The Muon Collider

Federico Meloni
DESY and University of Bern

2nd Hokkaido Workshop on Particle Physics at Crossroads
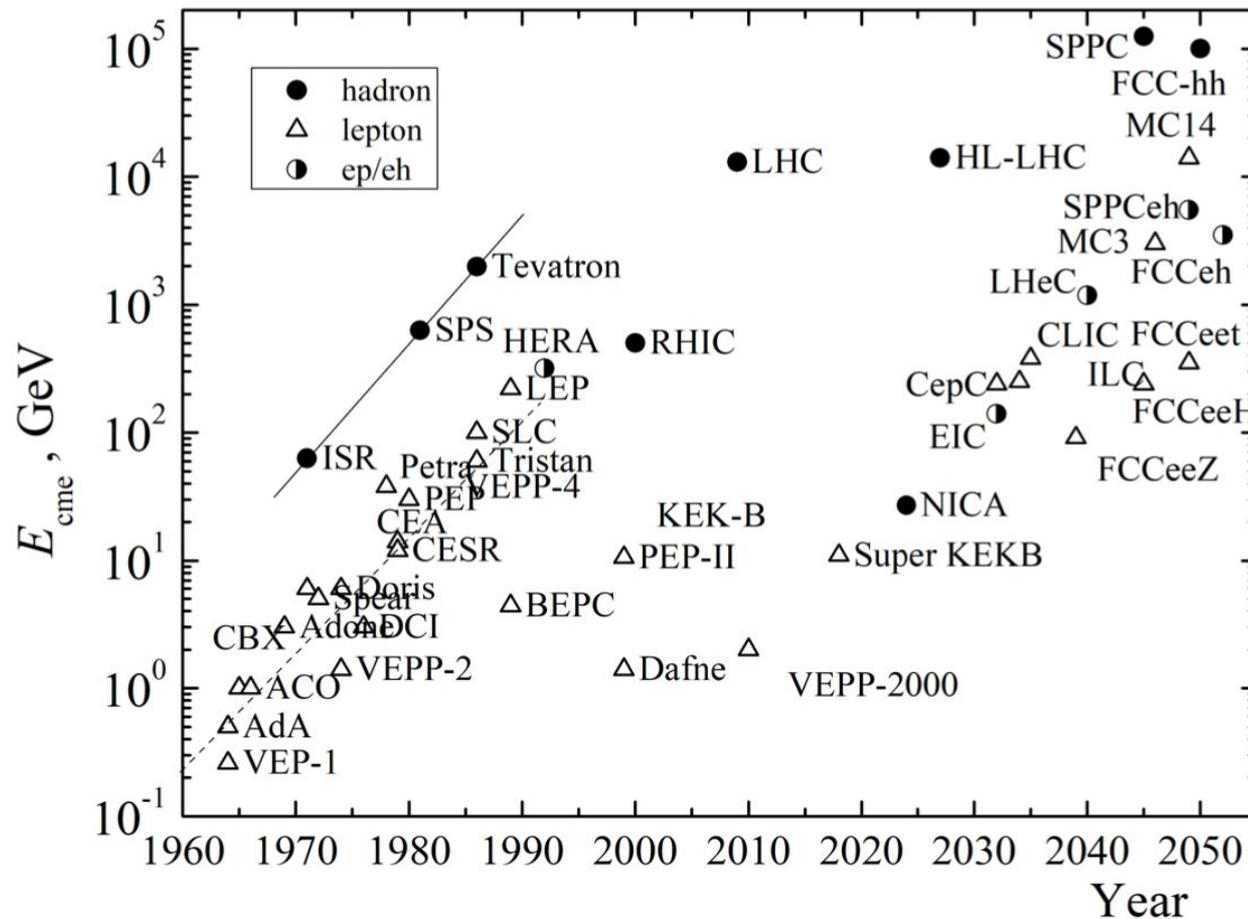03/03/2026

Colliders shaped modern particle physics

5 orders of magnitude in E$_{CM}$ in 6 decades (0.2 GeV → 14 TeV)!
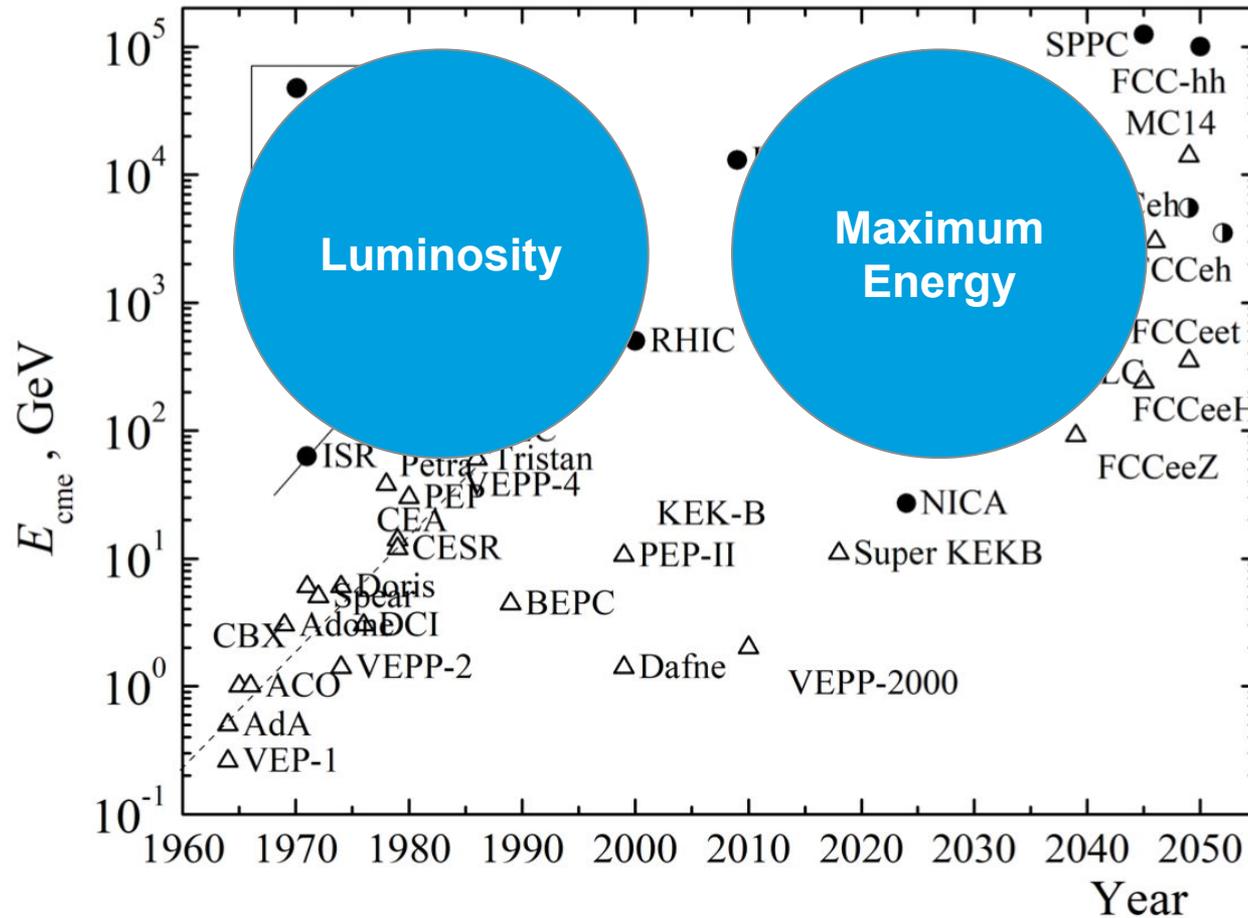
Development drivers

5 orders of magnitude in E_{CM} in 6 decades (0.2 GeV → 14 TeV)!

Development drivers

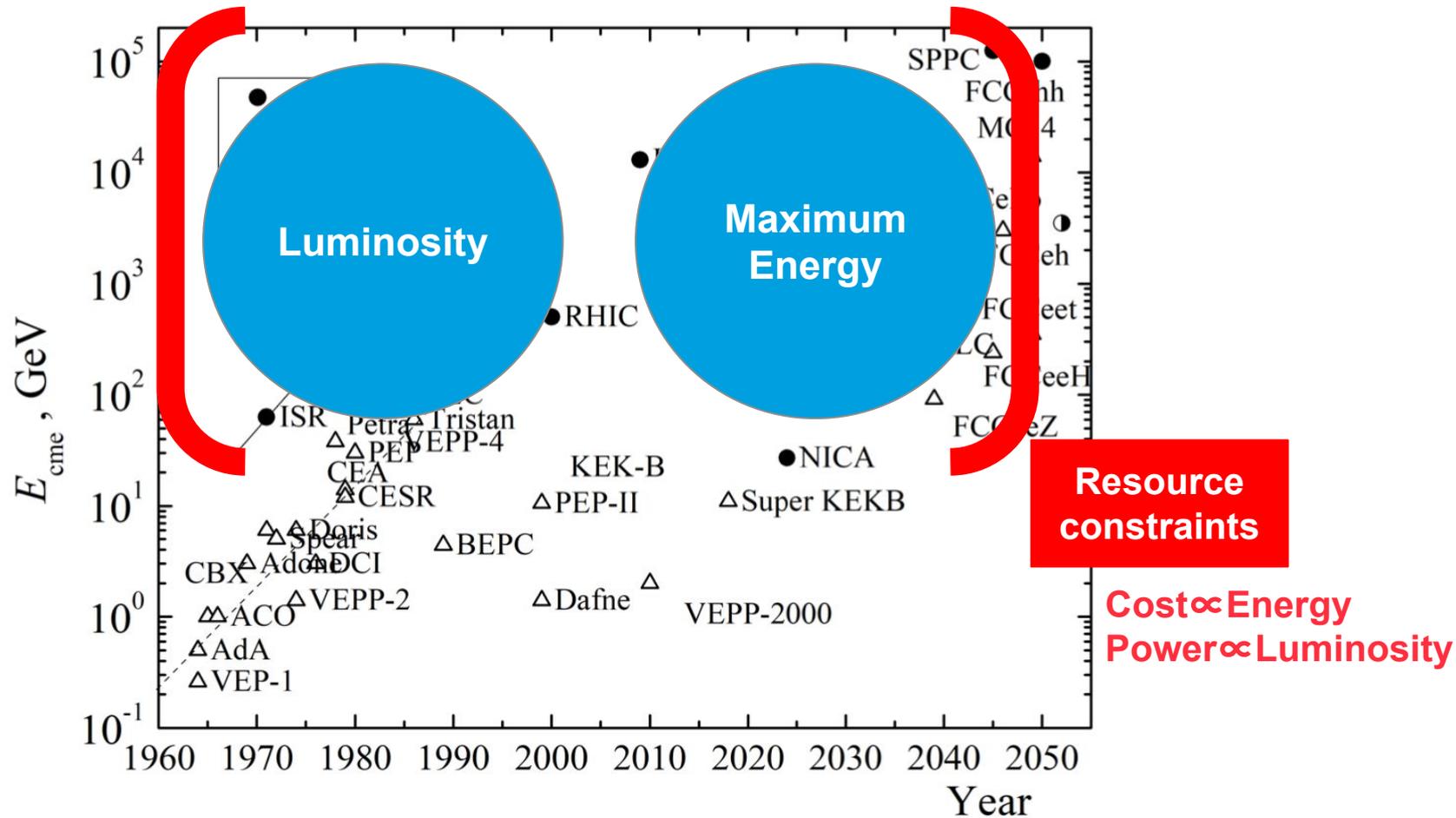**5 orders of magnitude in E_{CM} in 6 decades (0.2 GeV → 14 TeV)!**

Development drivers

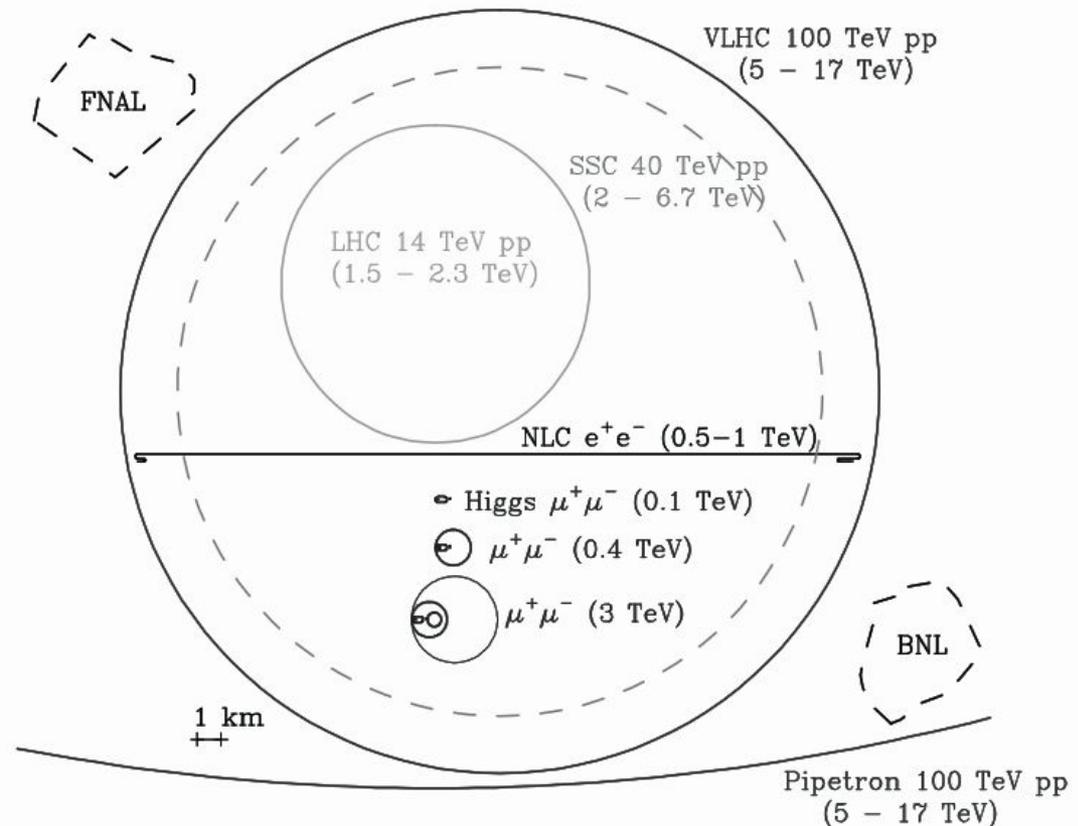**5 orders of magnitude in E$_{CM}$ in 6 decades (0.2 GeV → 14 TeV)!**

Why muons?

Historically, we probed shorter distances with either precision or energy

Muon colliders blur this dichotomy

They promise the **most cost effective** and **power efficient** path towards 10 TeV collisions

Muons are *elementary* particles with a mass large enough to make *radiation negligible*

VLHC 100 TeV pp
(5 − 17 TeV)

FNAL

SSC 40 TeV pp
(2 − 6.7 TeV)

LHC 14 TeV pp
(1.5 − 2.3 TeV)

NLC e$^+$e$^-$ (0.5−1 TeV)

Higgs $\mu^+\mu^-$ (0.1 TeV)

$\mu^+\mu^-$ (0.4 TeV)

$\mu^+\mu^-$ (3 TeV)

BNL

1 km

Pipetron 100 TeV pp
(5 − 17 TeV)

Why are we excited?

A physics programme that is more than the sum of its parts:

- High available energy for new heavy particle production

$$\beta \equiv [\hat{\sigma}]_p / [\hat{\sigma}]_\mu$$

$\beta = 1$

$\beta = 10$

(axes: $\sqrt{s_p}$ [TeV] vs $\sqrt{s_\mu}$ [TeV])

Why are we excited?

A physics programme that is more than the sum of its parts:
- High available energy for new heavy particle production
- High available statistics for precise measurements
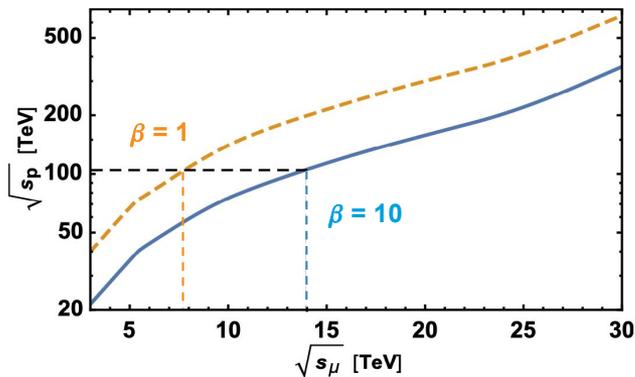
PRECISION

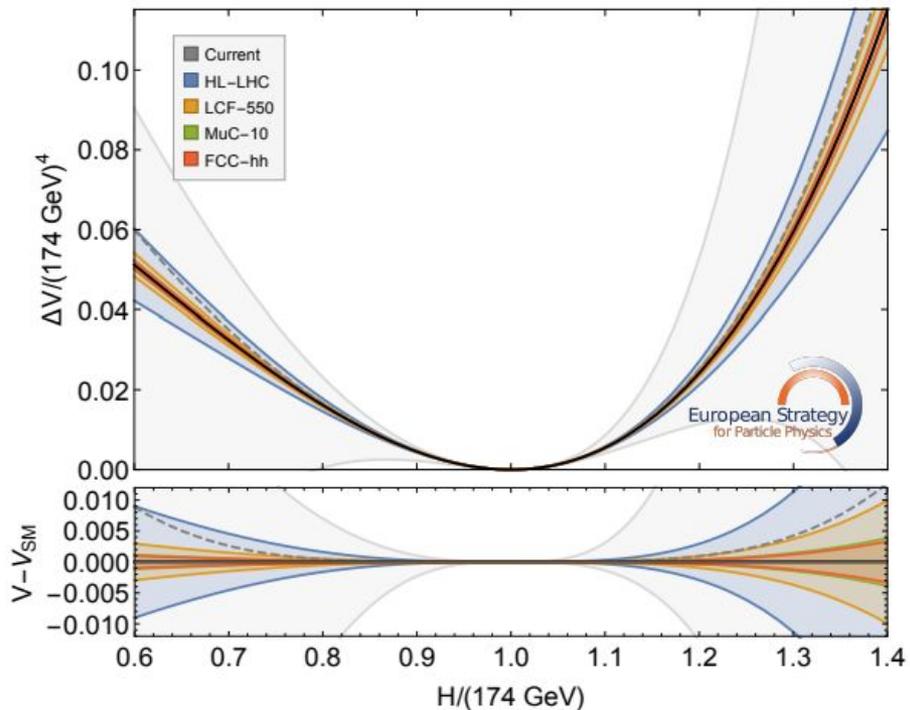**ENERGY**

Why are we excited?

