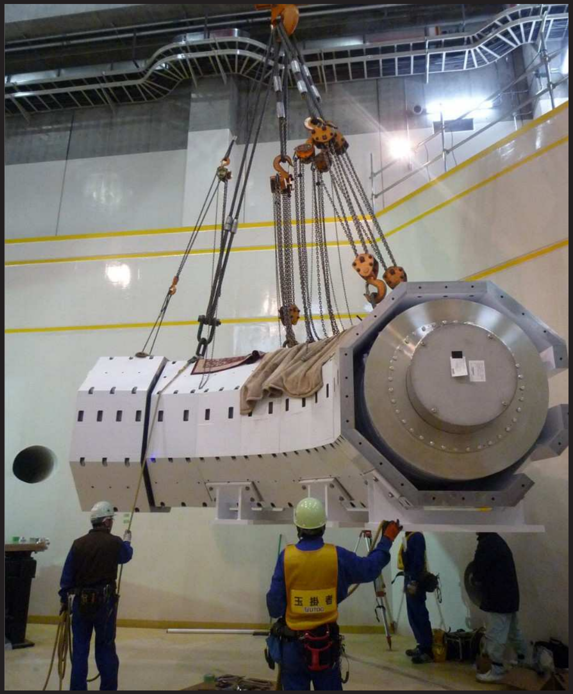


The COMET Experiment

10th August 2015
NuFact15
Rio De Janiero

Ben Krikler
on behalf of the
COMET collaboration

Imperial College London

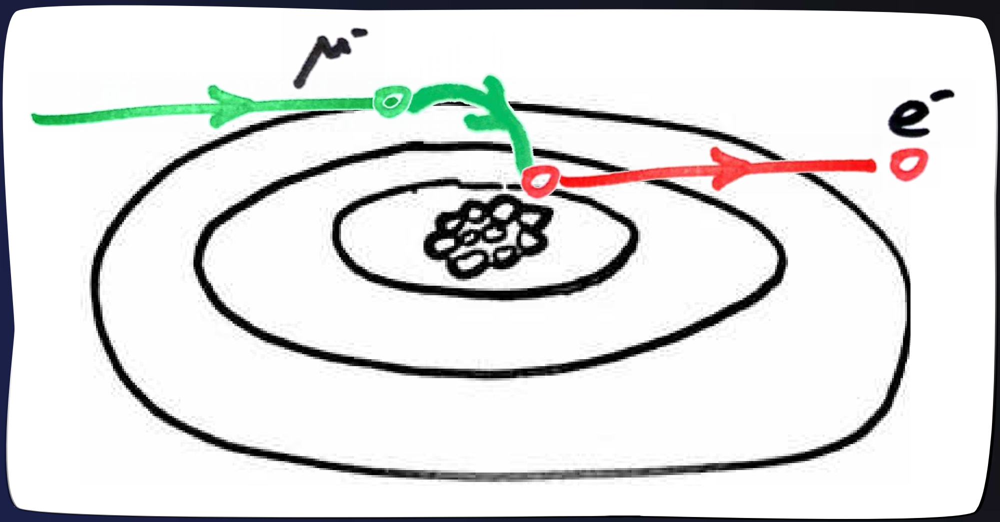
Overview

- Muon-to-Electron Conversion
- Experiment Design
  - Phase-I and Phase-II
- Status and R&D
  - Beamline
  - Detectors
  - Simulation

Muon to Electron Conversion

Charged Lepton Flavour Violation:

$$\mu^- + \mathrm{N(A,Z)} \rightarrow \mathrm{e}^- + \mathrm{N(A,Z)}$$



Nucleus is unchanged, process is coherent:

$$E_e = m_\mu - B_\mu - E_{\mathrm{recoil}}$$

On Aluminium, used by COMET:

$$E_e = 104.9 \text{ MeV}$$

Current limit from SINDRUM-II (90% C.L) on Gold:

$$\mathcal{R} < 7 \times 10^{-13}$$

Typically define the conversion rate as:

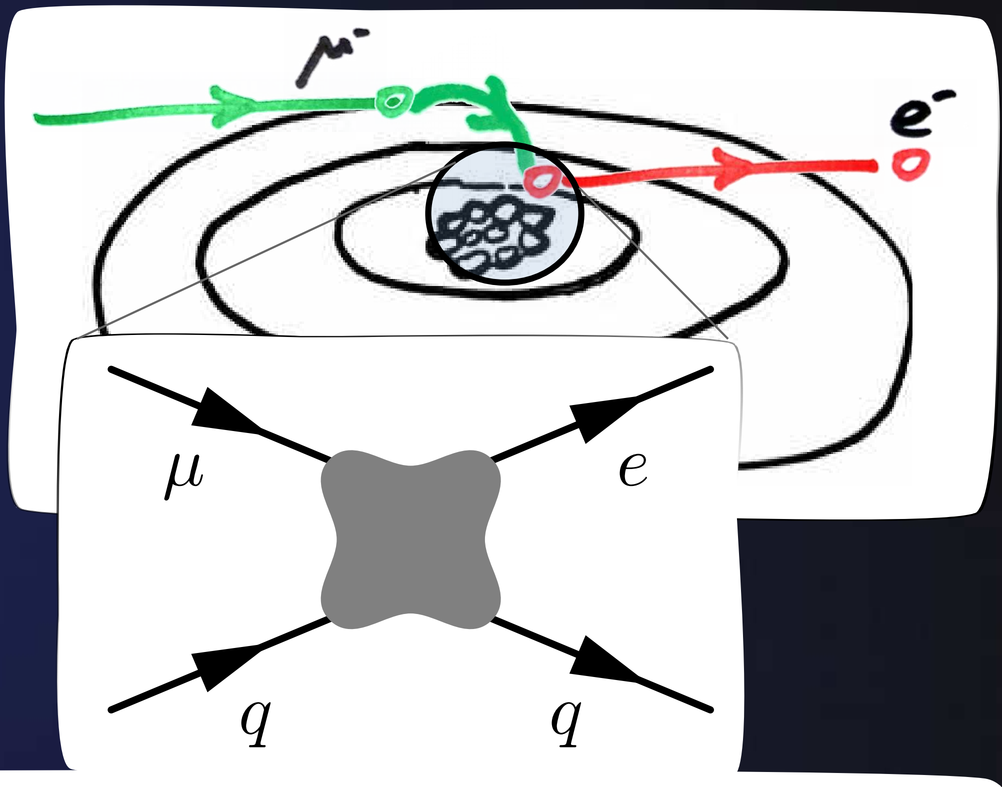
$$\mathcal{R} = \frac{\Gamma(\mu\text{-}e \text{ conversion})}{\Gamma(\mu \text{ capture})}$$

COMET Single-Event-Sensitivity:
Phase-I = 3×10^{-15}
Phase-II = 3×10^{-17}

Muon to Electron Conversion

Charged Lepton Flavour Violation:

$$\mu^- + \mathrm{N(A, Z)} \rightarrow \mathrm{e}^- + \mathrm{N(A, Z)}$$



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On Aluminium, used by COMET:

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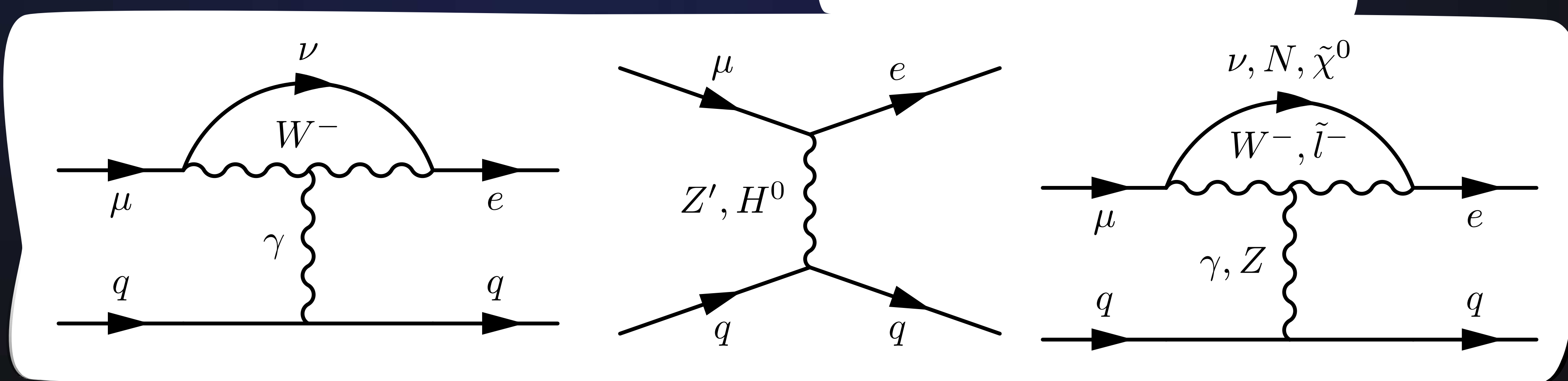
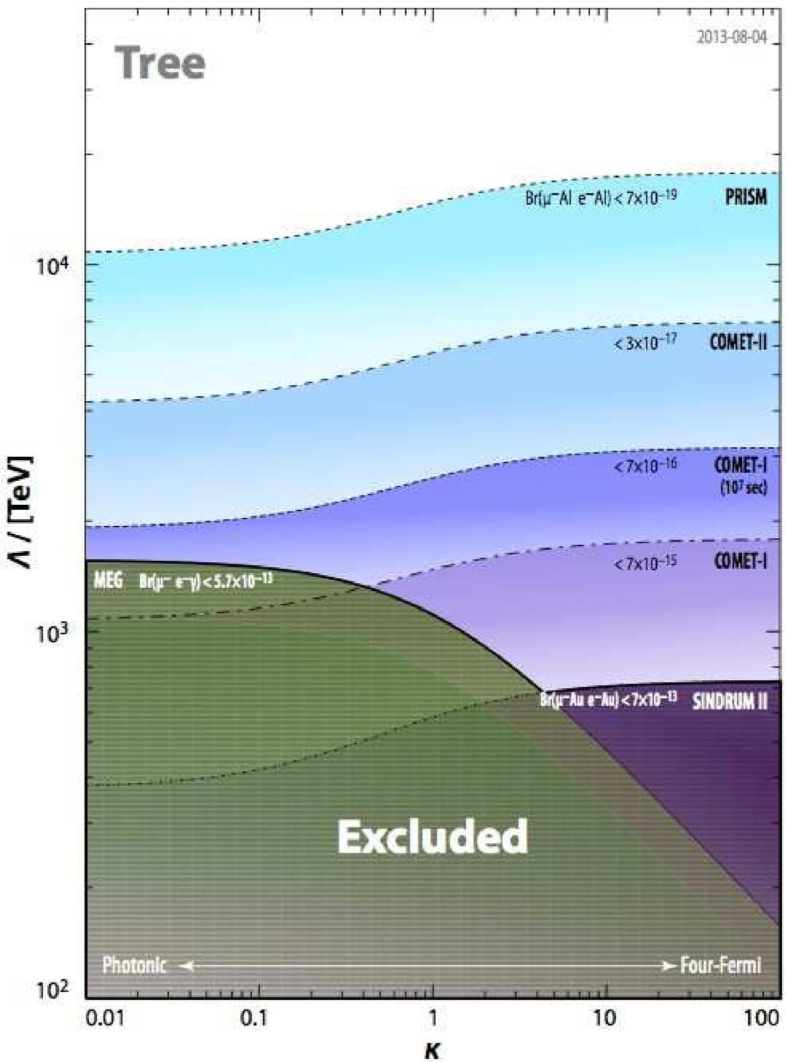


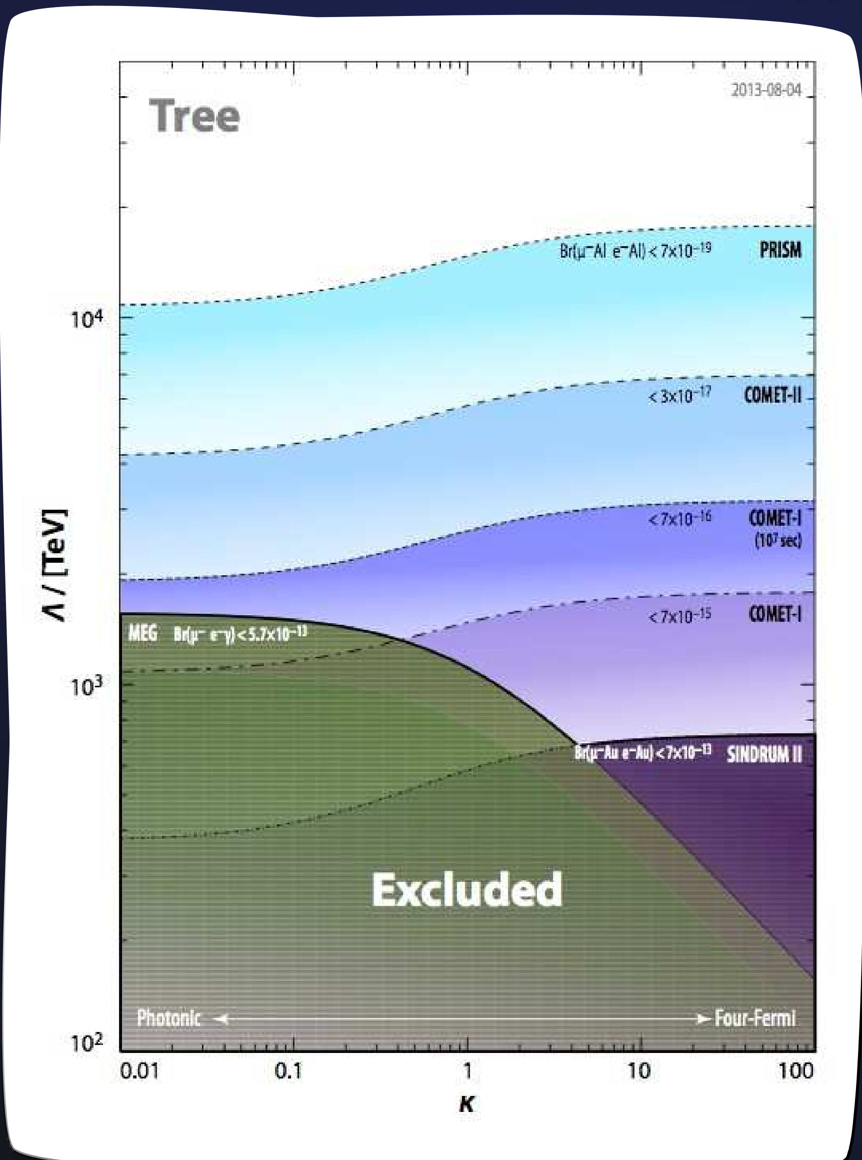
μ→e gamma vs μ−e conversion



- Relative sensitivity in μ-e conversion and μ-e gamma is model dependent
- Highly complementary searches

$$\mathcal{L} = \frac{1}{\kappa+1}\frac{m_\mu}{\Lambda^2}(\bar{\mu}_R\sigma^{\mu\nu}e_L F_{\mu\nu}) + \frac{\kappa}{\kappa+1}\frac{1}{\Lambda^2}(\bar{\mu}_L\gamma^\mu e_L)(\bar{q}_L\gamma_\mu q_L)$$

