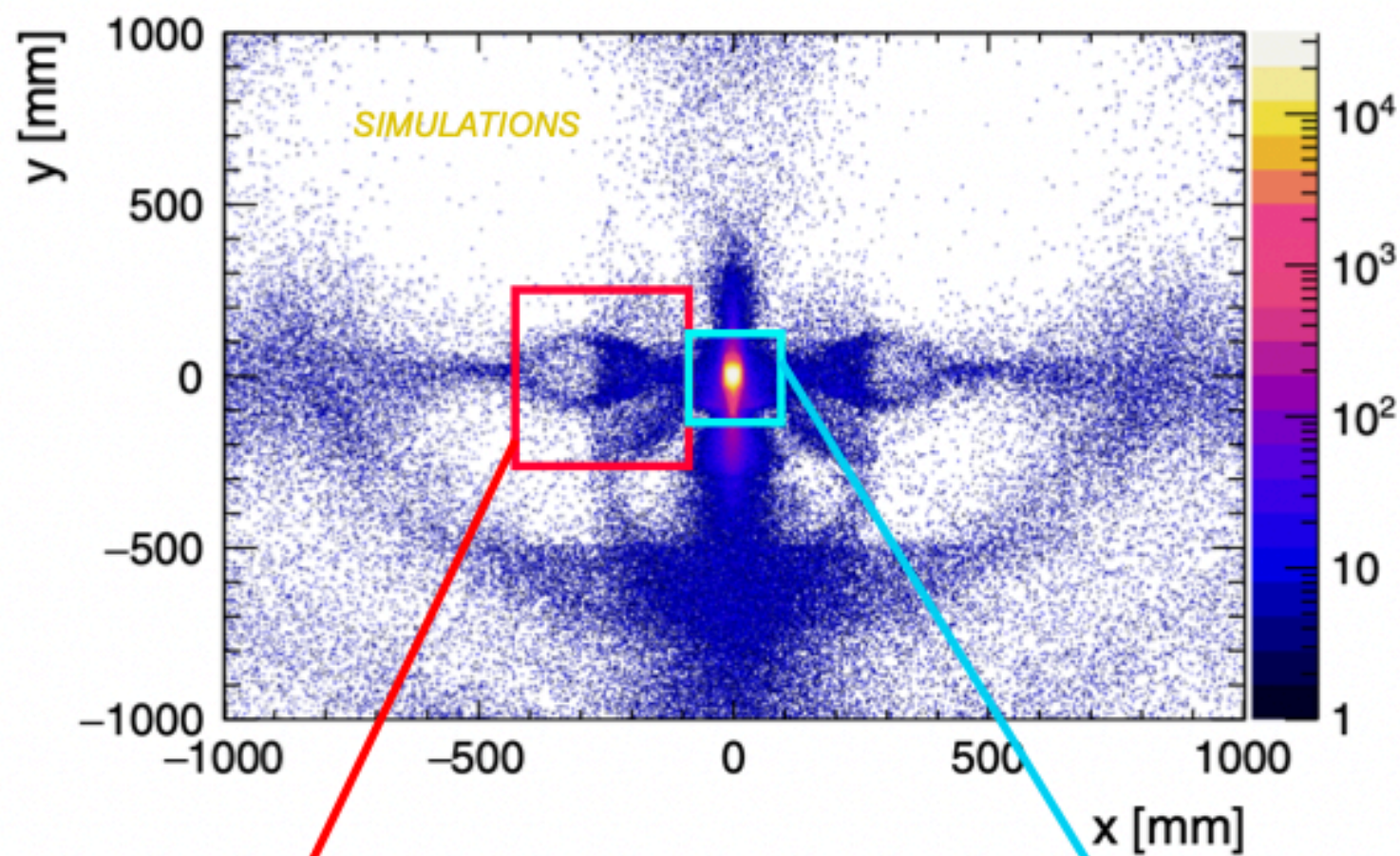


Adapted from D. Banerjee “The future of muon beams at CERN”, Muon4Future2025

Key aspects: Incoming momentum reconstruction

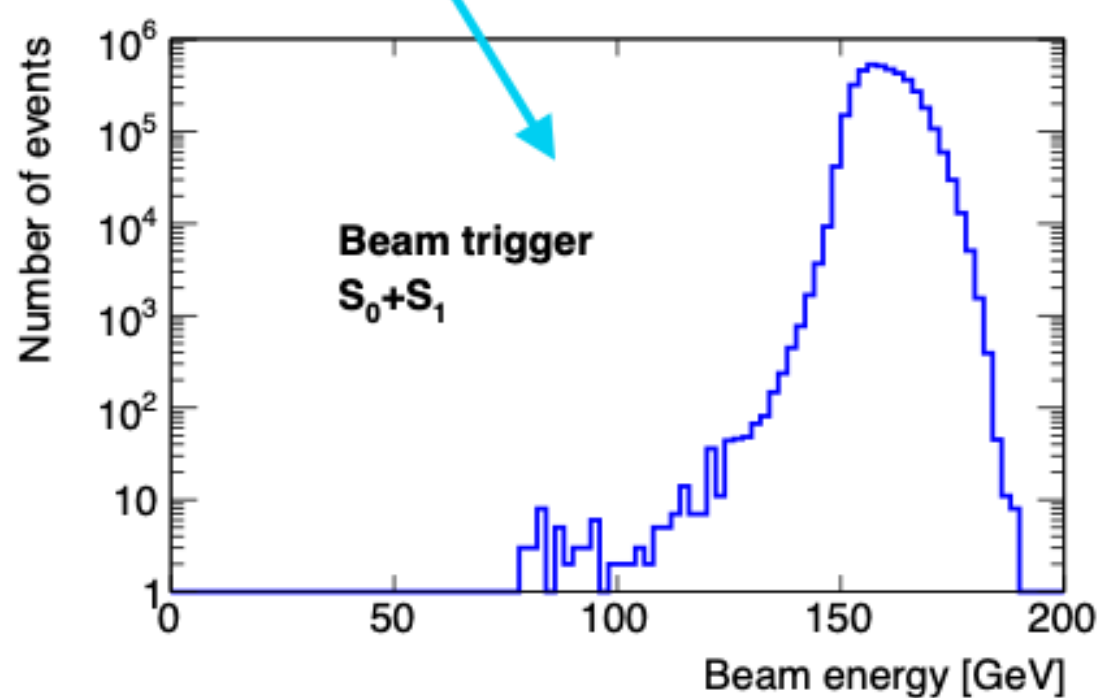
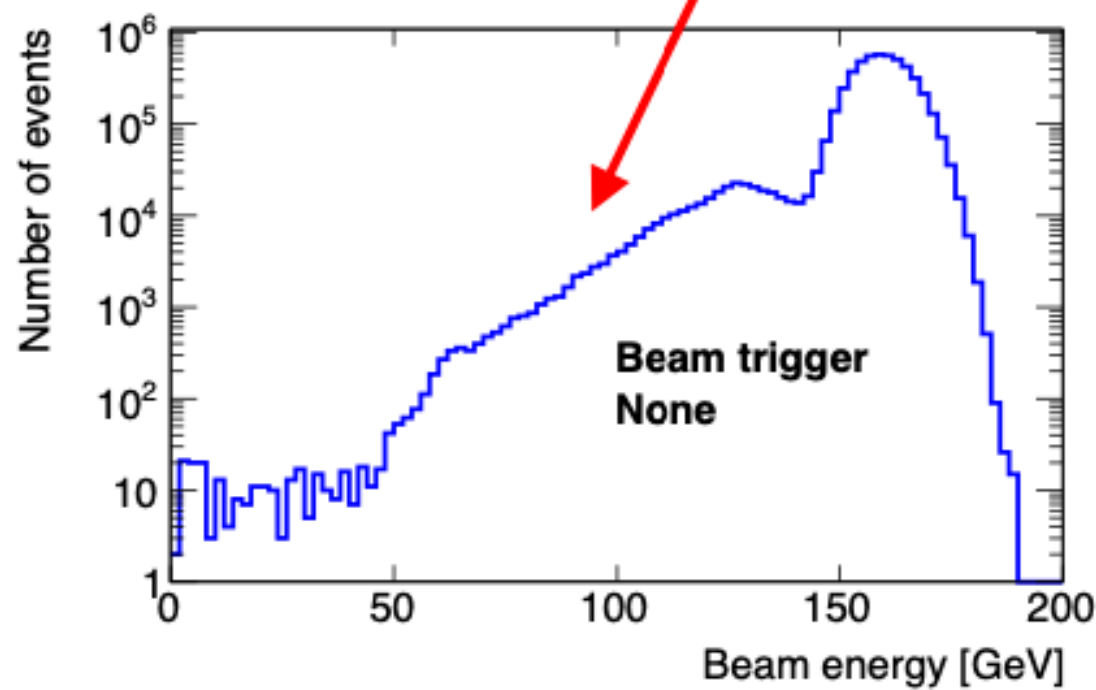
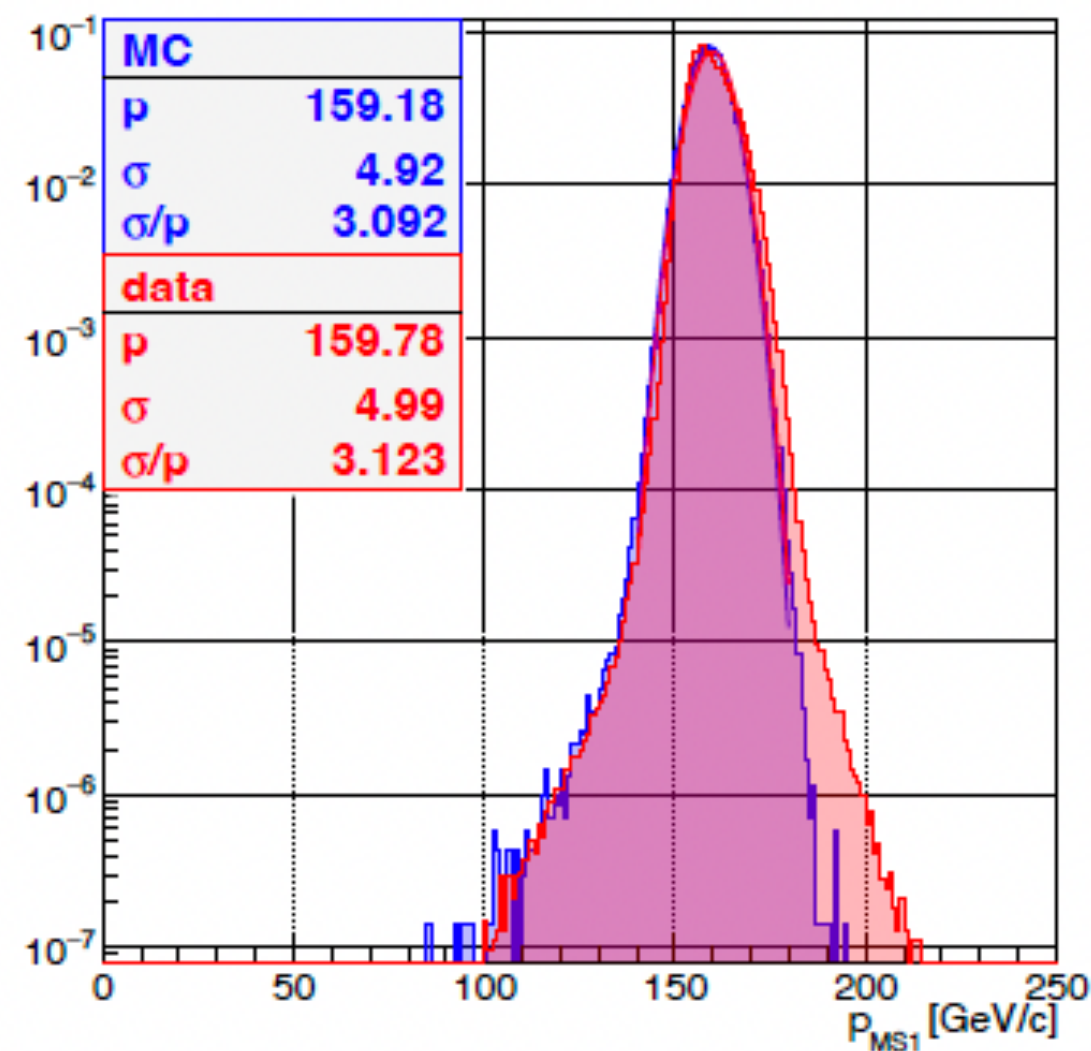


Scintillator-based trigger coincidence to select the core of the incoming beam

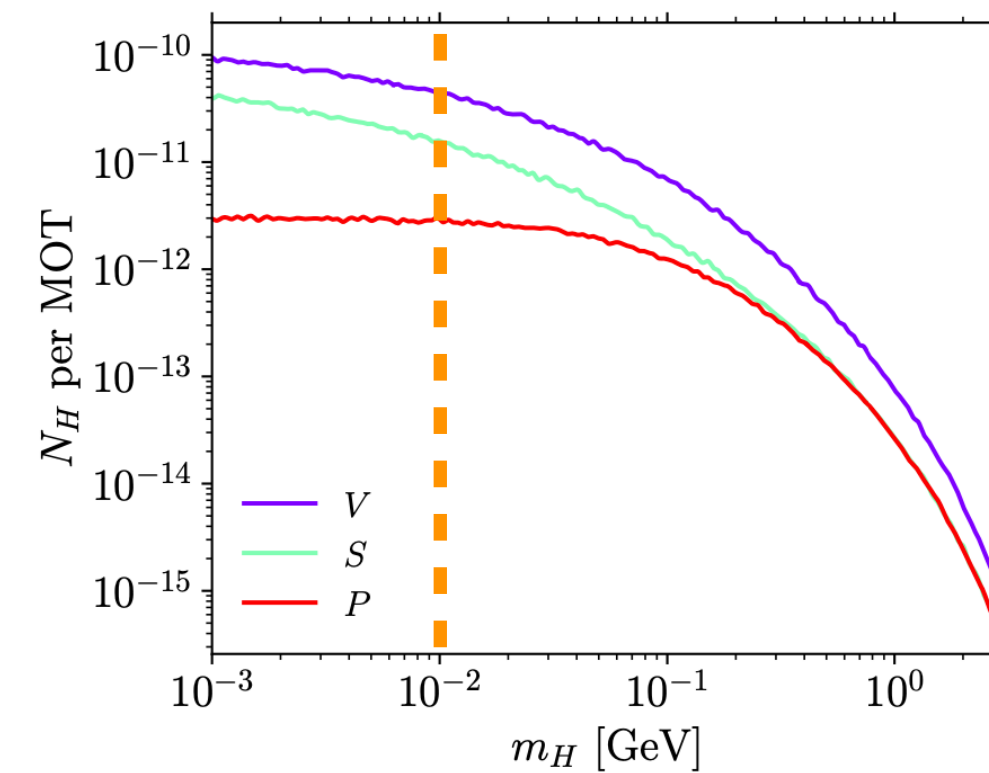
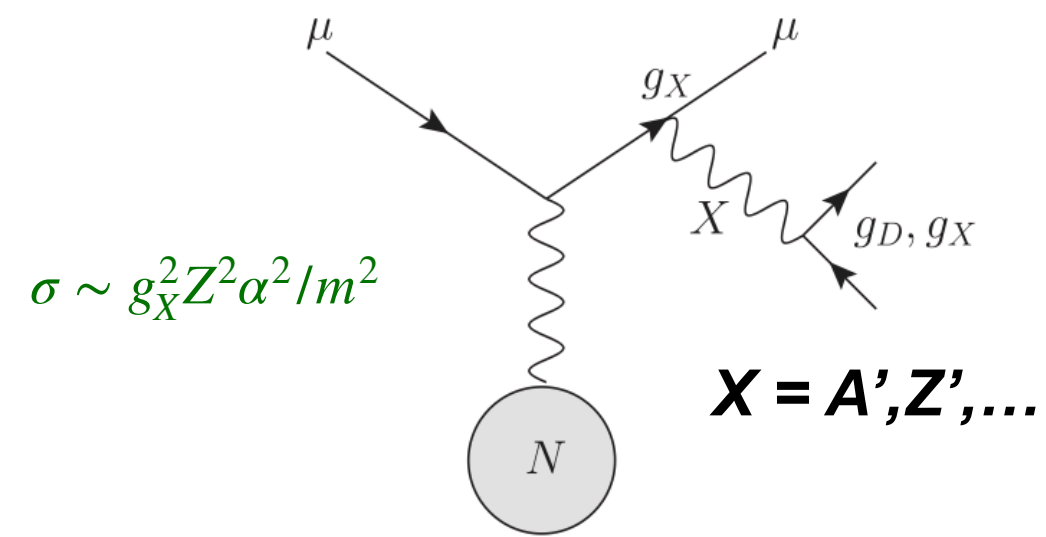
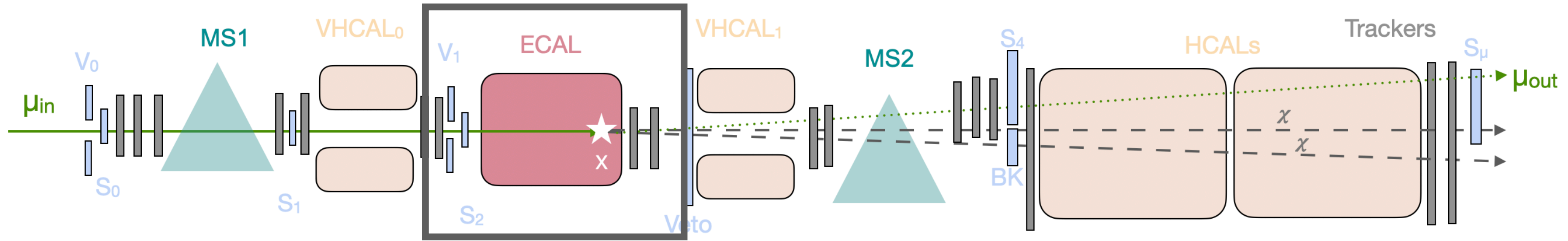


+

Magnet spectrometer at the beginning of the setup ($MS1$) to measure the initial muon momentum



Realistic Beam simulation developed in collaboration with CERN BE-EA department



Mediator between SM and DM produced via a **Bremsstrahlung-like** process.

The particle yield, $N_X \propto \frac{\rho N_{av}}{A} L_\mu \sigma_X^\mu$, ($L_\mu \sim 40X_0$ (whole calorimeter) while in the case of an initial electron is $\sim X_0$)

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

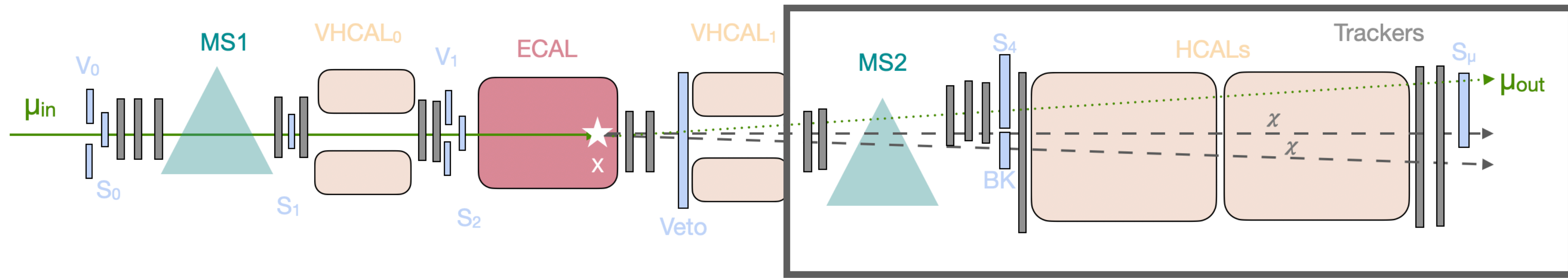
D.V. Kirpichnikov et al. Phys. Rev. D 104 (2021) no.7, 076012.

H. Sieber *et al.*, Phys. Rev. D 105 (2022) no.5, 052006

H. Sieber et al., Phys. Rev. D 108 (2023) no.5, 056018.

DMG4 [B.Banto Oberhauser et al. Comput. Phys. Commun. 300 (2024), 109199].

Key aspects: Tagging and measuring scattered muons



Beam trigger (BT): $S_0 \times \bar{V}_0 \times S_1 \times S_2 \times S_3 \times \bar{V}_1$

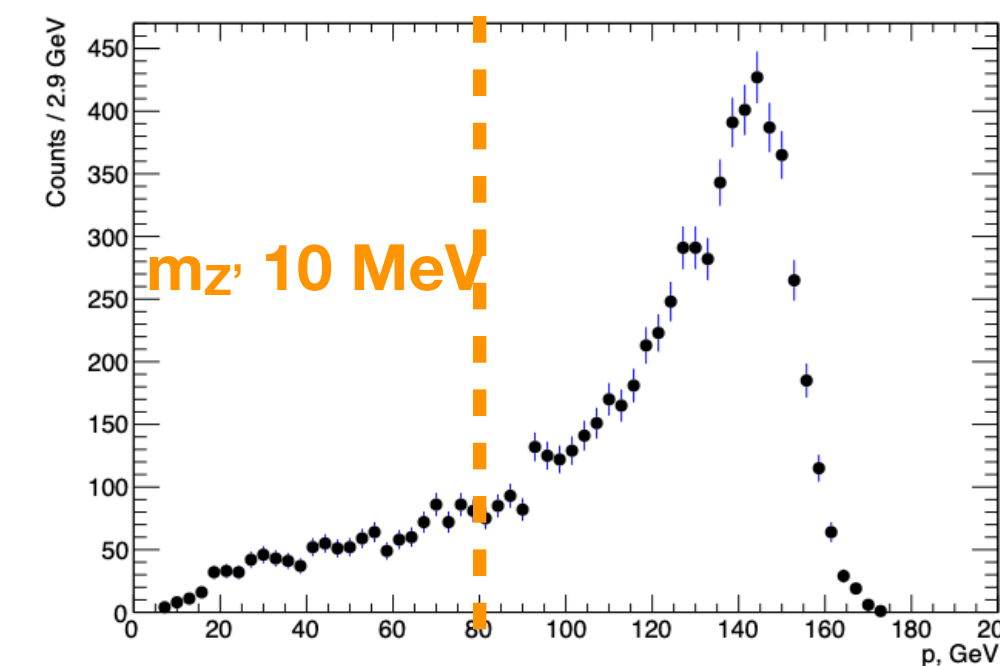
Physics: $BT \times S_4 \times \bar{BK} \times S_\mu$

Signal: Final state muon with

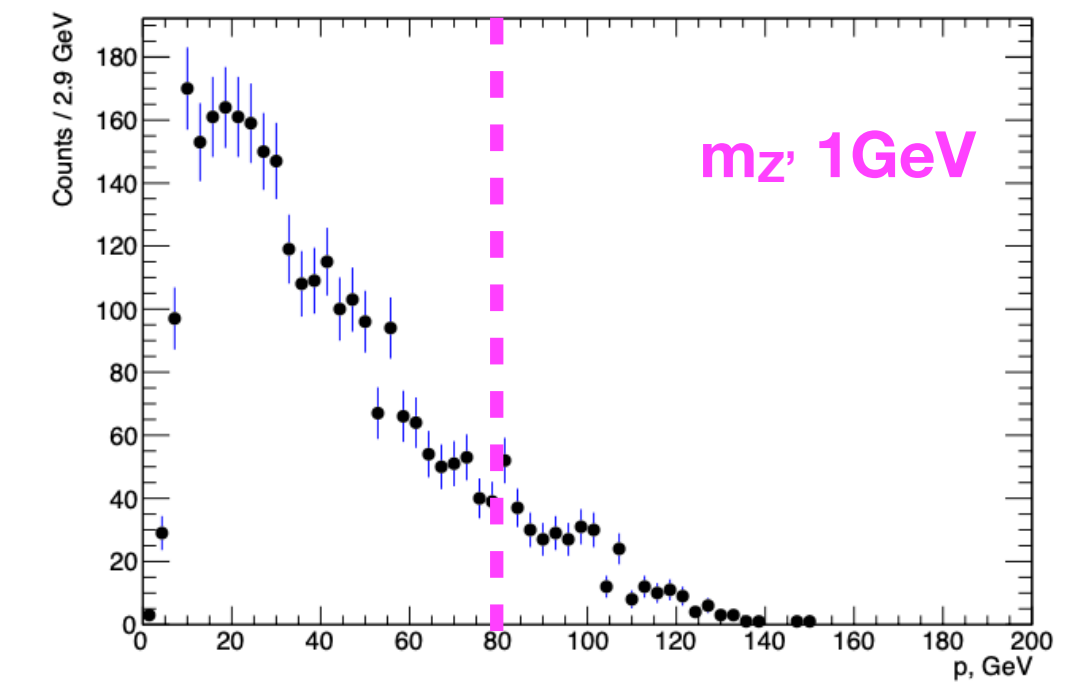
- **MIP compatible deposit** in all calorimeters and $p_{\text{out}} < 80 \text{ GeV}/c$
—> **compromise** between high **cross section** at low masses and better **trigger efficiency** at higher masses.
- **Trigger system** optimised for **deflection**.
—> Simple design for the demonstration of the detection of the scattered muon.

Trigger efficiency

Low-mass range



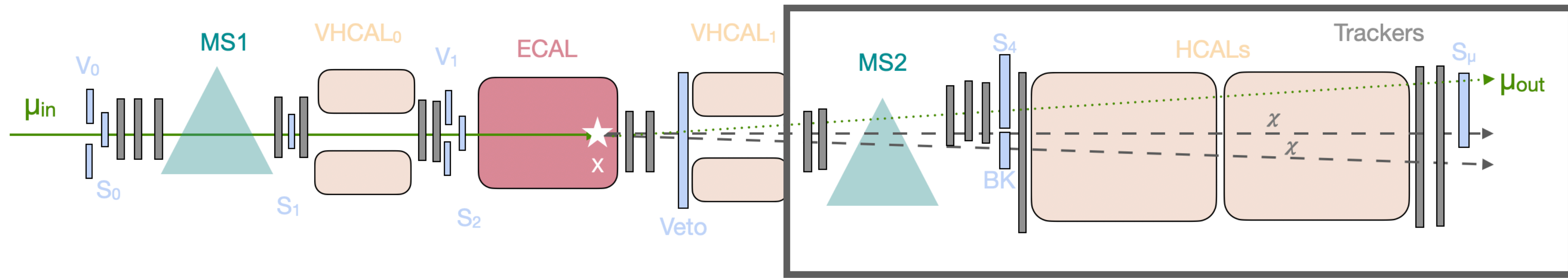
High-mass range



H. Sieber et. al. Phys. Rev. D **108** (2023) no.5 056018

H. Sieber et al. Phys. Rev. D **105** (2022) no.5 052006

Key aspects: Tagging and measuring scattered muons



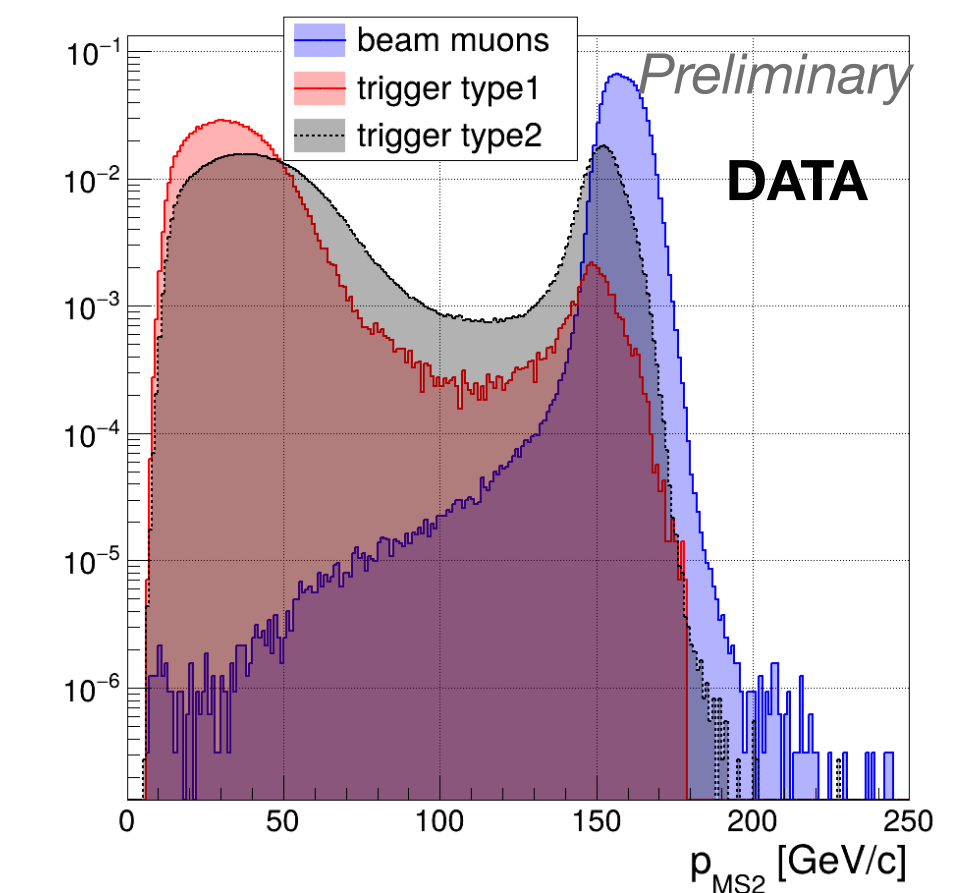
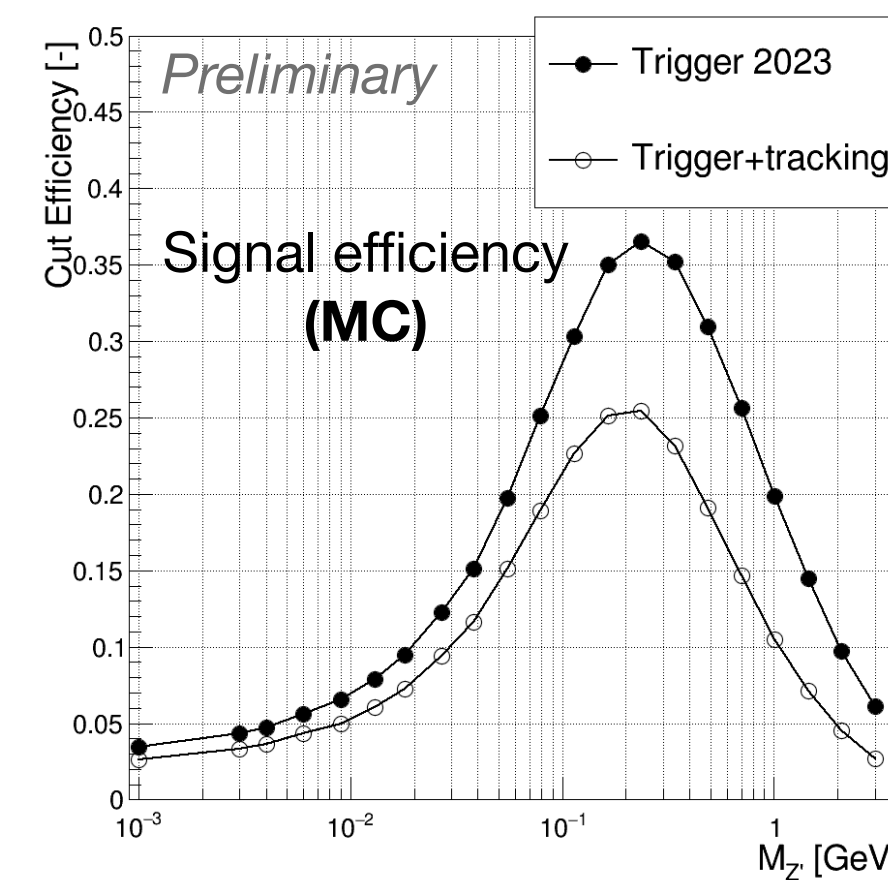
Two trigger types

