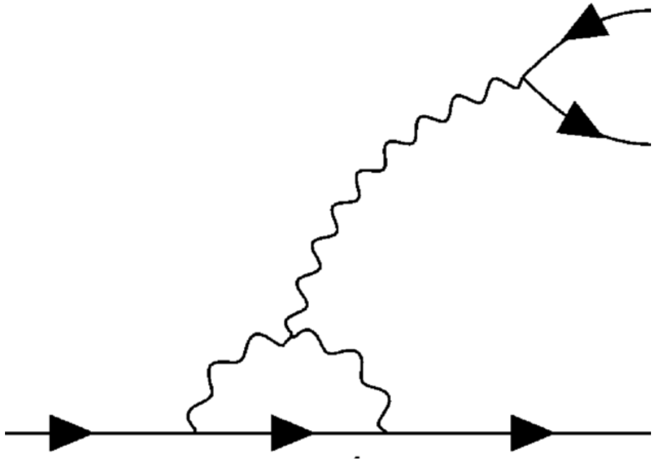
Report on UK involvement and leadership in LHCb, Belle-II, NA62, Muon Programme, and SHiP

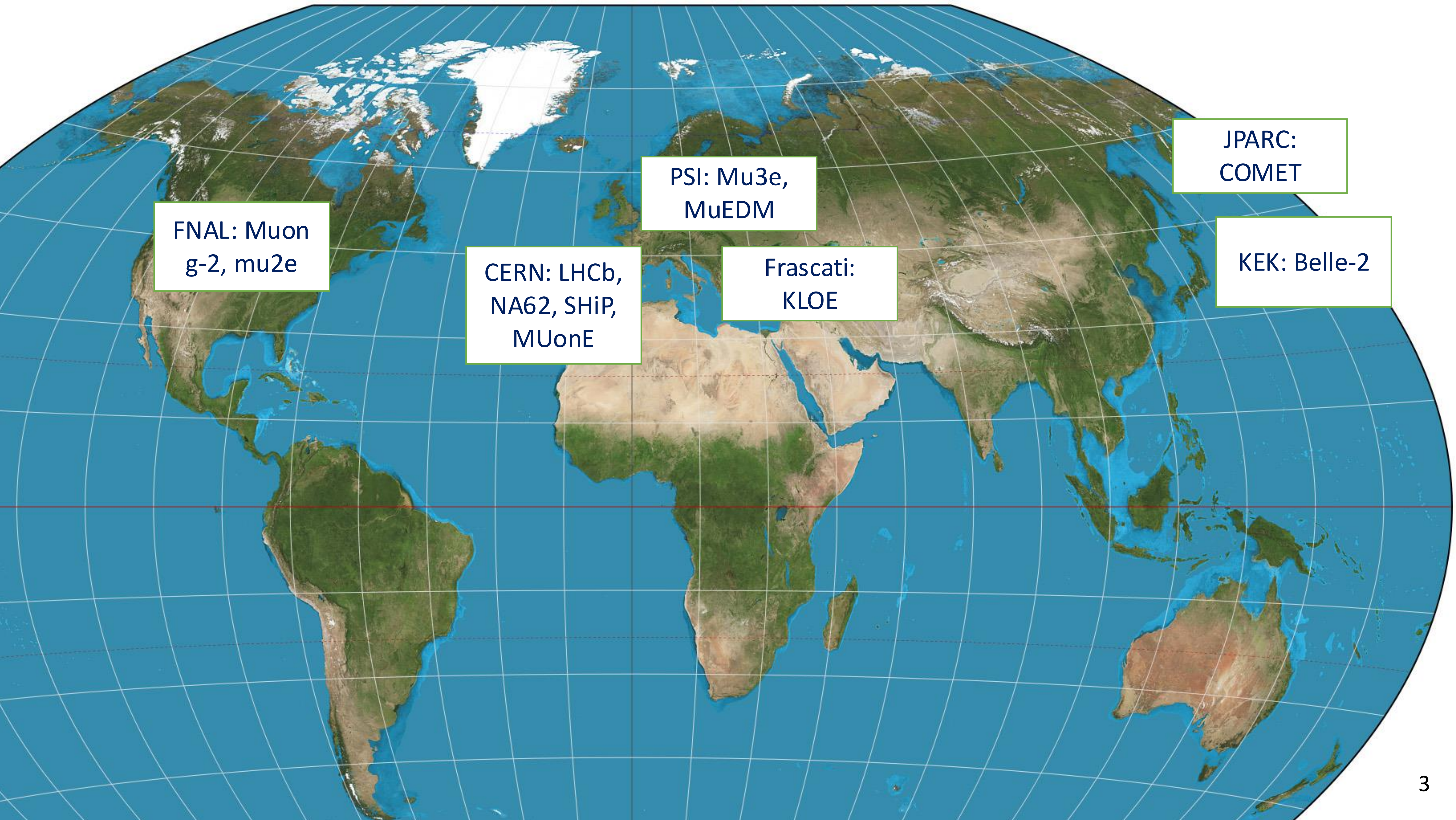
R-ECFA visit to the UK, Royal Society, 13/9/24

William Barter, University of Edinburgh

Introduction

- Flavour Physics provides an indirect search for New Physics with unique discovery potential.
- Complementary approach to direct searches: high precision measurements probe energy scales far beyond the direct range of particle collisions at the LHC.
- European Strategy Update (2020) notes "the full physics potential of the LHC and the HL-LHC, **including the study of flavour physics**…should be exploited" and that precision measurements of flavour physics "that offer potential high-impact particle physics programmes…should be supported."
- Will discuss quark flavour experiments (LHCb, Belle-II, NA62), lepton flavour measurements (Muon programme including g-2).
- Will also discuss SHiP – experiment providing highly sensitive direct searches for low-mass feebly-interacting particles.



