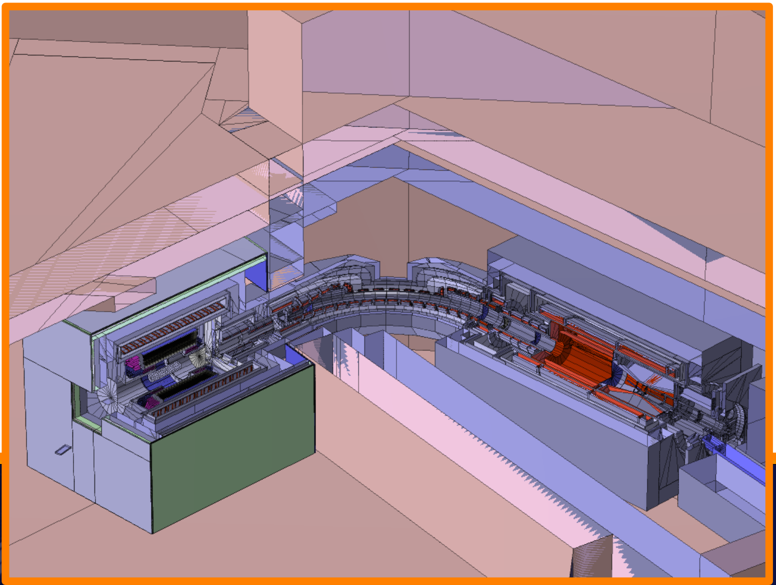
Imperial College London

The COMET Experiment:
Comparitive Studies for the Search of New BSM Physics



NA61++/SHINE Workshop
Location: CERN

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December 2022

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THE ROYAL SOCIETY
Newton Ungku Omar Fund
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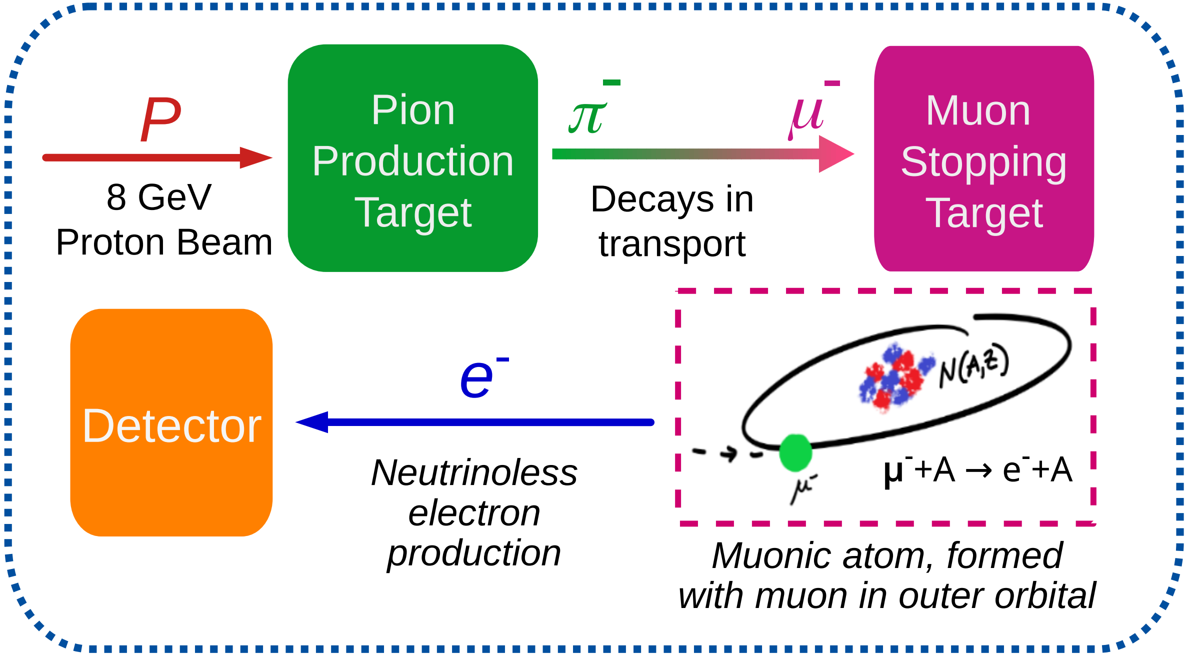
COMET

Coherent Muon to Electron Transition

- The **COMET** experiment at J-PARC, Japan, aims to observe the **BSM, Charged Lepton Flavour Violating** process of coherent, neutrinoless ***μ-e*** **conversion**



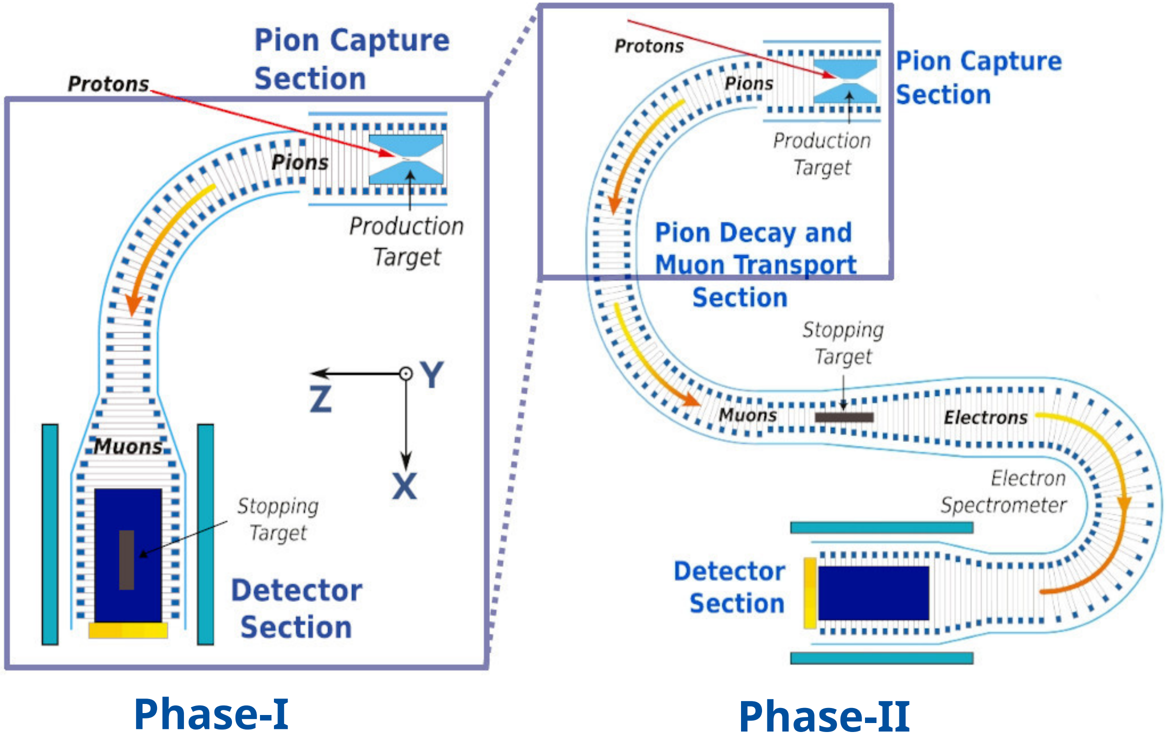
COMET

Coherent Muon to Electron Transition

- The COMET experiment at J-PARC, Japan, aims to observe the BSM Charged Lepton Flavour Violating process of coherent, neutrinoless μ-e conversion