1: $S_{4,\mu}$ shifted further from 0-line

2: $S_{4,\mu}$ closer to 0-line (signal efficiency shown for this type)

Signal: Final state muon with

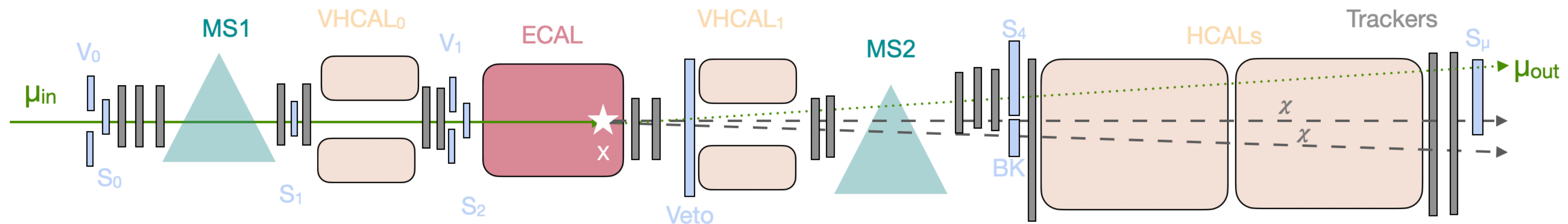
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H. Sieber et. al. Phys. Rev. D **108** (2023) no.5 056018

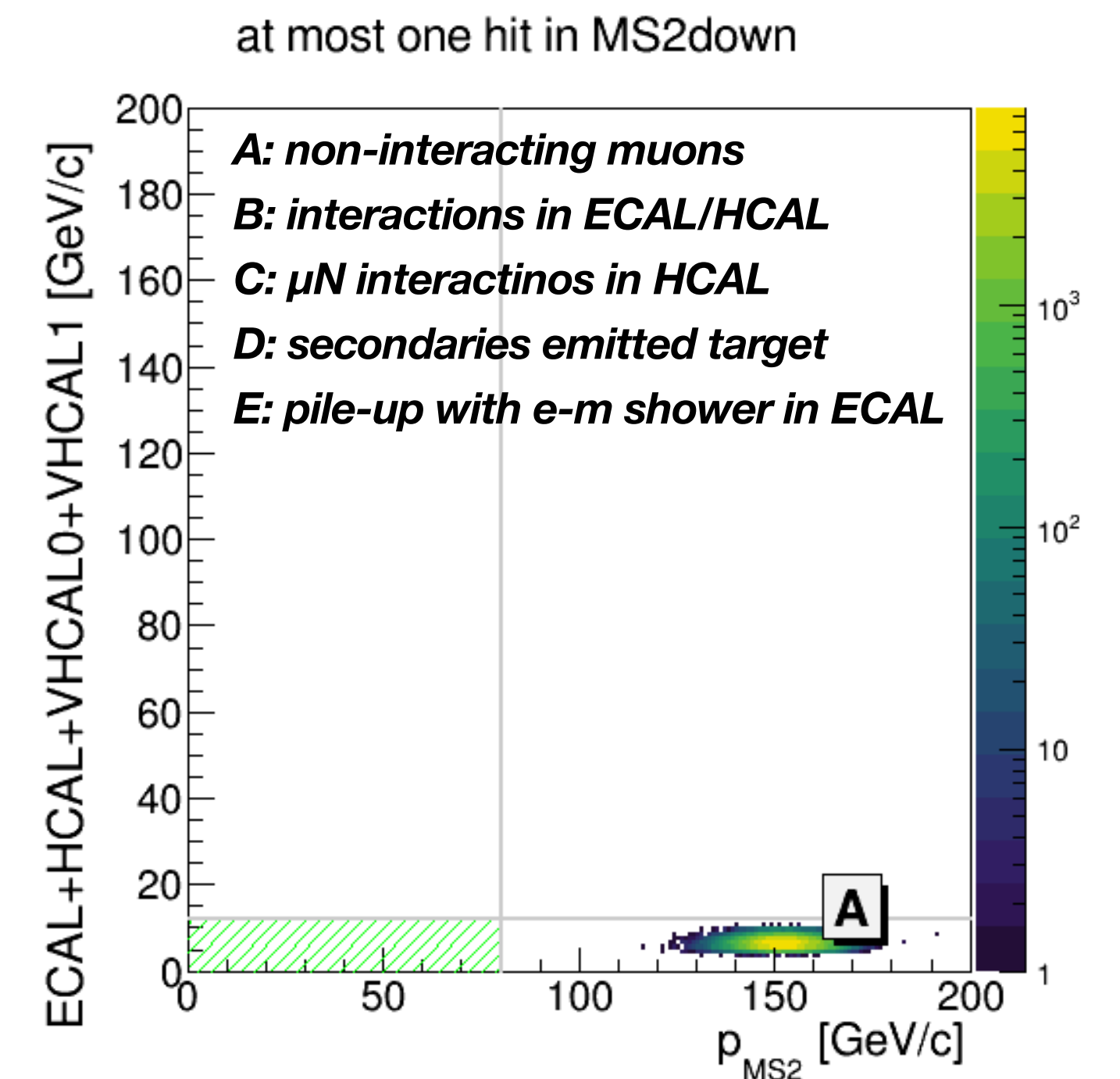
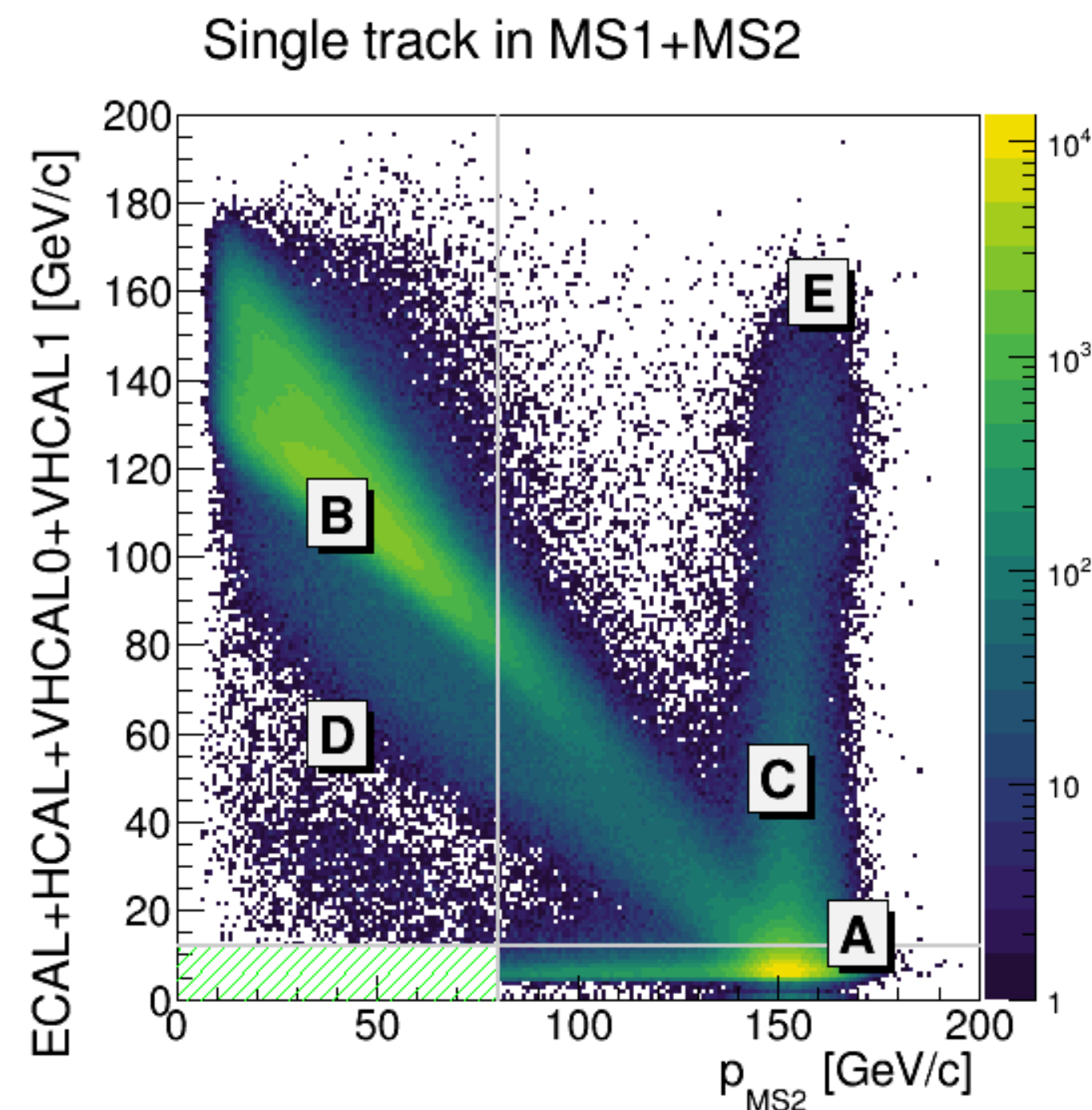
H. Sieber et al. Phys. Rev. D **105** (2022) no.5 052006

Definition of the final state muon

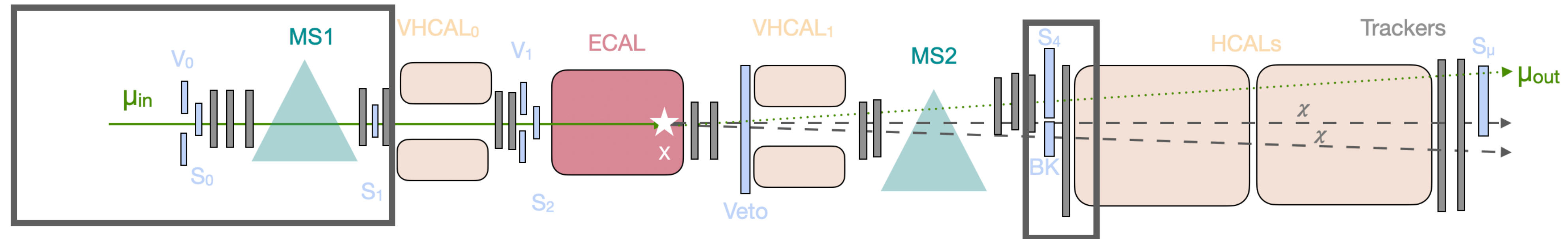


Selection criteria

- Time selection
- Single muon traversing the setup
- Well reconstructed single track in MS1
- Single track after MS2
- No energy in VHCALs and Veto outer cells
- MIP compatible energy in calorimeters with particle impinging on ECAL central cells



2023 data taking campaign – hardware upgrades



New Magnetic Spectrometer (MS1) with significantly reduced lever arm (from ~80 m to ~6m) —> in flight kaon decay background suppressed by factor 10

New veto scintillator to suppress pile-up triggers

- Further upgrades:
 - Include a pre-scaler: Allows to simultaneously collect data passing different trigger conditions
 - Double intensity: from $2.5 \times 10^6 \mu/\text{spill}^*$ to $5 \times 10^6 \mu/\text{spill}$
 - 8 additional trackers (23 in total)
- How did we cope with these upgrades in reconstruction and analysis? **See next slides**

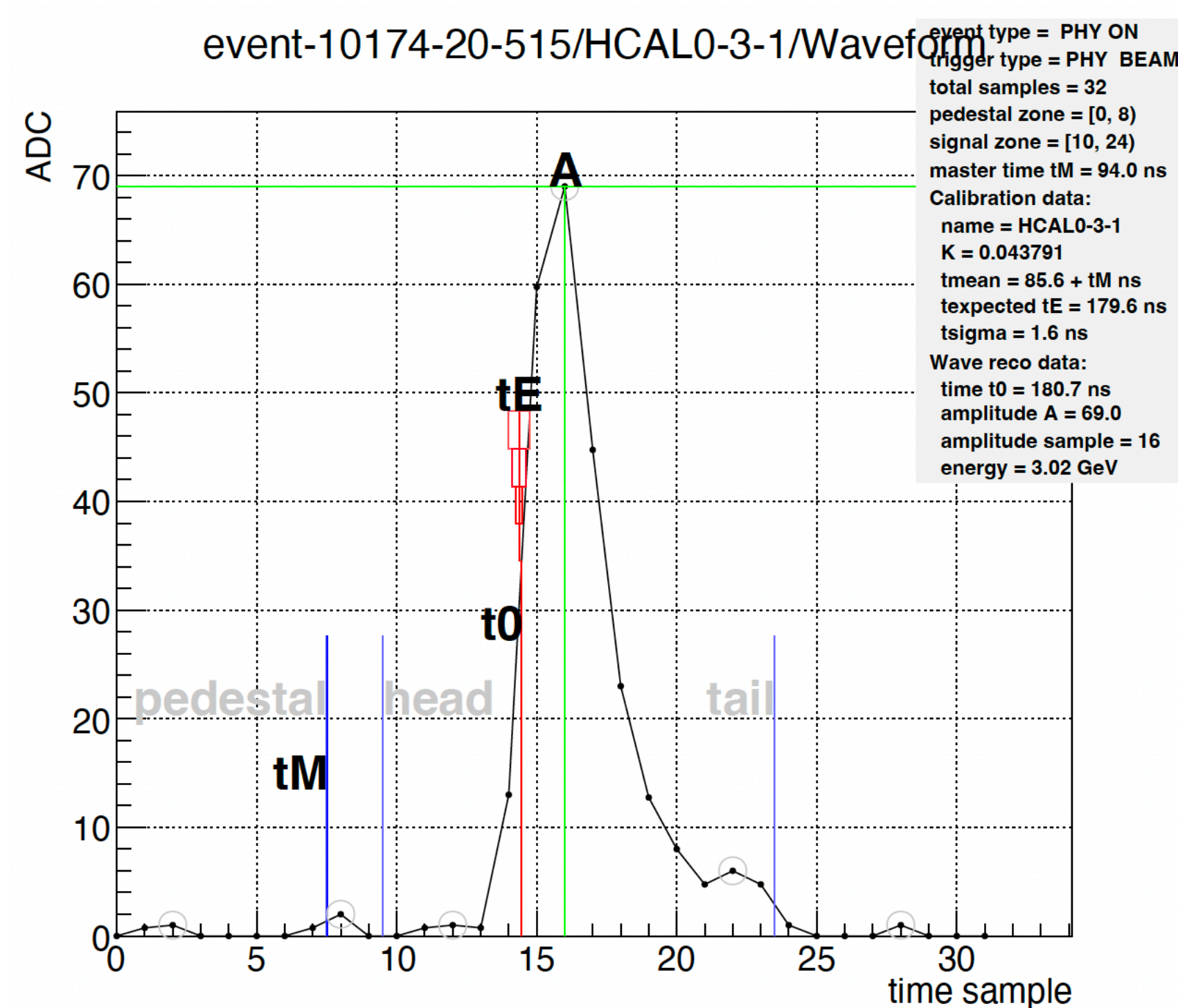
* a spill has a duration of 4.8 seconds, followed by a dead time of ~10-20 seconds (2-3 spills per „supercycle“, which is 48 seconds long)

2023 data taking campaign – raw data

- Two types of detectors: **calorimeters** (segmented in *cells*) and **trackers** (3 technologies: GEMs, Micromegas and Straws)

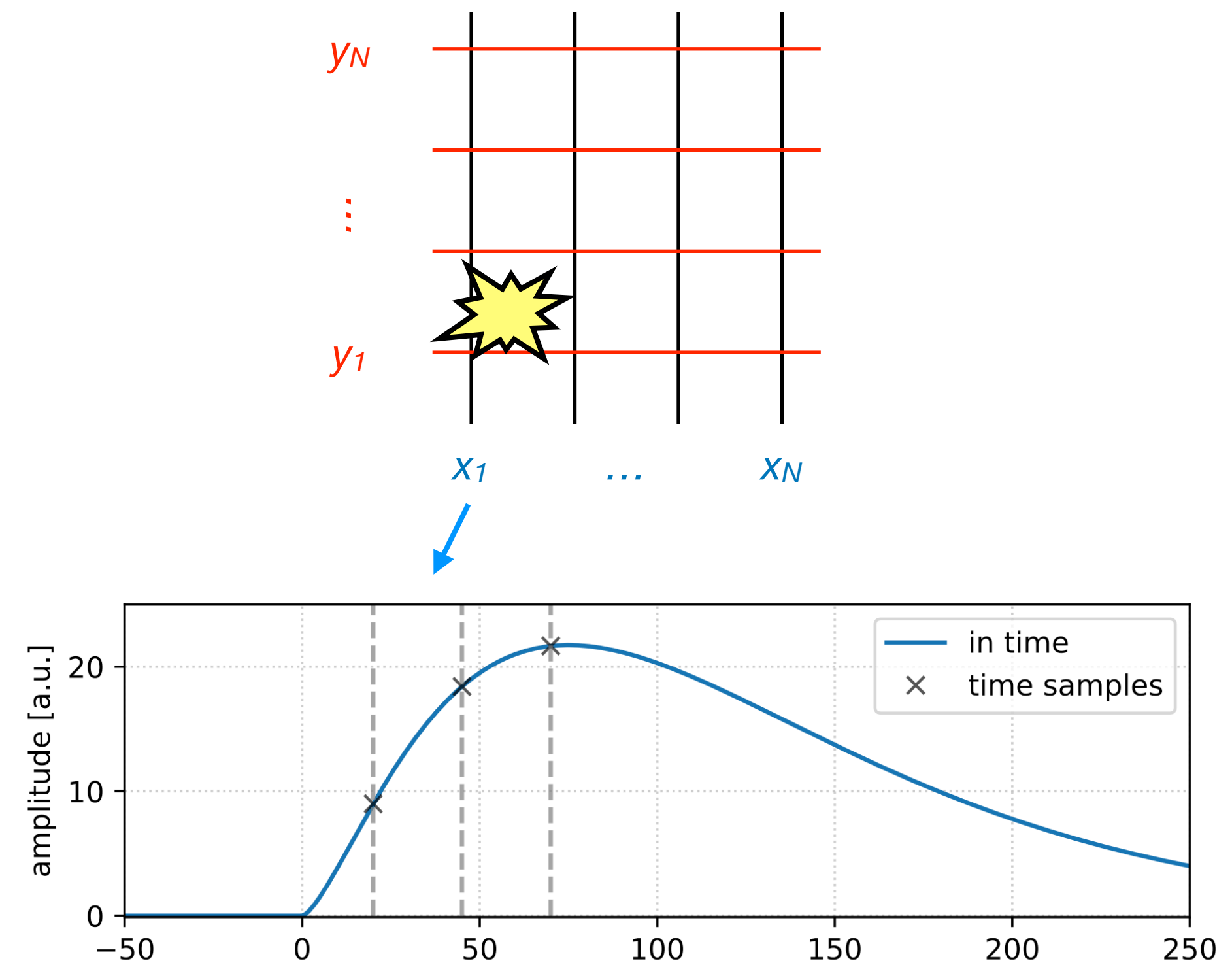
Calorimeters

- Measure energy deposit and time via scintillation light
- Readout device per cell: PMT
- Signal: Digitised waveform 32 samples each 12.5 ns



Trackers

- Measure position from electron shower in gas hitting a grid of wires
- Readout device for wires: APV chips (GEMs, MMs), TDC (Straws)
- Signal: Digitised waveform 3 samples each 25 ns (APV), time (TDC)



2023 data taking campaign – reconstruction

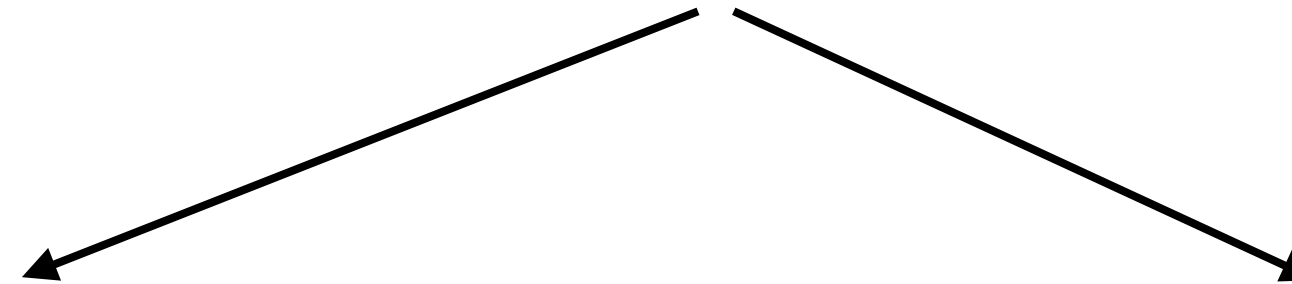
Load database: calibrations, channel IDs, geometry info (positions, dimensions, ...)



Decode event: store PMT and APV raw waveforms and TDC times



Reconstruct data



Calorimeters: peak finding algorithm (e.g. constant fraction discrimination or fit). ***Energy:*** peak of pulse x calib, ***time:*** time at half height of pulse closest to expected time



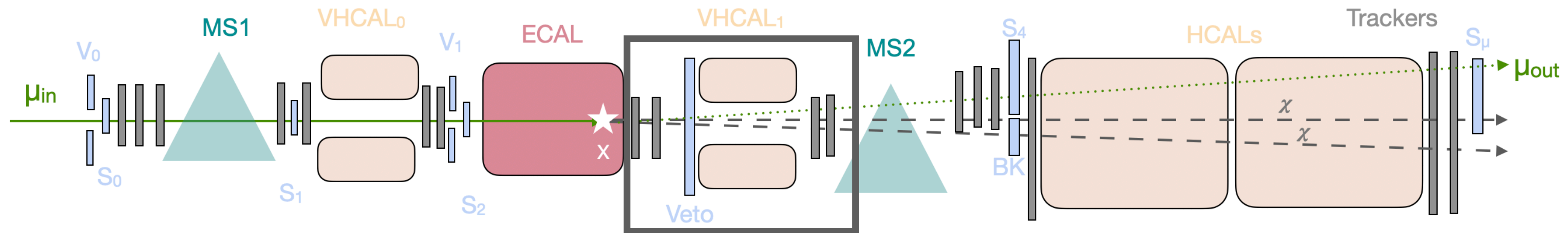
Total energy: in-time energy without noise for each cell. Combine the cell infos

Trackers: clusterisation, i.e. identify wires belonging to same particle, perform weighted average using wire charges for position, transform into spatial units

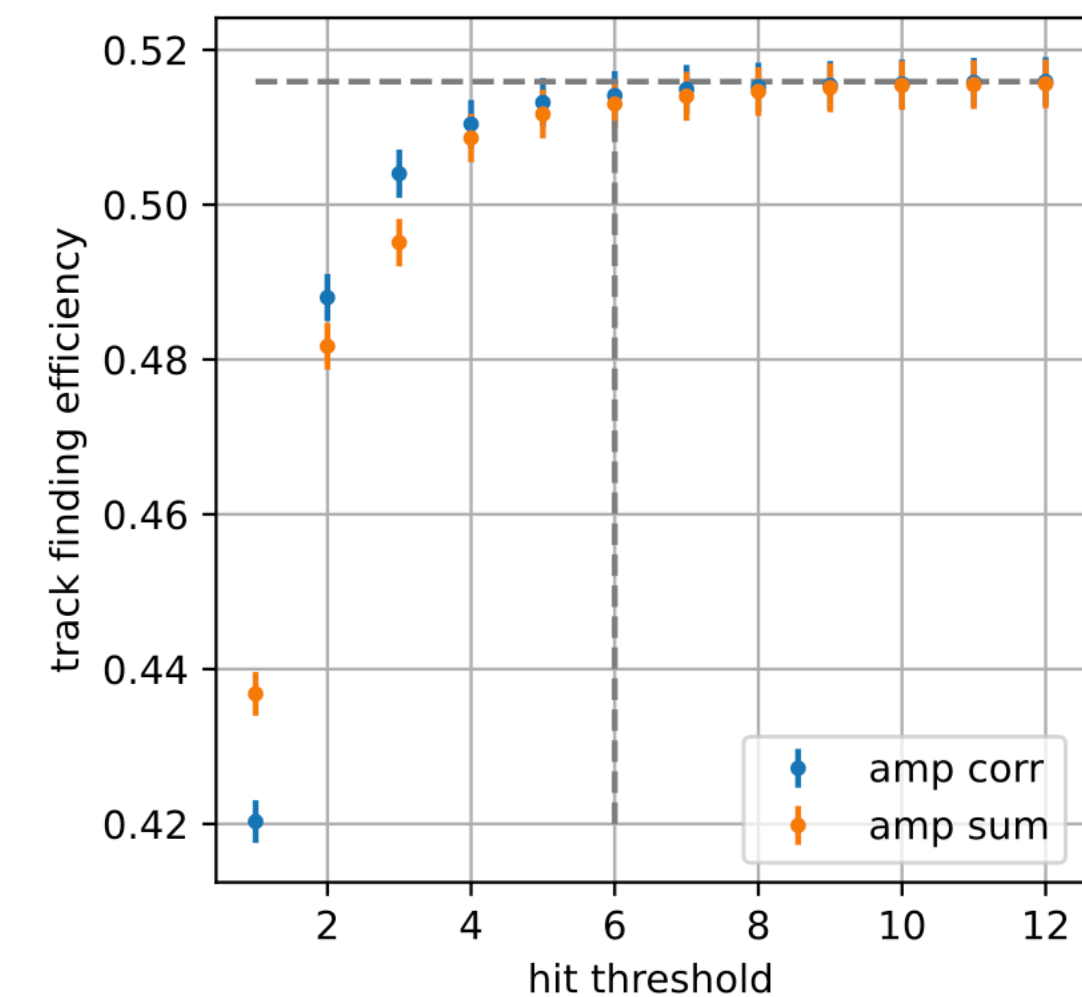
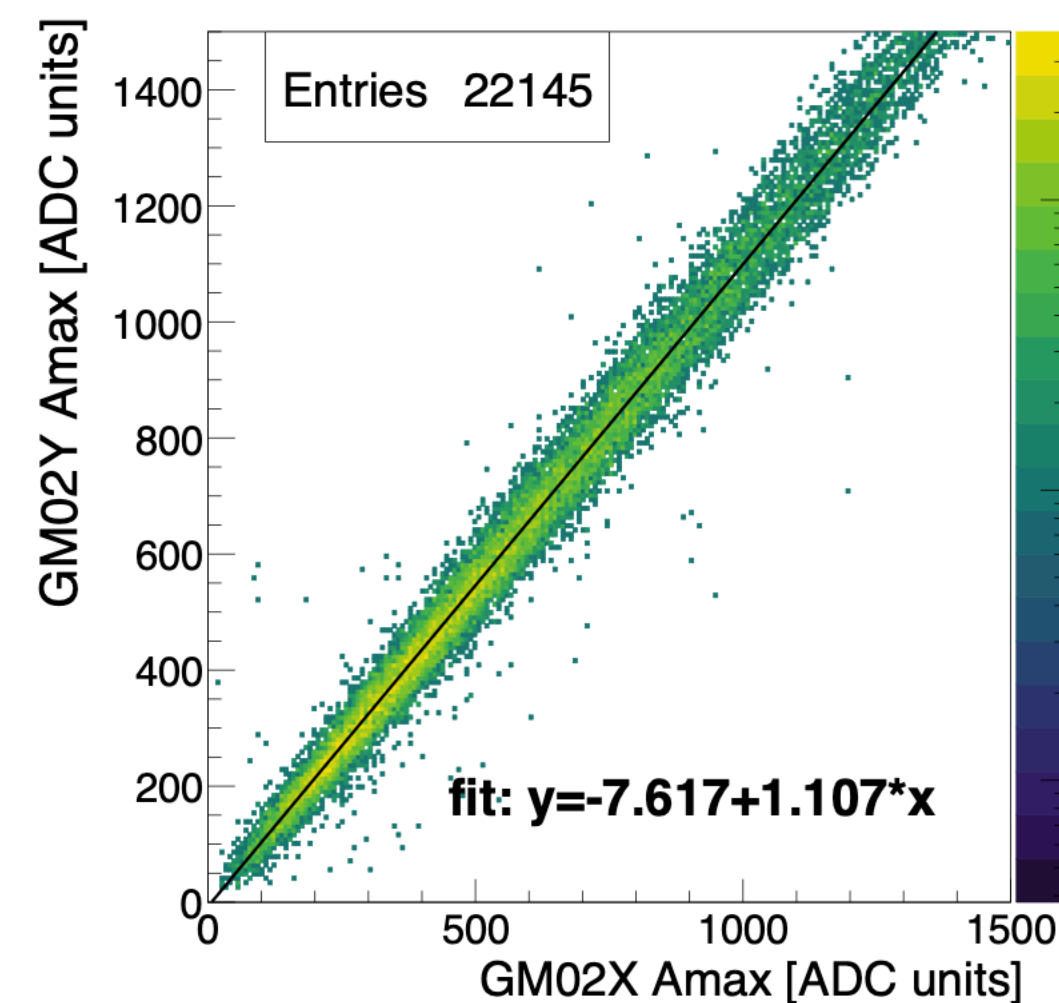
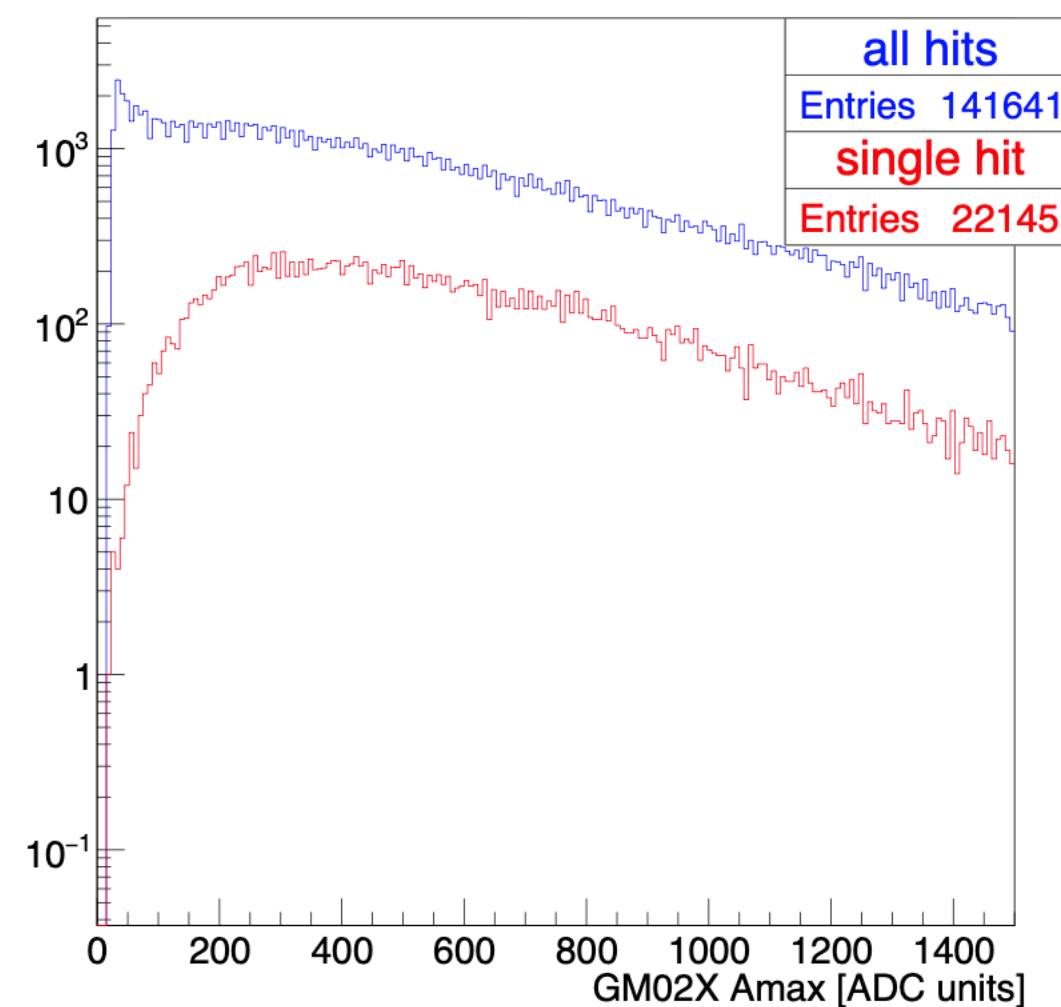