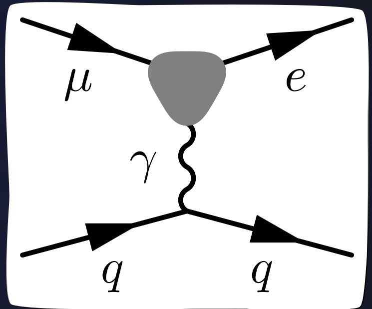
μ→e gamma vs μ–e conversion

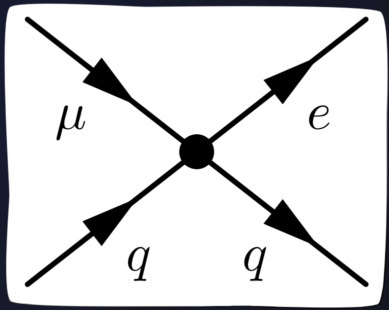


- Relative sensitivity in μ-e conversion and μ-e gamma is model dependent
- Highly complementary searches

Photonic $\kappa \to 0$

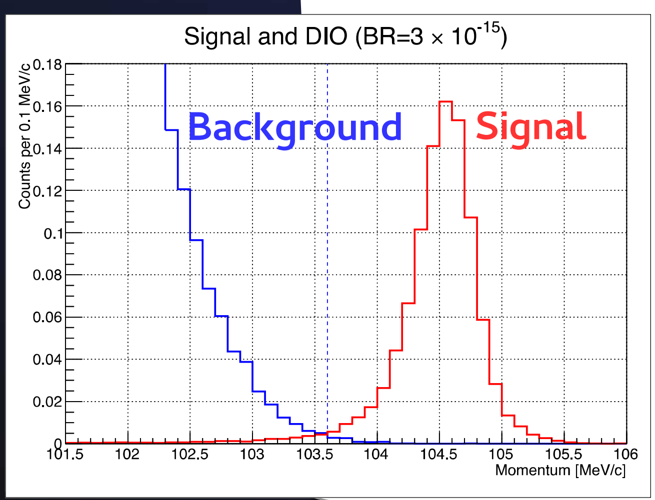
$$\mathcal{L} = \frac{1}{\kappa+1}\left\{ \right\} + \frac{\kappa}{\kappa+1}\left\{ \right\}$$

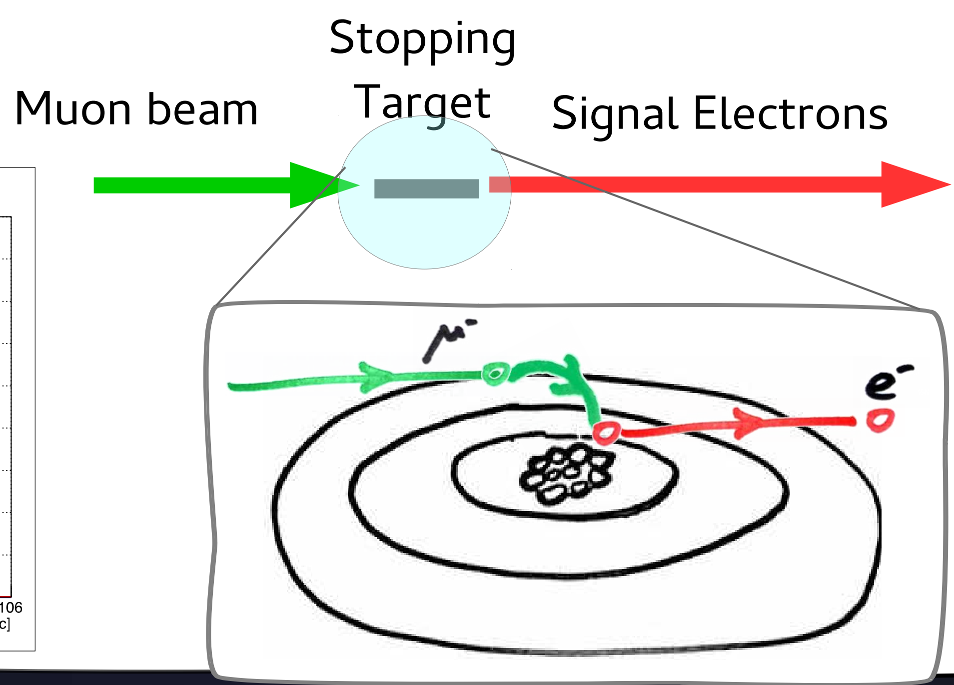




Four-fermi contact $\kappa \to \infty$

COMET


Signal and DIO (BR=3 × 10^-15)
Counts per 0.1 MeV/c
Momentum [MeV/c]
Background
Signal


Stopping Target
Muon beam
Signal Electrons
μ-
e-

COMET

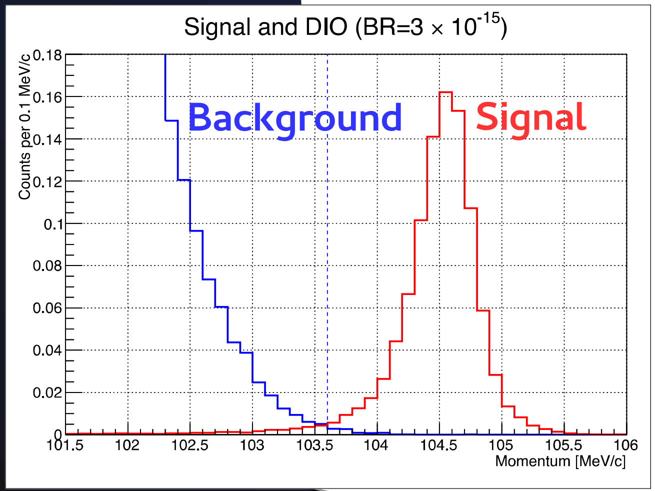
$$\text{S.E.S} < 10^{-17} \implies N_{\mu\,\text{stops}} > 10^{+17}$$

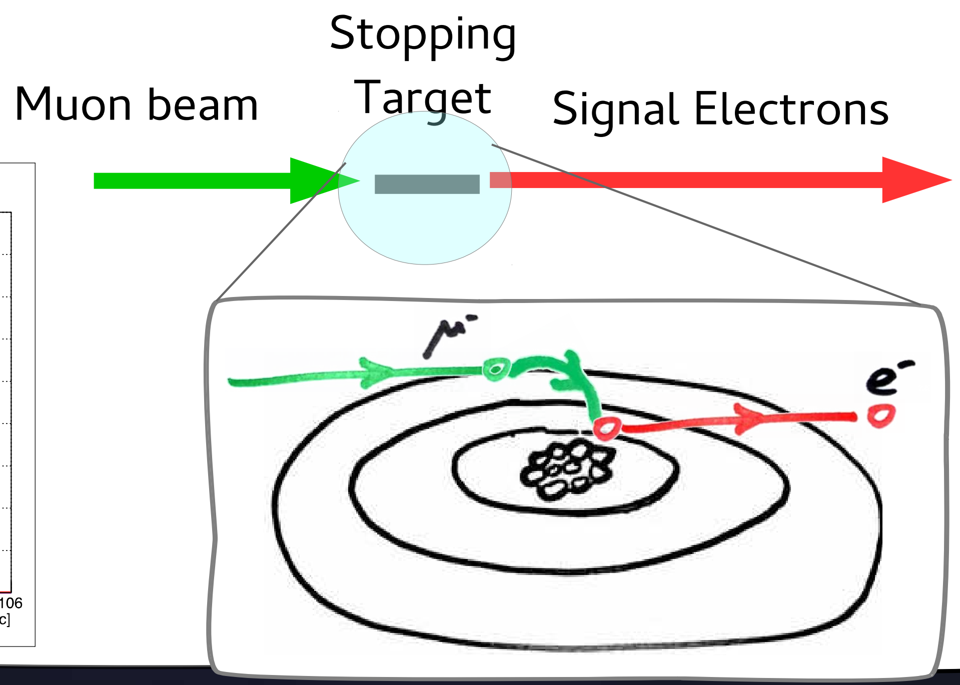
Need to stop many muons

- Intense muon beam
- High stopping efficiency ⇒ Low energy

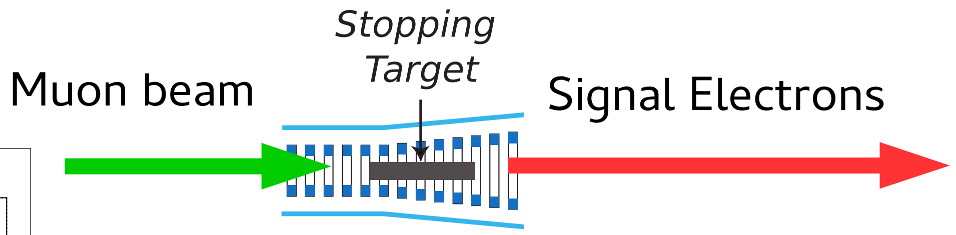
Assuming no background and perfect acceptance. To reduce these:

- Thin stopping target
- High beam purity

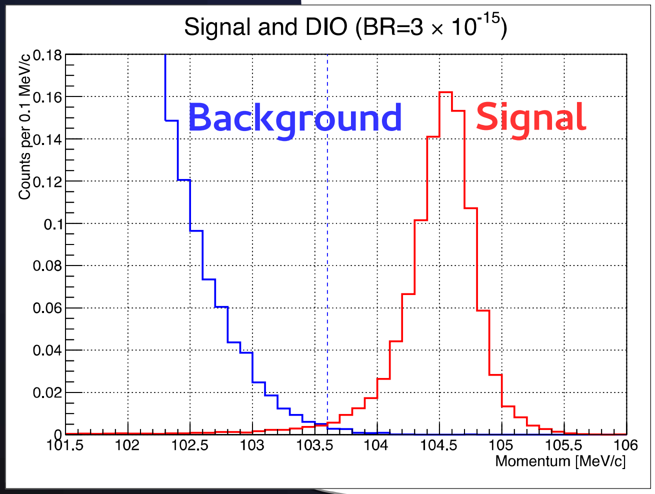




COMET



Stopping Target
Muon beam
Signal Electrons

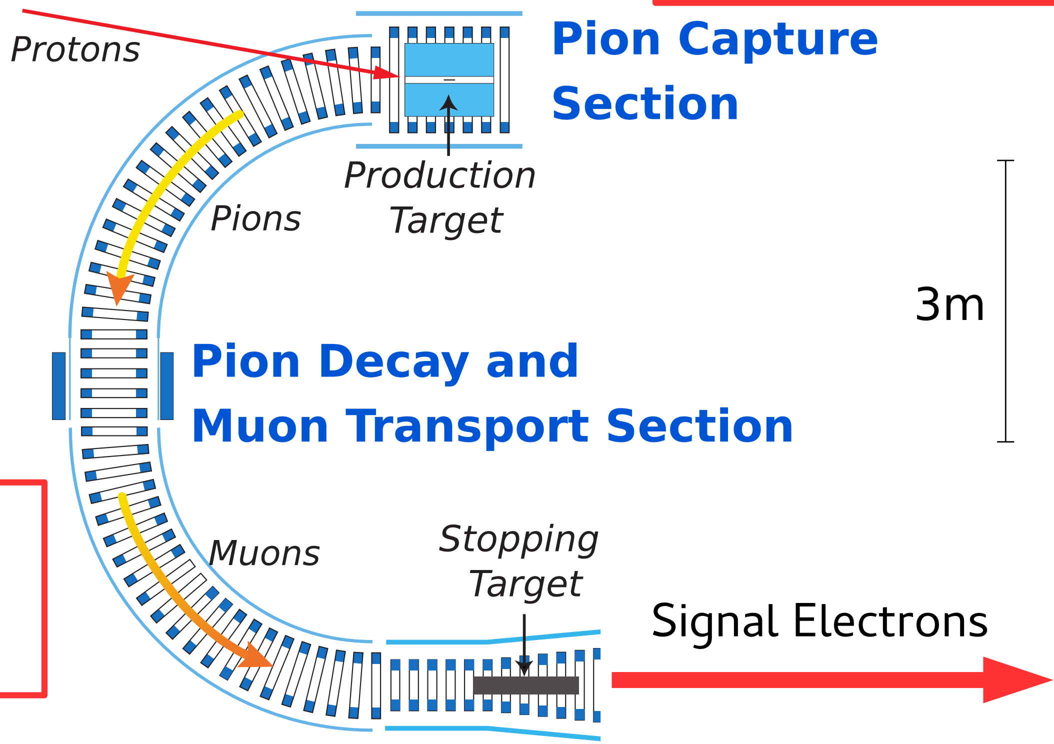


Signal and DIO (BR=3 × 10^-15)
Counts per 0.1 MeV/c
Momentum [MeV/c]
Background
Signal

COMET: Phase–II

Actively Cooled Tungsten Target in 5 T Superconducting Solenoidal Field

8 GeV proton beam at 56 KW



Bent solenoid field + compensating dipole fields

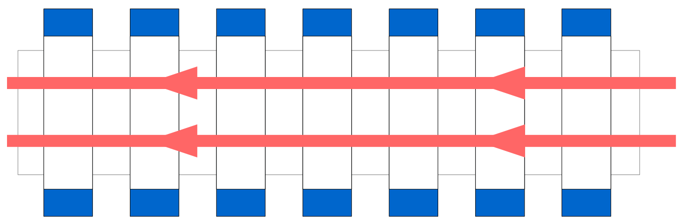
<u>**High beam purity**</u>

- Maximize decay channel length
- Bent solenoid + dipole field for charge selection

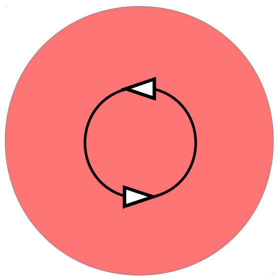
<u>**Low muon energy w. high intensity**</u>

