MuCol

LIP

INSTITUTO SUPERIOR TÉCNICO

International MUON Collider Collaboration

The Muon Collider

challenges and perspectives

European strategy discussion

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January 20, 2025

Co-Funded by the European Union (EU): MuCol HORIZON-INFRA-2022-DEV-01-01

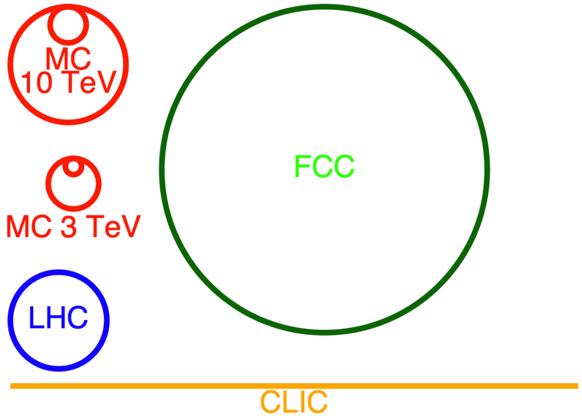
Why a muon collider?

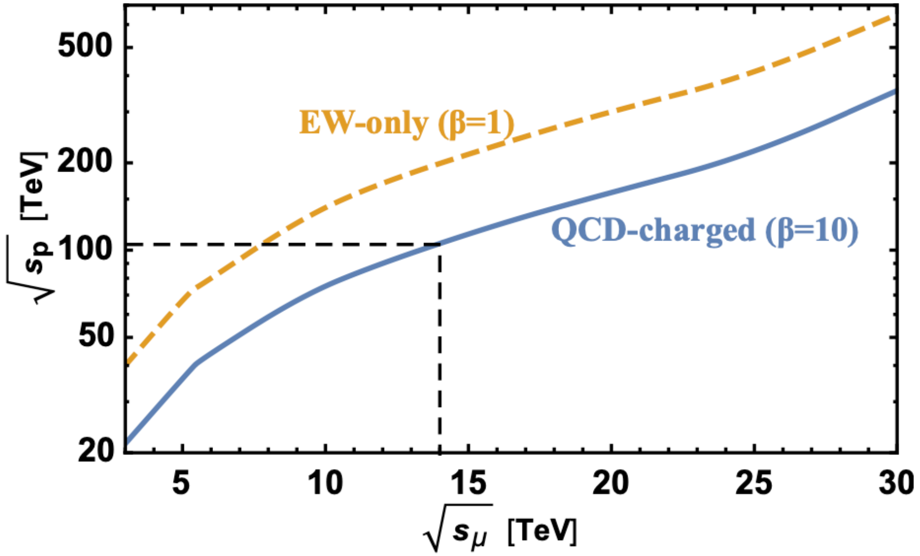
- Muons are elementary particles
  - – All the energy is used in the collision
- Muons emit little synchrotron radiation
  - – Acceleration to many TeV is possible

- In a Muon Collider, luminosity-to-power ratio improves substantially with energy
  - – Small footprint and better energy efficiency

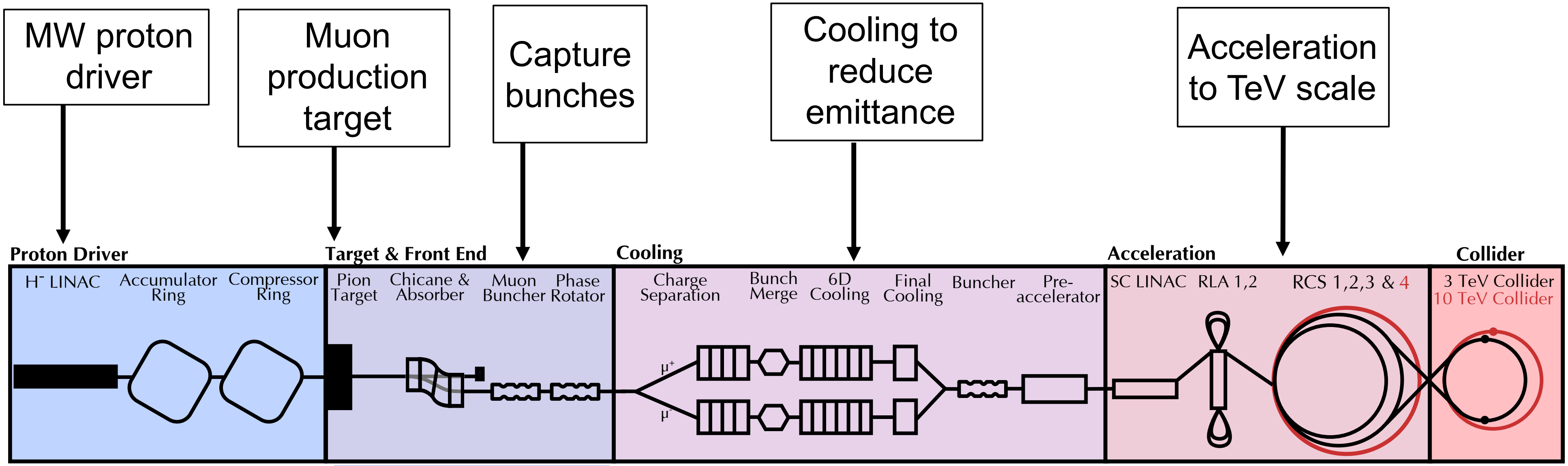
- Goal is a 10 TeV collider
  - – Staging with 3 TeV
- Aim to have 2 detectors