Track reconstruction: Separate algorithm to combine tracker (and magnet) info into a track (next slides)

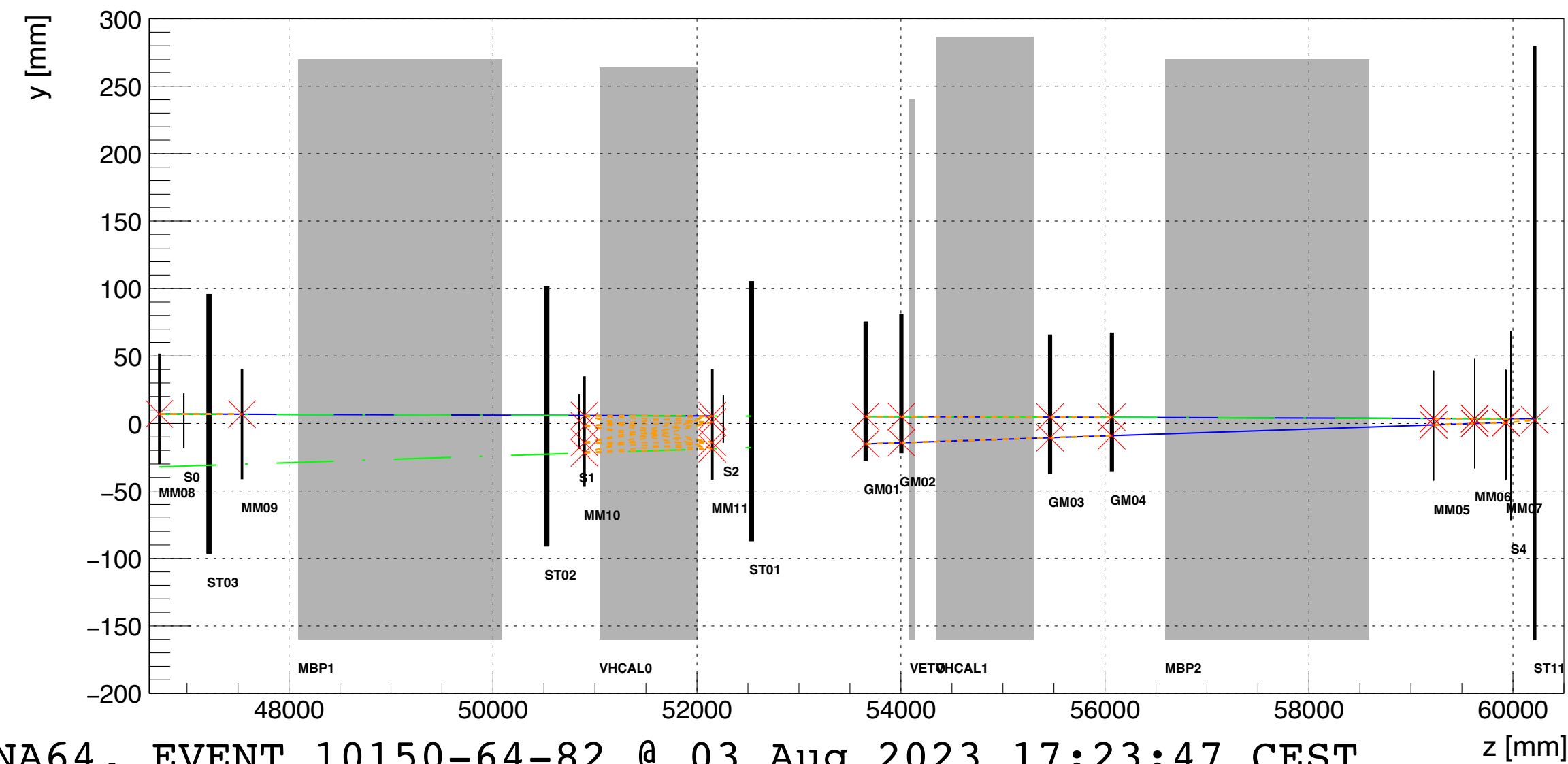
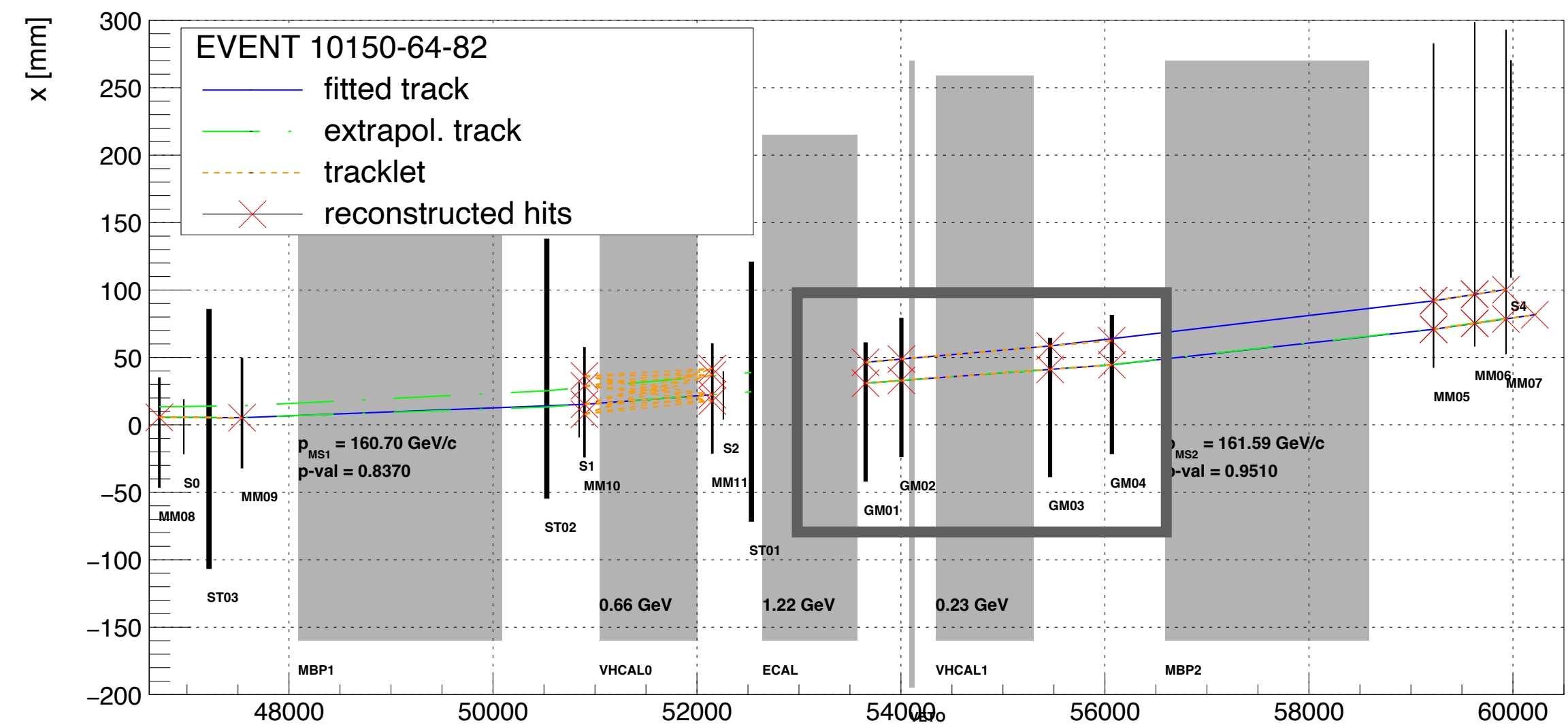
Hit reconstruction – multiple hit processing in GEMs



- Pile-up and secondaries from interactions in target require robust identification of the muon track
- In the past the best hit was used and the motivation to include additional hits was to deal with multiple tracks coming from higher intensities or secondaries emitted from the target
 - Key: Simple noise threshold on cluster charge and correlation of charge between x and y cluster



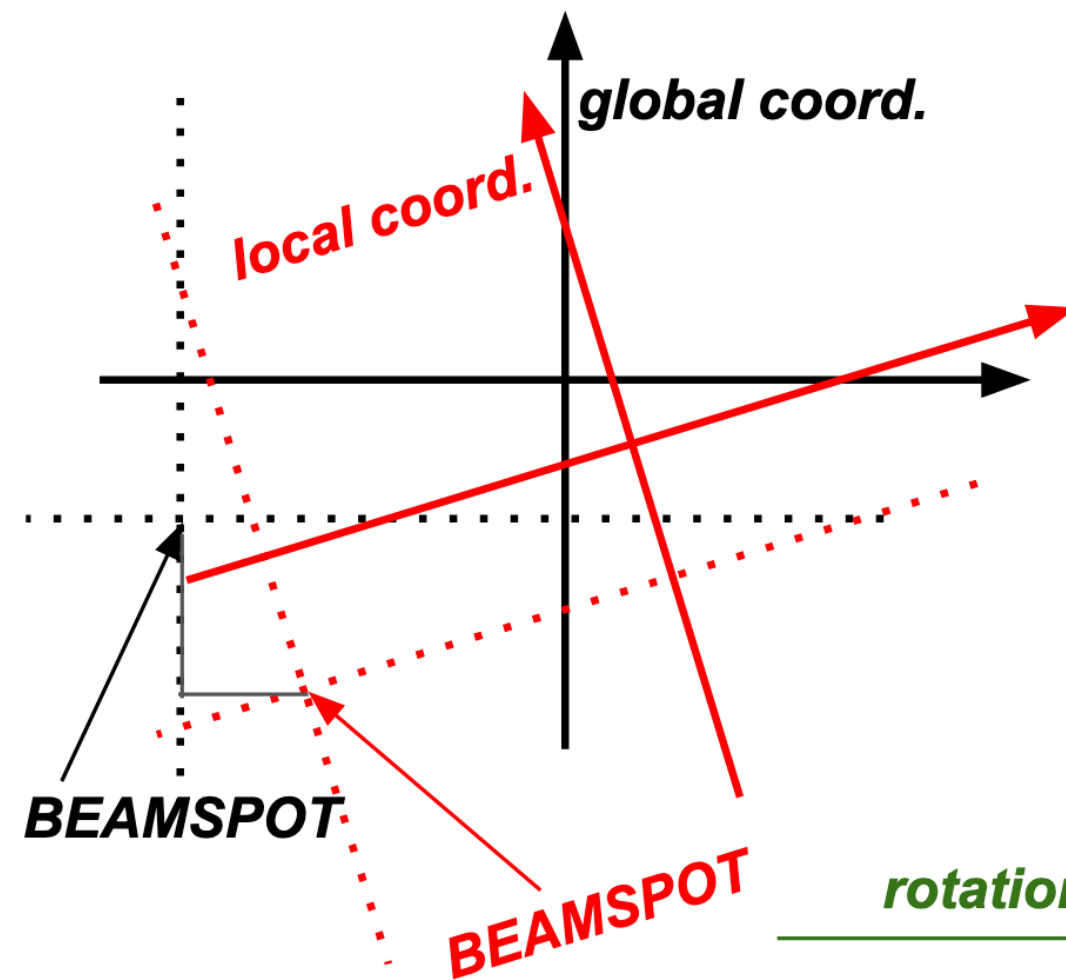
Real-event example – after upgrade



NA64, EVENT 10150-64-82 @ 03 Aug 2023 17:23:47 CEST

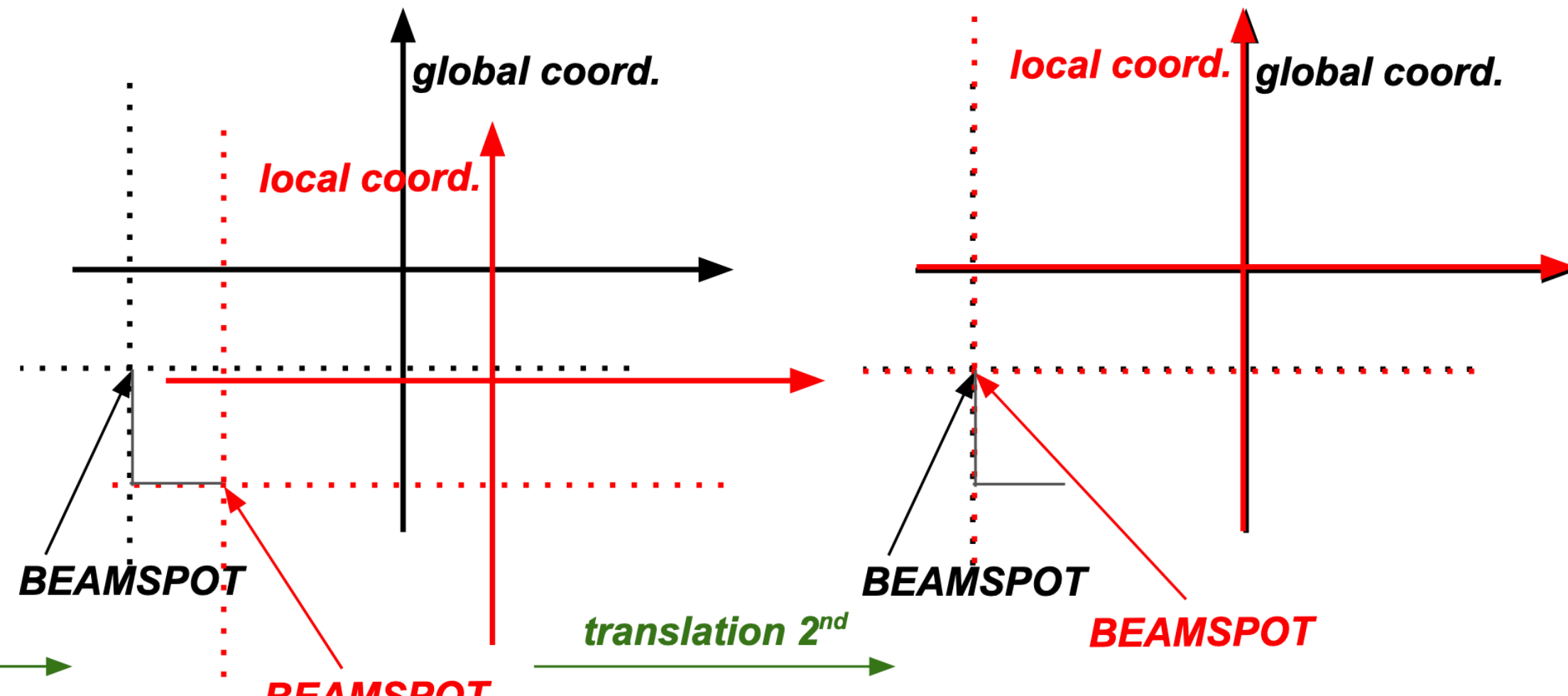
Alignment – precision in geometry

before alignment



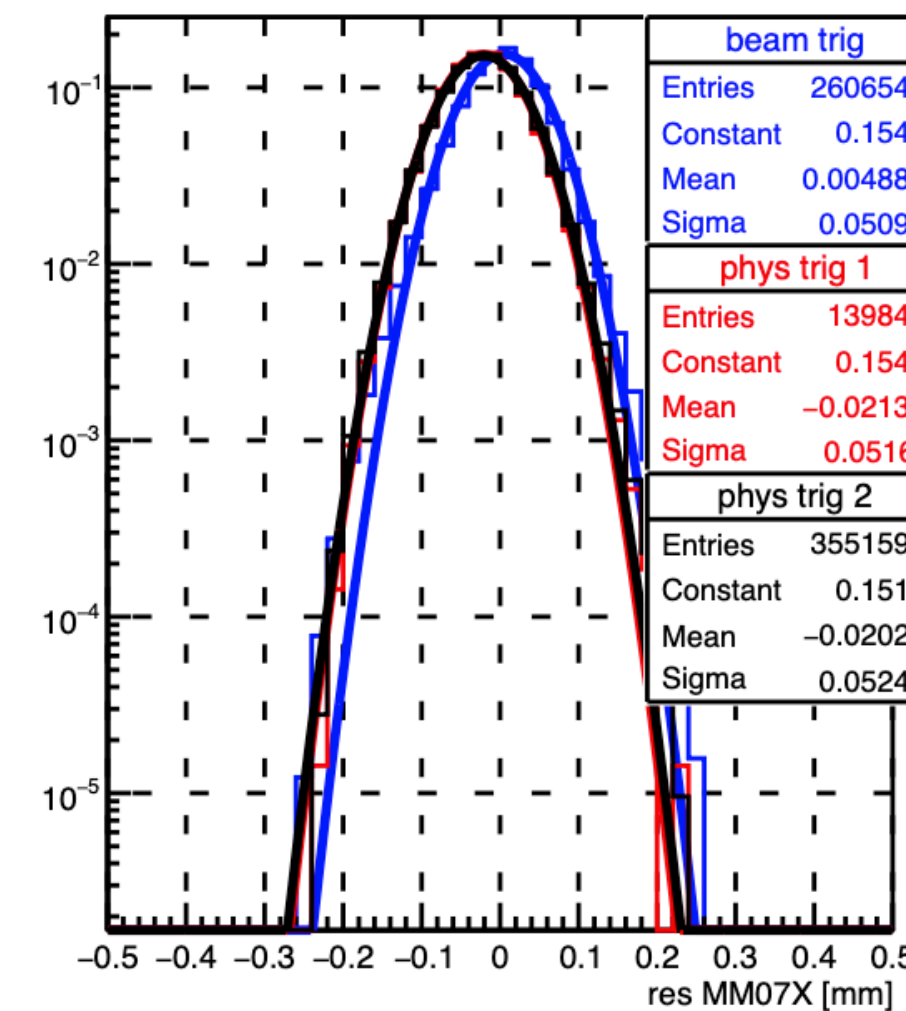
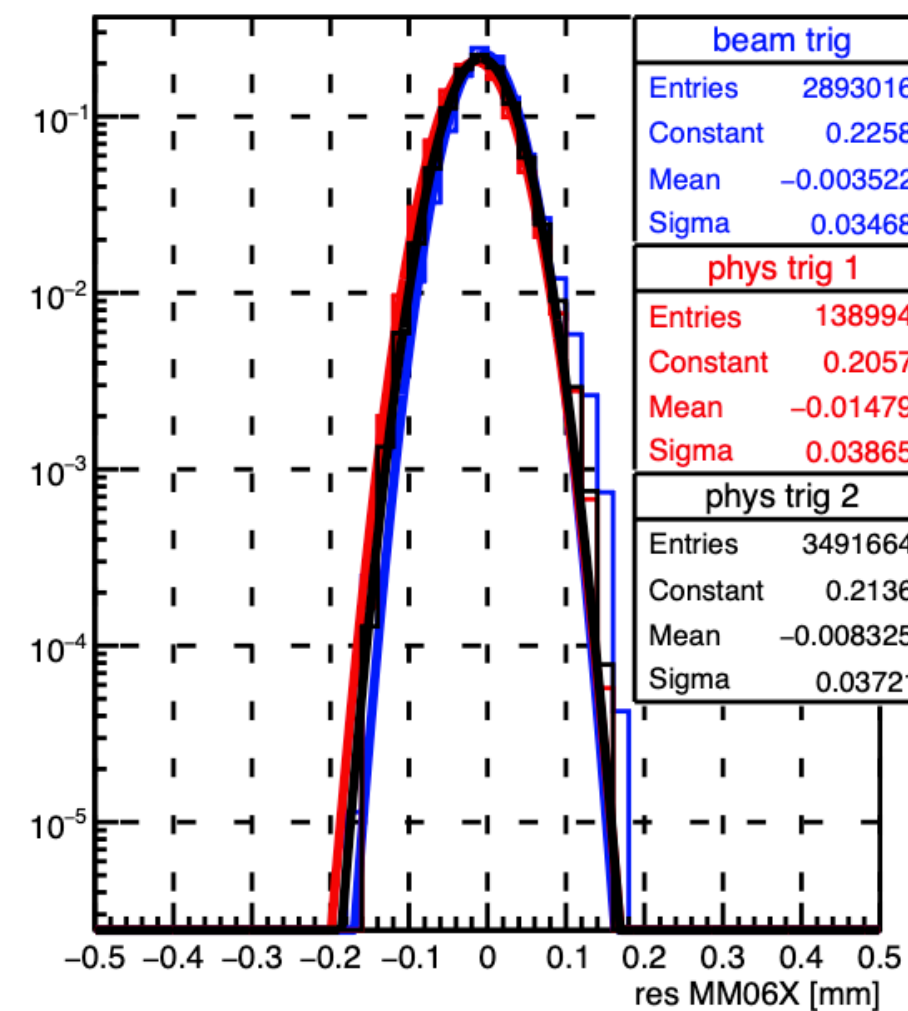
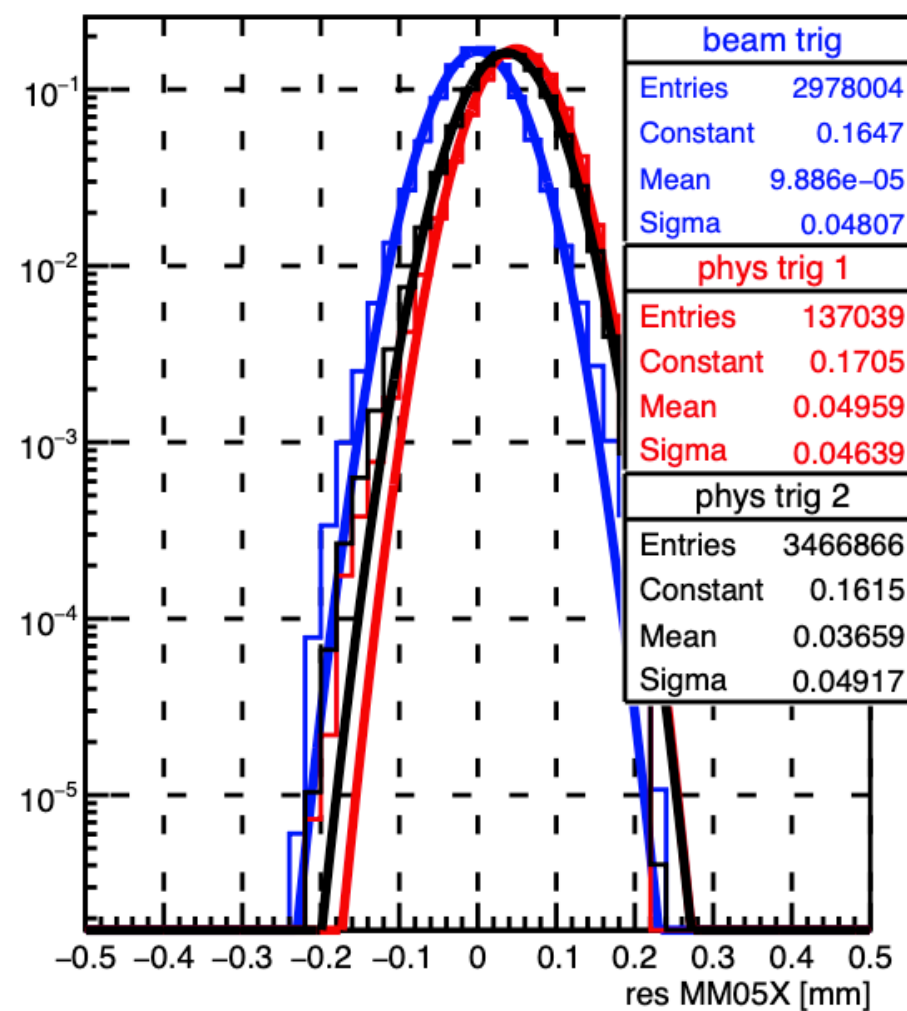
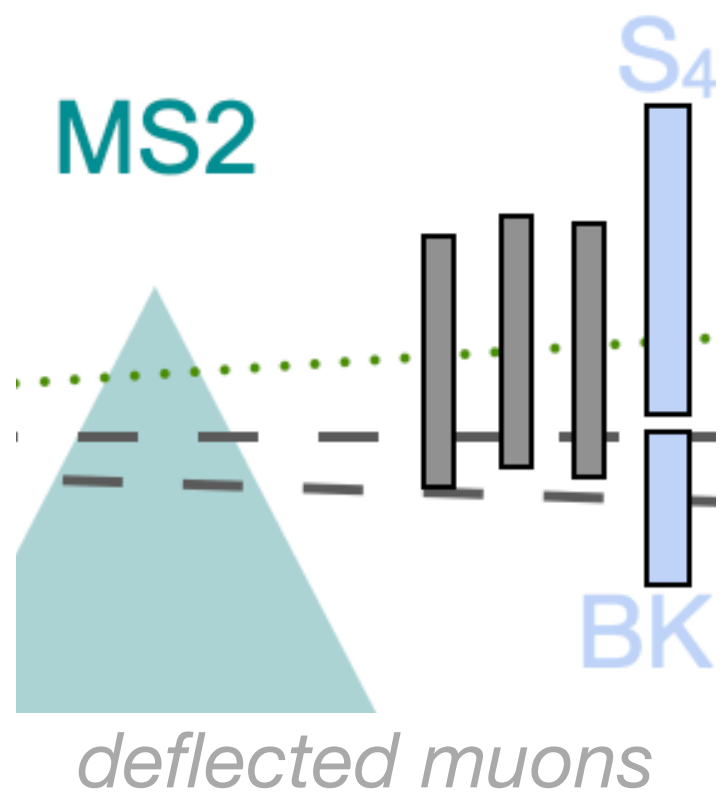
MM05x_ures

after alignment



MM06x_ures

MM07x_ures



„Angular alignment“ especially important for low momentum muons ($p_{MS2} < 80$ GeV/c) $\rightarrow$ bulk of physics trigger events

