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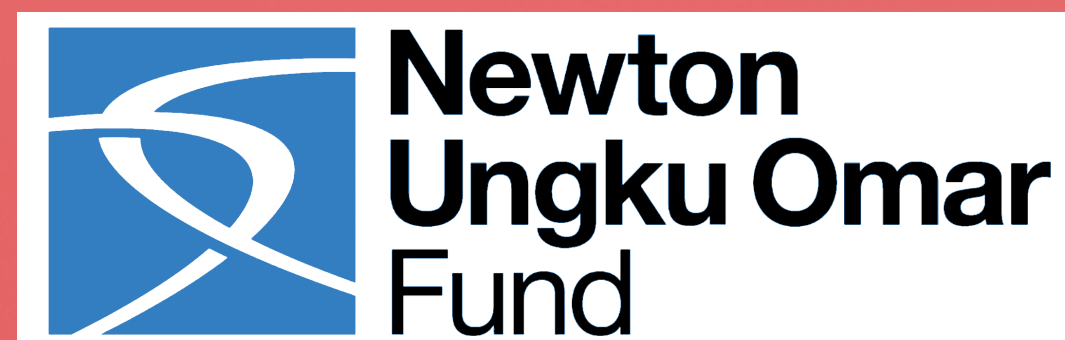
COMET PHASE-0

**Validation of the Muon Transport System
for a Muon-to-Electron Conversion Search at J-PARC**

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On behalf of the COMET Collaboration



NuFact 2026

Tsung-Dao Lee Institute, Shanghai, China

1st September 2026



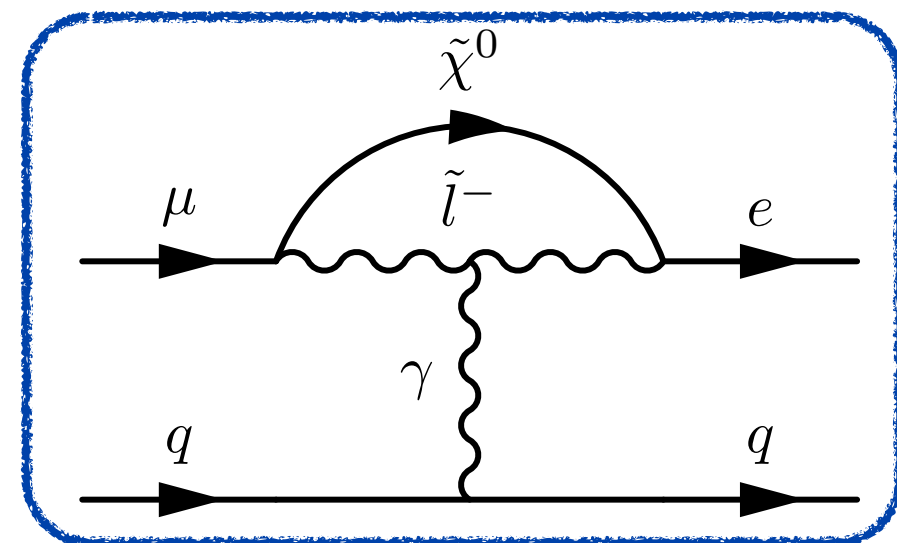
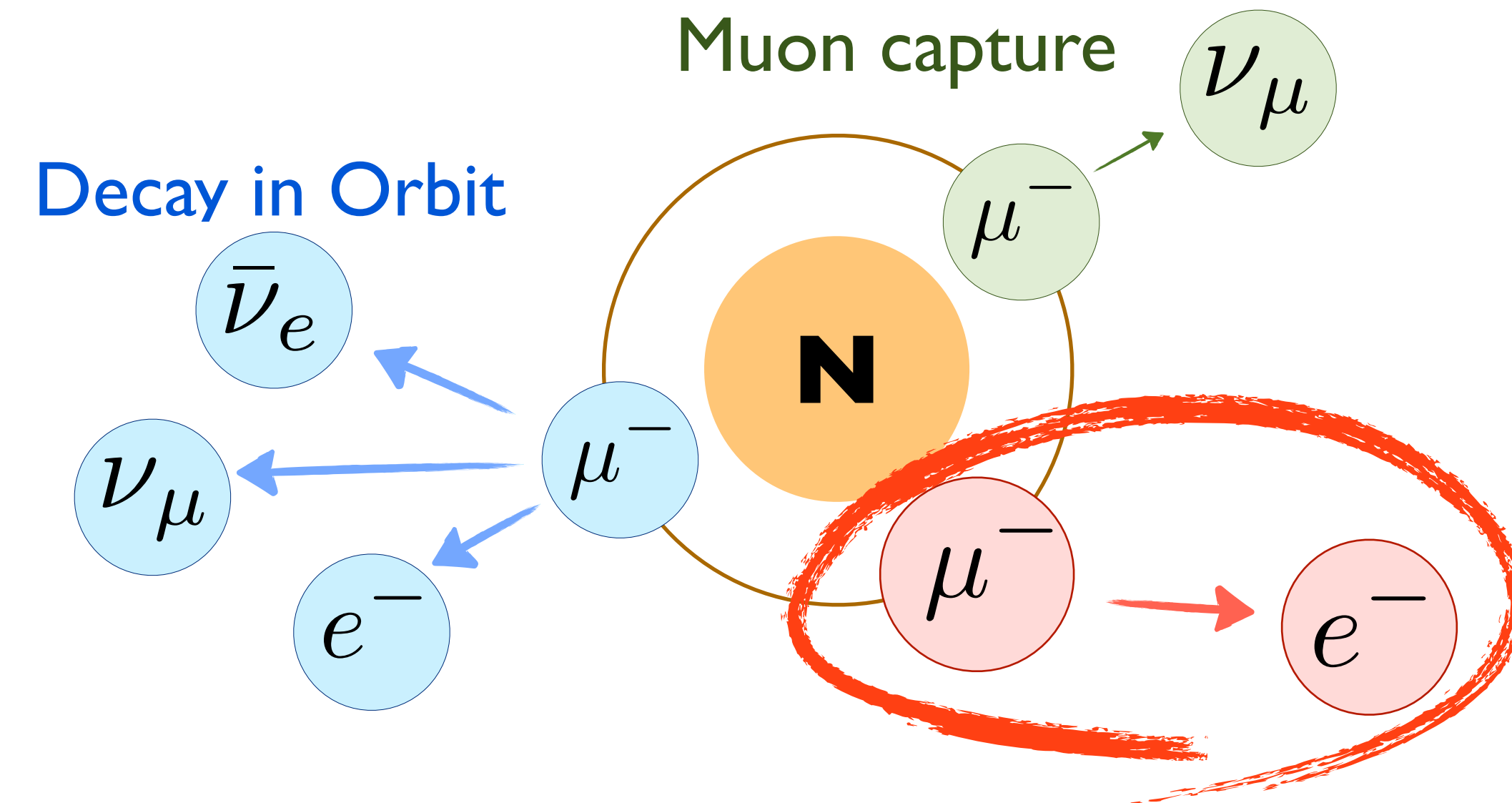
INTRODUCTION



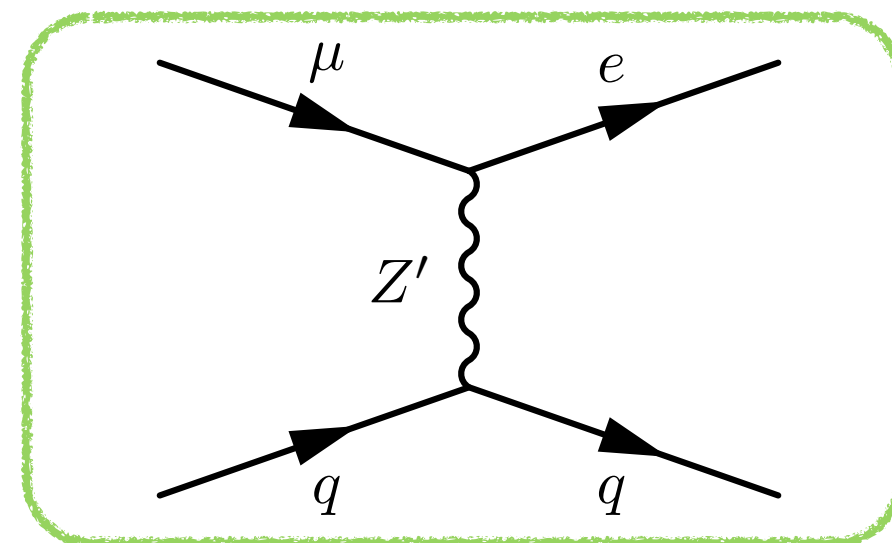
MUON-TO-ELECTRON CONVERSION

A charged lepton flavour-violating process

- ♦ Muon decays to single electron with no neutrino.
 - ★ Strongly suppressed in the SM including the neutrino oscillation.
 - ★ Branching ratio: $\text{BR}(\mu N \rightarrow e N) \sim \text{BR}(\mu \rightarrow e \gamma) < 10^{-54}$
- ♦ Reach up to $\sim 10^{-15}$ in several Beyond SMs.
 - ★ Z' , leptoquarks, heavy right-handed neutrinos, etc
 - ★ **Observation indicates new physics!**
- ♦ Model discrimination with $\mu \rightarrow e \gamma$ (MEG/MEG II) and $\mu \rightarrow e e e$ (Mu3e)



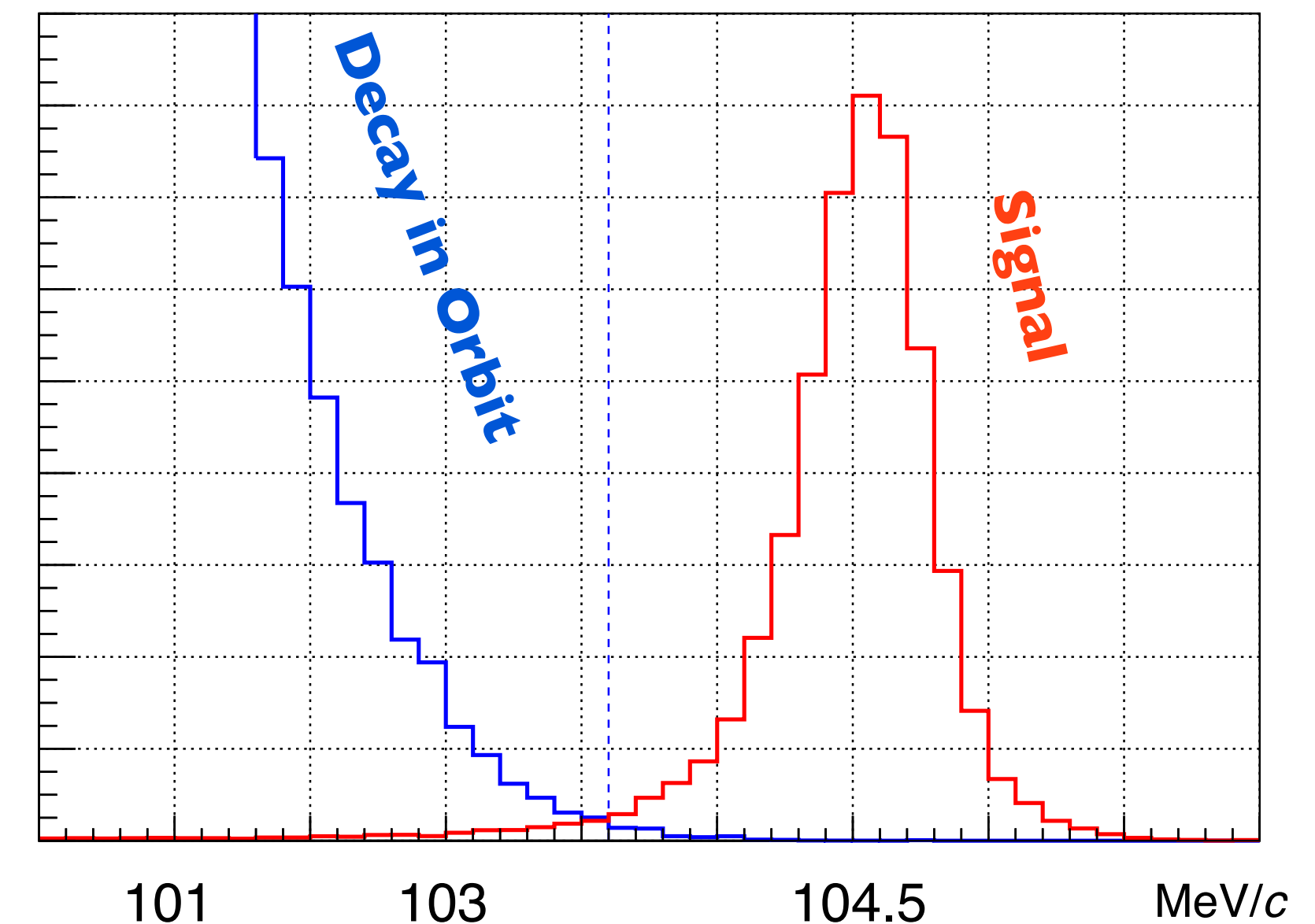
Photonic process



Four-fermion process

Representative Muon LFV operators

Electron momentum spectrum
(case of Aluminium)
w/ $\text{BR}(\mu N \rightarrow e N) = 10^{-15}$





COMET EXPERIMENT

Searching for μ -e conversion in aluminium at J-PARC

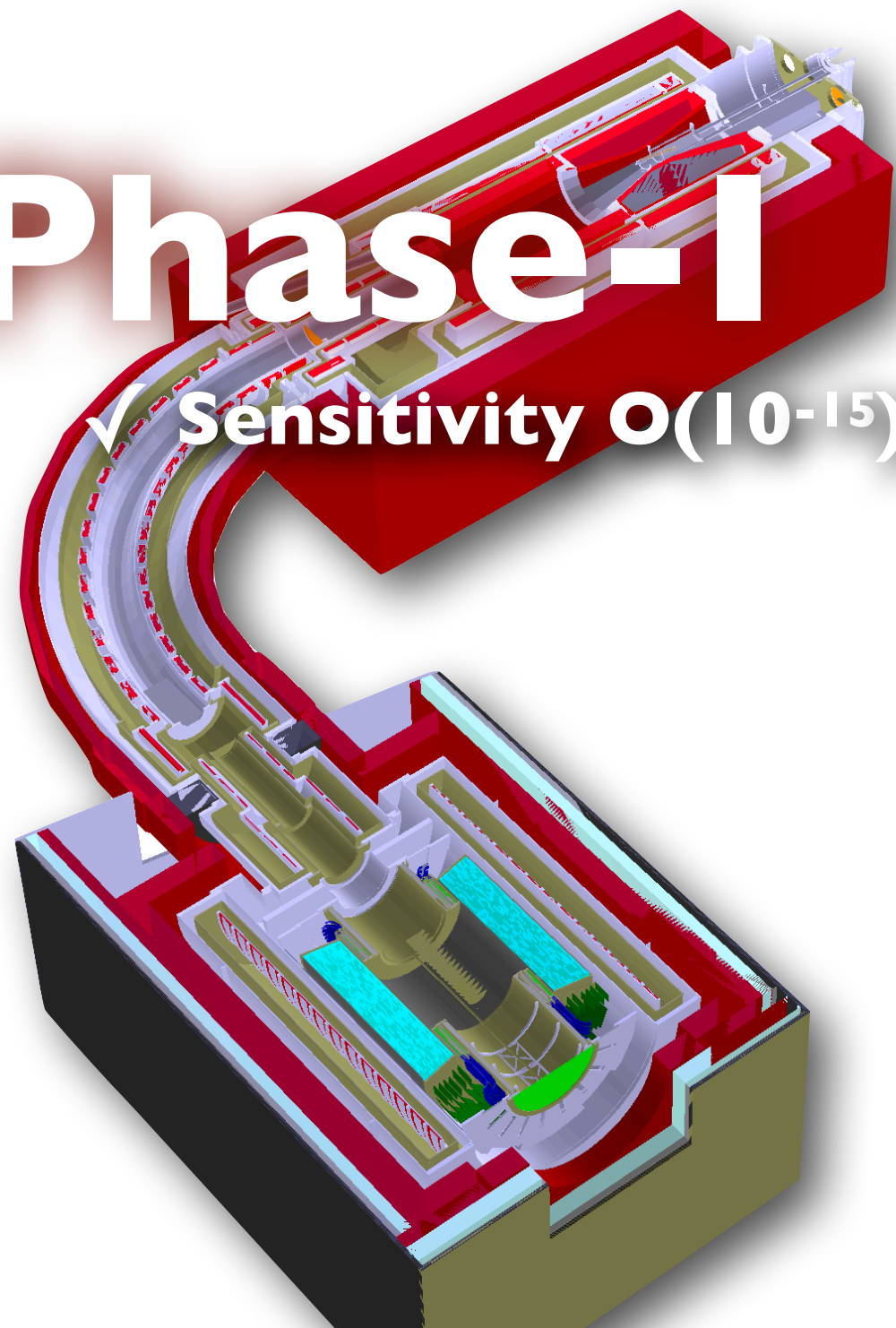
- ✦ The final single event sensitivity: $\mathcal{O}(10^{-17})$ 10,000× improvement from
 - ★ $R(\mu^- + \text{Au} \rightarrow e^- + \text{Au}) < 7 \times 10^{-13}$ by SINDRUM II @ PSI, Switzerland
 - ★ Bertl, W., et al. Eur. Phys. J. C 47, 337–346 (2006). DOI: 10.1140/epjc/s2006-02582-x
- ✦ Dedicated facility and muon transport line being constructed.
- ✦ Two-staged plan: Phase-I and Phase-II

