Non-Collider Digest

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UK ESPPU Drafting Day 3
Rutherford Appleton Laboratory, UK
28th April 2025

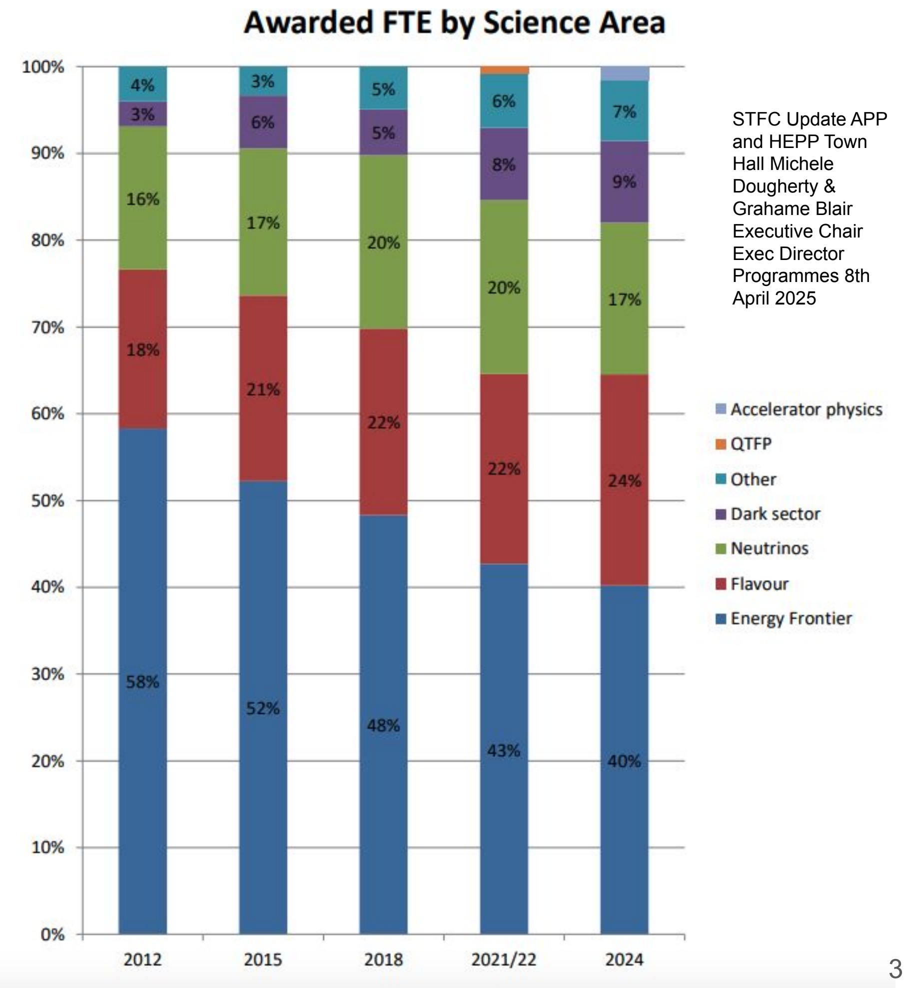
Setting expectations (a disclaimer)

1. The UK non-collider community is diverse.
   - ~ 25 experimental projects to cover.
2. A lot of numbers are estimates, likely realistic ballparks, but documented where possible.
   - Where possible, we have tried to ensure consistent CERN counting (£).
     i. US DOE ($) Project costs = x2 CERN estimates
   - We have not distinguished between already spent costs vs. future costs.
   - Cost estimates are detailed in backup slides.
3. We will undoubtedly have missed something, or will say or display something incorrect (sorry in advance!).
   - Can adjust slides straight after this talk to inform accurate discussion ✅
4. This talk is an opportunity to represent and recognise the value of a strong and diverse non-collider community.
5. It is <u>not</u> an attempt to prioritise the non-collider projects.
   - Either across or within different themes/areas.
6. It is an attempt to organise information by theme from the Daresbury meeting, updated with March 31 ESPPU submission info.

UK non-collider programme

- ~ 30% of the entire UK particle physics programme.
- Scale and ambition of a future collider demands sustained investment over several decades
  - May challenge the continuity of the broader programme.
- Firm interest from UK community to maintain + expand non-collider programme as strategic priority:
  - Scientifically rich, complementary to colliders.
  - Potential for discoveries in 10–20 years.
  - Smaller, shorter-timescale experiments.
  - Conducted in-parallel & between collider projects.
  - Provides essential continuity for our ECRs.