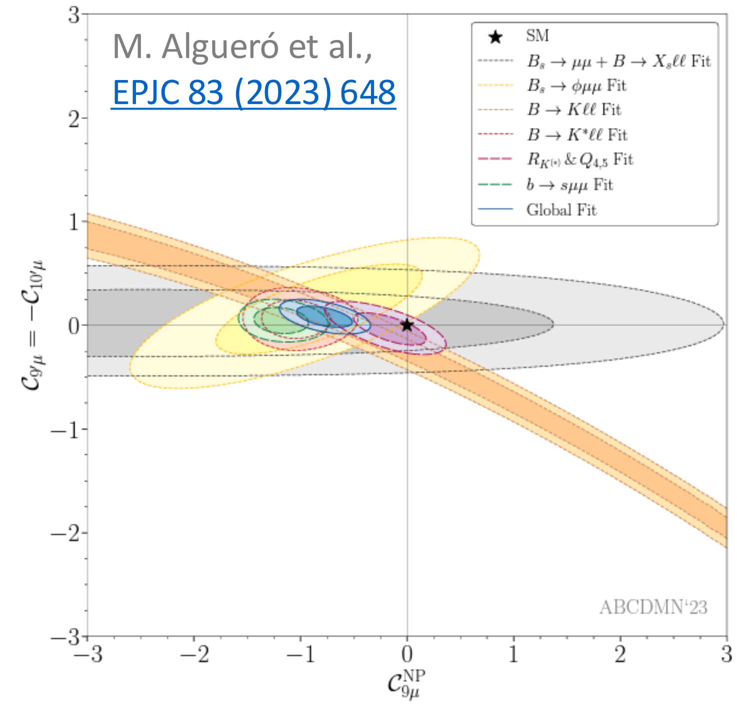

FNAL: Muon g-2, mu2e
CERN: LHCb, NA62, SHiP, MUonE
PSI: Mu3e, MuEDM
Frascati: KLOE
JPARC: COMET
KEK: Belle-2

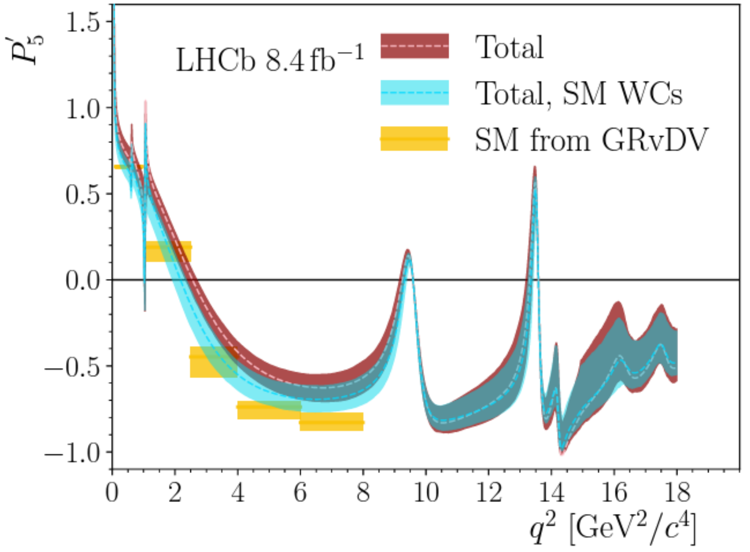
LHCb

- 11 participating UK institutes with 200 authors (15% of the collaboration by authorship) [50 academics/seniors, 70 PDRAs, 70 PhD students, 30 engineers and technicians]
- Funding from: Universities, STFC, UKRI, Royal Society, Leverhulme Trust, EU.
- Recent leadership positions in collaboration:
  - Spokesperson and Deputy Spokesperson
  - Upgrade II Planning Group Chair and Deputy Chair
  - Operations Coordinator, Deputy Run Coordinator
  - Editorial Board Chair and Deputy EB Chair, Speakers Bureau Chair
  - EDI Leadership (‘ECGD’)
  - Detector Leadership (RICH, VELO, TORCH, Mighty Tracker), Simulation Leadership, and Physics Working Group Leadership (convenership of 8 different top-level groups)

LHCb

- UK involvement across the LHCb research portfolio:
  - Studies of $b \to s\mu\mu$ transitions are in tension with current Standard Model expectations, and favour some new physics interpretations (e.g. the LHCb data can be easily explained using new Z’ bosons or leptoquarks).
  - UK leadership of these analyses, including new studies seeking to make sure long-distance effects are well understood.



