

Towards a muon collider

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DESY and University of Bern

IFIC Seminar
03/02/2026

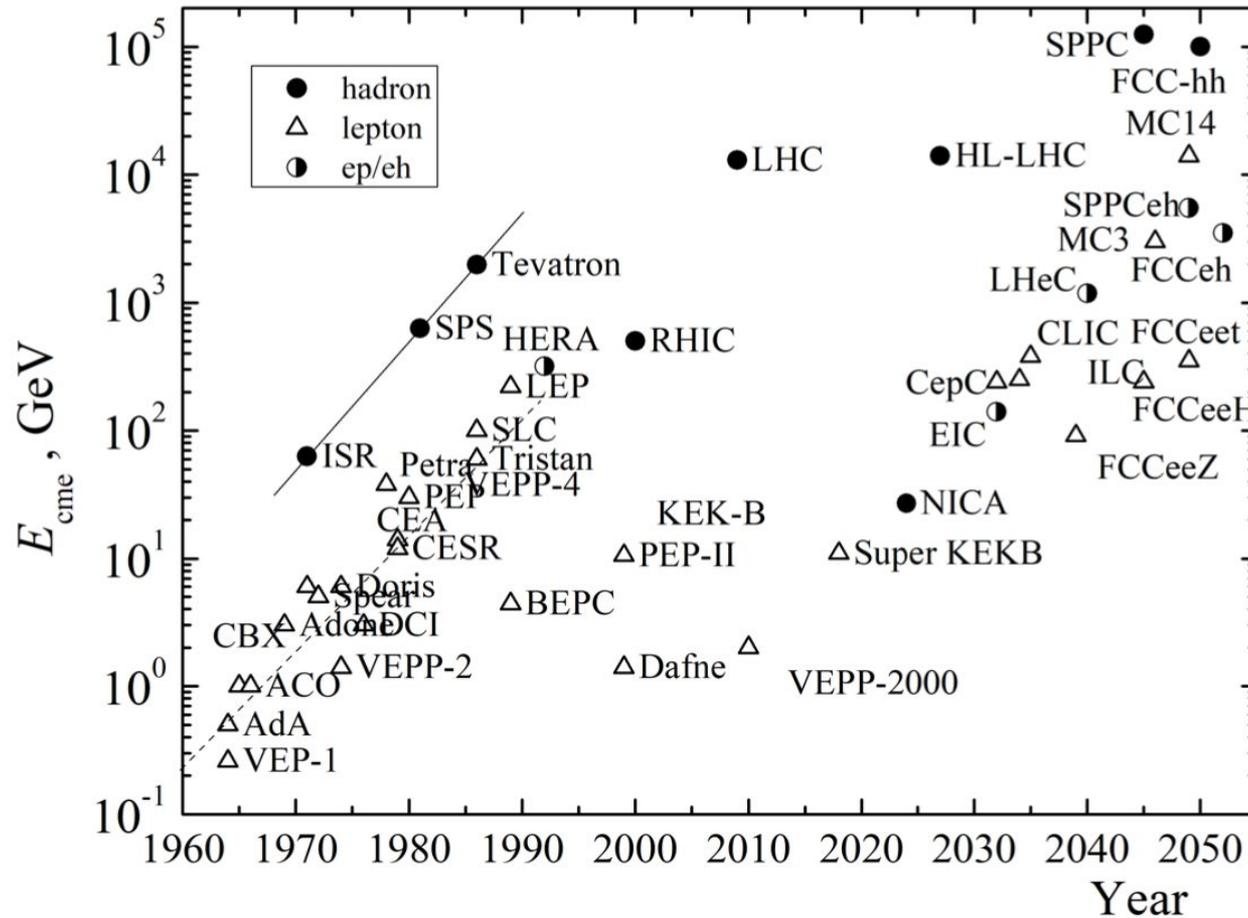
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES



Co-funded by
the European Union

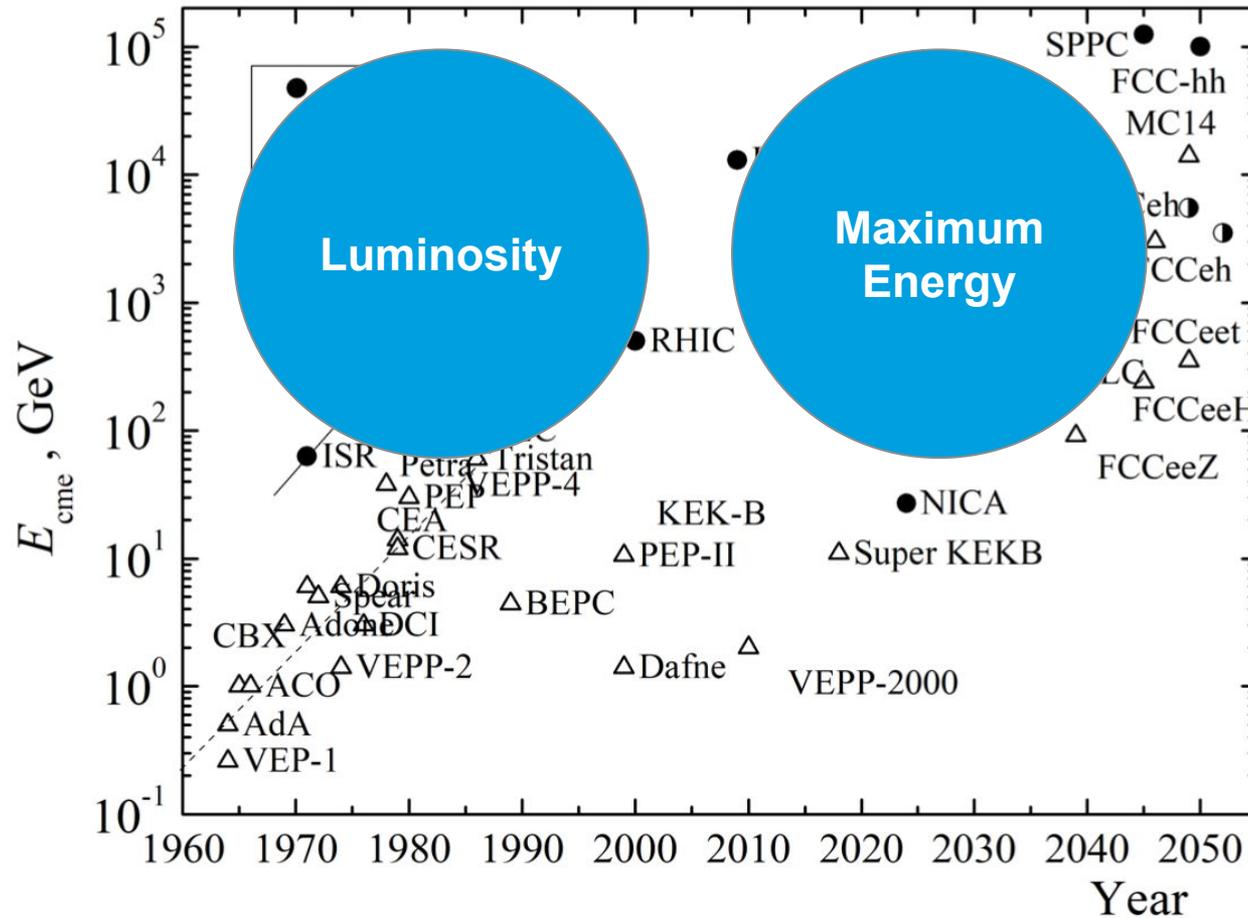
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Colliders shaped modern particle physics



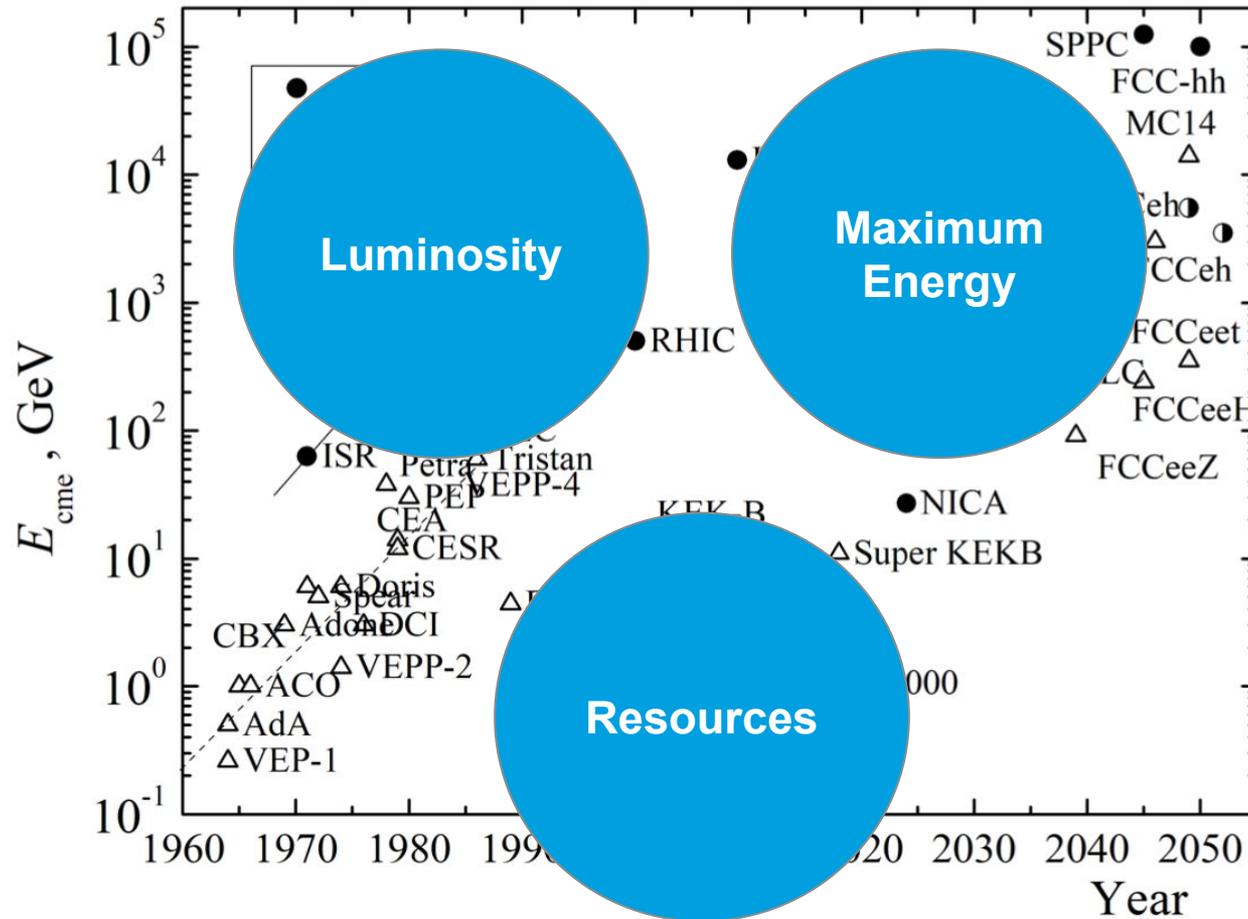
5 orders of magnitude in E_{CM} in 6 decades (0.2 GeV \rightarrow 14 TeV)!

Development drivers



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Development drivers

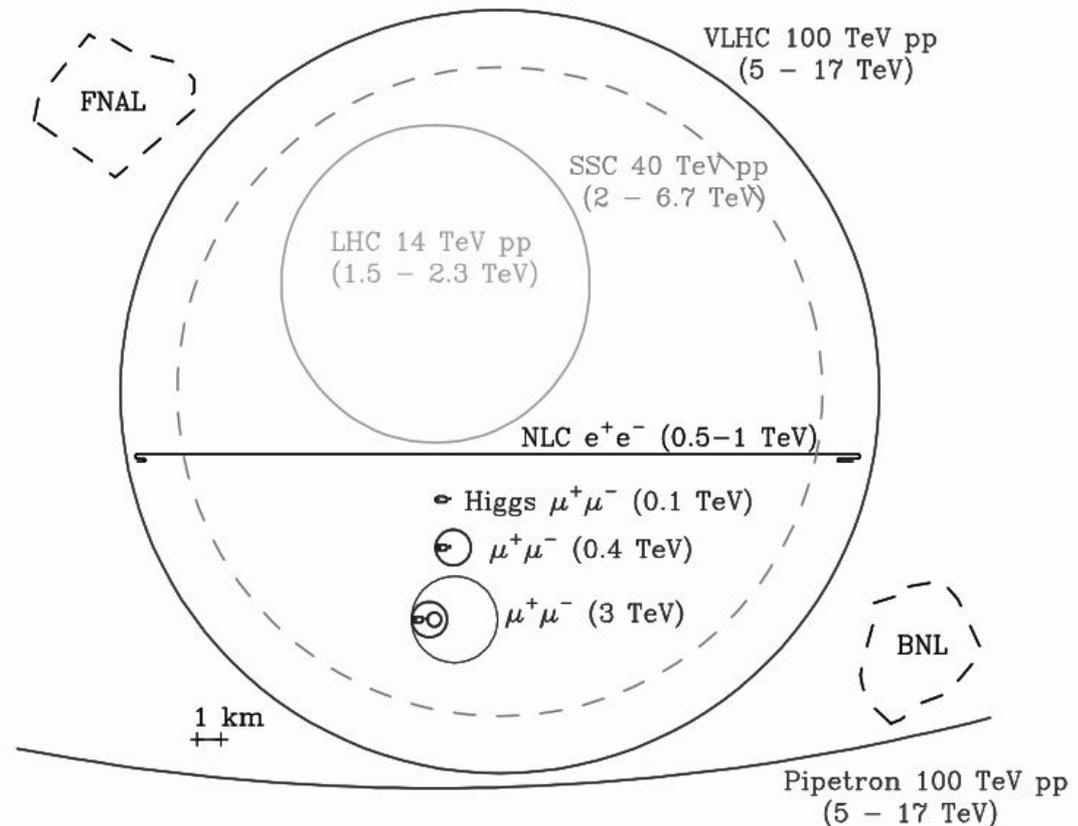


Why muons?

Historically, we probed shorter distances with either precision or energy

Muon colliders blur this dichotomy

Muons are *elementary* particles with a mass ($105.7 \text{ MeV}/c^2$, $207 \times e^\pm$ mass) large enough to make *radiation negligible*

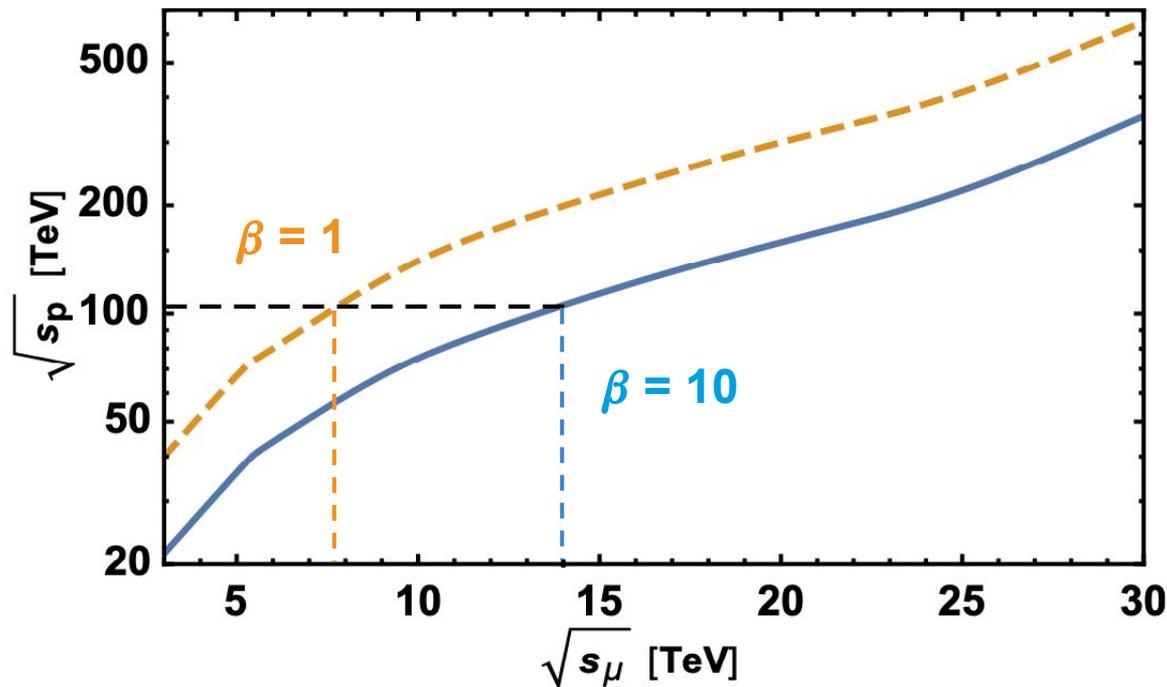


Why muons?

Leptons are the ideal probes of short-distance physics

- High-energy physics probed with much smaller collider energy

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



Why are we excited?

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

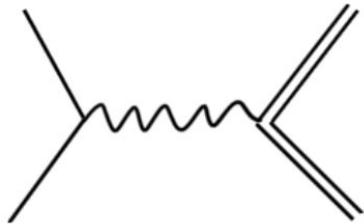
- High available energy for new heavy particle production



Energy

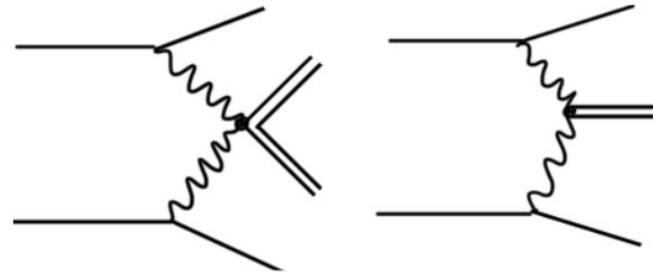
Why are we excited?

Direct searches for new particles



$\mu\mu$ annihilation

EW-charged particles up to $E_{\text{cm}}/2$



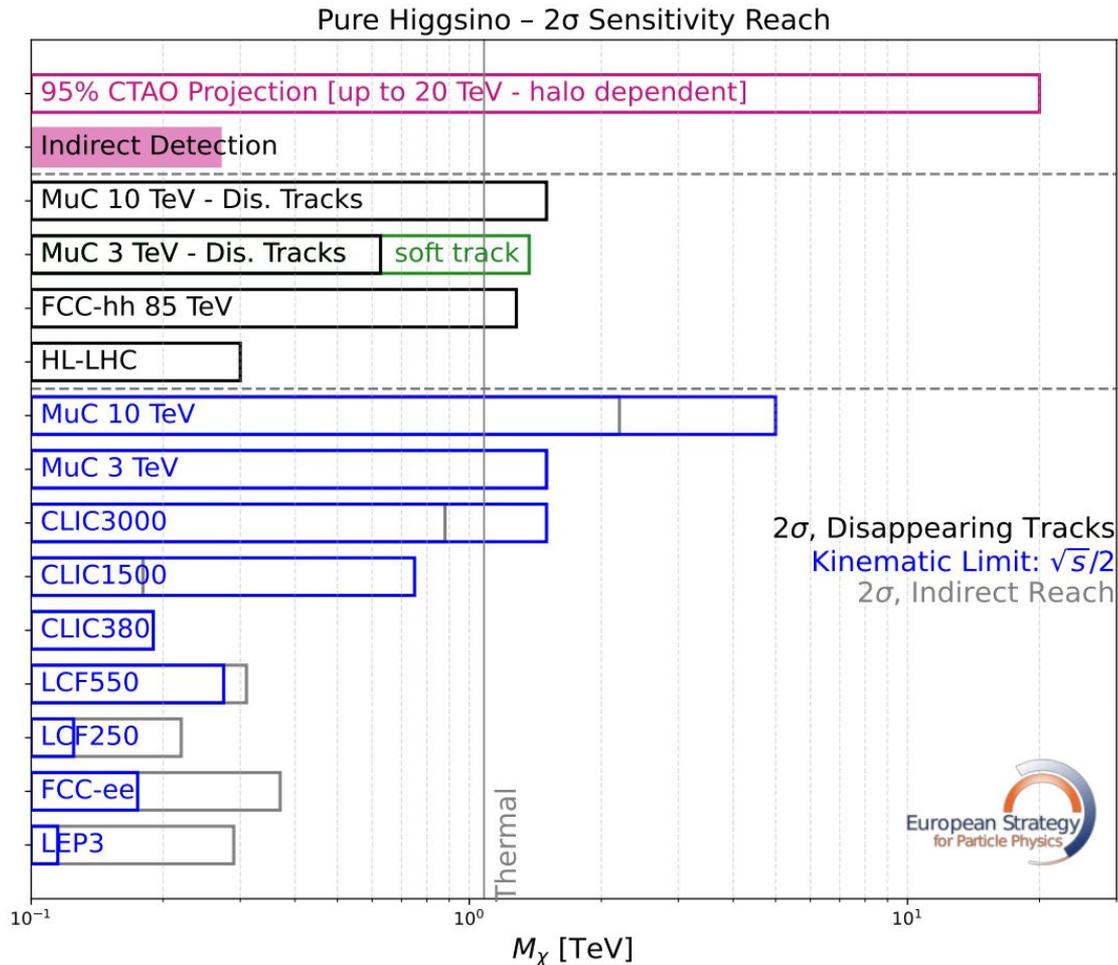
Vector Bosons Fusion

EW-neutral **Higgs-Portal** particles

Minimal dark matter

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

Only collider able to discover both Wino and Higgsino thermal targets



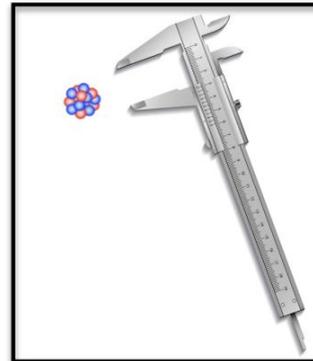
Why are we excited?

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



Energy



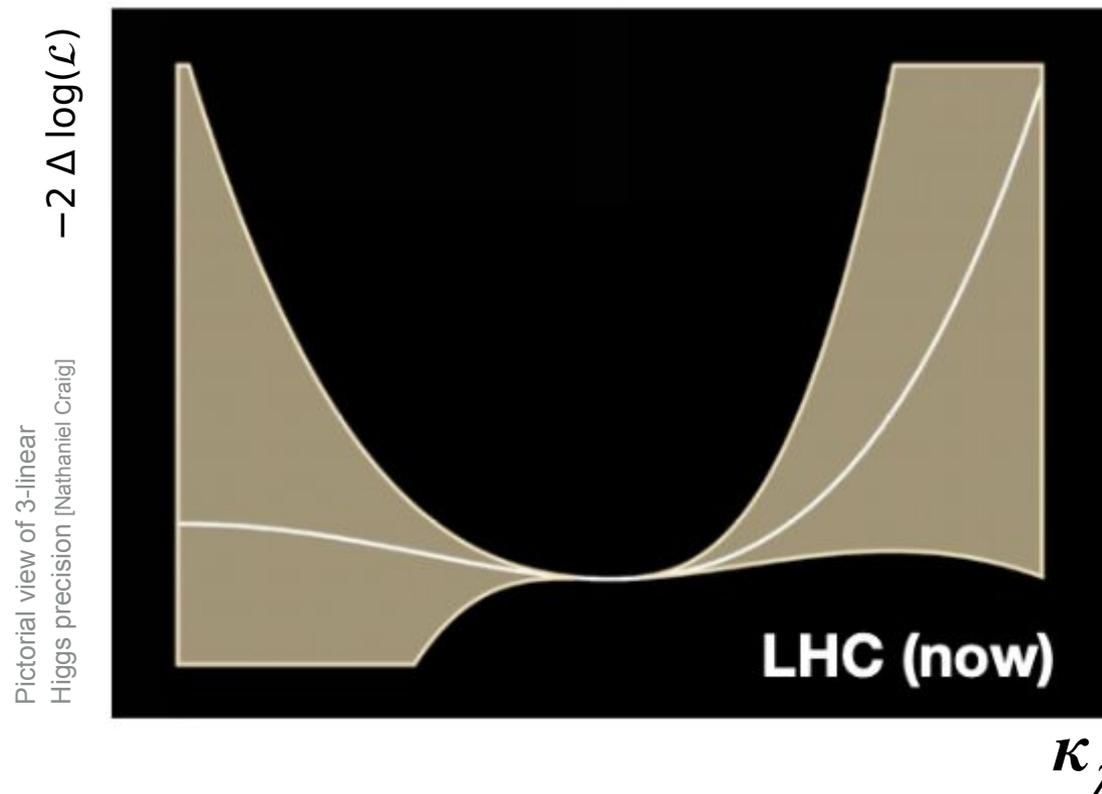
Precision

Why are we excited?