Tokai, Ibaraki



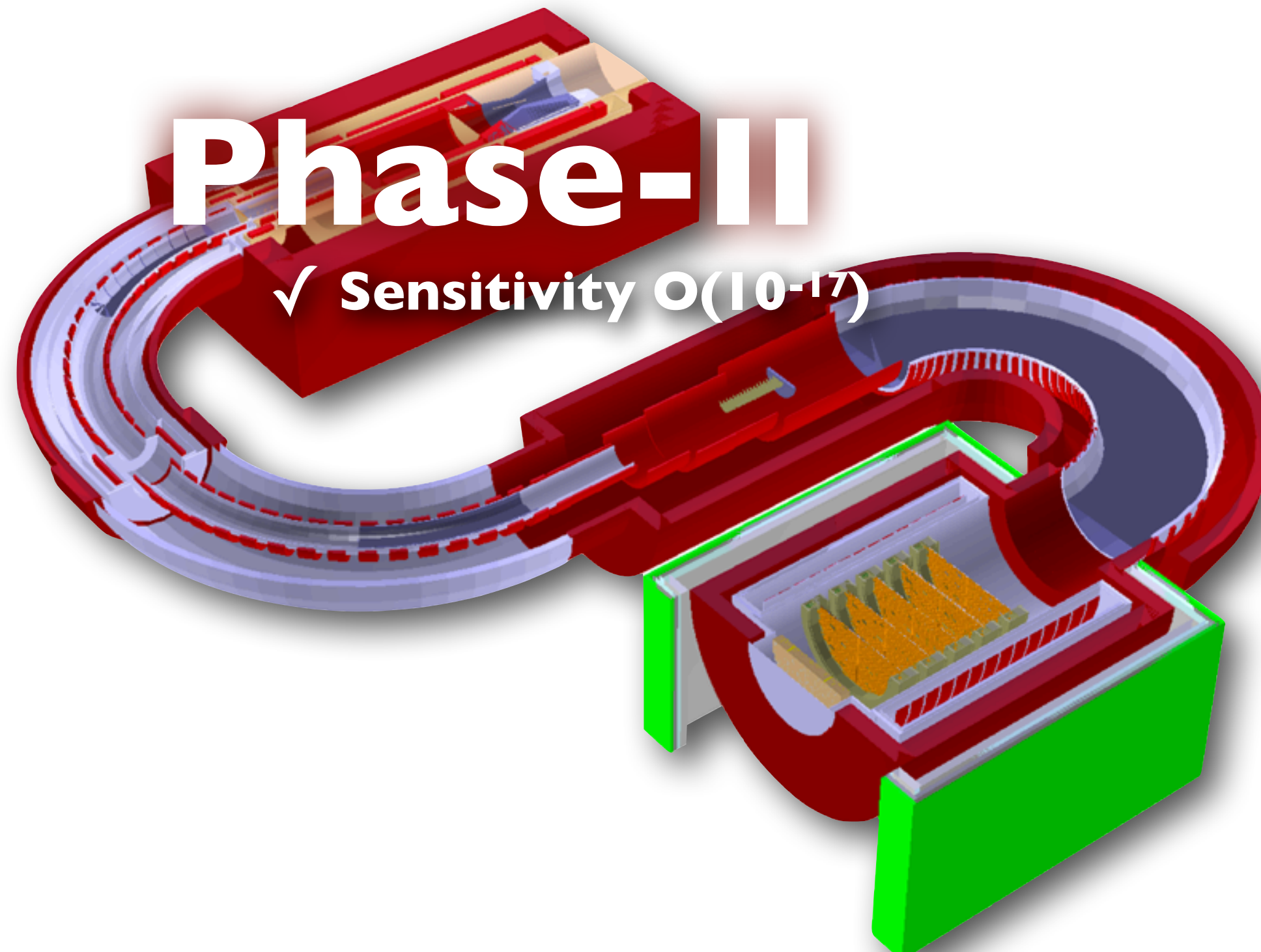
Phase-I

✓ Sensitivity $\mathcal{O}(10^{-15})$



Phase-II

✓ Sensitivity $\mathcal{O}(10^{-17})$



COMET Facility

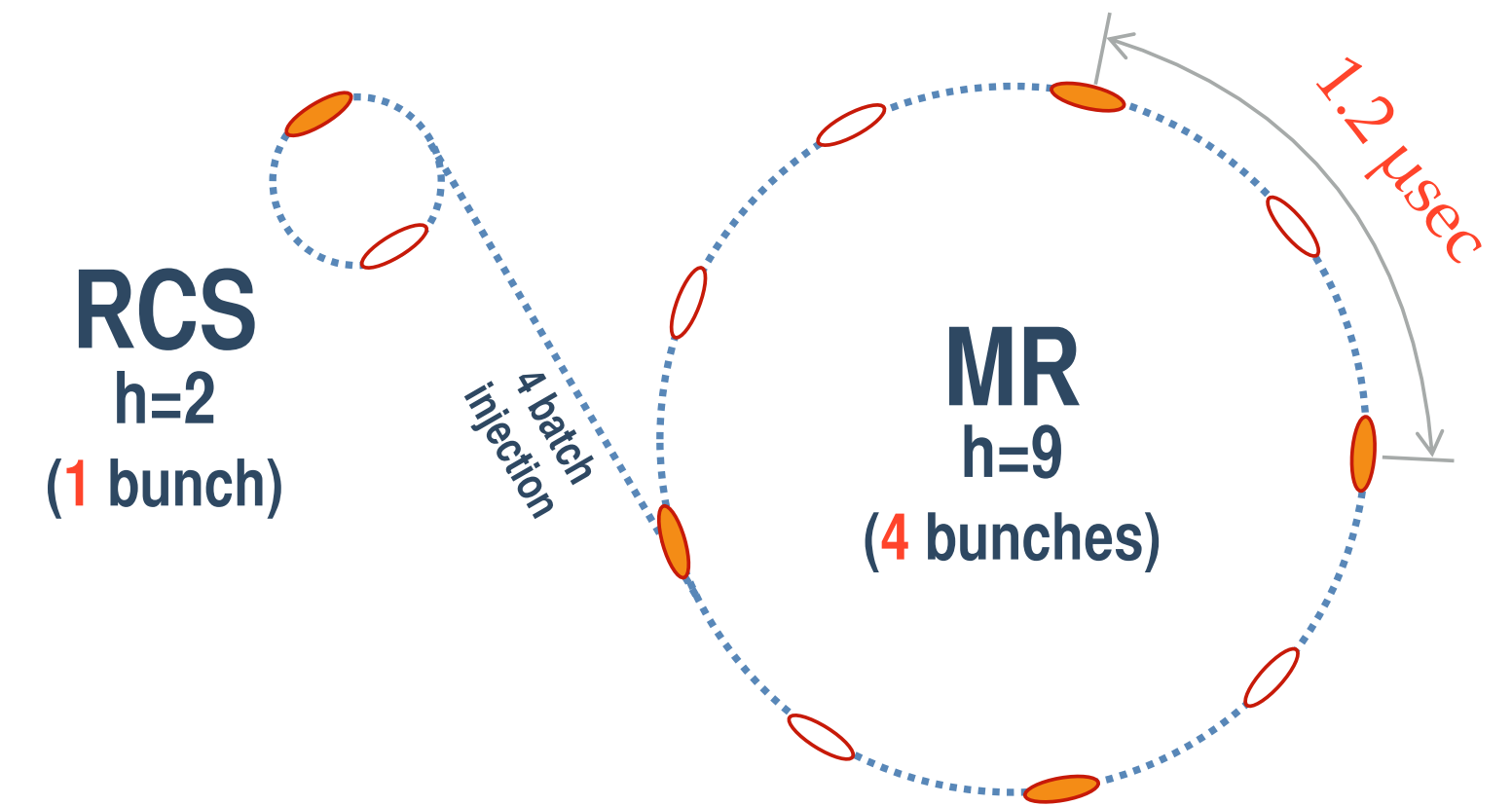




PROTON BEAM OPERATION

World-class intensity proton beam @ J-PARC MR

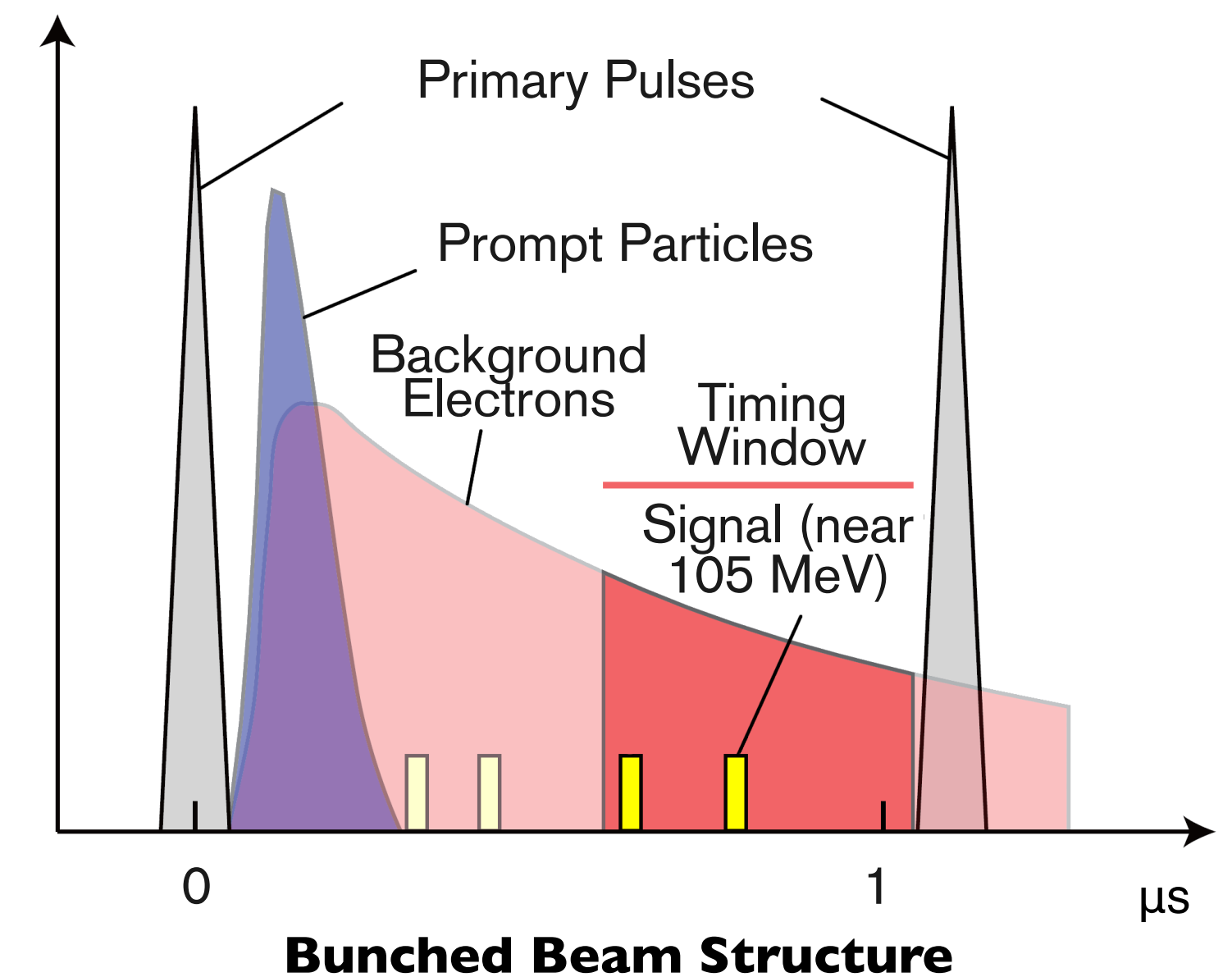
- ✦ To gain high statistics of muons.
- ✦ **Effective transport beamline** is essential.
- ✦ Backgrounds arise from the proton beam.
 - ★ Antiproton, radiative pion capture, muon decay in flight, etc...



Bunched beam filling for COMET

COMET's schemes against beam-induced BGs

- ✦ **Acceleration limited to 8 GeV**
 - ★ 30 GeV for other experiments.
 - ★ To minimise antiproton generation.
- ✦ **Bunched beam with delayed timing window**
 - ★ To mask the prompt beam BGs.





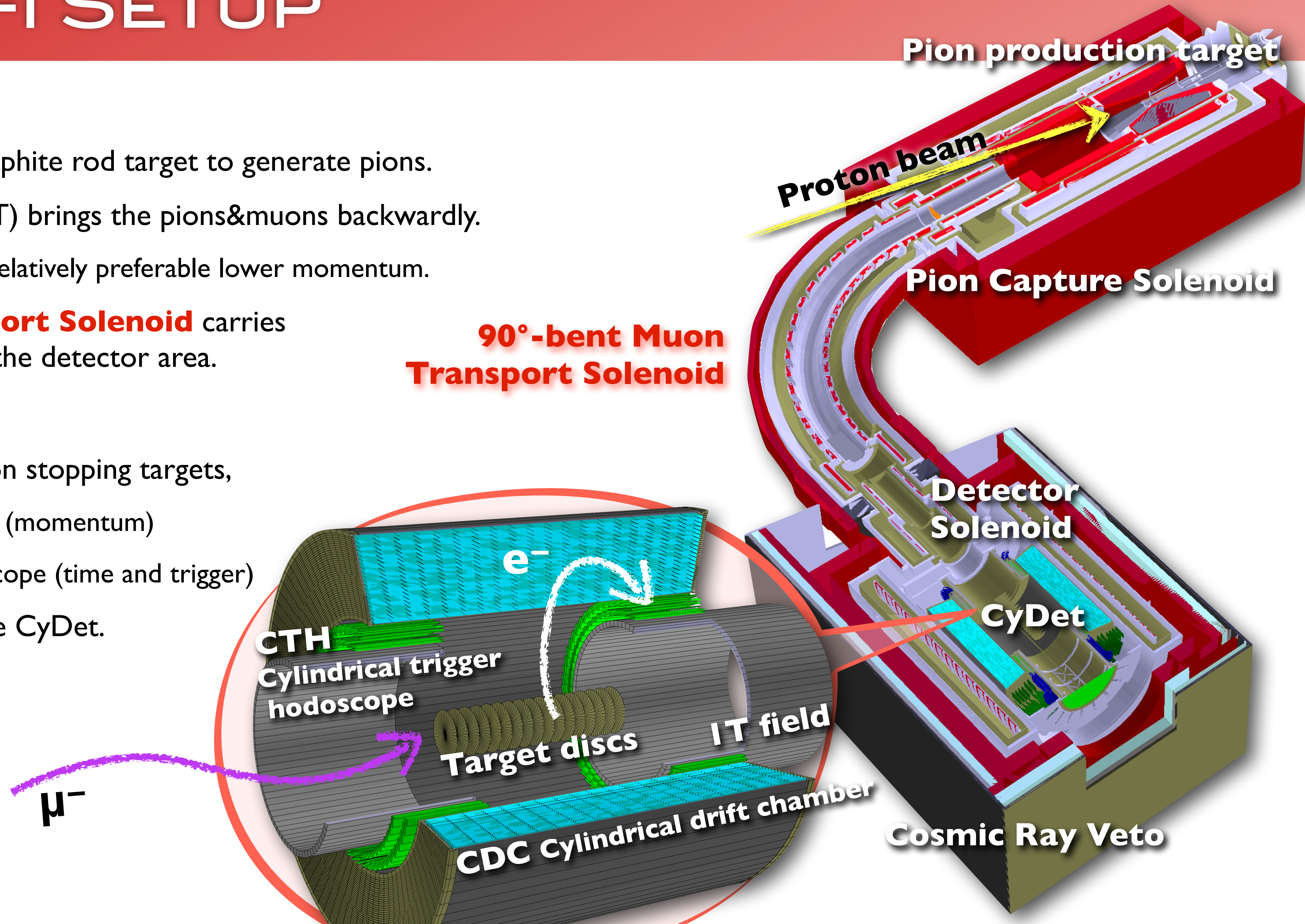
PHASE-I SETUP

Muon Beamline

- ✦ The proton beam hits a fixed graphite rod target to generate pions.
- ✦ The Pion Capture Solenoid (4.4 T) brings the pions&muons backwardly.
 - ★ Backward-produced pions have relatively preferable lower momentum.
- ✦ The **90°-bent Muon Transport Solenoid** carries the consequent muon beam to the detector area.