⇒ Muon Collider combines precision physics and high-discovery potential





Muon Collider Overview


MW proton driver

Muon production target

Capture bunches

Cooling to reduce emittance

Acceleration to TeV scale

Short, intense proton bunch

Protons produce pions which decay into muons which are captured

Ionisation cooling of muons in matter

Acceleration to collision energy

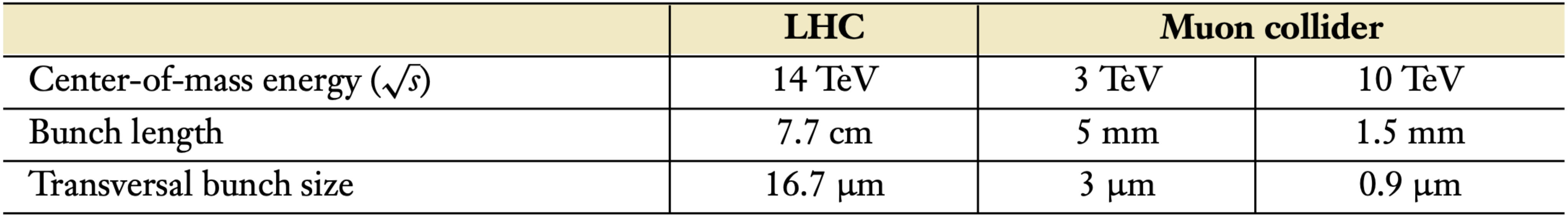
Collision

Luminosity

$$\mathcal{L} = \frac{n_c f N^+ N^-}{4\pi\sigma_x\sigma_y}$$

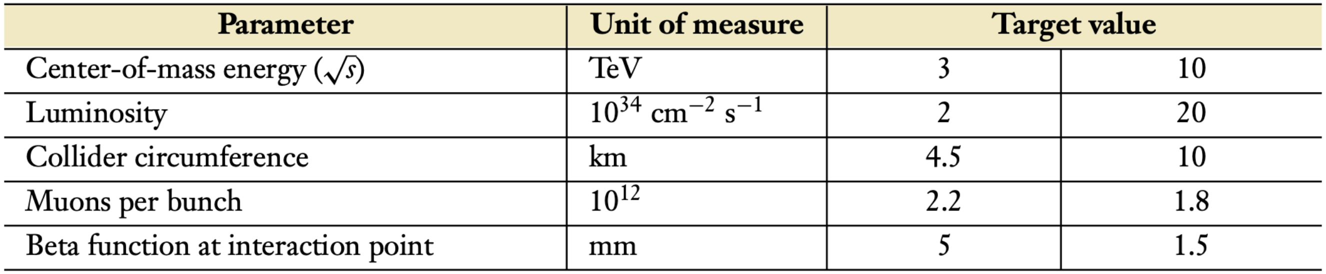
- High charge per muon bunch
  - Requires **powerful** proton driver, **high-yield** target, **fast** acceleration
- Small transverse beam size
  - Requires beam with **low** transverse emittance
  - Requires **strong** focusing magnets @IR
- Many collisions
  - Requires **strong** dipole magnets to minimize collider radius

Design parameters

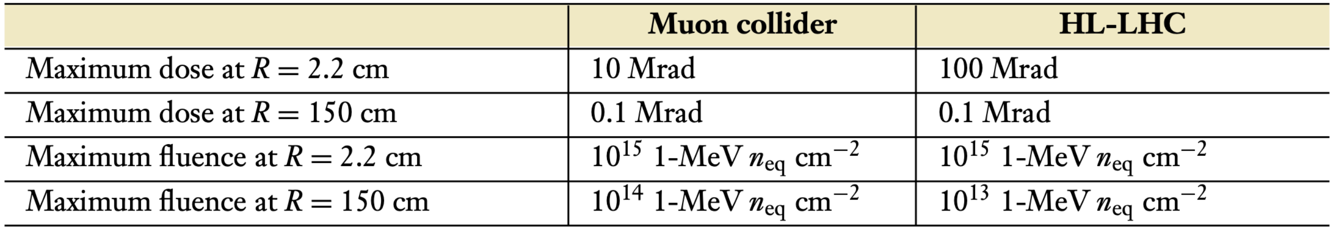


	LHC	Muon collider	
Center-of-mass energy ($\sqrt{s}$)	14 TeV	3 TeV	10 TeV
Bunch length	7.7 cm	5 mm	1.5 mm
Transversal bunch size	16.7 µm	3 µm	0.9 µm

