九州大学
KYUSHU UNIVERSITY

Optimisation of COMET Phase-I Sensitivity by Mitigating the Atmospheric Background

FJPPN/FKPPN 2025 @ Nantes May 12, 2025

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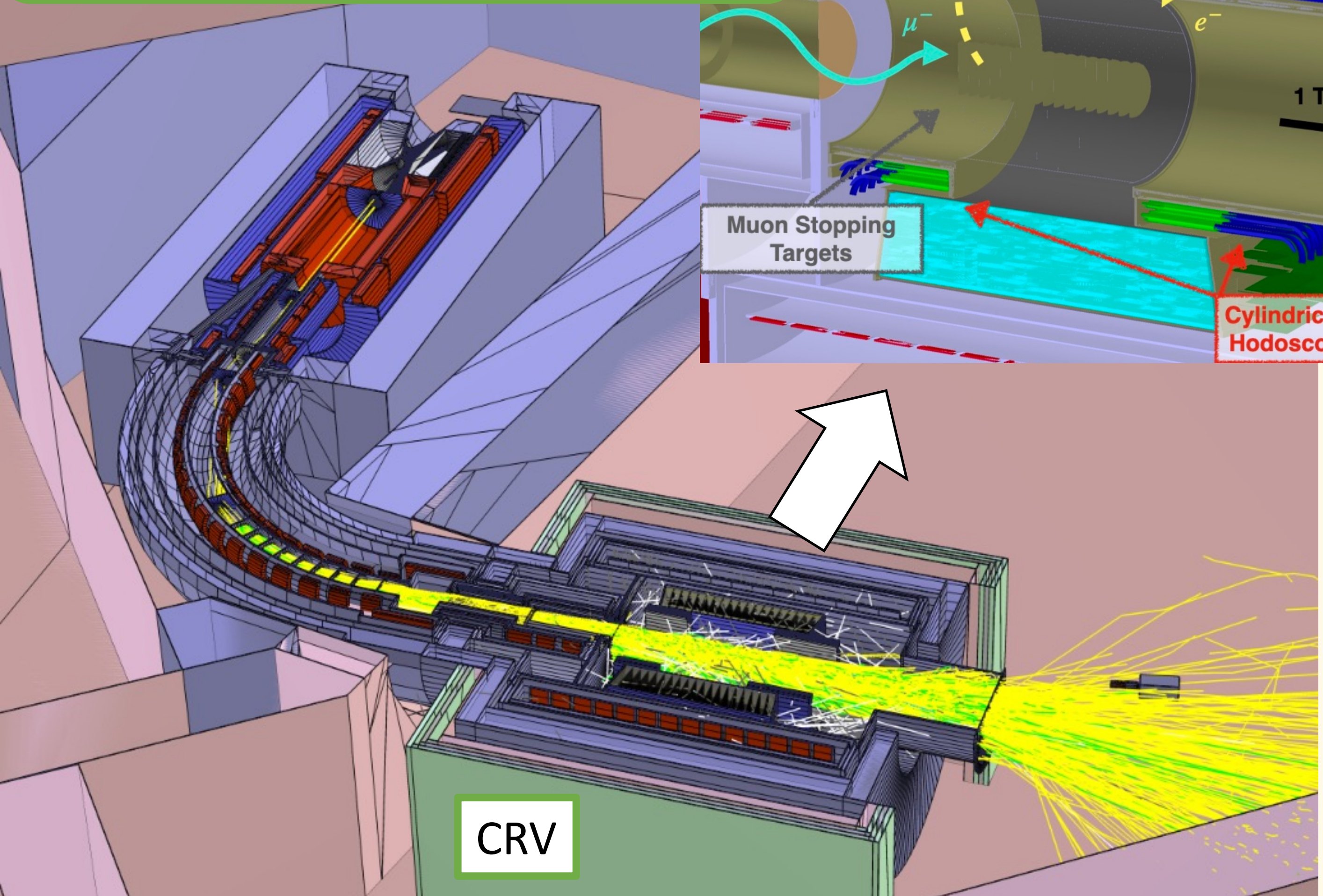
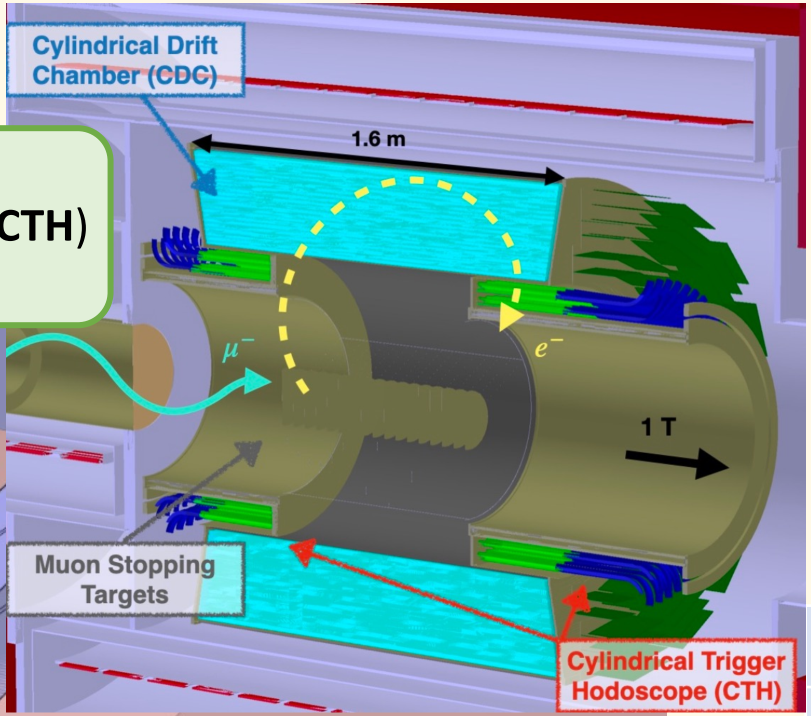
The Single-Event Sensitivity of COMET

Phase-I detectors

- Cylindrical Drift Chamber (**CDC**)
- Cylindrical Trigger Hodoscopes (**CTH**)
- Cosmic Ray Veto (**CRV**):





$$\mathrm{SES} = \frac{1}{\underbrace{T_{\mathrm{run}}(I_p/e)R_{\mu/p}}_{N_\mu^{\mathrm{stop}}}\mathcal{B}_{\mathrm{cap}}\mathcal{A}_{\mu\to e}}$$

$$\mathcal{A}_{\mu\to e} = \mathcal{A}_{\mathrm{geo}}\varepsilon_{\mathrm{trigger}}\varepsilon_{\mathrm{DAQ}}\varepsilon_{\mathrm{finding}}\varepsilon_{\mathrm{tracking}}\varepsilon_{\mathrm{quality}}\varepsilon_{p\mathrm{Window}}\varepsilon_{t\mathrm{Window}}$$

$\mathcal{A}_{\mu\to e}$	4.1%	Acceptance
$\mathcal{B}_{\mathrm{cap}}$	61%	Muon capture branching fraction
$R_{\mu/p}$	4.7×10^{-4}	Muon yield per POT
I_p	0.4 μA	Proton beam current
T_{run}	146 days	**Total run time**

To achieve a Phase-I SES of 3.1×10^{-15}

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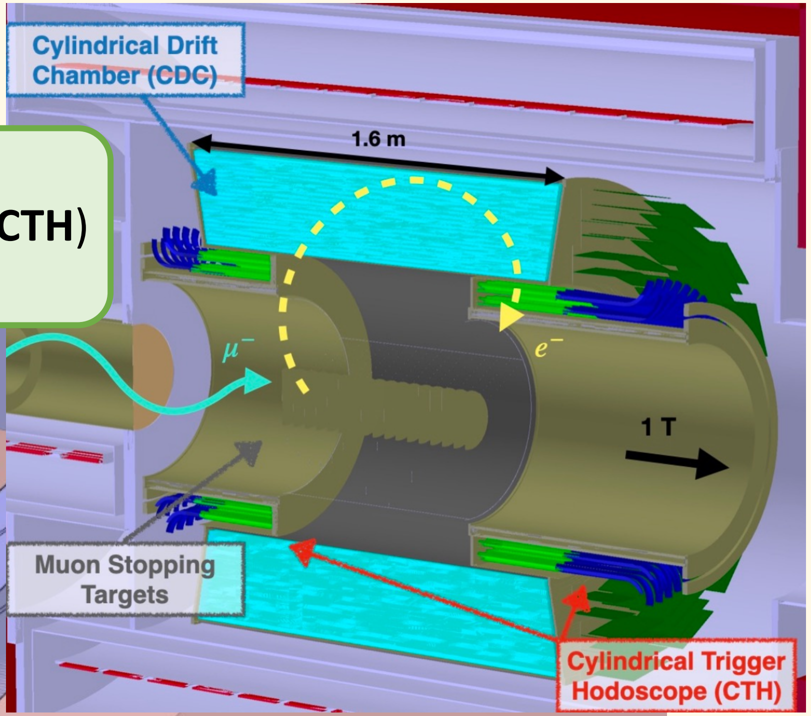