Magnetic field – fringe effects matter

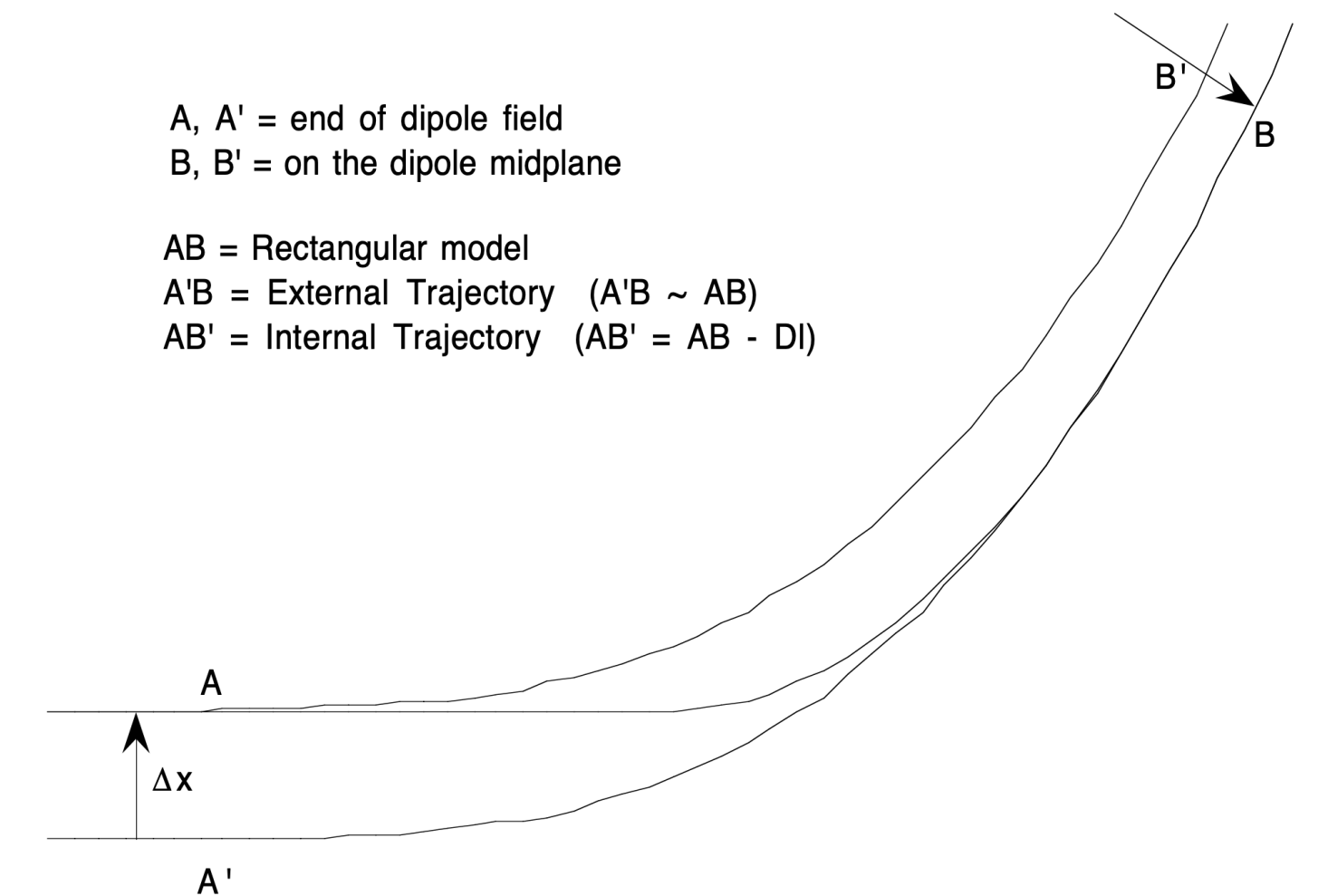
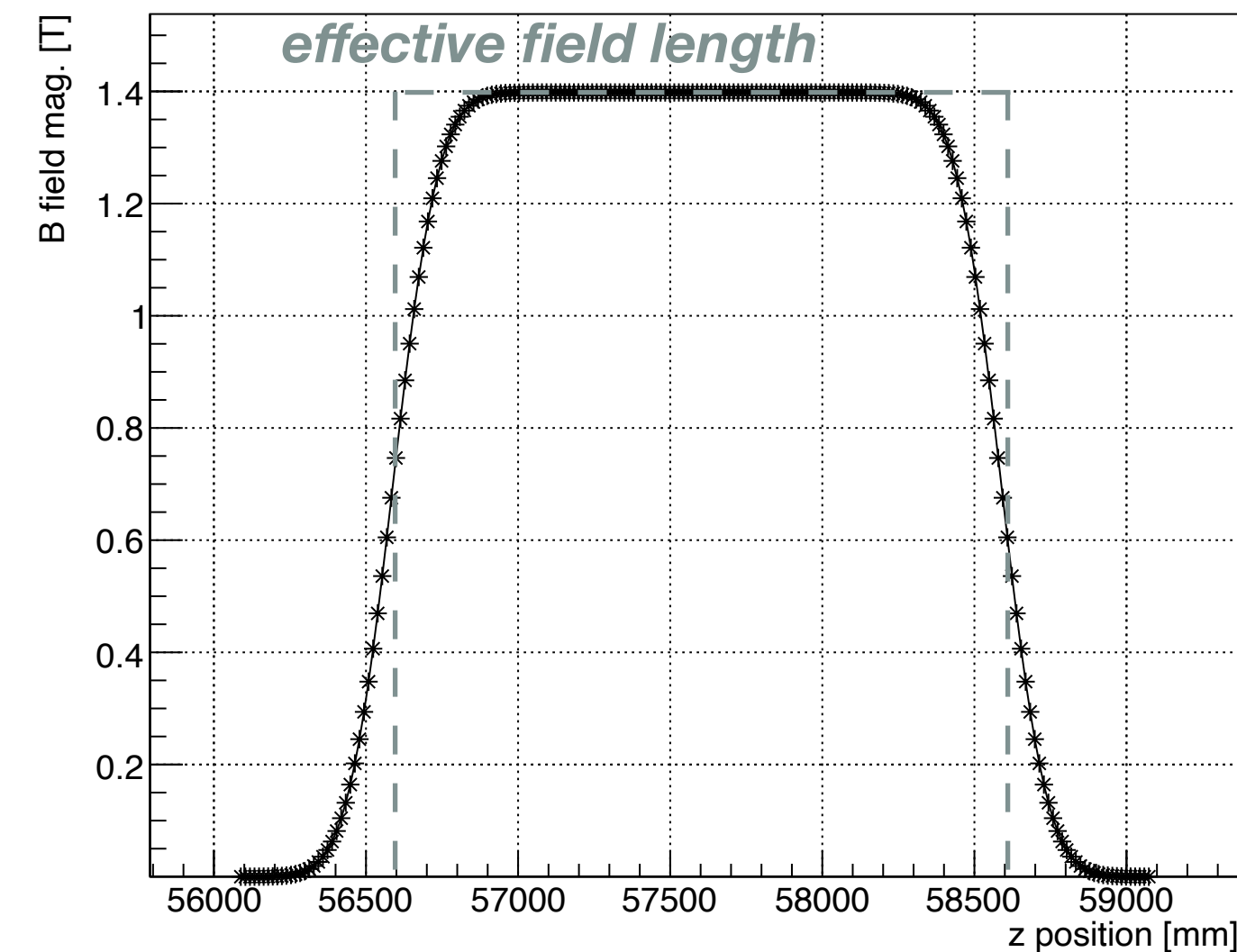
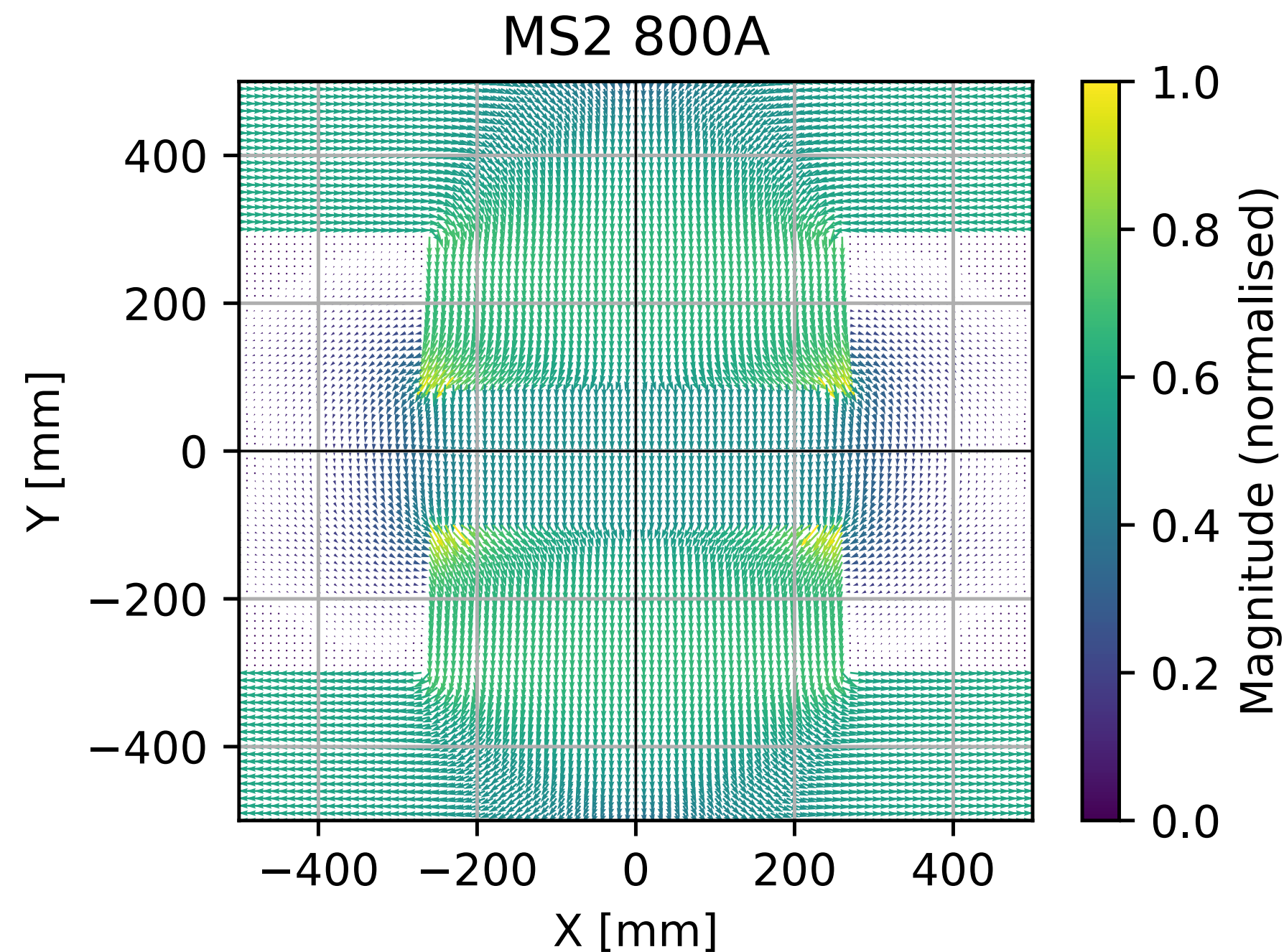


Fig. 2 - Beam reference trajectory with rectangular model and with fringing.

DaΦne collaboration. Note L-14 (1994) Dipole
Fringing Field Effect on reference orbit.

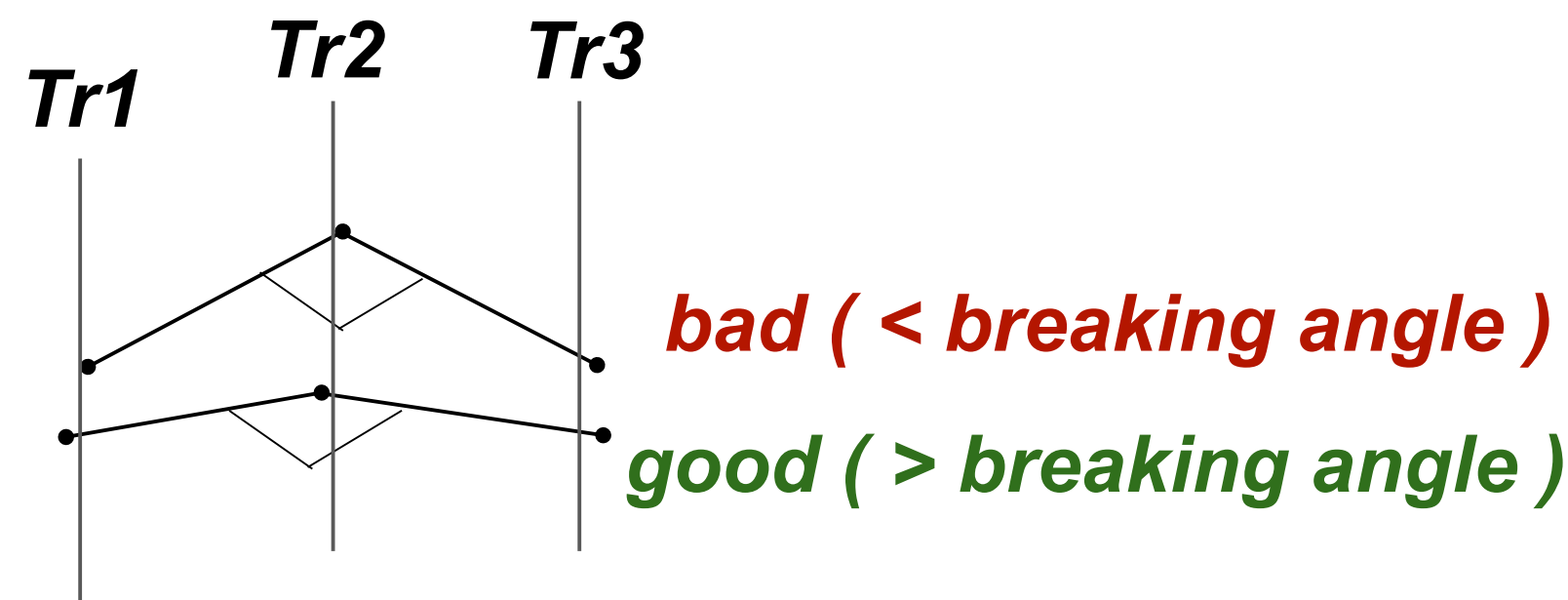
- Two ways to model magnetic field
 - Deflection based: only angle of deflection matters, precise trajectory does not factor in —> all I need is to know the effective length of the magnetic field
 - Propagation based: Use e.g. Runge Kutta method to solve equation of motion of charged particle in magnetic field —> **the trajectory is incorrectly reproduced without fringes**
 - Thus, fringing was introduced as a necessary component of the field model

Track finding – how to find the best hit combinations

- Before using the tracking for analysis: prepare the **alignment**, **magnetic field maps**
- Goal of track selection: **find good and physical track candidates** and **fit** using Kalman-filter.

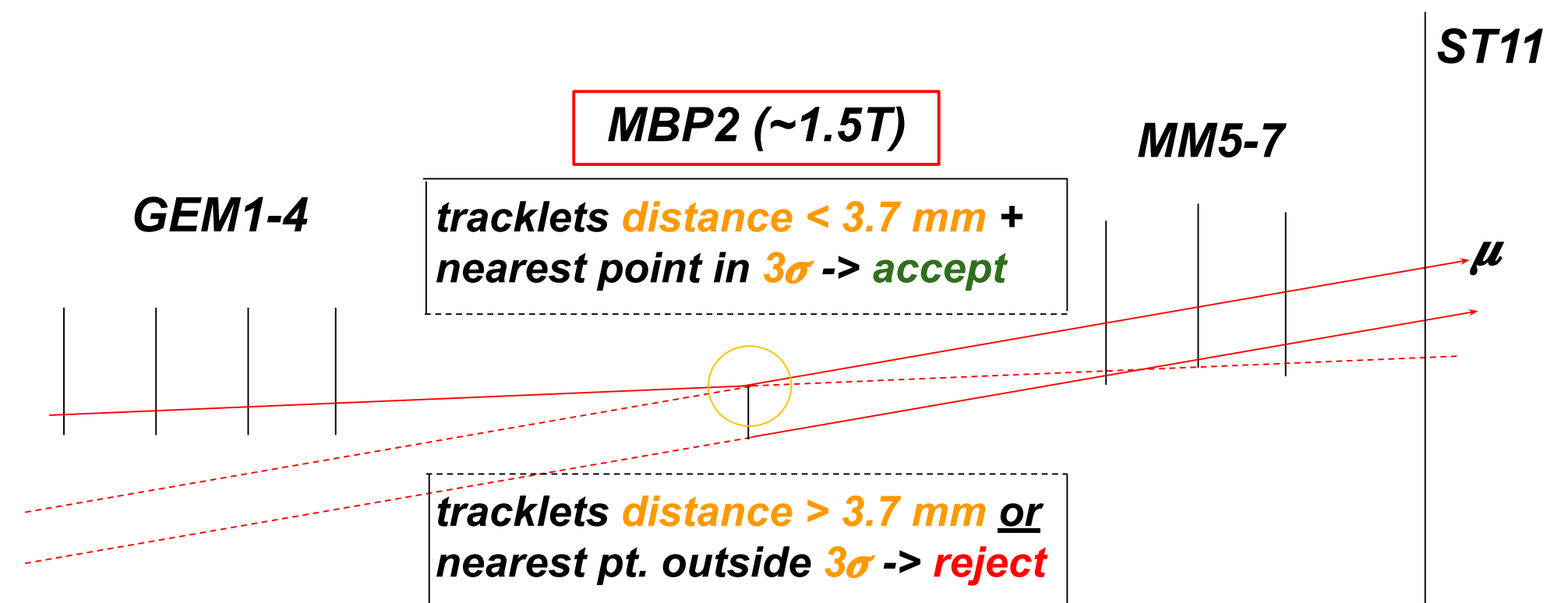
1) find good track candidates

- hits in at least 2 trackers before+after magnet
- if hits in 3 or more trackers, perform **pre-patterning**: find at least one **tracklet** before and one after magnet (principle shown below)
 - “Breaking angle” based on resolution and relative distances among trackers

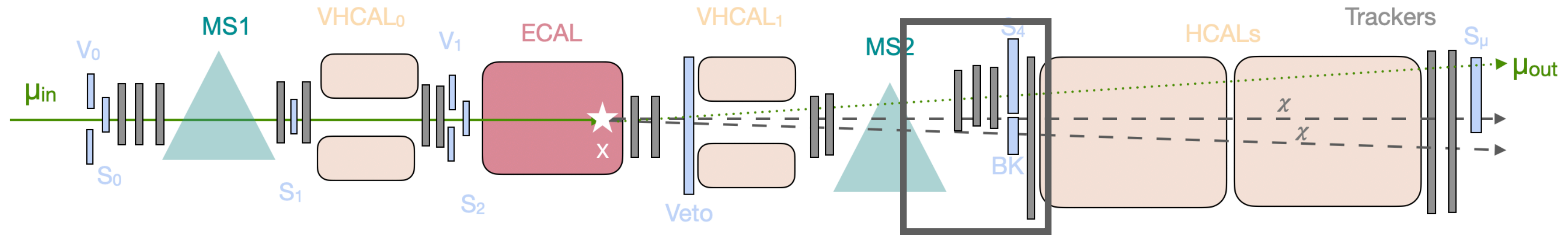


2) is track candidate physical?

- perform **weighted** linear fit on tracklets and check if they meet in the magnet centre
 - if yes → **track candidate**
- Compute p_{MS2} analytically as seed for **GenFit**

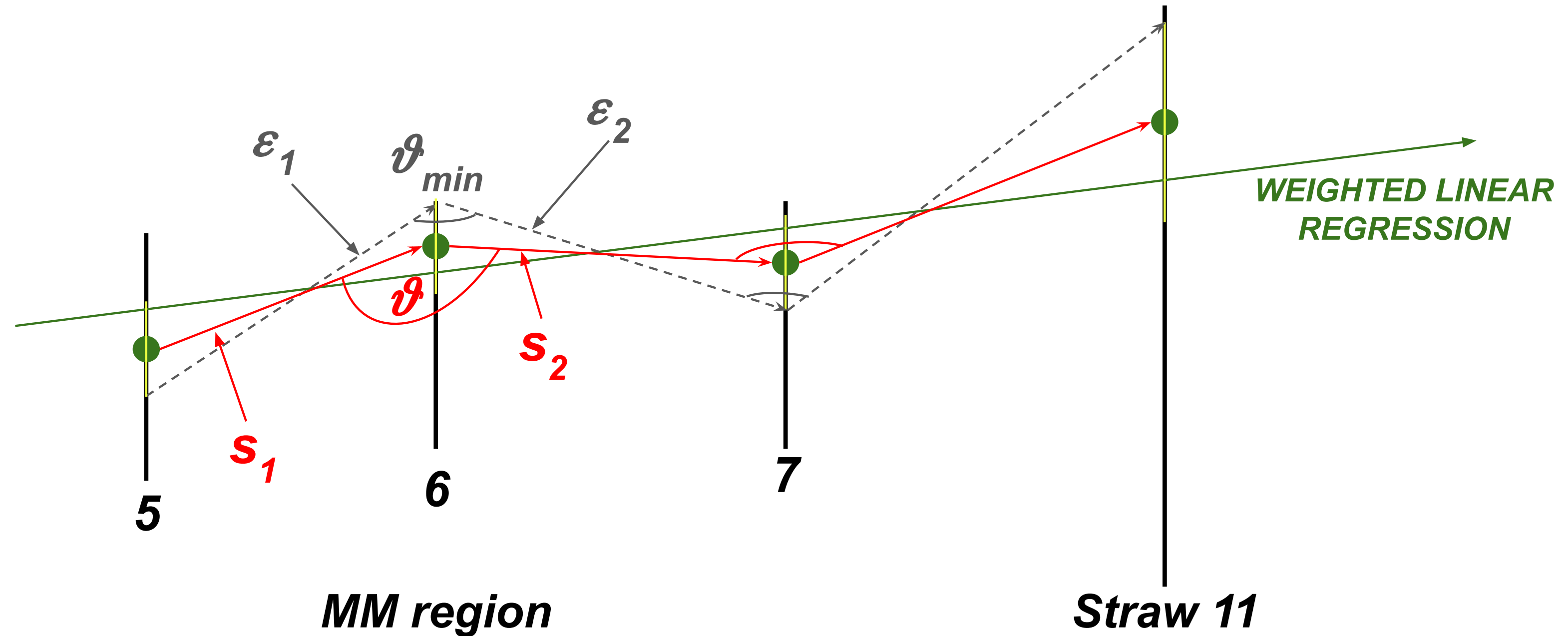


Track finding – Breaking angle



$$\vartheta_{min} = \pi - \arccos \frac{\vec{\varepsilon}_1 \vec{\varepsilon}_2}{|\vec{\varepsilon}_1| |\vec{\varepsilon}_2|}$$

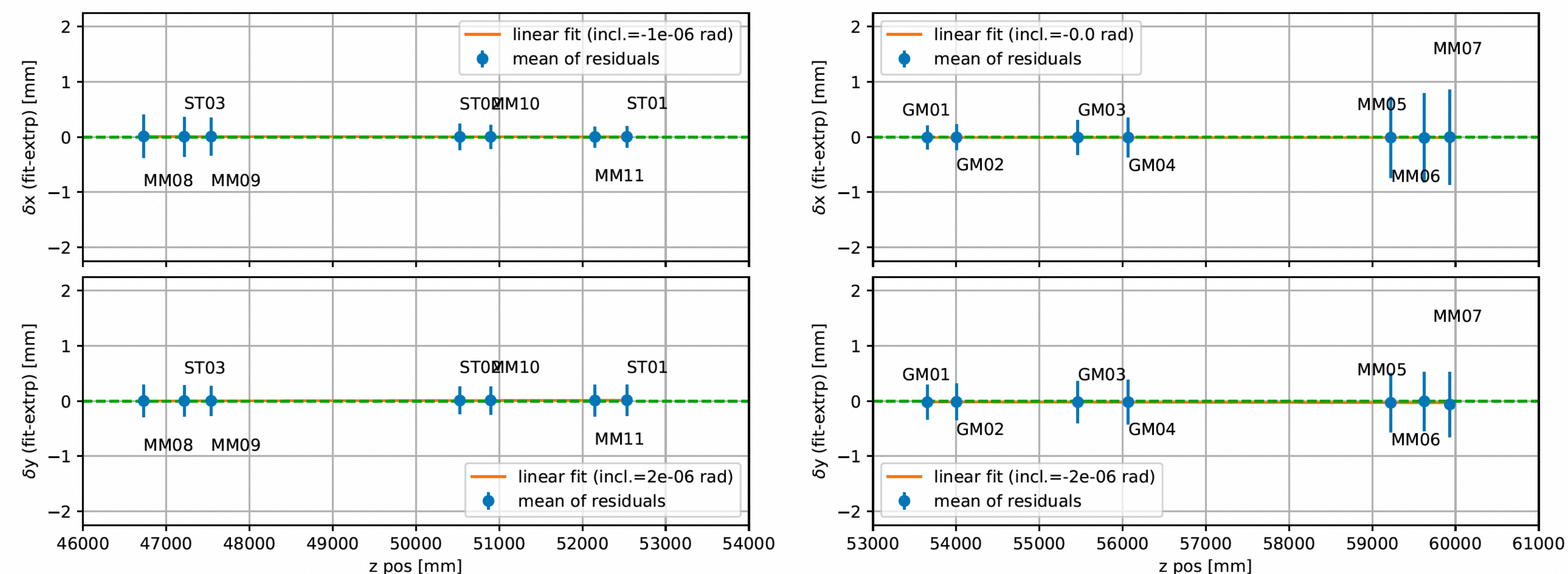
$$\vartheta = \pi - \arccos \frac{\vec{s}_1 \vec{s}_2}{|\vec{s}_1| |\vec{s}_2|}$$



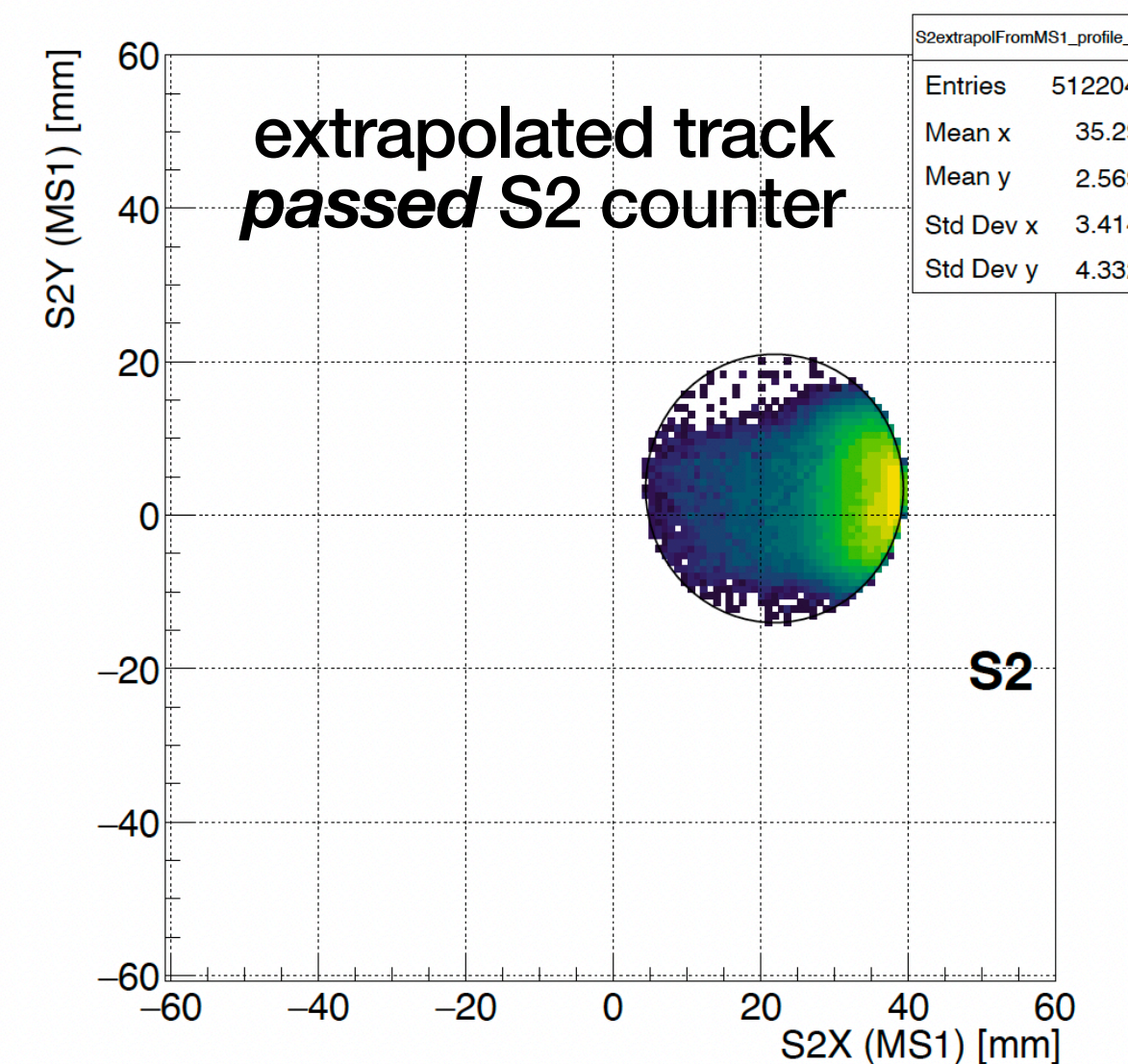
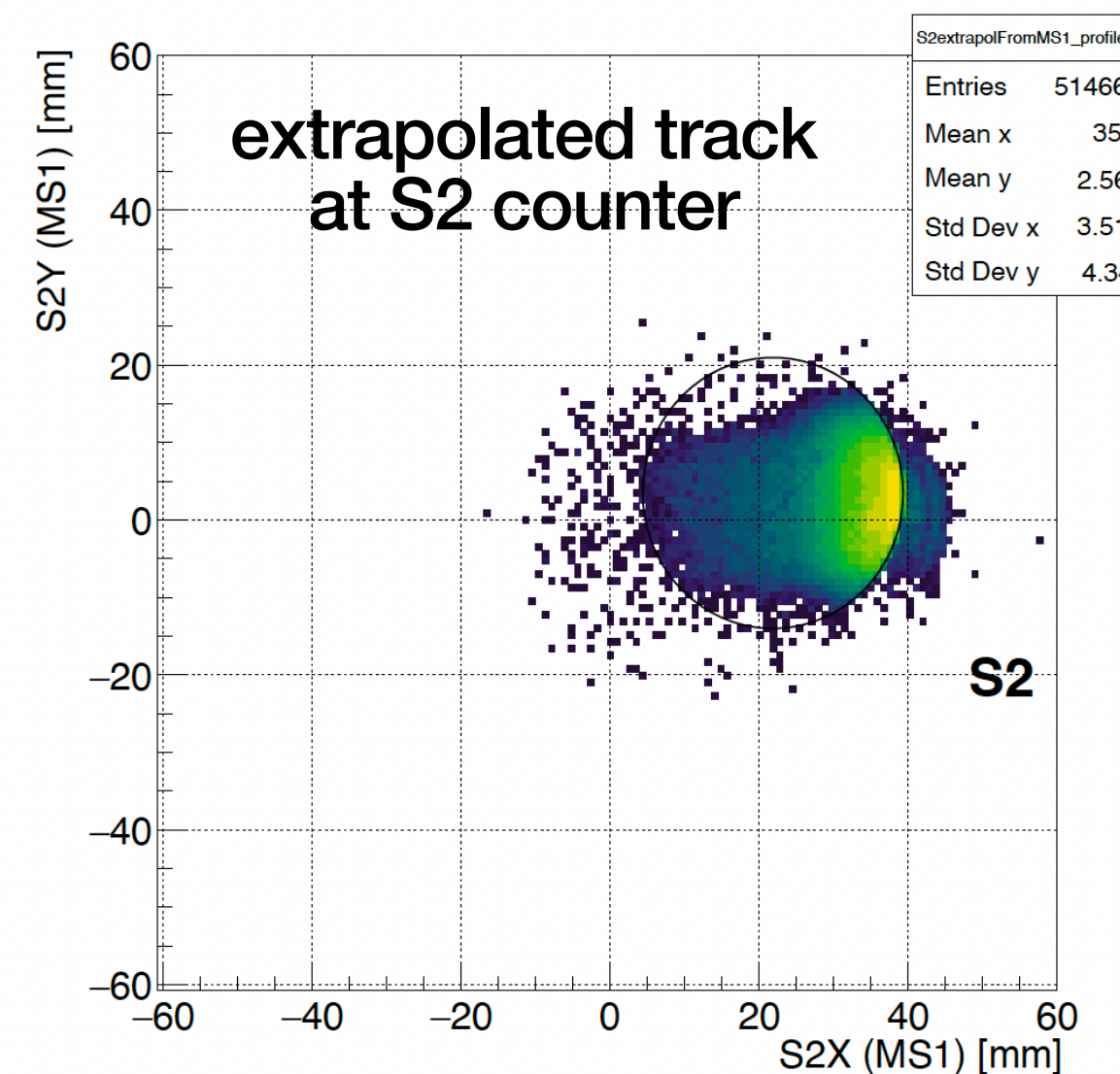
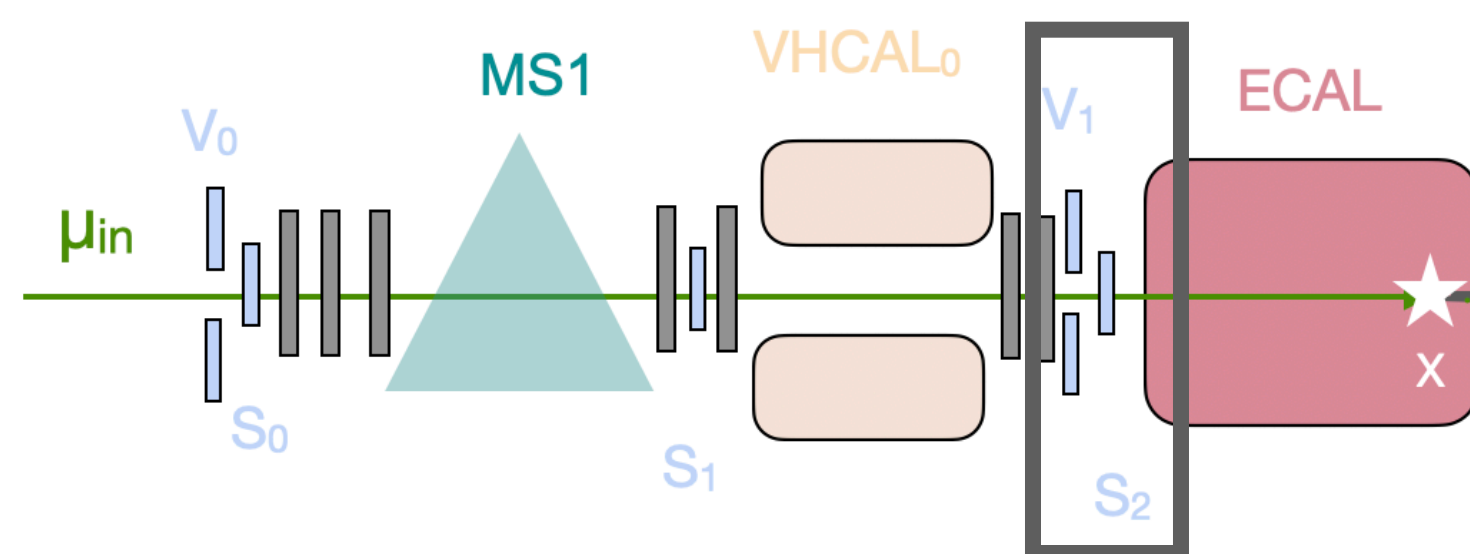
$$\vec{\varepsilon}_i = \boxed{\vec{p}_{i_2,fit}} + \boxed{n\sigma_{i_2}\vec{e}_{i_2}} - \left(\boxed{\vec{p}_{i_1,fit}} + \boxed{n\sigma_{i_1}\vec{e}_{i_1}} \right), \quad \vec{e}_{i_j} = \frac{\vec{p}_{i_j,reco} - \vec{p}_{i_j,fit}}{\|\vec{p}_{i_j,reco} - \vec{p}_{i_j,fit}\|}$$