Comparison to LHC/HL-LHC



Parameter	Unit of measure	Target value	
Center-of-mass energy ($\sqrt{s}$)	TeV	3	10
Luminosity	10^{34} cm^{-2} s^{-1}	2	20
Collider circumference	km	4.5	10
Muons per bunch	10^{12}	2.2	1.8
Beta function at interaction point	mm	5	1.5



	Muon collider	HL-LHC
Maximum dose at $R = 2.2$ cm	10 Mrad	100 Mrad
Maximum dose at $R = 150$ cm	0.1 Mrad	0.1 Mrad
Maximum fluence at $R = 2.2$ cm	10^{15} 1-MeV n_{eq} cm^{-2}	10^{15} 1-MeV n_{eq} cm^{-2}
Maximum fluence at $R = 150$ cm	10^{14} 1-MeV n_{eq} cm^{-2}	10^{13} 1-MeV n_{eq} cm^{-2}

A broad physics program

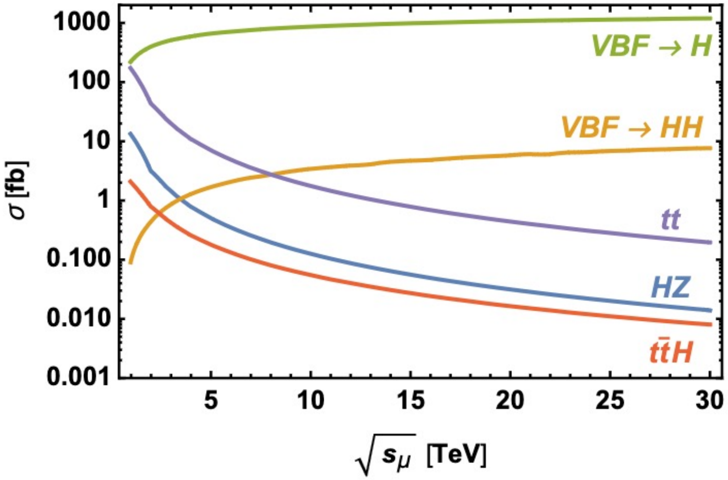
Rep.Prog.Phys.85 (2022)084201, Ann.Rev.Nucl.Part.Sci 74(2024)233)

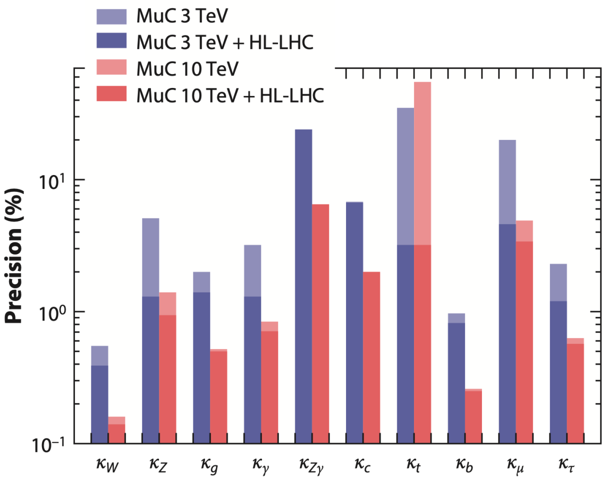
Multi-TeV lepton collisions enable a broad physics program

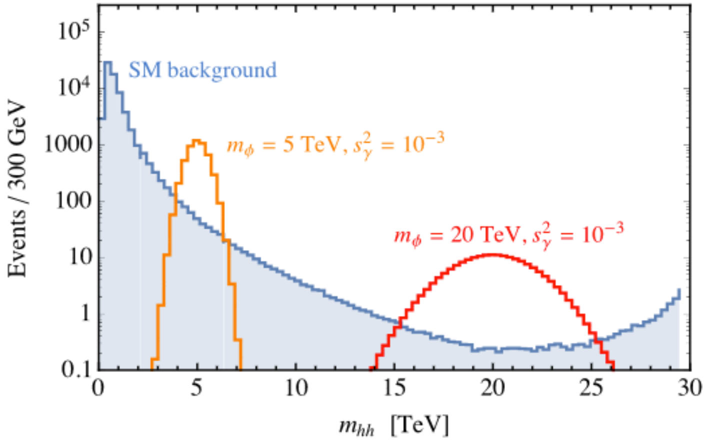
- Direct and indirect new physics searches
- Precise SM measurements in unexplored energy range
- Higgs boson couplings to fermions & bosons, trilinear and quartic couplings (λ_3,λ_4)