- Capture of backwards pions
- Bent solenoid + dipole field for momentum selection

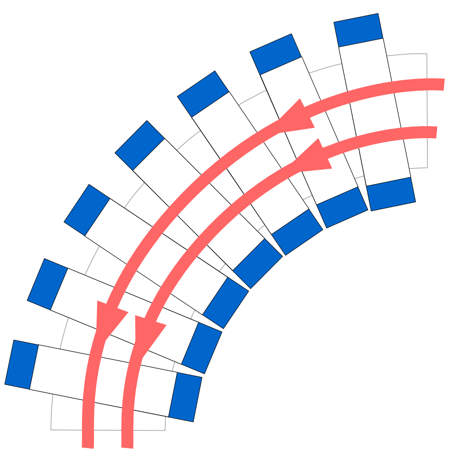
Muon Beam: Bent Solenoid Drifts



- Uniform B field
- Linear field lines



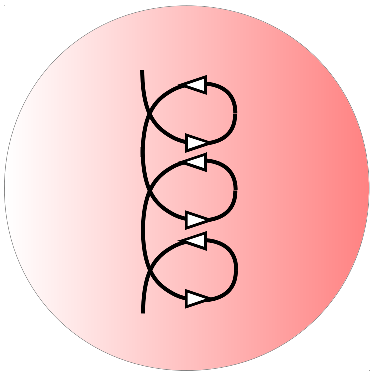
Circular motion about field lines



- Radial gradient in magnetic field
- Cylindrical field lines

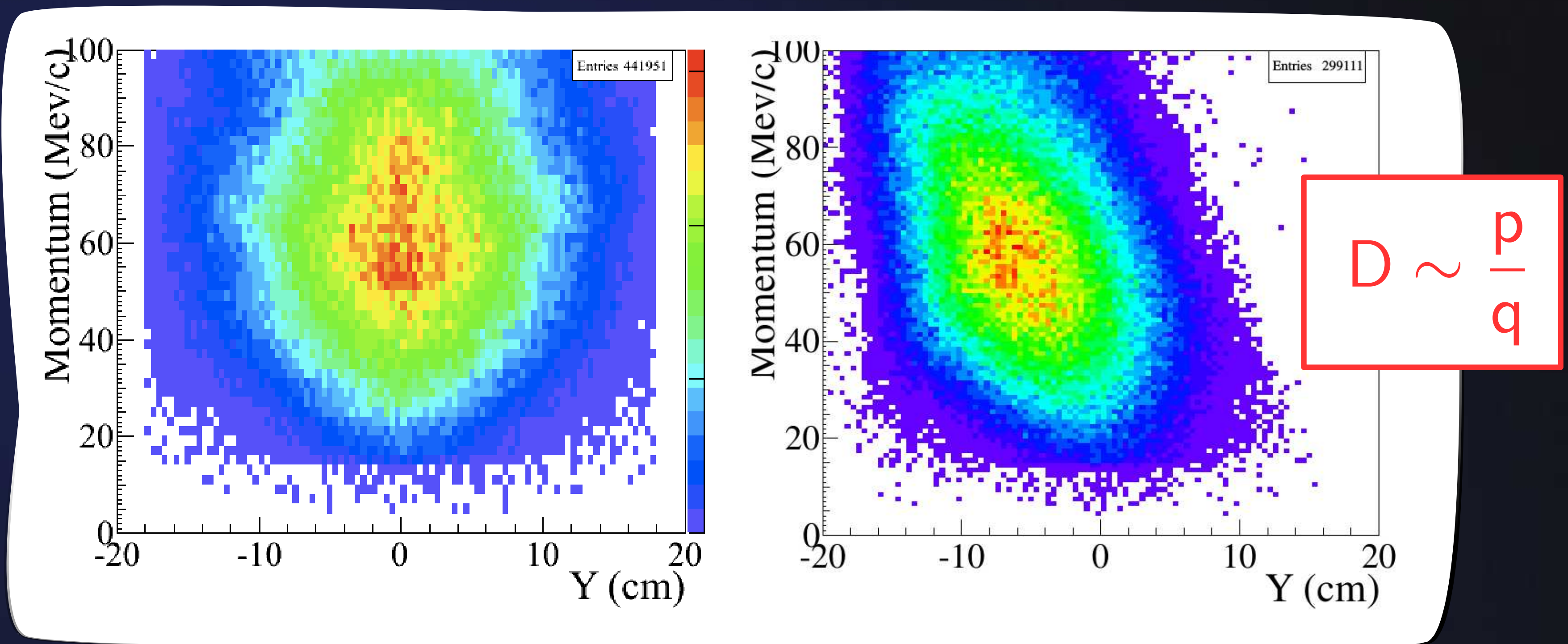
$$D \propto \frac{1}{qB}\left(\frac{p_l^2 + \frac{1}{2}p_t^2}{p_l}\right)$$

$$\propto \frac{1}{qB}\frac{p}{2}\left(\cos\theta + \frac{1}{\cos\theta}\right)$$



Circular motion about a drifting centre.

Muon Beam: Bent Solenoid Drifts



At entrance to bent solenoid

After 90° of bent solenoid

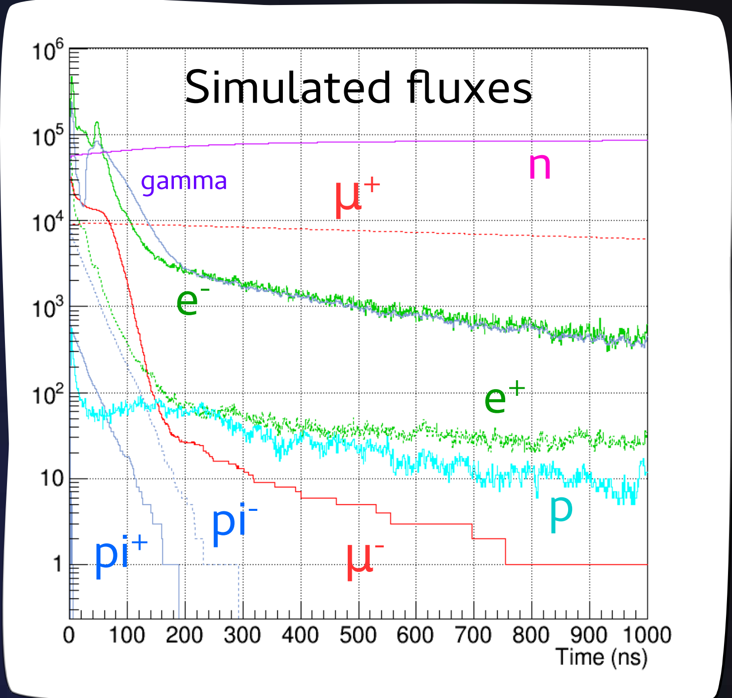
- Drift due to bent solenoid: position and momentum correlated
- Vertical dipole field applied
  - Tuned to maintain nominal momentum on axis
- Collimators select for charge and momentum

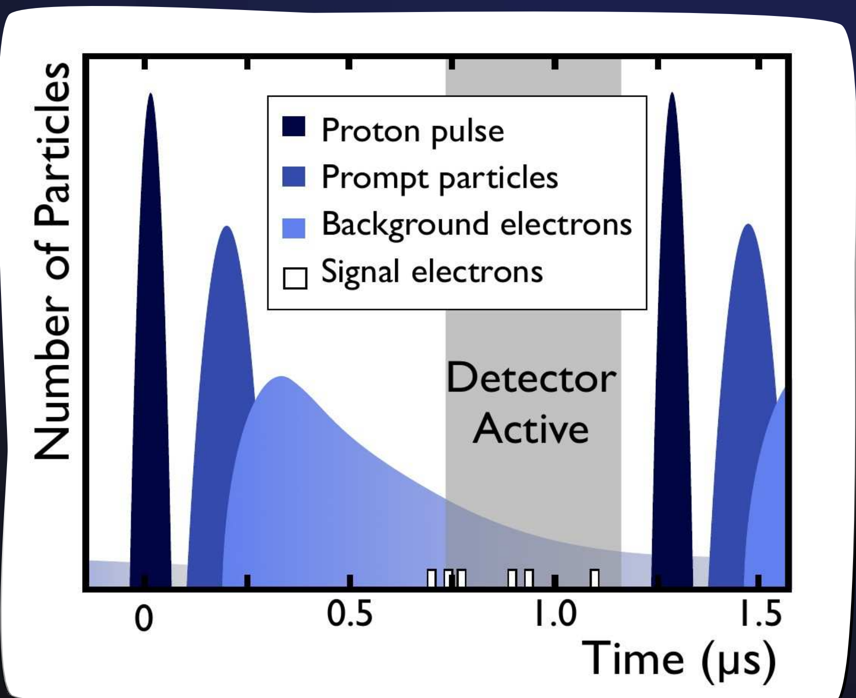
See talk by Yang Ye on Thursday

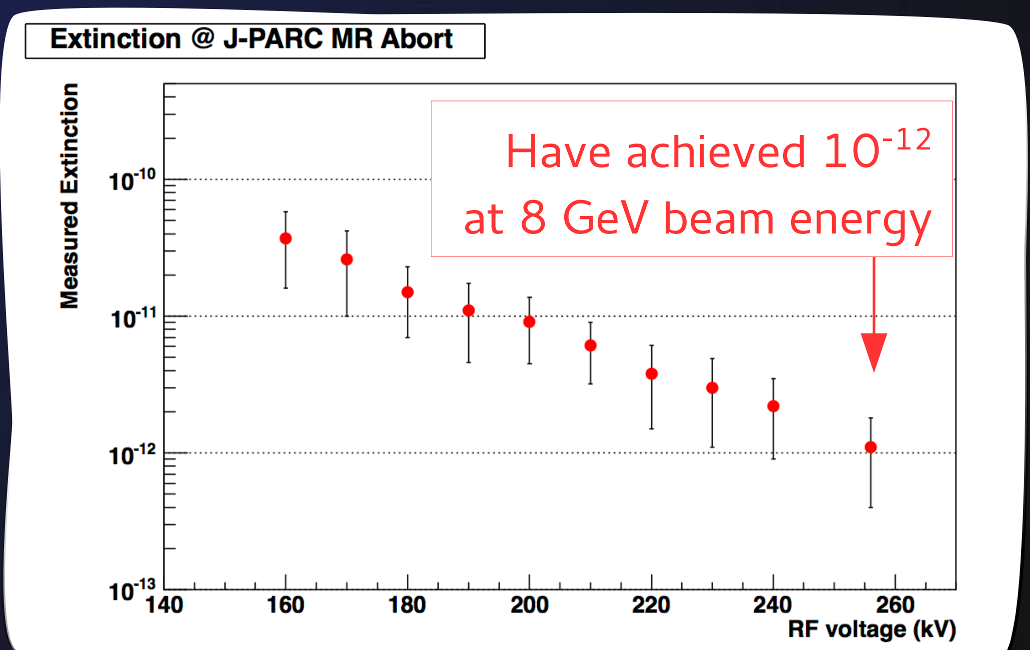
Proton Beam: Timing

- Pulsed beam removes beam-related backgrounds
- Need pulse timing > muon lifetime in aluminium
  - Muon lifetime on Aluminium: 864 ns
- As few protons between pulses as possible:
  - Extinction factor:

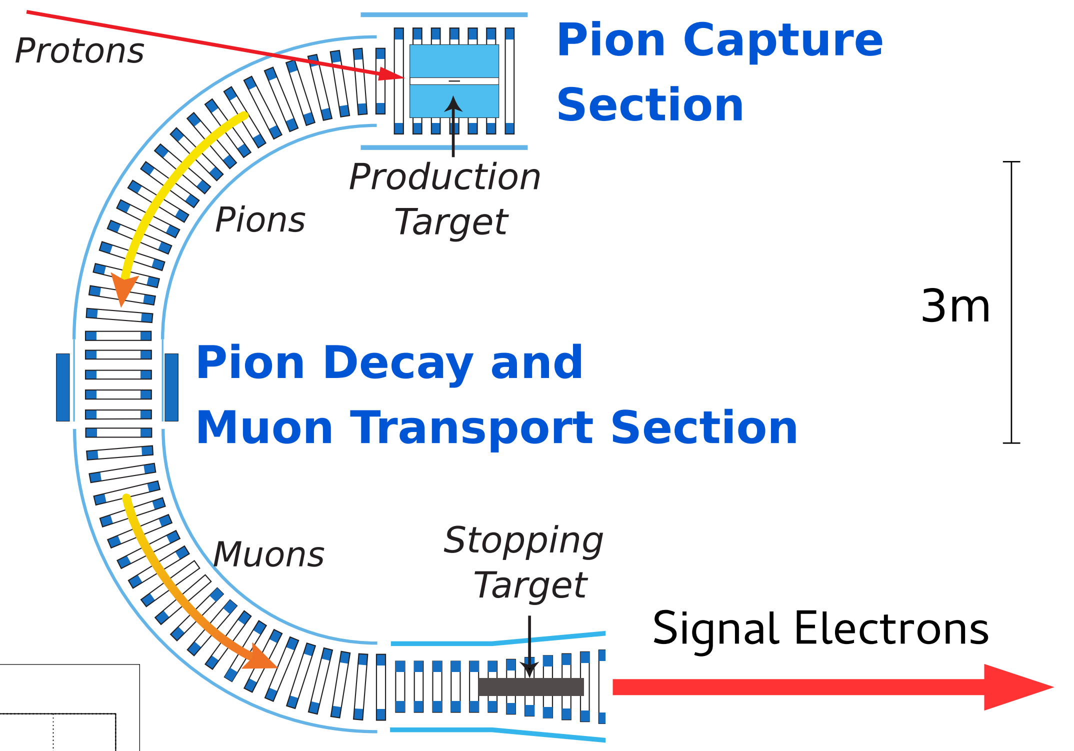
$$\text{Extinction} = \frac{N(\text{Protons between pulse})}{N(\text{Protons in bunch})}$$