Detectors

- ✦ **CyDet** combining with the muon stopping targets,
 - ★ **CDC**: Cylindrical Drift Chamber (momentum)
 - ★ **CTH**: Cylindrical Trigger Hodoscope (time and trigger)
- ✦ Cosmic Ray Veto surrounding the CyDet.



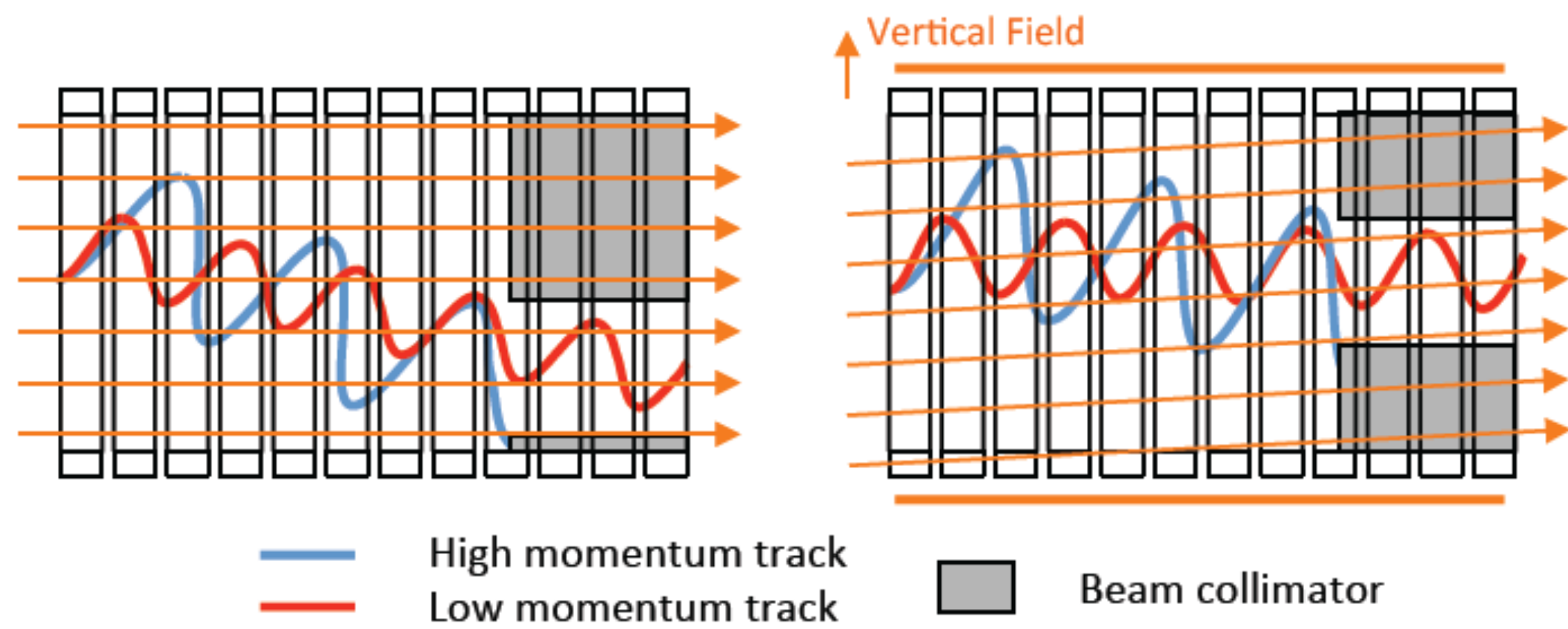


MUON TRANSPORT SOLENOID

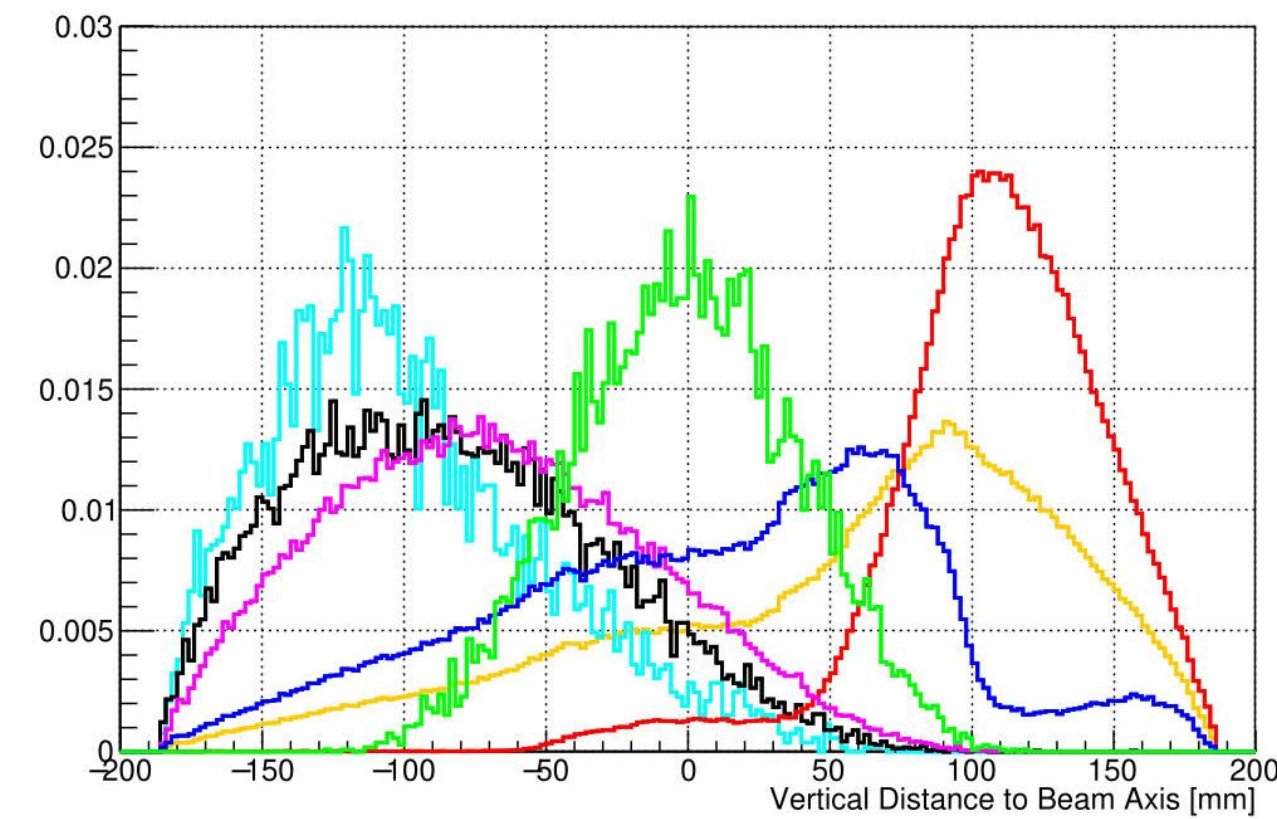
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Characteristic 90°-bent solenoid

- ♦ The centre of the helical trajectories drifts vertically.
 - ★ Sign-of-charge and momentum selection
 - ★ Additional dipole magnetic field for compensation
 - ❖ *c.f. Mu2e uses a S-shaped solenoid instead for the compensation.*
 - ★ Optimum collimators to select the specific momentum range.
- ♦ The magnet and beam collimator are designed to select the target low-momentum μ^- .
 - ★ μ^- of 30–50 MeV/c tend to stop in the aluminium target.

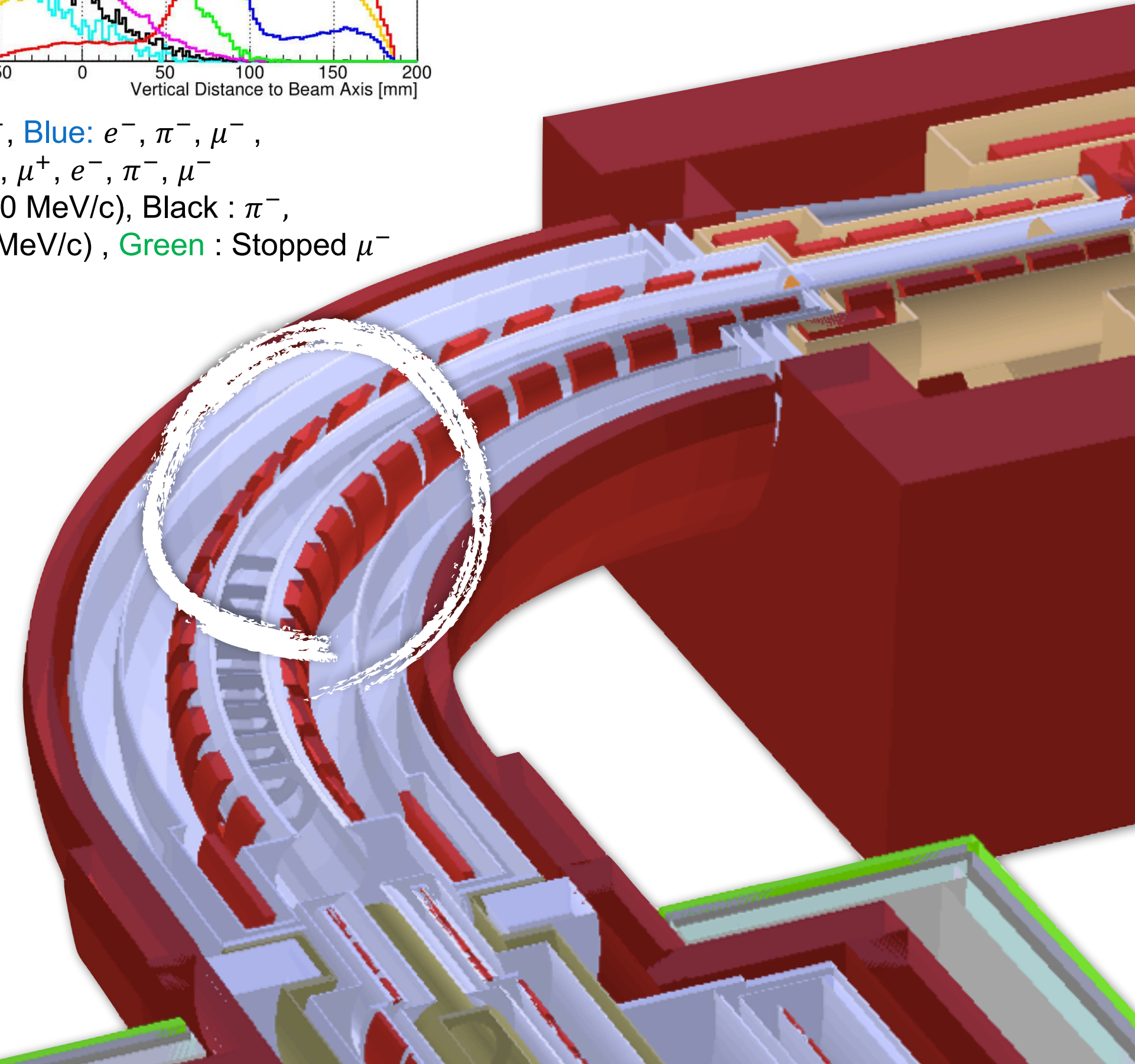


Trajectories in the transport solenoid



Vertical positions of different particle types before the collimator

Red : p, e^+, π^+, μ^+ , Blue: e^-, π^-, μ^- ,
 Orange : $p, e^+, \pi^+, \mu^+, e^-, \pi^-, \mu^-$
 Magenta: $\mu^- (p > 70 \text{ MeV/c})$, Black : π^- ,
 Cyan: $e^- (p > 100 \text{ MeV/c})$, Green : Stopped μ^-

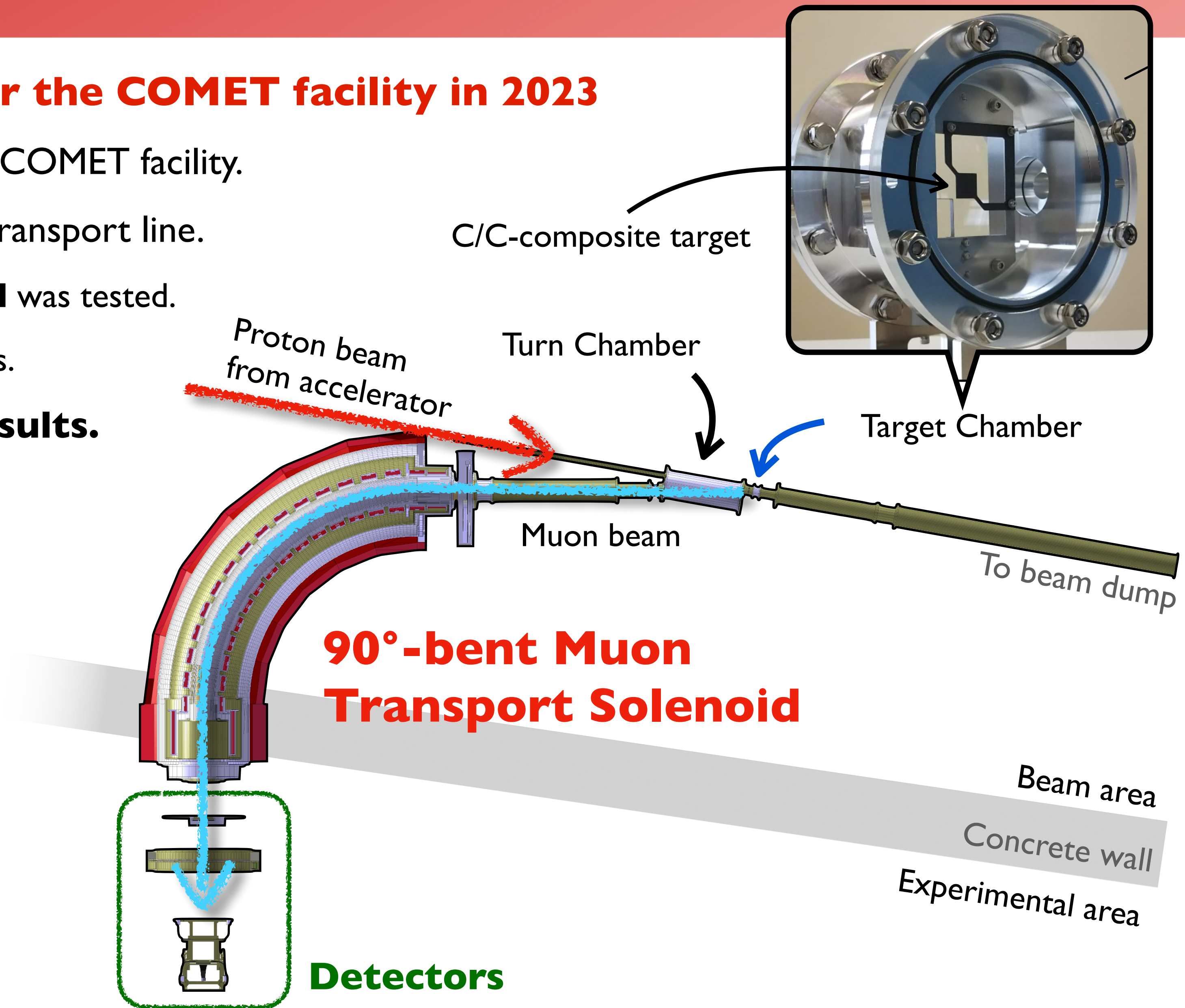
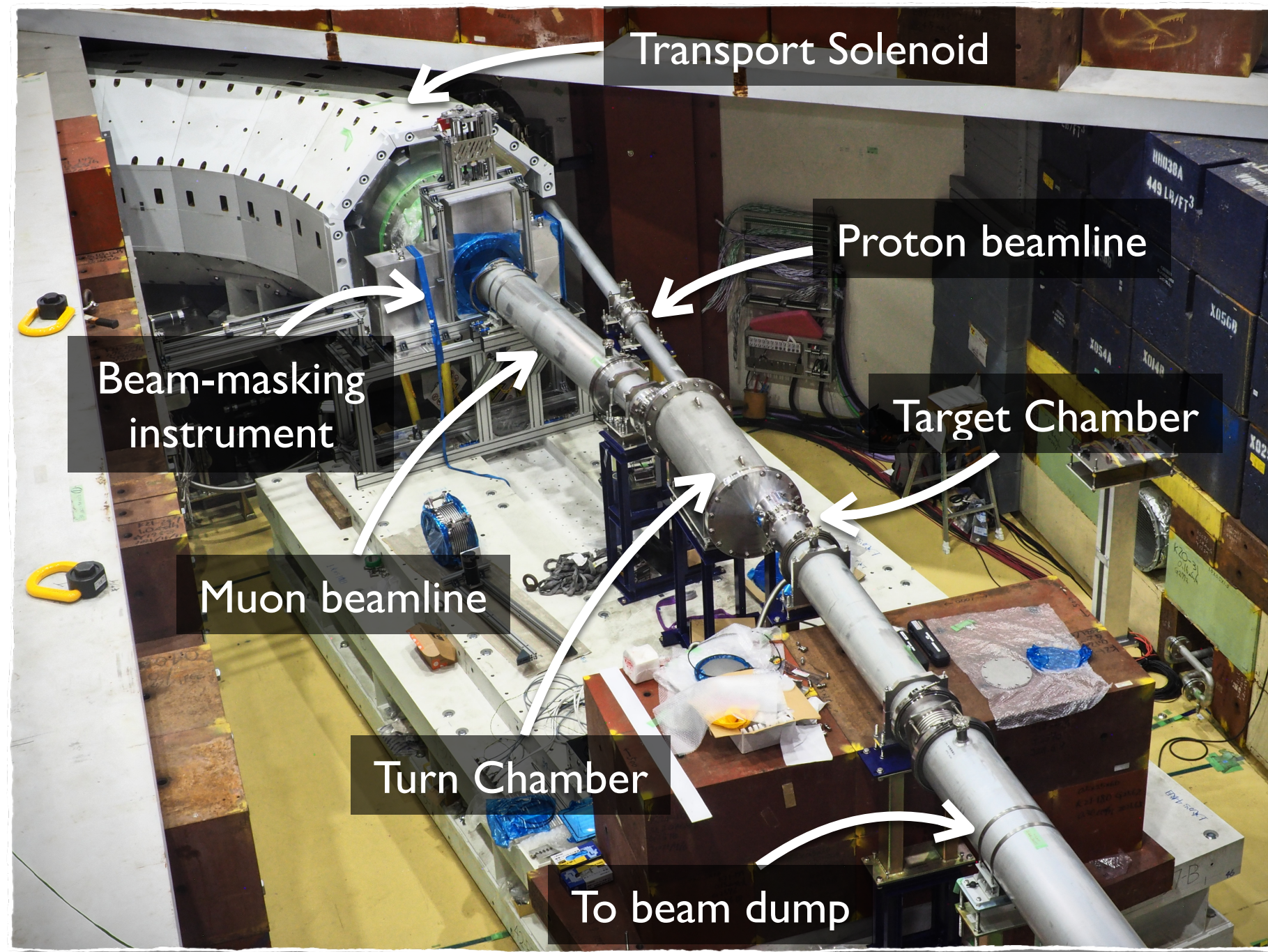