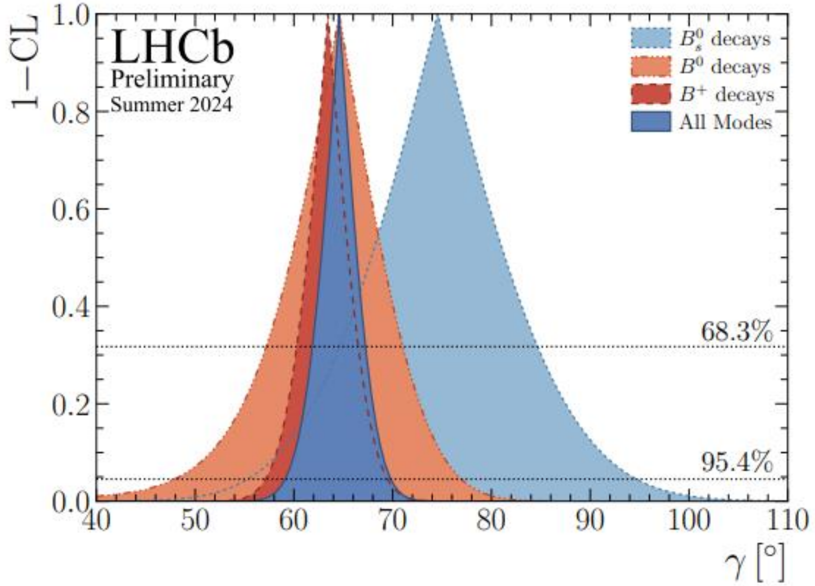


2405.17347
accepted by JHEP

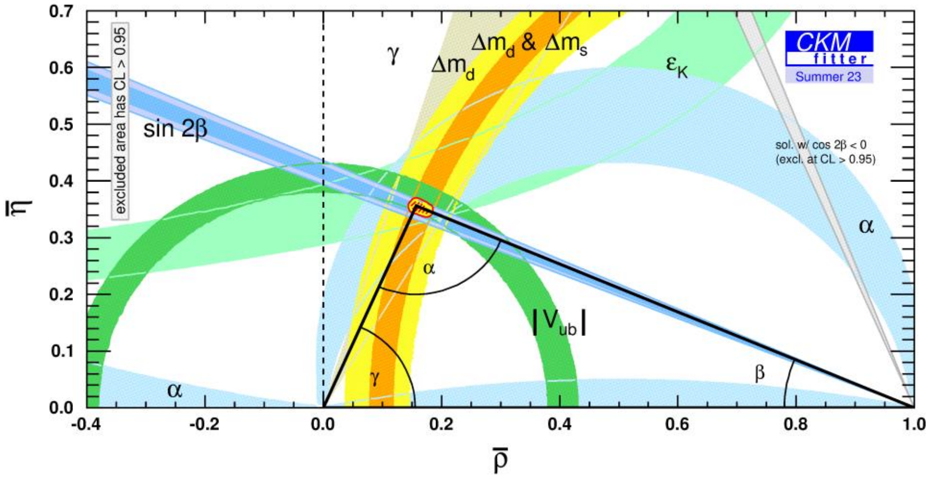
LHCb

- UK involvement across the LHCb research portfolio:
  - CKM angle γ now determined from direct measurements to precision better than 3° (cf > 20° in 2009).
  - Allows high-precision test of unitarity triangle closure and indirect search for new physics.

LHCb-CONF-2024-004



CKMFitter

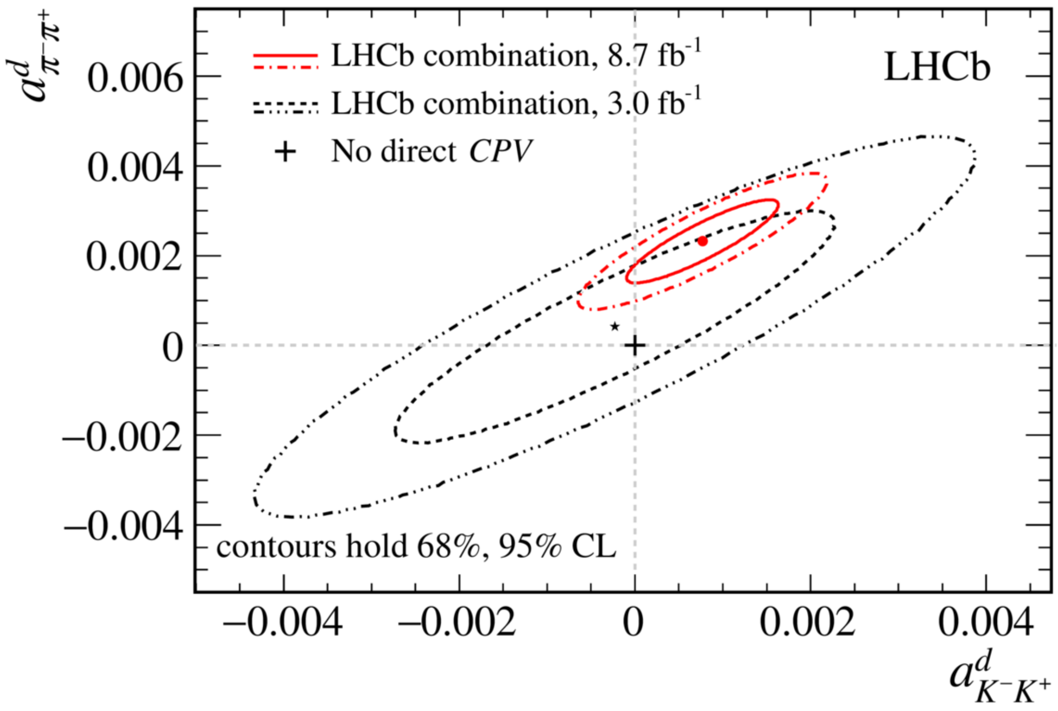


LHCb

- UK involvement across the LHCb research portfolio:
  - First observation of CP-violation in charm sector.
  - Observed at a rate 10 times larger than expected in Standard Model.
  - Ongoing research to determine if this is new physics.

