The COherent Muon to Electron Transition (COMET) Experiment

IOP HEPP Conference

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Imperial College London

Introduction

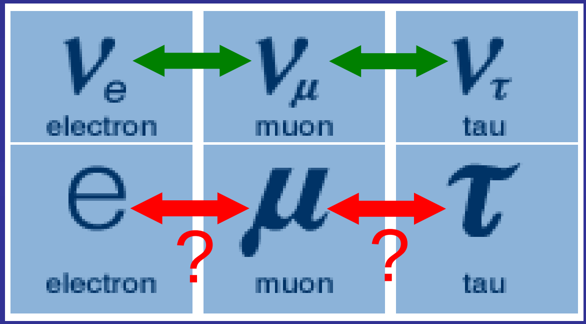
- COMET aims to search for muon to electron conversion with a single event sensitivity 2.6×10^{-17}.
  - Previous limit set by the SINDRUM-II experiment is 7×10^{-13}.
  - 4 orders of magnitude expected improvement!
- Very brief history and physics motivation for muon to electron conversion searches.
- Overview of the COMET experiment.
- Schedule, facility, detector construction status.

Why Charged Lepton Flavour Violation?

- We know the SM is at best incomplete.
  - Does not include gravity.
  - Certain predictions diverge with energy.

- Neutrinos in the SM are massless but observation of neutrino oscillations is direct evidence that neutrinos have mass.
  - First observation from Super Kamiokande, proof of non-conservation of neutral lepton flavour number.

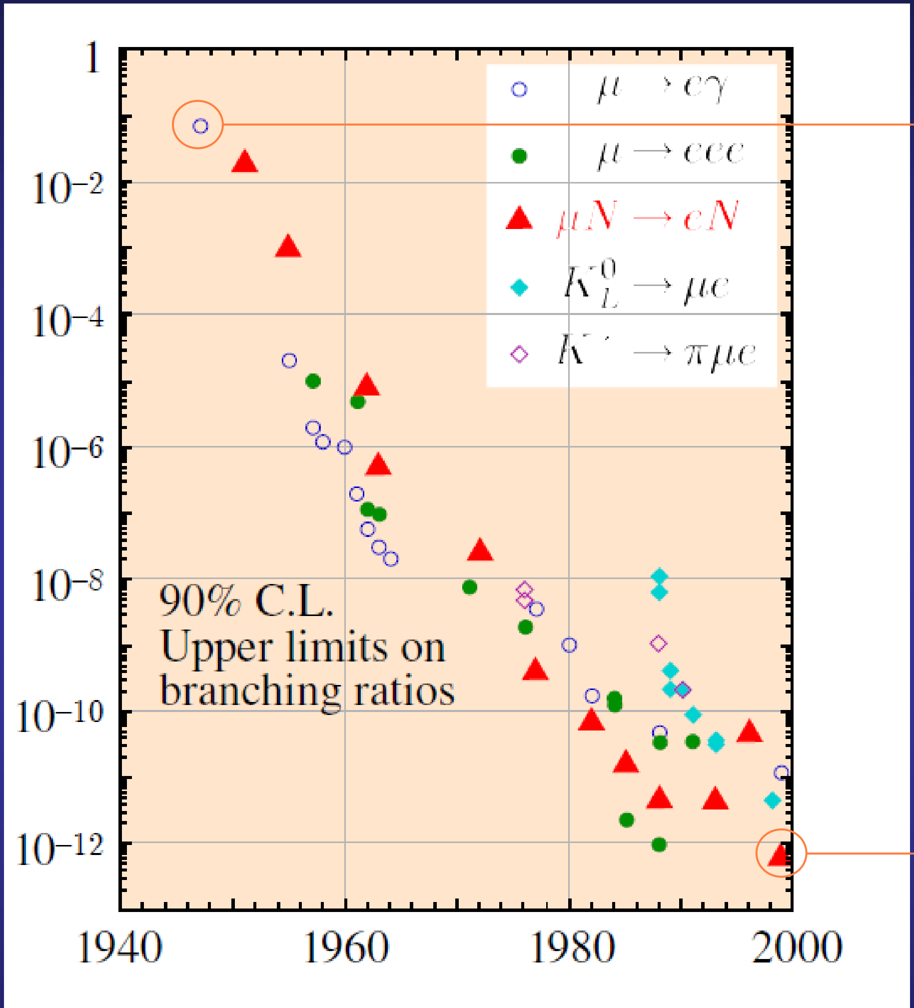
  → Possibility of Charged Lepton Flavour Violation.



- Some muon processes that could be studied
  - $\mu^- \rightarrow e^- \gamma$
  - $\mu^- \rightarrow e^- e^+ e^-$
  - $\mu^- (A,Z) \rightarrow e^- (A,Z)$ — Muon to electron conversion.

- Single particle final state can make best use of high intensity muon beams.

Brief History of CLFV Searches



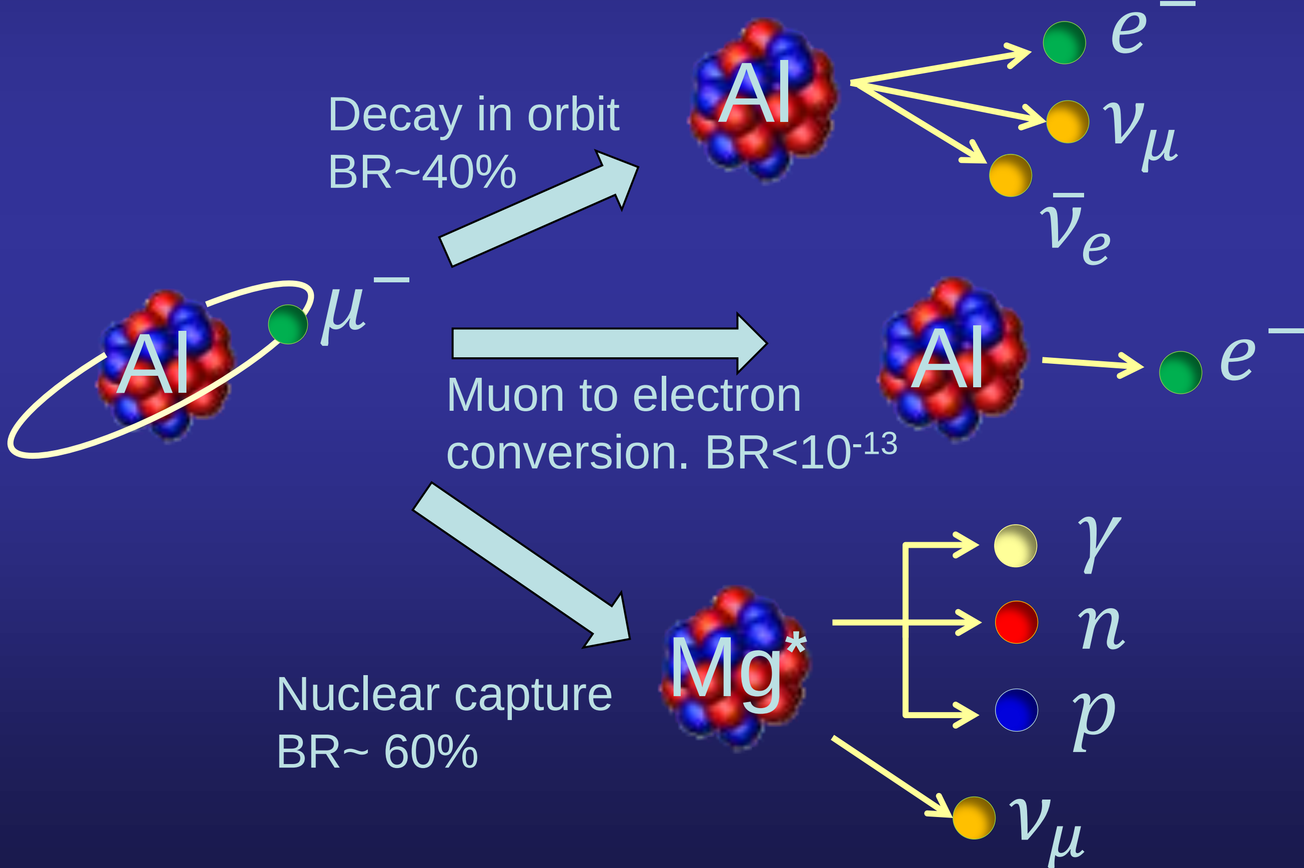
First CLFV search by Hincks and Pontecorvo in 1947 for $\mu^+ \rightarrow e^+ + \gamma$

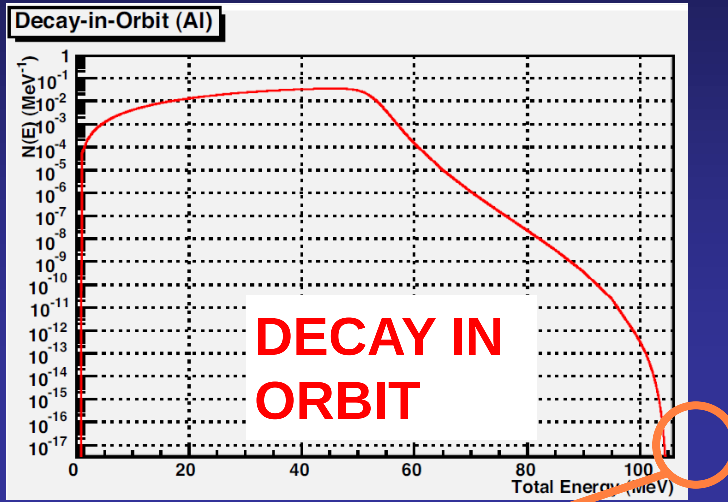
World's best limit on the muon to electron conversion branching ratio is 7×10^{-13} by the SINDRUM II collaboration.

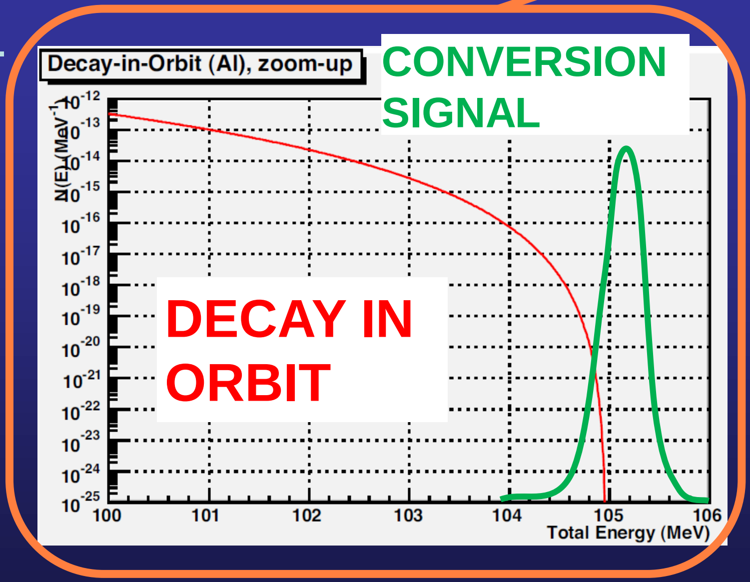
▲ Single event sensitivity of COMET is 2.6×10^{-17}.