High precision indirect probes

The Higgs is revolutionary!

Is it the SM Higgs Particle? What is it made of?



Why are we excited?

High precision indirect probes

The Higgs is revolutionary!

Is it the SM Higgs Particle? What is it made of?



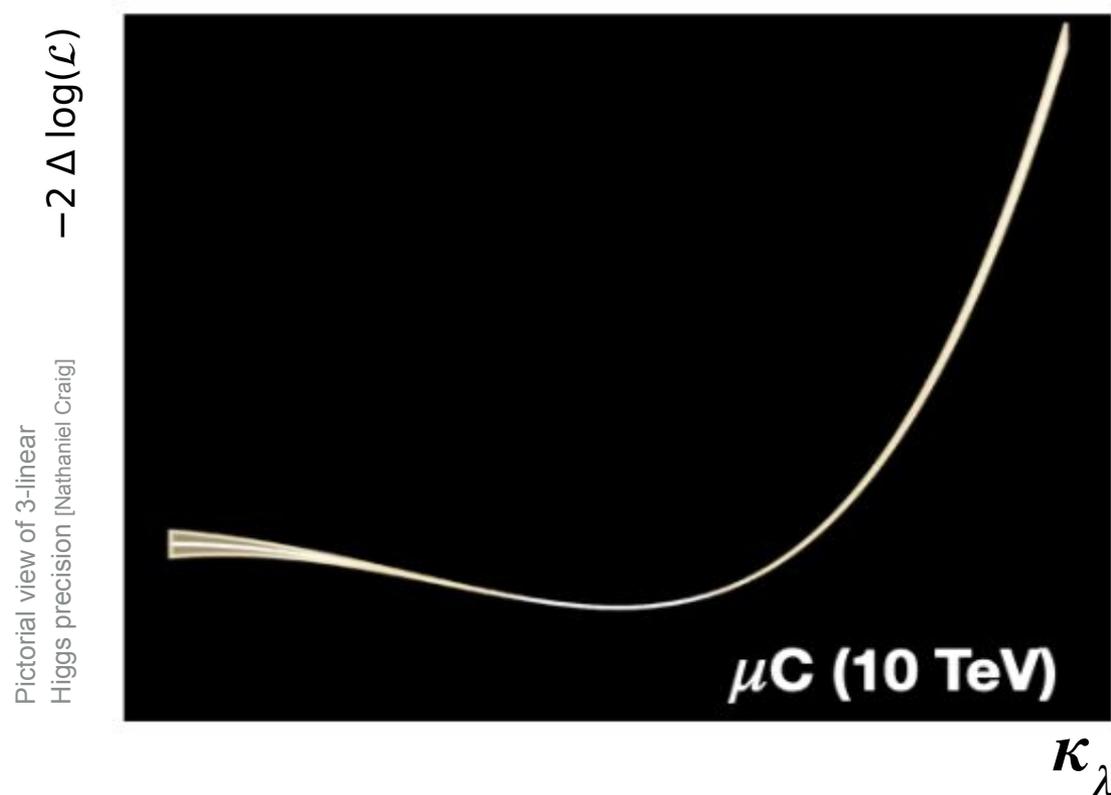
actually we'll
do a little better

Why are we excited?

High precision indirect probes

The Higgs is revolutionary!

Is it the SM Higgs Particle? What is it made of?

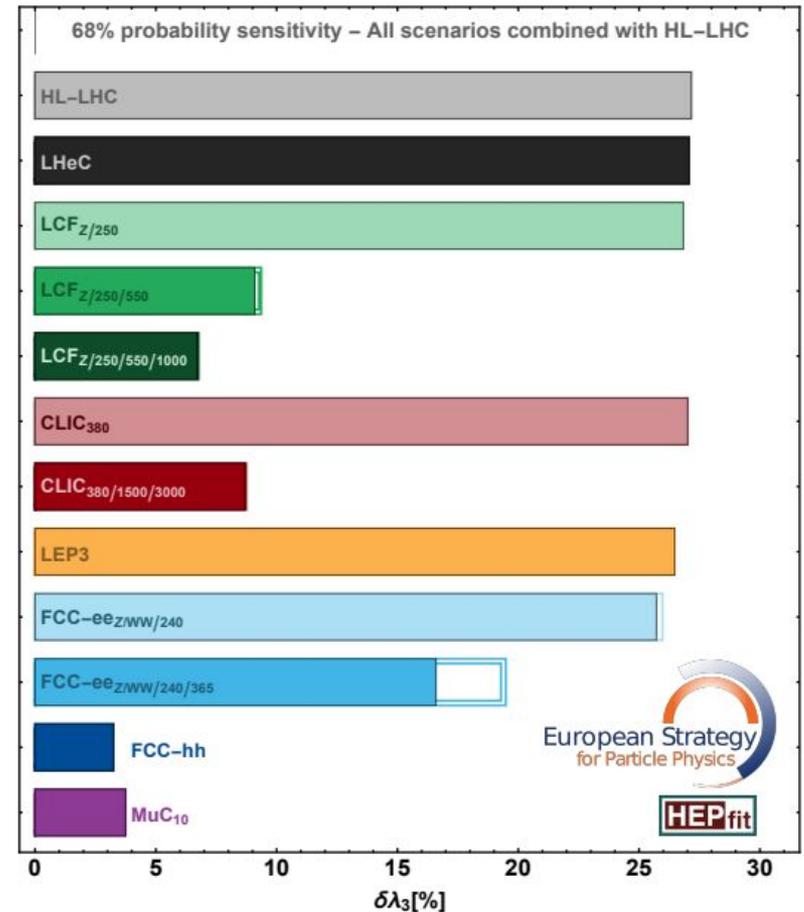


Exploring the Higgs potential

Expect $\sim 10x$ 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_T	1.9	0.6	0.4
κ_t^*	3.3	3.1	3.1

* No input used for the MuC



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

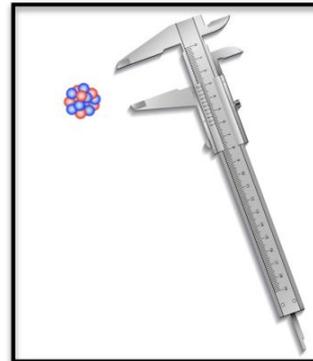
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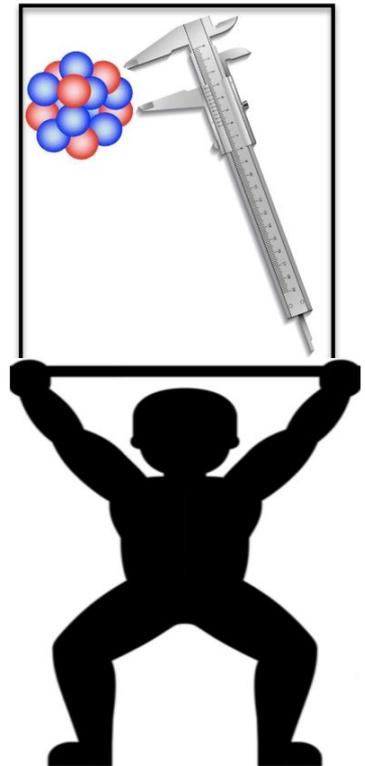
- High available energy for new heavy particle production
- High available statistics for precise measurements
- Can measure processes of very high energy



Energy



Precision



**High-energy
Precision**

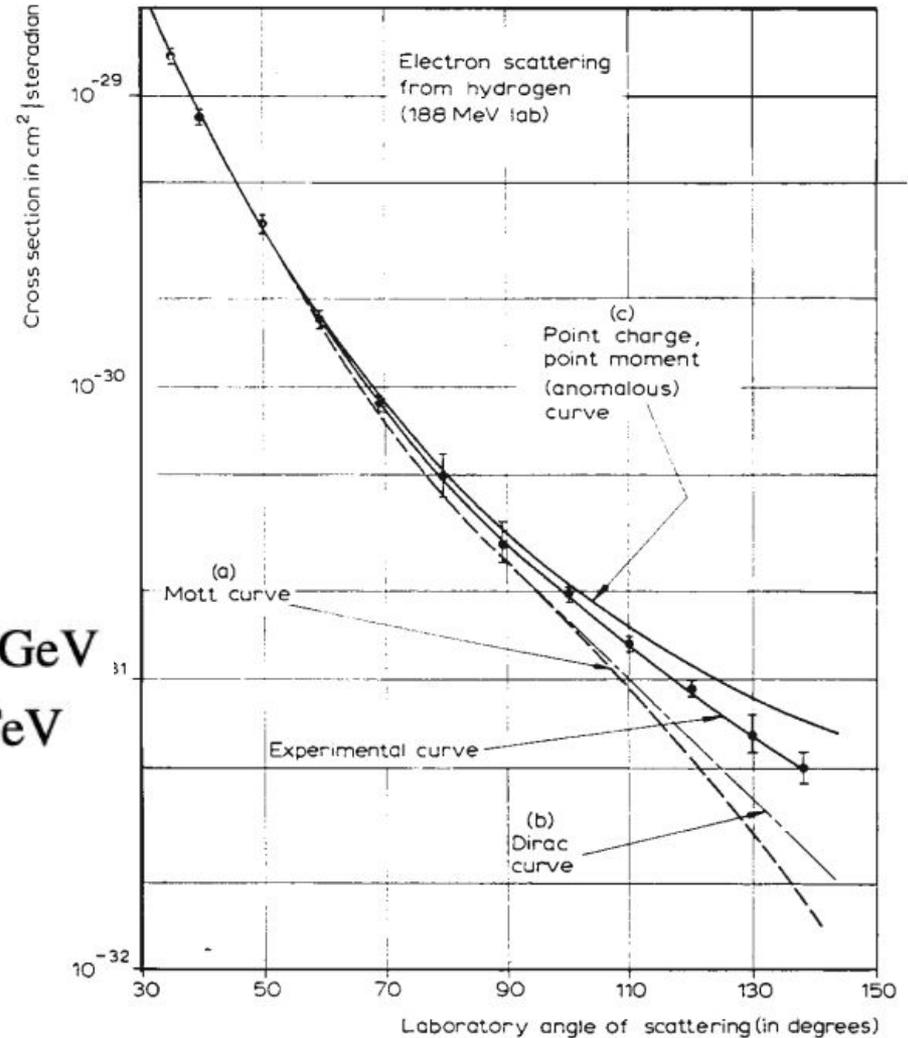
Why are we excited?

Energy helps accuracy

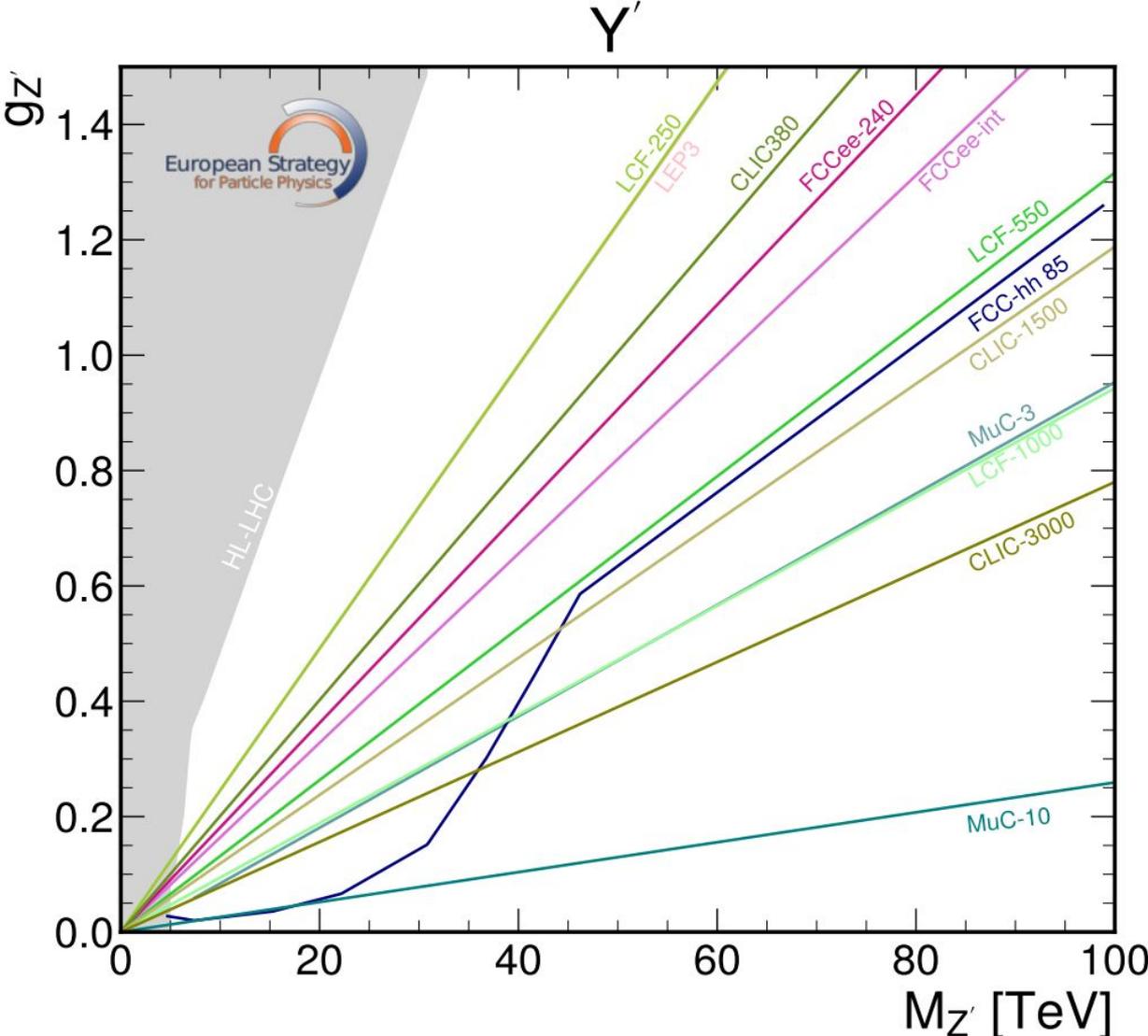
Many discoveries came neither from new particle detection, nor from extreme precision, **but needed energy**

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

ELECTRON-SCATTERING METHOD



Heavy resonances



A brief history of muon colliders



International
MUCON Collider
Collaboration

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

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

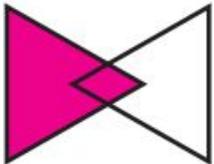
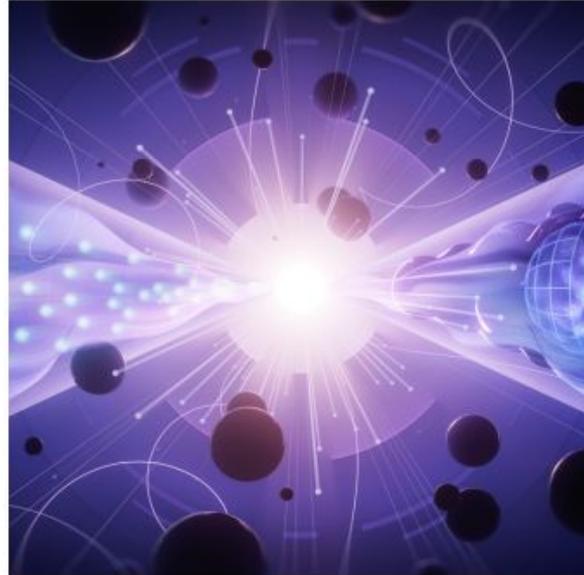
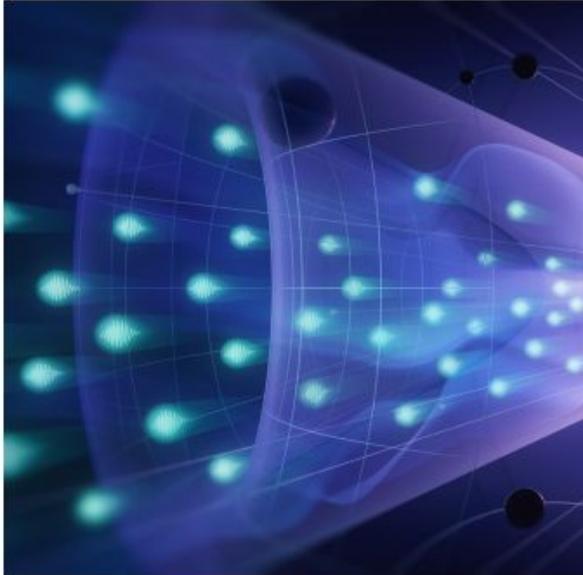
European Strategy for Particle Physics Update 2020

- Set up an international collaboration

2023 P5 process

- The Muon Shot

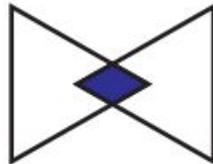
The Muon Shot



Decipher
the
Quantum
Realm

Elucidate the Mysteries
of Neutrinos

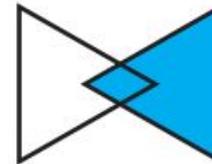
Reveal the Secrets of
the Higgs Boson



Explore
New
Paradigms
in Physics

Search for Direct Evidence
of New Particles

Pursue Quantum Imprints
of New Phenomena



Illuminate
the
Hidden
Universe

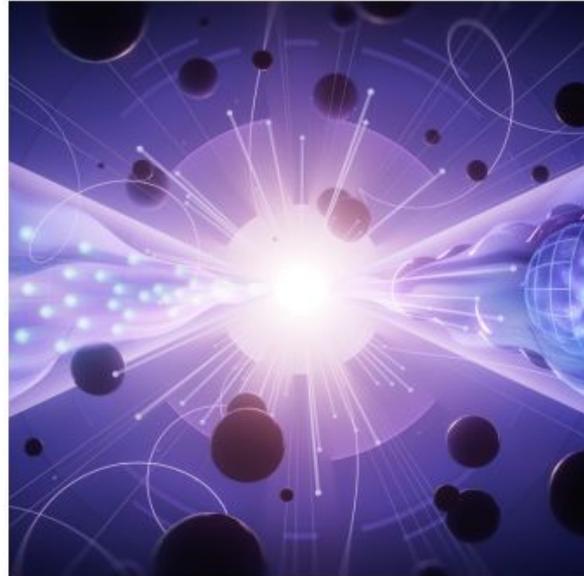
Determine the Nature
of Dark Matter

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 ESPPU input 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



European Strategy
for Particle Physics

The European Strategy for Particle Physics:
2026 Update

European strategy for particle physics

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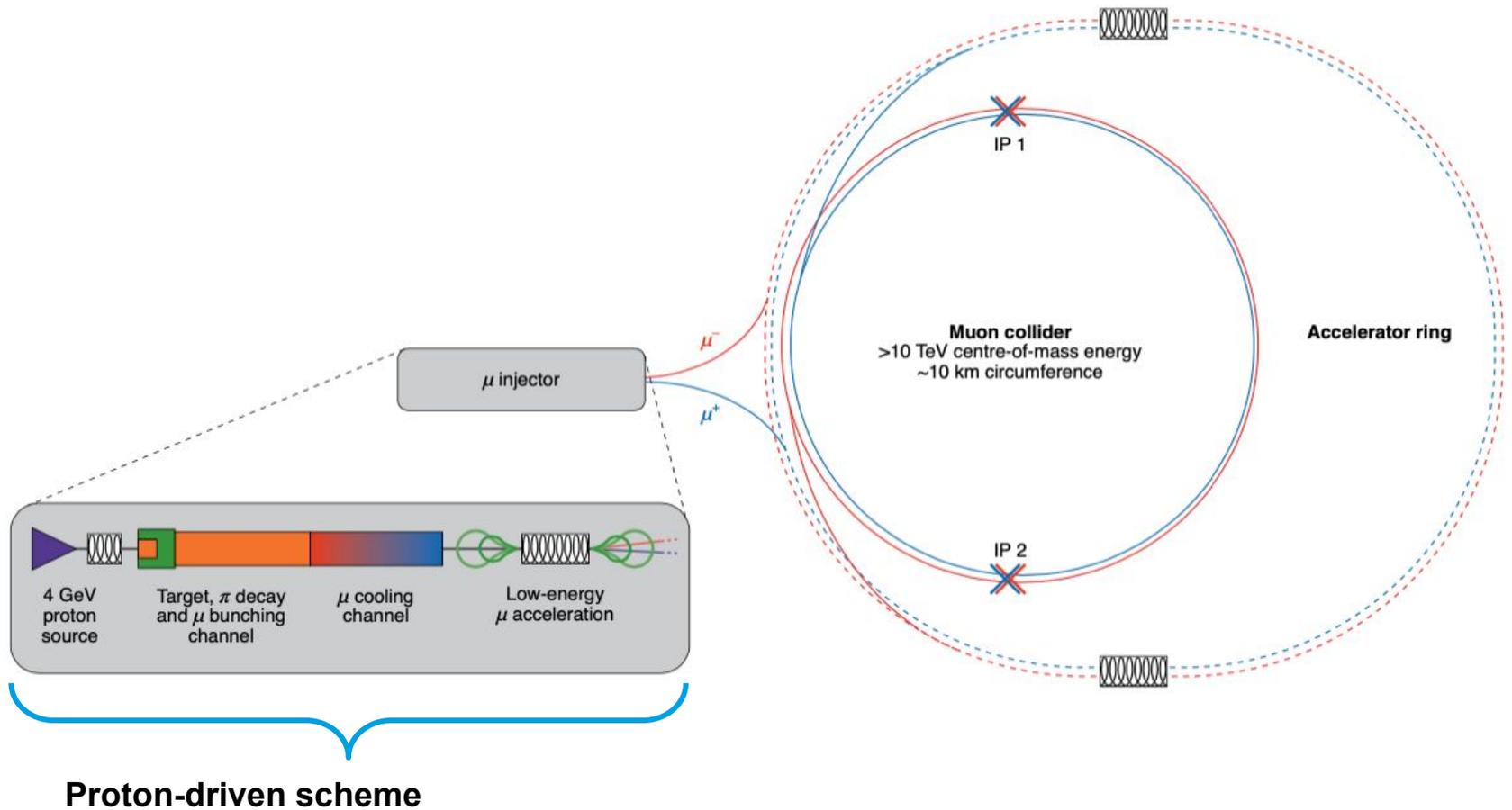
- 400 pages supplementary “backup” document, ~450 authors and supporters