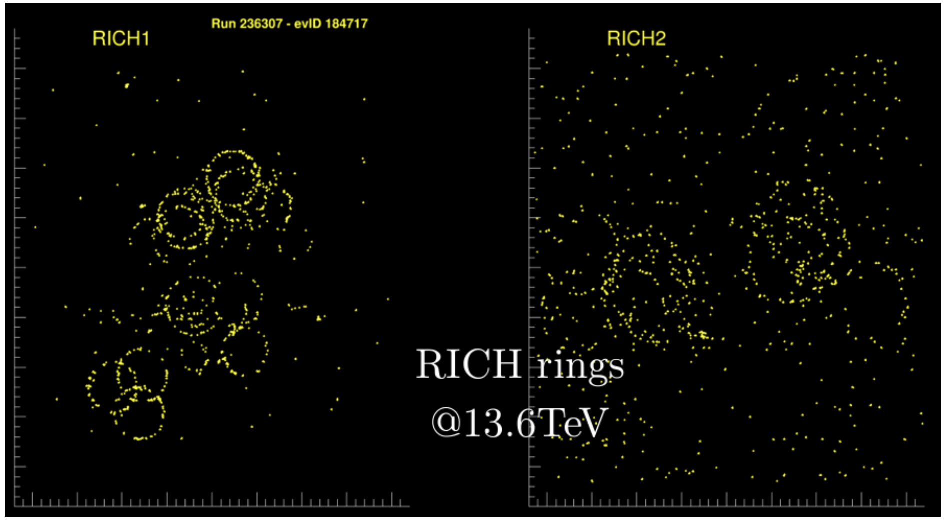
- + many more high profile areas of research not discussed today.

PRL 131 (2023) 091802



LHCb

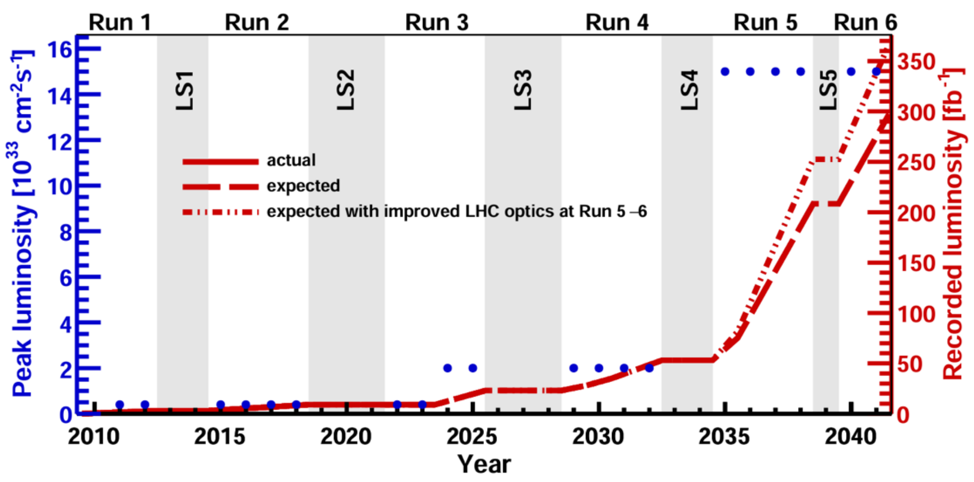
- Major UK contributions to LHCb Upgrade:
  - RICH – new photon detectors, optics and mechanics.
  - VELO – new silicon pixel detector.
  - Real Time Analysis – innovative analysis techniques that analyse data in real time without storing entire raw detector output.
- UK also committed to supporting the ongoing operation of these detectors and systems in the LHCb Upgrade era.



Purchases were made from 88 UK companies by the UK project and from common collaboration funds at CERN during the period of the LHCb UK Upgrade grant.

LHCb

- Upgrade II allows us to meet European strategy call for full exploitation of HL-LHC.
  - Scoping Document currently with LHCC.
- UK centrally involved in Upgrade-II plans, building on key existing expertise:
  - Vertexing and Tracking (VELO, Mighty Tracker)
  - Charged Hadron Particle Identification (RICH, TORCH)
  - Data Processing (Real Time Analysis, Simulation)
- UKRI infrastructure fund providing £49.4M.



Collaborations are already in place with UK industrial partners such as Graphcore, Micron, Photek and ZOT, as well as international companies including CNM, FBK, Hamamatsu, Incom Inc., Microsoft and NVidia.

LHCb

- LHCb-UK is playing a significant role fulfilling the European strategy update (2020) commitment to exploit the full physics potential of the LHC and HL-LHC, including the study of flavour physics.
- The UK's leadership in quark-flavour physics means that we are extremely well-placed to engage with international decision-making bodies to ensure that the unique discovery potential of quark-flavour physics receives appropriate support in the future particle physics programme.
- LHCb-UK members will be prominent in the coming years, sharing expertise e.g. for inputs to the next European Strategy update.

