UNIVERSITY OF BIRMINGHAM

10 TeV pCM Colliders Overview

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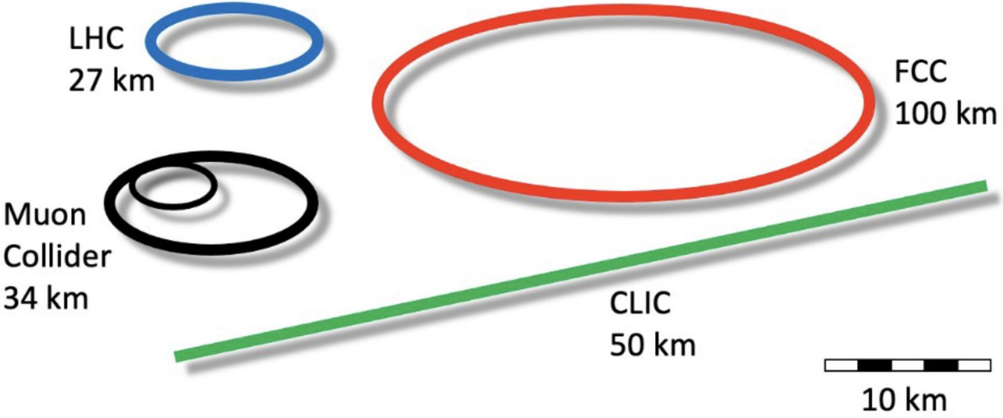
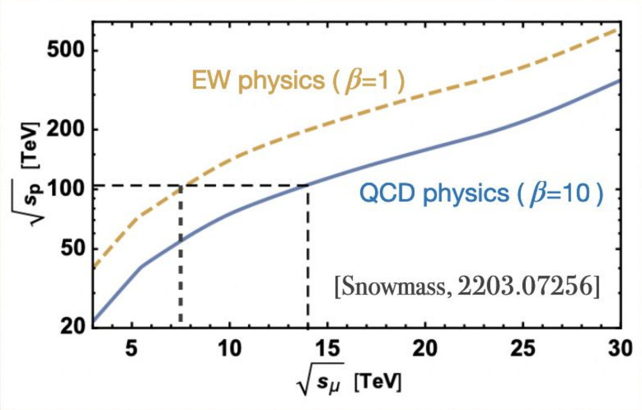


What is 10 TeV pCM?



10 TeV $\mu\mu$ stage option *roughly* equates to FCC-hh@100 TeV

...process dependent statement!

pp @ 100 TeV	$\mu\mu$ @ 10 TeV
‣ expand reach to coloured exotics (SUSY...)	‣ 2nd generation specific new physics
‣ multi-Higgs in WBF and GF	‣ a *W* collider!
‣ WBF + multi-boson in many channels	☛ fine-grained picture of EW/*H* sector
‣ challenging environment: QCD/pile-up...	☛ unitarisation, *H* off-shellness, ...
	☛ elw. Sudakovs...

See C Englert's talk!