*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

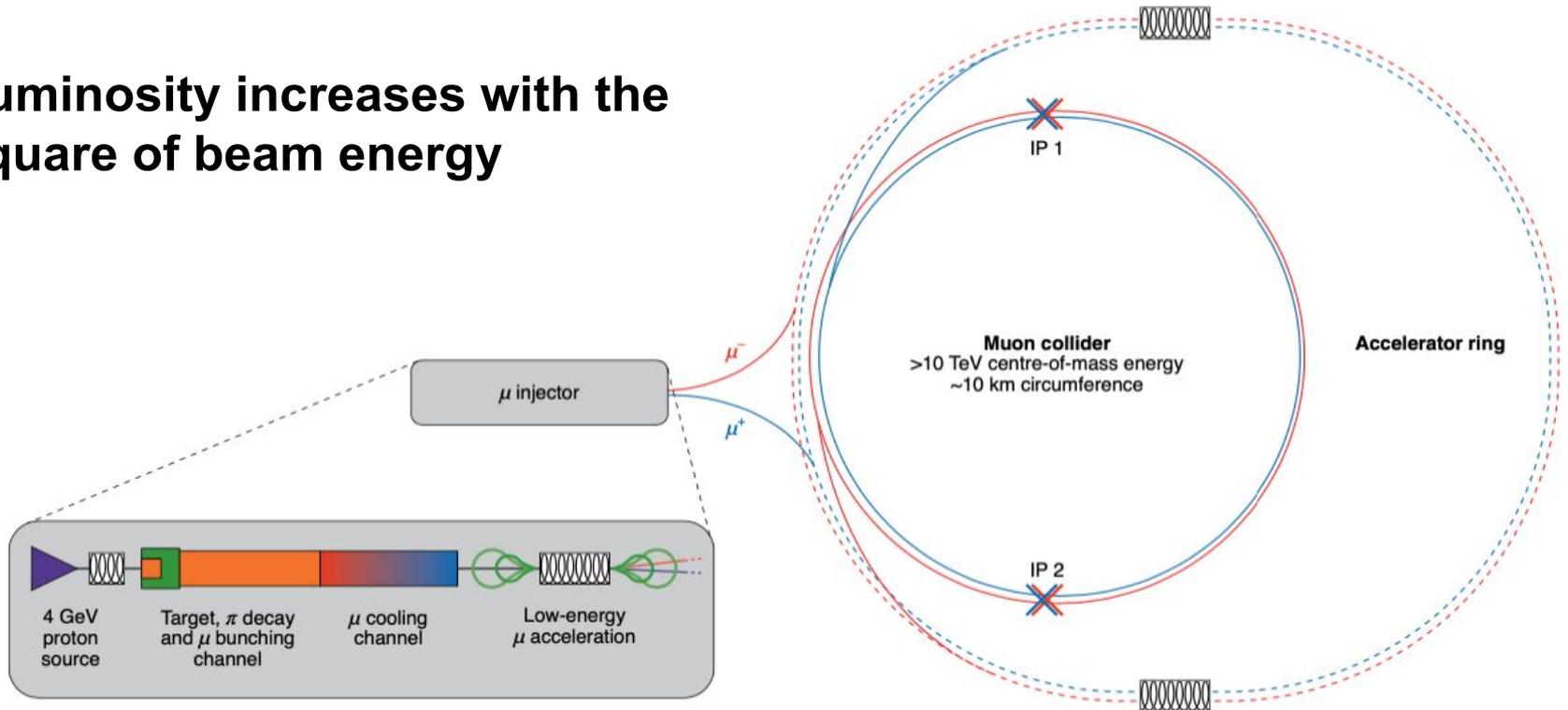
Collider overview



Collision paradigm

Circulate two bunches and re-fill when they are depleted

Luminosity increases with the square of beam energy

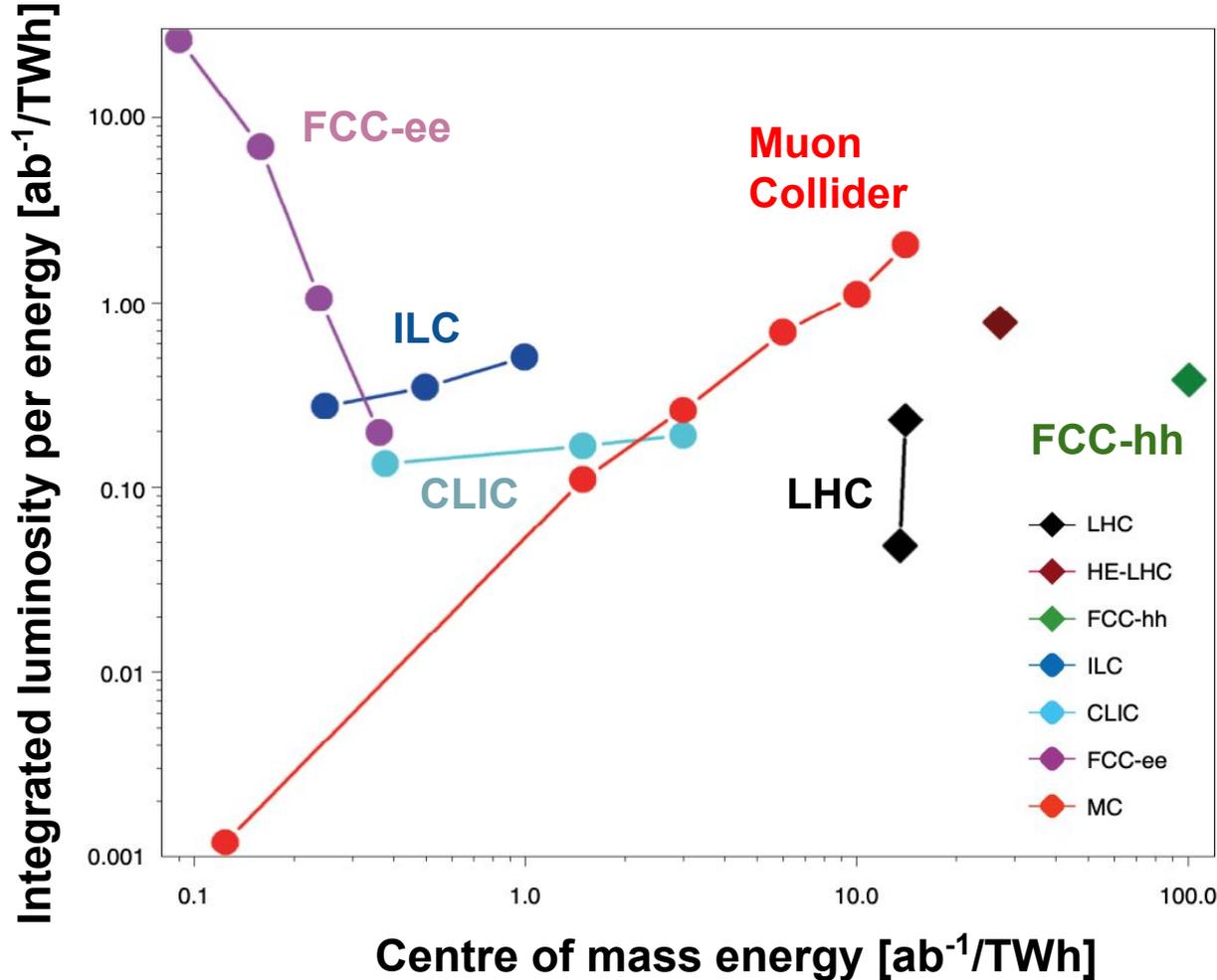


1000 times lower collision rate than LHC!

For the luminosity experts

$$L \approx \frac{\langle N_b^2 \rangle n_{\text{turns}} n_{\text{turns}} f_{\text{inj}} \gamma}{4\pi\beta^* \epsilon^*} R_{\text{HG}}$$

Sustainability



ROUGH RULE OF THUMB
Cost \propto Energy
Power \propto Luminosity

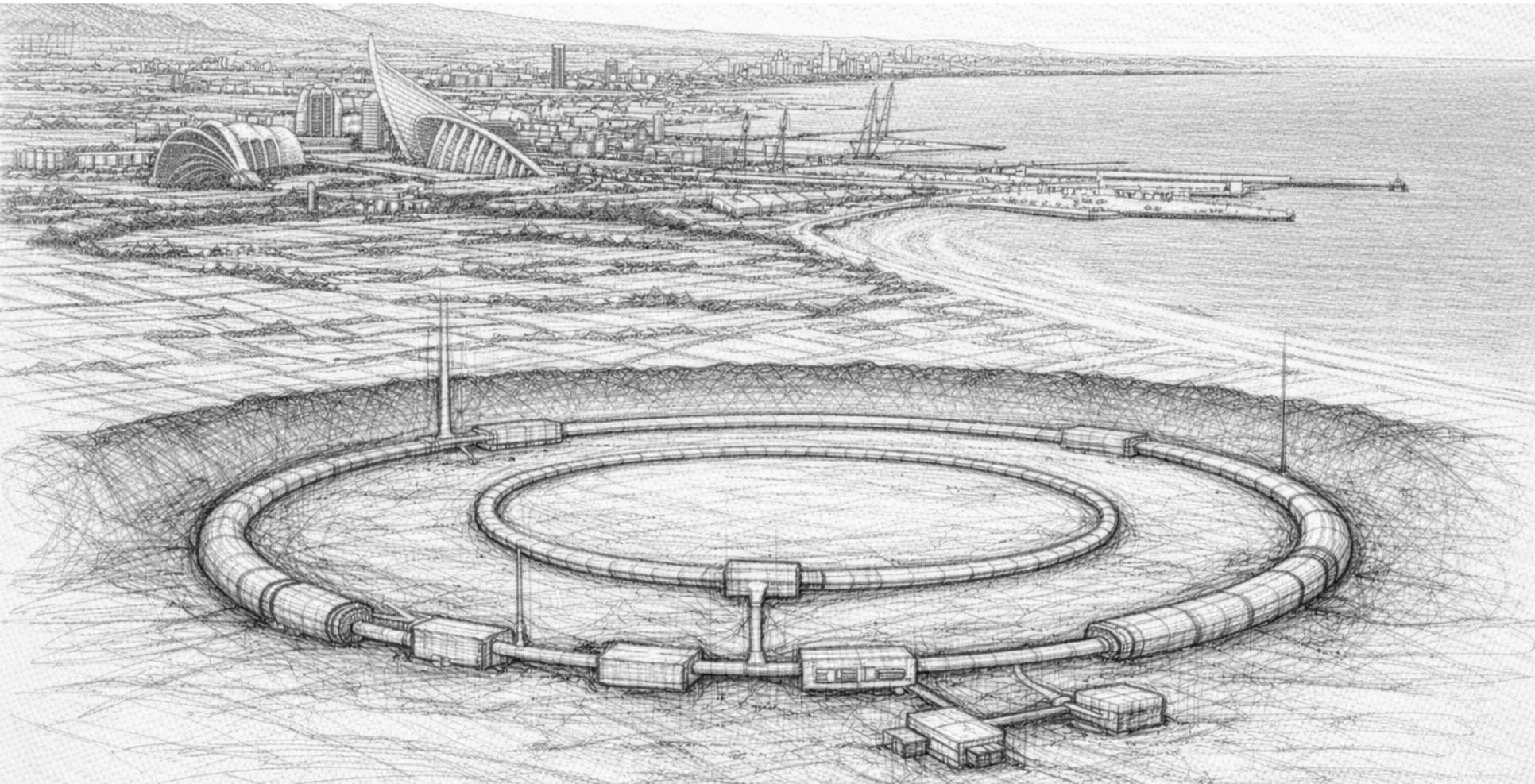
Cost-effective construction and operation
Possible staging / re-use of existing facilities

Target parameters

Site independent muon collider parameters						
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	$\int \mathcal{L}_{\text{target}}$	ab^{-1}	1	10	10	
Estimated luminosity	$\mathcal{L}_{\text{estimated}}$	$10^{34} \text{cm}^{-2} \text{s}^{-1}$	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 ₃ Sn	HTS	Nb ₃ Sn	Nb ₃ Sn
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	ε_{\parallel}	eVs	0.025	0.025	0.025	0.025
Norm. RMS transv. emittance	ε_{\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

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

The road to the muon collider

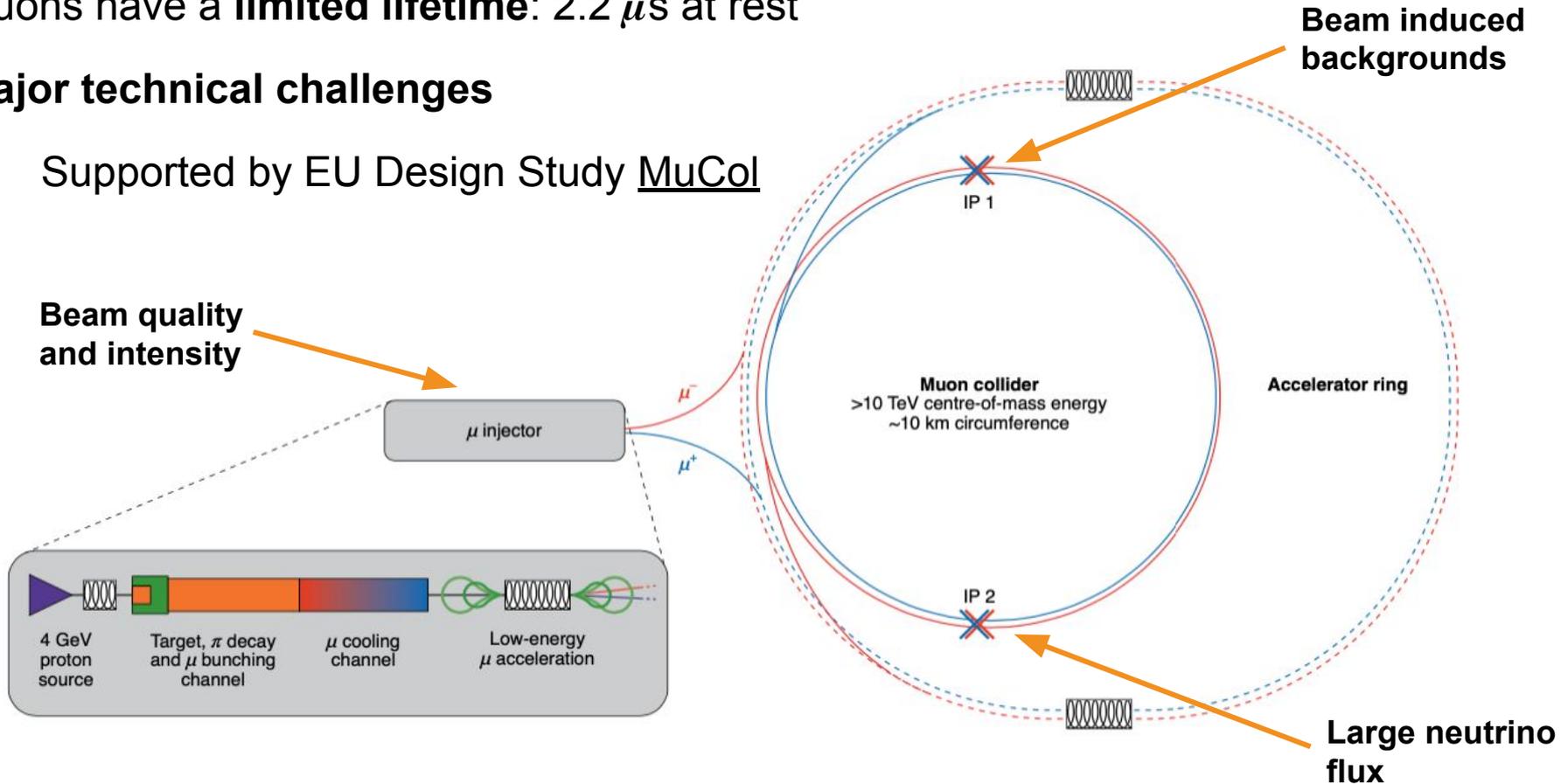


Key challenges

Muons have a **limited lifetime**: $2.2 \mu\text{s}$ at rest

Major technical challenges

- Supported by EU Design Study MuCol

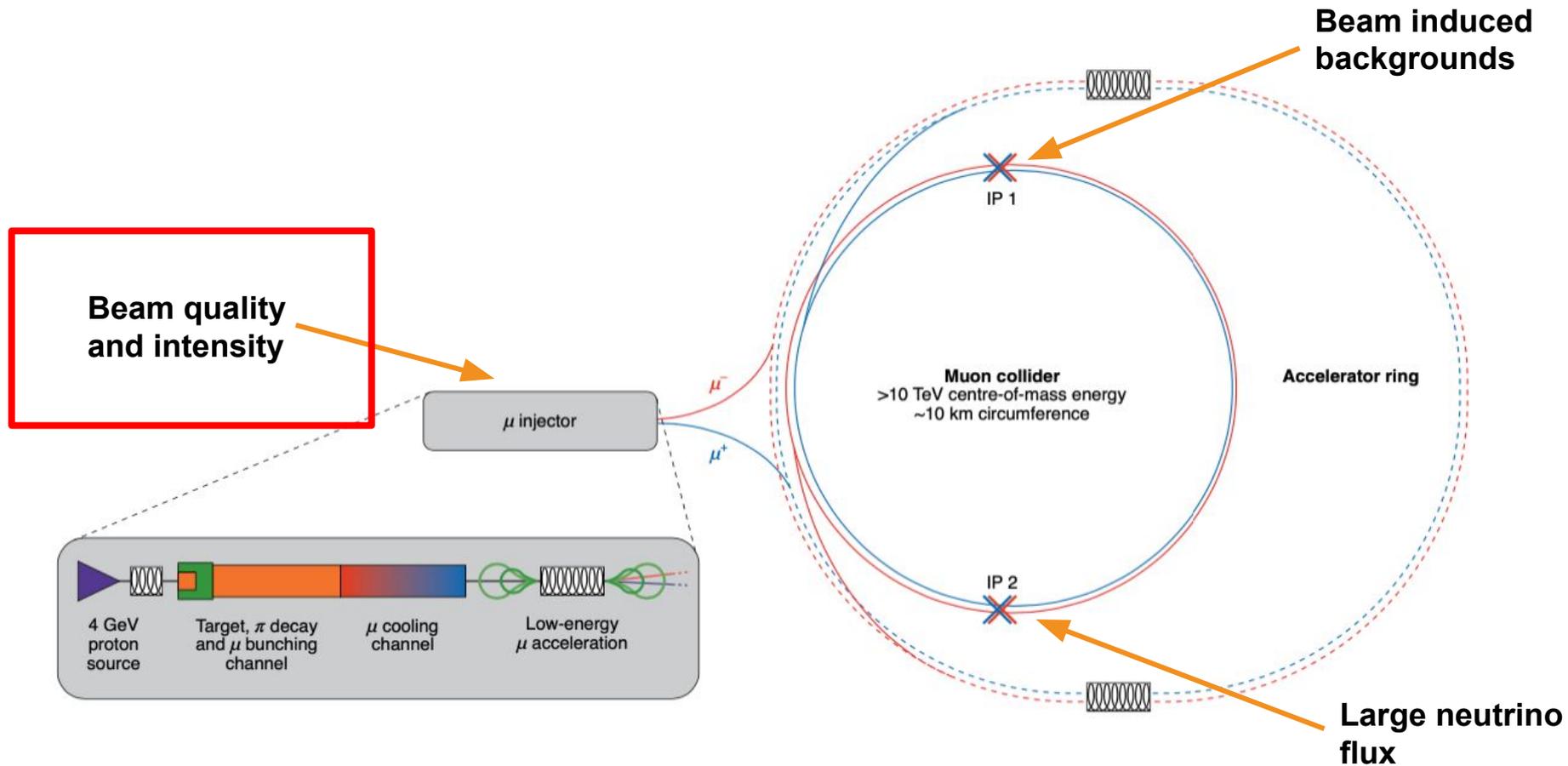


The 12 ~~miracles~~ challenges

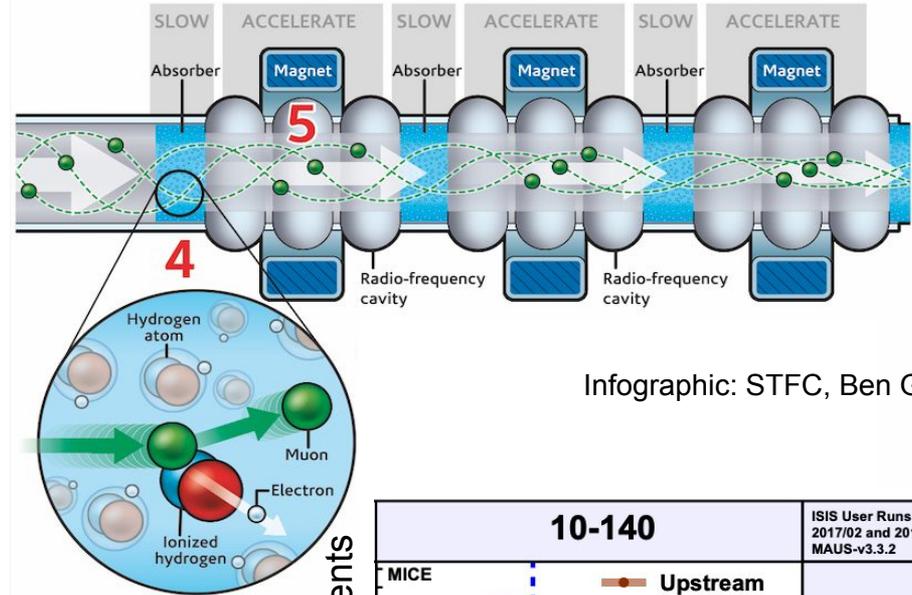
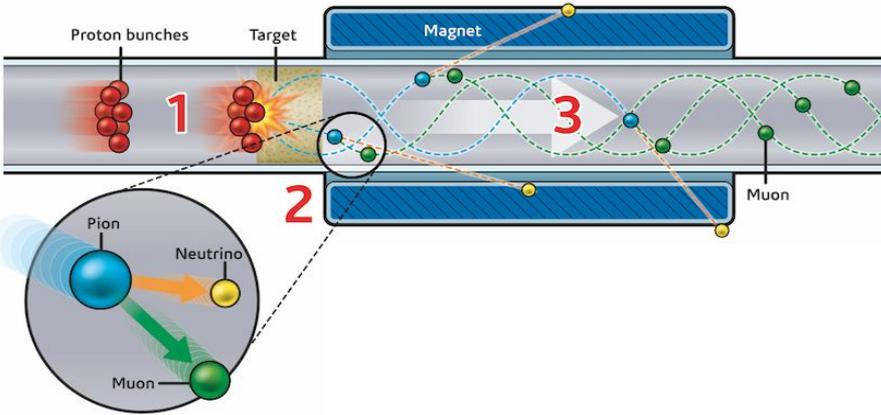
Many thanks to S. Jindariani,
D. Schulte, and M. Wing for inputs
and useful discussions

	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 μ Sv/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



Cooling the beams

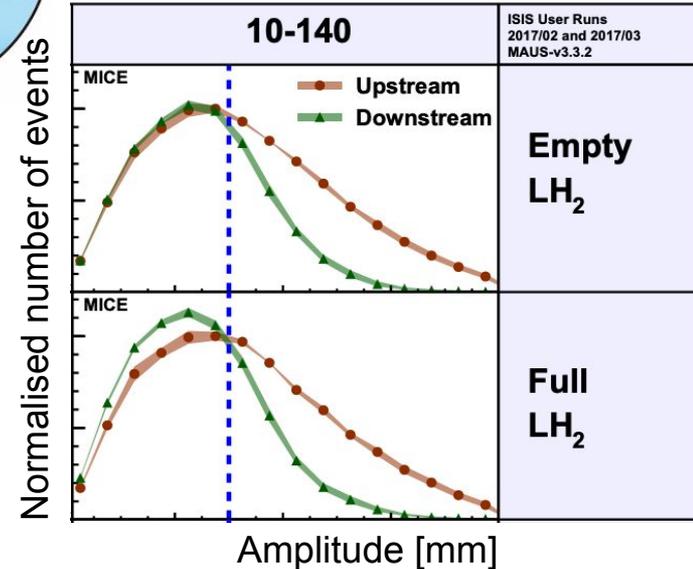


Infographic: STFC, Ben Gilliland

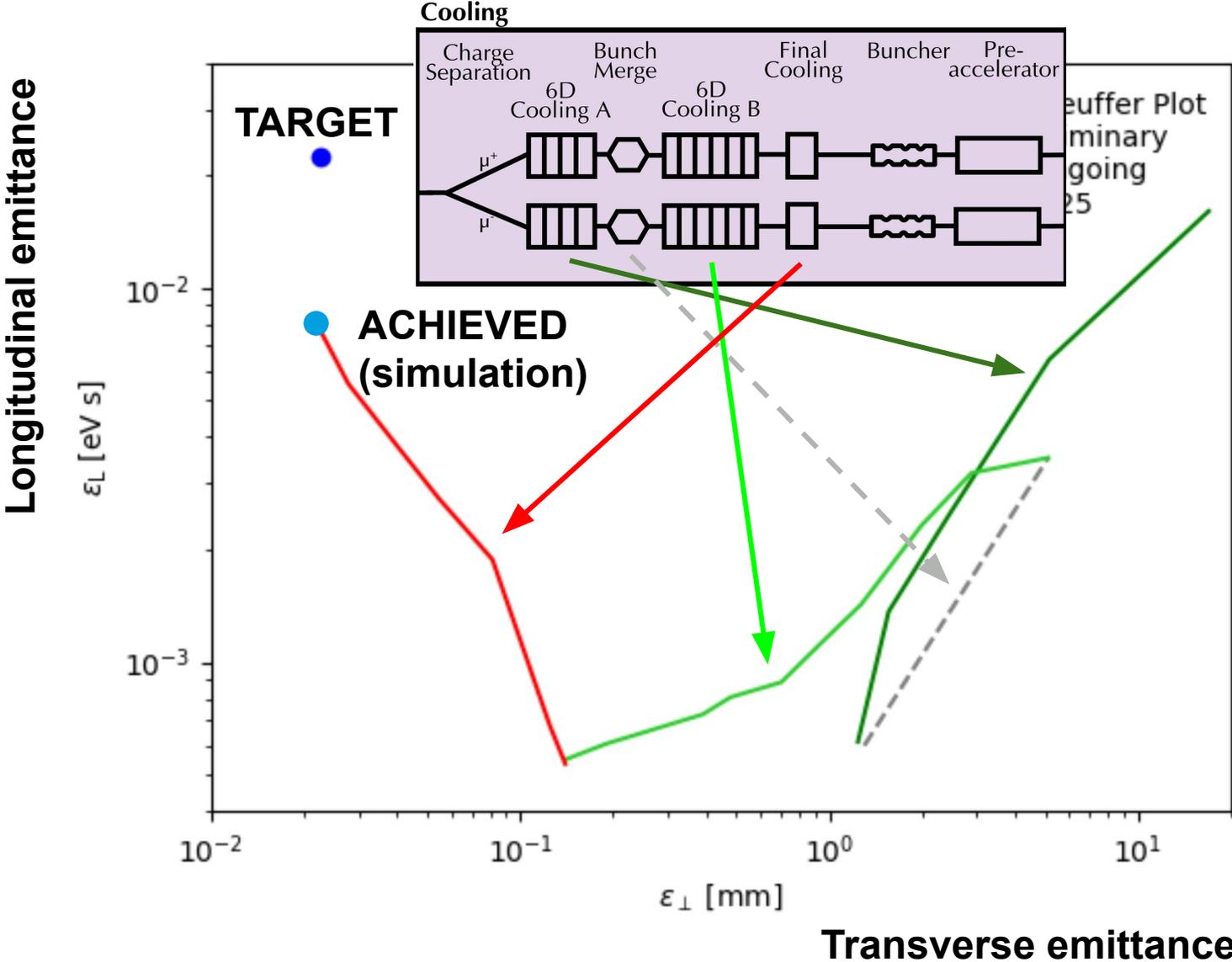
MICE Muon Ionization Cooling Experiment

Need 10^6 emittance reduction!

