The COMET Experiment

Searching for Muon-to-Electron Conversion

Ben Krikler 24th May 2017

Previously
Imperial College London

Currently
University of BRISTOL

Outline of this talk

Charged Lepton Flavour Violation

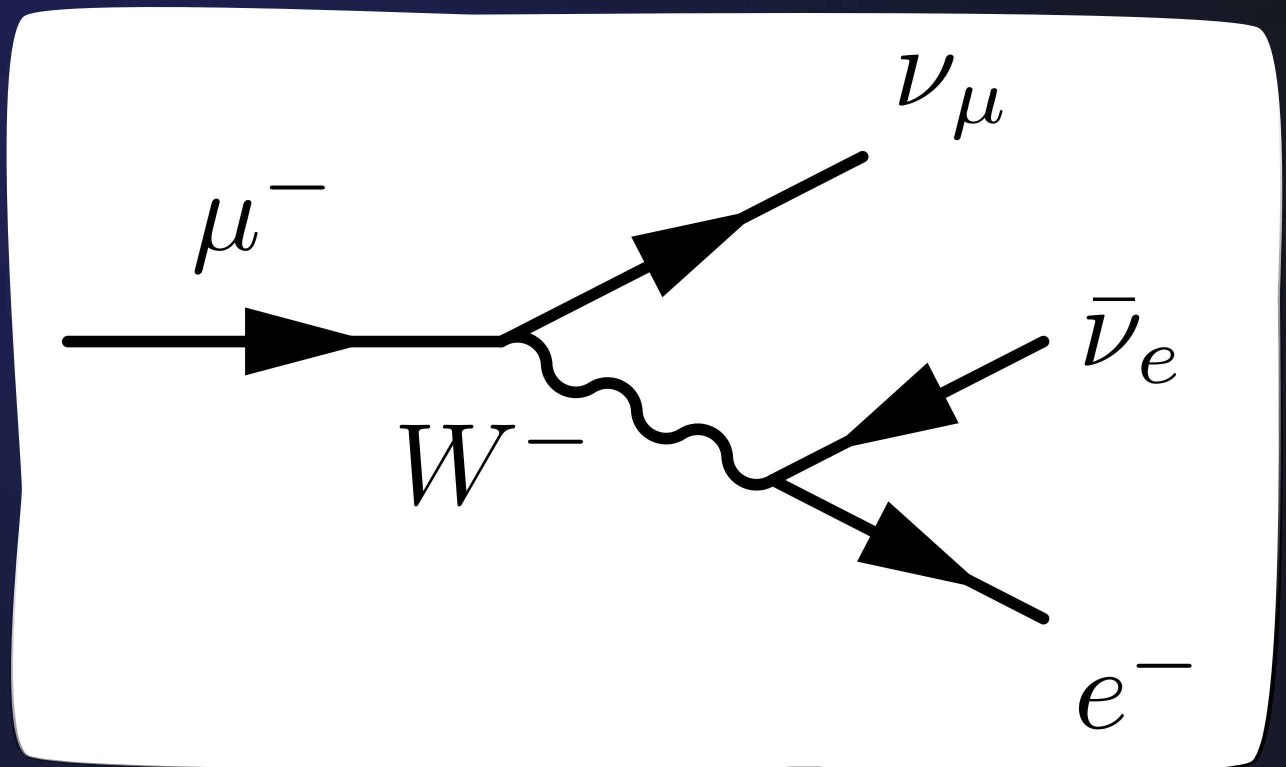
Muon-to-Electron Conversion

The COMET Experiment

Phase-I Status and Schedule

Charged Lepton Flavour Violation

Muon Decay

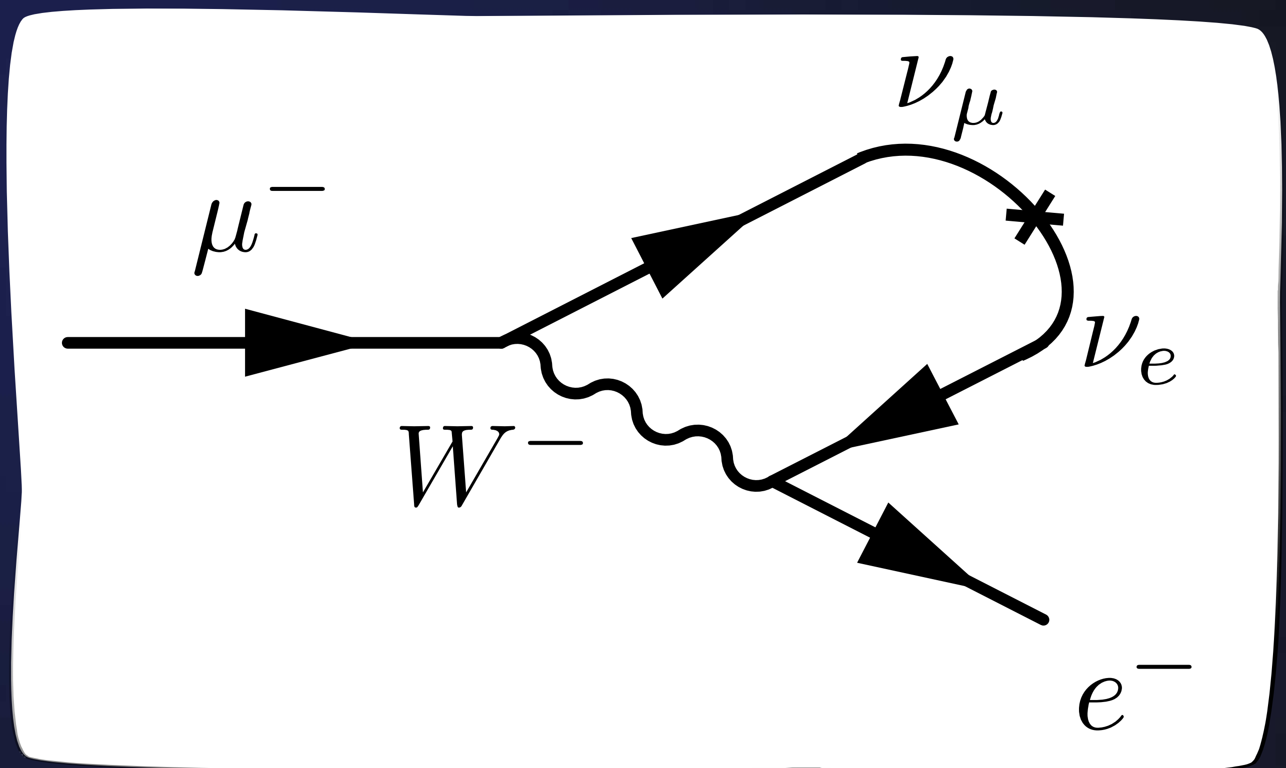


Conservation of Lepton Flavour:

1 muon → 1 muon-neutrino

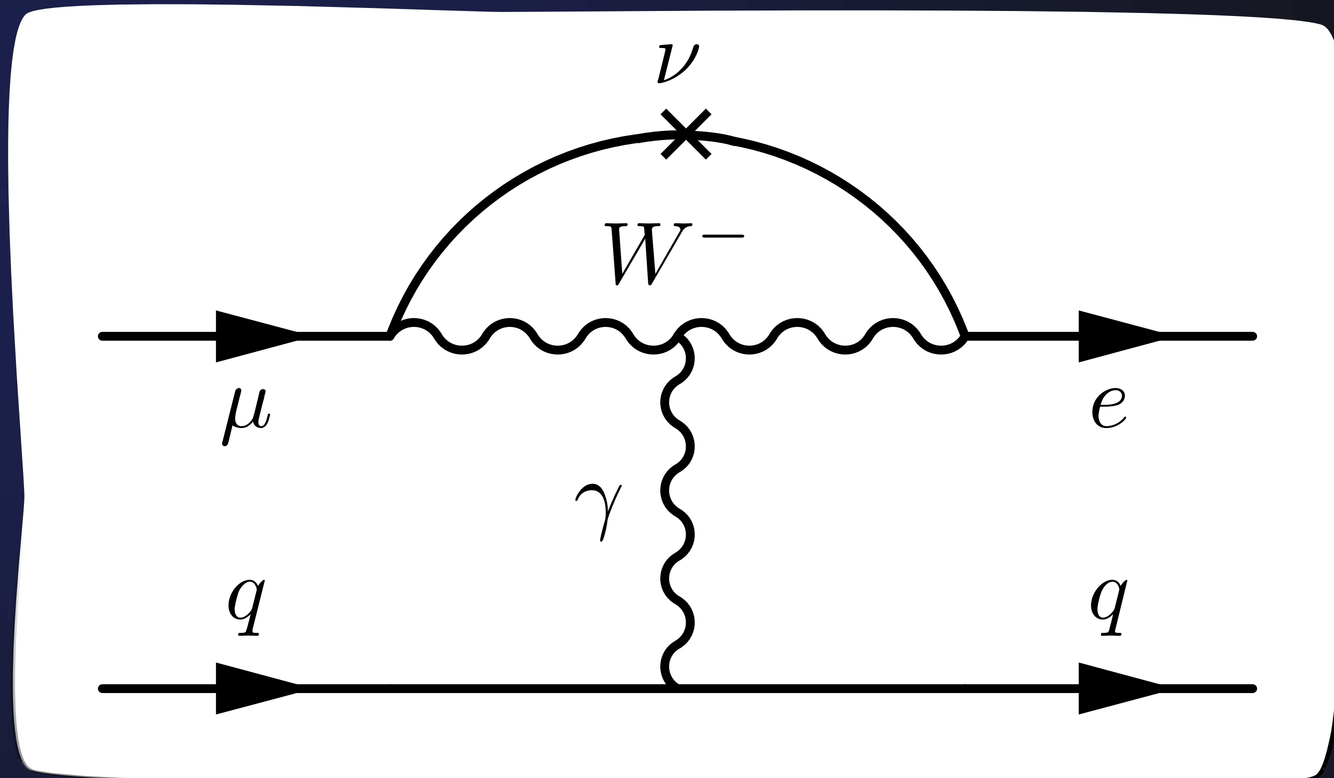
0 electrons → 1 electron + 1 anti electron-neutrino

Muon Decay + Neutrino Oscillations



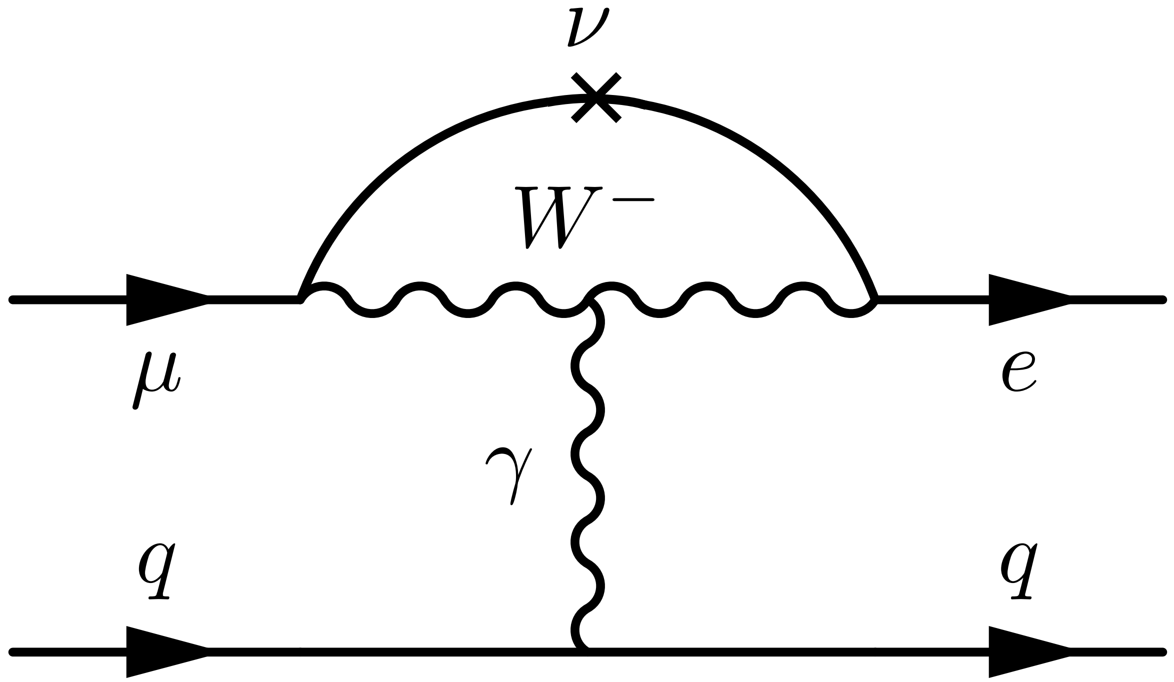
- 1 muon → 1 electron
- No outgoing neutrinos
- BUT: would not conserve energy and momentum

Muon-to-Electron Conversion
via Neutrino Oscillations



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

Muon-to-Electron Conversion
via Neutrino Oscillations



Conversion Rate:

GIM Suppressed

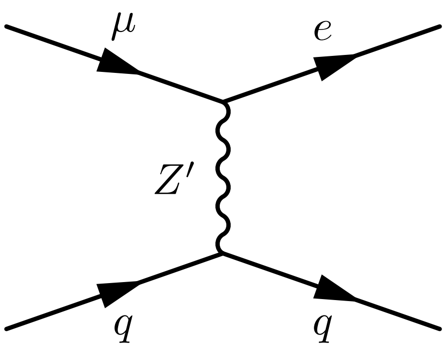
$$\mathcal{R} = \mathcal{O}\left(\frac{(\Delta M_\nu^2)^2}{(M_W^2)^2}\right) \sim 10^{-54}$$

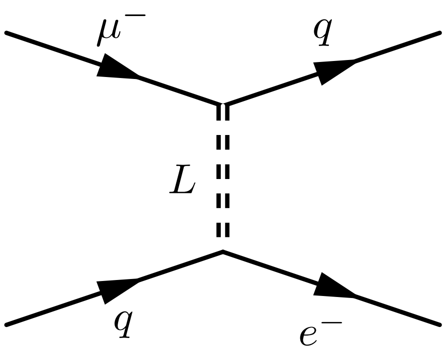
Heavily suppressed in the SM:

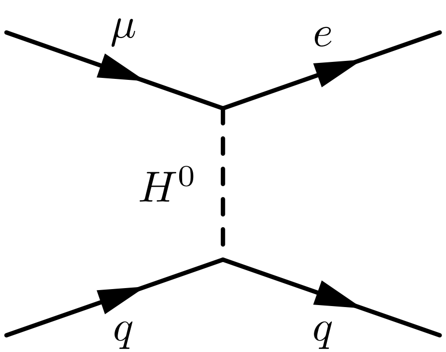
- Neutrino mass-mixing → GIM suppression
- Low-momentum transfer compared to mass of W boson

Muon to Electron Conversion

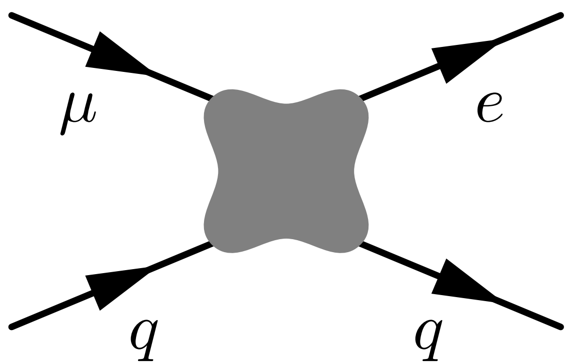
Beyond the Standard Model



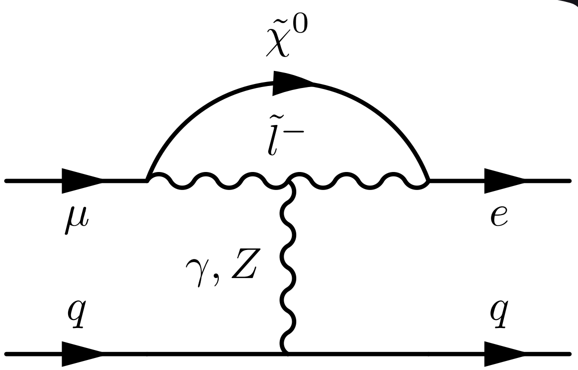


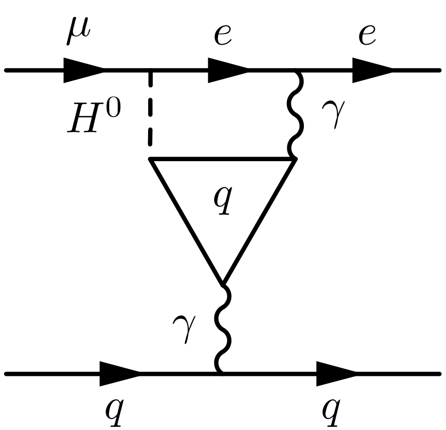


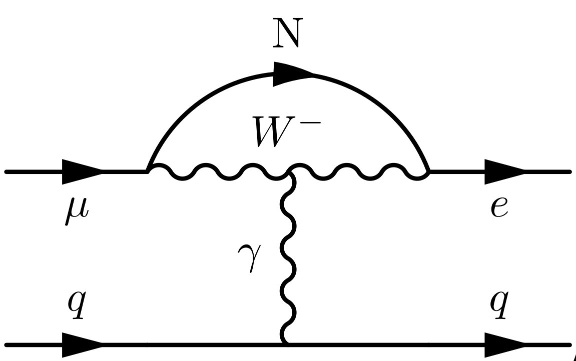
- Predicted in many Beyond the Standard Model theories
- Rate is model dependent but only constrained by direct CLFV searches



Current limits: $\mathcal{R} < \mathcal{O}(10^{-14})$

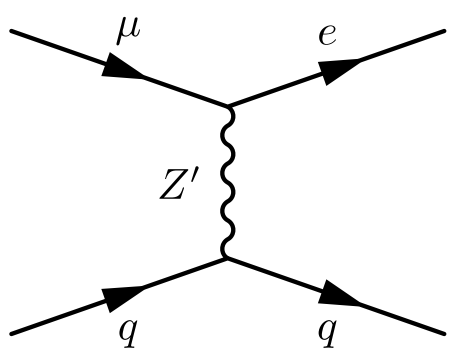


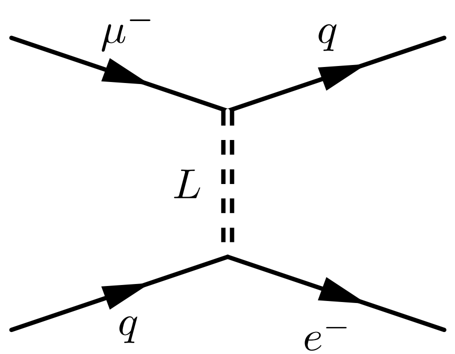


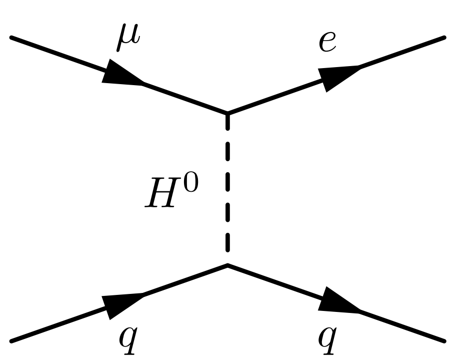


Muon to Electron Conversion

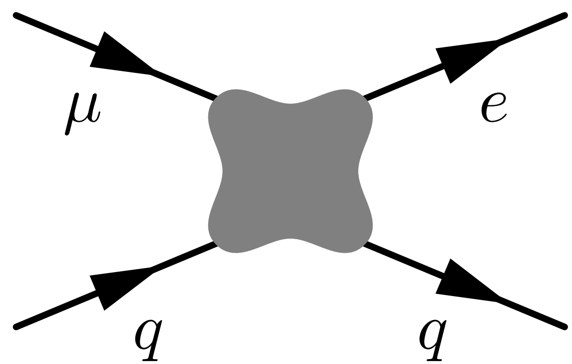
Beyond the Standard Model





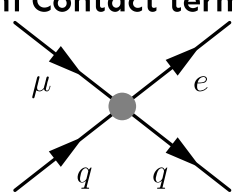


- Predicted in many Beyond the Standard Model theories
- Rate is model dependent but only constrained by direct CLFV searches

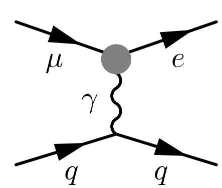


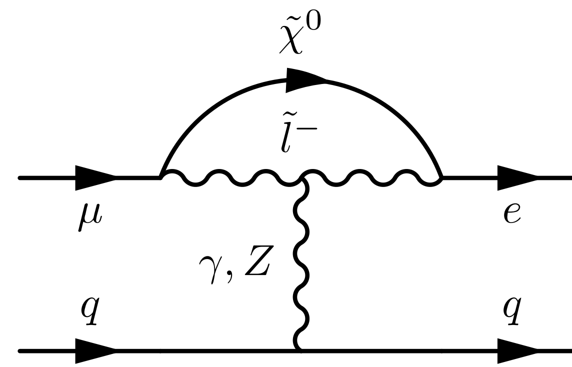
Current limits: $\mathcal{R} < \mathcal{O}(10^{-14})$

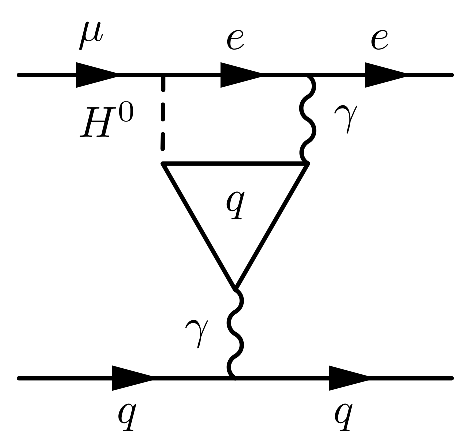
← New physics couples to quarks via new heavy exchange particle
4-Fermi Contact term