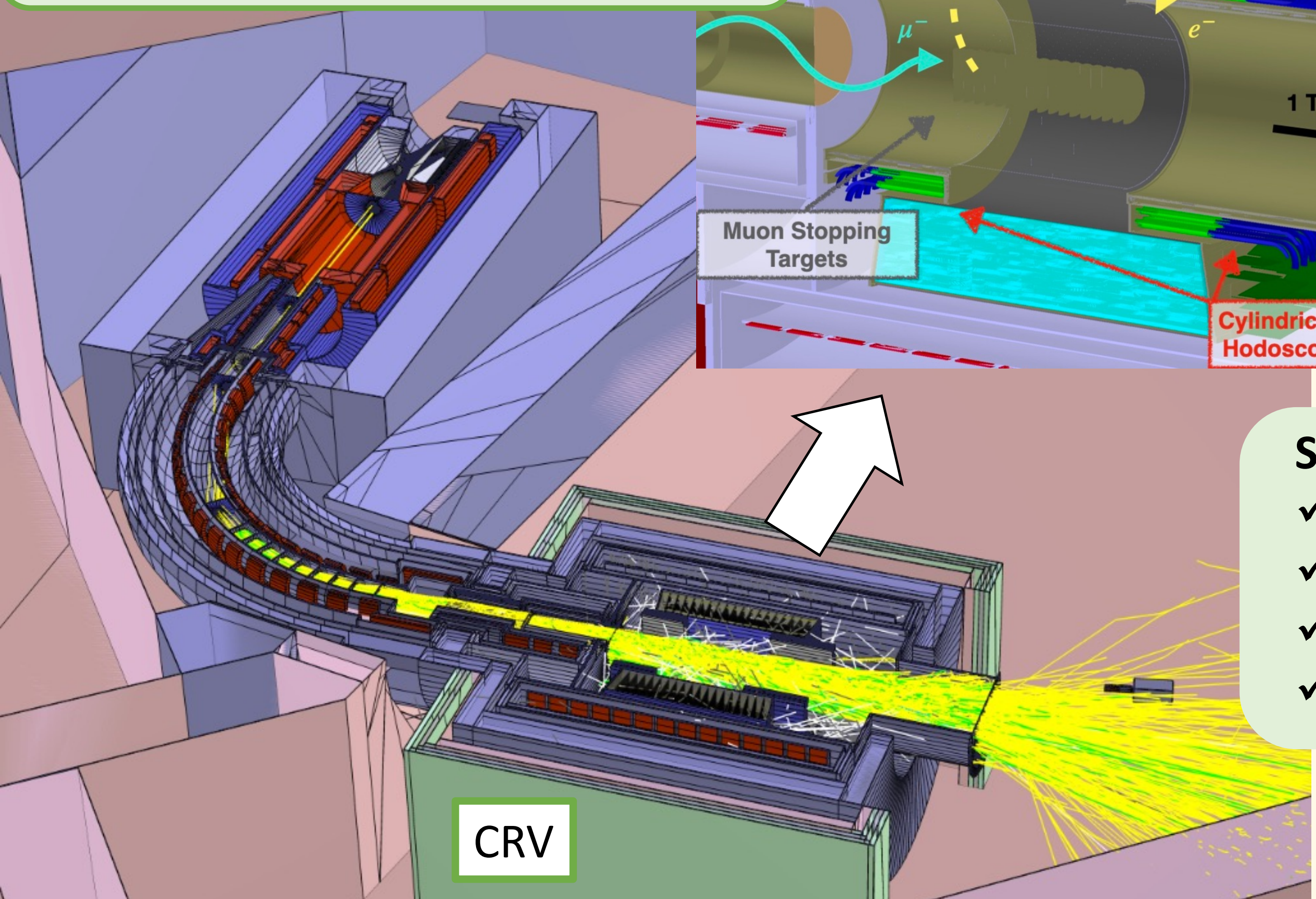

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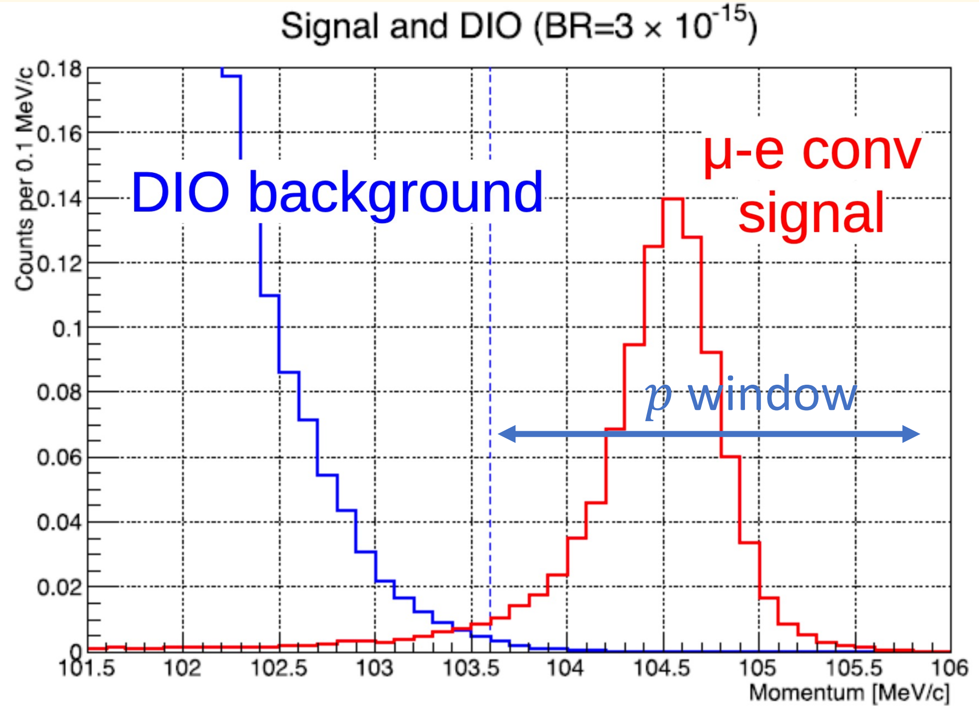
Signal:

- ✓ **CTH** 4-fold trigger within $700 < t < 1170$ ns
- ✓ Track in **CDC** pointing towards Al target
- ✓ Momentum $103.6 < p < 106$ MeV/c
- ✓ No coincident activity in **CRV**

Sources of background

Table 14. Summary of the estimated background events for a single-event sensitivity of 3×10^{-15} in COMET Phase-I with a proton extinction factor of 3×10^{-11}.

Type	Background	Estimated events
Physics	Muon decay in orbit	0.01
	Radiative muon capture	0.0019
	Neutron emission after muon capture	< 0.001
	Charged particle emission after muon capture	< 0.001
Prompt beam	* Beam electrons	
	* Muon decay in flight	
	* Pion decay in flight	
	* Other beam particles	
	All (*) combined	≤ 0.0038
	Radiative pion capture	0.0028
	Neutrons	$\sim 10^{-9}$
Delayed beam	Beam electrons	~ 0
	Muon decay in flight	~ 0
	Pion decay in flight	~ 0
	Radiative pion capture	~ 0
	Antiproton-induced backgrounds	0.0012
Others	Cosmic rays†	$N_{\mathrm{cosmicBG}} = 0.48$
Total		0.032



DIO e^- eliminated by momentum window

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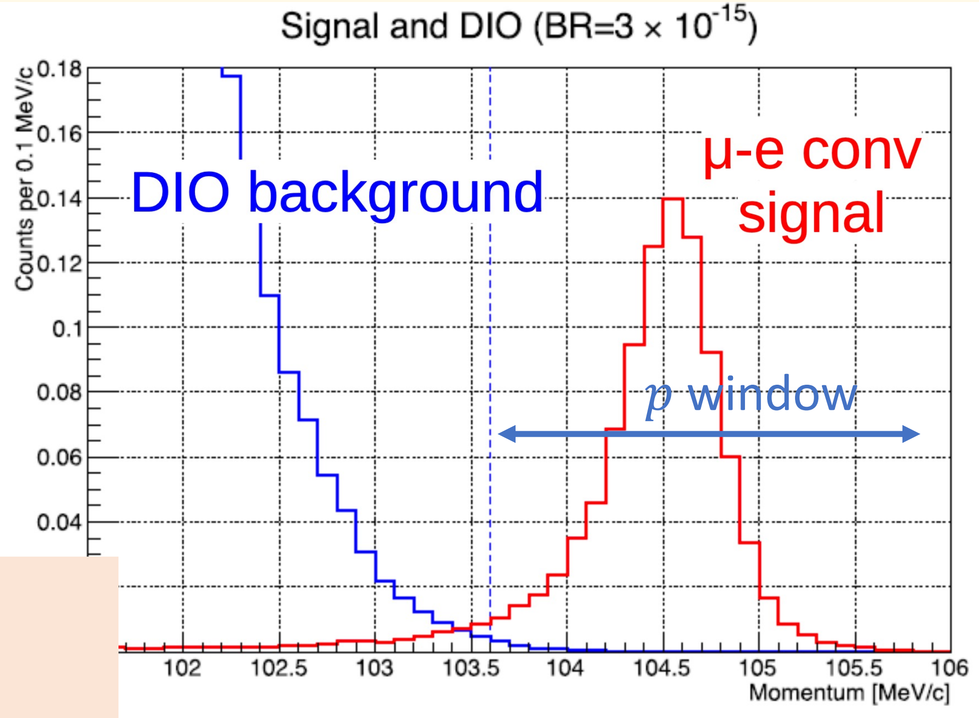
Assuming:

- 99.99% CRV detection efficiency
- Total CRV coverage
- No fake CRV triggers
- CDC rejection of μ^+ with 89% efficiency