Non-collider programme is integral to the overall strategy, irrespective of the outcome or timeline of future collider initiatives
(i.e. - not a contingency in the event that collider option 3.a proves unfeasible).



STFC Update APP and HEPP Town Hall Michele Dougherty & Grahame Blair Executive Chair Exec Director Programmes 8th April 2025

A strong and diverse UK non-collider community

Travelling Neutrinos

DUNE
JUNO
P-ONE
Hyper-Kamiokande

Quantum Technologies

QSNET
AION
QSimFP
QSHS
QUEST DMC
TVLBAI

Direct Dark Matter

SOLAIRE
DarkSphere
DARKSIDE
XLZD

0vBB & v mass

SNO+
next
LEGEND
QTNM

Flavour

Mu2e
KOTO
AMF

EDMs

PEDM
eEDM
nEDM

Neutrino physics: known unknown and timeline

Oscillation Parameters	Mass ordering & CP violation	Neutrino Mass & Nature
$\theta_{12}, \theta_{13}, \theta_{23}$		
$\Delta m^2, \delta m^2$	sign(Δm^2)	m_x
Octant θ_{23}	δ_{CP}	α_1, α_2

2025-2030: Mass ordering first evidence with JUNO+IceCube+global fit

2027-2040: first measurement of the size of CP violation in the neutrino sector & precise neutrino physics era (3ν paradigm) at long baseline (HK/DUNE)

2030-2040: planetary network of neutrino telescopes, era of high statistics neutrino astronomy (IceCube, KM3Net, GVD, P-ONE) → astrophysics + ultra-high energy electroweak physics

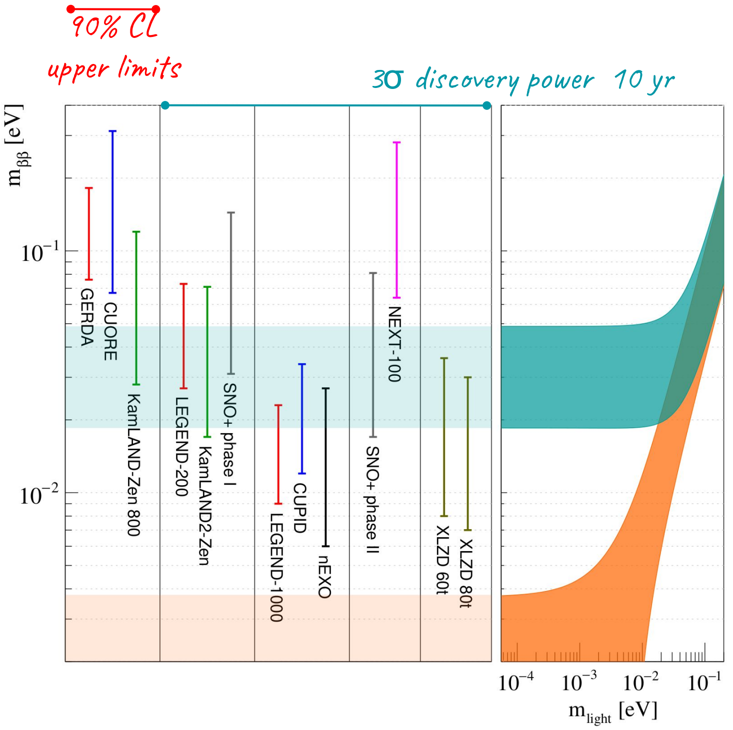
2030-2040: exploration of inverted-ordered majorana neutrinos with ton-scale experiments (LEGEND/CUPID/nEXO) + measurements of lightest neutrino mass if above 40 meV (Project 8/ QTNM) → unique inputs to the development of a theory of fermion masses