Searching for Muon to Electron Conversion

- Look for neutrino-less conversion of a muon into an electron in the presence of a nucleus.
- Stop muons in a Al target → muonic atoms.
  - Bound muon lifetime depends on Z (for Al 864ns)
  - SM processes produce intrinsic backgrounds.
  - Nucleus coherently recoils off outgoing electron, no breakup.
  - BSM processes can lead to conversion.
  - Electron energy depends on Z (for Al, E_e = 105 MeV)

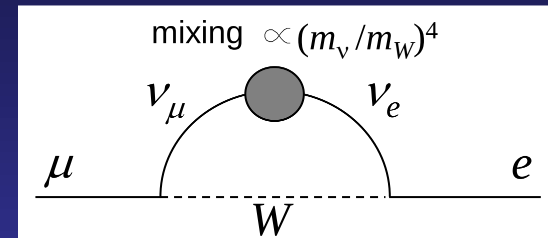


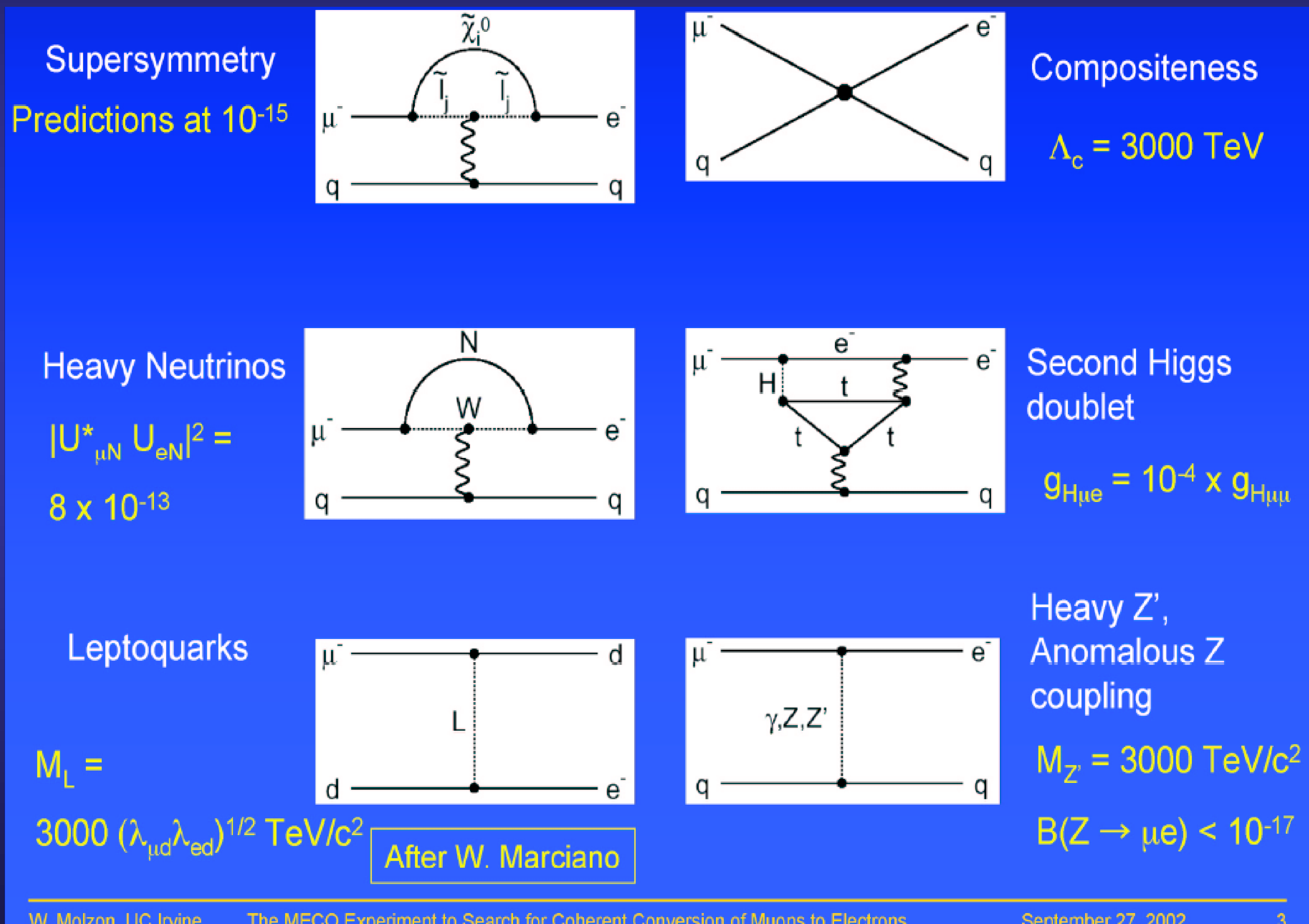




Sensitivity to Different Mechanisms

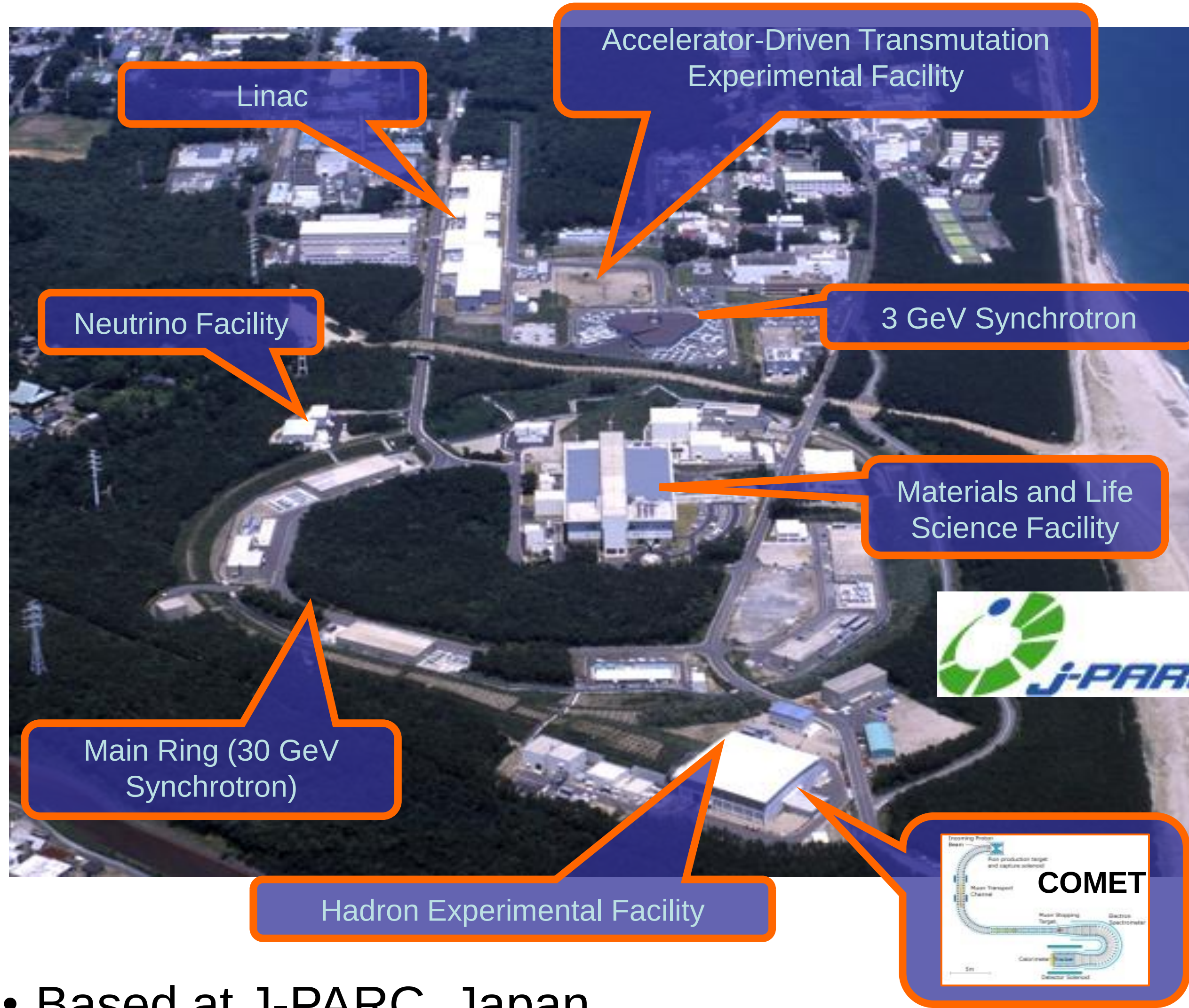
- If we include neutrino mixing in the SM, the probability for muon to electron conversion is $<10^{-52}$
  - Sensitive to physics beyond the SM.





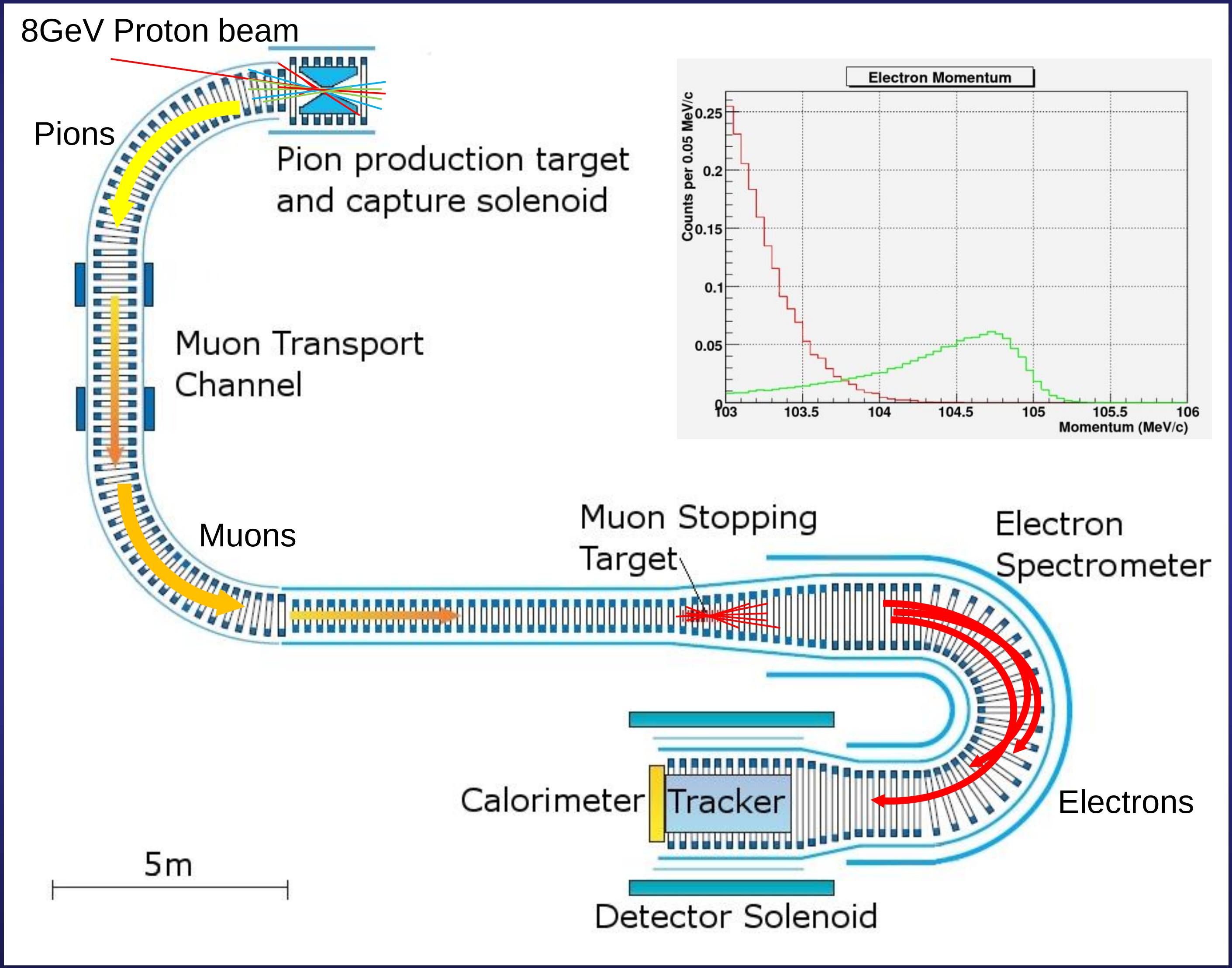
The COherent Muon to Electron Transition (COMET) Experiment

COMET



- Based at J-PARC, Japan.
- 176 Collaborators, 33 Institutes, 15 Countries.

