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The COMET *μ-e* Experiment:

Preparing for Real Data from BSM Physics

IOP HEPP & APP Annual Conference

Roden Derveni

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Meeting Location: Rutherford Appleton Laboratory

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Newton Ungku Omar Fund

THE ROYAL SOCIETY

UKRI Science and Technology Facilities Council

Contents

- The COMET Experiment
- Coherent $\boldsymbol{\mu} \rightarrow \boldsymbol{e}$ Conversion
- ICEDUST Simulations
- Validating Changes
- Data-Driven Validations

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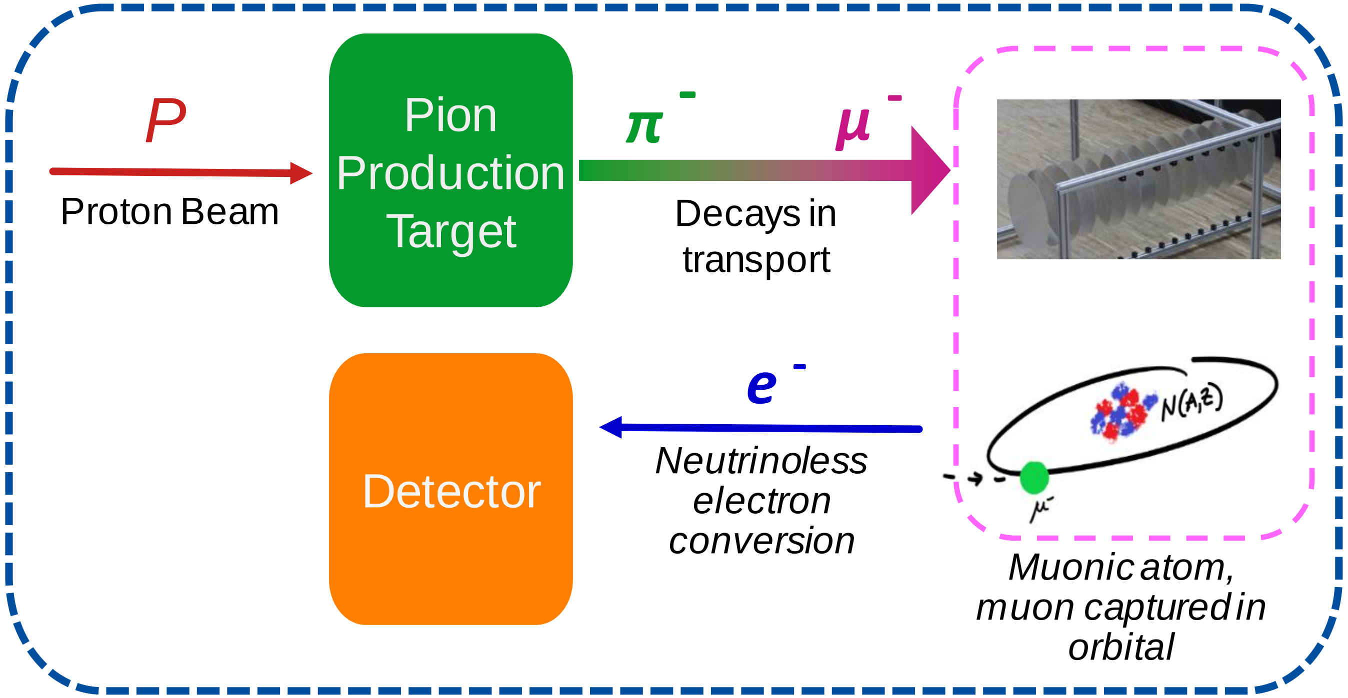
COherent Muon to Electron Transition

- The **COMET** experiment at J-PARC, Japan, aims to observe the BSM **charged lepton flavour violating** process of **neutrinoless μ-e** *conversion*

- Increase sensitivity by > **O(10^4)**
- **low-energy backgrounds**

- We use a **novel design** across **two main phases**



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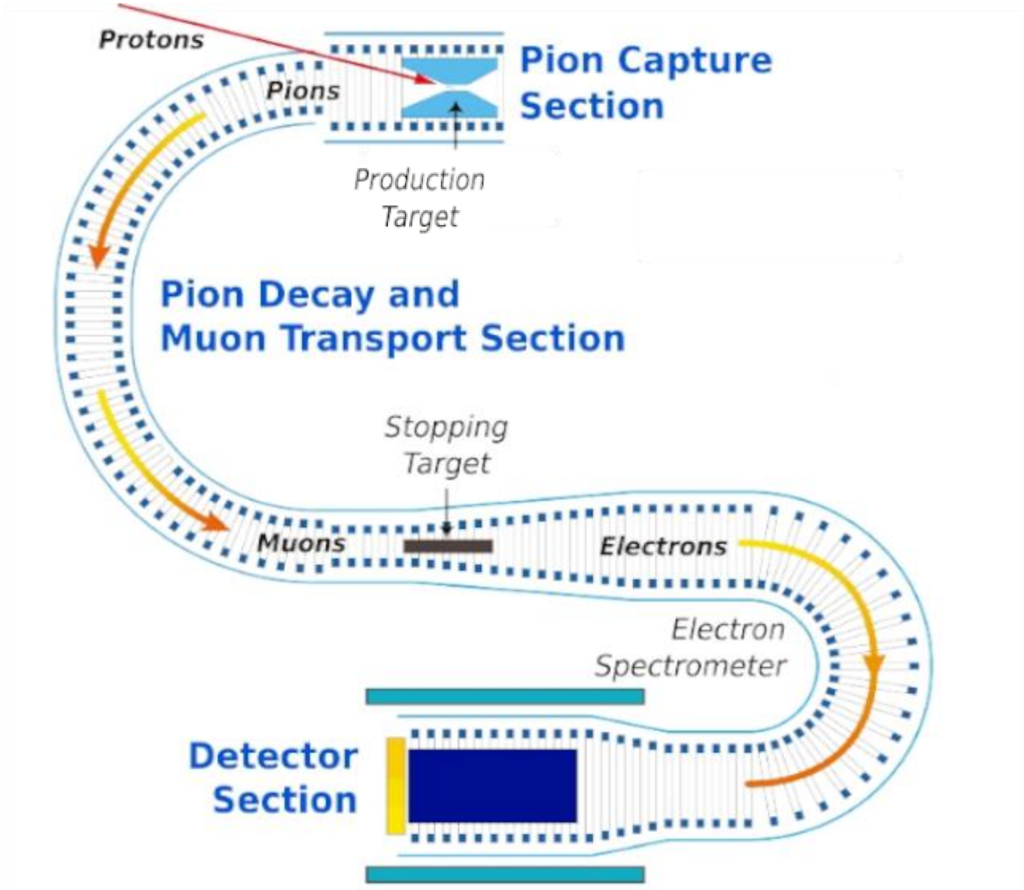