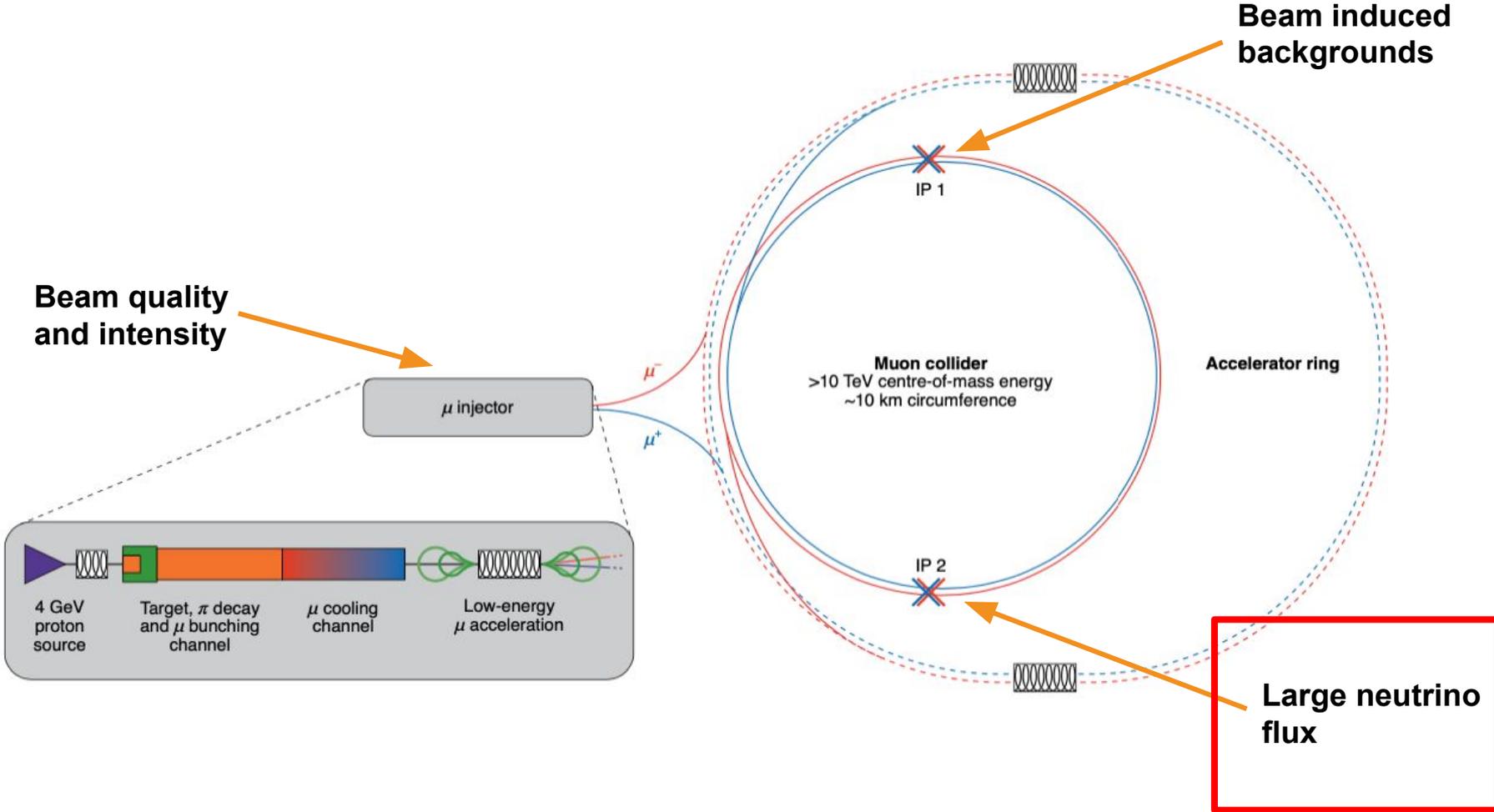
- Demonstrator with RF and more than one stage required



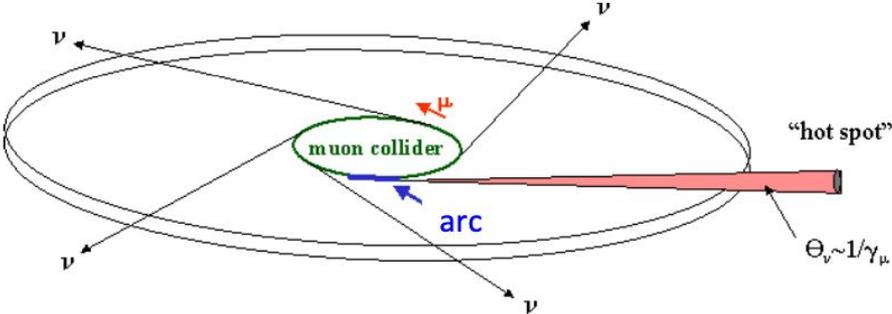
Cooling chain design



Key challenges



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



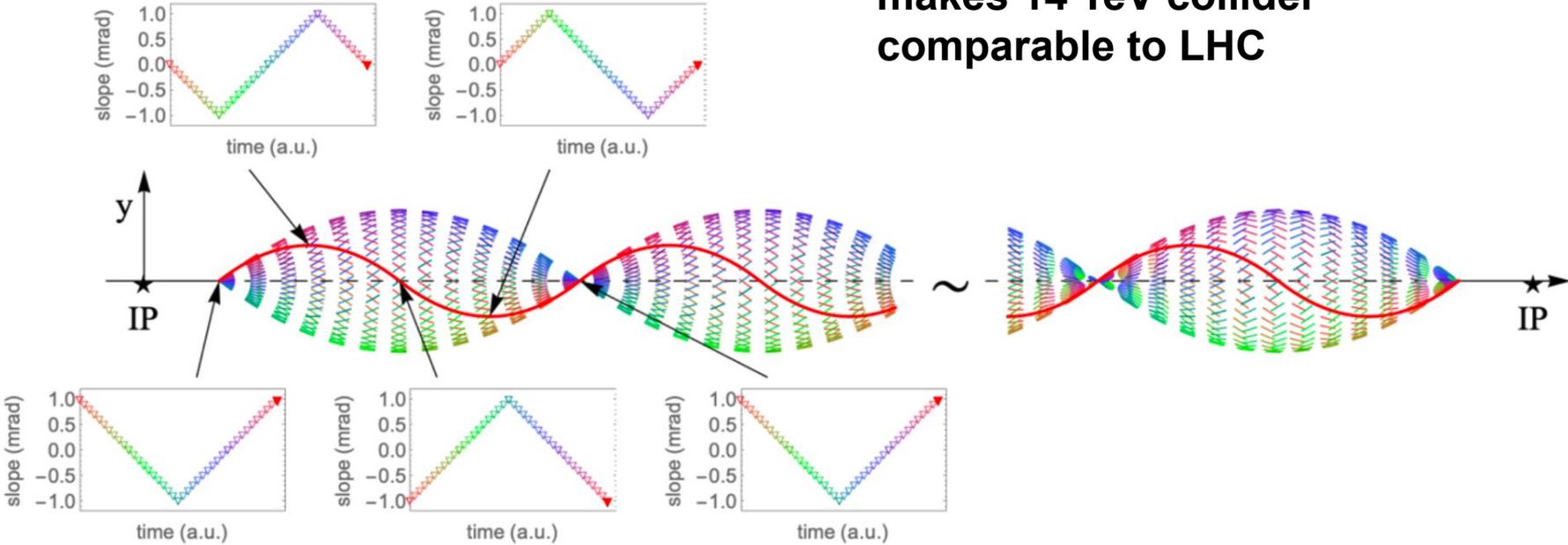
Sketch credit: D. Schulte

Neutrino flux mitigation

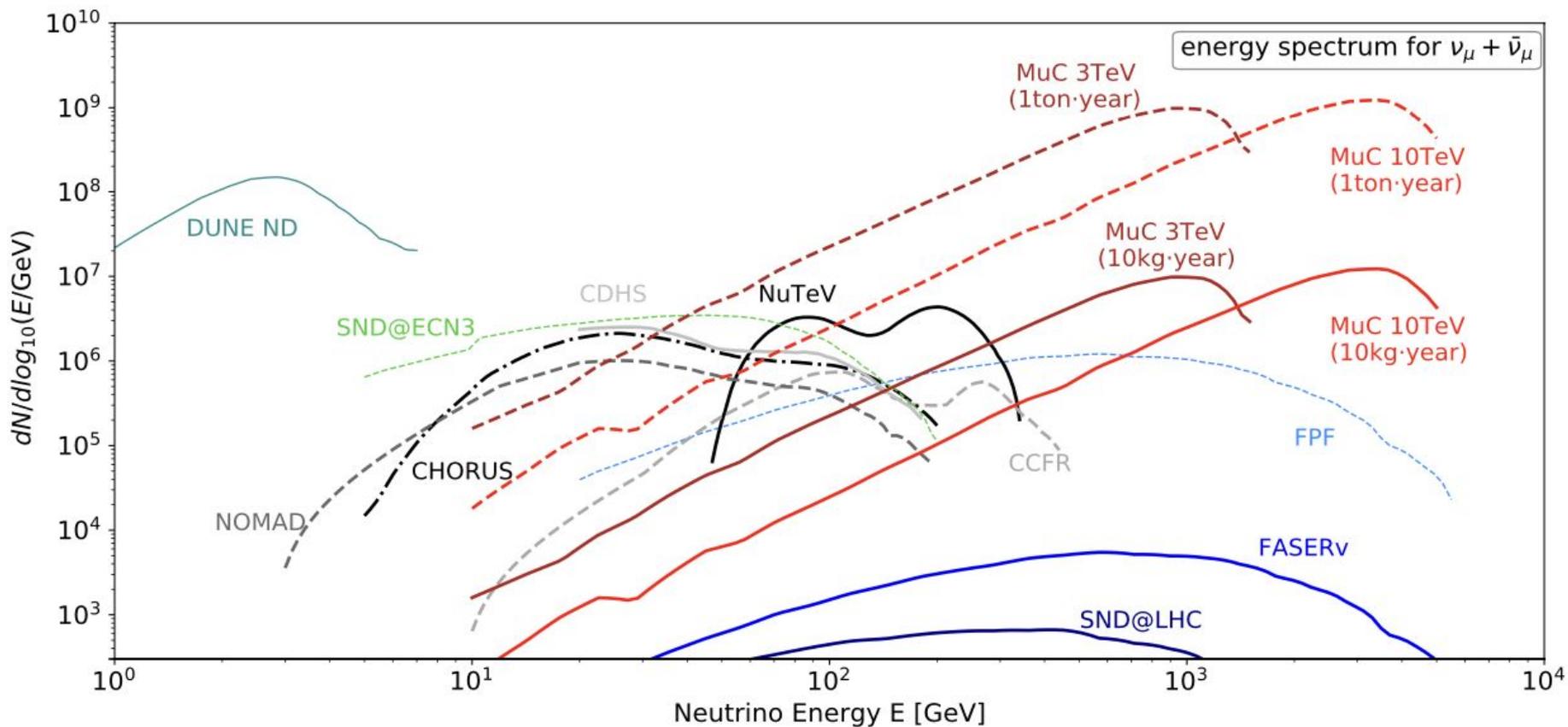
Need mitigation in collider arcs at 10+ TeV: move collider ring components

Example: vertical bending

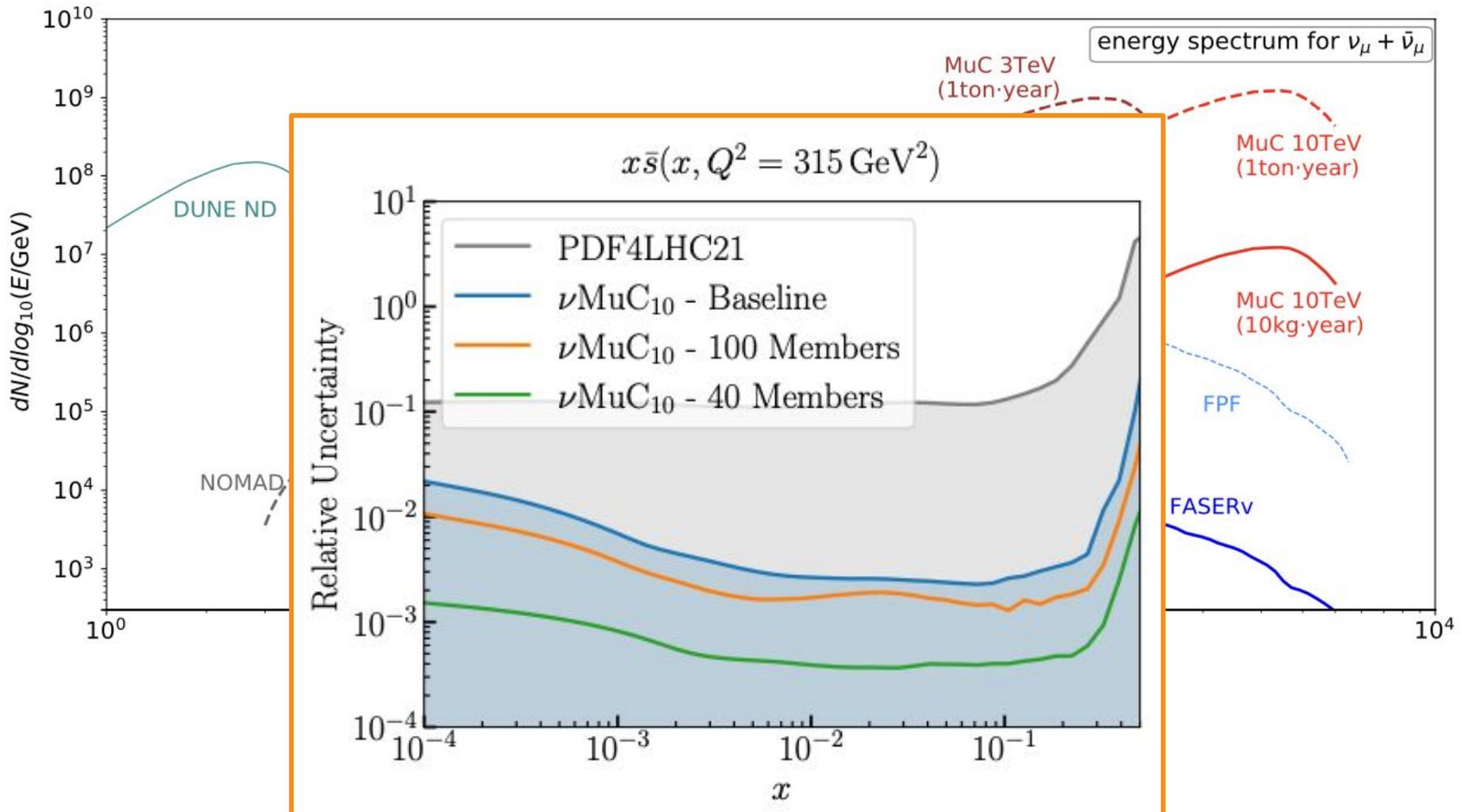
Opening angle of ~1 mradian makes 14 TeV collider comparable to LHC



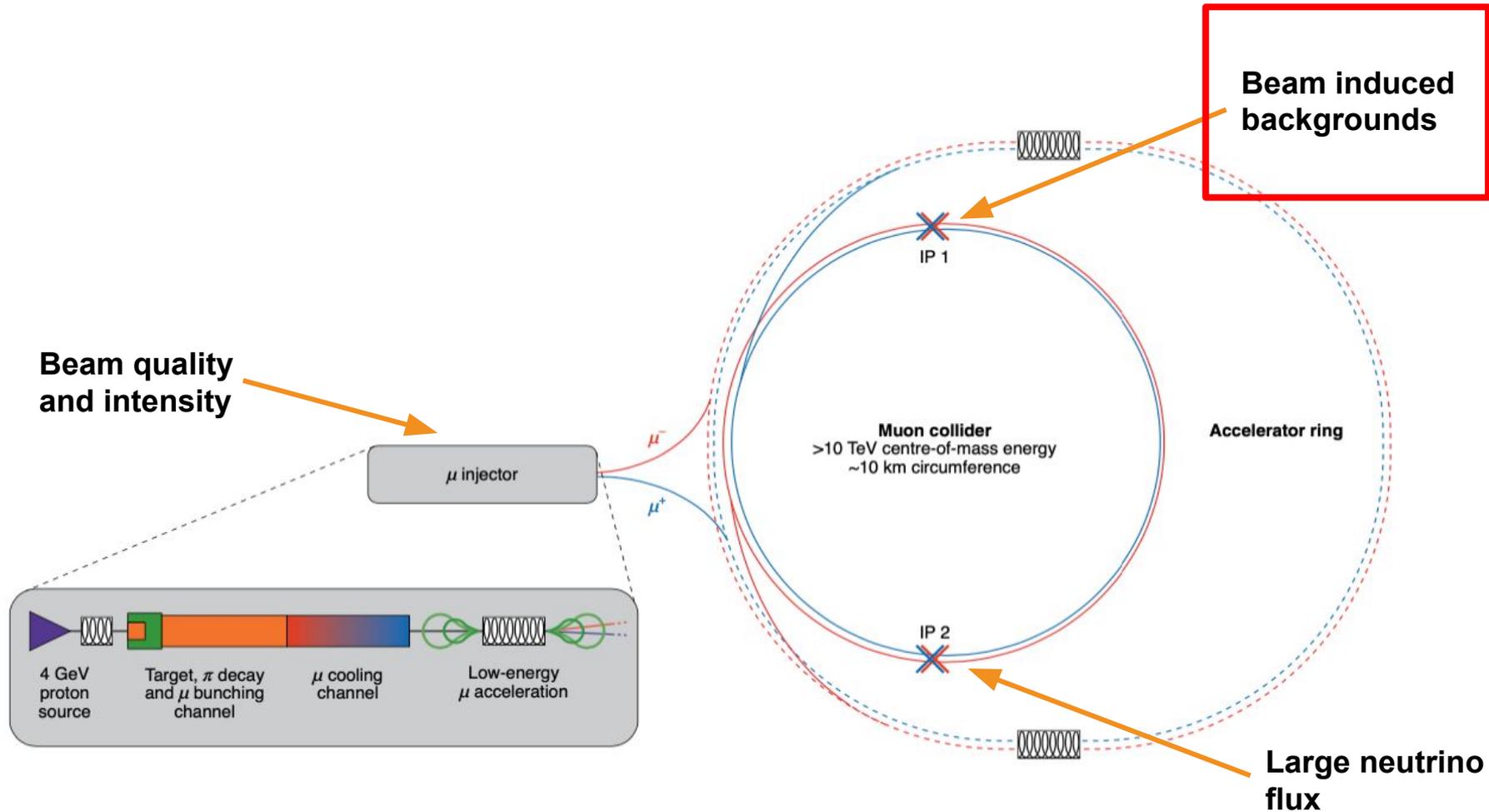
Neutrinos are an opportunity!



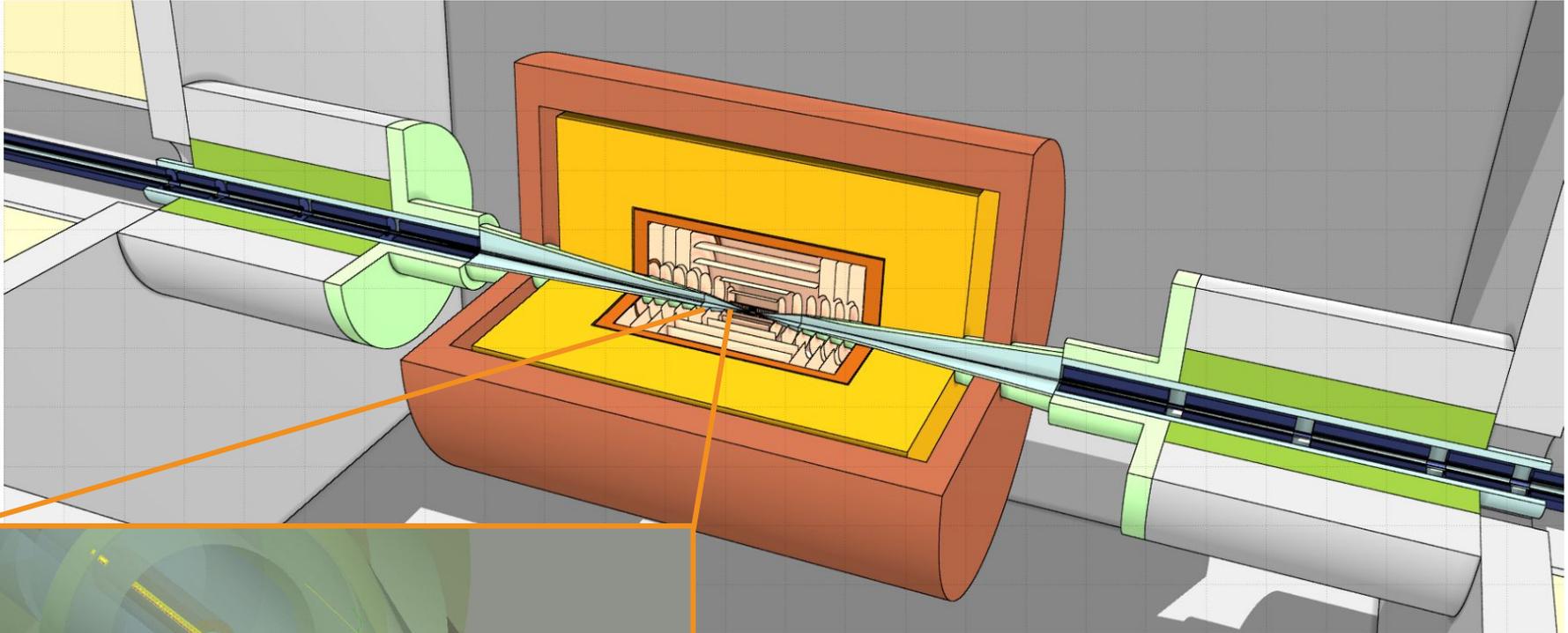
Neutrinos are an opportunity!