Travelling Neutrinos

	Construction		Exploitation	cost to the UK in £M	UK		International	
	start year	stop year			workforce	areas of involvement	int'n institutes	O(£) cost
DUNE	Phase I: now FD3: 2032 FD4: 2035 ND-GAr: 2035	Phase I: 2029 FD3: 2034 FD4: 2036 ND-GAr: 2036	2029+	BEIS(DSIT)/STFC £79.5M investment (already spent). Phase II R&D currently funded through non-project resources	18 institutes, 160+ UK authors	RF cavities, beam targets, LArTPC,GasTPC, DAQ, trigger, monitoring, evt reconstruction computing. Advanced charge readout R&D. Oscillation & low energy physics analysis	182	2B (e.g. $4B US DOE)
Hyper-K	now ND280 upgrade 2032-2037	2027	2027+	Supported by Infrastructure Grant. Exploitation: requested in CG Common funds starts in 2027.	8 institutes 91 UK authors	Electronic, beam target. DAQ for ND & FD Calibration, Outer Detector. Physics, Simulation and Computing	93	Unknown
JUNO (no DB slides)	Commissioning now	2025	2025+	Funded through STFC ERF, Royal Society, CSC studentships, and Warwick/Liverpool PP groups.	2 institutes	Reconstruction, analysis, event generators and related frameworks.	72	300M
P-ONE	first line deployment in 2025, staged deployment	2030+	2030-40	O(10) to become a stakeholder	1 active + several waiting for funding	trigger, module design and assembly, PMT and optical module characterisation	17	100M

	Construction timeline		Exploitation timeline		cost to the UK	UK contributions	
	start year	stop year	start year	stop year		community size	areas of involvement
LEGEND	host lab preparation started, construction starting in 2026-2027	2032	2029	2040	~£10M	12 institution, 37 academics	Cryogenic, Radiopurity, Computing and Analysis, HPGe detectors, underground assembly and characterisation
NEXT	2028	2031	2031	2041 TBC	Unknown	1 institution, 1 academic	sensor calibration, topology studies, energy resolution with SiPMs, readout plane
SNO+	started (currently operating with scintillator)	2028 (final loading)	2027	2033+	Unknown	5 institutions	scintillator loading, analysis
QTNM/P8	CRESDA-3H 2026 "Phase 2" 2030	2030 2040	now	2040+	Unknown	5 institutions	QTNM is 100% UK expertise. Project 8 is mostly international partners