A physics programme that is more than the sum of its parts:

- High available energy for new heavy particle production
- High available statistics for precise measurements
- Can measure processes of very high energy
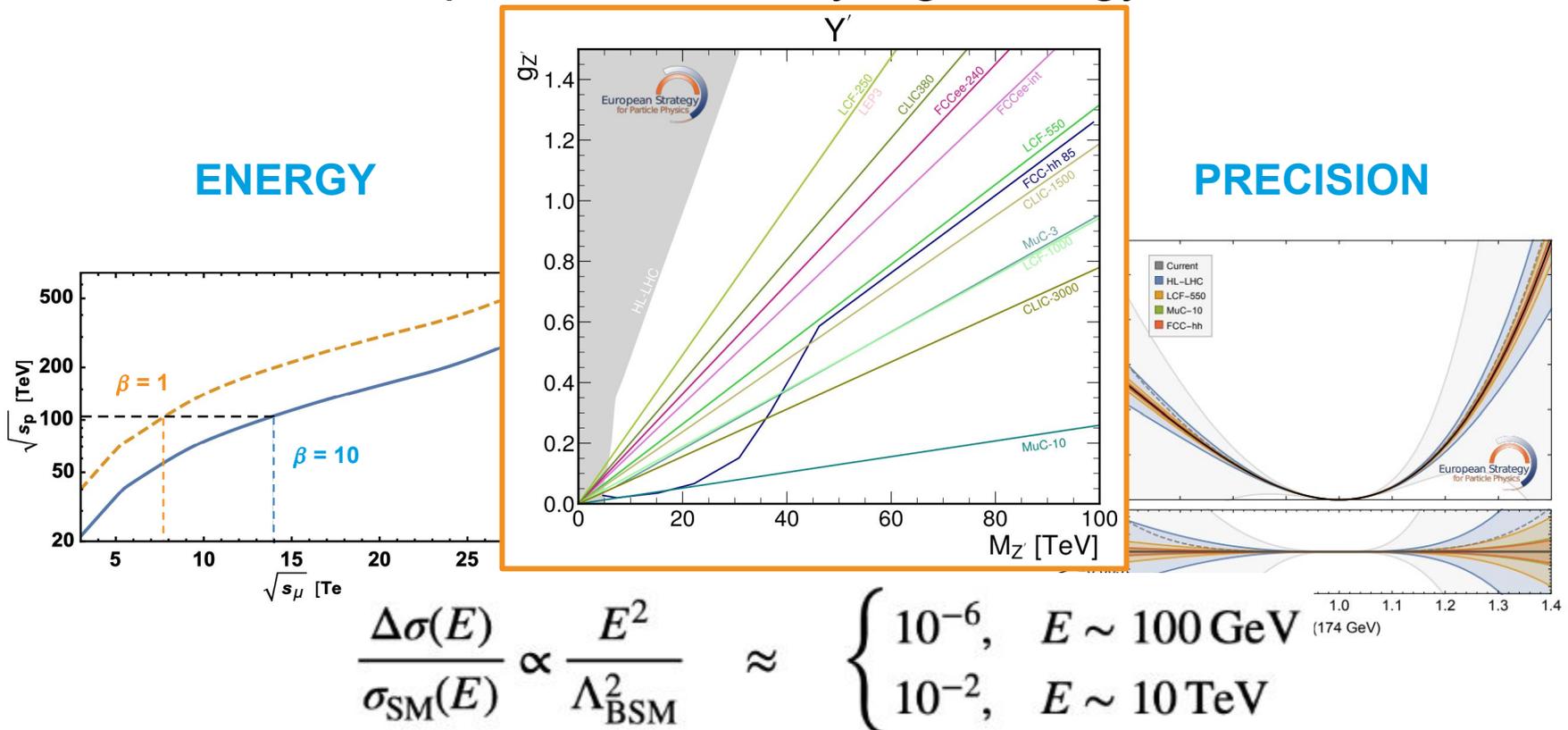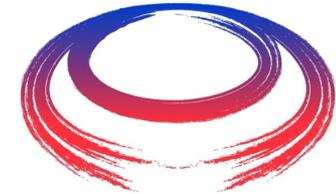
ENERGY

PRECISION

$$\frac{\Delta\sigma(E)}{\sigma_{\text{SM}}(E)} \propto \frac{E^2}{\Lambda_{\text{BSM}}^2} \approx \begin{cases} 10^{-6}, & E \sim 100\,\text{GeV} \\ 10^{-2}, & E \sim 10\,\text{TeV} \end{cases}$$

A brief history of muon colliders

1970/90 Initial proposal
G.I. Budker, Accelerators and colliding beams, 1969
A.N. Skirnsky, Intersecting storage rings at Novosibirsk, 1971
D. Neuffer, Multi-TeV muon colliders, 1986

2013 - LEMMA
- Propose positron-driven scheme

2019 - MICE
- Demonstrates ionisation cooling

IMCC

ESPPU 2026

International MUON Collider Collaboration

Time

2011 - 2014 US Muon Accelerator Program MAP
- Short- and long-baseline neutrino facilities
- Higgs factory with good energy resolution
- TeV-scale muon collider
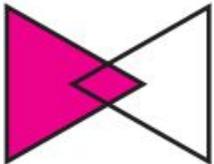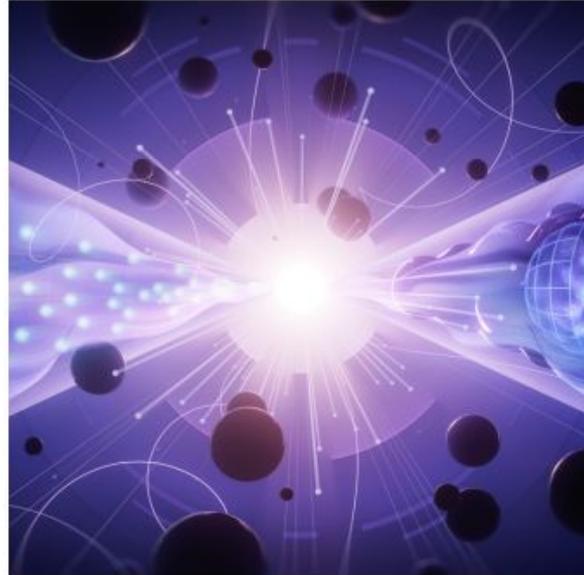
Muon Accelerators for Particle Physics

European Strategy for Particle Physics Update 2020
- Set up an international collaboration

2023 P5 process
- The Muon Shot

The Muon Shot
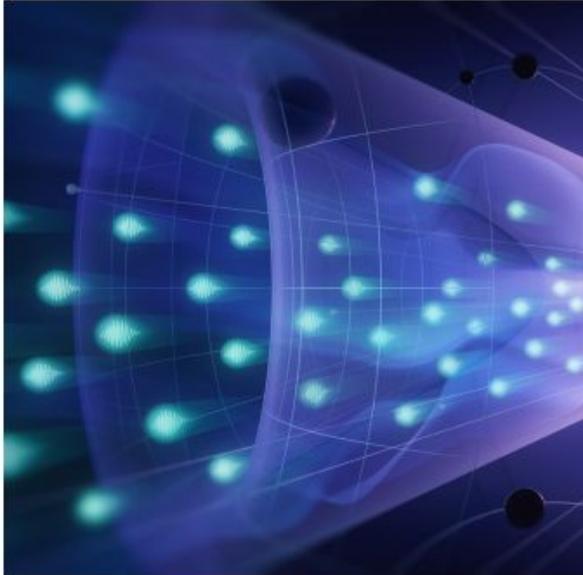
Decipher the Quantum Realm

Elucidate the Mysteries of Neutrinos

Reveal the Secrets of the Higgs Boson

Explore New Paradigms in Physics

Search for Direct Evidence of New Particles

Pursue Quantum Imprints of New Phenomena

Illuminate the Hidden Universe

Determine the Nature of Dark Matter

Understand What Drives Cosmic Evolution

The Muon Shot
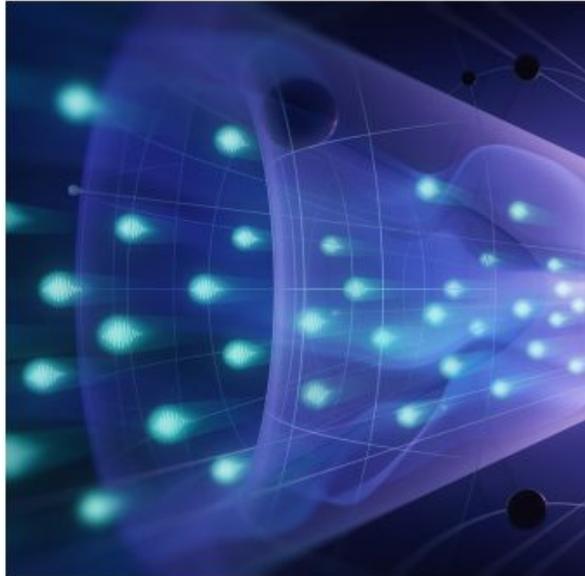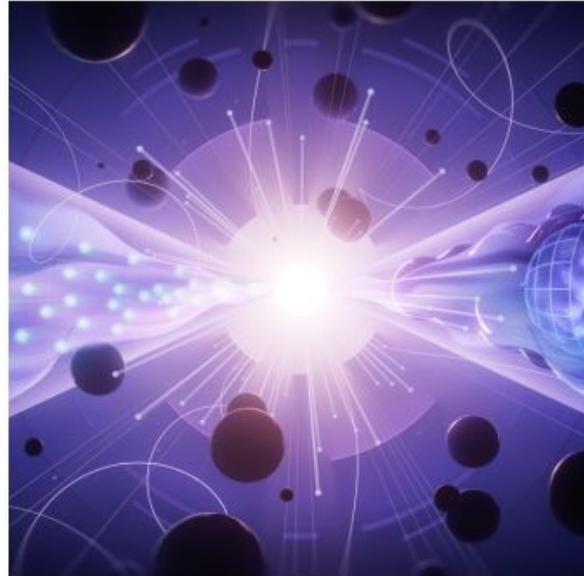
Decipher
Explore
Illuminate

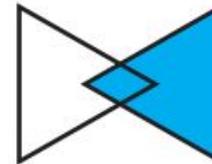**Support a comprehensive effort to develop the resources—theoretical, computational and technological—essential to our 20-year vision for the field. This includes an aggressive R&D program that, while technologically challenging, could yield revolutionary accelerator designs that chart a realistic path 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.

the Higgs Boson
of New Phenomena
Cosmic Evolution

European strategy for particle physics

Submitted <u>ESPPU input</u> as large project

Proposed an R&D plan that can make a muon collider reality by 2050

- 400 pages supplementary "backup" document, ~450 authors and supporters

The European Strategy for Particle Physics:
2026 Update

European strategy for particle physics

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B. *In order to realise the visionary plan presented, the highest priority must be the **development and industrialisation of key technologies: advanced superconducting and normal-conducting RF structures, efficient RF power sources and accelerator-quality magnets in the 14–20 T range, including those based on high-temperature superconductors.***

D. *The longer-term development of advanced technologies, such as high-gradient wakefield acceleration and those **underpinning bright muon beams, should be supported at an appropriate level. Synergies with the US initiative on muon collider R&D should be exploited.***

The European Strategy for Particle Physics:
2026 Update

Collider overview

Proton-driven scheme
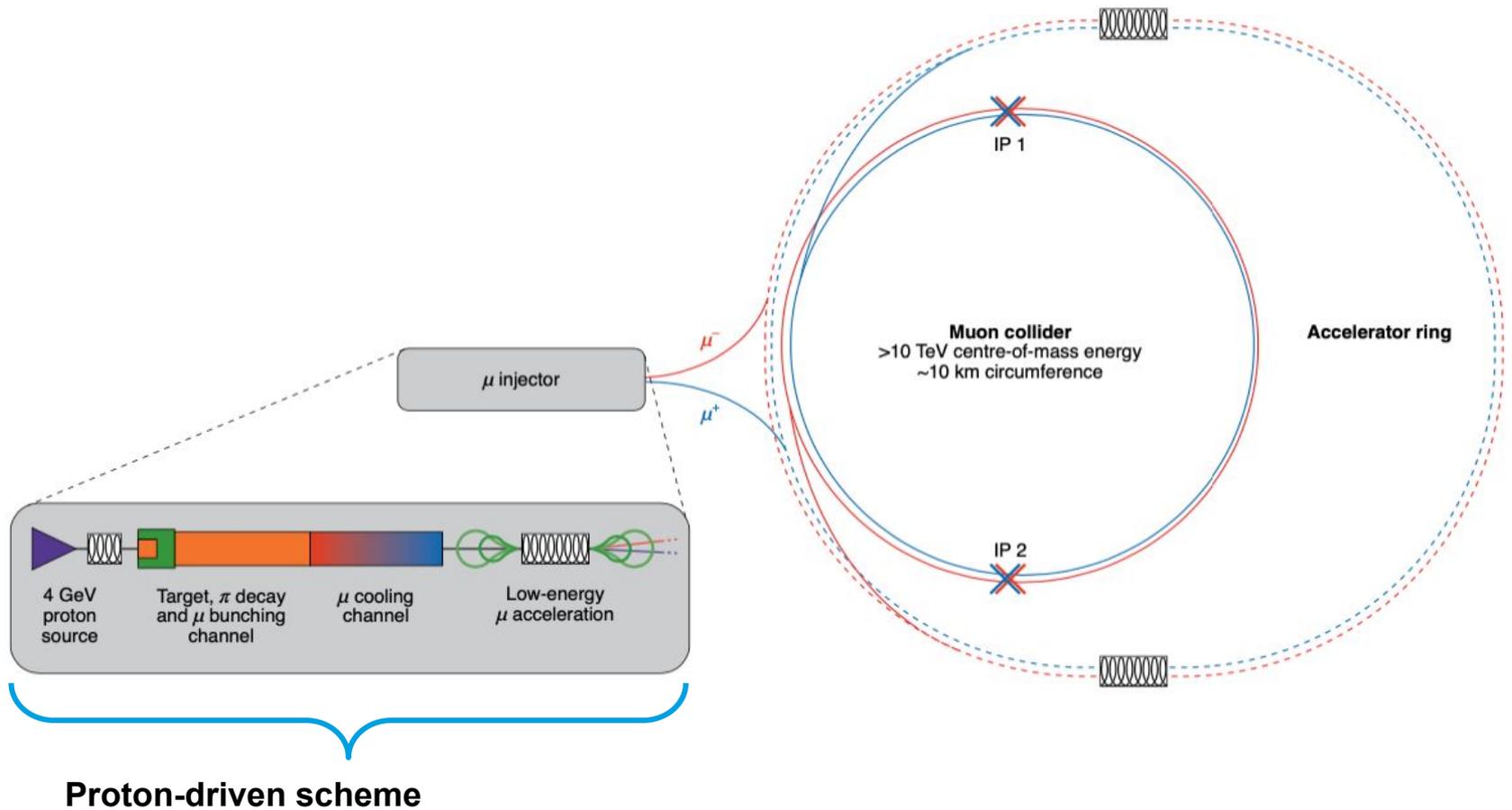
Collision paradigm

Circulate two bunches and re-fill when they are depleted

Luminosity increases with the square of beam energy
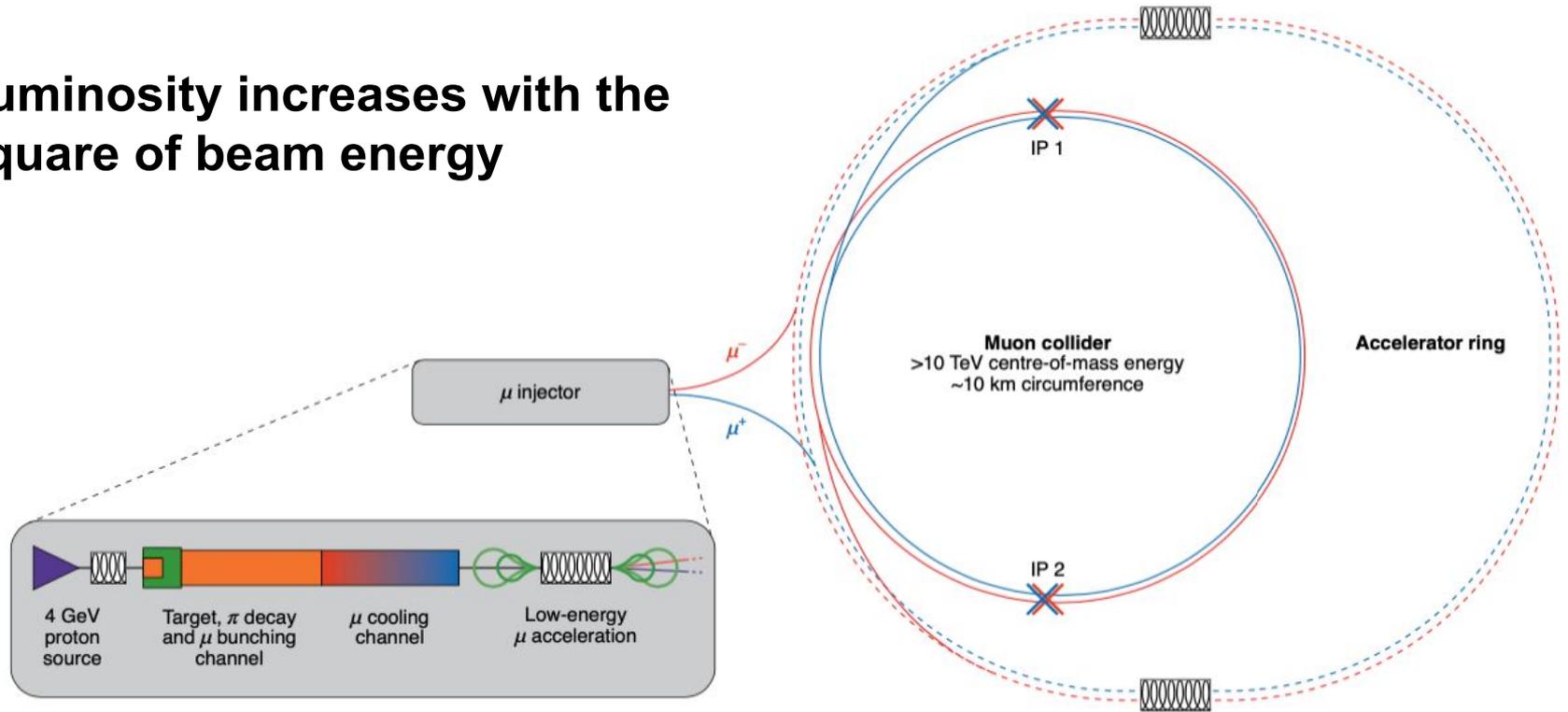
1000 times lower collision rate than LHC!

For the luminosity experts

$$L \approx \frac{\left\langle N_b^2 \right\rangle_{n_{\text{turns}}} n_{\text{turns}} f_{\text{inj}} \gamma}{4\pi \beta^* \varepsilon^*} R_{\text{HG}}$$

Sustainability

Cost-effective construction and operation

Possible staging / re-use of existing facilities

Parameters and operation

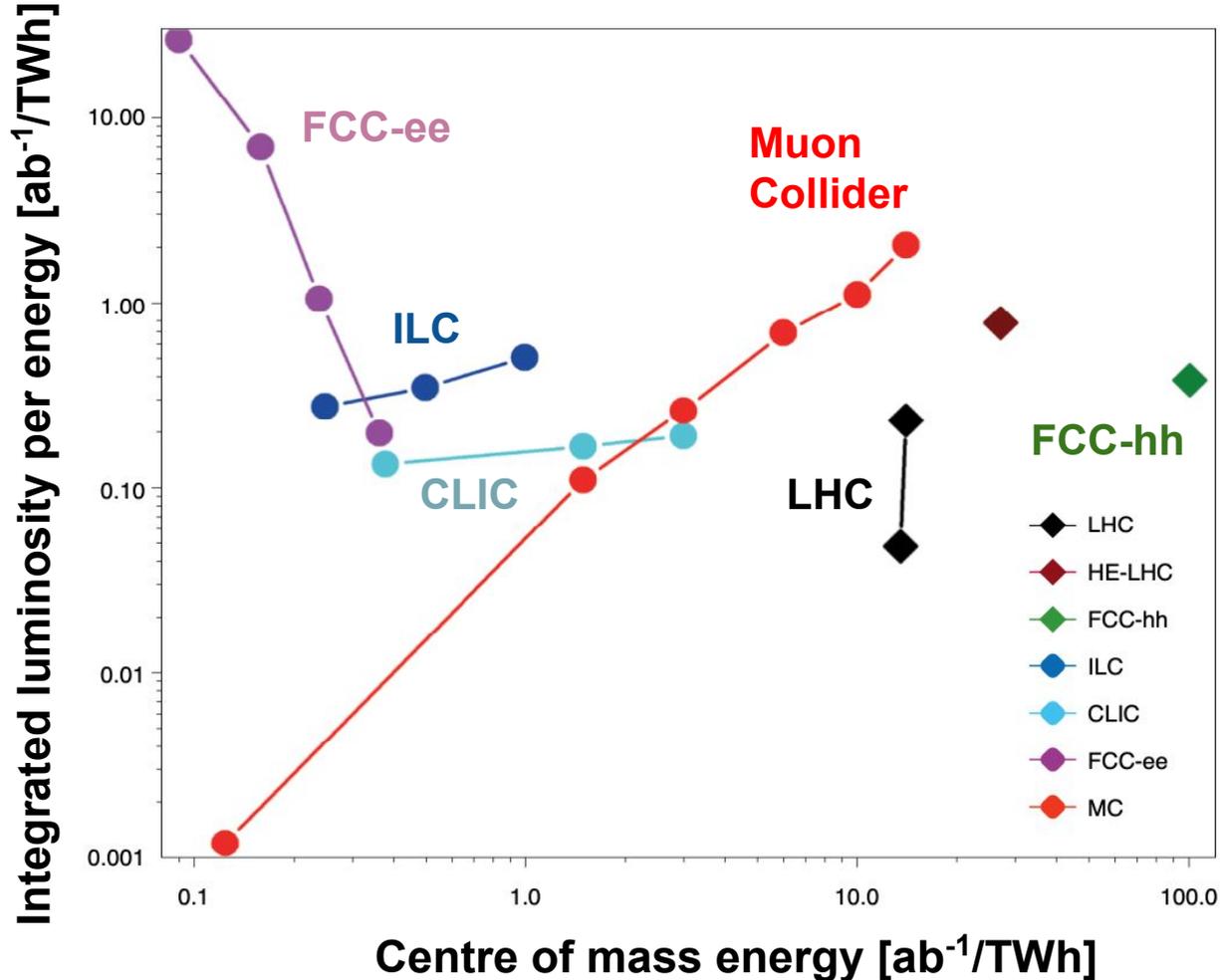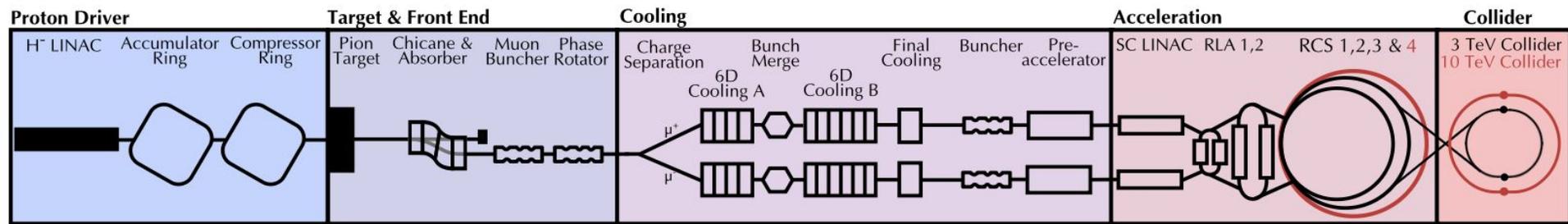| Parameter	Symbol	unit	Energy staging		Luminosity staging	
			Stage 1	Stage 2	Stage 1	Stage 2
Centre-of-mass energy	E_{cm}	TeV	3	10	10	10
Target integrated luminosity	$\int \mathcal{L}_{target}$	ab^{-1}	1	10	10	
Estimated luminosity	$\mathcal{L}_{estimated}$	$10^{34} cm^{-2} s^{-1}$	1.8	17.5	4 (tbc)	13.8
Collider circumference	C_{coll}	km	4.5	11.4	15	15
Collider arc peak field	B_{arc}	T	11	14	11	11
Collider dipole technology			Nb_3Sn	HTS	Nb_3Sn	Nb_3Sn
Luminosity lifetime	N_{turn}	turns	1039	1363	1039	1039
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 transv. emittance	$\varepsilon_{\perp}$	µm	25	25	25	25
IP bunch length	σ_z	mm	5	1.5	5 (tbc)	1.5
IP betafunction	β	mm	5	1.5	5 (tbc)	1.5
IP beam size	σ	µm	3	0.9	1.6	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

