Imperial College
London

The COMET Experiment:

Searching for Muon-to-Electron Conversion

Ben Krikler
9th March 2016
Presented at University of Birmingham

Overview

Charged Lepton Flavour Violation

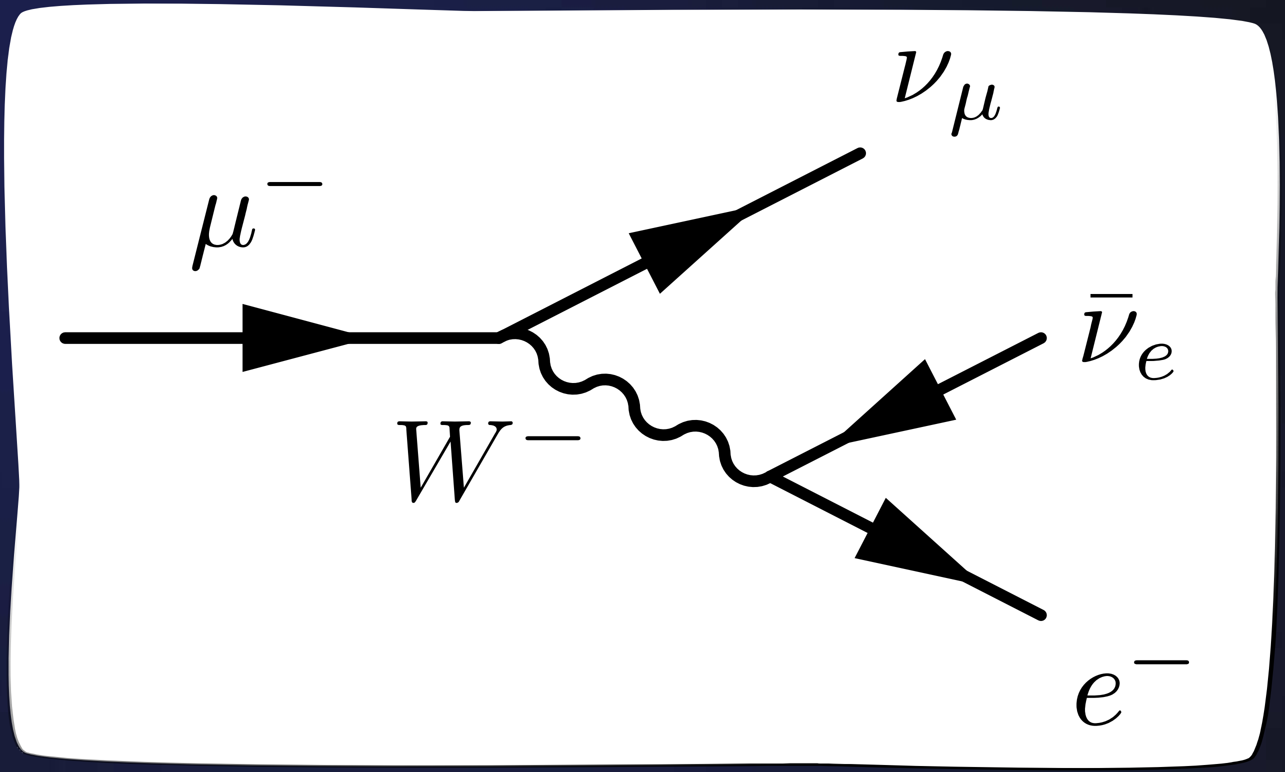
Bound muons and the μ–e conversion process

How to build a sensitive μ–e conversion experiment (COMET)

COMET Status and R&D

Charged Lepton Flavour Violation

Muon Decay

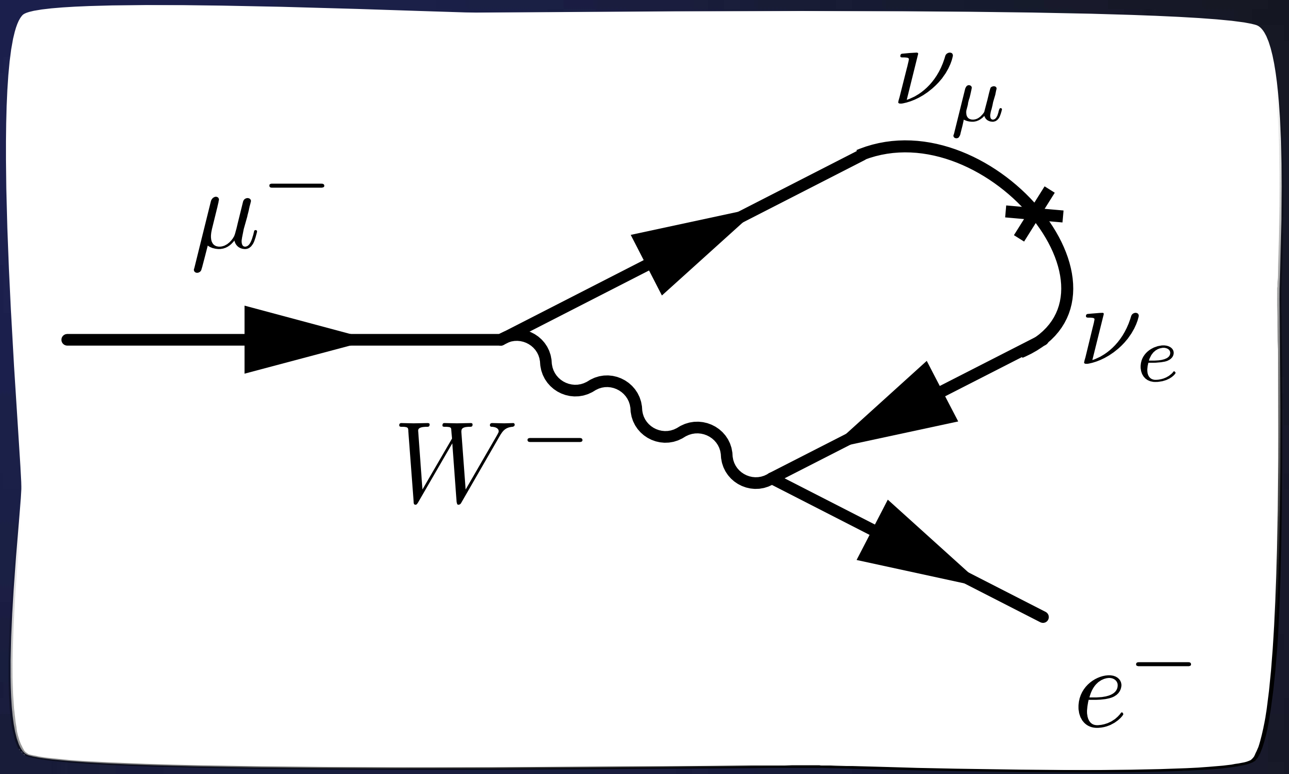


Conservation of Lepton Flavour:

1 muon → 1 muon-neutrino

0 electrons → 1 electron + 1 anti electron-neutrino

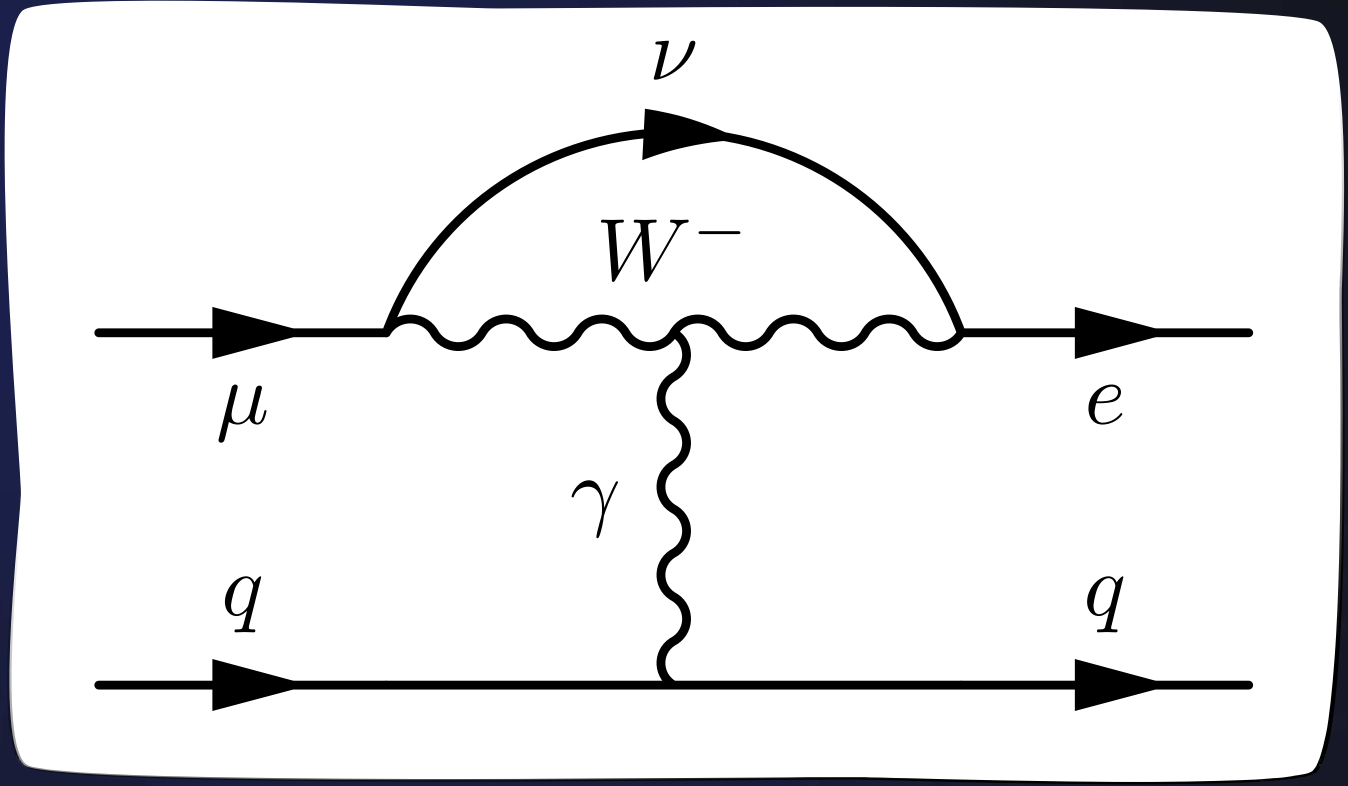
Muon Decay + Neutrino Oscillations



- 1 muon → 1 electron
- No outgoing neutrinos
- BUT: would not conserve energy and momentum

Muon to Electron Conversion

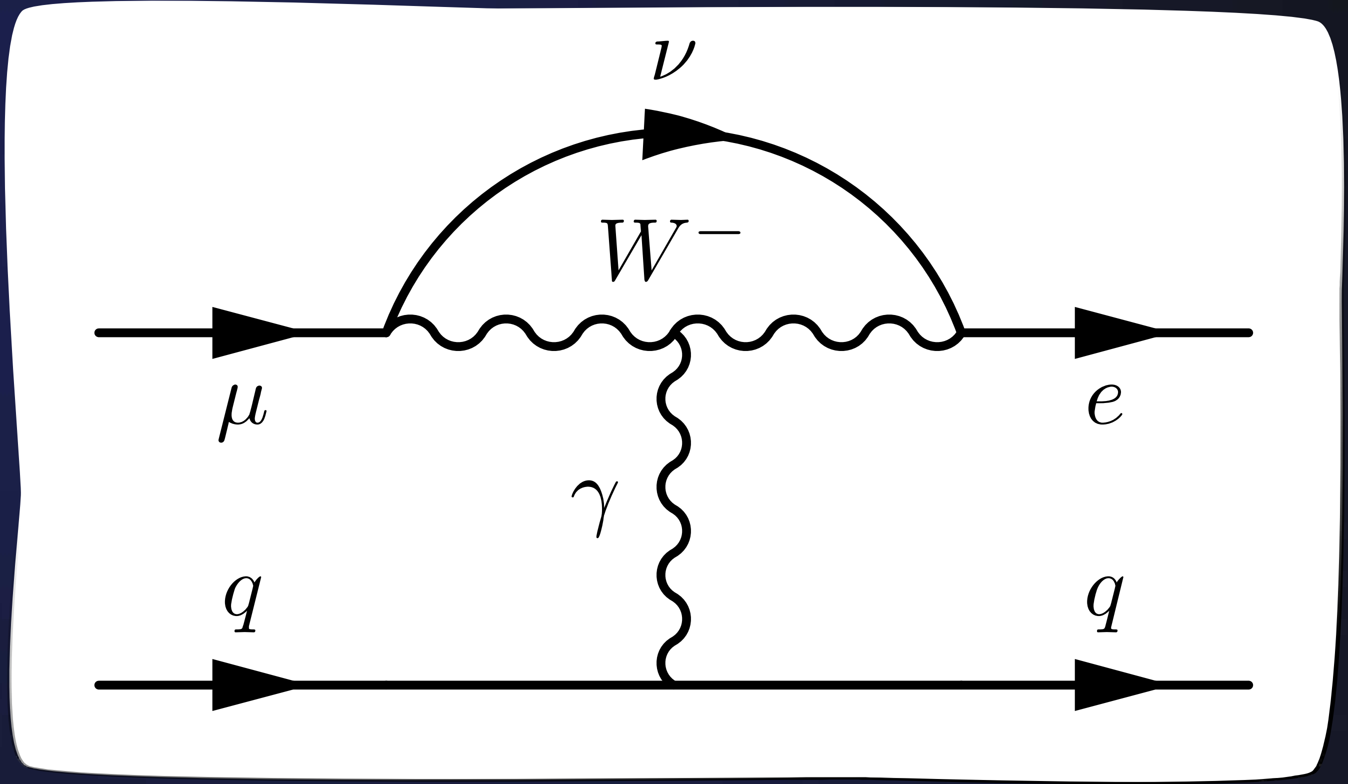
via Neutrino Oscillation



- $\mu^- + N(A,Z) \rightarrow e^- + N(A,Z)$
- No outgoing neutrinos
- Atomic nucleus: conserve energy and momentum
- Violates conservation of Charged Lepton Flavour

Muon to Electron Conversion

via Neutrino Oscillation



Conversion Rate:

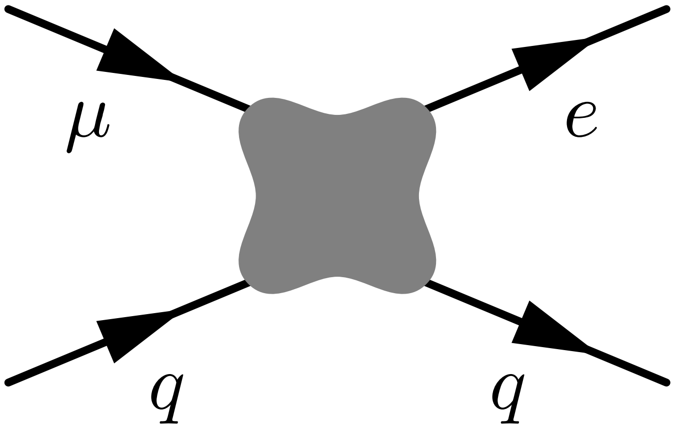
GIM Supressed

$$\mathcal{R} = \mathcal{O}\left(\frac{(\Delta \mathrm{M}_\nu^2)^2}{(\mathrm{M}_\mathrm{W}^2)^2}\right) \sim 10^{-54}$$

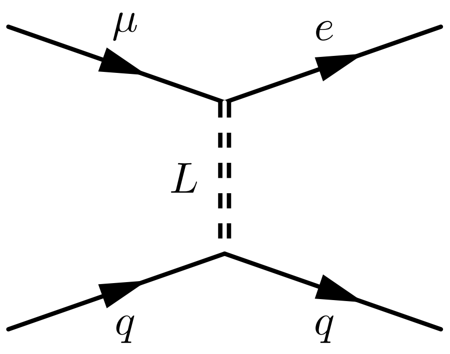
Muon to Electron Conversion

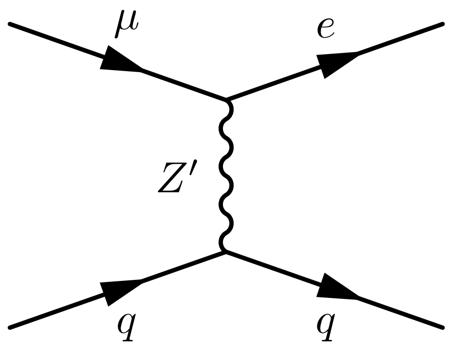
Beyond the Standard Model

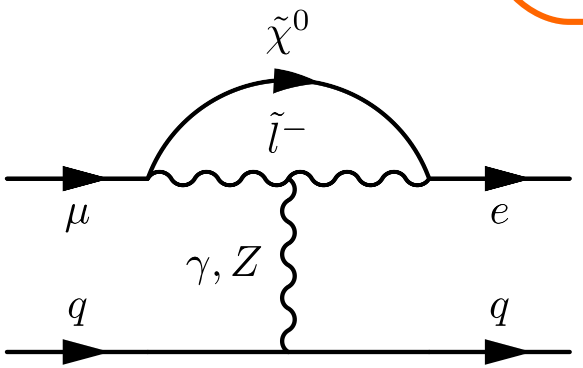
- Predicted in many Beyond the Standard Model theories
- Rate is model dependent

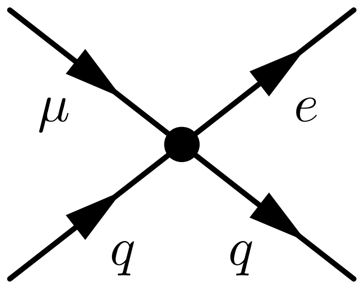


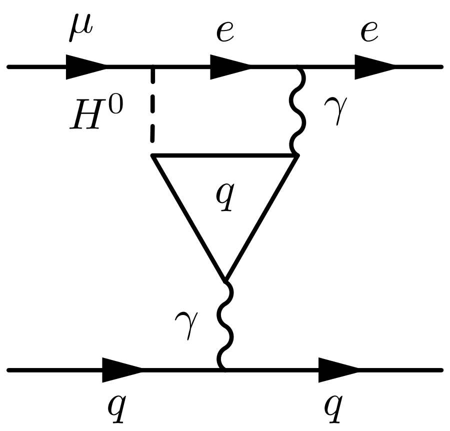
$$\mathcal{R} < \mathcal{O}(10^{-15})$$

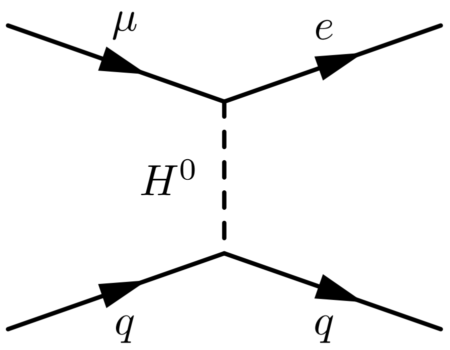


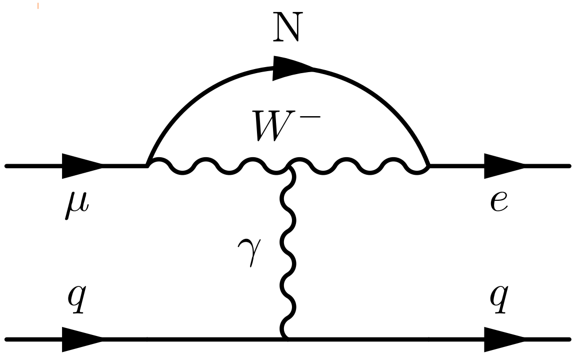




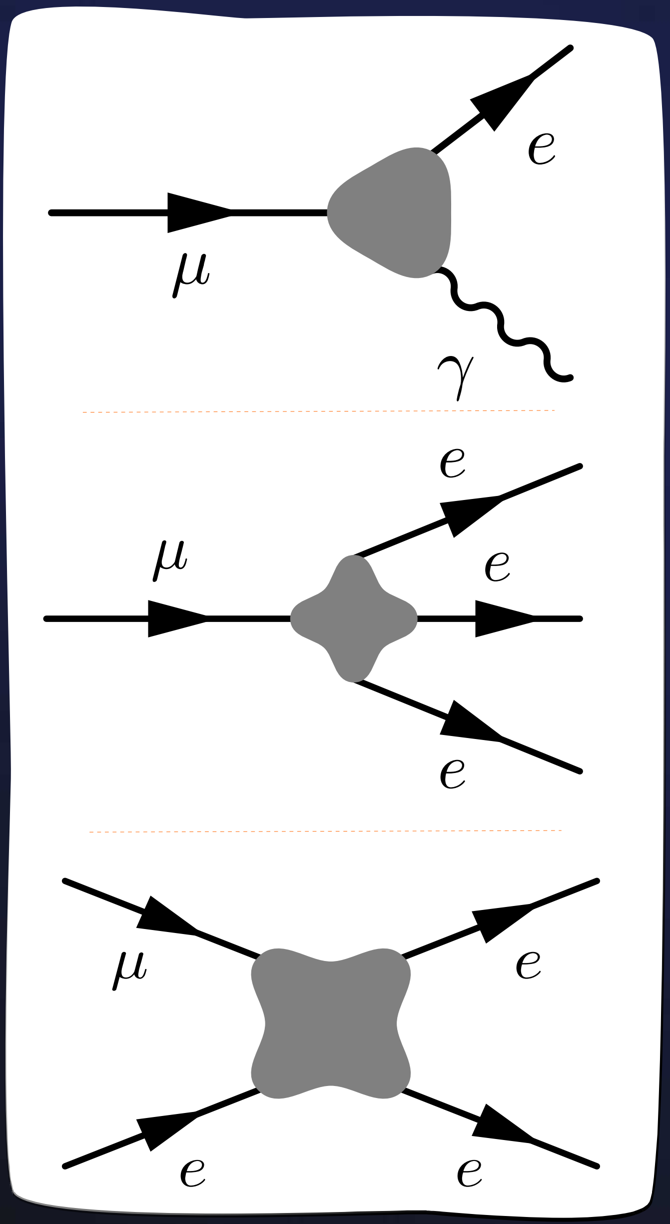








Complementarity with Other Muon LFV Channels



Muon to electron + gamma

- Emission of a photon
- MEG experiment at PSI
- Last published 2013
- Upgrade to begin running shortly

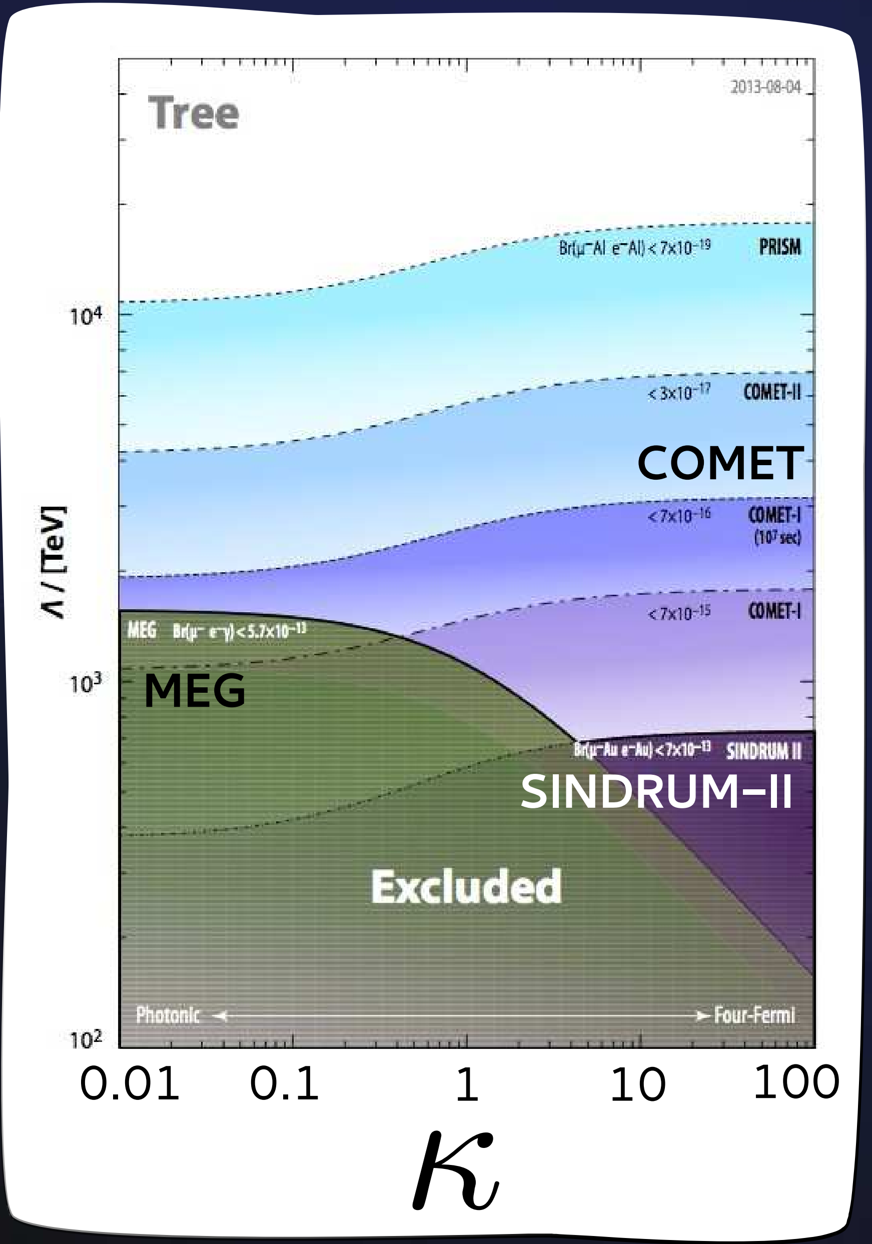
Muon to three electrons

- Mu3e experiment at PSI

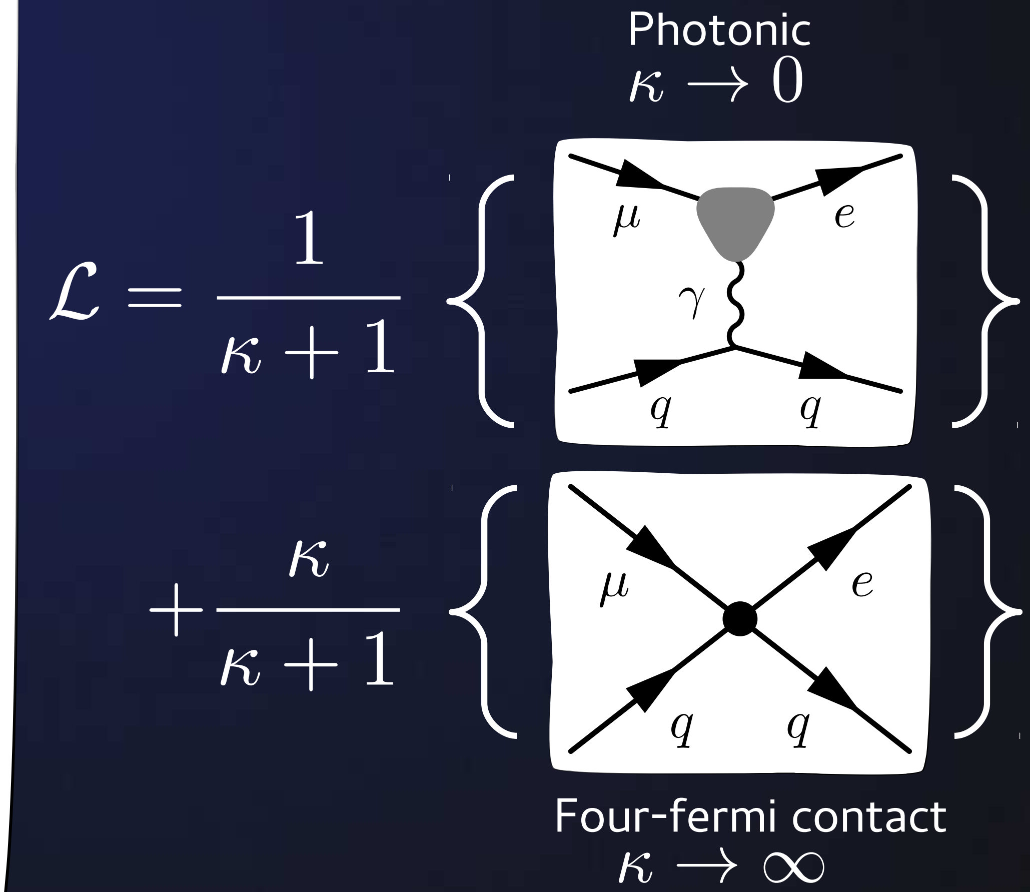
μ-e conversion against atomic electrons

- Replace quark in nucleus with atomic electron (at COMET ?)