Key challenges



The beam-induced backgrounds (BIB)



Huge number of particles from muon decays (4×10^5 per metre of lattice) and their byproducts

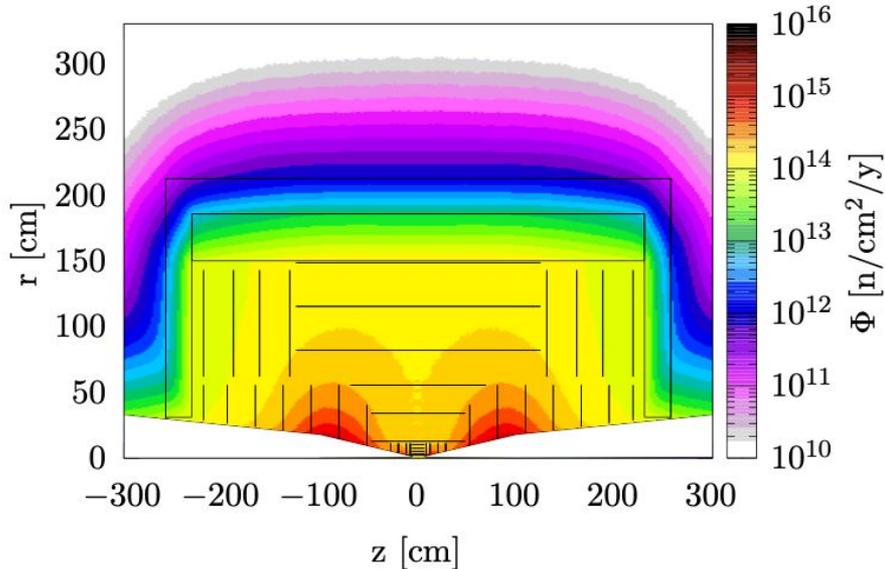
- Shielding with tungsten nozzles with borated polyethylene (BCH₂) coating

Unique challenge of Muon Colliders

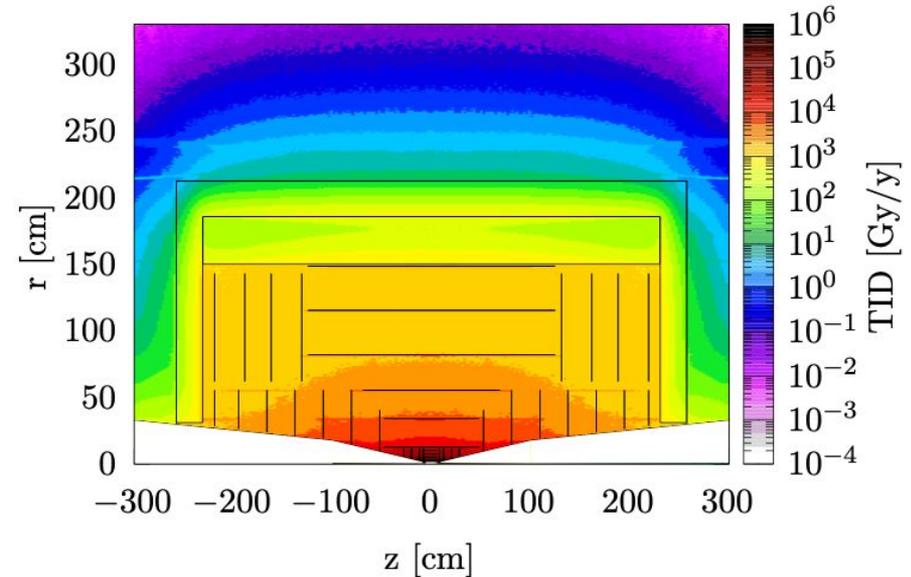


Detection Environment

FLUKA simulation



1-MeV- n_{eq}/cm^2 fluence for 200 days of operation



Total Ionising Dose for 200 days of operation

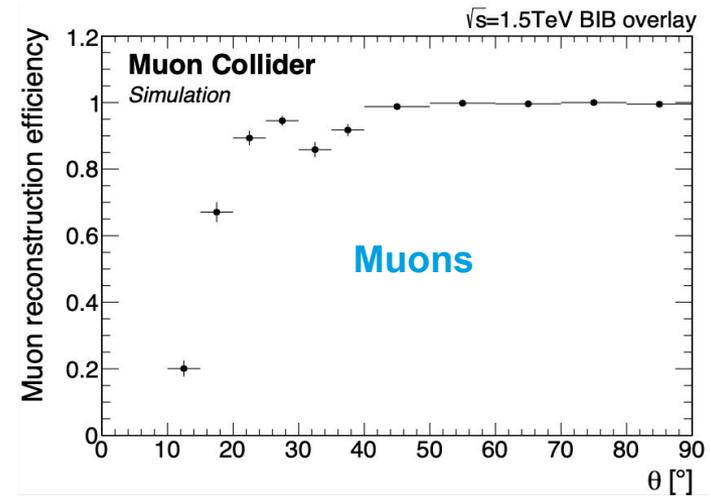
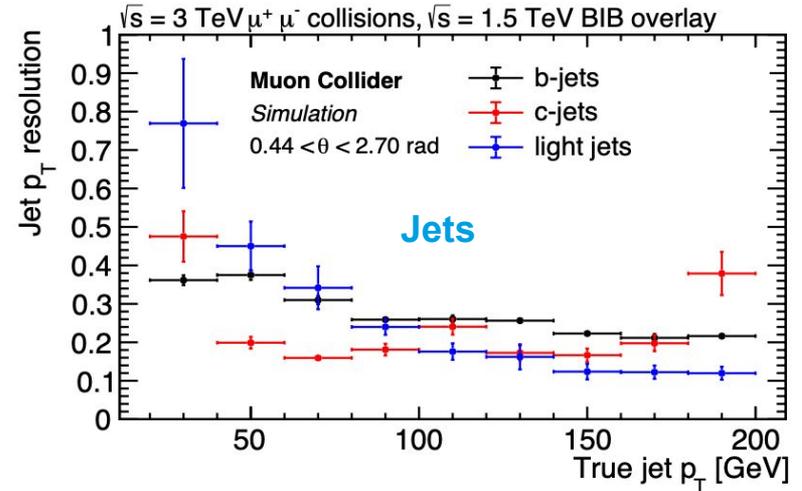
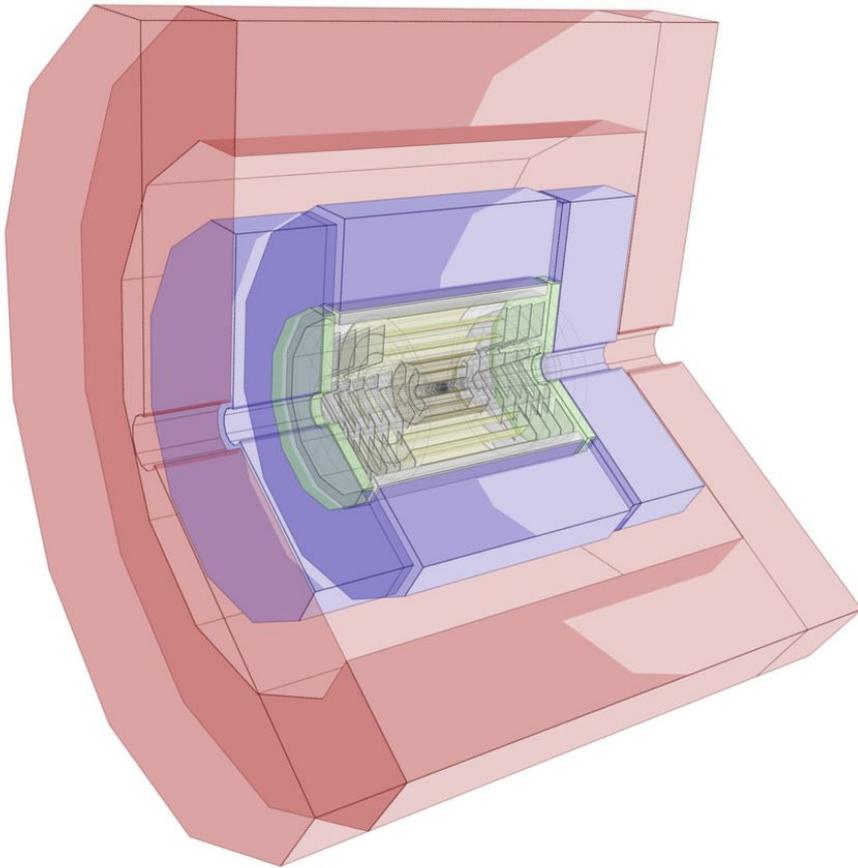
	Maximum Dose (Mrad)		Maximum Fluence (1 MeV-neq/cm ²)	
	R= 22 mm	R= 1500 mm	R= 22 mm	R= 1500 mm
Muon Collider (3 TeV)	10	0.1	10^{15}	10^{14}
HL-LHC	100	0.1	10^{15}	10^{13}
Muon Collider (10 TeV)	20	0.2	3×10^{14}	10^{14}

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

Previous achievements: 3 TeV detector

“LHC-level” performance without using dedicated techniques

- Huge potential to improve further

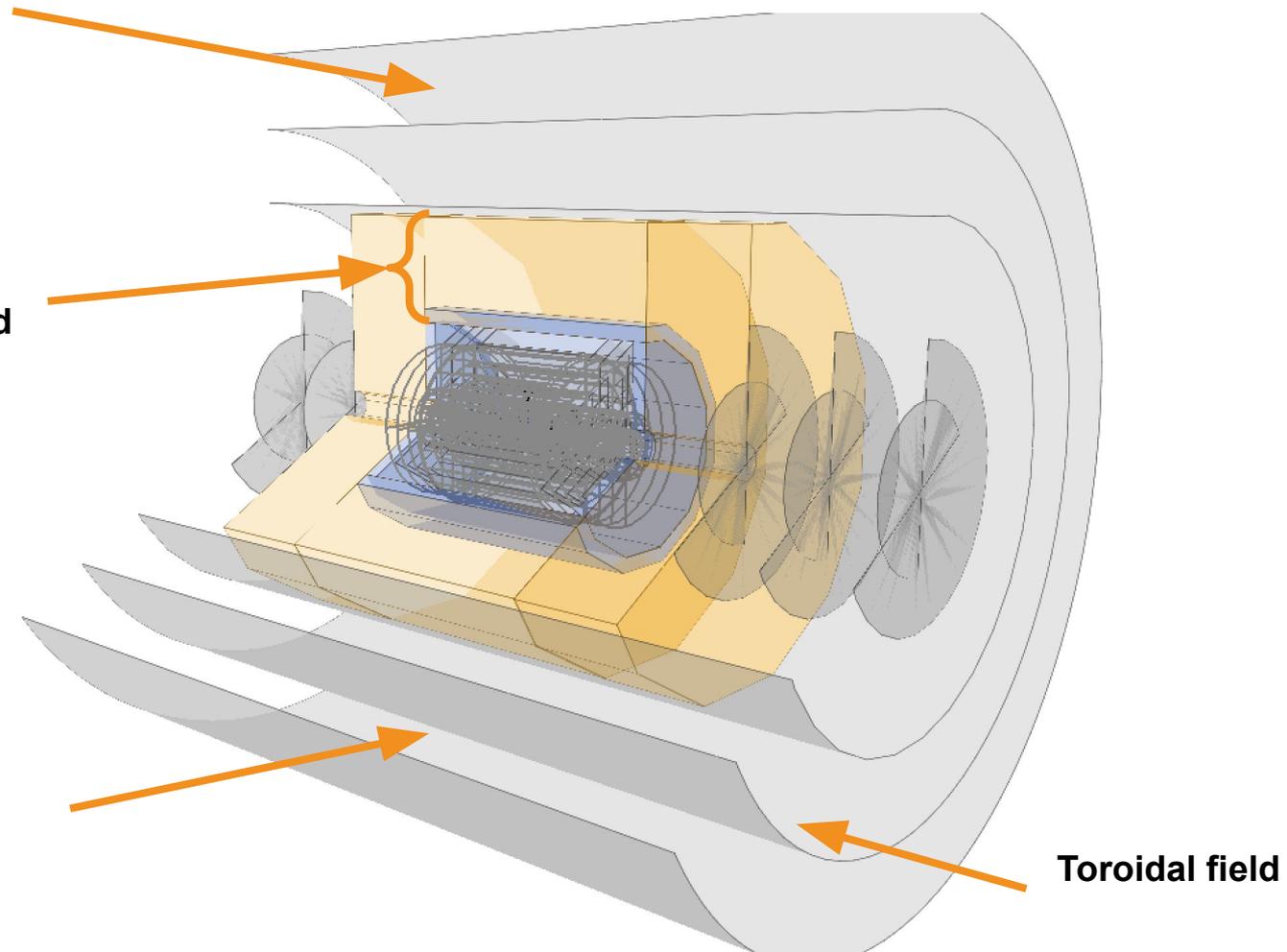


10 TeV: from sketch (March '23) ...

No need for
a Yoke

Calorimeter
depth optimised

Simplified
muon system

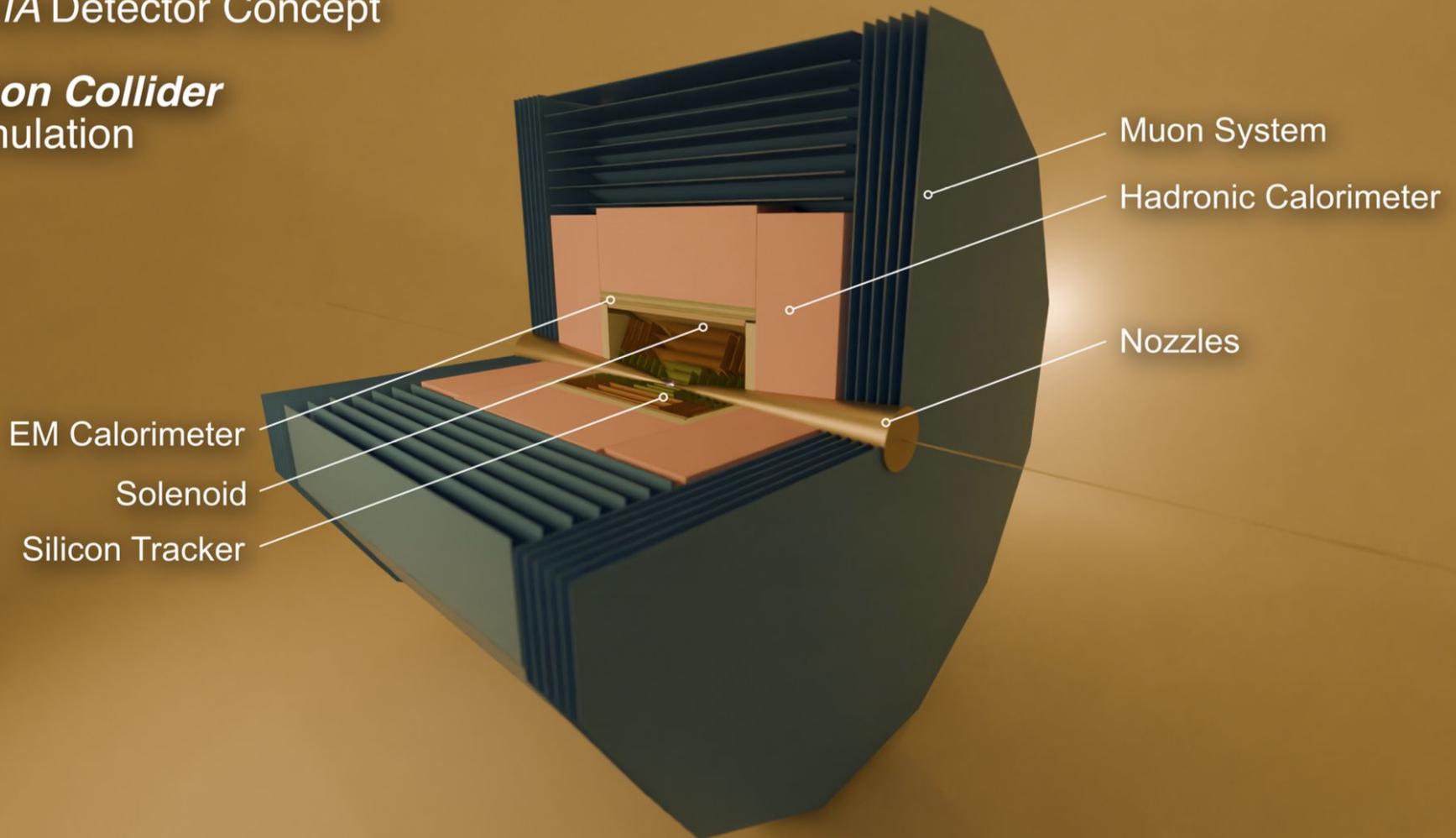


... to concept (October '23)



MAIA Detector Concept

Muon Collider Simulation

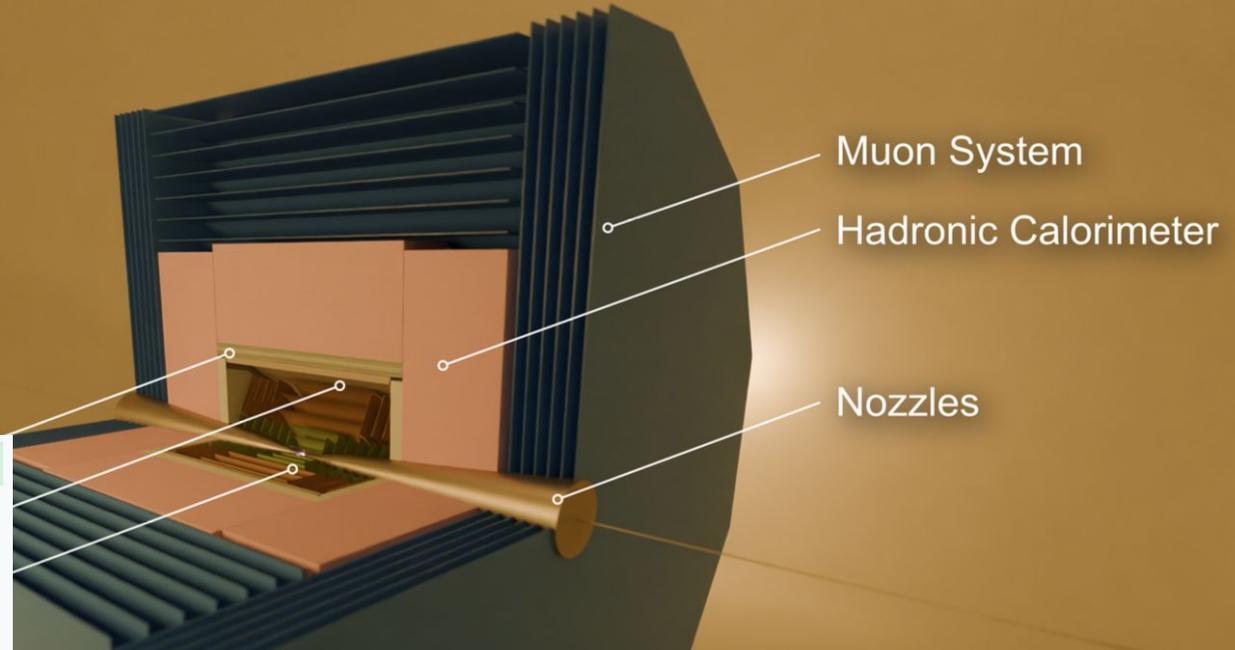


... to concept (October '23)



MAIA Detector Concept

Muon Collider Simulation



Maia

The Arcadian Pleiad Nymph

Member of the Pleiades



Hermes
Attic red-figure

Family [edit]

Maia is the daughter of Atlas^[3]^[4]

APS/123-QED

MAIA: A new detector concept for a 10 TeV muon collider

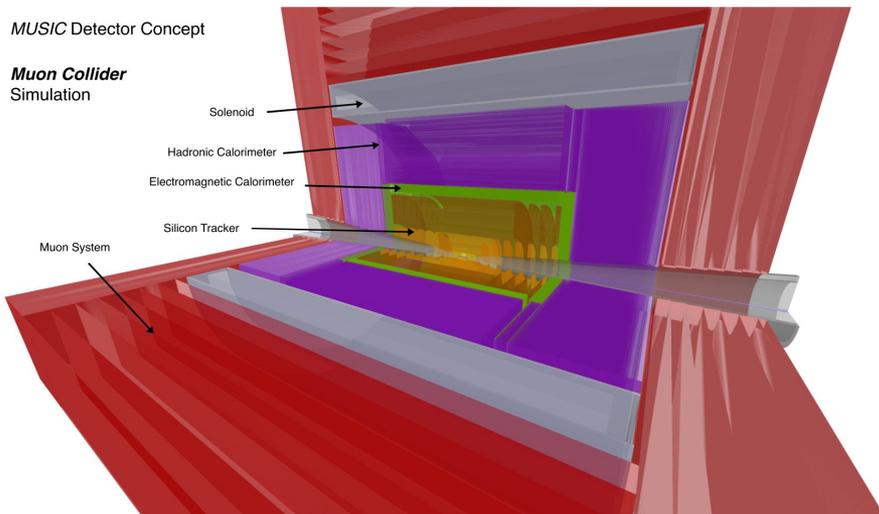
Charles Bell,¹ Daniele Calzolari,² Christian Carli,² Karri Folan Di Petrillo,³ Micah Hillman,¹ Tova R. Holmes,¹ Sergio Jindariani,⁴ Kiley E. Kennedy,⁵ Ka Hei Martin Kwok,⁴ Anton Lechner,² Lawrence Lee,¹ Thomas Madlener,⁶ Federico Meloni,⁶ Isobel Ojalvo,⁵ Priscilla Pani,⁶ Rose Powers,⁵ Benjamin Rosser,³ Leo Rozanov,³ Kyriacos Skoufaris,² Elise Sledge,⁷ Alexander Tuna,¹ and Junjia Zhang⁵

Not one, but two detector concepts

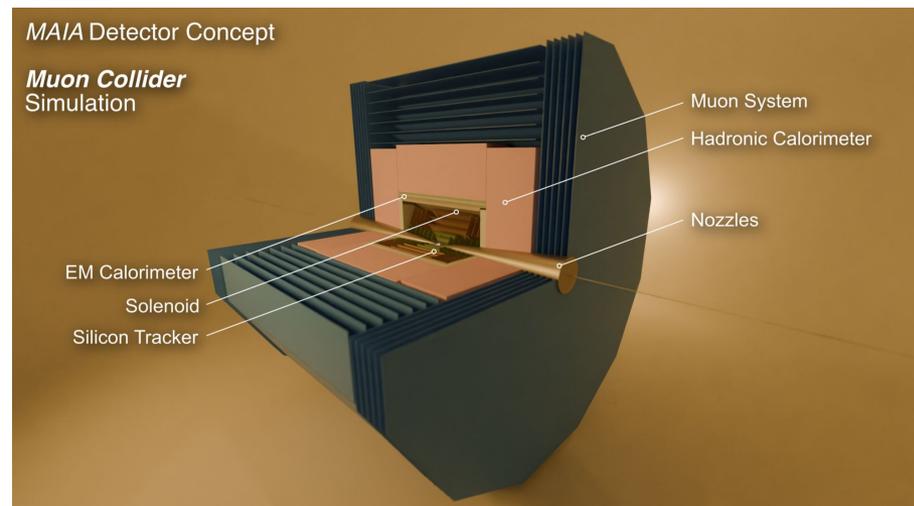
Two concepts making different choices, e.g.