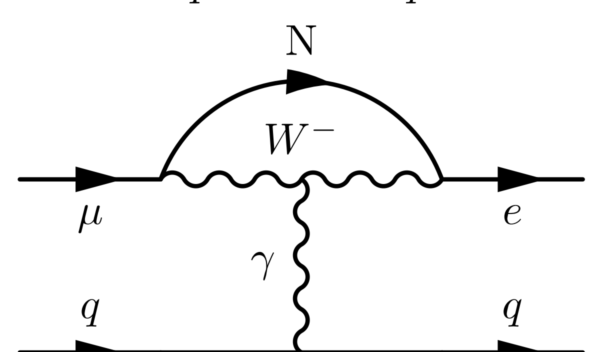


→ New physics couples to quarks via a photon:
Photonic term

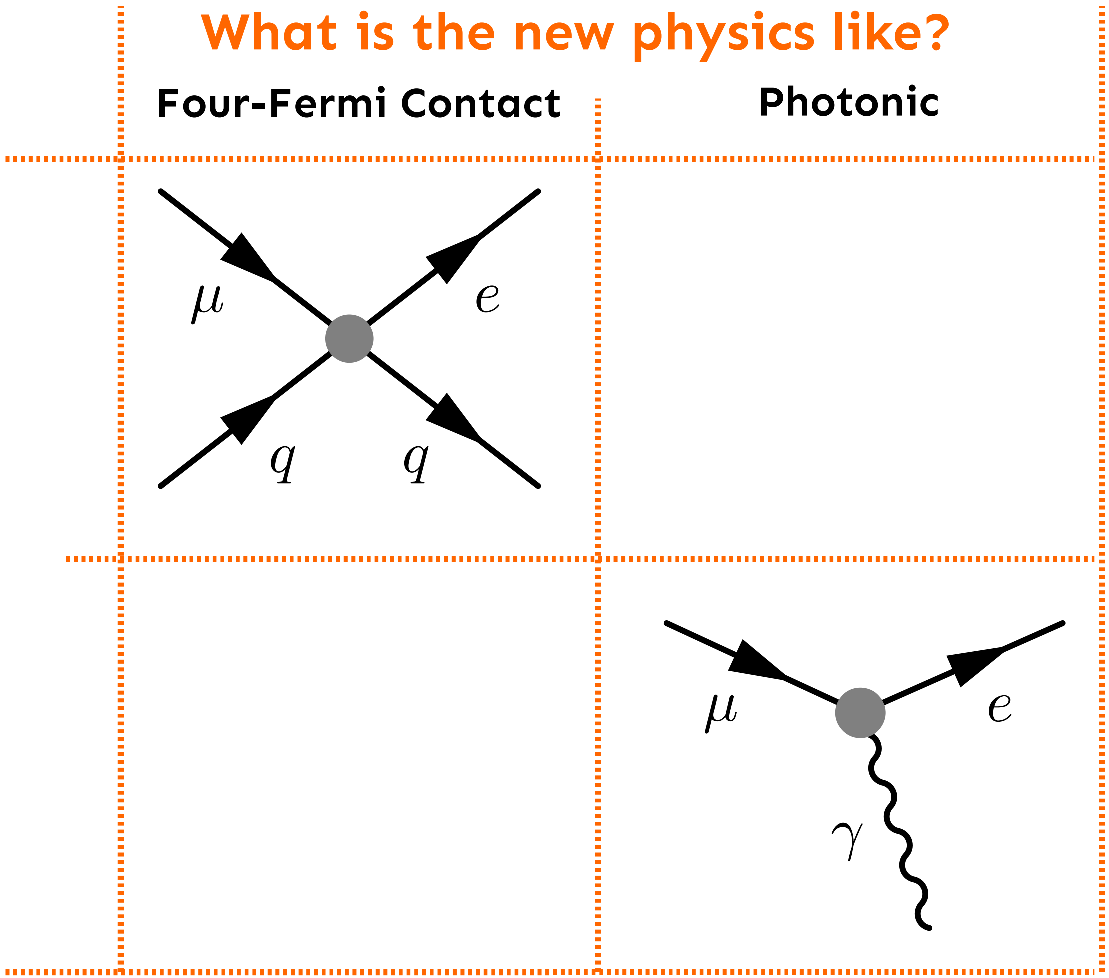








μ→e gamma vs μ-e conversion



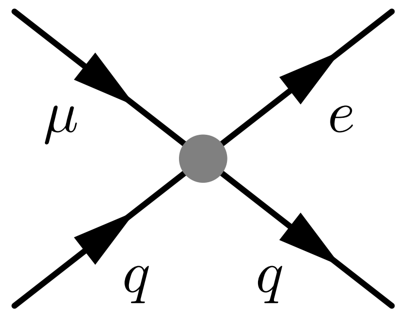
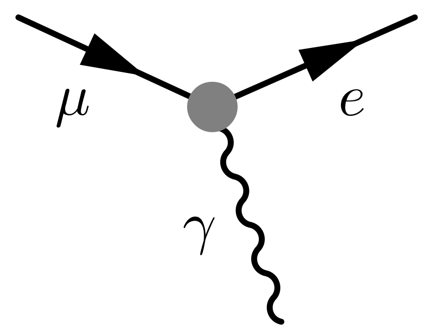
- Relative sensitivity in μ-e conversion and μ→e gamma is very model dependent

Highly complementary searches between μ→e gamma and μ-e conversion

μ→e gamma vs μ-e conversion

What is the new physics like?

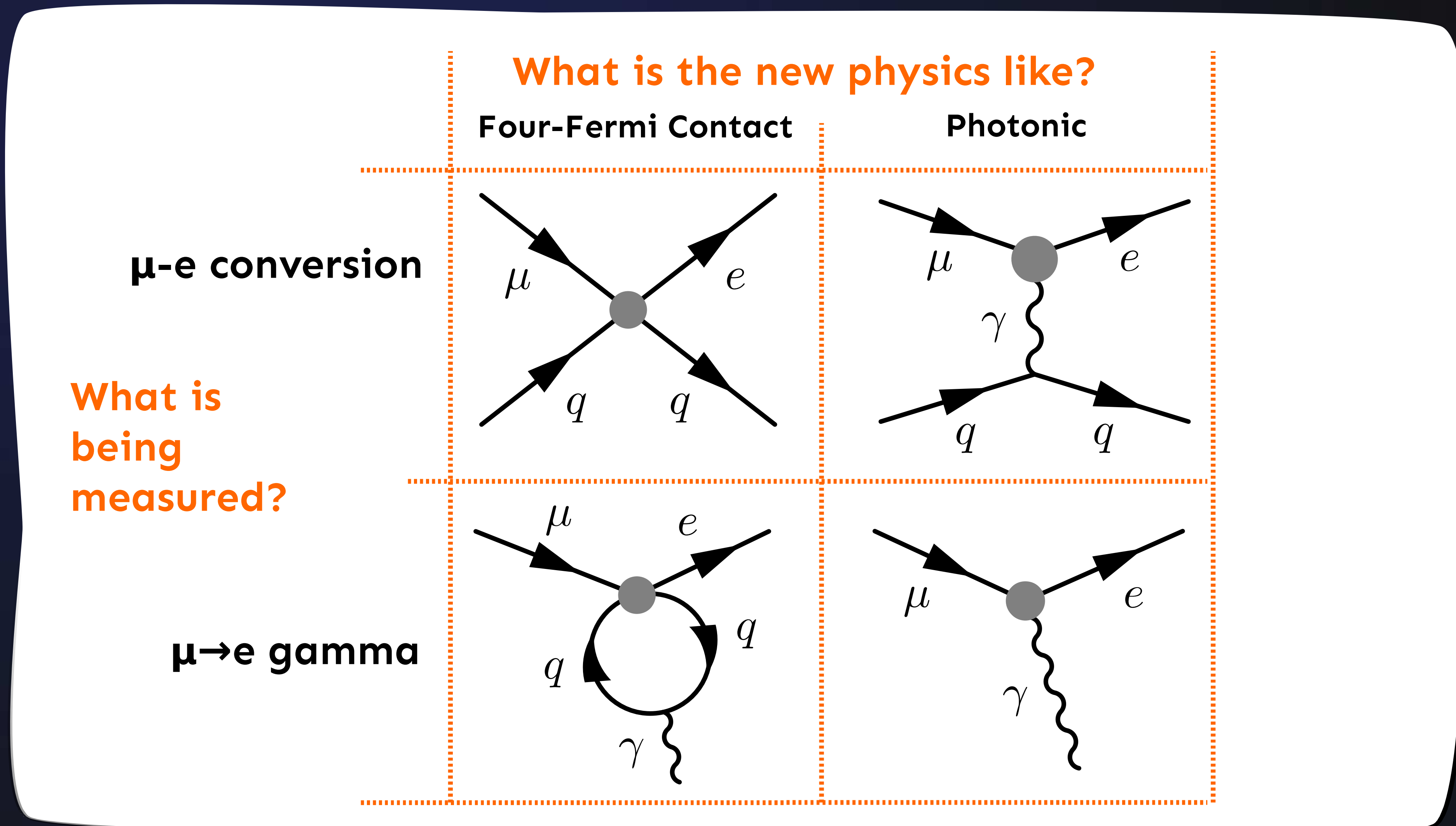
What is being measured?

	Four-Fermi Contact	Photonic
μ-e conversion		
μ→e gamma		

- Relative sensitivity in μ-e conversion and μ→e gamma is very model dependent

Highly complementary searches between μ→e gamma and μ-e conversion

μ→e gamma vs μ-e conversion

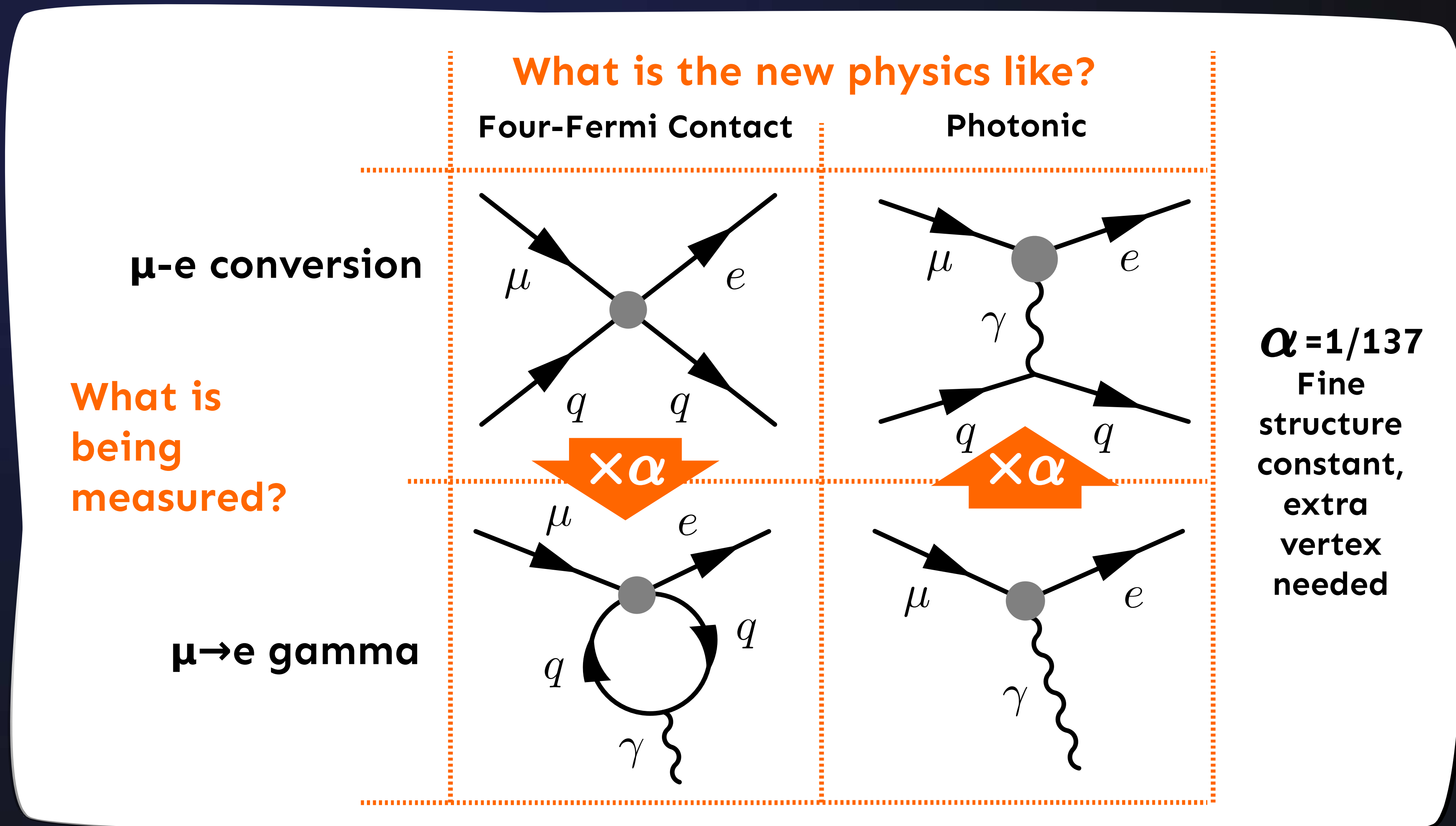


- Relative sensitivity in μ-e conversion and μ→e gamma is very model dependent

Highly complementary searches between μ→e gamma and μ-e conversion

Ben Krikler: b.krikler@bristol.ac.uk

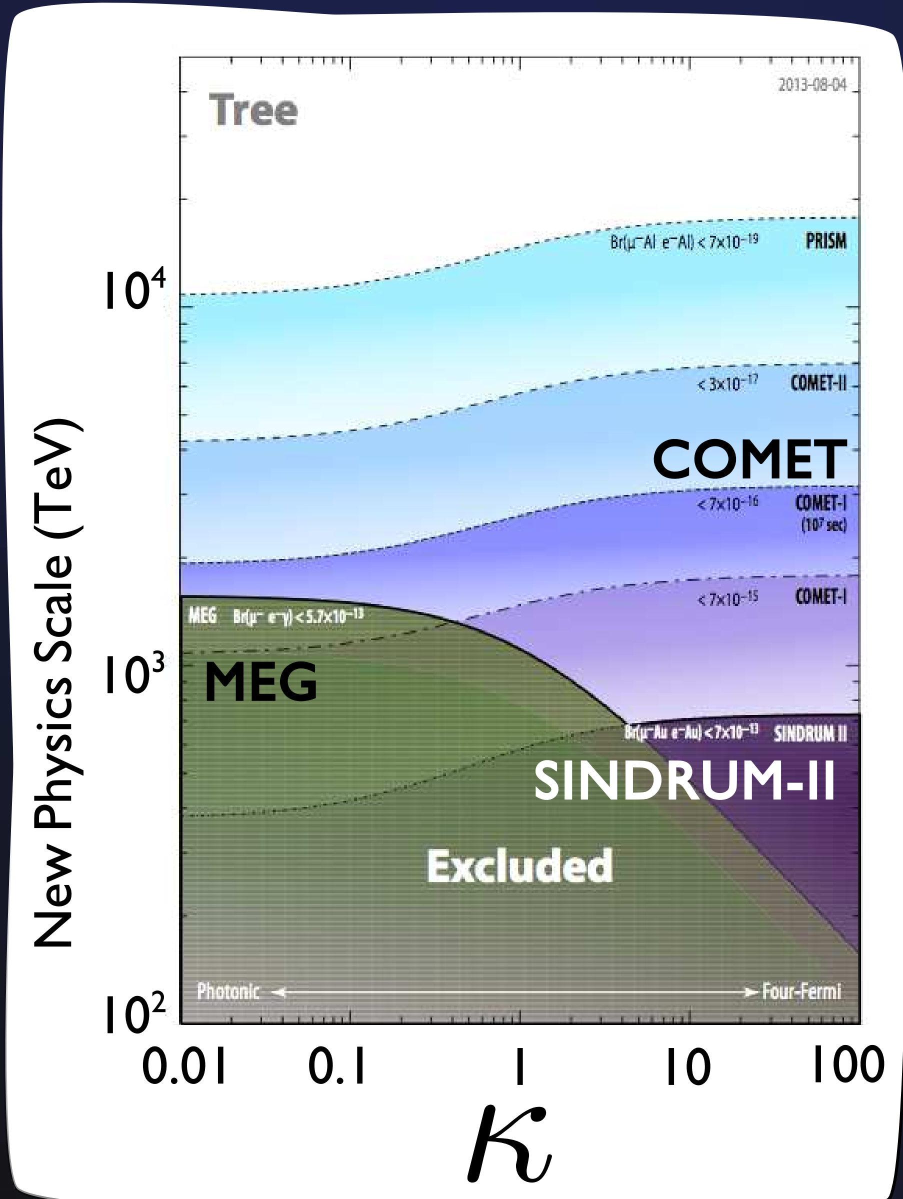
μ→e gamma vs μ-e conversion



- Relative sensitivity in μ-e conversion and μ→e gamma is very model dependent

Highly complementary searches between μ→e gamma and μ-e conversion

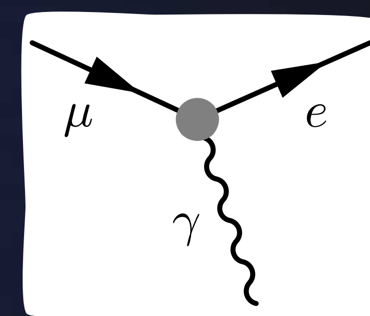
μ→e gamma vs μ-e conversion



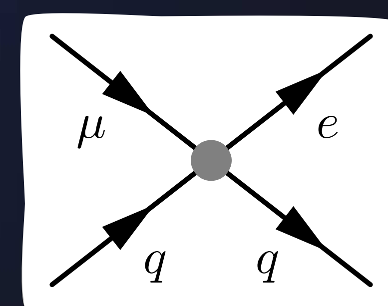
- In reality New Physics will not be one or the other but somewhere in between.
- Use a toy lagrangian to study sensitivity:

Photonic
$\kappa \rightarrow 0$

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



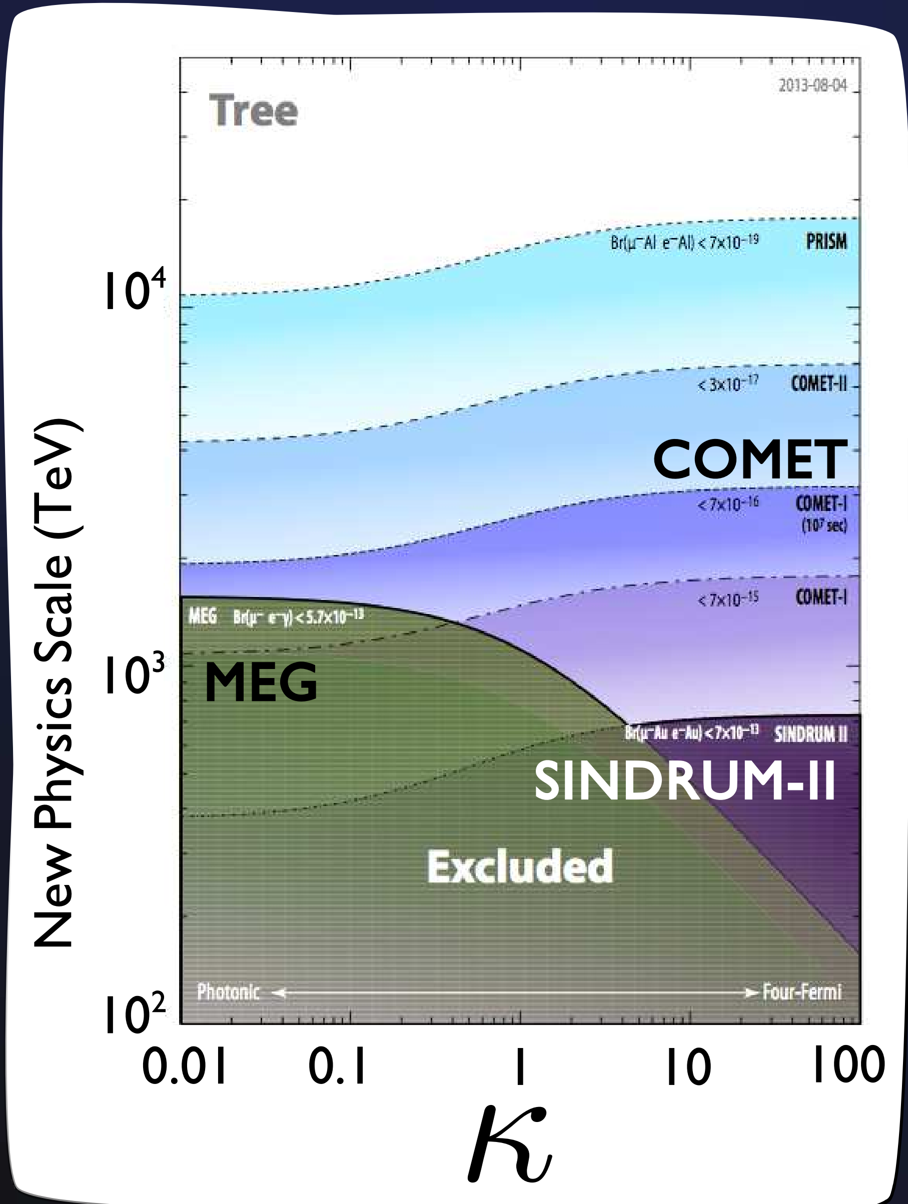
$$\left. \right\} + \frac{\kappa}{\kappa+1}\left\{ \right.$$



$$\left. \right\}$$

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

μ→e gamma vs μ-e conversion



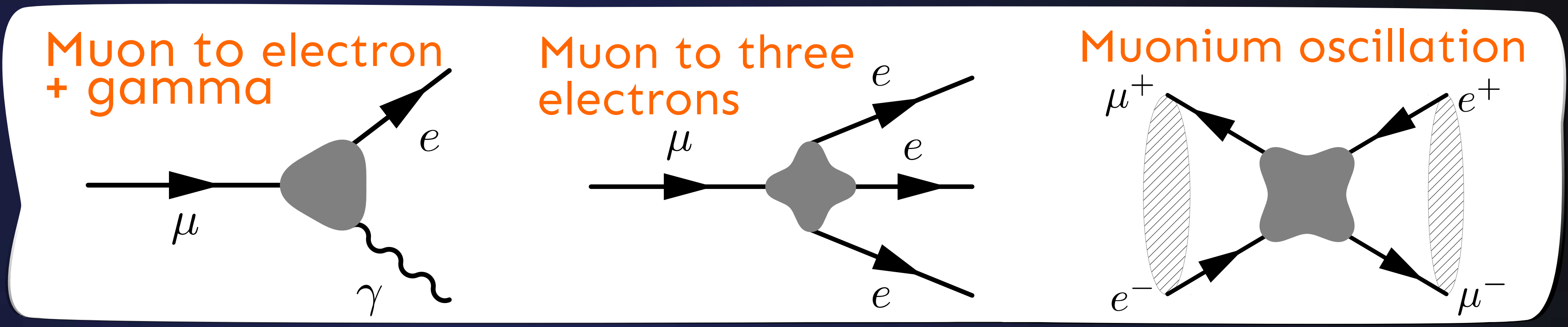
- In reality New Physics will not be one or the other but somewhere in between.
- Use a toy lagrangian to study sensitivity:

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

- Sensitive to energy scales a few orders of magnitude above direct searches

CLFV: Beyond mu-e conversion

- Current searches related to muon-to-electron conversion:



- Some tentative signs of new physics amongst charged leptons:
  - Several anomalies at LHCb and B-factories
  - Muon g-2 anomaly
  - Proton radius puzzle
- Charged Lepton Flavour Violation experiments help to understand:
  - The neutrino mass generation mechanism, the scale of the active neutrino masses and the possibility of heavy sterile neutrinos
  - Baryon assymmetry in the universe [Deppisch et al. PRD 92, 036005]
  - Lepton universality in the SM [Glashow et al. PRL 114 (2015) 091801]
  - The validity of Minimal Flavour Violation in BSM models?