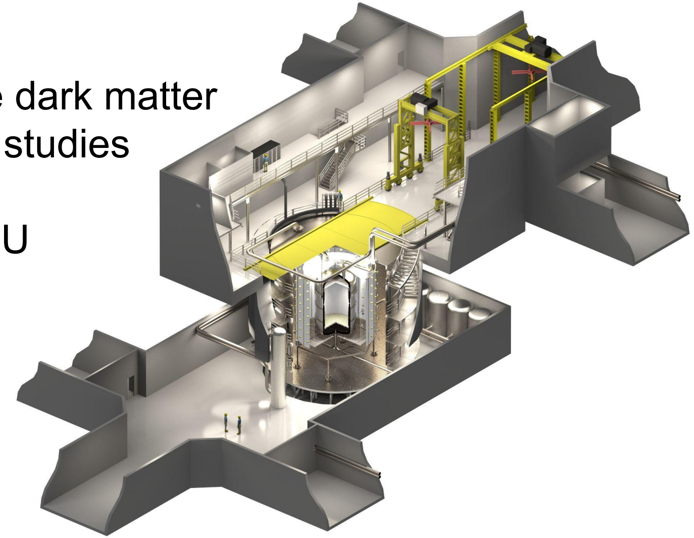
0νββ & ν mass

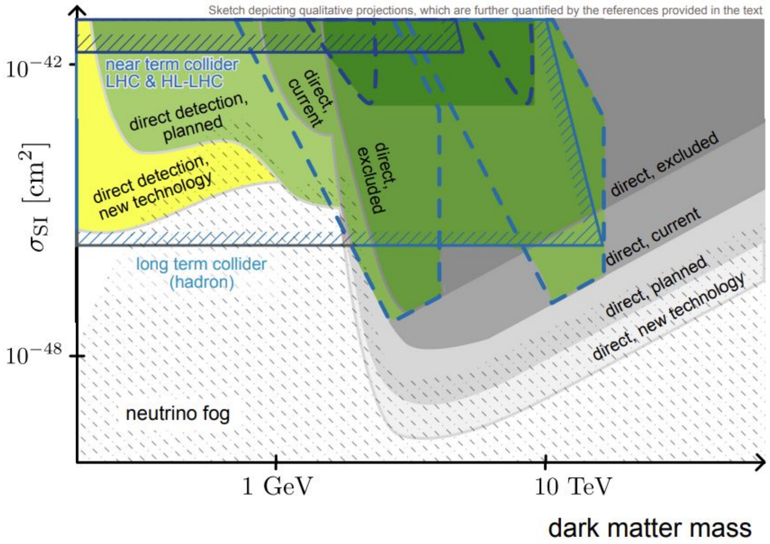


NMEs and sensitivities from Agostini, Benato, Detwiler, Menéndez, Vissani, Rev. Mod. Phys. 95, 025002 (2023)

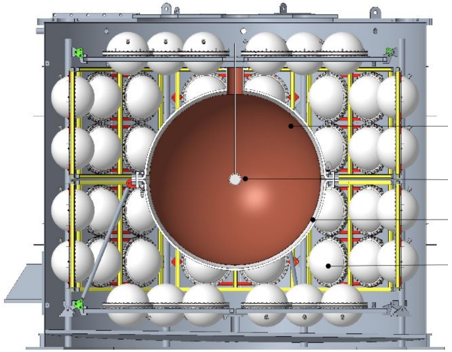
Direct Dark Matter Searches

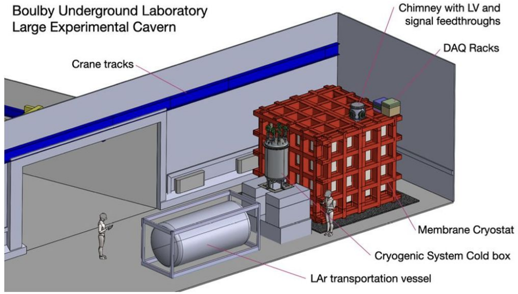
- **Large-scale detectors are multi-purpose**: performing multiple dark matter searches, as well as 0vbb, neutrino property and solar neutrino studies
- **Complementarity in dark matter searches** across sub-fields
- Dark Matter is a significant physics motivation across the ESPPU
- **UK ambition and opportunity to host at Boulby**





[Dark Matter Complementarity]





Direct Dark Matter Searches

	Construction		Exploitation	UK costs	UK contributions	
	start	stop	start	construction	FTE/year	areas of involvement
DarkSide-20k (DB and ESPPU) LAr TPC	in progress	2027	2028	£3.2M	~33 FTE (~45 UK members) at 11 institutions	7 m² SiPM for veto (25% of all SiPMs), photodetectors, background est./mitigation, DAQ
XLZD (DB and ESPPU) LXe TPC	2028	2034	2035	UK host: £200M (1/3 of XLZD), £300M for Boulby non-UK host: £50M	currently ~80 members at 14 institutions	1/3 of scope: xenon (1/3) procurement and storage, outer detector, cryostats, part of main xenon detector, computing, and engineering, cleanliness, & sustainability
SOLAIRE (DB) LAr TPC		4 years from funding	5 years from funding	£10M	~13 FTE (>25 UK PIs)	infrastructure, TPC, readout components, DAQ
DarkSphere (no DB, ECFA-UK) gas (multi-target), spherical proportional chamber		3 years from funding	4 years from funding	£10M (incl. Initial ops)	17 UK PIs, 9 Institutions	full programme

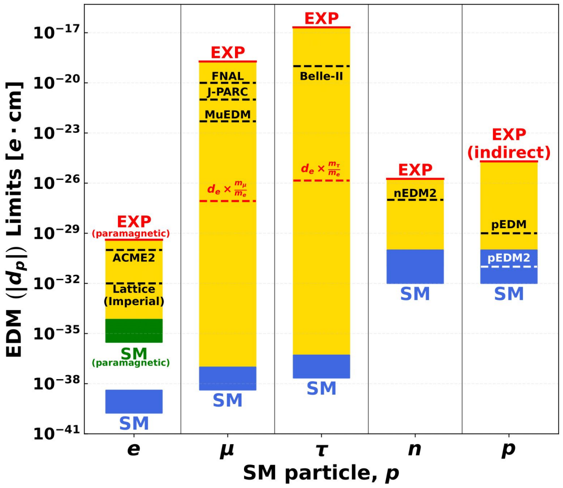
Quantum technologies & tests of fundamental physics

