Comprehensive Paper:
Accettura, C. et al. Towards a muon collider. Eur. Phys. J. C 83, 864 (2023).

Muon Collider ESPPU Plans

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on behalf of the UK Muon Collider Community

May 1, 2024

International MUON Collider Collaboration

UNIVERSITY OF BIRMINGHAM

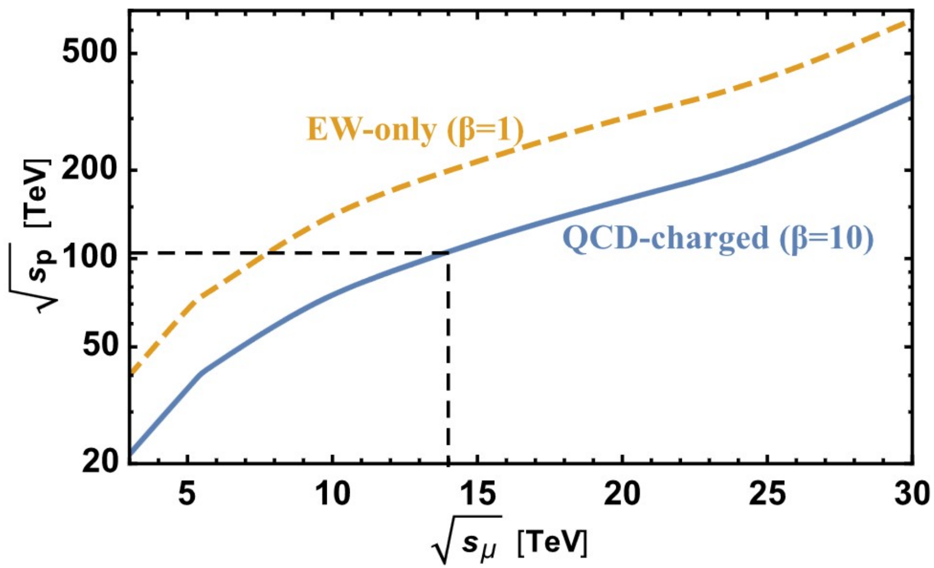
UK-ECFA Kickoff

Physics Case in a Nutshell

Combines future collider needs in **one** facility targeting operations in **2050**.

	HL-LHC	ILC (500)	FCCee+hh	μC (10 TeV)
hZZ	1.5	0.17	**0.12**	0.33
hWW	1.7	0.20	0.14	**0.10**
hbb	3.7	0.50	0.43	**0.23**
hγγ	3.4	0.58	**0.44**	0.55
hgg	2.5	0.82	0.49	**0.44**
hcc	-	1.22	**0.95**	1.8
hττ	1.8	1.22	**0.29**	0.71
hγZ	9.8	10.2	**0.69**	5.5
hμμ	4.3	3.9	**0.41**	2.5
htt	3.4	2.82	1.0	3.2
Γ_{tot}	5.3	0.63	1.1	**0.5**

"clean" environment
for precision measurements



100 TeV pp ≈ 10-15 TeV μμ

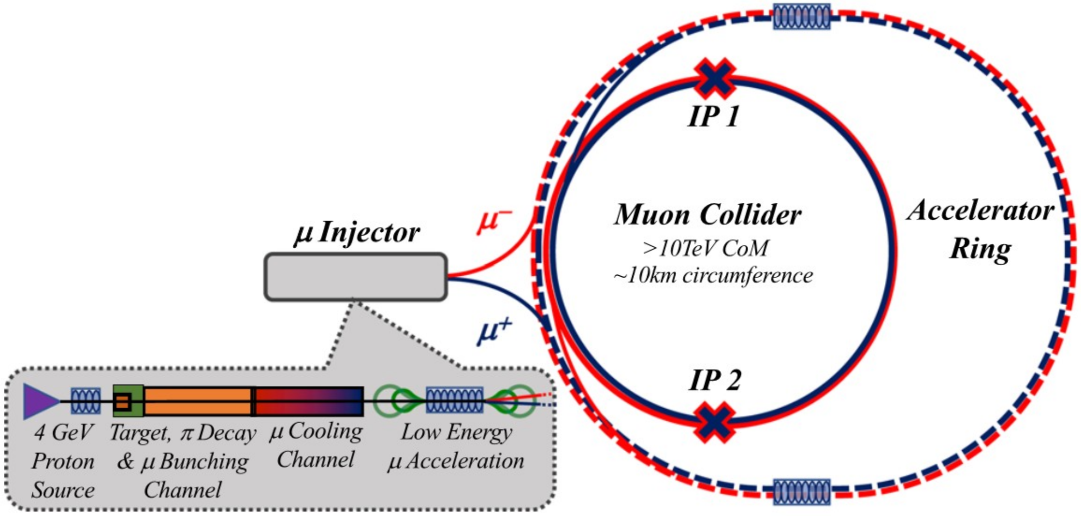
Theory summary: The muon Smasher's guide