COMET

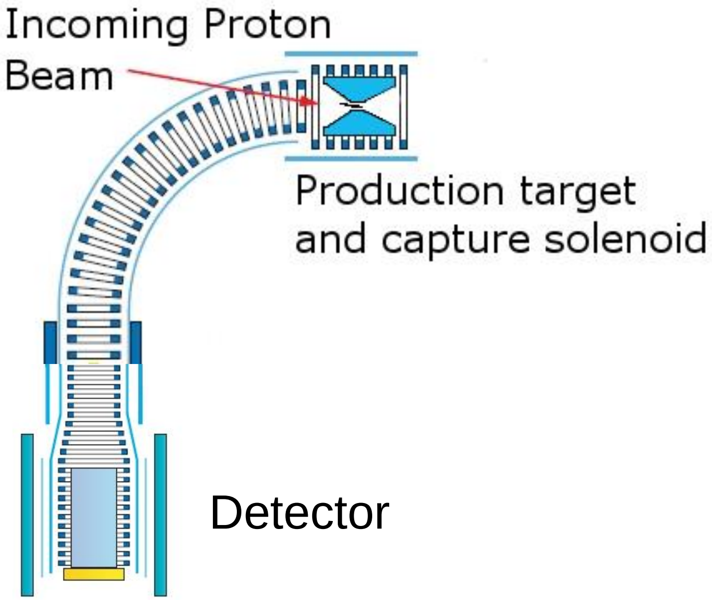


8GeV Proton beam
Pions
Pion production target
and capture solenoid
Muon Transport
Channel
Muons
Muon Stopping
Target
Electron
Spectrometer
Calorimeter
Tracker
Electrons
5m
Detector Solenoid
Electron Momentum
Counts per 0.05 MeV/c
0.25
0.2
0.15
0.1
0.05
0
103
103.5
104
104.5
105
105.5
106
Momentum (MeV/c)

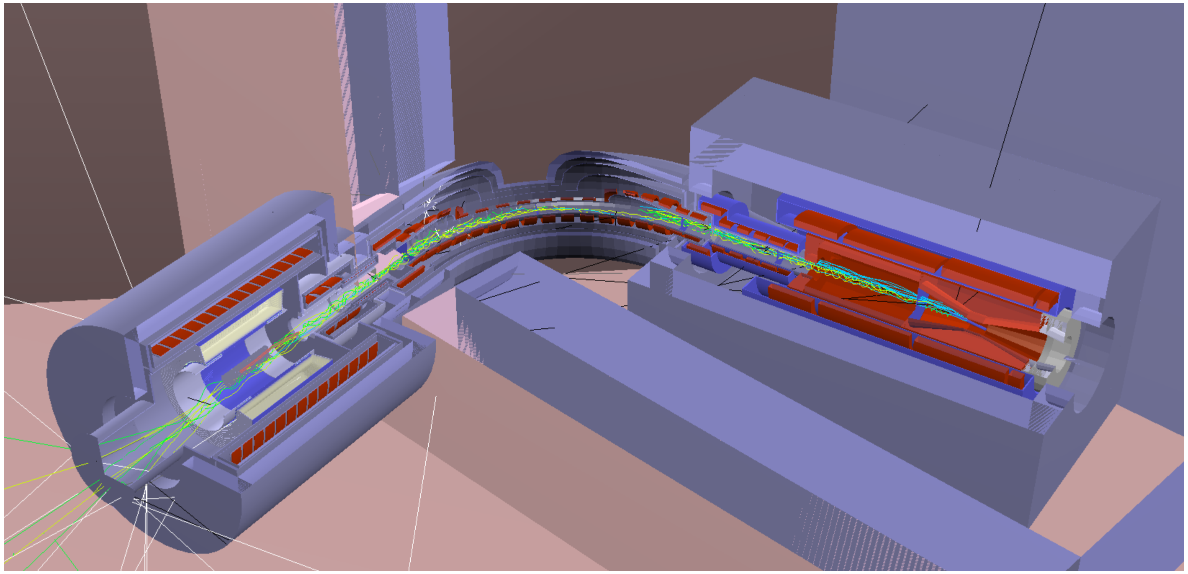
Two Stage approach

- Allows beam characterisation.
  - COMET has a long continuous solenoid channel with little space for beam diagnostic devices.
    - Beam emittance.
    - Particle composition is very important for understanding backgrounds.
  - Potential field bumps can lead to late arriving particles.
    - Look at arrival time distribution.
- Simulation validation.
  - Large variations of the pion and muon yield depending on hadron production model.
  - Field map tracking.
    - Compare tracking field maps with measurements
      - Effect of adjusting fields on beam composition.
- Detector prototype testing with high intensity, large emittance muon beam.

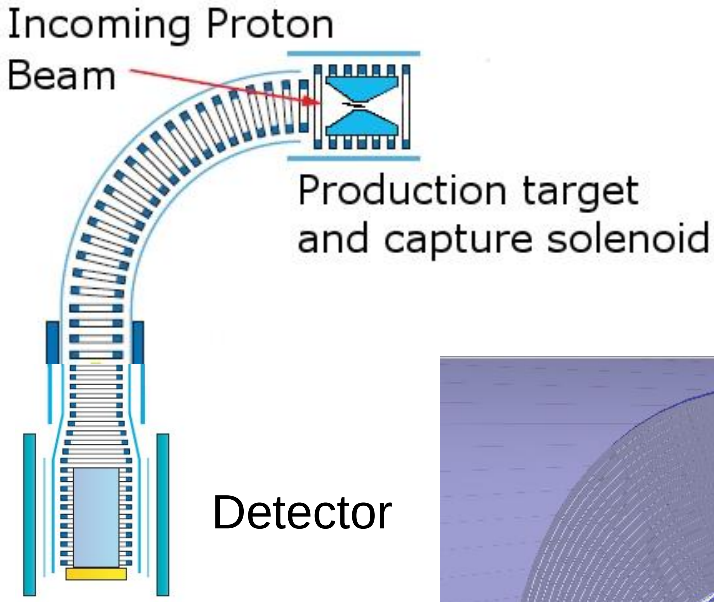
COMET Phase-I



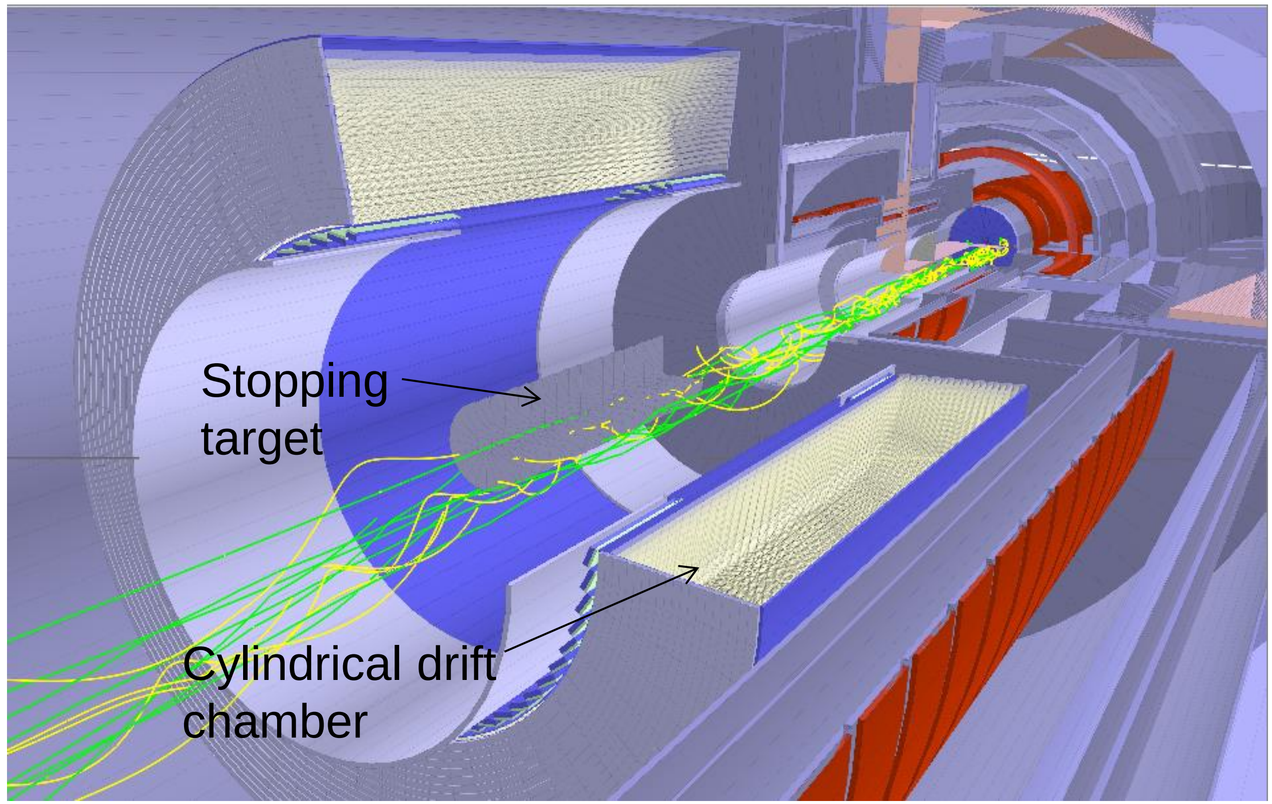
- 3kW, 8GeV proton beam. Graphite target.
- Allows for testing experimental method.
- Sensitivity of 3×10^{-15}
  - 90 days running.