- QTFP seeded new projects demonstrating how quantum technologies can be utilised to investigate key fundamental physics questions
- QTFP1 was a £40 million Strategic Priorities Fund (2021 - now) & additional institutional co-funding and in-kind contributions.
- Programme is very ambitious and includes searches for: ***dark matter, dark energy, gravitational waves, stability of fundamental constants, violations of Lorentz Invariance, absolute mass of neutrinos, phenomena linked to quantum gravity, and dynamics of the early universe and black holes***
- See also QTNM (neutrinos) and QUEST-DMC (direct searches)

	Construction		Exploitation	UK			International Context
	start	stop	start	cost to the UK in £M	Workforce	areas of involvement	
QSHS Resonant cavity search for halo axions	2021	now	2025+	~£10M	6 institutes, 16 UK academics	Axion detection, Cryogenics, Superconducting materials, Novel resonator technologies.	Collab. with ADMX (US)
QSNET network of atomic clocks	now	5+ years	5+ years	~£10M	4 institutes, 20 UK academics	optical clocks (neutral atoms, ions, highly charged ions, molecules and nuclei), fibre link expertise	With European collab, operate diffuse network across Europe
TVLBAI 100m+ baseline atom interferometry (incl. AION groups)	2029	2034	2035+	~£20M	7 institutes, 20 UK academics	UK leading international collab building. 5 Ultra Cold Sr Labs at Imperial, Oxford, Cambridge, RAL and Birmingham provide 25% of worldwide Strontium R&D efforts	Proto-collab. with 51 institutes (UK, Europe, US, Australia)
QUEST/UltraDark (no DB, ECAF-UK) superfluid ^{3}He with quantum sensing		3 years from funding	4 years from funding	£8M	~29 members, ~6 institutions	full programme	

Electric Dipole Moments

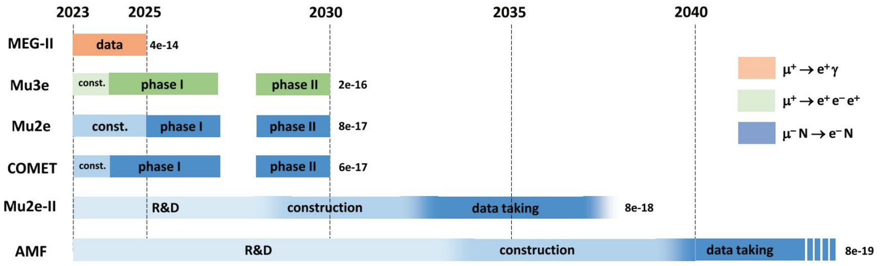
- Science case: new sources of CP violation/baryon asymmetry, strong CP violation/strong CP problem, axionic DM, BSM models with mass ranges up to PeV scale.
- **Entire program cost O(£10M) to UK.**
- Entire program runs from now → ~ 2050.
- Potential in each case to probe order(s) of magnitude better than current limits.



	Construction		Exploitation	UK			International	
	start	stop	start	cost to the UK in £M	Workforce	areas of involvement	# institutes	O(£) cost
pEDM Brookhaven National Laboratory	2035	2040	2040+	~£3M	3 institutes, 9 UK authors	High voltage deflectors, proton polarimeters, analysis.	47	100M
nEDM European Spallation Source	2030	2035	2035+	Unknown	1 institute, 3 UK authors	Cryogenics, high voltage, magnetic environment and sensors, design and engineering	13	Unknown
MuEDM Paul Scherrer Institut PSI	2027	2032	2032+	~£2M	4 institutes, 11 UK authors	HV-MAPS silicon positron tracker + DAQ - Solenoid / coil work	21	Unknown
eEDM Imperial College London	now	2026	2026+	University costs only	1 institute, 8 UK authors	Laser cooled beam experiment and trapped YbF (laVce) experiment	1	Staff costs only

Flavour: Charged Lepton Flavour Violation & Kaon Decays

- Science case: e.g. BSM models (up to PeV scale), neutrino mass generation, flavour symmetries/breaking, minimal flavour violation (MFV), new CP-violating phases.
- **Entire program cost O(£10M) to UK**.
- Entire program runs from now → ~ 2050.
- Potential for order(s) of magnitude better than current limits.