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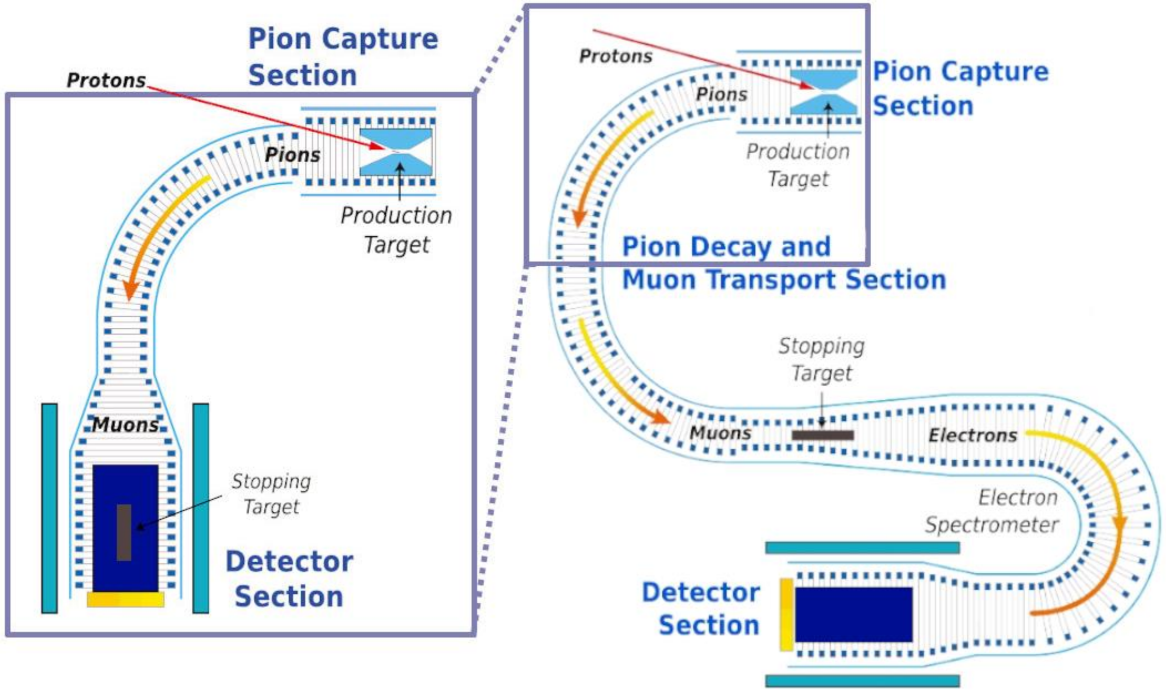

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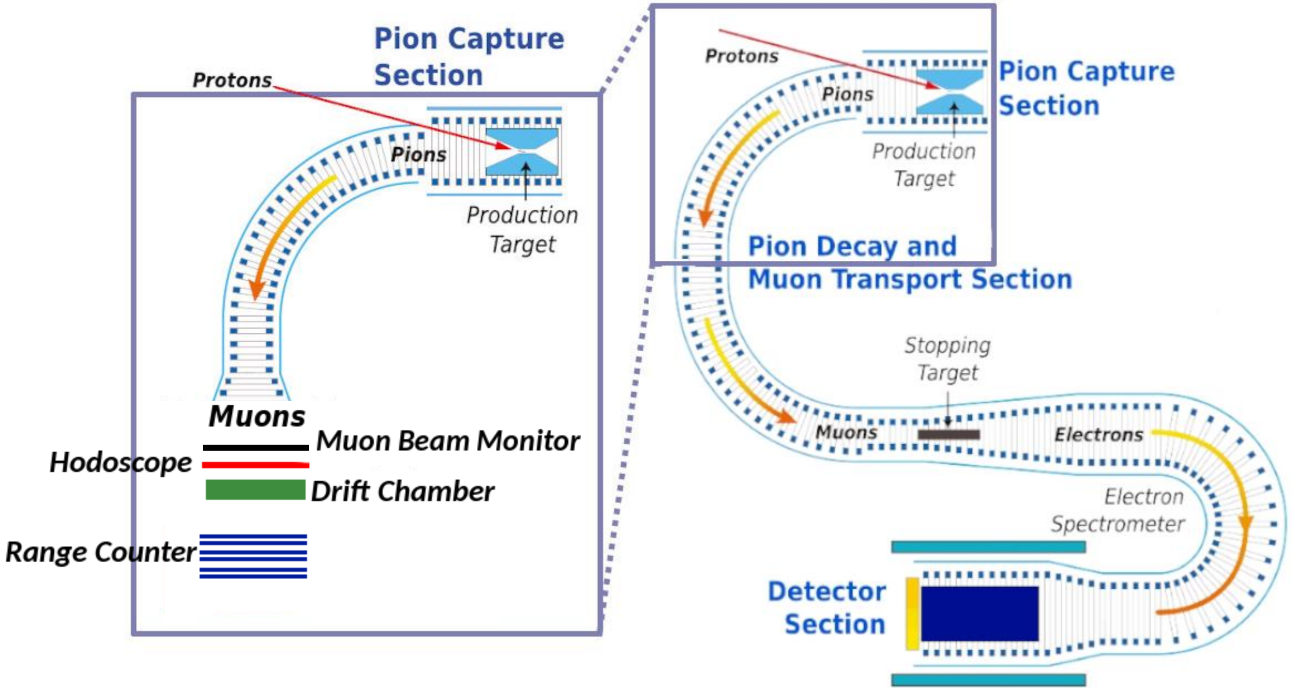

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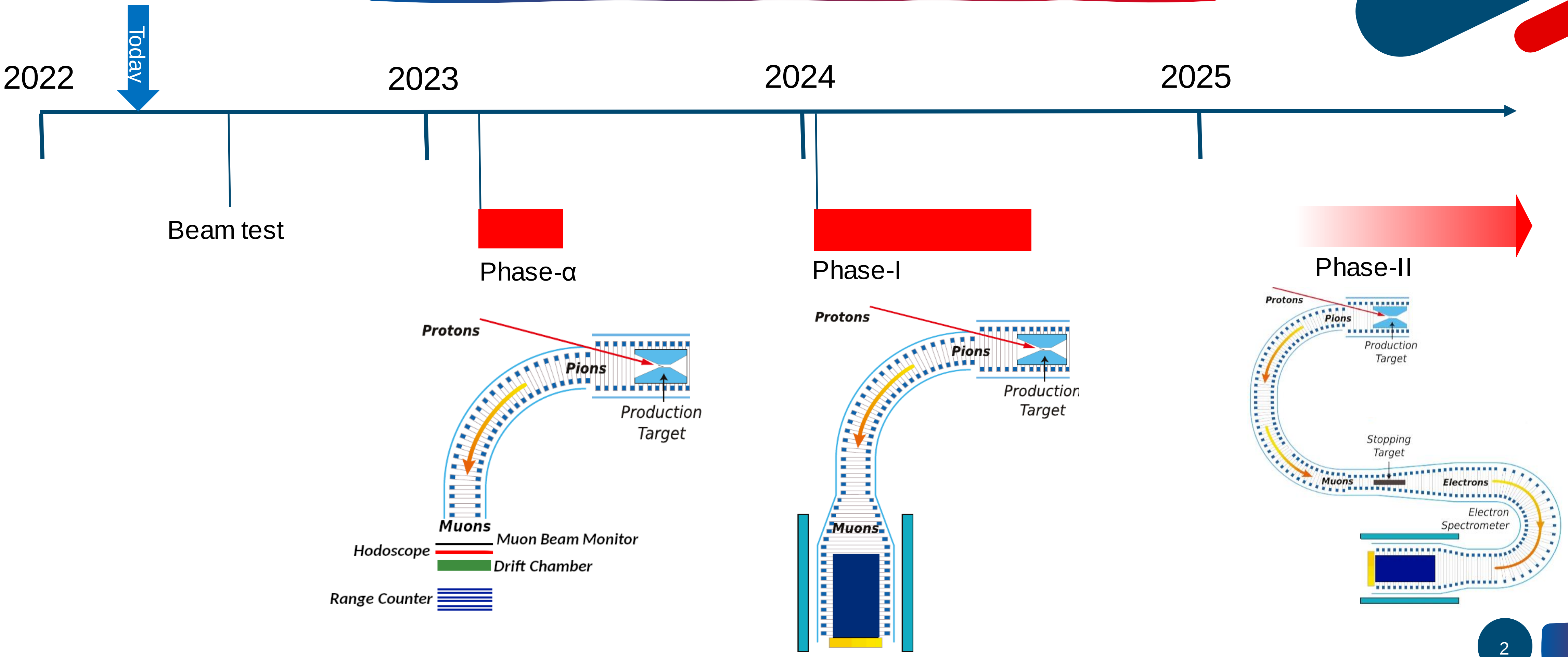
Data-Taking Timeline