- We use a **novel design** across **two** main phases, each with increasing sensitivity

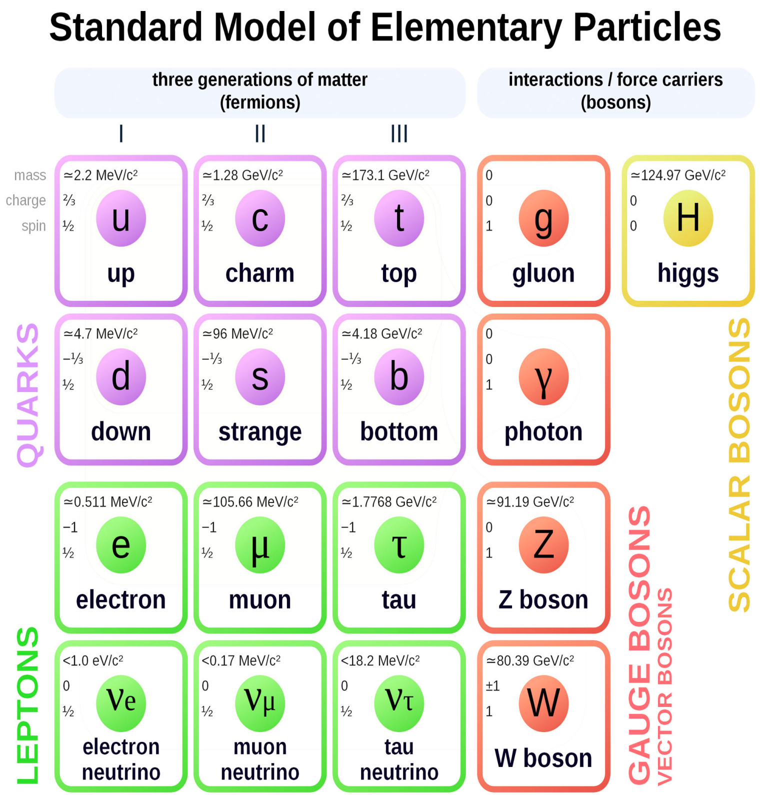
- We aim to observe **~105 MeV electron** with **no Standard Model backgrounds**, improving the current sensitivity limit by at least $O(10^4)$



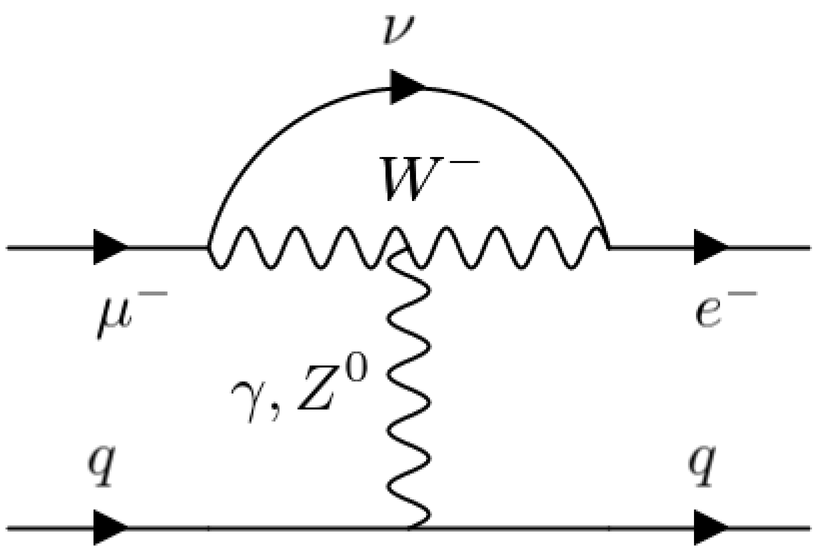
CLFV?

Charged **L**epton **F**lavour **V**iolation

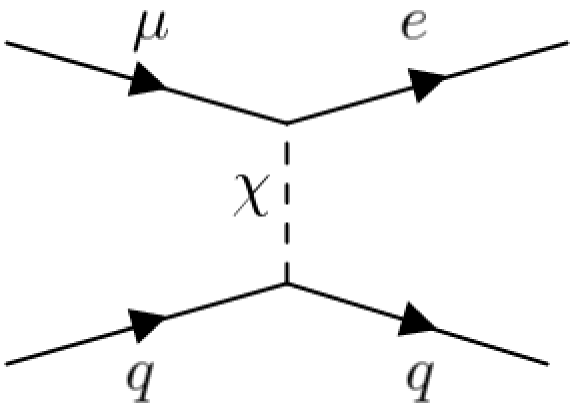
- Muons and electrons were eventually known to be **fundamentally unique leptons**
- **Lepton flavour is conserved** in the SM, in this case **through neutrinos**
- But some BSM theories predict **valid charged lepton flavour-violating processes!**