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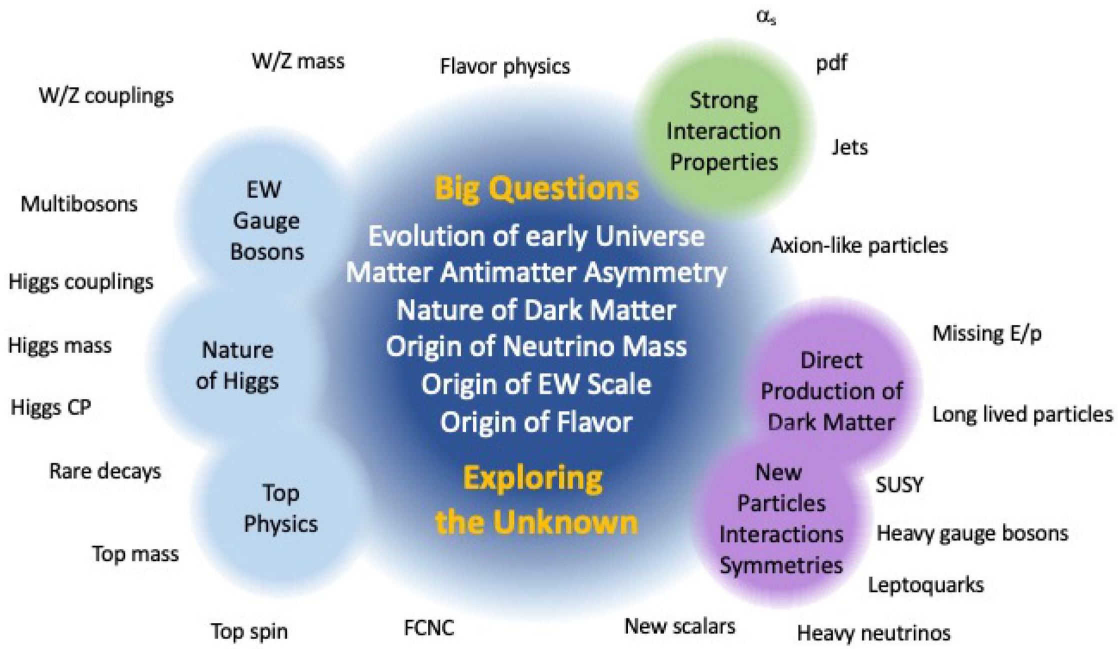
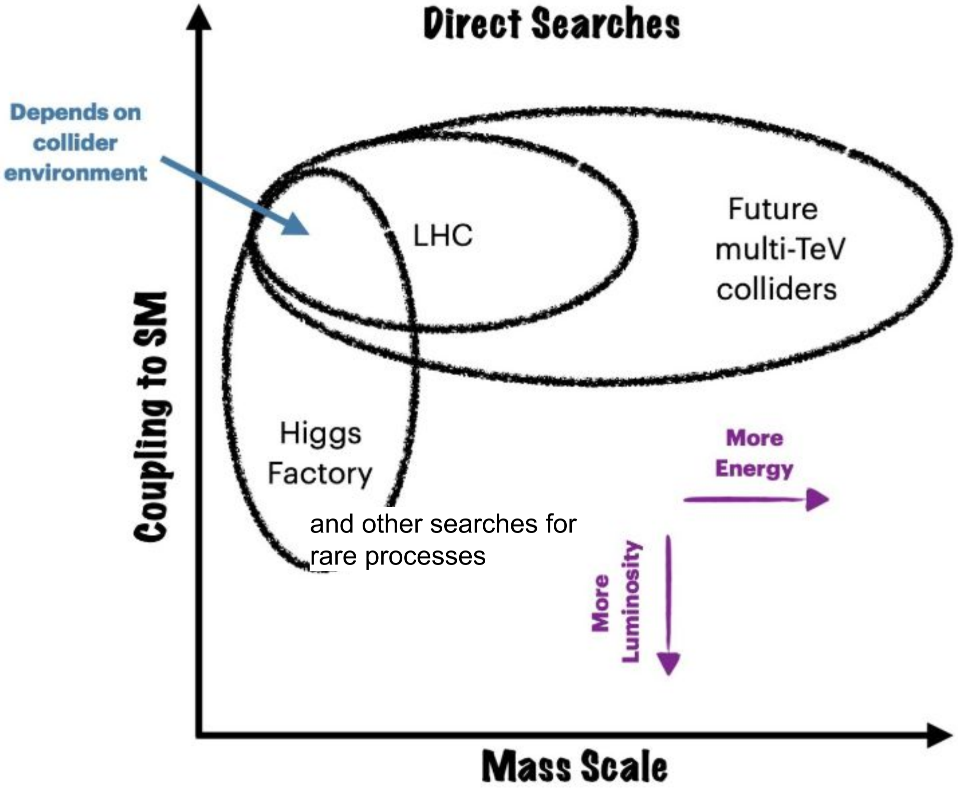
Why collider experiments?

Collider experiments allow you to sample a **huge space of theories** with **one experimental setup**!



Very useful if you don't know **where to look**...

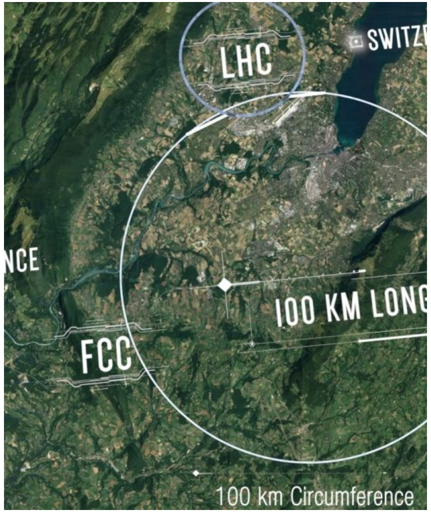
Why 10 TeV pCM?