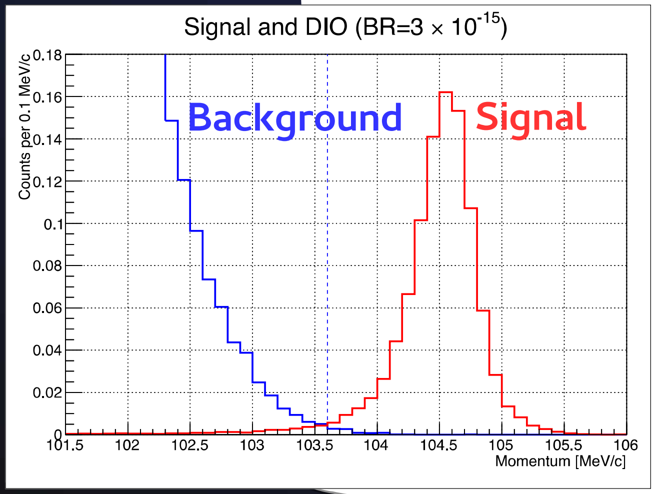




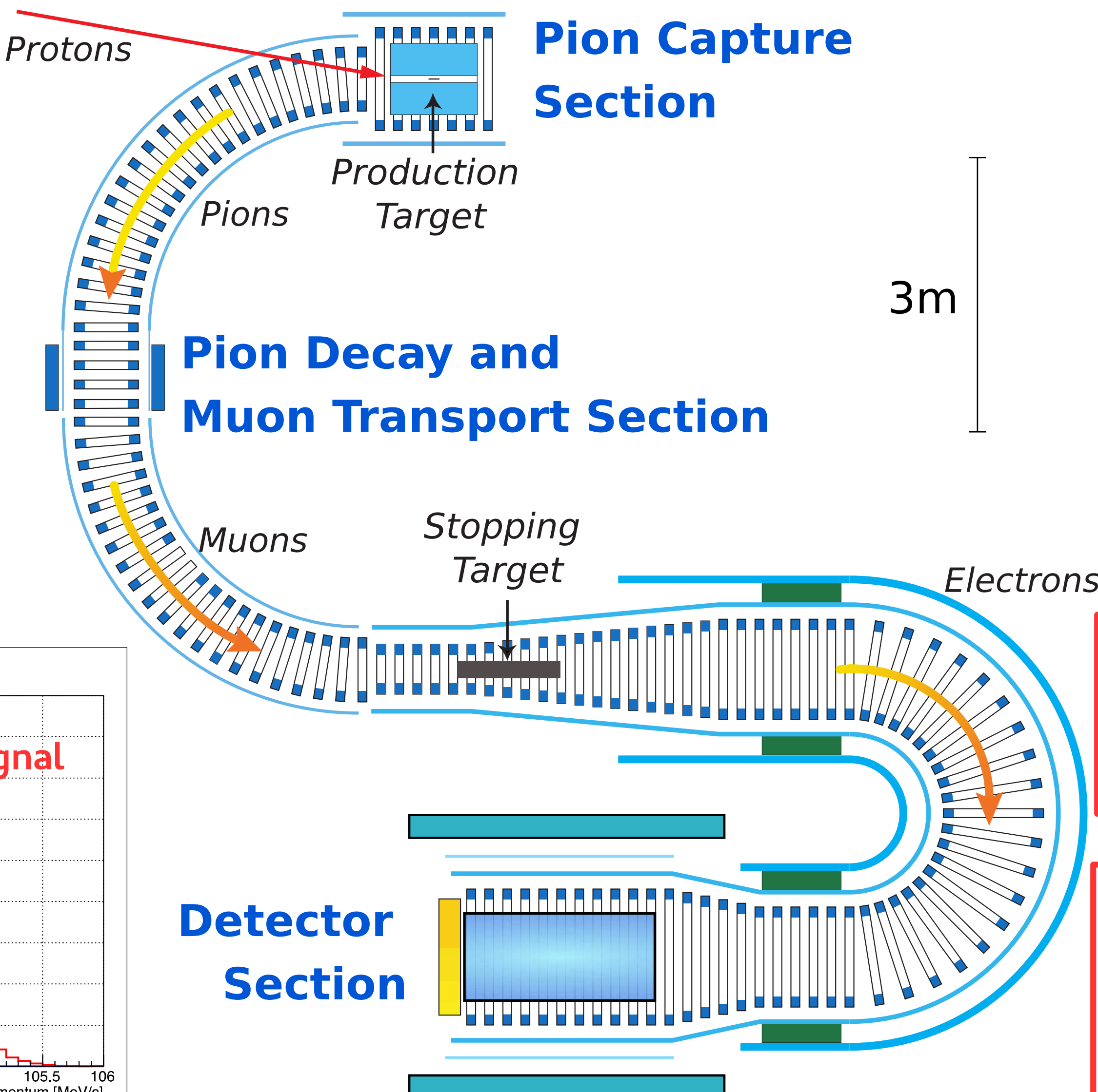


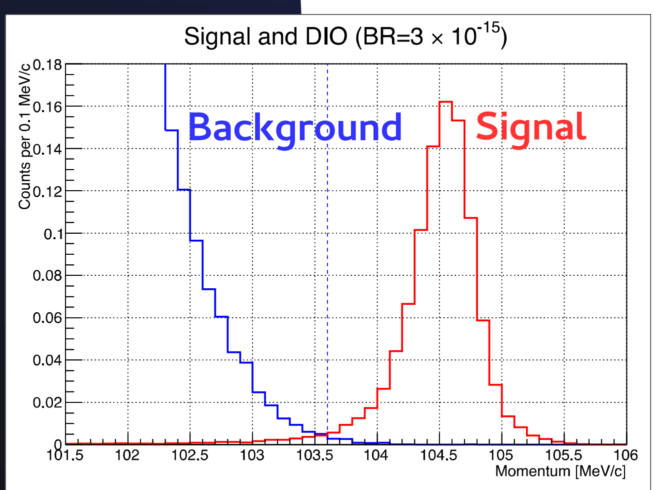
COMET: Phase–II





COMET: Phase–II



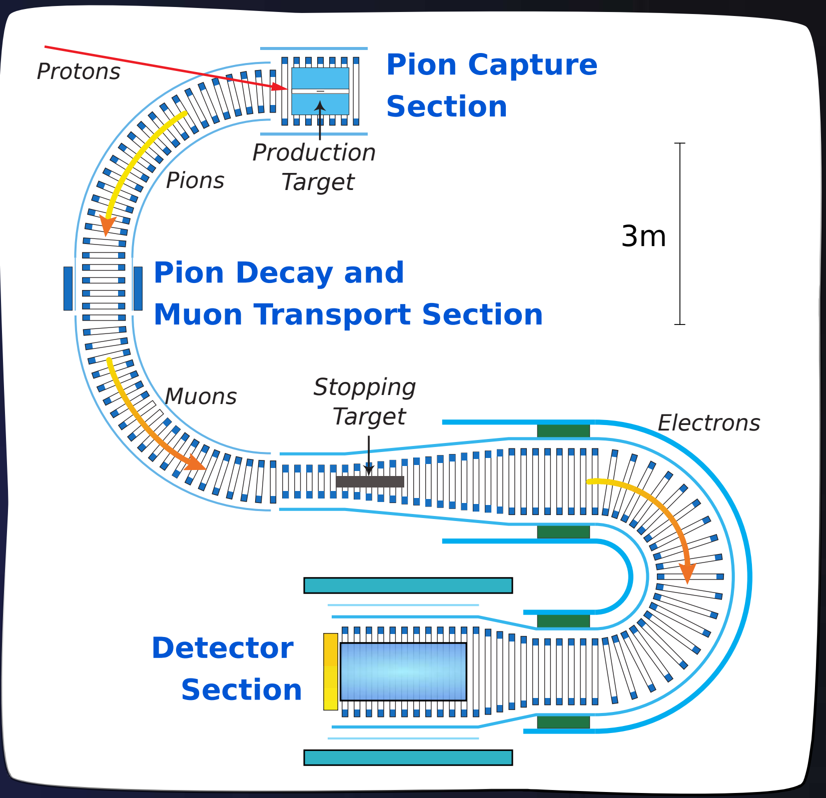


No line of sight between target and detector

Select for high energy electrons using bent solenoid and dipole field

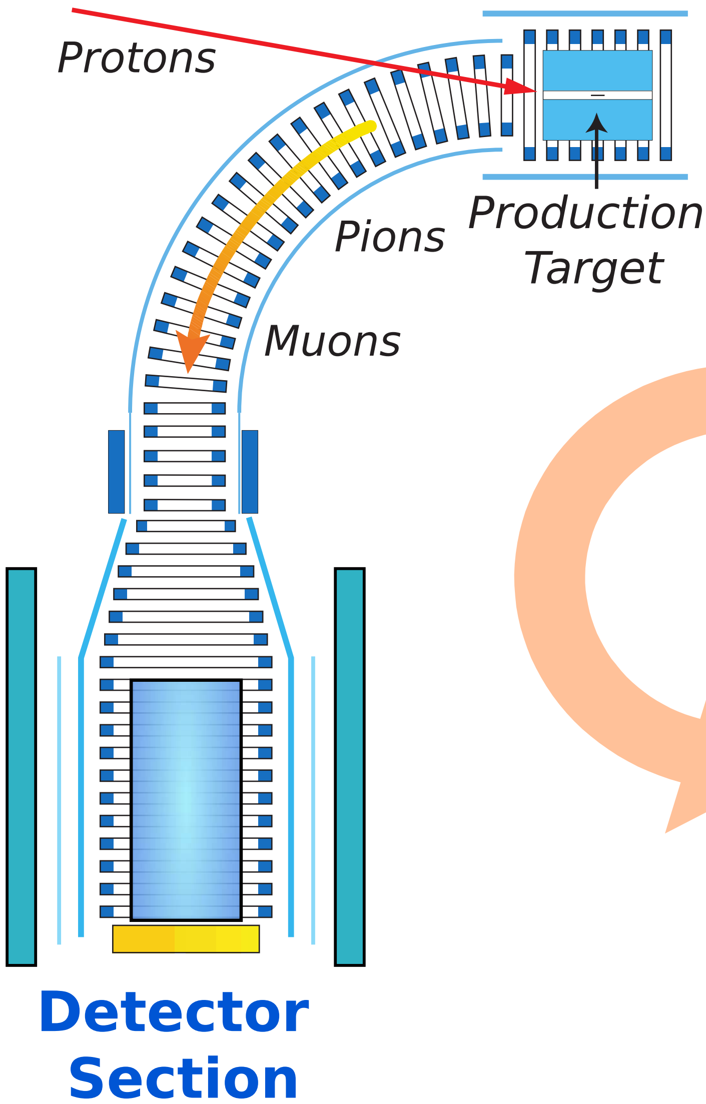
COMET: Phase–II

- Many novel techniques:
  - Production Target:
    - Super-conducting capture solenoid
    - Pions in backwards direction
    - 8 GeV protons
  - Muon beam-line
    - Bent solenoid drifts
    - Dipole and collimator tunes
  - Detector system
    - Bent solenoids
    - Bound muon decay spectrum near signal window



⇒ Need to understand and model each sub-section accurately

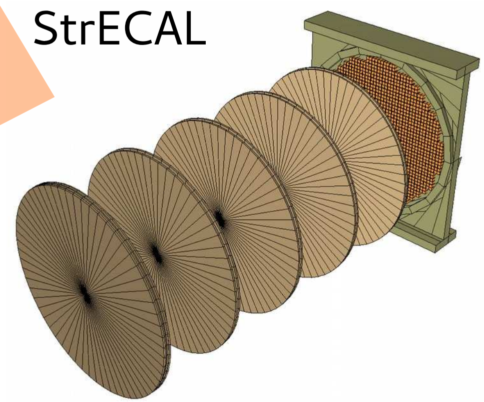
COMET: Phase–I



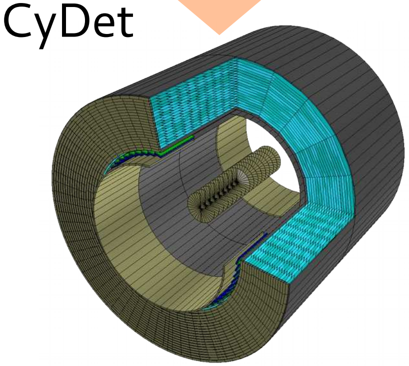
Goals of Phase–I

- Understand production system
- Understand bent solenoid dynamics
- Prototype the detector
- Measurement of background sources
- μ-e conversion search at: 3×10^{-15}

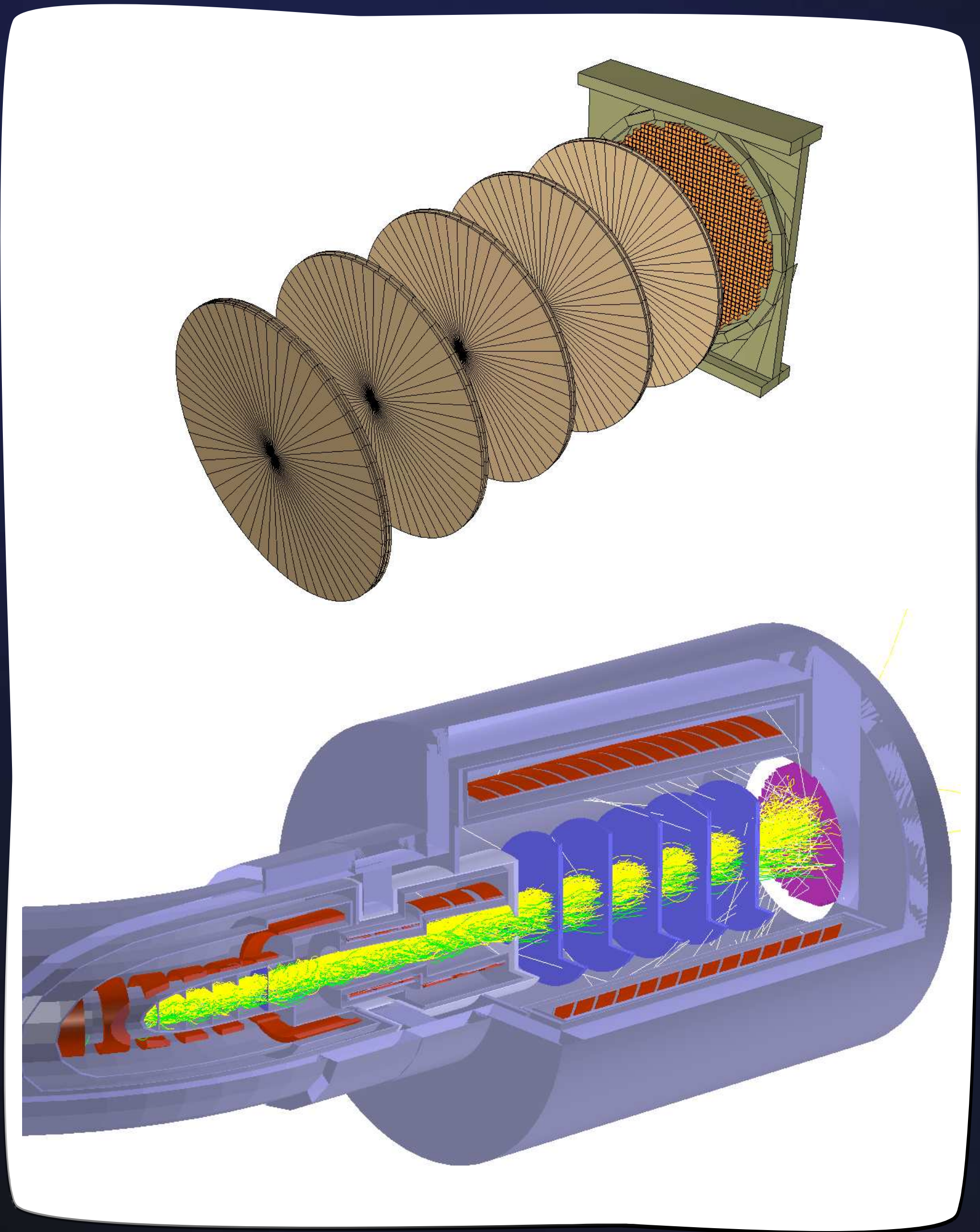
StrECAL



CyDet



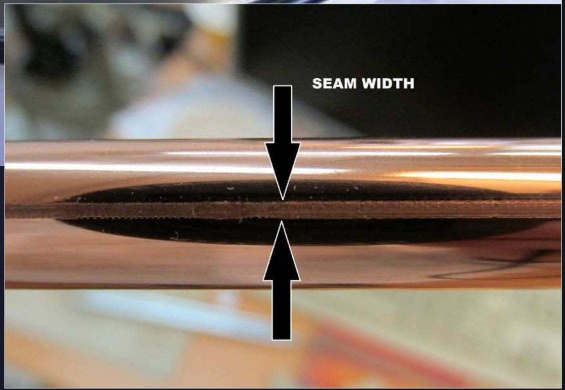
Straw Tube Tracker + ECAL (StrECAL)