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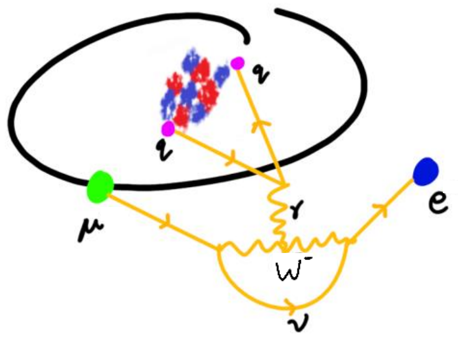
* The COMET Collaboration: COMET Phase-I technical design report, *Progress of Theoretical and Experimental Physics*, Volume 2020, Issue 3, March 2020, 033C01, https://doi.org/10.1093/ptep/ptz125

Neutrinoless *μ-e* Conversion

- A muon is captured by atom, falls to 1s shell, decays into an electron – **LFV**
- Massive-neutrino SM extension, requires interchange of a W-boson
- Neutrino mass GIM suppression **~ O(10^{-54})**



μ-e conversion in the massive neutrino SM extension

Neutrinoless μ-e

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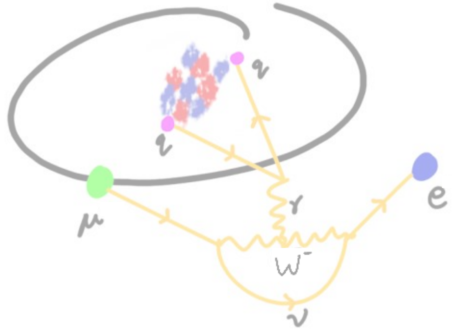
- Massive-neutrino SM extension, requires interchange of a W-boson
- Neutrino mass GIM suppression ~ **O(10^{-54})**
- BSM predictions of **neutrinoless *μ-e*** conversion;
- Rates may be as high **~ O(10^{-15})** !
  - Finding **Charged** LFV is a **sign of new physics**
- Provides a **model-independent search**



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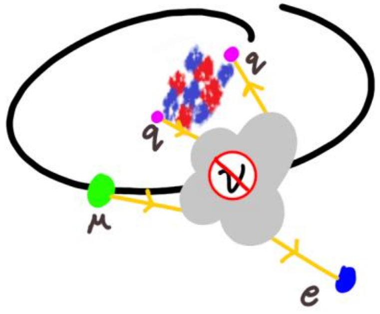
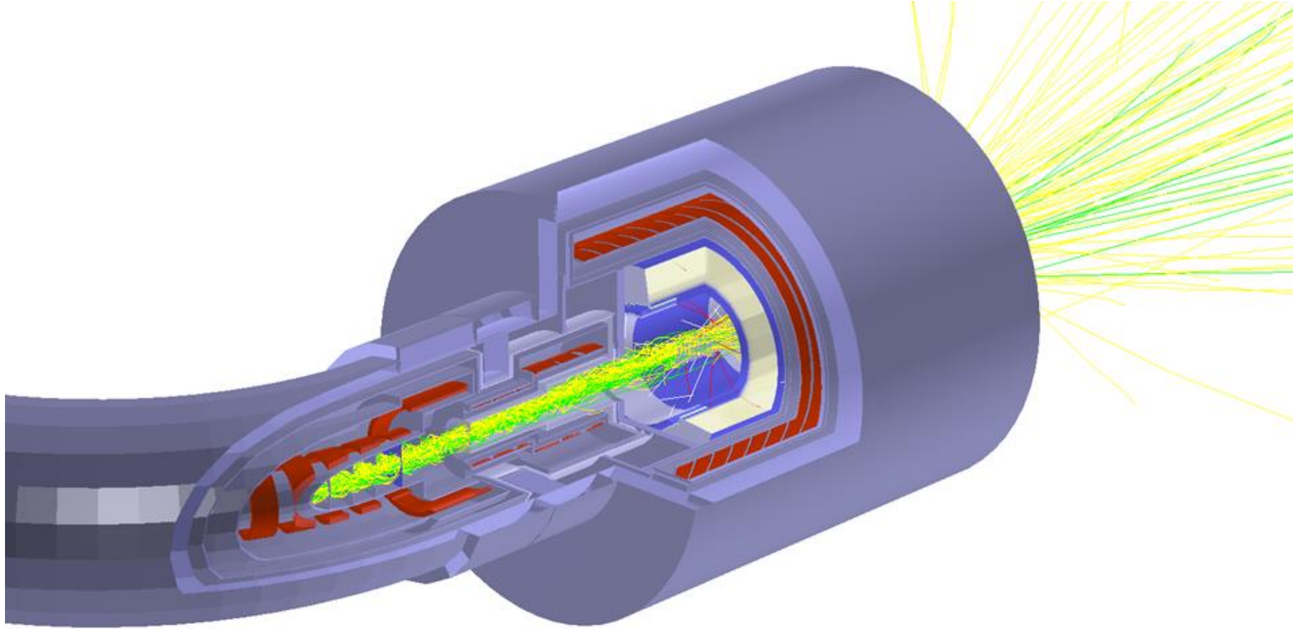
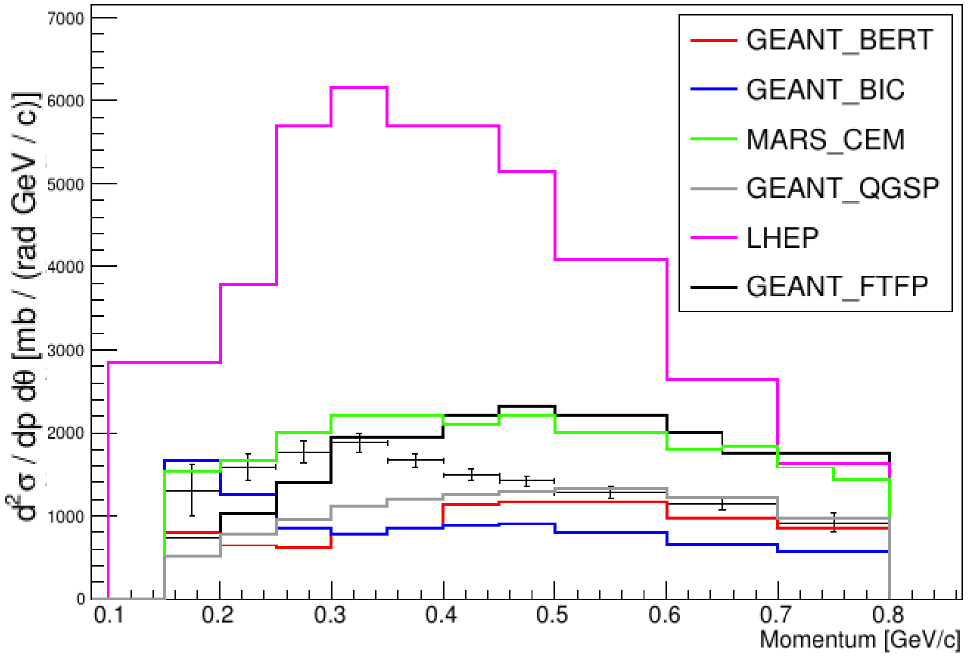