High precision track extrapolation

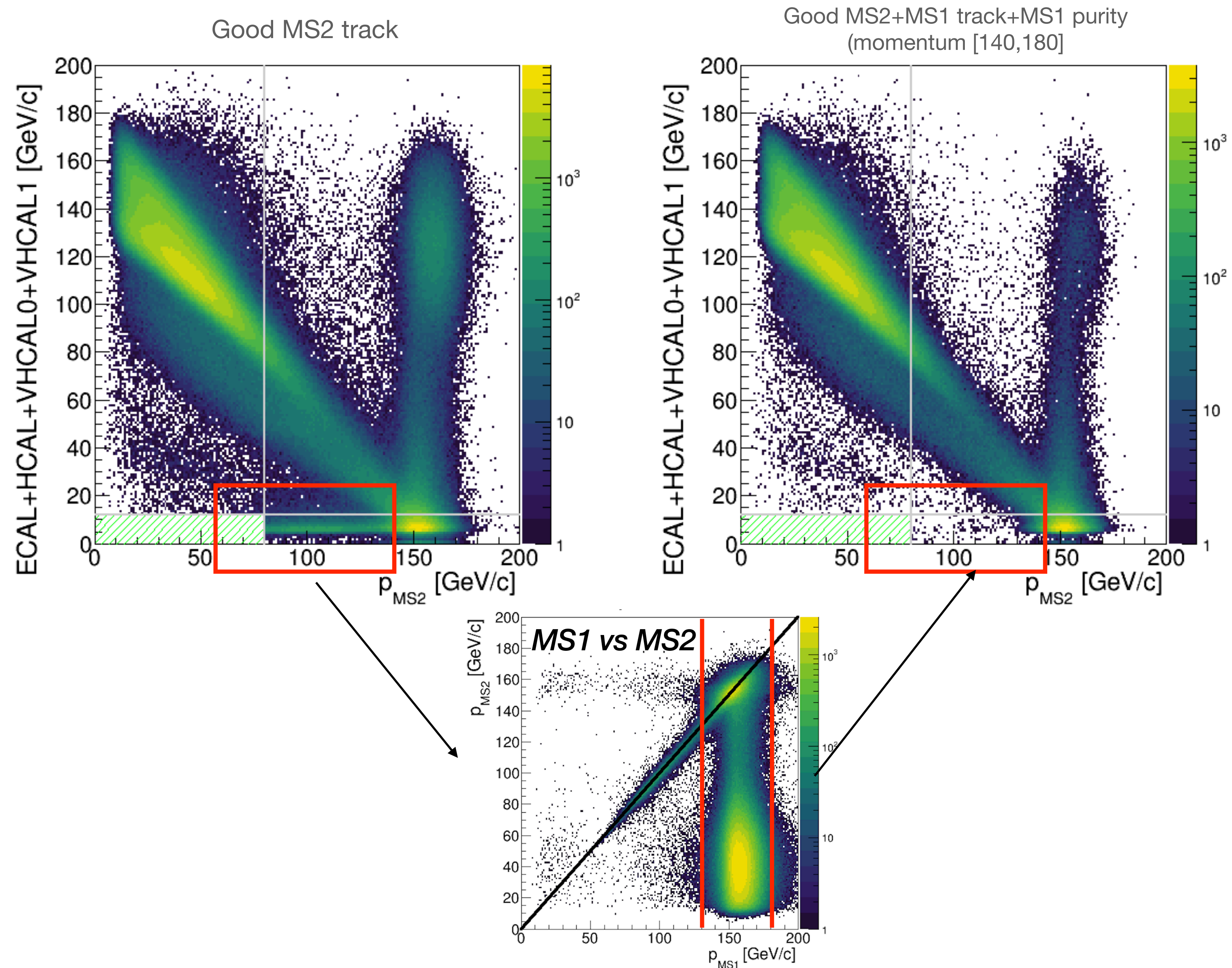
For global alignment



For analysis



MS1 momentum selection



Overview

The Dark Matter problem

The NA64 experiment

NA64 μ : muon mode

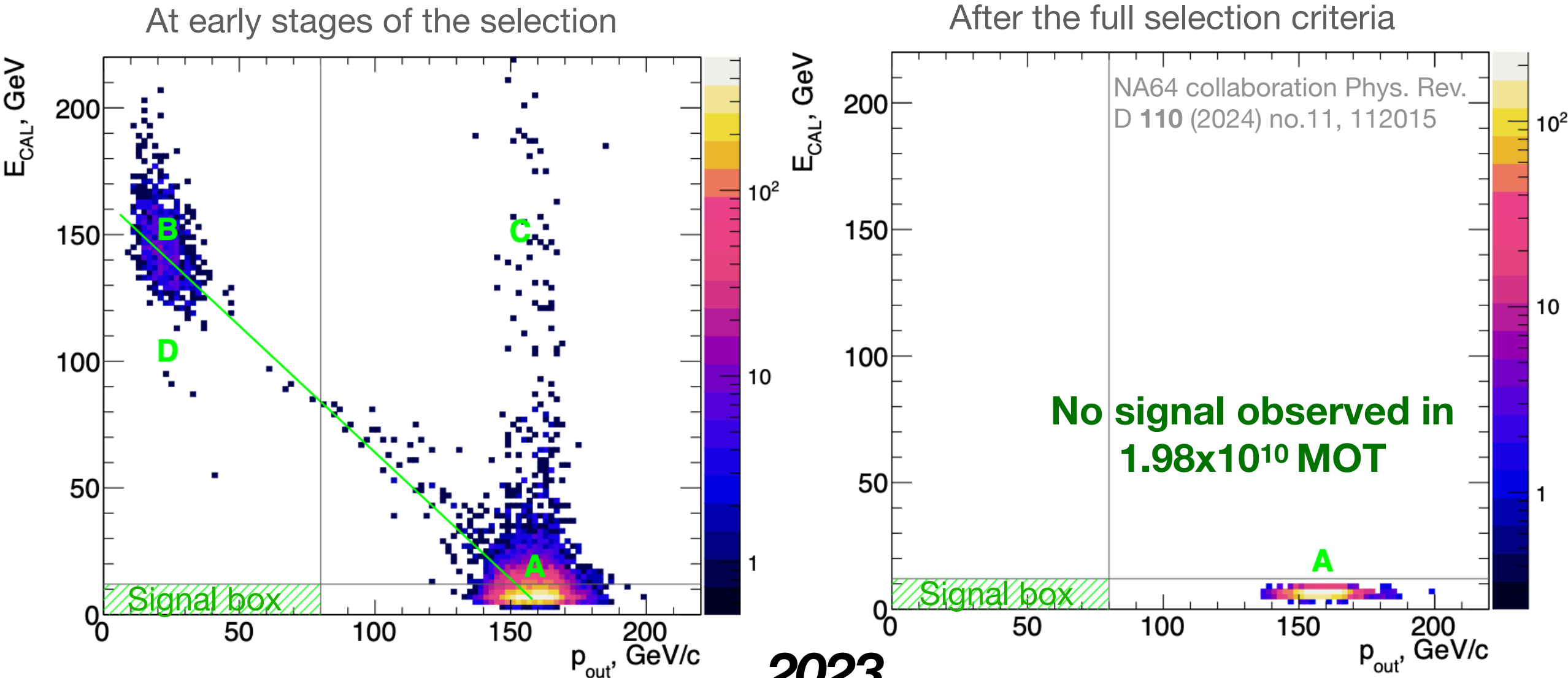
Technique + reconstruction

Analysis and results

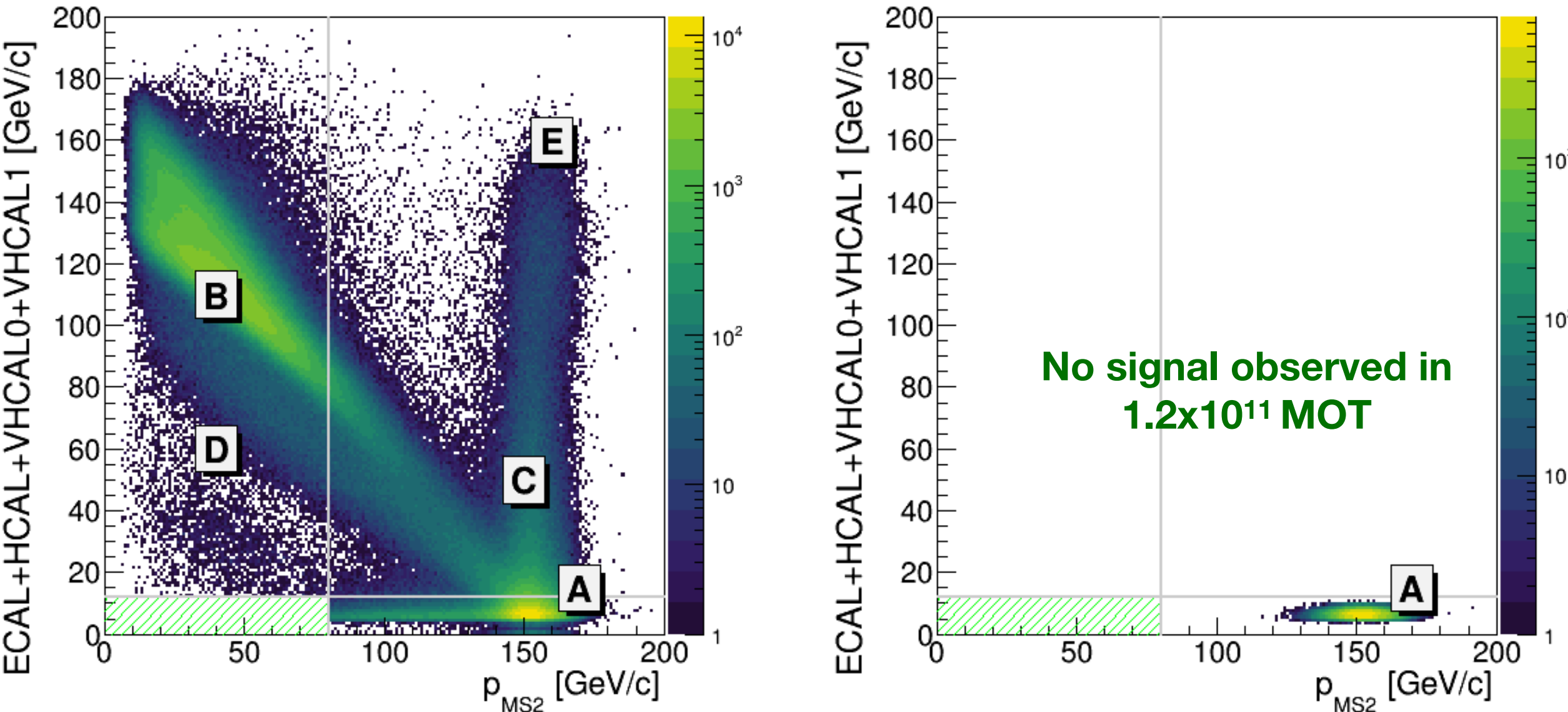
Outlook and summary

2023 campaign: impact of upgrades on analysis

2022

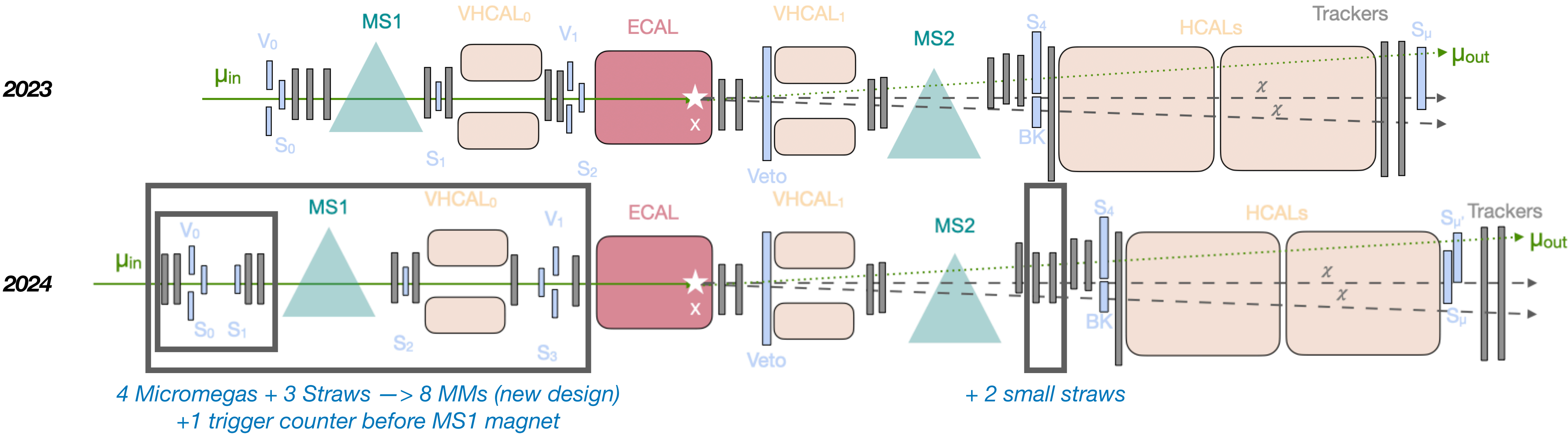


- As a result of improvements, the preliminary data selection efficiency was improved by a factor ~ 4 while running at $\sim 2\times$ higher intensity: **8x higher data extraction efficiency per time period**



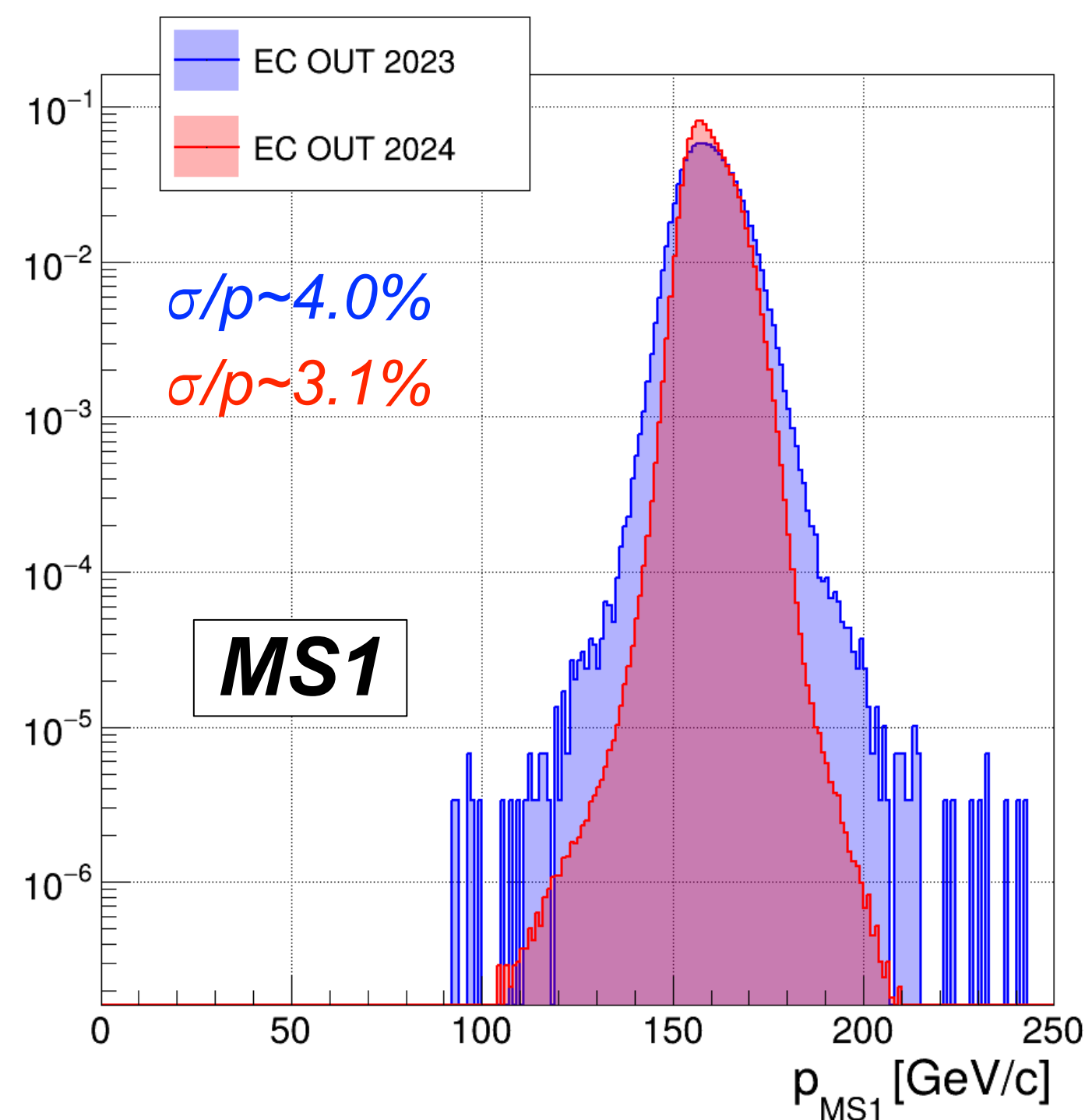
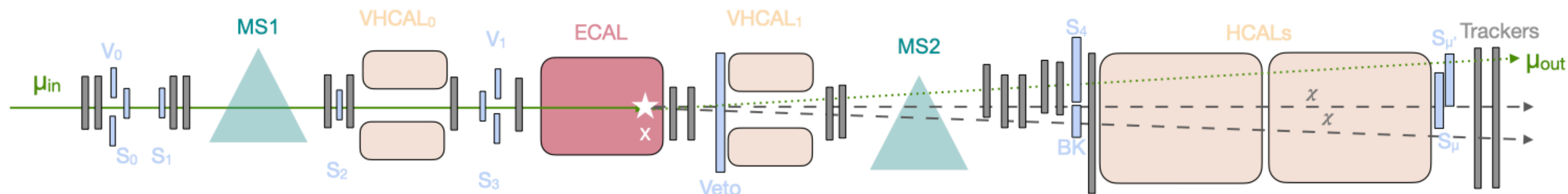
- Main bottleneck: Tracking efficiency ($\sim 20\%$) especially in MS1 due to low tracker efficiency and „multiplexing“ technology used in some of the trackers

2024 campaign: upgrades

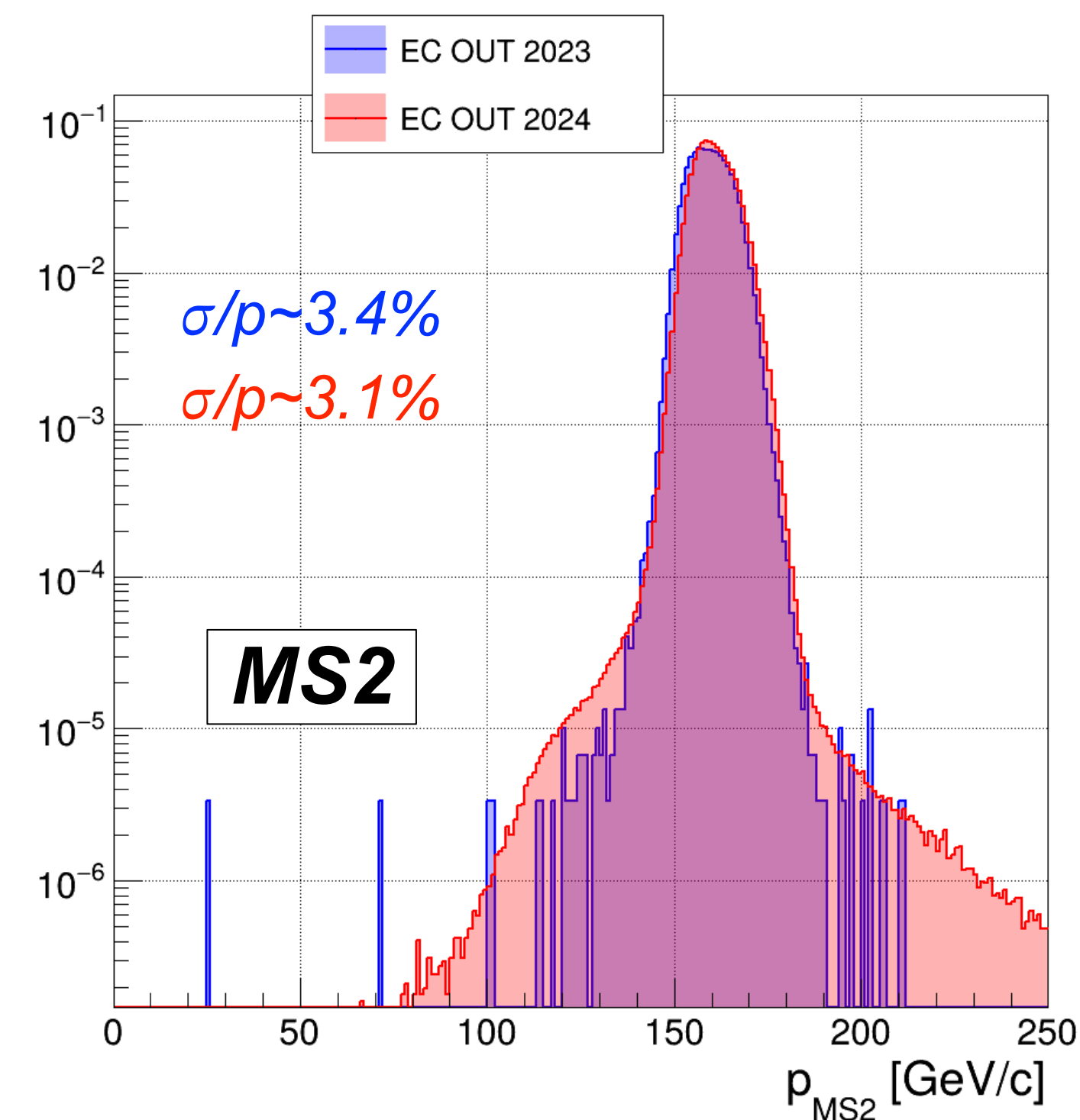


- Further upgrades (trigger): Beam trigger rate increased by factor 100

2024 campaign: same analysis as in 2023, but improved



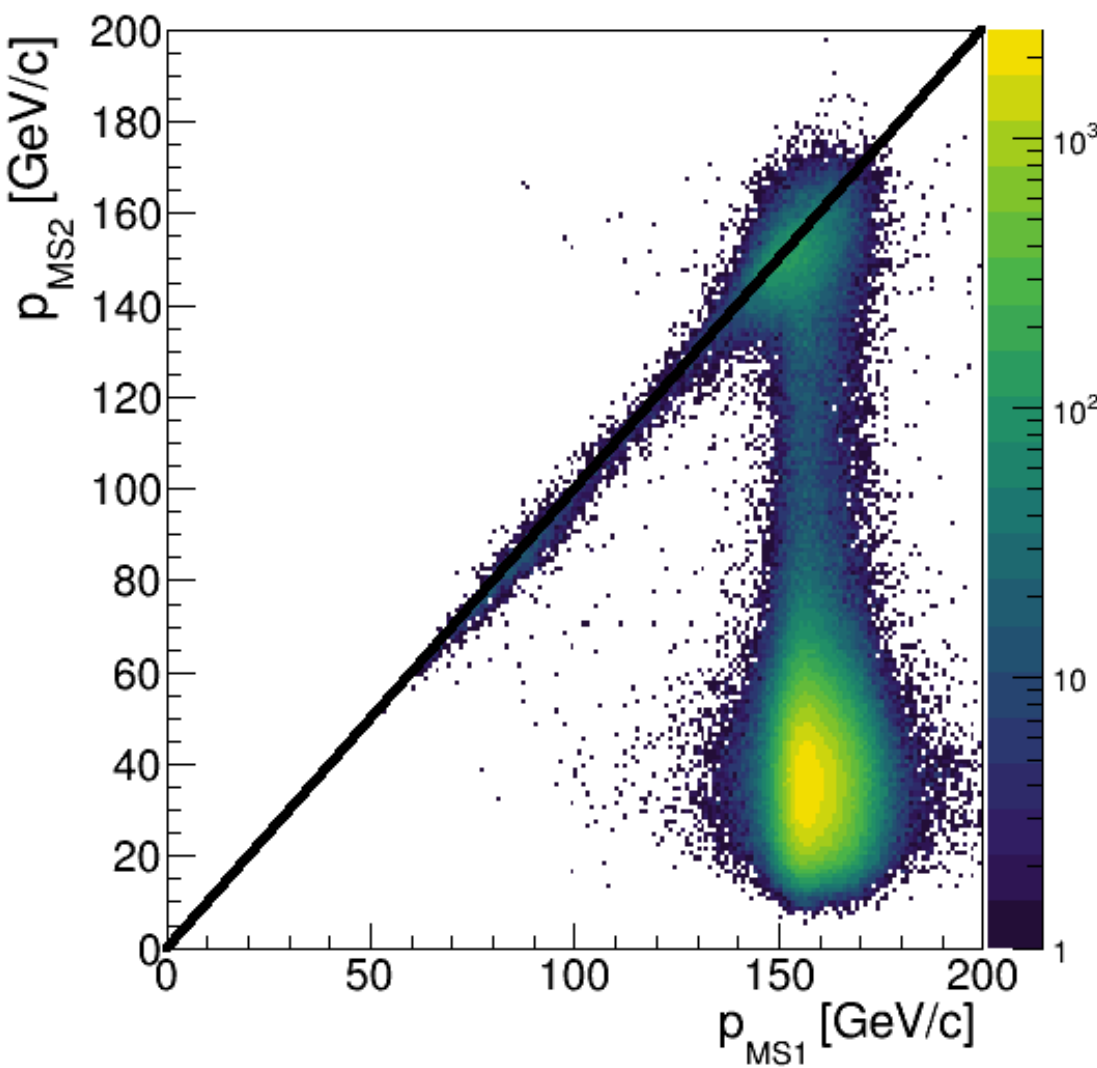
	eff. 2023	eff. 2024
MS2	52%	67%
MS1	42%	67%
MS1+MS2	22%	45%



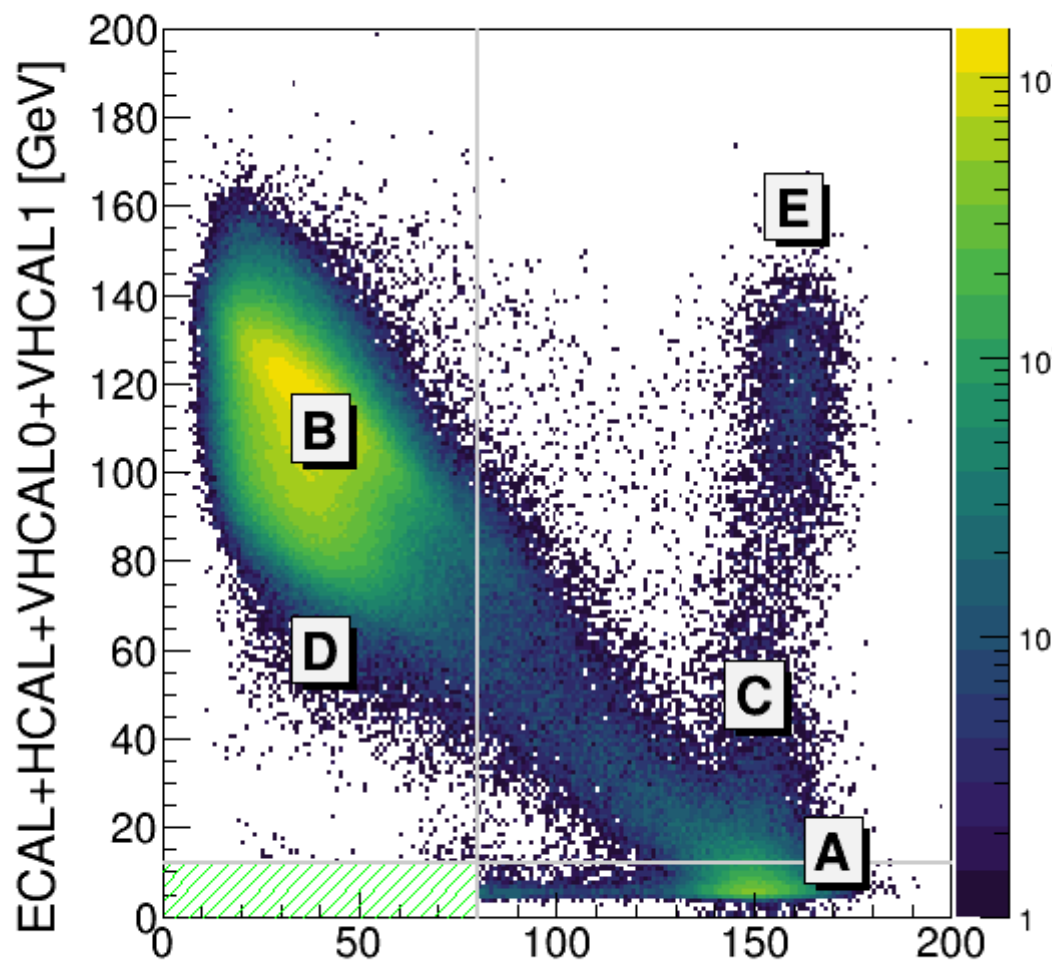
- Tracking efficiency doubled. Compared to 2022, that is **16x more data** in the same amount of time!
- Main bottleneck: still tracking efficiency. This can be improved by a factor 2-3 by using unmultiplexed MMs, improving the straw reconstruction and adapting the selection criteria to fully exploit the performance upgrade