Collider Concepts

FCChh

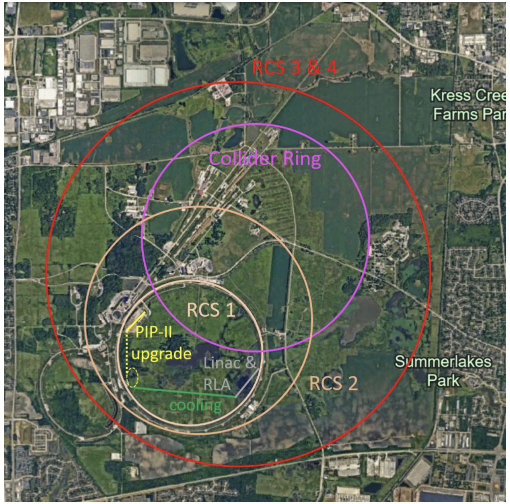
- Mostly existing technologies in a big (~100 km) tunnel.
- Potential e^+e^- collider as first stage.
- Alternatively the SppC in China.



Muon Collider

- Precision of a lepton collider with energy reach of a hadron collider.
- Significant accelerator R&D needed.
- No official site.

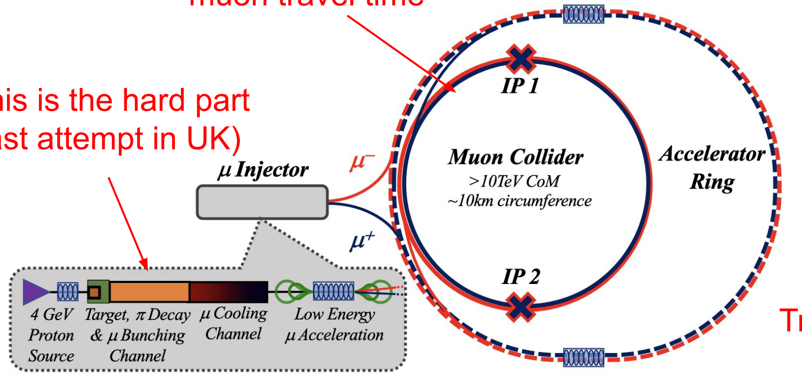
P5 report mentions Fermilab…



Muon Collider: Accelerator Complex

Compact ring to minimize muon travel time

This is the hard part (last attempt in UK)



C Rogers this morning

Scale as $1/s^2$

Triggerless

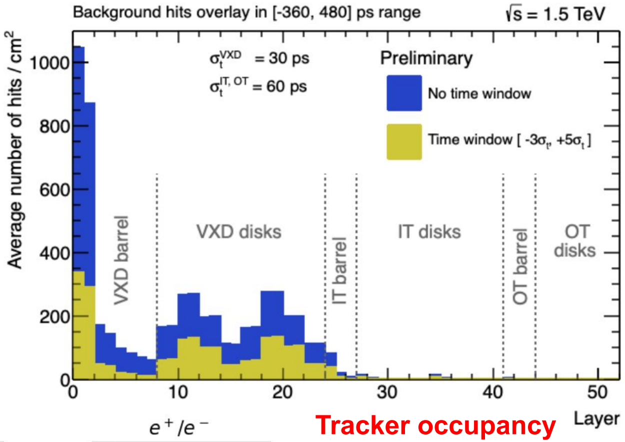
			Energy Staging		Luminosity Staging	
Parameter	Symbol	unit	Scenario 1		Scenario 2	
			Stage 1	Stage 2	Stage 1	Stage 2
Centre-of-mass energy	E_{cm}	TeV	3	10	10	10
Target integrated luminosity	$\int \mathcal{L}_{\mathrm{target}}$	ab^{-1}	1	10	10	
Estimated luminosity	$\mathcal{L}_{\mathrm{estimated}}$	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	2.1	21	tbc	14
Collider circumference	C_{coll}	km	4.5	10	15	15
Collider arc peak field	B_{arc}	T	11	16	11	11
Luminosity lifetime	N_{turn}	turns	1039	1558	1040	1040
Muons/bunch	N	10^{12}	2.2	1.8	1.8	1.8
Repetition rate	f_{r}	Hz	5	5	5	5
Beam power	P_{coll}	MW	5.3	14.4	14.4	14.4
RMS longitudinal emittance	$\varepsilon_{\parallel}$	eVs	0.025	0.025	0.025	0.025
Norm. RMS transverse emittance	$\varepsilon_{\perp}$	µm	25	25	25	25
IP bunch length	σ_z	mm	5	1.5	tbc	1.5
IP betafunction	β	mm	5	1.5	tbc	1.5
IP beam size	σ	µm	3	0.9	tbc	0.9
Protons on target/bunch	N_{p}	10^{14}	5	5	5	5
Protons energy on target	E_{p}	GeV	5	5	5	5
BS photons	$N_{\mathrm{BS},0}$	per muon	0.075	0.2	tbc	0.2
BS photon energy	$E_{\mathrm{BS},0}$	MeV	0.016	1.6	tbc	1.6
BS loss/lifetime (2 IP)	$E_{\mathrm{BS,tot}}$	GeV	0.002	1.0	tbc	0.67