R&D Need 1: Accelerator Complex

A muon collider would be a first-of-its-kind.

Main R&D:

- Muon production and cooling.
- Rapid acceleration.
- Neutrino flux.



UK has a strong participation in the accelerator R&D.

Joint Autumn Meeting of nuSTORM and UK Muon Beams Collaboration 2023

Delays in demonstrator of cooling stage funding push start date (2050).

Accelerator Synergies

Accelerator R&D also helps other fields.

Stepping stones and other synergies take full advantage of ambitious R&D program.

- **NuSTORM: Intense neutrino beam.**
  - Same injection chain, but accelerator ring replaced with storage ring.
- **Radiation tolerant and high-field solenoids.**
  - Accelerator science, imaging technology, mu2e
- **High field dipoles.**
  - Developments would also aid FCChh.

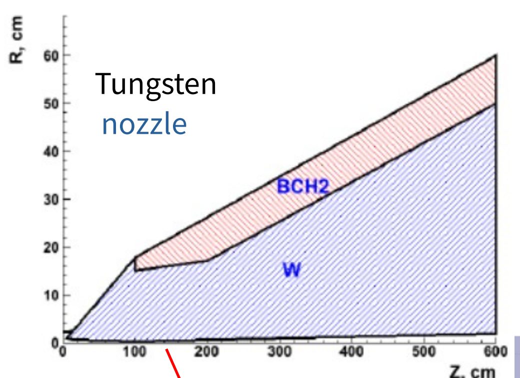
See Muon4Future workshop last year.

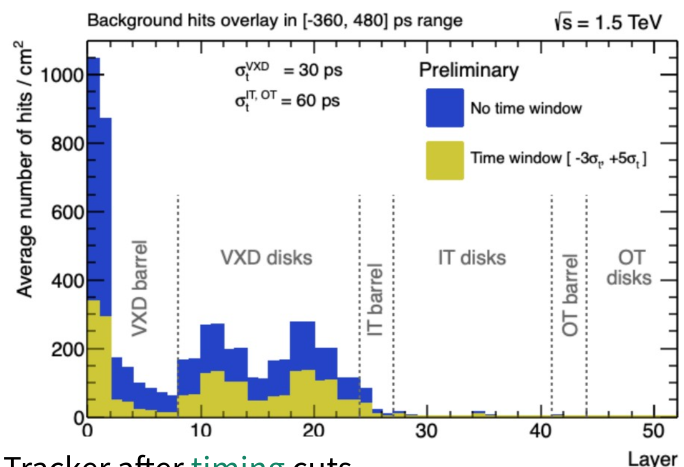
R&D Need 2: Beam Induced Background

- **BIB = muon beam decays and strike the detector**
- **Several main mitigation**
  - 10° tungsten nozzle to shield from beam decay products
  - Precision timing information from detectors

Hit density **after timing cuts** **10x HL-LHC**

	ATLAS ITk Hit Density [mm^{-2}]	MCC Equiv. Hit Density [mm^{-2}]
Pix Lay 0	0.643	3.68
Pix Lay 1	0.022	0.51
Str Lay 1	0.003	0.03