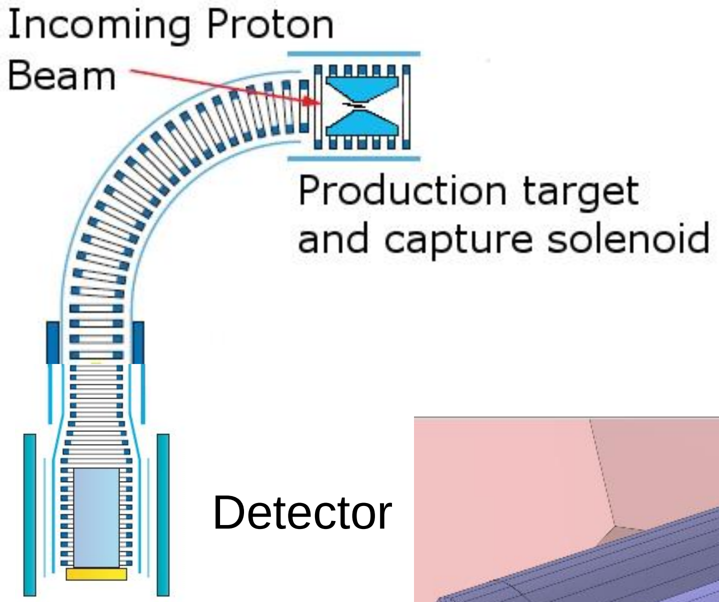
COMET Phase-I



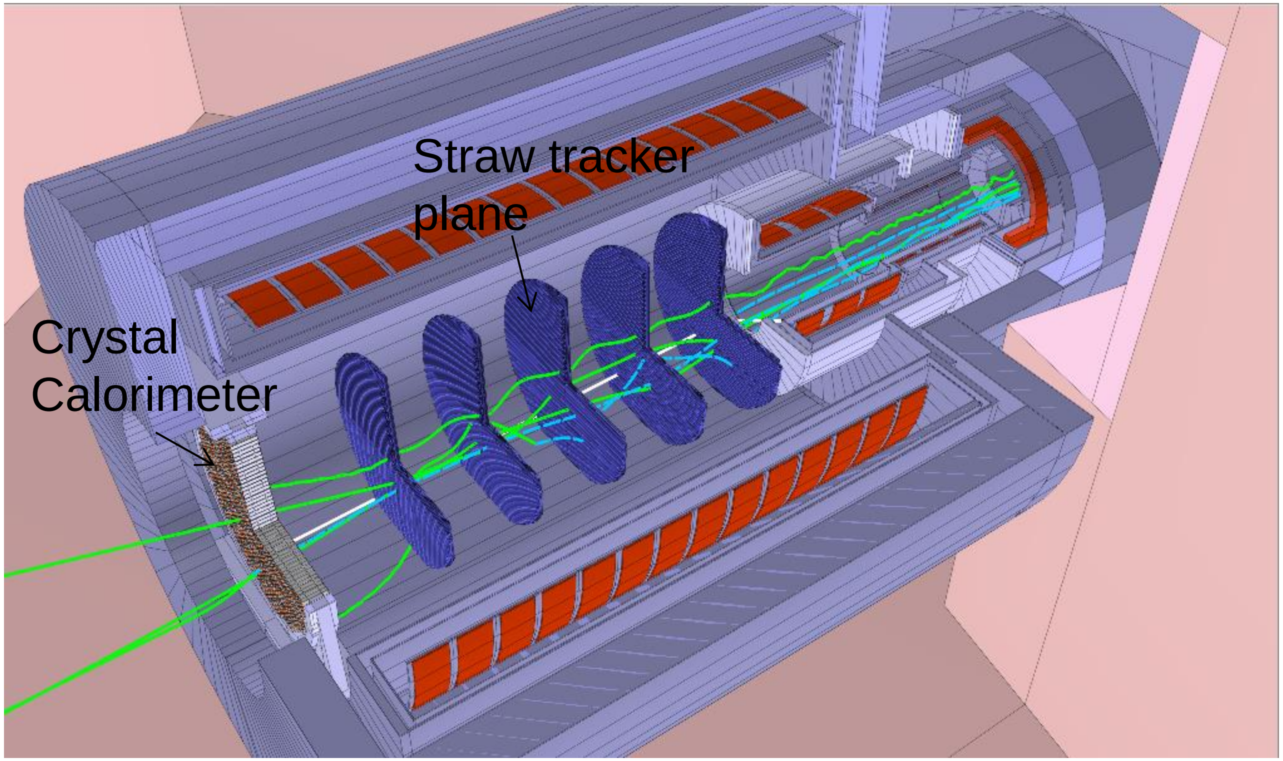
- Muon to electron conversion search using a cylindrical drift chamber.



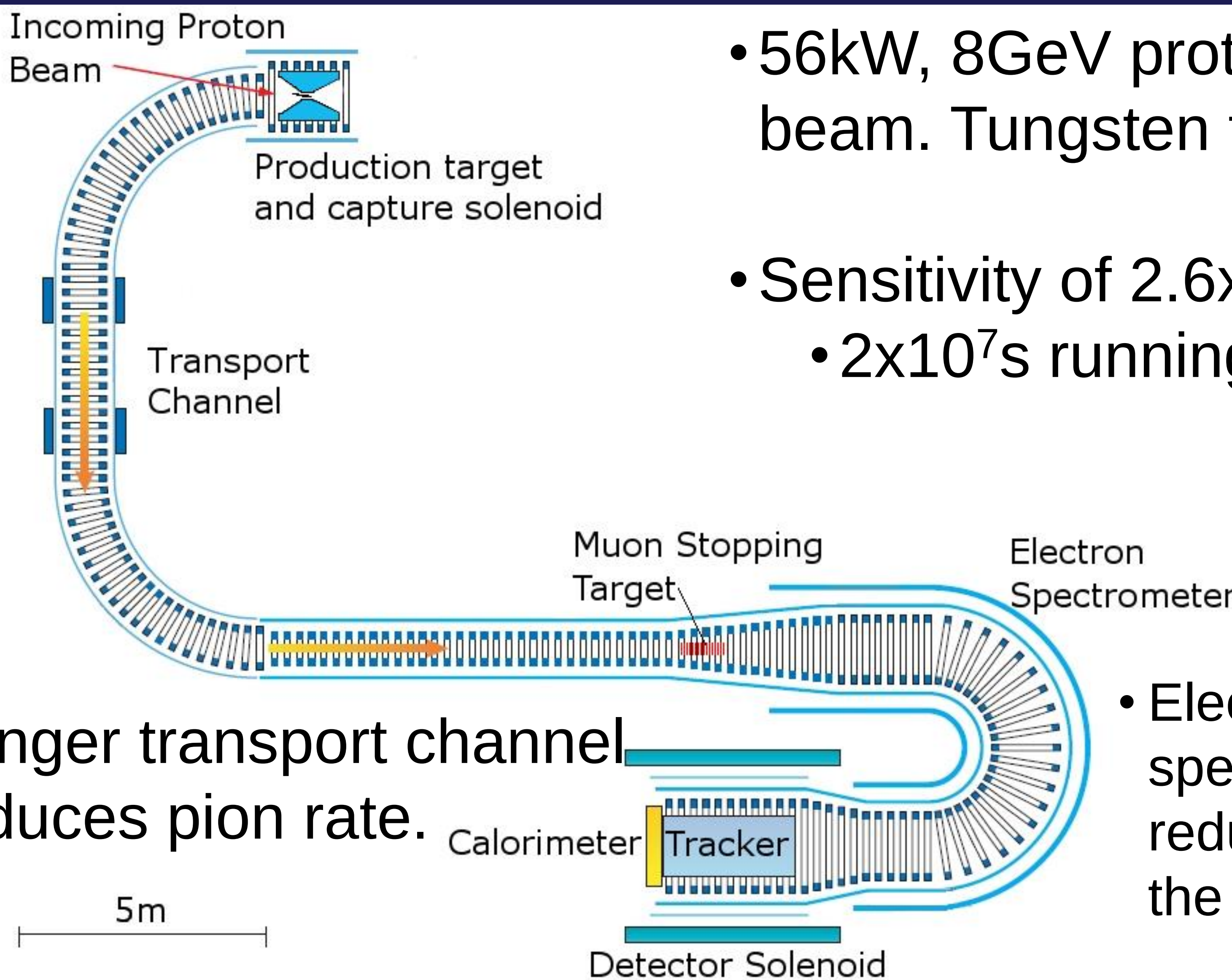
COMET Phase-I



- Straw tracker and calorimeter (Phase-II detector) test.
- Beam characterisation.



COMET Phase-II



- 56kW, 8GeV proton beam. Tungsten target.
- Sensitivity of 2.6×10^{-17}
  - 2×10^{7}s running.
- Longer transport channel reduces pion rate.
- Electron spectrometer reduces rate in the detectors.