The Muon-to-electron Conversion Process

Muon to Electron Conversion

Charged Lepton Flavour Violation:

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

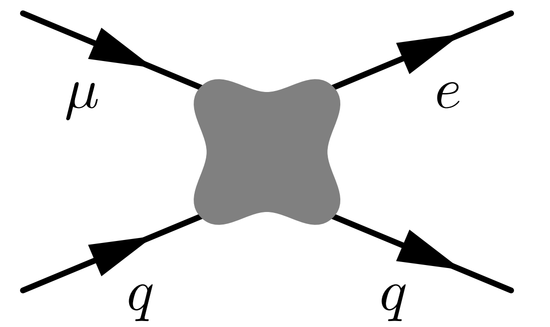
Require that nucleus is unchanged:

- coherent terms dominate
- conversion rate grows with number of nucleons
- fixes the kinematics:

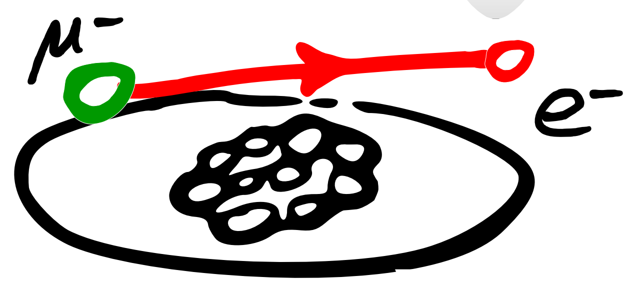
$$\mathrm{E_e} = \mathrm{m}_\mu - \mathrm{B}_\mu - \mathrm{E}_{\mathrm{recoil}}$$

On aluminium, used by COMET:

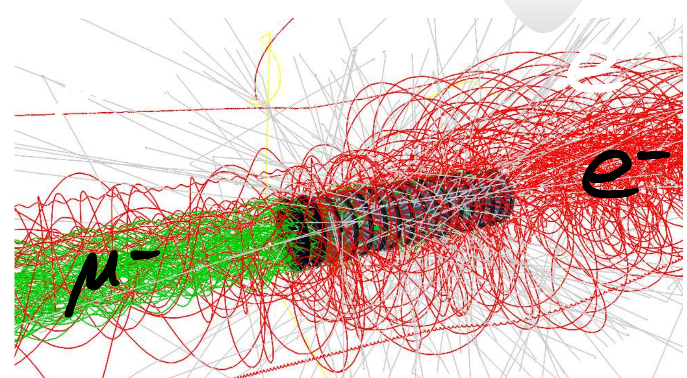
$$\mathrm{E_e} = 104.9\ \mathrm{MeV}$$



Underlying process



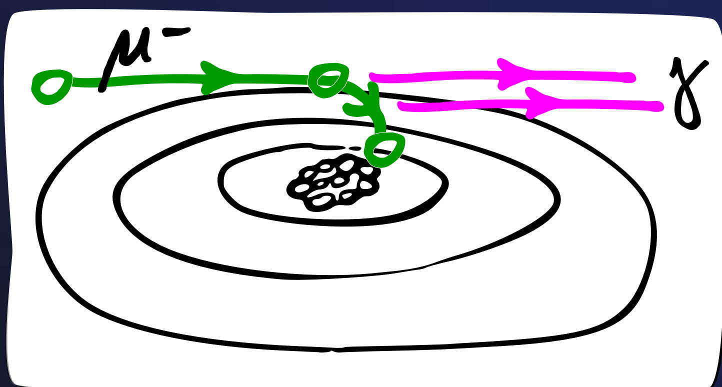
Ground state muonic atom



Beam stopped in a target

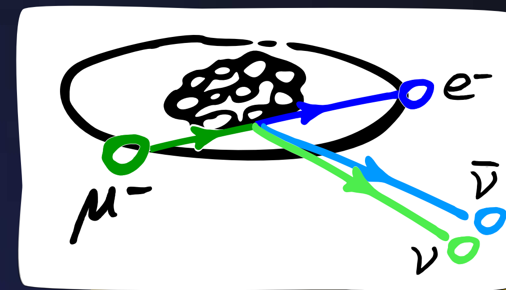
Bound Muons

Electromagnetic cascade to the ground state orbital



$\mathcal{T}$ = 864 ns
in aluminium

Bound Muon Decay



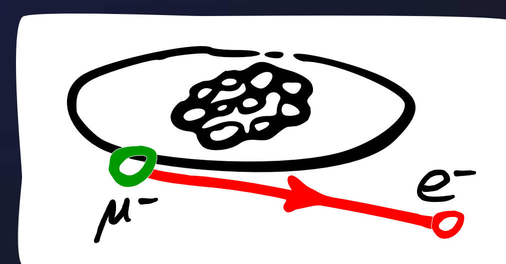
$\mathcal{BR} = 39\%$
in aluminium

Standard Model Processes

$\mathcal{BR} = 61\%$
in aluminium

Muon Nuclear Capture

Muon to Electron Conversion



$\mathcal{R} < 7 \times 10^{-13}$
90% C.L in gold
(SINDRUM-II, 2006)

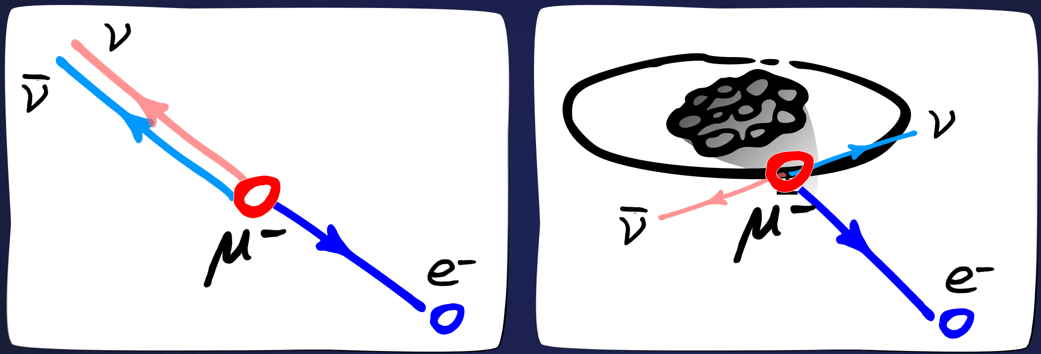
Typically define the conversion rate as:

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

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

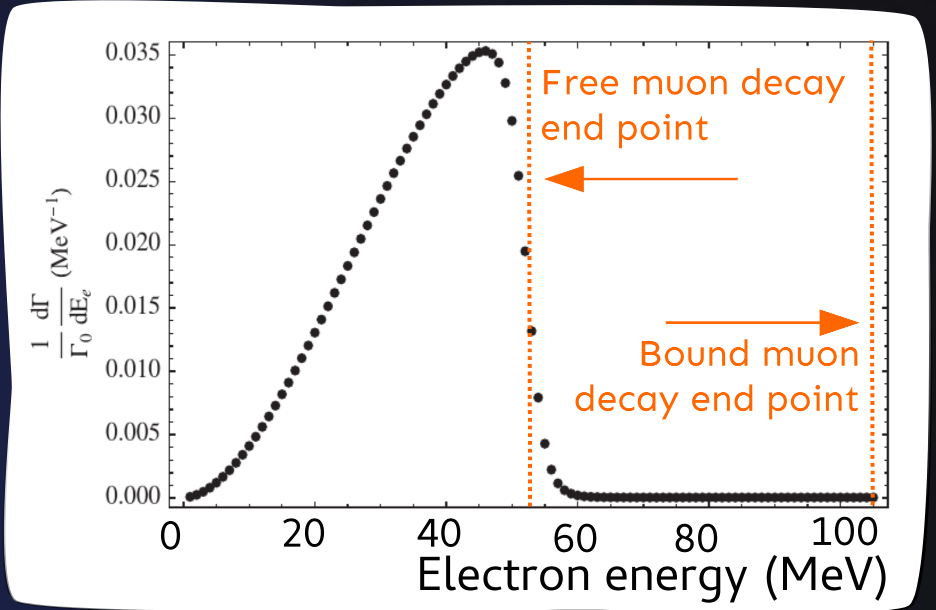
Bound Muon Decay

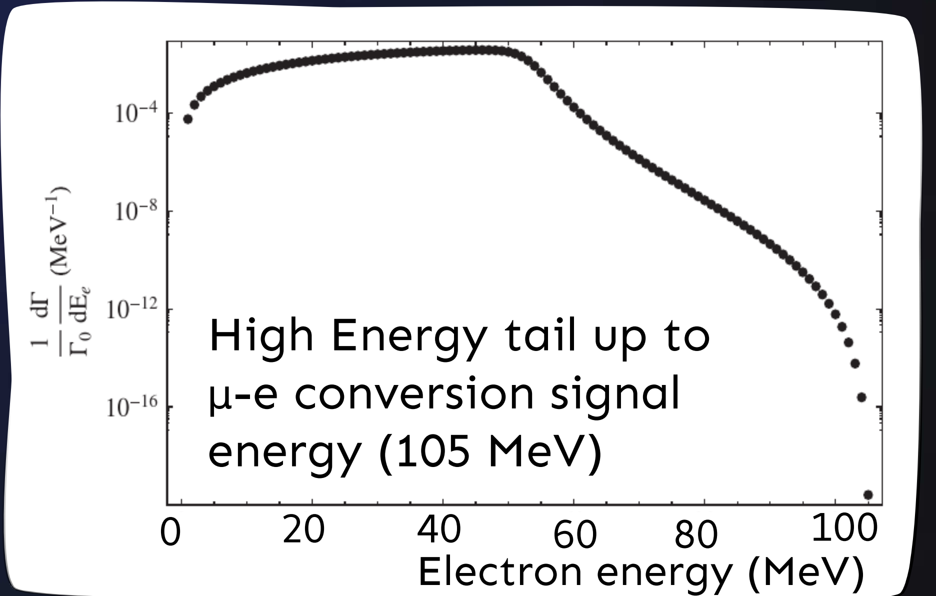
Maximum electron energy configurations:



Free muon decay | Bound muon decay

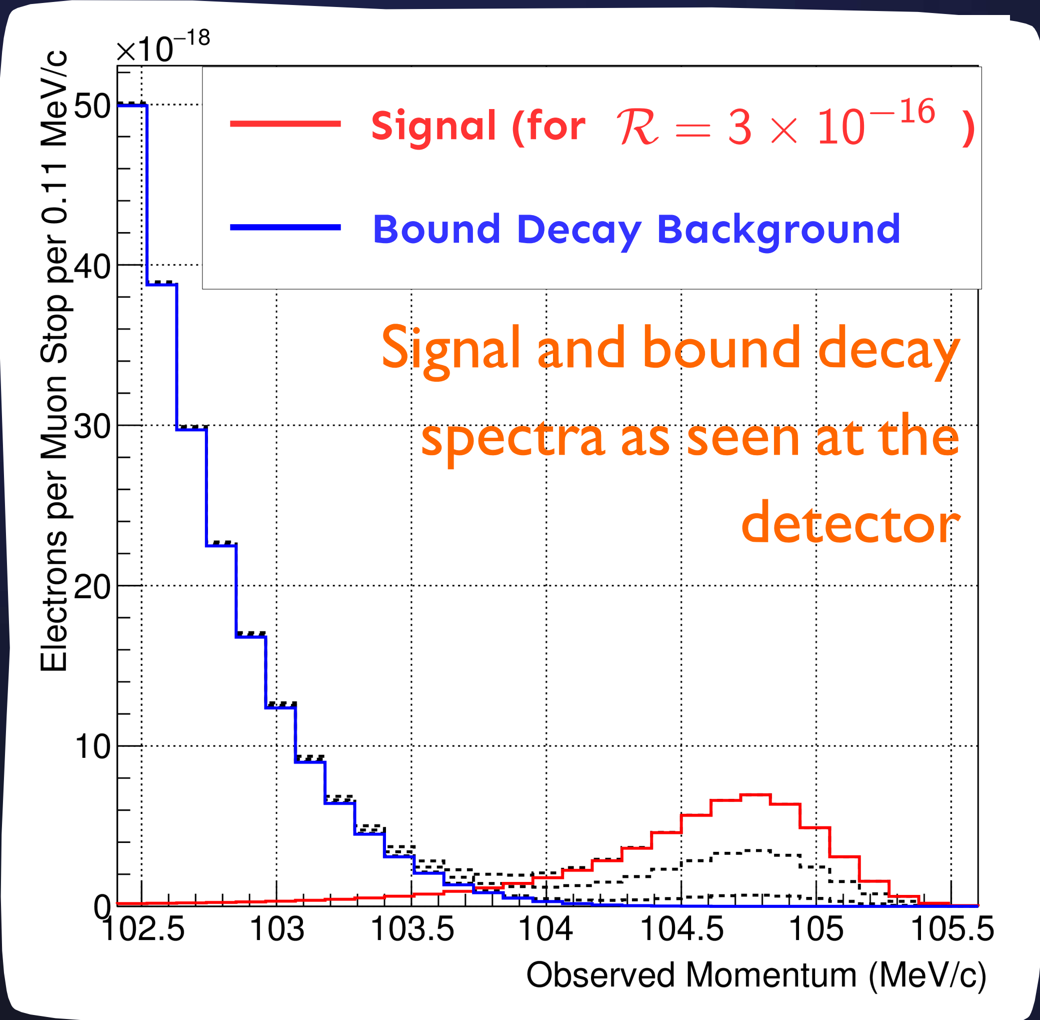
- Maximum energy for electrons from free muon decay = Half of muon mass = 55 MeV
- Bound decay around nucleus:
  - End-point close to muon mass
  - Very steeply falling spectrum above 55 MeV
- Theoretical uncertainty on spectrum from initial muon wavefunction
- No accurate measurement at the end point

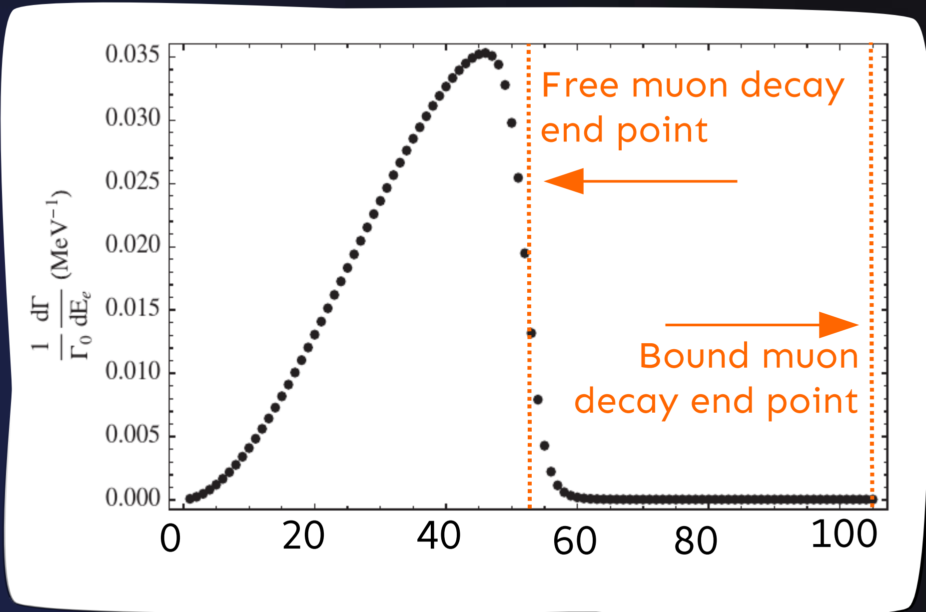


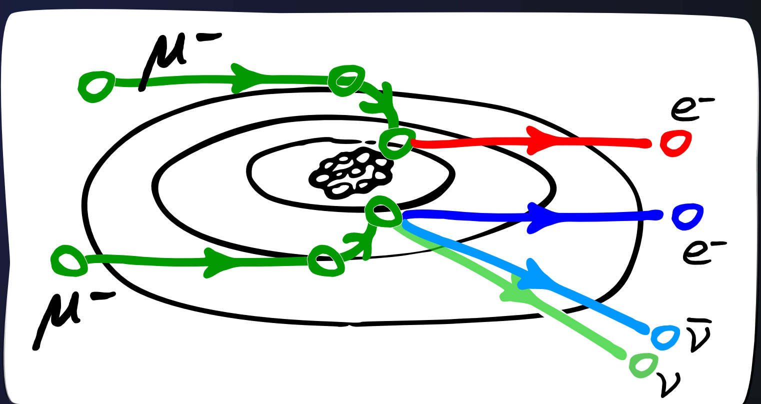


Czarnecki et al. 2011 DOI: 10.1103/PhysRevD.84.013006

Muon to Electron Conversion



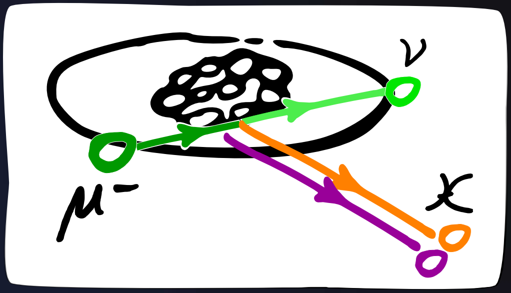


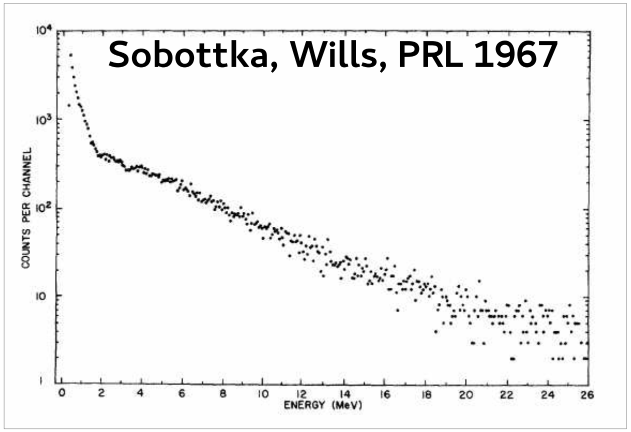


- Low-energy tail for signal electrons appears due to scattering and energy loss in target and detector
- Need to be very careful with energy resolution of experiment
- At the sensitivity we want for COMET the end-point region of bound muon decay could provide a comparable rate

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)

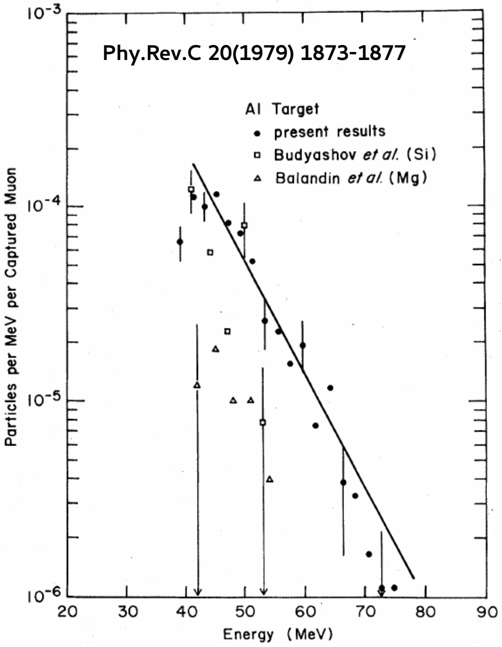




Inclusive Emission of charged particles from capture on silicon

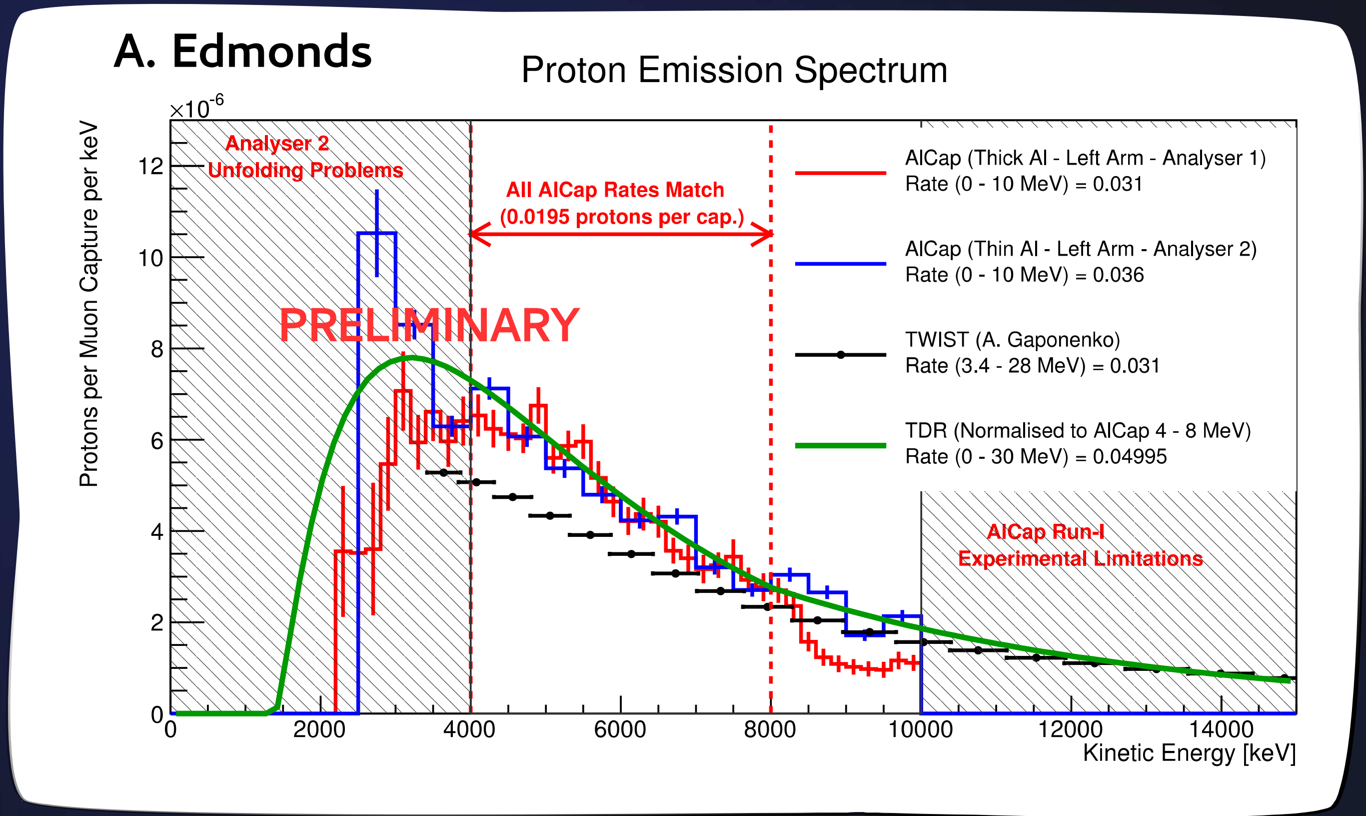
Target A, Z	$A-2, Z-2$ (μ^-, pn) (10^{-3})	$A-4, Z-3$ (μ^-, α) (10^{-3})
$^{27}_{13}Al$	28 ±4	7.6 ±1.1

Proton and alpha emission per muon capture
Wyttenbach et al. Nuc. Phys. 1978



Proton emission spectrum above 40 MeV

AlCap: Aluminium Capture of Muons

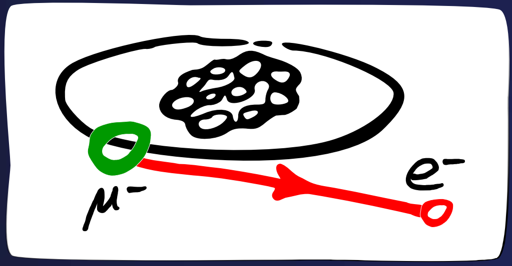


- Joint effort between Mu2e and COMET
- 3 runs at Paul Scherrer Institute from 2013 to 2015
- Studying charged and neutral particles emitted following muon capture on aluminium

The COMET Experiment

COMET:

COherent Muon to Electron Transitions



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

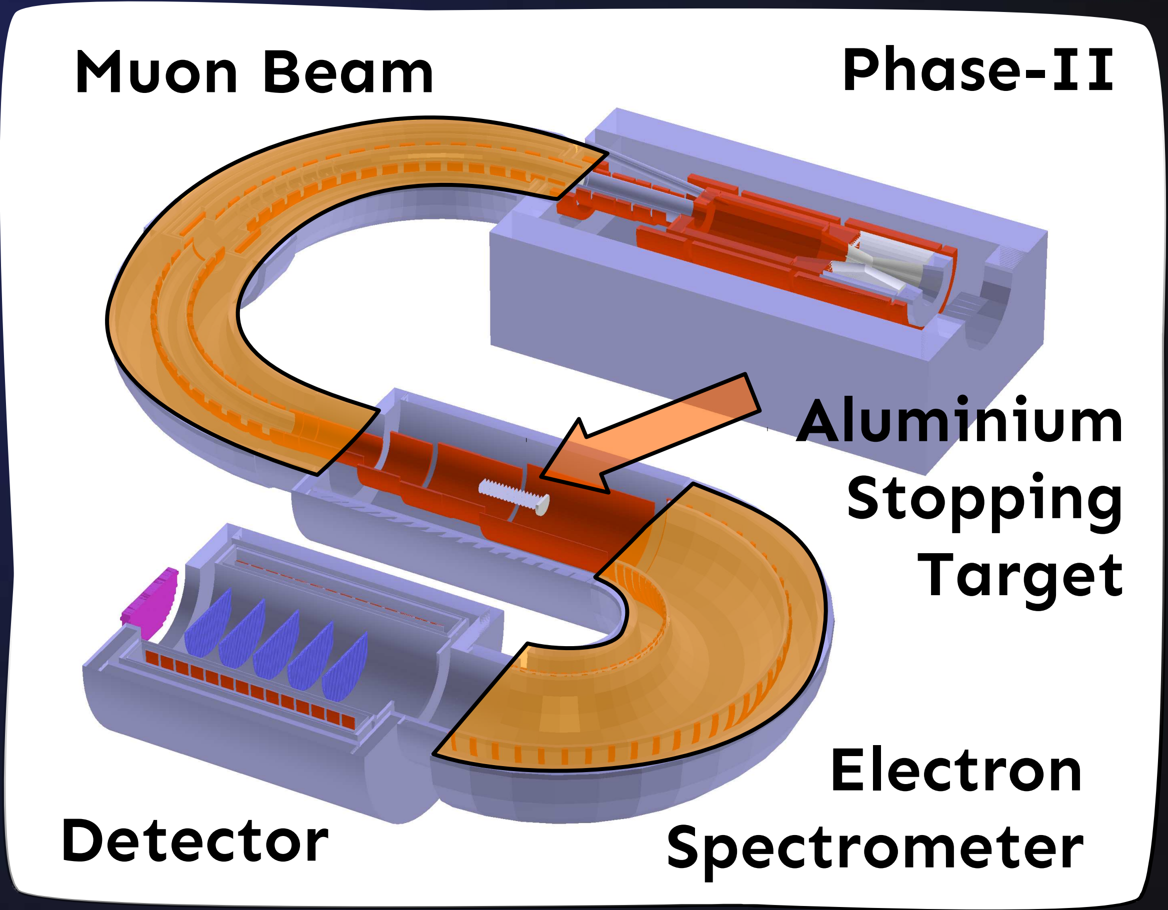
Present limits by SINDRUM-II (2006):

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

COMET Single-Event-Sensitivity:

Phase-I (2018) = 3×10^{-15}

Phase-II (2021) = 3×10^{-17}



Signal vs. Background Rates

- Want to see mu-e conversion with sensitivity around:

Single-event-sensitivity: 10^{-17}

Signal vs. Background Rates

- Want to see mu-e conversion with sensitivity around:

Single-event-sensitivity: 10^{-17}

- Typical total signal acceptance is about:

$$5\%$$

Signal vs. Background Rates

- Want to see mu-e conversion with sensitivity around:

  Single-event-sensitivity: 10^{-17}

- Typical total signal acceptance is about:

  $$5\%$$

- To see a *single* signal electron need to stop around:

  2×10^{18} muons stopped

Signal vs. Background Rates

- Want to see mu-e conversion with sensitivity around:

  Single-event-sensitivity: 10^{-17}

- Typical total signal acceptance is about:

  5%

- To see a *single* signal electron need to stop around:

  2×10^{18} muons stopped

- Muons stopped per proton-on-target (POT):

  0.2% muons stop per POT

Signal vs. Background Rates

- Want to see mu-e conversion with sensitivity around:

  Single-event-sensitivity: 10^{-17}

- Typical total signal acceptance is about:

  $$5\%$$

- To see a *single* signal electron need to stop around:

  2×10^{18} muons stopped

- Muons stopped per proton-on-target (POT):

  0.2% muons stop per POT

- Necessary protons-on-target during Phase-II:

  10^{21} POT

Signal vs. Background Rates

- Want to see mu-e conversion with sensitivity around:

Single-event-sensitivity: 10^{-17}

- Typical total signal acceptance is about:

$$5\%$$

- To see a *single* signal electron need to stop around:

2×10^{18} muons stopped

- Muons stopped per proton-on-target (POT):

0.2% muons stop per POT

- Necessary protons-on-target during Phase-II:

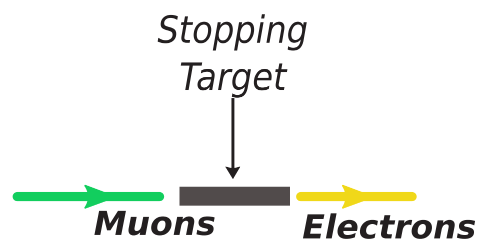
10^{21} POT

- To be confident an observed event is signal the background rate must be much lower

Background Rates

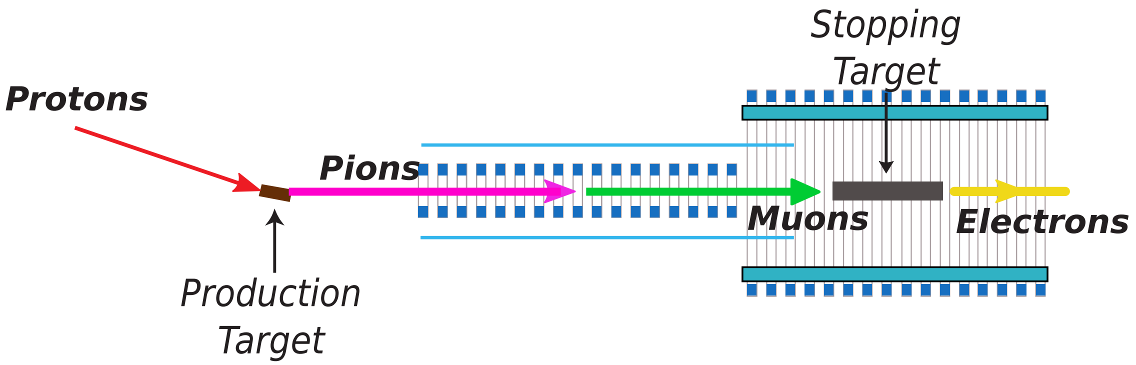
www.thegreenmvmt.com/blog/earth-day-great-sand-dunes-national-park/

The COMET Experiment Phase-II



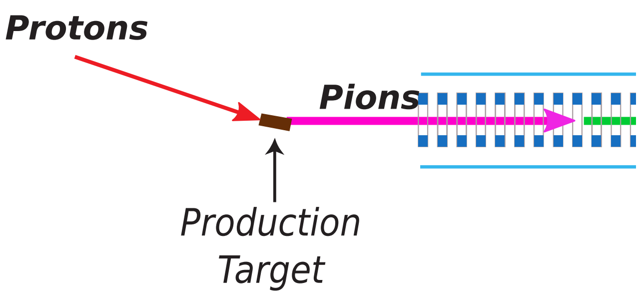
The COMET Experiment Phase-II

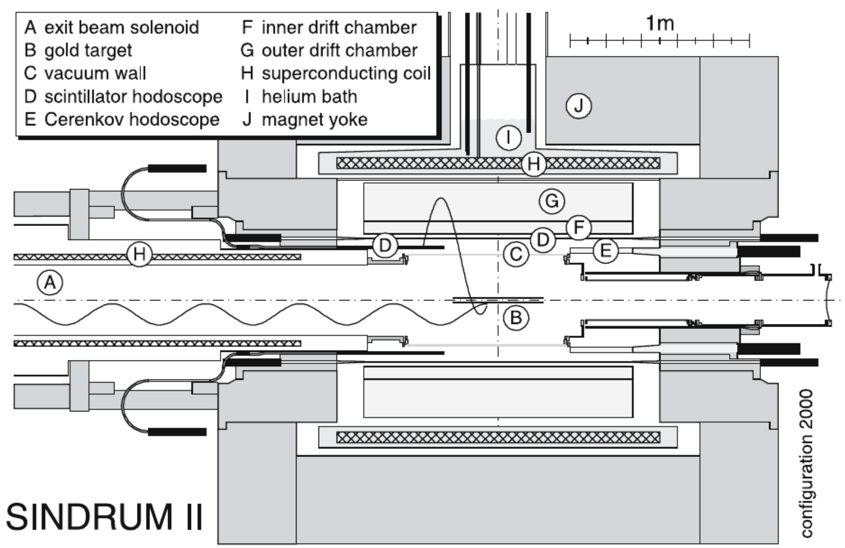
- **Generate muon beam:**
  - Proton beam hitting a target
  - Produces pions, which decay to muons
- **Detector around the stopping target**
  - Large signal acceptance



The COMET Experiment Phase-II

- **SINDRUM-II Experiment**
  - Current limit on mu-e conversion: $< 7 \times 10^{-13}$, 90% C.L.
  - Used a lead target
- **Backgrounds dominated by pions in the beam and cosmic rays**

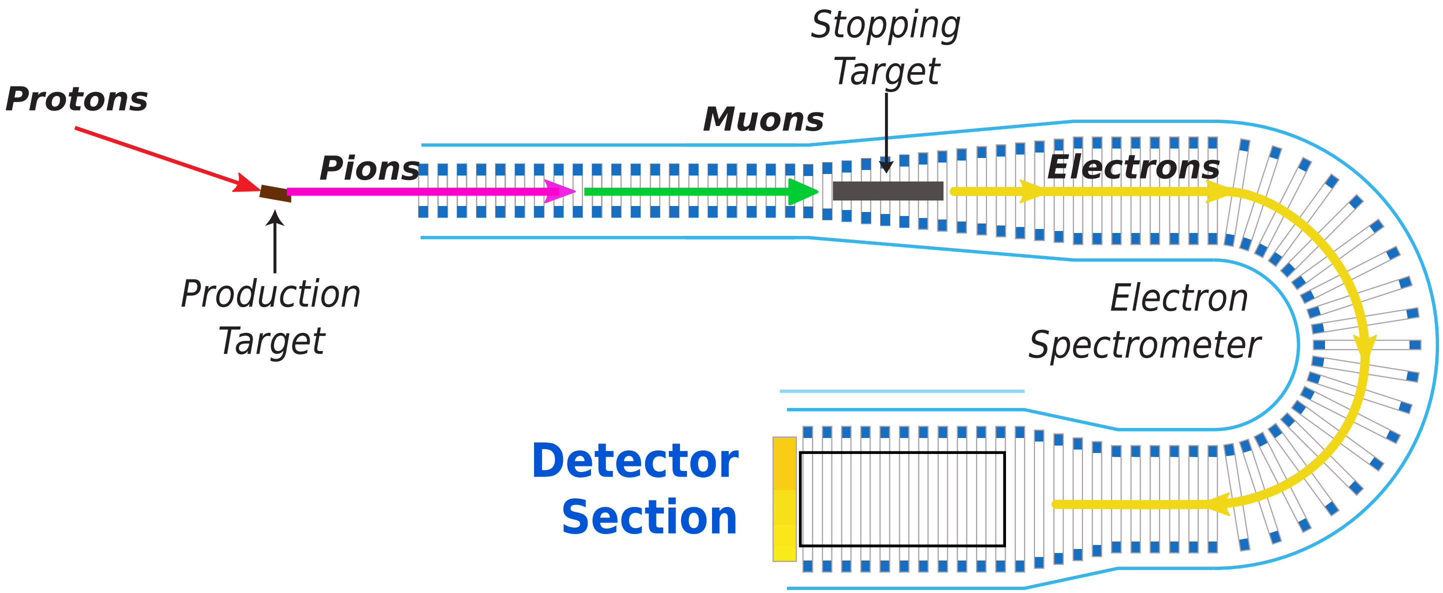




DOI: 10.1140/epjc/s2006-02582-x

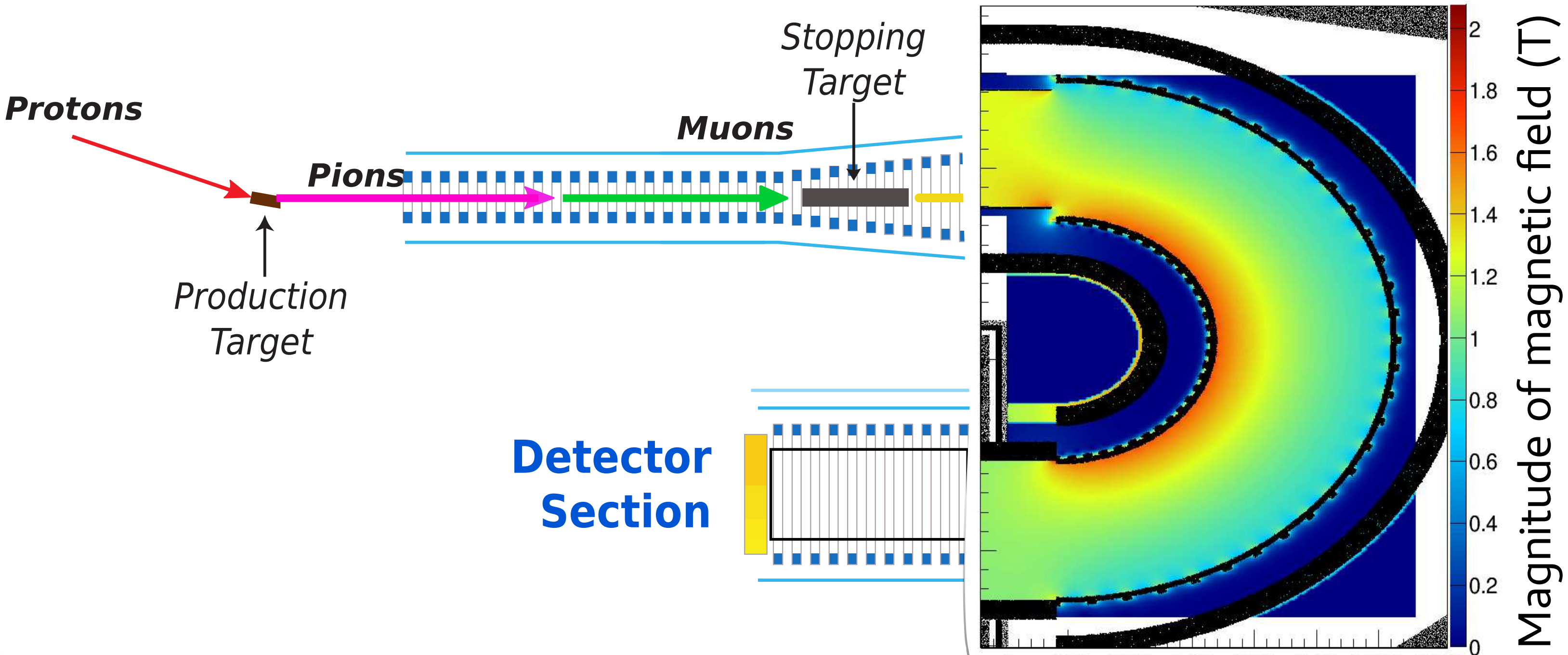
The COMET Experiment Phase-II

- **Bent solenoid between stopping target and detector**
  - Remove line-of-sight
  - Reduce the hit rate from low-energy electrons



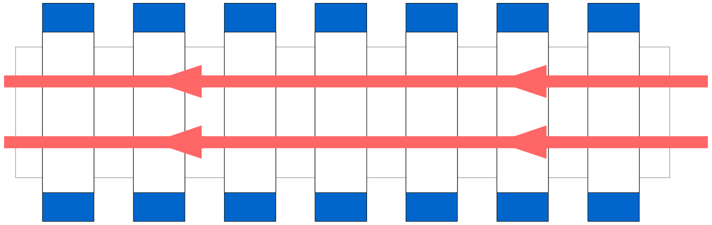
The COMET Experiment Phase-II

- **Bent solenoid between stopping target and detector**
  - Remove line-of-sight
  - Reduce the hit rate from low-energy electrons



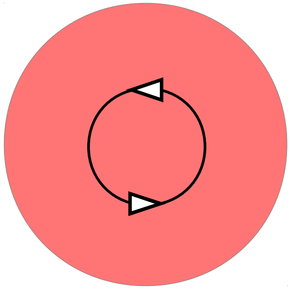
Bent Solenoid Drifts

View from above solenoid:



- Uniform B field
- Linear field lines

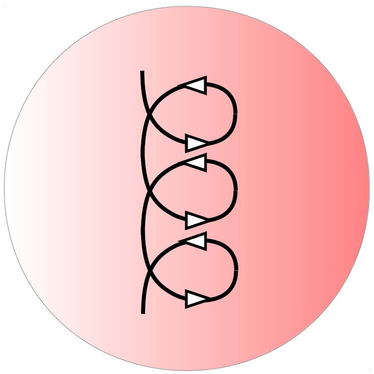
Looking into the solenoid:



Circular motion parallel to field lines

- Radial gradient in magnetic field
- Cylindrical field lines

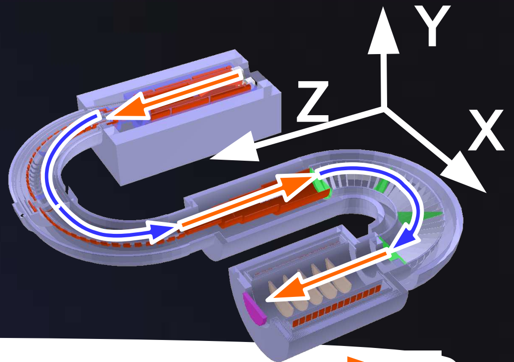
Which both cause particles to drift out of the plane that the solenoid is bent in.



Circular motion about a drifting centre:

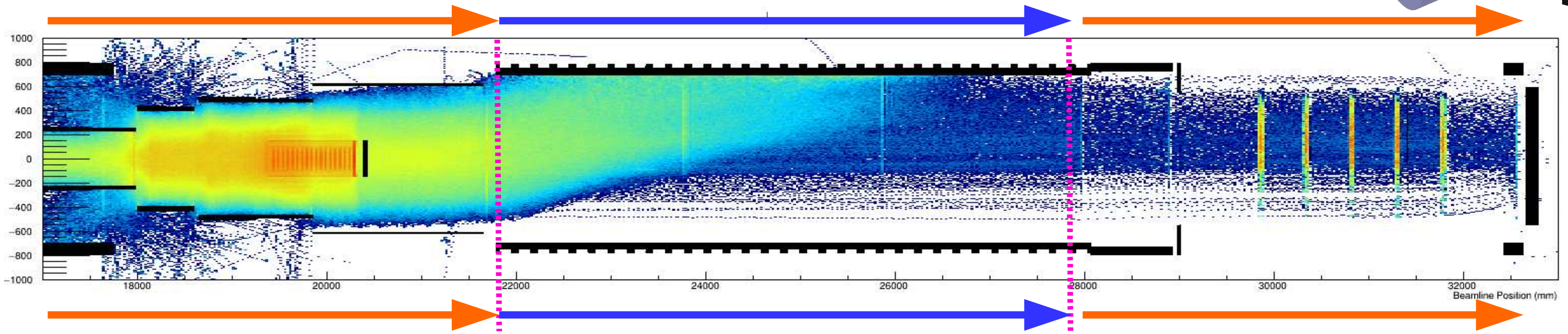
$$D \propto \frac{p}{qB} f(\theta)$$

Bent solenoids + Dipole



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

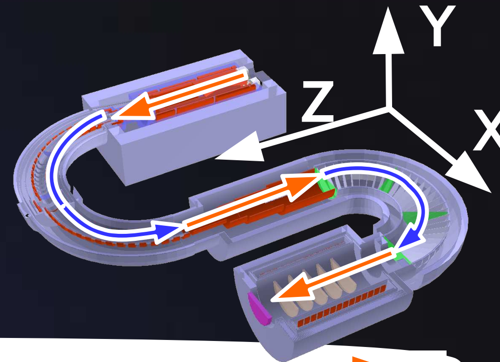
No Dipole

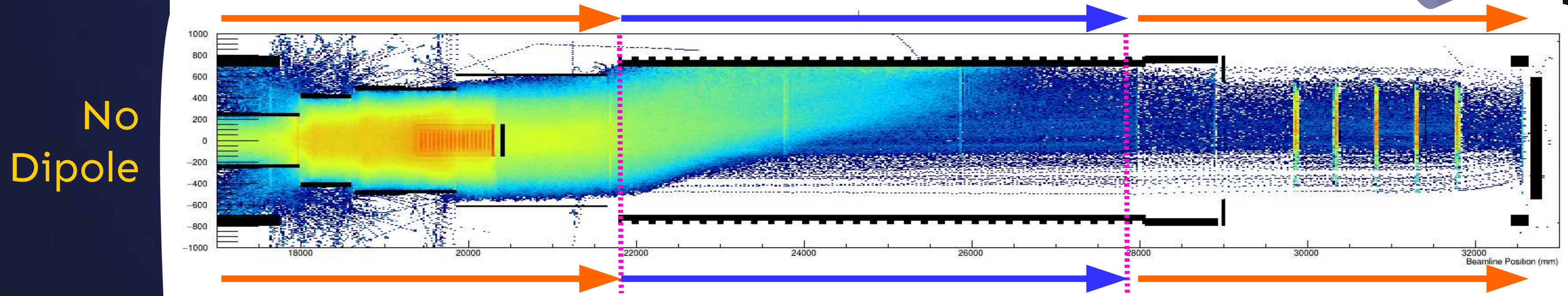


- Simulation of Signal Electrons (105 MeV/c) coming from the stopping target.
- No dipole: Signal electrons drift upwards and hit the beam pipe. Very low energy secondary electrons remain on axis however.

