

Mu3e-2 upgrade

Physics Deliverables:

Target search

- Search for CLFV in the decay
 $\mu^+ \rightarrow e^+ e^+ e^-$

Other competitive BSM searches:

- $e^+ e^-$ resonance in
 $\mu^+ \rightarrow e^+ e^+ e^- \nu_e \bar{\nu}_\mu$
(dark photons, ALPs)
- LFV in 2-body decays
 $\mu^+ \rightarrow e^+ X$ (familons,..)

Mu3e Phase 1 (STFC approved project currently under construction)

- 3 years of physics operation during 2026, 2029 and 2030 (interrupted by HIMB upgrade).
- Using $\pi e 5$ muon beamline ($10^8 \mu/s$), shared with MEG-II
- The projected sensitivity on $BR(\mu^+ \rightarrow e^+ e^+ e^-)$ is 2×10^{-15} . (x 500 improvement on current limit)

Mu3e Phase 2

- 3 years of physics operation with upgraded detector, most likely from 2033
- Dedicated Mu3e beamline after HIMB upgrade ($2 \times 10^9 \mu/s$)
- The projected sensitivity on $BR(\mu^+ \rightarrow e^+ e^+ e^-)$ is 10^{-16} (**x 10,000 improvement on current limit**)

UK contributions

Mu3e-I (STFC approved project currently under construction, TDR: [arXiv2009.11690](https://arxiv.org/abs/2009.11690))

- UK groups deliver the clock-and-reset system for all Mu3e subdetectors and the construction of the HVMAPS outer pixel tracker layers. The latter represent $\sim 96\%$ of the overall silicon area covered by the inner and outer pixel tracker layers
- UK leadership positions include the current physics coordinator, pixel tracker coordinator and MC production coordinator.

Mu3e-II experiment (design and R&D phase started)

- The High Intensity Muon Beam upgrade (HIMB) at PSI is approved and will be implemented in 2027 – 2028.
- Mu3e will be upgraded with added timing layers (not a UK deliverable) to cope with the increased rate of muon decays, and the acceptance of the MUIX tracker will be extended.
- The most likely UK contribution to the phase-2 construction project is to deliver the upgrades to the systems built for phase-1

Cost estimates

The expected UK contribution to the capital investment and effort for the phase-2 detector upgrade and for M&O and exploitation costs are estimated in the context of the UK forming approximately 1/3 of the Mu3e collaboration and the expectation that the UK groups would make a fair-share contribution to the construction and operation costs of Mu3e. (This excludes any facilities, services or access to beams, which are provided free of charge to the collaboration by PSI.)

All costings are full economic costs.

M&O and exploitation of Mu3e-2

Effort levels required for Phase 1 and Phase 2 operations are foreseen to be similar. Phase-2 cost estimates are therefore based on costings for Phase-1.

- Effort for M&O and exploitation is awarded at the digression of PPGP. Our request, commensurate with the UK taking its fair share, is for the support of 3.9 FTE of PDRA effort and 3.5 FTE of core effort, corresponding to approximately £770k p.a.
- Similarly, common fund, travel and consumable costs, are also awarded through PPGP. Our request is for support at the level of approximately £220k p.a.

Cost estimates

R&D and construction of Mu3e-2

For the Mu3e-2 upgrade we foresee a UK contribution focused on upgrading the systems for which the UK also has responsibility in the phase-1 detector.

- The clock-and-reset distribution system will be upgraded to serve cover more systems.
- New HVMAPS pixel layers, to achieve an extended acceptance.

UK development and design work invested the development of the phase-1 detector will be key to constraining costs for the upgrade project.

Costings assume the availability of CG core expert support, at a level similar to that for Mu3e phase-1

We foresee a short 1-2 year development and design phase followed by a 3-year construction project.

- Development and design phase (2028-2029):
 - Effort £730k (4 FTEyears PDRA + 3 FTEyears Eng /Tech); Capital, consumables, SRFs £200k
- Construction phase (3 years, 2029-2033):
 - Effort £2,370k (12 FTEyears PDRA + 12 FTEyears Eng/Tech) ; Capital, consumables, SRFs £550k
- Travel cost will be modest at around £15k p.a.

Other questions / comments

Planned submission ESPPU: A joint submission is foreseen between the CLFV experiments: Mu3e, Mu2e, COMET and MEG-II.

Location: The Mu3e physics programme requires access to the high intensity DC muon beams only available at PSI

Environmental costs of construction & operation We don't not have a quantitative evaluation. But can make a few comments.

- Neither the Mu3e-2 or HIMB upgrades require major civil engineering or building construction work.
- The high intensity beams provided by PSI account for a substantial share of the overall energy budget. These facilities are shared between multiple users, including material science, muon and pion experiments and isotope production for medicine
- In 2023, 64% of energy generation in Switzerland was already derived from renewable sources. This fraction is increasing.
- Where possible the collaboration relies on online meeting, with only a limited number of in-person meetings per year.
- The PSI laboratory in its Environmental Mission Statement has set out the ambition to reduce greenhouse gasses emissions by 50% between 2006 and 2030 ([PSI Environmental Mission Statement](#)).

Main risks/obstacles: Risks to the phase 2 programme moderate to low

- The HIMB facility is approved and the detailed engineering studies have validated the target muon beam intensities.
- The phase-1 programme demonstrates most of the technology options used for the Mu3e-2 upgrade
- The main new technology is that to instrument a fast-timing silicon pixel layer. This is a high priority for many experiments and therefore a high priority for the wider community. This is not foreseen to be a UK deliverable to the Mu3e-2 upgrade.

Beyond Phase-2 (late 2030s)

The Mu3e large-bore high-field solenoid as well as the low-mass fast CMOS tracker technology developed, offer the opportunity to achieve the world-best sensitivity on the branching ration for the $\mu \rightarrow e \gamma$ CLVF decay, well beyond the limits the current leading experiment MEG-2 can set. This is a possible future direction of the PSI muon programme in the late 2030s, beyond the case we make here.