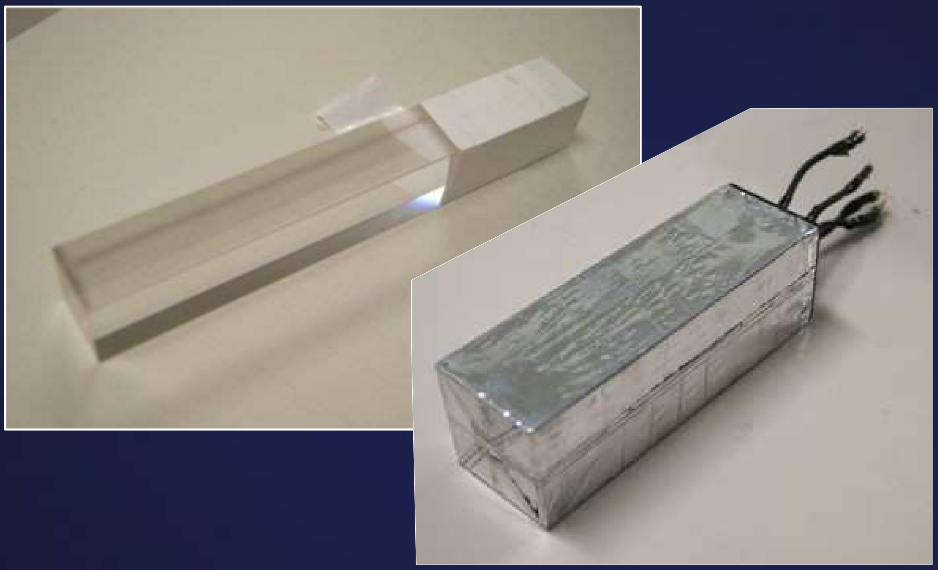
- Straw Tube Tracker planes + Crystal ECAL
  - Straw Tracker ⇒ Momentum measurement
  - ECAL ⇒ Energy measurement
  - Combination ⇒ PID
- Used for beam characterisation in Phase-I
- Main detector design for Phase-II

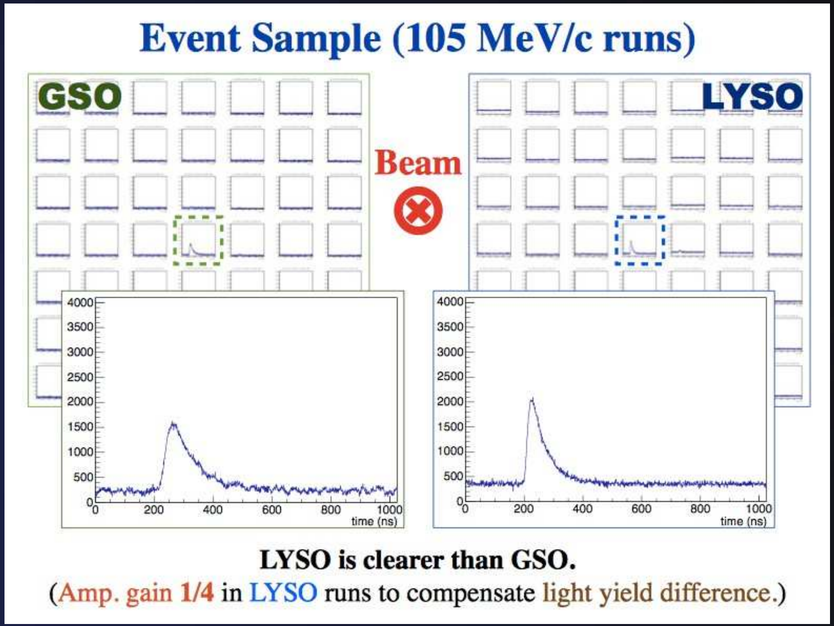
Straw Tracker

- Phase-I Straw Design
  - Based on NA62 Straws with single seam weld
  - 20 micron aluminised mylar
  - 9.8 mm diameter tubes
- Phase-II possibilities:
  - 5 mm diameter
  - 12 micron Al-mylar
- Status
  - Phase-I production finished (2500 straws)
  - Aging tests, resolution studies underway



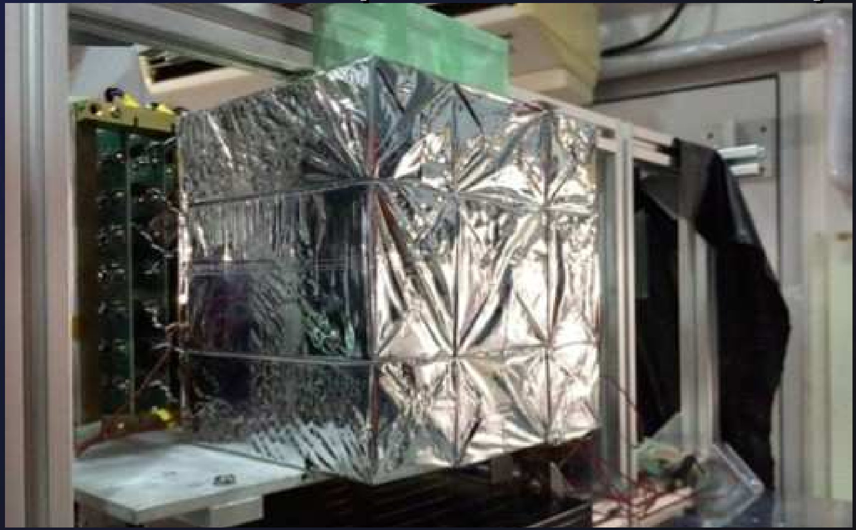
ECAL *StrECAL Trigger and Energy Measurement for PID*





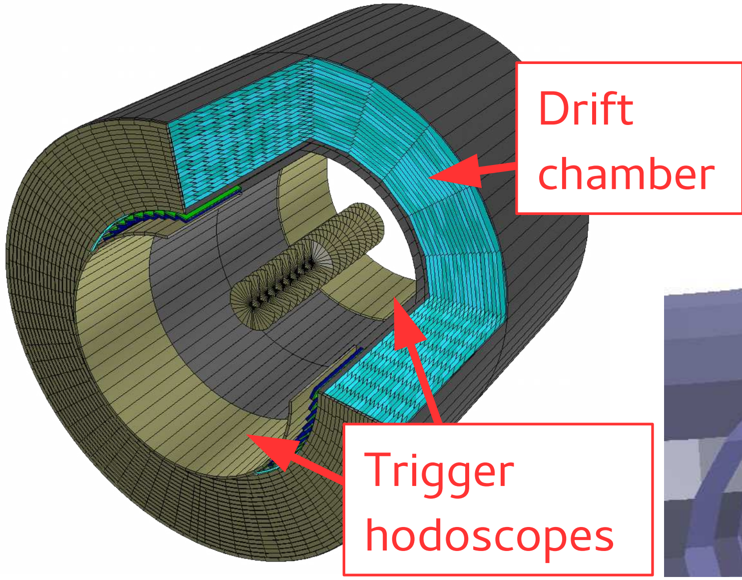
- 2272 LYSO Crystals
  - Dimensions: 2x2x12 cm
- Status:
  - Crystal purchasing on-going
  - Test bench being built
  - Beam tests for resolution studies, PID and DAQ underway
  - Calibration system being designed

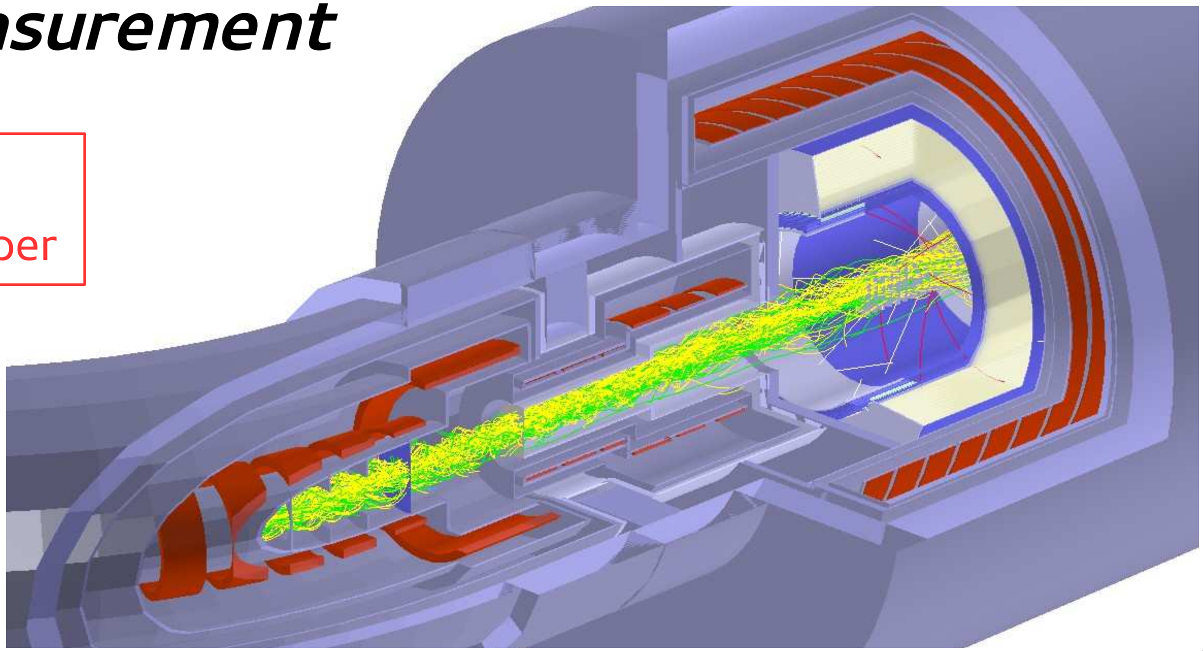
Beam test setup for resolution study



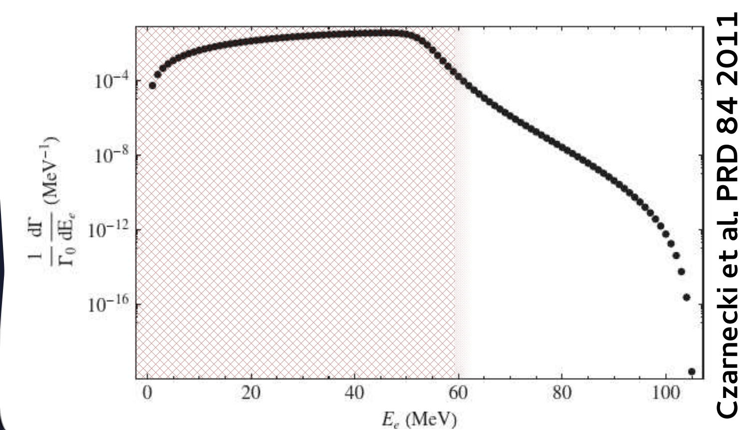
Cylindrical Detector (CyDet)

Phase-I Physics Measurement





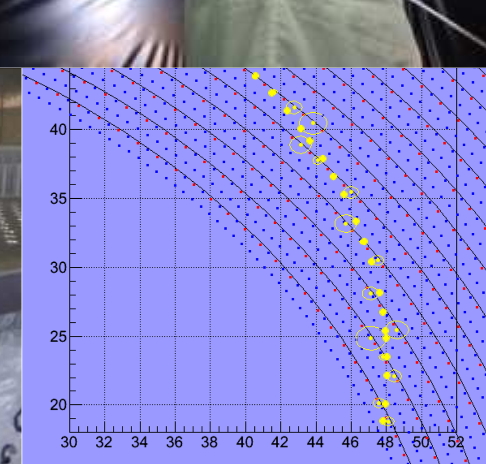
- Cylindrical Drift Chamber (CDC) triggered from hodoscopes made of Cherenkov counters and plastic scintillators
- 60 cm inner radius
  - ⇒ Blind to particles with momentum less than 60 MeV/c
  - Avoids beam flash and most electrons from bound muon decay
- Momentum measurement using drift chamber
  - Low material budget improves resolution
  - All stereo wires to recover Z information
- Possible Track Trigger being investigated for running at high rates
  - four fold coincidence of hodoscopes + drift chamber hits
  - 30~40 kHz has been studied.