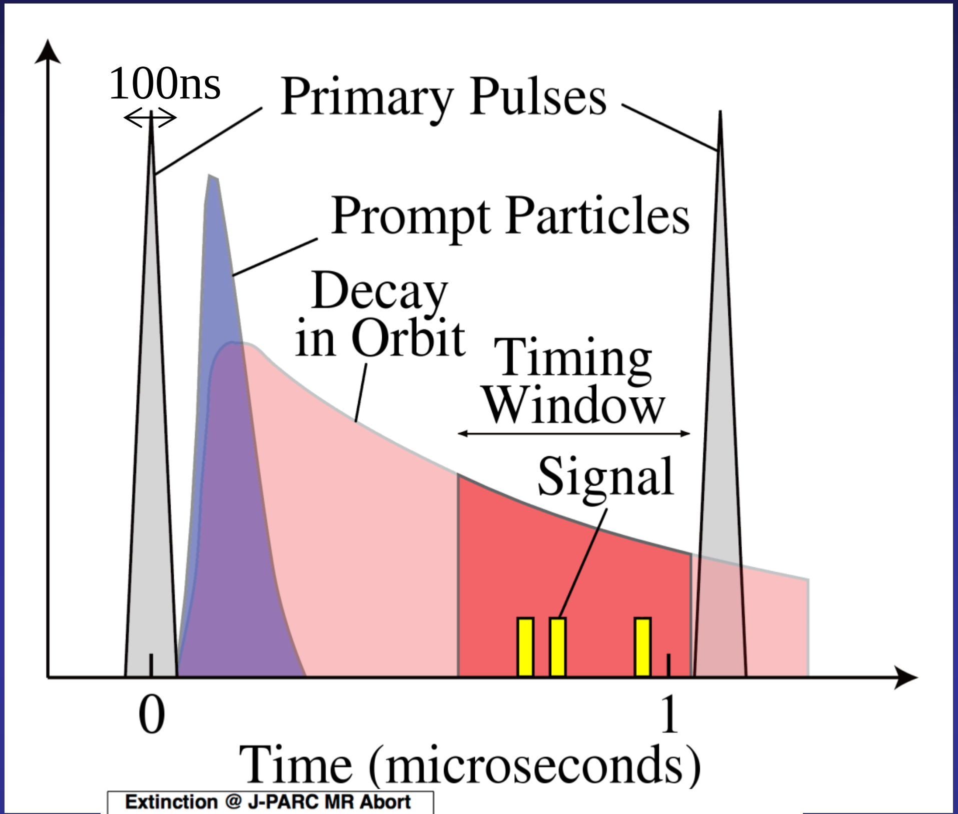
Backgrounds and How They are Minimised

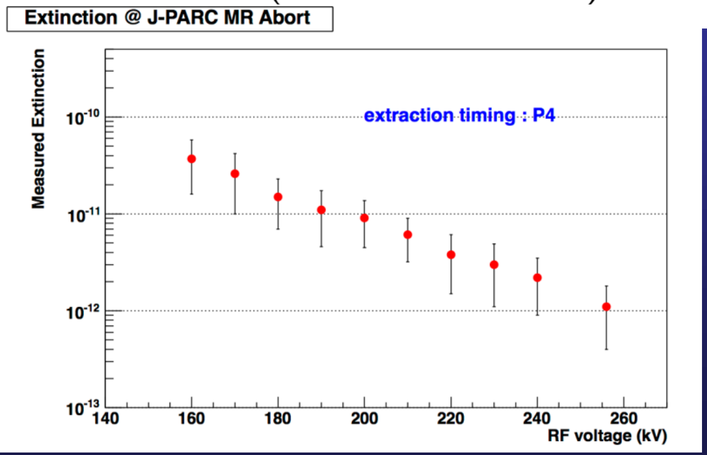
Background Sources

- Intrinsic backgrounds
  - Muon decay in orbit.
    - Electron recoil off nucleus → endpoint is near 105MeV.
  - Radiative muon capture
    - $\mu^- + A \rightarrow A' + \nu + \gamma$
    - $\mu^- + A \rightarrow A' + \nu + n$
    - $\mu^- + A \rightarrow A' + \nu + p$
- Prompt, beam related backgrounds.
  - Muon decay in flight.
    - If P>75MeV/c can yield signal like electron.
  - Radiative pion capture
    - $\pi^- + A \rightarrow A' + \gamma$
  - Electrons, neutrons, anti-protons.
- Scattered electrons, cosmic rays and neutron induced backgrounds.

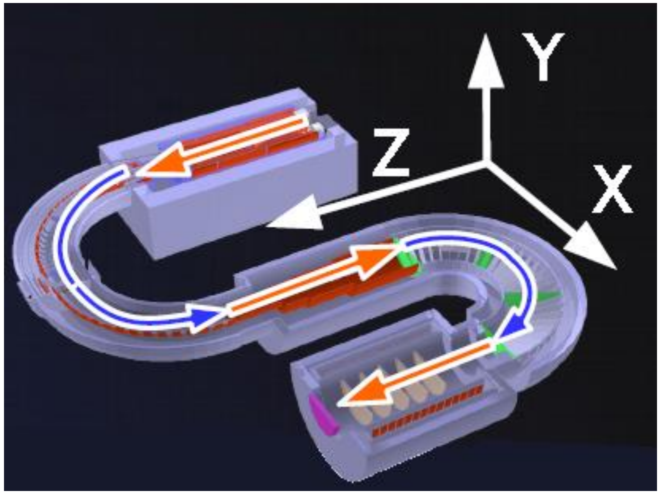
Pulsed Proton Beam

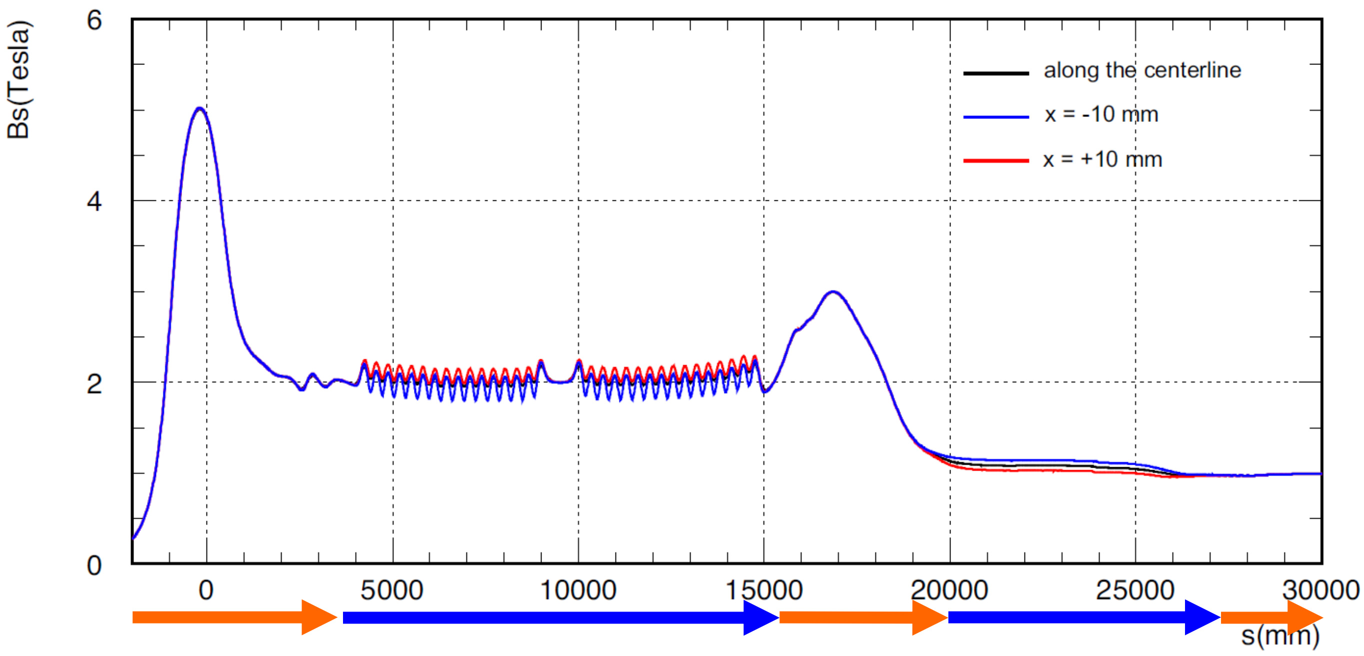
- Pulse structure mainly determined by muonic lifetime which is dependent on the stopping target Z. For Al lifetime is 864ns.
- Background rate needs to be low in order to achieve sensitivity of $<10^{-16}$.
- $\text{Extinction} = \frac{\text{Number of protons between bunches}}{\text{Number of protons in a bunch}}$
- Without sufficient extinction, all processes in the prompt background category could become a problem.
    - Needs to be $<10^{-9}$
- Intrinsic extinction of J-PARC's main ring has been measured be 10^{-12} with an 8GeV beam!





Charge and Momentum Selection

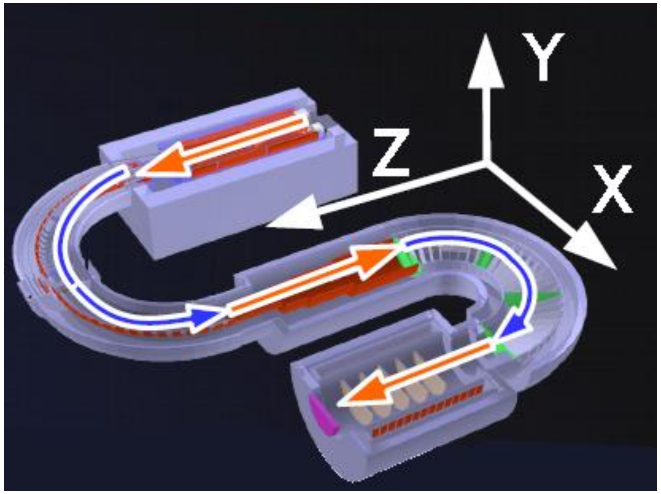


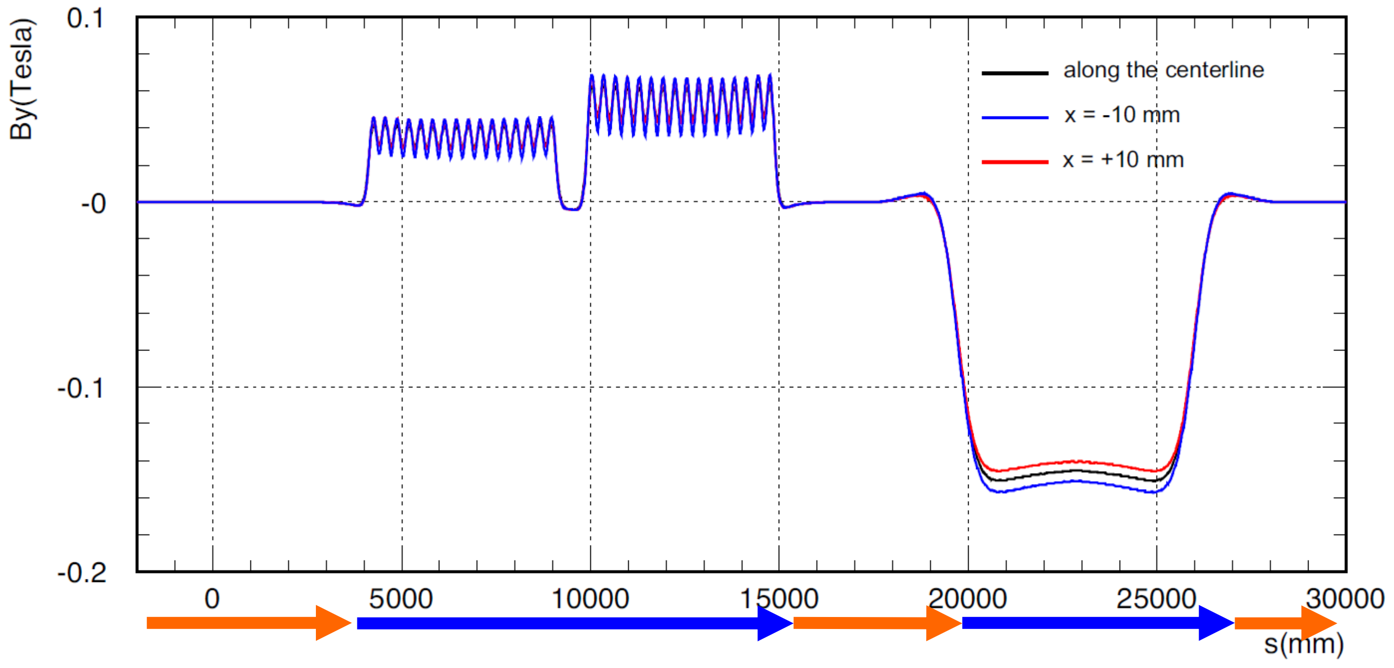


- Continuous superconducting solenoid channel from 5T to 1T.
- Bent solenoid allows selection of charge and momentum.

$$drift = \frac{1}{qB}\left(\frac{s}{R}\right)\frac{P_L^2 + \frac{1}{2}P_T^2}{P_L}$$