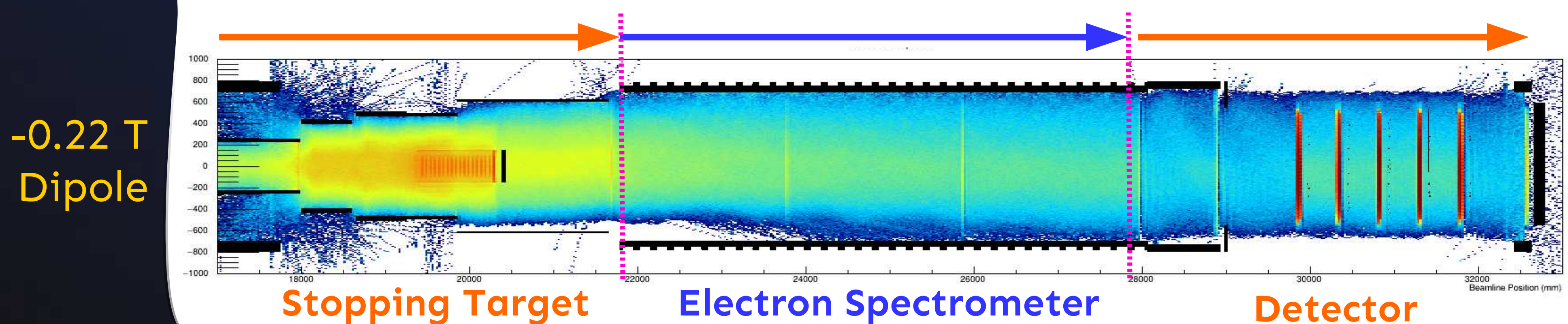
Bent solenoids + Dipole

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





- Simulation of Signal Electrons (105 MeV/c) coming from the stopping target.
- No dipole: Signal electrons drift upwards and hit the beam pipe. Very low energy secondary electrons remain on axis however.
- Optimised dipole: Signal electrons remain on axis, low energy electrons removed



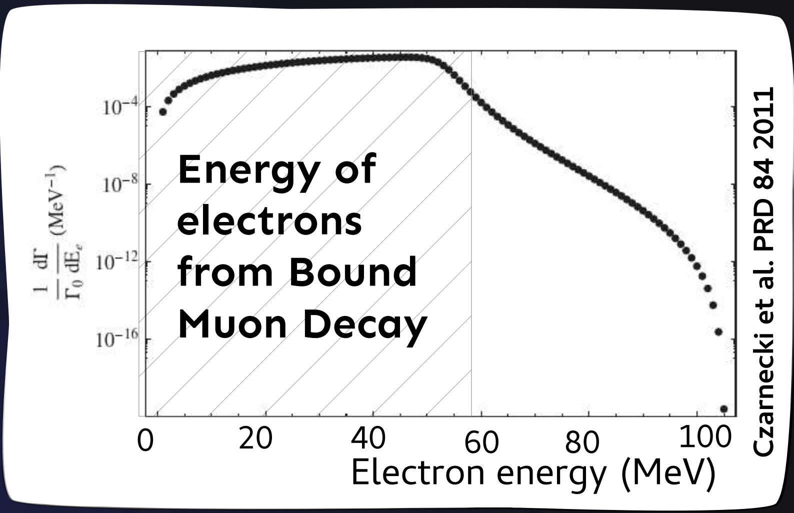
Removing Low-energy Electrons

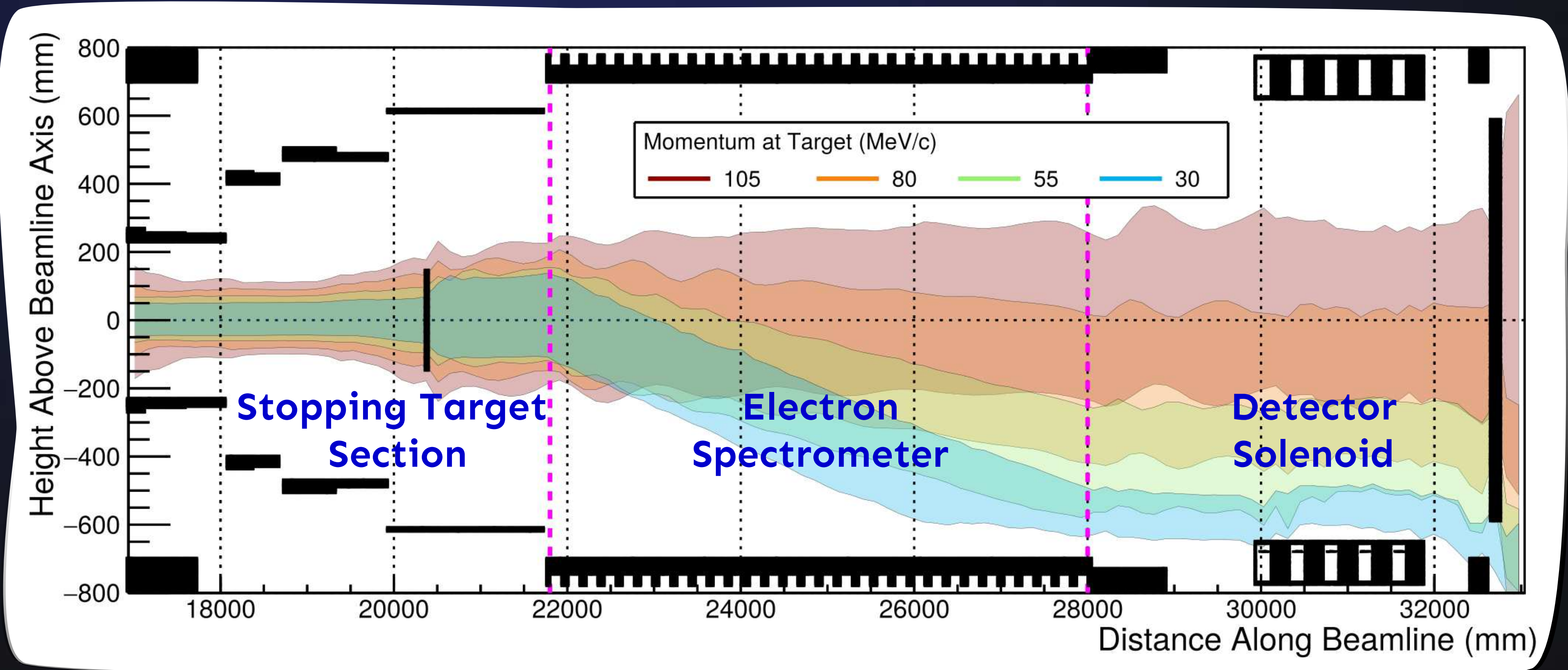
Bent solenoidal field separates electrons depending on their momentum

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

Each line shows envelope for electrons of different momenta

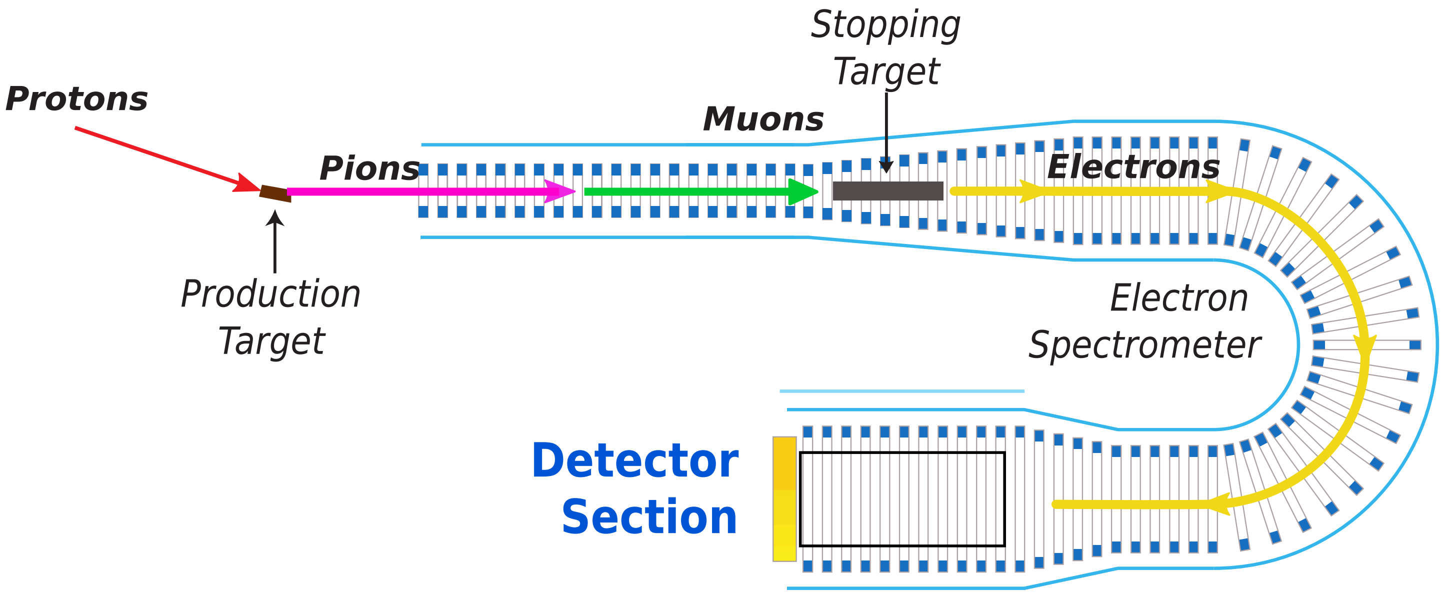
Mean height of electrons drift proportional to momentum





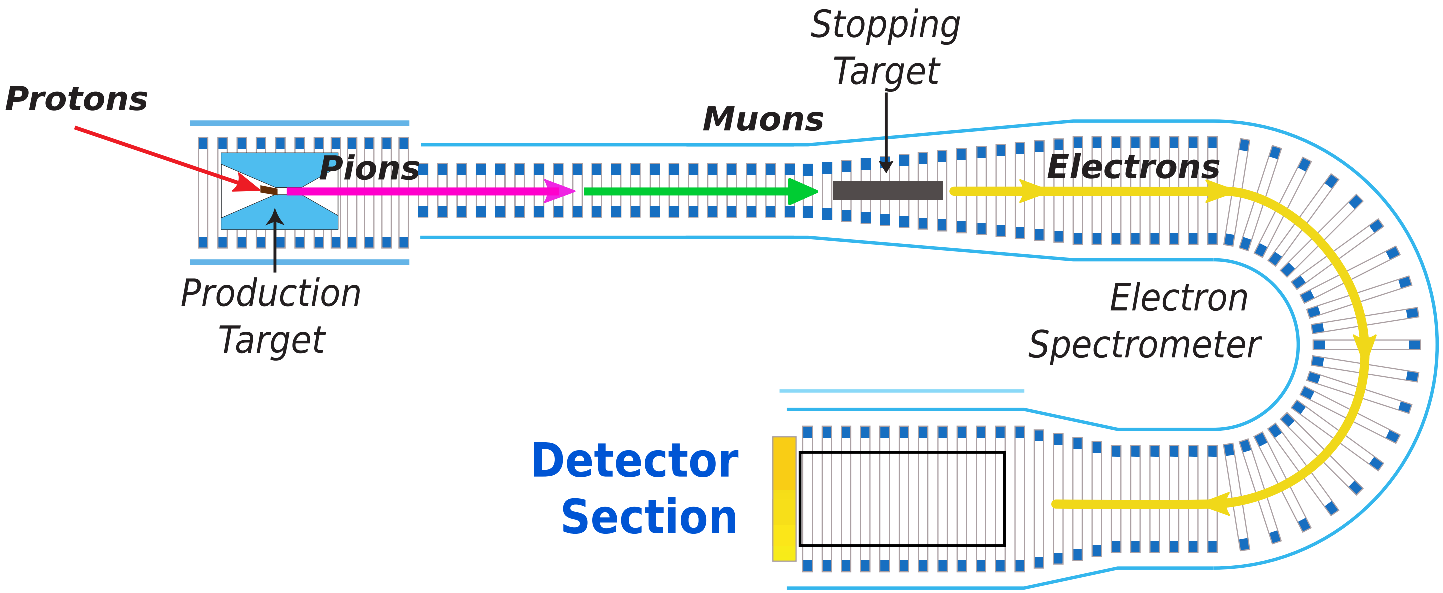
The COMET Experiment Phase-II

- **Bent solenoid between stopping target and detector**
  - Remove line-of-sight
  - Reduce the hit rate from low-energy electrons



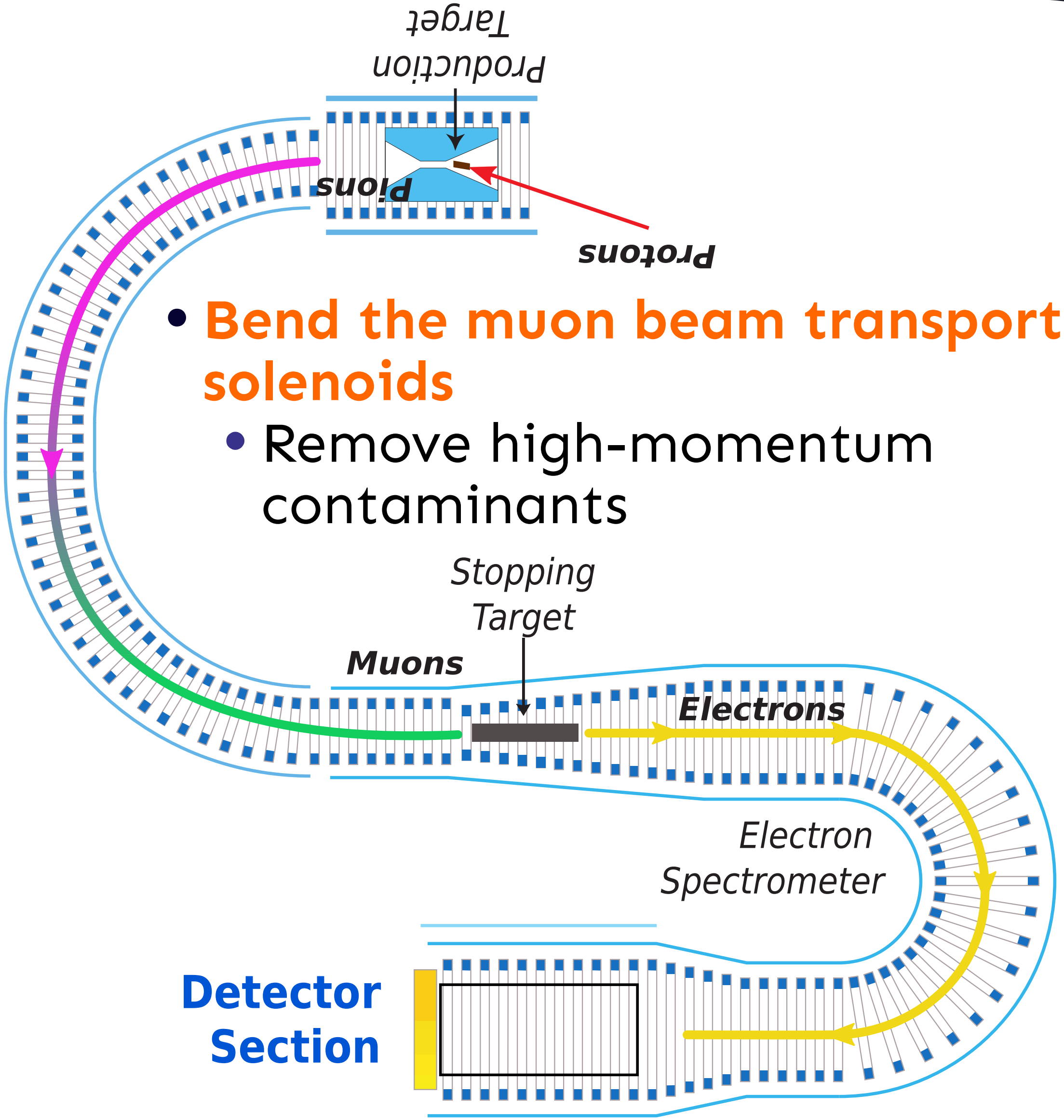
The COMET Experiment Phase-II

- **Put the production target in a (superconducting) solenoidal field**
  - Capture more pions



The COMET Experiment **Phase-II**

- **Bend the muon beam transport solenoids**
  - Remove high-momentum contaminants



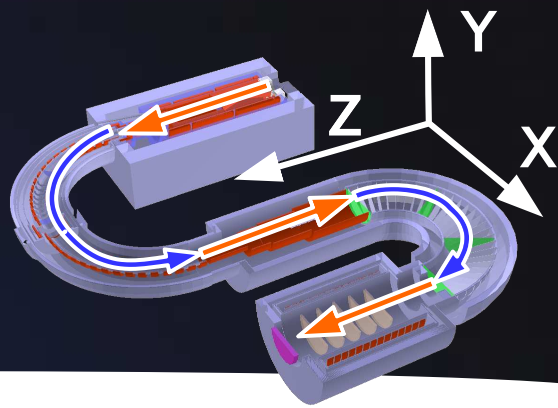
Bent Solenoid Drifts

(Geant4 Simulation)

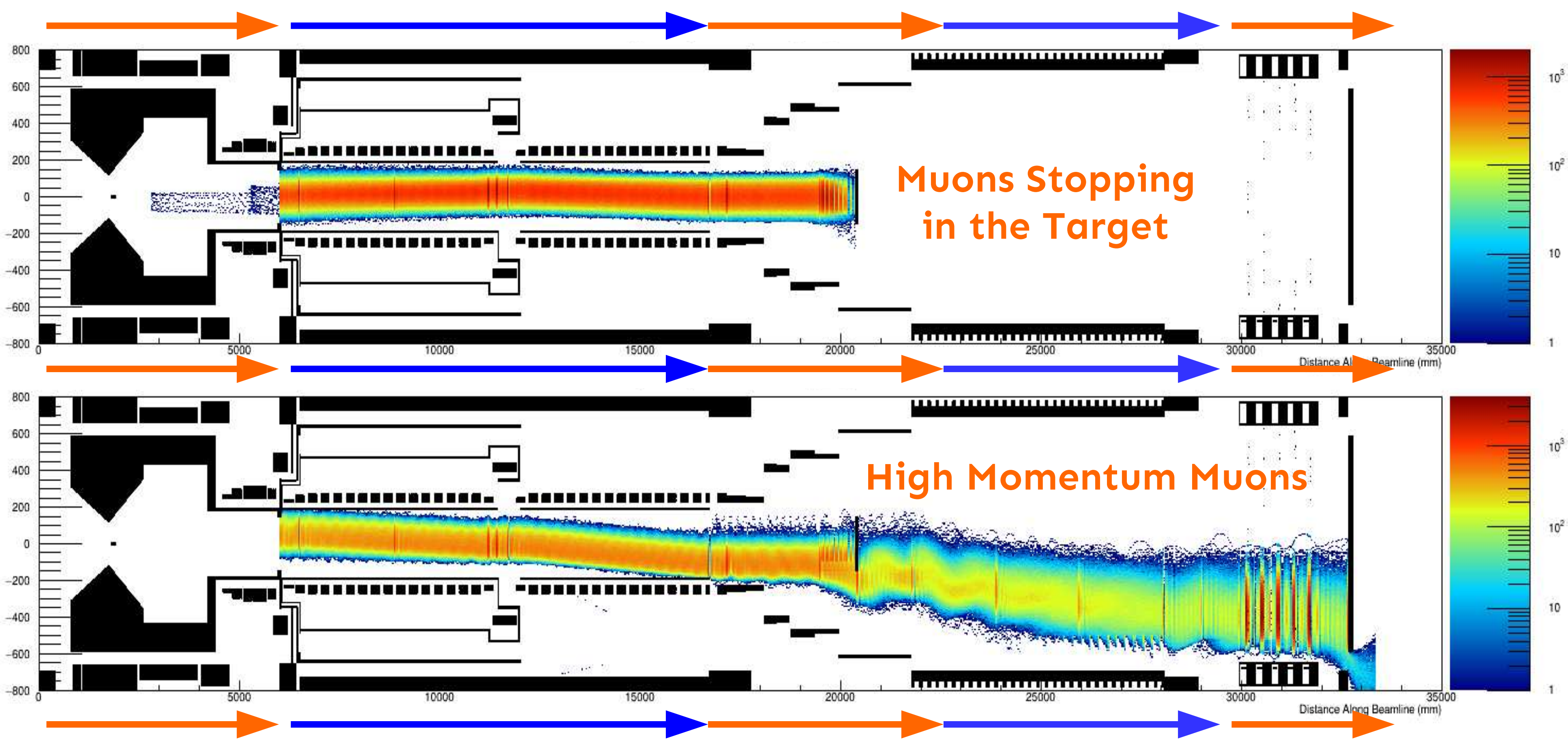
- High momentum particles drift down more than low momentum particles
- Additional tunable dipole field
  - Can select which momenta remain on-axis

Bent Muon Transport

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

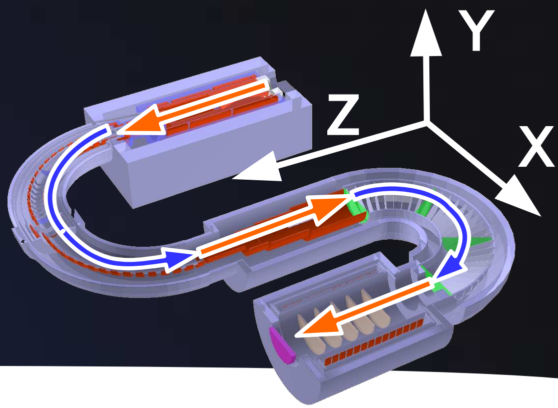


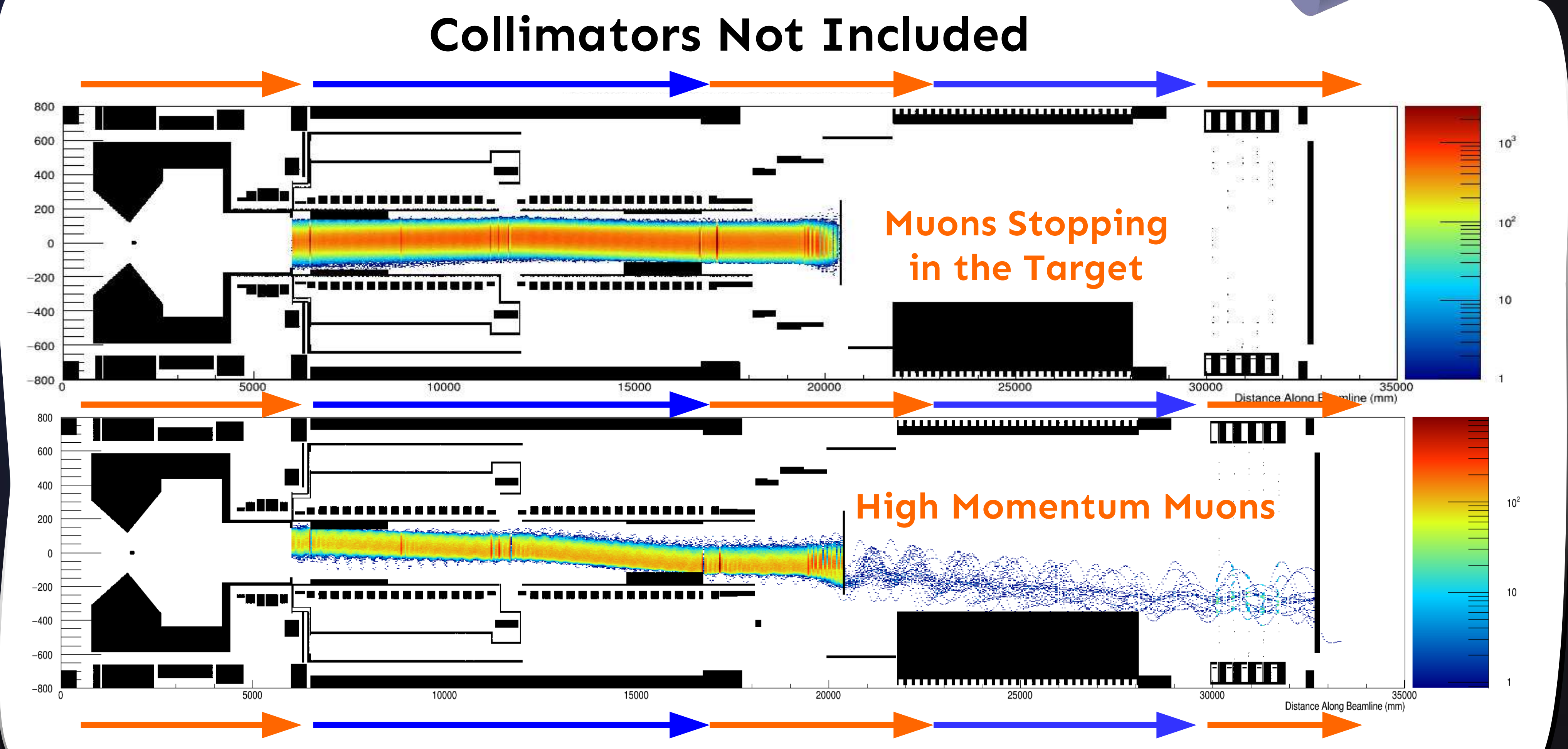
Collimators Not Included



Bent Muon Transport

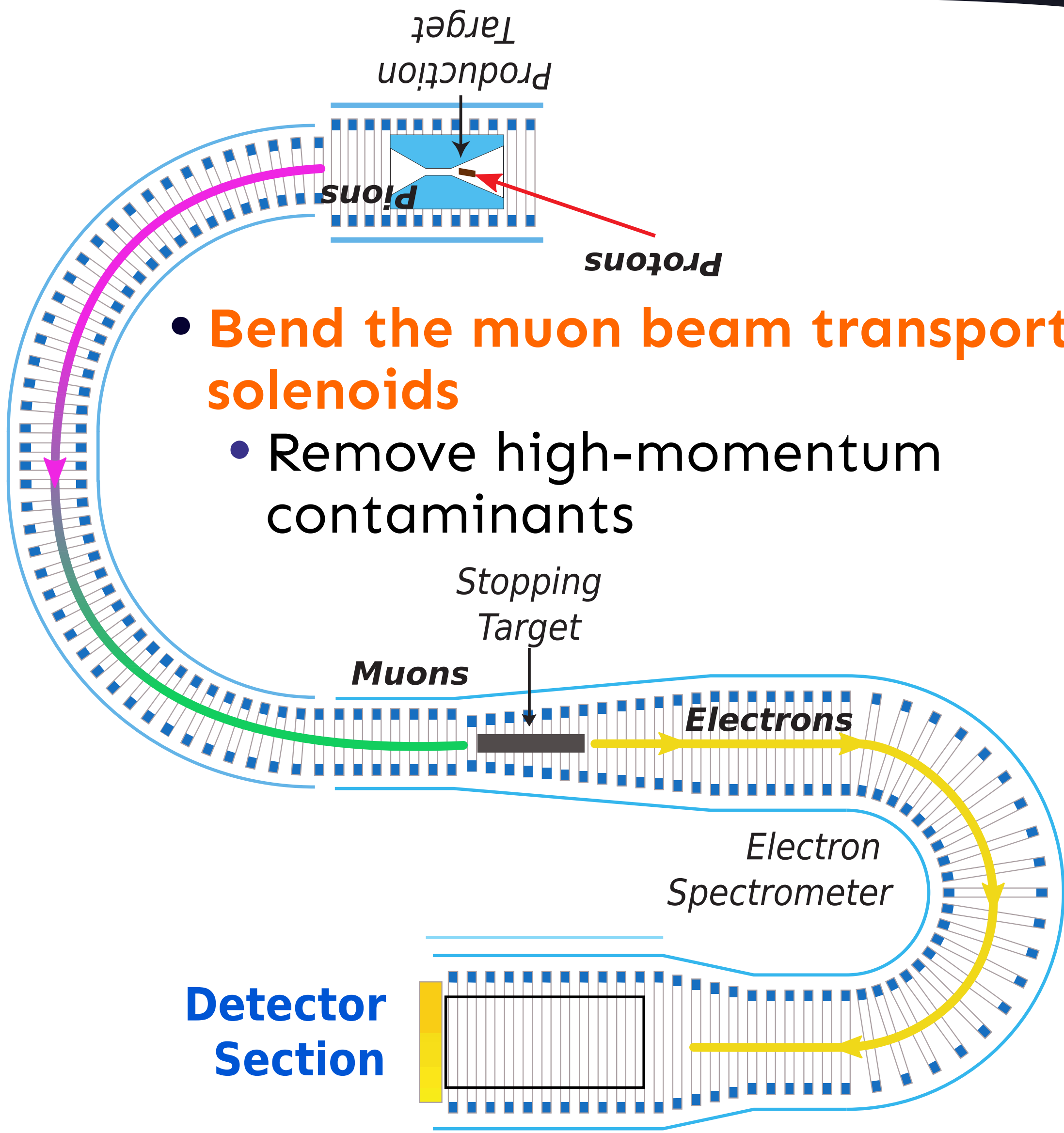
- Remove high momentum muons and pions
- Maintain low momentum muons