Electrons from Bound Muon Decay

Cylindrical Drift Chamber (CDC)

- 20 layers with alternating stereo angles of ±4°
  - Sense wires: Gold plated tungsten, 25 μm
  - Field wires: Pure Aluminium, 120 μm
  - Between 800 and 1200 wires per layer
- Status:
  - Wire stringing:
    - 150 days total
    - 40% complete



Backgrounds

From Phase-I TDR (2014)

From Phase-II CDR (2009)

Type	Background	Predicted number of events per run Phase-I [5]	Phase-II [3]
Intrinsic	Muon Decay-in-Orbit	0.01	0.15
	Radiative Muon Capture	0.00056	< 0.001
	μ^- Capture w/ n Emission	< 0.001	< 0.001
	μ^- Capture w/ Charged Part. Emission	< 0.001	< 0.001
Prompt	Radiative Pion Capture	0.00023	0.05
	Beam Electrons	0.00083	$< 0.1^*$
	Muon Decay in Flight	≤ 0.0002	< 0.0002
	Pion Decay in Flight	≤ 0.00023	< 0.0001
	Neutron Induced	–	0.024
	Other beam induced B.G.	$< 2.8 \times 10^{-6}$	–
Delayed	Delayed Radiative Pion Capture	~ 0	0.002
	Anti-proton Induced	0.007	0.007
	Other delayed B.G.	~ 0	–
Cosmic	Cosmic Ray Muons	–	0.002
	Electrons from Cosmic Ray Muons	< 0.0001	0.002
	Total background	0.019	0.34
	Signal (Assuming $B = 1 \times 10^{-16}$)	0.31	3.8

Assumed extinction factors:

Phase-I: 10^{-11}

Phase-II: 10^{-9} (to be updated)

Run times:

Phase-I: 110 days

Phase-II: 1 year

Backgrounds

From Phase-I TDR (2014)

From Phase-II CDR (2009)

Type	Background	Predicted number of events per run Phase-I [5]	Phase-II [3]
Intrinsic	Muon Decay-in-Orbit	0.01	0.15
	Radiative Muon Capture	0.00056	< 0.001
	μ^- Capture w/ n Emission	< 0.001	< 0.001
	μ^- Capture w/ Charged Part. Emission	< 0.001	< 0.001
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	Beam Electrons	0.00083	$< 0.1^*$
	Muon Decay in Flight	≤ 0.0002	< 0.0002
	Pion Decay in Flight	≤ 0.00023	< 0.0001
	Neutron Induced	–	0.024
	Other beam induced B.G.	$< 2.8 \times 10^{-6}$	–
Delayed	Delayed Radiative Pion Capture	~ 0	0.002
	Ant[illegible]	0.007	0.007
	Other delayed B.G.	~ 0	–
Cosmic	Cosmic Ray Muons	–	0.002
	Electrons from Cosmic Ray Muons	< 0.0001	0.002
	Total background	0.019	0.34
	Signal (Assuming $B = 1 \times 10^{-16}$)	0.31	3.8

Stopped muon processes

Beam contaminants (Extinction Supressed)

Beam contaminants

Cosmic

Assumed extinction factors:
Phase-I: 10^{-11}
Phase-II: 10^{-9} (to be updated)

Run times:
Phase-I: 110 days
Phase-II: 1 year

Software and Simulation

Looking for a rare process:

- Chance of conversion per capture at least (Phase-I): 10^{-15}

Need many muons:

- Stopped muons: 1×10^{16} muons
- Protons needed: 2×10^{19} protons

Software challenges:

High Statistics

- Killing volumes
- Resampling
- Factorisation of spectra

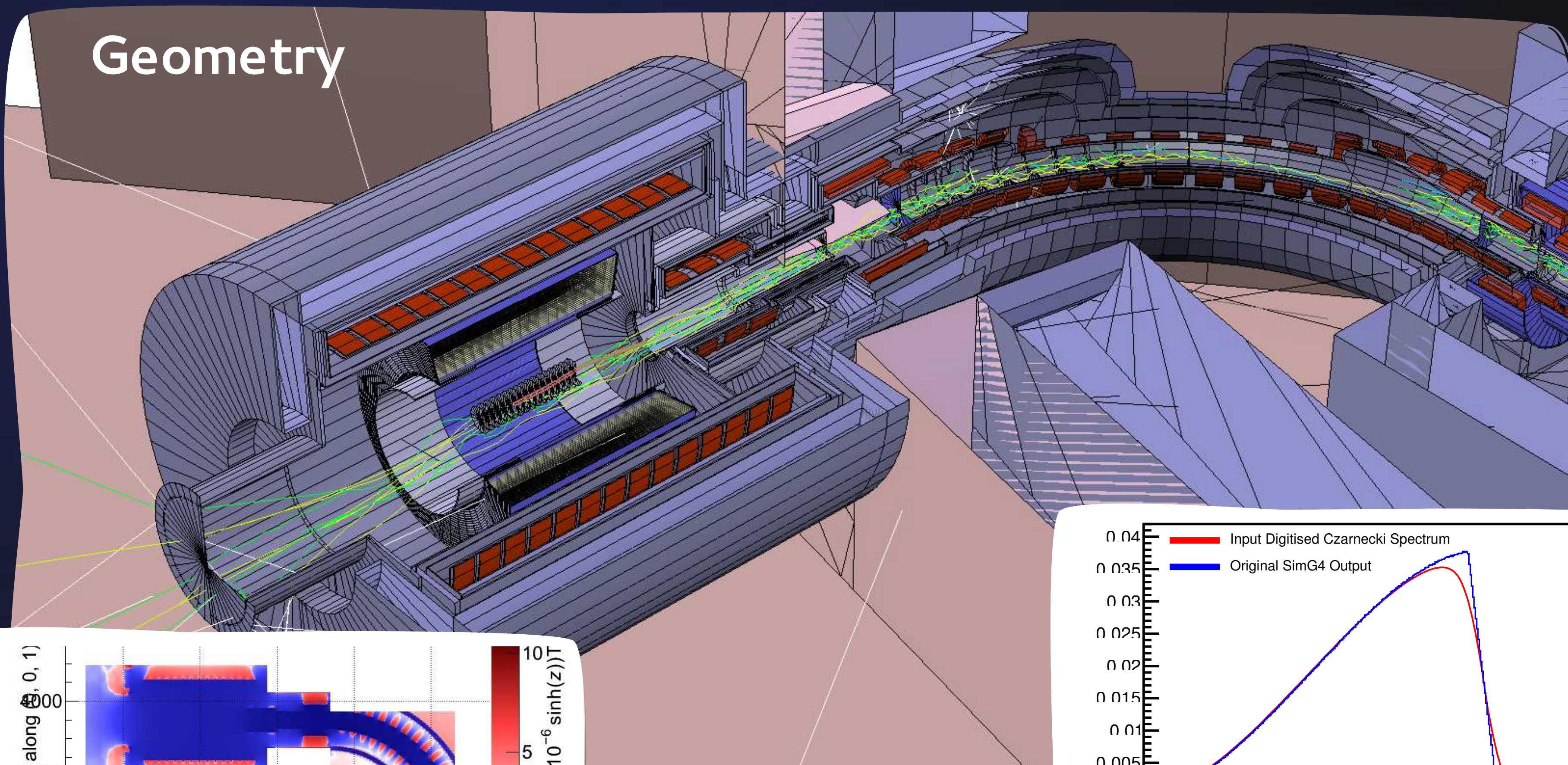
Detail

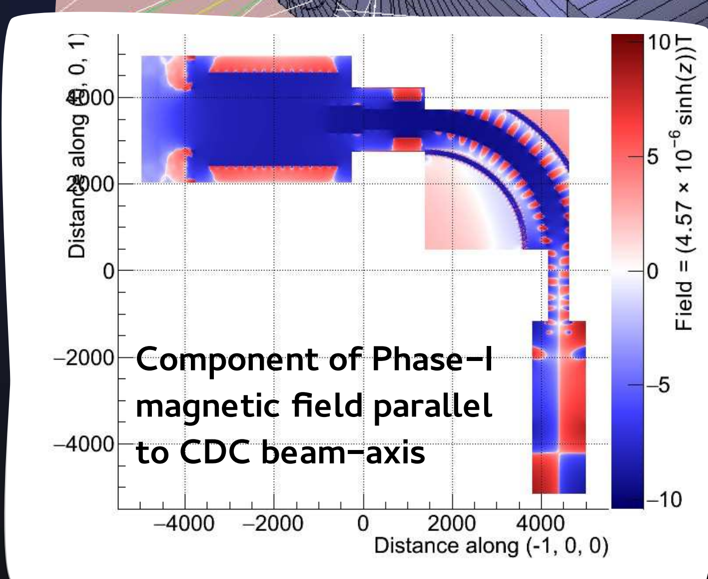
- Geometry
- Fieldmaps
- Physics processes (hadron models, stopped muon processes)

Offline Software

- Based on framework for the T2K near-detector, ND280
- Re-uses low-level code already tested on real data
- First stable release for COMET in April
- 2nd major Monte Carlo production recently finished

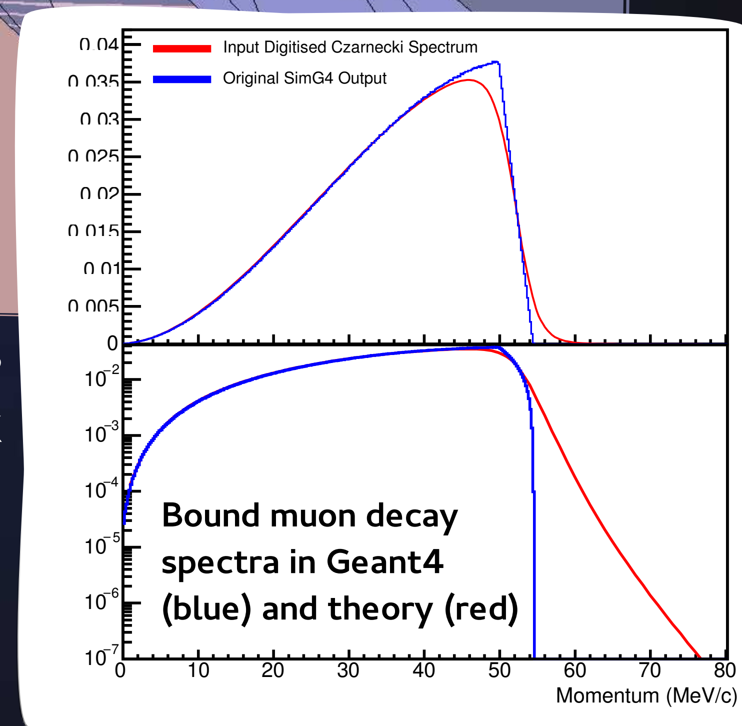
Software and Simulation



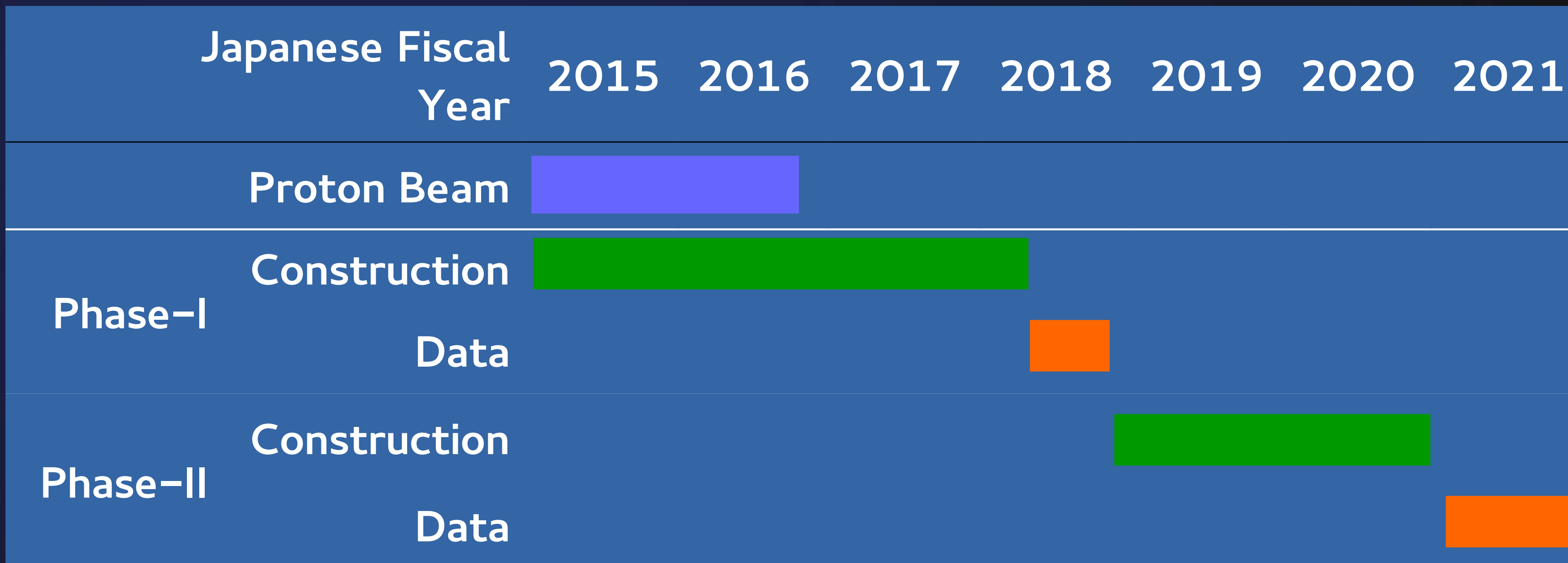


Fieldmaps

Physics Processes (See AlCap talk tomorrow)