μ→e gamma vs μ–e conversion

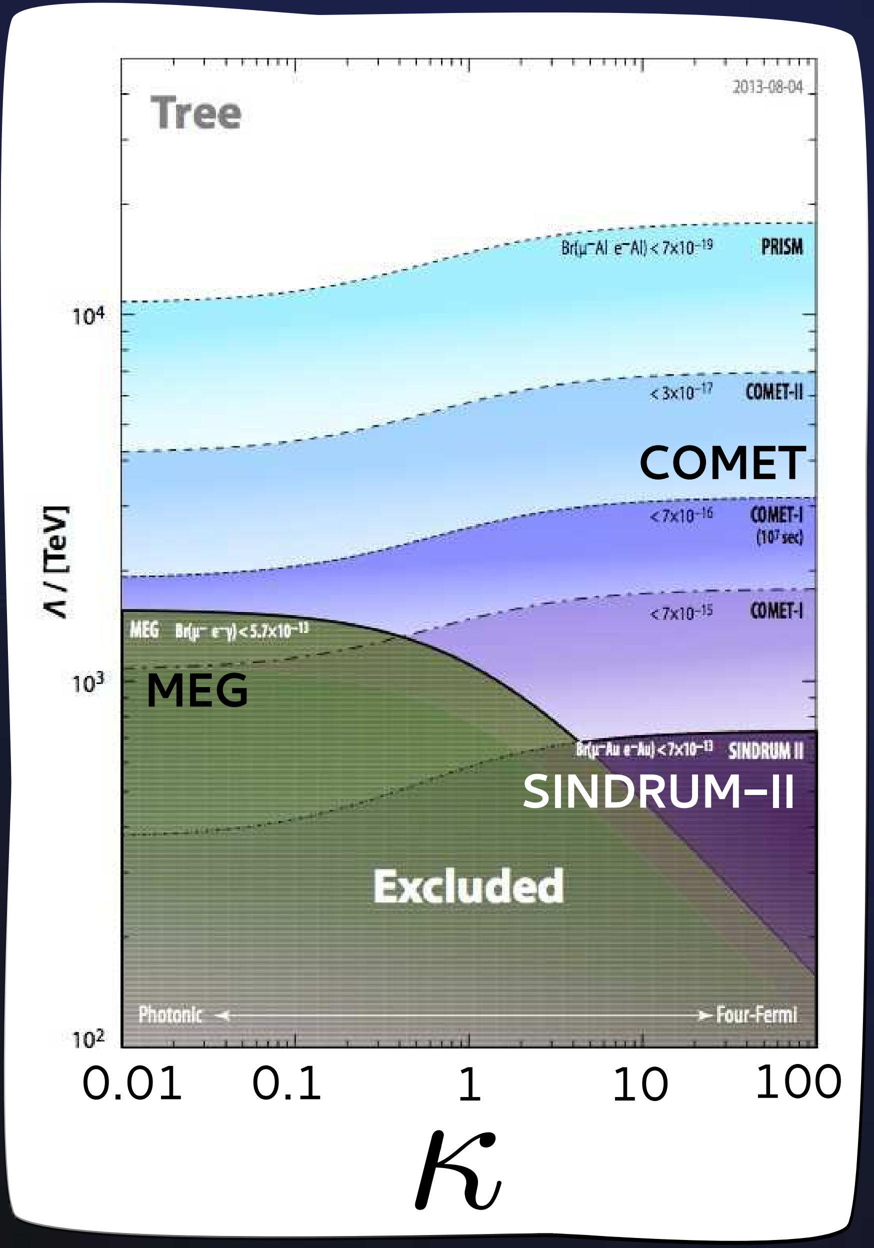


- Relative sensitivity in μ-e conversion and μ-e gamma is model dependent
- Highly complementary searches



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

μ→e gamma vs μ–e conversion



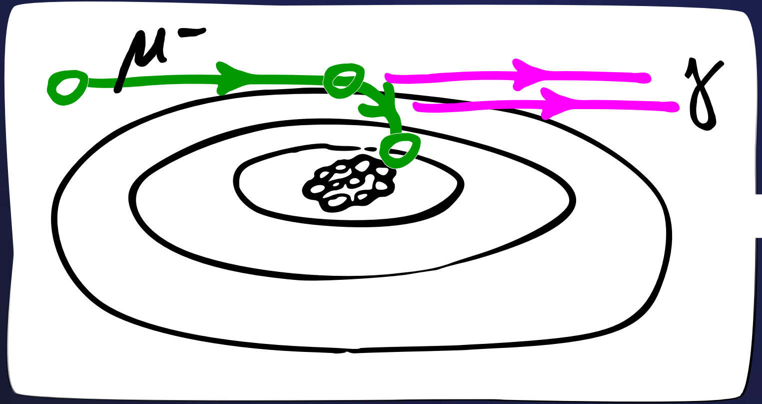
- Relative sensitivity in μ-e conversion and μ-e gamma is model dependent
- Highly complementary searches

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

Bound Muon Physics and the μ-e Conversion Process

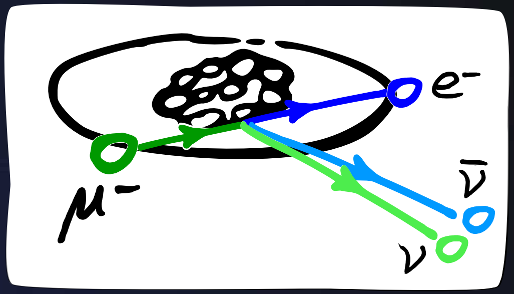
Bound Muons

- Everything starts by stopping muons around a nucleus

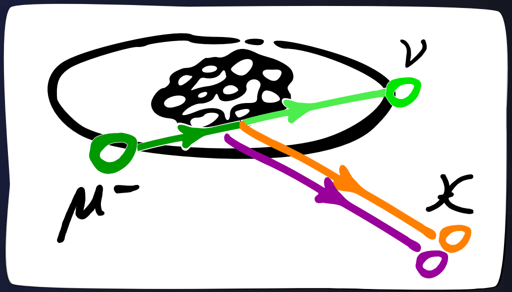


Electromagnetic cascade to the ground state orbital

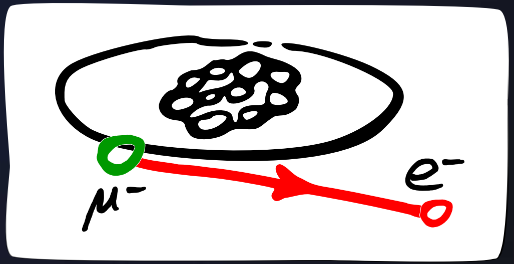
Bound Muon Decay



Muon Nuclear Capture

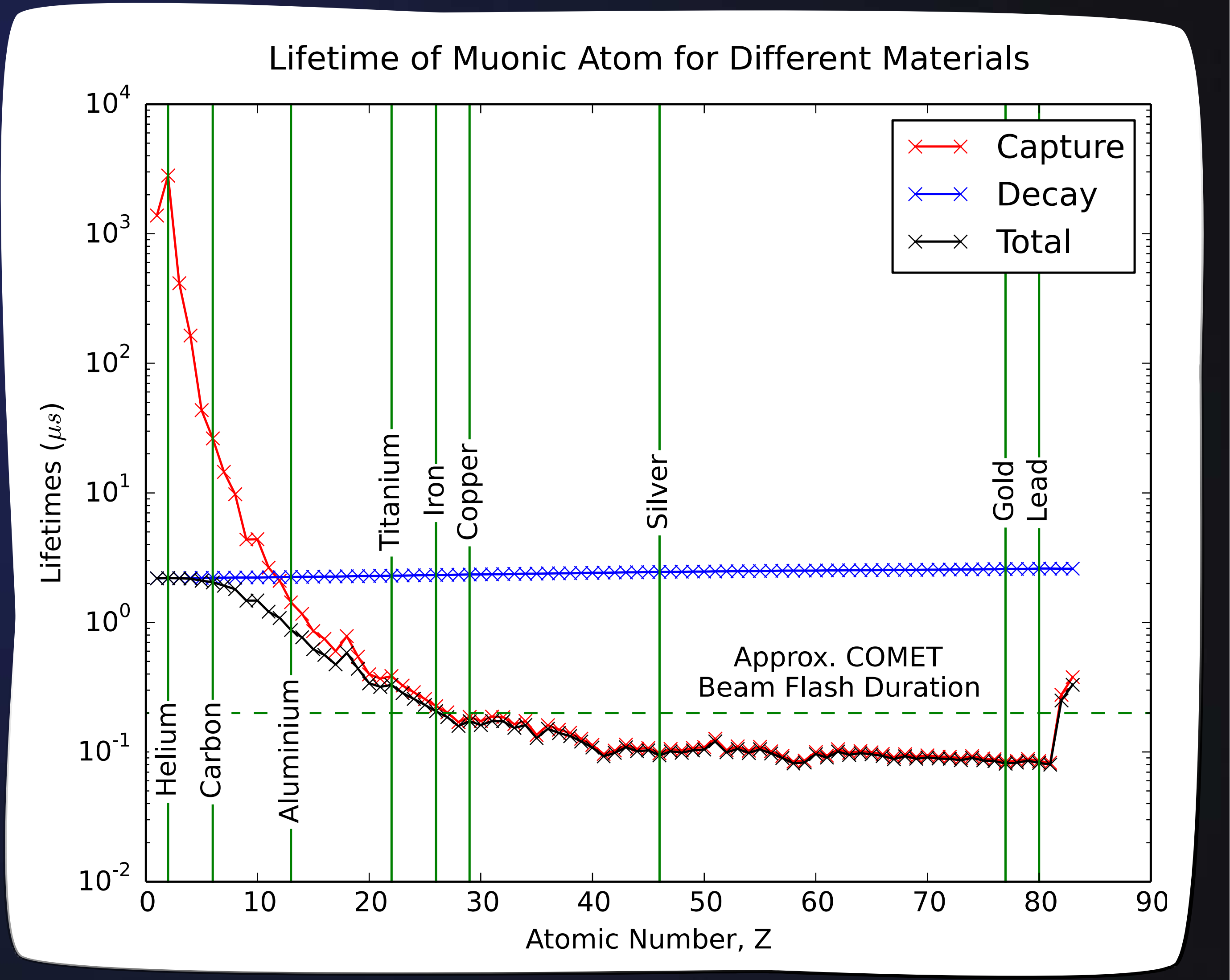


Muon to Electron Conversion

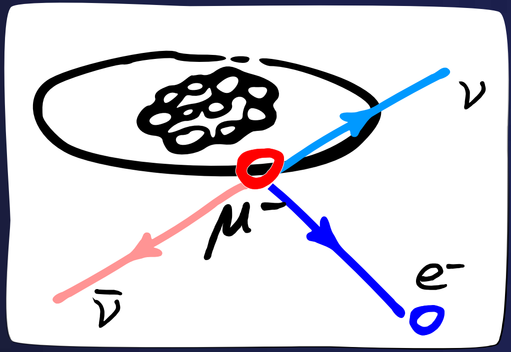


Muon Lifetime

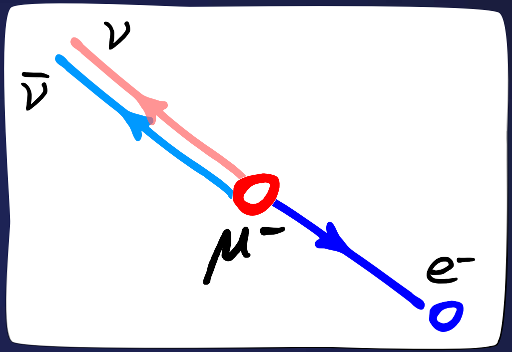
- Decay partial lifetime
  - Increases with Z
  - Bound muon momentum increases ⇒ Time dilation
- Capture partial lifetime
  - Incoherent ⇒ Grows linearly with Z
  - Eventually muon completely contained in nucleus ⇒ levels out



Bound Muon Decay

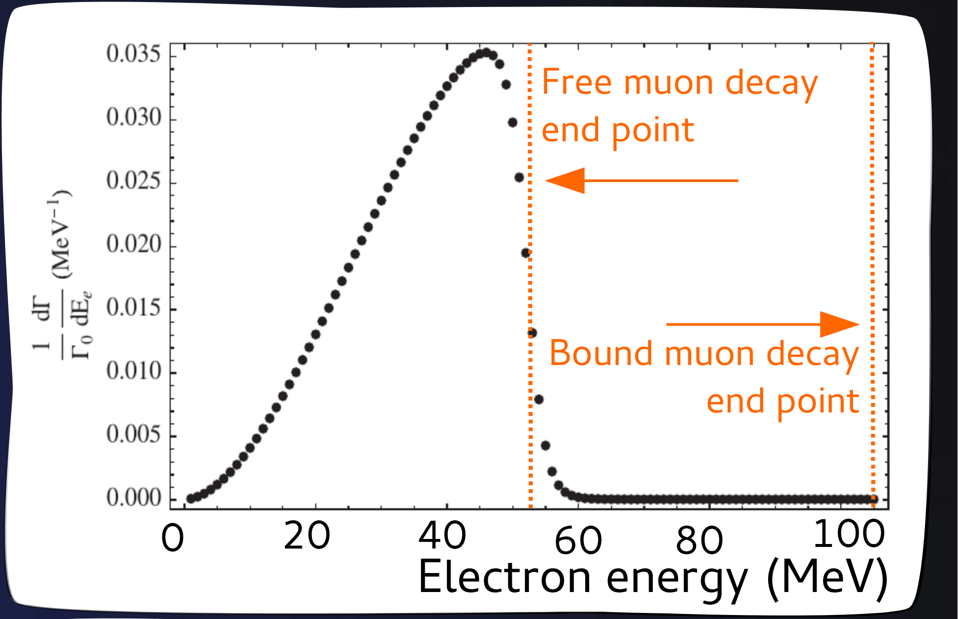


Bound muon decay



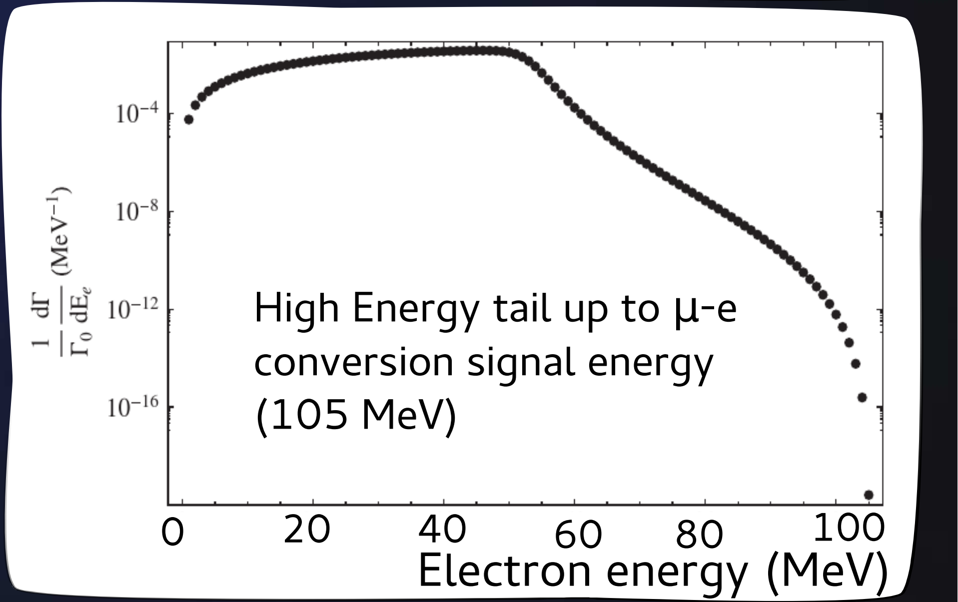
Free muon decay

- Maximum energy for electrons from free muon decay = Half of muon mass
- Bound decay around nucleus
  - End-point close to muon mass
  - Very steeply falling spectrum above 60 MeV
- Theoretical uncertainty on spectrum from initial muon wavefunction
- No accurate measurement at the end point



Free muon decay end point

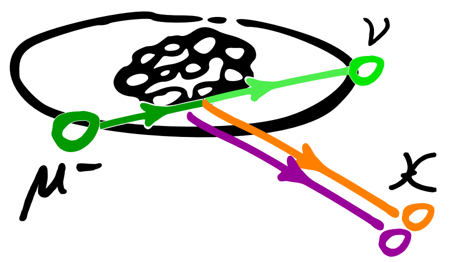
Bound muon decay end point



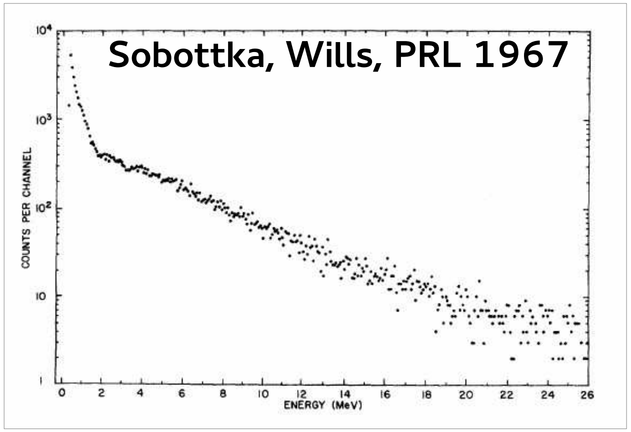
High Energy tail up to μ-e conversion signal energy (105 MeV)

Czarnecki et al. 2011 DOI: 10.1103/PhysRevD.84.013006

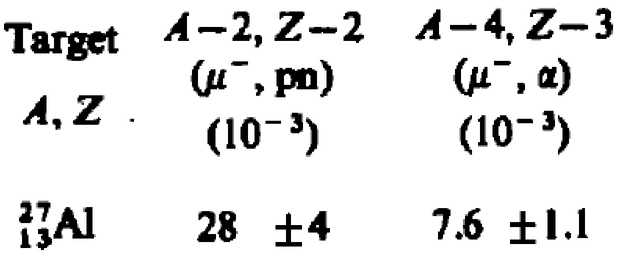
Muon Nuclear Capture



- Nuclear capture dumps about 50 MeV into nucleus
- Often followed by particle emission:
  - Photons, neutrons
  - Protons, deuterons, alphas
- Products of muon capture on Aluminium are not well known
- Had to measure this (AlCap experiment)



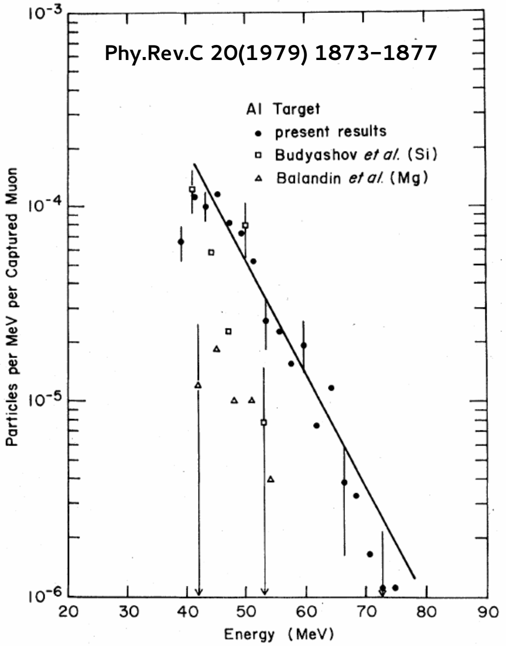
Inclusive Emission of charged particles from capture on silicon



Target A, Z	$A-2, Z-2$ (μ^-, pn) (10^{-3})	$A-4, Z-3$ (μ^-, α) (10^{-3})
$^{27}_{13}$Al	28 ±4	7.6 ±1.1

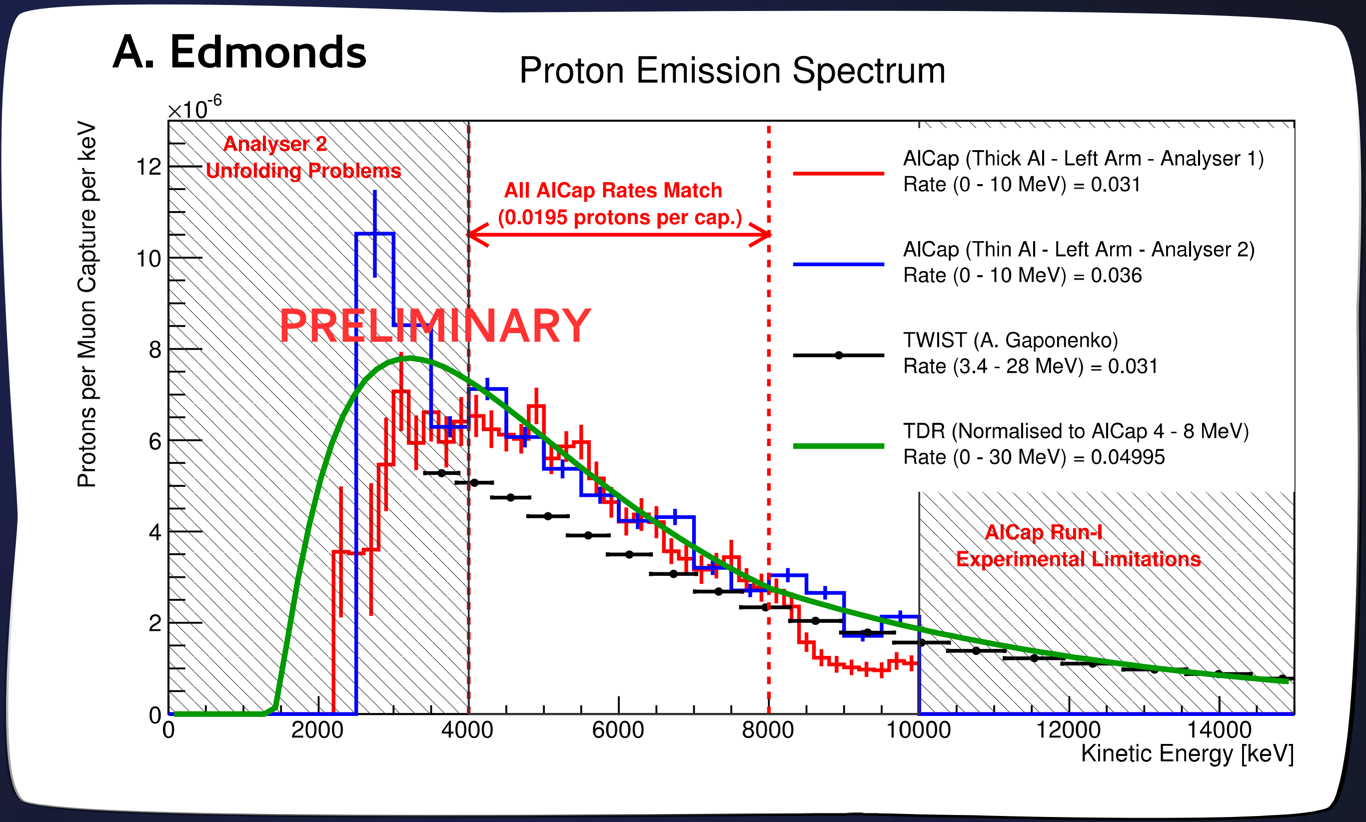
Proton and alpha emission per muon capture

Wyttenbach et al. Nuc. Phys. 1978



Proton emission spectrum above 40 MeV

AlCap: Aluminium Capture of Muons


A. Edmonds

- Joint effort between Mu2e and COMET
- 3 runs at Paul Scherrer Institute from 2013 to 2015
- Studying charged and neutral particles emitted following muon capture on aluminium

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:

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

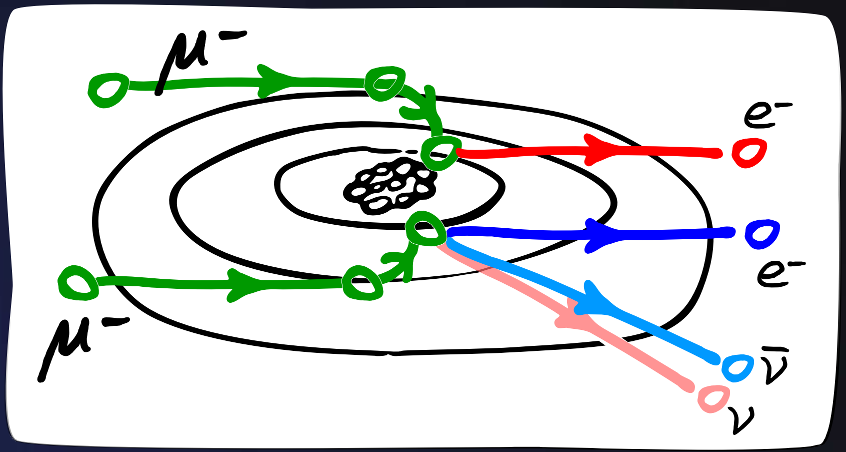
On Aluminium, used by COMET:

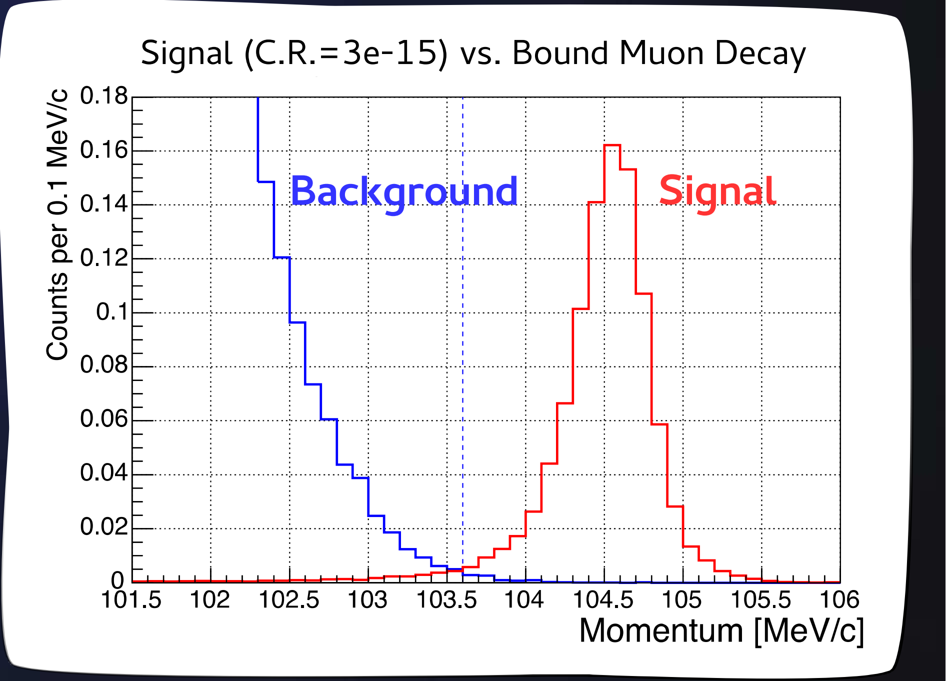
$$E_e = 104.9\ \text{MeV}$$

Typically define the conversion rate as:

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

Current limit from SINDRUM-II (90% C.L) on Gold: $\mathcal{R} < 7 \times 10^{-13}$

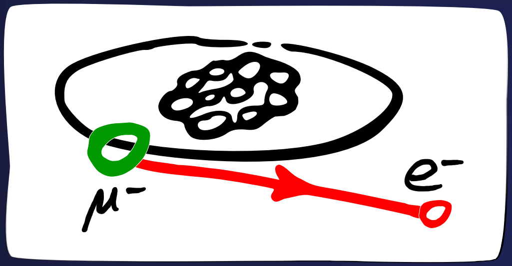




Designing the COMET Experiment

COMET:

COherent Muon to Electron Transitions



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

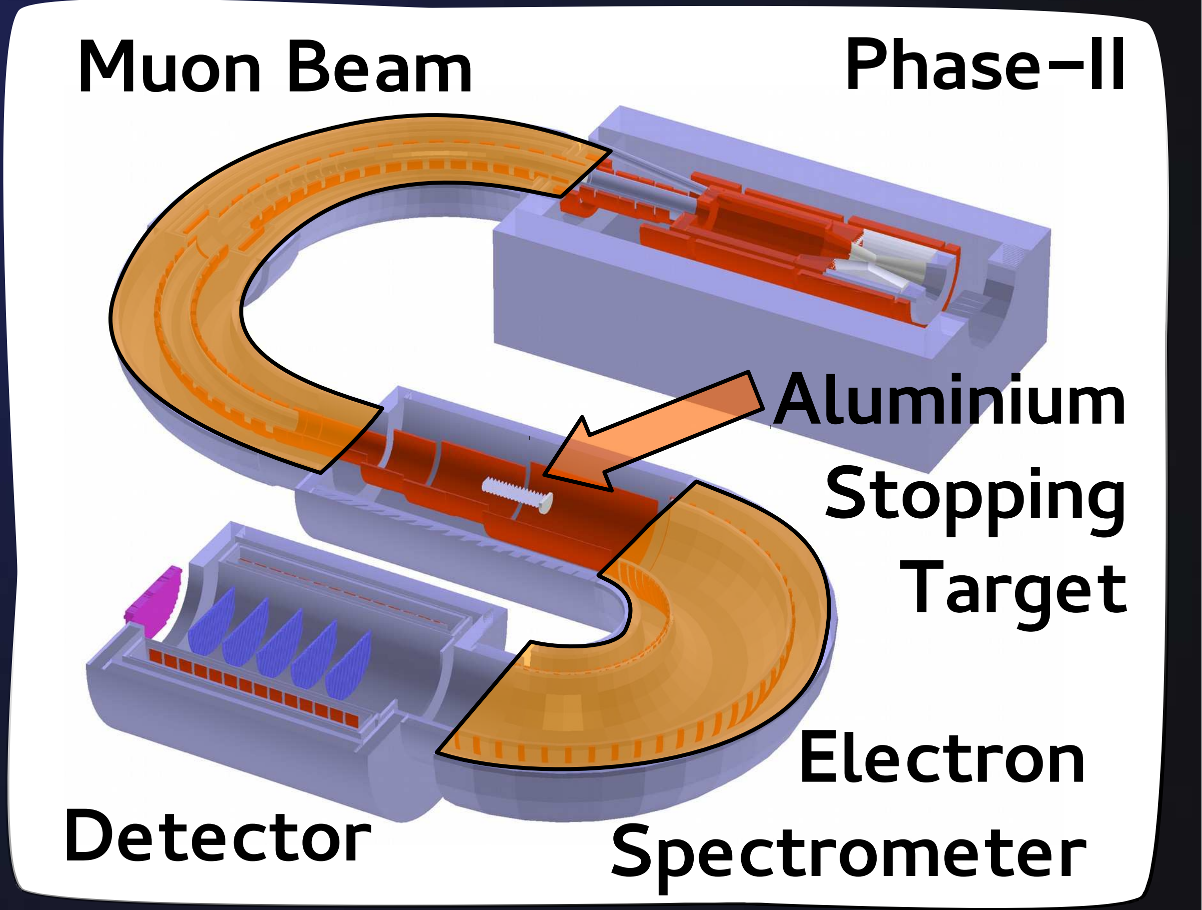
Present limits by SINDRUM-II (2006):

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

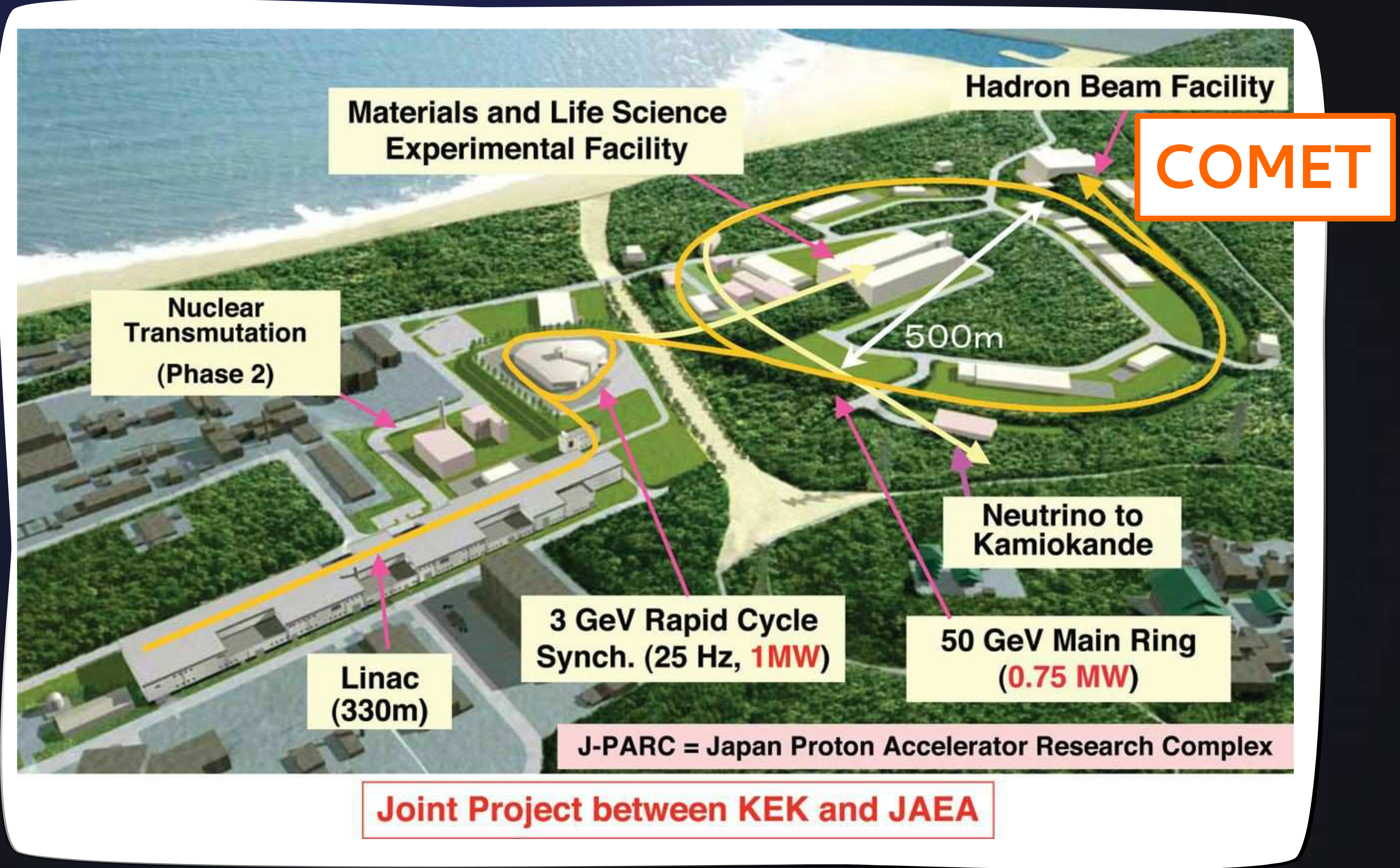
COMET Single-Event-Sensitivity:

Phase-I = 3×10^{-15}

Phase-II = 3×10^{-17}



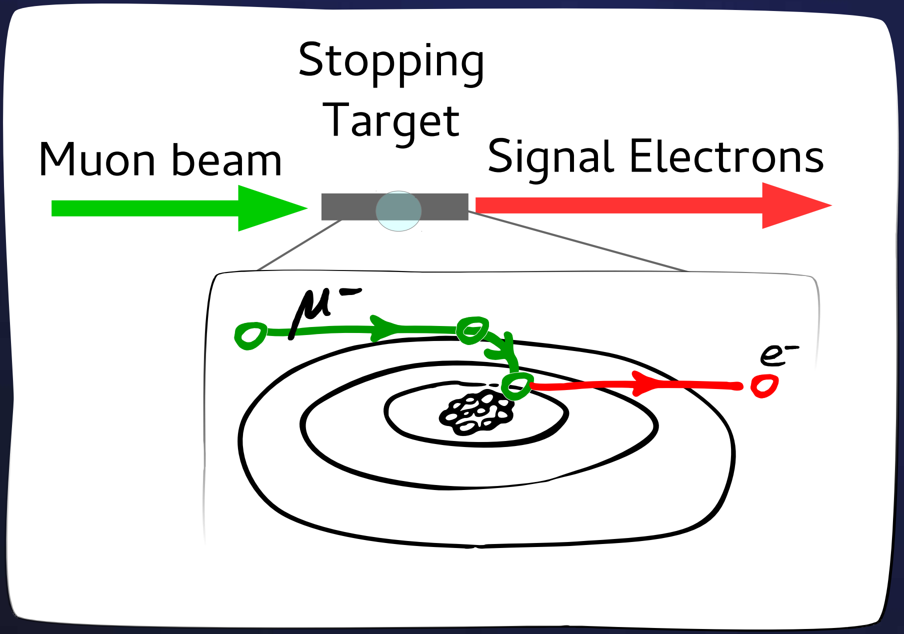
COMET at J-PARC

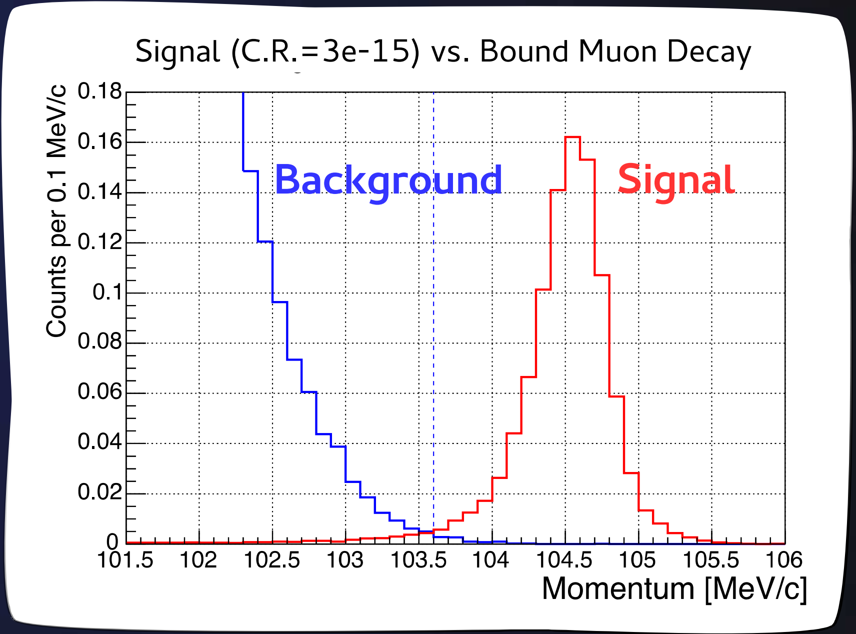


Achieving High Sensitivity

Overall Goals

- Many stopped muons
- High signal acceptance
- Fewer than 1 expected background events during the run