PHASE- α

COMET's first commissioning project for the COMET facility in 2023

- ✦ *Objective 1*: Introduction of the proton beam to the COMET facility.
- ✦ *Objective 2*: Muon-beam measurements after beam transport line.
 - ★ Only the most crucial **Muon Transport Solenoid** was tested.
 - ★ Simulation was to be validated with the measurements.
 - ★ **This talk presents the measurement results.**

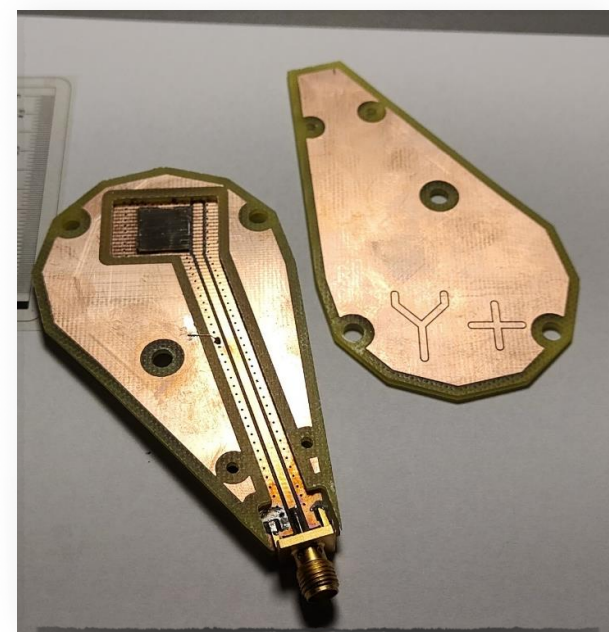




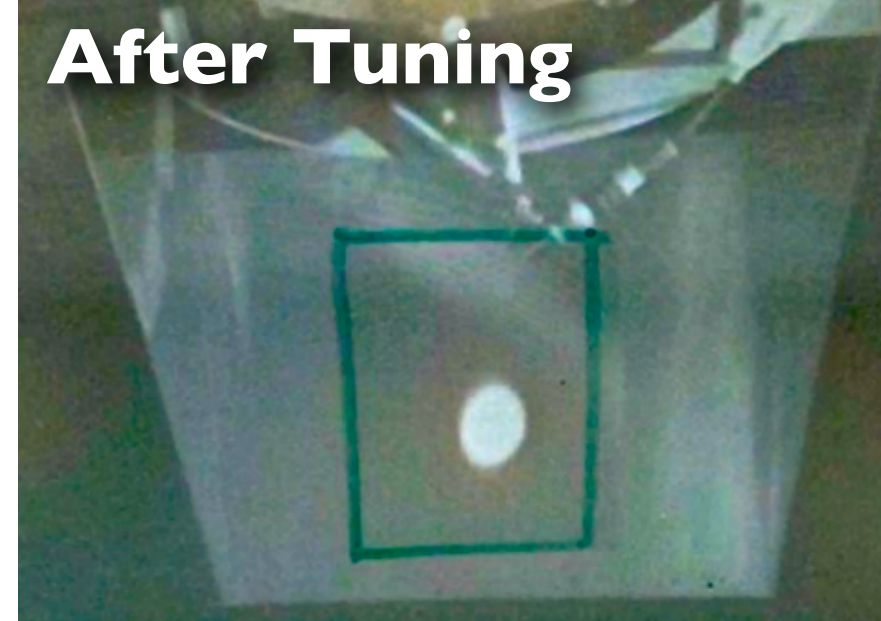
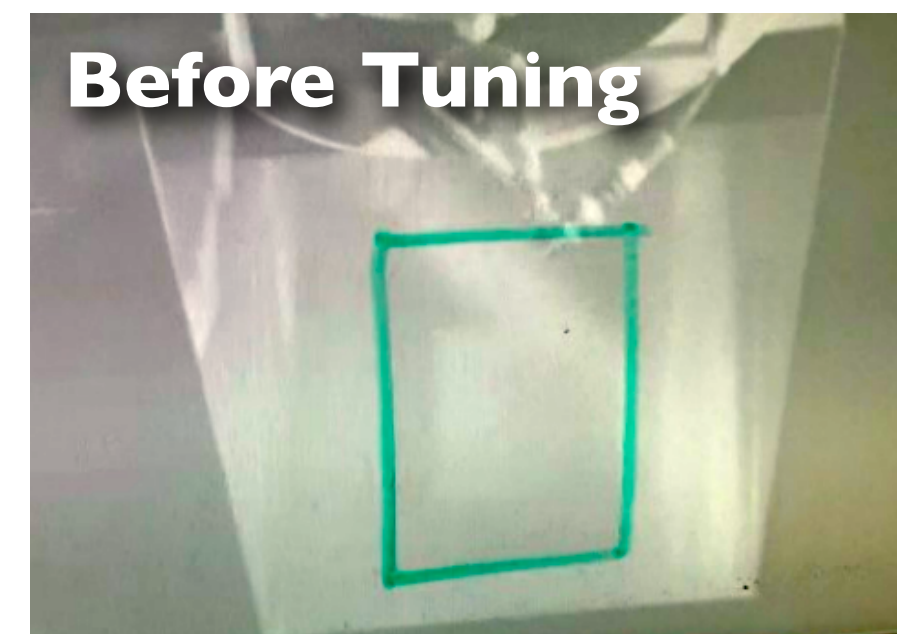
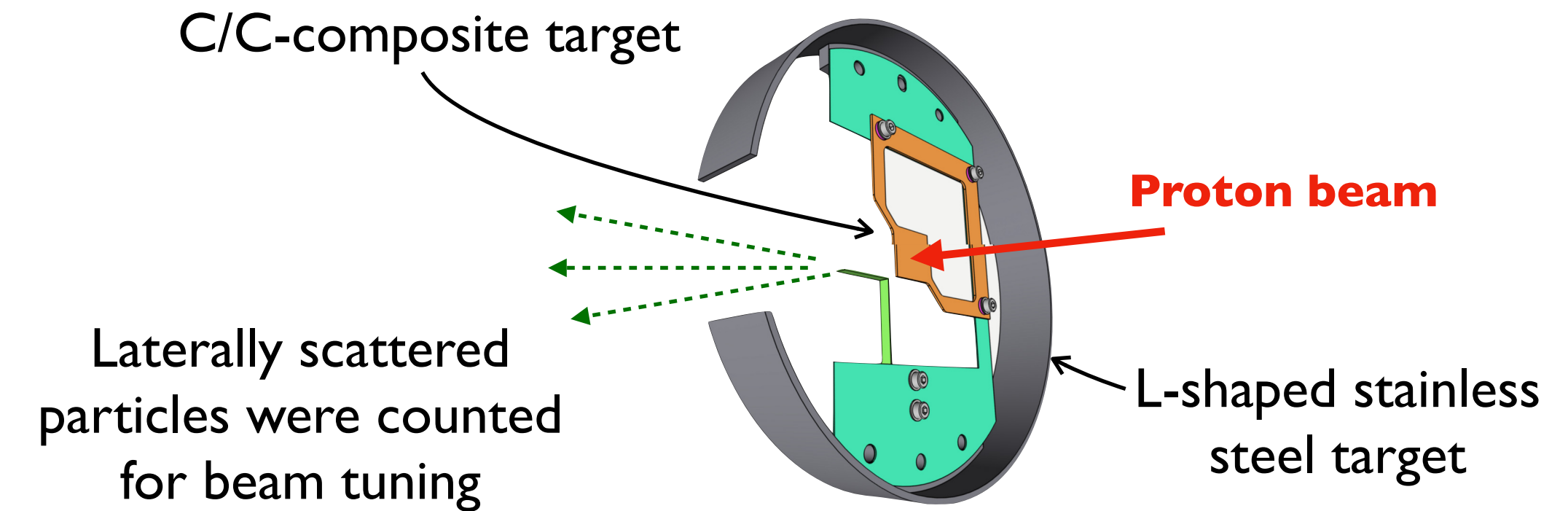
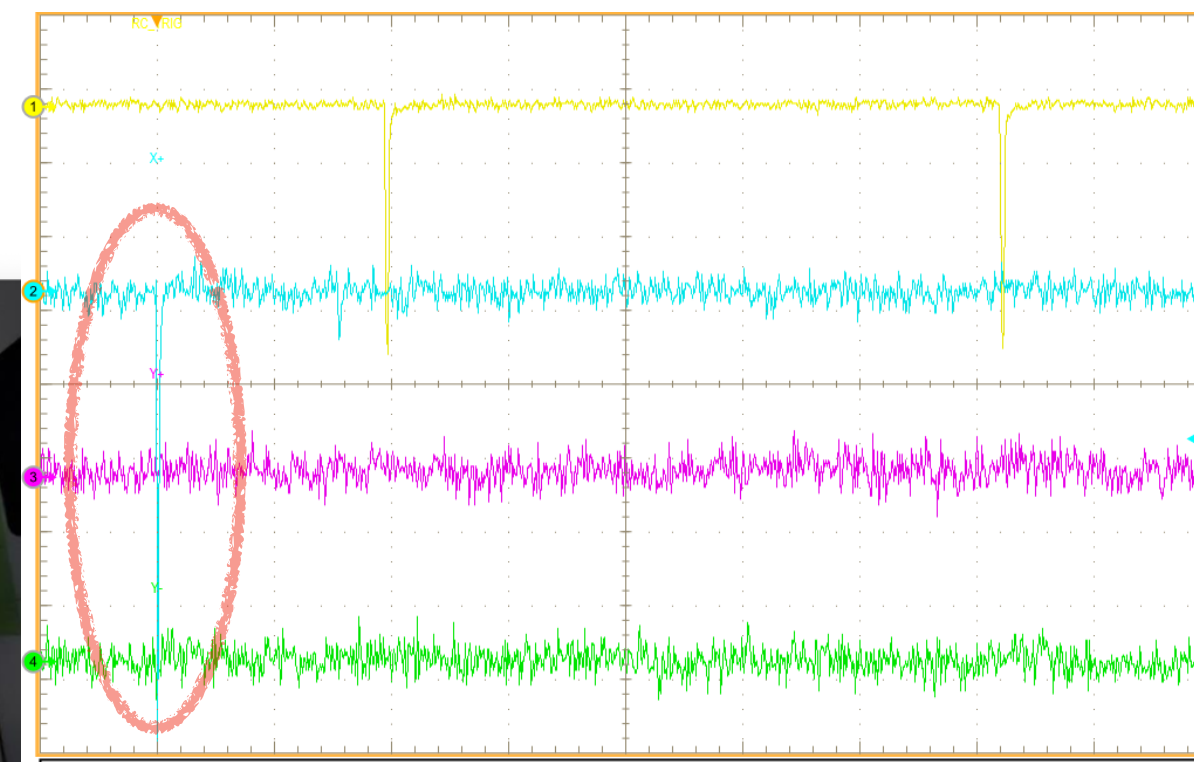
PROTON BEAM COMMISSIONING

Proton beam introduction succeeded.

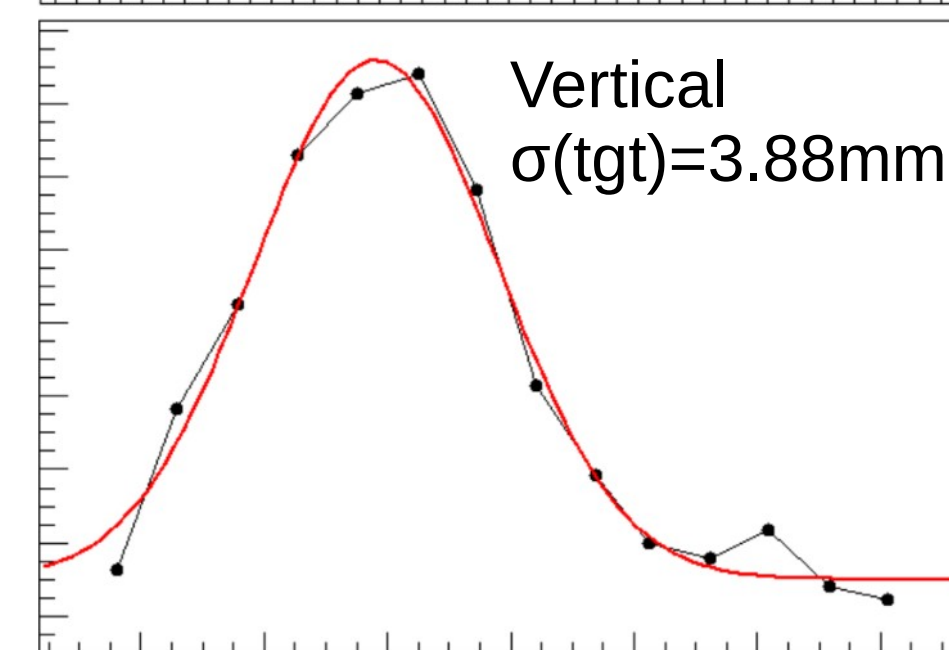
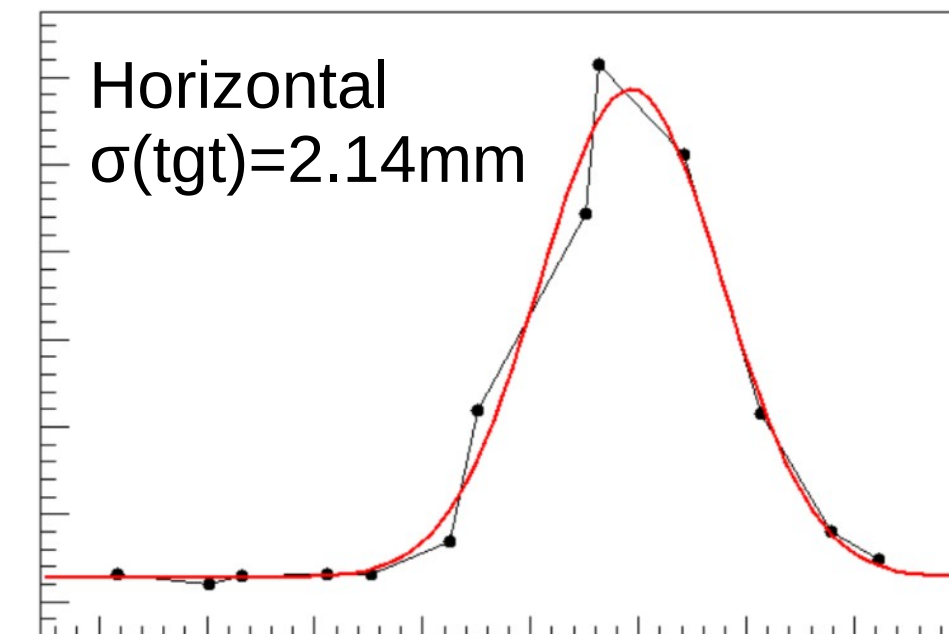
- ✦ 8 GeV proton beam extracted at 260 W (10% of Phase-I).
- ★ No operational problem during Phase- α .
- ✦ Beam tuning and beam profile measurements well performed.
- ✦ Our proton beam monitor observed proton signals.
 - ★ Made from original TiO_2 semiconductor sensors
 - ★ DOI: [10.1109/JSEN.2022.3224809](https://doi.org/10.1109/JSEN.2022.3224809)