⇒ Determination of Higgs potential

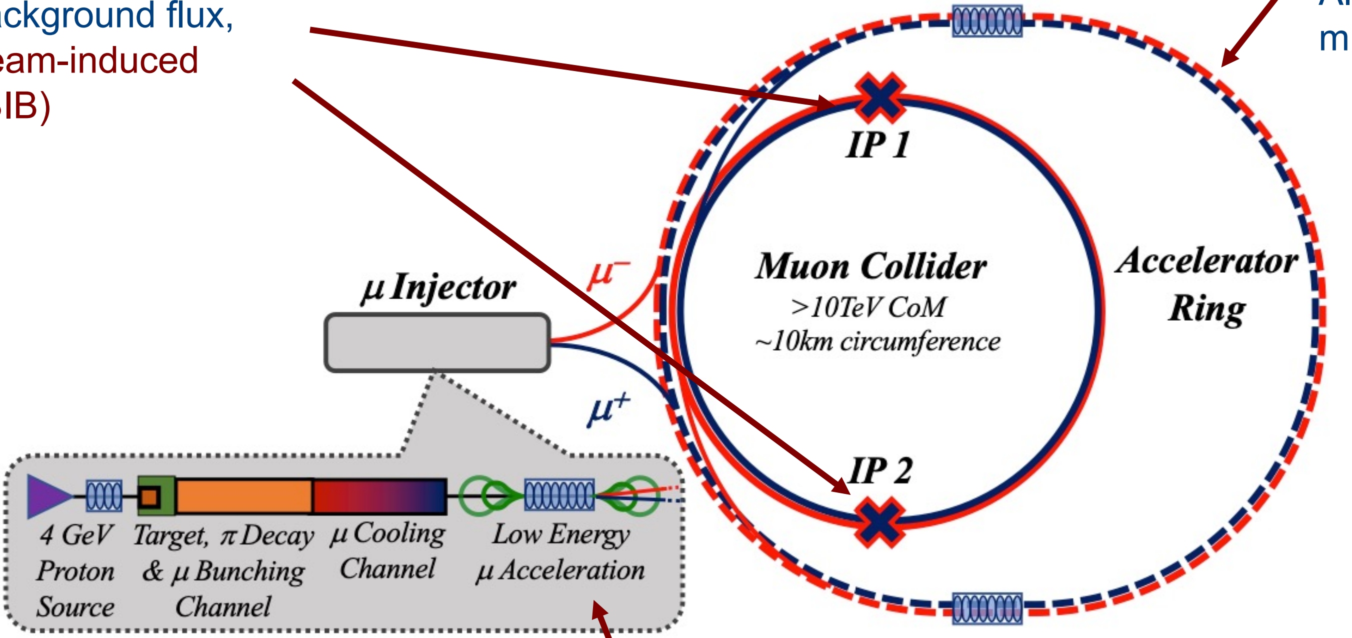
$$V(h) = \frac{1}{2}m_h^2 h^2 + \lambda_3 v h^3 + \frac{1}{4}\lambda_4 h^4$$







Key challenges



Experimental apparatus to deal with a huge background flux, mainly from beam-induced background (BIB)

Machine background

All machine elements must be properly shielded

Neutrino flux

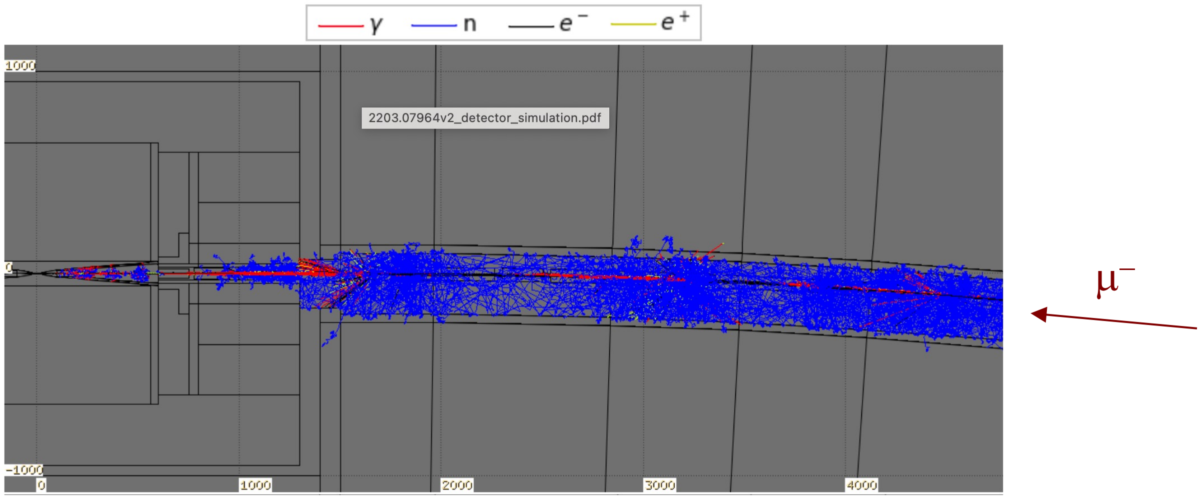
Intense and highly collimated neutrino beams even far from the collider complex may cause severe radiation hazard