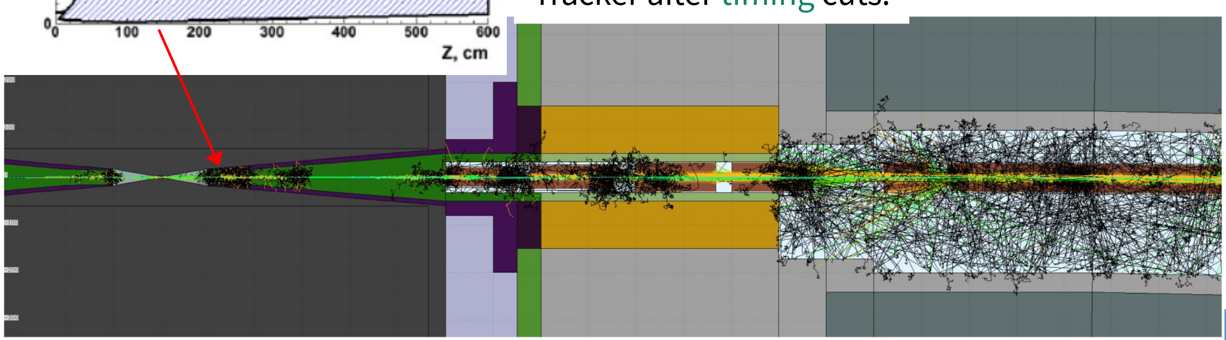




Tracker after timing cuts.

Expected dose in innermost tracking layer.

Experiment	1 MeV n_{eq} / cm²	GRad
HL-LHC (ATLAS)	1.87 x 10^{16}	1.268
µC (1.5 TeV)	5 x 10^{15}	0.05
FCChh	8 x 10^{17}	27
FCCee	? not big ?	? not big ?



FLUKA simulation of BIB before reaching the detector.

Simulation/Reconstruction Software

- **Based on ILC reconstruction software (Marlin framework).**
  - Detector optimized for $\sqrt{s} = 1.5$ TeV, prototypes for 10 TeV exist (link 1, link 2).
- **BIB overlay generated using LineBuilder+FLUKA.**
- **Latest tutorial: CERN 2023**
  - Generating events, running simulation and reconstruction…
- **Work on-going to migrate to key4HEP.**
  - Good for synergy with FCC and other Higgs factories.

Instrumentation R&D

The 2021 ECFA detector research and development roadmap (with updates).

"Technical" Start Date of Facility (This means, where the dates are not known, the earliest technically feasible start date is indicated - such that detector R&D readiness is not the delaying factor)				< 2030					2030-2035					2035 - 2040	2040-2045		> 2045		
				Panda 2025	CBM 2025	HIKE 2030	Belle II 2026	ALICE LS3 [1)]	ALICE 3	LHCb (≳LS4)[1)]	ATLAS/CMS (≳ LS4)[1)]	EIC	LHeC	ILC [2)]	FCC-ee	CLIC [2)]	FCC-hh 2070	FCC-eh	Muon Collider 2050
Vertex Detector[3)]	MAPS Planar/3D/Passive CMOS LGADs	DRDT 3.1 DRDT 3.4	Position precision σ_{hit} (μm)		≃ 5		≲ 5	≃ 3	≲ 3	≲ 10	≲ 15	≲ 3	≃ 5	≲ 3	≲ 3	≲ 3	≃ 7	≃ 5	≲ 5
			X/X_0 (%/layer)	≲ 0.1	≃ 0.5	≃ 0.5	≲ 0.1	≃ 0.05	≃ 0.05	≃ 1		≃ 0.05	≲ 0.1	≃ 0.05	≃ 0.05	≲ 0.2	≃ 1	≲ 0.1	≲ 0.2
			Power (mW/cm^2)		≃ 60			≃ 20	≃ 20			≃ 20		≃ 20	≃ 20	≃ 50			
			Rates (GHz/cm^2)		≃ 0.1	≃ 1	≲ 0.1		≲ 0.1	≃ 6		≲ 0.1	≃ 0.1	≃ 0.05	≃ 0.05	≃ 5	≃ 30	≃ 0.1	50
			Wafers area (")[4)]					12	12			12			12		12		12
		DRDT 3.2	Timing precision σ_t (ns)[5)]	10		≲ 0.05	100		25	≲ 0.05	≲ 0.05	25	25	500	25	≃ 5	≲ 0.02	25	≲ 0.02
		DRDT3.3	Radiation tolerance NIEL (x 10^{16} neq/cm^2)			1				≃ 6	≃ 2						≃ 10^2		0.5
			Radiation tolerance TID (Grad)							≃ 1	≃ 0.5						≃ 30		0.05

Same pathway as for many experiments!

Synergy with many future projects.