Charge and Momentum Selection

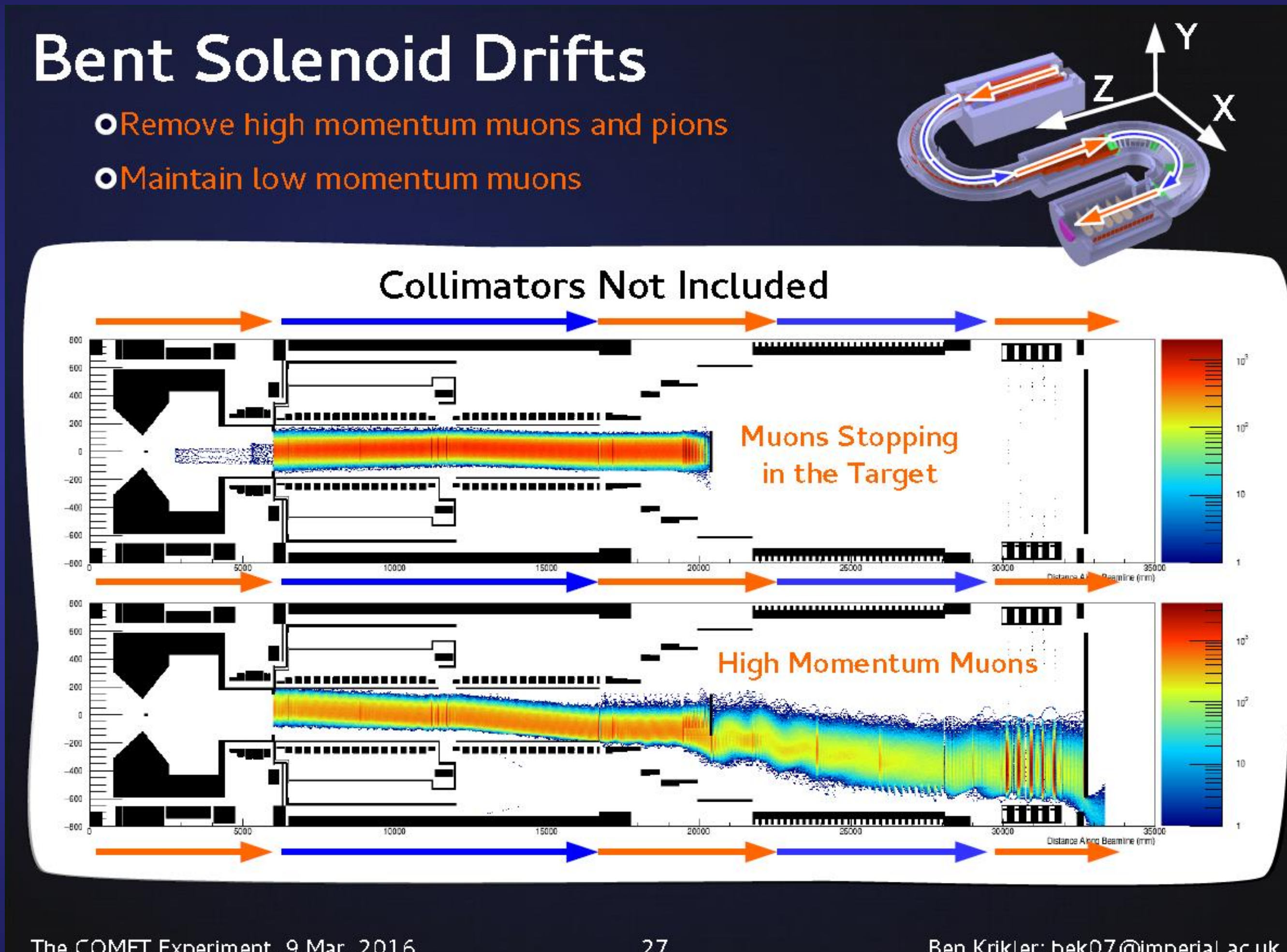


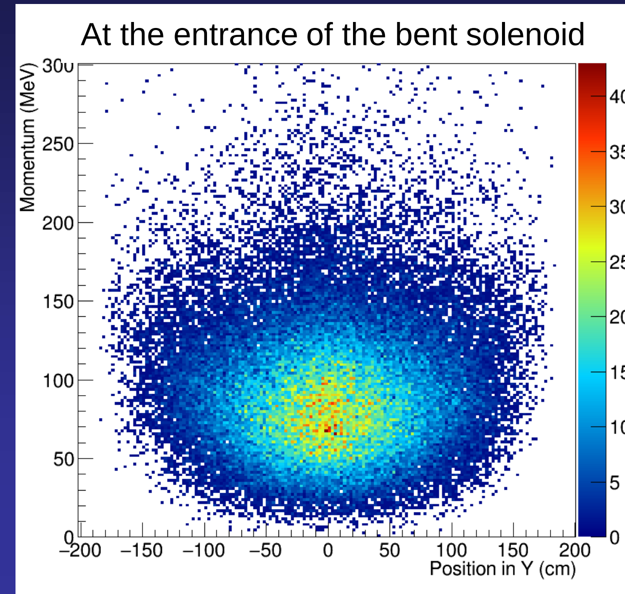


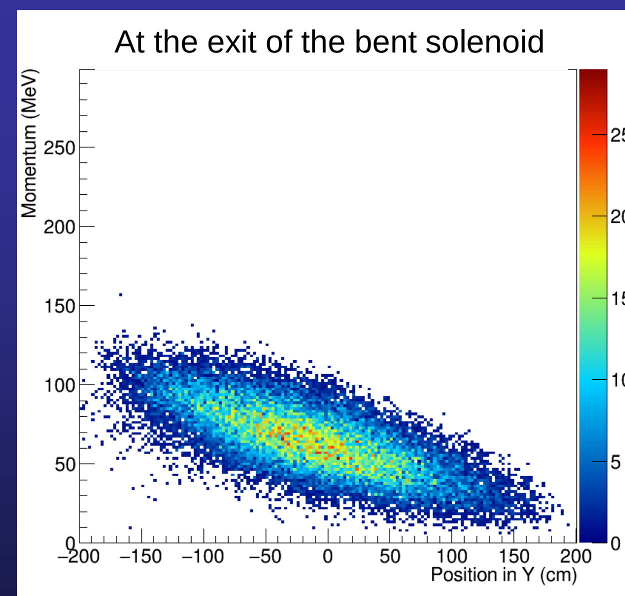
- Use a vertical dipole field to keep *P*=40MeV/c muons on axis.