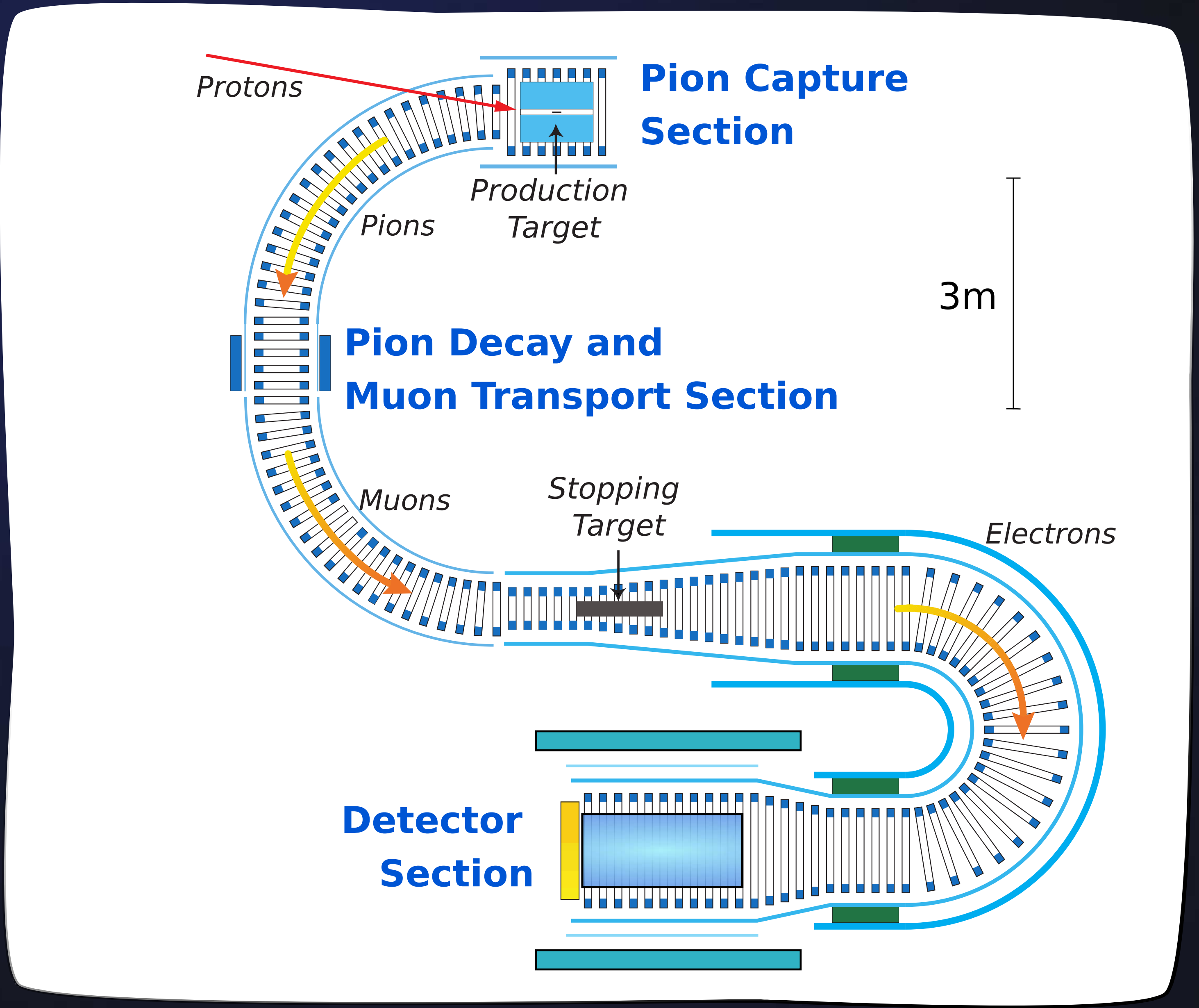




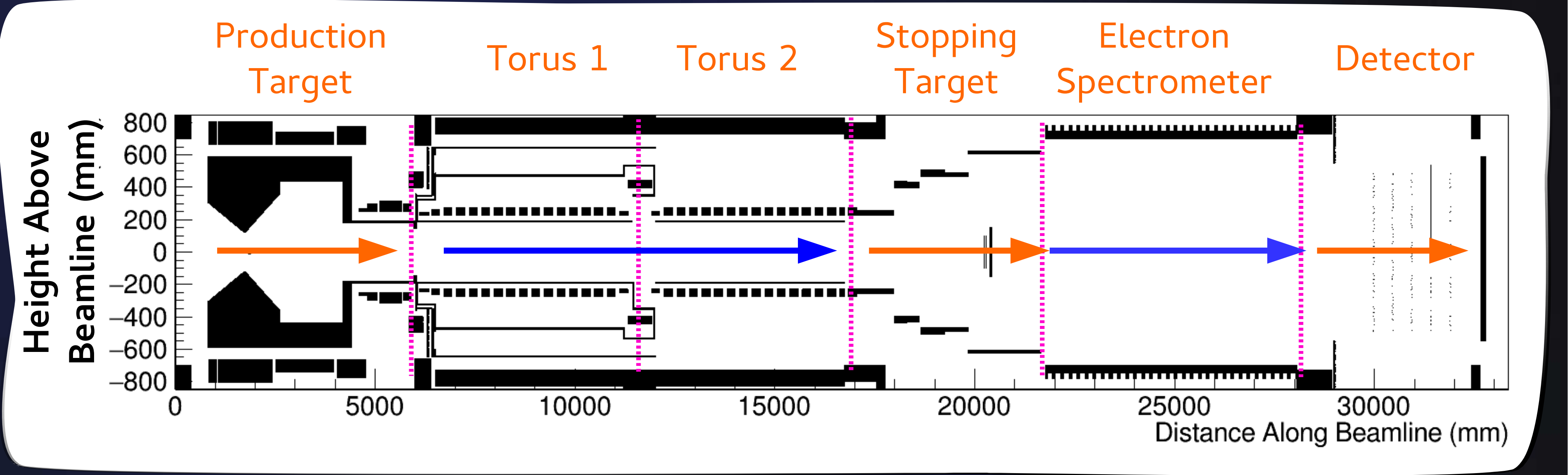
Design Considerations

- Intense, low-energy muon beam at the target
- Low detector occupancy
- Low material budget (Stopping Target and Detector)

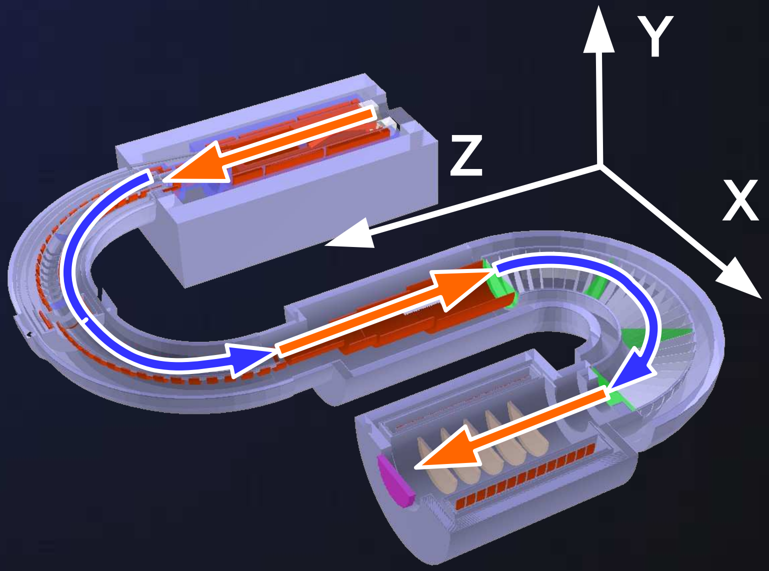
COMET: Phase–II



The COMET Beamline



- Beamline coordinate system
  - Distance along beamline
  - Curved sections appear straight



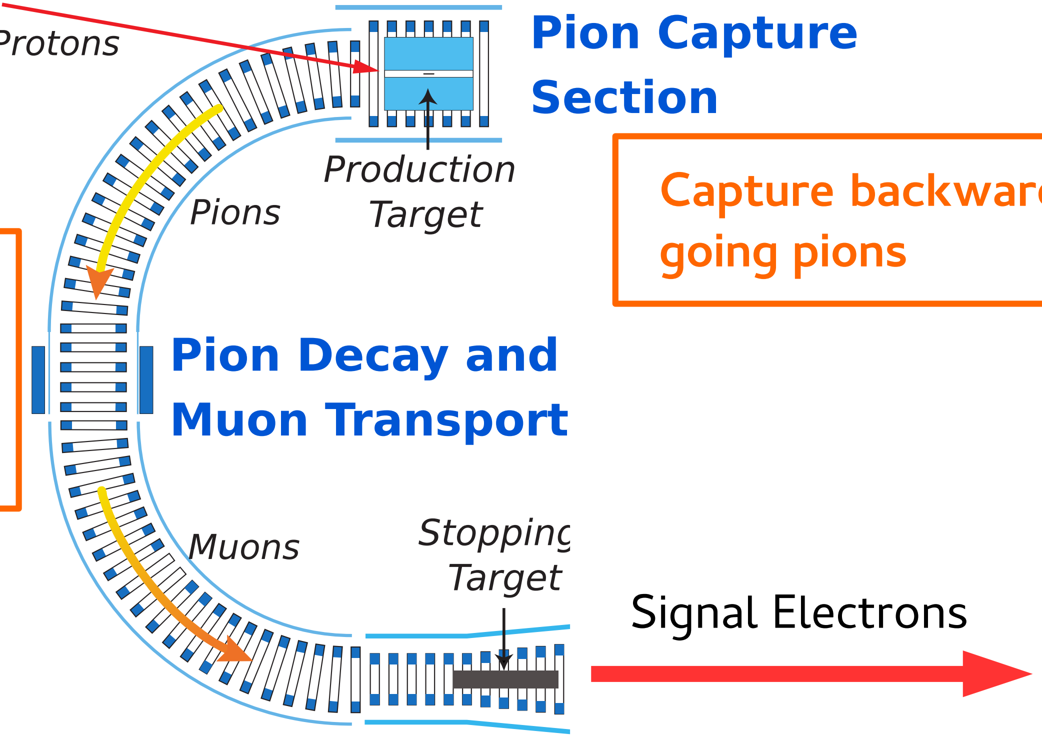
An Intense Muon Beam but Few Backgrounds

8 GeV proton beam at 56 kW

Actively Cooled Tungsten Target in 5 T Superconducting Solenoidal Field

Capture backwards going pions

Bent solenoid field + compensating dipole fields + collimators



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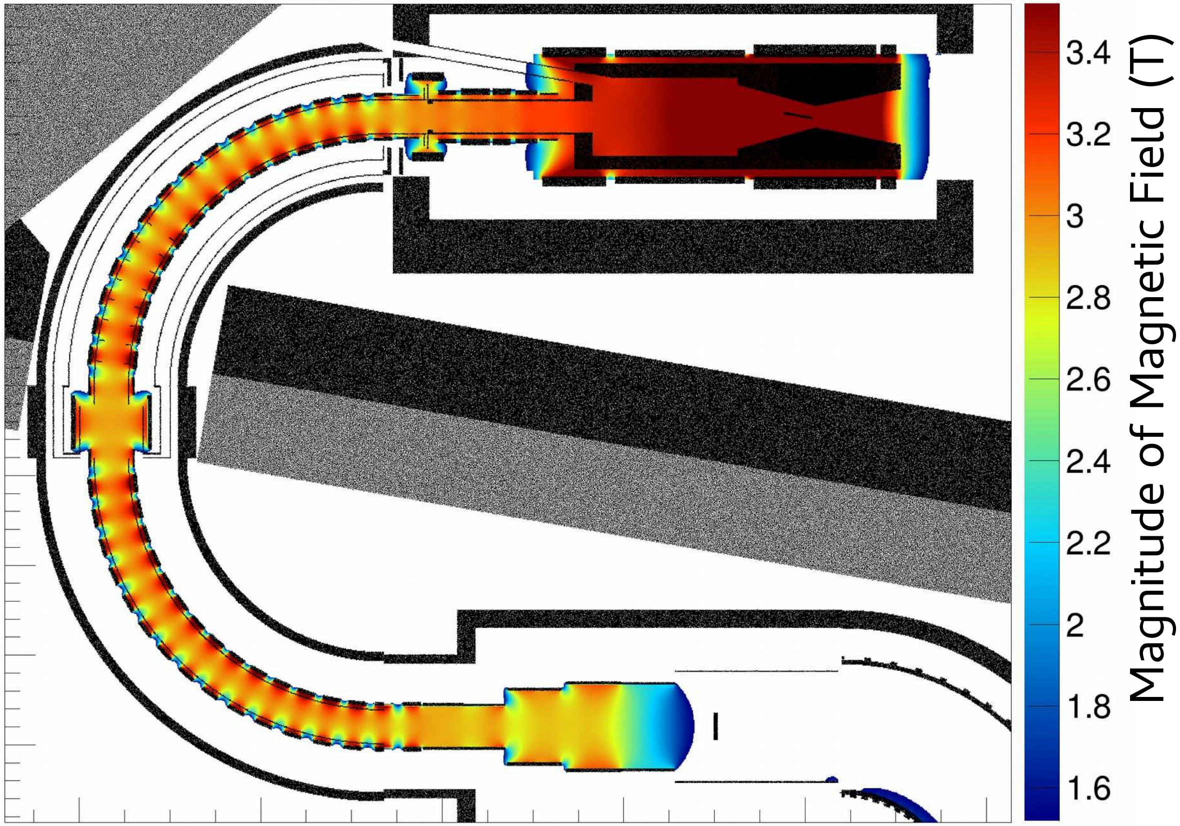
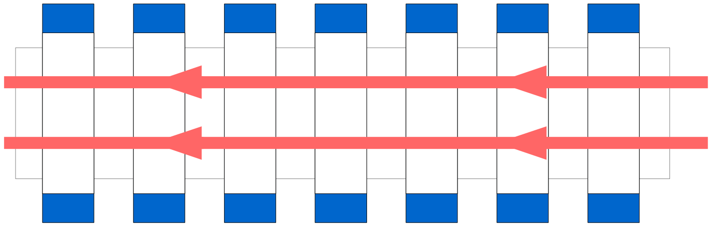


8 GeV proton beam at 56 kW

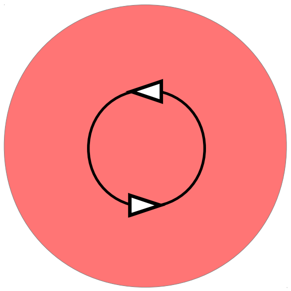
Actively Cooled Tungsten Target in 5 T Superconducting Solenoidal Field

Bent solenoid field + compensating dipole fields + collimators

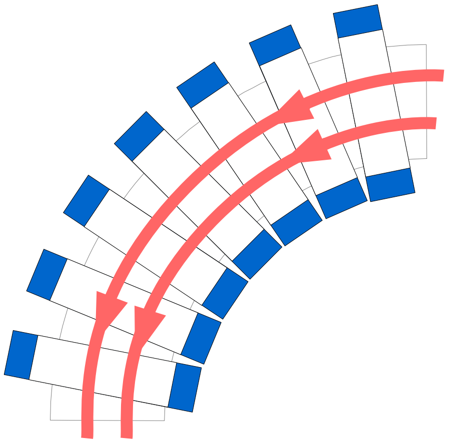
Bent Solenoid Drifts



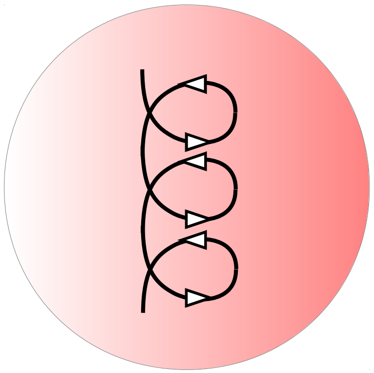
- Linear field lines
- Uniform B field



Circular motion about field lines



- Cylindrical field lines
- Radial gradient in magnetic field

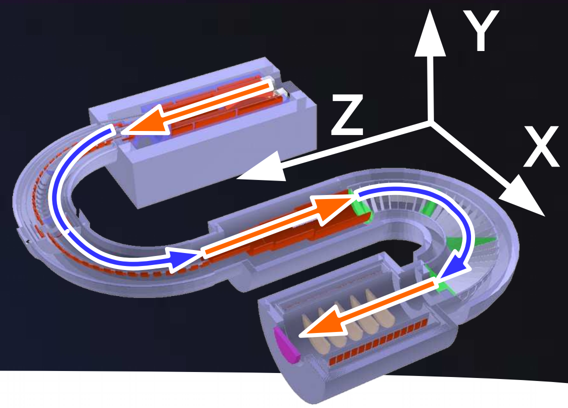


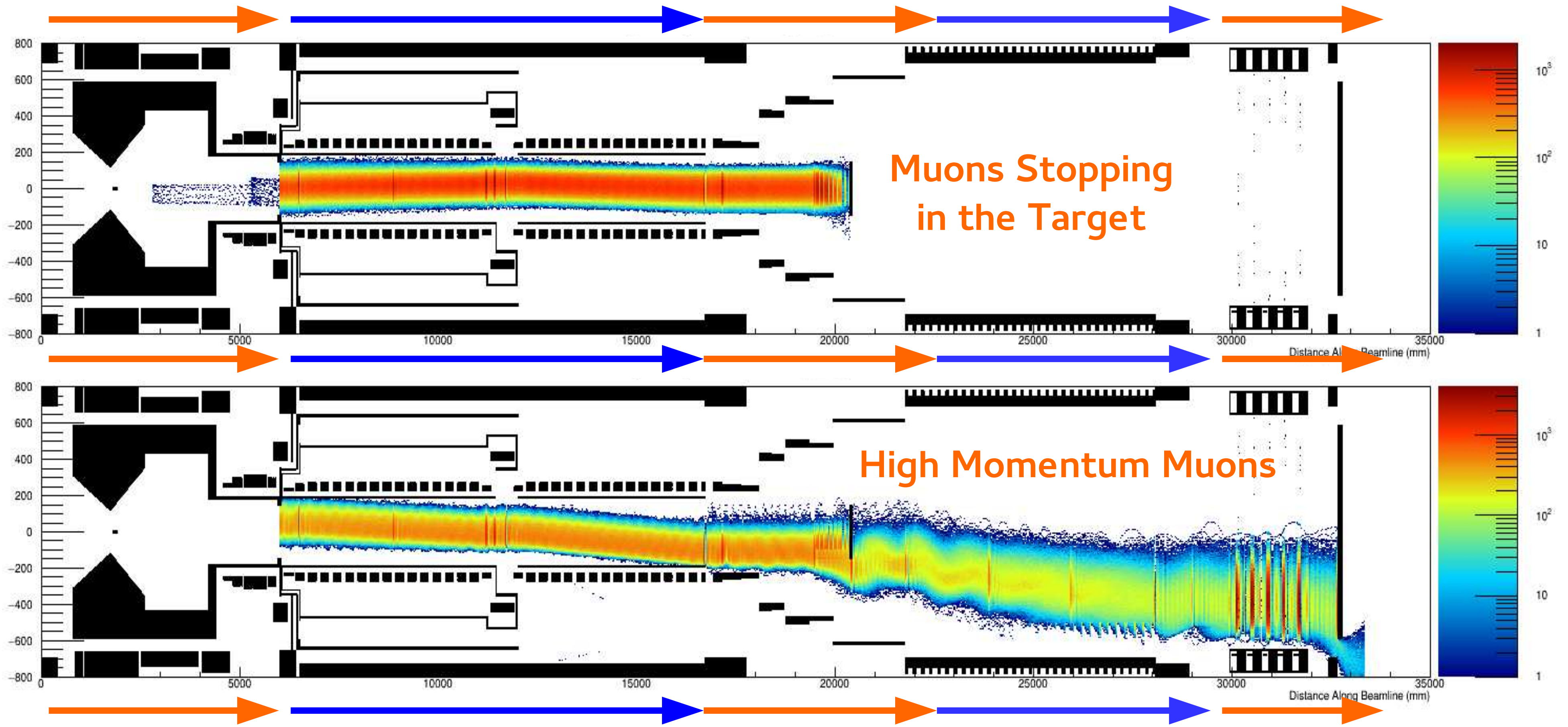
Circular motion about a drifting centre:

$$D \propto \frac{p}{qB} f(\theta)$$

Bent Solenoid Drifts

- Remove high momentum muons and pions
- Maintain low momentum muons



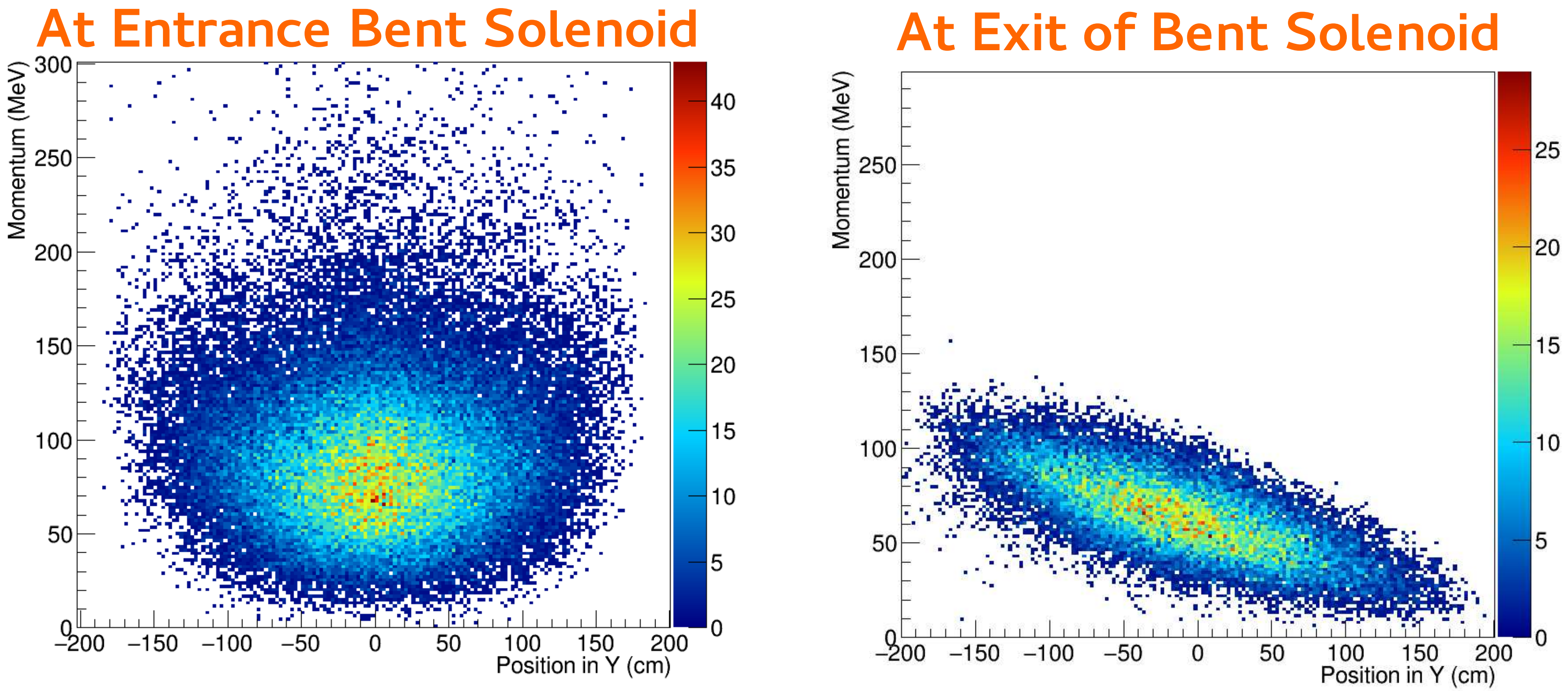

Collimators Not Included

Muons Stopping in the Target

High Momentum Muons

Bent Solenoid Drifts

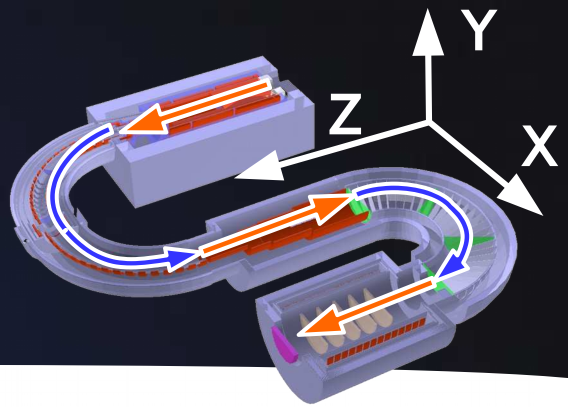
(Geant4 Simulation)



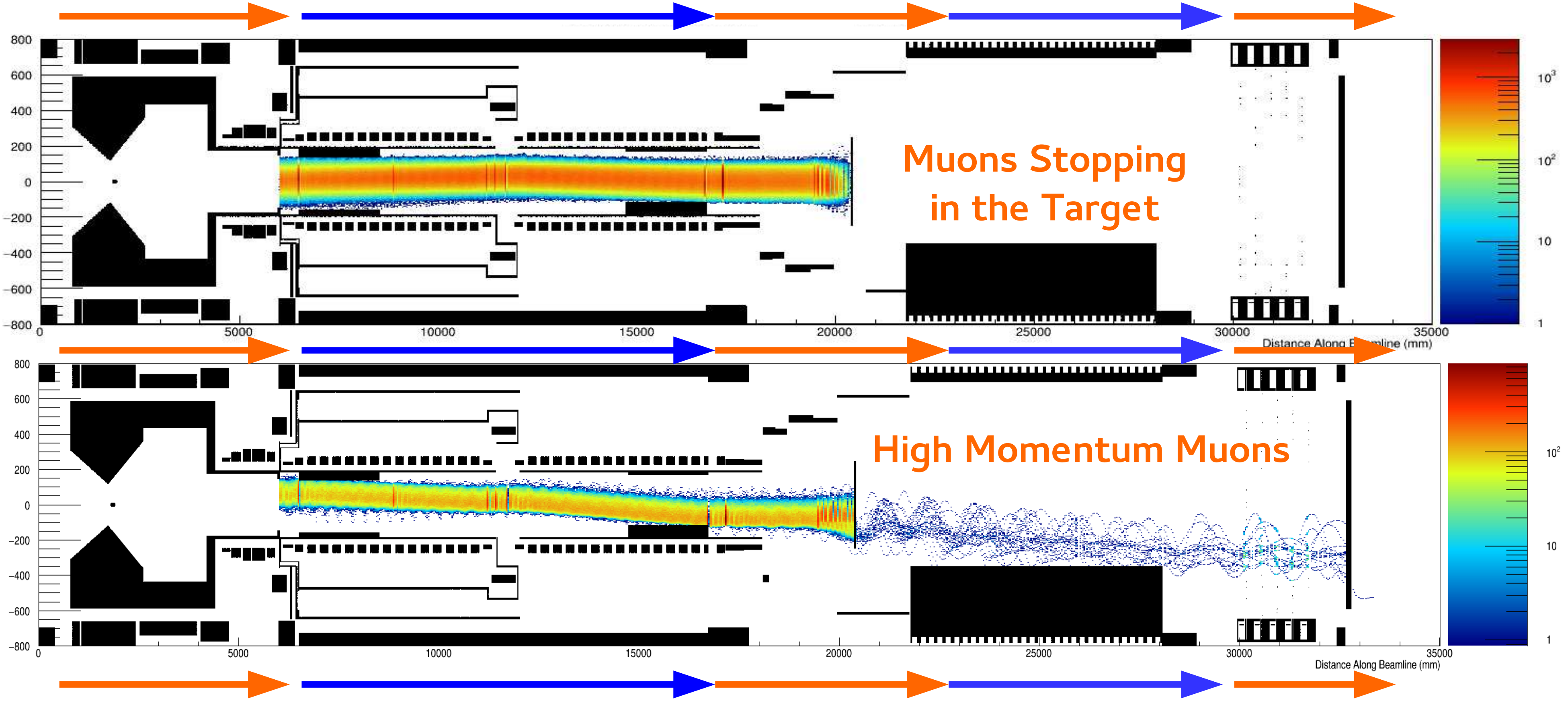
- High momentum particles drift down more than low momentum particles
- Additional tunable dipole field
  - Can select which momenta remain on-axis

Dipoles and Collimators

- Remove high momentum muons and pions
- Maintain low momentum muons



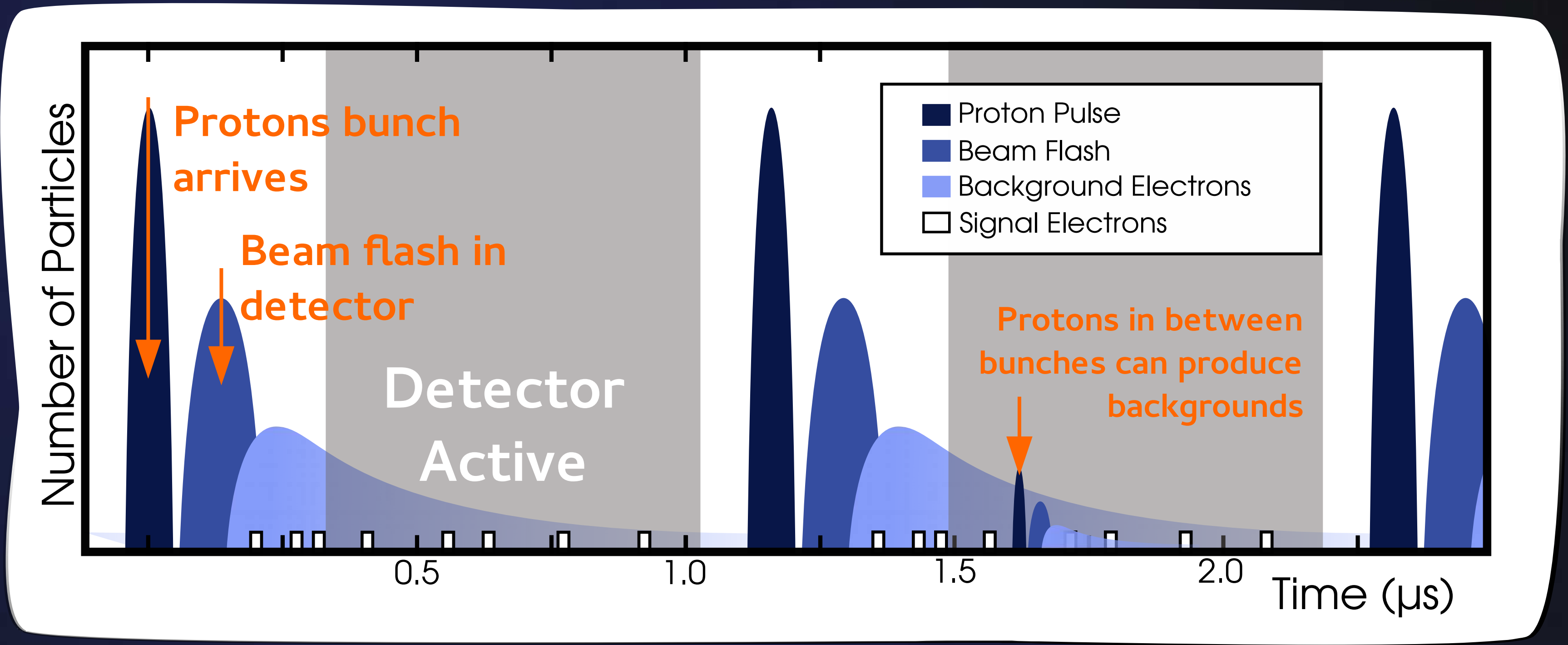
With Collimators Included



Muons Stopping in the Target

High Momentum Muons

Pulsed Proton Beam Reduces Backgrounds



Protons bunch arrives

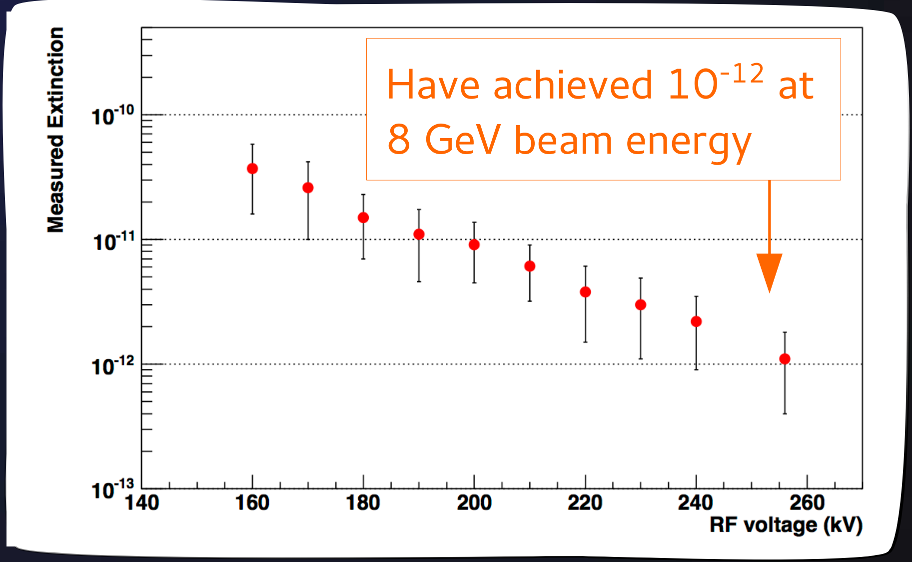
Beam flash in detector

Protons in between bunches can produce backgrounds

- Muon lifetime on Aluminium: 864 ns
- Pulsed beam removes beam-related backgrounds, typically up to 200 ns
- Few protons between pulses as possible:
    - Extinction factor:

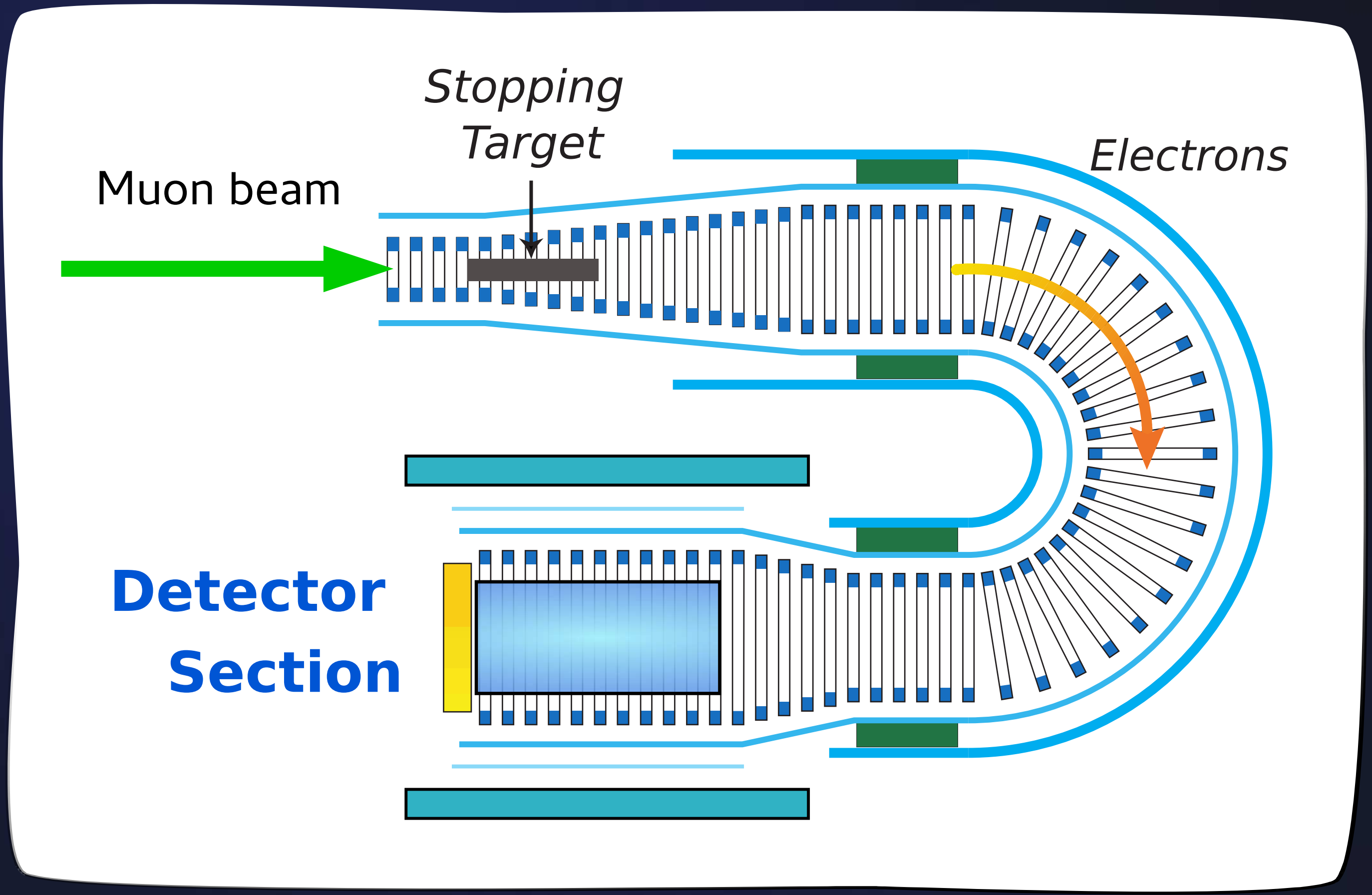
$$\text{Extinction} = \frac{\text{N(Protons between pulse)}}{\text{N(Protons in bunch)}}$$

    - Aiming for 10^{-9}



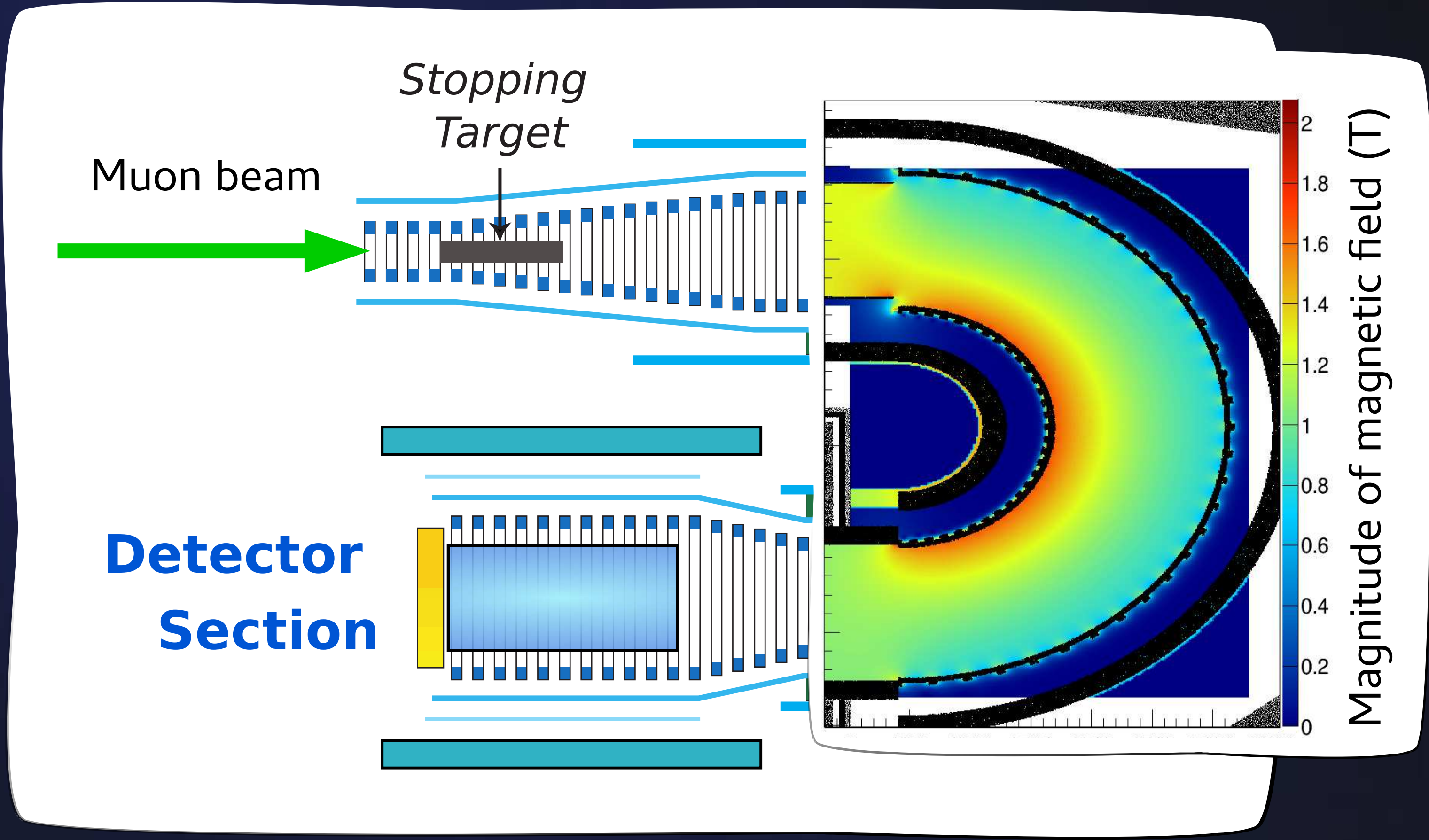
Have achieved 10^{-12} at 8 GeV beam energy

Phase–II Detection



- No line of sight between detector and target
- Select for high momentum electrons using bent solenoid and tuneable dipole field
- Straw Tracker and ECAL detector

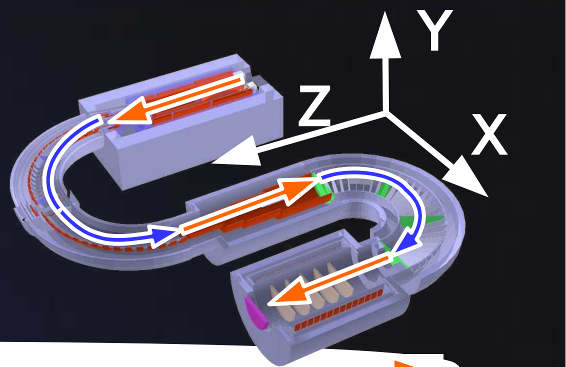
Phase–II Detection

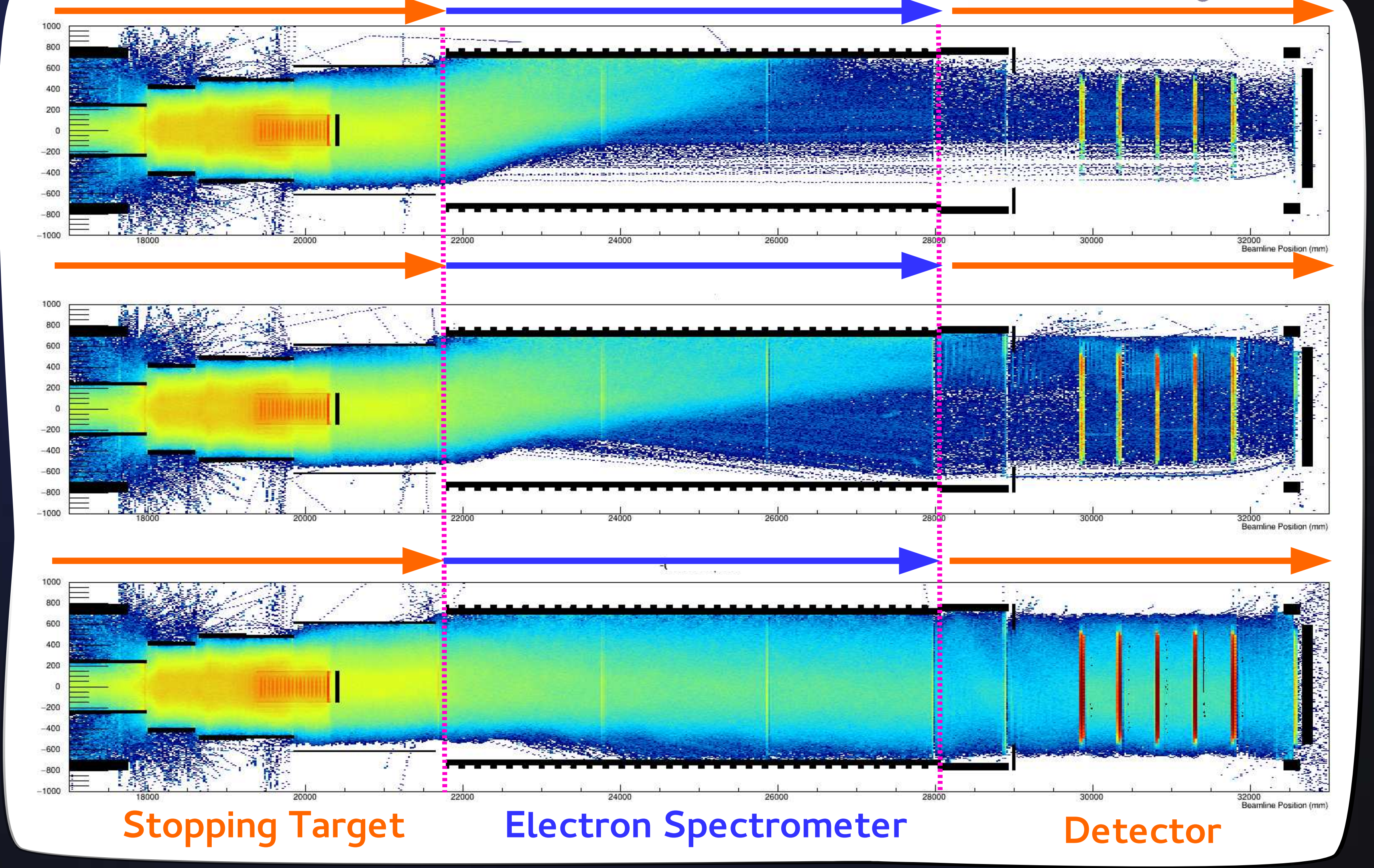


- No line of sight between detector and target
- Select for high momentum electrons using bent solenoid and tuneable dipole field
- Straw Tracker and ECAL detector

Bent solenoids + Dipole

- A correcting dipole field allows us to select the momentum that remains on axis. Eg. 105 MeV/c:





No Dipole

−0.08 T Dipole

−0.22 T Dipole

Stopping Target

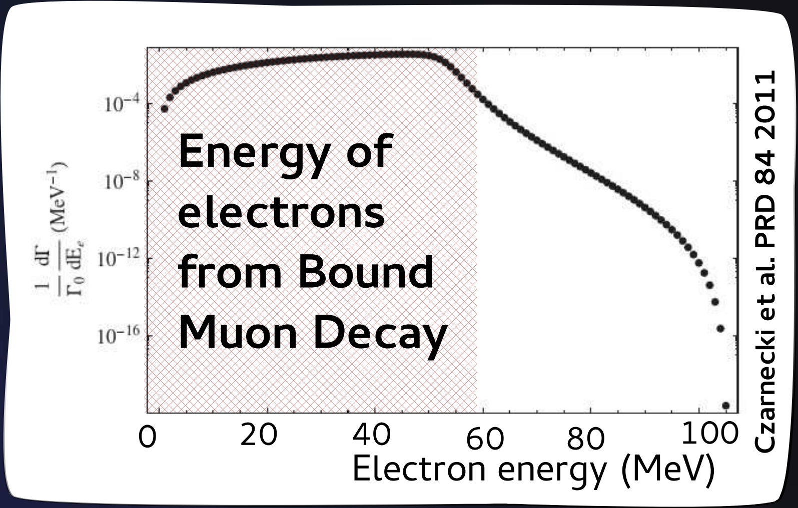
Electron Spectrometer

Detector

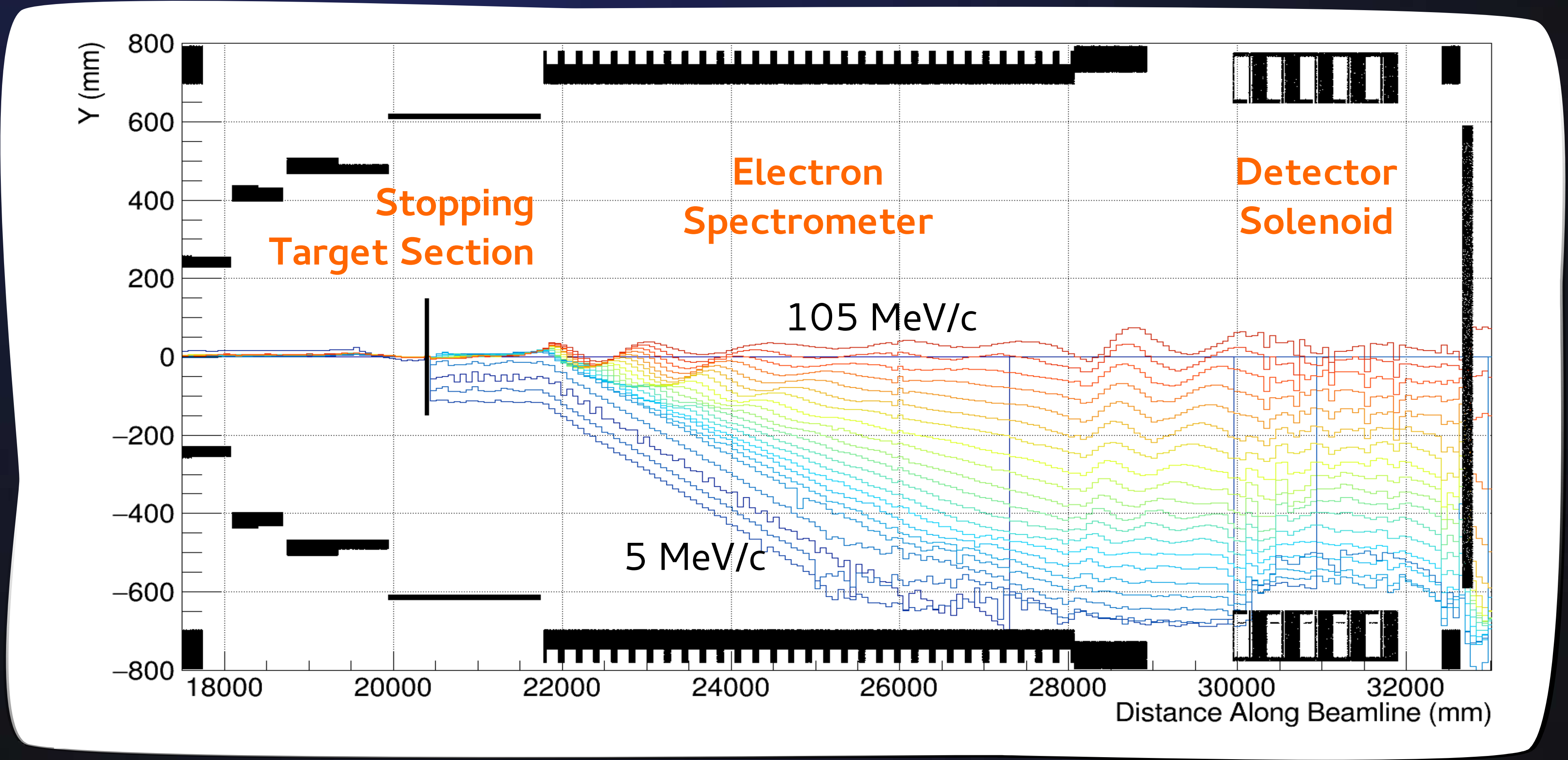
Momentum Separation

Bent solenoidal field separates electrons depending on their momentum

$$D \propto \frac{p}{qB} f(\theta)$$

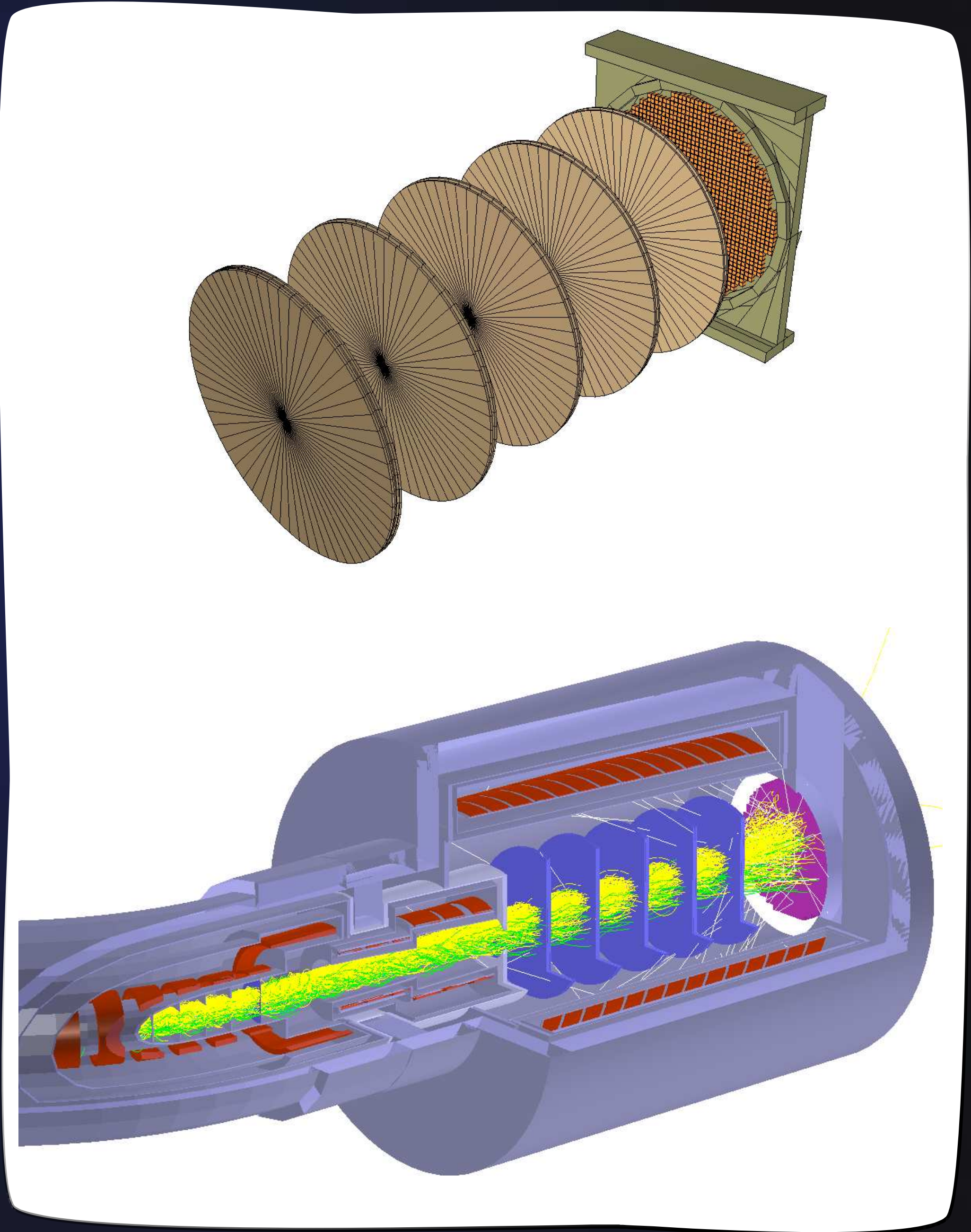


Czarnecki et al. PRD 84 2011

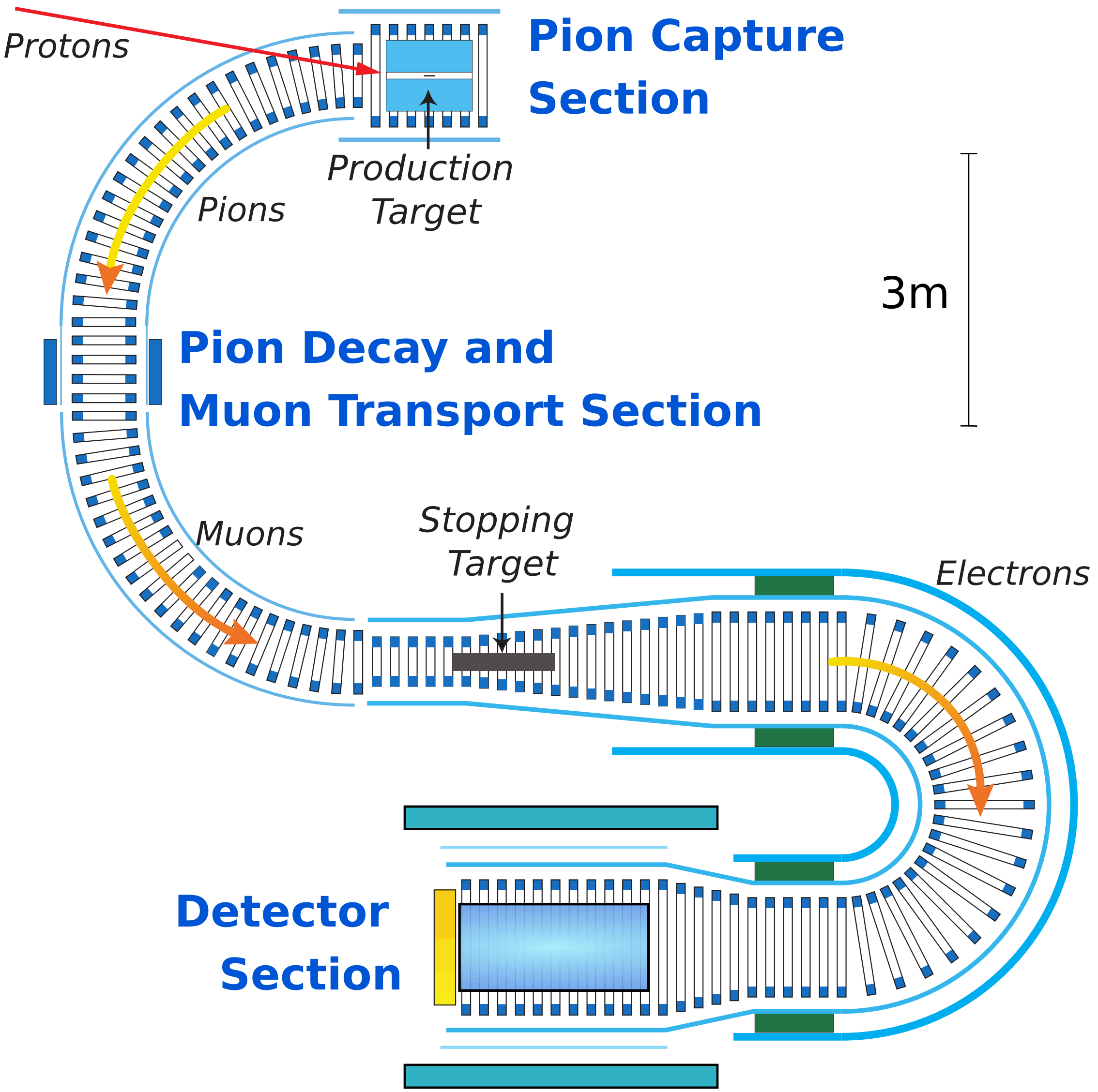


Phase–II Detector

- Straw Tube Tracker planes + Crystal ECAL
  - Straw Tracker ⇒ Momentum measurement
  - ECAL ⇒ Energy measurement
  - Combination ⇒ PID
- Low material budget
- High momentum resolution
  - About 200 KeV/c at 105 MeV/c
- Proto-typed in Phase-I



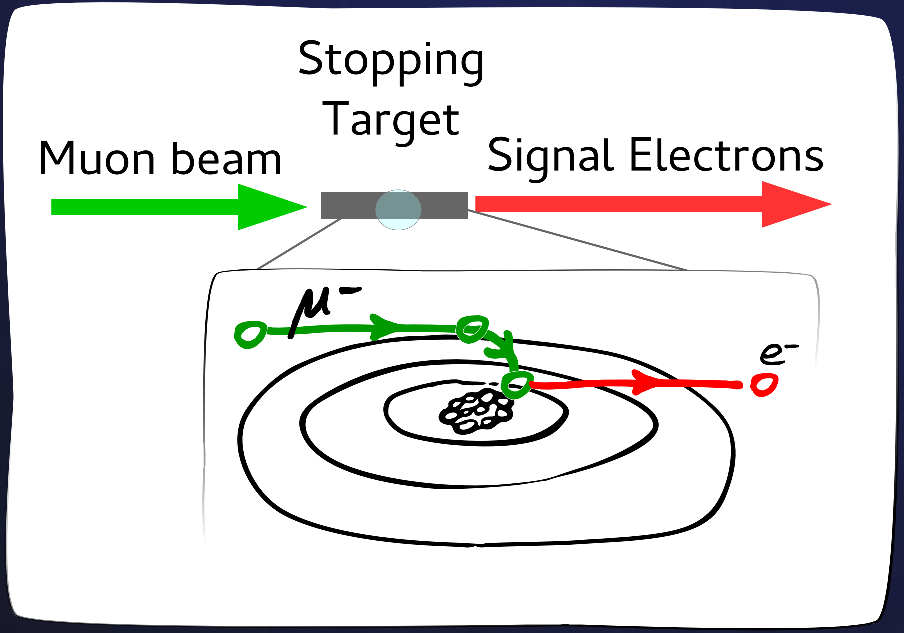
COMET: Phase–II

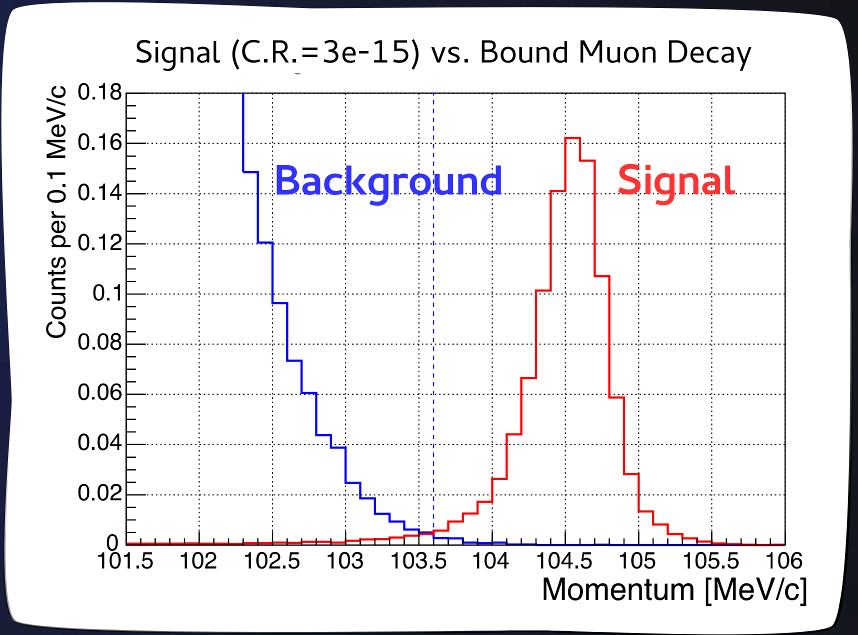


Achieving High Sensitivity

Overall Goals

- Many stopped muons
- High signal acceptance
- Fewer than 1 expected background events during the run

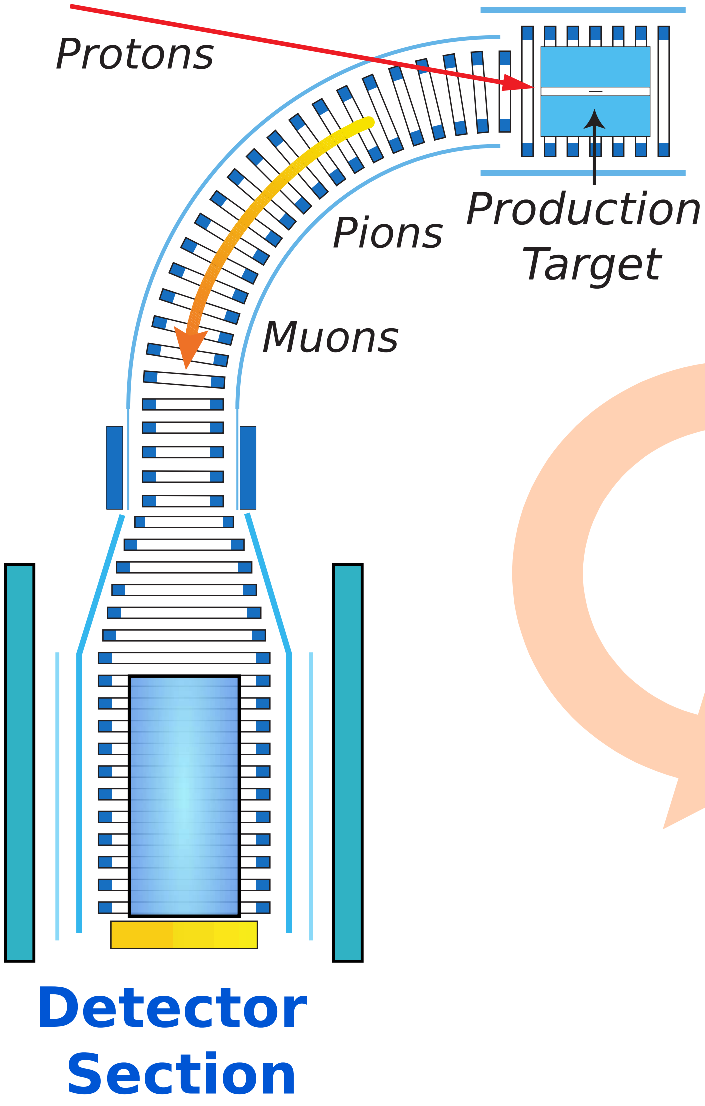




Design Considerations

- Intense, low−energy muon beam at the target
- Low detector occupancy
- Low material budget (Stopping Target and Detector)