Neutrinoless ***μ-e*** conversion in the BSM

Needing Physics Validations



Muon beam exiting through the back of the detector solenoid



Double differential cross section of pion production
across different hadron production codes

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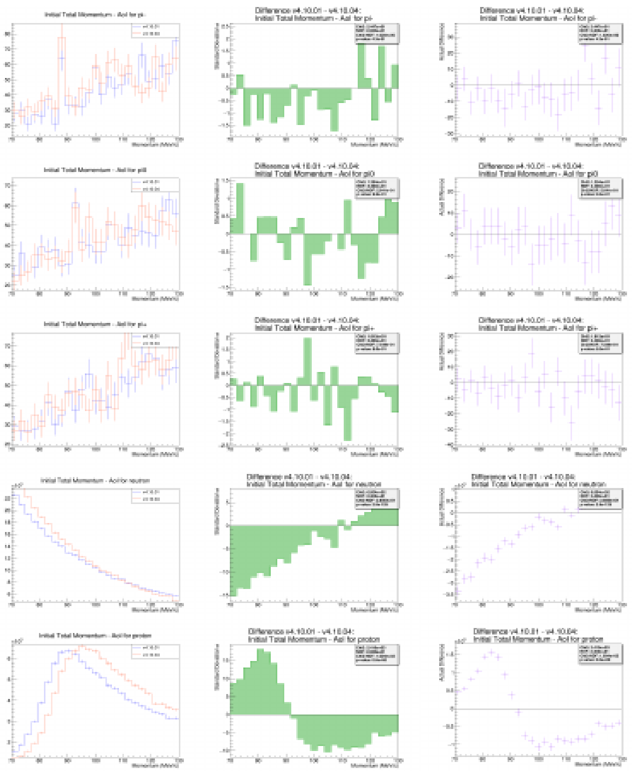
Detailed Validations

- Reduces the comparisons of all changes into a single set of histograms, **quantifying differences statistically**
- **Relative difference** of each bin

$$\sigma_i \simeq \frac{\Delta_i}{\delta\Delta_i} = \frac{a_i - b_i}{\sqrt{(\delta a_i)^2 + (\delta b_i)^2}}$$

- Most have no significance in differences, or are in-line with expectations



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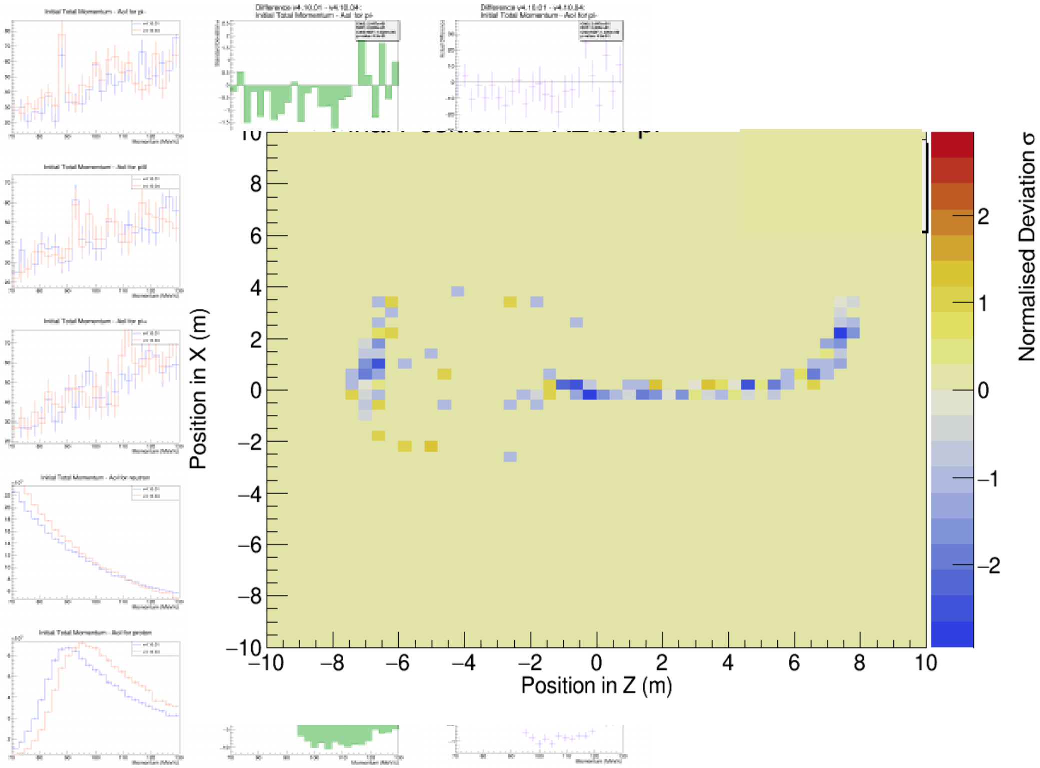