IMCC Interim Report

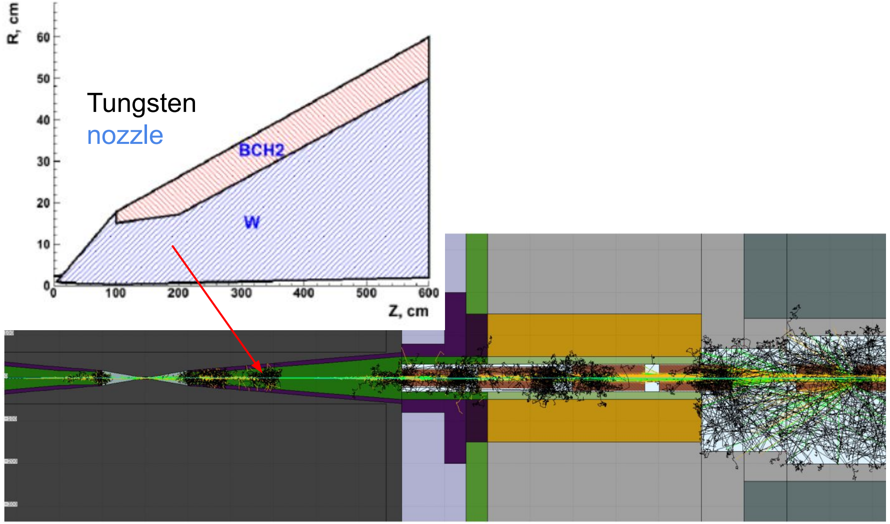
Muon Collider: Beam Induced Background

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

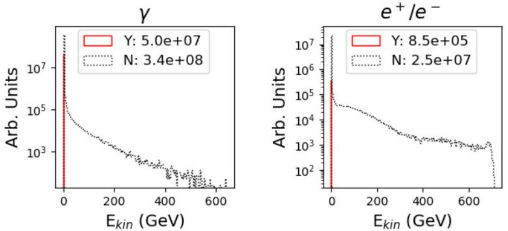
Tracker occupancy after timing cuts.

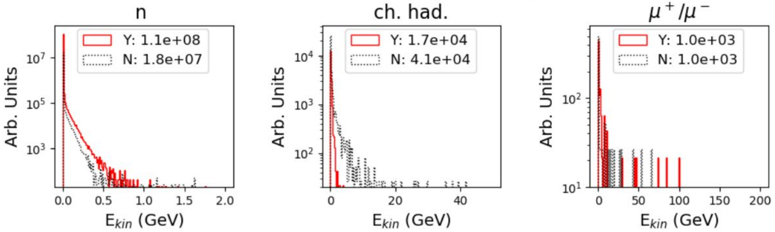


Tracker occupancy 10x that of HL-LHC!



FLUKA simulation of BIB before reaching the detector.





Particle energy spectra with (Y) and without (N) nozzle.

Muon Collider: Detector Concept

hadronic calorimeter

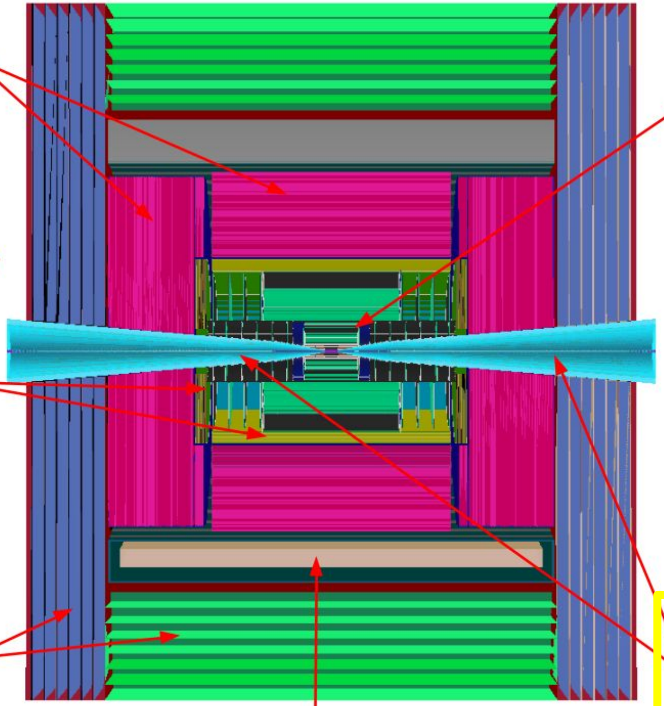
- 60 layers of 19-mm steel absorber + plastic scintillating tiles;
- 30x30 mm^2 cell size;
- 7.5 λ_I.