International Collaboration

https://muoncollider.web.cern.ch

WP	Title	Coordinator	Institutes
1	Coordination and Communication	Roberto Losito (CERN)	**CERN**
2	Physics and Detectors Requirements	Donatella Lucchesi (UNIPD)	**UNIPD**, INFN, CEA, DESY, UOS, LIP, CERN
3	Proton Complex	Natalia Milas (ESS)	**ESS**, UU, CERN
4	Muon Production & Cooling	Chris Rogers (STFC - UKRI)	**UKRI**, Imperial, UWAR, CERN
5	High Energy Complex	Antoine Chancé (CEA)	**CEA**, INFN, CERN
6	RadioFrequency System	Claude Marchand (CEA	**CEA**, ULA, UROS, INFN, CERN, Strathclyde
7	Magnet Systems	Luca Bottura (CERN)	**CERN**, CEA, INFN, SOTON, TUDa, UTWENTE
8	Cooling cell Integration	Lucio Rossi (CERN)	**UMIL**, INFN, Imperial, CERN

IMCC Annual Meeting 2023 (Orsey, France)

- 188 participants

IMCC and MuCol Annual Meeting 2024 (CERN)

- 192 participants

Interim MuCol report out soon

- 388 authors
- Major progress towards a CDR

- **Formed as a result of *European Strategy for Particle Physics Update* 2020 report**
- **Hosted by CERN**
- **Covers all necessary areas**
  - Accelerator
  - Detector
  - Physics
- **Main driver for the experimental work**
- **Some funding via MuCol project**

Snowmass 2021

- **Energy Frontier: 40/150 contributed papers from μC! (link)**
  - Key reports: Higgs Boson Physics, Muon Collider Forum, Detector Simulations, Higgs Boson Physics
  - Main message: 10 TeV is required to meet key physics goals.
- **Report of the P5 (full report)**

The panel recommends dedicated R&D to explore a suite of promising future projects. One of the most ambitious is a future collider concept: a **10 TeV parton center-of-momentum (pCM) collider** to search for direct evidence and quantum imprints of new physics at unprecedented energies. Turning this concept into a cost-effective, realistic collider design demands that we aggressively develop multiple innovative accelerator and detector technologies. This process will establish whether a proton, electron, or muon accelerator is the optimal path to our goal.

As part of this initiative, we recommend **targeted collider R&D** to establish the feasibility of a **10 TeV pCM muon collider**. A key milestone on this path is to design a muon collider demonstrator facility. If favorably reviewed by the collider panel, such a facility would open the door to building facilities at Fermilab that test muon collider design elements while producing exceptionally bright muon and neutrino beams. By taking up this challenge, the US blazes a trail toward a new future by advancing critical R&D that can benefit multiple science drivers and ultimately bring an unparalleled global facility to US soil.

DOE/Fermilab is taking concrete steps based on the recommendation.

EPSS (Detector) Plans

Demonstrate that a muon collider is an option for ~2050.

Further building on results from Snowmass and Interim MuCol report.

- **Solidify the physics case for a $\sqrt{s}$ = 10 TeV collider.**
  - Key will be updated full detector simulation studies at 10 TeV.
  - Important to include in combined papers (ie: ECFA Higgs Summary).
- **Development of novel techniques for BIB reduction.**
  - Plenty of room to innovate. Demonstrates a rich program for the future.
- **Show that near-future technologies meet the requirements.**
  - Helped by the much smaller radiation requirement.

UK-ECFA: Need to make a decision at what level UK will support (US-based?) experiment.

UK Effort (Accelerator)

- **Huge UK involvement already.**
  - Mostly on the accelerator side.
  - Increased participation for detector would be good synergy.

UK Effort (Detector)

- **Catch-up meetings:** ***first Monday of Month at 3pm***
  - UK Mailing List: UK-MUON-DETECTOR@JISCMAIL.AC.UK
  - Also attended by some of our accelerator friends.
- **In-person meeting on July 3 in Birmingham.**
  - Goal is to drive interest in the µC physics program in UK!
  - Indico page: https://indico.stfc.ac.uk/event/983/

The µC accelerator technology is currently UK driven.

Let's expand to physics.

Conclusion

- **A muon collider at $\sqrt{s}$=10 TeV has a strong physics case.**
  - Full program starts at 2050 (aka for most of our careers).
- **Requires a challenging accelerator R&D effort.**
  - Huge progress as part of Snowmass and MuCol project.
  - Funding for a cooling demonstrator is critical to timeline.
  - A lot of this is UK driven!!!
- **Being taken seriously in the US.**
- **Plan is to provide a ambitious plan going into 2030x.**