TiO_2 sensor



Phosphor plate reaction
before&after the beam tuning



Measured beam sizes



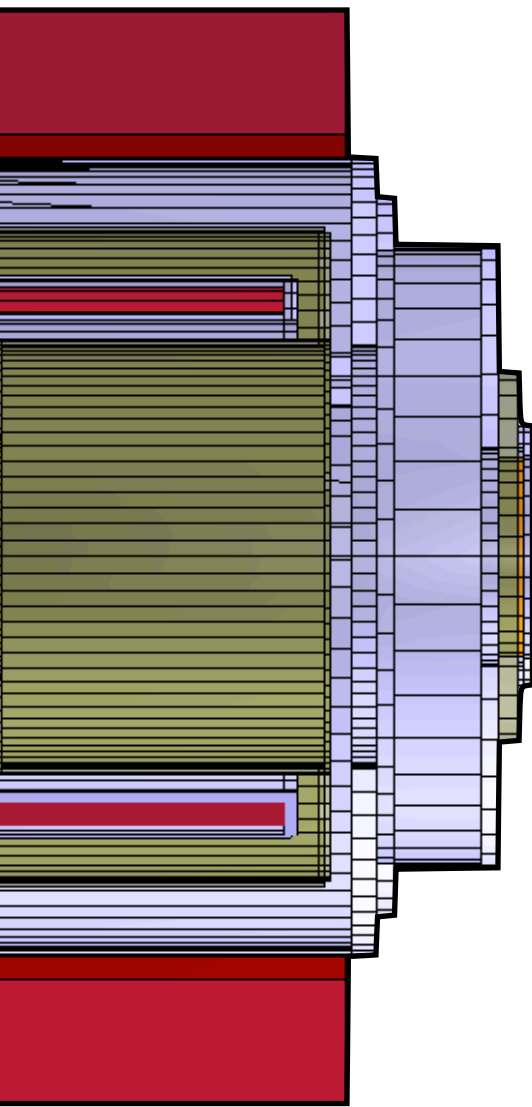
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MUON BEAM MEASUREMENT

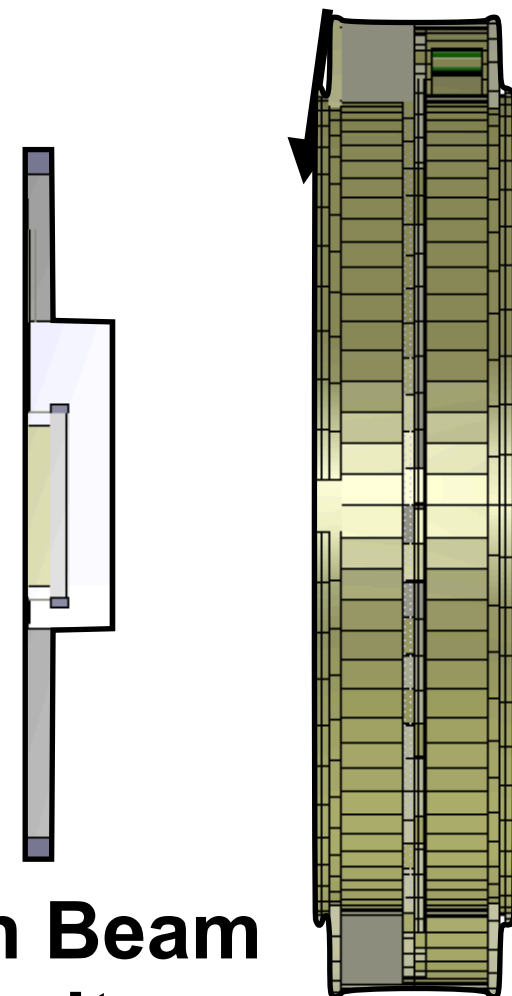


DETECTORS

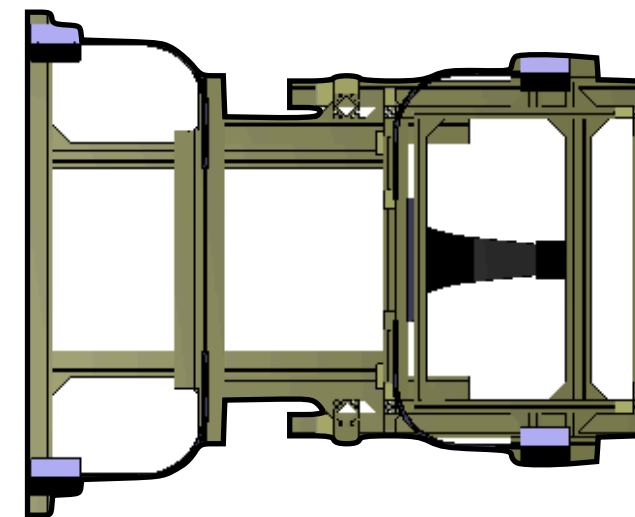
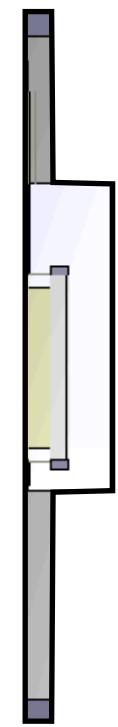
Transport
Solenoid



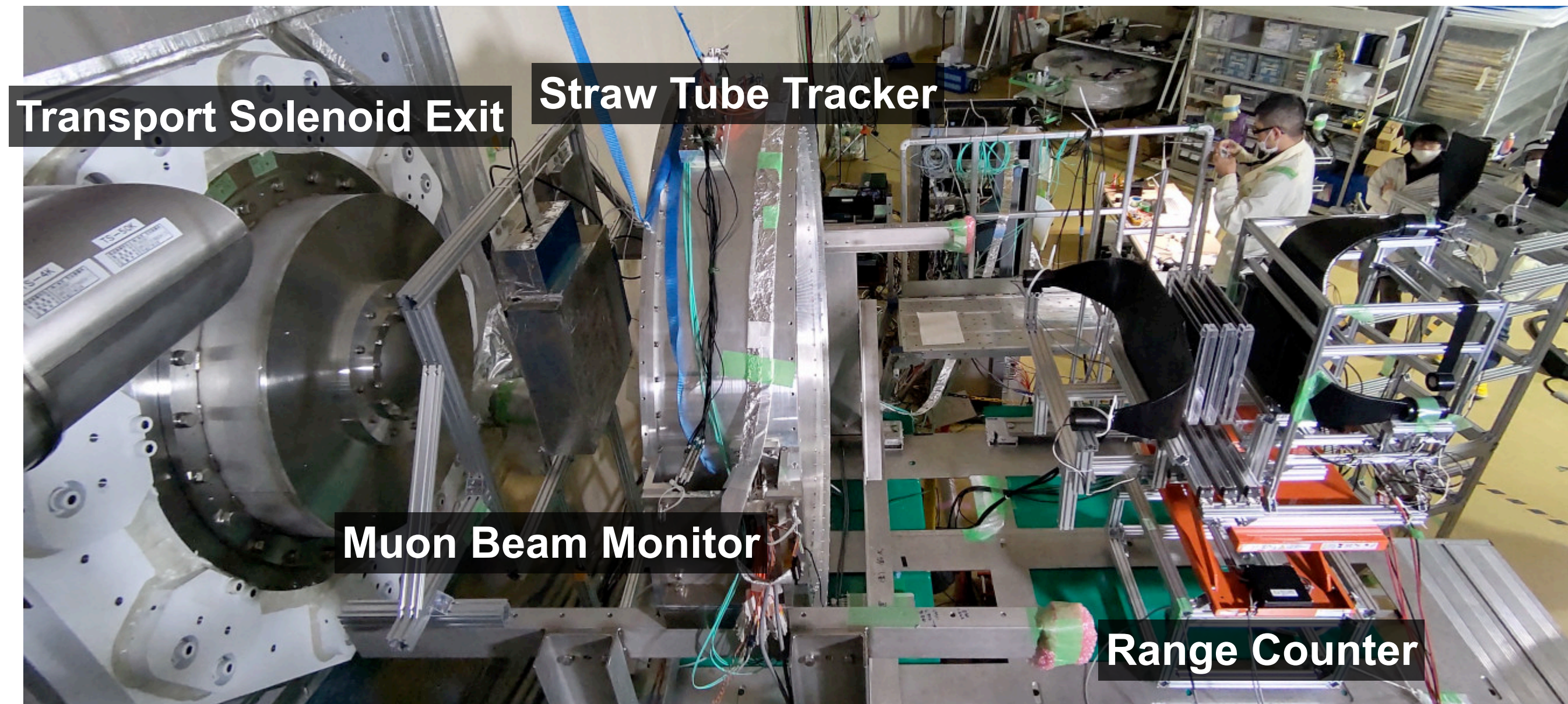
Straw Tube Tracker



Muon Beam
Monitor



Range Counter



Muon Beam Monitor (DOI: [10.1007/s41365-024-01442-0](https://doi.org/10.1007/s41365-024-01442-0))

- ✦ Scintillator fibre hodoscope
- ✦ Measure beam position

Straw Tube Tracker (DOI: [10.1016/j.nima.2016.06.082](https://doi.org/10.1016/j.nima.2016.06.082))

- ✦ Straw-tube gaseous tracking chambers
- ✦ Measure beam position and direction

Range Counter (DOI: [10.1016/j.nima.2025.170904](https://doi.org/10.1016/j.nima.2025.170904))

- ✦ The main detector in Phase- α .
 - ✦ This talk presents analysis results for this detector.
- ✦ Identify negative muons and generate trigger signals.



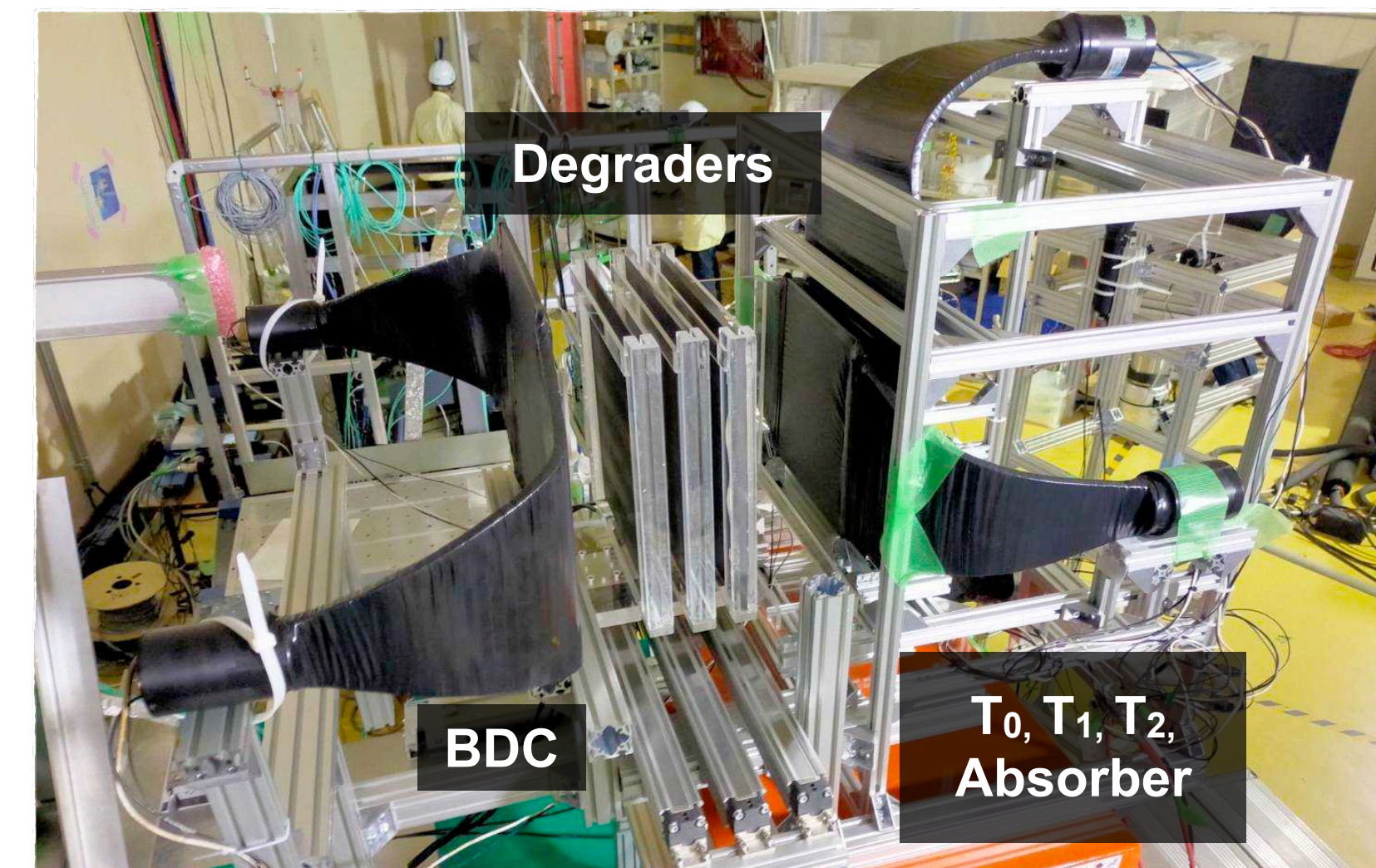
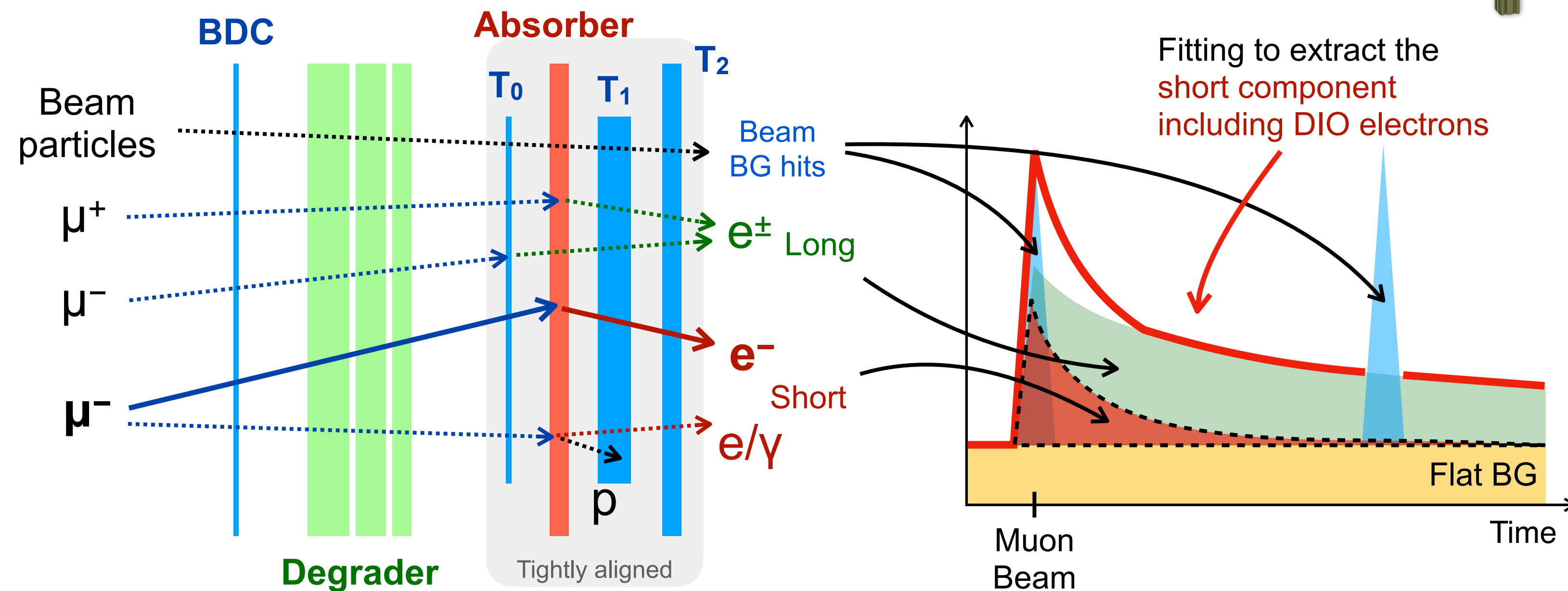
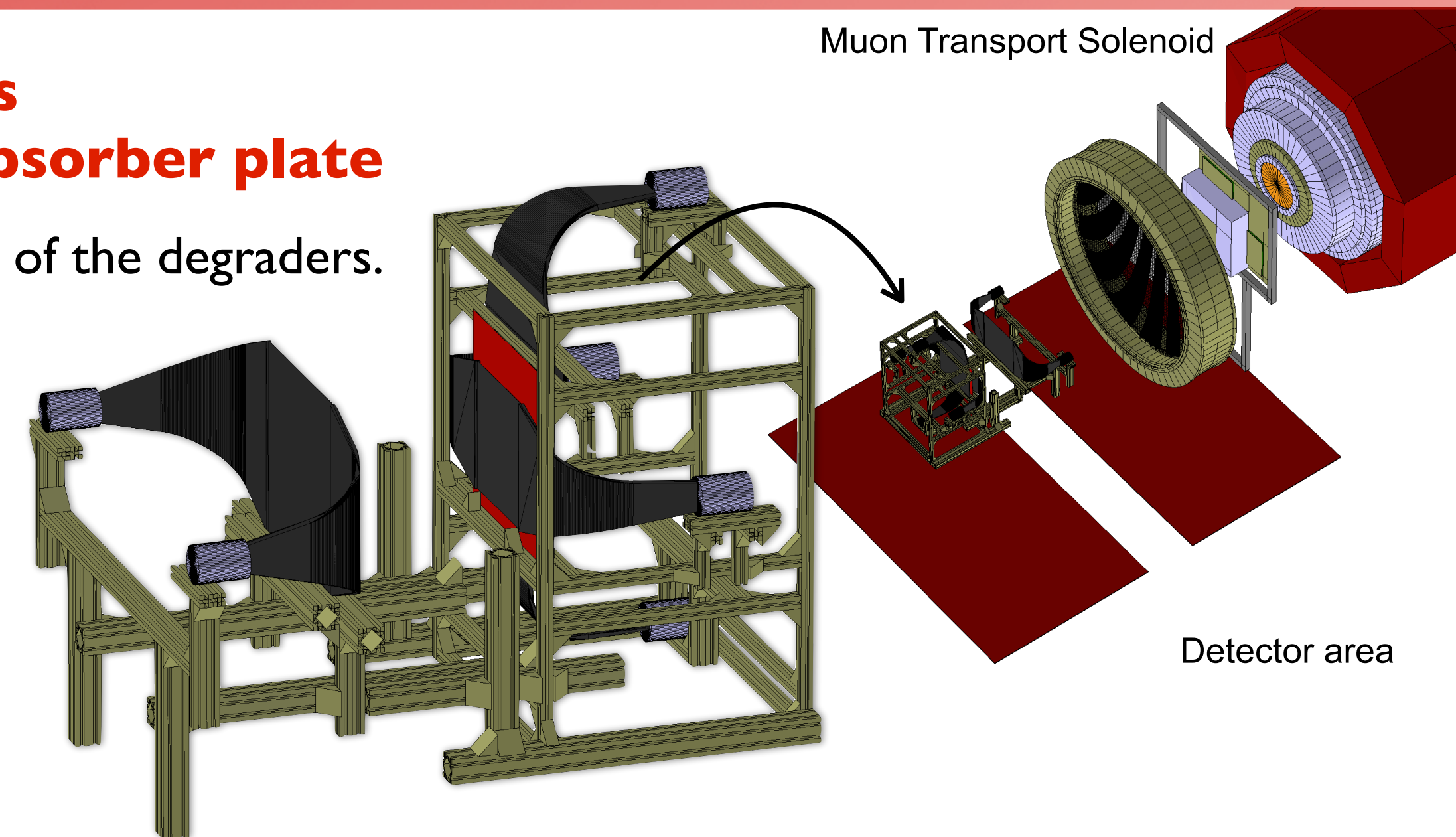
MAIN DETECTOR: RANGE COUNTER