LHCb

- Challenges:
  - maintaining exploitation of LHCb data when funding uncertainties arise.
  - delivering Upgrade 2 within a fixed financial envelope that does not include inflation and future changes in LHC schedule.
  - ensuring timely and longer-term allocation of funding, with clear advance communication, to enable smooth project management and the best outcomes from UK investment.
  - retaining skilled researchers when research jobs do not compete financially with industry.

Belle-II

- 1 participating UK institute + 3 groups interested in upgrade work. Formal involvement (QMUL) since October 2023.
- Funding from: Universities, Royal Society.
- Work split between Data Taking (2 academics/seniors, 1 PhD student) and Upgrades (3 academics/seniors, 1 PhD student, 1 technician). Leadership includes Publication Committee role, and positions on Funding Board and Funding Oversight Panel.
- Research includes time-dependent CP, T, CPT violation analysis, as well as collaboration involvement in other key analyses. Academic expertise also includes over 20 years of leadership in unitarity triangle fits.
- Detector work includes Belle-II beam spot analysis which will inform forthcoming CP violation analyses.
- Work can inform future FCC-ee flavour physics research.

Belle-II

- Challenges:
  - This activity is not funded as a project yet by STFC. However, a small investment in the activity can have a large impact on the international particle physics scene to cover travel, M&O and a modest scientific team.
  - Work on the upgrades could be used to upgrade beam monitors for international laboratories with large area CMOS test beam telescopes (e.g. for DESY, KEK, CERN, Diamond, for example) as well as leading to a silicon detector upgrade for Belle-II.

NA62

- 4 participating UK institutes with 15 researchers. [3 academics/seniors, 5 research fellows, 2 honorary research fellows, 5 PhD students, with small fractions of electronics engineer and technician]
- Funding from: Universities, STFC, EU.
- Recent leadership positions in collaboration:
  - Spokesperson, Deputy Spokesperson
  - Physics Coordinator
  - Rare Decay Analysis Convener, $K \rightarrow \pi \nu \nu$ decay analysis Convener
  - Chair of the Editorial Board, Chair of the Conference Committee
  - KTAG Detector Project Leader, High-Level Trigger Project Leader
  - Run Coordinators

NA62

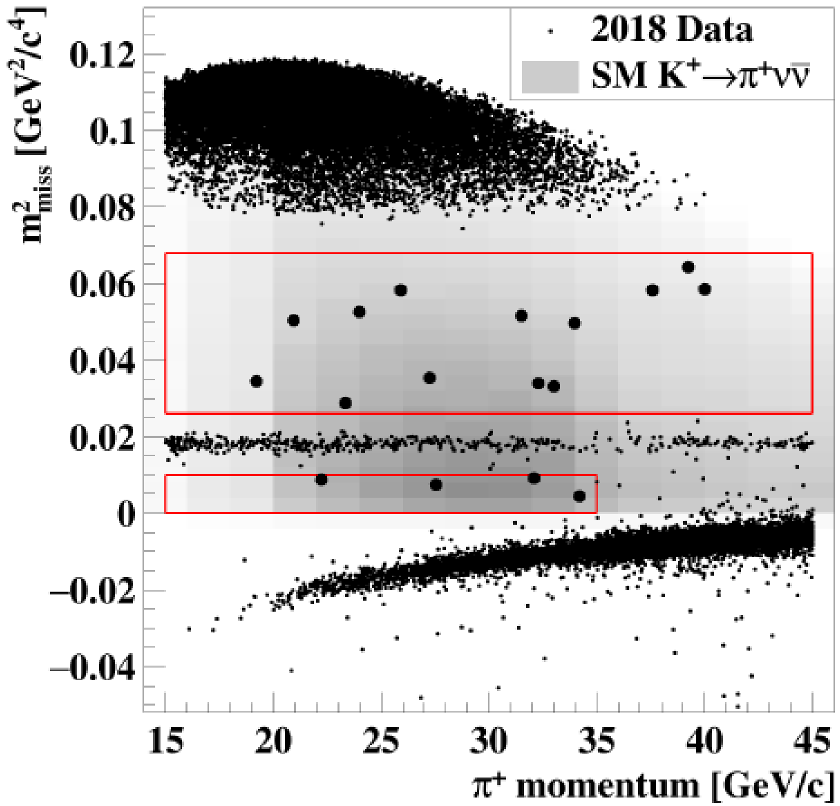
- The UK group maintains a leading role across the broad NA62 physics programme:
  - Rare Decays
  - Precision Measurements
  - LFV/LNV
  - Exotic Searches

- 8 of the 13 publications in 2021-2023 were led by UK physicists.

NA62

- UK physicists led study that found first evidence of the $K \rightarrow \pi\nu\nu$ decay.
  - Golden Mode providing important test of CKM paradigm and BSM physics.
  - One of rarest decays ever measured, BR$\sim10^{-10}$.
  - Result based on Run 1, with Run 2 (2021-LS3) to come – final dataset will be five times larger than Run 1.

JHEP 06 (2021) 093



NA62

- NA62 Run2 approved until LS3. If LS3 is delayed by a year, and if that delay is confirmed also for SPS experiments like NA62, then the extra year of data:
  - could give a definite indication of a deviation from the SM if the the current BR for $K \rightarrow \pi v v$ is confirmed
  - would give a 5σ observation for $K \rightarrow \pi v v$ with the SM BR.
  - would allow a large minimum-bias dataset for a precision measurement of the CKM parameter $|V_{us}|$, important in view of the current CKM 1st row unitarity tension.