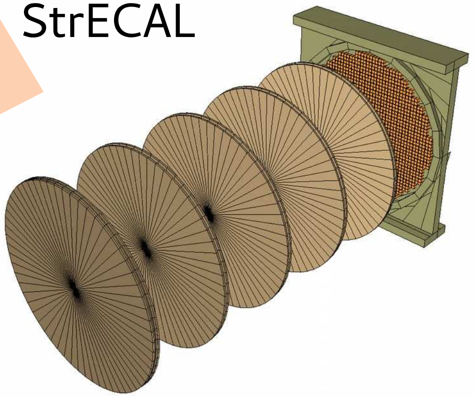
COMET: Phase–I



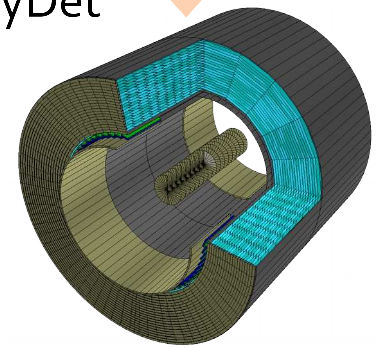
Goals of Phase–I

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

StrECAL



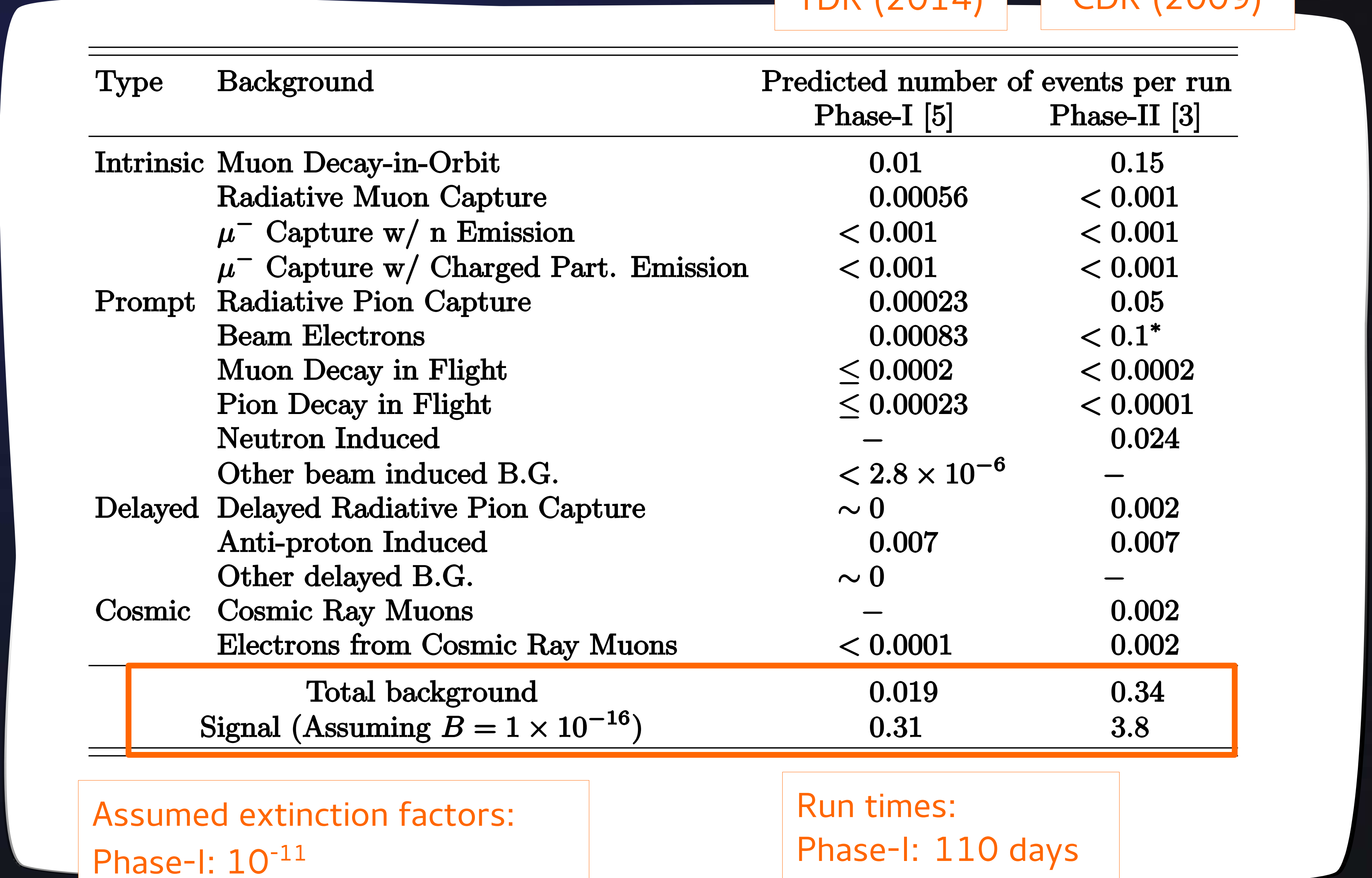
CyDet



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

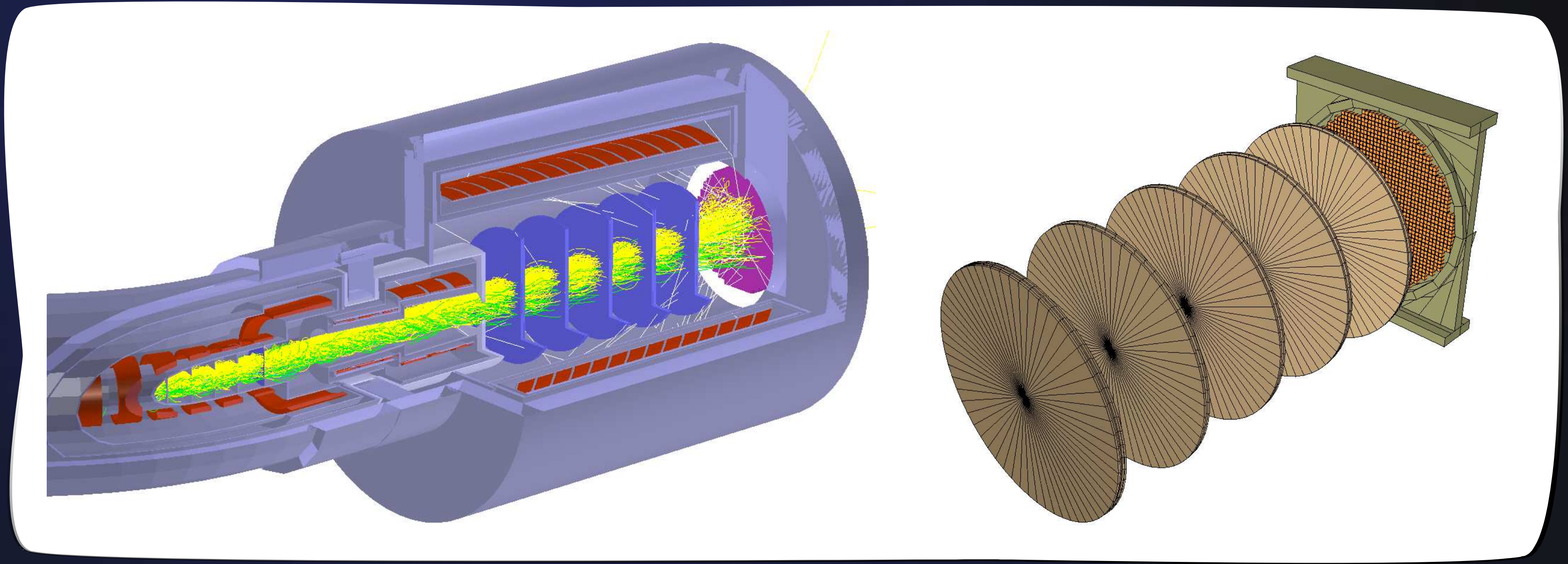
Assumed extinction factors:
Phase-I: 10^{-11}
Phase-II: 10^{-9} (to be updated)

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

COMET Phase-I, Status and R&D

StrECAL Detector

Straw Tracker + ECAL



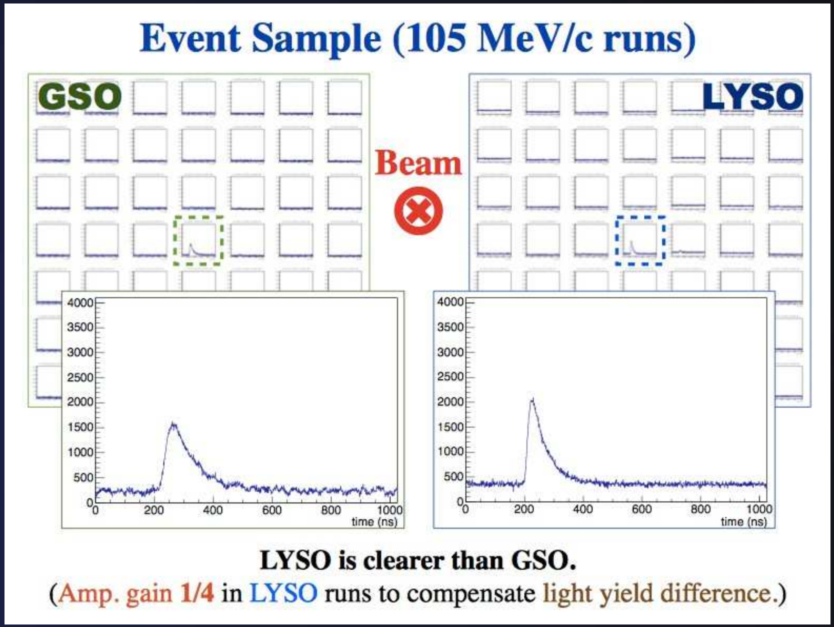
- Phase-II Detector prototype
- Used to characterise beam in Phase-I

Ben Krikler: bek07@imperial.ac.uk

Straw Tracker

- Phase-I Straw Design
  - Based on NA62 Straws with single seam weld
  - Using same production technique
  - 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

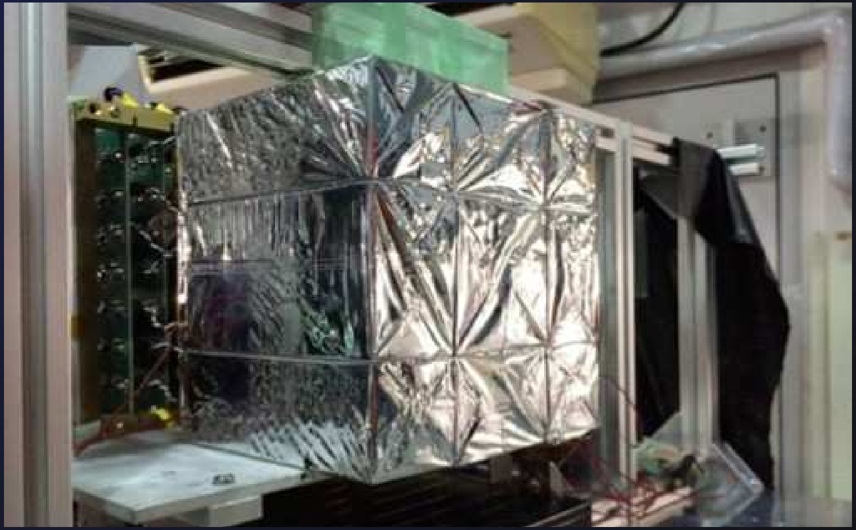
ECAL *StrECAL Trigger and Energy Measurement for PID*


Event Sample (105 MeV/c runs)

LYSO is clearer than GSO.
(Amp. gain 1/4 in LYSO runs to compensate light yield difference.)

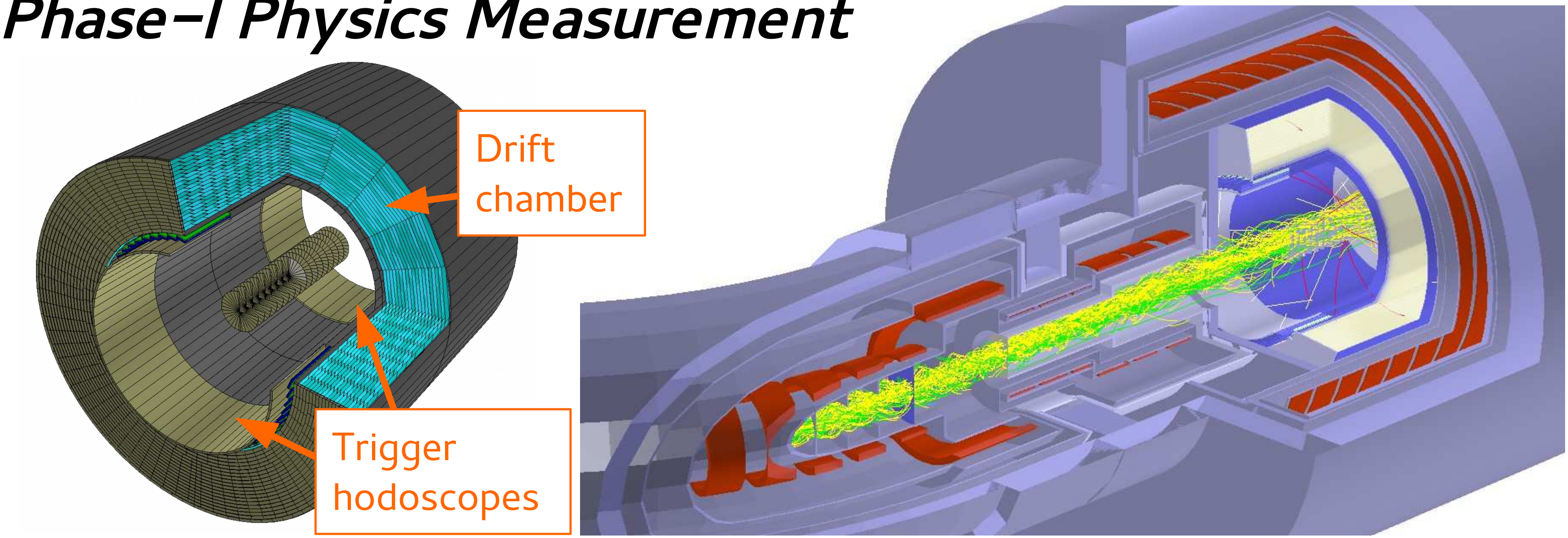
- 2272 LYSO Crystals
  - Dimensions: 2x2x12 cm
- Status:
  - Crystal purchasing on-going
  - Test bench being built
  - Beam tests for resolution studies, PID and DAQ underway
  - Calibration system being designed

Beam test setup for resolution study

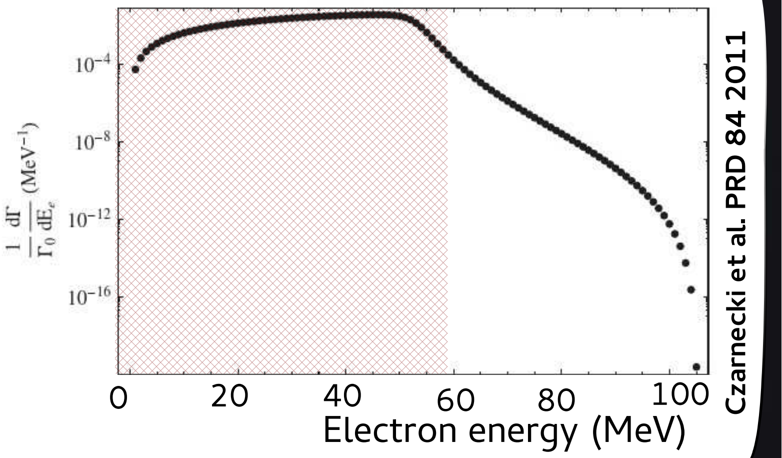


Cylindrical Detector (CyDet)

Phase–I Physics Measurement



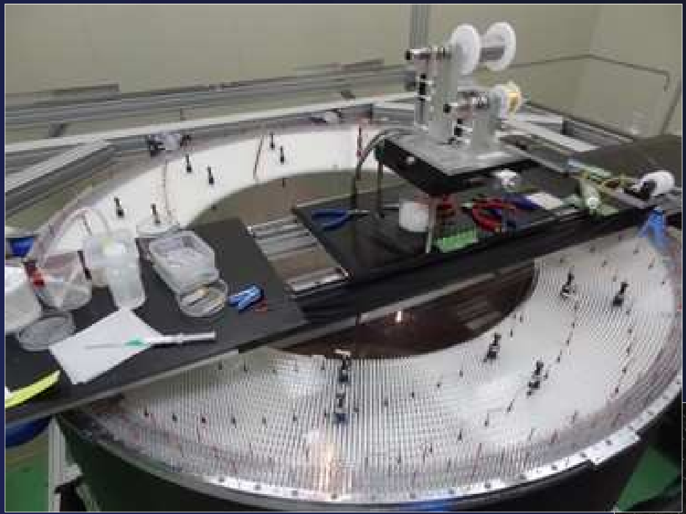
- Cylindrical Drift Chamber (CDC) triggered from hodoscopes made of Cherenkov counters and plastic scintillators
- 60 cm inner radius
  - Only accept particles with momentum greater than 60 MeV/c
  - Avoids beam flash and most electrons from bound muon decay
- Momentum measurement using drift chamber
  - Low material budget improves resolution
  - All stereo wires to recover Z information



Czarnecki et al. PRD 84 2011

Electrons from Bound Muon Decay

Cylindrical Drift Chamber (CDC)



- 20 layers with alternating stereo angles of ±4°
- 20,000 wires total
- Fully strung as of November 2015
- Wire tension checking

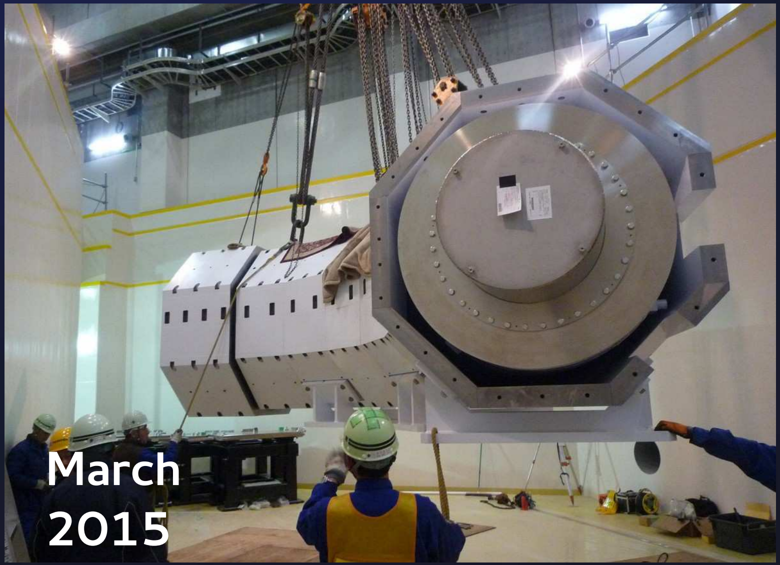
Facility Status and Beamline


June 2014


October 2014

- Building and hall completed
- Phase-I bent solenoid built and installed

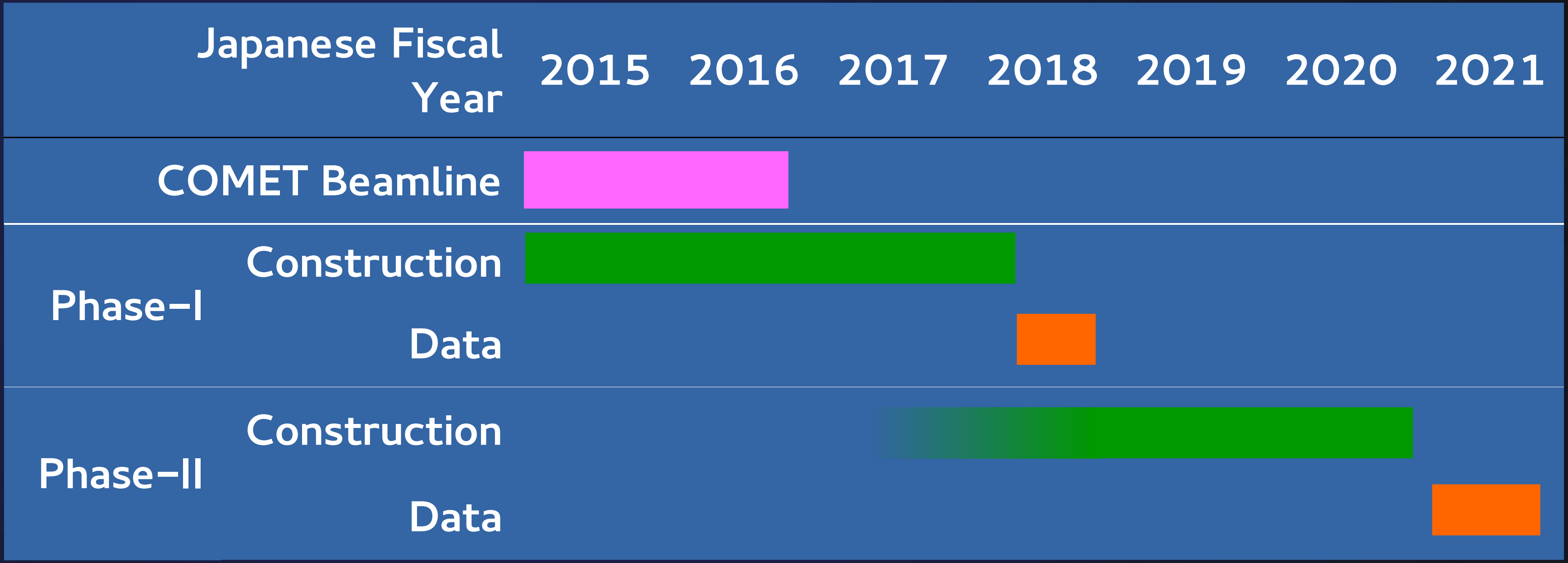

January 2015



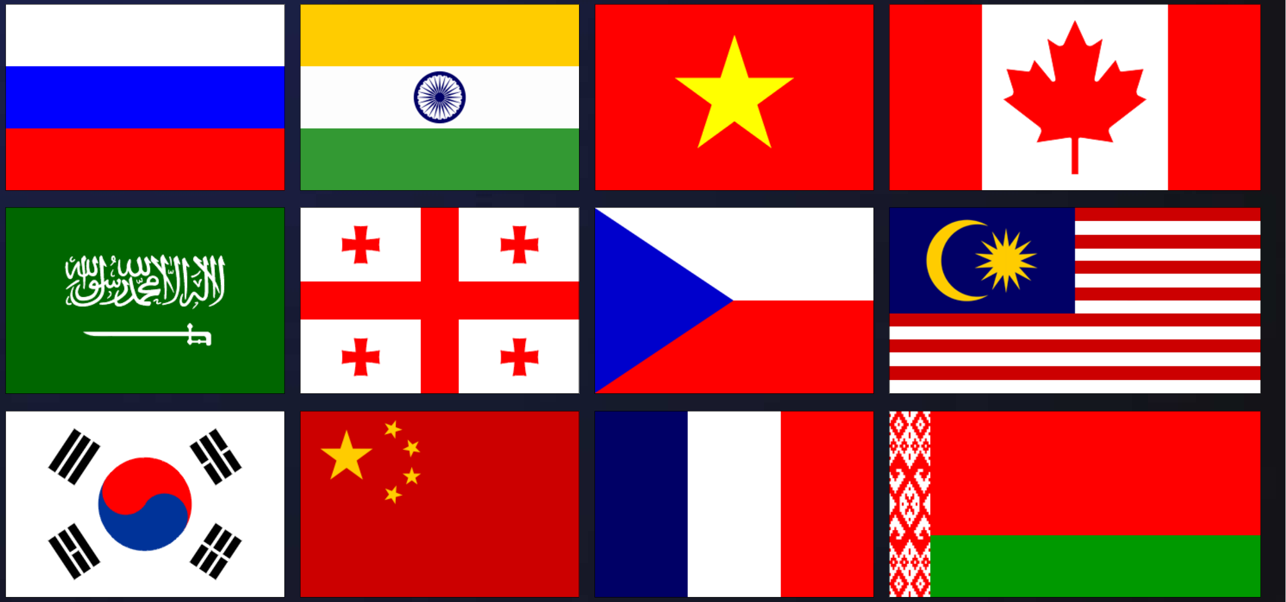
March 2015

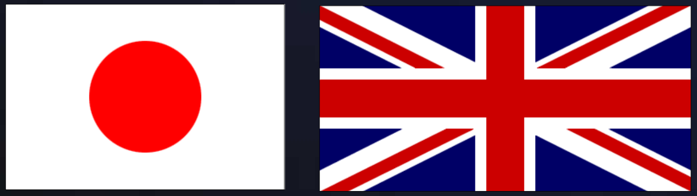
December 2015

Schedule and 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

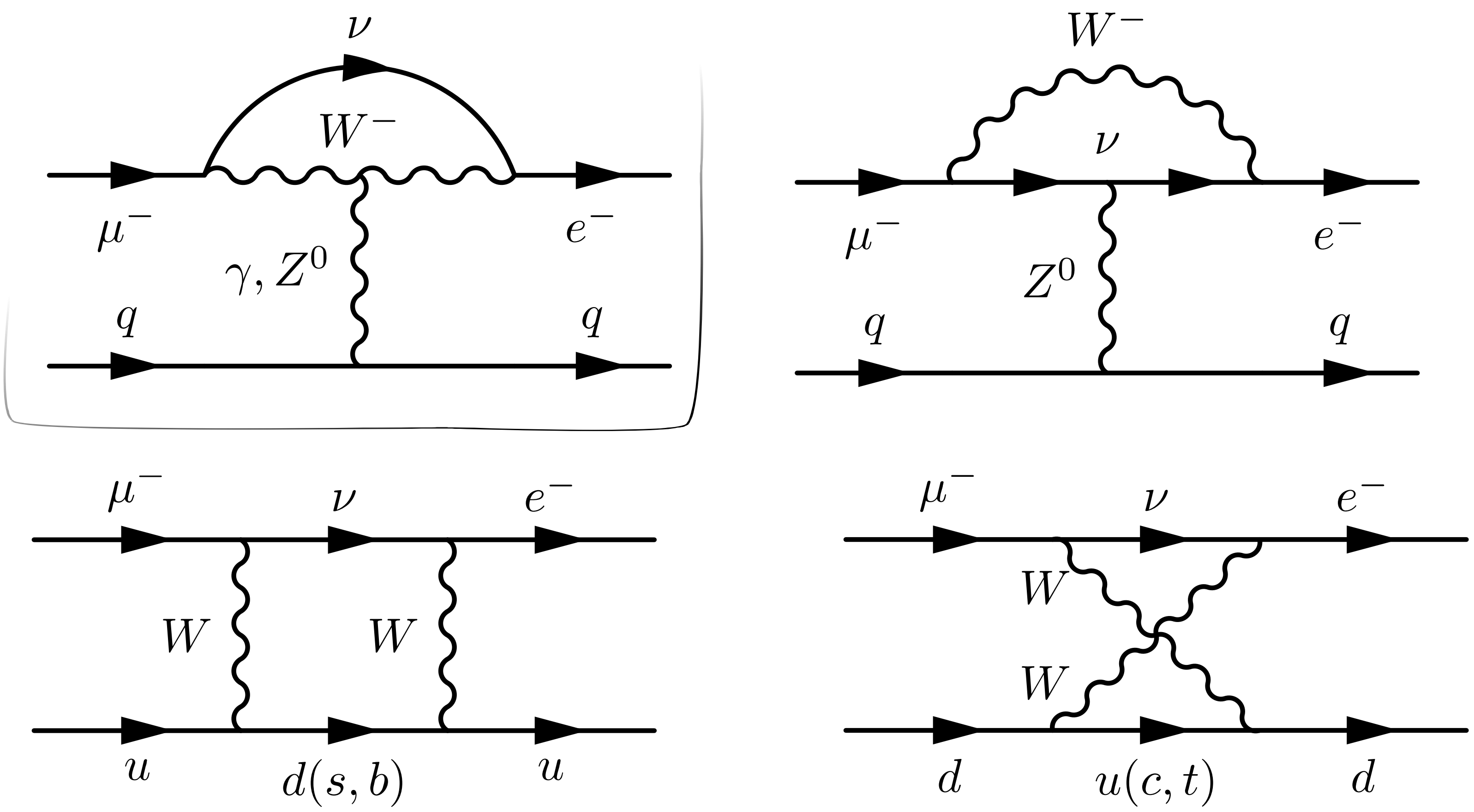
COMET Phase–II
2021
Sensitivity $< 3 \times 10^{-17}$
1 Year
56 kW proton beam

Back-ups

Muon to Electron Conversion

via Neutrino Oscillation

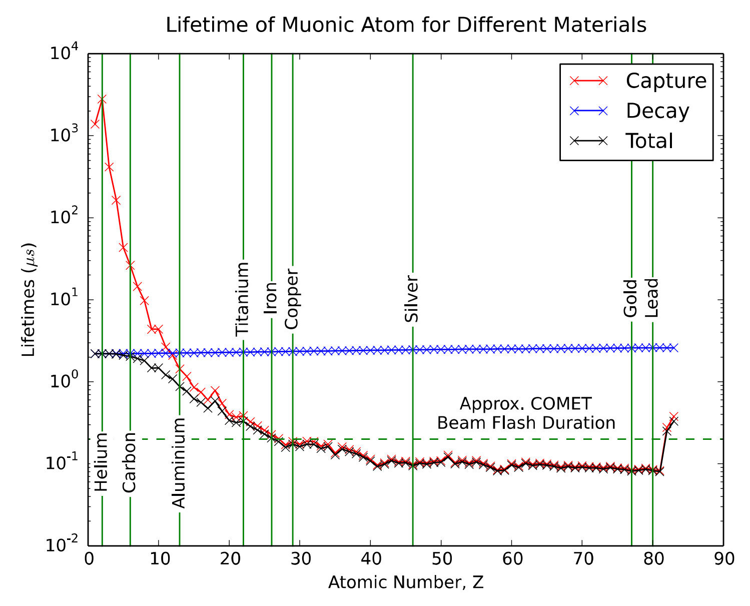
All diagrams involving Neutrino Oscillations

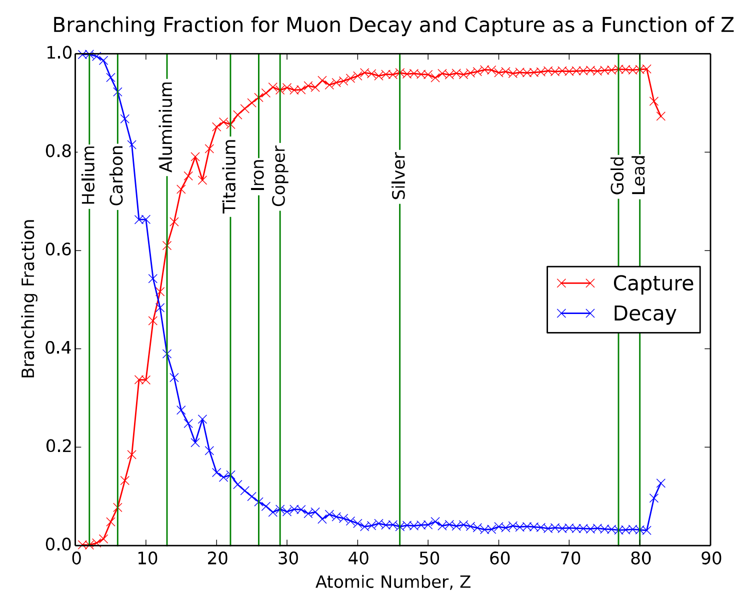


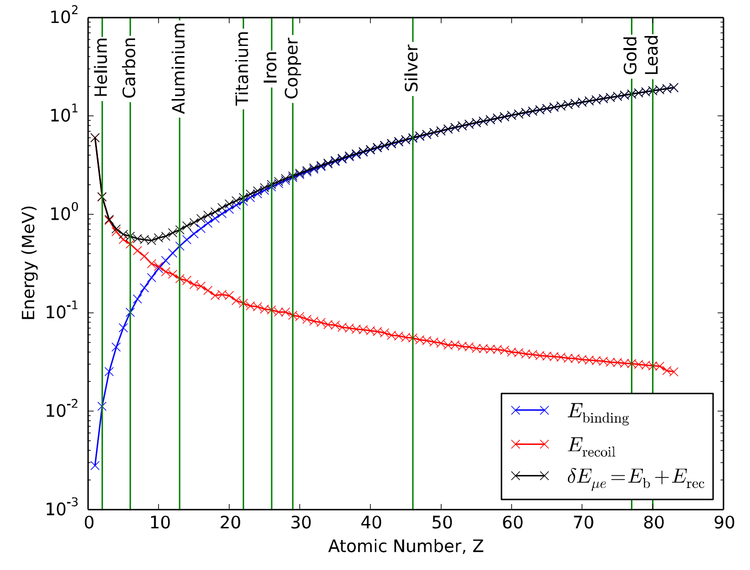
Although things still aren't especially simple:

- Cancellations, coherences, form factors

Why an Aluminium Target?