electromagnetic calorimeter

- 40 layers of 1.9-mm W absorber + silicon pad sensors;
- 5x5 mm^2 cell granularity;
- 22 X_0 + 1 λ_I.

muon detectors

- 7-barrel, 6-endcap RPC layers interleaved in the magnet's iron yoke;
- 30x30 mm^2 cell size.



superconducting solenoid (3.57T)

4D tracking with 30-60 ps resolution.

- Vertex Detector:
  - double-sensor layers (4 barrel cylinders and 4+4 endcap disks);
  - 25x25 μm^2 pixel Si sensors.
- Inner Tracker:
  - 3 barrel layers and 7+7 endcap disks;
  - 50 μm x 1 mm macro-pixel Si sensors.
- Outer Tracker:
  - 3 barrel layers and 4+4 endcap disks;
  - 50 μm x 10 mm micro-strip Si sensors.

shielding nozzles

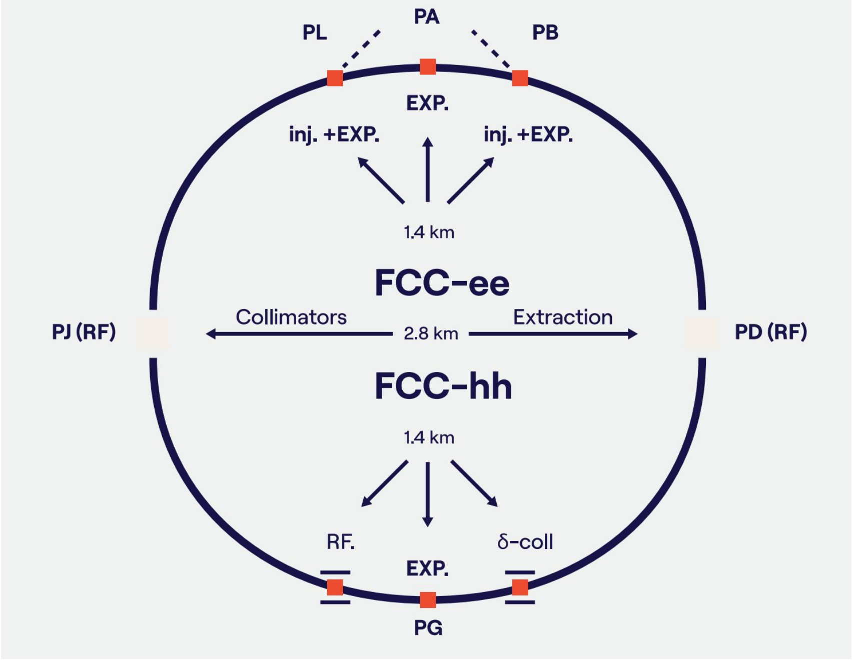
- Tungsten cones + borated polyethylene cladding.

Could be instrumented?

S Gibson this morning

FCC-hh: Accelerator Complex

The LHC tunnel could be used for injection at 3.3 TeV.