- Position of solenoid
- Tracker layouts
- ECal technology

Compare performances to validate findings, quickly iterate and improve

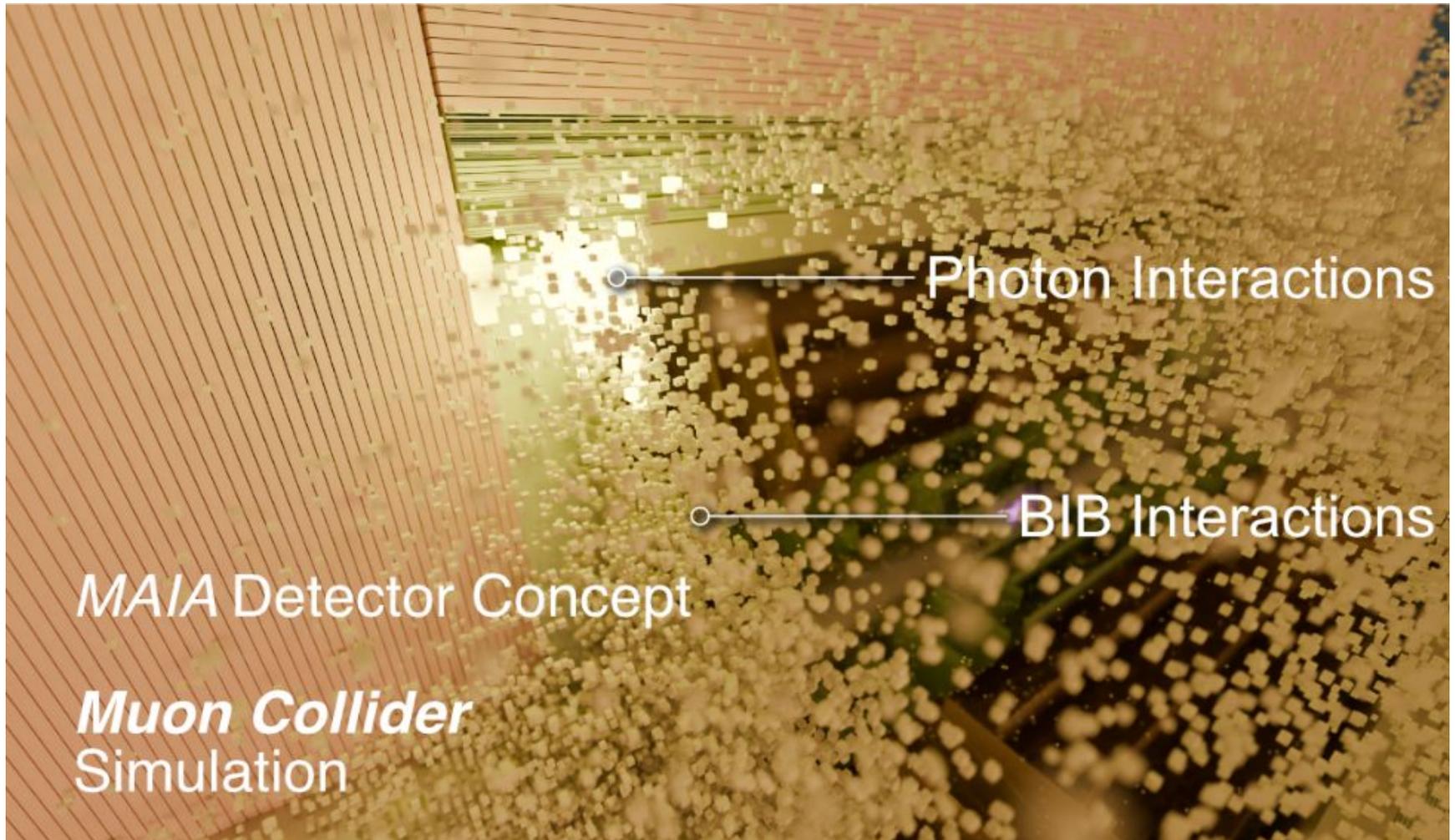


**MUSIC - MUon System
for Interesting Collisions**

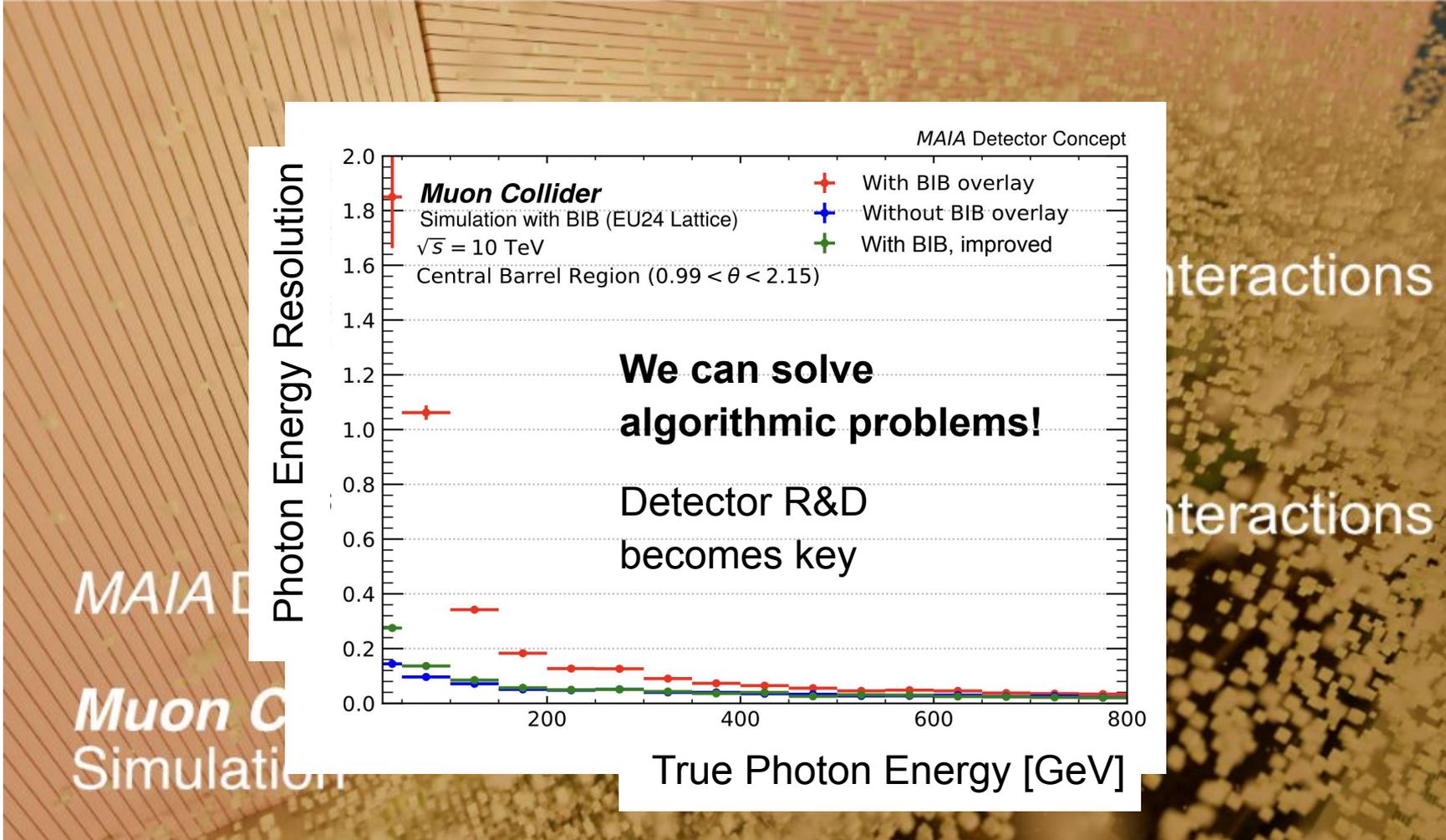


**MAIA - Muon Accelerator
Instrumented Apparatus**

Photon reconstruction



Photon reconstruction



R&D and HL-LHC “technology transfer”

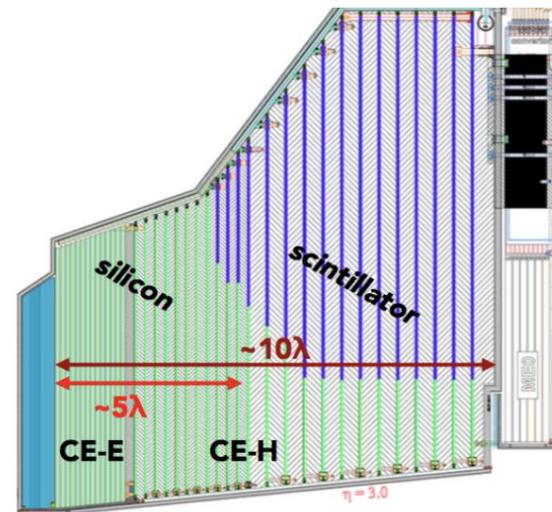
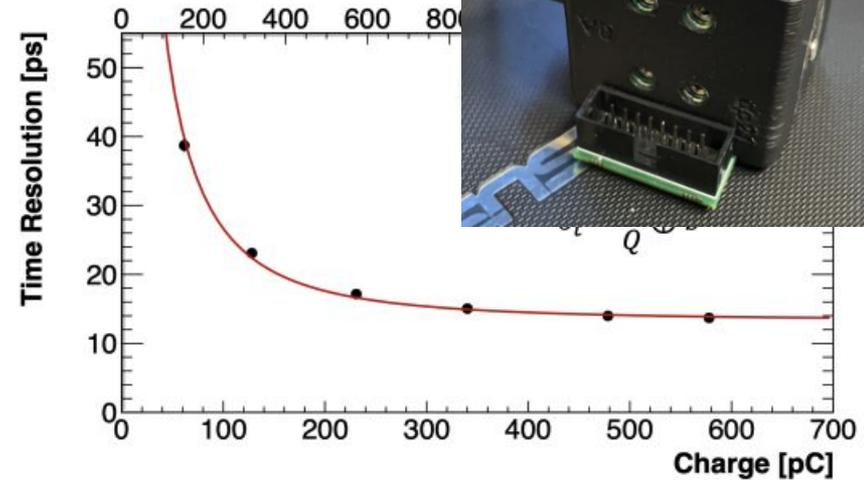
Crilin calorimeter

Semi-homogeneous calorimeter based on Lead Fluoride (PbF_2) crystals

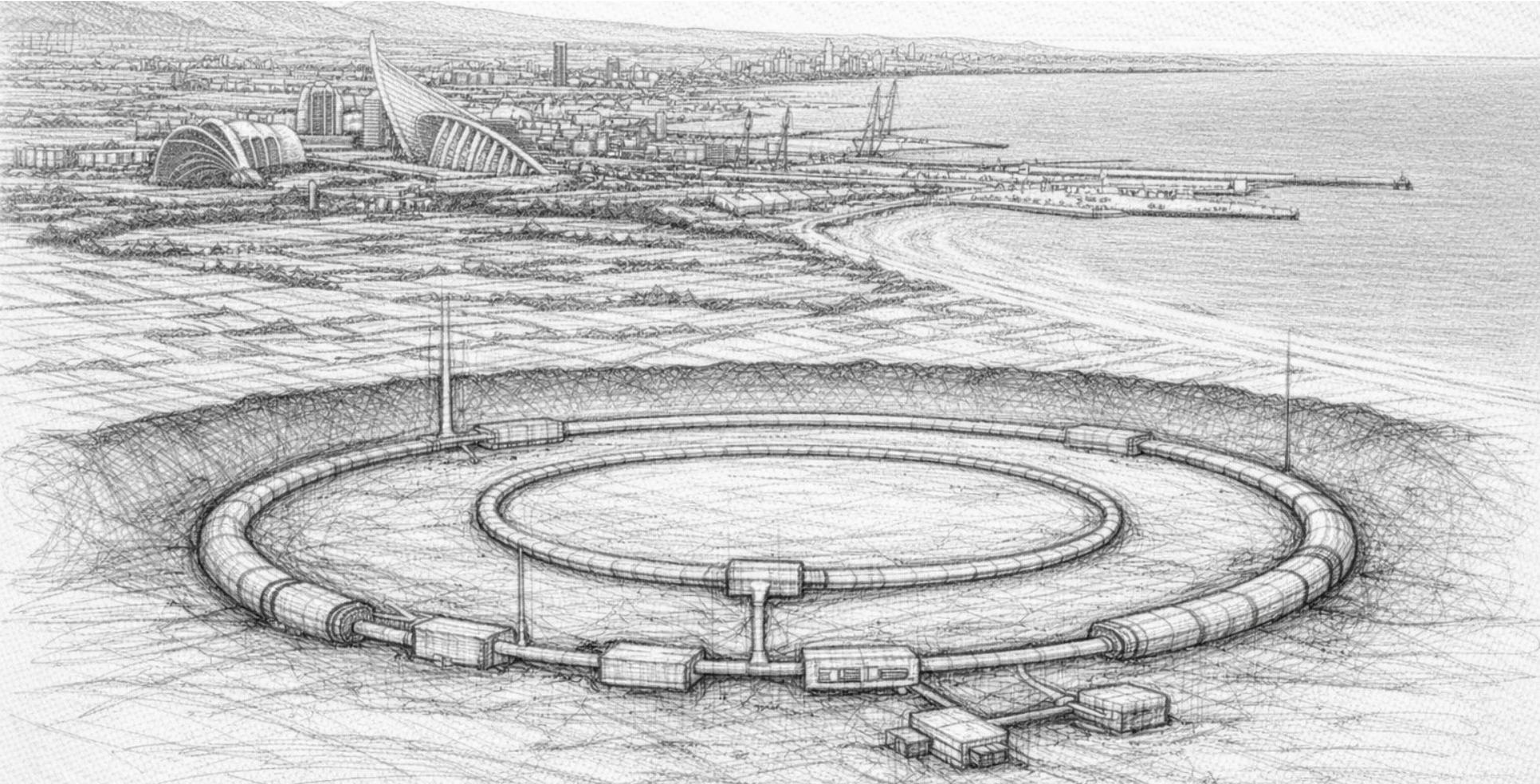
CMS High-granularity Calorimeter

Mix of silicon and scintillator-based high-granularity cells (6.5M channels)

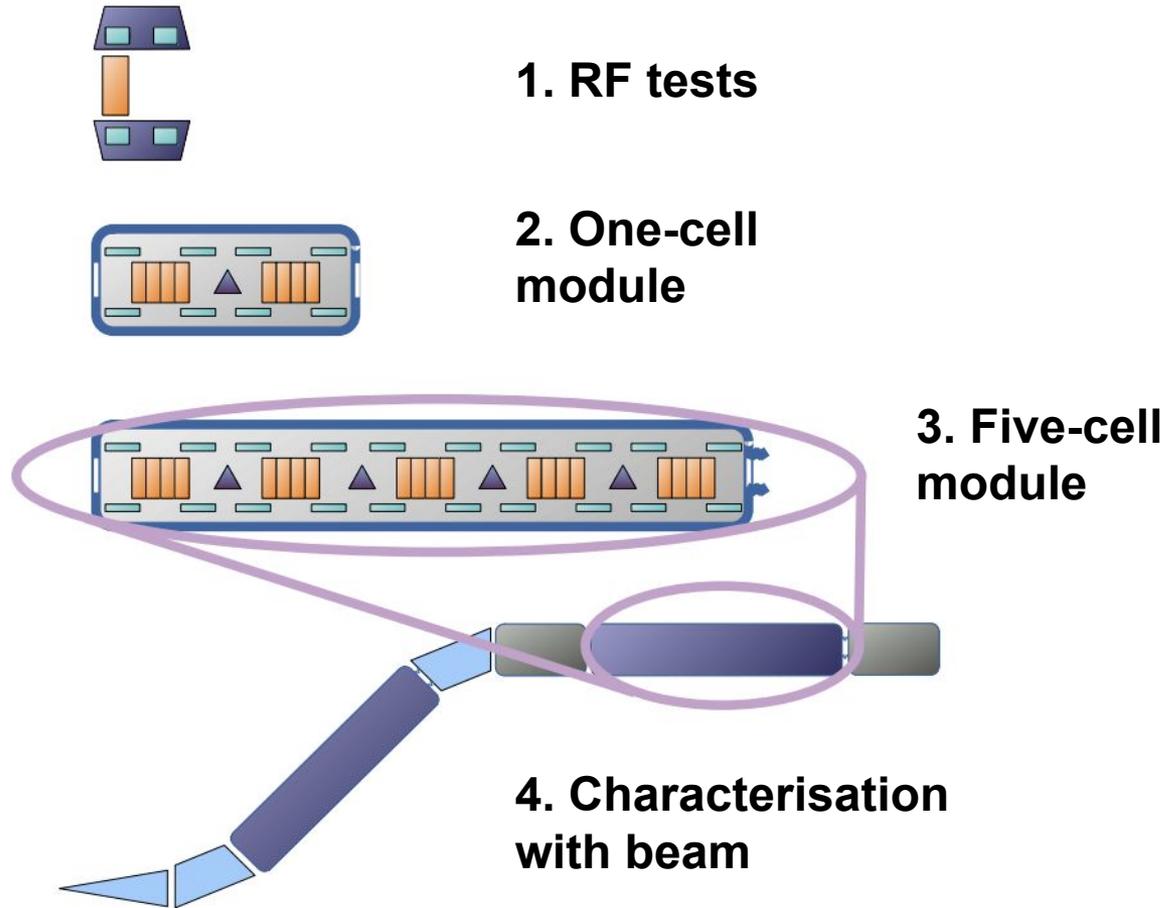
- Large-scale particle flow demonstration



Demonstrator and implementation



Muon Cooling Demonstrator Programme



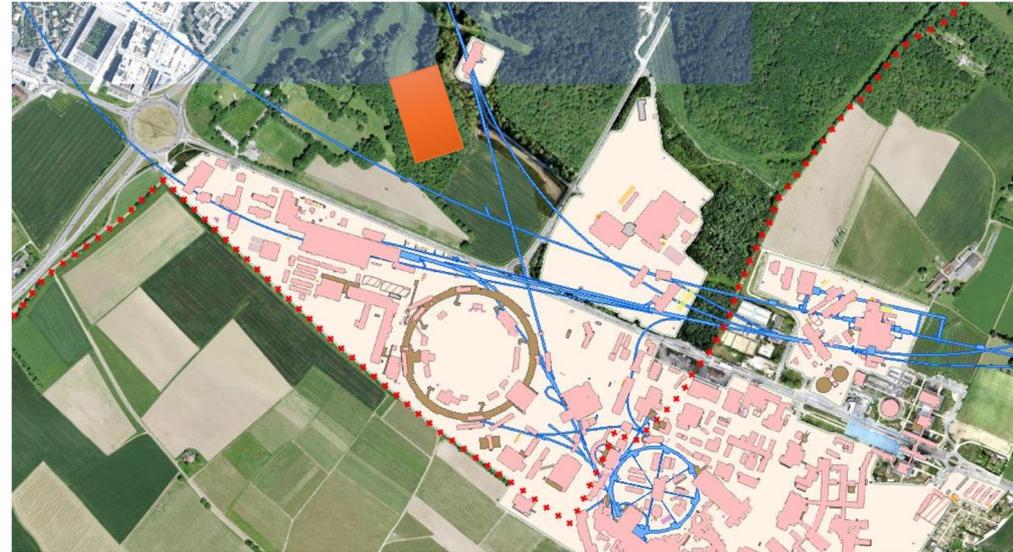
Demonstrator with beams

BA1-TT10 @ CERN

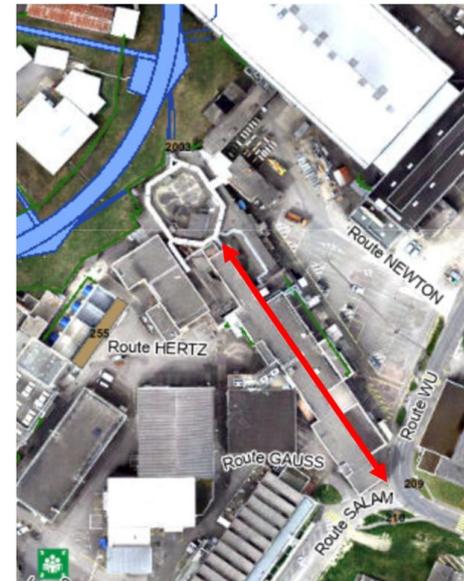
Tests with beam in **order to demonstrate commissioning and operation**

Demonstrator TDR for 2028-2030
(Infrastructure TRL 7)

Add more modules to optimise technologies and performance

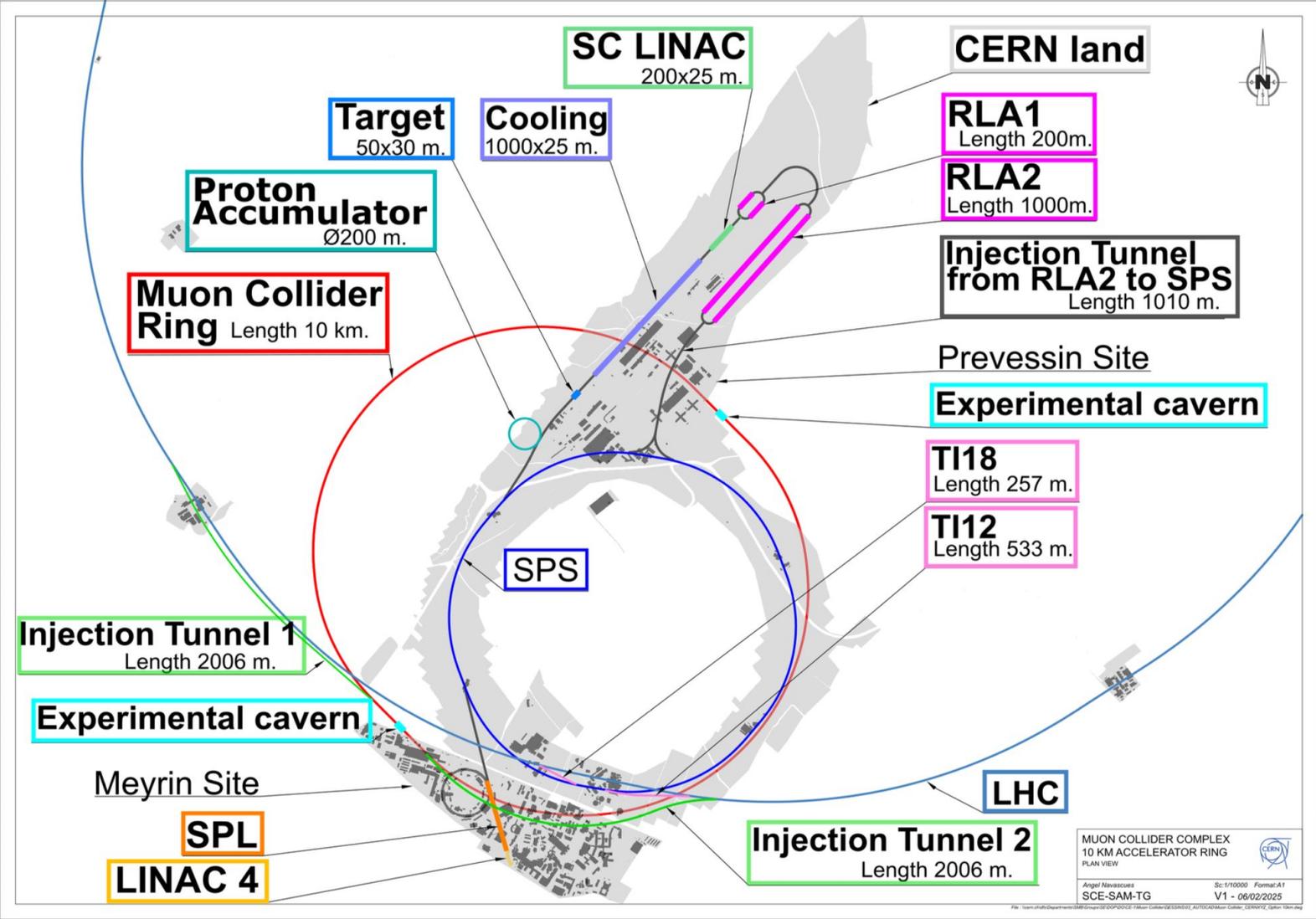


TT7 @ CERN



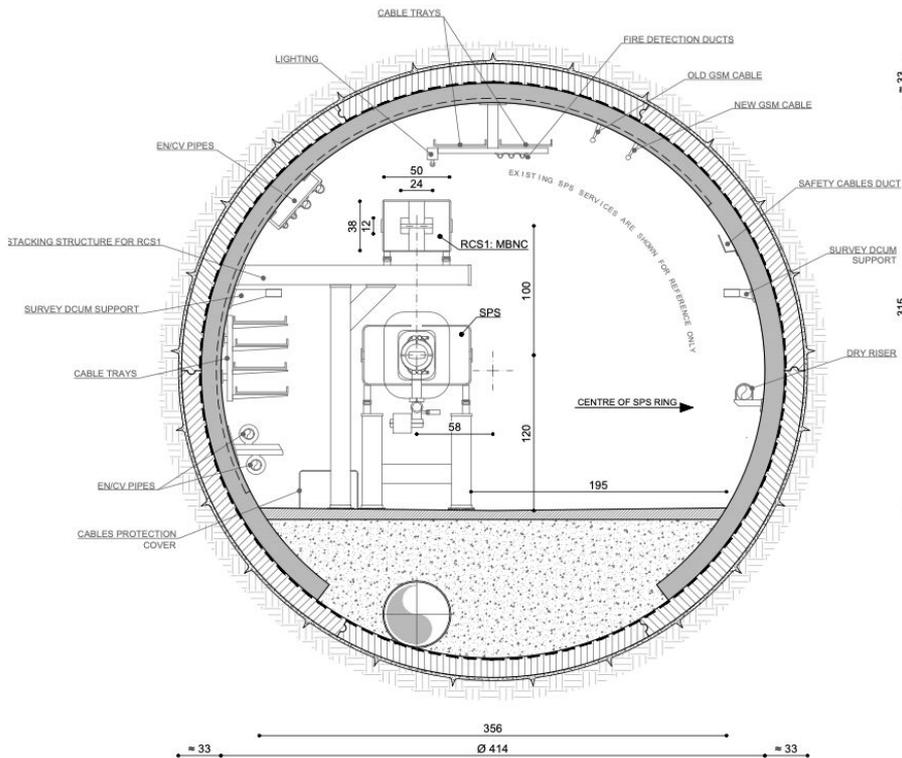
CTF3 @ CERN

Collider implementation

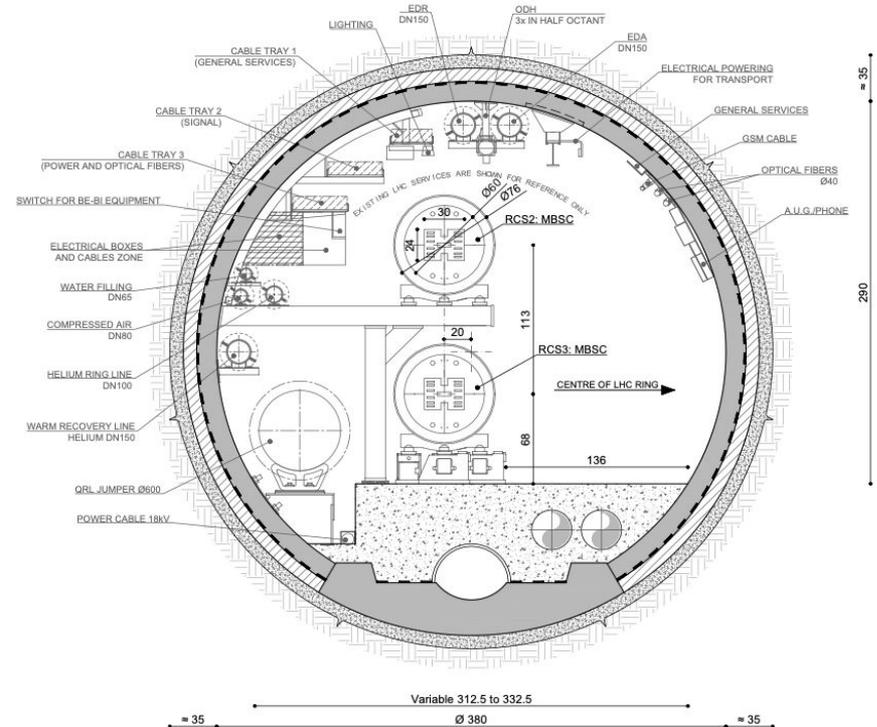


FNAL site also being investigated

SPS and LHC tunnel re-use



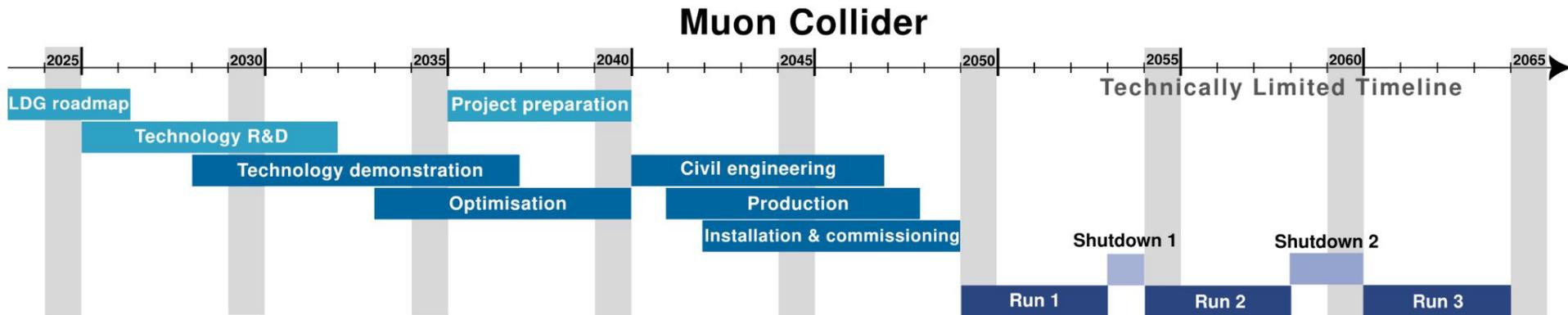
**TYPICAL CROSS SECTION
ACCELERATOR IN THE SPS TUNNEL**
RCS1: MBNC
SPS