NA62

- Challenges:
  - The main challenge for the NA62 group was to secure funding at the start of the project. The primary hardware contribution (the KTAG detector) was financed by an ERC Advanced Grant awarded in 2010. Without ERC support, the UK would probably have been unable to contribute significantly to the detector.
  - It is essential to maintain the breadth and diversity of the physics programme by implementing funding schemes for small/medium experiments as well as large ones.

Muon Programme

- 7 participating UK institutes with 50 scientists [20 academics/seniors, 10 PDRAs, 10 Students, 10 Engineers/Technicians].
- Funding from: Universities, STFC, Royal Society, Leverhulme Trust, EU.
- Wide participation in experiments
  - Fermilab: Muon g-2, Mu2e
  - PSI: Mu3e, MuEDM
  - JPARC: COMET
  - CERN: MUonE
  - Frascati: KLOE
- Along with theoretical contributions particularly in the SM prediction for Muon g-2 both using e+e- data and lattice QCD.

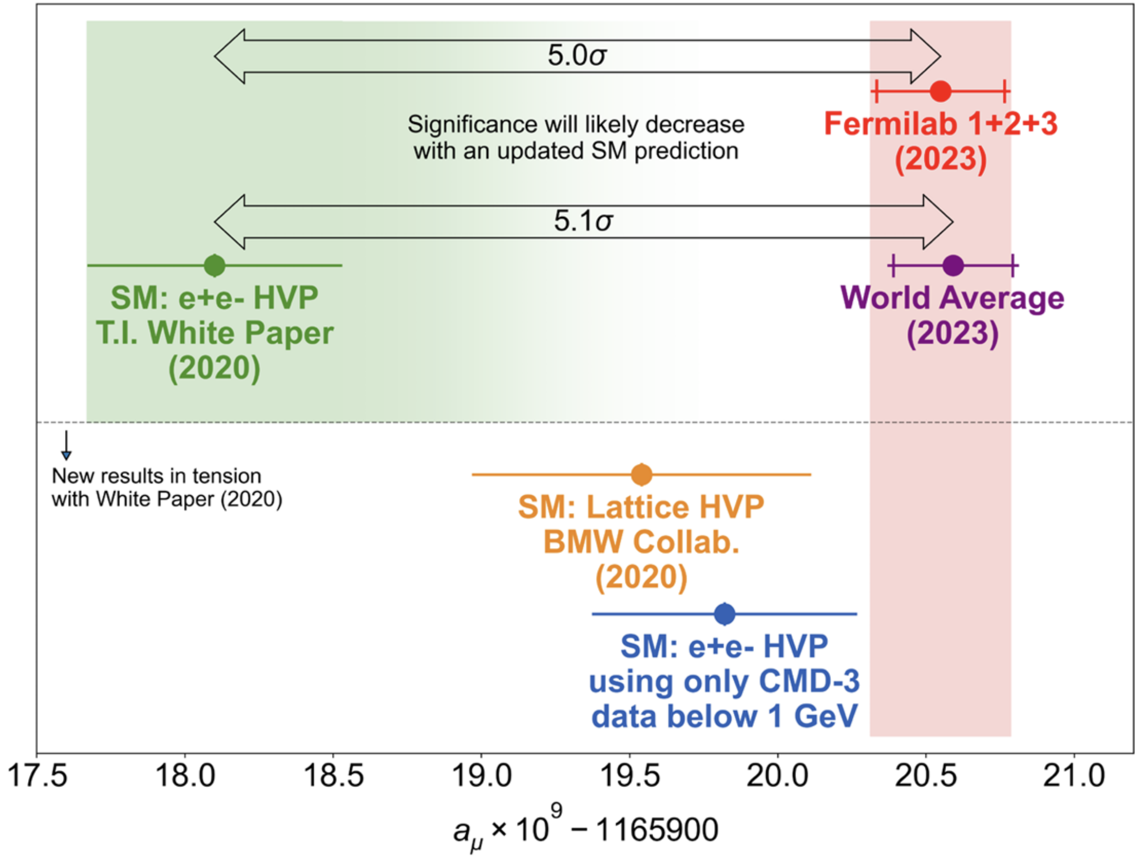
Muon Programme

- Key roles:
  - Two spokespeople for the FNAL Muon g-2 experiment
  - Physics Coordinator for Mu3e
- Detector responsibilities:
  - tracking e.g. straw trackers for Muon g-2, and silicon detectors for Mu3e, MUonE
  - X-ray detector for Mu2e
  - DAQ/readout and simulation leadership for several of the experiments
- Highlights:
  - FNAL Muon g-2 results
  - Muon EDM at FNAL (soon to be published, UK leadership)

Muon Programme

- g-2 (FNAL) measurements:
  - Two measurements of a_μ so far, with precision currently 0.2ppm.
  - Data for the 2021 publication was taken, analysed and published with spokespeople from UK institutes.
  - Results in tension with SM expectation from 2020 theory initiative at the 5σ level, but further studies necessary given more recent tensions in theoretical predictions.