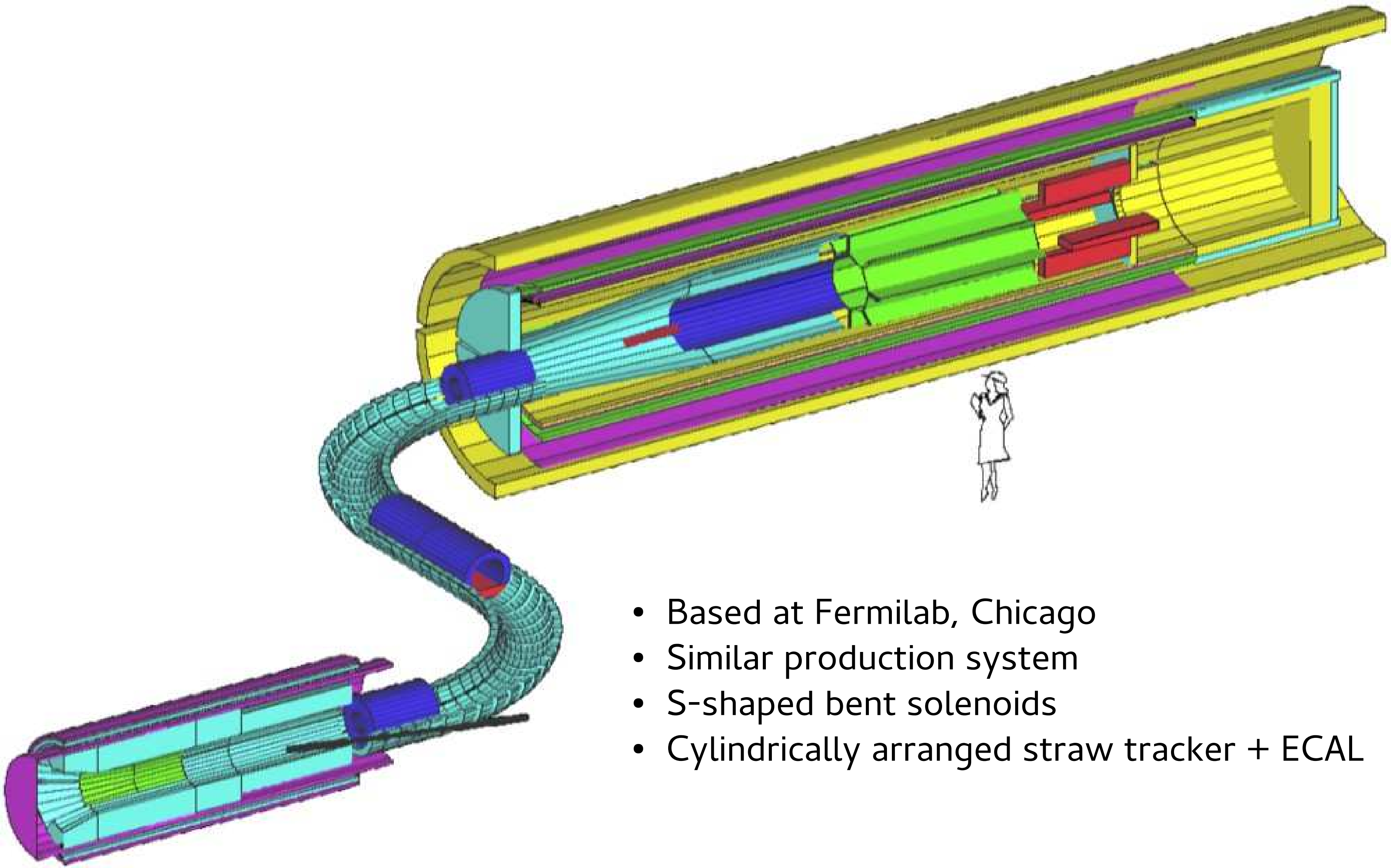

Lifetime of Muonic Atom for Different Materials


Branching Fraction for Muon Decay and Capture as a Function of Z


Binding and Nuclear Recoil Energies as a Function of Z

- 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)

Mu2e



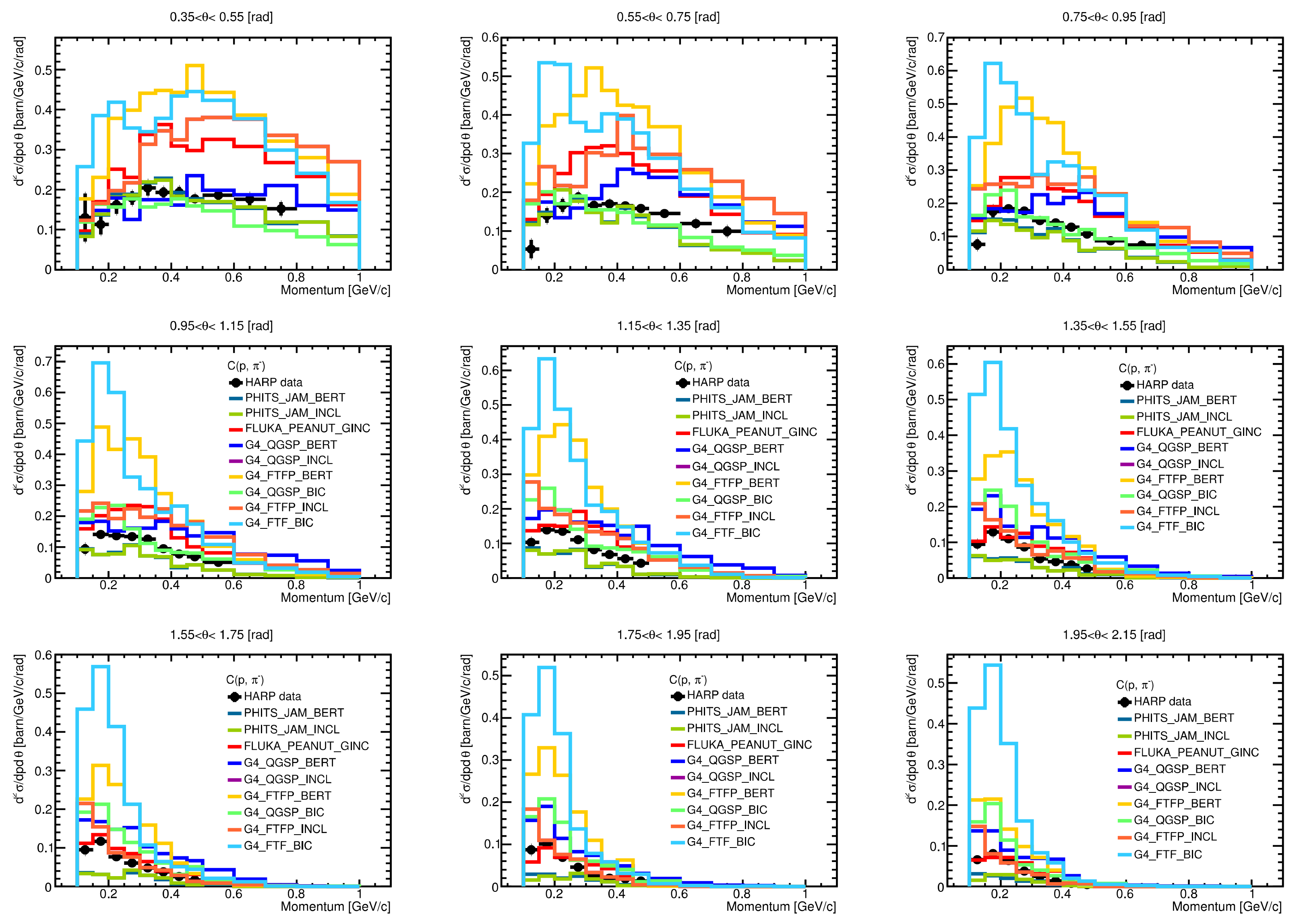
- Based at Fermilab, Chicago
- Similar production system
- S-shaped bent solenoids
- Cylindrically arranged straw tracker + ECAL

Mu2e vs COMET

- COMET has tunable dipole fields
  - Can select during running which momenta are accepted
- COMET has a staged approach
  - Will understand beamline and detector systems at Phase-II thanks to Phase-I knowledge
  - Uncertainty on Pion yield at production target
  - Mu2e will also be able to use COMET Phase-I knowledge
- No line-of-sight between COMET Phase-II detector and stopping target
  - Neutral particles are much less of a concern
  - Separation of low to high momentum electrons
- COMET runs at a higher beam power
  - 1 year to achieve same sensitivity
- Mu2e can run simultaneously to g-2 and other experiments
  - COMET uses dedicated accelerator mode so other experiments (eg. T2K / T2HK) wouldn't run

Production Target

Pion yield for a graphite target at different angles based on HARP data and different hadron codes



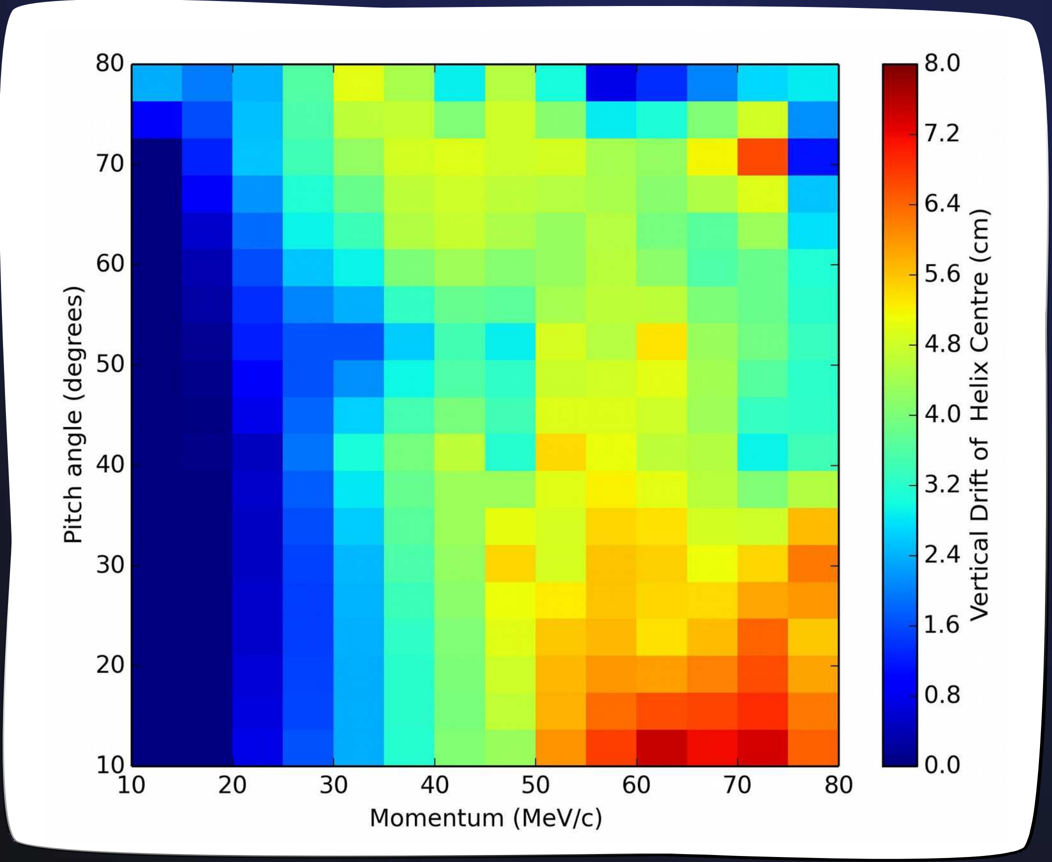
Ye Yang, KEK

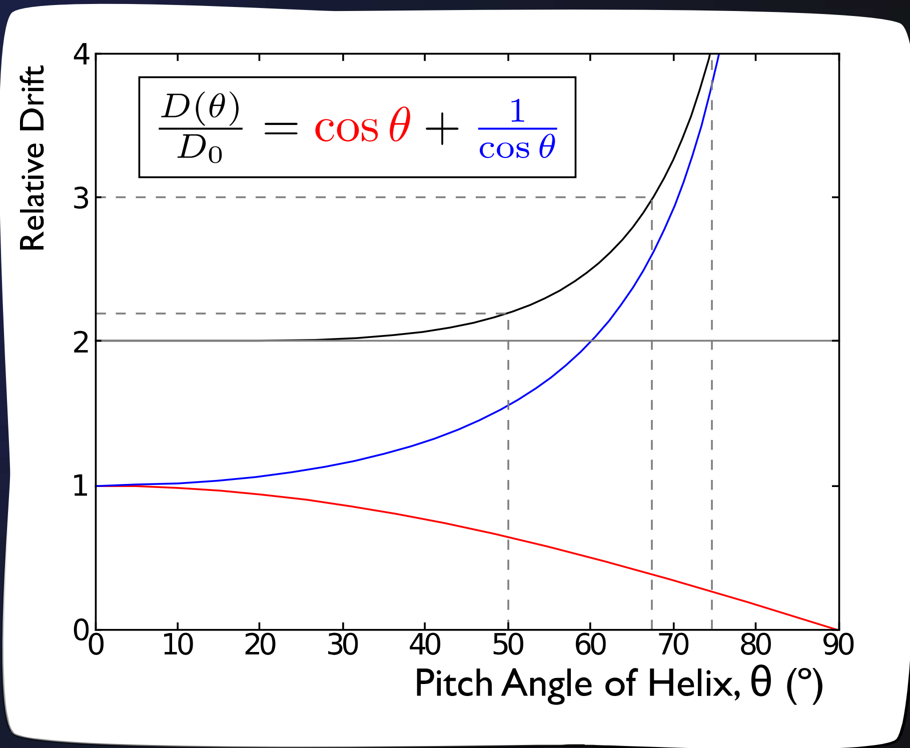
Muon Beam: Bent Solenoid Drifts

- Helical centres follow cylindrical fieldlines ⇒ Pseudo-electric field radially ⇒ ExB drift
- Gradient in radial direction ⇒ Grad B drift

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

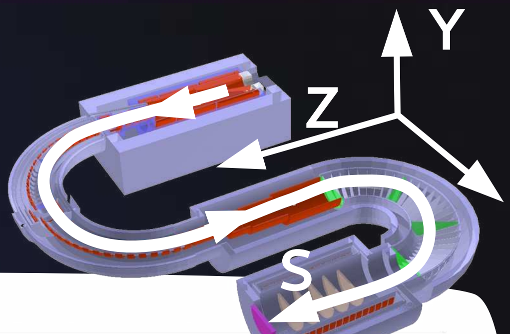
$$\propto \frac{1}{qB}\frac{p}{2}\left(\cos\theta + \frac{1}{\cos\theta}\right)$$





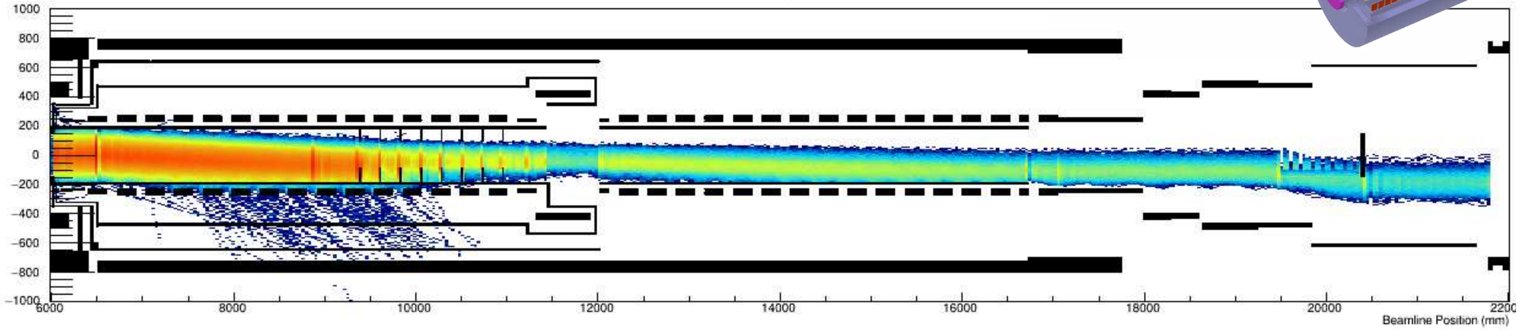
Muon Beam Height

For Three Different Dipole 1 & Dipole 2 Values



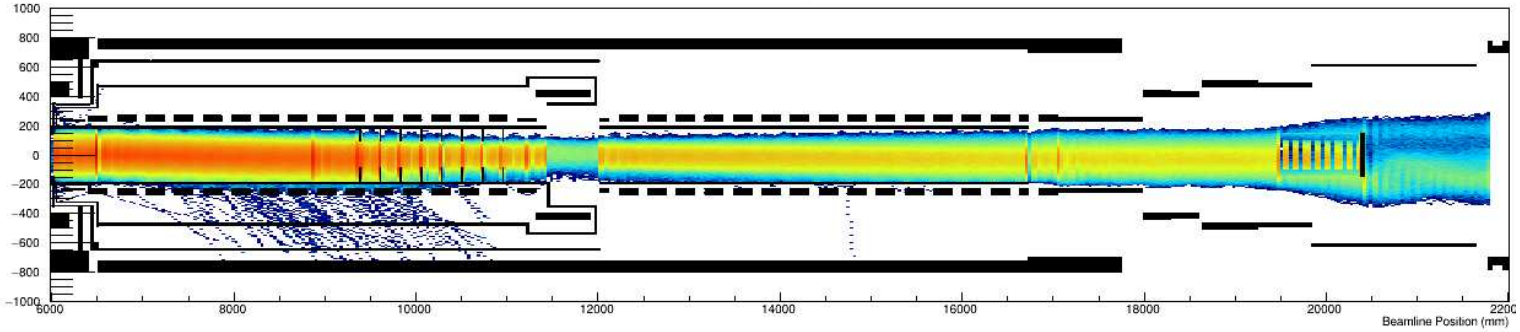
No Dipole

No Dipoles



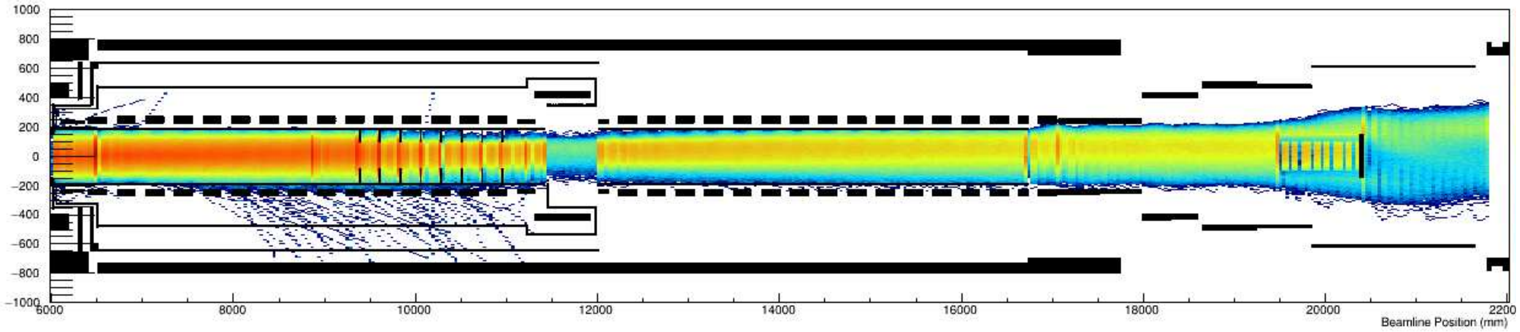
0.055T Dipole

0.055 T

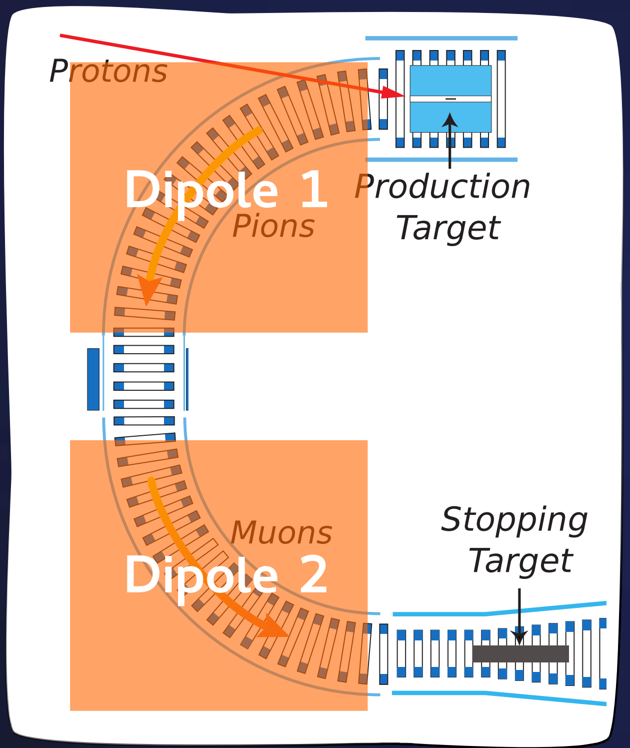


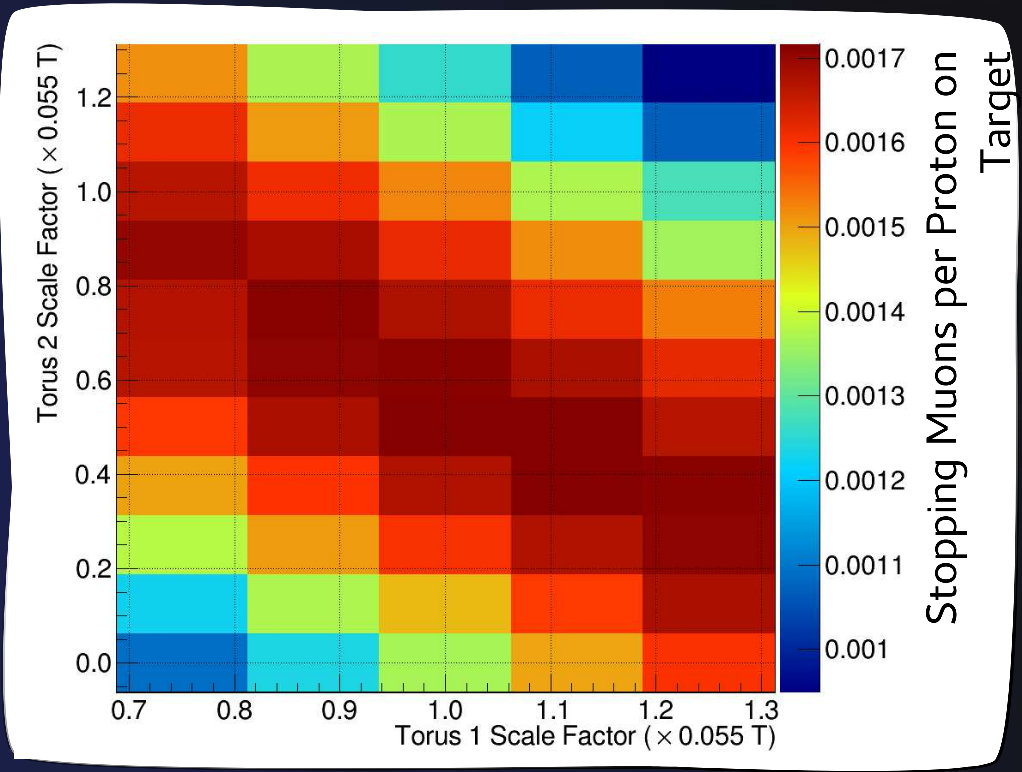
0.11T Dipole

0.11 T

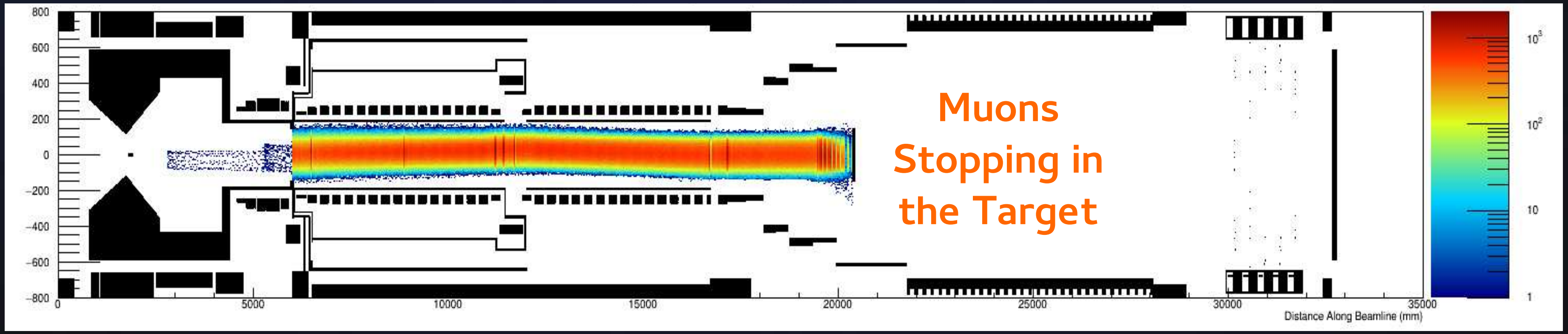


Muon Beam Dipole Optimsation



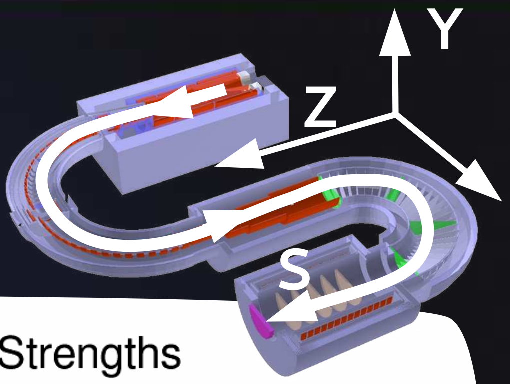


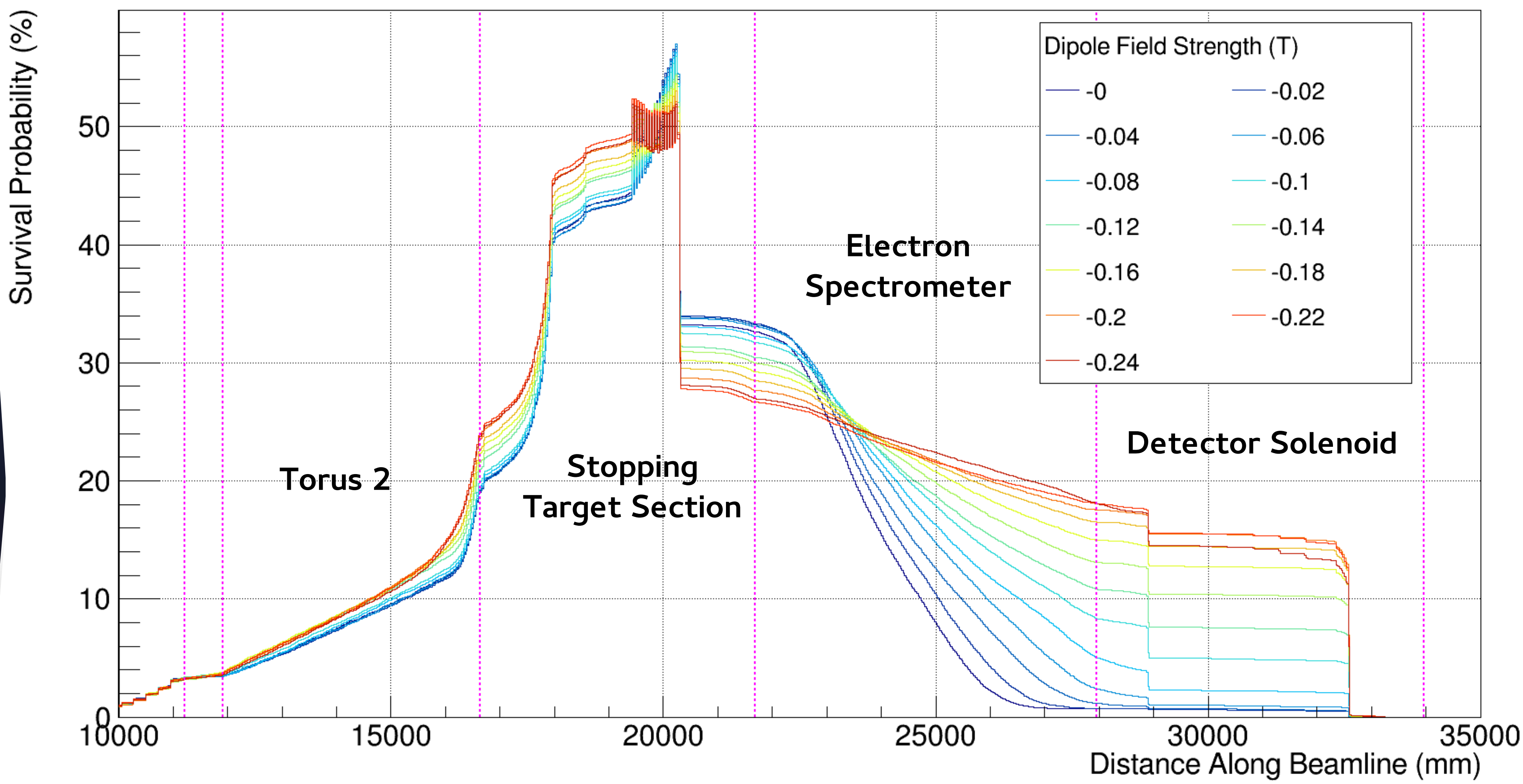
- Sum of Dipole 1 and Dipole 2 should be constant
  - Total drift experienced by low energy muons should be the same



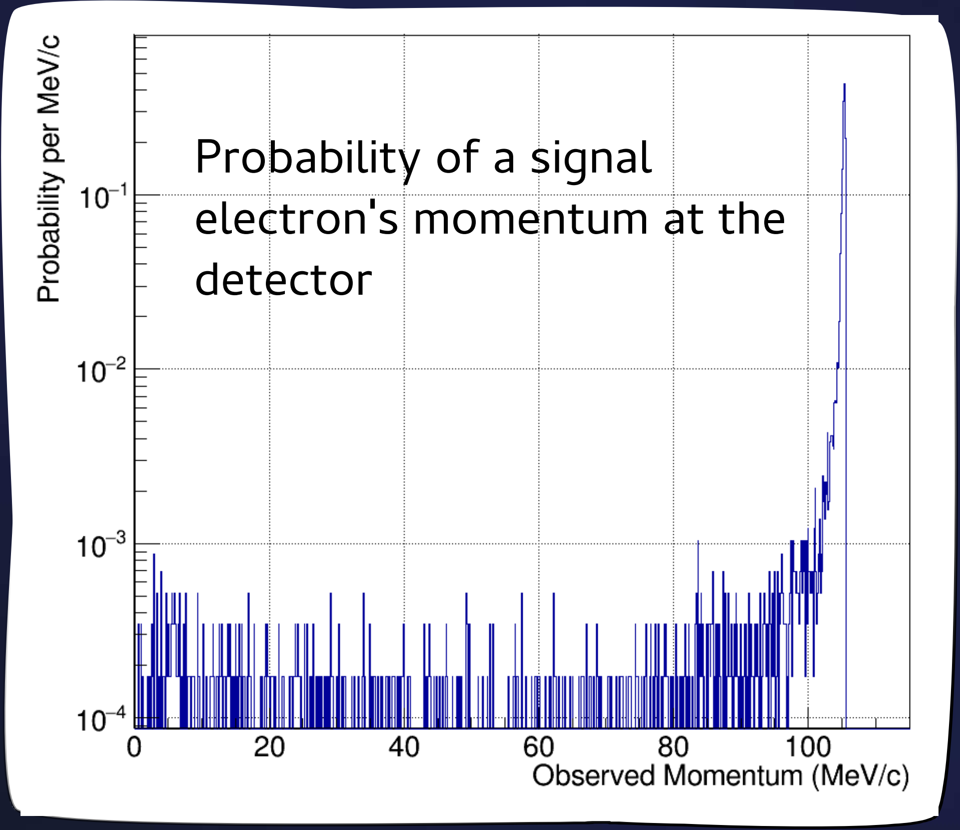
Muons Stopping in the Target

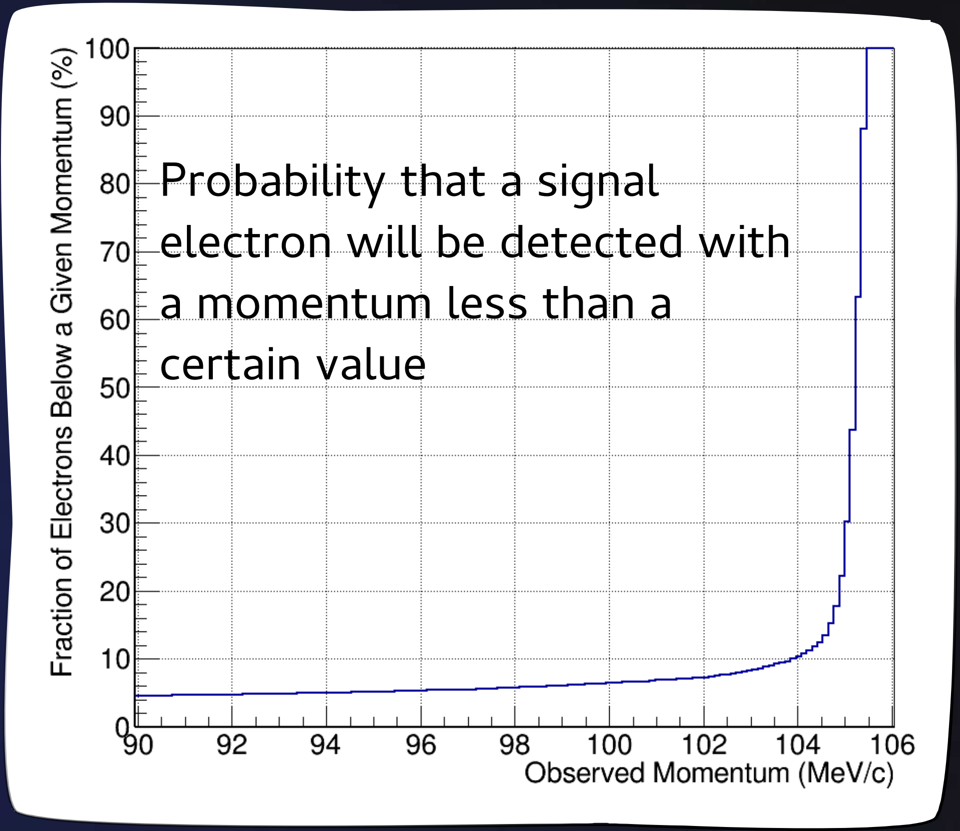
Dipole Scan: Survival Probability




Signal Acceptance Along Beam Axis for Different Dipole Field Strengths

Energy Losses Before The Detector





- Probability of a signal electron arriving with momentum less than:
  - $p(P < 104\ \mathrm{MeV/c}) = 10\%$
  - $p(P < 100\ \mathrm{MeV/c}) = 6.5\%$