O e^- eliminated by momentum window

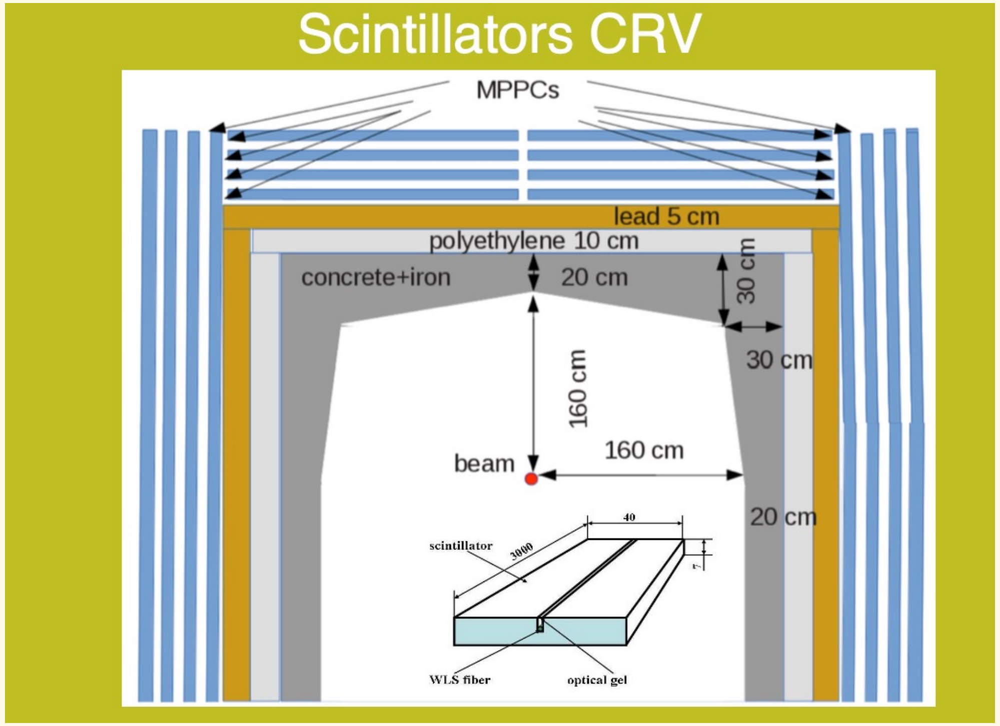
Cosmic ray muons will be the largest background.

Atmospheric muons: the dominant background

Two types of cosmic background:

- Atm muon misidentified as electron
- Electron induced by atm muon

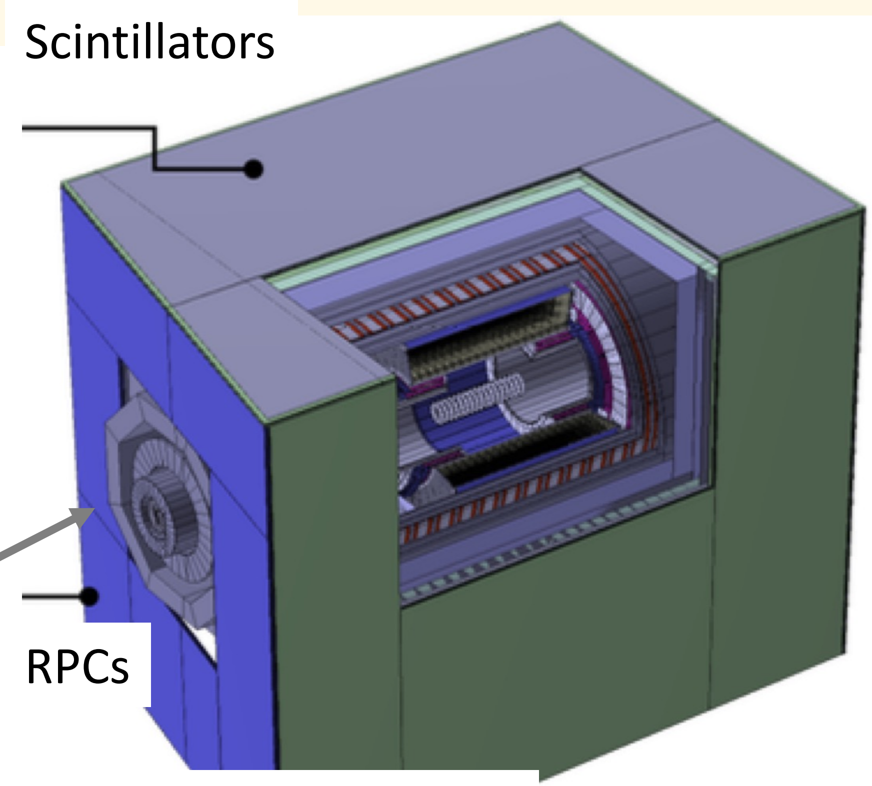
Backgrounds rejected if activity inside the **Cosmic Ray Veto (CRV)** within time window of CTH/CRV event.

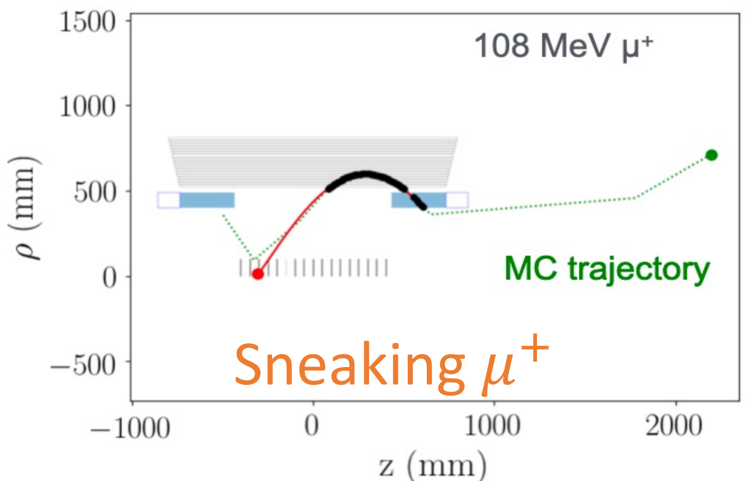


The CRV covers:

- ➢ Upstream and downstream sides (high radiation) with **Resistive Plate Chambers** (RPCs)
- ➢ Top, left, and right sides with **scintillators**

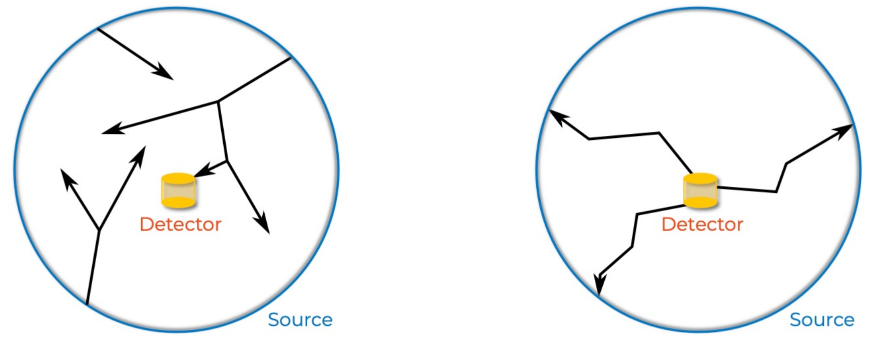
... but some openings could let "sneaking muons" in (CDC/CTH hit but no CRV hit).