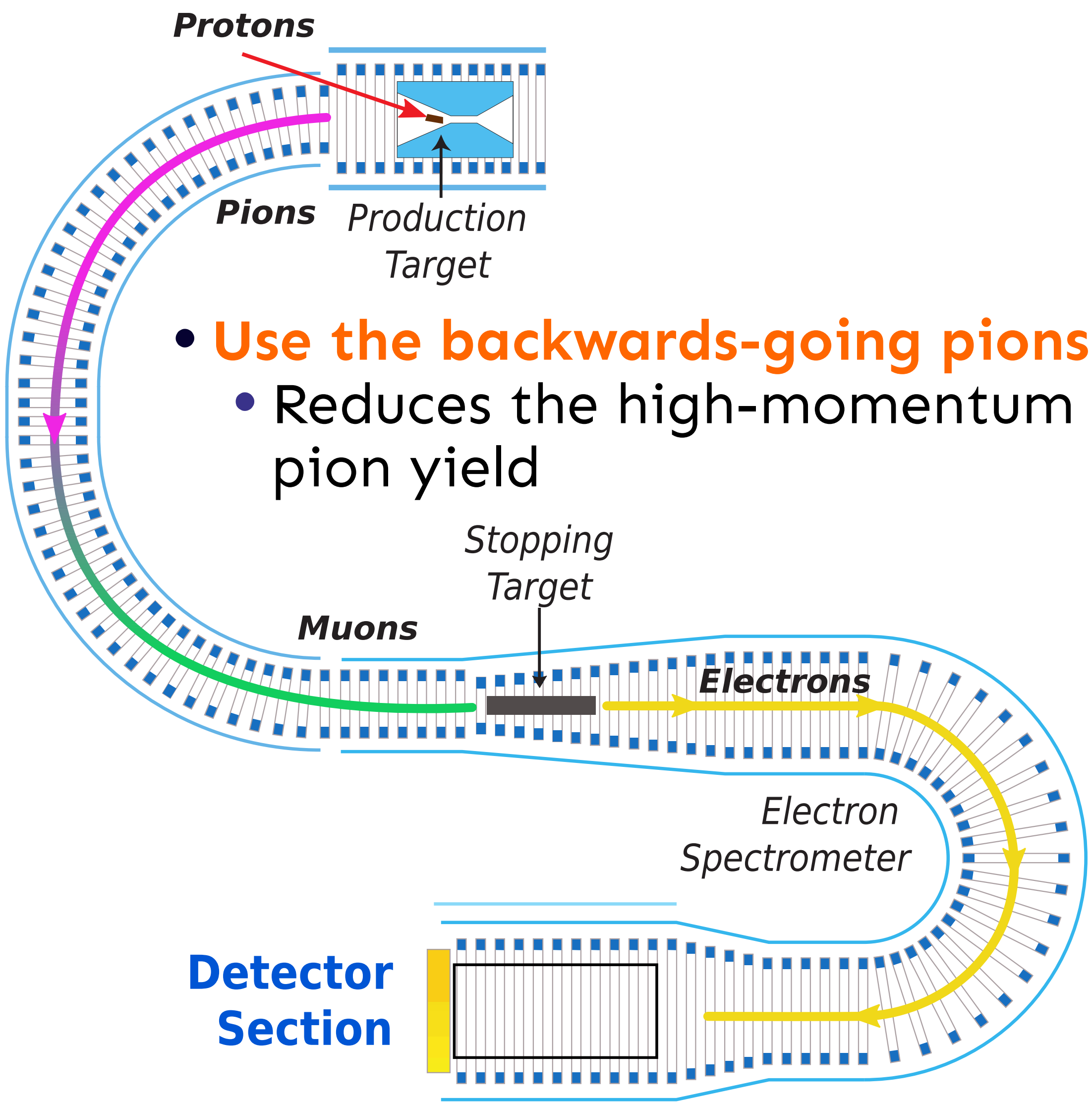


The COMET Experiment Phase-II

- **Bend the muon beam transport solenoids**
  - Remove high-momentum contaminants



The COMET Experiment Phase-II



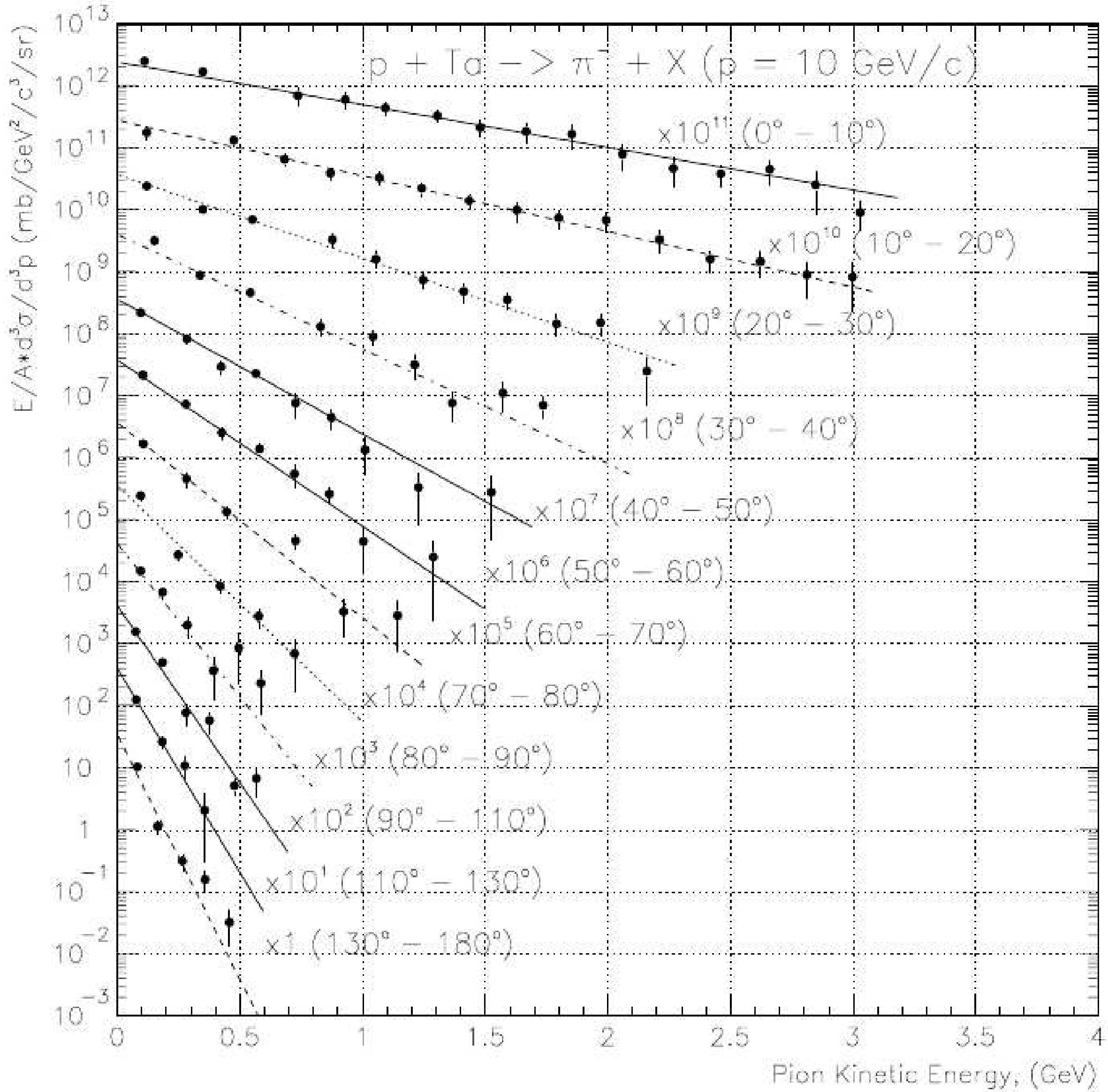
- **Use the backwards-going pions**
  - Reduces the high-momentum pion yield

Backwards Going Pions

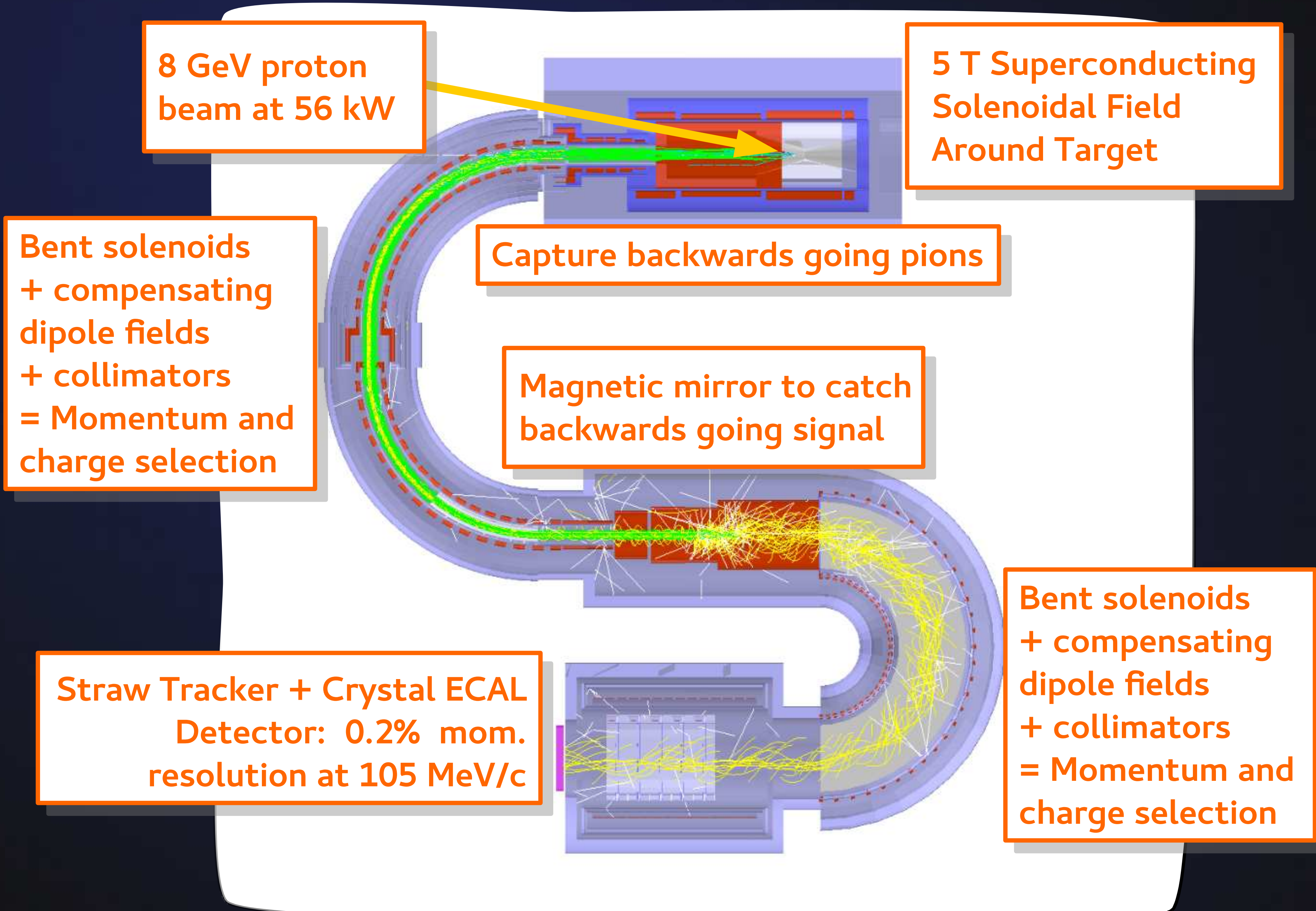
D. Artmutliski et al., Sov. J. Nucl. Phys. 48, 161 (1988), Prep. JINR P1-91-191 (1991).

Diff. Cross section for -ve pion production with 10 GeV protons on Tantalum

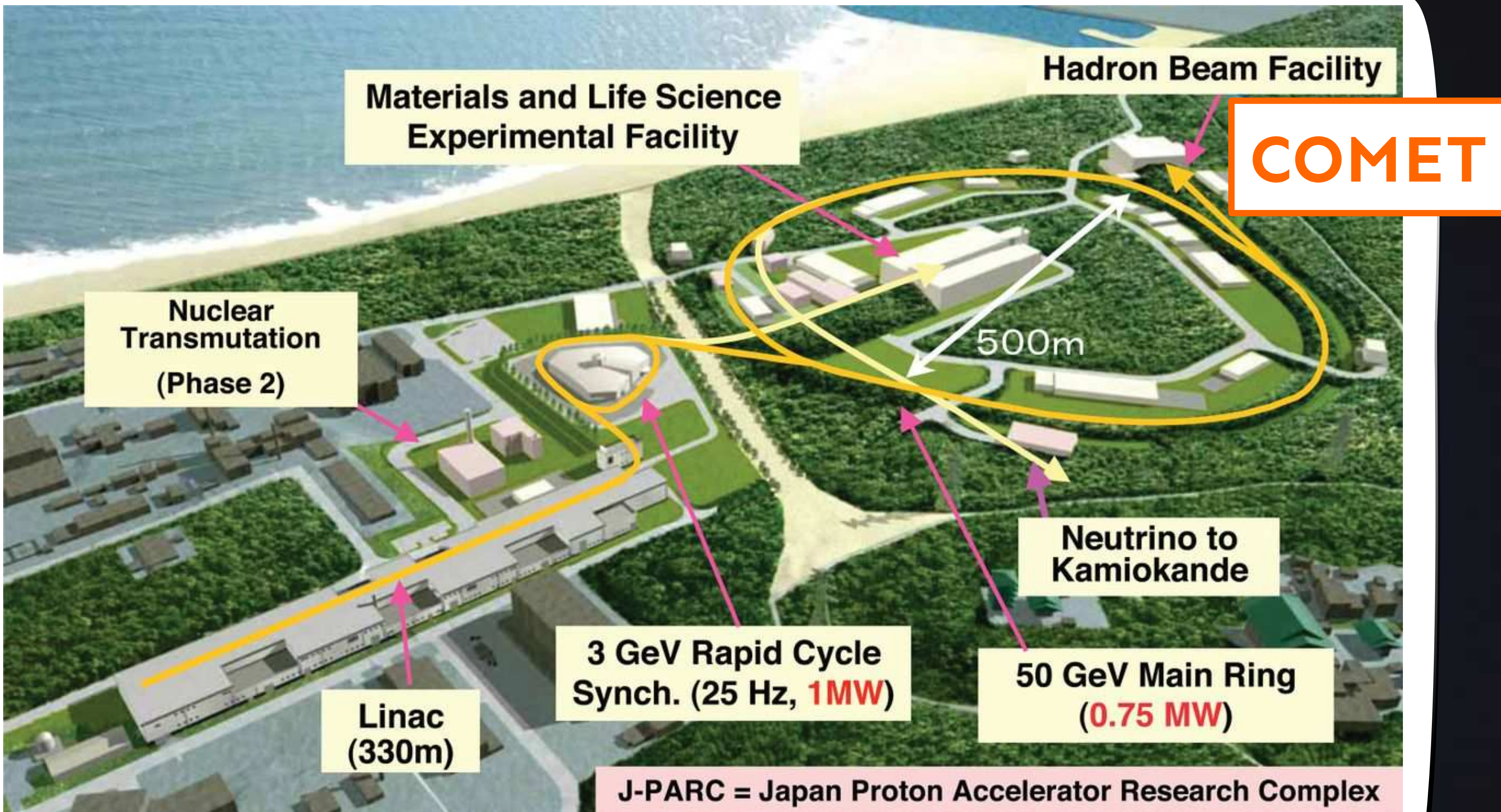
Backwards going pions have much lower momentum



The COMET Experiment Phase-II

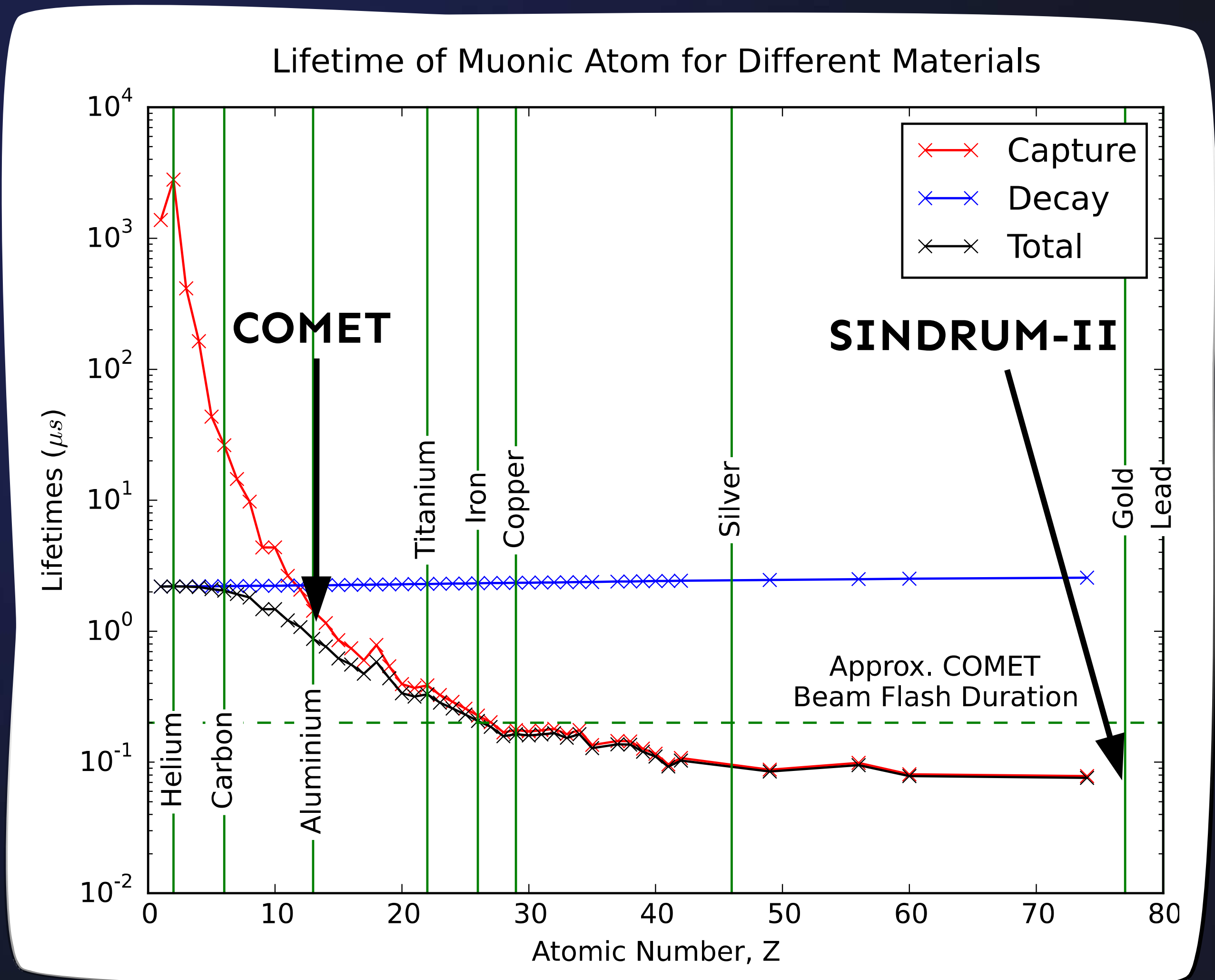


COMET at J-PARC in Japan



Joint Project between KEK and JAEA

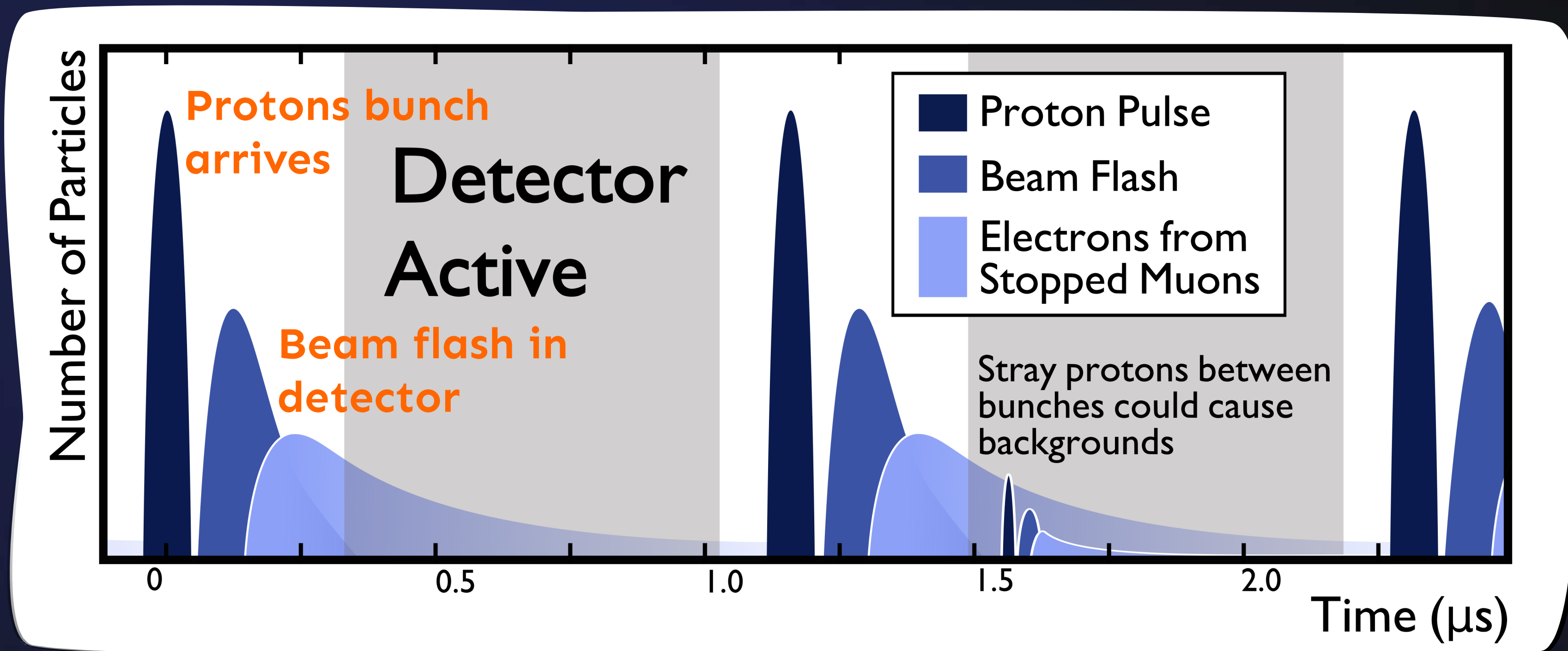
Stopping Target Choice



Based on parametrisation in Geant4 v10.2

- Coherent μ-e conversion process favours high-Z target
- Long signal lifetime favours low-Z target