Site independent muon collider parameters

Plan to operate **each stage** for **5-10 years**

The road to
the muon collider

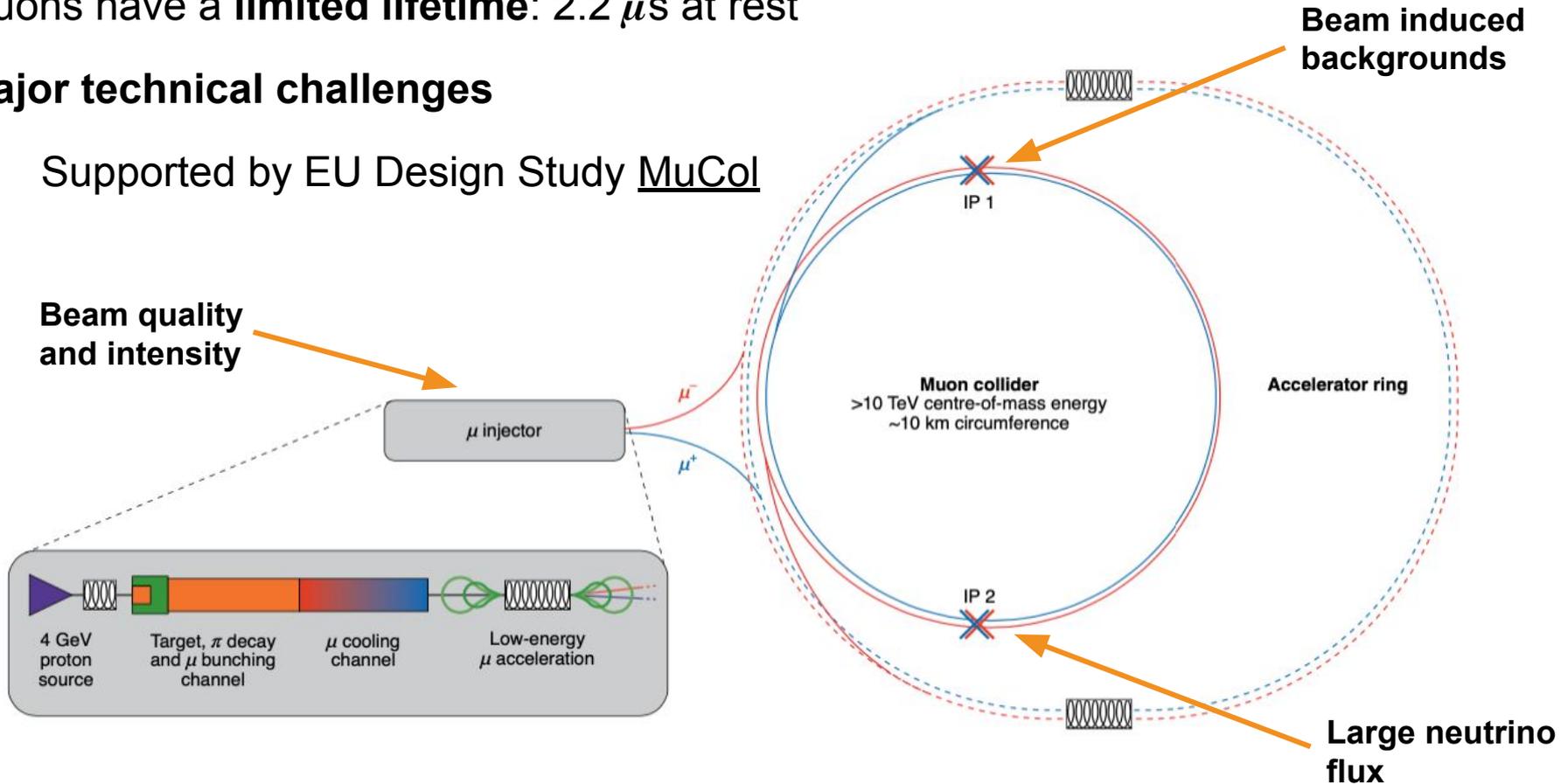| Proton Driver			Target & Front End				Cooling						Acceleration			Collider
H⁻ LINAC	Accumulator Ring	Compressor Ring	Pion Target	Chicane & Absorber	Muon Buncher	Phase Rotator	Charge Separation	Bunch Merge	Final Cooling	Buncher	Pre-accelerator		SC LINAC RLA 1,2	RCS 1,2,3 & 4		3 TeV Collider 10 TeV Collider

Key challenges

Muons have a **limited lifetime**: 2.2 μs at rest

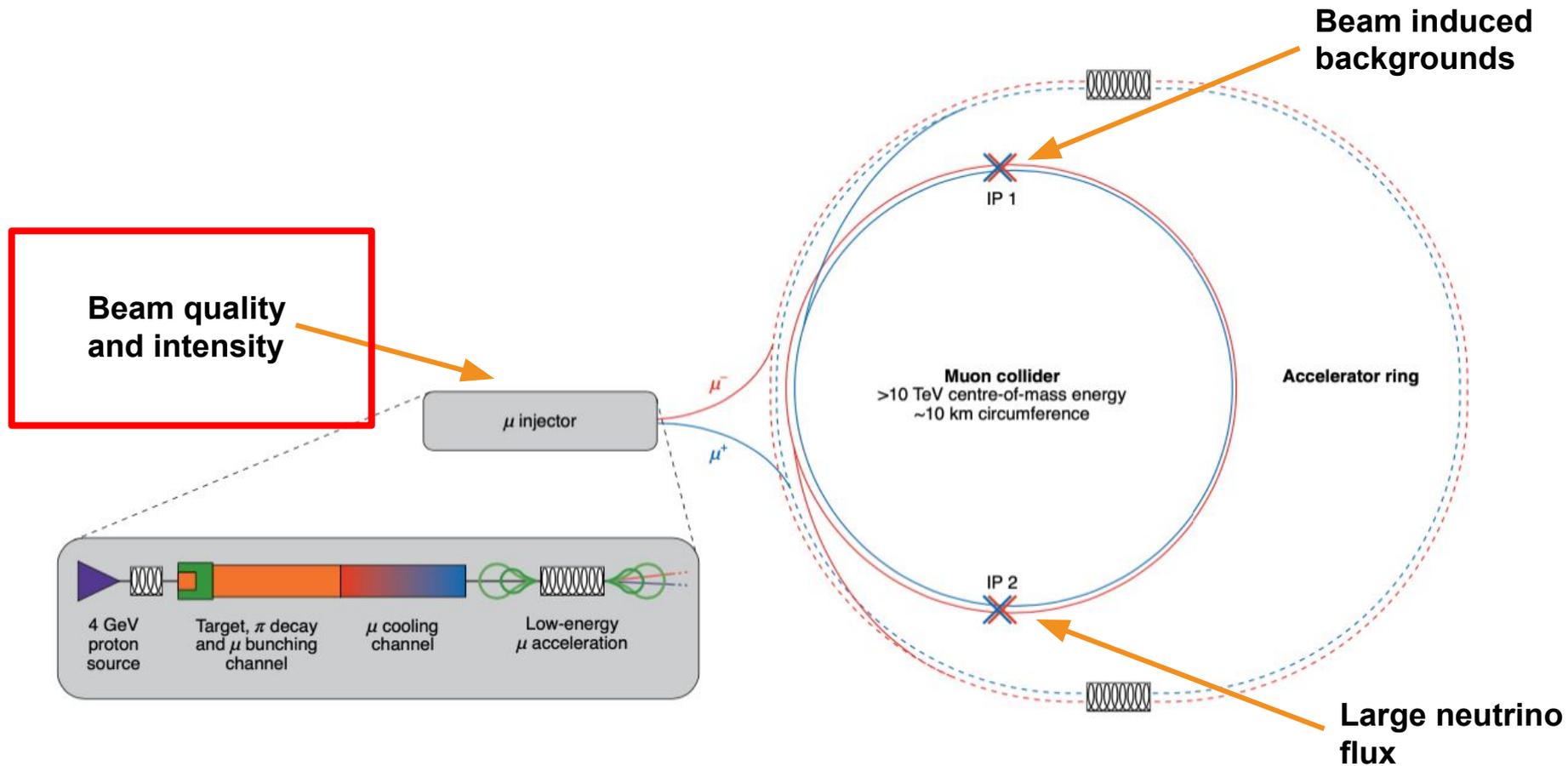## Major technical challenges

- Supported by EU Design Study <u>MuCol</u>

Beam quality and intensity

Beam induced backgrounds

Large neutrino flux

IP 1

IP 2

Muon collider
>10 TeV centre-of-mass energy
~10 km circumference

Accelerator ring

μ^-

μ^+

μ injector

4 GeV proton source

Target, π decay and μ bunching channel

μ cooling channel

Low-energy μ acceleration

The 12 ~~miracles~~ challenges

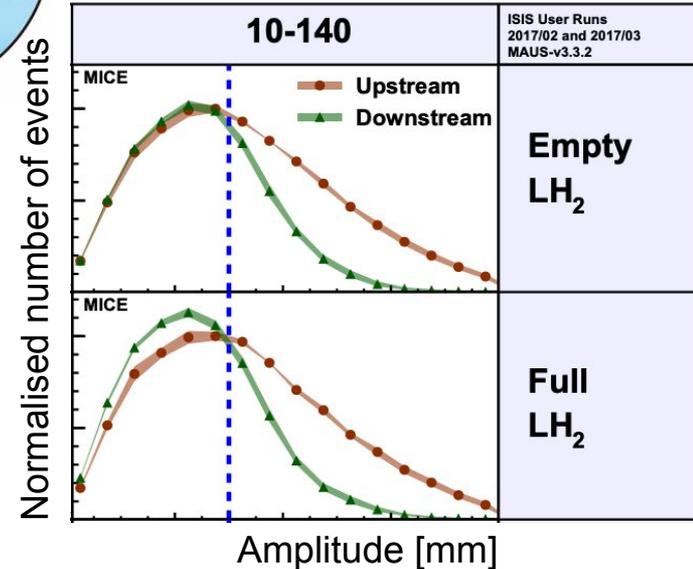|	Target	Status	Notes	Future work
Pulse compression	1-3 ns	SPS does O(1) ns	Need higher intensity. O(30) ns loses only factor 2 in the produced muons.	Refine design, including proton acceleration. Accumulation and compression of bunches.
High-power targets	2 MW	2 MW	Available for neutrino and spallation neutrons. Aim for 4 MW to have margin.	Develop target design for 2 MW, O(1) ns bunches create larger thermal shocks. Prototype in 2030s.
Capture solenoids	15 T	13 T	ITER central solenoid.	Study superconducting cables and validate cooling. Investigate HTS cables.
Cooling solenoids	50 T	30-40 T	30 T leads to a factor 2 worse transverse emittance with respect to design.	Extend designs to the specs of the 6D cooling channel. Demonstrator.
RF in magnetic field	>50 MV/m	65 MV/m	MUCOOL published results. Requires test in non-uniform B.	Design to the specs of 6D cooling. Demonstrator.
6D cooling	10^{-6}	0.9 (1 cell)	MICE result (no re-acceleration). Emittance exchange demonstrated at g-2.	Optimise with higher fields and gradients. Demonstrator.
RCS dynamics	-	-	Simulation. 3 TeV lattice design in place.	Develop lattice design for a 10 TeV accelerator ring.
Rapid cycling magnets	2 T/ms 2 T peak	2.5 T/ms 1.81 T peak	Normal conducting magnets. HTS demonstrated 12 T/ms, 0.24 T peak.	Design and demonstration work. Optimise power management and re-use.
Ring magnets aperture	20 T quads	12-15 T (Nb3Sn)	Need HTS or revise design to lower fields.	Design and develop larger aperture magnets, 12-16 T dipoles and 20 T HTS quads.
Collider dynamics	-	-	3 TeV lattice in place with existing technology.	Develop lattice design for a 10 TeV collider.
Neutrino radiation	10 μSv/year	-	3 TeV ok with 200 m deep tunnel. 10 TeV requires a mover system.	Study mechanical feasibility of the mover system impact on the accelerator and the beams.
Detector shielding	Negligible	LHC-level	Simulation based on next-gen detectors.	Optimise detector concepts. Technology R&D.

Key challenges

Beam induced backgrounds

Beam quality and intensity

μ injector

μ⁻

μ⁺

Muon collider
>10 TeV centre-of-mass energy
~10 km circumference

Accelerator ring

IP 1

IP 2

4 GeV proton source

Target, π decay and μ bunching channel

μ cooling channel

Low-energy μ acceleration

Large neutrino flux

Cooling the beams
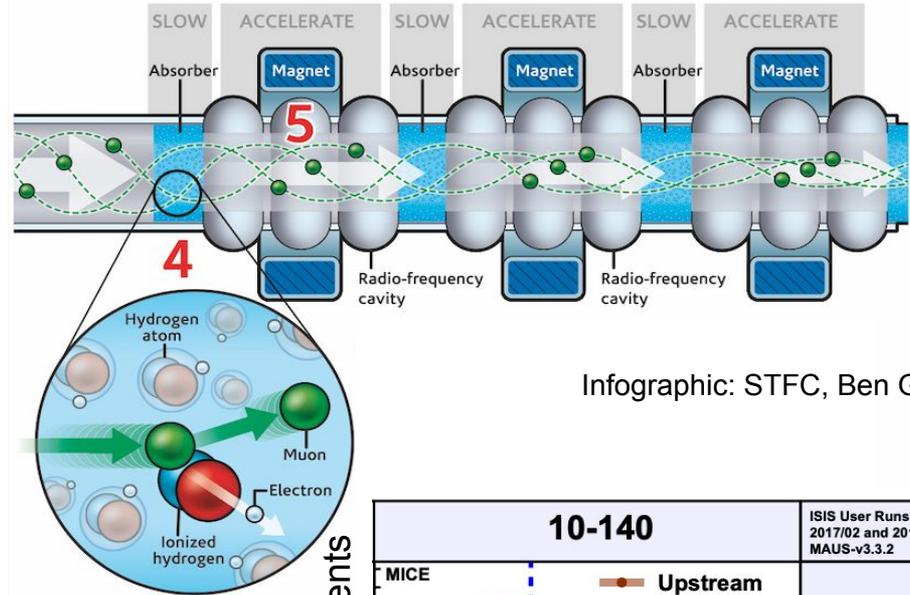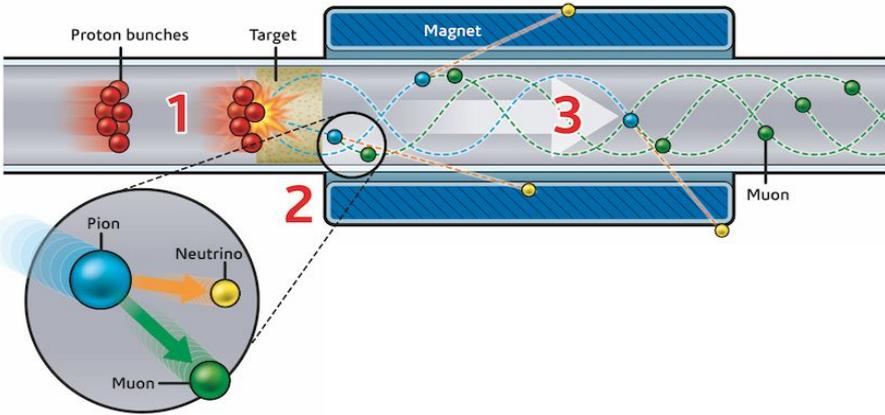
Infographic: STFC, Ben Gilliland

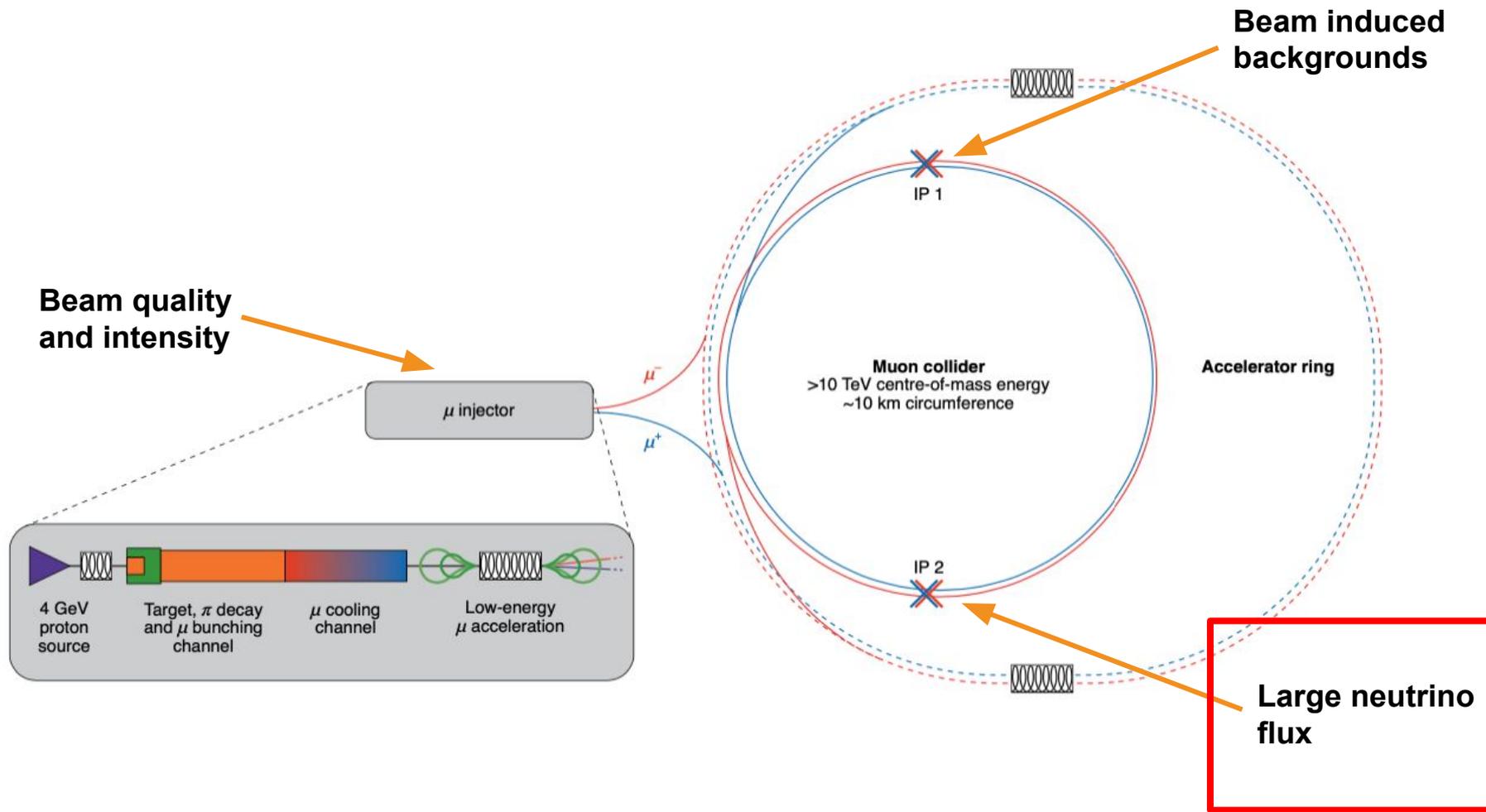MICE Muon Ionization Cooling Experiment

Need 10^6 emittance reduction!