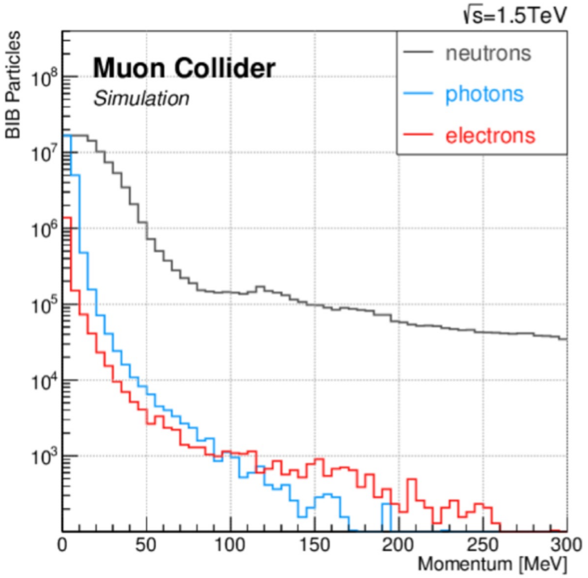
Muon beam production and cooling, i.e. reduction of transverse phase-space volume by more than O(10^5) is crucial

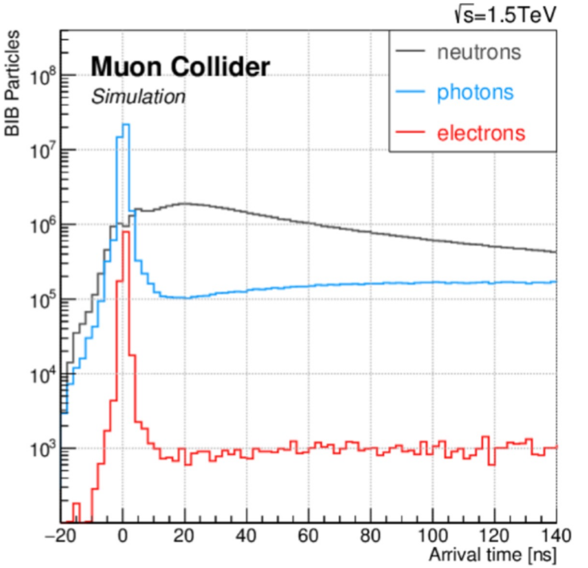
Muon beams must be prepared and accelerated as quick as possible to exploit relativistic time dilation in the lab system (t_μ=105ms in the lab @5TeV)

Background from muon decays

arXiv:2203.07964, arXiv:2407.12450







- Beam induced background (BIB) from muon decays products interacts with machine components and shields inside the detector (nozzles)
- Soft particles are mostly out-of-time wrt bunch crossing
- $\sim 10^8$ photons, $\sim 10^7$ neutrons, $\sim 10^5$ e^+/e^- enter the detector at every bunch crossing in [-1,15] ns window
- Extensive simulation studies performed

IMCC

- R&D studies are coordinated by the International Muon Collider Collaboration (IMCC), established at CERN in 2022 as a result of the recommendations of ESPP2020
- Main goals
  - Assess and develop muon collider concept
  - Identify potential sites
  - Develop R&D roadmap towards the collider
  - Develop an initial muon collider stage that could start operations ~2050

International
MUON Collider
Collaboration

muoncollider.web.cern.ch

- Fruitful collaboration with US HEP community
  - Studies began where US MAP program (2010-2014) left
- Outcome of US Snowmass 2021 very favorable. P5 final report recommends pursuing R&D on a machine with *partonic center of mass energy of 10 TeV* and above

IMCC partners

IEIO	**CERN**
FR	**CEA-IRFU**
	CNRS-LNCMI
	Mines St-Etienne
DE	DESY
	Technical University of Darmstadt
	University of Rostock
	KIT
UK	**RAL**
	UK Research and Innovation
	University of Lancaster
	University of Southampton
	University of Strathclyde
	University of Sussex
	Imperial College London
	Royal Holloway
	University of Huddersfield
	University of Oxford
	University of Warwick
	University of Durham
	University of Birmingham
	University of Cambridge

IT	**INFN**
	INFN, Univ., Polit. Torino
	INFN, LASA, Univ. Milano
	INFN, Univ. Padova
	INFN, Univ. Pavia
	INFN, Univ. Bologna
	INFN Trieste
	INFN, Univ. Bari
	INFN, Univ. Roma 1
	ENEA
	INFN Frascati
	INFN, Univ. Ferrara
	INFN, Univ. Roma 3
	INFN Legnaro
	INFN, Univ. Milano Bicocca
	INFN Genova
	INFN Laboratori del Sud
	INFN Napoli
Mal	**Univ. of Malta**
EST	**Tartu University**
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SE	**ESS**
	University of Uppsala
NL	**University of Twente**
FI	**Tampere University**
LAT	**Riga Technical University**
CH	**PSI**
	University of Geneva
	EPFL
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AU	**HEPHY**
	TU Wien
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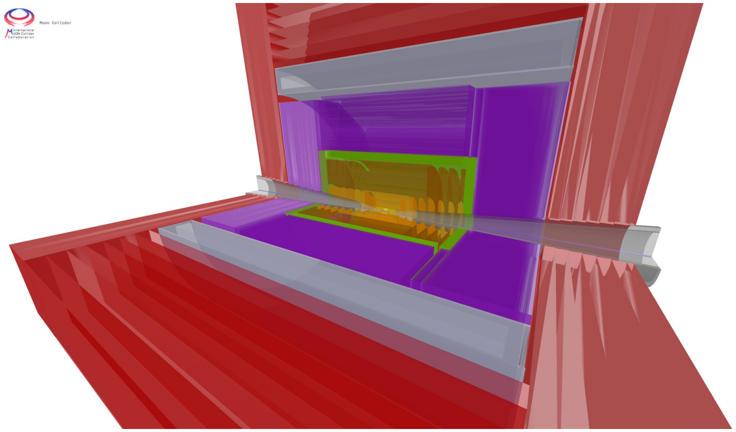
	CIEMAT
	ICMAB
China	***Sun Yat-sen University***
	IHEP
	Peking University
	Inst. Of Mod. Physics, CAS
KO	**Kyungpook National University**
	Yonsei University
	Seoul National University
India	***CHEP***