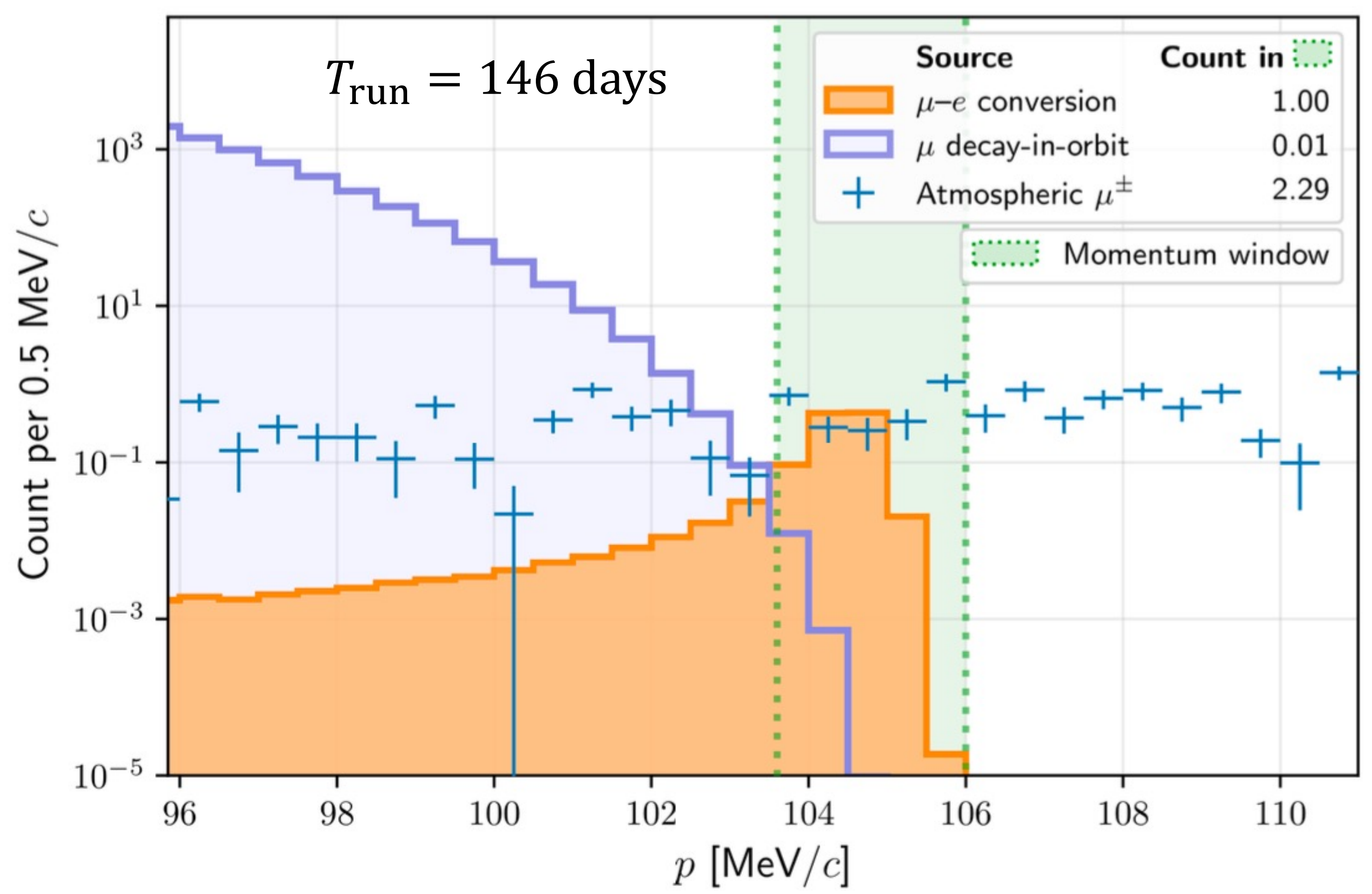


Simulating the atmospheric background

Because of the low trigger acceptance and large multiple scattering of low momentum muons, the atmospheric background is very expensive to simulate with direct Monte-Carlo:
→ Use **backward Monte-Carlo**



(a) Forward MC. **(b)** Backward MC.



Assuming:

- 99.99% CRV detection efficiency
- Total CRV coverage
- No fake CRV triggers
- No μ^{+} rejection from CDC
- No μ/e discrimination from CTH

→ $N_{\mathrm{cosmicBG}} = 2.29$

M. Moritsu, V. Niess, M. Dubouchet, G. Faure
Activity led by French team at LPC

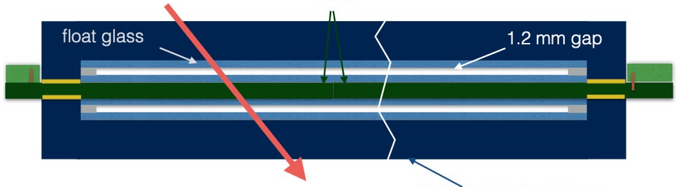
Rejecting cosmic muons with CRV

Current situation: CDC/CTH gives signal while CRV serves as veto.

Before we started refining the muon beamline, with a simple model of the CRV (timing window $\Delta t = 10$ ns) we had a **high accidental veto rate**

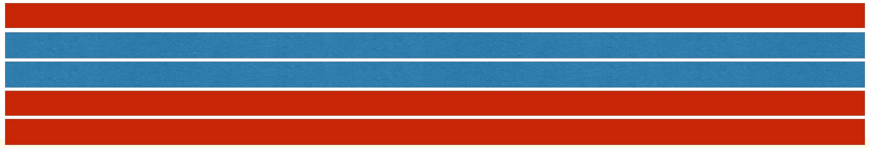
- The faster RPCs ($\Delta t \sim \mathrm{ns}$) are essential on upstream CRV

Detector module: 2 RPCs



- Increased number of layers and segmentation are needed

Tracker module: 5 detector modules



Triple-coincidence rates in CRV

$$N_{coin} = {}_4C_3 \times \left(\frac{N_{inner} + N_{outer}}{2}\right)^3 \times (\Delta t)^2 \qquad \Delta t = 10\,\mathrm{ns}$$

$$N_{side} = N_{coin} \times N_{strip}$$

	N_{coin} (Hz)	N_{strip}	N_{side} (kHz)
top	7.8	204	1.61
right	21.9	206	4.52
left	27.6	206	5.68
front	6.33x10^3	192*	1214
back	1.07x10^4	192*	2053
total			3279

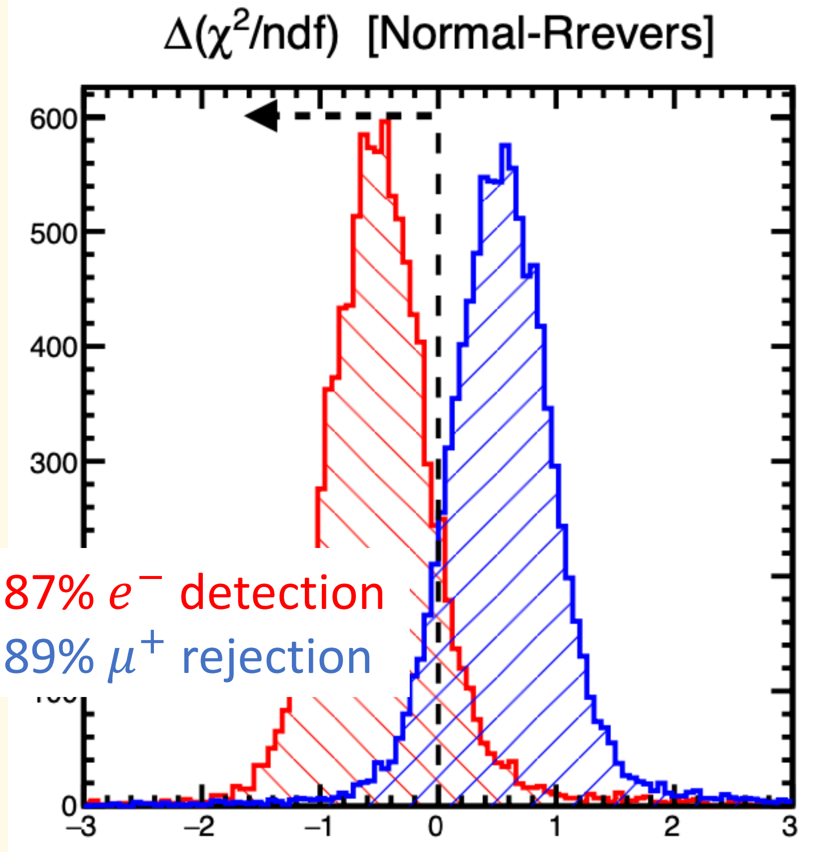
→ leads to 33% accidental veto (Valentin Niess, 2021)

- Rather relying on temporal coincidence, we are now trying to use spatial information in a global tracking algorithm

e^-/μ^+ discrimination with CTH and CDC

Current situation: CDC/CTH gives signal while CRV serves as veto. But CTH and CDC can also reject sneaking muons.

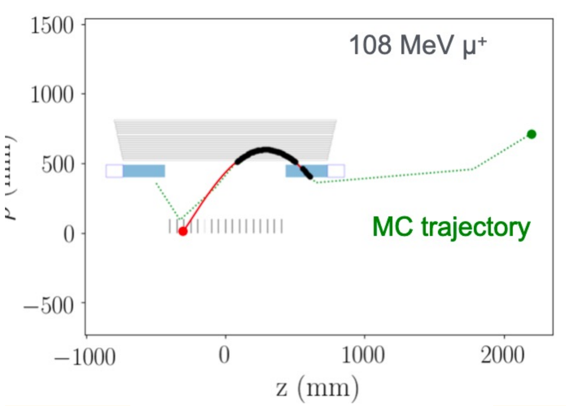
CDC discrimination from dE/dx



87% e^- detection

89% μ^+ rejection

M. Moritsu



Sneaking μ^+

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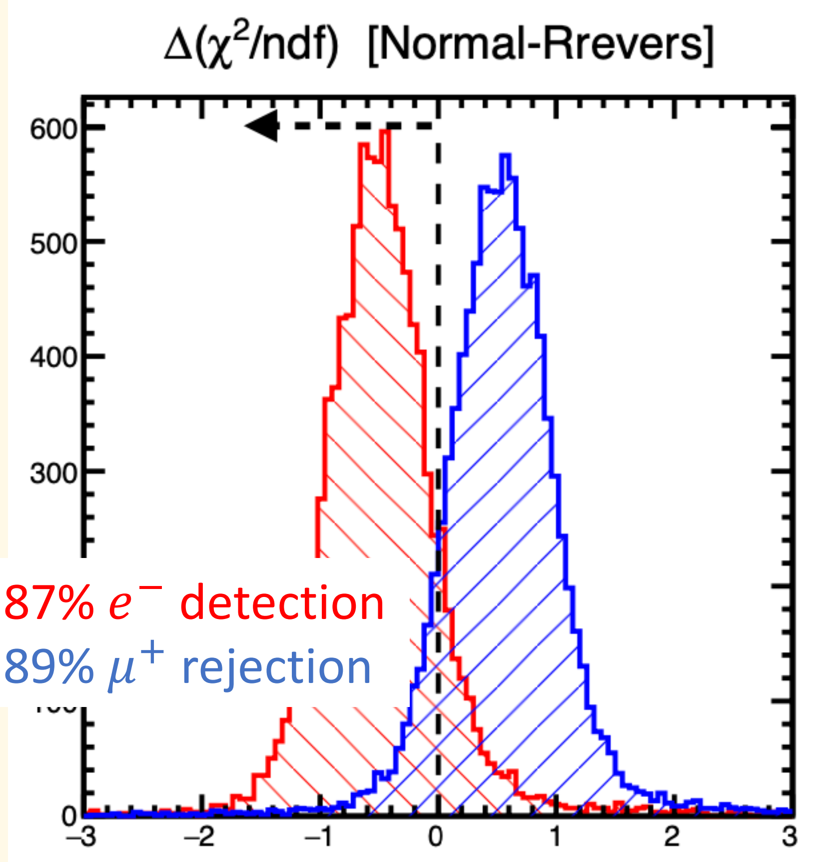