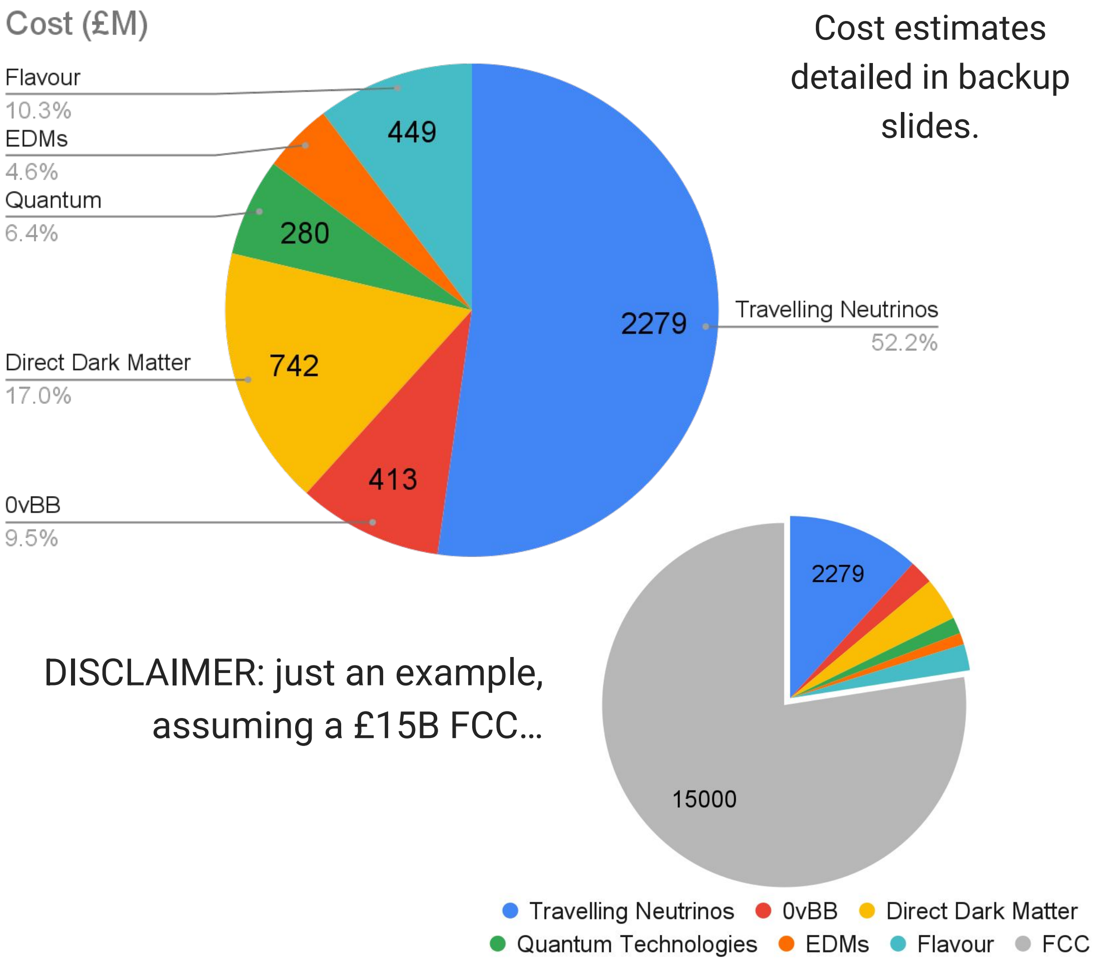


		Construction		Exploitation	UK			International	
		start	stop	start	cost to the UK in £M	Workforce	areas of involvement	# institutes	O(£) cost
	AMF Fermilab	2040	2045	2045+	~£3M	5 institutes, 11 UK authors	Low mass detectors, muon collider R&D (FFAG ring & production target).	32	200M
Charged Lepton Flavour Violation	Mu2e Fermilab	Now	2027	2027+	~£2M	3 institutes, 14 UK authors	Stopping Target Monitor Detector, Tracking, Analysis	38	100M
	Mu3e-II PAUL SCHERRER INSTITUT PSI	2027	2030	2030+	~£2M	4 institutes, 26 UK authors	Clock-and-reset system for all Mu3e sub-detectors and the construction of the HVMAPS outer pixel tracker layers.	13	Unknown
	Mu2e-II Fermilab	2030	2035	2035+	~£2M	2 institutes, 3 UK authors	Low mass detectors	34	50M
Kaon Decays	KOTO-II J-PARC	2027	2033	2034+	£3M	6 institutes, 10 UK authors	Detector design; construction of tracker and charged-particle veto; computing; physics analysis.	42	20M