2024 campaign: cut-flow analysis (still blinded)

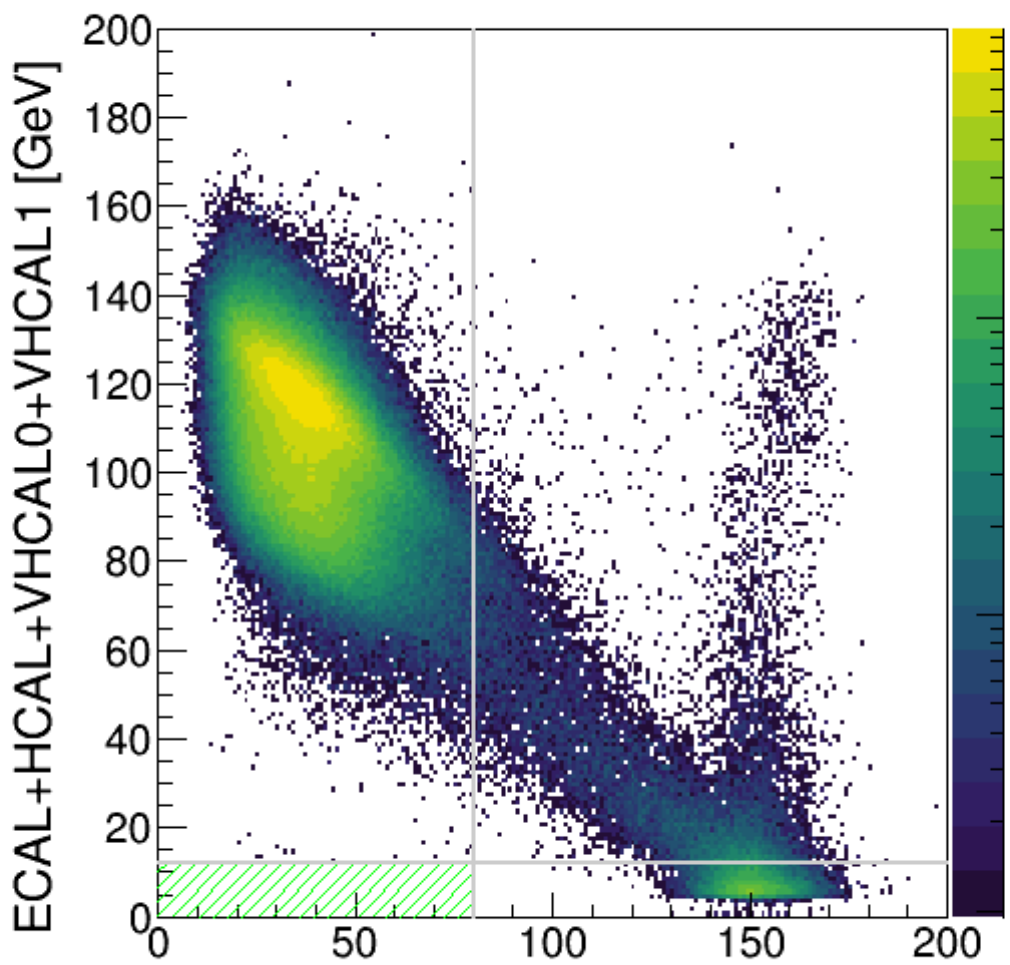
ECAL IN + phys trig. p2.3 (2023, 2.4e10 MOT)



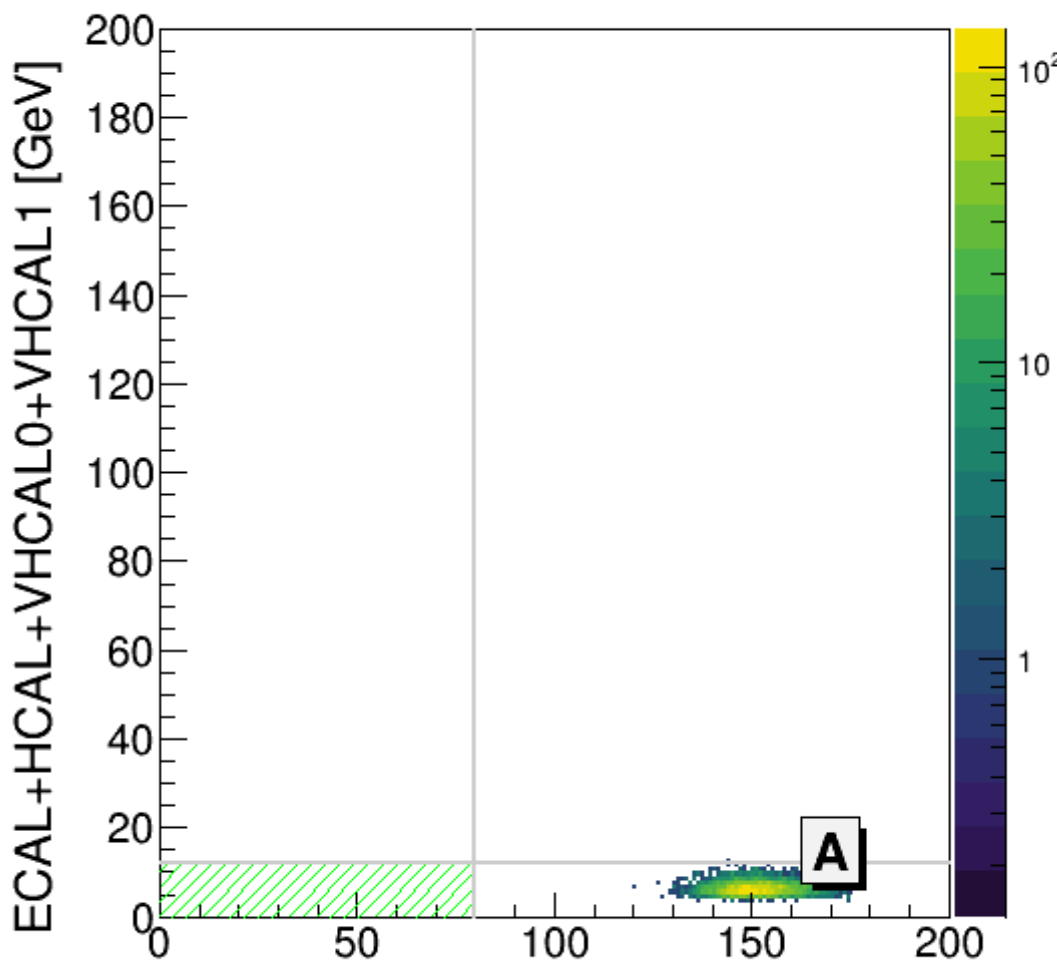
Good MS2 track



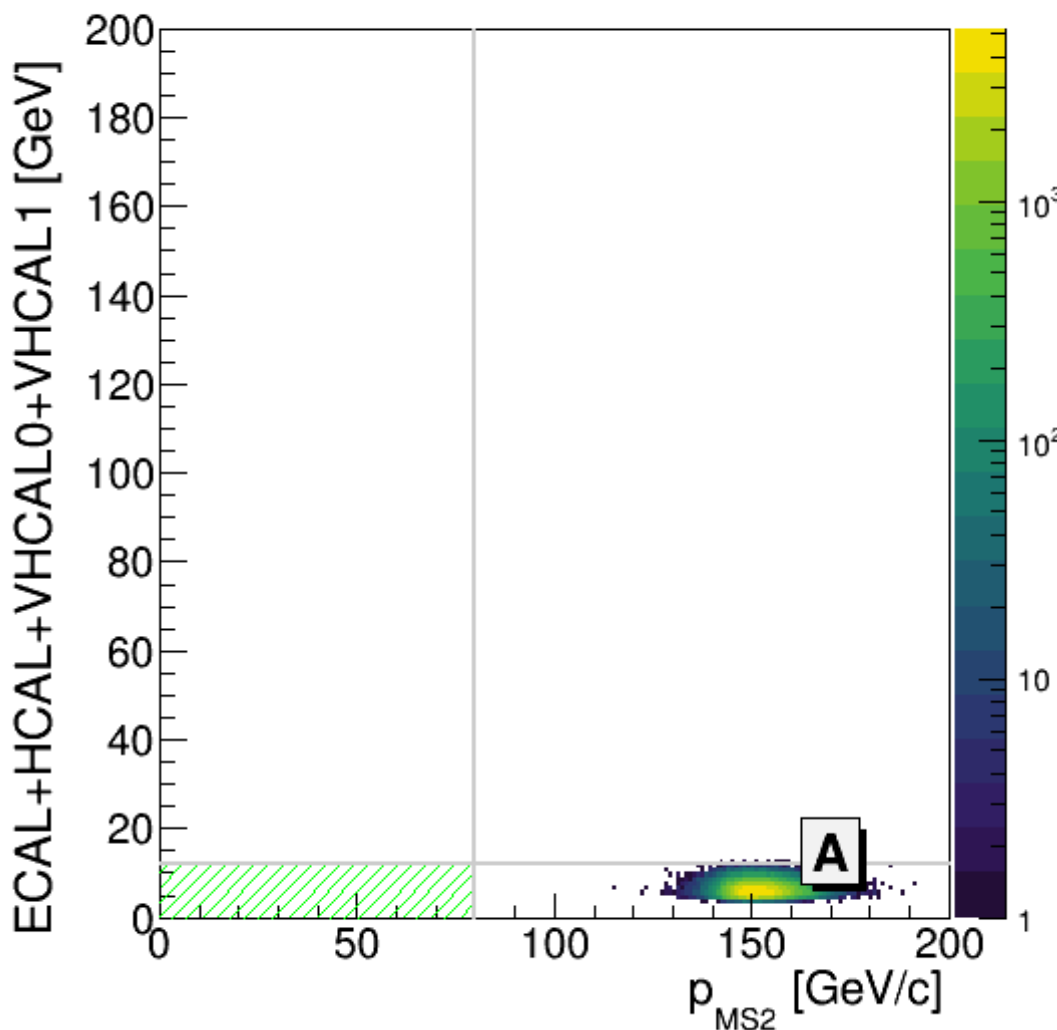
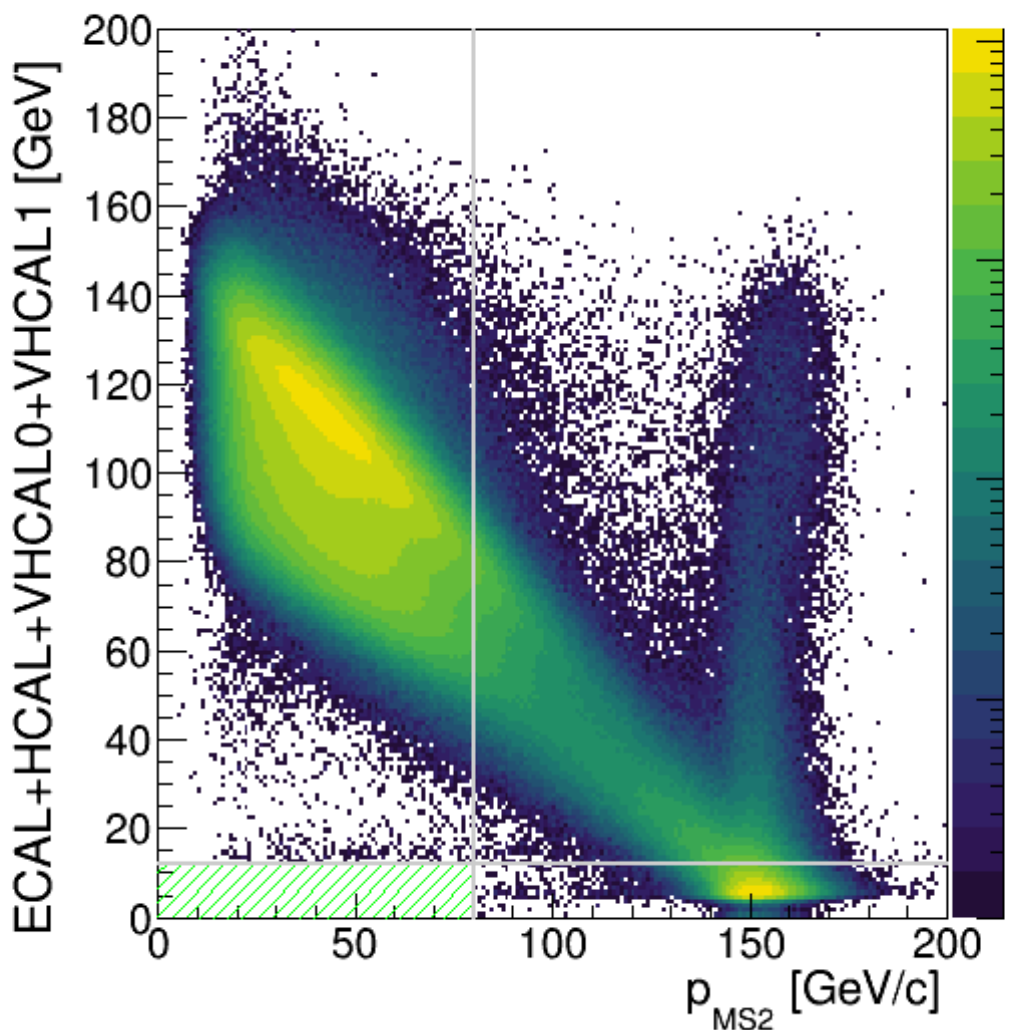
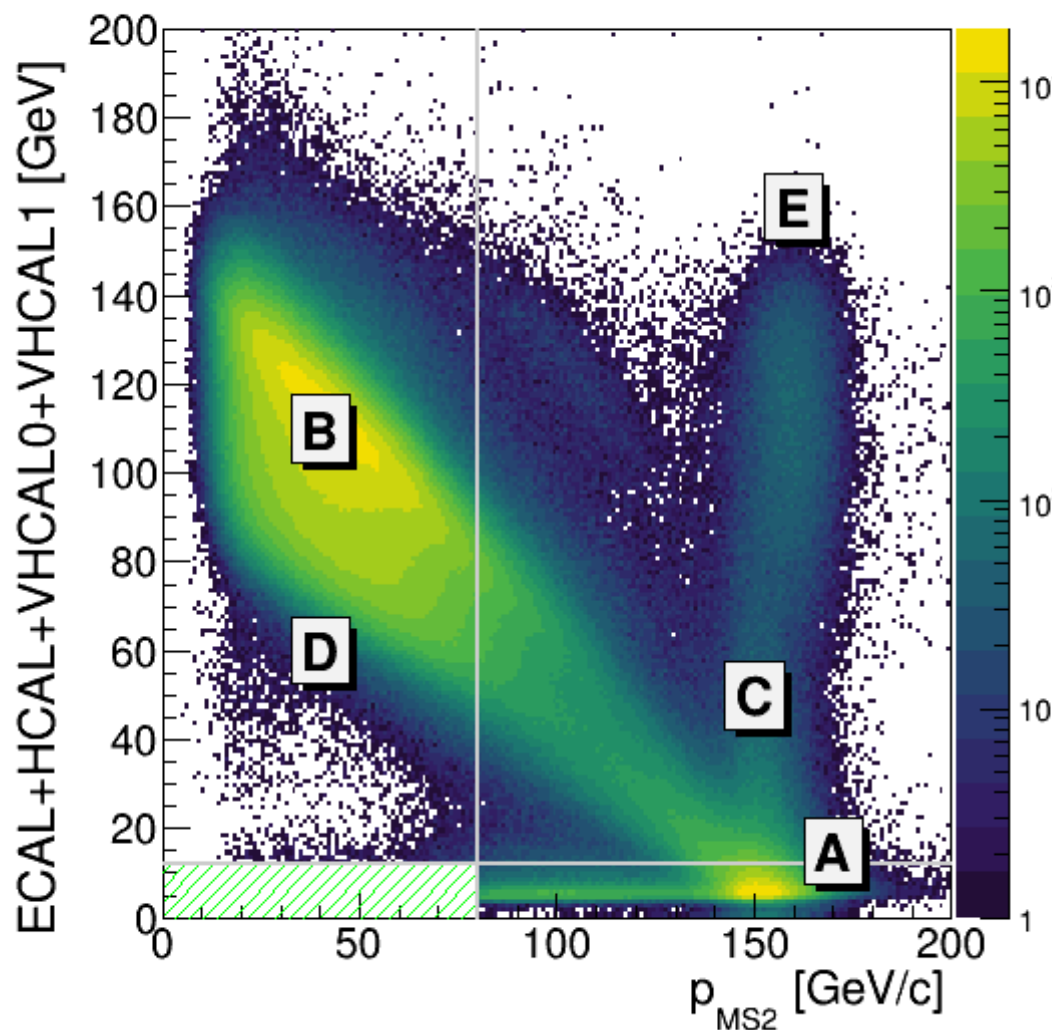
Good MS2+MS1 track+MS1 purity
momentum [140,180]



After all cuts



ECAL IN + phys trig. p3 (2024, 1.92e11 MOT)

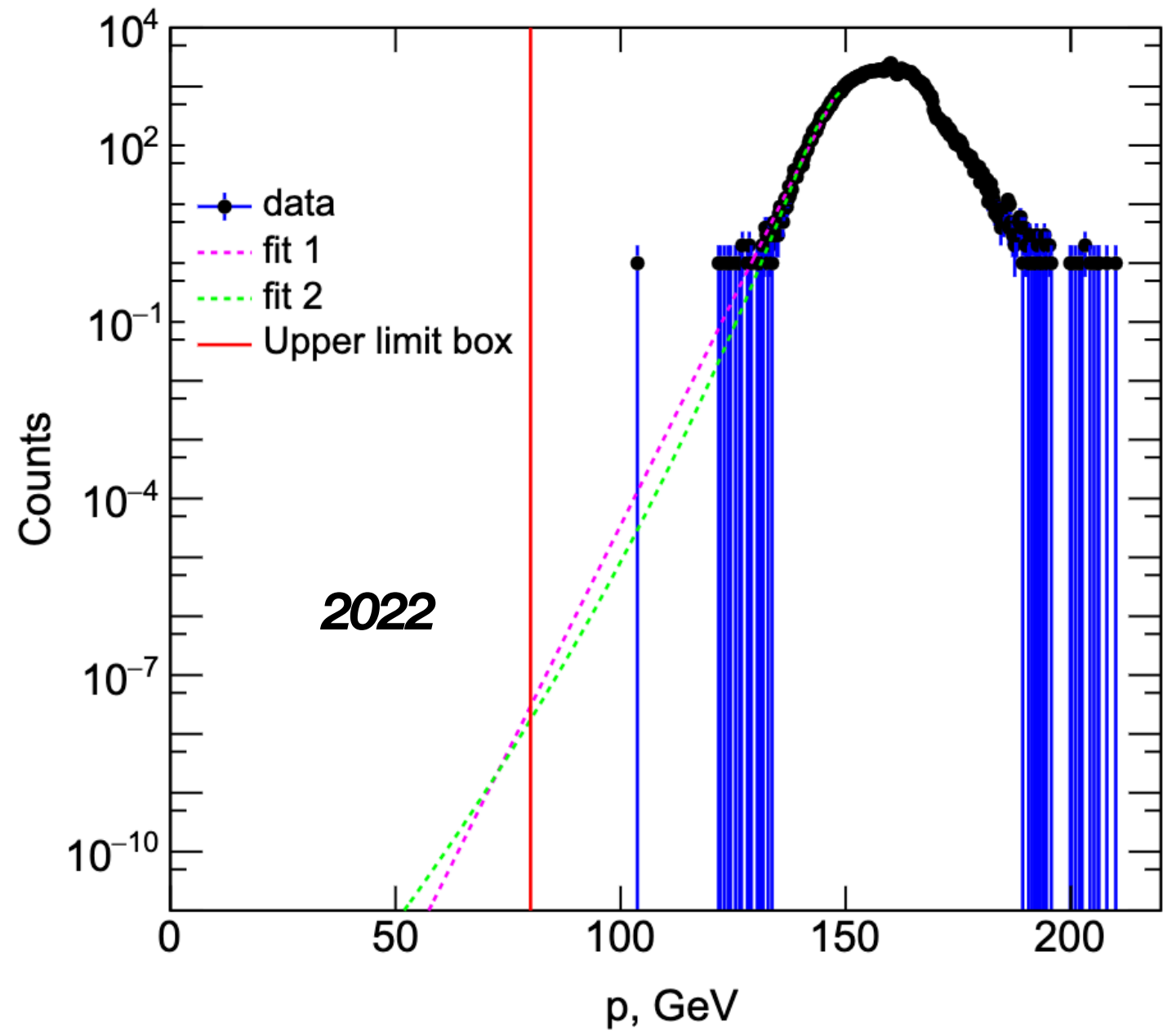


Backgrounds

2022

Background source	Background, n_{bkg}
(i) Single-hadron punch-through	$\ll 0.01$
(ii) Dimuon production	$\ll 0.01$
(iii) Detector nonhermeticity	< 0.01
(iv) Hadron in-flight decays	0.010 ± 0.001
(v) Momentum misreconstruction	0.045 ± 0.039
Total (conservatively) n_{bkg}	0.07 ± 0.04

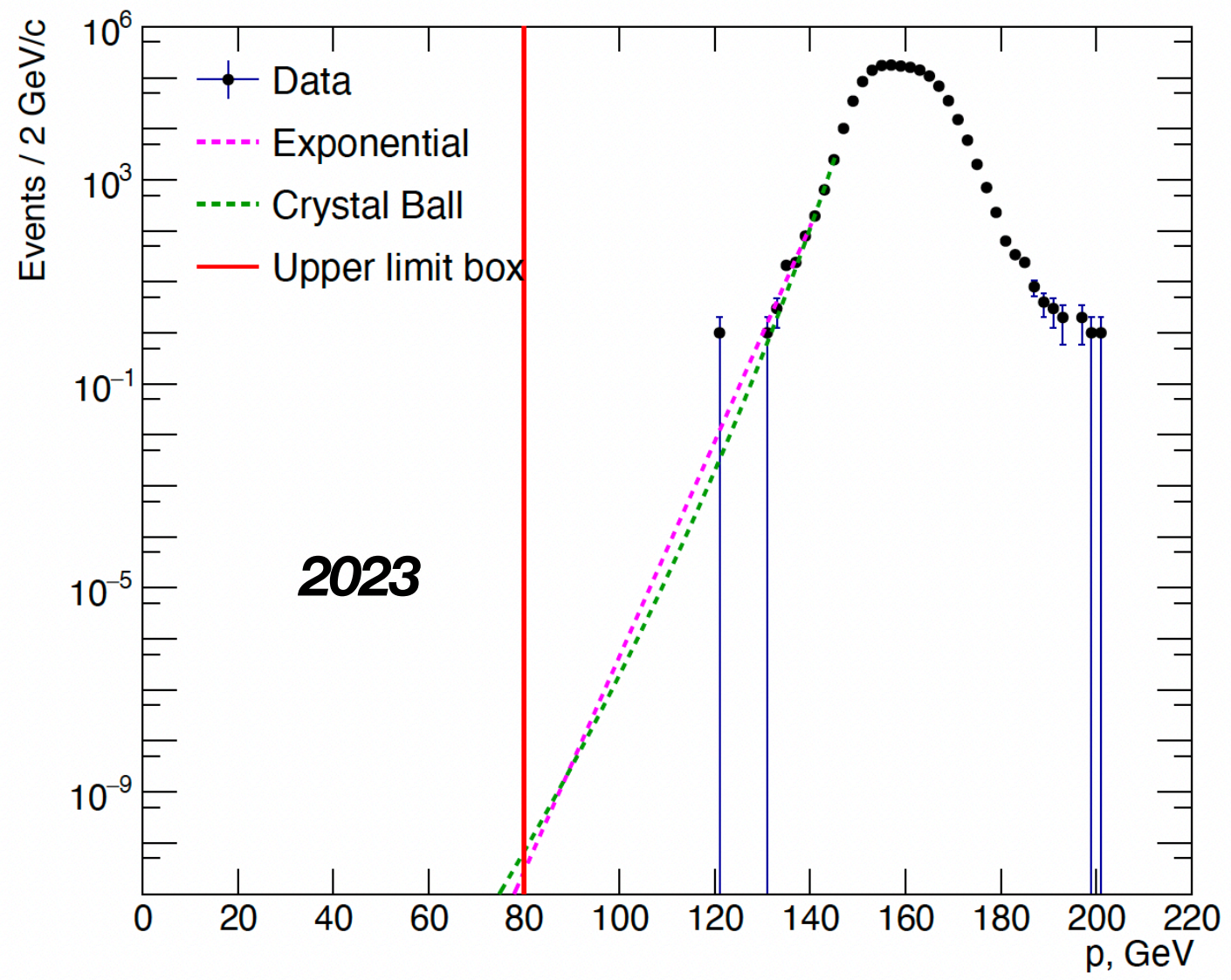
NA64 collaboration Phys. Rev. D **110** (2024) no.11, 112015



2023

Background source	Background, $n_{\text{bkg},2023}$	Upper limit
Momentum mis-reconstruction	$(7.6 \pm 2.5) \times 10^{-7}$	$< 10^{-5}$
Detector non-hermeticity	$(2.6 \pm 2.7) \times 10^{-6}$	$< 10^{-4}$
Multiple muons	$(2.1 \pm 0.06) \times 10^{-7}$	$< 10^{-6}$
Muon decay	$(2.9 \pm 0.2) \times 10^{-3}$	$< 10^{-2}$
Pile-up mis-reconstruction	$(1.108 \pm 0.001) \times 10^{-3}$	$< 10^{-2}$
Total (conservatively) n_{bkg}	$(4.0 \pm 0.2) \times 10^{-3}$	$< 2 \times 10^{-2}$

Similar backgrounds apply for 2024



Results: Sensitivity – what does it mean? (Z' example)

- The sensitivity is extracted from the total number of expected signal events $\mathcal{N}_{Z'}(M_{Z'}, \varepsilon_{Z'})$ at a trigger configuration t :

$$\mathcal{N}_{Z'}(M_{Z'}, \varepsilon_{Z'}) = \sum_t N_{Z'}^t = \sum_t \boxed{N_{MOT}^t} \cdot \boxed{\lambda_{pile-up}} \cdot \boxed{\kappa_{Z'}^t(M_{Z'})} \cdot \boxed{N_\sigma(M_{Z'})} \cdot \left(\frac{\boxed{\varepsilon_{Z'}}}{\varepsilon_{Z',bench}} \right)^2$$

• $\boxed{N_{MOT}^t}$: Number of muons hitting the target

• $\boxed{\lambda_{pile-up}}$: A correction factor accounting for tracking inefficiency arising from **pile-up**

• $\lambda_{pile-up} = 0.4 \rightarrow$ extracted from data for $5 \times 10^6 \mu/\text{spill}$ (all our good quality data collected with this intensity)

• $\boxed{\kappa_{Z'}^t(M_{Z'})}$: trigger $\times$ cut-flow $\times$ signal efficiency from MC signal events relative to beam trigger

• $\boxed{N_\sigma(M_{Z'})}$: cross-section normalisation factor

• $\boxed{\varepsilon_{Z',bench}}$: coupling parameter. $N_\sigma(M_{Z'}) \propto \varepsilon_{Z'}$, so normalisation factor is given for $\varepsilon_{Z',bench} = 10^{-4}$

- Assuming no systematics and **no background***, we can reject $S_{excluded} = \left\{ (M_{Z'}, \varepsilon_{Z'}) \mid \mathcal{N}_{Z'}(M_{Z'}, \varepsilon_{Z'}) > 2.3 \right\}$ at the 90% confidence level.