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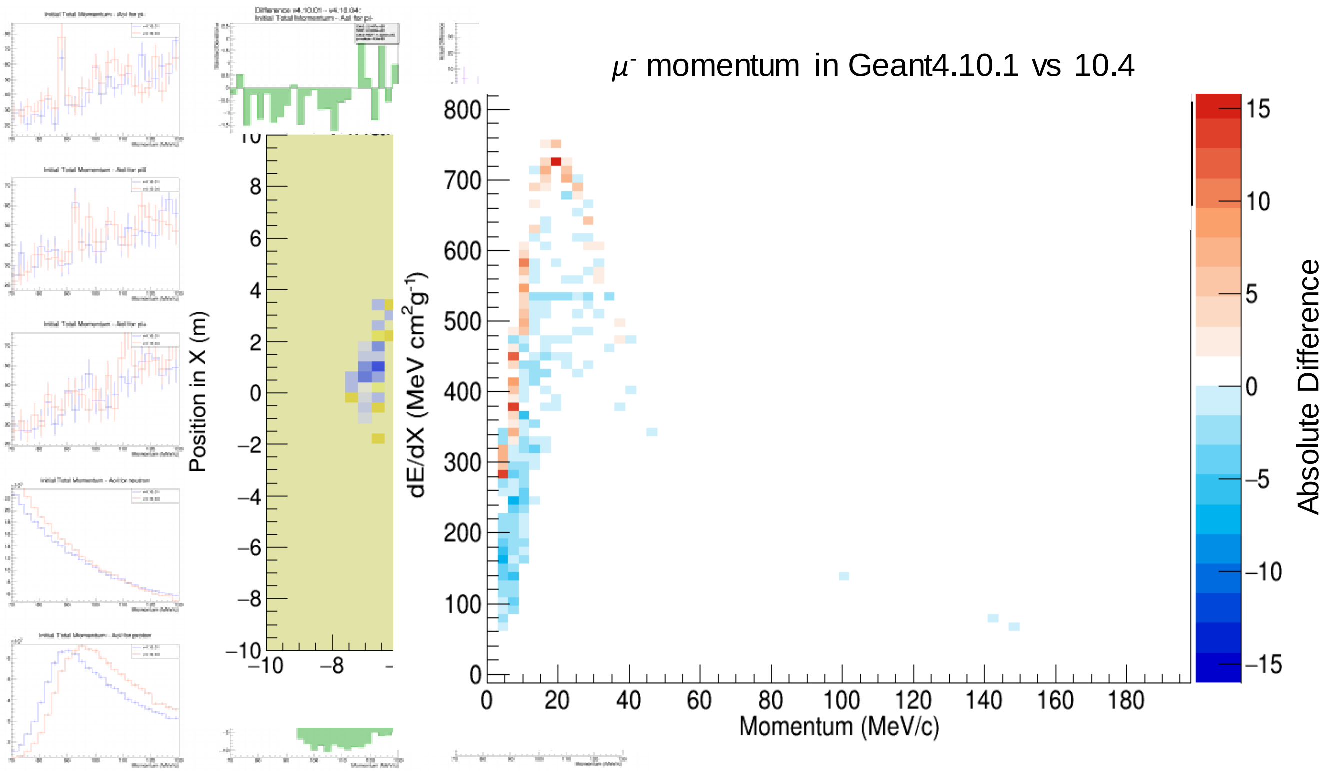

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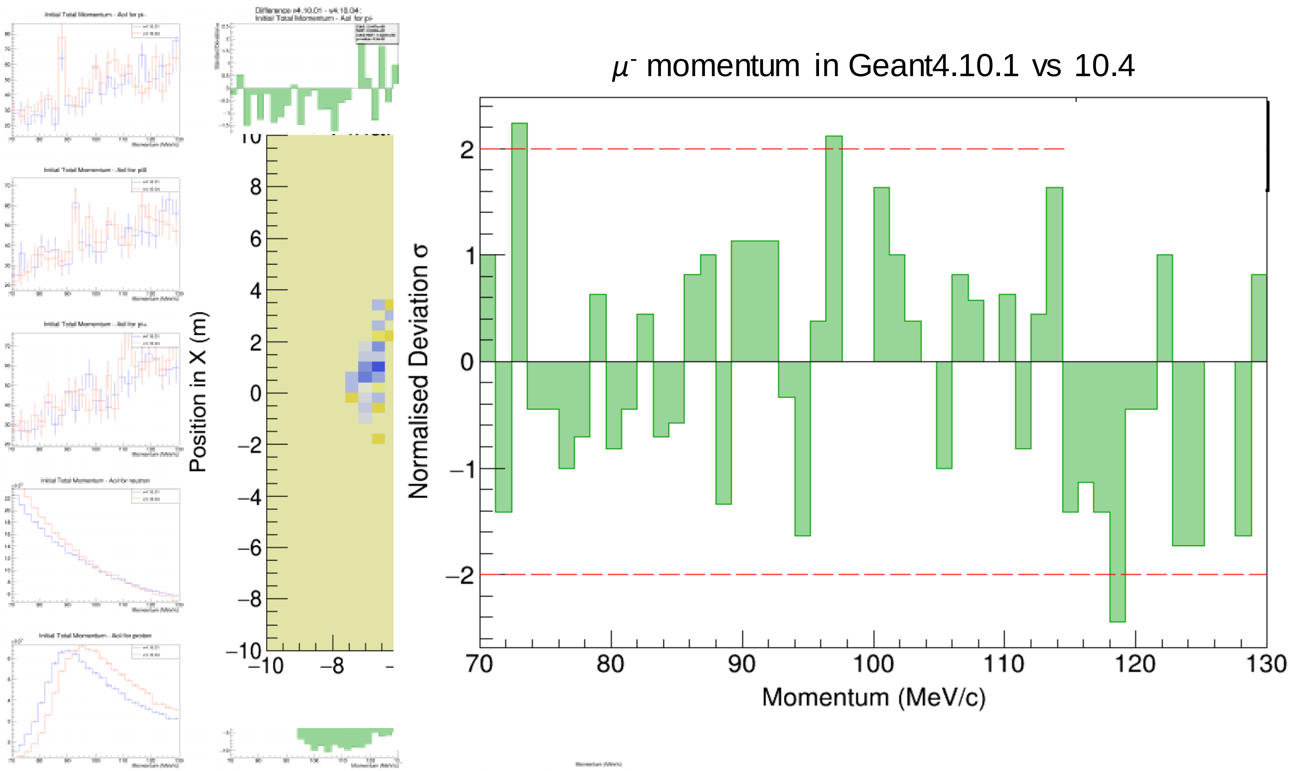
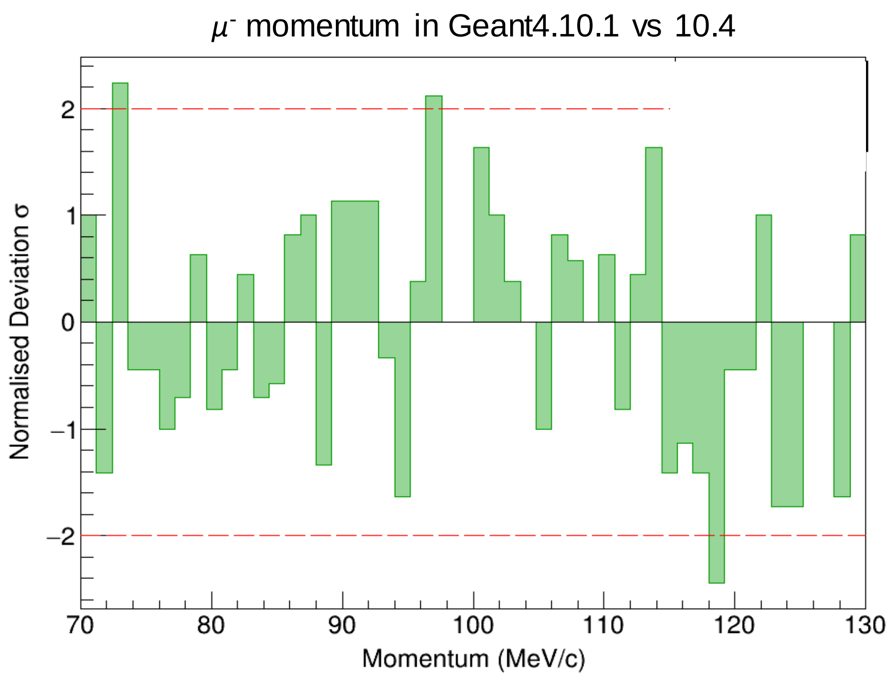


(and many, many more...)