Pulsed Beam and Timing Information

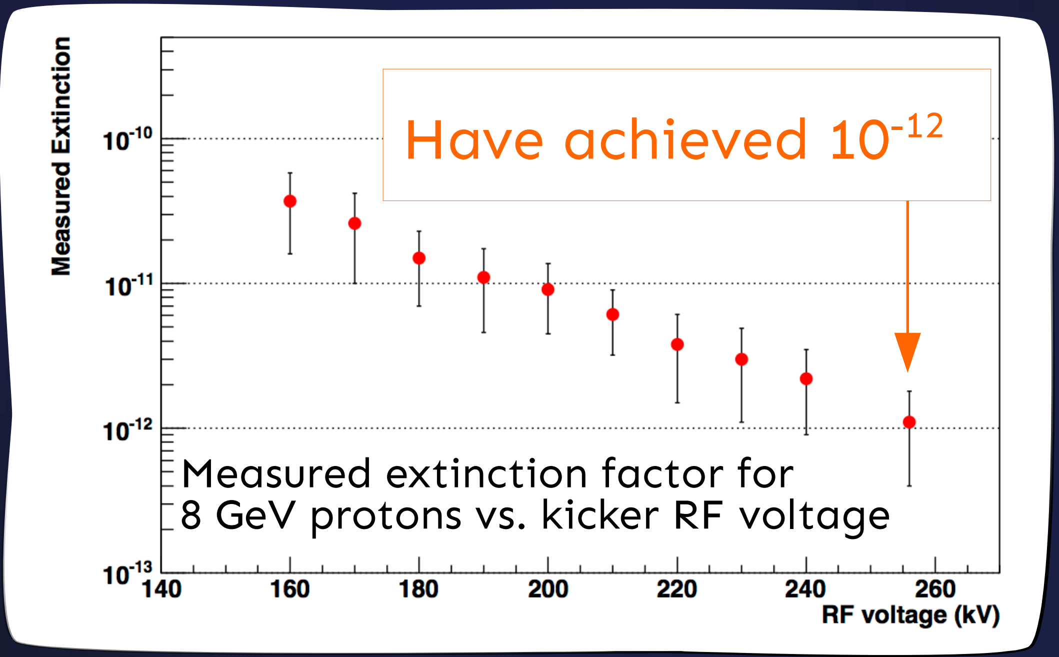


- Muon lifetime on Aluminium: 864 ns
- Pulsed beam removes beam-related backgrounds, typically up to 200 ns
- Few protons between pulses as possible:
  - Extinction factor:

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

  - Originally aiming for 10^{-9}
- Diamond detector to measure extinction during running

Pulsed Beam and Timing Information



- 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:

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

  - Originally aiming for 10^{-9}
- Diamond detector to measure extinction during running

Predicted Backgrounds

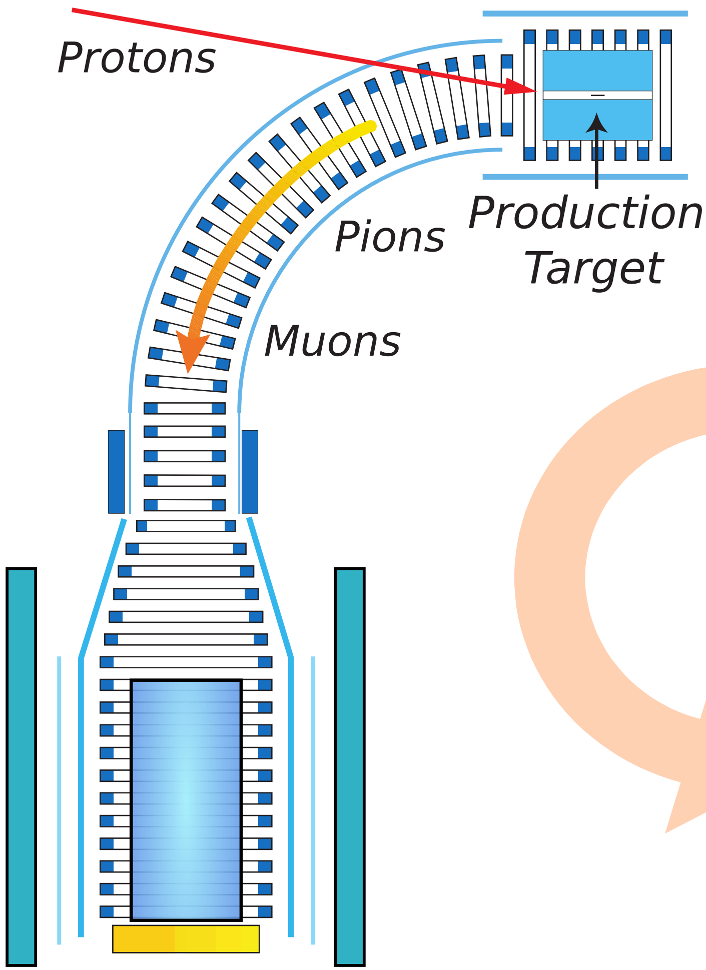
Type	Background	Number of events during run Phase-I (TDR 2016)	Phase-II (Krikler)
Intrinsic	Muon Decay-in-Orbit	0.01	0.068
	Radiative Muon Capture	0.0019	4.10×10^{-13}
	μ^- Capture w/ n Emission	< 0.001	-
	μ^- Capture w/ Charged Part. Emis.	< 0.001	-
Prompt	Radiative Pion Capture	0.00028	0.00124
	Beam Electrons	< 0.0038	0.00191
	Pions from antiprotons	–	2.43×10^{-8}
Delayed	Delayed Radiative Pion Capture	~ 0	1.18×10^{-6}
	Antiproton Induced	0.0012	0.296
	Pions from antiprotons	–	1.33×10^{-9}
	Other delayed B.G.	~ 0	0.00100
Cosmic	Cosmic Ray Muons	< 0.01	0.294
	Total background	< 0.032	0.662
	Signal (Assuming $B = 1 \times 10^{-16}$)	0.031	3.8

Extinction factor: 10^{-11}
Resolution: 200 keV/c

Phase-I: 150 days
Phase-II: 1 year

Phase-I Status and Schedule

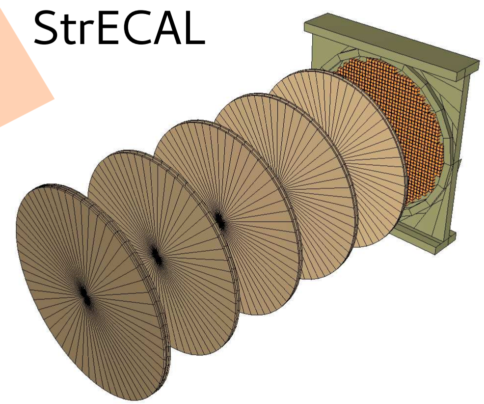
COMET: Phase-I



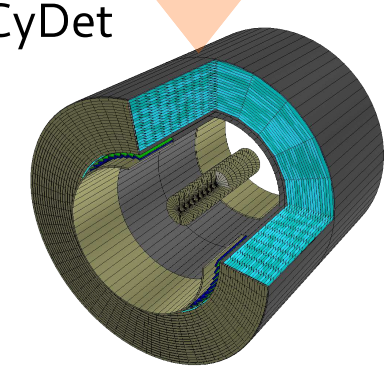
Goals of Phase-I

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

StrECAL

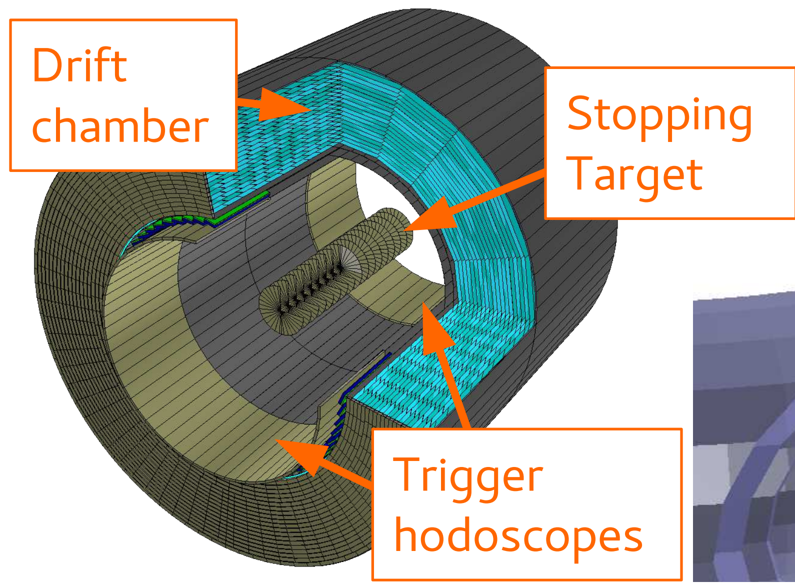


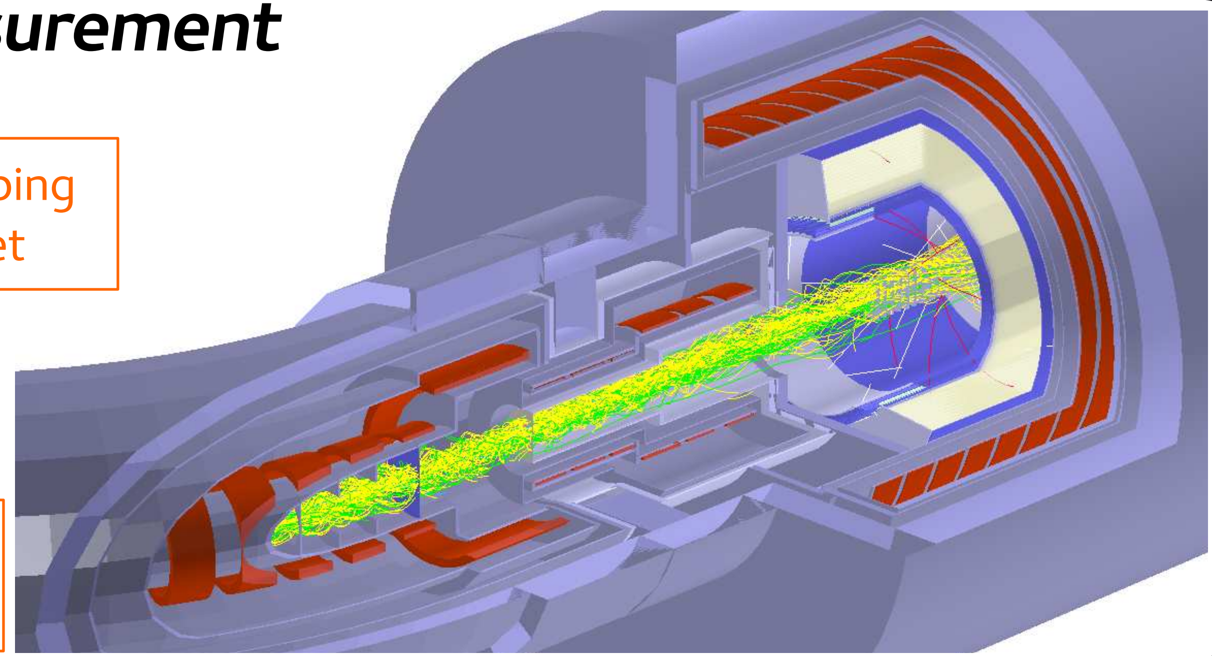
CyDet



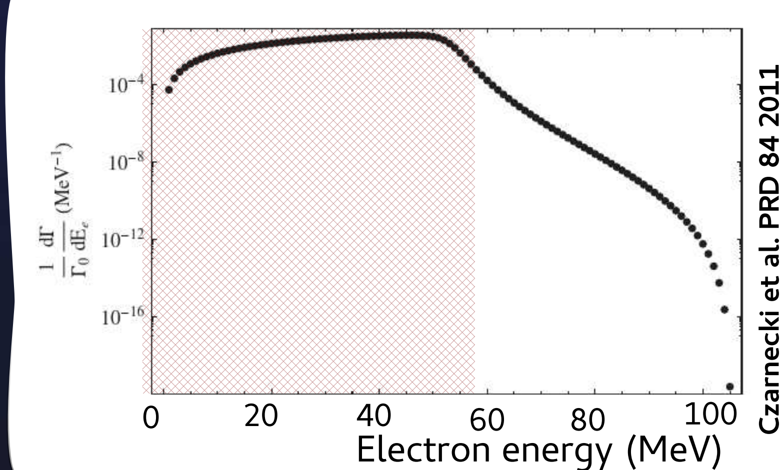
Cylindrical Detector (CyDet)

Phase-I Physics Measurement



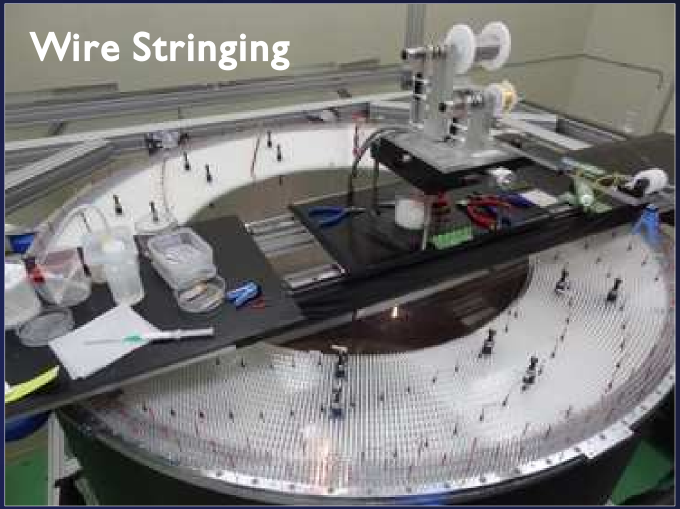


- Cylindrical Drift Chamber (CDC) triggered from hodoscopes made of Cherenkov counters and plastic scintillators
- 60 cm inner radius
  - Only accept particles with momentum greater than 60 MeV/c
  - Avoids beam flash and most electrons from bound muon decay
- Momentum measurement using drift chamber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



Electrons from Bound Muon Decay

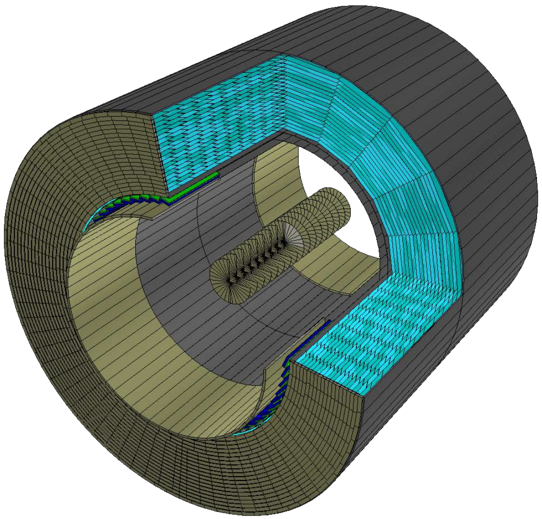
Cylindrical Drift Chamber (CDC)

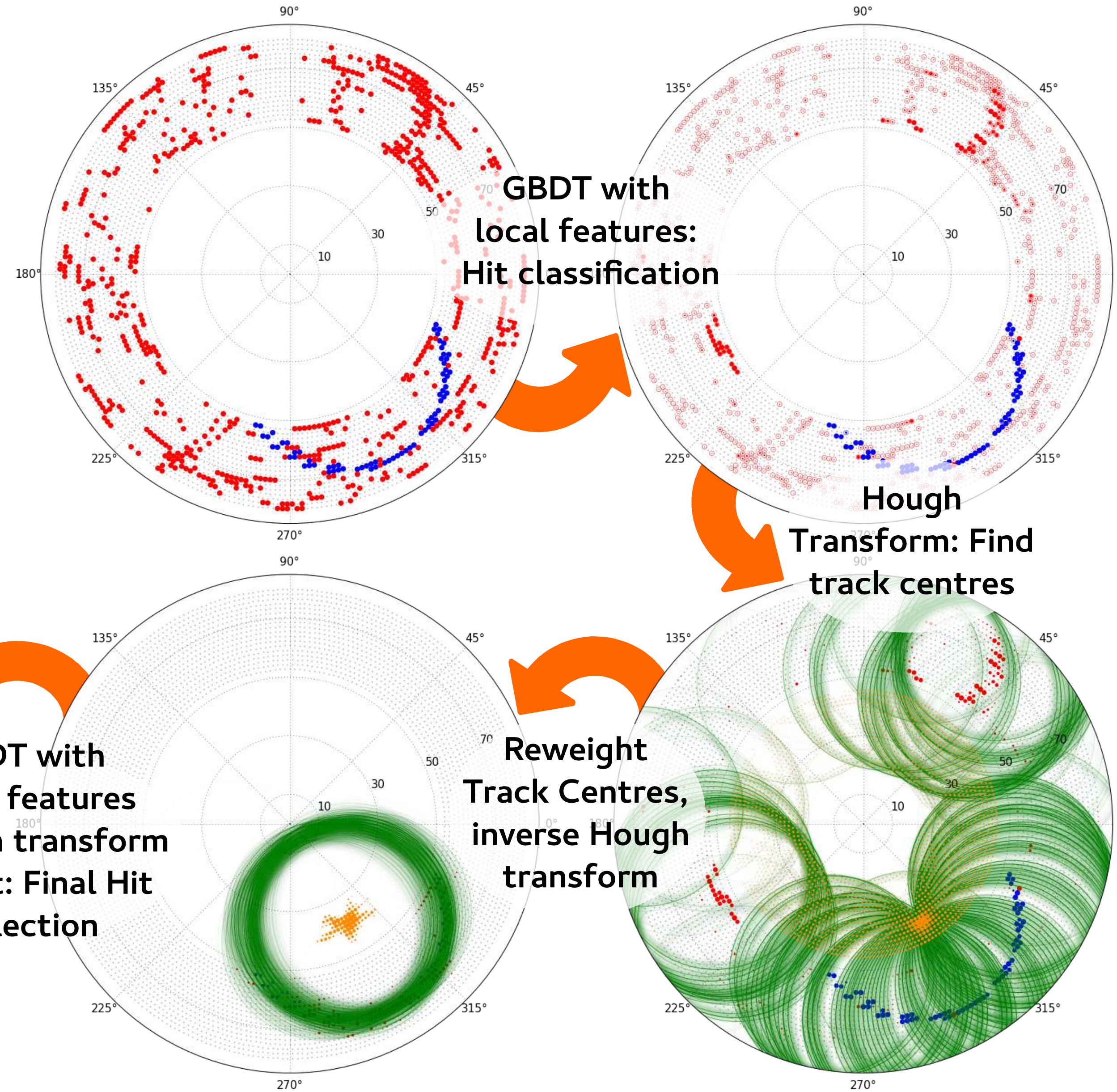


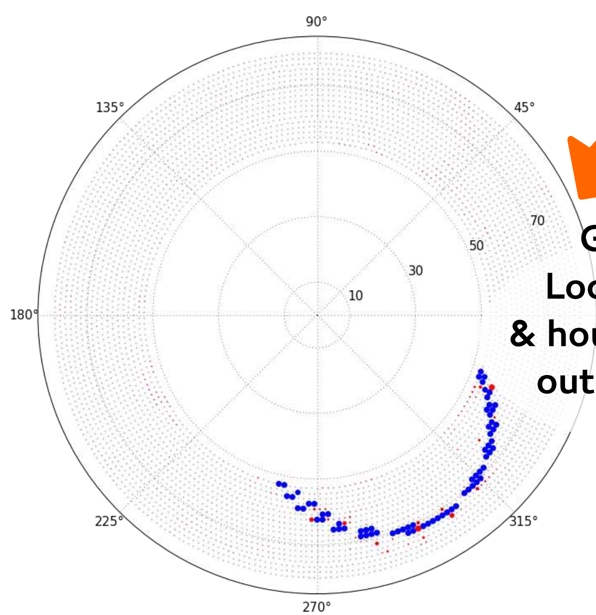
- 20 layers with alternating stereo angles of ±4°
- 20,000 wires total
  - About 5000 sense wires
- Fully strung as of November 2015
  - Wire tensions tested with resonance-based wire tension checking
- CDC completed in July 2016 with installation of inner wall
- Reconstruction software being finalised
- Cosmic and beam tests to optimise gas choice and study resolution and drift time
  - Achieved the 200 keV/c resolution