**TYPICAL CROSS SECTION
ACCELERATOR IN THE LHC TUNNEL**
RCS2: MBSC
RCS3: MBSC

LHC could host up to 3.8 TeV beams, with hybrid RCS

Plans and technically limited timeline



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**

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

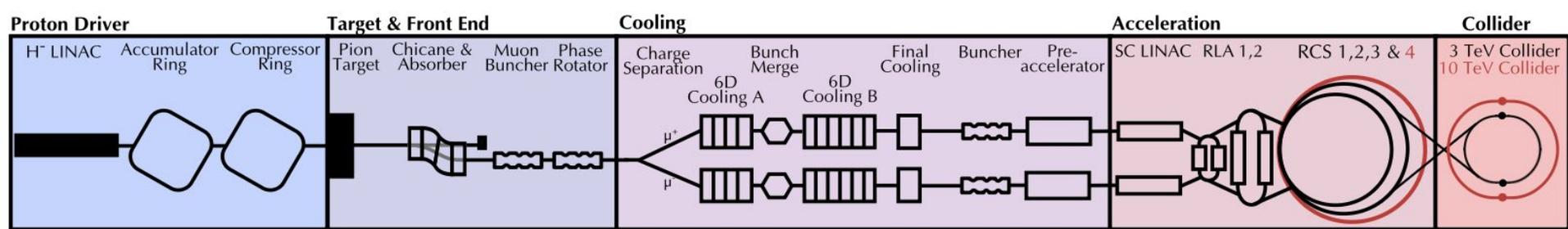
Thank you!

The background features a dark blue field with a faint, light-colored grid. Overlaid on this is a complex network diagram. A central hub of nodes is connected to many other nodes, which are further connected to each other, forming a dense web. The nodes are represented by small, multi-colored dots (red, green, blue, yellow, purple). The connections are thin, light-colored lines. The overall appearance is that of a data visualization or a network graph.

Contact

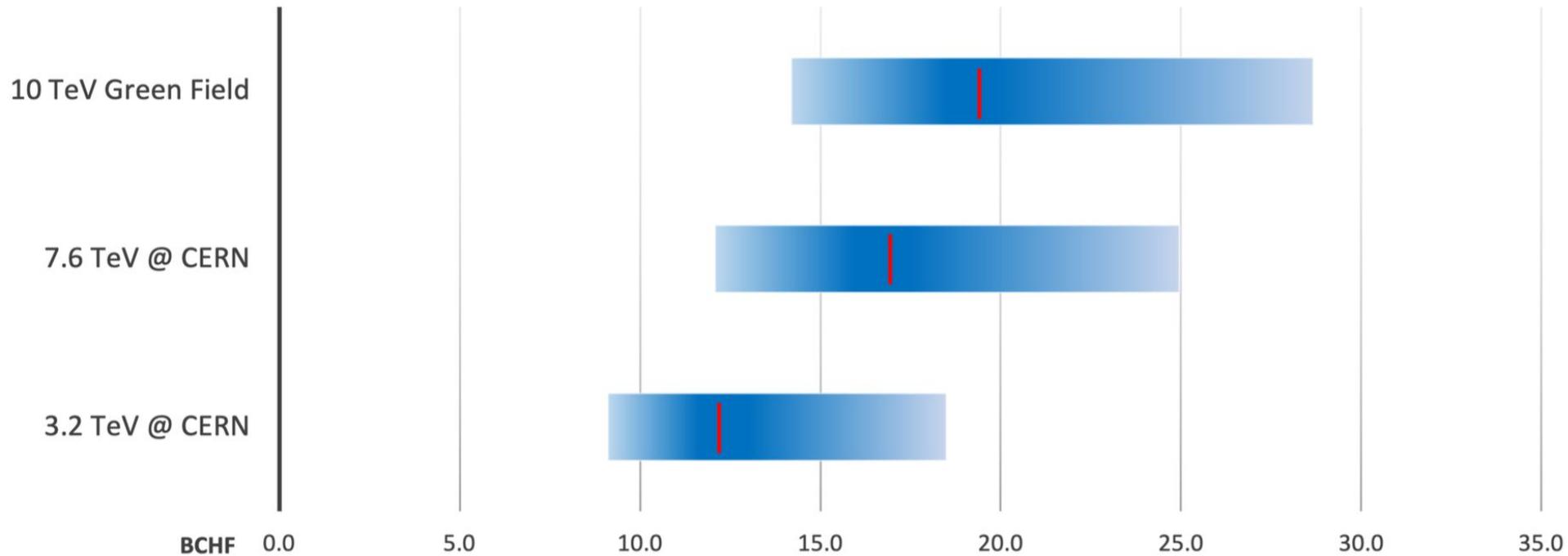
Federico Meloni
DESY-FH
federico.meloni@desy.de

Detailed collider complex overview



Facility cost range

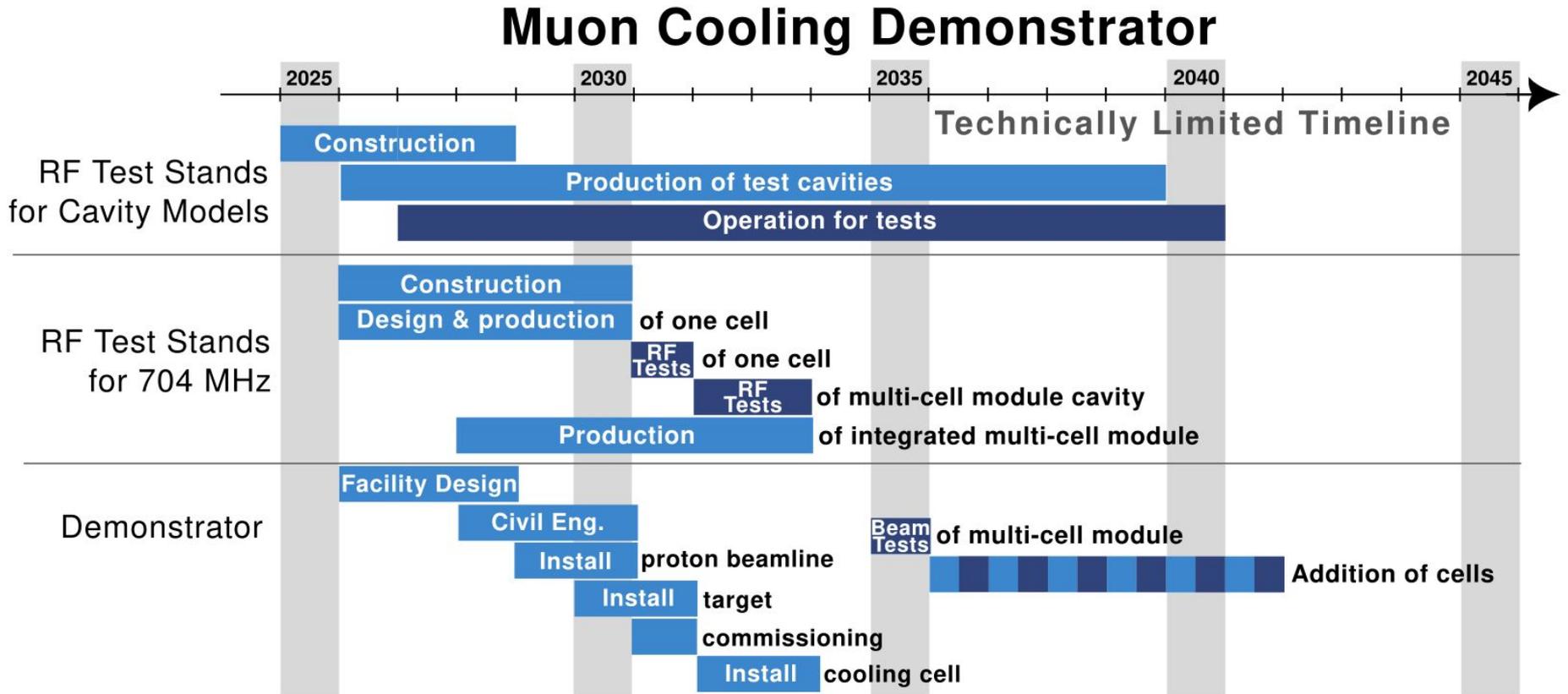
Cost range for Muon Collider scenarios



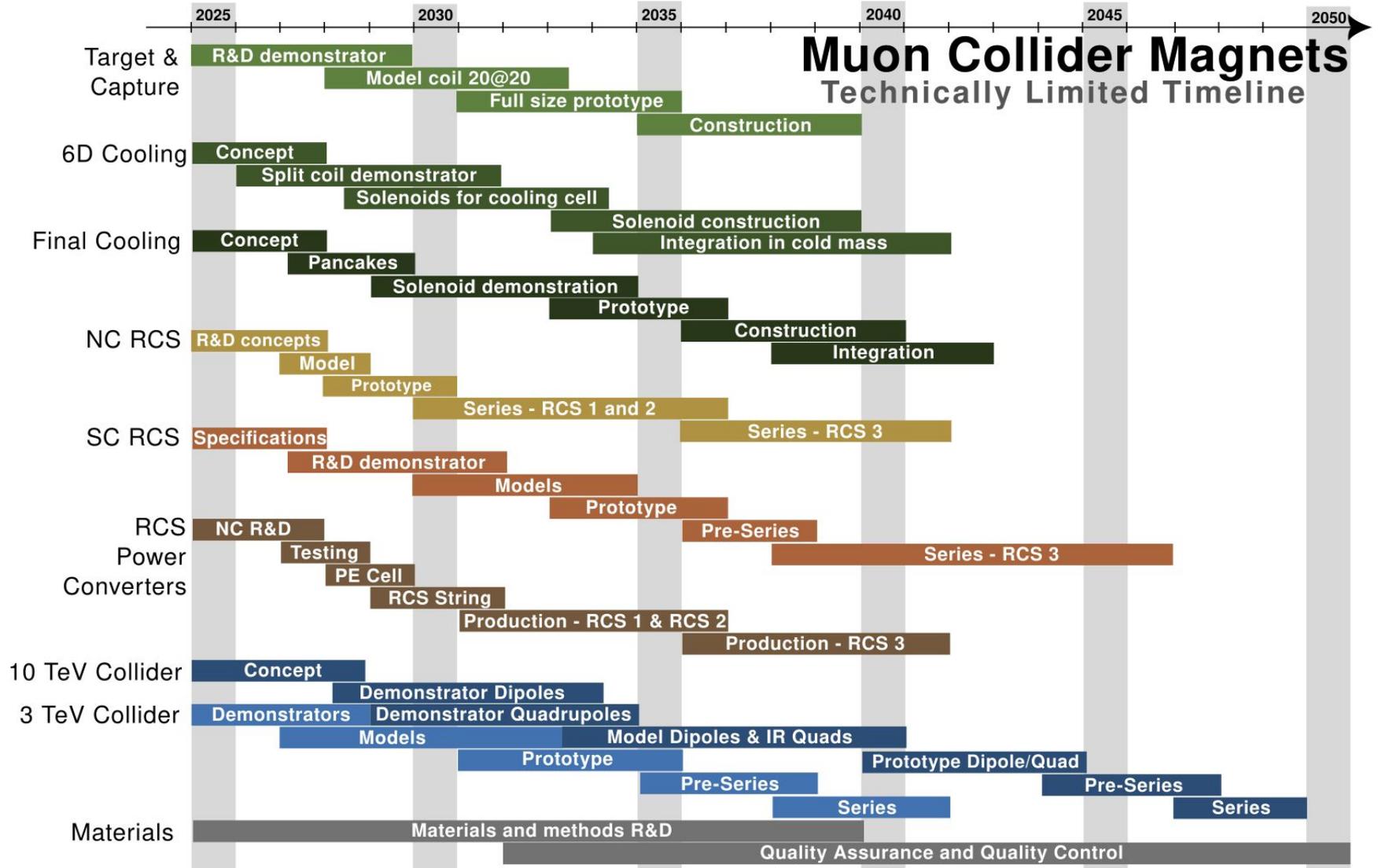
R&D resources breakdown

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



Magnet timescales

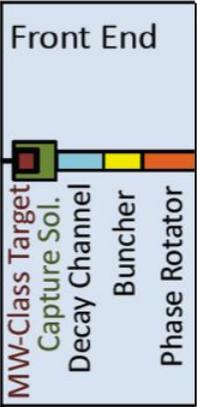


CERN-specific implementation

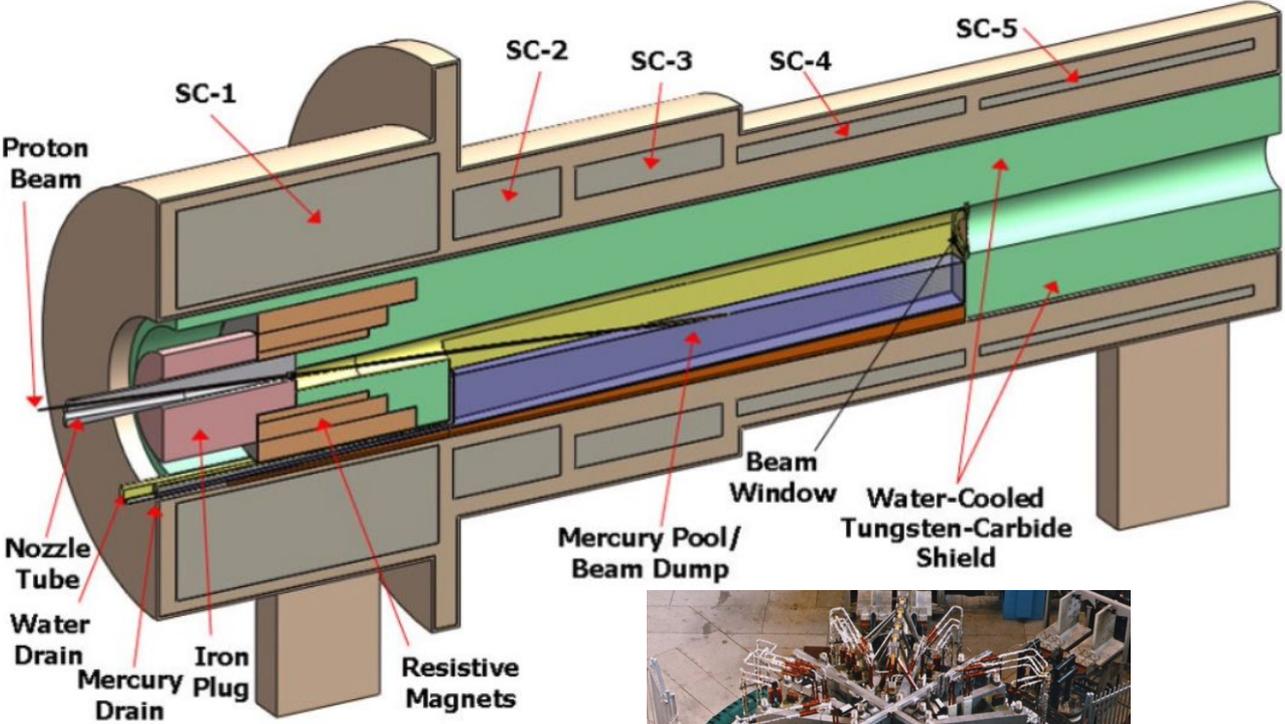
CERN-specific muon collider parameters						
Parameter	Symbol	unit	Scenario 1		Scenario 2	
			Stage 1	Stage 2	Stage 1	Stage 2
Centre-of-mass energy	E_{cm}	TeV	3.2	7.6	3.2	7.6
Target integrated luminosity	$\int \mathcal{L}_{\text{target}}$	ab^{-1}	1	10	1	10
Estimated luminosity	$\mathcal{L}_{\text{estimated}}$	$10^{34} \text{cm}^{-2} \text{s}^{-1}$	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 ₃ Sn or HTS	Nb ₃ Sn	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

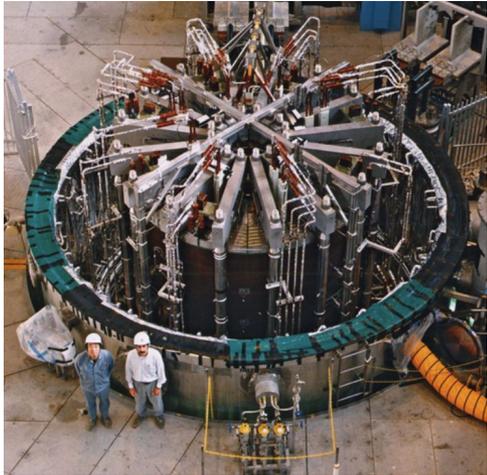


High-field required to efficiency collect pions and muons

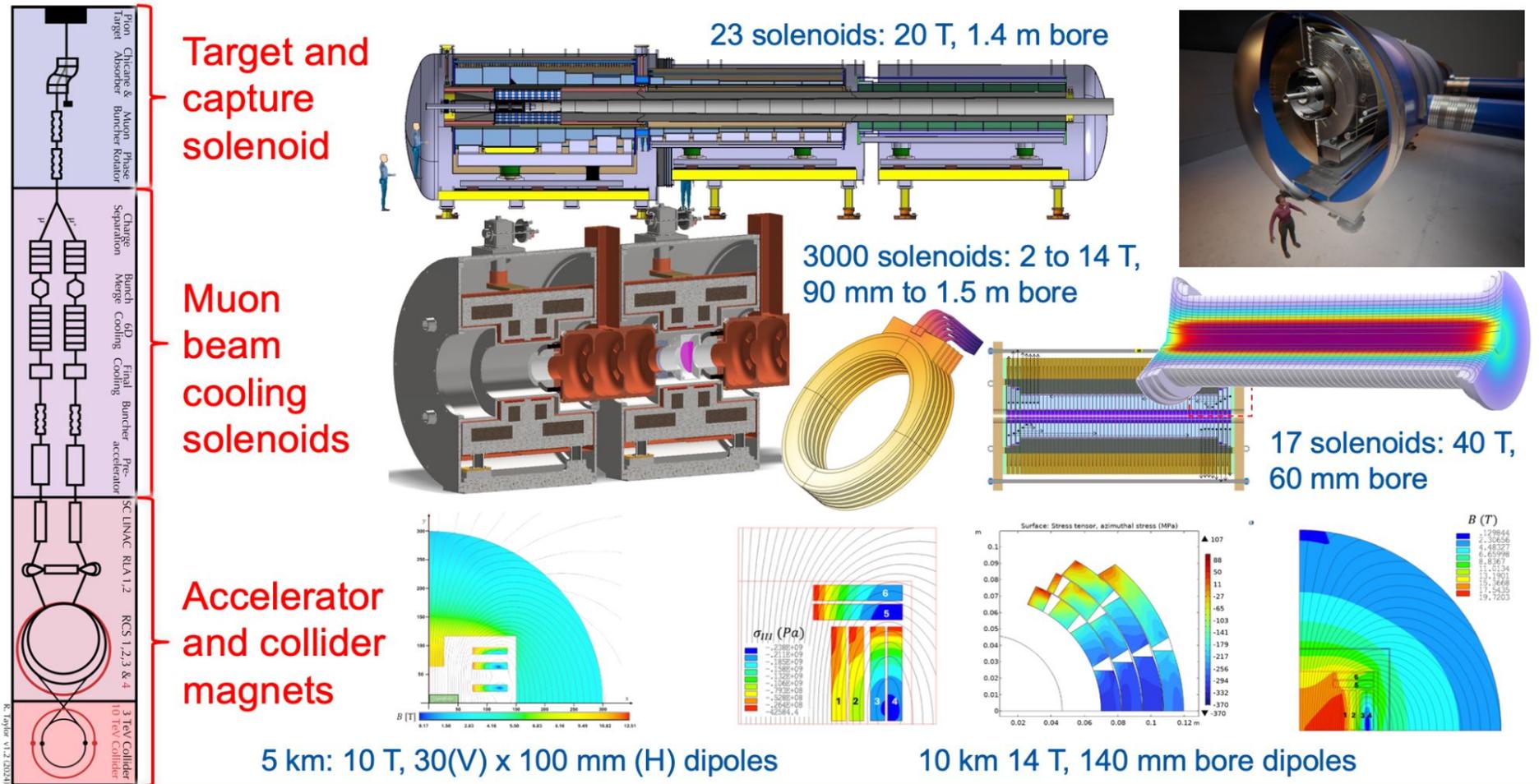


- 2-4 MW proton beam**
- Simulated graphite target ok
 - Operation at 2000°C

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



Magnets



From [L.Bottura](#), HFM meeting 10-12.2.2025

9

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

Magnet R&D plans

Experimental programme is now essential

Technology-driven R&D programme

- ReBCO tape identified as enabling technology

- **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)

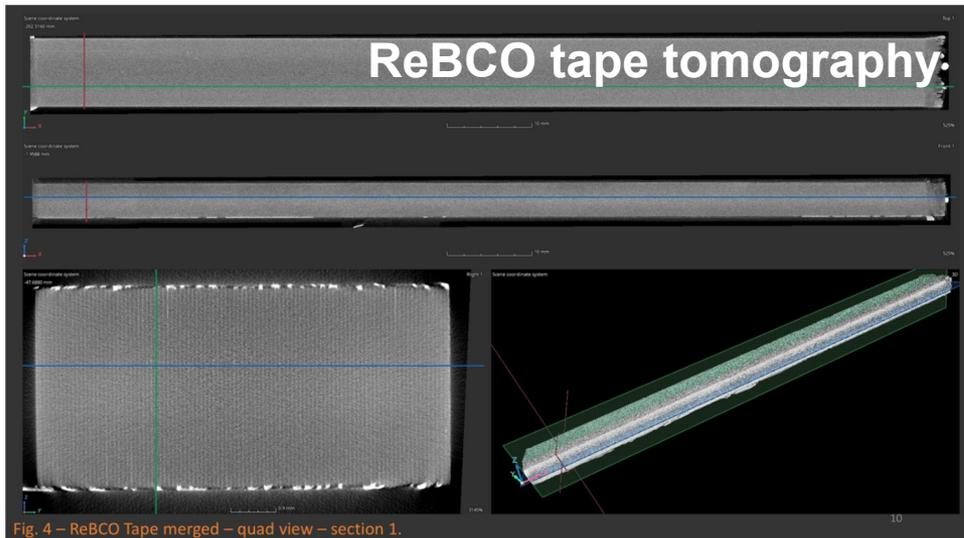
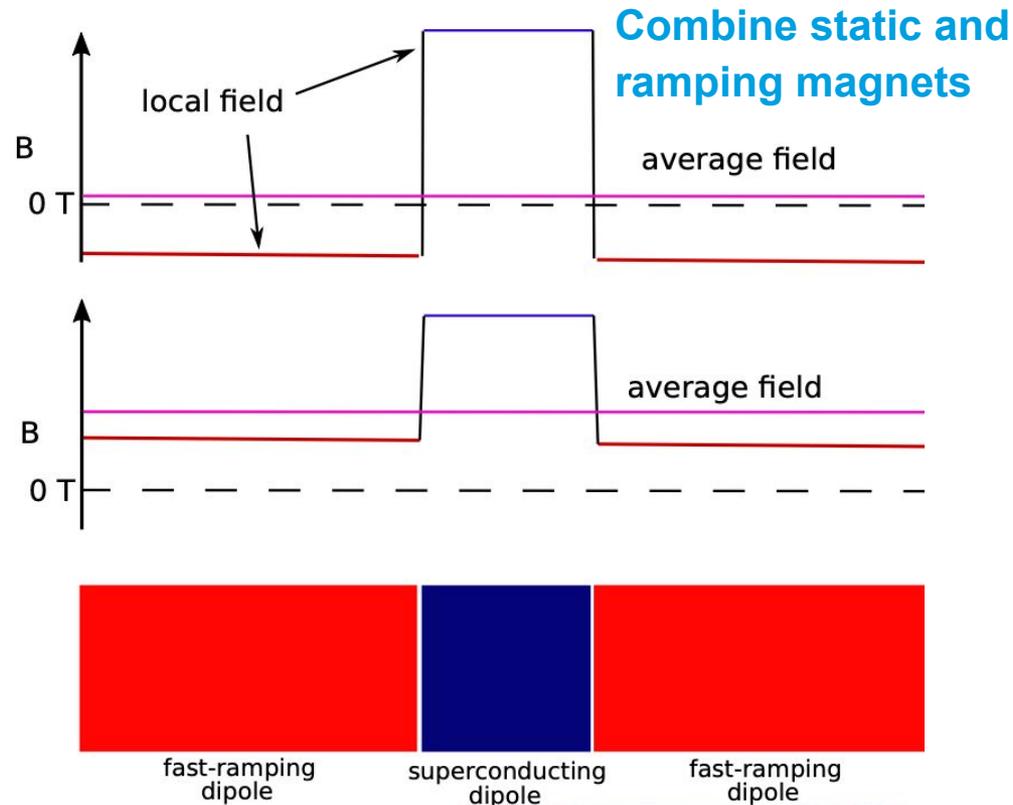


Fig. 4 – ReBCO Tape merged – quad view – section 1.