Cost comparison

- The future collider (whichever preferred option) is key to the future of particle physics.
- But, so is the non-collider programme.
- And for ~ 30% of e.g. an FCC estimated cost of £15B.
- DUNE is a large fraction of the non-collider programme.
- Assuming both the FCC and DUNE, the remainder constitutes ~ 15% of the overall potential future experimental particle physics programme.
- That’s a lot of great physics for 15% of the total spend…

Cost estimates detailed in backup slides.



DISCLAIMER: just an example, assuming a £15B FCC…

Take-away and conclusions

- There is a strong and diverse UK (and international) non-collider community.
- It has been consistently growing and currently constitutes ~30% of the entire UK particle physics community.
- Each of the projects has the potential for groundbreaking discoveries within the next 10-20 years.
- The entire non-collider programme is ~30% of an FCC estimated cost of £15B.
- The **non-collider programme is integral to the overall strategy and not a collider backup contingency.**
  - There is a firm interest from UK community to maintain + expand it as strategic priority.
  - Irrespective of the outcome or timeline of future collider initiatives.
  - The science is entirety complementary to the future collider(s).
  - Experiments are smaller, shorter-timescale, conducted in-parallel & between collider projects.
  - Provides essential continuity for our ECRs.
- Proposals in backup slides to strengthen non-collider statements in UK submissions.

Backup

Strengthening non-collider statements in UK submission (1)

Current text in 1. Executive summary:

> *Beyond collider physics, the UK community emphasises the importance of a strong and sustainable non-collider particle physics programme, which has the potential for groundbreaking discoveries in the next 10–20 years.*

Proposal replacement text:

> ***In parallel to collider physics, the UK community advocates for the simultaneous continued expansion of a strong and sustainable non-collider particle physics programme (cLFV searches, direct dark matter and axion searches, EDMs, neutrinos, list to be completed) which has the potential for groundbreaking discoveries in the next 10–20 years.***

Strengthening non-collider statements in UK submission (2)

Current text in 2. Priorities for the future:

> *Smaller, shorter-timescale experiments carried out in parallel to, and in-between, major collider projects will offer continuity for ECRs during long stages of collider R&D in addition to their inherent valuable physics research potential.*

Proposal replacement text:

> ***The non-collider program, along with smaller, shorter-timescale experiments conducted in parallel with and between major collider projects, provides essential continuity for early-career researchers during extended phases of collider R&D. In addition to their inherent scientific value, these efforts help sustain research momentum, capitalize on existing infrastructures, and ensure continued opportunities during the long intervals between collider construction and operation.***

Strengthening non-collider statements in UK submission (3)

Current text in 4.a What other areas of physics should be pursued, and with what relative priority?:

> *A key message in UK discussions is that diversity of our physics programme should remain a priority in the coming decades.*

Proposal replacement text:

> ***The non-collider programme constitutes a scientifically rich and complementary avenue of discovery that is essential to a balanced European particle physics strategy. There is a firm interest within the UK community in maintaining and expanding this programme as a strategic priority in the coming decades—irrespective of the outcome or timeline of future collider initiatives. The UK community also recognises that the scale and ambition of a future collider demands sustained investment over several decades, which may challenge the continuity of the broader programme. In this context, a strong non-collider programme not only ensures ongoing scientific activity and knowledge retention, but also supports training and career development for early-career researchers. It should be seen as an integral component of the overall strategy, not merely a contingency in the event that collider option 3.a proves unfeasible.***