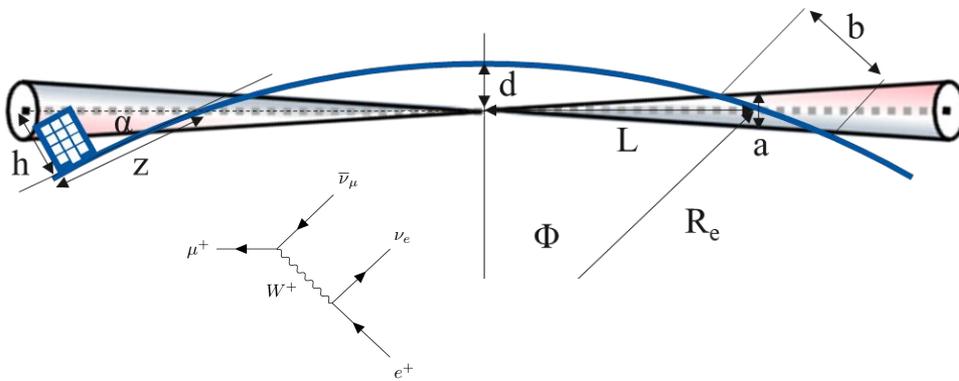- Demonstrator with RF and more than one stage required

Cooling chain design

Key challenges

Beam induced backgrounds

Beam quality and intensity

Large neutrino flux

μ injector

μ⁻

μ⁺

IP 1

IP 2

Muon collider
>10 TeV centre-of-mass energy
~10 km circumference

Accelerator ring

4 GeV proton source

Target, π decay and μ bunching channel

μ cooling channel

Low-energy μ acceleration
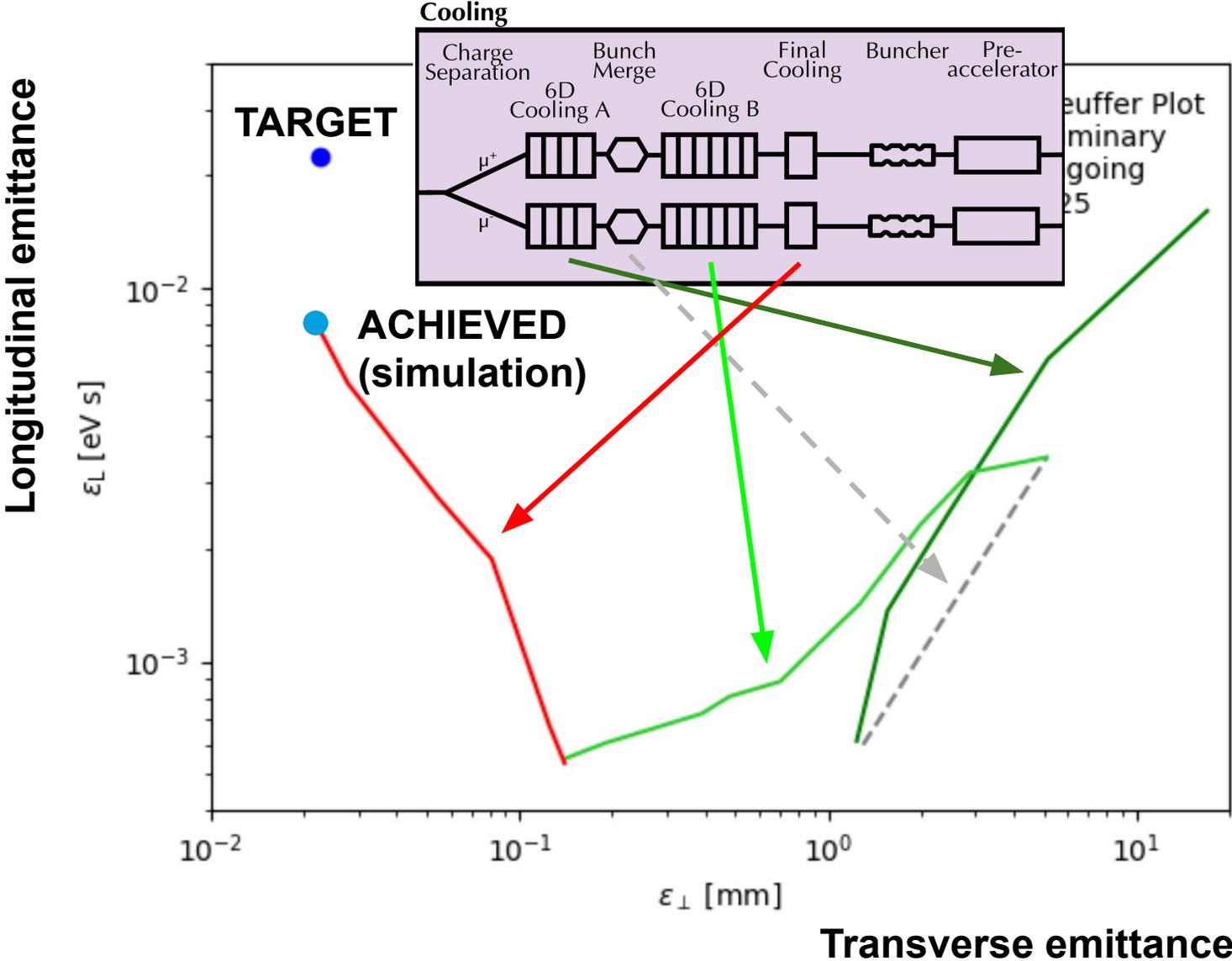
Neutrino flux

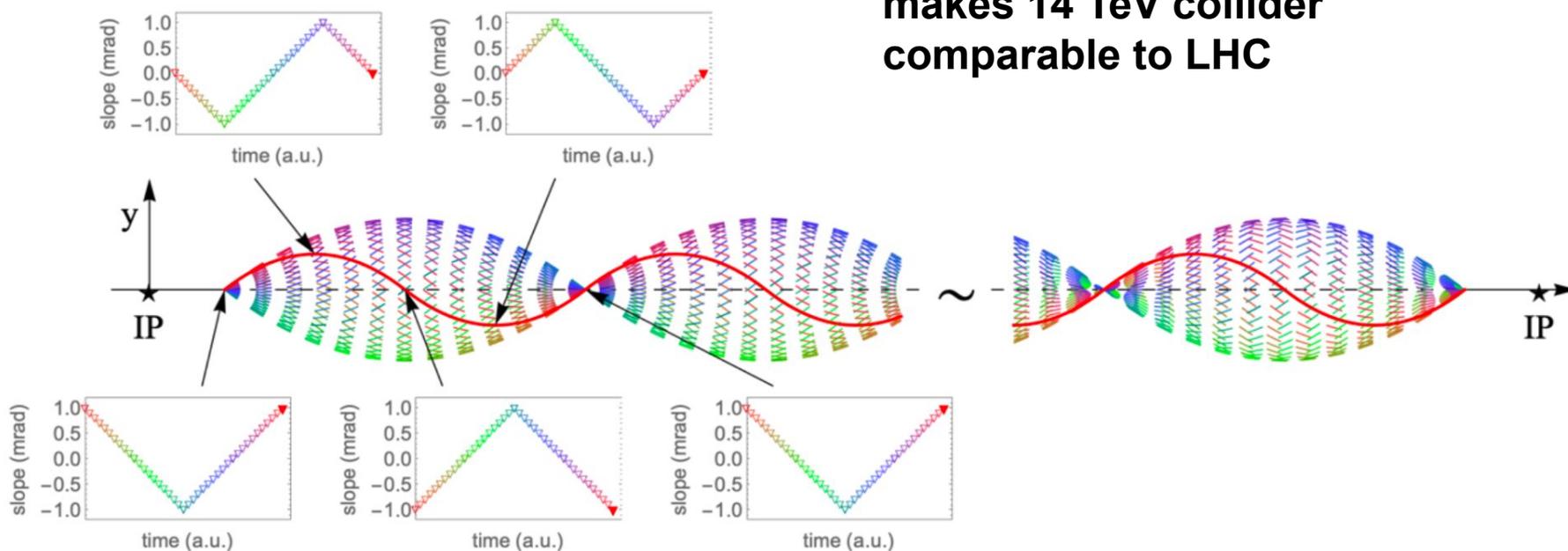| Legal limit:	1 mSv/year
MAP goal:	< 0.1 mSv/year
IMCC goal:	arcs below threshold for legal procedure < 10 µSv/year
LHC achieved:	< 5 µSv/year

3 TeV, 200m-deep tunnel ~ OK
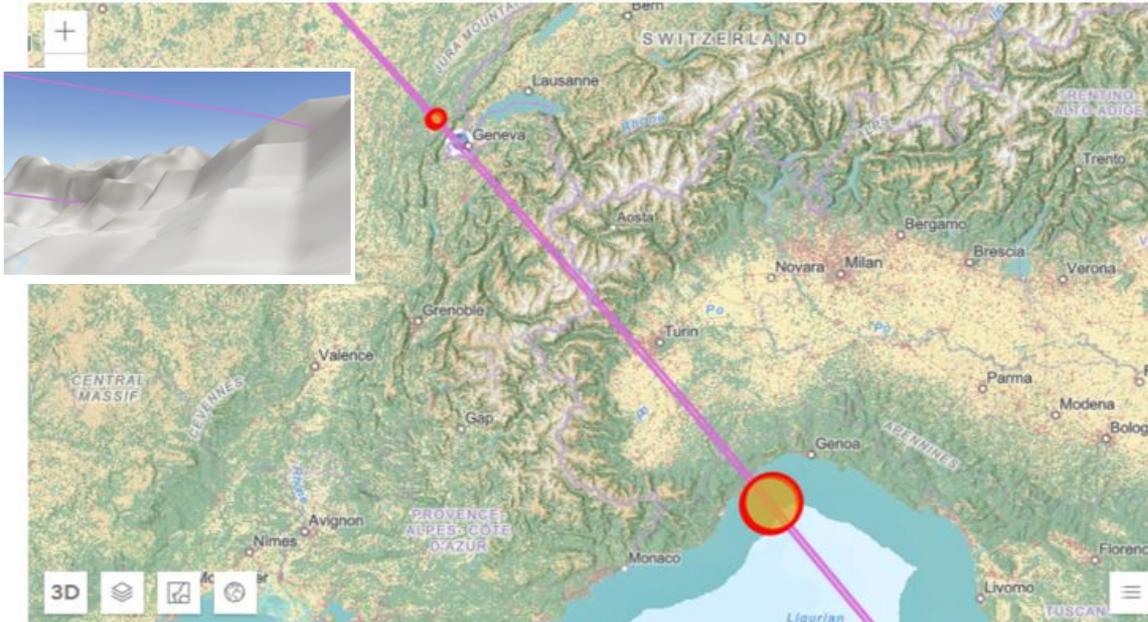
Status
- Close to a solution
- Arcs impact similar to current CERN impact
- Hottest spot inside fence is like sitting in a plane

Neutrino flux mitigation

Need mitigation in collider arcs at 10+ TeV: move collider ring components
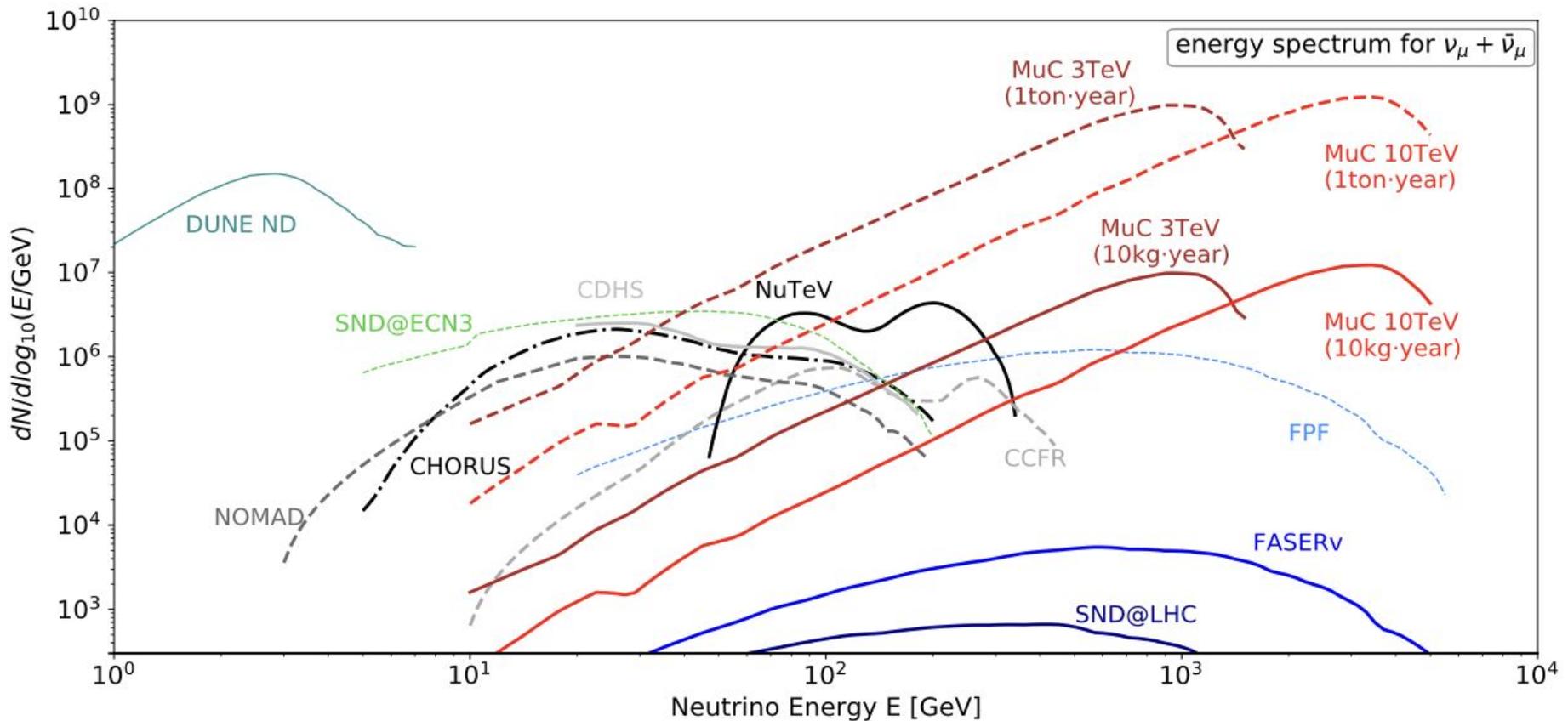
Example: vertical bending

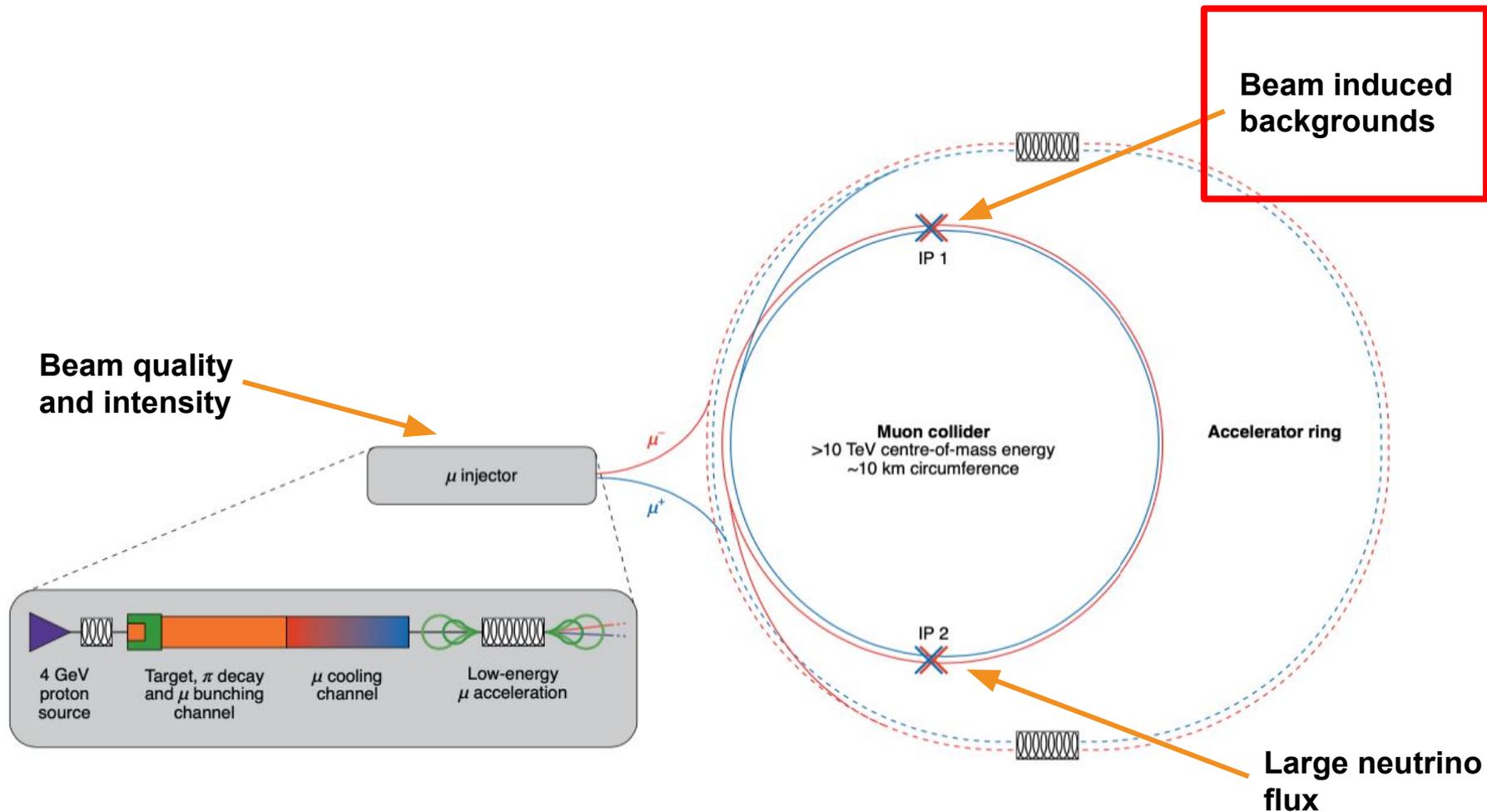**Opening angle of ~1 mradian makes 14 TeV collider comparable to LHC**
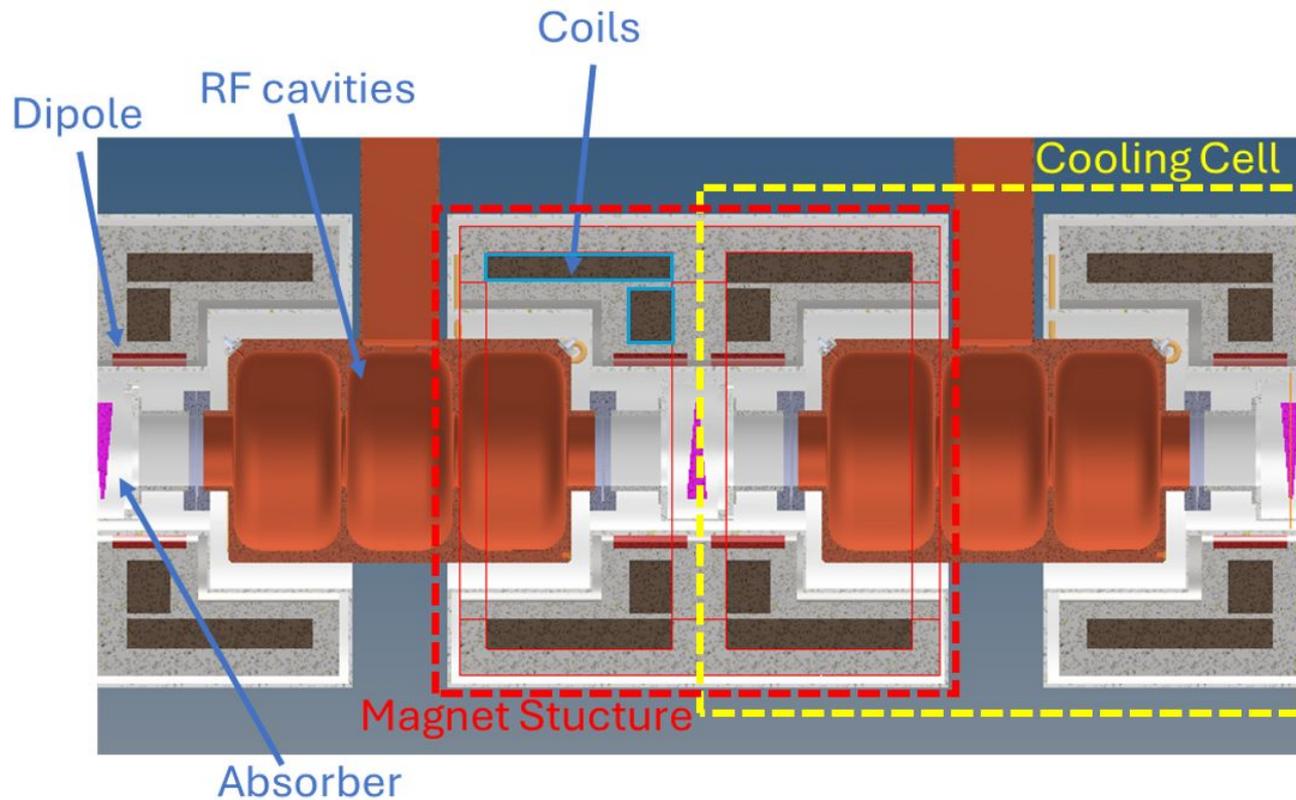
Neutrinos are an opportunity!
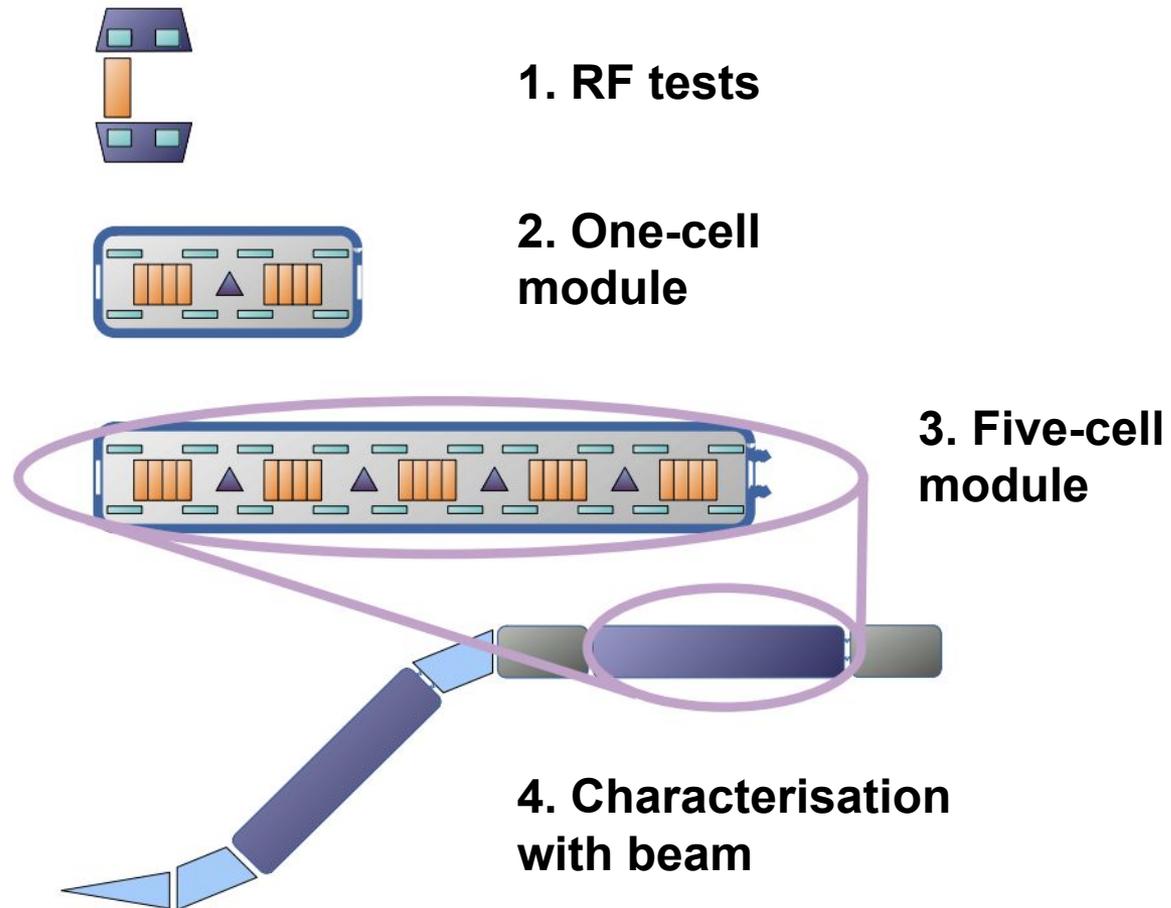
See Zhen's talk!