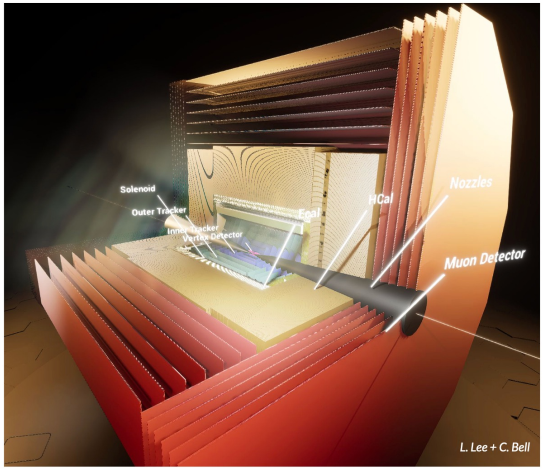
US	**Iowa State University**
	University of Iowa
	Wisconsin-Madison
	University of Pittsburgh
	Old Dominion
	Chicago University
	Florida State University
	RICE University
	Tennessee University
	MIT Plasma science center
	Pittsburgh PAC
	Yale
	Princeton
	Stony Brook
	Stanford/SLAC
	…
DoE labs	FNAL
	LBNL
	JLAB
	BNL
Brazil	***CNPEM***

Detector concepts

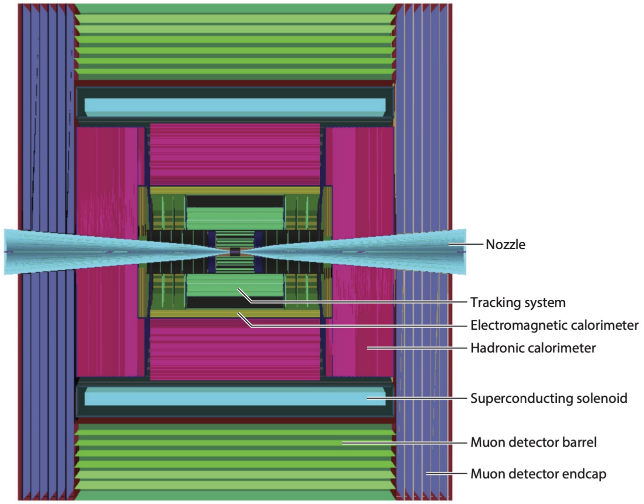
MUSIC
(MUon System for Interesting Collisions)



MAIA
(Muon Accelerator Instrumented Apparatus)



L. Lee + C. Bell



Two detector concepts being developed

- Required resolutions
- MDI and background suppression
- …

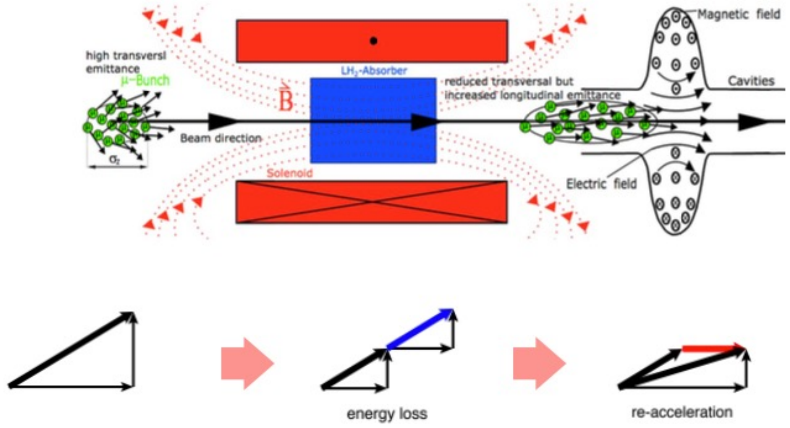
Increasing efforts for further improvements and exploiting AI, ML and new technologies

- Synergies with HL-LHC developments
- Close integration with ECFA detector R&D

Muon cooling demonstrator

- First step towards a muon collider is to build a demonstrator facility
  - Demonstrate reduction of beam emittance
- Test cooling cell technology in operational environment
- Study and test production target
- Develop new beam monitoring instrumentation
- Depending on available resources, the muon beam could be accelerated for muon and neutrino physics

Ionization cooling principle



Muons have large transverse momenta at production.