The main detector with multi-layer plastic scintillating counters + graphite momentum degrader plates + copper absorber plate

- Count incoming muons with specific momentum range, controlled by total thickness of the degraders.
- Negative muons stop in the copper absorber and form muonic atoms.
 - ★ Their effective lifetime is ~ 160 ns, exclusively shorter for identification.

Data taking

- Trigger condition: BDC & T_0 & $(T_1 \mid T_2)$
- Fine-mesh PMT readout $\rightarrow$ Waveform digitised for waveform analysis.





BEAM TIME AND OBTAINED DATASETS

Beam times

- ✦ 10–14 February 2023
 - ★ Beam commissioning and tuning
 - ★ Trigger & DAQ establishing.
- ✦ **3–4 & 9–15 March 2023**
 - ★ Main data taking (to be presented in this talk.)

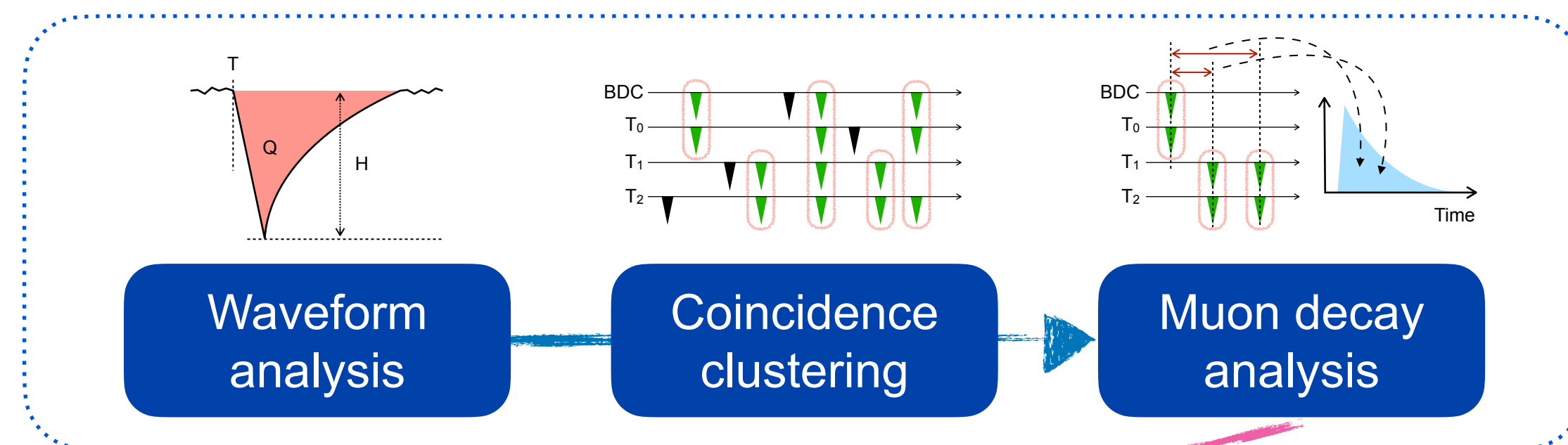
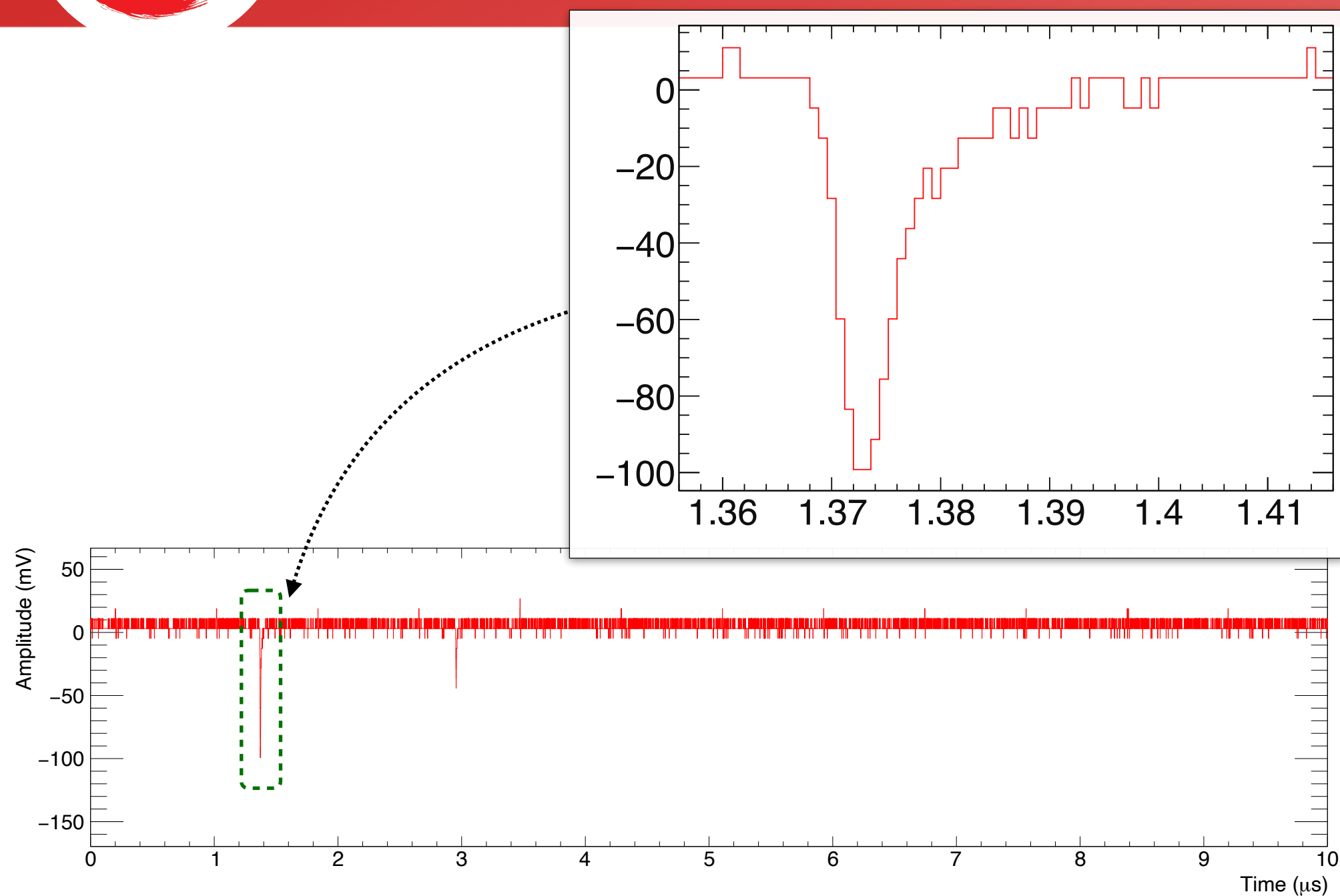
!! datasets

- ✦ **Degrader (momentum) scan**
 - ★ Six setups with different total degrader thicknesses.
- ✦ **Beam-position scan**
 - ★ The RC was moved to *five* positions around the beam centre.
 - ★ No degrader used.



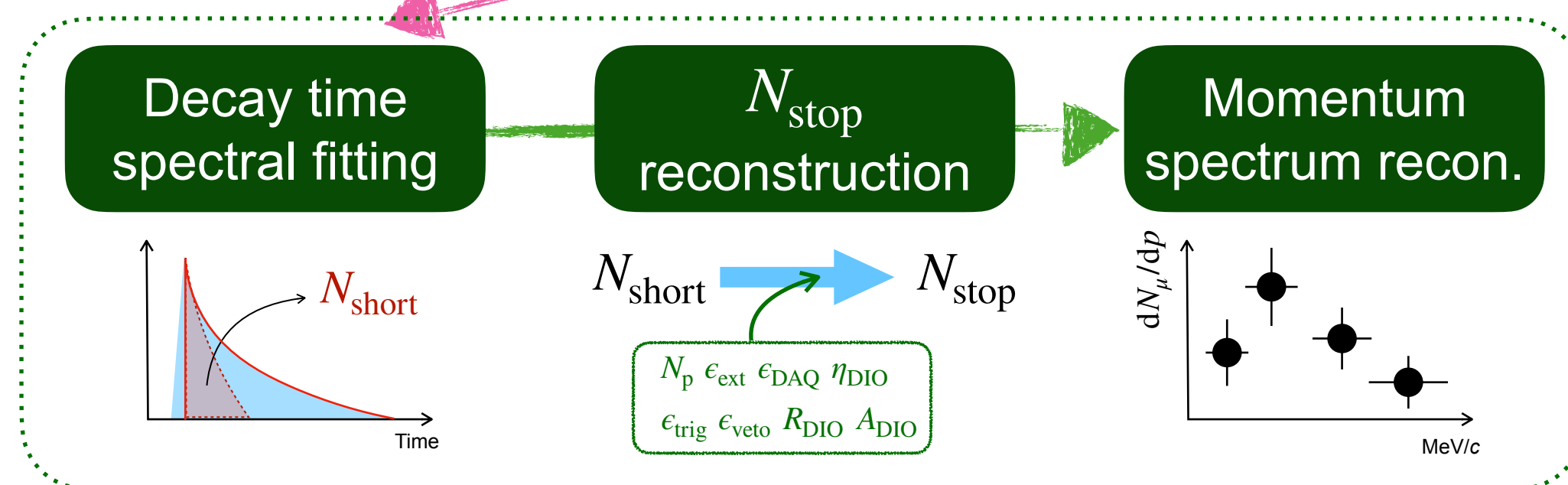


DATA ANALYSIS FLOW



Event-by-event analysis

Statistical analysis



Event-by-event analysis

- ✦ Waveform analysis to identify pulses and obtain their time and charge.
- ✦ Coincidence analysis to construct muon decay time distributions.

Statistical analysis

- ✦ Time-spectral fit to the obtained distributions to reconstruct N_{short} : normalisation of the short-lifetime component.
- ✦ Reconstruction of N_{stop} : the number of muons stop in the copper absorber, then converted to the momentum spectrum dN_{μ}/dp .

Comparison with simulation based on Geant4



SPECTRAL FIT

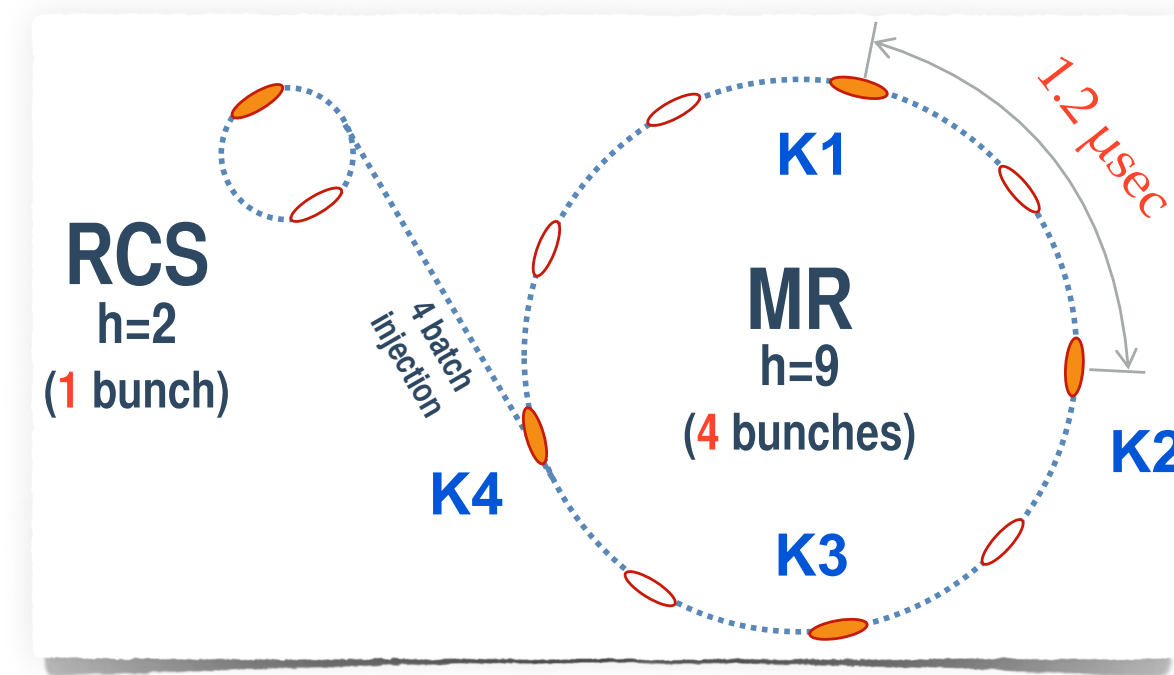
All the 11 datasets are fitted simultaneously.