Key challenges

Beam induced backgrounds

Beam quality and intensity

Large neutrino flux

μ injector

μ^-

μ^+

Muon collider
>10 TeV centre-of-mass energy
~10 km circumference

Accelerator ring

IP 1

IP 2

4 GeV proton source

Target, π decay and μ bunching channel

μ cooling channel

Low-energy μ acceleration

Demonstrator and implementation

Muon Cooling Demonstrator Programme

1. RF tests

2. One-cell module
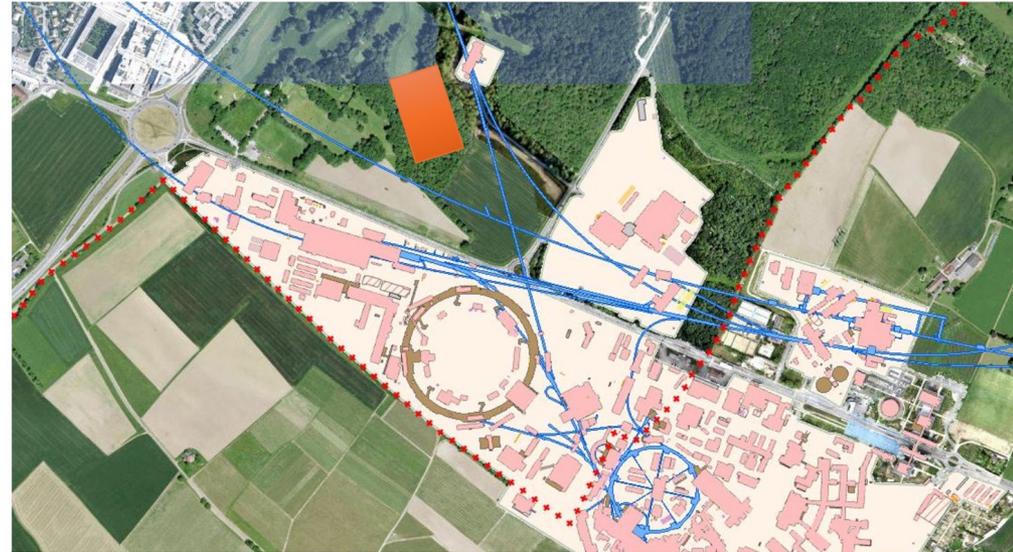
3. Five-cell module

4. Characterisation with beam
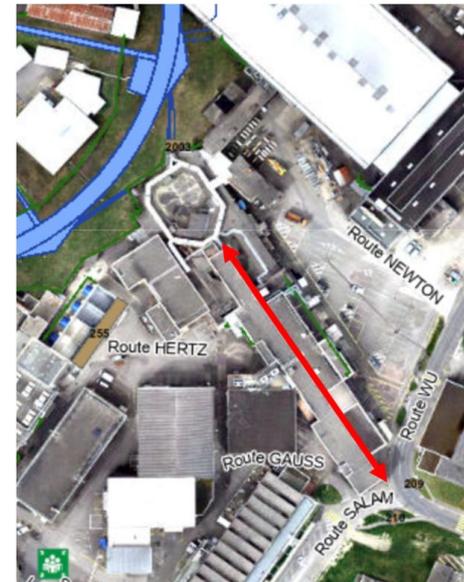
Demonstrator with beams

Tests with beam in **order to demonstrate commissioning and operation**

Demonstrator TDR for 2028-2030 (Infrastructure TRL 7)

Add more modules to optimise technologies and performance
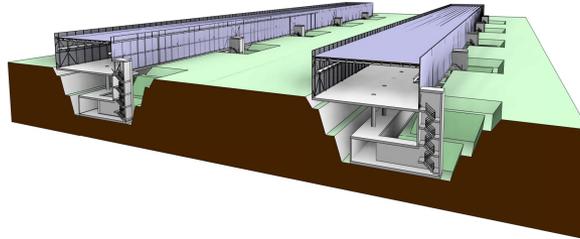

TT7 @ CERN

CTF3 @ CERN

Collider implementation

Started studies for siting at CERN and Fermilab
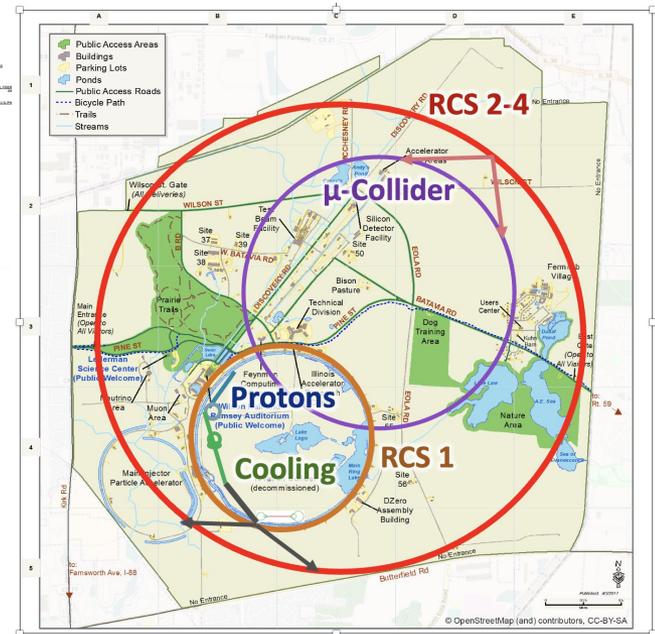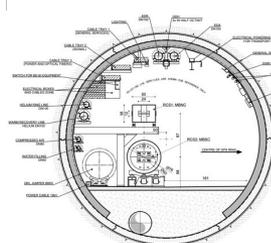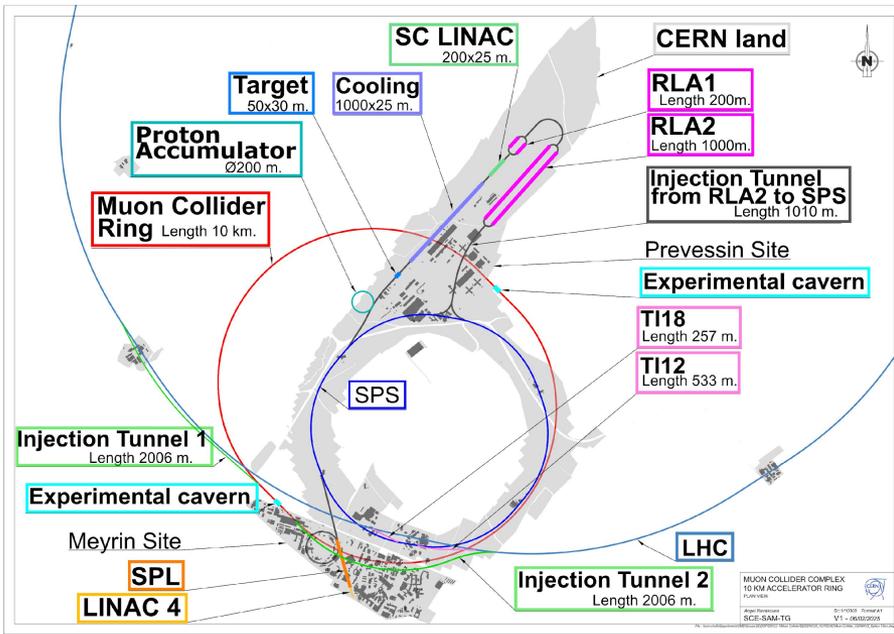
CERN
One RCS in SPS and two in LHC
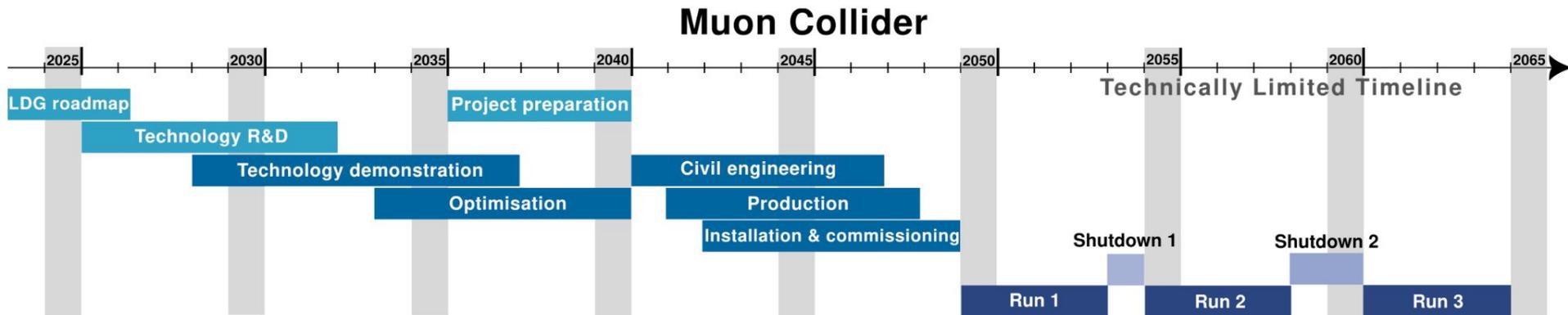Construct facility on CERN land
- 3.2 and 7.6 TeV, 10 TeV maybe possible

Fermilab
One RCS in Tevatron tunnel, Three RCSs in one site-filler tunnel

Plans and technically limited timeline

Muon Collider

Timeline showing phases: LDG roadmap, Technology R&D, Technology demonstration, Project preparation, Optimisation, Civil engineering, Production, Installation & commissioning, Shutdown 1, Shutdown 2, Run 1, Run 2, Run 3. Technically Limited Timeline spanning 2025 to 2065.

10 years R&D programme to reach the maturity to initiate the approval process

Require: **~300 MCHF** material budget and 1800 FTEy for the accelerator
              20 MCHF and 900 FTEy for detectors

This would enable a first muon collider with a **start of operation around 2050**

Early career researchers

It is **critical to attract young people to HEP** we are in competition with other fields of science

The ECR inputs to ESPP highlighted the requirements for a new collider project:

- Drive technology R&D and innovation
- Ambitious baseline physics programme

Recommendation 4.7: European laboratories should assign **greater value to innovation** in preparation for the next generation of particle physics facilities
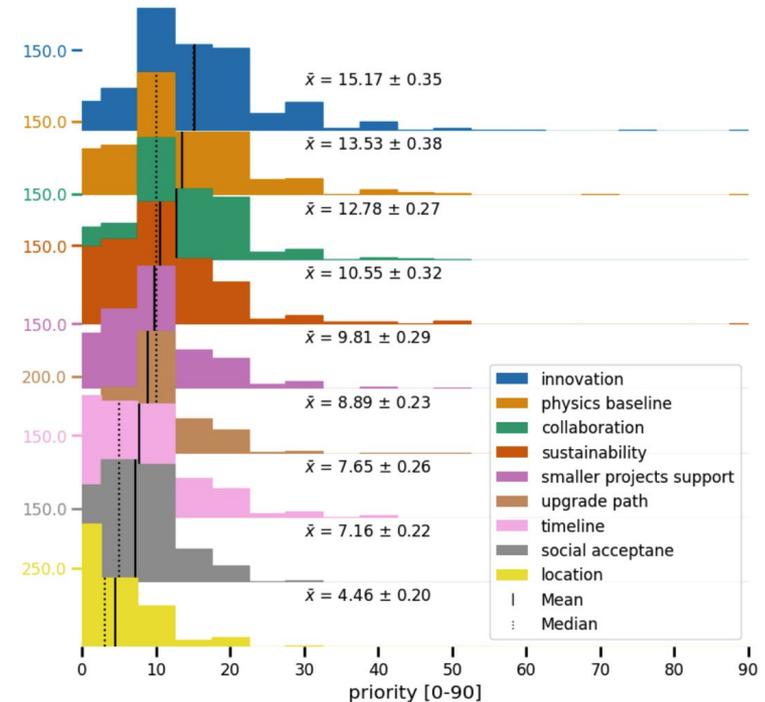
Summary

Why waiting for a muon collider?
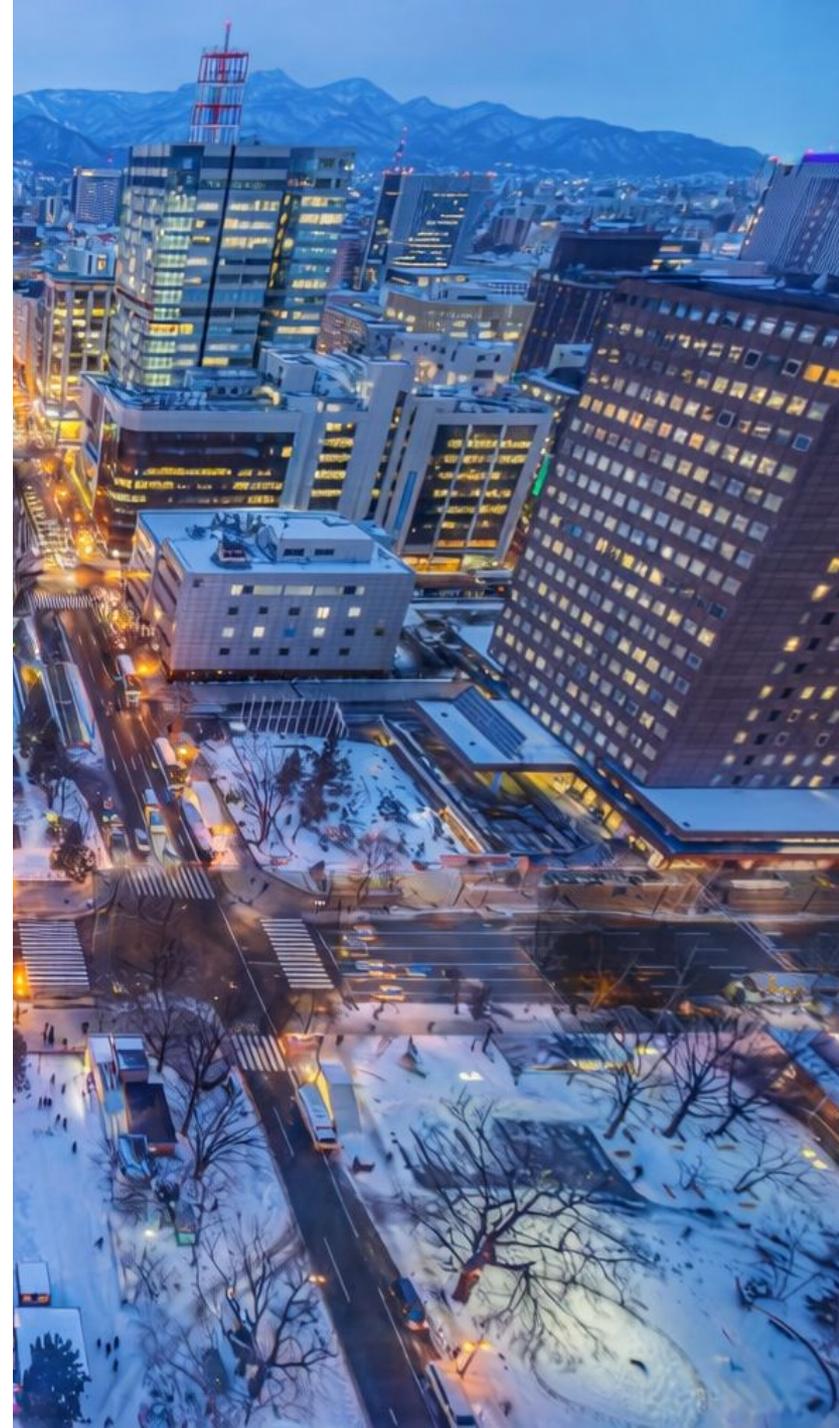*We are not waiting, but working on it.*

- F. Maltoni

The muon collider presents **enormous potential for fundamental physics research** at the energy frontier that justifies further investment

The road ahead is filled with challenging and interesting R&D, spanning across **theory, accelerator and experiment!**

Join IMCC!
muon.collider.secretariat@cern.ch

Thank you!