Simulating COMET

Backgrounds at Phase–II

Looking for a rare process:

- A single event if conversion per capture at least: 10^{-17}

Need many muons:

- Stopped muons: 1×10^{18} muons
- Protons needed: 2×10^{22} protons

And fewer than 1 background event

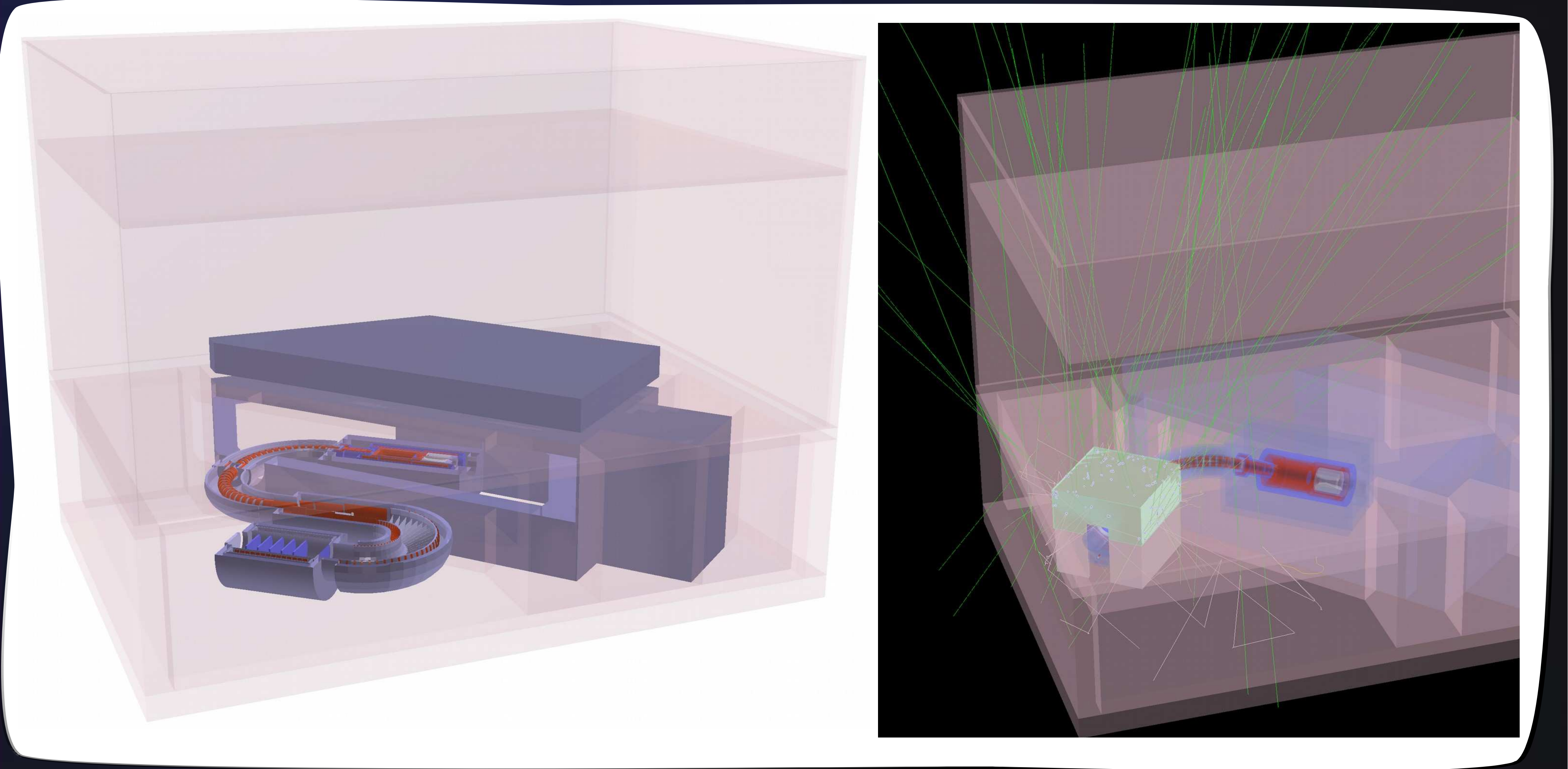
⇒ Want to understand behaviour of 1 electron coming from 20 quintillion protons

⇒ What things can fake that signal?

Accurate and Efficient Simulation

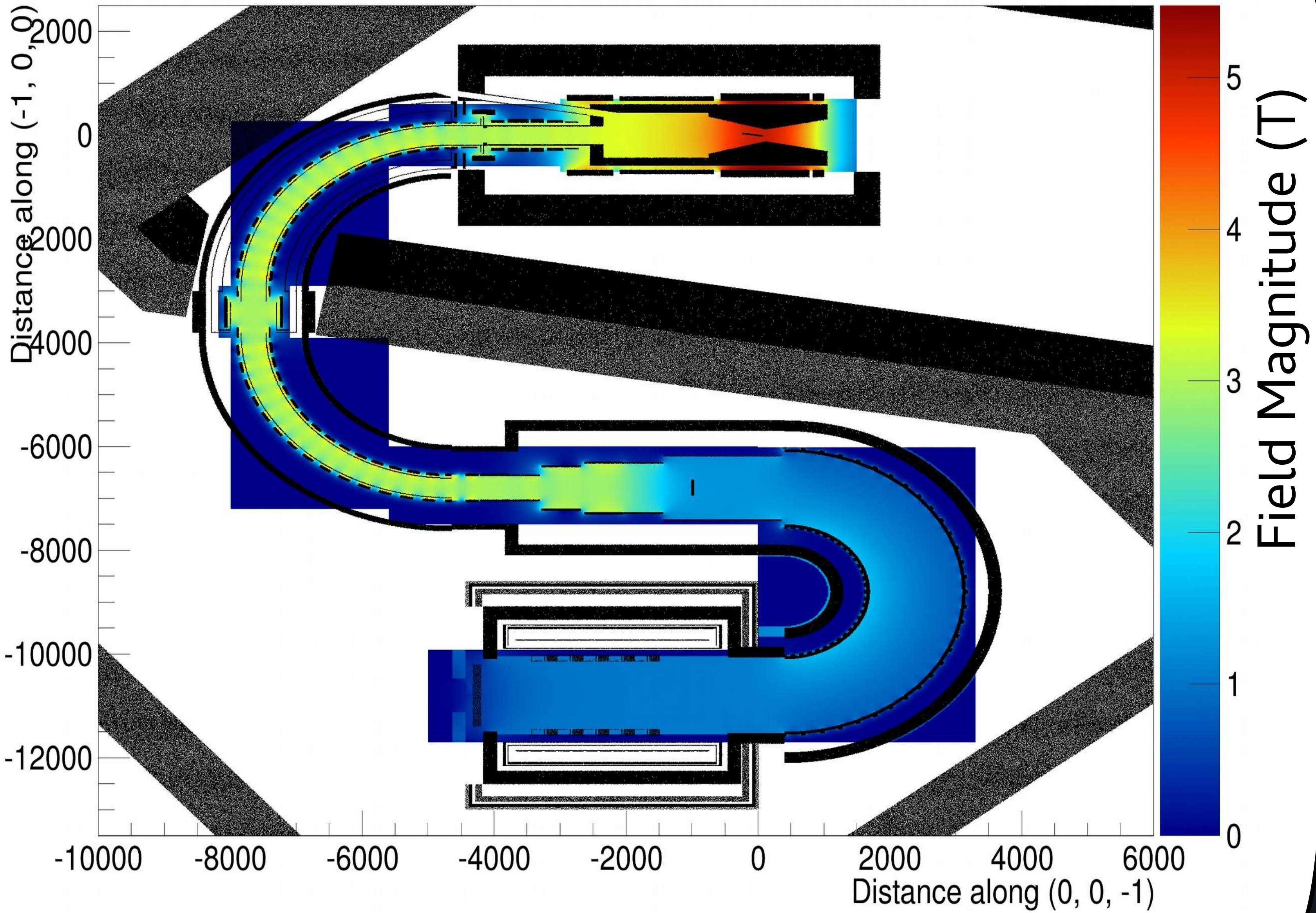
- Accuracy:
  - Geometry
  - Magnetic Field
  - Physics models
    - Hadron production with 8 GeV in backwards direction from Tungsten (and Graphite)
    - Physics of stopped muons
- Efficiency:
  - Resampling algorithms
  -

Geometry



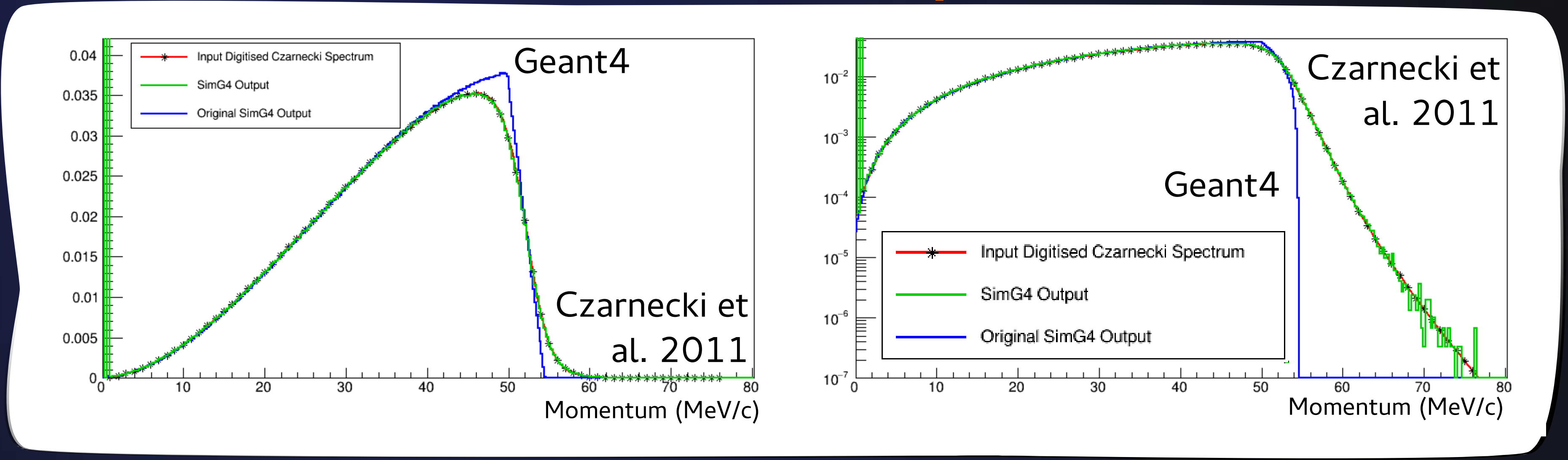
- Detailed detector and beamline description
- Full experimental hall design for Cosmic Ray studies

Fieldmap

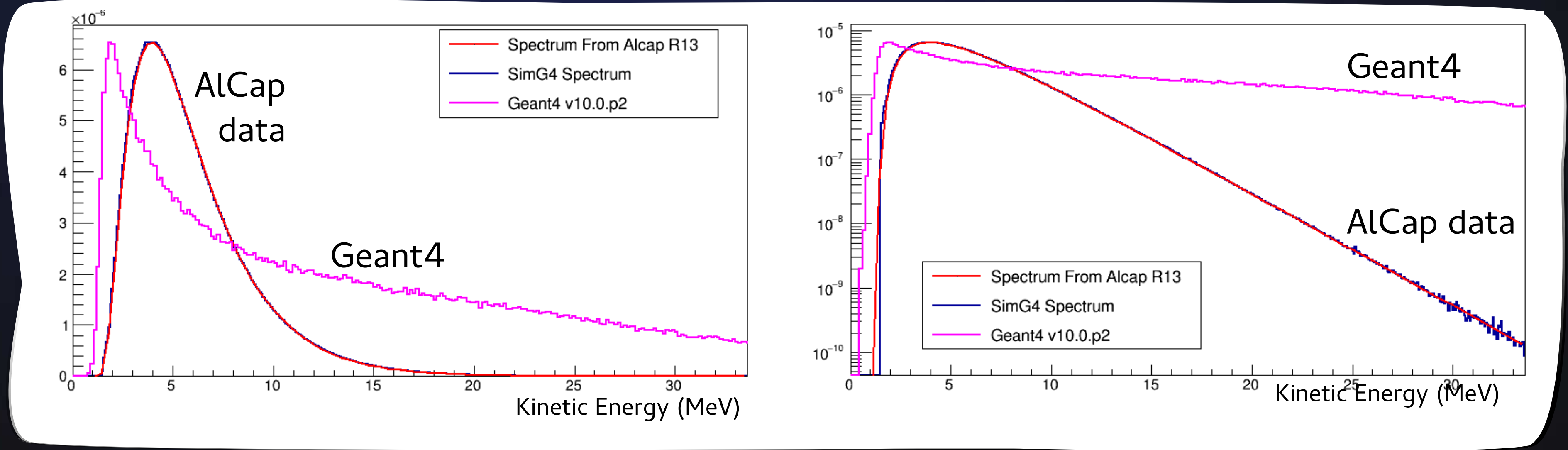

Distance along (-1, 0, 0)
2000
0
-2000
-4000
-6000
-8000
-10000
-12000
-10000
-8000
-6000
-4000
-2000
0
2000
4000
6000
Distance along (0, 0, -1)
Field Magnitude (T)
0
1
2
3
4
5

Custom Physics Models

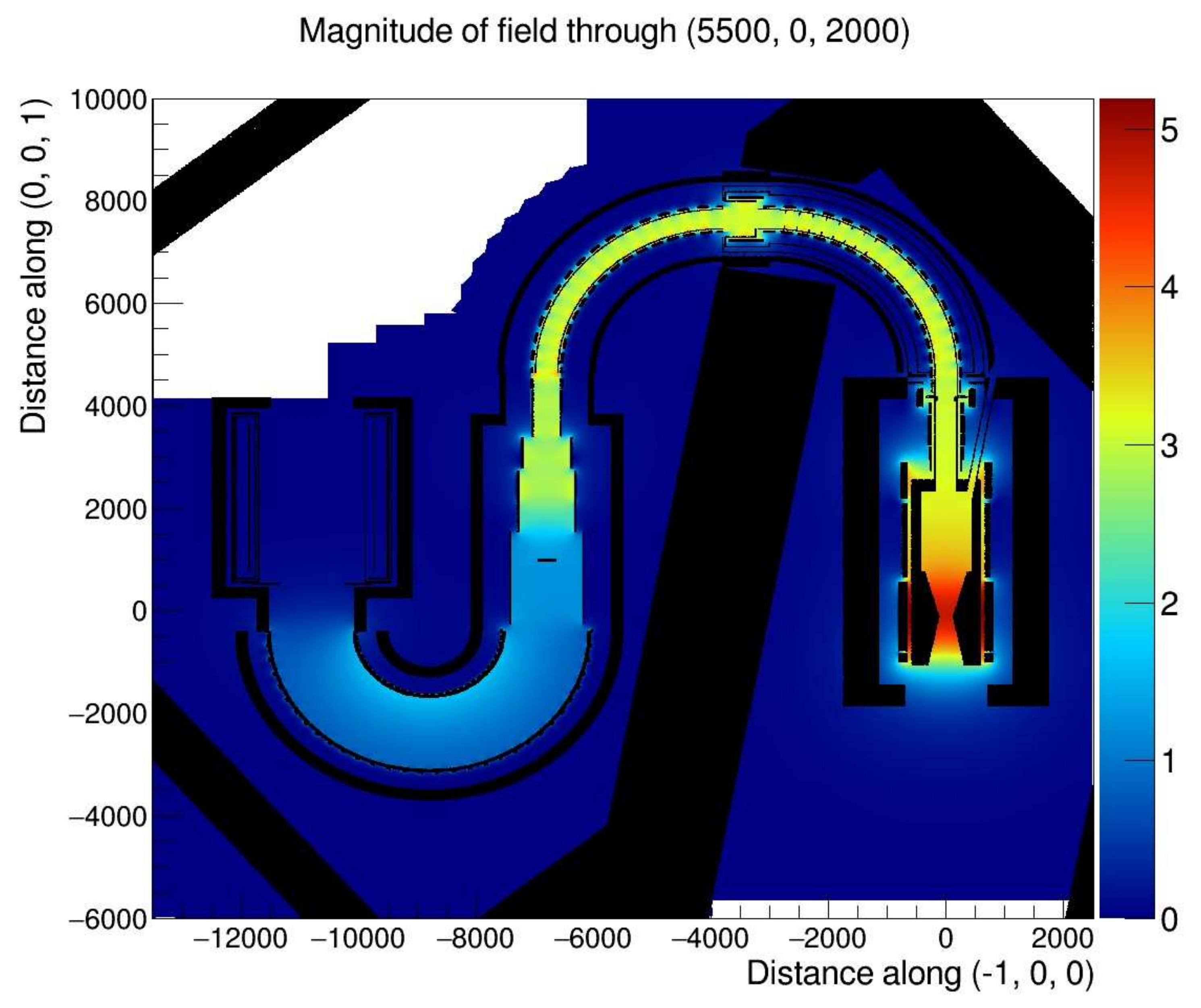
Electrons from Bound Muon Decay



Protons from Muon Nuclear Capture

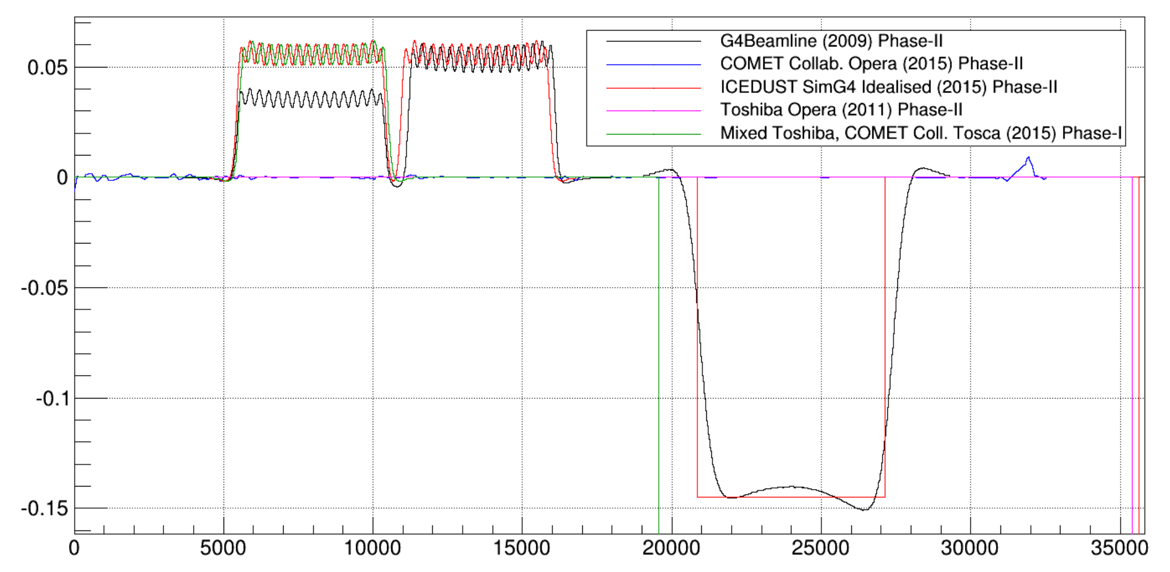


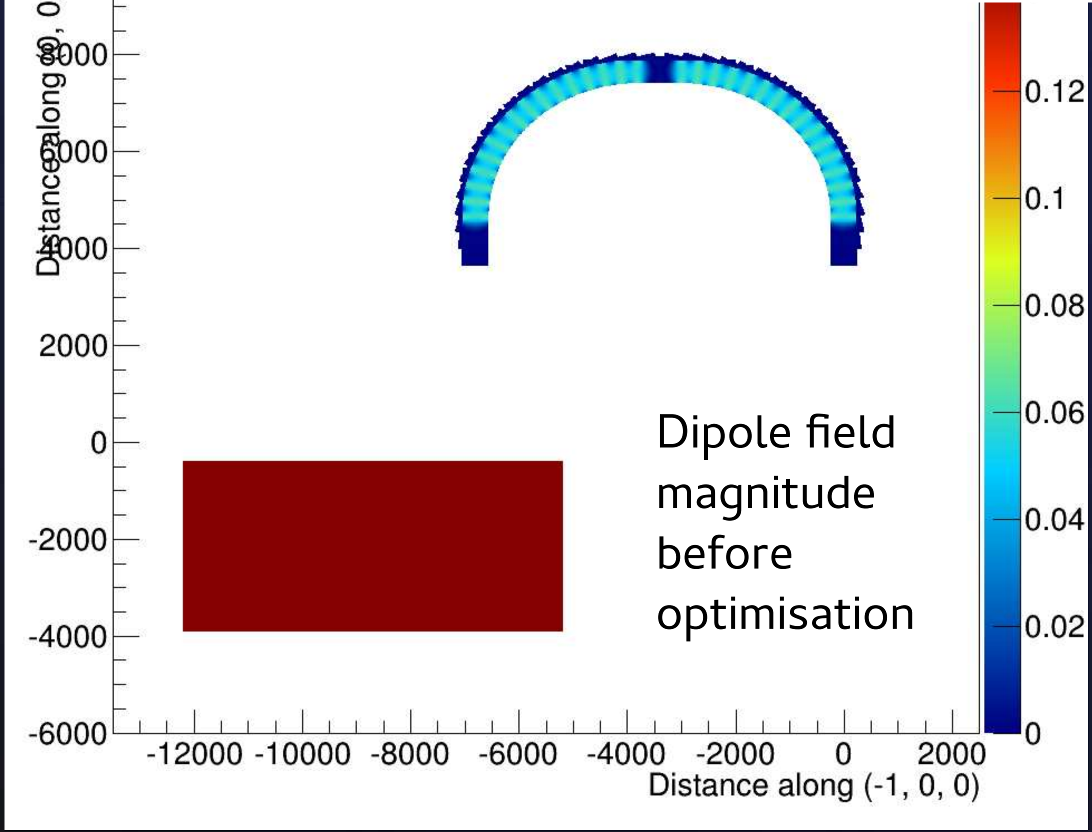
Fieldmap (G4Beamline)



- No field in detector solenoid

Dipole Field

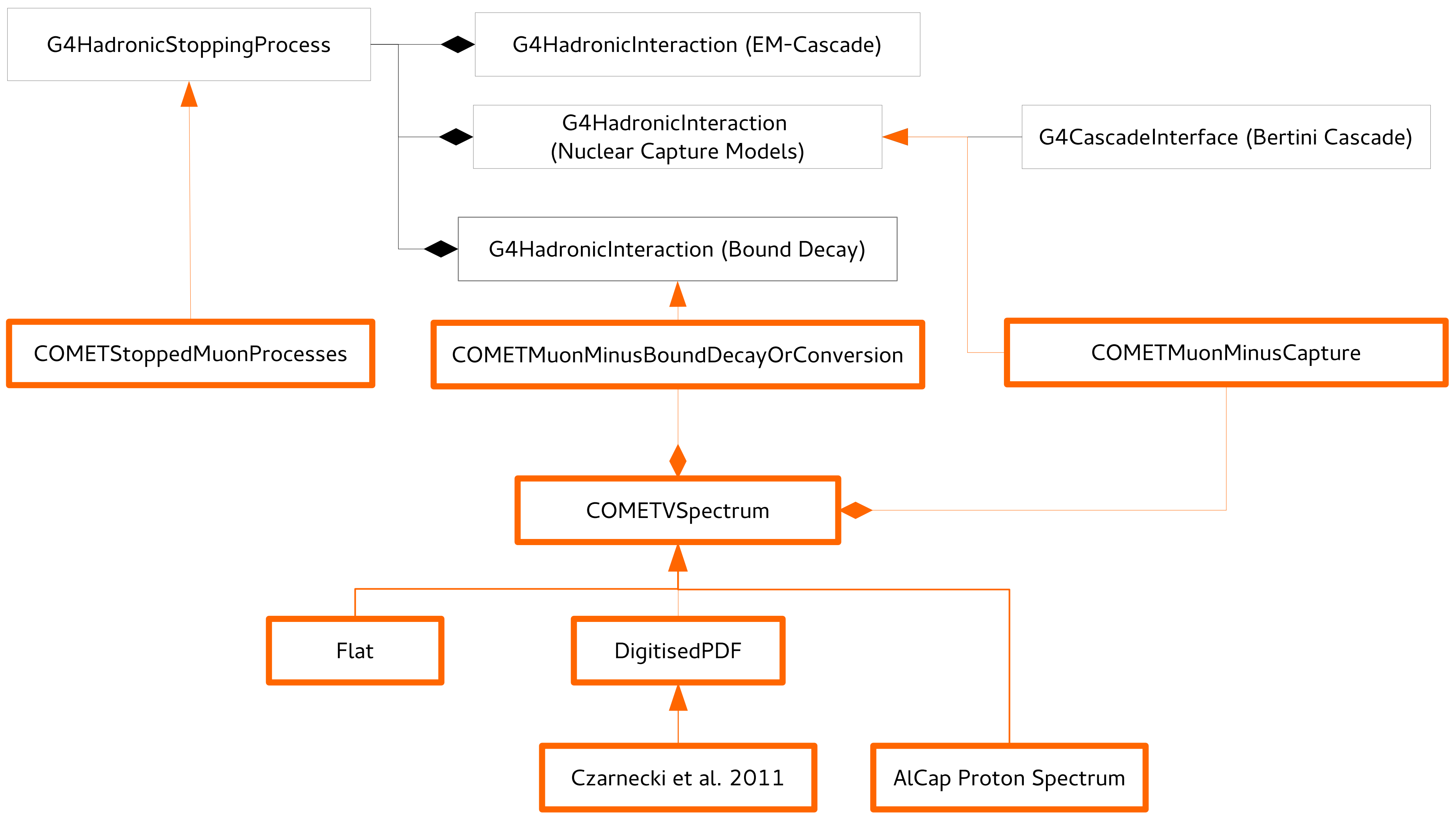




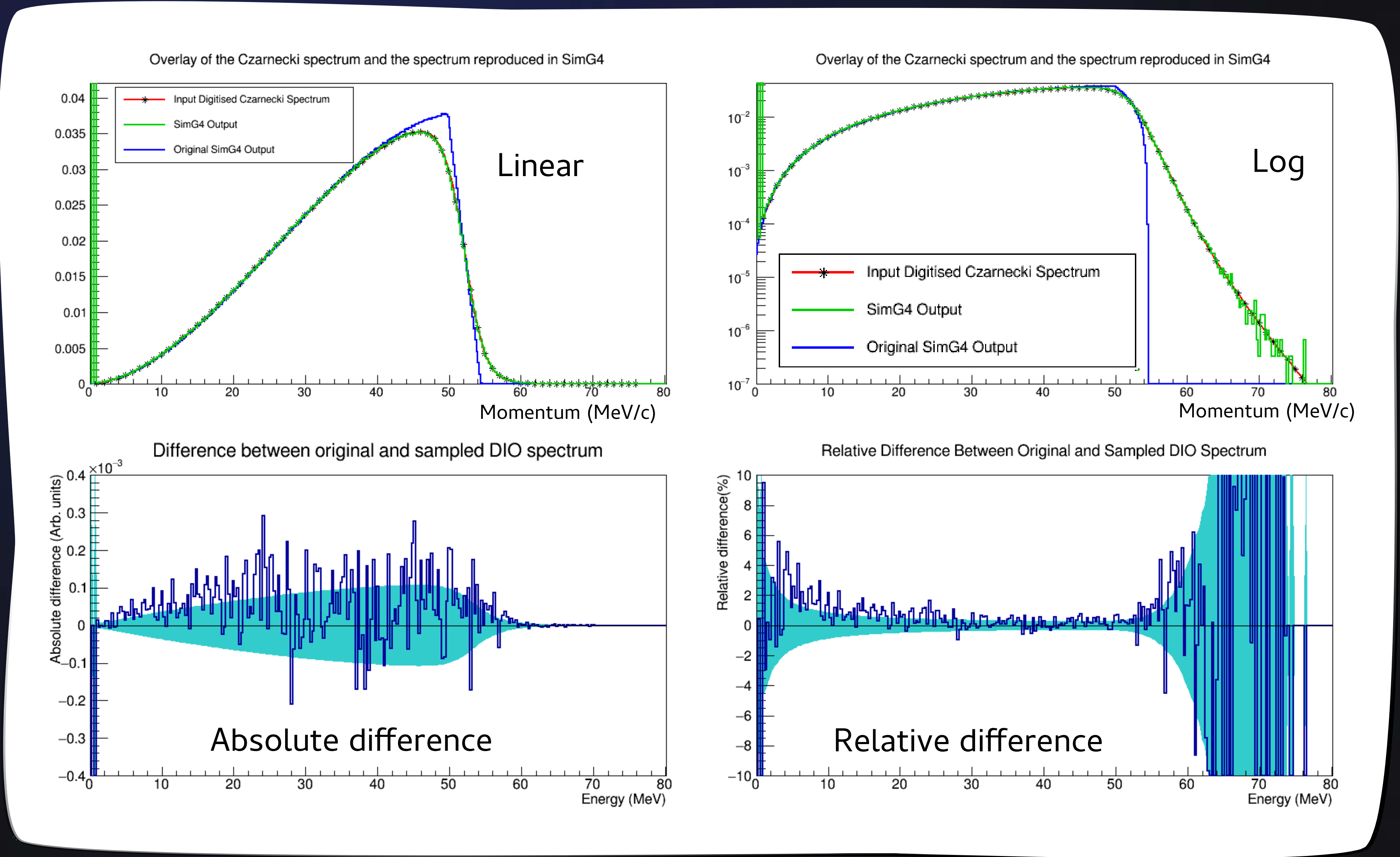
Dipole field magnitude before optimisation

- Have realistic dipole field calculation by Toshiba for the bent muon beam transport (TS2 and TS4)
- No calculation for Electron Spectrometer
  - Use uniform field