From J. Mott, Fermilab Seminar



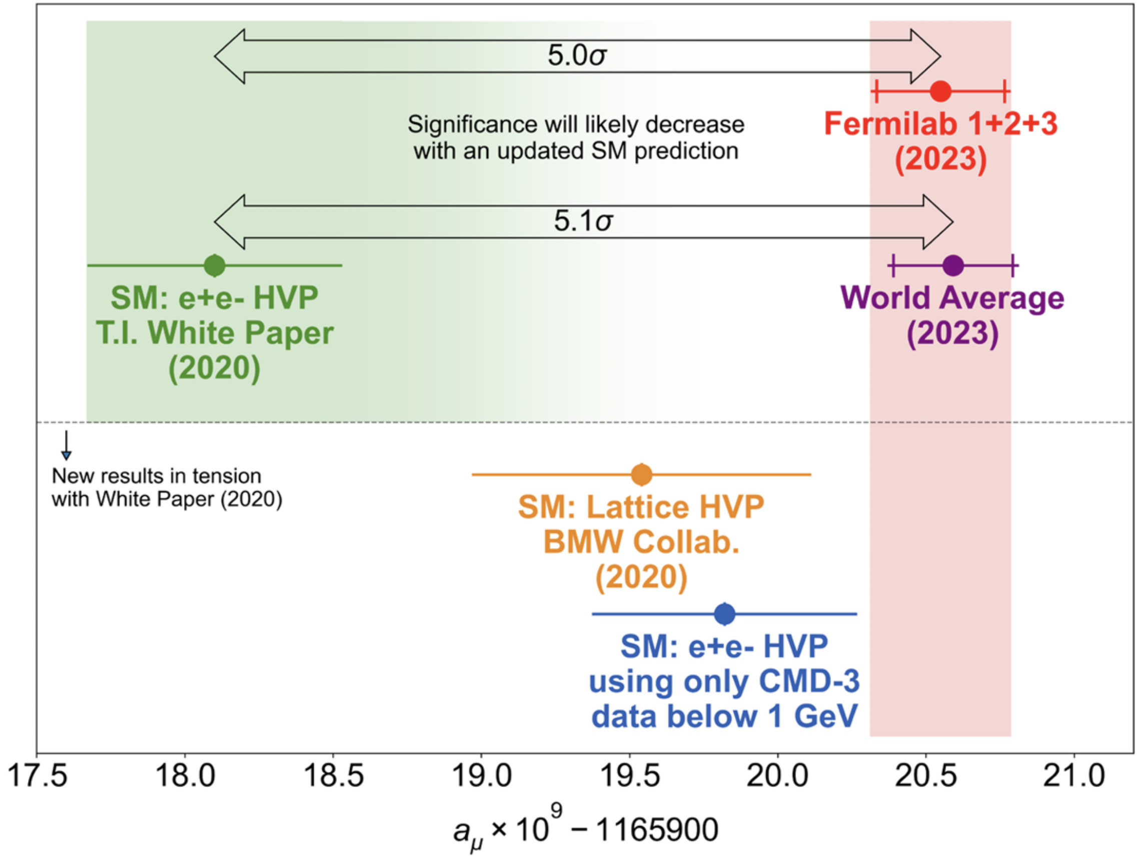
Disclaimer from A. Keshavarzi's Lattice 2023 talk:

IMPORTANT: THIS PLOT IS VERY ROUGH!
- TI White Paper result has been substituted by CMD-3 only for 0.33 → 1.0 GeV.
- The NLO HVP has not been updated.
- It is purely for demonstration purposes → should not be taken as final!

Muon Programme

- g-2 (FNAL) measurements:
  - 2021 g-2 publications now have 2250 citations. Outside of the discoveries of the Higgs boson and neutrino oscillations these are therefore among the most cited papers in experimental particle physics.
  - FNAL commissioned study shows that 2021 result covered in media outlets that reach 3.5 billion people.

From J. Mott, Fermilab Seminar



Disclaimer from A. Keshavarzi's Lattice 2023 talk:

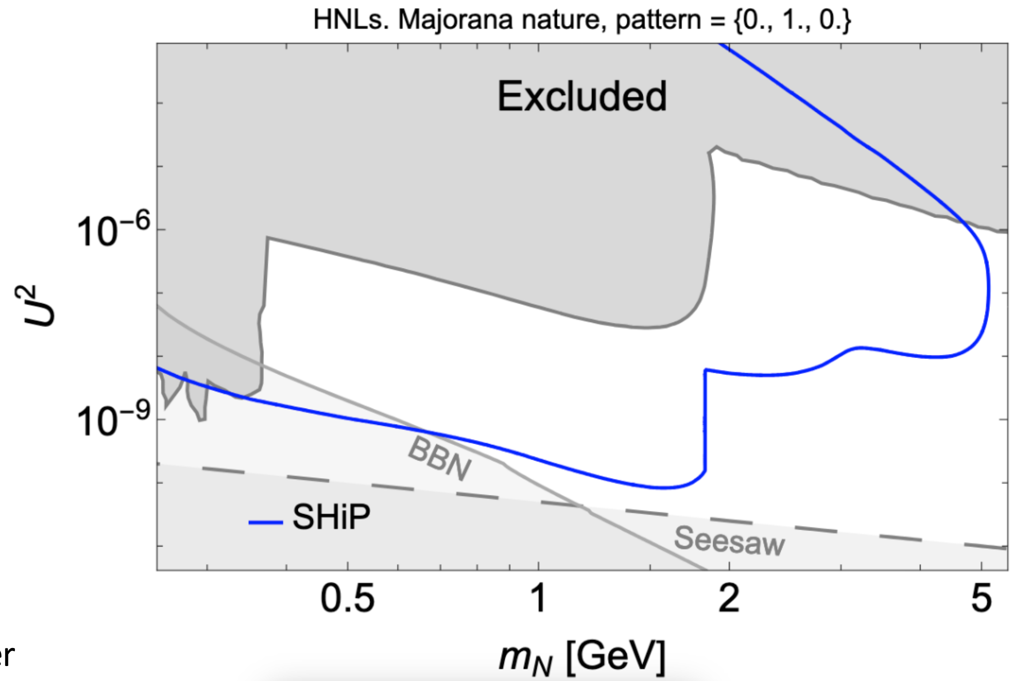
IMPORTANT: THIS PLOT IS VERY ROUGH!
- TI White Paper result has been substituted by CMD-3 only for 0.33 → 1.0 GeV.
- The NLO HVP has not been updated.
- It is purely for demonstration purposes → should not be taken as final!