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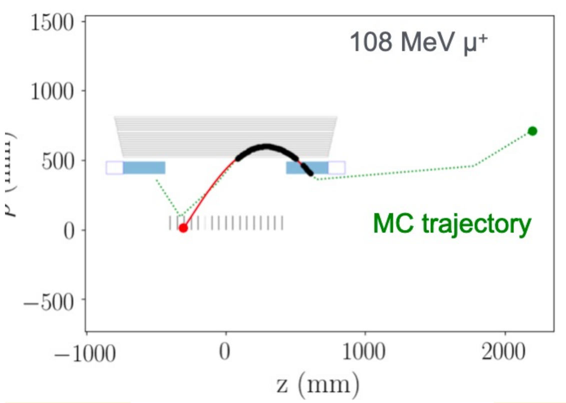
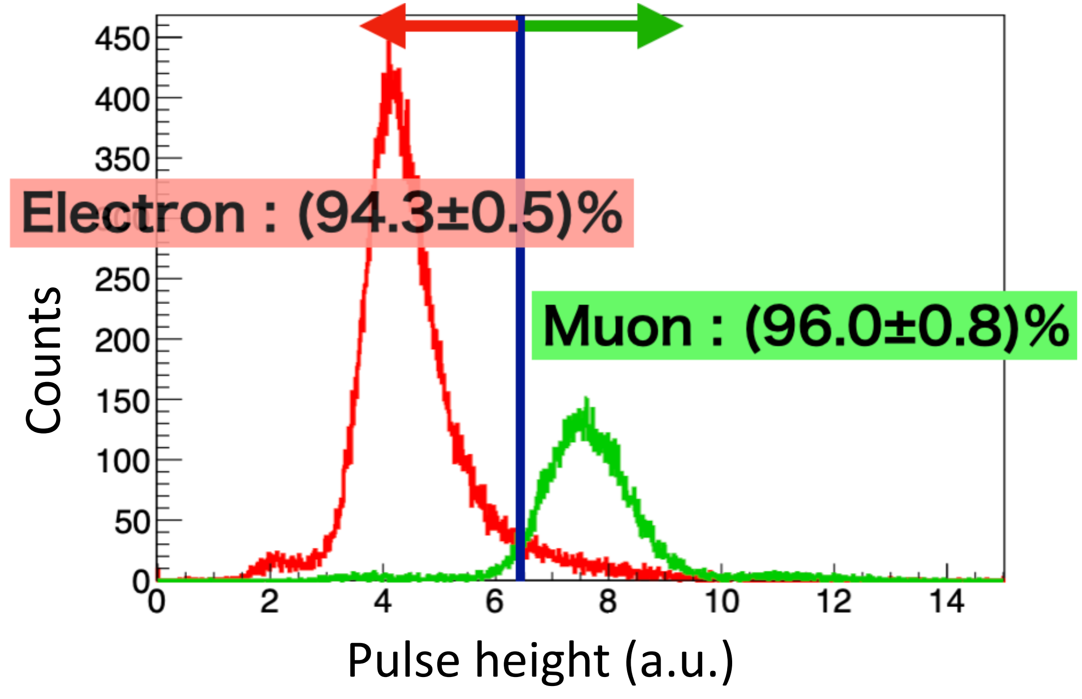


Sneaking μ^+

CTH discrimination from dE/dx (PSI beamtest, 2023)



e^-/μ^+ discrimination with CTH and CDC

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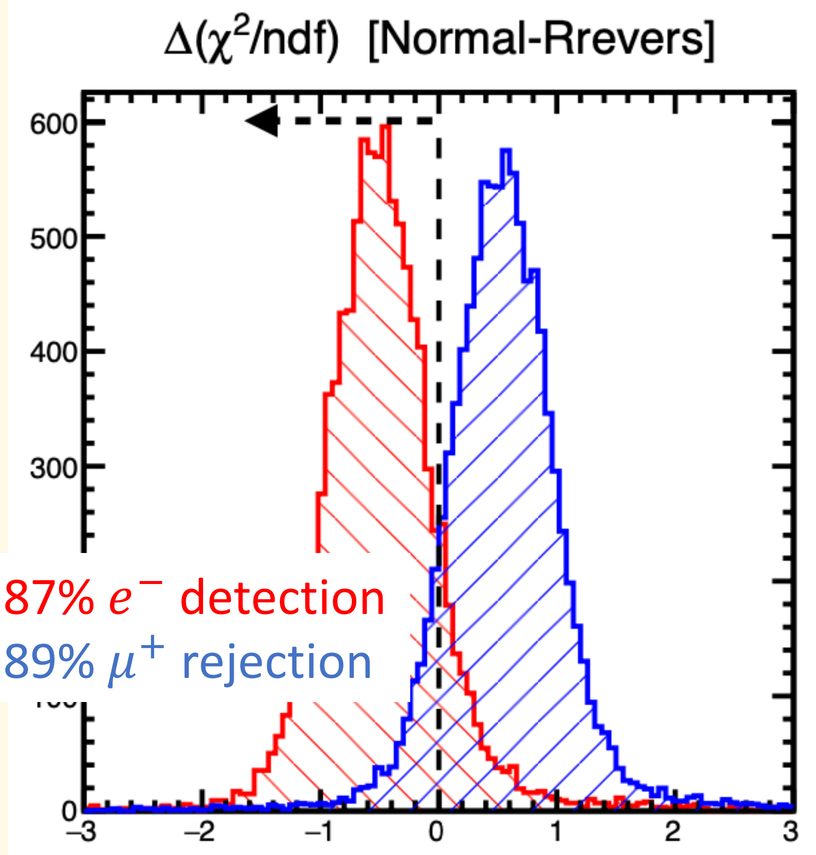

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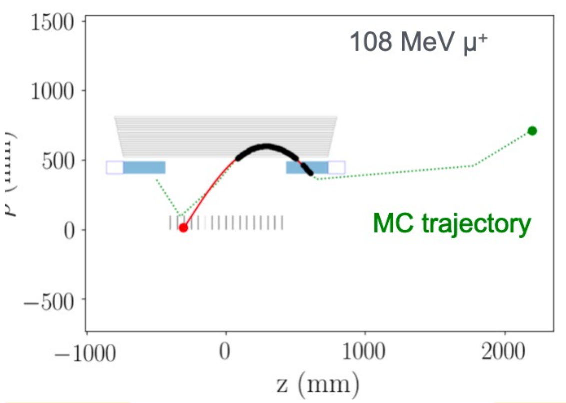