Contact

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DESY-FH
federico.meloni@desy.de

Towards resource loading

We have an R&D plan widely recognized as a good planning base

Current focus on establishing an overview of available resources, potential resources, interested partners for **next five years**
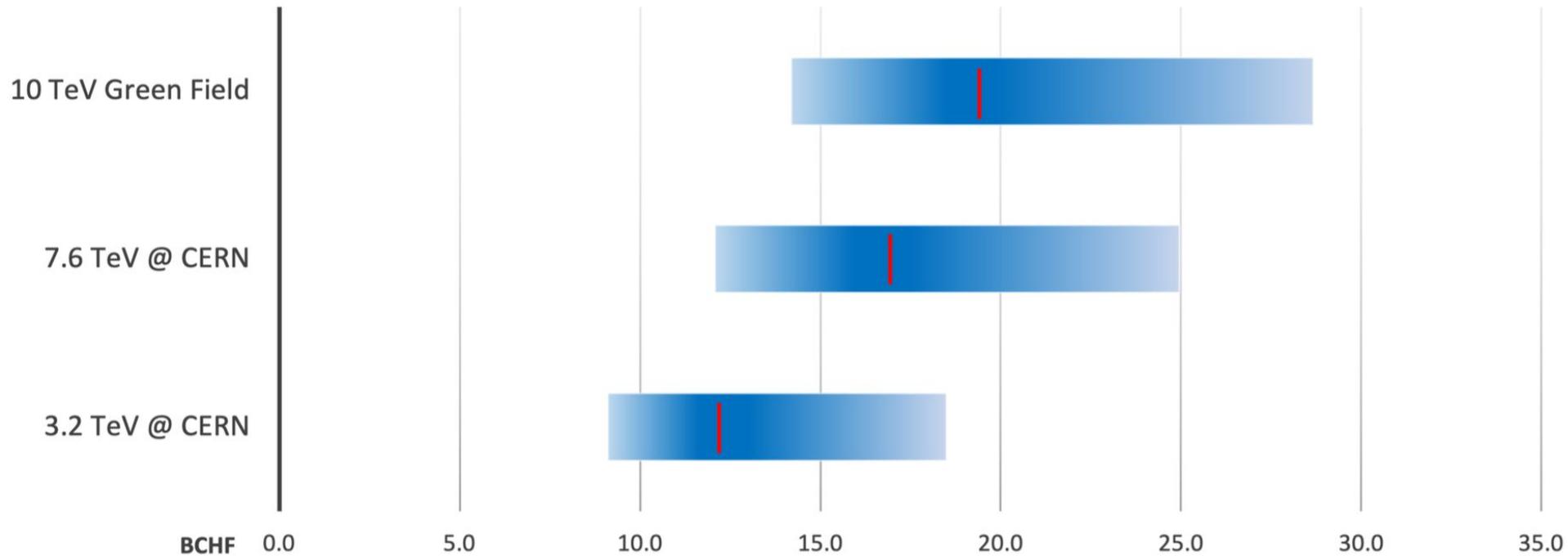
Processes:
- IMCC-wide R&D task force refining the plan and identifying interested partners
- US process to review lab interests and capabilities
- EU project possibilities

High-energy acceleration CEA, CERN, BNL, STFC(?)	**Demonstrator** CERN, INFN, FNAL, SLAC, STFC
RCS powering CERN, U. Bologna, KIT, Tu-Chemnitz Infineon Bipolar (DE), Hitachi semiconductors (CH)	**Magnets** CERN, INFN, U. Bologna, Poli Torino, U. Twente, EPFL/SPC, KEK, U. Southampton, TU Tampere, PSI, CEA, TU Darmstadt Tape manufacturers, ASG, ICAS, ENI, Gauss Fusion, EUROFusion
MDI CERN, INFN, U. Padova, FNAL, other US?	
RF CERN, LBNL, IIT, NIU, INFN, SLAC, CEA, Daresbury/ULAN, U. Strathclyde, U. Helsinki, U. Tartu, U. Rostock THALES	*Legend* **Academic partners/interest** **Industrial partners/interest**

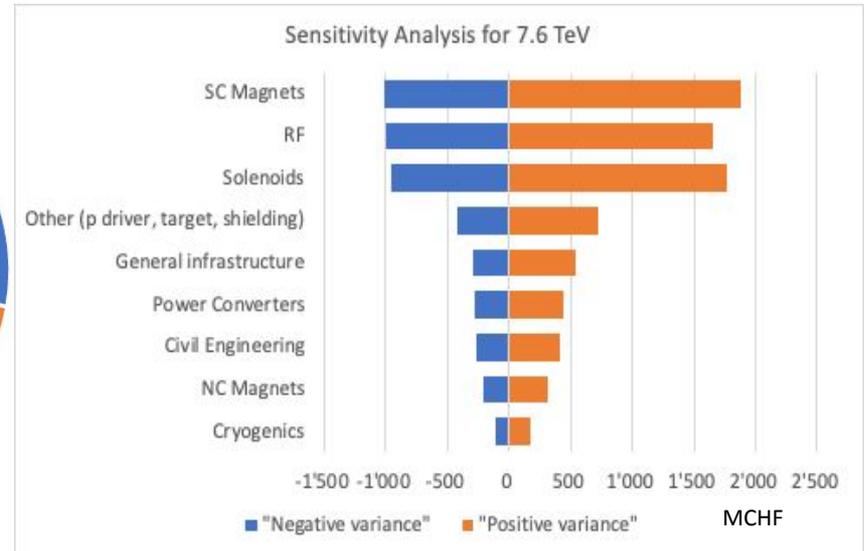# Facility cost range

Cost range for Muon Collider scenarios

Cost estimate details

Relative cost for 7.6 TeV
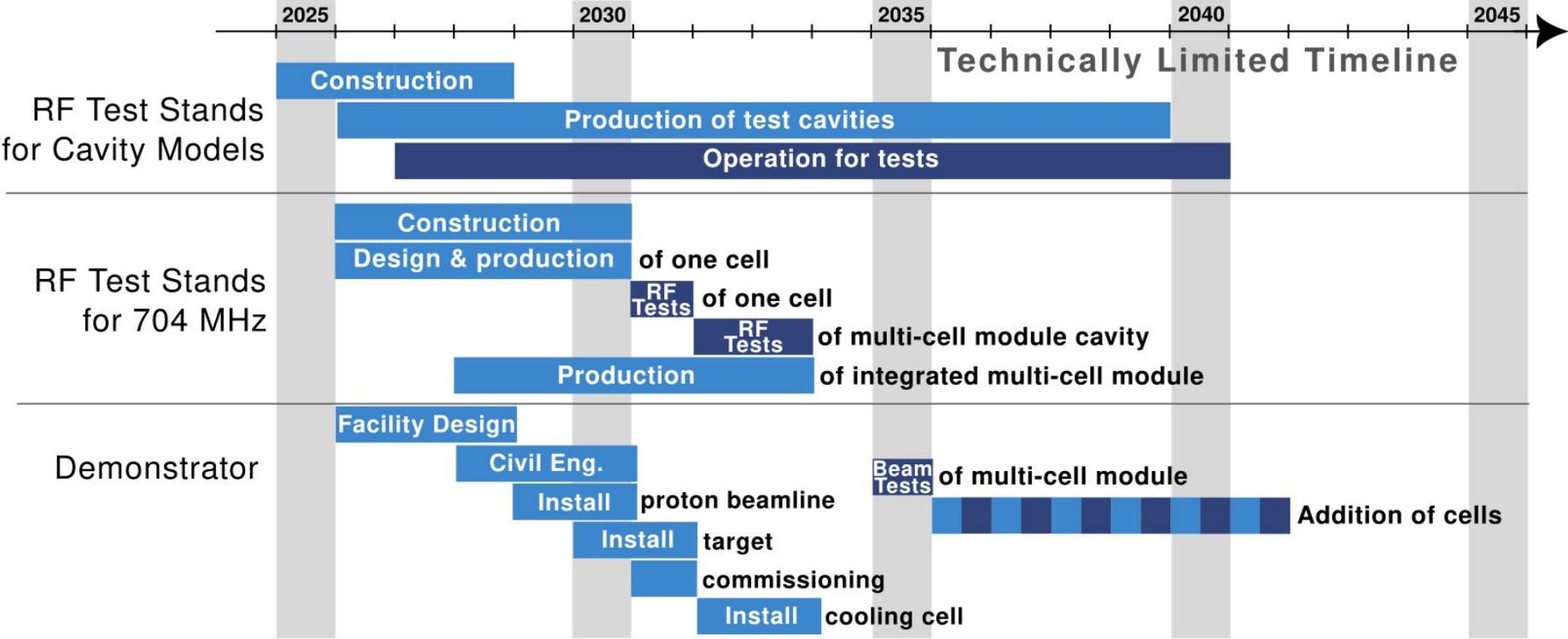
- RF — 27.7%
- Other Magnets — 25.2%
- Power Converters — 7.9%
- Solenoids — 17.0%
- Civil Engineering — 7.4%
- General infrastructure — 8.3%
- Other — 6.6%

Sensitivity Analysis for 7.6 TeV

"Negative variance"   "Positive variance"   MCHF
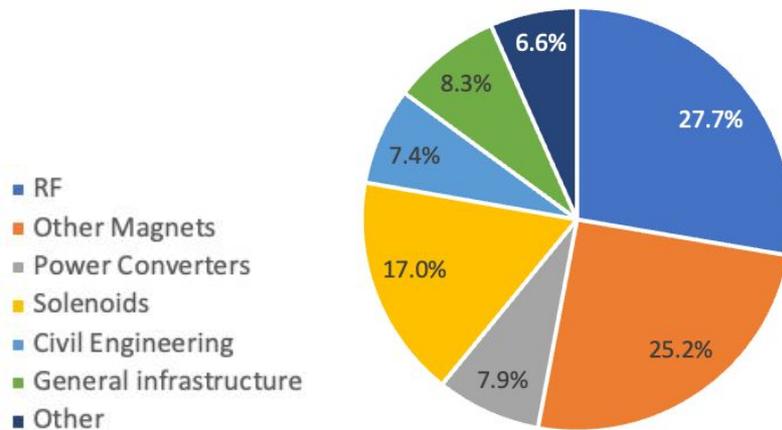
R&D resources breakdown

Year	I	II	III	IV	V	VI	VII	VIII	IX	X
Accelerator Design and Technologies										
Material (MCHF)	1.6	3.2	4.8	6.4	9.6	10.8	12.0	12.0	12.0	12.0
FTE	47.1	60.6	75.0	85.0	100.0	120.0	150.0	174.6	177.2	185.1
Demonstrator										
Material (MCHF)	0.6	2.2	3.9	5.4	7.8	15.1	25.9	32.4	31.8	12.6
FTE	9.5	11.0	12.5	29.2	29.7	30.5	25.5	27.7	26.7	25.5
Detector										
Material (MCHF)	0.5	1.1	1.6	2.1	2.1	2.1	2.1	2.6	3.1	3.1
FTE	23.4	46.5	70.0	93.0	93.0	93.0	93.0	116.4	139.5	139.5
Magnets										
Material (MCHF)	3.0	4.9	10.1	10.0	11.0	13.4	11.7	7.2	6.6	4.7
FTE	23.3	28.4	36.4	40.9	44.3	47.1	46.2	37.7	36.1	29.4
TOTALS										
Material (MCHF)	5.7	11.4	20.3	23.9	30.6	41.4	51.7	54.2	53.5	32.4
FTE	103.3	146.5	194.0	248.1	267.0	290.6	314.8	356.3	379.4	379.6

Demonstrator timescales

Muon Cooling Demonstrator

Magnet timescales

Muon Collider Magnets
Technically Limited Timeline

Category	Timeline items
Target & Capture	R&D demonstrator; Model coil 20@20; Full size prototype; Construction
6D Cooling	Concept; Split coil demonstrator; Solenoids for cooling cell; Solenoid construction; Integration in cold mass
Final Cooling	Concept; Pancakes; Solenoid demonstration; Prototype
NC RCS	Construction; Integration; R&D concepts; Model; Prototype; Series - RCS 1 and 2; Series - RCS 3
SC RCS	Specifications; R&D demonstrator; Models; Prototype; Pre-Series; Series - RCS 3
RCS Power Converters	NC R&D; Testing; PE Cell; RCS String; Production - RCS 1 & RCS 2; Production - RCS 3
10 TeV Collider / 3 TeV Collider	Concept; Demonstrator Dipoles; Demonstrators; Demonstrator Quadrupoles; Models; Model Dipoles & IR Quads; Prototype; Prototype Dipole/Quad; Pre-Series; Pre-Series; Series; Series
Materials	Materials and methods R&D; Quality Assurance and Quality Control

DESY.

CERN-specific implementation

Parameter	Symbol	unit	Scenario 1		Scenario 2	
CERN-specific muon collider parameters						
			Stage 1	Stage 2	Stage 1	Stage 2
Centre-of-mass energy	E_{cm}	TeV	3.2	7.6	3.2	7.6
Target integrated luminosity	$\int \mathcal{L}_{target}$	ab^{-1}	1	10	1	10
Estimated luminosity	$\mathcal{L}_{estimated}$	$10^{34} cm^{-2} s^{-1}$	0.9	7.9	2.0	10.1
Collider circumference	C_{coll}	km	11	11	4.8	8.7
Collider arc peak field	B_{arc}	T	4.8	11	11	14
Collider dipole technology			NbTi	Nb_3Sn or HTS	Nb_3Sn	HTS
Muons/bunch	N	10^{12}	2.2	1.8	2.2	1.8
Beam power	P_{coll}	MW	5.6	10.9	5.6	10.9
IP bunch length	σ_z	mm	4.7	2	4.7	2
IP betafunction	β	mm	4.7	2	4.7	2
IP beam size	σ	μm	2.8	1.2	2.8	1.2

Highest centre of mass energy compatible with LHC tunnel re-use ~10.5 TeV
(with fast ramping HTS dipoles)

Proton target

Front End

High-field required to efficiency collect pions and muons
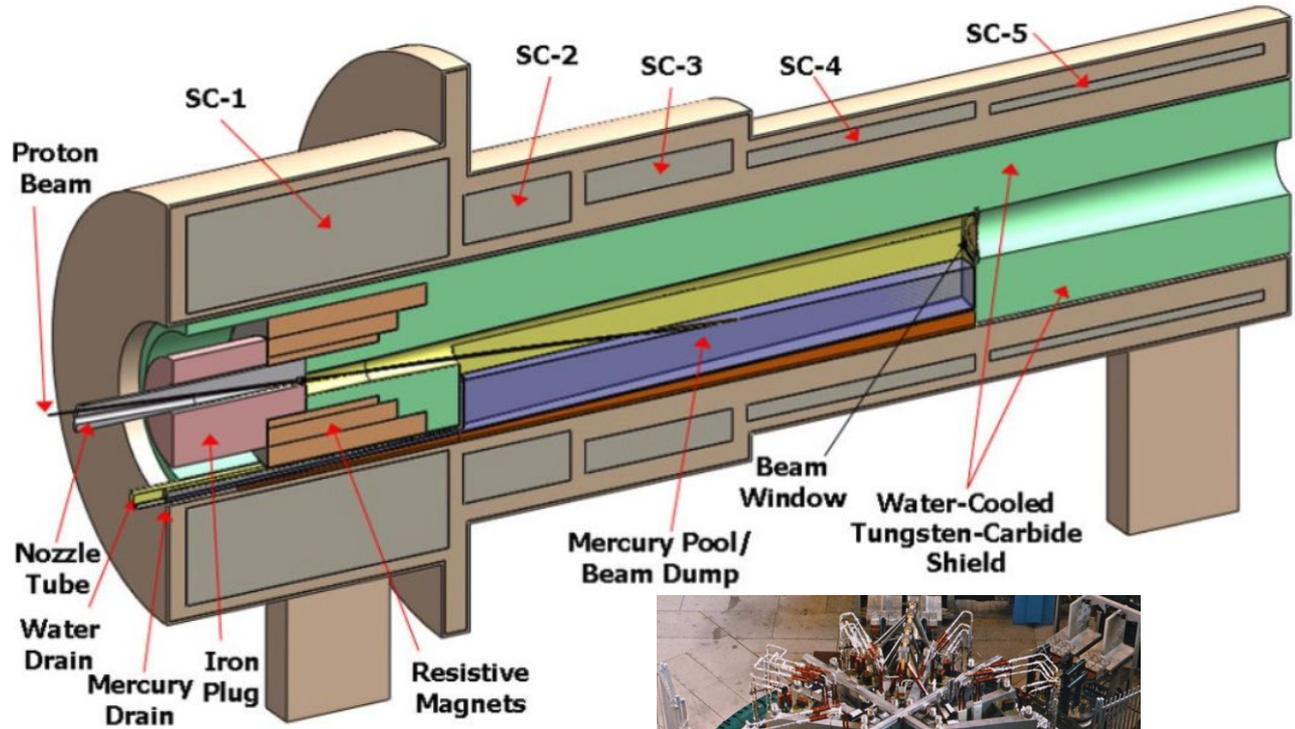
2-4 MW proton beam
- Simulated graphite target ok
- Operation at 2000°C

Large aperture O(1m) to allow shielding
- Synergy with ITER 13 T in 1.7 m
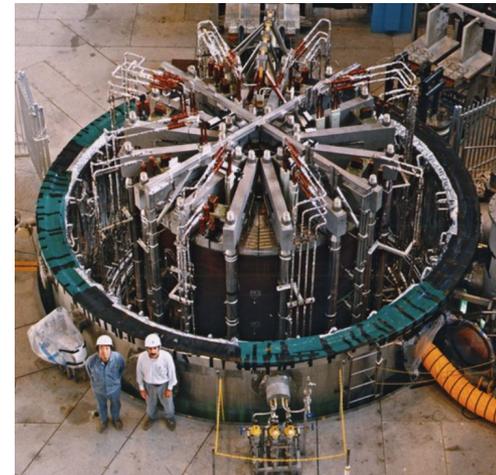
Target

Challenges:
- 2 MW, 5 Hz, 400 MJ/pulse target
- Can we use graphite?

Achieved:
- Initial 2 MW graphite target conceptual design, pion yield optimised
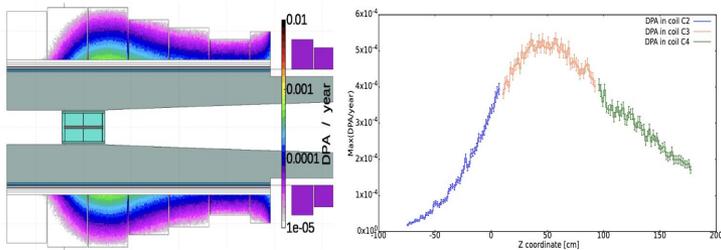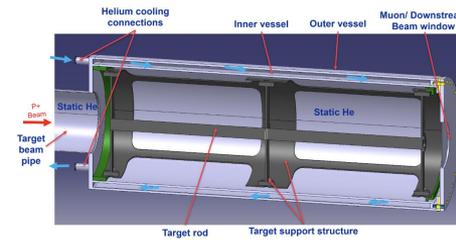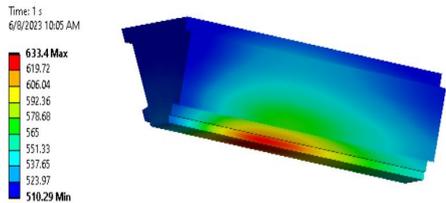- HTS solenoid and shielding concept developed
- Study of proton removal ongoing

US-MAP LTS+resistive hybrid solenoid

All-HTS solenoid

Target & Front End

Pion Target | Chicane & Absorber

Helium cooling connections | Inner vessel | Outer vessel | Muon/ Downstream Beam window

P+ Beam | Static He | Static He

Target beam pipe

Target rod | Target support structure

Time: 1 s
6/8/2023 10:05 AM

633.4 Max
619.72
606.04
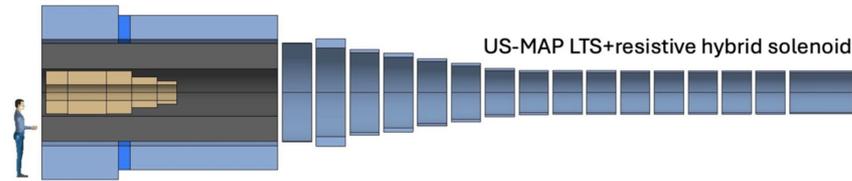592.36
578.68
565
551.33
537.65
523.97
510.29 Min
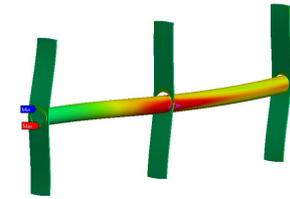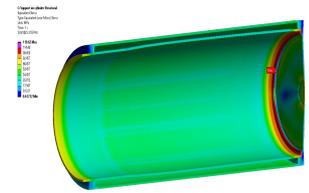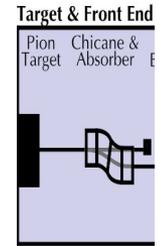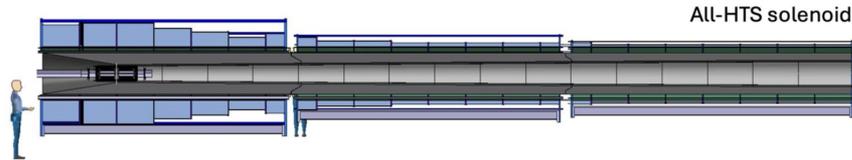
Fig. 6.5.1: 2D map of the displacement per atom (DPA) in the superconducting magnets of the target area (left) and the peak DPA in the coils most exposed to radiation (right).
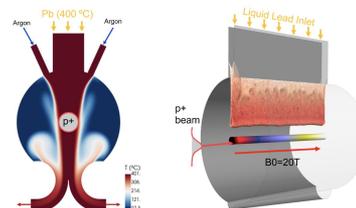
DPA in coil C2
DPA in coil C3
DPA in coil C4

Pb (400 °C)
Argon | Argon
p+ beam
B0=20T
Liquid Lead Inlet

Fig. 6.4.4: Liquid lead target curtain concept.

Key conclusions:
- Yield, magnet shielding, target stress, cooling, radiation are OK
- Components survive 2 MW beam
- Higher power alternatives to study:
  - Graphite
  - Liquid metal

Slide design: D. Schulte, S. Stapnes

Magnet R&D plans

Experimental programme is now essential

Technology-driven R&D programme
- ReBCO tape identified as enabling technology

Fig. 4 – ReBCO Tape merged – quad view – section 1.