μ-e in the SM & BSM



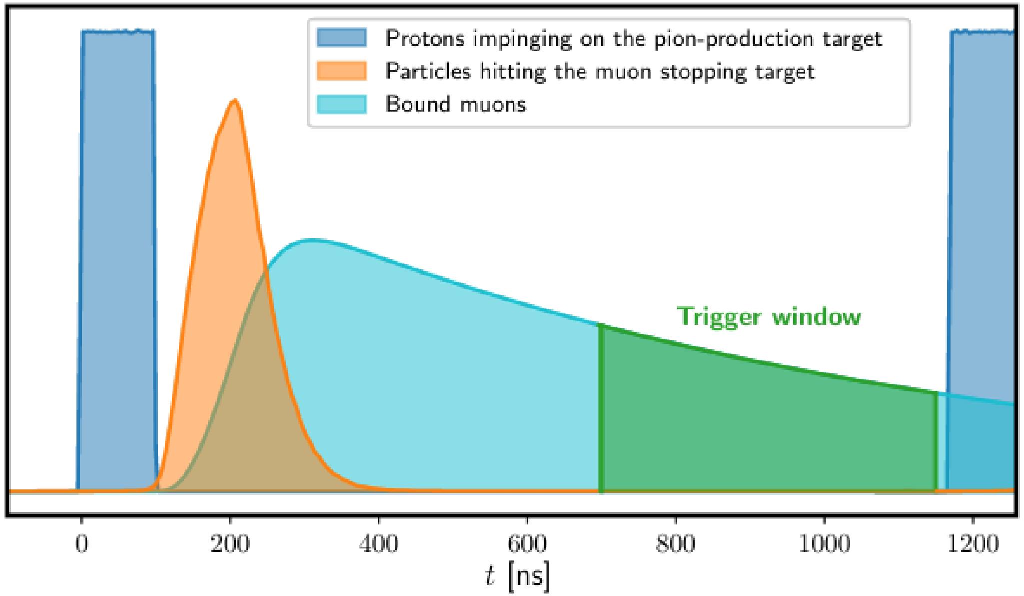
A possible conversion in an extended SM, facilitated by neutrino oscillation. GIM suppression from tiny neutrino mass makes rates as small as 10^{-54}



A possible BSM channel through interchange of an new heavy particle, GIM suppression is absent as CLFV avoids including a neutrino; rates may be as high as 10^{-17}

Beamline

- We employ an **8 GeV** proton beam with **100 ns pulses** separated by **1170 ns**
- Muons **bound in the aluminium** muon stopping target (in the detector region) have a lifetime of 864 ns
- The separation allows enough time for *most of* the **beam flash backgrounds to subside** and for cleaner measurements to be taken



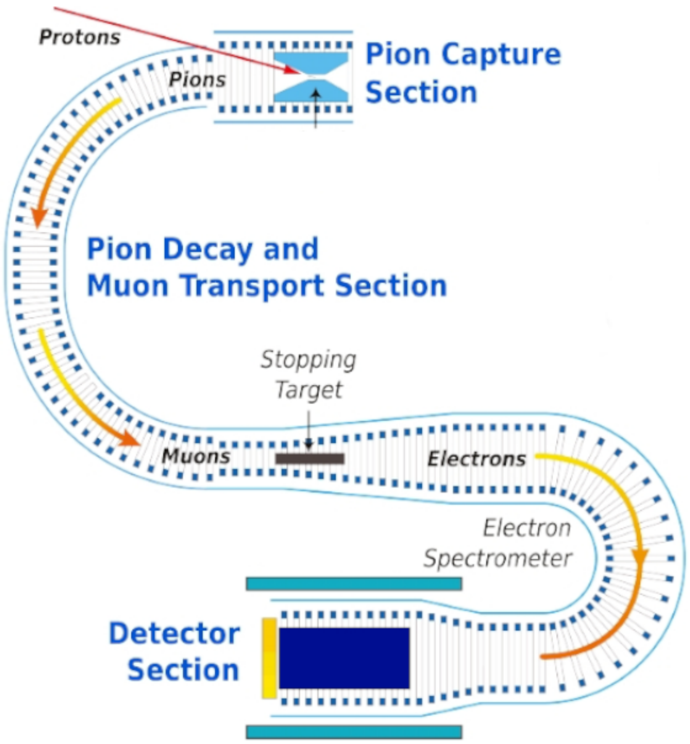
Beamline

- A 5 T solenoid captures pions which travel down a **curved solenoid, separating trajectories** by charge and momentum

- Secondary beamline uses **backward pions** for more **appropriate momenta and reduced backgrounds** (especially anti-protons)

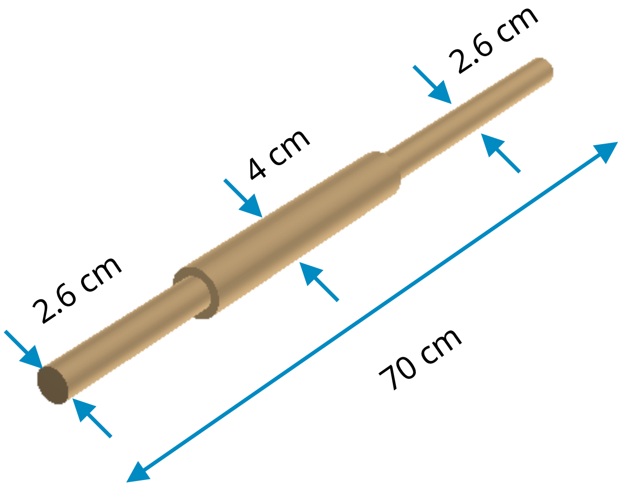
- A superimposed **vertical dipole field** facilitates further selection of charged particles, propagating selection to the solenoid center

- This ensures a cleaner beam of **low-energy, negatively charged muons** reaching the detector solenoid

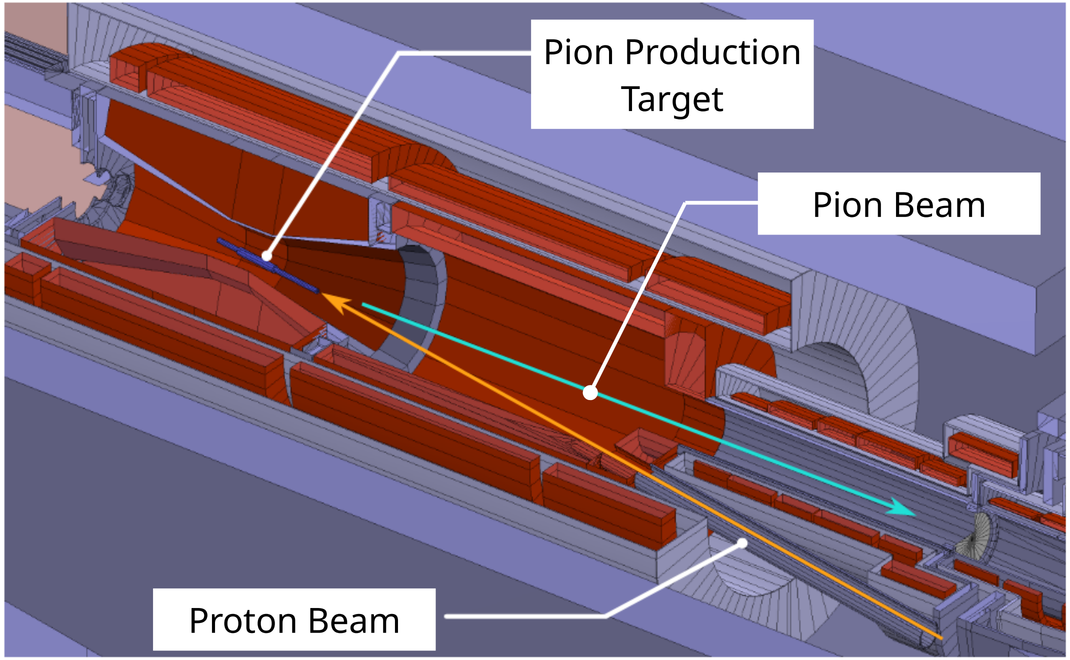


COMET Pion Production

Coherent **M**uon to **E**lectron **T**ransition



The Phase-I pion production target.
Here it is made from graphite, but for Phase-II a heavier material is planned for use, such as tungsten or SiC