Internal Simulation Validations

- Some differences are within expectations
  - **< 3σ** bin heights
  - No **consistency** or '**shape**'
  - Differences in-line with physics changes

- Comparison of muon momentum
  - We see **nothing alarming** or **noteworthy**
  - No indication of any unexpected effects on processes related to *μ-e*

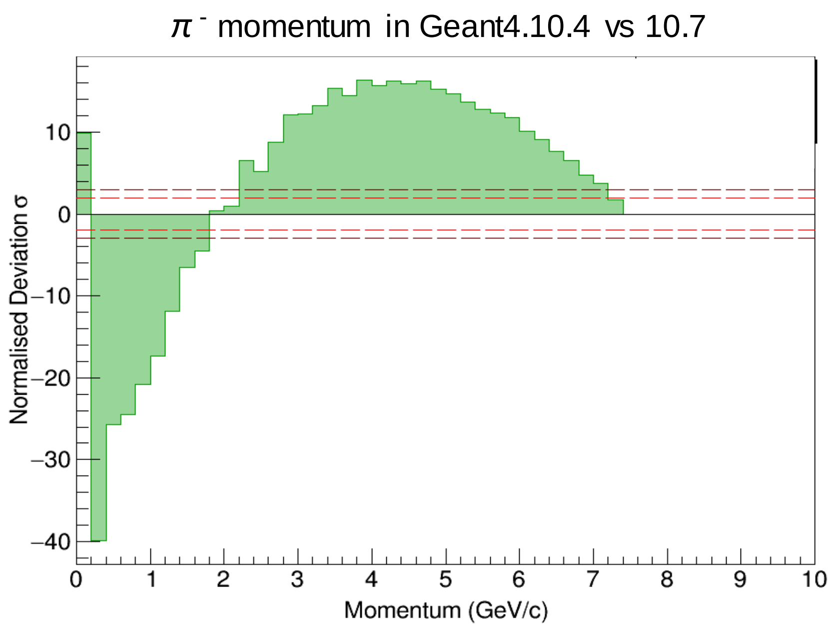


μ^- momentum bin contents from a Geant4.10.1.p03 distribution minus that of Geant4.10.4.p03

Internal Simulation Validations

- Others show 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!**

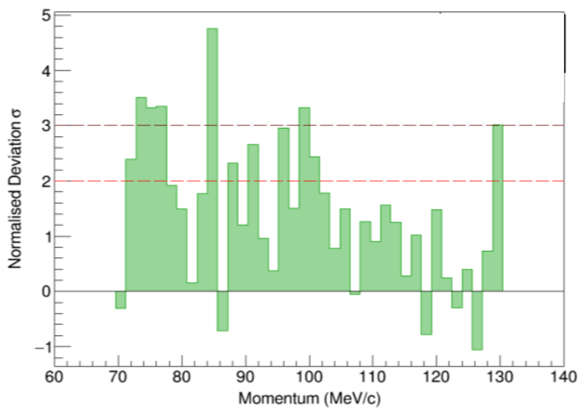


π^- momentum bin contents from a Geant4.10.4.p03 distribution minus that of Geant4.10.7

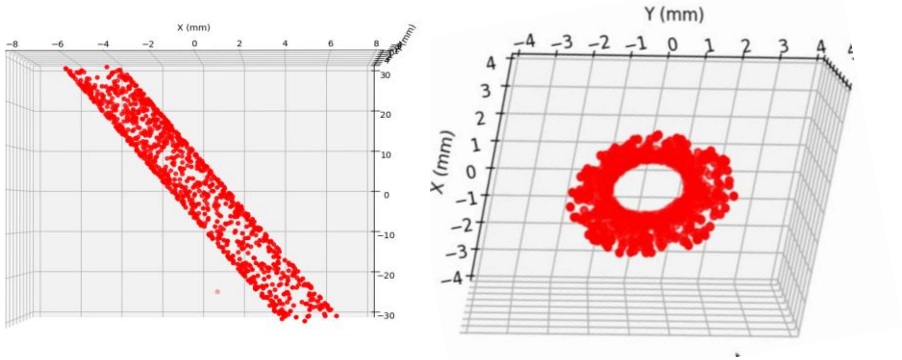
Internal Simulation Validations

- Less innocent changes: sharp reduction in low energy muons instead due to a **Geant4 bug**
  - 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...**
- Unofficial compilation/discussion of Geant4 checks with Low-E focus: https://www.hep.ph.ic.ac.uk/~rd1519/Geant4/

μ^- momentum in Geant4.10.4 vs 10.7



μ^- momentum bin contents from a Geant4.10.4.p03 distribution minus that of Geant4.10.7.p00



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

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Data-driven Validations

- Must also compare simulated data against both our own hardware and well-established experimental results

- **Internal Validations:**
  - Treatment of cosmic ray backgrounds (in commission)
  - Prototype test-beam studies
  - Beam studies in Phase-α
  - Particle hits and tracking in Phase-I detectors

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- **Internal Validations:**
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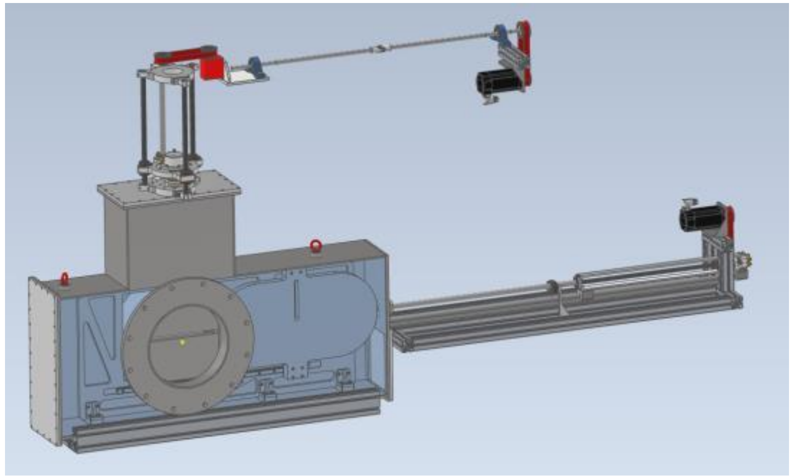
  - Beam studies in Phase-α
  - Particle hits and tracking in Phase-I detectors