$$B_{comp} = \frac{1}{qR}\frac{P_L^2 + \frac{1}{2}P_T^2}{P_L}$$

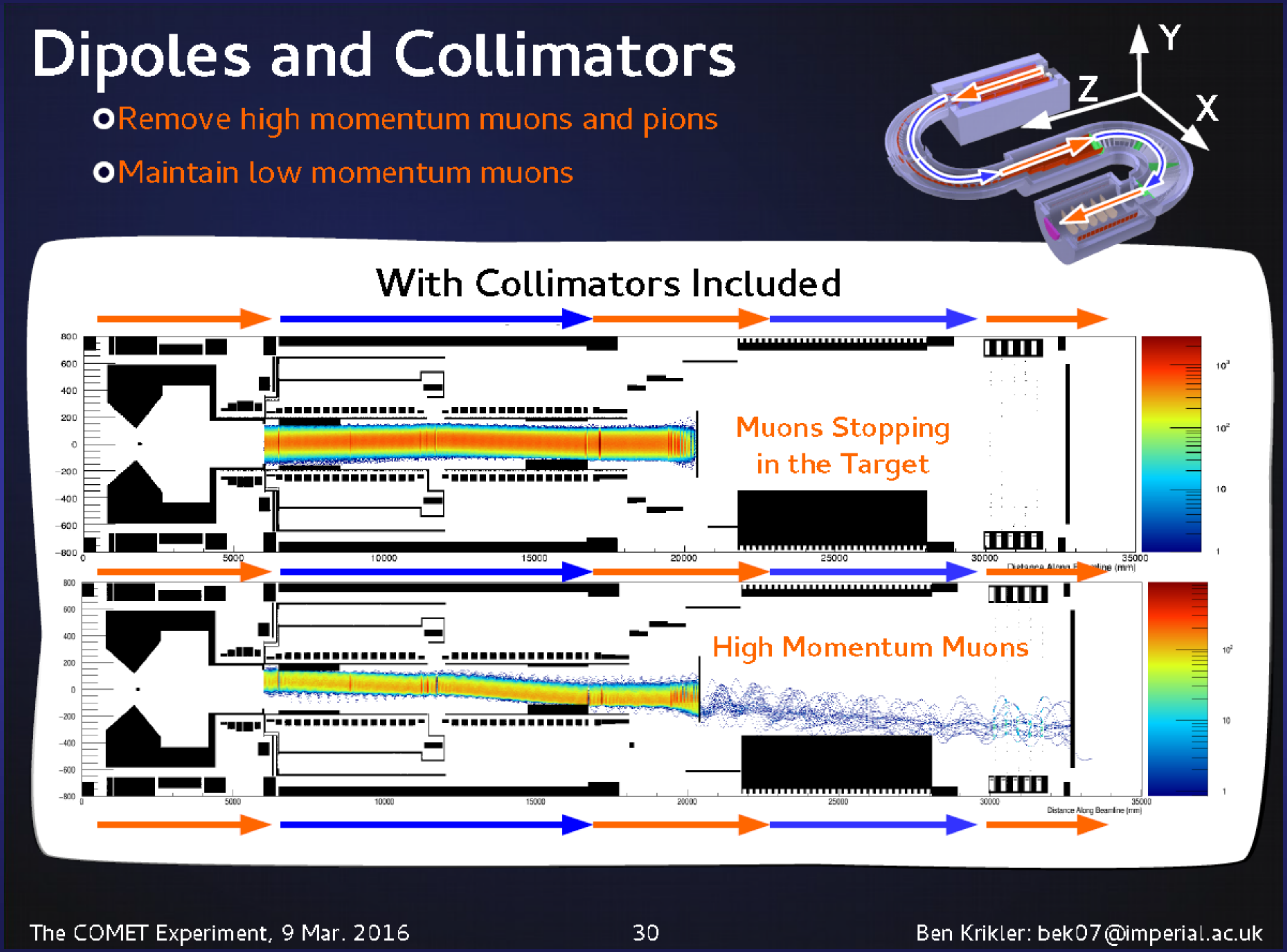
Charge and Momentum Selection



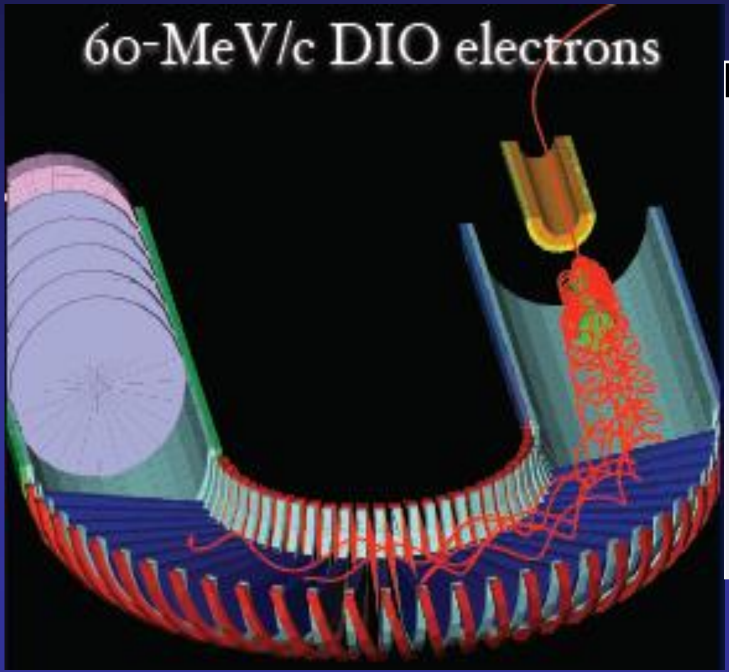


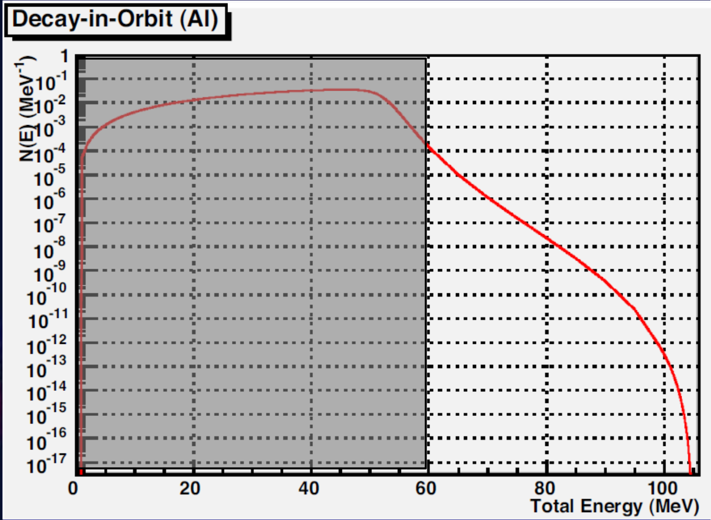


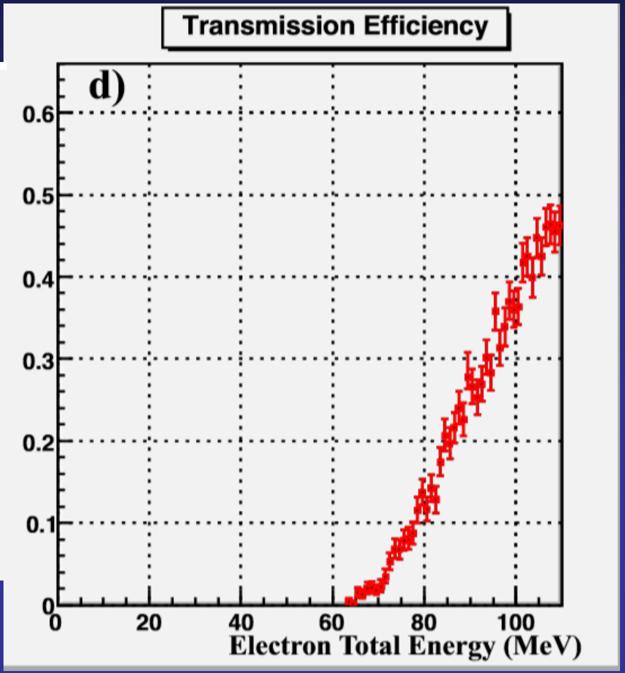
Charge and Momentum Selection



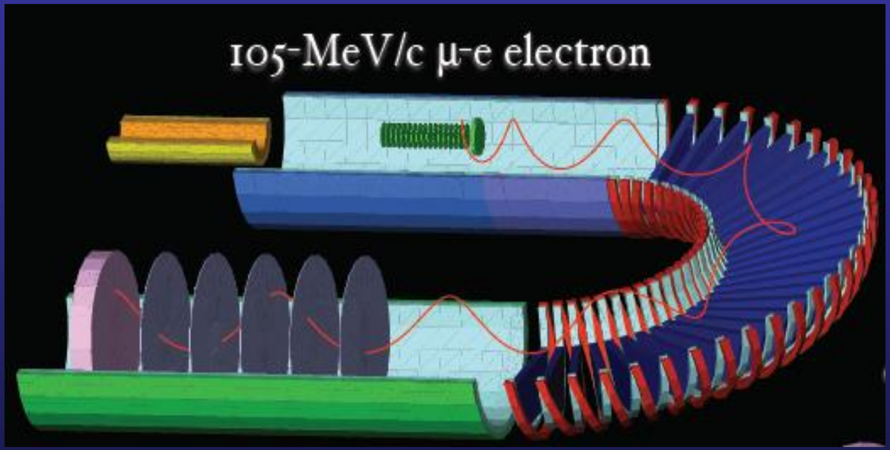
Electron Spectrometer



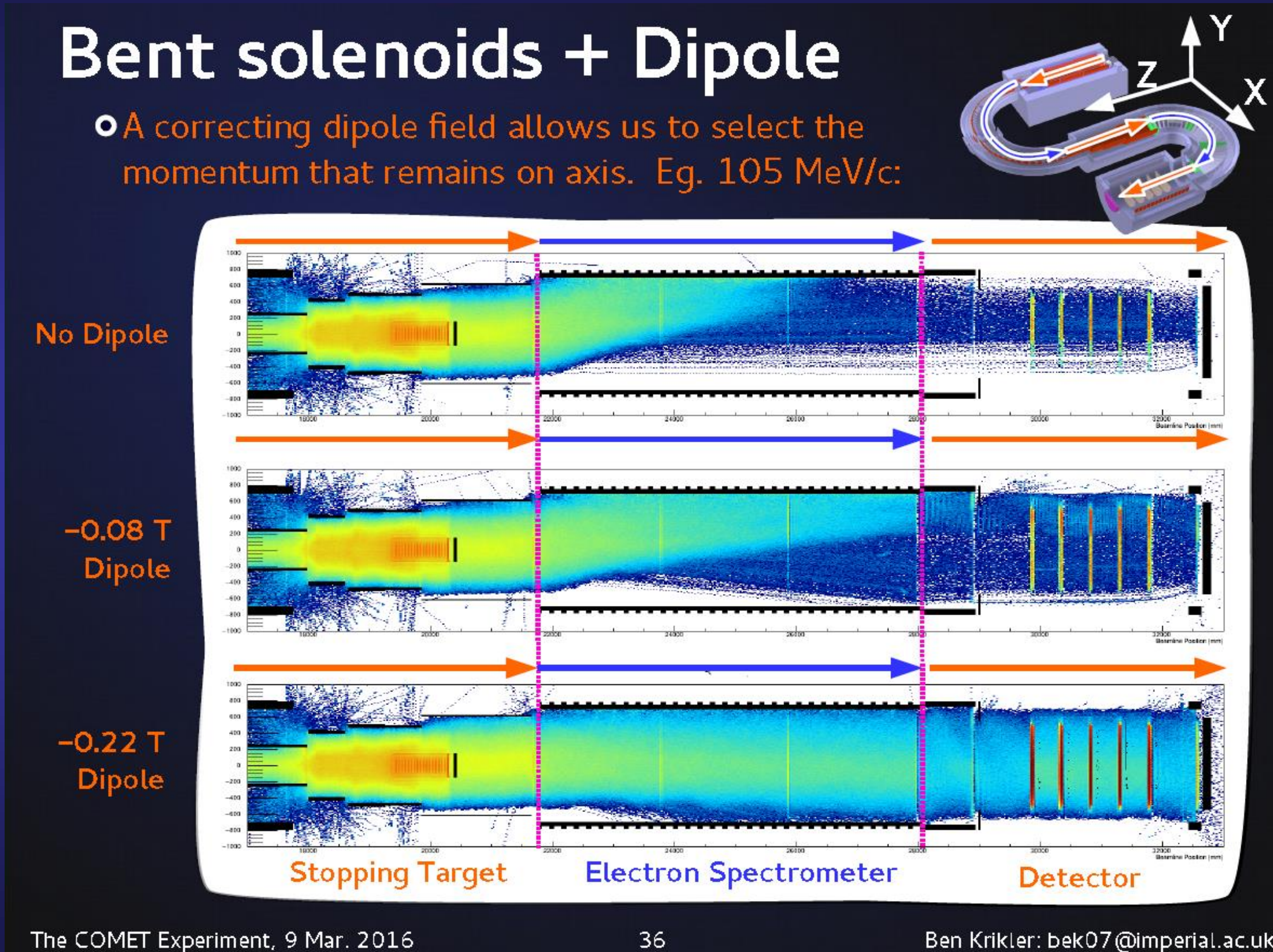




- 180° bent 1T solenoid with a 0.17T dipole field.
- Vertical dispersion of toroidal field allows electrons with P<60MeV/c to removed.
  - reduces trigger rate to ~1kHz.