Drawing of the COMET pion production region, showing the incident primary proton beam and direction of backwards secondary pion beam

Important Backgrounds

- Low energy **anti-protons can annihilate** into photons that can produce signal-like electrons
  - The slow, stable, anti-protons may pass through the charge/momentum selection and **produce signals in the delayed analysis window**
  - The 8 GeV beam energy is chosen to **restrict backwards anti-proton production**, but forwards **anti-protons can reflect** into the beamline
  - Would be helpful to **understand threshold behaviour** at beam energies near 8 GeV

- Some other important backgrounds
  - Radiative muon/pion capture
  - Decay-in-orbit (DIO)
  - Cosmic Rays

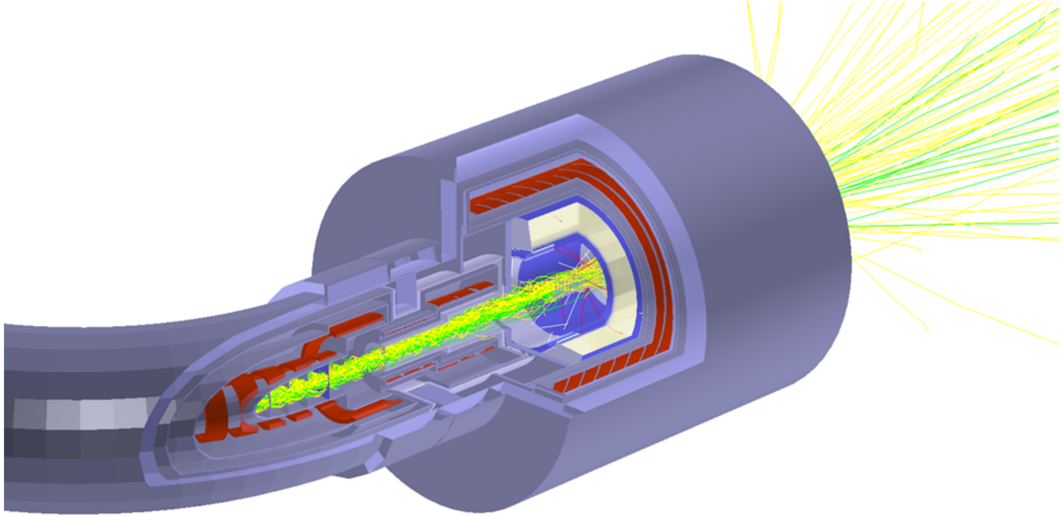
Type	Background	Estimated events
Physics	Muon decay in orbit	0.01
	Radiative muon capture	0.0019
	Neutron emission after muon capture	< 0.001
	Charged particle emission after muon capture	< 0.001
Prompt beam	* Beam electrons	
	* Muon decay in flight	
	* Pion decay in flight	
	* Other beam particles	
	All (*) combined	≤ 0.0038
	Radiative pion capture	0.0028
	Neutrons	$\sim 10^{-9}$
Delayed beam	Beam electrons	~ 0
	Muon decay in flight	~ 0
	Pion decay in flight	~ 0
	Radiative pion capture	~ 0
	Antiproton-induced backgrounds	0.0012
Others	Cosmic rays†	< 0.01
Total		0.032

† This estimate is currently limited by computing resources.

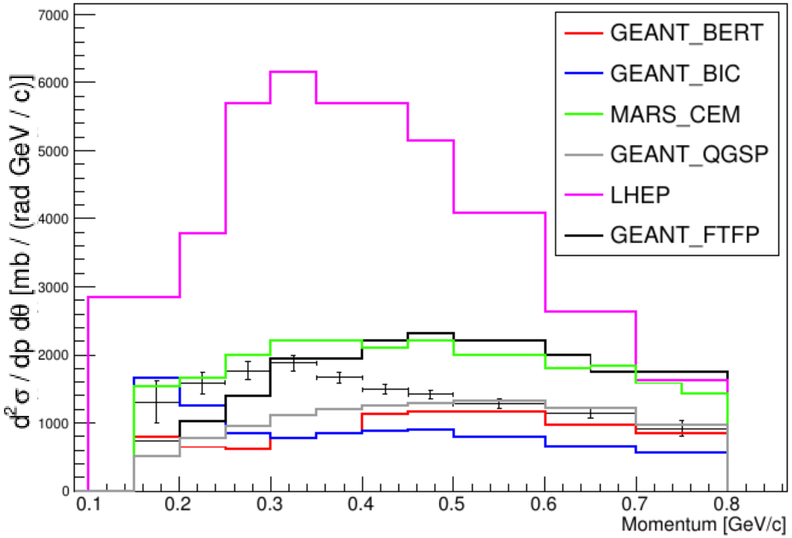
Summary of estimated background events in the COMET Phase-I runtime*

* COMET collaboration, Abramishvili, R., Adamov, G., Akhmetshin, R. R., Allin, A., Angélique, J. C., ... & Tachimoto, T. (2020). COMET Phase-I technical design report. Progress of Theoretical and Experimental Physics, 2020(3), 033C01

Current Work: Validation



Muon beam exiting through the back of the detector solenoid



Interaction rates (cross section) of pion production across different production models vs data from HARP *

*A. W. J. Edmonds. “An Estimate of the Hadron Production Uncertainty and a Measurement of the Rate of Proton Emission after Nuclear Muon Capture for the COMET Experiment”. PhD thesis. U. Coll. London, 2015. url: http://discovery.ucl.ac.uk/1468926 (cit. on pp. 79–80, 91).