Tracking with Machine Learning

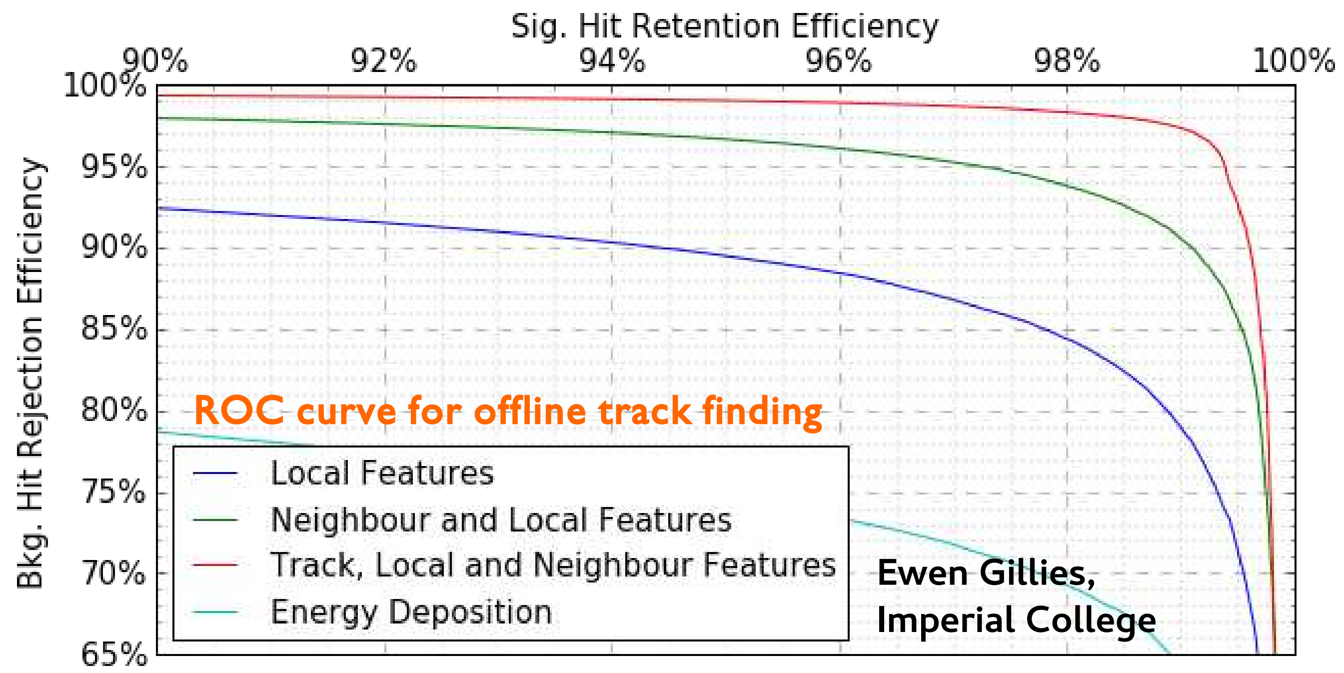
Ewen Gillies, Imperial College







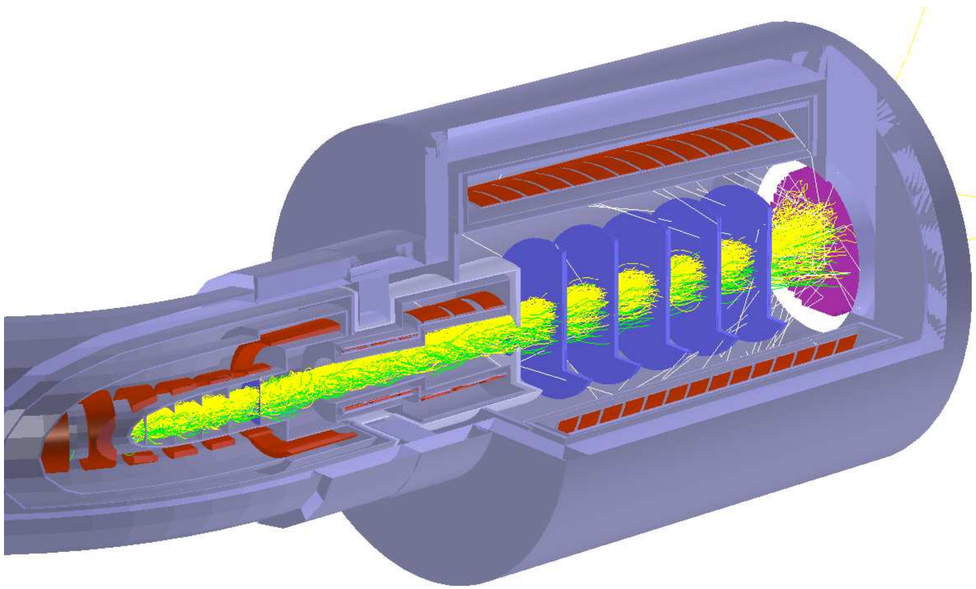
Tracking with Machine Learning

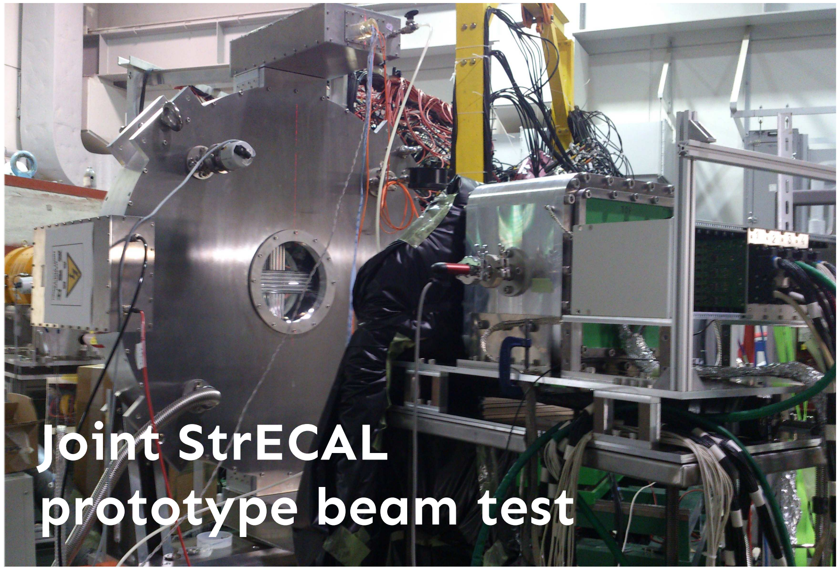


- Keep 98.5% of hits due to signal, while removing 98% of background hits
- Typical events have 15% occupancy but can be up to 30%
- Feeds in to multi-turn track fitting based on Genfit2
- Online track-trigger in development, based on this
  - Coarse energy (wire + L/R neighbours), board ID → Look-up table
  - Bonsai Decision tree (ie. a look-up table)
  - Event classifier using weighted sums of all hit classifier outputs

StrECAL Detector

Straw Tracker + ECAL

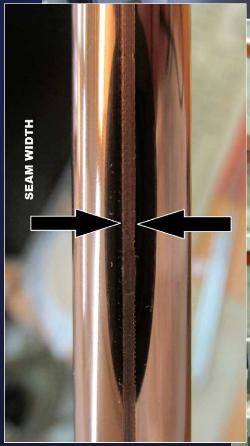




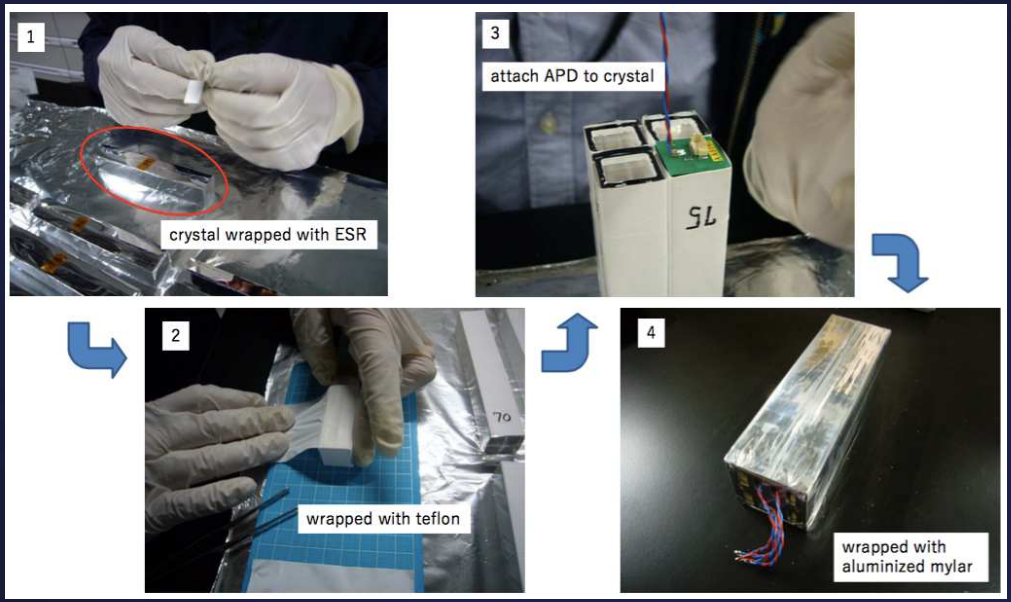
- Phase-II Detector prototype
- Used to characterise beam in Phase-I

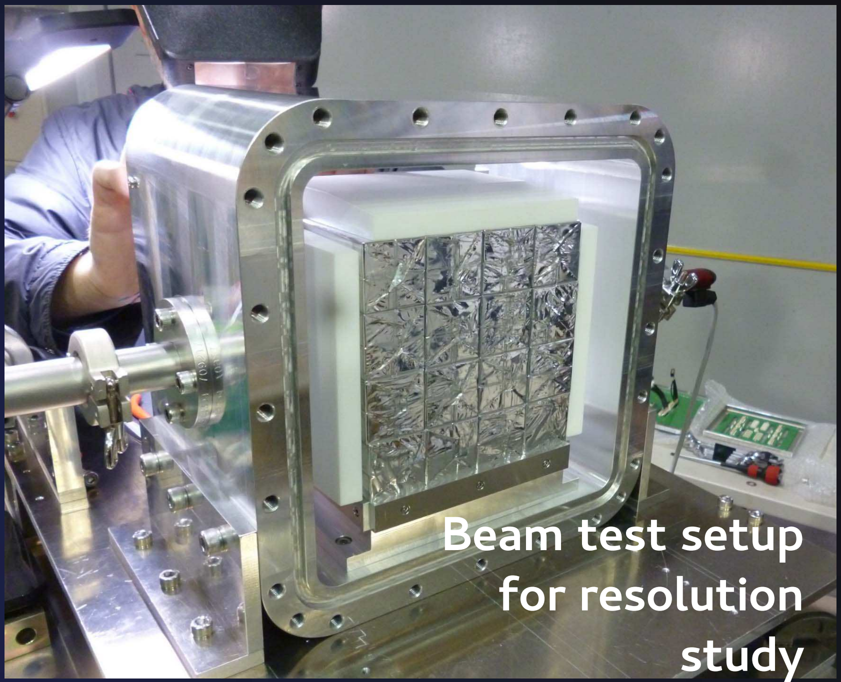
Straw Tracker

- 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 and vacuum tests at KEK
  - Resolution studies from beam tests better than 200 micron resolution across straw

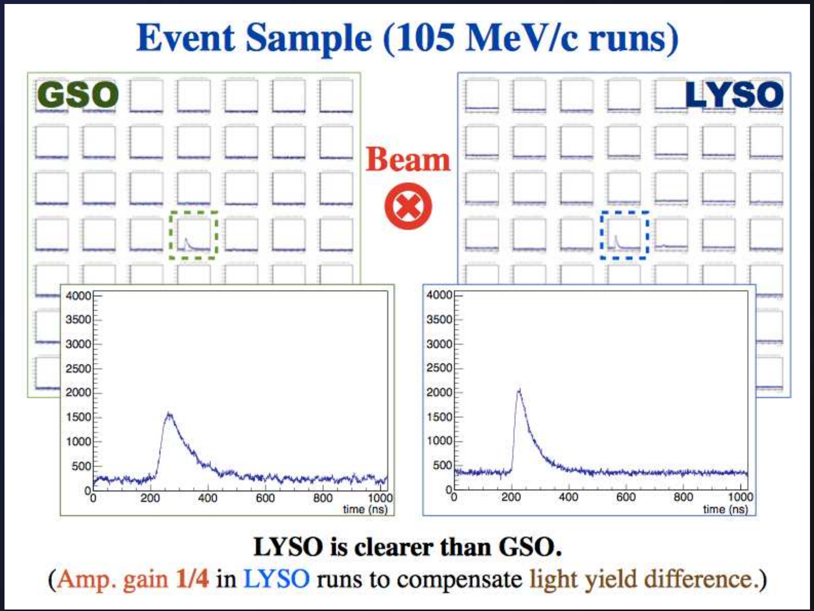


LYSO Crystal Calorimeter



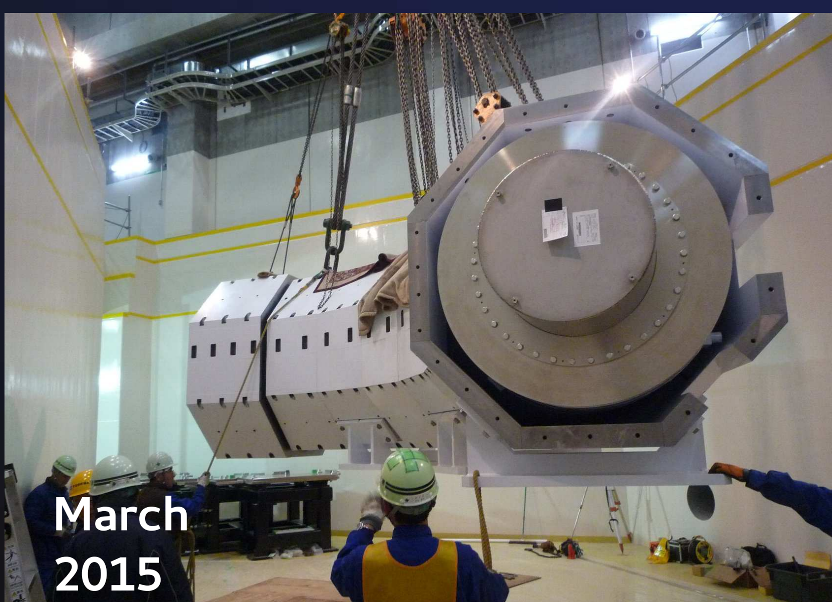


- 2272 LYSO Crystals
  - Dimensions: 2x2x12 cm
- Status:
  - Crystal purchasing on-going
  - Test bench being built
  - Beam tests for resolution studies, PID and DAQ underway
  - Calibration system being designed

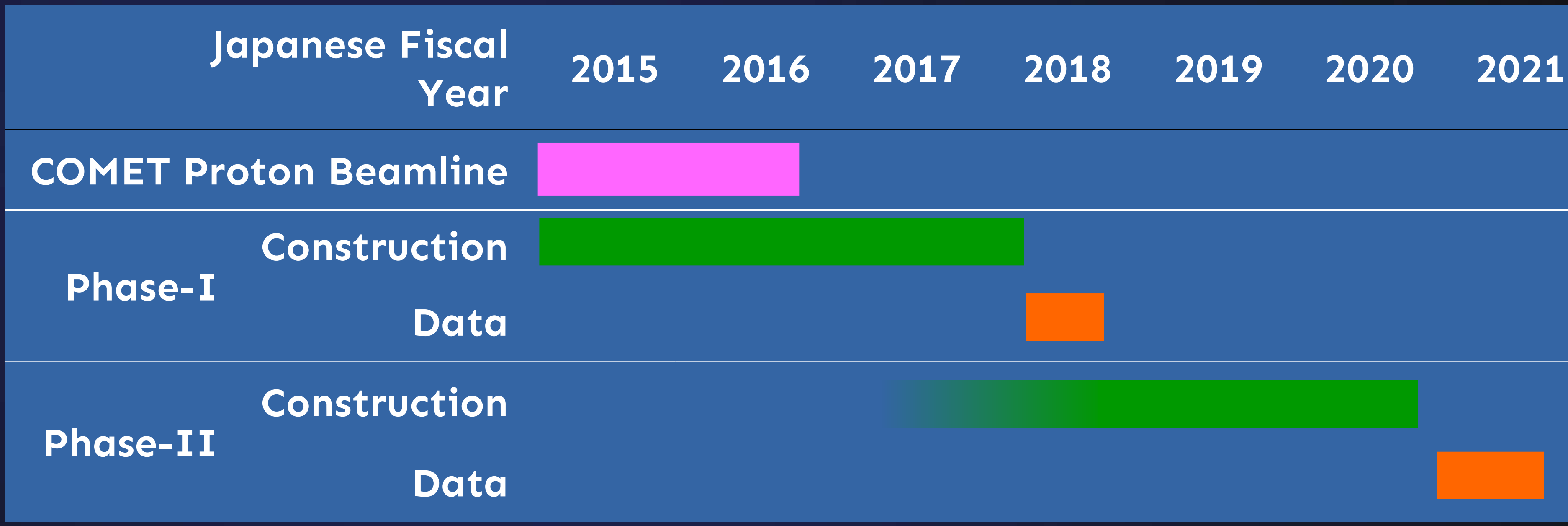


Facility Status and Beamline

- Building and hall completed
- Phase-I bent solenoid built and installed, remaining solenoids nearly finished
- Proton beamline being commissioned



Schedule and Collaboration

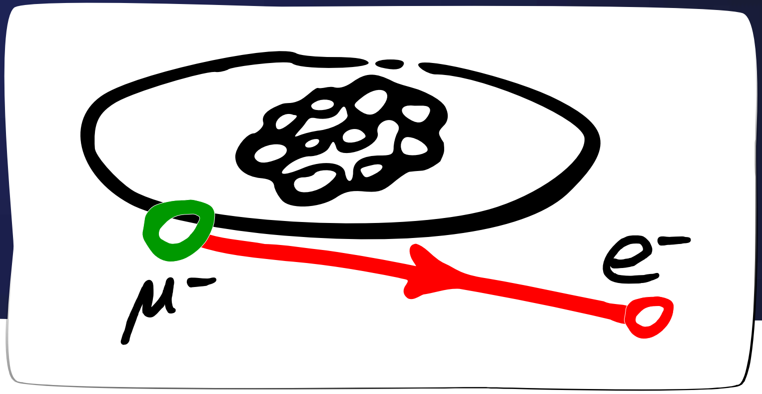


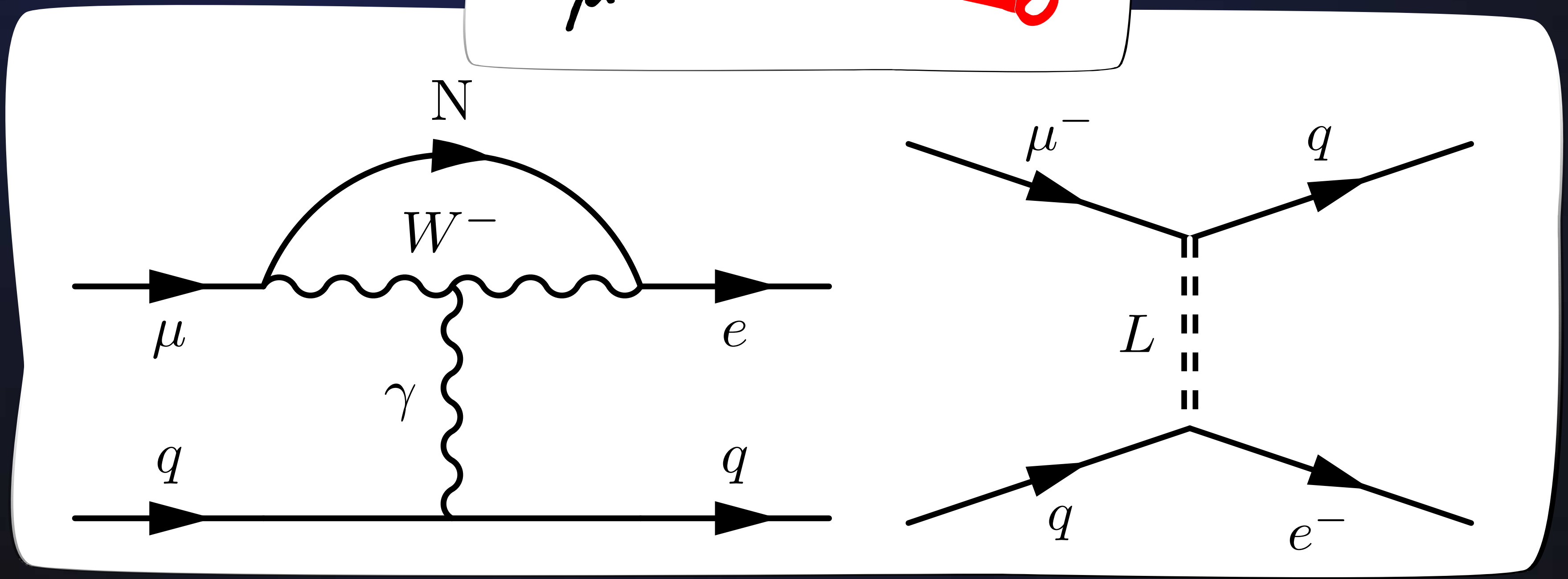
15 Countries, 33 institutes
180 participants

 Ben Krikler: b.krikler@bristol.ac.uk

Summary

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





Ben Krikler: b.krikler@bristol.ac.uk

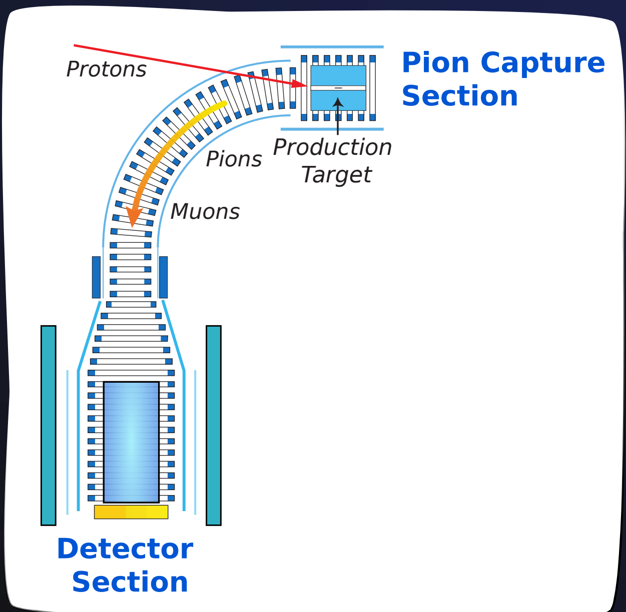
Summary

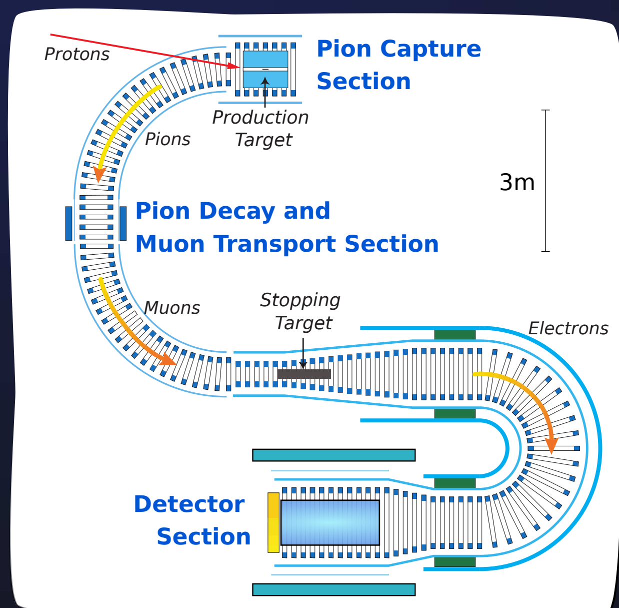
Muon-to-electron conversion is a strong probe of new physics

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

COMET Phase-I
2018, for 150 days
Sensitivity $< 3 \times 10^{-15}$

COMET Phase-II
2021, for 1 year
Sensitivity $< 3 \times 10^{-17}$





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, for 150 days
Sensitivity $< 3 \times 10^{-15}$

COMET Phase-II
2021, for 1 year
Sensitivity $< 3 \times 10^{-17}$