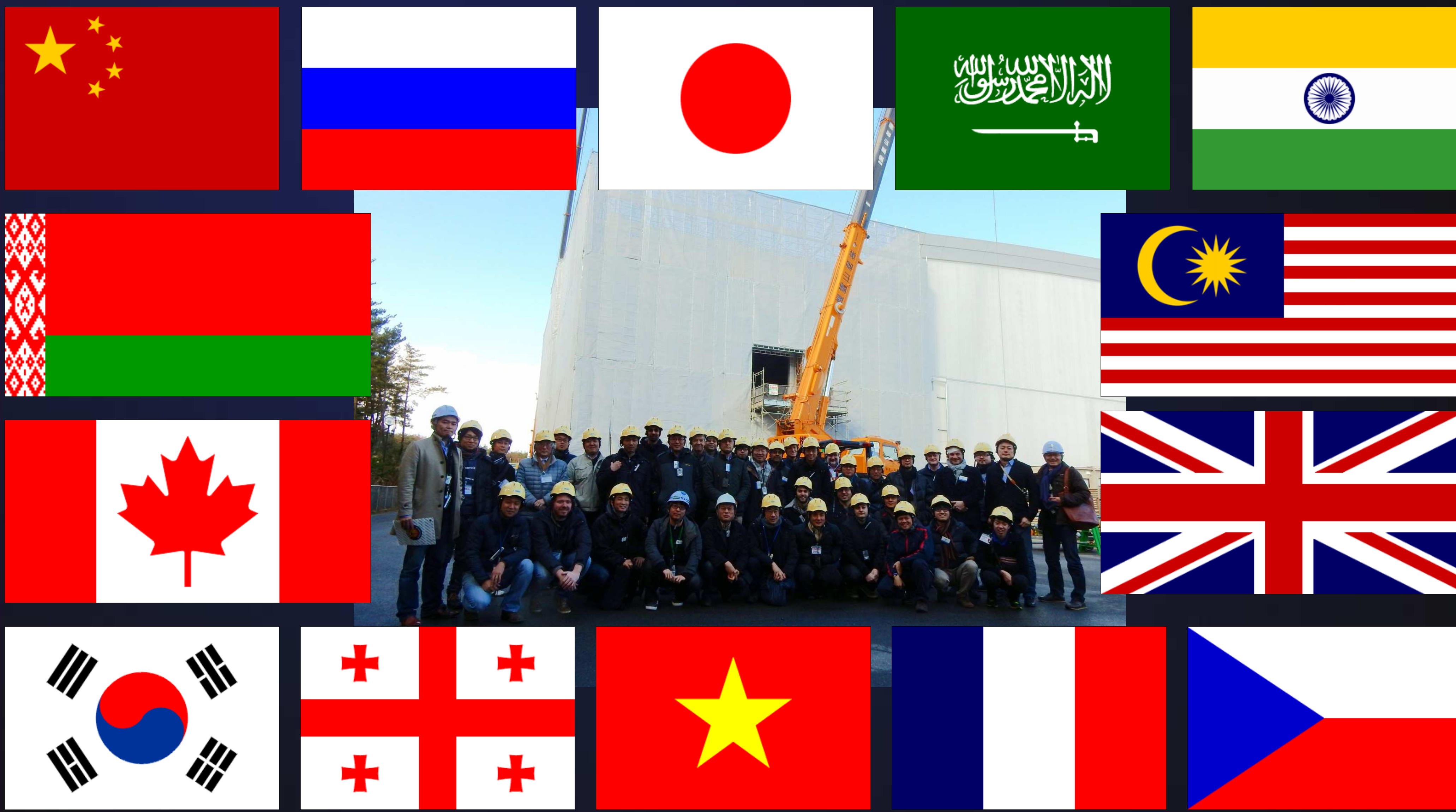
Schedule



Ben Krikler: bek07@imperial.ac.uk

Collaboration

14 Countries, 32 institutes, 177 participants



Summary

Muon–to–electron conversion is a strong probe of new physics

COMET's staged approach and unique design makes it highly sensitive to this process

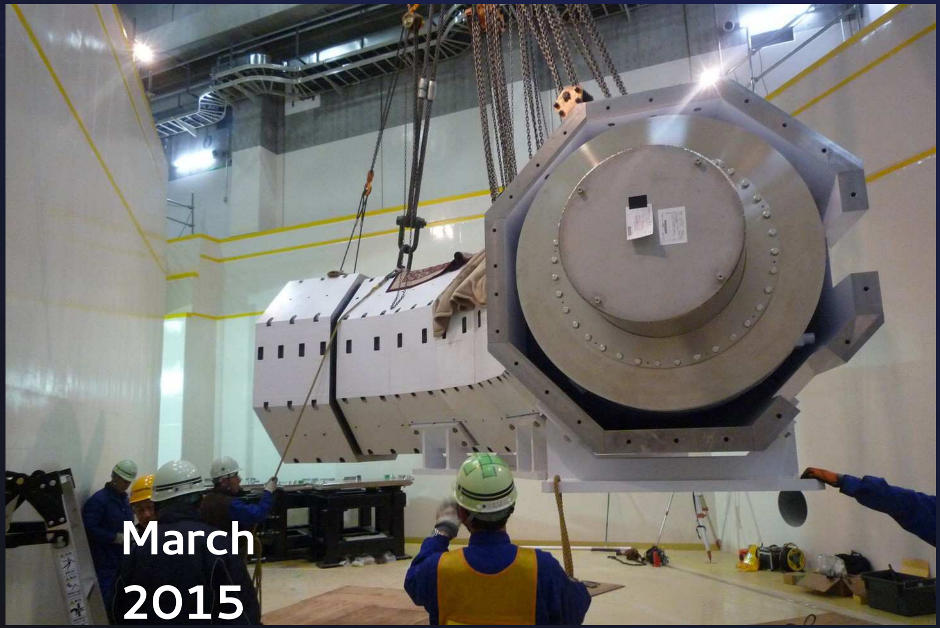
Development and construction are well under way

COMET Phase–I
2018
Sensitivity $< 3 \times 10^{-15}$
110 days
3.2 kW proton beam

COMET Phase–II
2021
Sensitivity $< 3 \times 10^{-17}$
1 Year
56 kW proton beam

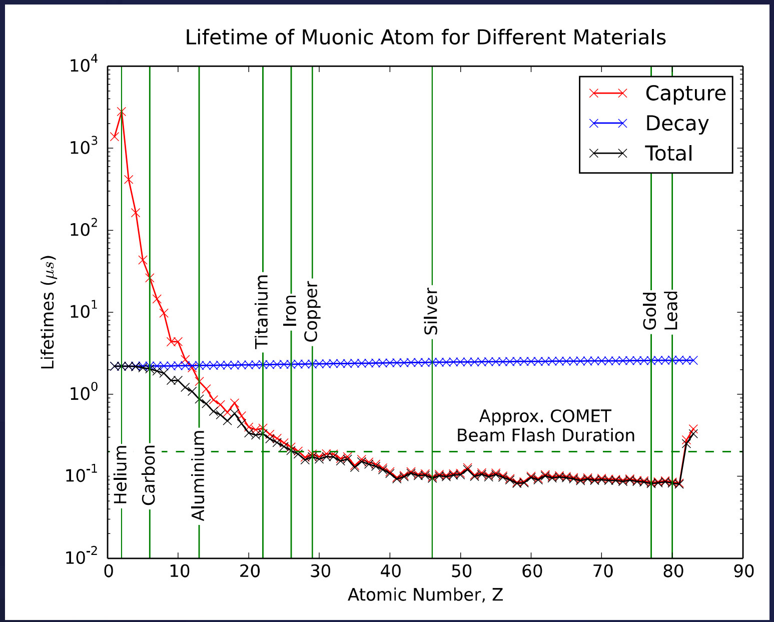
The future:
PRISM / PRIME
Sensitivity $\ll 10^{-18}$
See talk by J. Pasternak

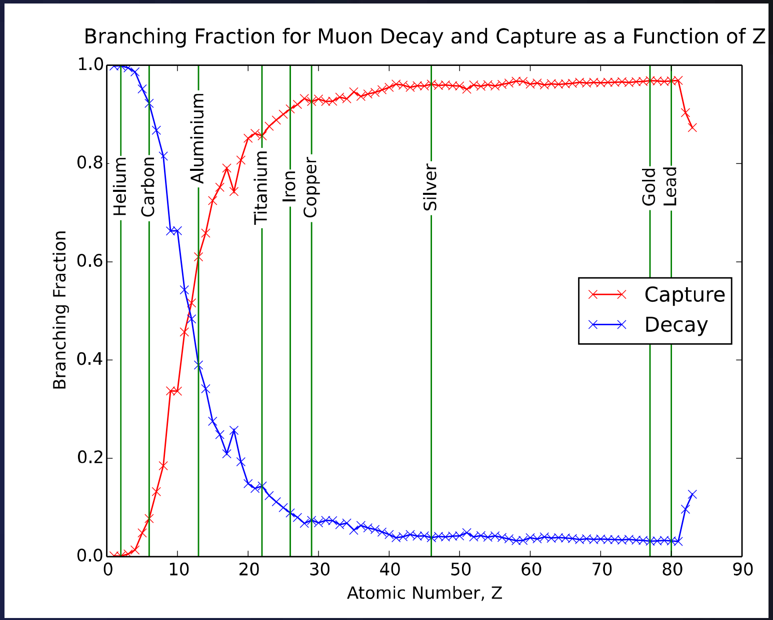
Muito Obrigado!

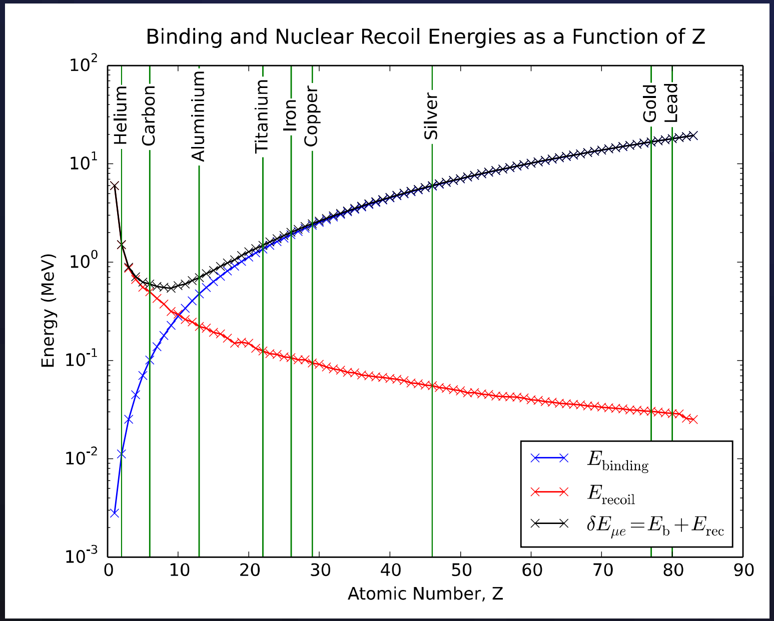


Back-ups

Why an Aluminium Target?





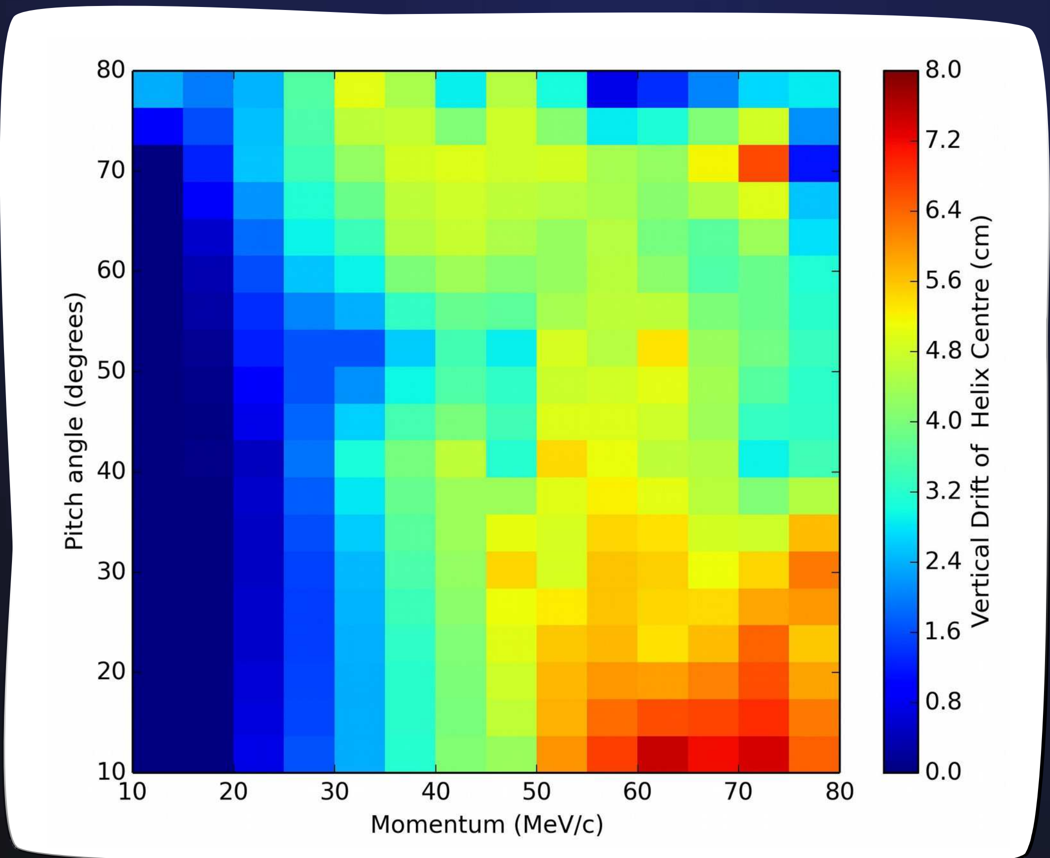


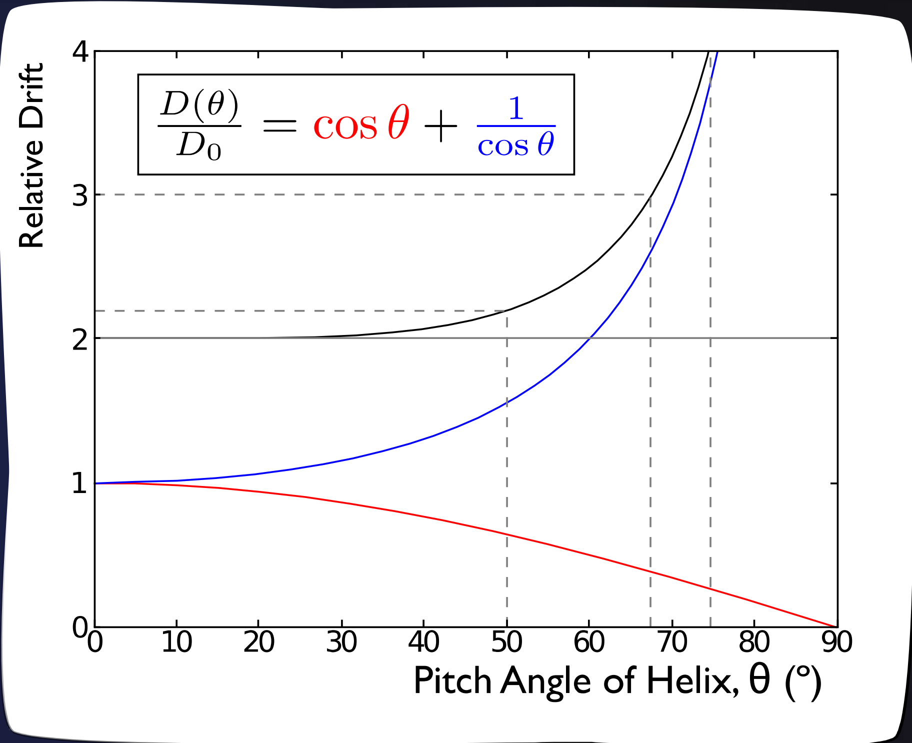
- Maximise atomic lifetime compared to beam flash duration
- Minimise binding and nuclear recoil energies
- Maximise capture branching ratio
- (Phase-I: Minimise emissions following muon nuclear capture)