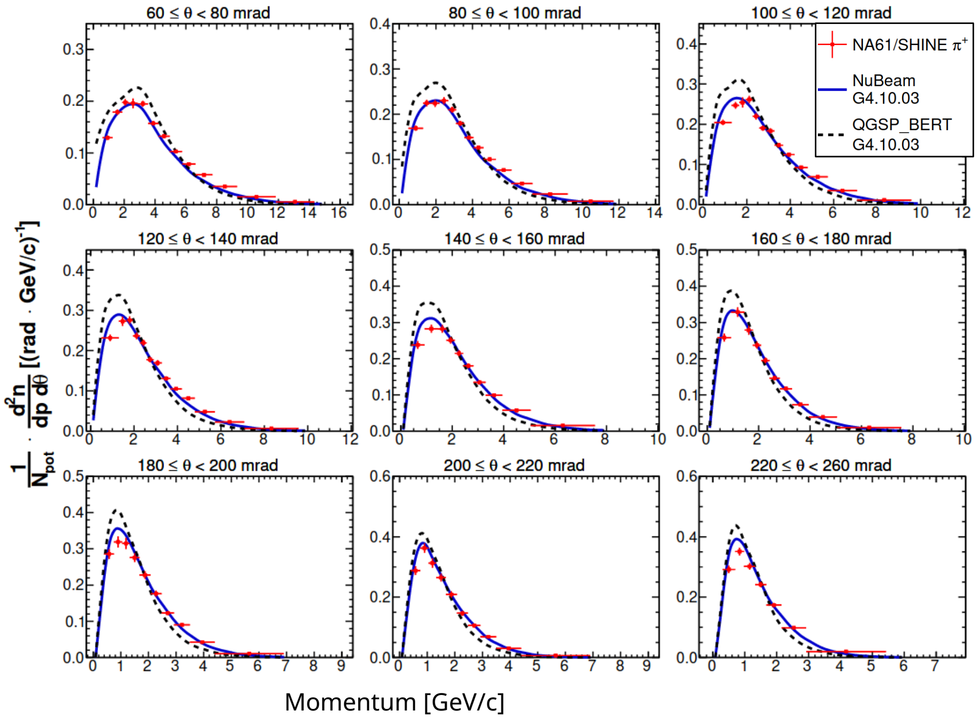
NA61 and ICEDUST

- NA61 is among the best sources for a baseline to **validate COMET's** simulation framework's (ICEDUST) **pion production**, despite the non-ideal energy scale

- We create the NA61 long-target geometry within the ICEDUST to test the physics models, by directly tracking particles from **target interaction to surface**

- Current COMET physics set-up for Geant4 is:
  - G4.10.6.p03 + relevant retroactive patches
  - EM Opt4 + QGSP_BERT_HP

- Comparing against M. Pavin's 2017 analysis for 2010 NA61 data and Geant4 simulations[1]



NA61 data vs pure Geant4 simulations with certain physics lists[2]

[1] Pavin, M. (2017). Measurements of hadron yields from the T2K replica target in the NA61/SHINE experiment for neutrino flux prediction in T2K (Doctoral dissertation, Université Pierre et Marie Curie-Paris VI)

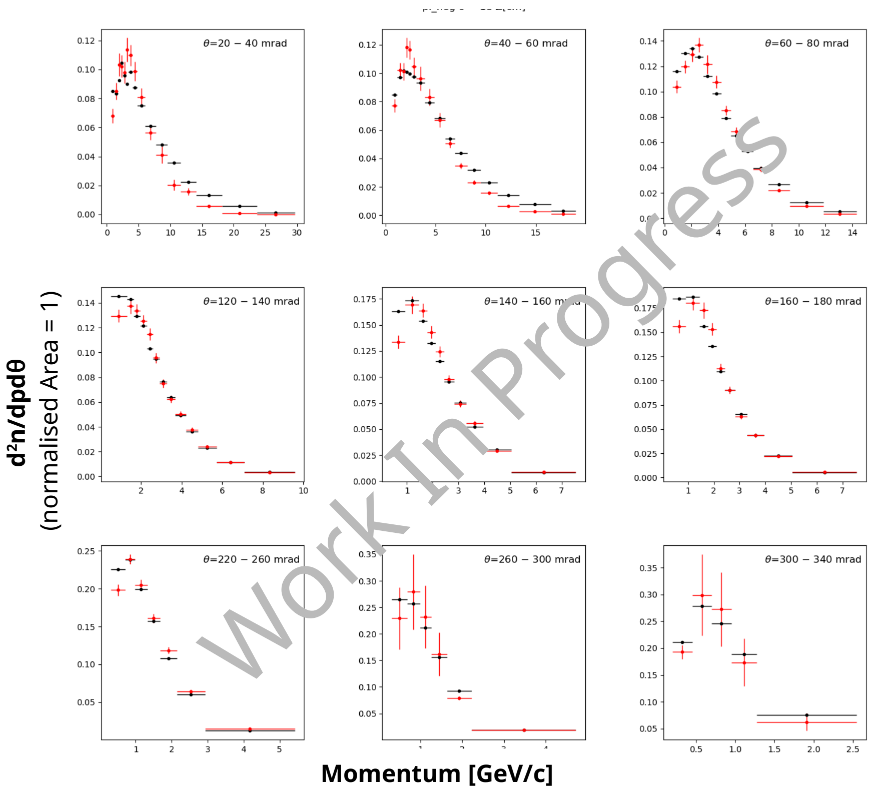
[2] Abgrall, N., Aduszkiewicz, A., Andronov, E.V. et al. Measurements of $\pi\pm$, $K\pm$ and proton double differential yields from the surface of the T2K replica target for incoming 31 GeV/c protons with the NA61/SHINE spectrometer at the CERN SPS. Eur. Phys. J. C 79, 100 (2019). https://doi.org/10.1140/epjc/s10052-019-6583-0

NA61/SHINE

- Simulated **particle distributions from target surface** binned identically for **direct comparisons** to 2010 NA61 double differential rates
  - Binned into a range of momenta, angles, and across 6 regions down the target

- Current iteration of results has **good shape agreement** but aiming to resolve uncertainties at the smallest angles, and beginning and end of the target
  - Lowest momenta <3 GeV/c are amongst the most different

- Ongoing work implementing details on reproducing data from M. Pavin's thesis



A sample of NA61 data (red) vs ICEDUST simulations (black) for negative pions in the first 18 cm of the target, visualising shape-only comparisons

NA61++/SHINE

What would we want from a future NA61++/SHINE?