- Regions of the beam-induced BG peaks are masked from the fit.

- The peak positions differ depending on the proton bunch index (K1–K4)

- Every dataset is split into four sub spectra to gain statistics.

- 44 spectra (11 datasets × 4 bunch indices)



Bunch filling in MR cycle

- Individual spectra are fitted by two exponential curves and a BG constant.

- Only the two lifetimes (τ_{short} and τ_{long}) are shared among the datasets.

The simultaneous fit converges properly.

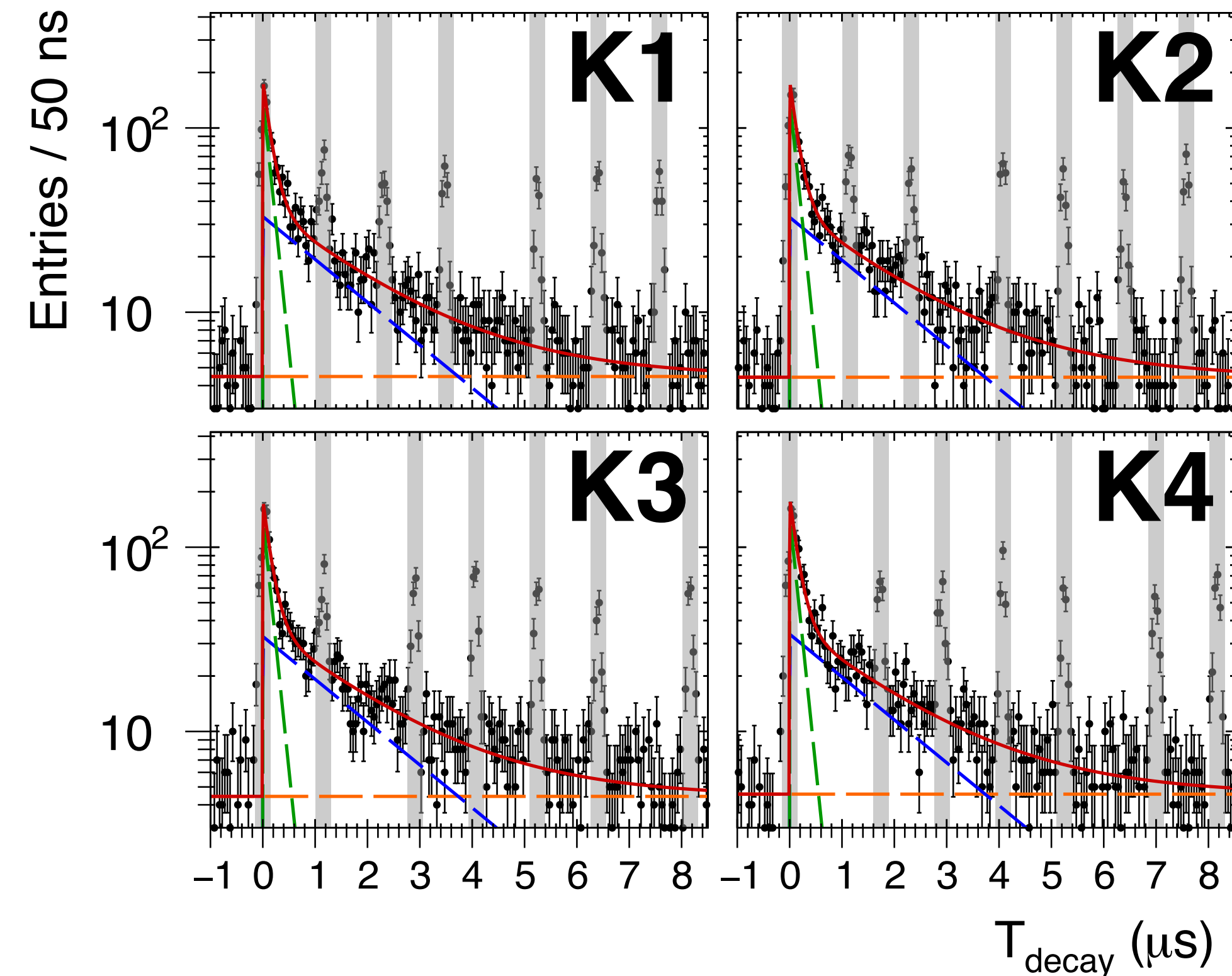
- The obtained lifetime parameters are consistent with expectations.

- τ_{short} : Negative muon lifetime in copper (160–170 ns)

- τ_{long} : Due to mix of other lighter materials dominated by carbon ($\sim 2 \mu\text{s}$)

- Likely shorten a little by the aluminium assembly frames of the RC.

Fit results for dataset: no degrader & centre pos.



Lifetime	Value (μs)
τ_{short}	$0.1694^{+0.0122}_{-0.0117} {}^{+0.0002}_{-0.0009}$
τ_{long}	$1.9082^{+0.0615}_{-0.0593} {}^{+0.0004}_{-0.0033}$

Fit results of the lifetime parameters



RECONSTRUCTION OF STOPPED MUONS

Reconstruction of N_{stop} : the number of stopped muons per beam proton

$$N_{\text{stop}} = \frac{1}{N_p \epsilon_{\text{ext}} \epsilon_{\text{DAQ}}} \quad \frac{\overset{\text{Fit result}}{N_{\text{short}}} \eta_{\text{DIO}}}{\epsilon_{\text{trig}} f_{\text{trig}} (1 - \epsilon_{\text{veto}}) R_{\text{DIO}} A_{\text{DIO}}}$$

Experimental **Range Counter's performance**

Evaluated based on dedicated simulation studies
and performance evaluation test experiment
[DOI:10.1016/j.nima.2025.170904](https://doi.org/10.1016/j.nima.2025.170904)

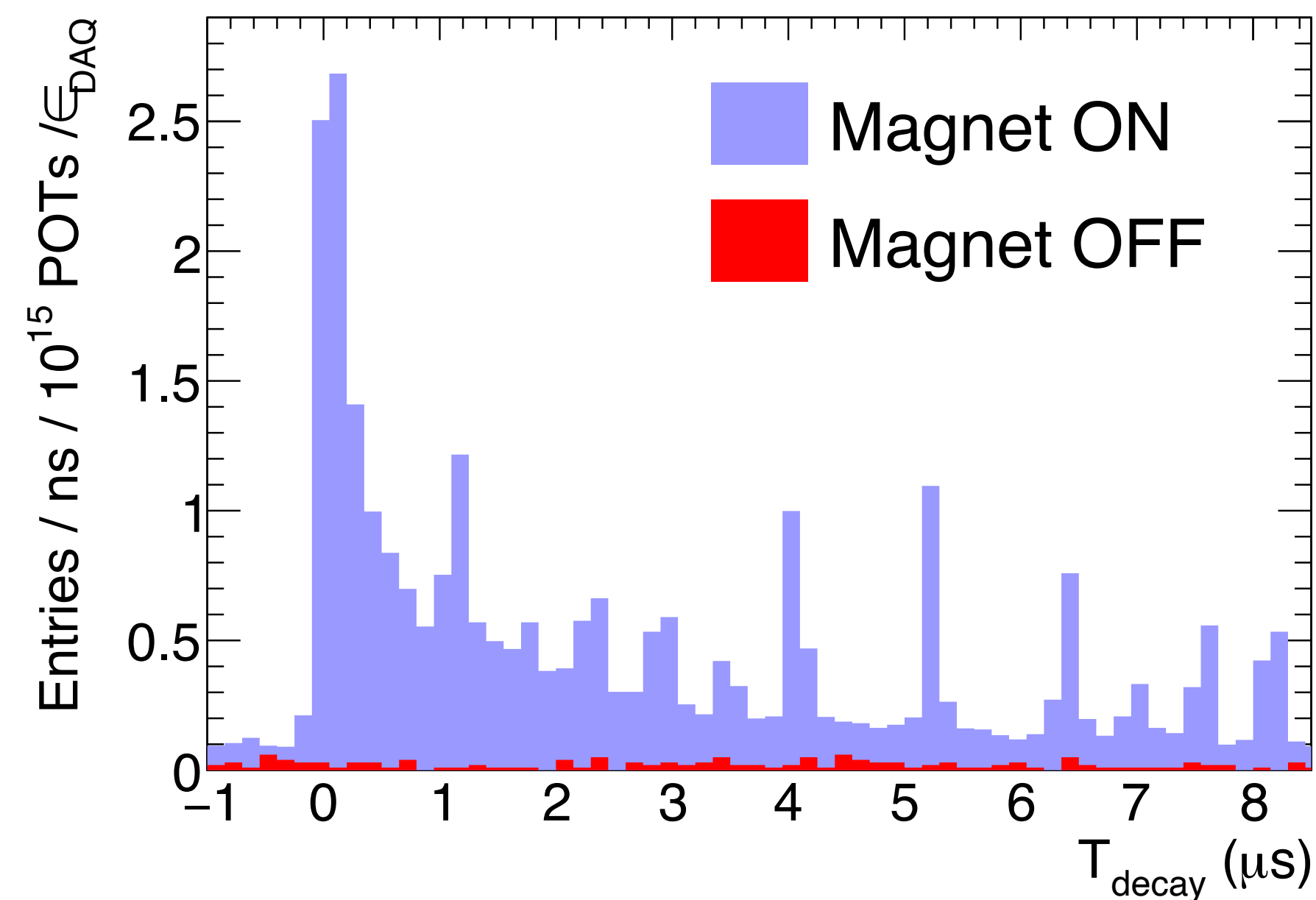
- ✦ N_p : Number of protons in the Main Ring accelerator.
- ✦ ϵ_{ext} : Proton extraction efficiency to the COMET facility
- ✦ ϵ_{DAQ} : DAQ efficiency, suppressed due to a fixed DAQ dead time.
- ✦ ϵ_{trig} : Muon-trigger efficiency of the BDC and T₀ Counter for slow muons, as a function of muon momentum
- ✦ ϵ_{veto} : Trigger inefficiency due to vetoing by T₁ and/or T₂.
- ✦ R_{DIO} : The DIO rate of negative muons in copper: 0.0720 and RMS 0.0004, averaged from Ref. to DOI:10.1103/PhysRevC.35.2212;
- ✦ A_{DIO} : Geometrical and analytical acceptance for DIO electrons
- ✦ η_{DIO} : DIO signal purity in N_{short} .
- ✦ f_{trig} : Correction factor to ϵ_{trig} due to the instability of the trigger rate.

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RESULTS



VALIDATION (1): MTS MAGNETIC FIELD

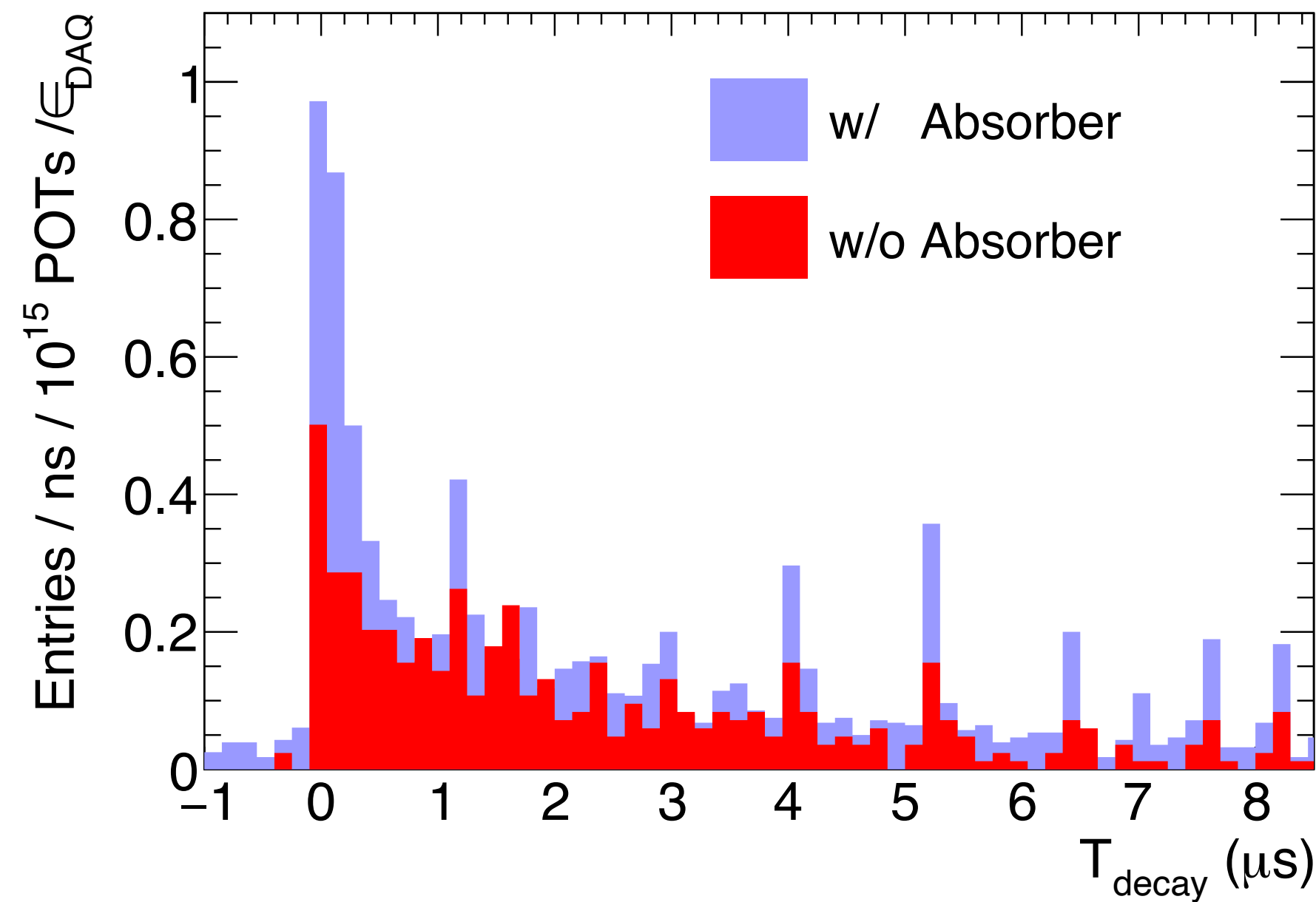


Comparison in terms of the existence of the MTS magnetic field.