- Solving for $\varepsilon_{Z'}$:

$$\varepsilon_{Z'}(M_{Z'}) > \varepsilon_{Z',bench} \sqrt{\frac{2.3}{\boxed{N_{MOT}^t} \cdot \boxed{\lambda_{pile-up}} \cdot \boxed{\kappa_{Z'}^t(M_{Z'})} \cdot \boxed{N_\sigma(M_{Z'})}}}$$

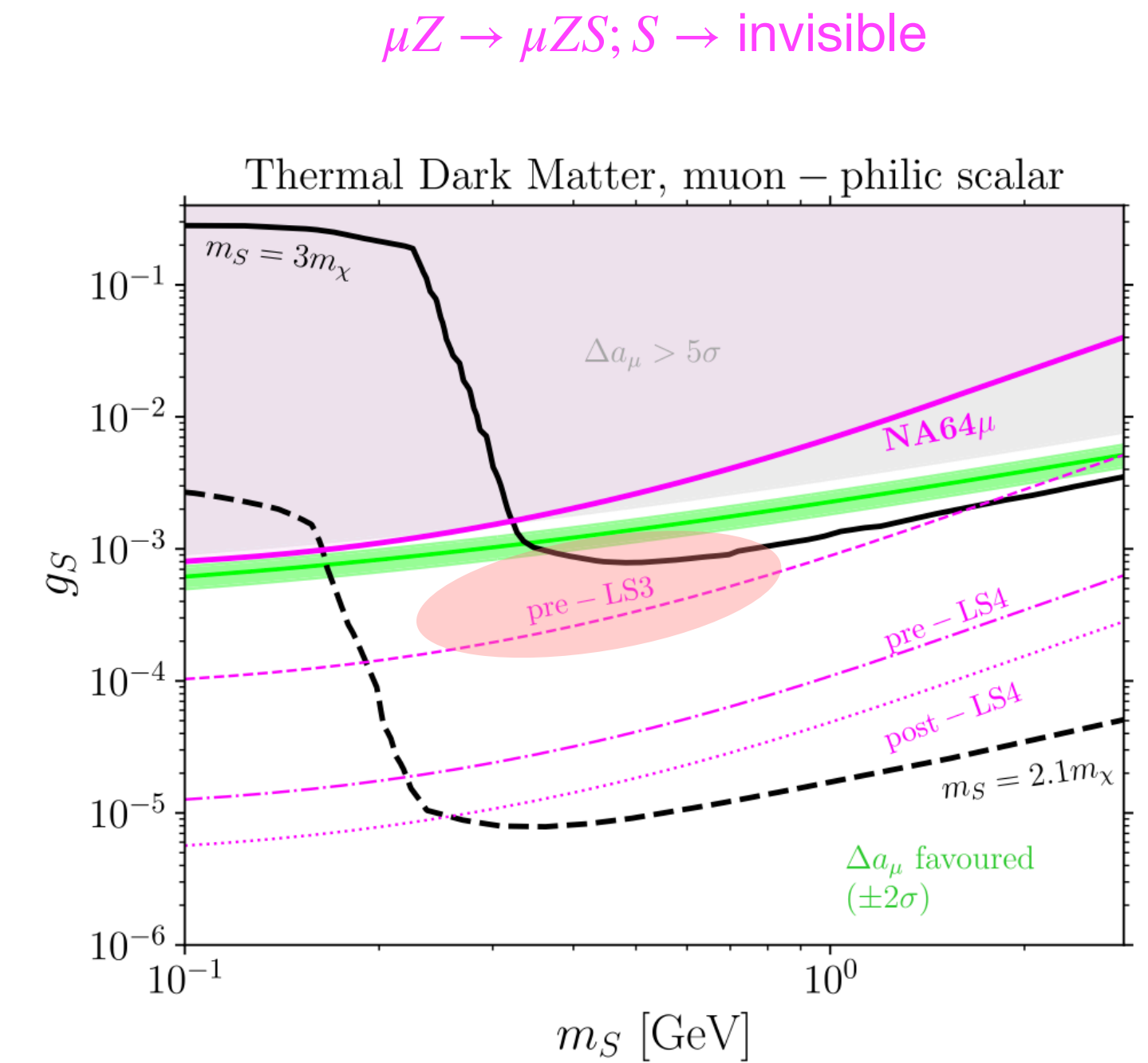
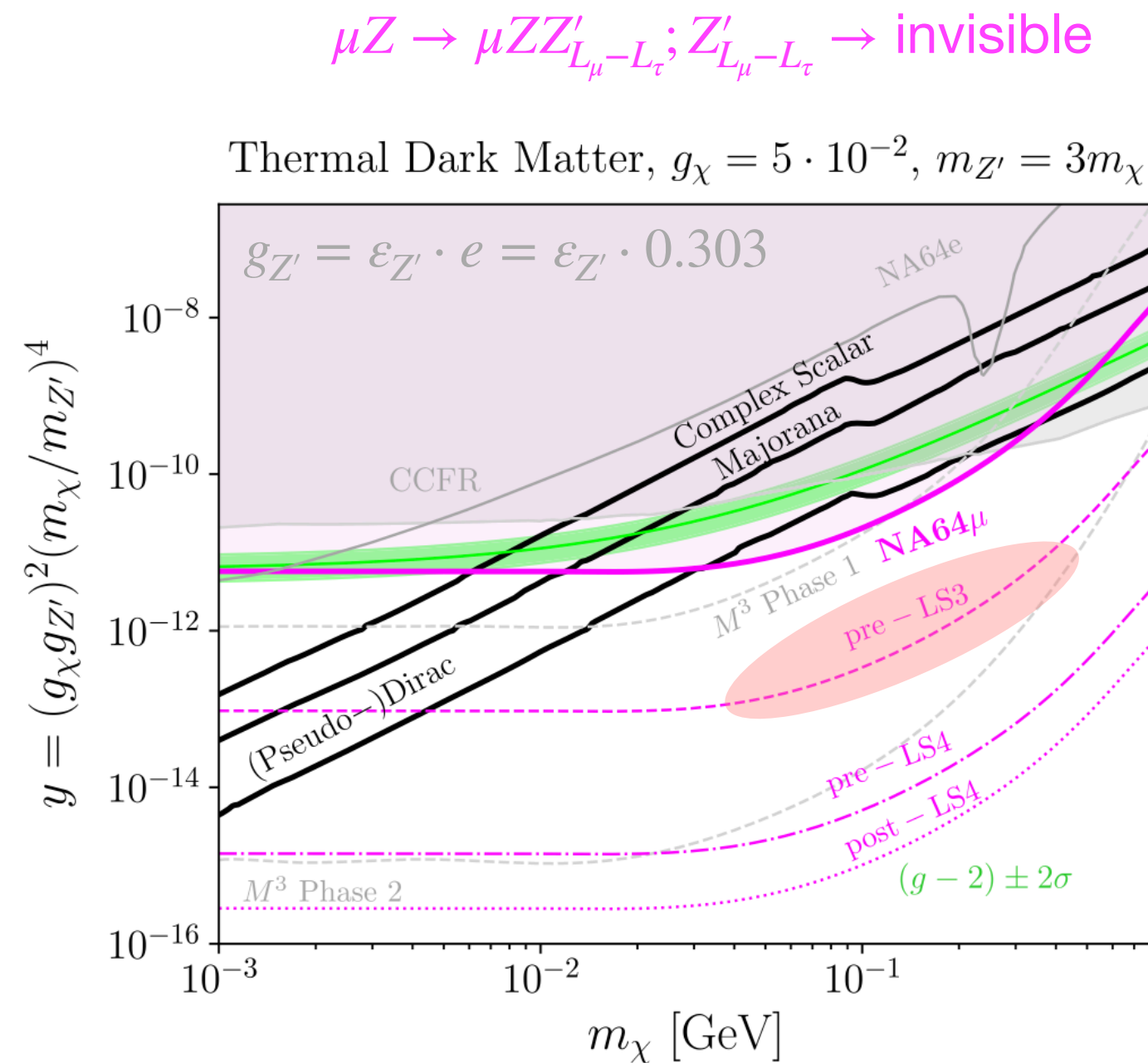
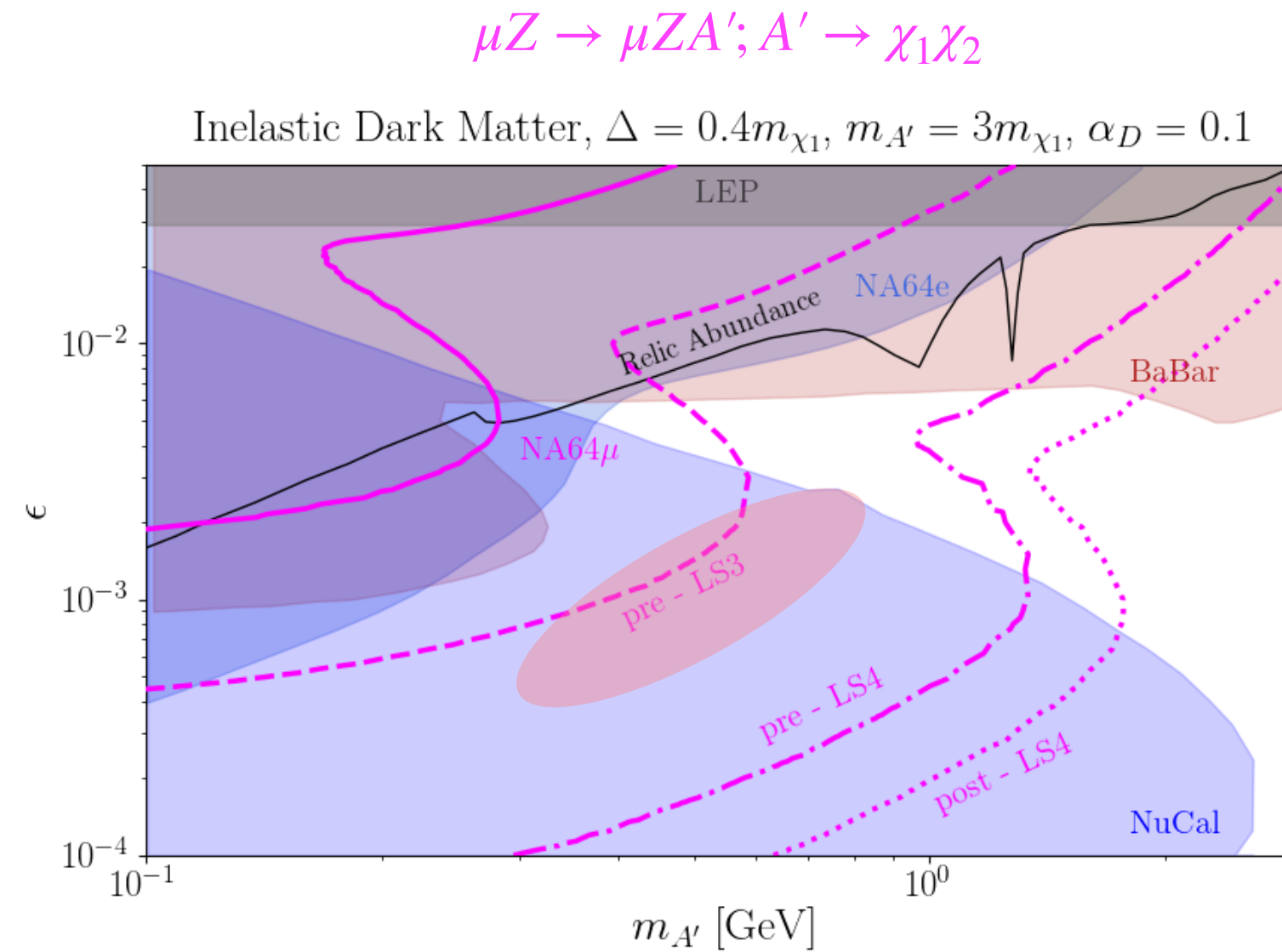
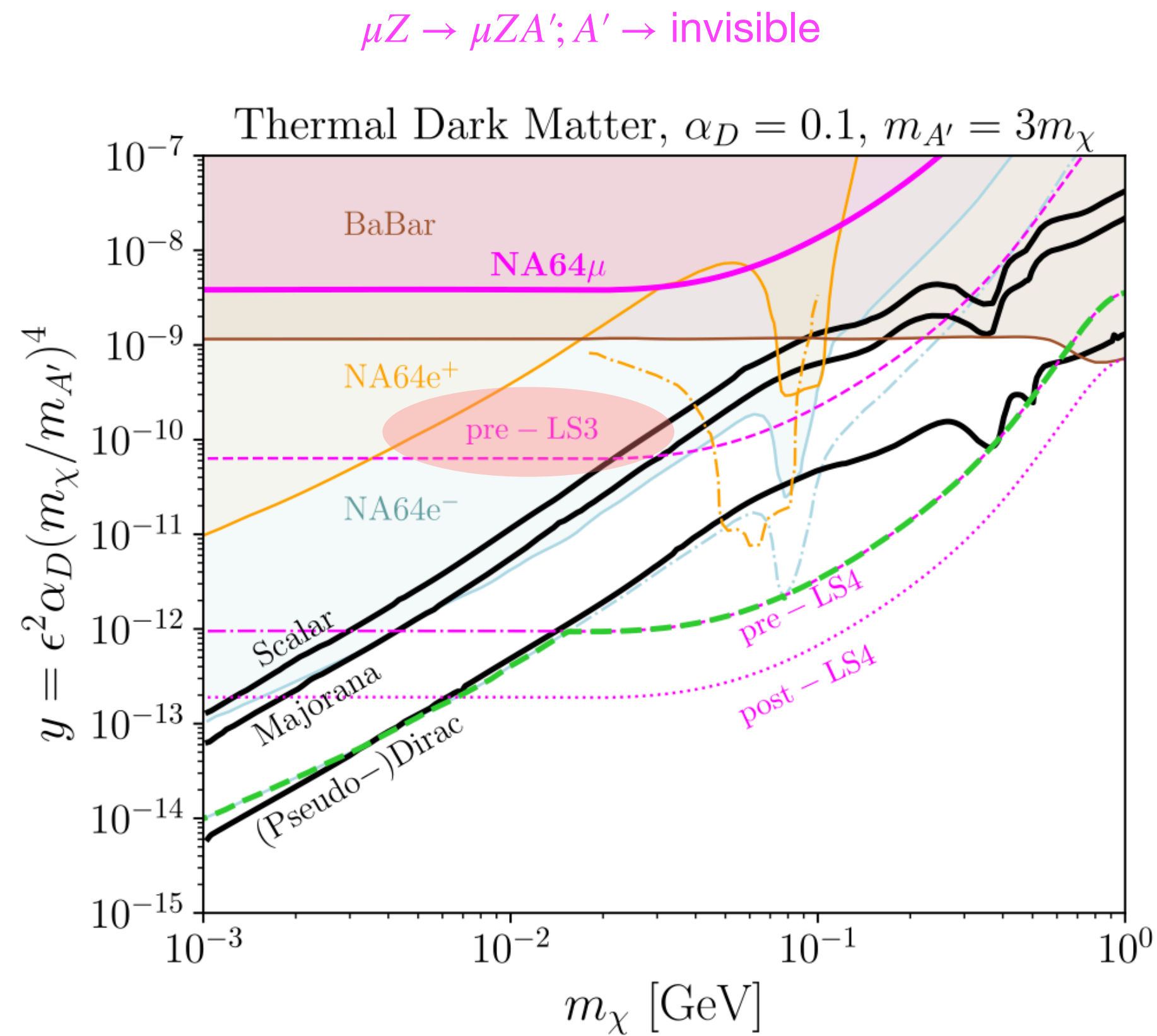
- The coupling can be scaled to other observables such as e.g. the annihilation rate: $y = \left(g_\chi \cdot 0.303 \cdot \varepsilon_{Z'} \right)^2 \left(m_\chi / m_{Z'} \right)^4 \rightarrow$ **see next slide**

* for the final sensitivity calculation, we use the combine tool of the CMS collaboration: <https://doi.org/10.1007/s41781-024-00121-4>

Prospects for LDM: *NA64μ*

NA64 collaboration Phys. Rev. D **110** (2024) no.11, 112015

LDM projections with the 2023-2024 (pre-LS3) statistics



We are currently designing the upgrade of the setup for the next phase after CERN shutdown.

Overview

The Dark Matter problem

The NA64 experiment

NA64 μ : muon mode

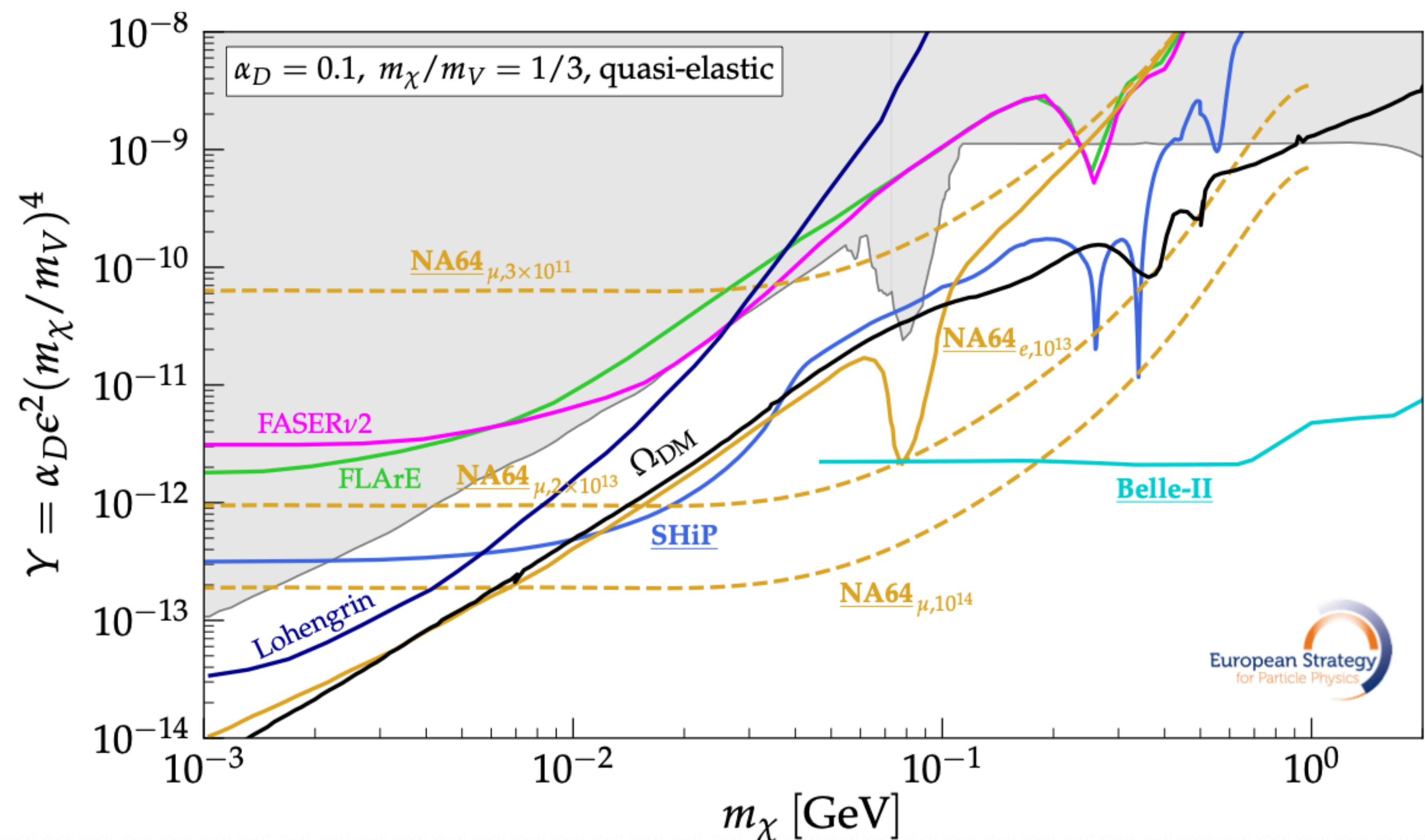
Technique + reconstruction

Analysis and results

Outlook and summary

Outlook and Summary

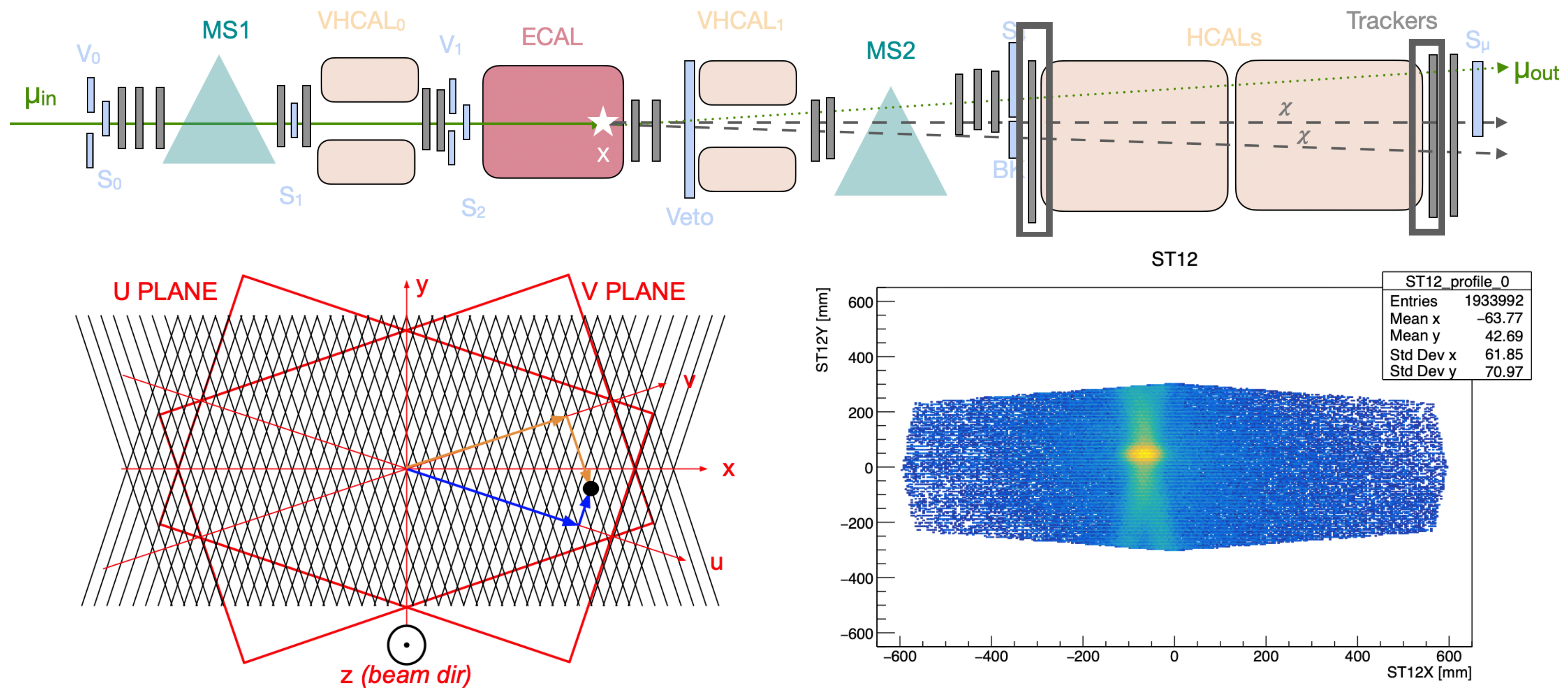
- The existence of Dark Sectors is an excellent framework to explain the composition of Dark Matter.
- Accelerator-based experiments offer unique opportunities to probe complementary to direct detection experiments the Light Dark Matter parameter space.
- Present and future fixed-target experiments offer unique sensitivity in probing the origin of DM and many other well-motivated New Physics scenarios below the electroweak scale such as ALPs, scalar, HNLs, ...



Thanks for your attention

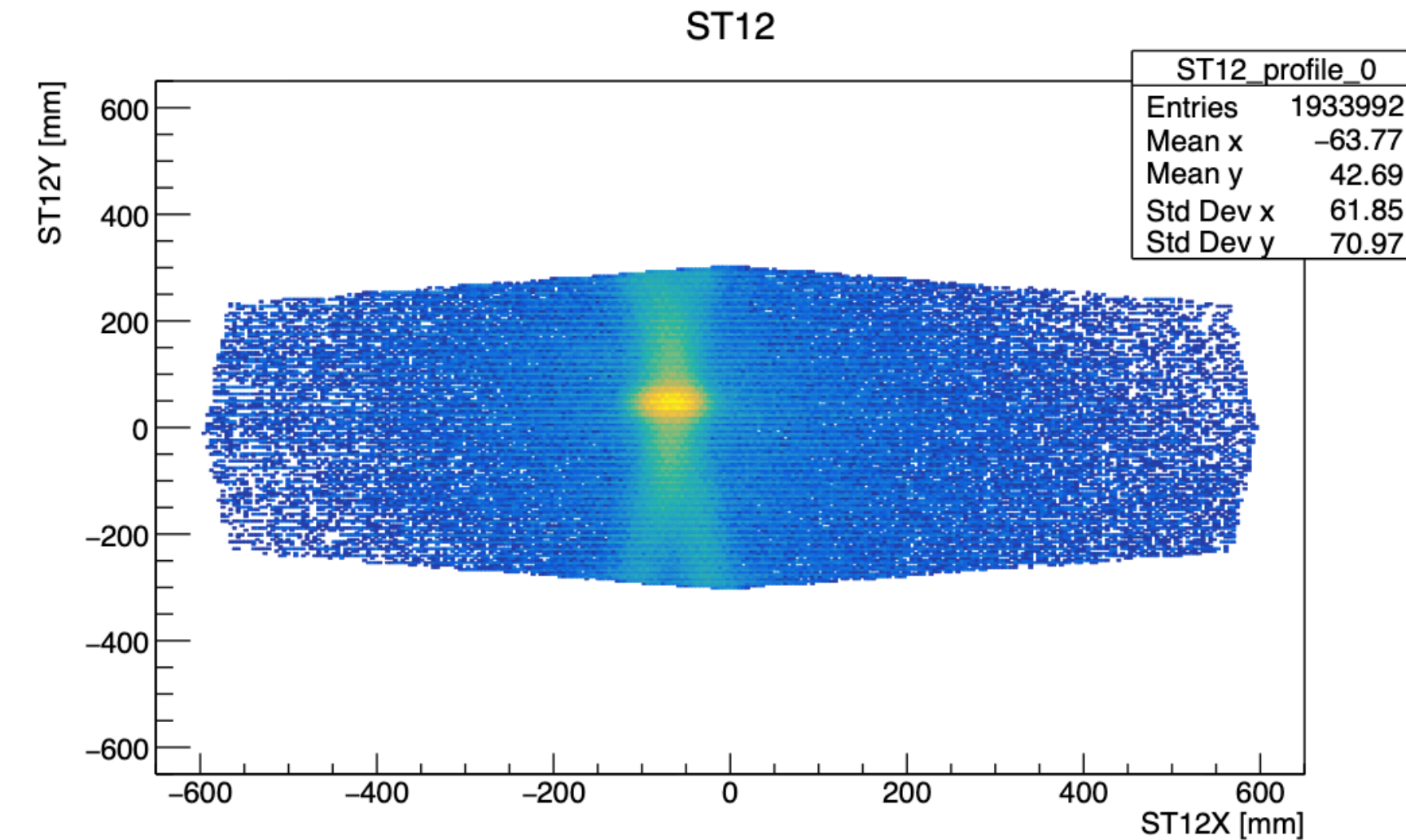
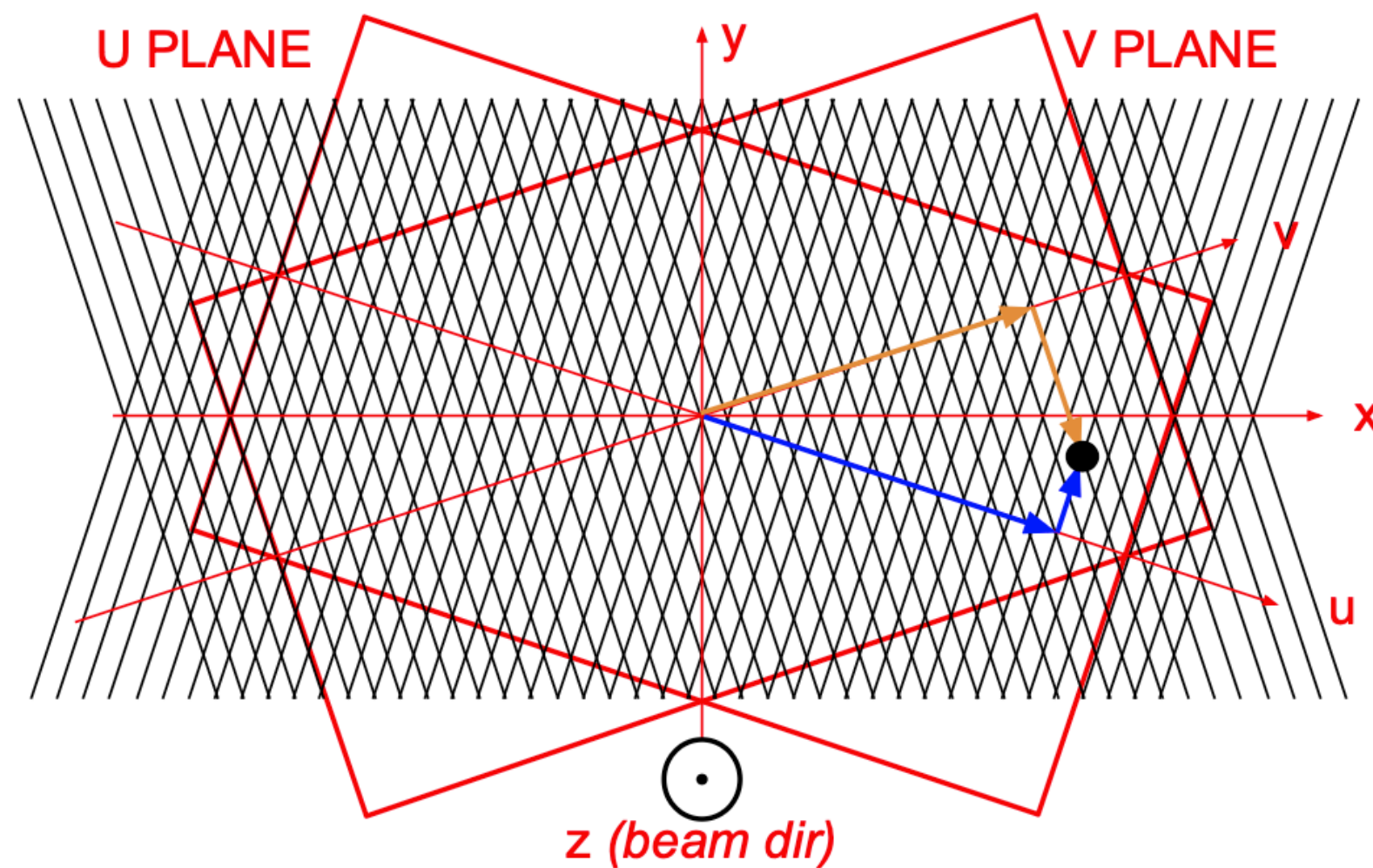
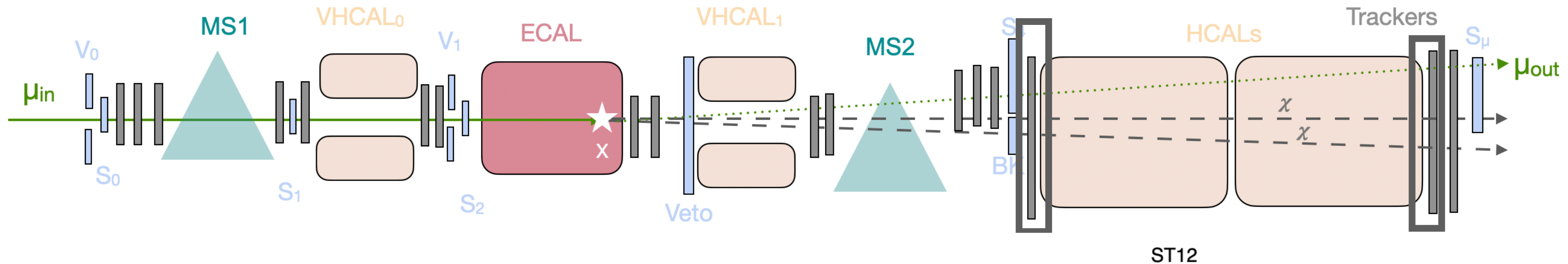


Hit reconstruction – UV straw chambers



- Big (120x60cm²) trackers to determine particle position at end of setup with more precision
- Unique property: wires are not orthogonal („UV“) —> transform coordinates!