- In the first instance, any **relevant data with carbon production target** and **8 GeV proton beam**
- Ideally, a **novel set-up to study <80 MeV/c backwards pion** production
  - Rates, energies and angular distributions
- **Anti-protons** (in forward direction) as a function of primary beam energy near 8 GeV
- Data on **heavier target materials**, like tungsten, would also be useful for Phase-II

Note: Mu2e experiment at Fermilab has very similar physics needs

Conclusion

- COMET aims to search for **signs of BSM** physics by **observing CLFV with low-energy, neutrinoless, coherent μ-e conversion**

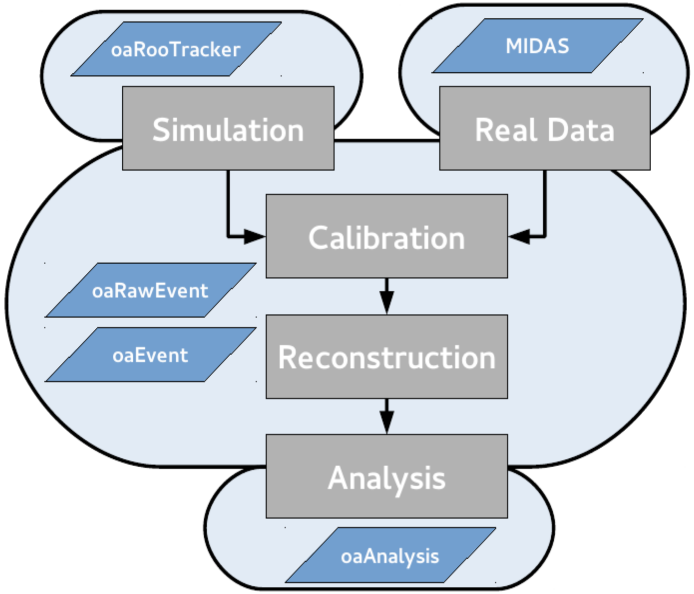
- **Validations necessary to** ensure a capacity for the **highest ever sensitivity on CLFV** processes
  - For COMET, it is useful to have proton-on-graphite data at 8 GeV, ideally in the backwards direction, and quantify <80 MeV/c pions and anti-protons

COMET μ beam exit!

Extra Slides

ICEDUST

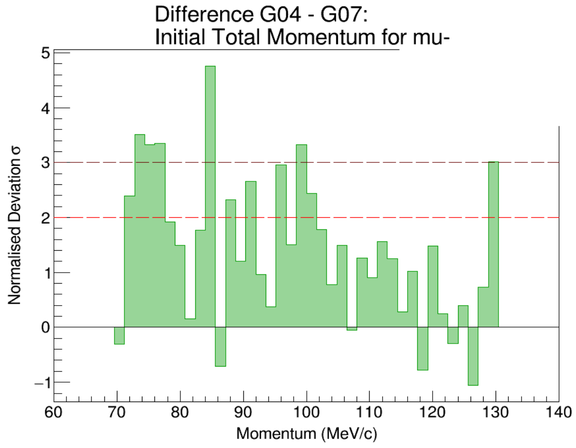
- COMET's main software framework, based on T2K ND280, for simulation, reconstruction, analysis and more.
- Uses Geant4 for Monte-Carlo propagation, and primary choice for target interactions
- Can treat **simulated and real** data **identically**
  - Simulations provide normally unobtainable data (true trajectories and parent particles)
  - Work towards creating **realistic 'mock' data**



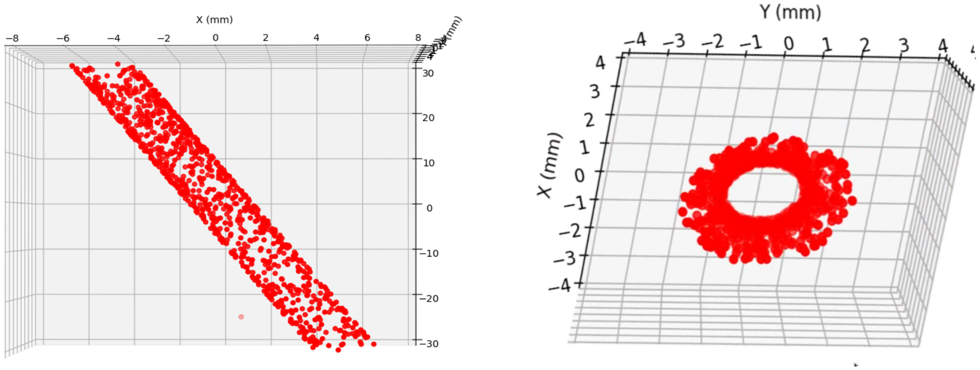
ICEDUST data flow

Missing Hadrons

- Less innocent changes: sharp reduction in low energy muons instead due to a **bug in Geant4.10.7**
  - Will **silently** create and kills low-energy, unphysical hadrons crossing different volumes, which **drastically changes propagated results**
  - A **big problem that only shows as a 5% reduction in particles…**



μ^- momentum bin contents from a Geant4.10.4.p03 distribution minus that of Geant4.10.7

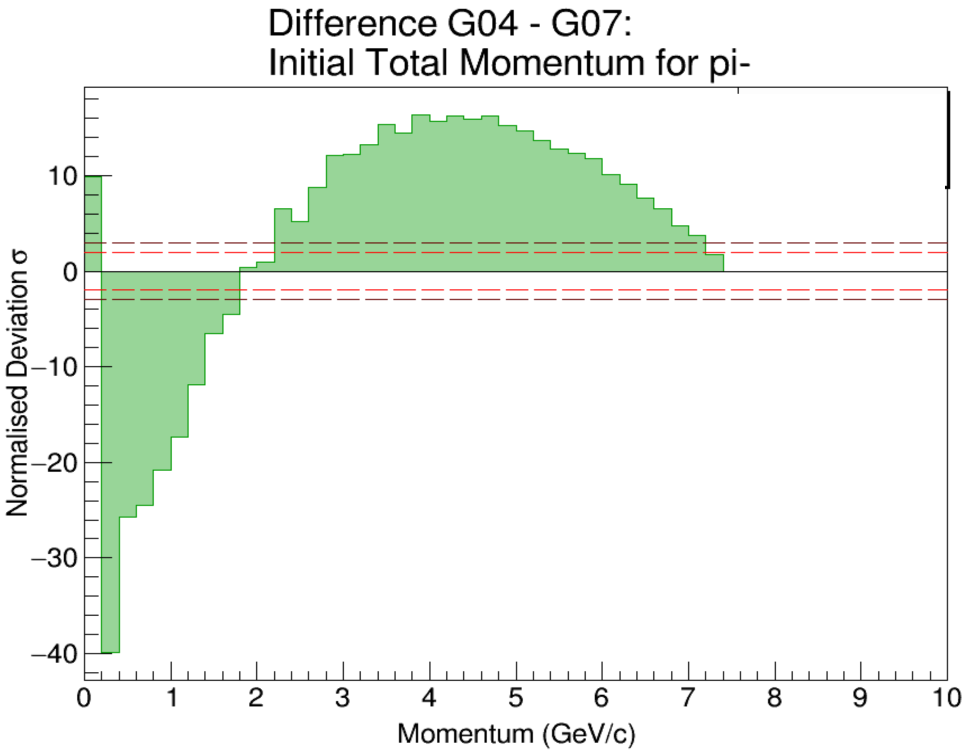


Locations of silently killed muons (when killed) showing a hollow production target shape