- ✦ The same analysis and reconstruction procedures were applied.
 - ★ Entries are properly normalised for fair comparison.
- ✦ The RC did not observe any clear exponential curve.
 - ★ Negative muons (or even charged particles) hardly reached the RC to satisfy the trigger logic.
- ✦ **The magnetic fields of the MTS certainly transports beam muons.**



VALIDATION (2): COPPER ABSORBER



Dataset	N_{long}	N_{short}
abs.off	$296.26^{+24.36}_{-23.77}$	$0.00^{+12.50}_{-0.00}$
abs.on	$950.98^{+59.01}_{-58.23}$	$354.29^{+53.00}_{-50.51}$

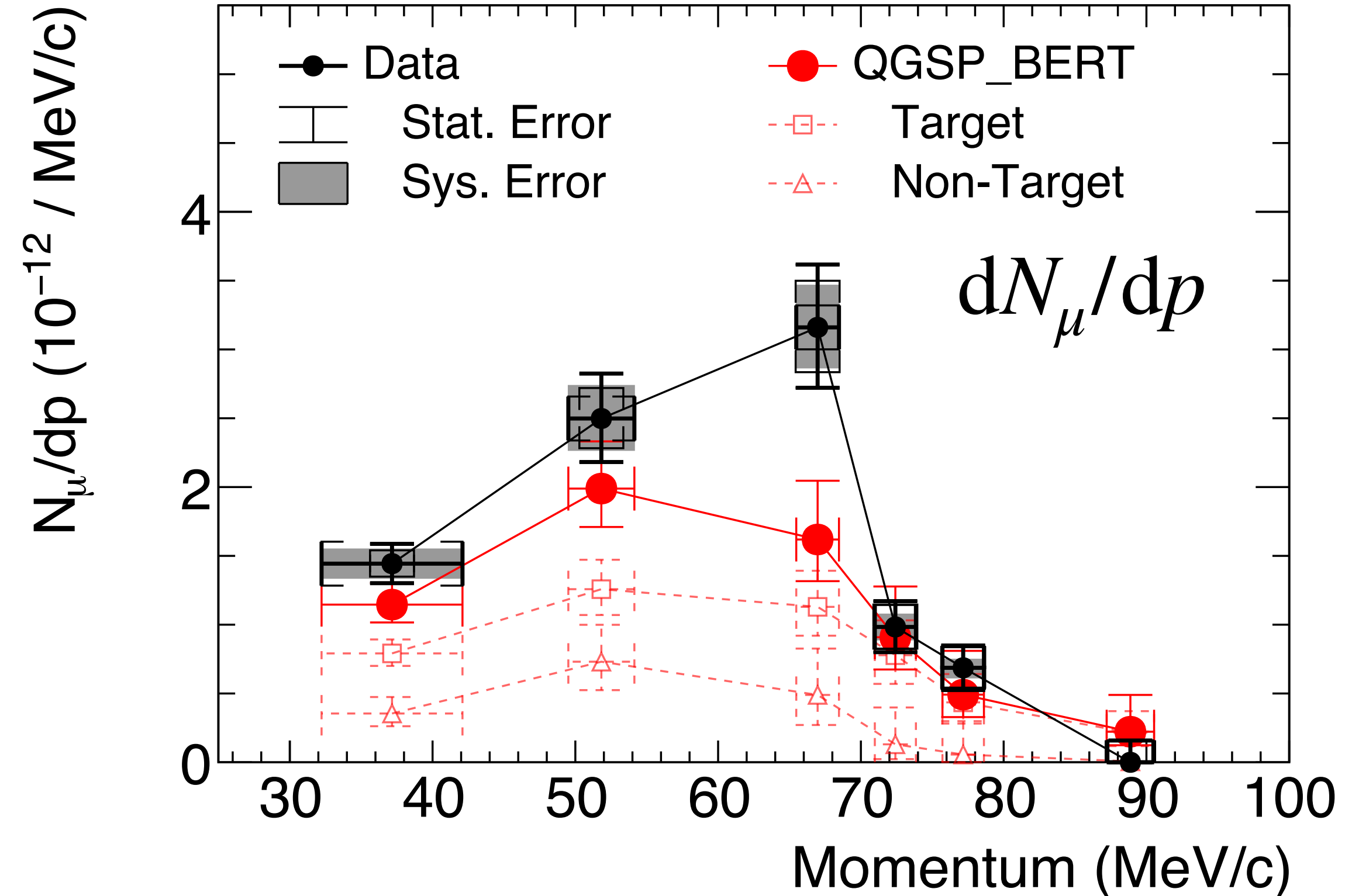
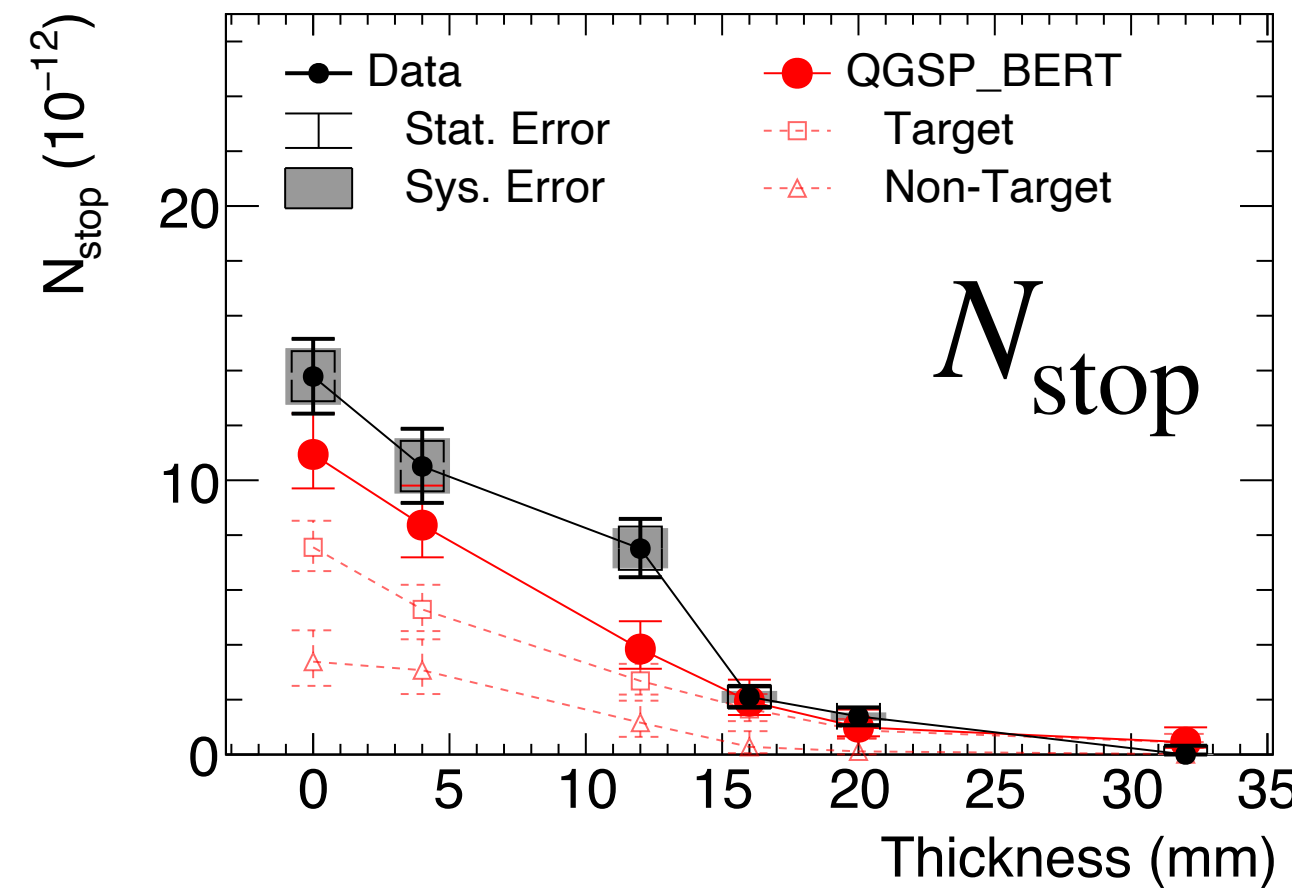
Results of the simultaneous spectral fit

Comparison in terms of the existence of the copper absorber in the RC.

- ✦ No finite short component is identified without the absorber.
 - ★ After the fit, N_{short} resulted in zero.
 - ★ The RC does not observe anything that mimics a signal-like short-component in the distribution.
- ✦ **The analysis flow certainly measures the muons stopping in the copper absorber.**



RESULT (1): DEGRADER SCAN



Overall behaviour is consistent with our expectations.

- ✦ The stopped muon count (N_{stop}) decrease as the degrader becomes thicker.
 - ★ High-momentum region is well surpassed.

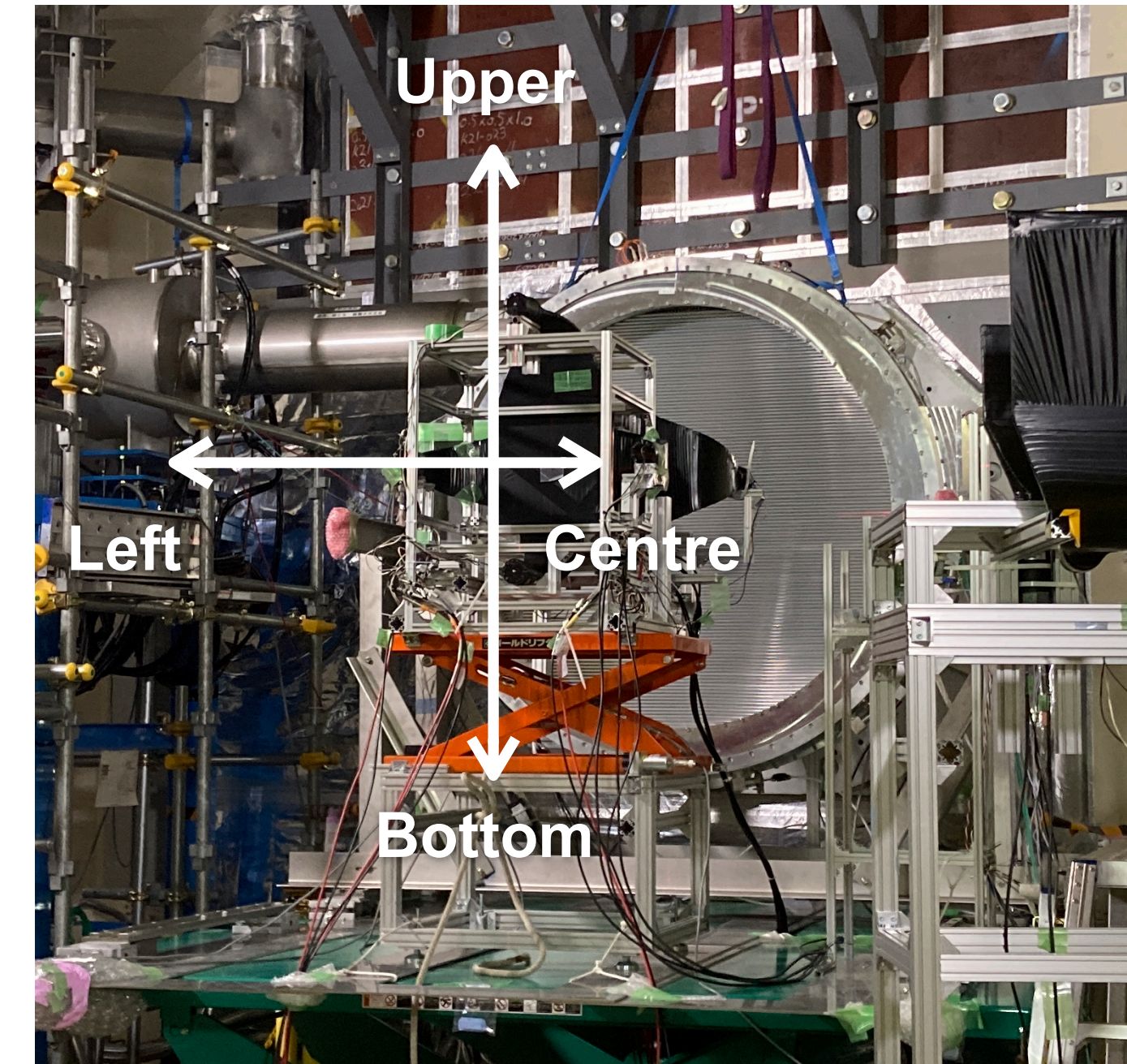
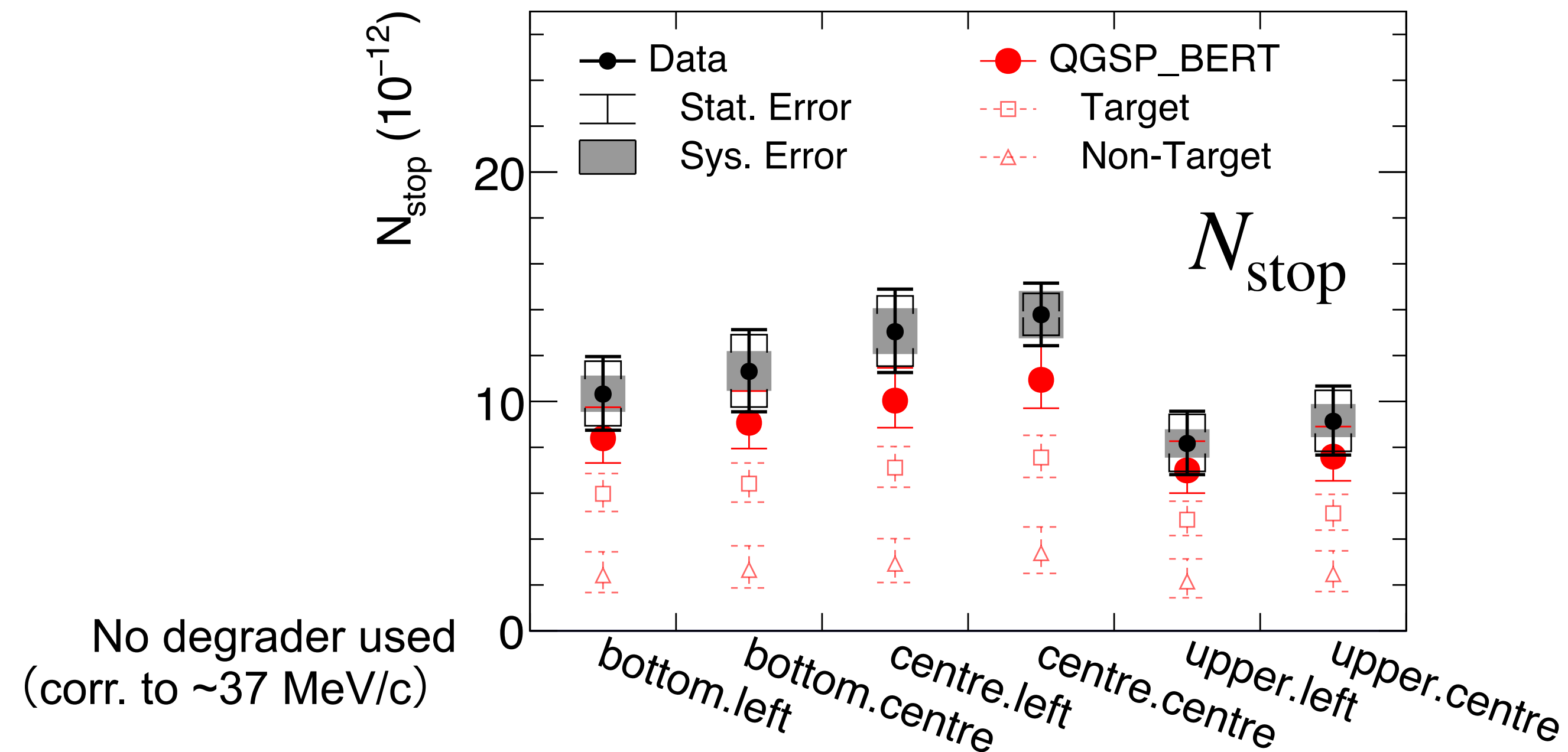
✦ **The MTS transports negative muons to the experimental area as expected.**

Comparison with the estimation based on Geant4 (QGSP_BERT)

- ✦ Mean values ~30% higher than the estimation on average, but still consistent within uncertainties.
 - ★ **The simulation could be further tuned based on the measurements.**
 - ★ Only the dataset with the 12 mm^T degrader setup shows an exceptional divergence; still under investigation.
- ✦ Non-negligible contribution induced by non-target components such as the proton beam dump.



RESULT (2): BEAM-POSITION SCAN



The Range Counter was moved by 25 cm steps, seen from the downstream side

The Beam-position Scan results also show the expected behaviour.

- ♦ The observed muon flux is maximised at the beam centre.
 - ★ Significant decrease in the upper region as negative muons drift downwards through the MTS.
- ♦ Again, the observed values exhibit the same overall excess as that of the Degradation Scan.

The dipole field was confirmed to focus the muon beam as expected.

- ♦ For example, the simulation with a 20% lower dipole field does not reproduce it.

SUMMARY

COMET has constructed a brand-new muon beamline.

- ✦ Bunched proton beam extraction from the J-PARC Main Ring accelerator.
- ✦ 90°-bent Muon Transport Solenoid is optimised to transport slow negative muons.
- ✦ See Yuki Fujii's COMET status report at 5pm today in WG4 for details.

Phase- α succeeded as the first COMET muon beamline commissioning.

- ✦ The first-ever introduction of the 8 GeV bunched proton beam to the COMET facility.
 - ★ Beam tuning and profiling were successfully performed.
- ✦ The Muon Transport Solenoid surely carries the produced negative muon beam.
 - ★ Selectively for slow negative muons.
 - ★ The observed beam profile also proves that the compensating dipole field works as expected.

Muon transport by the COMET beamline has been validated.

- ✦ The first measurement of muons from backward pion production.
- ✦ The observation exceeds the Geant4 estimation.
 - ★ The simulation could be further tuned based on this measurement.

Upcoming updates...

- ✦ A paper will be soon published based on the results presented today.
- ✦ Physics result? such as the backward pion production cross section.