Muon Beam: Bent Solenoid Drifts

$$D \propto \frac{1}{qB}\frac{p}{2}\left(\cos\theta + \frac{1}{\cos\theta}\right)$$

$$\implies D \sim \frac{p}{q}$$





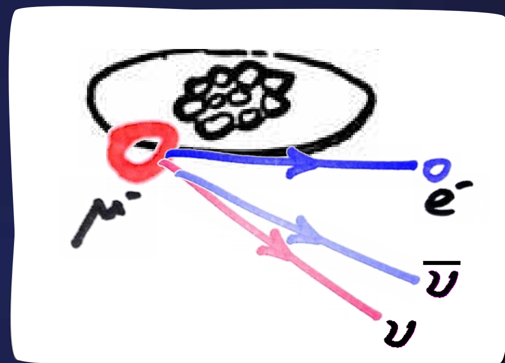
A collimator can then select for:

- Momentum
- Charge

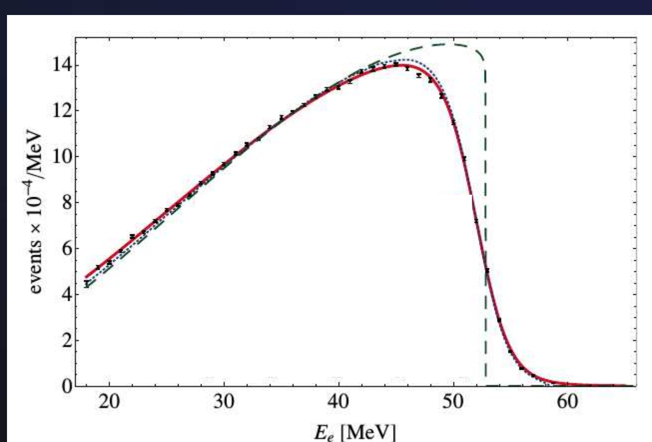
See talk by Yang Ye on Thursday

Stopped Muon Processes

Bound Decay

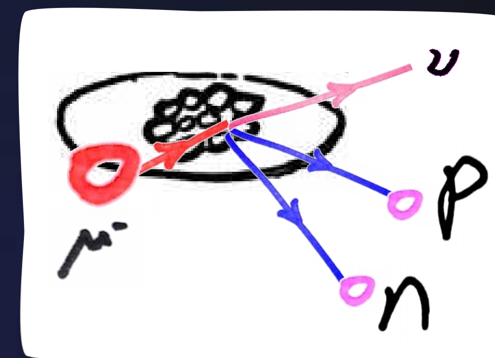


- B.R. = 45% (on Aluminium)
- Free Michel decay spectrum modified by presence of nucleus
- Background: Electrons close to signal window



Czarnecki 1406.3575

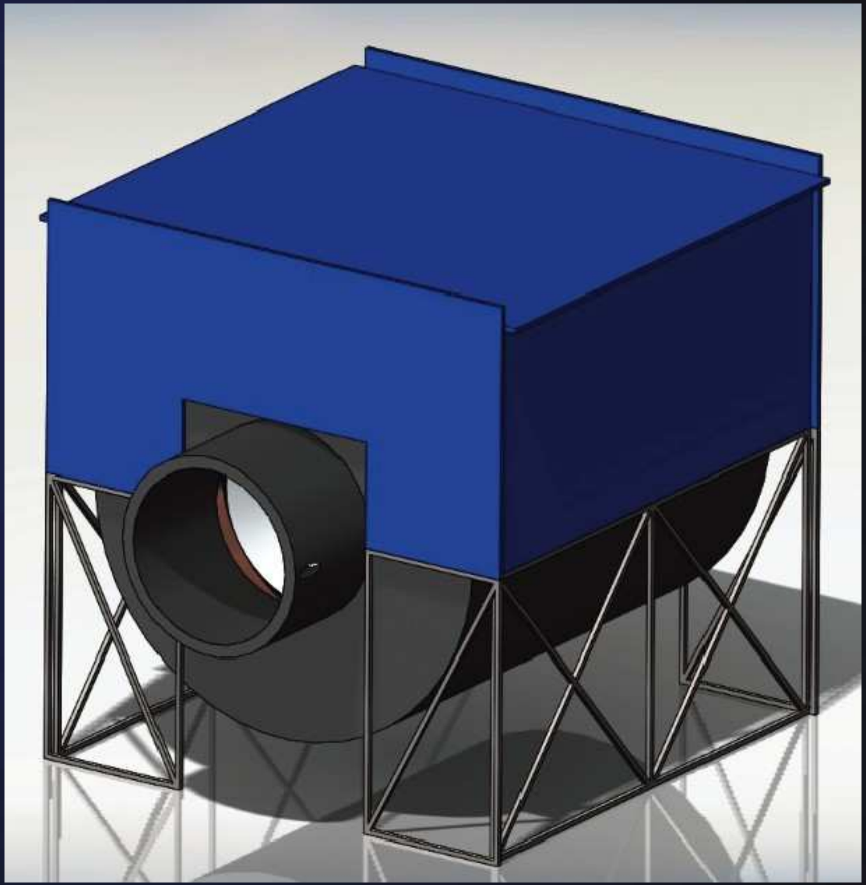
Nuclear Capture



- B.R. = 55% (on Aluminium)
- Often followed by charged or neutral particle emission
- Background: Asymmetric pair-production of emigtted gamma rays
- Detector complications
- See Alcap talk on Wednesday

Cosmic Ray Veto

- Particle mis-identification
- Signal-like electrons:
  - Delta ray from detector material
  - Decaying muons



Ben Krikler: bek07@imperial.ac.uk

J-PARC

Read-out, DAQ and Triggers

- DAQ and read-out:
  - Full waveform digitisation
  - Straw Tubes, ECAL and Cherenkov Triggering
    Hodoscopes read-out with ROESTI developed at KEK
  - CDC will use RECBE board from Belle-II
  - MIDAS DAQ system
- Trigger
  - Separate trigger primitives produced at each sub-detector
  - FC7 board developed for CMS used to make global trigger decision
  - Hardware and software R&D for CDC Track-trigger

Proton extinction methods

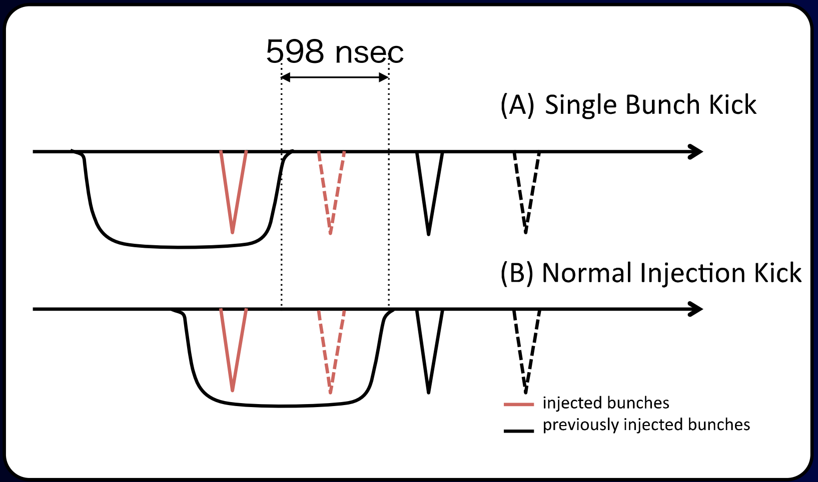
Yoshitaka Kuno

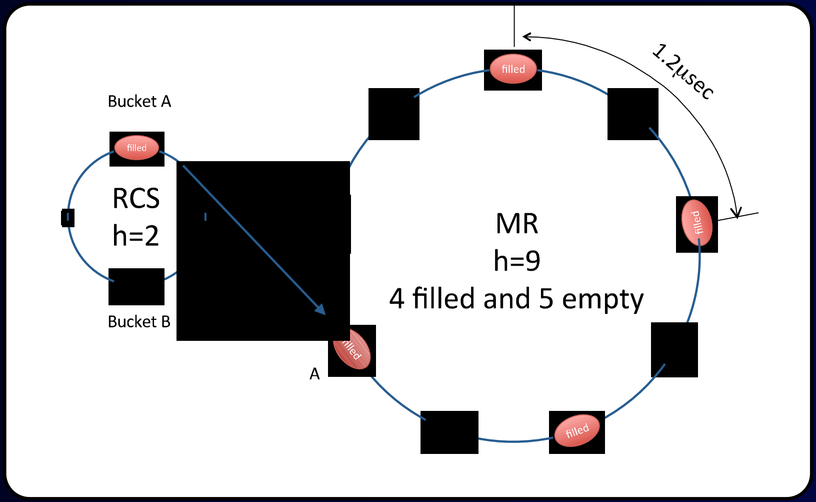
Proton Extinction Factor

single bunch kicking

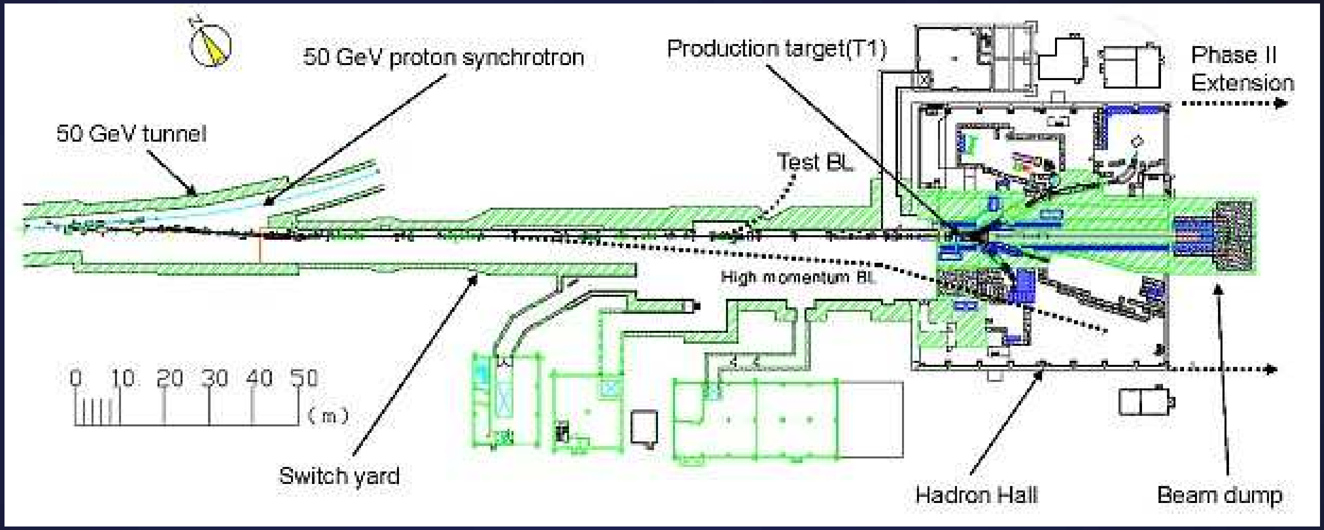
- Protons remaining in empty buckets cause deterioration of the extinction factor
- confirmed in previous studies with FX and SX (30GeV), $R_{ext} = O(10^{-7})$
- Double injection kicking

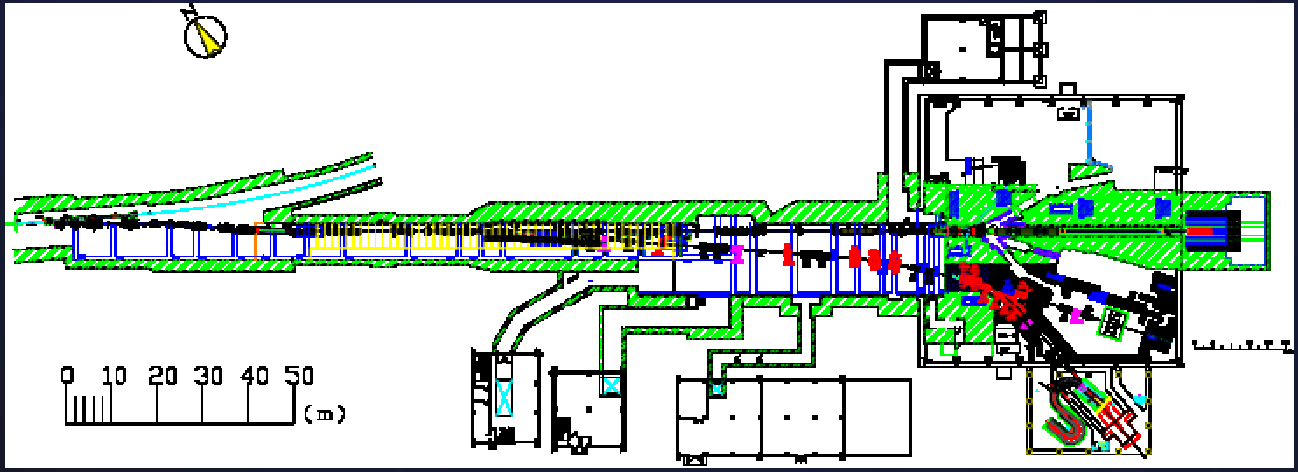
- **Single Bunch Kicking**
- Delay the injection kicker excitation timing by 598 nsec
- Measure the beam directly at the MR abort line (FX)
- extensive study with 10^{11} protons in a bunch cf. 10^{7} p's in the previous study at FX





Proton Beamline





- Hadron Experimental Facility (HD) is currently under modification to have more beam lines; High-p beam line & the COMET beam line.!
- Realized by putting a Lambertson magnet and extending the experimental hall.

CDC Beam Tests

- Proto-type detector using same wire configuration as final CDC
- Beam test this spring
  - Analysis on-going
- Cosmic tests with 1 T magnetic field later this year