False Alarms

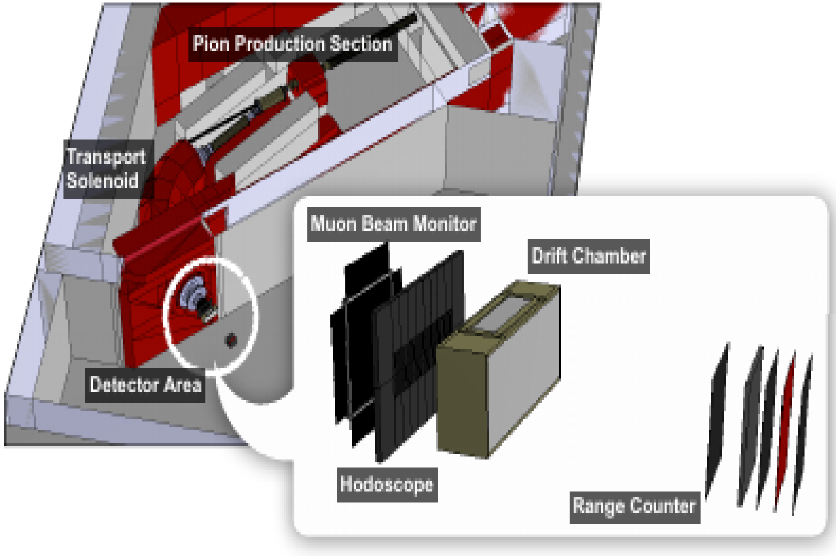
- Some **large,** very **distinctive** change that hints towards a drastic difference in the **physics handling**

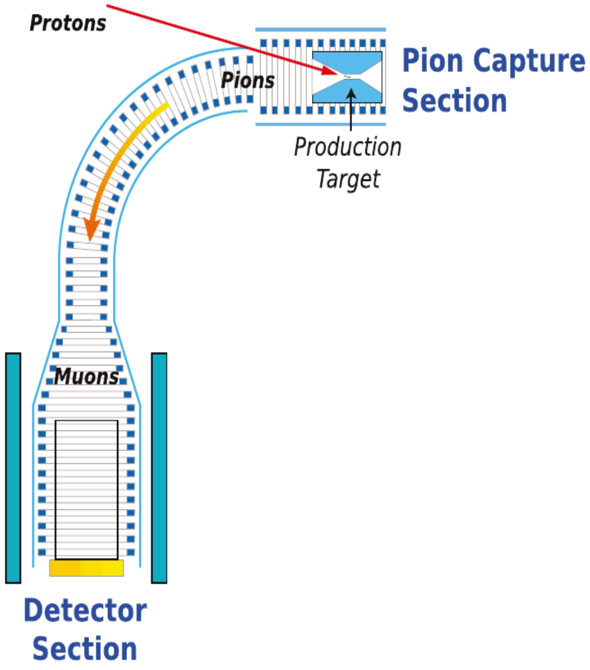
- Comparing pion momentum
  - Energy ranges at which certain **physics** models becomes active was changed – **it's okay!**

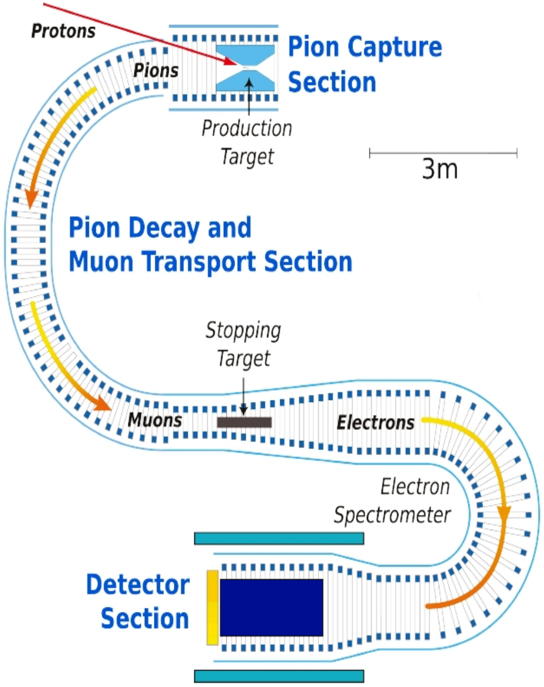


π^- momentum bin contents from a Geant4.10.4.p03 distribution minus that of Geant4.10.7

The COMET Stages







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Backgrounds

Summary of the estimated background events for a single-event sensitivity of 3×10^{-15} in COMET Phase-I with a proton extinction factor of 3×10^{-11}.

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	Radiative muon capture	0.0019
	Neutron emission after muon capture	< 0.001
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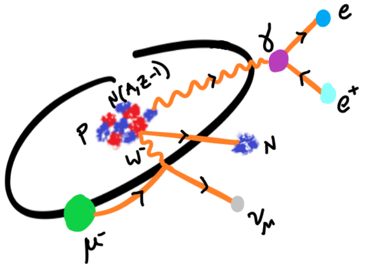
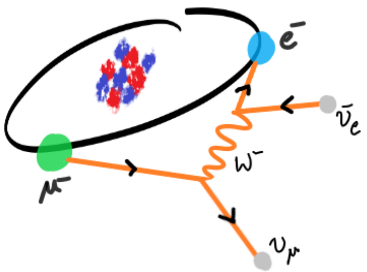
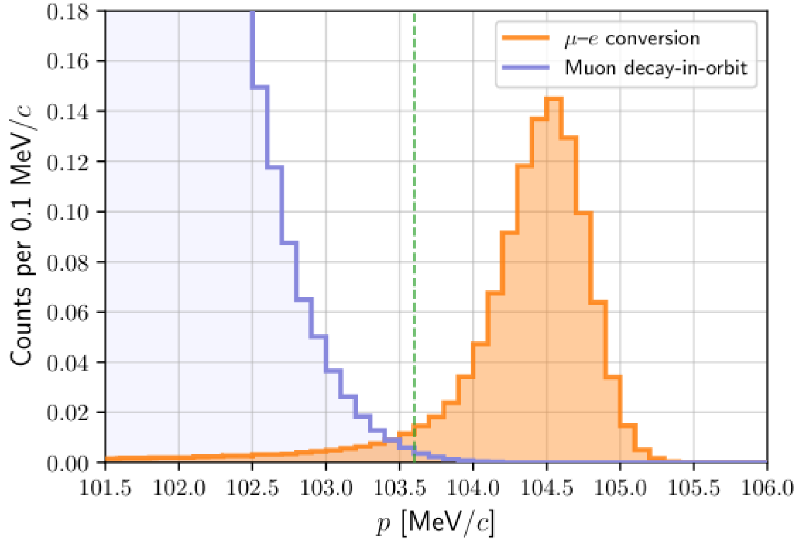