Hit reconstruction – UV straw chambers



$$p_u = u \begin{pmatrix} \cos \varphi \\ -\sin \varphi \end{pmatrix} + s \begin{pmatrix} \sin \varphi \\ \cos \varphi \end{pmatrix} = \begin{pmatrix} \cos \varphi & \sin \varphi \\ -\sin \varphi & \cos \varphi \end{pmatrix} \begin{pmatrix} u \\ s \end{pmatrix}$$

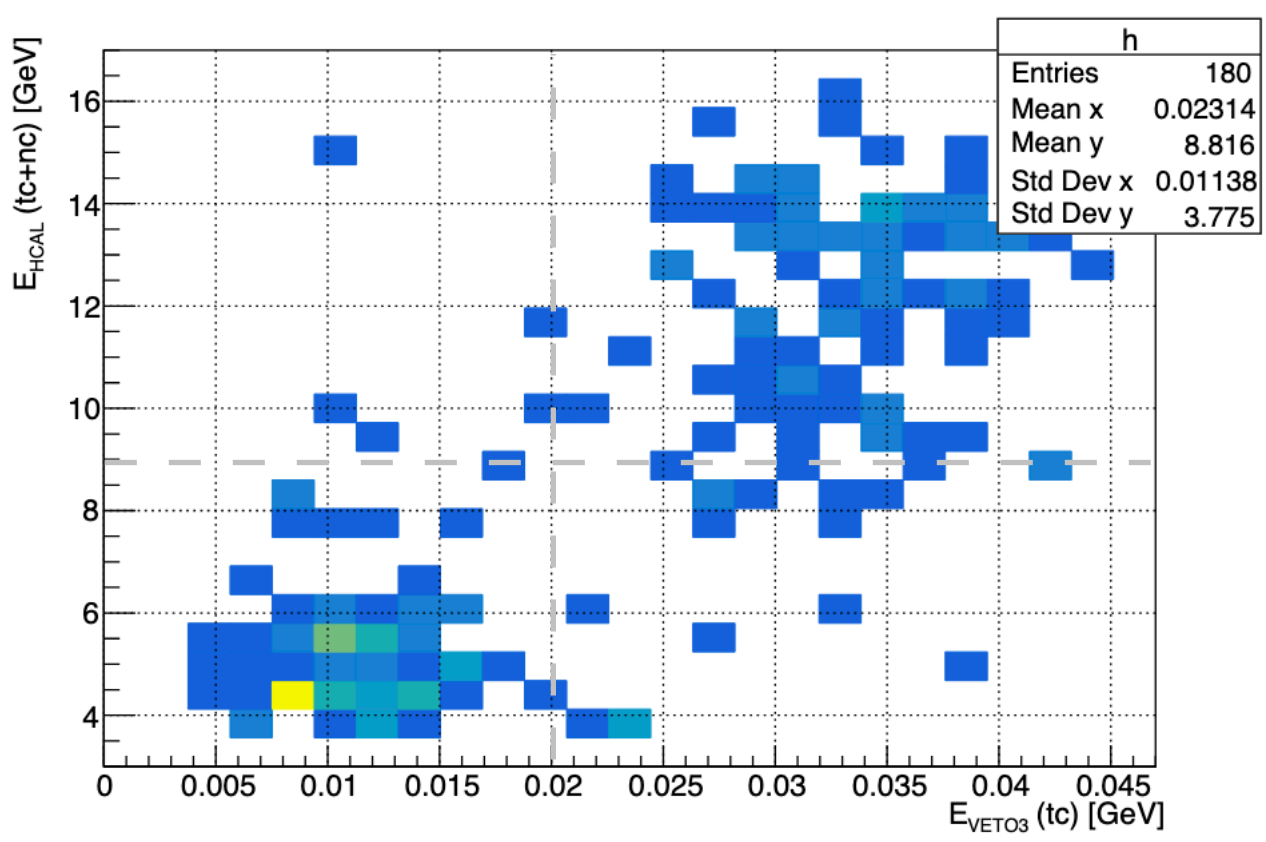
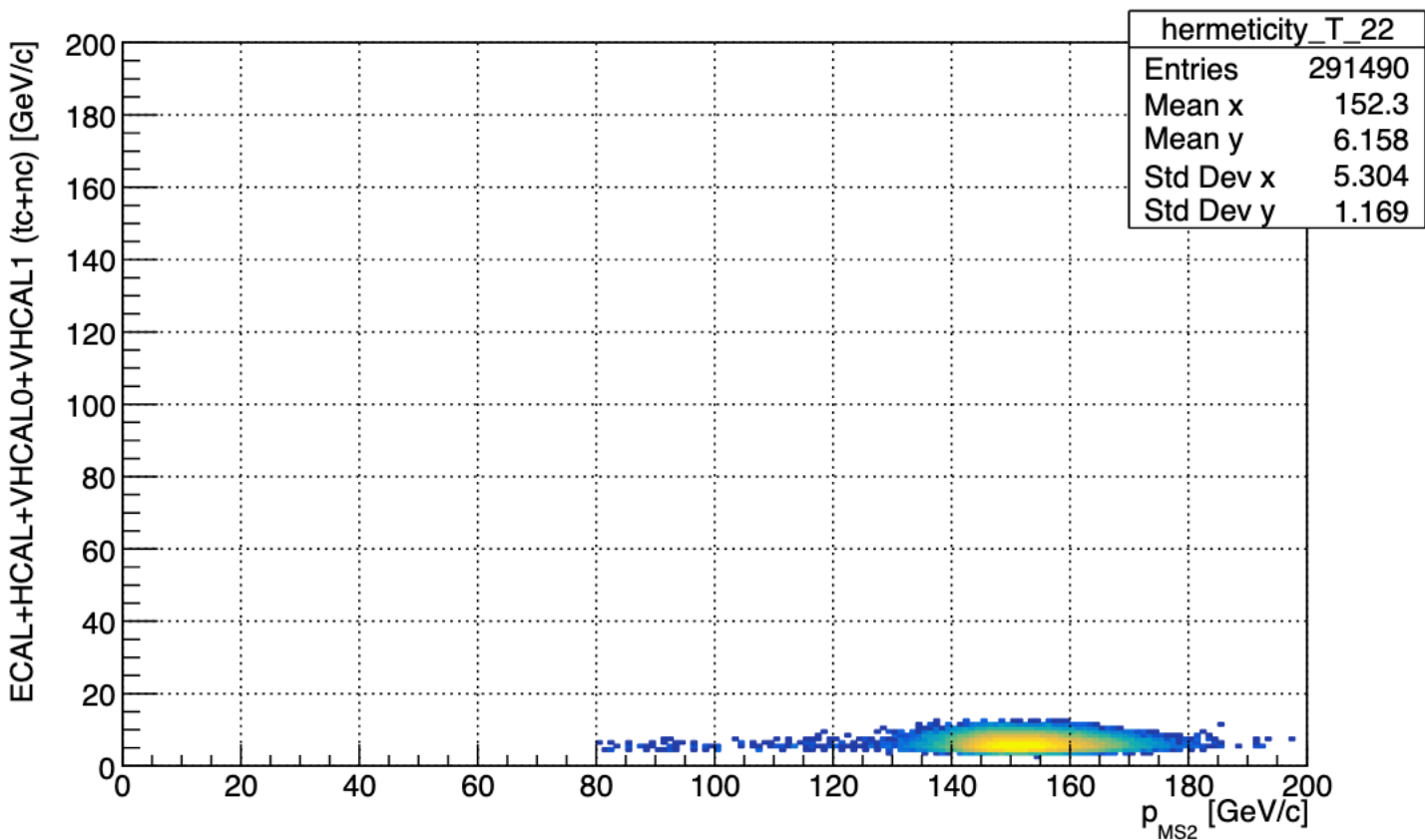
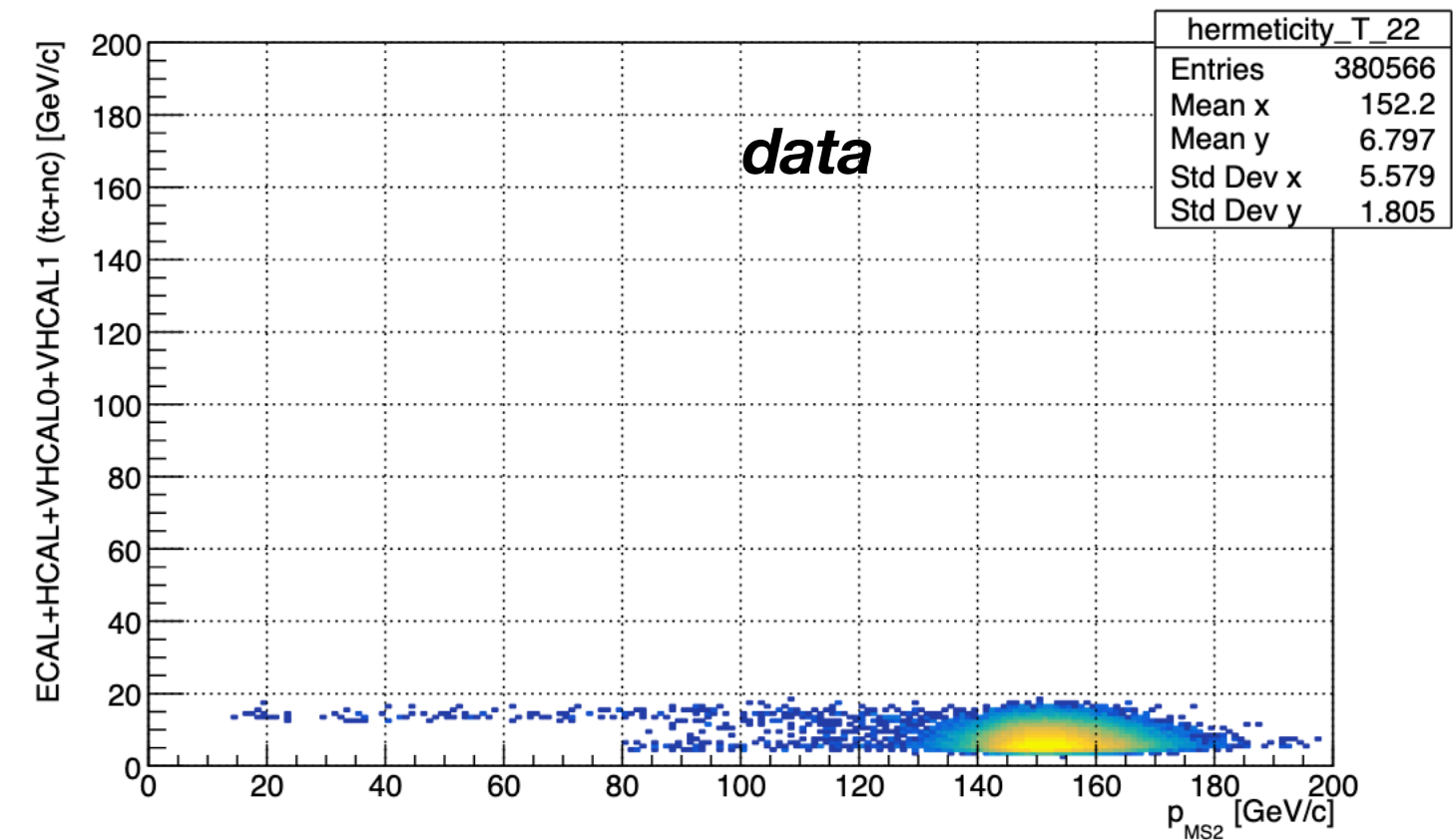
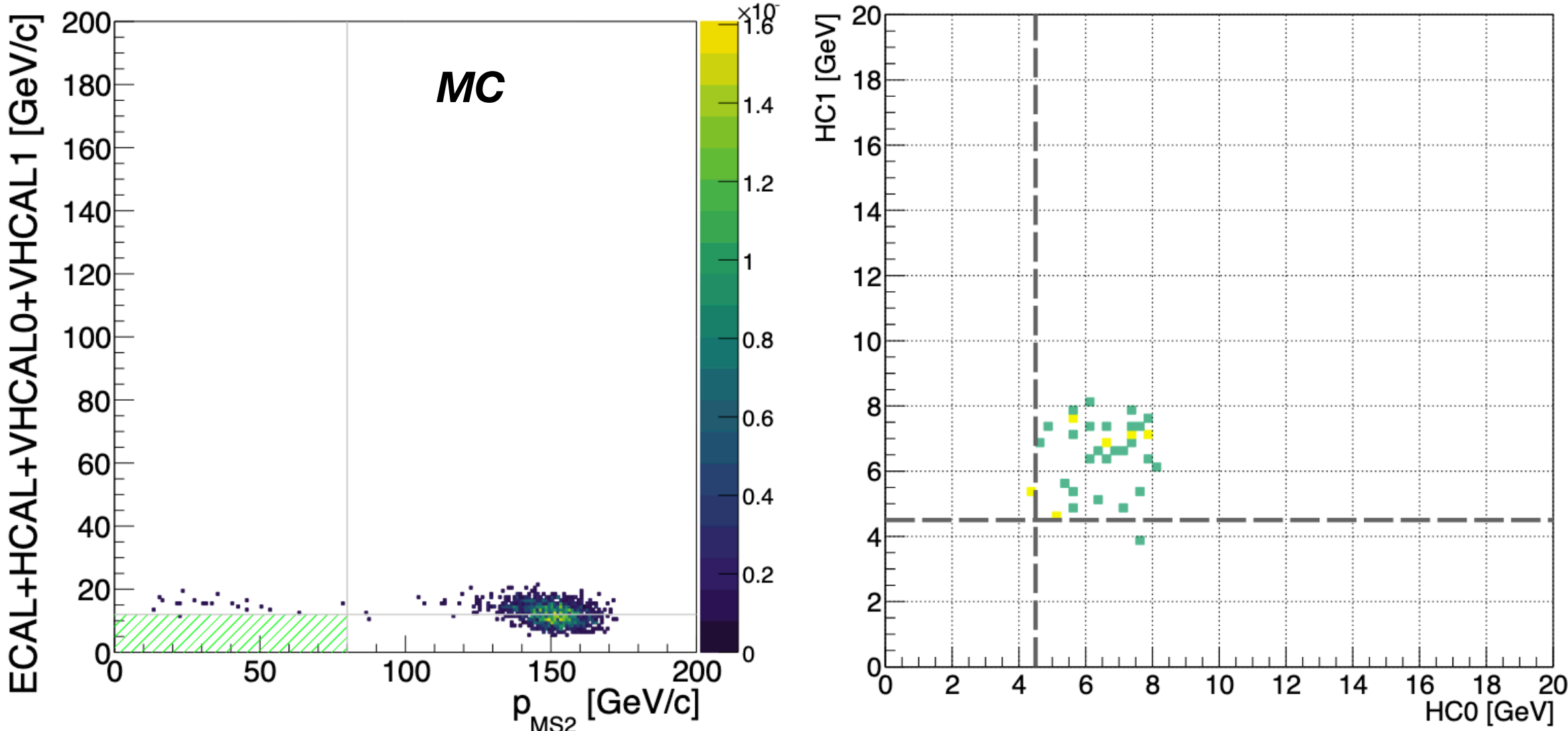
$$p_v = v \begin{pmatrix} \cos \varphi \\ \sin \varphi \end{pmatrix} + t \begin{pmatrix} -\sin \varphi \\ \cos \varphi \end{pmatrix} = \begin{pmatrix} \cos \varphi & -\sin \varphi \\ \sin \varphi & \cos \varphi \end{pmatrix} \begin{pmatrix} v \\ t \end{pmatrix}$$

$$s = \frac{v - u \cdot \cos 2\varphi}{\sin 2\varphi} \quad t = \frac{v \cdot \cos 2\varphi - u}{\sin 2\varphi} \quad s, t \in (-300, 300)$$

$$\begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} u \cos \varphi + \left(\frac{1}{2} (v - u) \cot \varphi + \frac{1}{2} (v + u) \tan \varphi \right) \sin \varphi \\ -u \sin \varphi + \left(\frac{1}{2} (v - u) \cot \varphi + \frac{1}{2} (v + u) \tan \varphi \right) \cos \varphi \end{pmatrix}$$

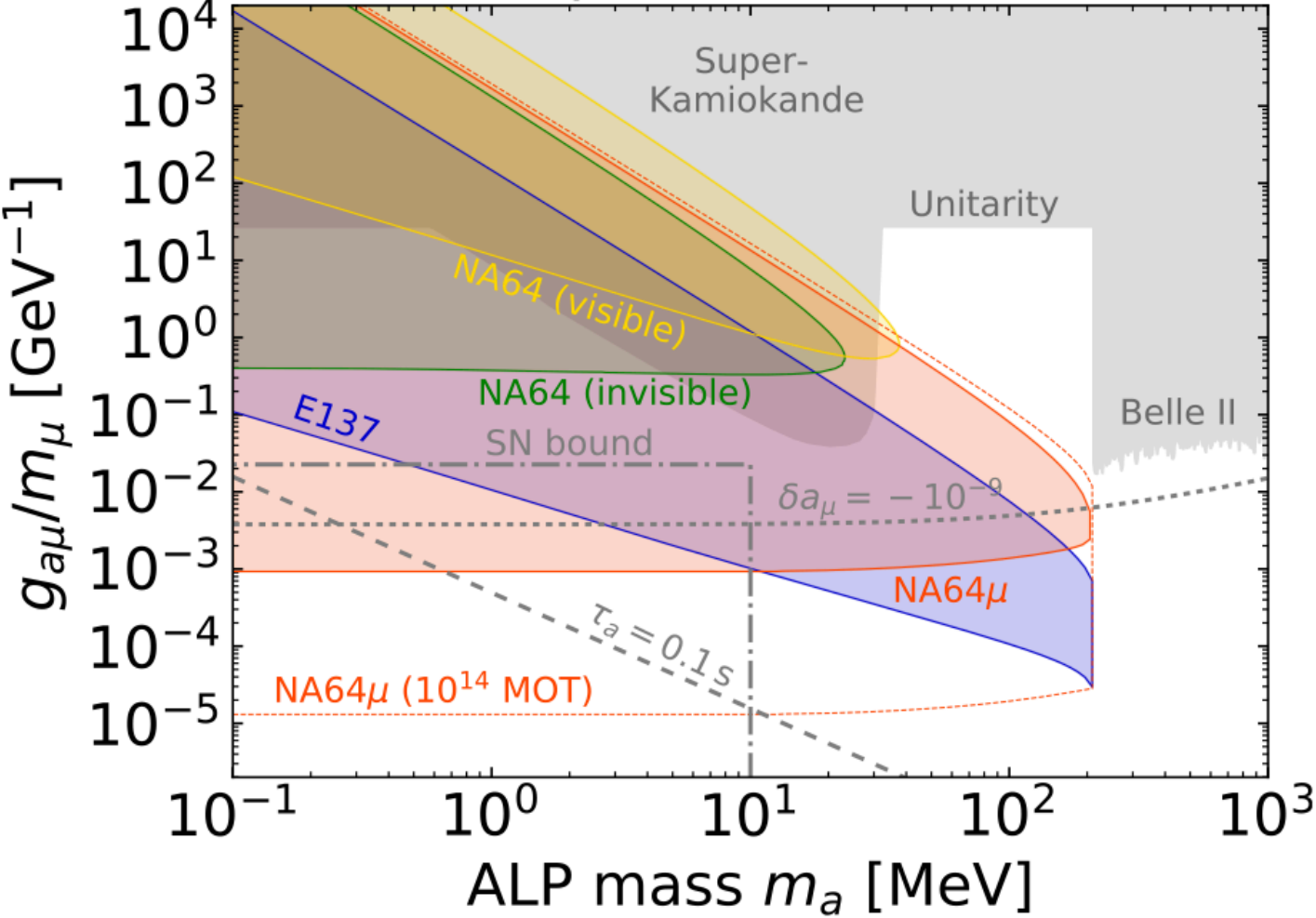
—> These conditions are essential to impose the limits of physical solutions which also gives rise to the octagonal shape

Backgrounds: dimuons

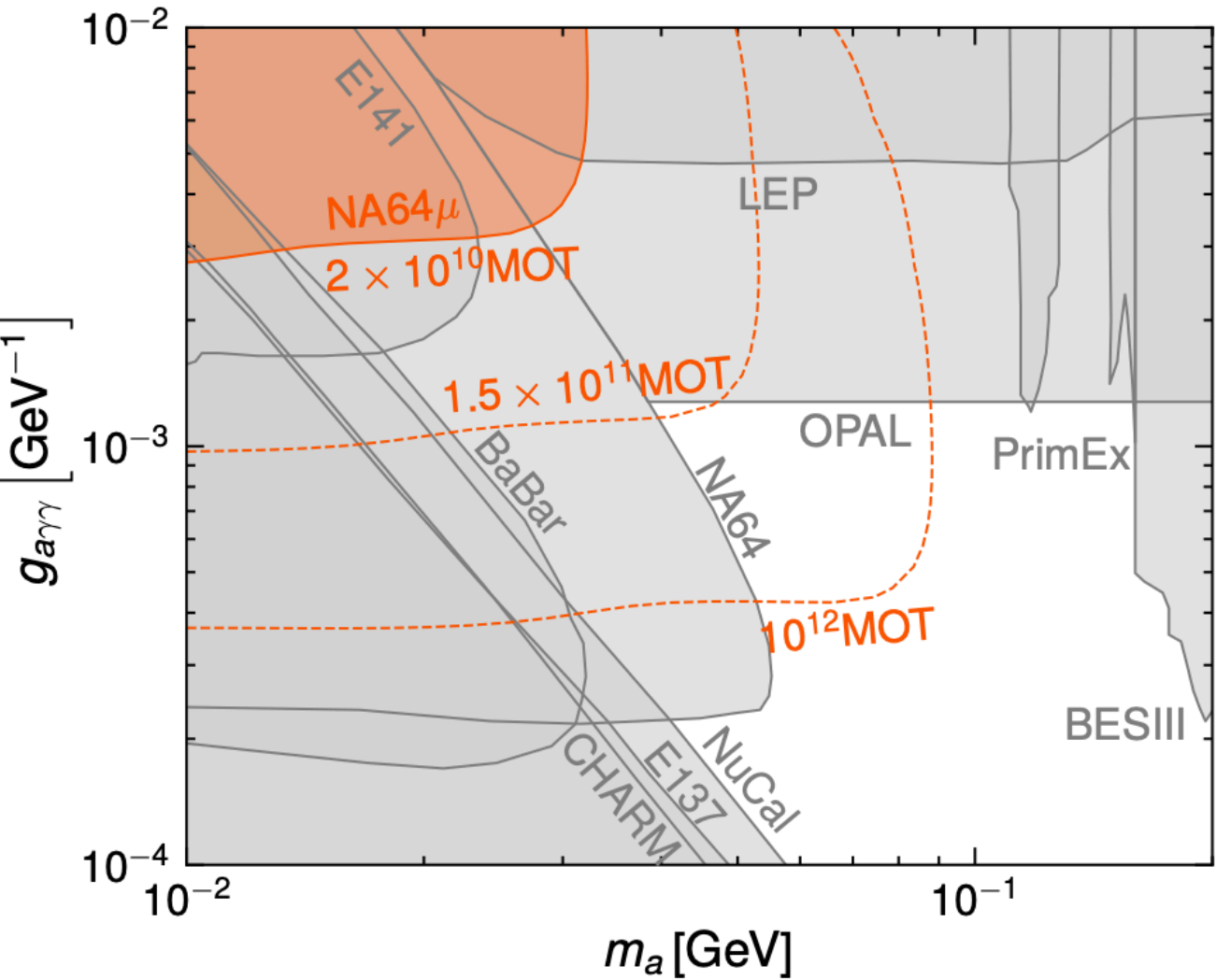


Axion and *Axion-like particles*

$\mu Z \rightarrow \mu Z a; a \rightarrow \mu\mu$ A. Eberhart *et al.*, [arXiv:2504.05873 [hep-ph]].
Muonphilic Scenario (P)



$\mu Z \rightarrow \mu Z a; a \rightarrow \gamma\gamma$ H. Li, Z. Liu and N. Song, [arXiv:2501.06294 [hep-ph]].



Outlook – Roadmap to Run 4

Aspect	Plan	Improvement
Beam and location	• Further suppress the beam hadron contamination	• K background
	• Is the initial energy optimal?	• Compromise between hermeticity and trigger efficiency
	• New semi-permanent area in M2 with ~25m available (under discussion with CERN BE-EA group, more details in D. Banerjee presentation)	• Reducing installation time
	• Vacuum in the line (ongoing for other users)	• Suppression of muon interactions along the line
Tracking detectors	• Optimisations ongoing (final design after 2023/2024 analysis)	Efficiency
Target	• Optimizations under study (length, material,..)	Increase the signal yield
Spectrometer	• Do we need two magnets in the downstream spectrometer?	More deflection (increase efficiency but trade off with hermeticity)
Hermeticity and acceptance	• New detectors under design and optimisation of the setup during CERN LS3 • New VHCAL and HCAL	No BKG up to 2×10^{-13}
Intensity	• New faster electronics for the calorimeters (developed by INFN Genova for electron and positron and to be included in the muon) • New electronics for the tracking detectors (VMM solution under study) • New trigger under development using the tracking as trigger via FPGA	Higher intensities up to a factor 20 Expand the physics case

Cut-flow efficiencies

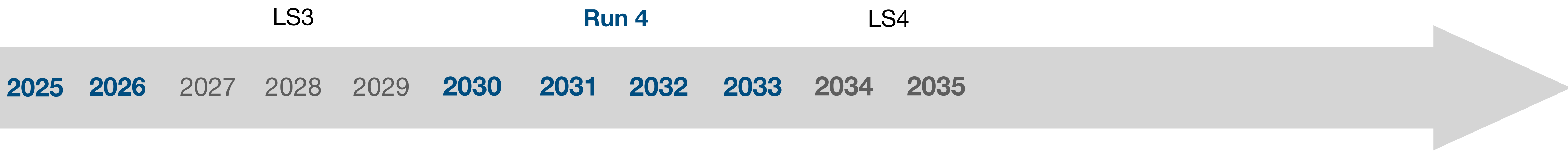
2023

	Cut ID	cut name	Events	ϵ_{tot} (%)	ϵ_{rel} (%)
MS2	1	Trigger Time	15743276	99.93	99.93
	2	MS2 3 hits before MBPL	15139790	96.10	96.17
	3	MS2 2 hits after MBPL (large MMs)	14531019	92.24	95.98
	4	MS2 upstream tracklet candidates	13918843	88.35	95.79
	5	MS2 downstream tracklet candidates	9587310	60.86	68.88
	6	MS2 physical track candidate	8403046	53.34	87.65
	7	MS2 momentum candidate	8399662	53.32	99.96
	8	MS2 good track	7647952	48.55	91.05
MS1	9	MS1 2 hits before MBPL	7507634	47.66	98.17
	10	MS1 2 hits after MBPL	7031749	44.64	93.66
	11	MS1 upstream tracklet candidates	5684249	36.08	80.84
	12	MS1 downstream tracklet candidates	4822011	30.61	84.83
	13	MS1 physical track candidate	3492283	22.17	72.42
	14	MS1 momentum candidate	3491166	22.16	99.97
	15	MS1 good track	3235267	20.54	92.67
Calo MIP	16	Single track in MS1+MS2	3173236	20.14	98.08
	17	MS1 purity	3150194	20.00	99.27
	18	MIP in VETO	2801295	17.78	88.92
	19	no energy in VHCAL0	2790540	17.71	99.62
	20	no energy in VHCAL1	2778509	17.64	99.57
	21	no HCAL out of time energy	2754591	17.49	99.14
	22	MIP in HCAL0 && HCAL1	2151128	13.65	78.09
	23	no ECAL out of time energy	2058995	13.07	95.72
mis-ID	24	MIP in ECAL	1864342	11.83	90.55
	25	ECALcc track-ene match	1856254	11.78	99.57
	26	HCAL track-ene match	1856248	11.78	100.00
	27	MS1 track within S2 trigger	1833582	11.64	98.78
	28	at most one hit in GEMs	1466932	9.31	80.00
	29	at most one hit in MS2down	1330051	8.44	90.67

2024

	Cut ID	cut name	Events	ϵ_{tot} (%)	ϵ_{rel} (%)
MS2	1	Trigger Time	223474236	100.00	100.00
	2	MS2 3 hits before MBPL	220718461	98.76	98.77
	3	MS2 2 hits after MBPL (large MMs)	220335093	98.59	99.83
	4	MS2 upstream tracklet candidates	215184202	96.29	97.66
	5	MS2 downstream tracklet candidates	195305100	87.39	90.76
	6	MS2 physical track candidate	163592175	73.20	83.76
	7	MS2 momentum candidate	163524332	73.17	99.96
	8	MS2 good track	149972952	67.11	91.71
MS1	9	MS1 2 hits before MBPL	148994160	66.67	99.35
	10	MS1 2 hits after MBPL	148987390	66.67	100.00
	11	MS1 upstream tracklet candidates	133522007	59.75	89.62
	12	MS1 downstream tracklet candidates	120676611	54.00	90.38
	13	MS1 physical track candidate	111347547	49.82	92.27
	14	MS1 momentum candidate	111345890	49.82	100.00
	15	MS1 good track	98571531	44.11	88.53
Calo MIP	16	Single track in MS1+MS2	94332446	42.21	95.70
	17	MS1 purity	93751646	41.95	99.38
	18	MIP in VETO	83520542	37.37	89.09
	19	no energy in VHCAL0	82838555	37.07	99.18
	20	no energy in VHCAL1	82403477	36.87	99.47
	21	no HCAL energy mis-reconstruction	81883658	36.64	99.37
	22	MIP in HCAL0 && HCAL1	64231980	28.74	78.44
	23	no ECAL energy mis-reconstruction	57111599	25.56	88.91
mis-ID	24	MIP in ECAL	55667228	24.91	97.47
	25	ECALcc track-ene match	55476144	24.82	99.66
	26	HCAL track-ene match	55466328	24.82	99.98
	27	MS1 track within V1 hole	55097701	24.65	99.34
	28	at most one hit in GEMs	40452930	18.10	73.42
	29	at most one hit in MS2down	35515527	15.89	87.79

The NA64 programme



Beamline	Particle	Energy [GeV]	Motivation	Published	Current statistics	Run 4 [particles on target]
H4	NA64e ⁻	100	Leptophilic Dark Sectors coupled to e ⁻ : LDM, inelastic DM, ALPs, scalar, Z', X17 ...	0.937x10 ¹²	2.7x10 ¹²	10 ¹³
	NA64e ⁺	150-40	LDM (masses <0.25 GeV), several mediators: axial, vector, pseudoscalar, scalar, ...	10 ¹⁰ @100 GeV 1.3x10 ¹⁰ @100 GeV	10 ¹⁰ @100, 70, 40 and 45 GeV	> 10 ¹¹ for different energies
M2	NA64μ ⁺	160	Leptophilic DS coupled to μ: LDM (masses > 0.1 GeV), ALPs, Z', muon g-2, scalar, millicharge, μ→τ...	1.98x10 ¹⁰	3.5x10 ¹¹	2x10 ¹³
	NA64h	20-50	Hadrophilic DS Invisible η, η', K ₀ decays	Adenda to be prepared next year Proof-of-principle published! Phys. Rev. Lett. 133, 121803 (2024)		