- **Target solenoid** - 20 T at 20 K model coil (20@20)
- **6D cooling** - split solenoid integration demonstrator (SOLID)
- **Final cooling** - UHF solenoid demonstrator (UHF-Demo)
- **Fast pulsed for RCS** - magnet string and power systems (RCS-String)
- **Nb3Sn dipole** - wide-aperture, steady state Nb3Sn (MBHY)
- **HTS dipole for accelerator** - rectangular aperture (MBHTS)
- **HTS dipole for collider** - wide aperture (MBHTSY)
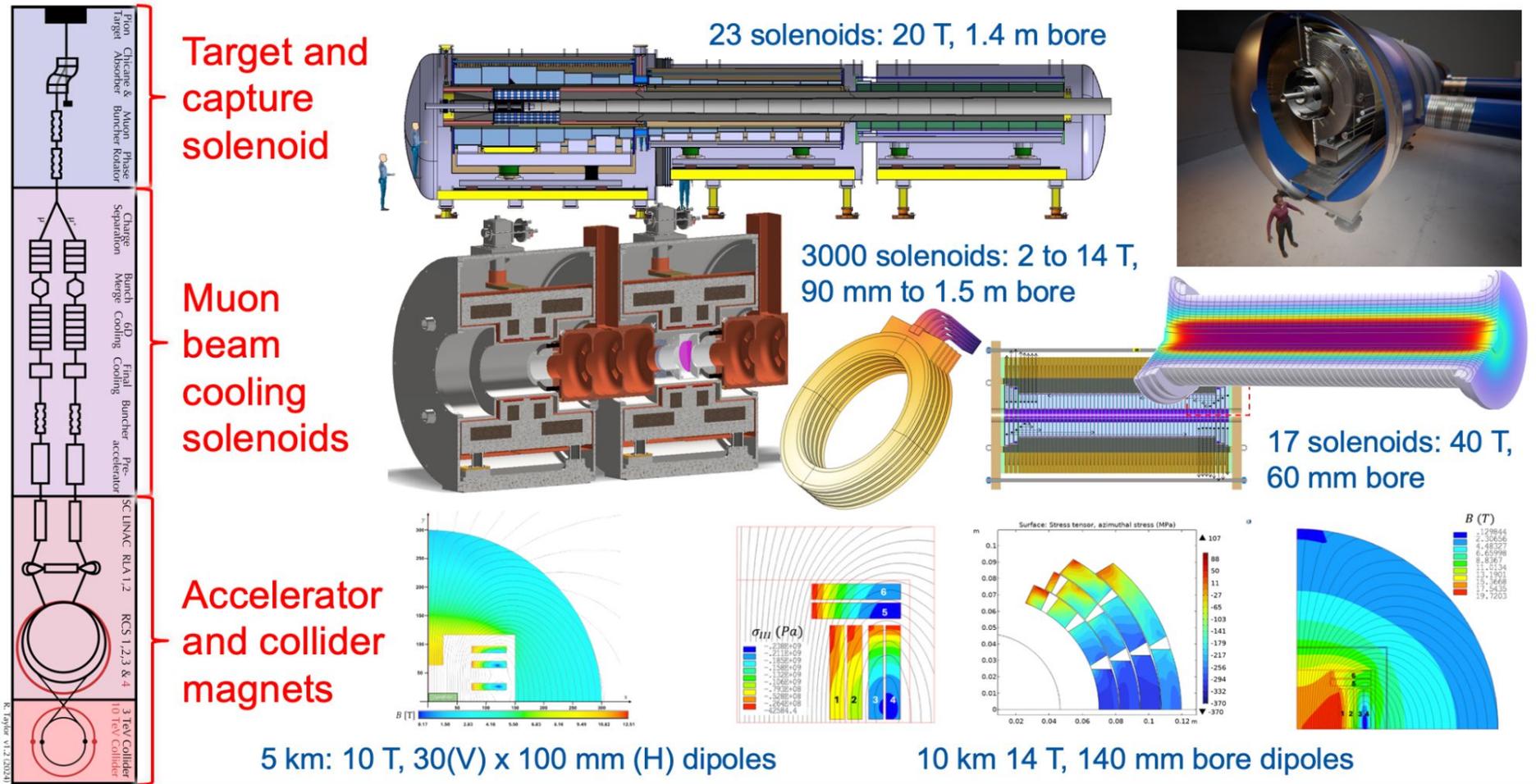- **HTS IR quadrupole** - wide aperture (MQHTSY)

Magnets

Target and capture solenoid

Muon beam cooling solenoids

Accelerator and collider magnets

23 solenoids: 20 T, 1.4 m bore

3000 solenoids: 2 to 14 T, 90 mm to 1.5 m bore

17 solenoids: 40 T, 60 mm bore

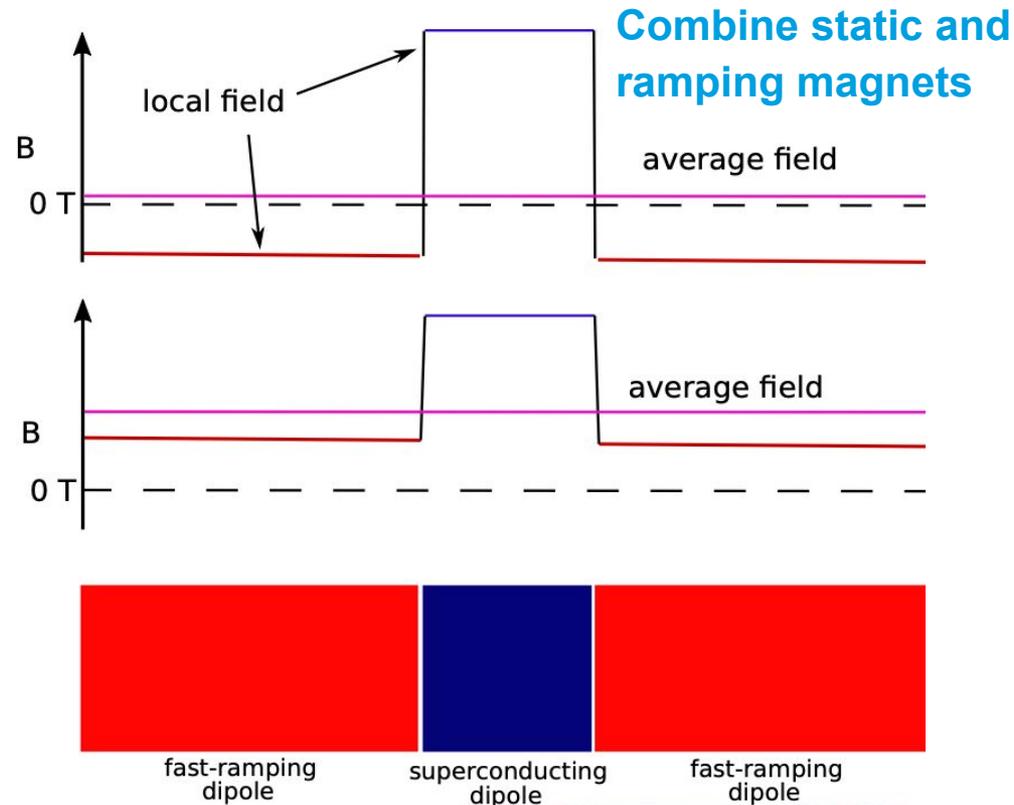5 km: 10 T, 30(V) x 100 mm (H) dipoles

10 km 14 T, 140 mm bore dipoles

From L.Bottura, HFM meeting 10-12.2.2025

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Main difference with other projects: **solenoid R&D is relevant for society!**

Hybrid magnet concept

Combine static and ramping magnets

Ramp magnets to follow E_{beam}

- **Fast-ramping synchrotron magnets** (−2T to 2T in 2 ms)

Need 5 km of 2T magnets per TeV or fast HTS dipoles

Sustainability

	Unit	CERN 3.2 TeV	CERN 7.6 TeV	Green Field 10 TeV
Proton Driver	MW	16.70	16.70	16.70
6D Cooling	MW	11.76	11.76	11.76
RLAs	MW	10.77	10.77	10.77
RCSs	MW	44.19	108.93	124.68
Collider	MW	10.00	4.10	4.10
General Cooling and Ventilation	MW	20.00	20.00	20.00
Total Power consumption	MW	113.42	172.26	188.01

A site reusing existing infrastructure such as CERN for 7.6 TeV center of mass would only need **15 km of tunnels** primarily limited to the muon source, cooling channel and the collider ring

Slide 50

Detector design targets

Requirement	Baseline	Aspirational
Angular acceptance $\eta = -\log(\tan(\theta/2))$	$\|\eta\| < 2.5$	$\|\eta\| < 4$
Minimum tracking distance [cm]	~ 3	< 3
Forward muons ($\eta > 5$)	tag	$\sigma_p/p \sim 10\%$
Track σ_{p_T}/p_T^2 [GeV^{-1}]	4×10^{-5}	1×10^{-5}
Photon energy resolution	$0.2/\sqrt{E}$	$0.1/\sqrt{E}$
Neutral hadron energy resolution	$0.4/\sqrt{E}$	$0.2/\sqrt{E}$
Timing resolution (tracker) [ps]	$\sim 30 - 60$	$\sim 10 - 30$
Timing resolution (calorimeters) [ps]	100	10
Timing resolution (muon system) [ps]	~ 50 for $\|\eta\| > 2.5$	< 50 for $\|\eta\| > 2.5$
Flavour tagging	b vs c	b vs c, s-tagging
Boosted hadronic resonance ID	h vs W/Z	W vs Z

R&D deliverables (magnets)

Technologies	Deliverables	Key parameters and goals
	Magnets	
Target solenoid	Develop conductor, winding and magnet technology	1 m inner / 2.3 m outer diameters, 1.4 m length, 20 T at 20 K
Split 6D cooling solenoid	Demonstration of solenoid with cell integration	510 mm bore, gap 200 mm, 7 T at 20 K
Final cooling solenoid	Build and test HTS prototype	50 mm bore, 15 cm length, 40 T at 4 K
Fast-ramping magnet system	Prototype magnet string and power converter	30 mm x 100 mm, 1.8 T, 3.3 T/s
LTS collider dipole	Demonstrate Nb_3Sn collider dipole	160 mm diameter, 11 T, 4.5 K, 5 m long
HTS RCS dipole	Demonstrate RCS HTS dipole	30 mm x 100 mm, 10 T, 20 K, 1 m long
HTS collider dipole	Demonstrate HTS collider dipole	140 mm diameter, 14 T, 20 K, 1 m long
HTS collider quadrupole	Demonstrate HTS IR quadrupole	140 mm diameter, 300T/m, 4.5K, 1m long

R&D deliverables (RF and cooling)

Technologies	Deliverables	Key parameters and goals
Radiofrequency		
Muon cooling RF cavities	Design, build and test RF cavities	352 MHz and 704 MHz in 10 T field
Klystron prototype	Design/build with Industry 704 MHz (and later 352 MHz) klystron	20 MW peak power, 704 MHz / 352 MHz
RF test stands	Assess cavity breakdown rate in magnetic field	20-32 MV/m, 704 MHz–3 GHz cavities in 7–10 T
SCRF cavities	Design SRF cavities, FPC and HOM couplers, fast tuners, cryomodules	352 MHz, 1056 MHz, 1.3 GHz, 1 MW peak power (FPC)
Muon Cooling		
First 6D cooling cell	Build and test first cooling cell	
5-cell module	Build and test first 5-cell cooling module	
Cooling demonstrator	Design and build cooling demonstrator facility	Infrastructure to test cooling modules with muon beam
Final cooling absorber	Experimental determination of final cooling absorber limit	3×10^{12} muons, 22.5 μm emittance, 40 T field

R&D deliverables (design and other)

Technologies	Deliverables	Key parameters and goals
Design & Other Technologies		
Neutrino flux mover system	Protoype components and tests as needed	Range to reach O($\pm$1mradian)
Beam Instrumentation	Instrumentation component designs	Protoype components and tests as needed
Target Studies	Target design and test of relevant components	0.4 MJ/pulse, 5 Hz
Start-to-End Facility Design	A start-to-end model of the machine consistent with realistic performance specifications	Lattice designs of all beamlines, simulation codes with relevant beam physics, tuning and feedback procedures

Detection Environment

FLUKA simulation
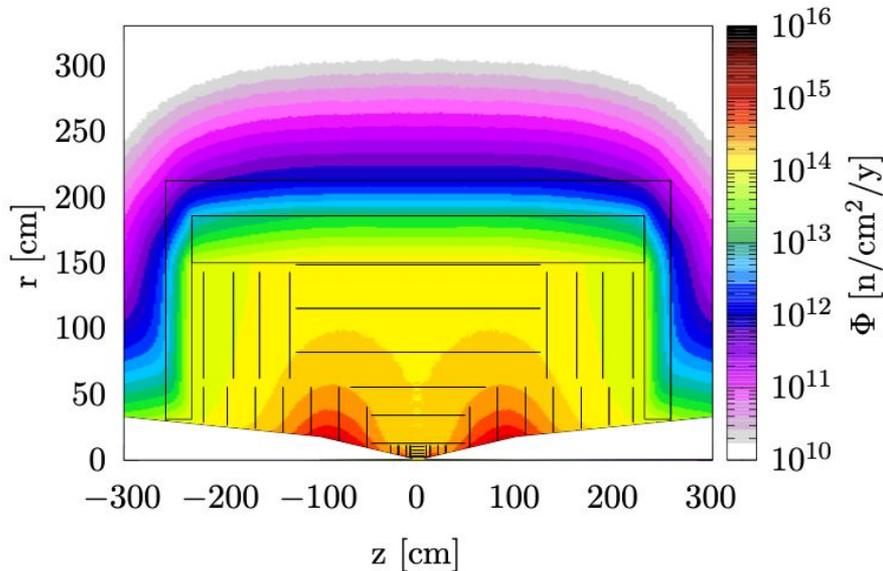
1-MeV-n_{eq}/cm^2 fluence for 200 days of operation
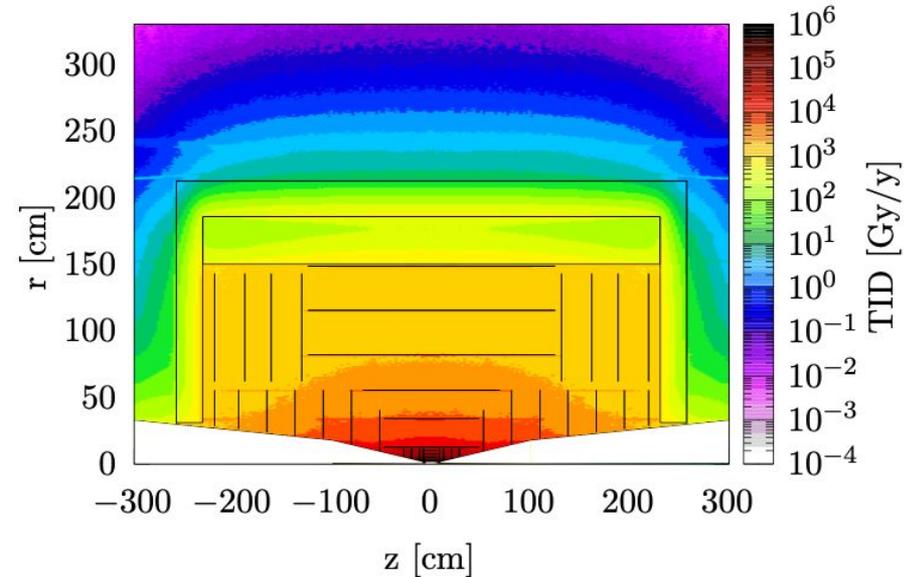
Total Ionising Dose for 200 days of operation

	Maximum Dose (Mrad)		Maximum Fluence (1 MeV-neq/cm^2)	
	R= 22 mm	R= 1500 mm	R= 22 mm	R= 1500 mm
Muon Collider (3 TeV)	10	0.1	10^{15}	10^{14}
HL-LHC	100	0.1	10^{15}	10^{13}
Muon Collider (10 TeV)	20	0.2	3×10^{14}	10^{14}

FCC-hh requirements
~10^{18} 1 MeV-n_{eq}/cm^2

Not one, but two detector concepts

Two concepts making different choices, e.g.

- Position of solenoid
- Tracker layouts
- ECal technology

Compare performances to validate findings, quickly iterate and improve
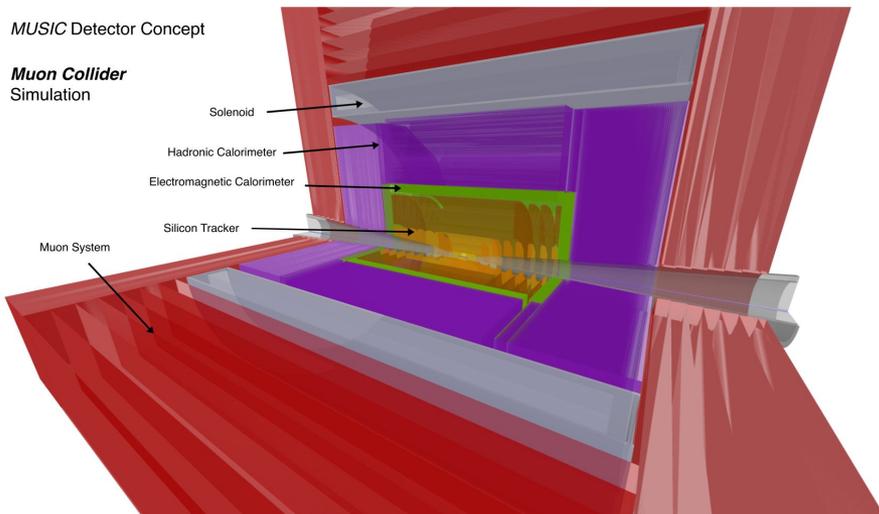
**MUSIC - MUon System
for Interesting Collisions**
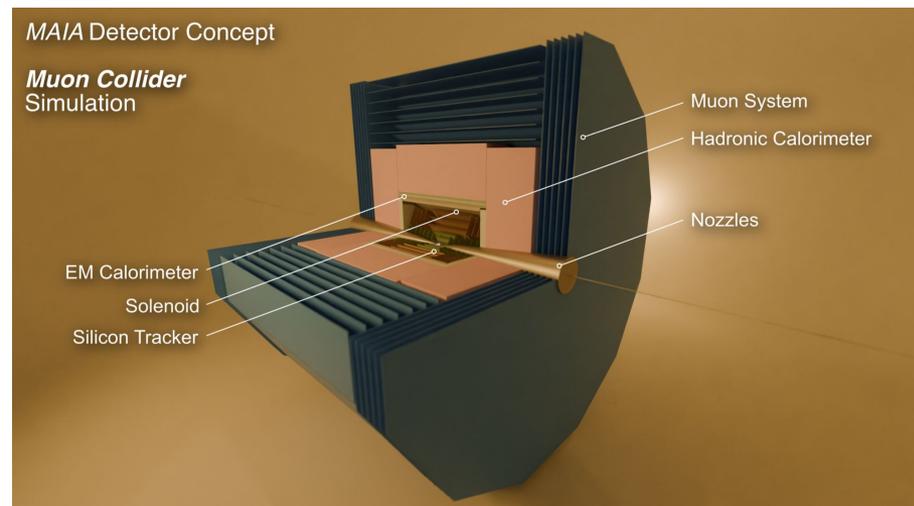
**MAIA - Muon Accelerator
Instrumented Apparatus**

Readout and DAQ

Instantaneous luminosity of $\mathbf{10^{34}\text{-}10^{35}\ cm^{-2}s^{-1}}$

Beam crossings **every 10 µs**

Streaming approach: availability of the full event data → better trigger decision, easier maintenance, simplified design of the detector front-end…

	Hit	On-detector filtering	Number of Links (20 Gbps)	Data Rates
Tracker	32-bit	$t-t_0 < 1$ ns	~3,000	30 Tb/s
Calorimeter	20-bit	$t-t_0 < 0.3$ ns E>200 KeV	~3,000	30 Tb/s

Table credit: S. Jindariani
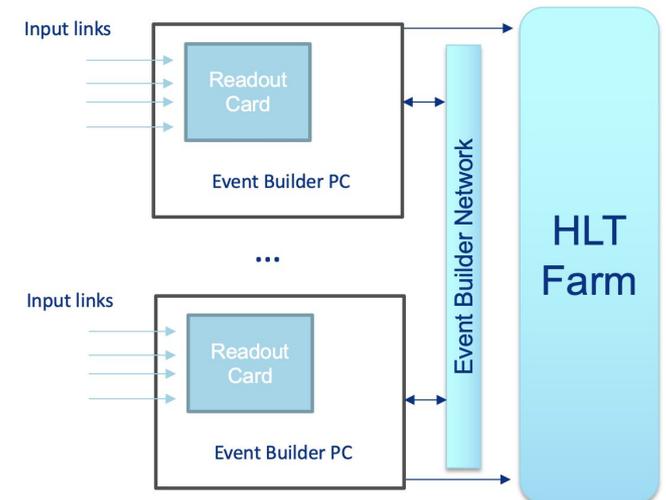
Total data rate similar to HLT at HL-LHC

- **Streaming operation likely feasible**

Muon Cooling Technology

Challenges:
- NC RF cavities in magnetic field (30 MV/m)
- HTS magnets (up to 40 T in final cooling)
- Bright beam hard on absorbers and windows
  - Can evaporise liquid hydrogen
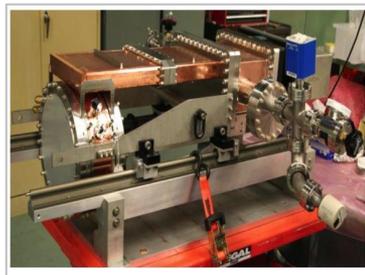
MuCool demonstrated >50 MV/m in 5 T
- H2-filled copper
- Be end caps
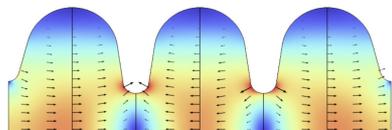
MAP proved gradient
- Initial RF designs
- More RF design ongoing to optimise beamloading

- First window tests performed with protons
- Use of H2 gas in final absorbers

Dipole
RF cavities
Coils
Cooling Cell
Magnet Stucture
Absorber
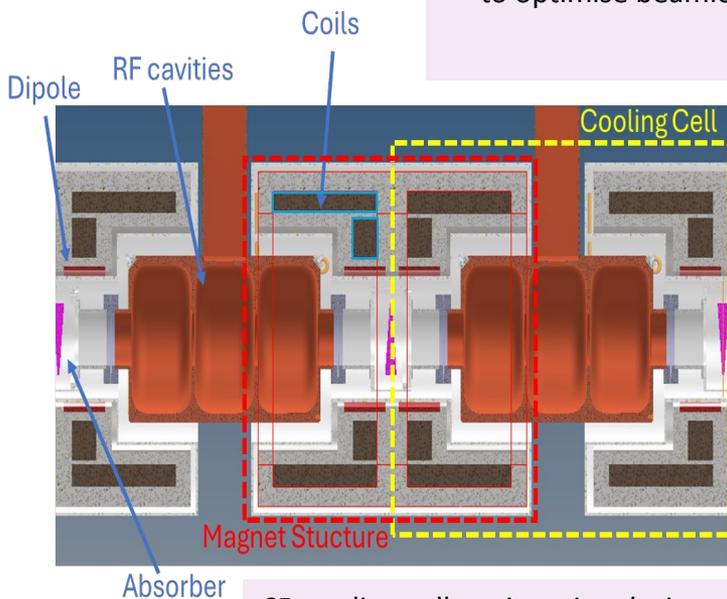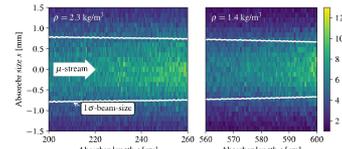
6D cooling cell engineering design almost ready
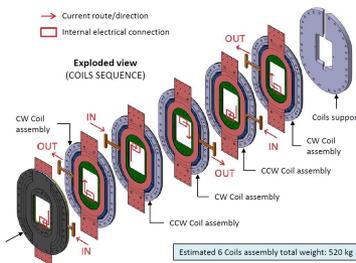
Key conclusions:
- Ready to **ramp-up effort**, in particular prototyping and experimental work, also beamdynamics
- **Need RF test stands** for experimental optimization