Crossing an absorber, muons loose energy in longitudinal and transverse directions.

Muon acceleration in the longitudinal direction.

Summary

- MC offers a unique opportunity for energy frontier with high luminosity
- No fundamental showstoppers found
- Highly motivated community
- Technology needs a strong R&D program
  - Complete end-to-end simulation
  - Develop cooling technology (klystron, cavities, HTS solenoids, etc) from single to multiple cells
  - Dedicated HTS magnet program
  - Progress towards CDR/TDR (~2030) for the demonstrator

⇒ Muon Collider combines precision physics and high-discovery potential

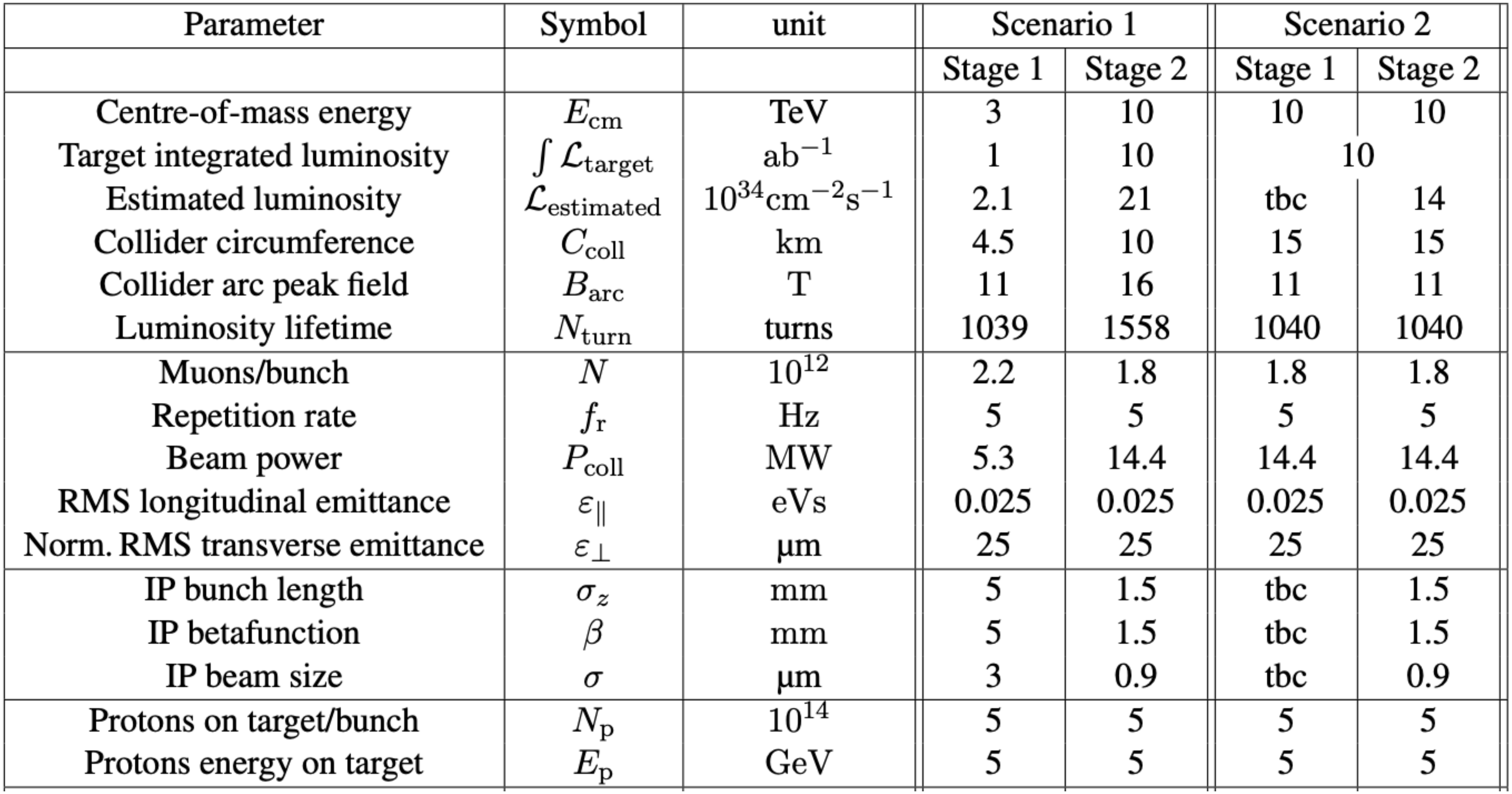
Numerous opportunities for everyone to get involved!