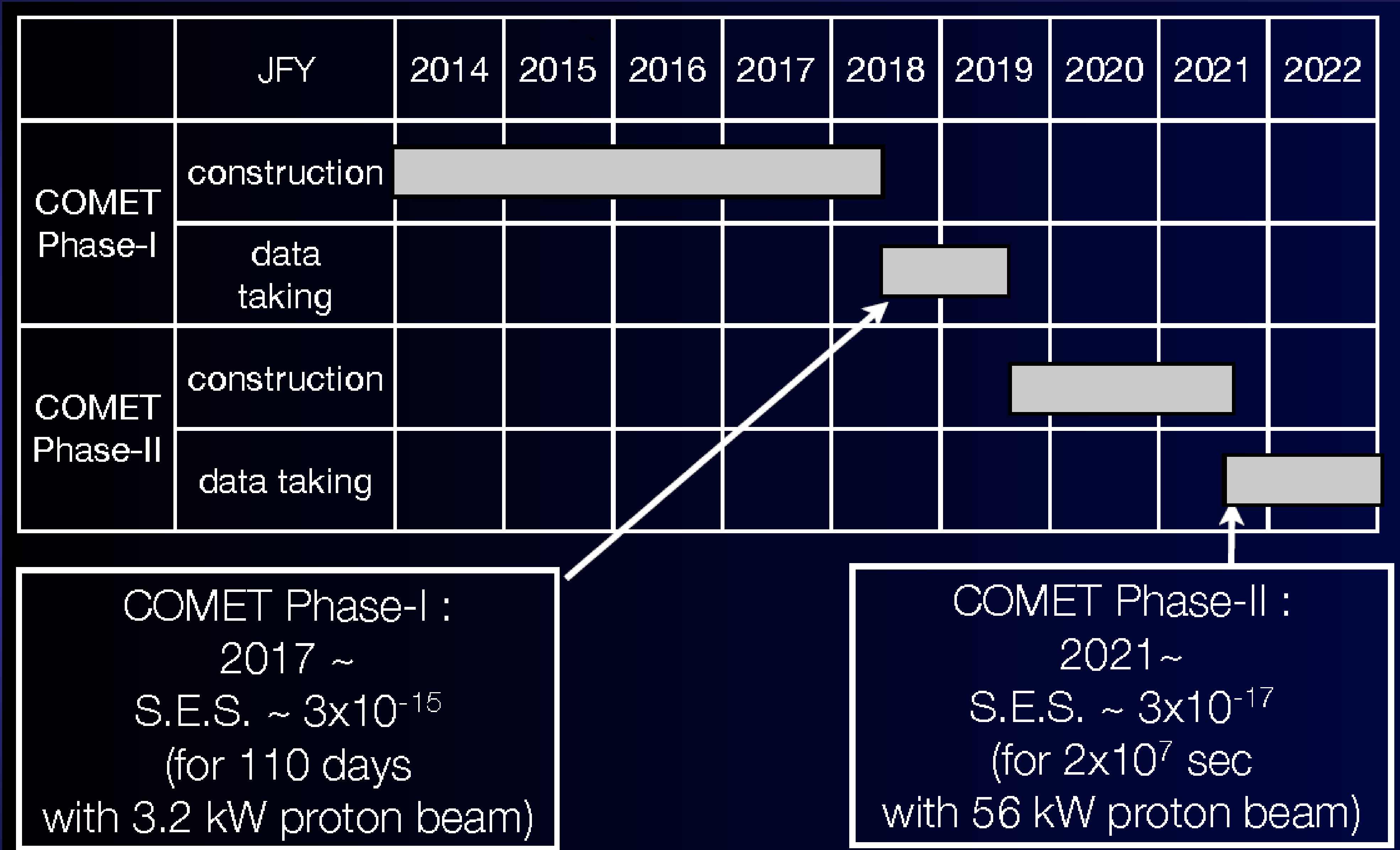


Electron Spectrometer

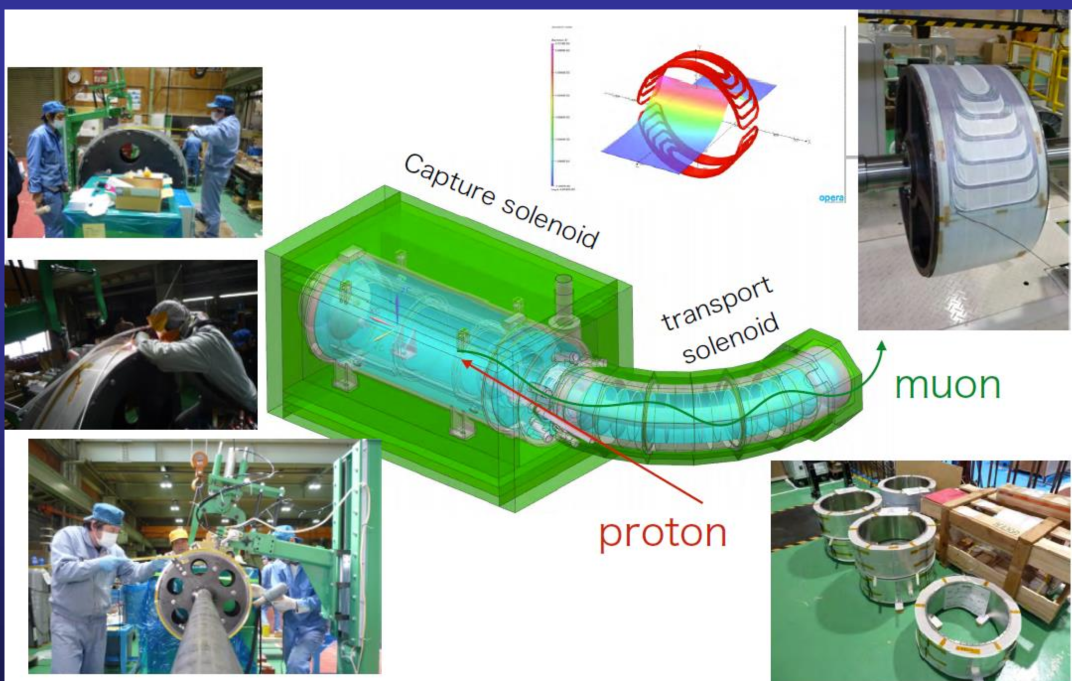


Facility and Detector Construction Status

Schedule

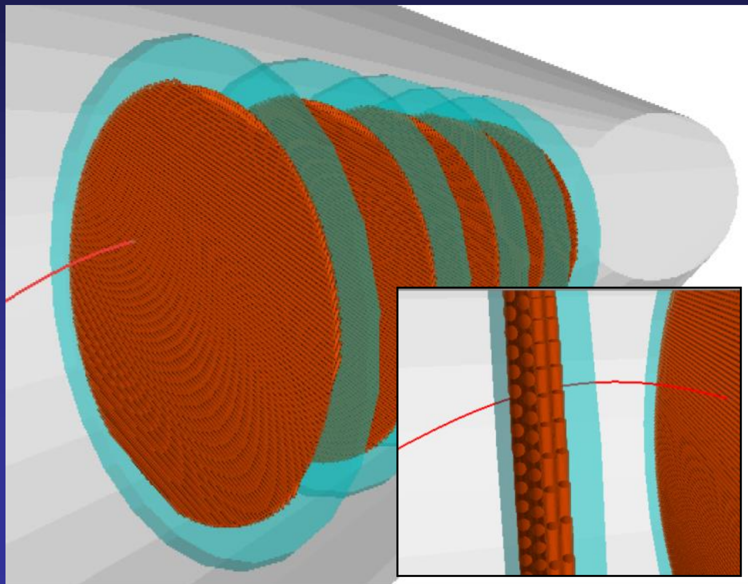

JFY
2014
2015
2016
2017
2018
2019
2020
2021
2022
COMET Phase-I
construction
data taking
COMET Phase-II
construction
data taking
COMET Phase-I :
2017 ~
S.E.S. ~ 3x10^-15
(for 110 days
with 3.2 kW proton beam)
COMET Phase-II :
2021~
S.E.S. ~ 3x10^-17
(for 2x10^7 sec
with 56 kW proton beam)

Facility and Magnet Construction



Integration Workshop October 2015

Straw Tracker Prototyping and Testing

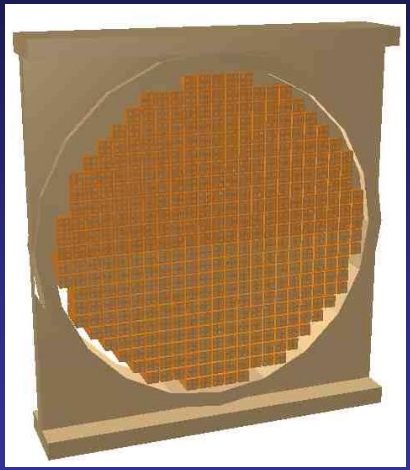


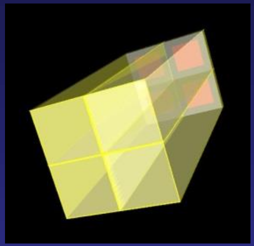
- Requirements
  - operate in a 1T solenoid field.
  - operate in vacuum (to reduce multiple scattering of electrons).
  - 800kHz charged particle rate and 8MHz gamma rates.
  - 0.4% momentum and 700μm spatial resolution.
- 5 planes 48cm apart with 2 views (x and y) per plane and 2 layers per view (staggered by one straw radius).
- Gas filled straw tubes made from metalised polyimide with a gold coated tungsten anode wire.

Prototype tests in December 2015

- Mass production of straws completed for Phase-I.
- 2700 tubes 20μm thick Al-mylar.
- 1.6m length and 9.8mm diameter.

Calorimeter

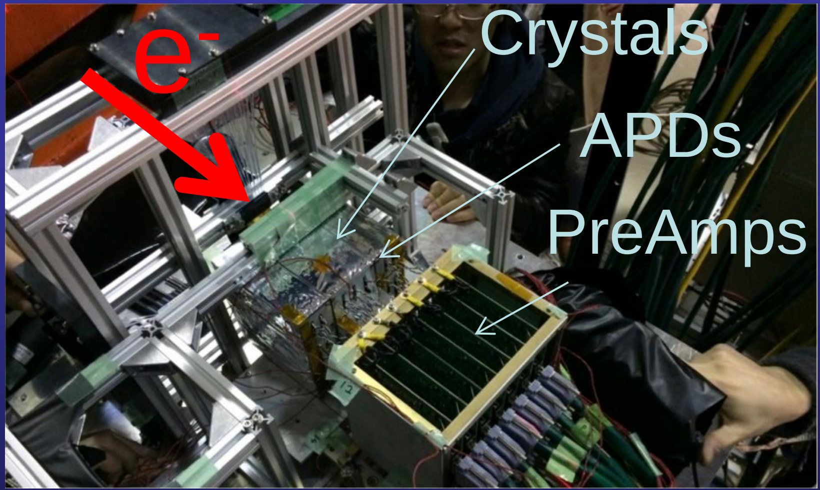




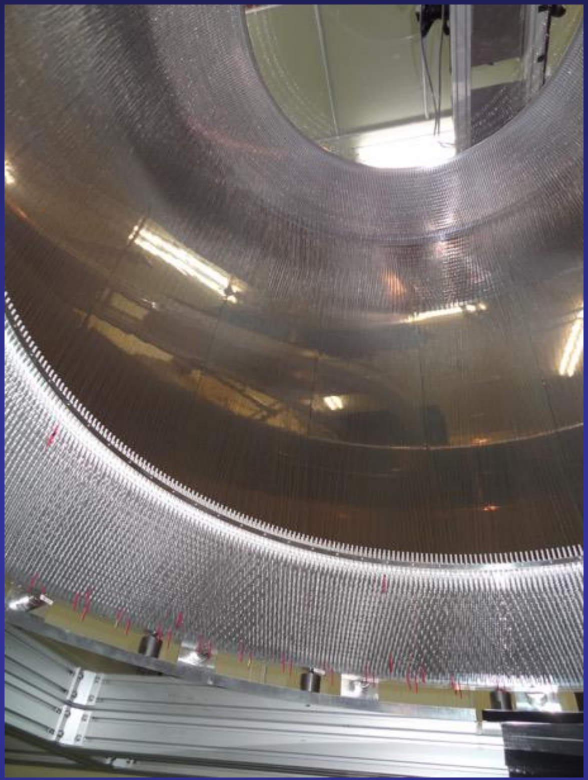
2x2 crystal module

Prototype 2x2 crystal module wrapped with teflon and Al-mylar and 4 APDs.

- Requirements
  - Measure energy, PID and give additional position information. Can be used to make a trigger decision.
  - 5% energy and 1cm spatial resolution at 100MeV.
  - Operation in 1T magnetic field.
- Inorganic scintillator Lutetium Yttrium Orthosilicate (LYSO).
- APD photo detector with a custom pre-amp.
- Beam tests in Tohoku March 2014.
- Prototype module built including vacuum vessel and feedthroughs for readout.
- Integrated beam test with the straw tracker March 2016.



CDC Construction



- Stringing complete.
- Tensioning tests ongoing.
- Mass production of the front-end boards completed.

Summary

- COMET will search for muon to electron conversion with a single event sensitivity 10^4 better than the current limit!
  - Model independent probe of BSM physics.

- The COMET facility and detector construction is well underway with data taking to start in 2018.
  - Phase-I will search for muon to electron conversion with a single event sensitivity of $3x10^{-15}$.
  - Phase-I will be the World's most intense muon beam facility and is the best place to test the Phase-II detector prototypes.
  - Experience with Phase-I (especially beam and beam line characterisation) will be used to fine tune Phase-II (if needed!).
  - Phase-II will start data taking in 2021.