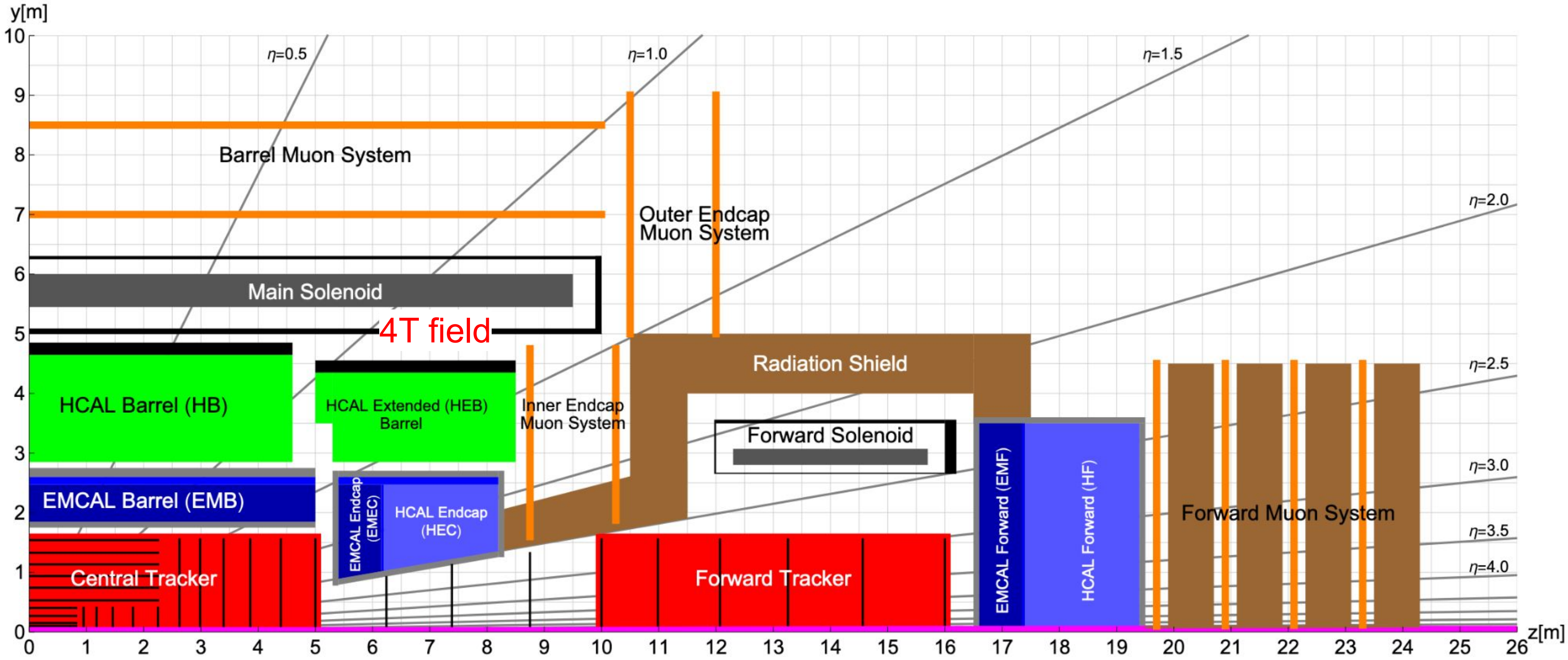
Parameter	FCC-hh		HL-LHC	LHC
collision energy cms [TeV]	80-116		14	14
dipole field [T]	14 (Nb_3Sn) – 20 (HTS/Hybrid)		8.33	8.33
circumference [km]	90.7		26.7	26.7
beam current [A]	0.5		1.1	0.58
bunch intensity [10^{11}]	1	1	2.2	1.15
bunch spacing [ns]	25	25	25	25
synchr. rad. power / ring [kW]	1020-4250		7.3	3.6
SR power / length [W/m/ap.]	13-54		0.33	0.17
long. emit. damping time [h]	0.77-0.26		12.9	12.9
beta* [m]	1.1	0.3	0.15 (min.)	0.55
normalized emittance [μm]	2.2		2.5	3.75
peak luminosity [10^{34} $cm^{-2}s^{-1}$]	5	30	5 (lev.)	1
events/bunch crossing	170	1000	132	27
stored energy/beam [GJ]	6.1-8.9		0.7	0.36
integrated luminosity [fb^{-1}]	20000		3000	300

Main challenge is high field magnets.

Discuss: At what level does FCChh imply an FCCee?

Delphes card available for quick studies.