Collider Ring

Challenges:
500 W/m loss, magnet strength, lattice design with beta 1.5-5 mm, 0.1% beam energy spread

Achieved:
- Magnet shielding design
- Magnet performance model and conceptual designs
- Cryogenics conceptual design
- Lattice reaches target beta-functions but not yet full target energy acceptance
- First studies of mover system impact on beam
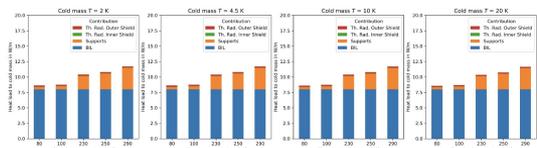- Impedance is OK

Shielding (30-40 mm)

Cryogenic loads at different temperatures

Fig. 6.7.2: Estimated heat load deposited on the cold mass in W/m, as a function of absorber temperature, for an absorber thickness of 30 mm, for nominal magnet operating temperatures of 2 K, 4.5 K, 10 K and 20 K (from [351]). The thermal shields (inner shield between absorber and coil, and outer

β = 1.5 mm
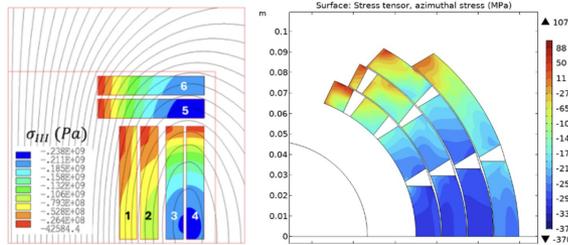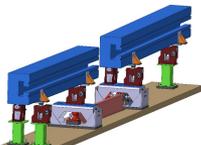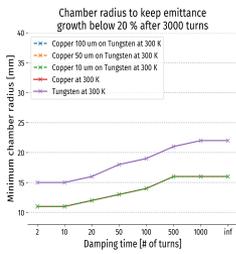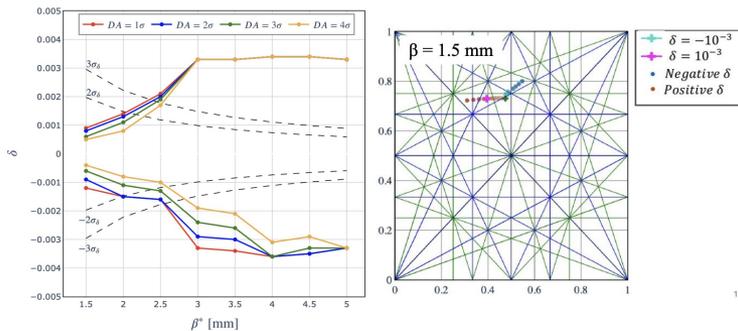
Fig. 6.1.31: Mechanical stress on conductor under Lorentz Forces at nominal current for both block coil and cos-theta magnet configurations.

Magnet Designs

Key conclusions:
Further improve energy acceptance, but OK with energy spread predicted in muon cooling
Mover system OK for beam in regular arcs
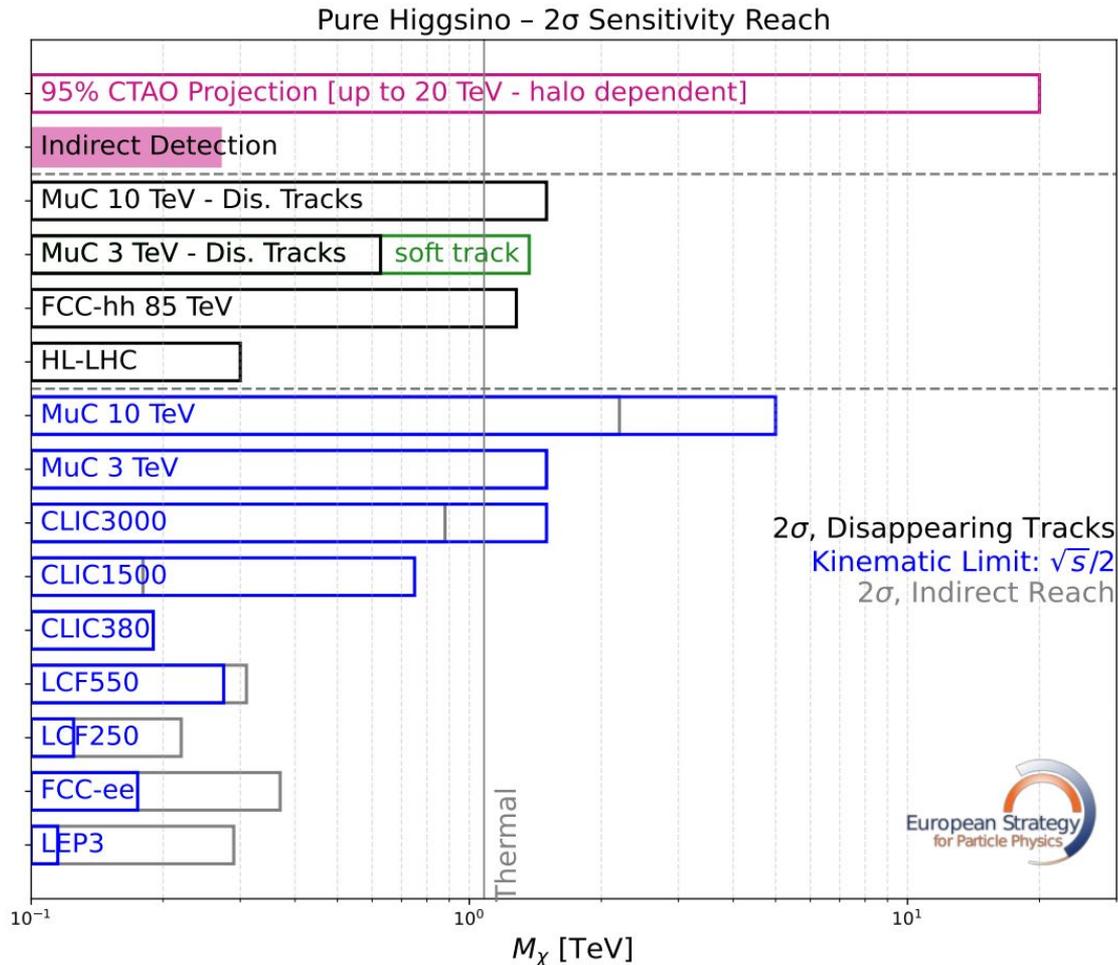Address imperfections next

Slide design: D. Schulte, S. Stapnes

16
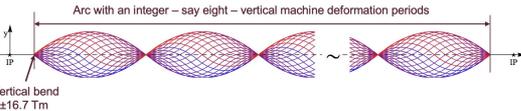
Minimal dark matter

Amazing **WIMP** or **minimal dark matter** search programme

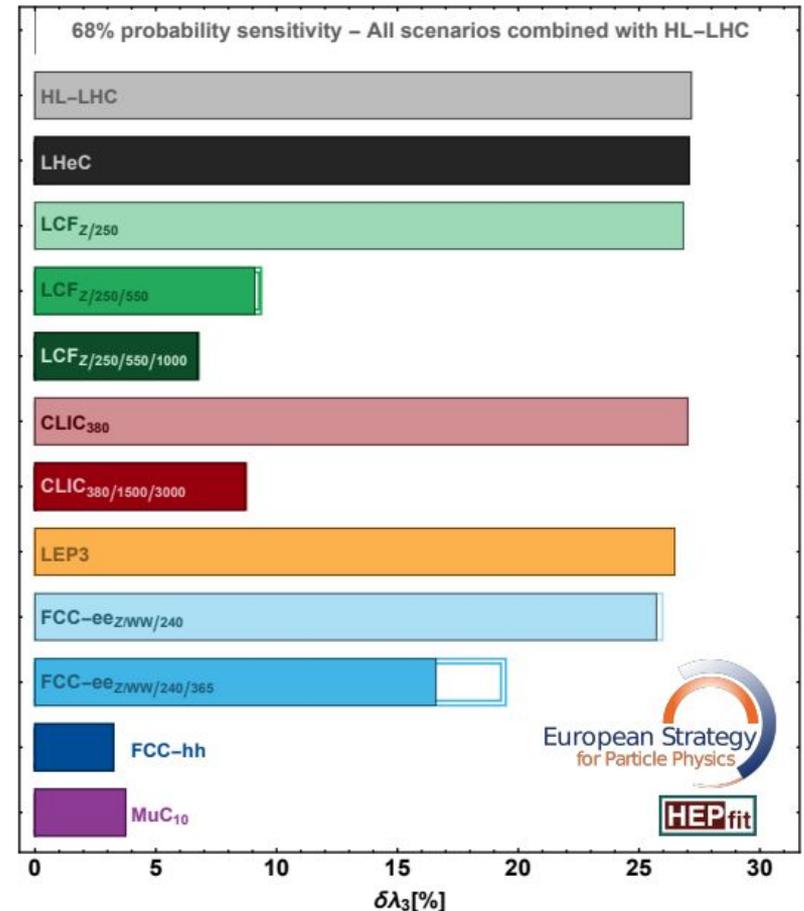**Only collider able to discover** both Wino and Higgsino thermal targets

Pure Higgsino – 2σ Sensitivity Reach

Exploring the Higgs potential

Expect ~10x Higgses wrt e^+e^- Higgs factories, with nearly same S/B conditions

	HL-LHC	HL-LHC +10 TeV	HL-LHC +10 TeV + ee
κ_W	1.7	0.1	0.1
κ_Z	1.5	0.4	0.1
κ_g	2.3	0.7	0.6
κ_γ	1.9	0.8	0.8
$\kappa_{Z\gamma}$	10	7.2	7.1
κ_c	-	2.3	1.1
κ_b	3.6	0.4	0.4
κ_μ	4.6	3.4	3.2
κ_τ	1.9	0.6	0.4
κ_t^*	3.3	3.1	3.1

* No input used for the MuC
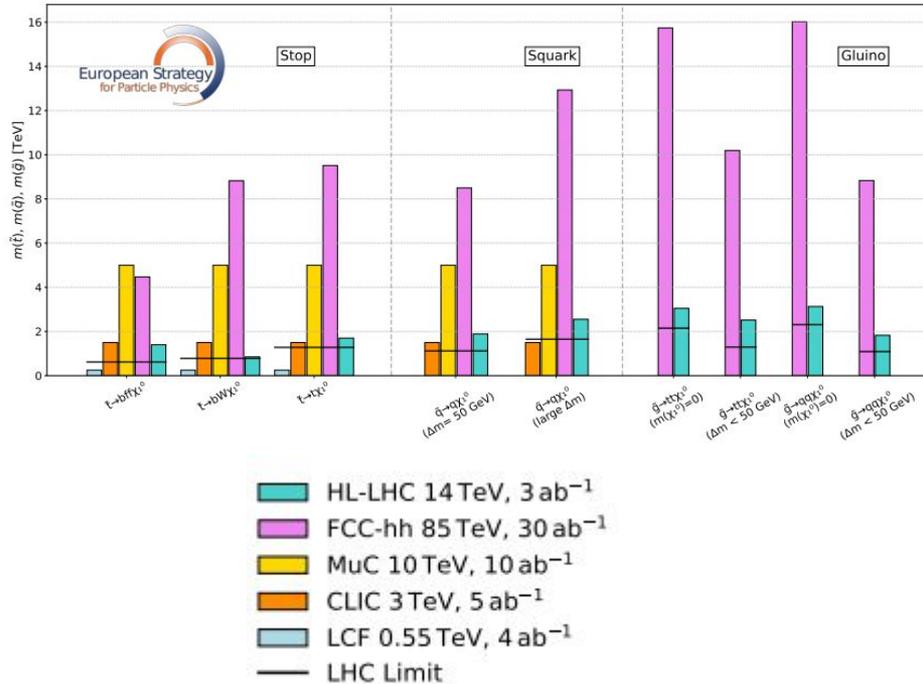

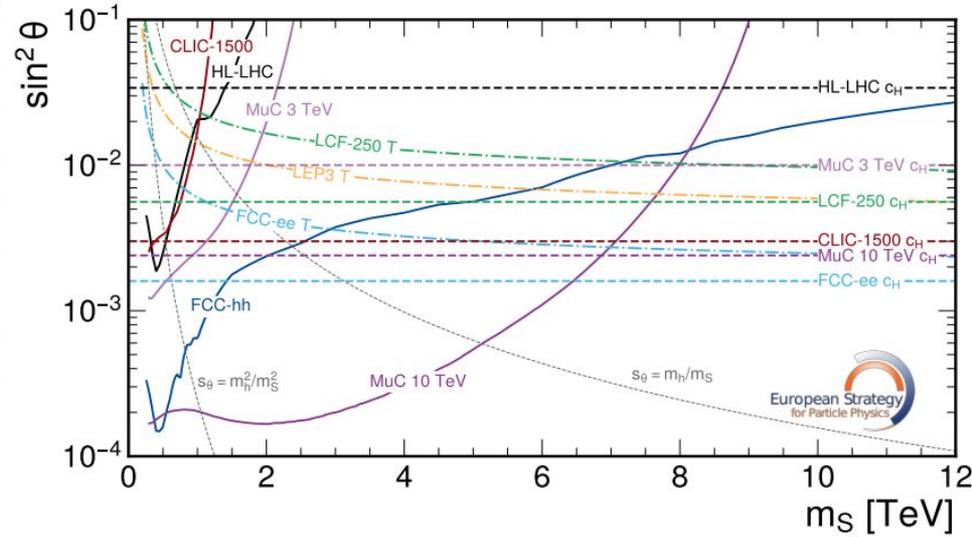68% probability sensitivity – All scenarios combined with HL–LHC

Total inclusive Higgs cross-section potentially accessible via Z-fusion processes
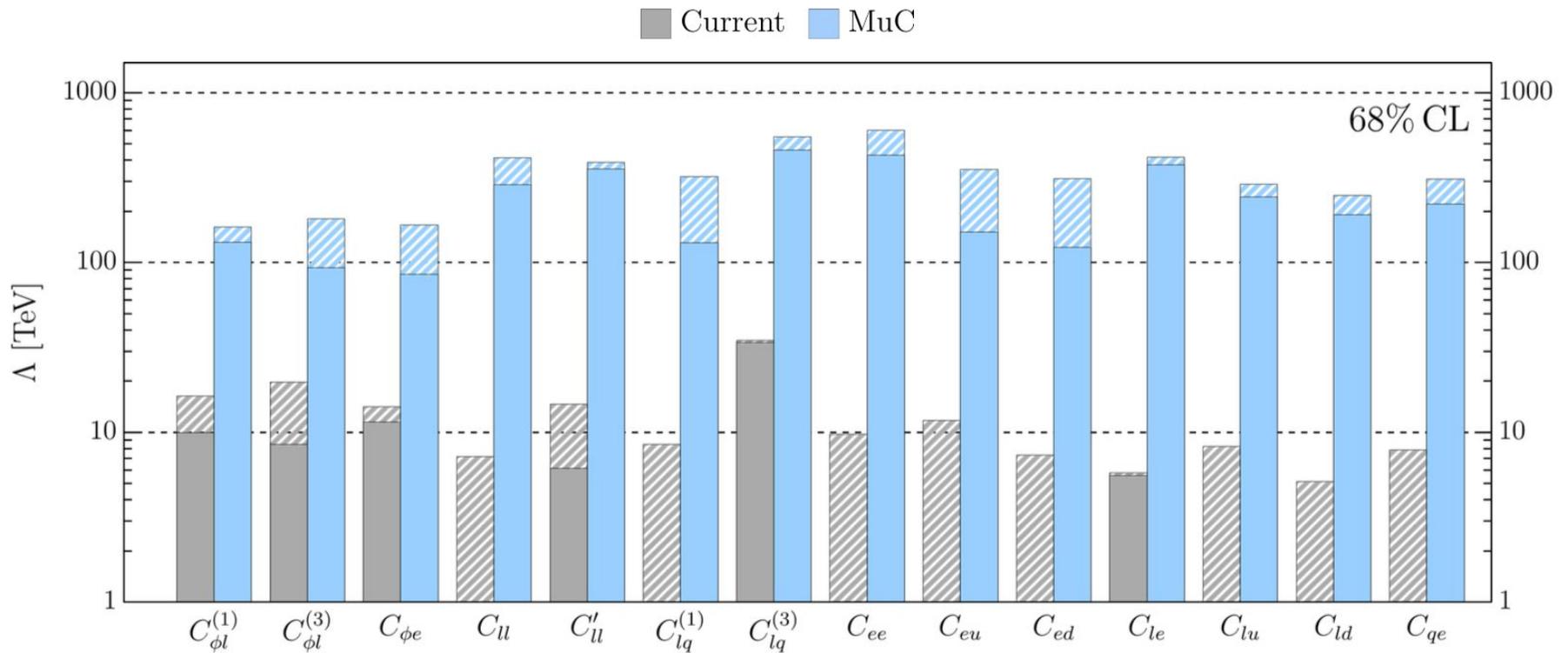
Direct mass reach

SUSY

Scalar singlet
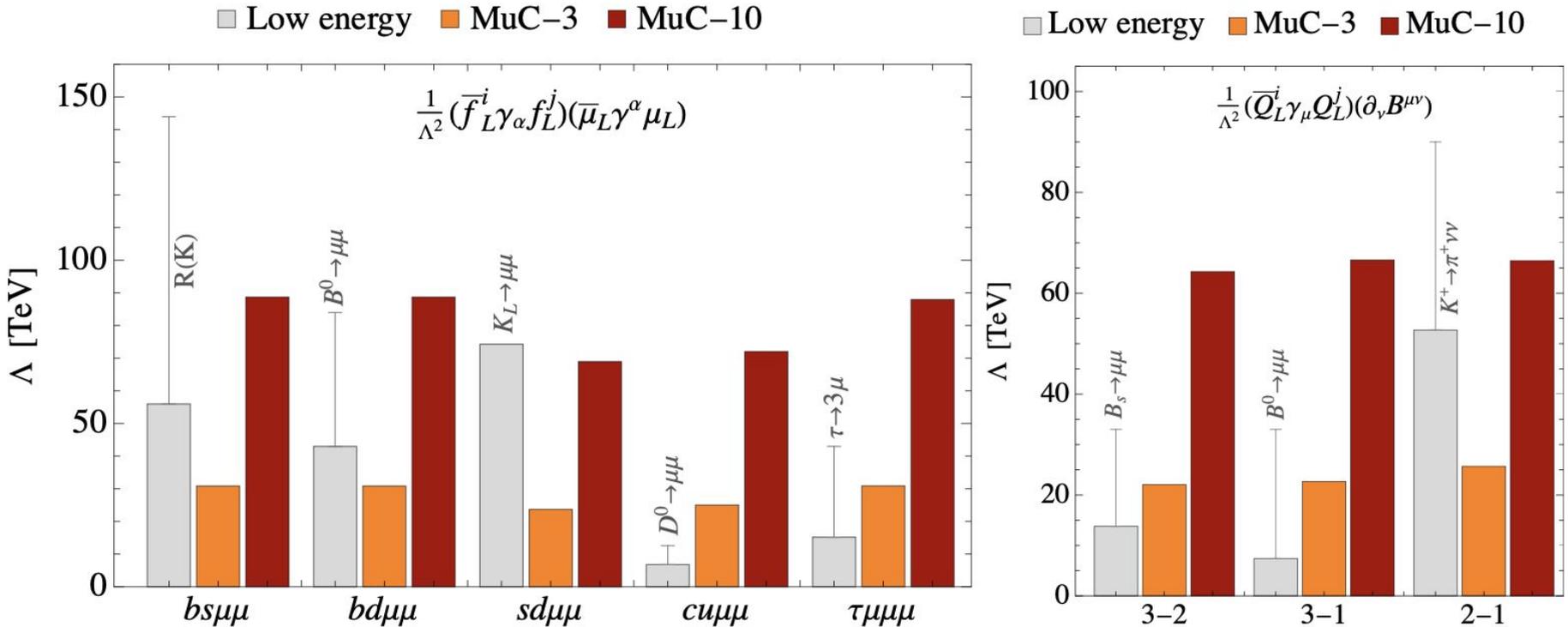
EFT

Warsaw basis operators that grow with the energy and interfere with the SM in di-fermion and di-boson production

Flavour

Sensitivity reach in the effective scale Λ of effective operators containing a quark or lepton flavour-violating current, coupled to either a muon current (left panel) or a flavour-blind gauge current.