Custom Muon Physics Implementation

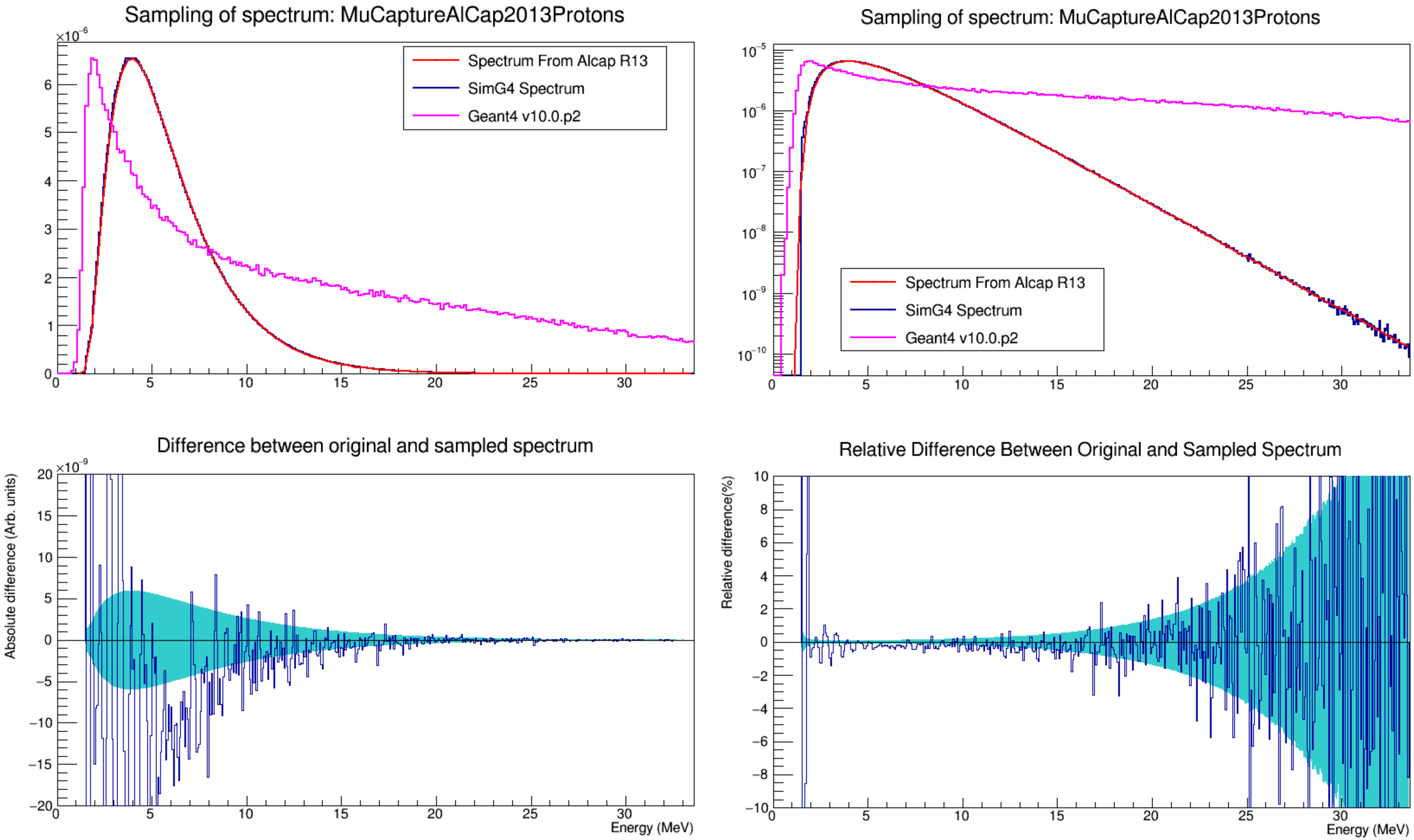


Decay-in-Orbit Spectrum

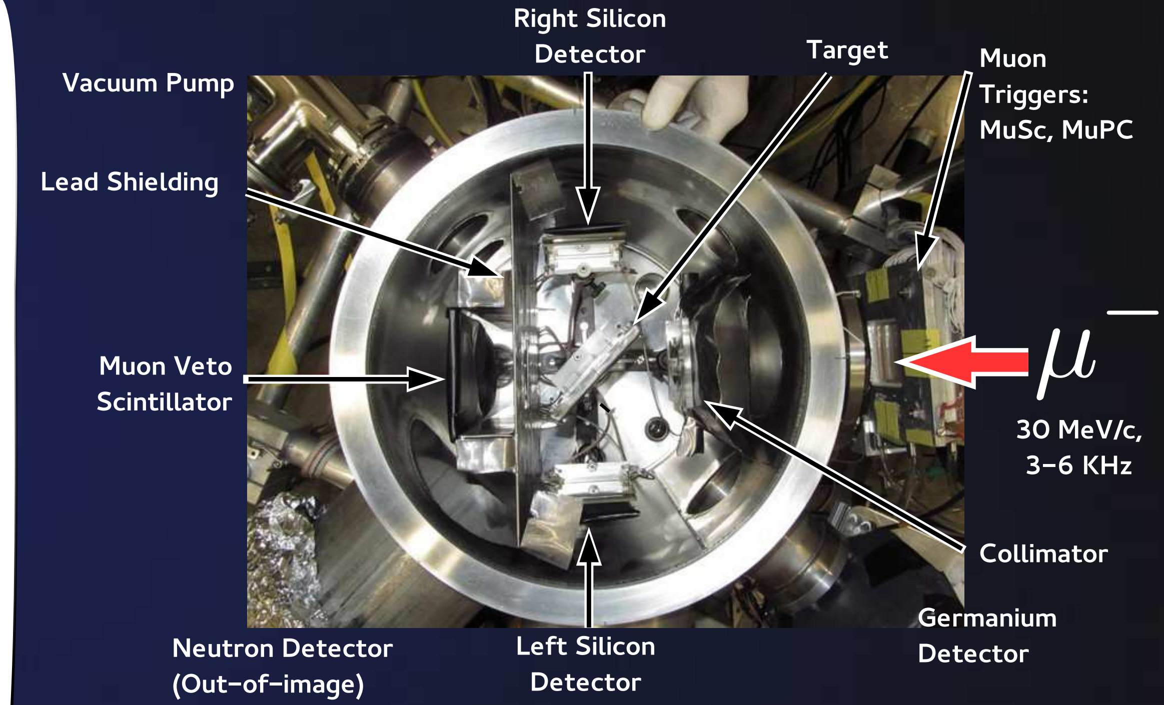


Proton Emission Following Muon Capture

AlCap Result



The AlCap Measurement



- COMET:
  - Osaka University
  - IHEP China
  - Imperial College London
  - University College London
- Mu2e
  - Argonne NL
  - Boston University
  - BNL
  - INFN
  - Fermilab
  - Univ. of Houston
  - Univ. of Washington

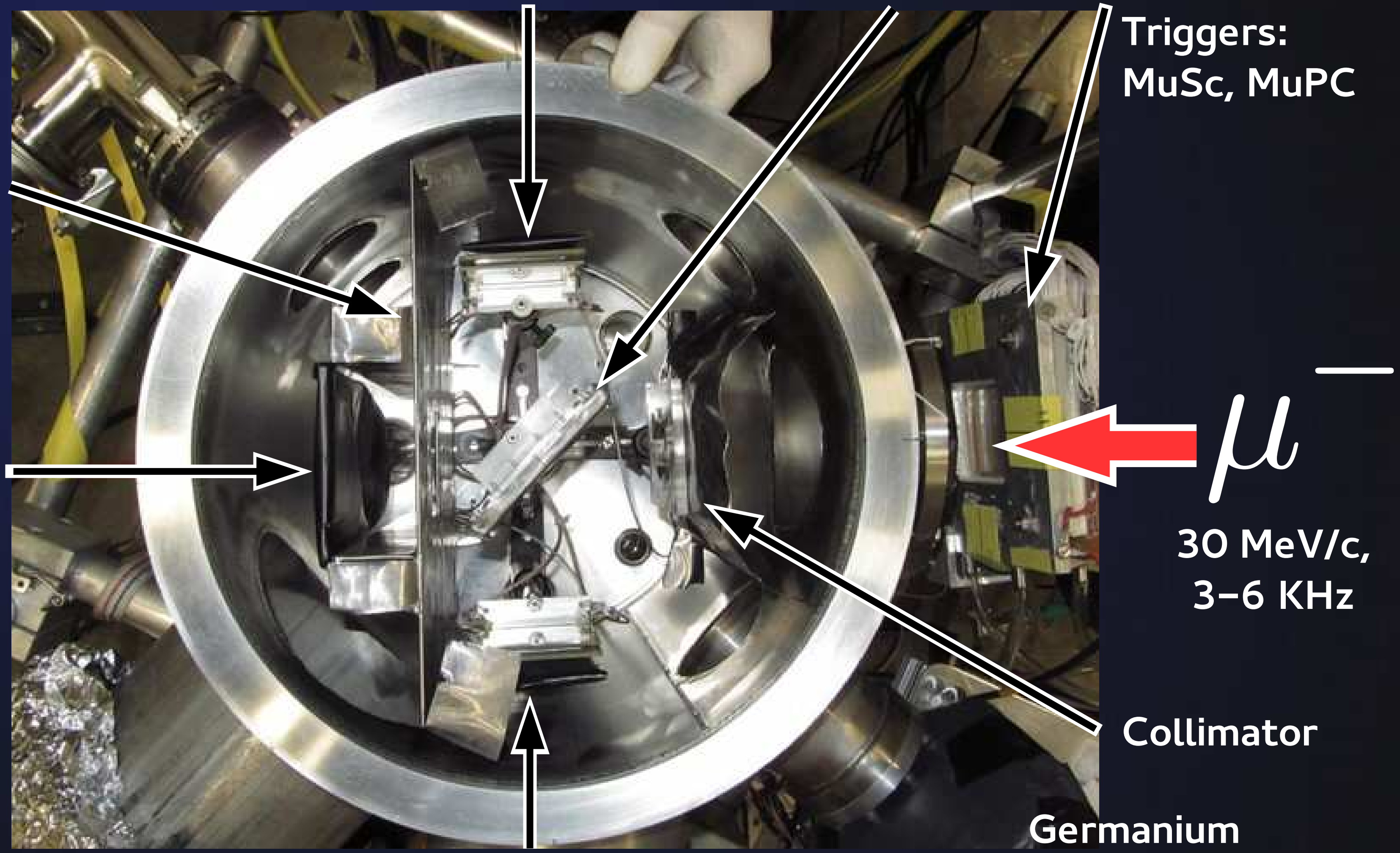
- 3 Runs at PSI:
  - 2013 for charged particles
  - 2015a for neutral particles
  - 2015b for charged particles

AlCap Work Packages

- WP1: Charged Particle emission after Muon Capture
  - Rate and spectrum with precision 5-10% down to 2.5 MeV
  - Dominant rate in tracker for Mu2e and COMET Phase-I
- WP2: X-ray and Gamma Emission after Muon Capture
  - X-ray and gamma ray for normalization (by Ge detector), radiative muon decay (by NaI detector)
- WP3: Neutron Emission after Muon Capture
  - Rate and spectrum from 1 MeV up to 10 MeV
  - BG for calorimeters and cosmic-ray veto, damage to electronics

Run 1 (2013)	**Run 2 (2015)**	**Run 3 (2015)**
WP1 and WP2	WP2 and WP3	WP1 and WP2

Run–1: Setup



Right Silicon Detector

Target

Muon Triggers: MuSc, MuPC

Vacuum Pump

Lead Shielding

Muon Veto Scintillator

μ^-

30 MeV/c, 3–6 KHz

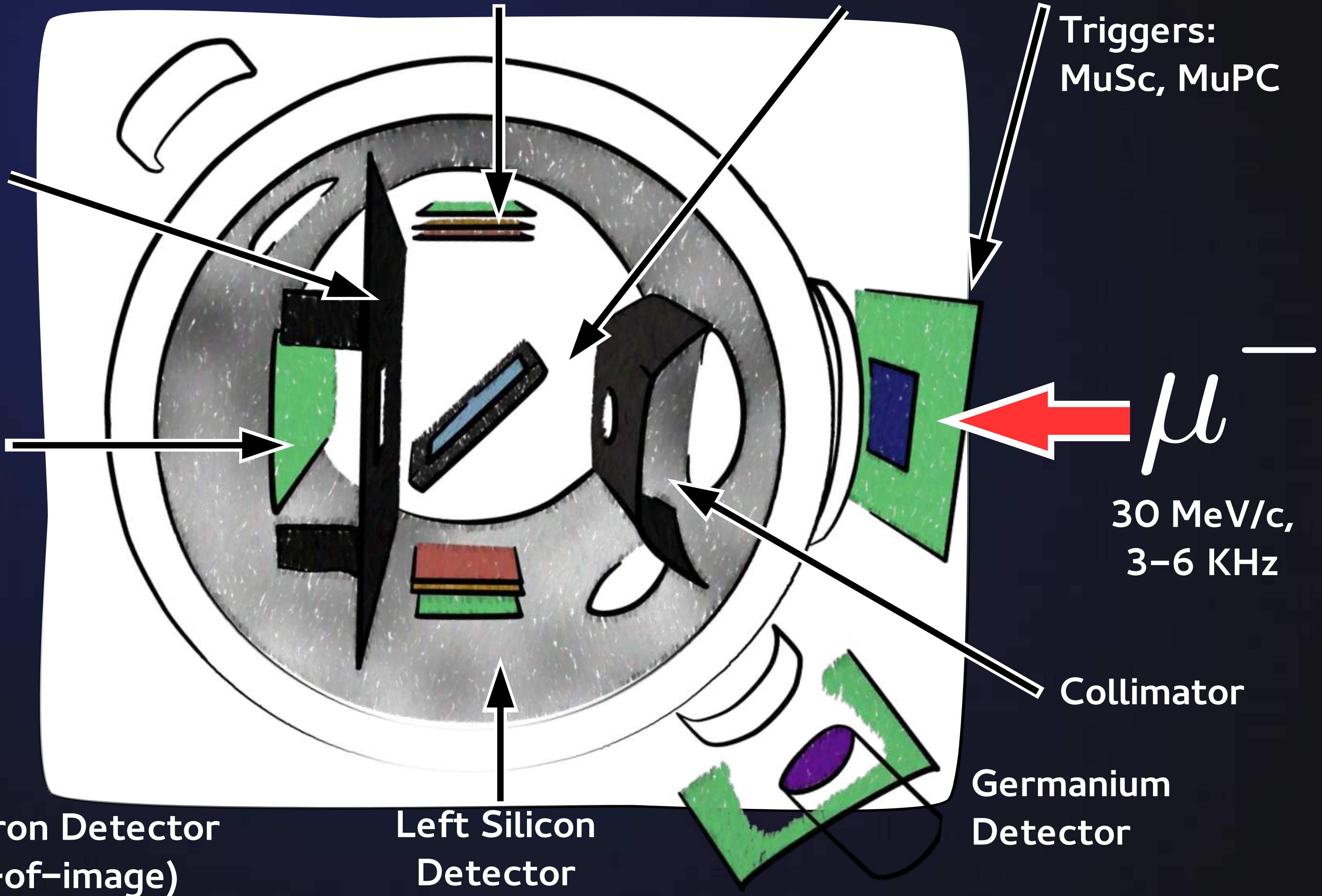
Collimator

Germanium Detector

Neutron Detector (Out–of–image)

Left Silicon Detector

Run–1: Setup



Right Silicon Detector

Target

Muon Triggers: MuSc, MuPC

Vacuum Pump

Lead Shielding

Muon Veto Scintillator

μ^-

30 MeV/c, 3–6 KHz

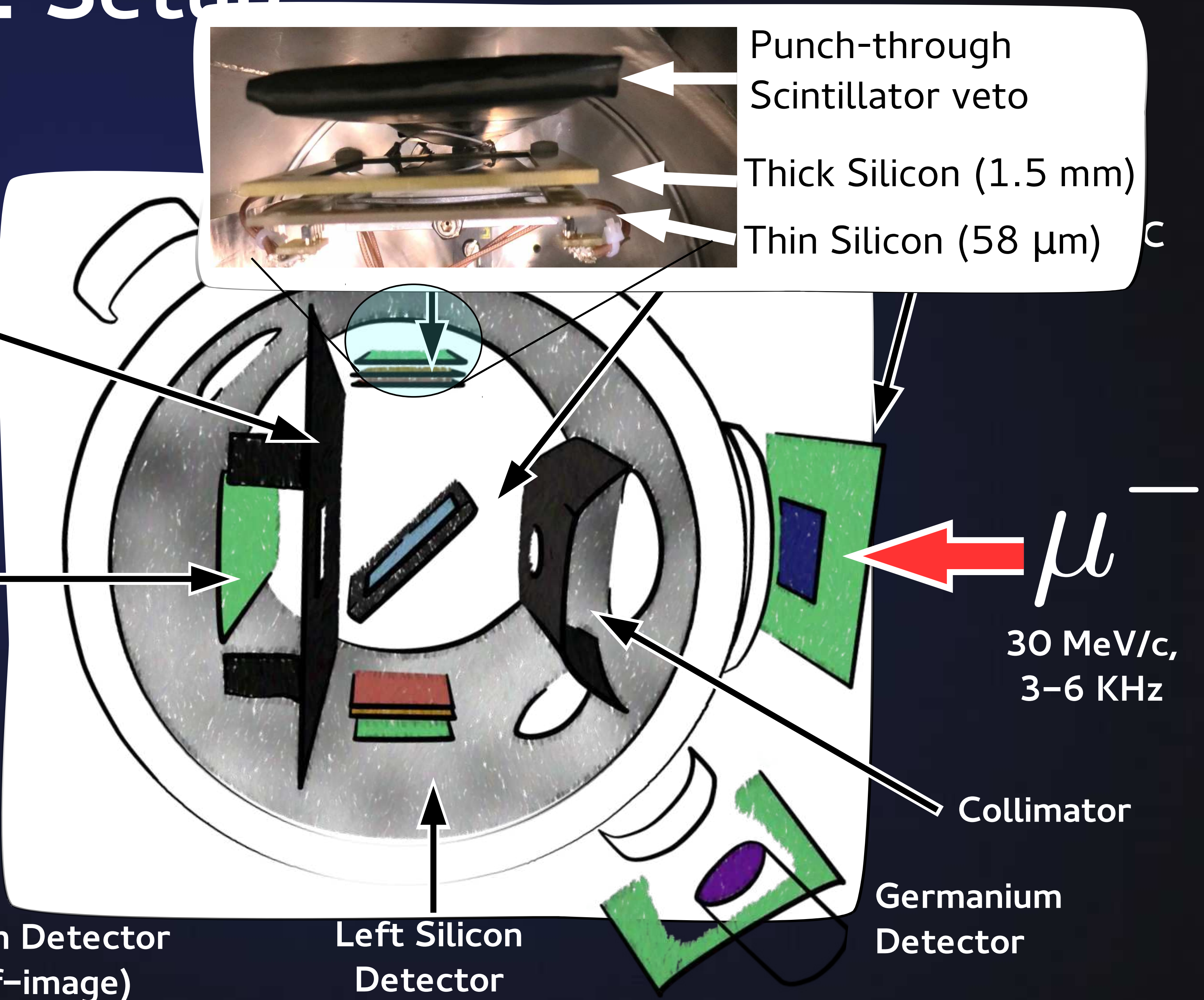
Collimator

Germanium Detector

Neutron Detector (Out–of–image)

Left Silicon Detector

Run−1: Setup



Vacuum Pump

Lead Shielding

Muon Veto Scintillator

Punch-through Scintillator veto

Thick Silicon (1.5 mm)

Thin Silicon (58 µm)

c

μ^-

30 MeV/c, 3−6 KHz

Collimator

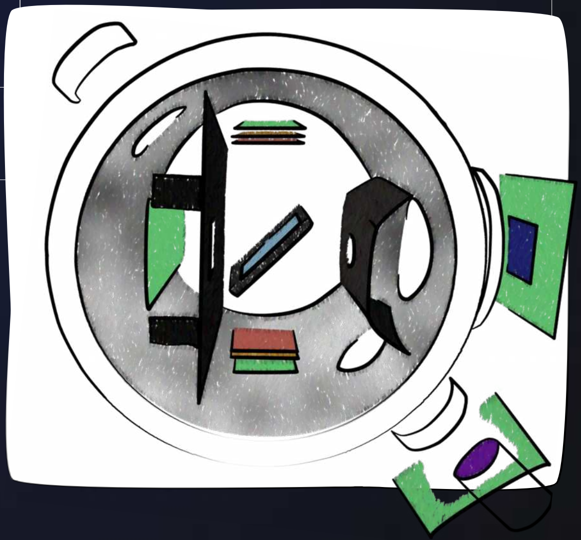
Germanium Detector

Neutron Detector (Out-of-image)

Left Silicon Detector

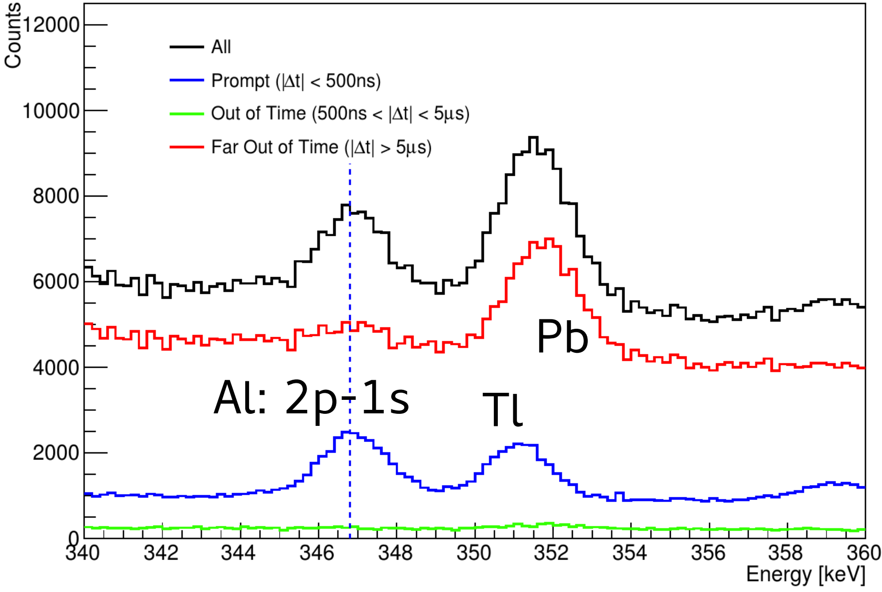
Run–1: Datasets

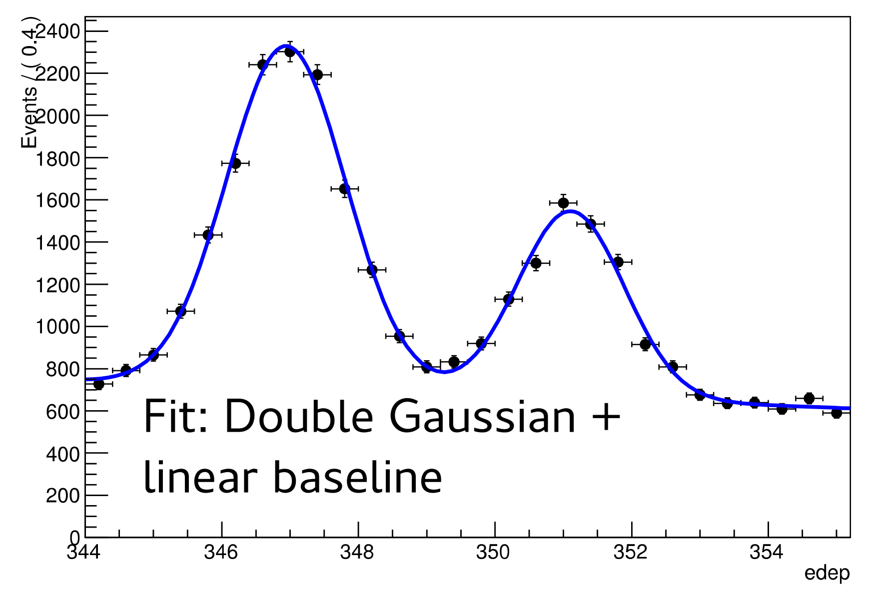
Target	Beam Momentum (x28 MeV/c)	Number of Muons ($\times 10^7$)	Comments
Si (1500 µm)	1.32	2.78	Active Target
	1.30	28.9	Cross check with existing Si data
	1.10	13.7	
Si (62 µm)	1.06	1.72	Passive Target
Al (100 µm)	1.09	29.4	
	1.07	4.99	
Al (50 µm)	1.07	88.1	



Number of Stopped Muons

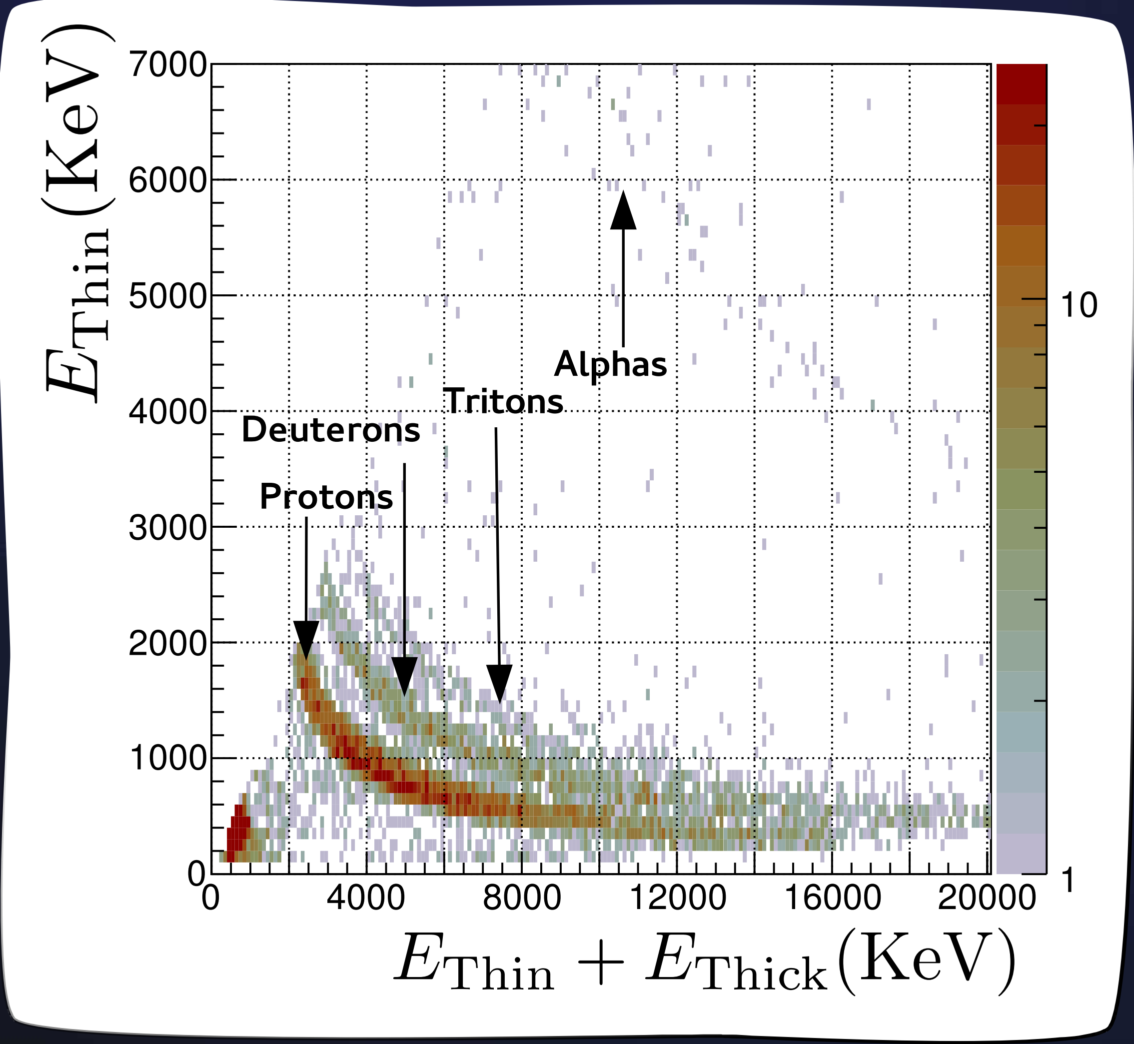
- Germanium detector
  - X-rays from muon electromagnetic cascade to 1s orbital
- Muon selection criteria
  - Incoming muon cuts
    - Muon scintillator energy
  - Muon pile-up protection
  - Prompt X-rays (<500ns)
- Fit 2p-1s peak at 347 KeV
  - Gaussian
  - Background:
    - Linear baseline
    - Second Gaussian for nearby Pb/Tl capture peak

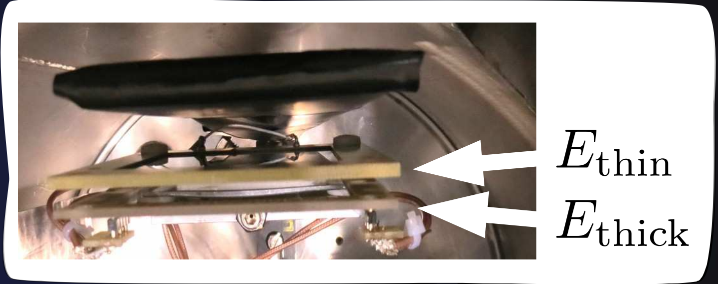




Fit: Double Gaussian + linear baseline

Charged Particle Measurement





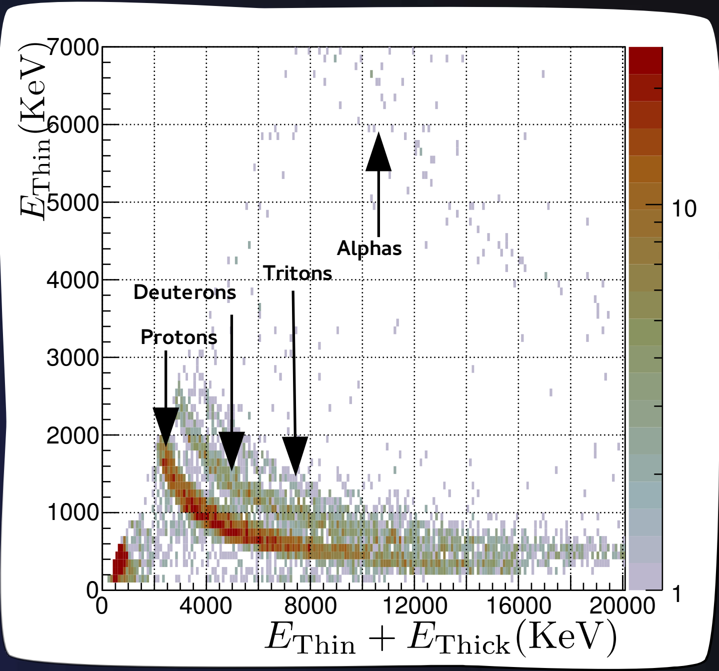
Identification of Stopped Particle Species using Thin and Thick energy deposits:

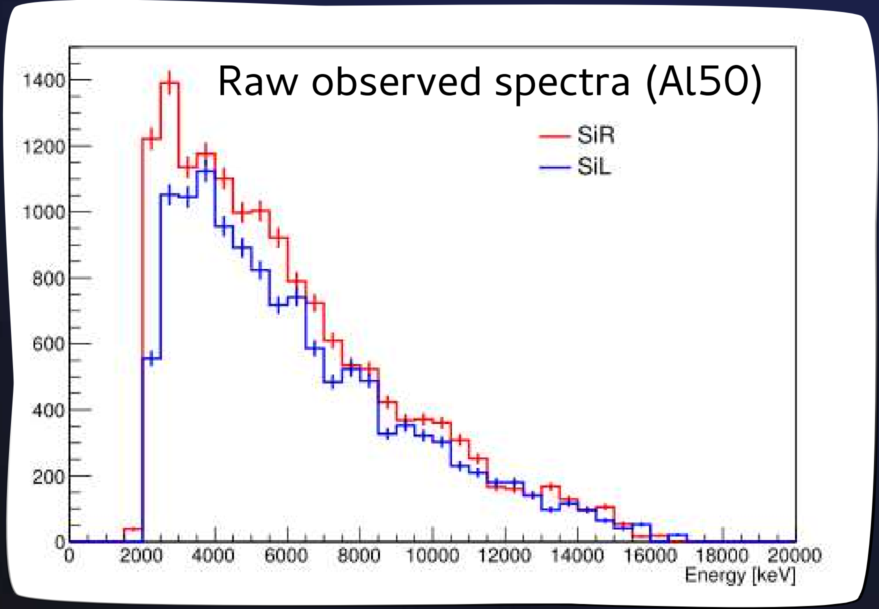
$$E_{\text{Thin}} = \frac{dE}{dx}\Delta x$$

$$E_{\text{Thin}} + E_{\text{Thick}} = E_{\text{Total}}$$

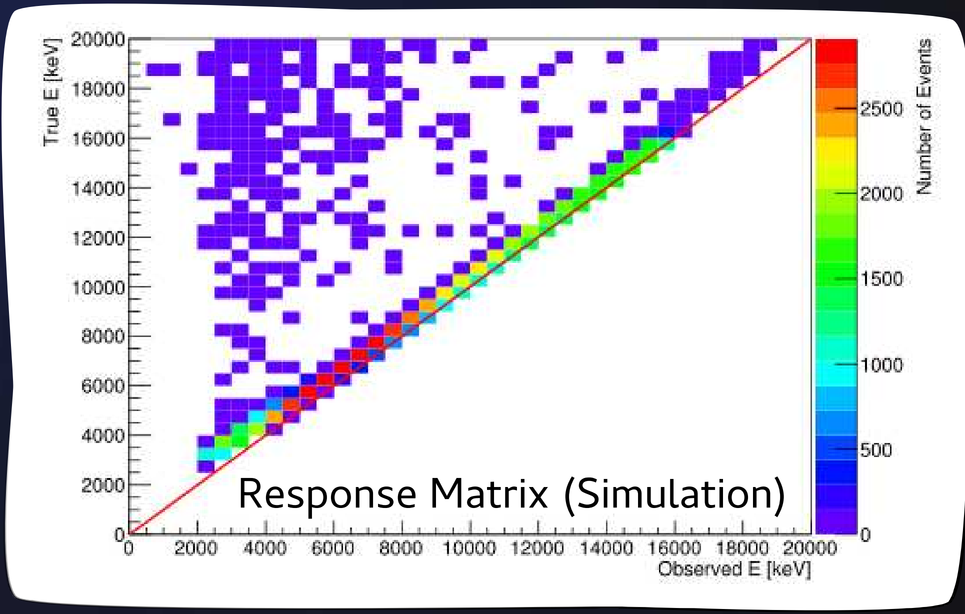
Charged Particle Measurement

- Hit selection criteria:
  - Time of hit > 100 ns since muon (removes scattered muons, lead capture products)
  - PID cut
    - Geometric
    - Probability based on Monte Carlo





Raw observed spectra (Al50)



Response Matrix (Simulation)

First Tentative Signs?

- Higgs to Tau-mu
- Lepton non-universality:
  - Muon G-2
  - Lamb shift in muonic hydrogen
- Ratio of $\mathcal{BR}(\mathrm{B_s} \to \mu\mu)/\mathcal{BR}(\mathrm{B_s} \to \mathrm{ee})$
- Angular distribution in $\mathrm{B^0} \to \mathrm{K^*}\mu\mu$