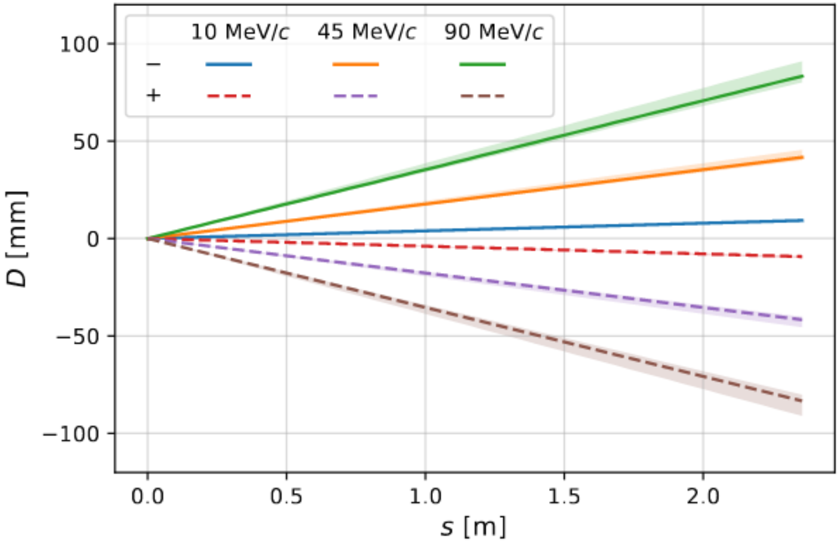
Radiative Muon Capture + N emission



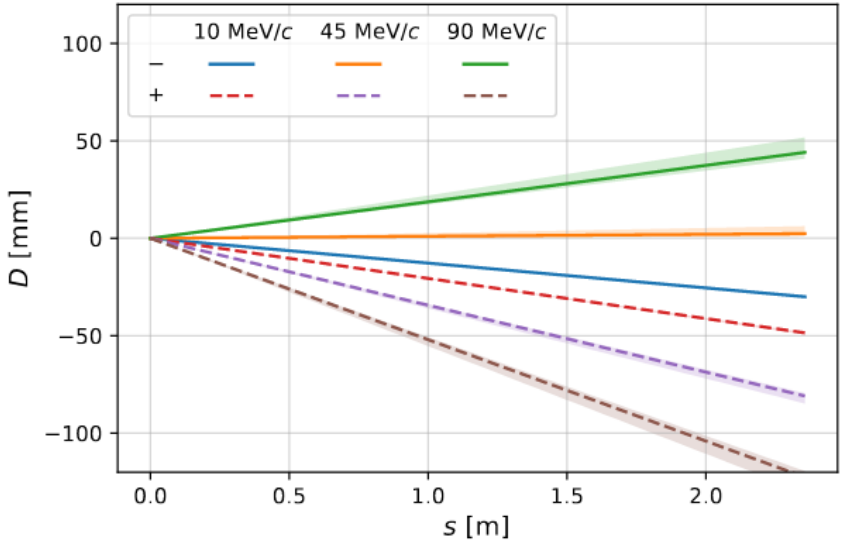
Decay in orbit



Dipole Field Momentum Selection



(a) No dipole field.

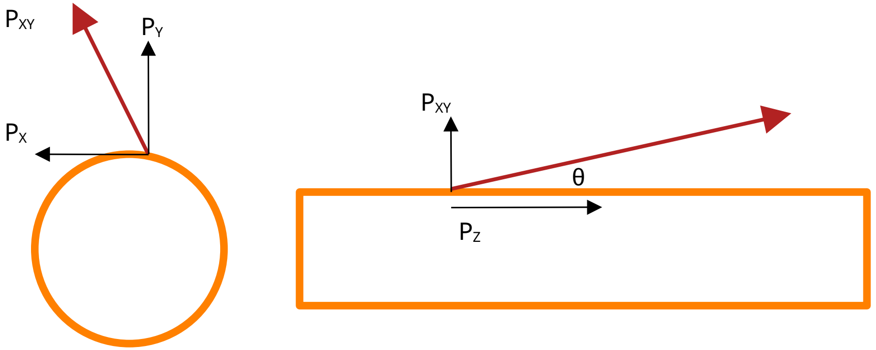


(b) 0.05 T vertical dipole field.

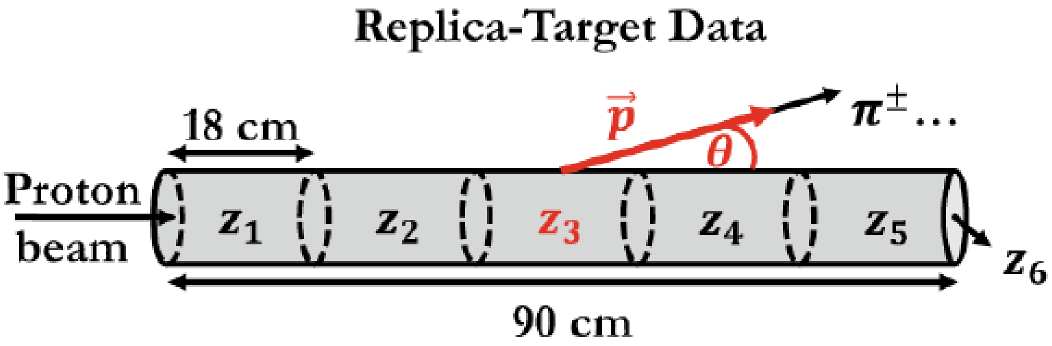
Vertical drift of helical trajectories for particles of different charges and momenta, with and without a dipole field presence.

Source: Matthias Doubouchet, Imperial College London , PhD thesis (submitted, not yet published)

NA61 Target Description



$\theta = \arctan(P_{xy}/P_z)$



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