FCC-hh: Detector Concept

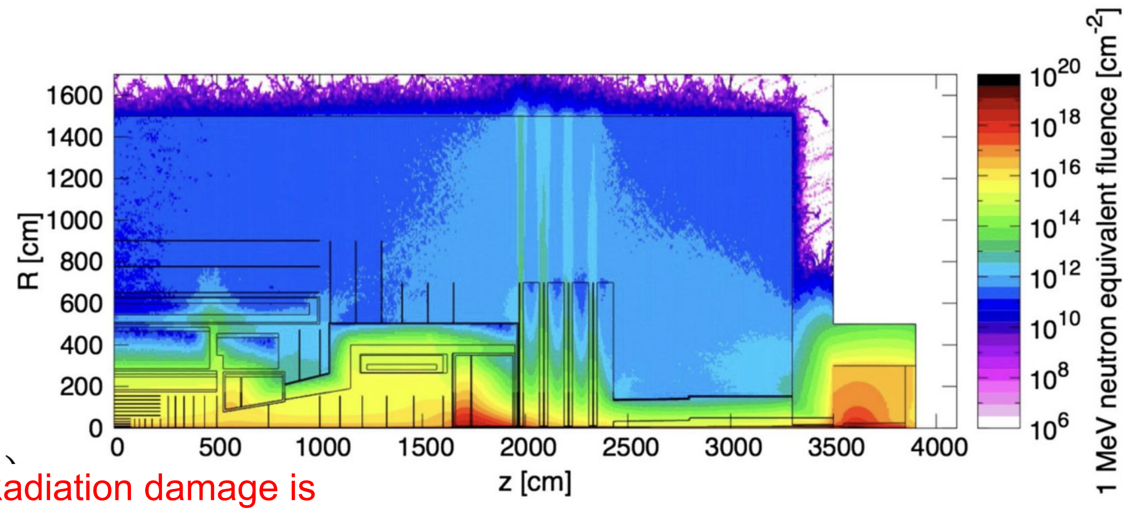


Roughly same size as ATLAS.

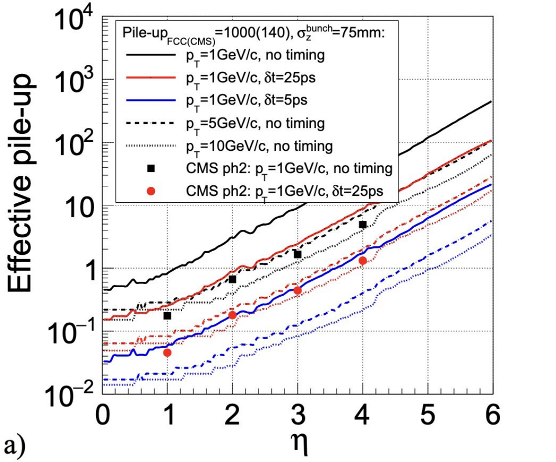
Increased focus on forward object (ie: tracking up to |η|<6)

- Needed for pile-up rejection and VBF processes.

FCC-hh: Pile-up of 1000

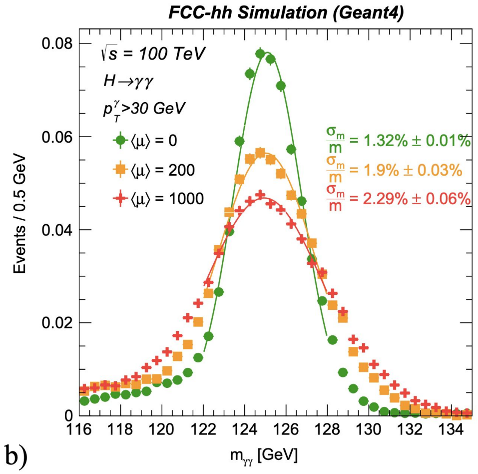


Radiation damage is
100x that of HL-LHC (and μC)



a)

5 ps timing required for forward tracker.



b)

Object reconstruction studies are very advanced.
However **studies with pile-up 1000 are important**.

Impact on calorimeter can be managed.

Detector R&D

Very similar requirements for both machines.