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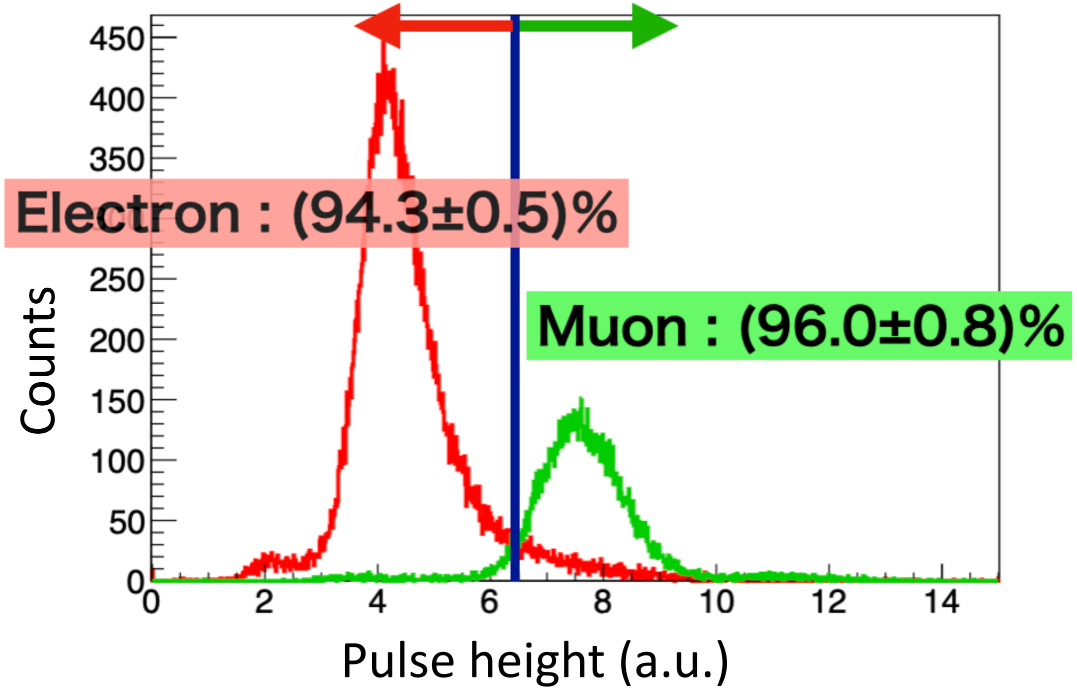
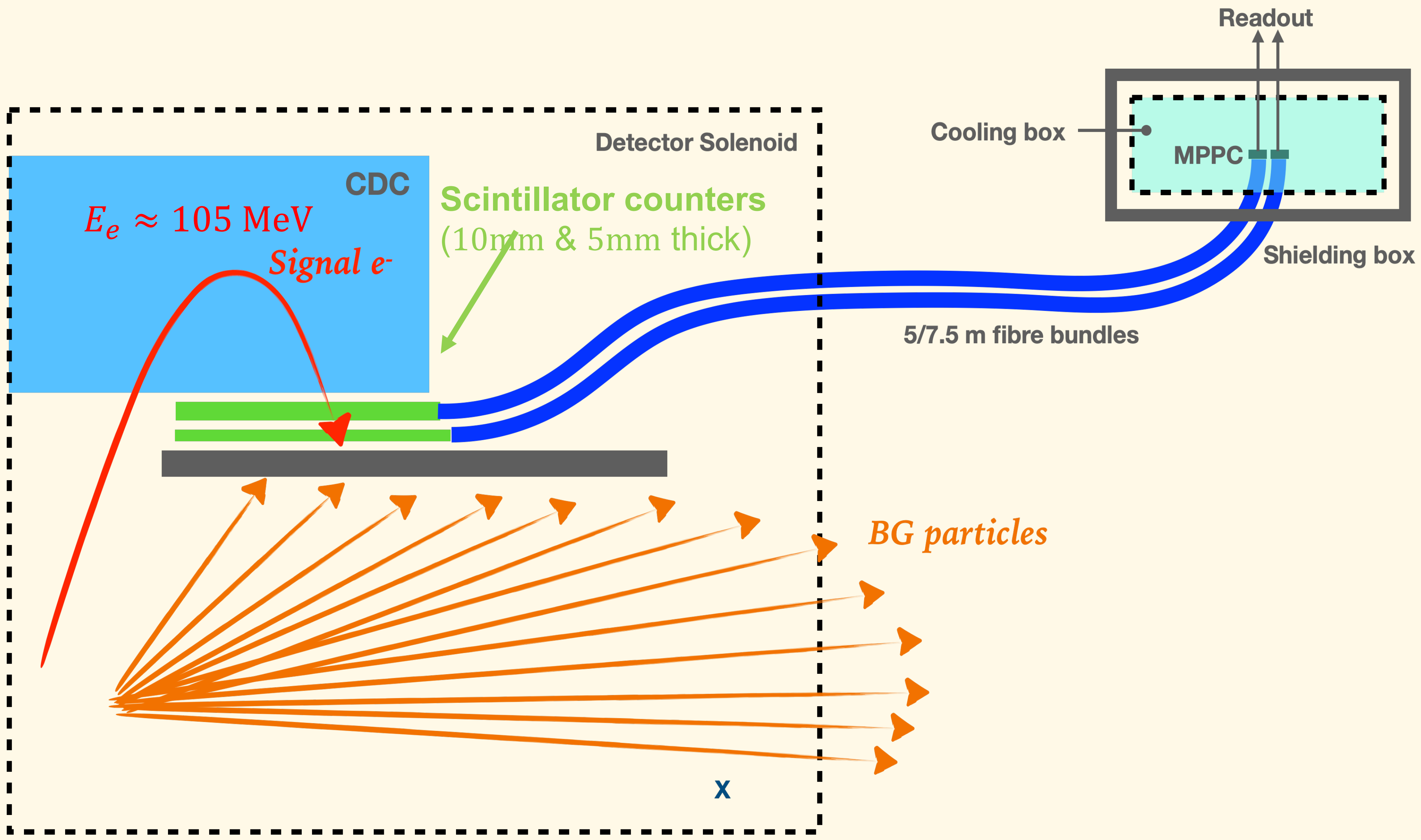


Limitations:

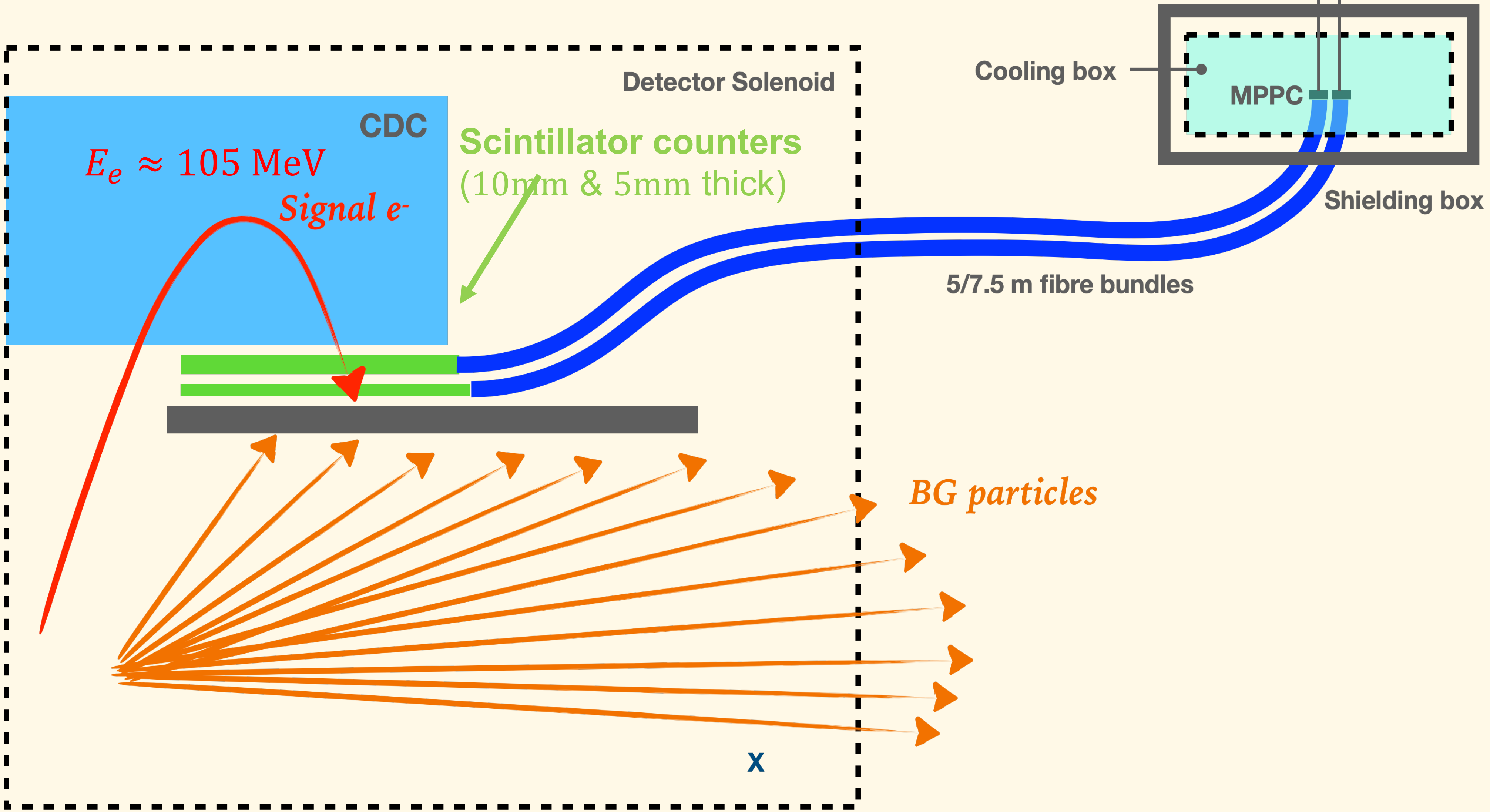
- In Phase-I full luminosity we expect high pile-up which would reduce discrimination efficiency with CDC and CTH
  →importance of realistic beam-induced background simulations
- Discrimination with CTH depends on light collection efficiency

CTH hardware



CTH hardware

Readout: DASH board
→Prototype produced and tested in LPC in collaboration with J-PARC