Project Cost Estimates

	DOE counting ($M)	CERN counting (£M)	Reference
Travelling Neutrinos			
DUNE	4000	1500	https://conference.ippp.dur.ac.uk/event/1391/contributions/7953/attachments/6252/8441/DUNE-ESPPUdrafting-Project-input-request.pdf
Hyper-K		578	UNKNOWN - Estimated to be 1/n of sum of n other known projects in theme
JUNO	311	117	https://economictimes.indiatimes.com/news/science/juno-china-has-a-new-lab-2300-feet-underground-to-solve-a-physics-mystery/articleshow/114320177.cms?from=mdr
P-ONE		85	https://conference.ippp.dur.ac.uk/event/1391/contributions/7939/attachments/6258/8448/ECFA-P-ONE.pdf
	Total:	**2279**	
0vBB			
LEGEND		160	https://conference.ippp.dur.ac.uk/event/1391/contributions/7937/attachments/6251/8440/ECFA-LEGEND.pdf
NEXT	100	50	https://conference.ippp.dur.ac.uk/event/1391/contributions/7958/attachments/6265/8462/NEXT.pdf
SNO+		103	UNKNOWN - Estimated to be 1/n of sum of n other known projects in theme
QTNM/P8		100	https://conference.ippp.dur.ac.uk/event/1391/contributions/7949/attachments/6247/8431/QTNM-ESPPU-drafting.pdf
	Total:	**413**	
Direct Dark Matter			
Darkside-20k		120	https://conference.ippp.dur.ac.uk/event/1391/contributions/7929/attachments/6227/8409/DarkSide-20k%20Input%20to%20UK%20Drafting%20Session.pdf
XLZD		600	https://docs.google.com/presentation/d/187aonxuq70Y6ngp2RqHmyGm9OT8umWwo_bjCXR5Yg2E/edit?slide=id.g2fc6ca4d06b_0_51#slide=id.g2fc6ca4d06b_0_51
SOLAIRE		20	https://conference.ippp.dur.ac.uk/event/1391/contributions/7938/attachments/6228/8410/SOLAIRE%20Input%20to%20UK%20Drafting%20Session%202.pdf
Darksphere		2	https://indico.kcl.ac.uk/event/154/contributions/602/attachments/177/210/boulbyFeasibilityStudyDay2_NEWSG.pdf
QUEST/UltraDark		186	UNKNOWN - Estimated to be 1/n of sum of n other known projects in theme
	Total:	**742**	
Quantum Technologies			
QSHS		70	UNKNOWN - Estimated to be 1/n of sum of n other known projects in theme
QSNET		100	https://conference.ippp.dur.ac.uk/event/1391/contributions/7951/attachments/6246/8430/QSNET_ESPPU.pptx
TVLBAI		40	https://conference.ippp.dur.ac.uk/event/1391/contributions/7951/attachments/6246/8430/QSNET_ESPPU.pptx
	Total:	**210**	
EDMs			
pEDM		100	https://conference.ippp.dur.ac.uk/event/1391/contributions/7947/attachments/6239/8423/pEDM.pdf
nEDM		50	UNKNOWN - Estimated to be 1/n of sum of n other known projects in theme
MuEDM		50	UNKNOWN - Estimated to be 1/n of sum of n other known projects in theme
eEDM		0	https://conference.ippp.dur.ac.uk/event/1391/contributions/7955/attachments/6253/8442/eEDM.pdf
	Total:	**200**	
Flavour			
AMF	500	188	https://conference.ippp.dur.ac.uk/event/1391/contributions/7945/attachments/6241/8425/Mu2e-Mu2e-II-AMF.pdf
Mu2e	300	113	https://conference.ippp.dur.ac.uk/event/1391/contributions/7945/attachments/6241/8425/Mu2e-Mu2e-II-AMF.pdf
Mu3e-II		93	UNKNOWN - Estimated to be 1/n of sum of n other known projects in theme
Mu2e-II	150	56	https://conference.ippp.dur.ac.uk/event/1391/contributions/7945/attachments/6241/8425/Mu2e-Mu2e-II-AMF.pdf
KOTO-II	44	17	https://arxiv.org/pdf/2501.14827
	Total:	**449**	

Conversions	
DOE --> CERN	0.5
USD --> GBP	0.75

Theme Cost Estimates

Themes	Cost (£M)
FCC	15000
Travelling Neutrinos	2279
0vBB	413
Direct Dark Matter	742
Quantum Technologies	280
EDMs	200
Flavour	449
Total Programme Cost	**19364**
Non-Collider Total	**4364**
Non-Collider Fraction of Total Programme Cost	**22.54%**
Non-Collider Fraction of FCC cost	**29.09%**
Non-DUNE	2864
Non-FCC/DUNE fraction of total	14.79%