MuCol

INFRA-2022-DEV:
A Design Study for
a Muon Collider
complex at 10 TeV

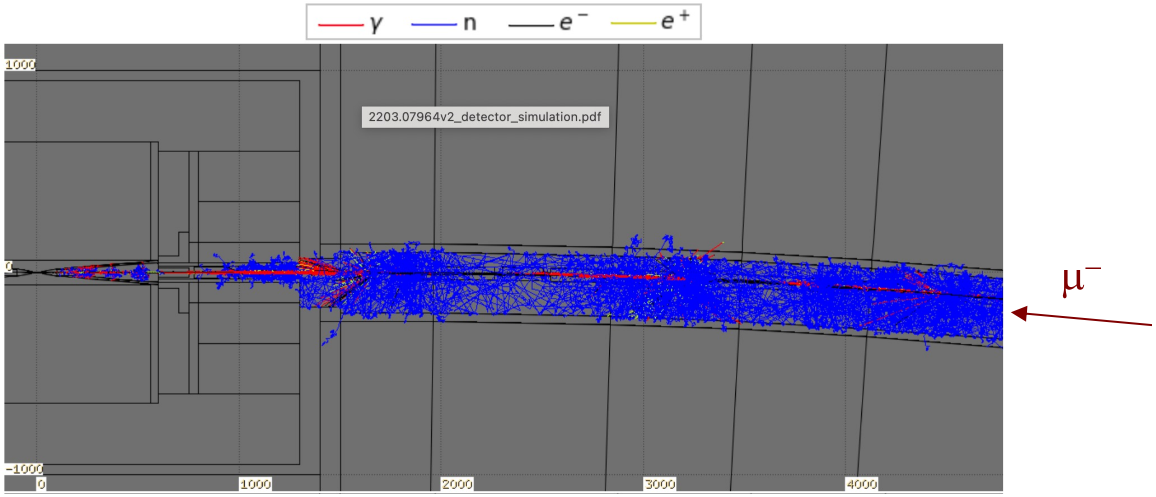
backup

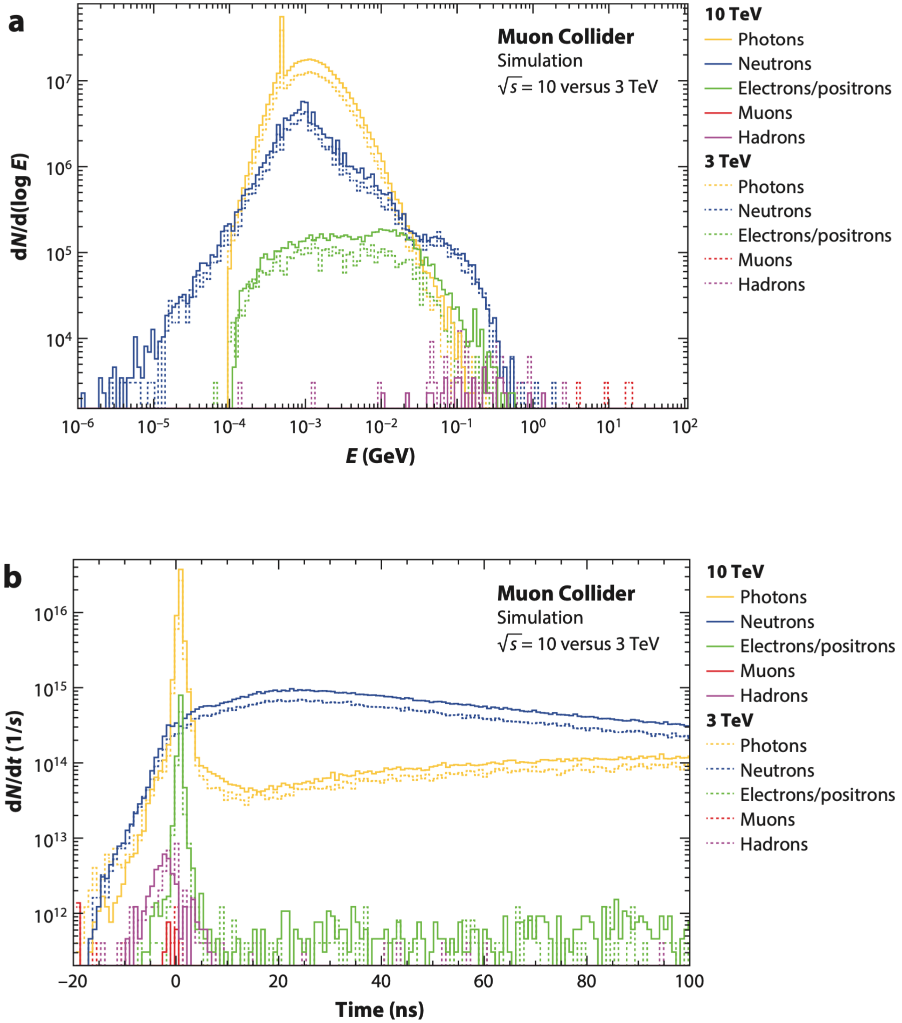
Design parameters: Staging



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	$\int \mathcal{L}_{\text{target}}$	ab^{-1}	1	10	10	
Estimated luminosity	$\mathcal{L}_{\text{estimated}}$	$10^{34}\text{cm}^{-2}\text{s}^{-1}$	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

Background from muon decays





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