** Sorry for tracking bias.

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

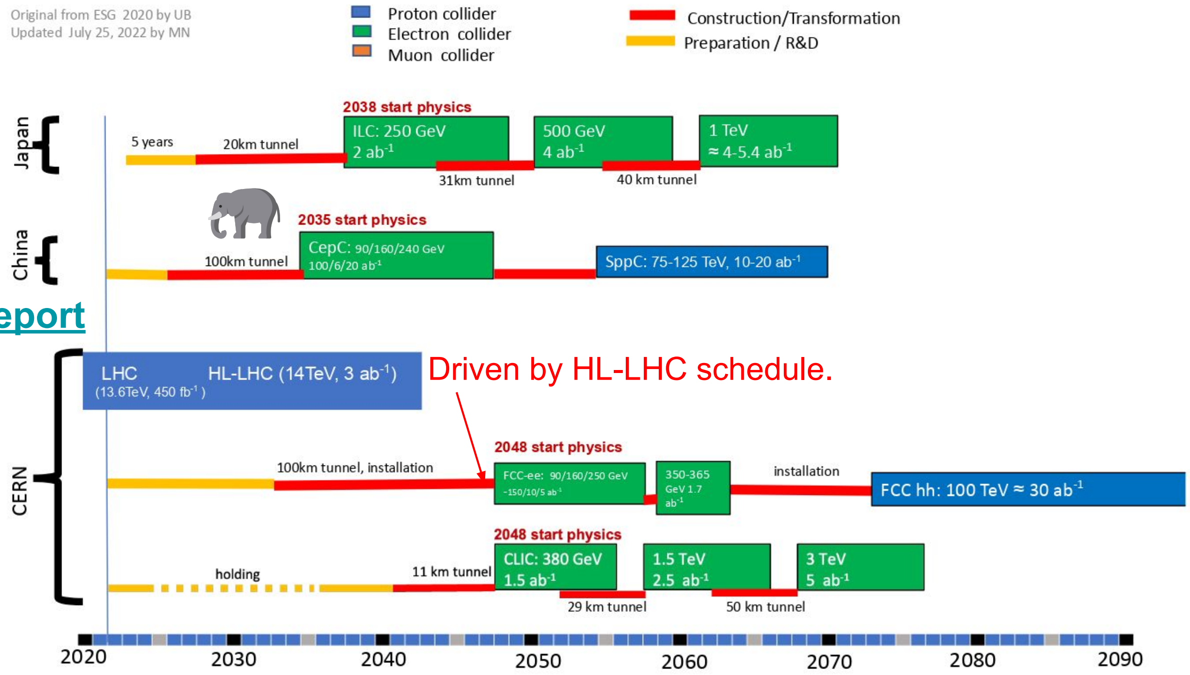
"Technical" Start Date of Facility (This means, where the dates are not known, the earliest technically feasible start date is indicated - such that detector R&D readiness is not the delaying factor)				< 2030					2030-2035					2035 - 2040	2040-2045		> 2045		
				Panda 2025	CBM 2025	HIKE 2030 ☹	Belle 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 ~2045
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

Technology demonstrators?

4D tracking, high data rates, rad hard

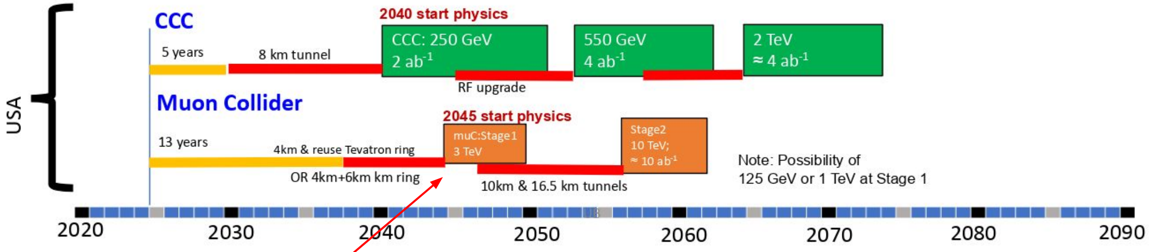
Timelines

Source:
[Snowmass 2021 Energy Frontier Report]



Add your own uncertainties!

Estimated cost of FCChh is *2.5x* μC.



Will slip 1 year / 1 year without R&D funding.

International Considerations

P5 Panel Report

US has shown strong interest in a μC, but nothing decisive.

Support a comprehensive effort to develop the resources—theoretical, computational and technological—essential to our 20-year vision for the field. This includes an aggressive R&D program that, while technologically challenging, could yield revolutionary accelerator designs that chart a realistic path to a 10 TeV parton center-of-momentum (pCM) collider. In particular, the muon collider option builds on Fermilab strengths and capabilities and supports our aspiration to host a major collider facility in the US.

Status of the CEPC Project (ICHEP 2024)

CEPC Planning and Development

- **CAS is planning for the 15th 5-year plan for large science projects, and a steering committee has been established, chaired by the president of CAS.**
- **High energy physics and nuclear physics is one of eight groups (fields).**
- **CEPC is ranked No. 1, by every committee (2 domestic and 1 international).**
- **A final report was submitted to CAS for consideration, this process is within CAS, and the following national selection process will be decisive.**

Chinese 100 TeV pp collider is not constrained by HL-LHC timelines.

Go directly to FCChh?

Final Thoughts

Contact Andy, Sarah or I if you would like to get involved!

- **100 TeV pp and 10 TeV μμ colliders *physics competitive by design*.**
- Accelerator: μC requires significant R&D for novel collider.
  - FCChh does require much larger infrastructure.
- Detector: high pile-up makes FCChh environment more challenging.
  - μC has similar challenges due to BIB, but “easier”.
- FCChh studies are advanced, but μC is ramping up.
  - Improved understanding of pile-up/BIB is important for predictions.
- Don’t forget the non-scientific considerations.

Further Reading:

- Future Circular Collider Conceptual Design Report Volume 3
- Towards a muon collider