Muon Programme

- Challenges:
  - many projects are coming online at a similar time with several people having commitments to more than one project. This has for example diverted some UK resources onto e.g. Mu2e commissioning instead of g-2 analyses.
  - to attract significant funding for UK involvement in future projects e.g. MuEDM or proton EDM, the project needs to be demonstrated to be feasible. This requires new resources to be allocated to R&D (prior to a major funding bid) or the diversion of existing resources. This can leave us behind compared to other countries where funding is more readily available for initial efforts, which then establishes leadership in those areas e.g. a lead in the silicon detectors for Phase-II of MuEDM or the electrostatic quadrupoles for a proton EDM experiment. A leading role in future projects requires an investment for new RAs and technical support to be made at the R&D stage of the projects.

SHiP

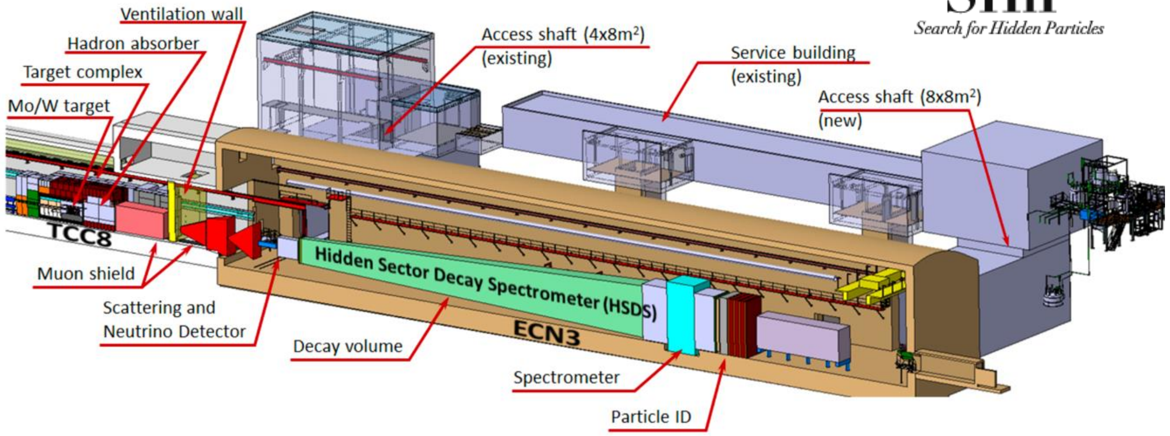
- Low-mass, feebly-interacting particles could solve many problems of the SM, including the pattern of neutrino masses and oscillation parameters, properties of dark matter and the origin of cosmic inflation.



- SHiP will make the world's leading (direct) searches for such particles, as well as key measurements of tau (anti-) neutrinos:
  - Improve on sensitivity of previous experiments by 3-4 orders of magnitude for e.g. heavy neutral leptons, dark photons, dark scalars.
  - Most precise measurements of tau (anti-) neutrino cross-sections, structure functions, first observation of tau antineutrino; and unique tests of lepton universality in neutrino sector.

SHiP

- CERN approved SHiP experiment in March 2024, and has committed CHF 69M to the construction of the required beam-dump facility, for which SHiP is sole user.
  - only major new direct-search experiment envisaged at CERN for the next 20+ years.
  - aim to take first data before LS4.
- 5 participating UK institutes (4 universities + RAL-TD), in discussion with 3 more.
- Led and initiated by UK physicists:
  - Spokesperson since inception of collaboration; chair of collaboration board; convener of the group responsible for major detector system ("muon shield").



Significant opportunities for industrial return from CERN to the UK:
Aim to build large systems of magnets that are essential to sweep out beam-induced muon backgrounds in the UK.
This muon shield will also incorporate the SHiP neutrino detector.

Conclusions

- Flavour physics provides key sensitivity to BSM physics that is complementary to direct searches at colliders.
  - European Strategy Update (2020) notes “the full physics potential of the LHC and the HL-LHC, **including the study of flavour physics** and the quark-gluon plasma, should be exploited.”

- The UK community plays key roles in flavour physics experiments (LHCb, Belle-II, NA62, muon programme including g-2). The UK also stands ready to lead in new direct-search experiments such as SHiP.

- The UK community has delivered exciting physics in recent years already, and is excited for the opportunities in the future.

Conclusions

- Challenges include:

  - Ensuring adequate investment to maintain existing breadth and exploitation of running experiments while new experiments come on-line.

  - Ensuring sufficient flexibility to quickly establish leadership in future projects, including ensuring we have significant and flexible R&D funding.

  - Retaining expertise (e.g. software experts) when industry careers can offer more enticing career prospects.