- **External Validations:**
  - Proton collision data with HARP and NA64/SHINE:
    - http://harp.web.cern.ch/harp/Classified/PUBLICATIONS/Papers/P-Al/p-Al129.pdf
    - http://arxiv.org/pdf/1603.06774.pdf
  - Antiproton production studies

Conclusion

- COMET aims to provide a **window into BSM physics**
- Phase-α **data** in **early 2023**
- Must ensure simulation and analysis software is prepared
- Understanding the finest details of beam and backgrounds

- **Important to validate simulations** between versions, and against real data when and where available
  - **Influence hardware** design and **understand data**
  - Helps ensure **robust measurements** while increasing sensitivity



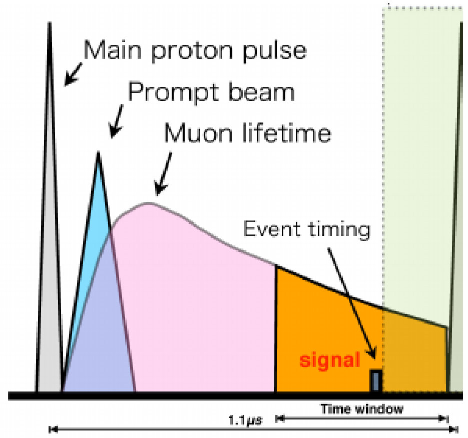
Latest design for a dynamic beam collimator, testing varied beam configurations

Fin

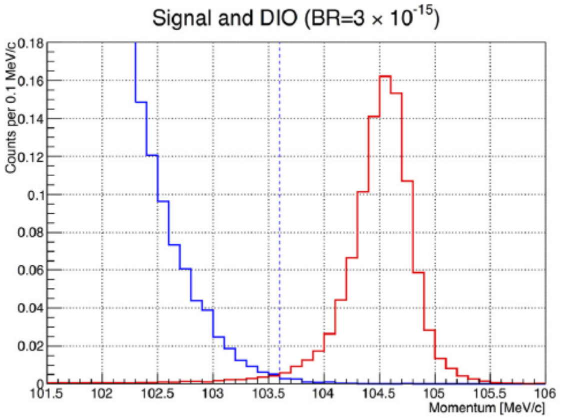
Extra Slides

App

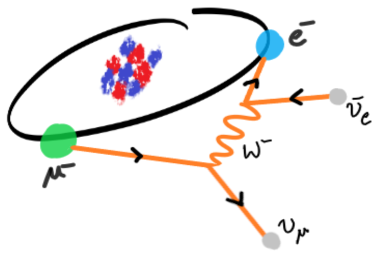
Backgrounds

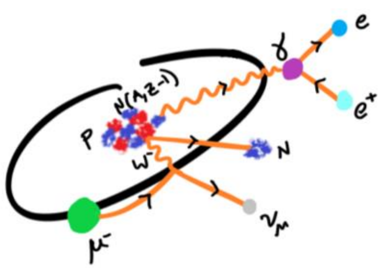


Pulsed beam timing, gives muons time to decay and stops flooding of detector by prompt beam



Momentum distribution from Decay in Orbit background (left) and from μ-e signal (right)





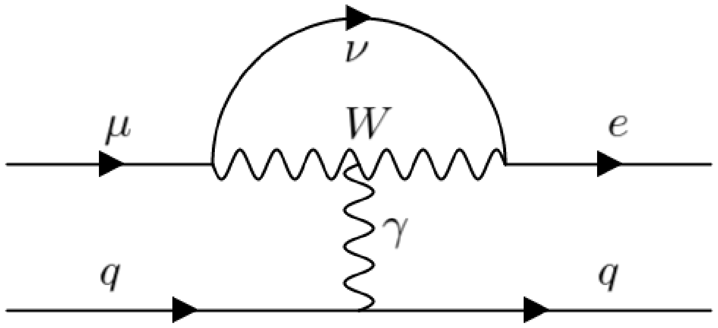
Type	Background	Events
Physics	Muon DIO	0.1
	Radiative μ capture	0.0019
	Neutron emission after μ capture	< 0.001
	Charged particle emission after μ capture	< 0.001
Prompt beam	Radiative π decay	0.0028
	Neutrons	$\sim 10^{-9}$
	Others	≤ 0.0038
Delayed beam	Beam electrons	~ 0
	μ decay in flight	~ 0
	π decay in flight	~ 0
	Radiative π capture	~ 0
	Anti-proton induced backgrounds	0.0012
Others	Cosmic rays	< 0.1
Total		0.032

BSM μ-e

- SM says that leptons (***e, μ***) and their neutrinos (***ν***) must **conserve flavour**

- Some observations cannot be described within the SM framework, such as the **observation of 'neutrino flavour oscillations'**, a lepton flavour violation **(LFV)!**

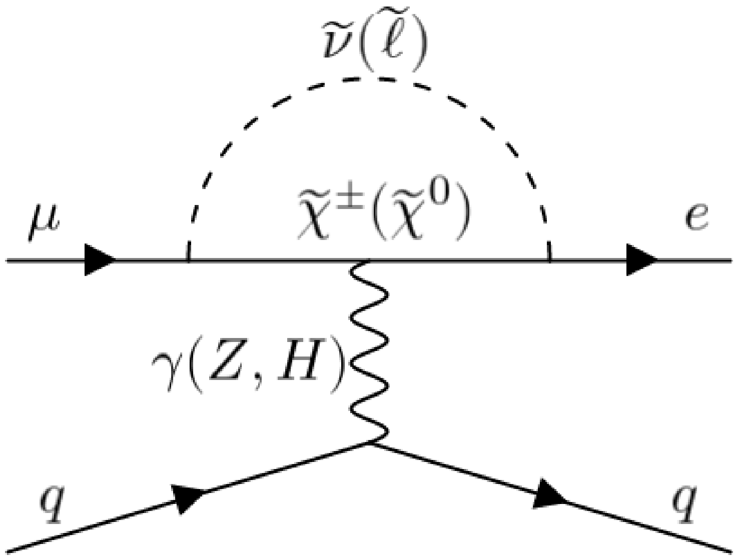
- A modified SM with non-zero *ν* mass describes *μ*-*e* conversion, but requires a *ν* and W-boson which have wildly different masses, causing a **tiny branching ratio of O(10^{-54})**



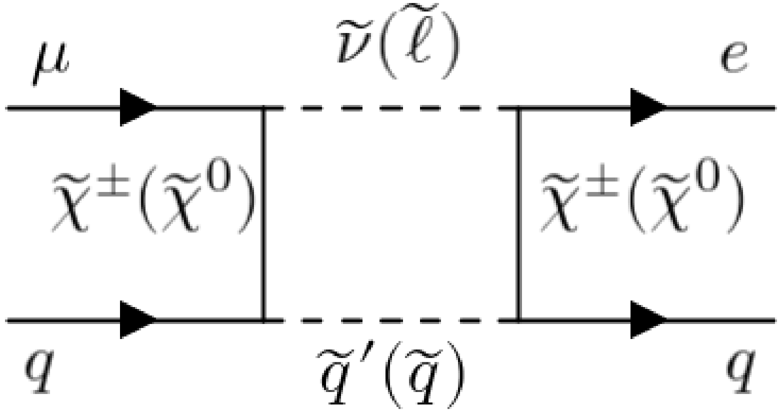
$$\mathrm{BR}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=1}^{3} U^*_{\mu i}U_{ei}\frac{M^2_{v_i}}{M^2_W}\right| \simeq \mathcal{O}\left(10^{-54}\right)$$