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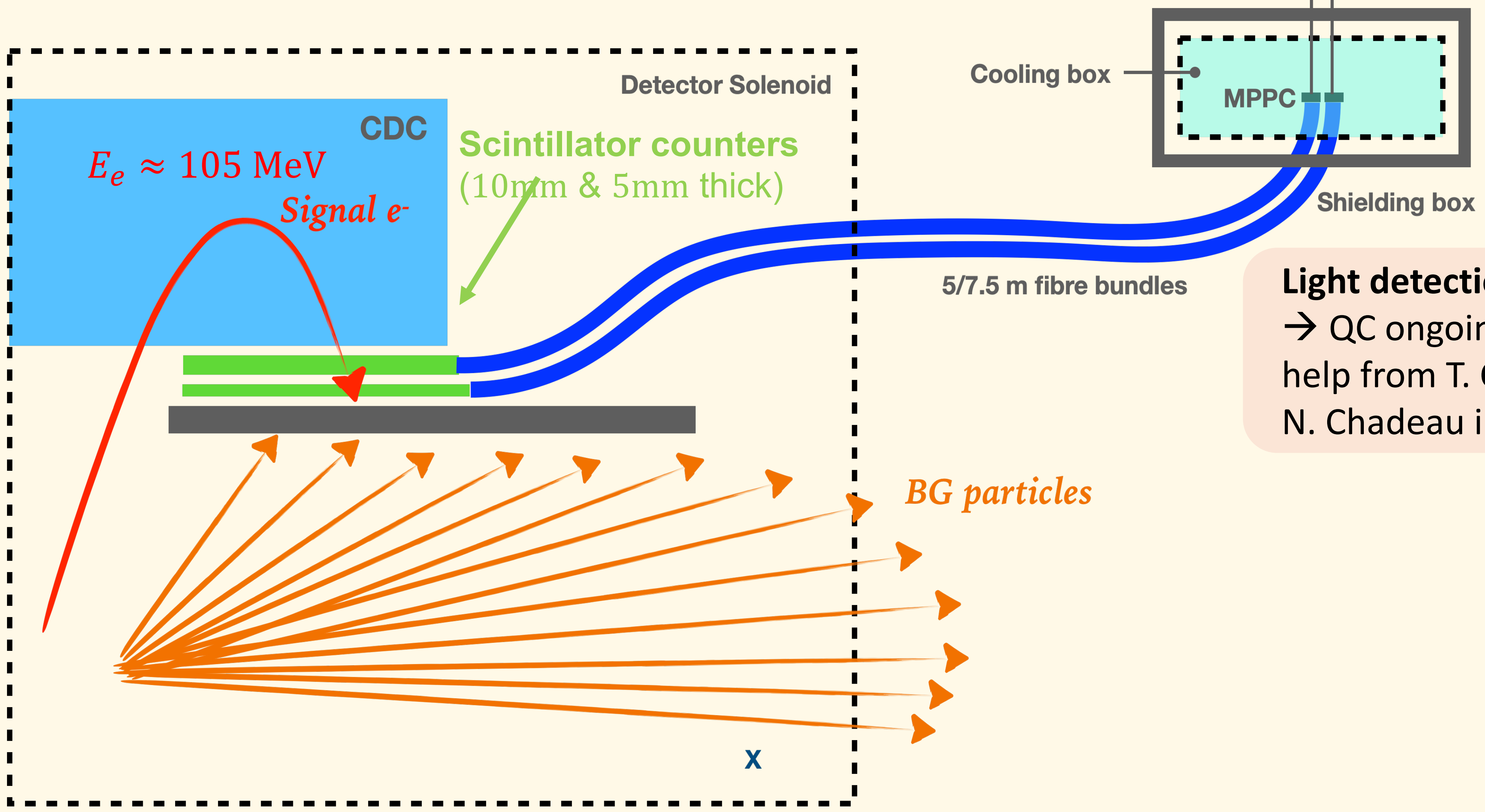

Light detection: MPPCs
→ QC ongoing in J-PARC with help from T. Clouvel and N. Chadeau in June-July 2024

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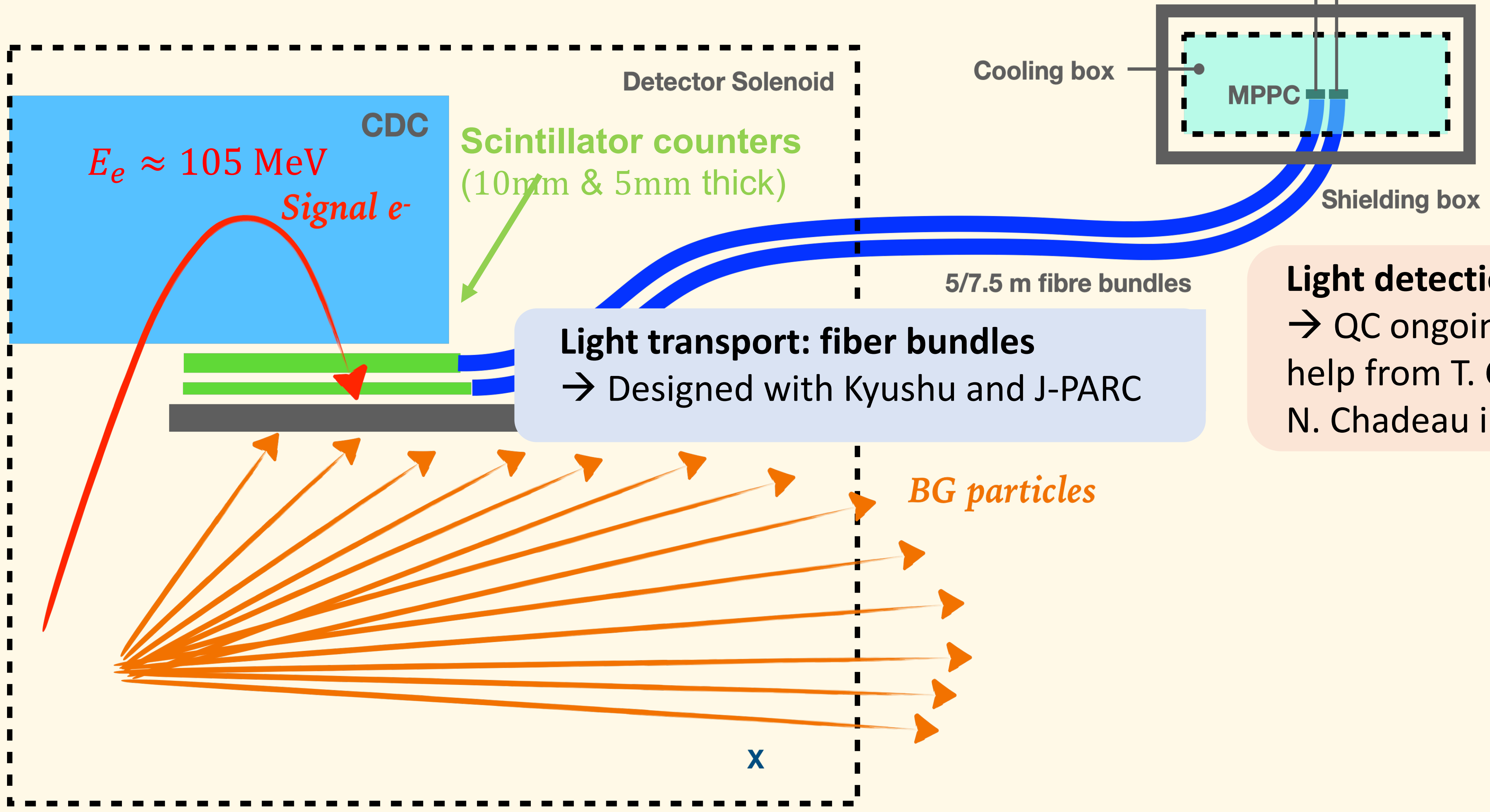
Light transport: fiber bundles
→ Designed with Kyushu and J-PARC



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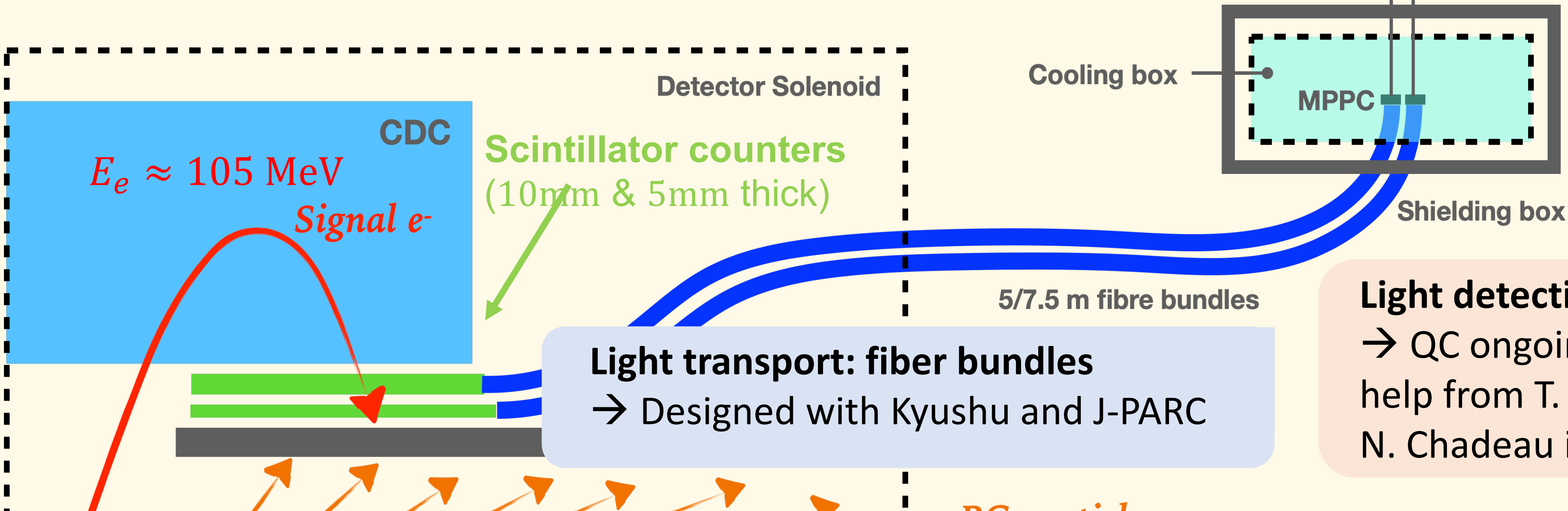