Charged Lepton Flavour Violation

- Conserve lepton number but **not flavour**
- BSM **coherent, neutrinoless** ***μ-e*** conversions
- Provides a **model-independent search**



Penguin (left) and Box (below) diagrams from SUSY R-parity conserving interactions, adapted from the COMET Phase-I TDR *



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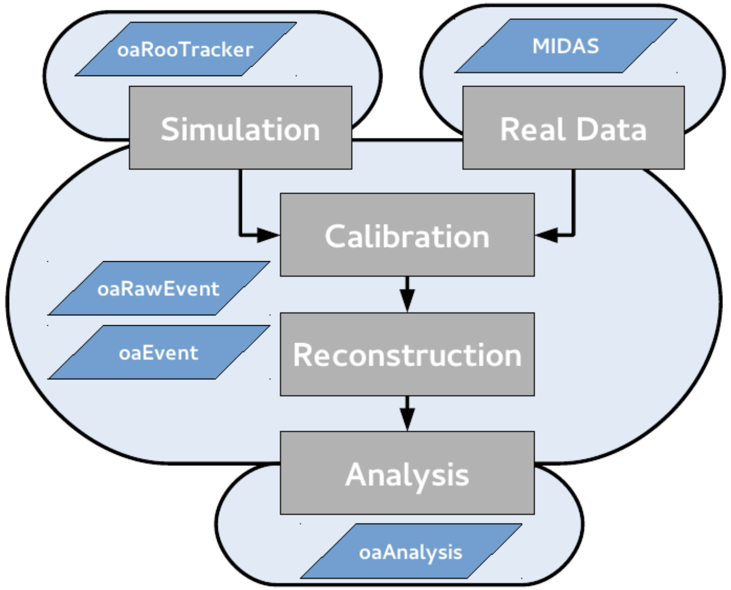
ICEDUST

- 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

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Checking Simulations

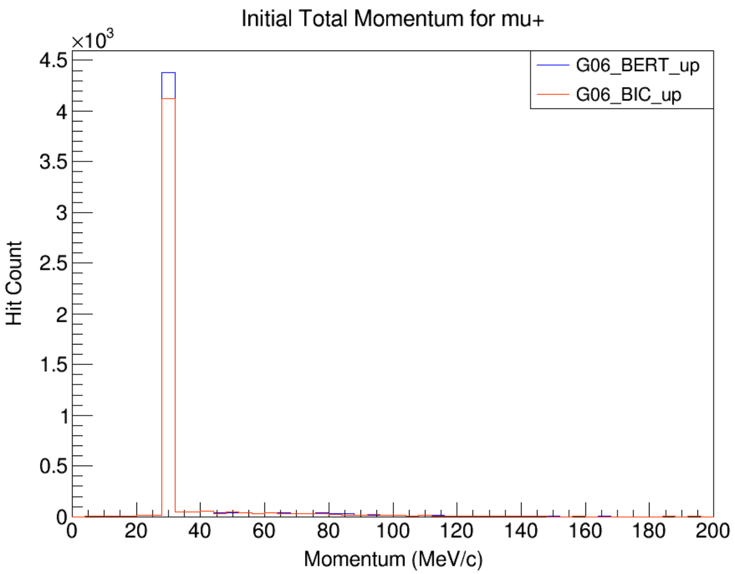
- Large-scale MC production sets, equivalent to 1e9 Protons, using the latest hardware designs, internal software and suitable versions of external software
  - Takes **several weeks to run** across the UK GridCC Network, to simulate **~1 ms of beam data** in the shorter Phase-I

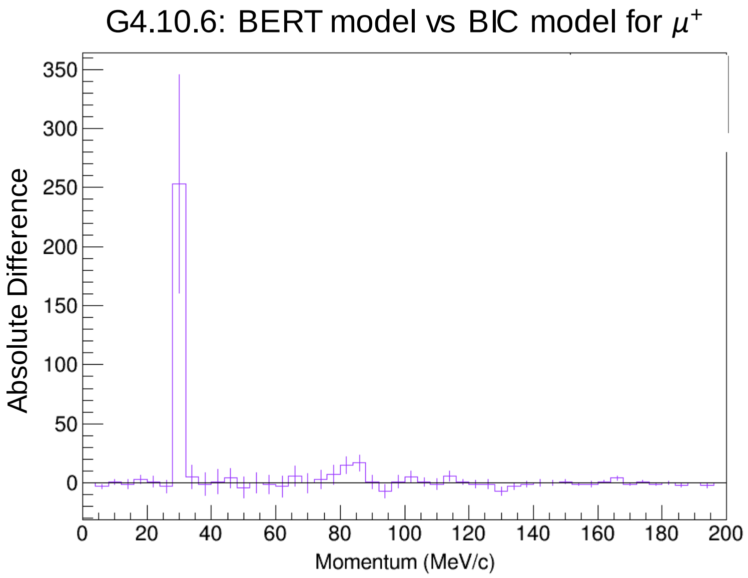
- Must ensure computing resources are put to good use, and that researcher time and decision making in post-simulation is not in vain...

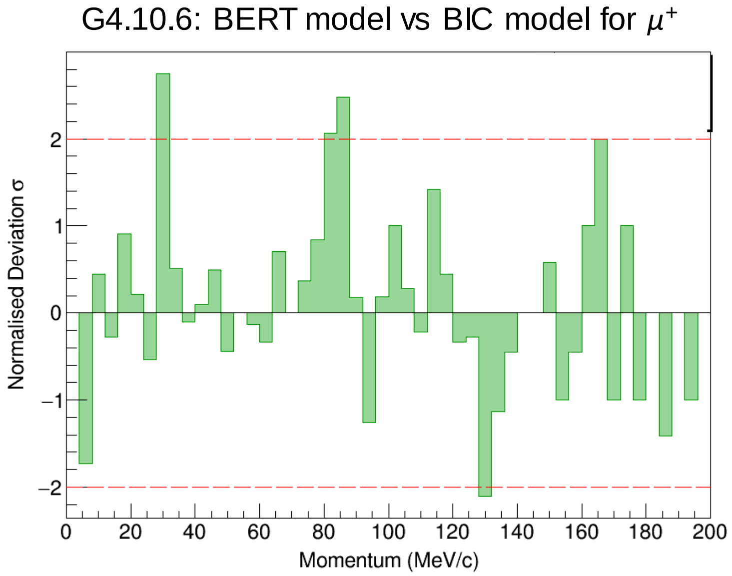
- Can **compare smaller datasets** between versions to look for any **unexpected differences** due to **small or large-scale changes**

- Can also **compare** simulations against **real data**, both internally and externally

Absolute vs Relative







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