Light detection: MPPCs
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Light transport: fiber bundles
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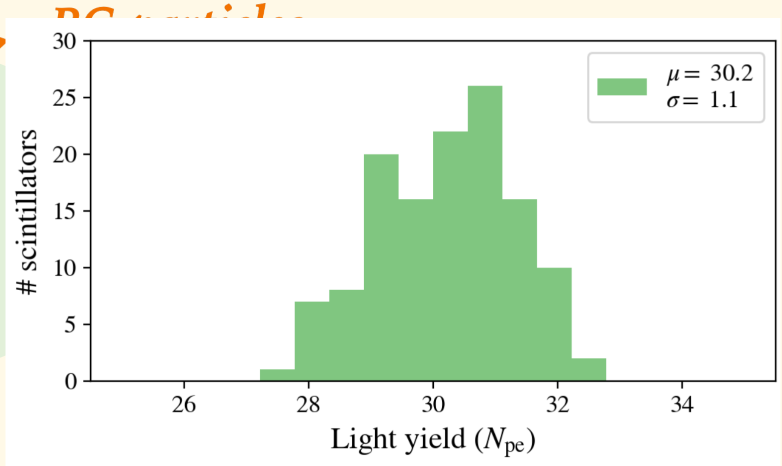
Detection: scintillators
→ Wrapping and QC performed at Kyushu
Results show 30pe light yield / scintillator.
Can still be increased (more fibers)



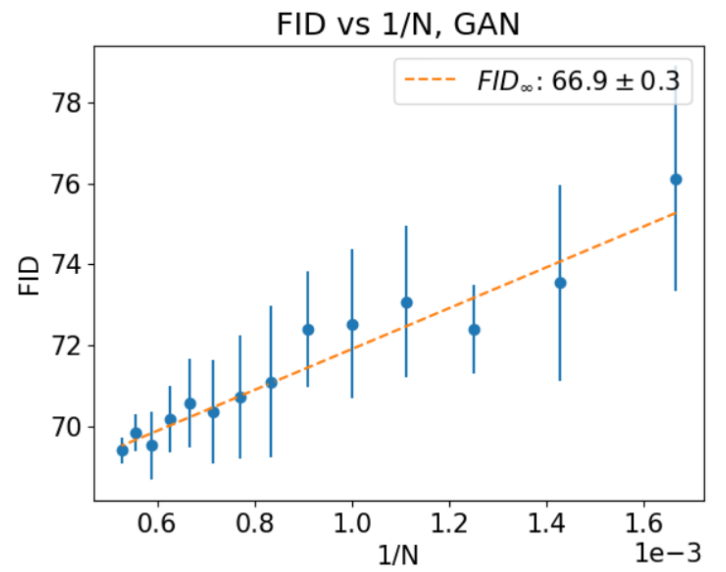
Generative Adaptive Networks (GAN) to generate background data

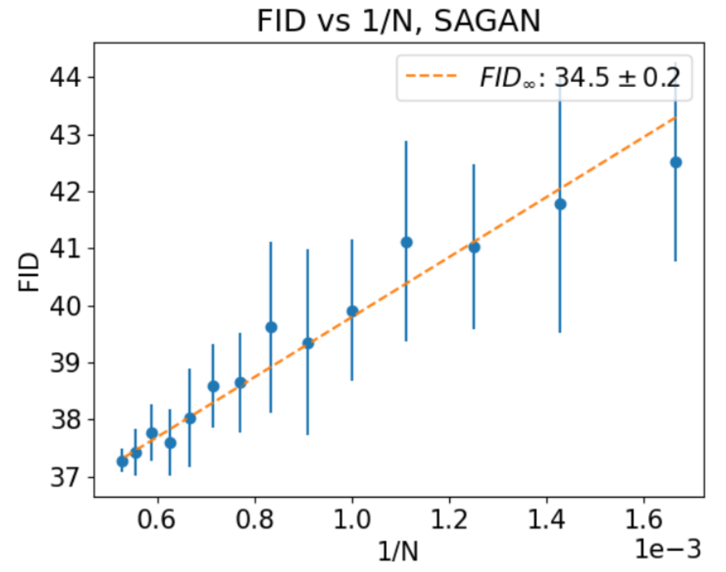
GAN models can be used to easily and quickly generate noise events.

In *JINST 18 P06007*, a proof-of-concept is discussed, in which 2 GAN models are studied: a ‘simple’ GAN and a second one with a Self-Attention layer, allowing it to take into account spatial correlation.

With the unbiased Fréchet Inception Distance (FID) metric, the SAGAN model gives better results than the GAN.

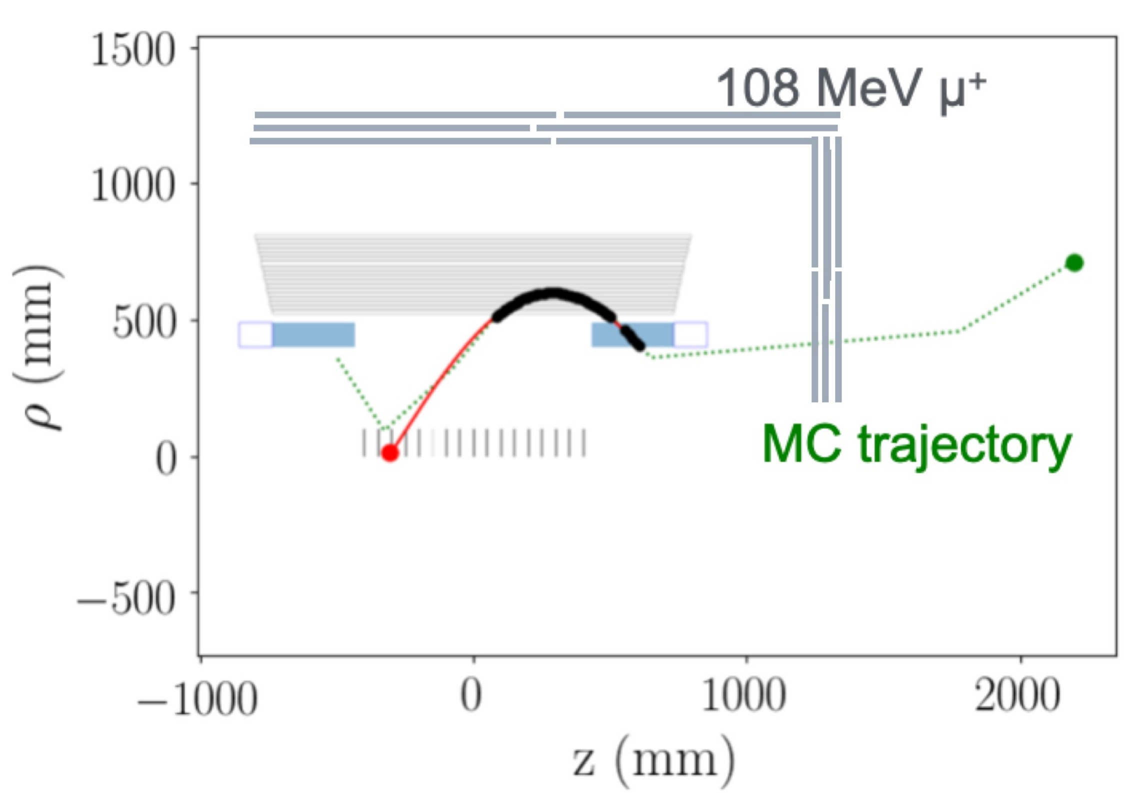
- G. Faure and C. Carloganu plan to have students at **LPC** (engineer or/and M2) apply this on the CDC & CTC.
- S. Gradat will provide **CCin2p3** support
- Discussion with other experiments doing such R&D (such as CMS)





Global tracking for better cosmic μ rejection

Instead of relying on temporal coincidence in CRV for cosmic veto, we propose instead to implement a global tracking combining CTH/CDC/CRV data.



- CRV RPCs and scintillators provide spatial information, which opens up the possibility of global tracking.
- Construct a likelihood for the CRV activity to be of atmospheric origin including detailed CRV information around the track extrapolation (instrumented area or not, local efficiency and average noise, etc.)
- Will be led jointly by LPC and Kyushu U.
  →T. Bouillaud will visit Clermont for 3 months this summer to implement it with T. Clouvel.

Conclusion

- The **sensitivity** of COMET Phase-I critically depends on the control of the **atmospheric background.**

- The **CRV** is the main detector responsible for cosmic event rejection, but may let in "**sneaking muons**" and suffers from high radiation.

- **CTH and CDC** can also be used for **cosmic μ rejection**, but more realistic background estimations are needed.
  → **Generative Adaptive Networks** would help us generate this **background data**.

- Finally, a **global tracking algorithm** combining data from **CRV/CDC/CTH** is crucially needed to reach the target sensitivity.

- **LPC Clermont** is leading the CRV activity and fully involved in CTH hardware:
  - Thomas Clouvel and Nicolas Chadeau long-term stay in J-PARC (summer 2024) for CTH MPPC quality control
  - Cristina Carloganu and Géraldine Faure visits to J-PARC (CM, …)
  - Boards in Clermont

- **Kyushu University** and J-PARC lead CTH activities and contribute to software:
  - I (Thomas Bouillaud) will visit Clermont LPC for 3 months this summer to work on the global tracking with Thomas Clouvel.
  - Junji Tojo will also visit the LPC this summer.