Hybrid magnet concept



Ramp magnets to follow E_{beam}

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

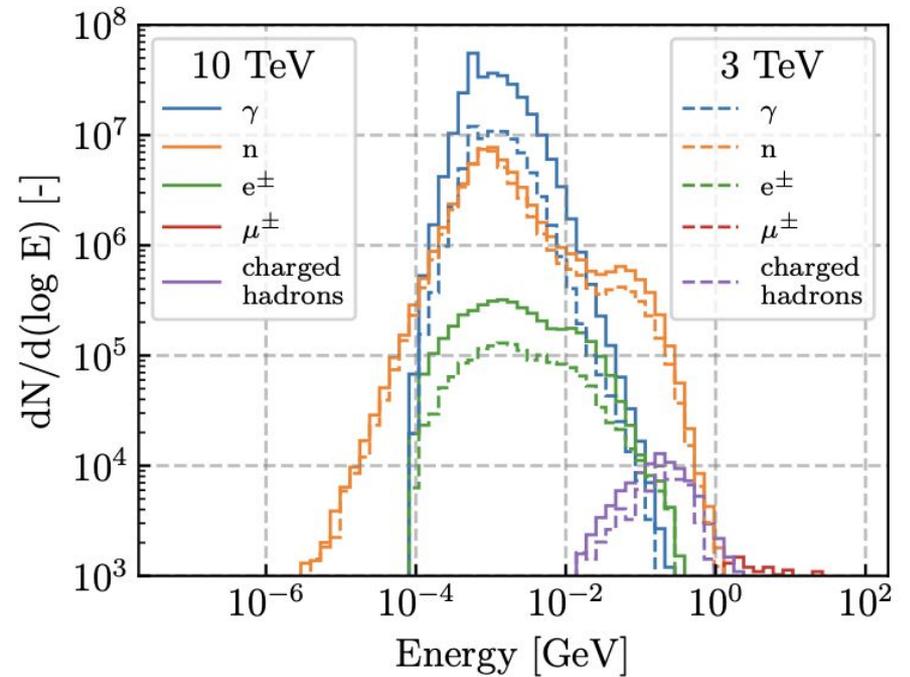
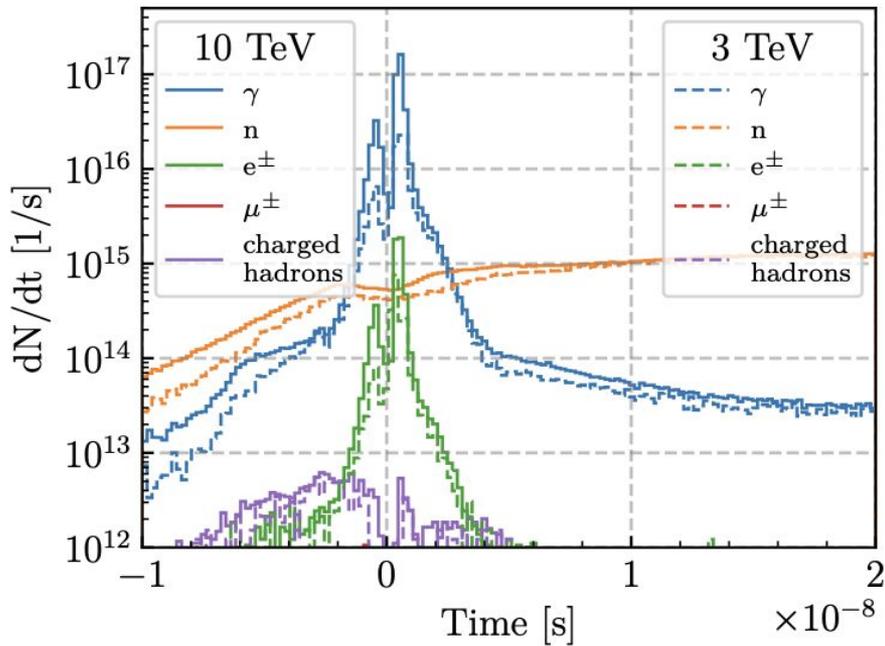
Need 5 km of 2T magnets per TeV or fast HTS dipoles

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

BIB properties



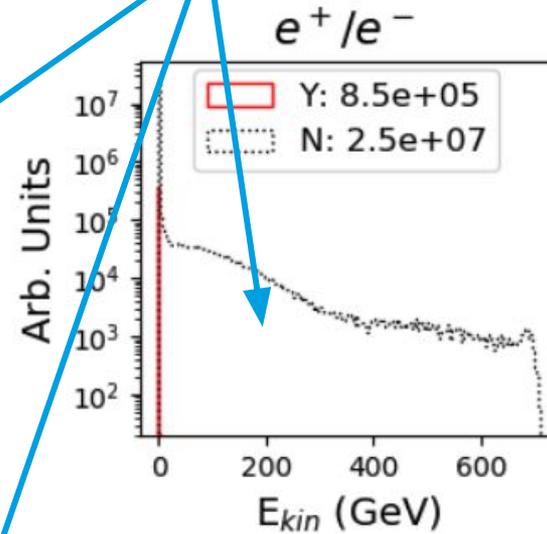
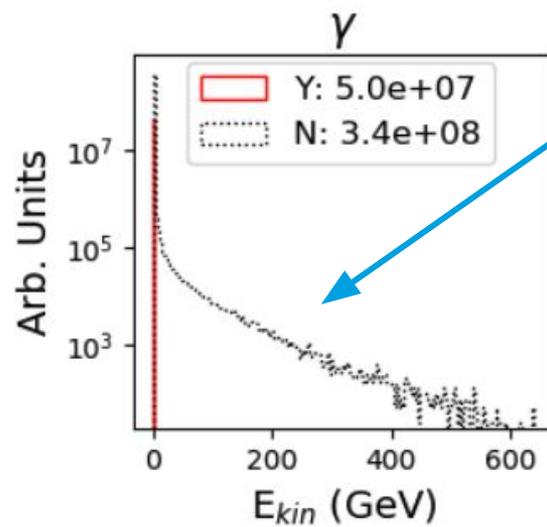
Detector design targets

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

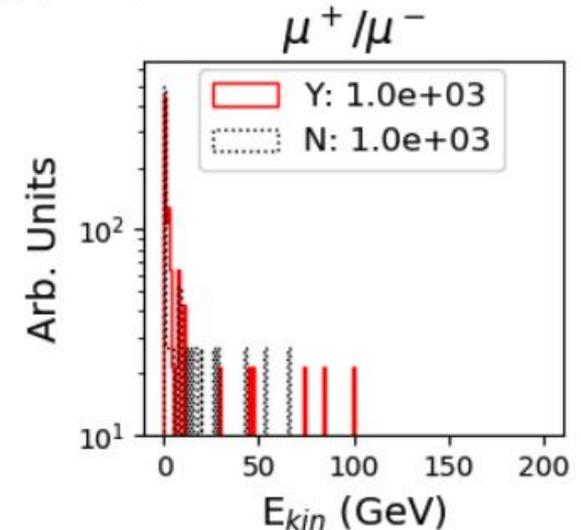
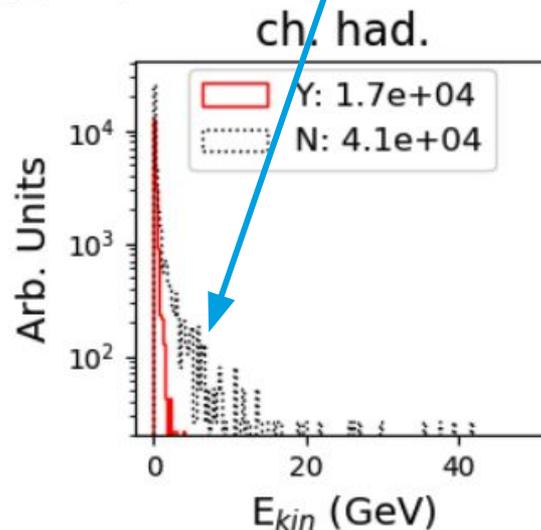
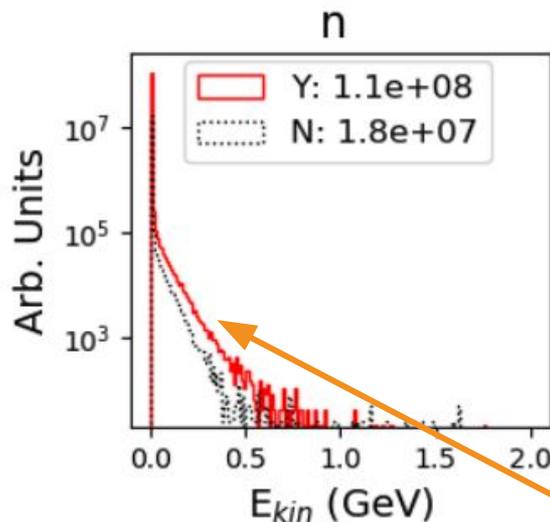
Impact of nozzles

Y: with nozzle
N: w/o nozzle

High-energy component absorbed



BIB rates in detector volume
~constant wrt \sqrt{s}



Increase in neutron flux

R&D: 4D tracking detectors

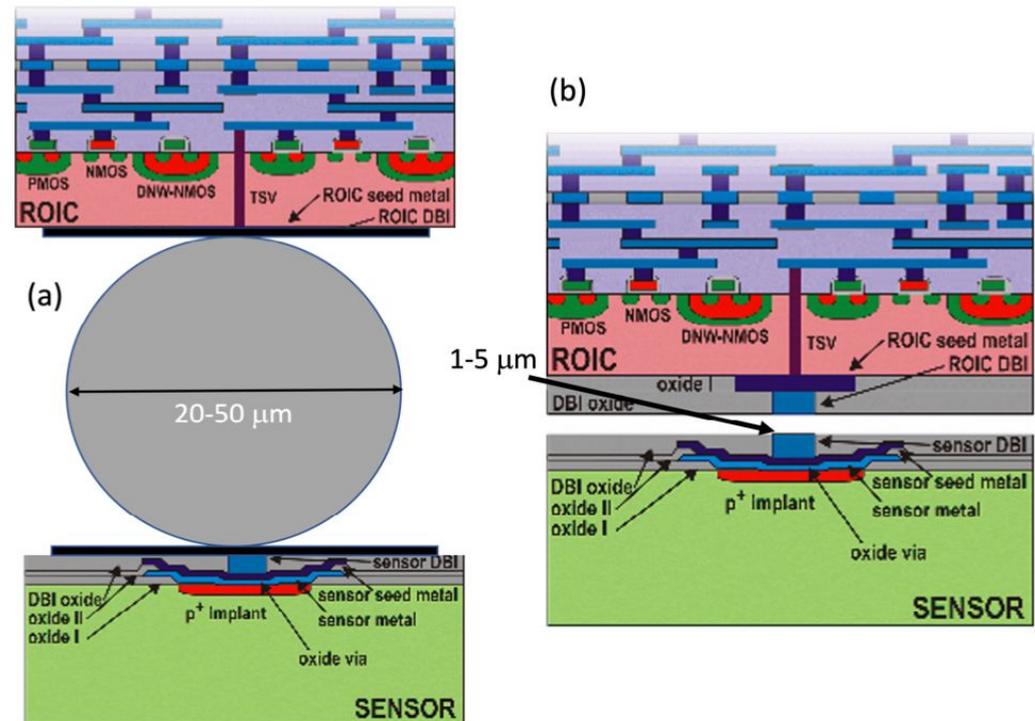
	Vertex Detector	Inner Tracker	Outer Tracker
Cell type	pixels	macropixels	microstrips
Cell Size	$25\ \mu\text{m} \times 25\ \mu\text{m}$	$50\ \mu\text{m} \times 1\ \text{mm}$	$50\ \mu\text{m} \times 10\ \text{mm}$
Sensor Thickness	$50\ \mu\text{m}$	$100\ \mu\text{m}$	$100\ \mu\text{m}$
Time Resolution	30 ps	60 ps	60 ps
Spatial Resolution	$5\ \mu\text{m} \times 5\ \mu\text{m}$	$7\ \mu\text{m} \times 90\ \mu\text{m}$	$7\ \mu\text{m} \times 90\ \mu\text{m}$

R&D efforts crucial

Promising technologies exist

Example: Advanced hybrid bonding tech can give $< 5\ \mu\text{m}$ pitch and low input capacitance

- 20-30 ps time resolution



Readout and DAQ

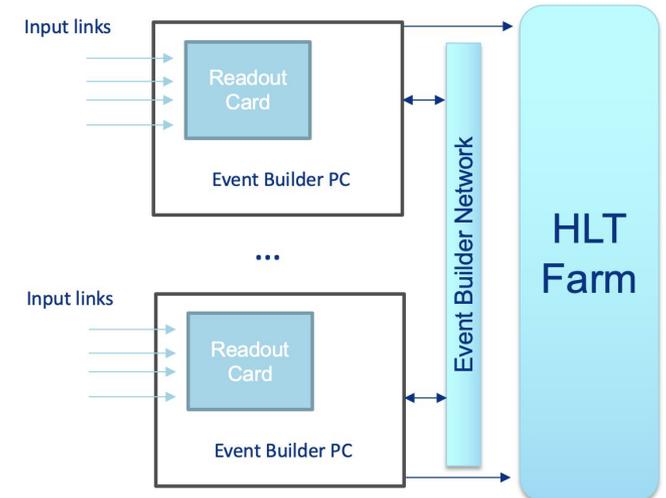
Instantaneous luminosity of 10^{34} - $10^{35} \text{ cm}^{-2}\text{s}^{-1}$

Beam crossings **every 10 μs**

Streaming approach: availability of the full event data \rightarrow 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	$t-t_0 < 1 \text{ ns}$	$\sim 3,000$	30 Tb/s
Calorimeter	20-bit	$t-t_0 < 0.3 \text{ ns}$ $E > 200 \text{ KeV}$	$\sim 3,000$	30 Tb/s

Table credit: S. Jindariani

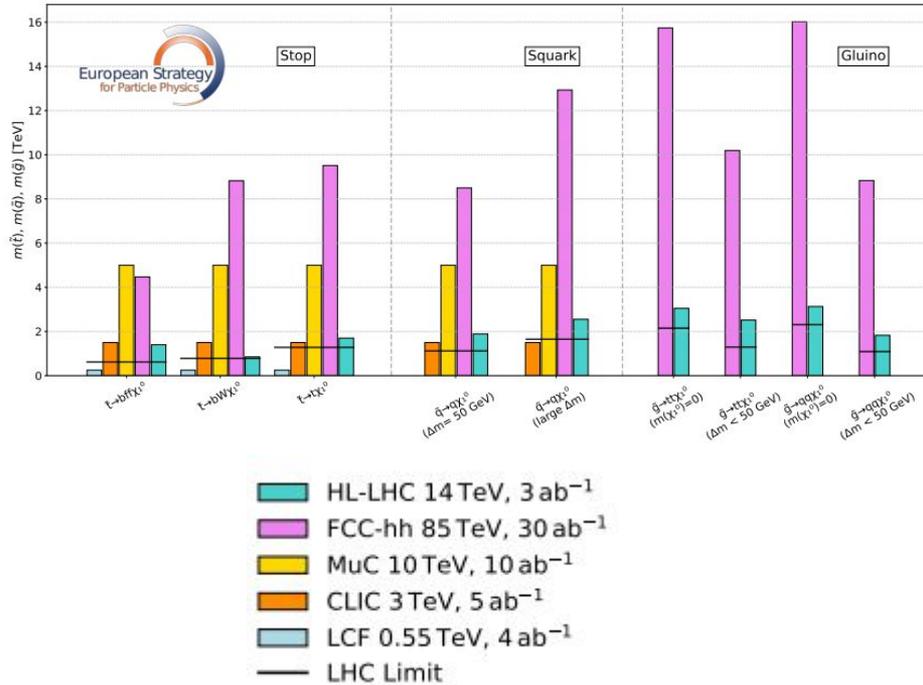


Total data rate similar to HLT at HL-LHC

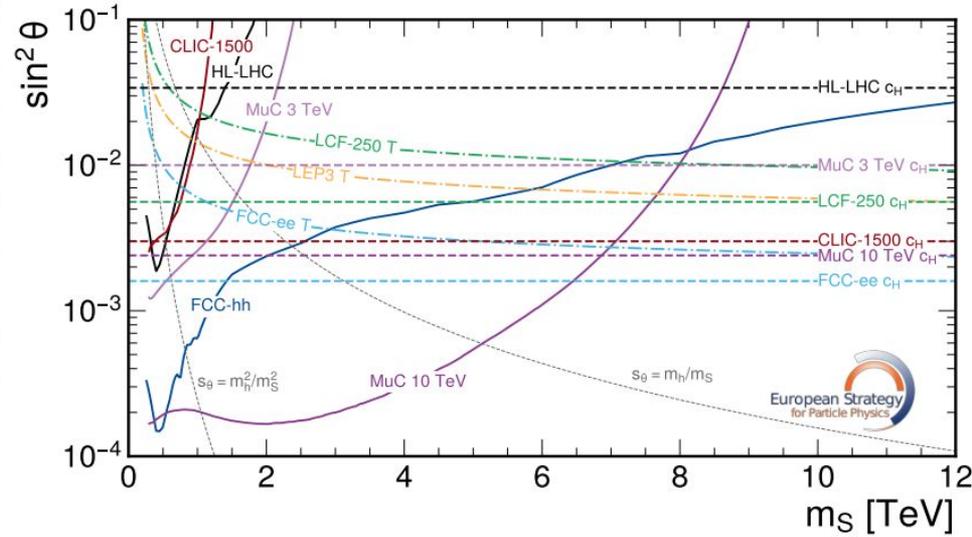
- **Streaming operation likely feasible**

Direct mass reach

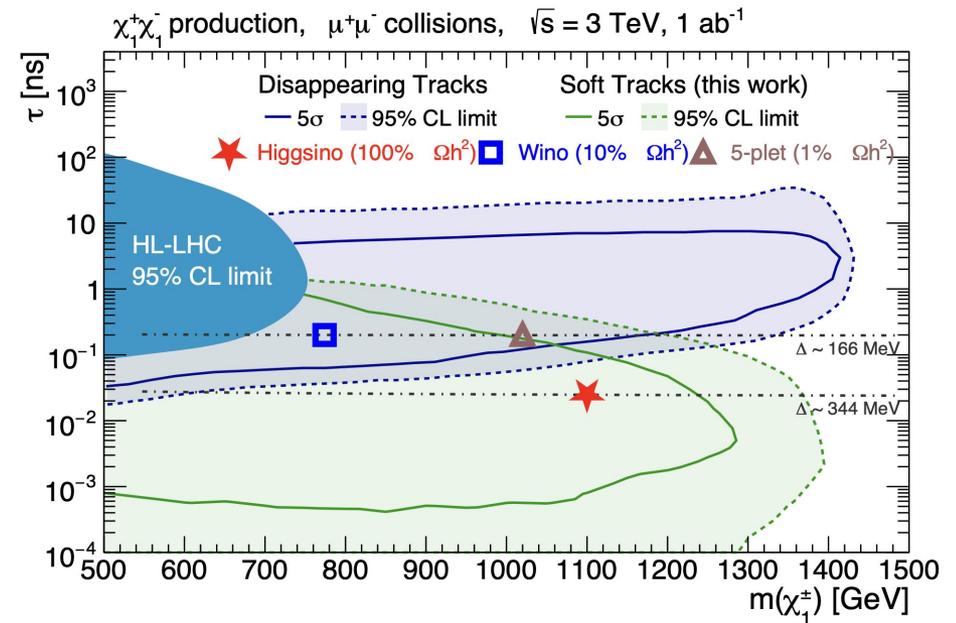
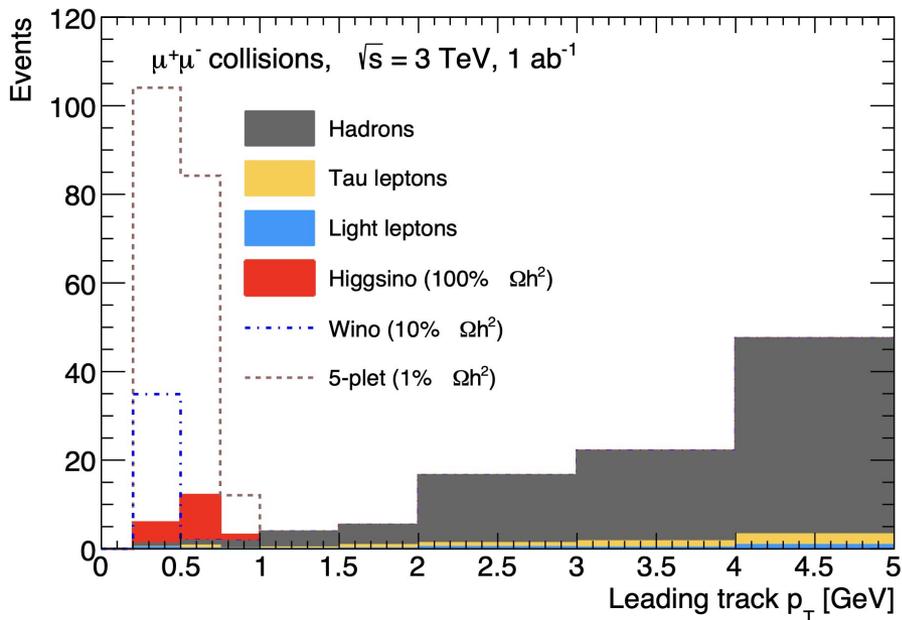
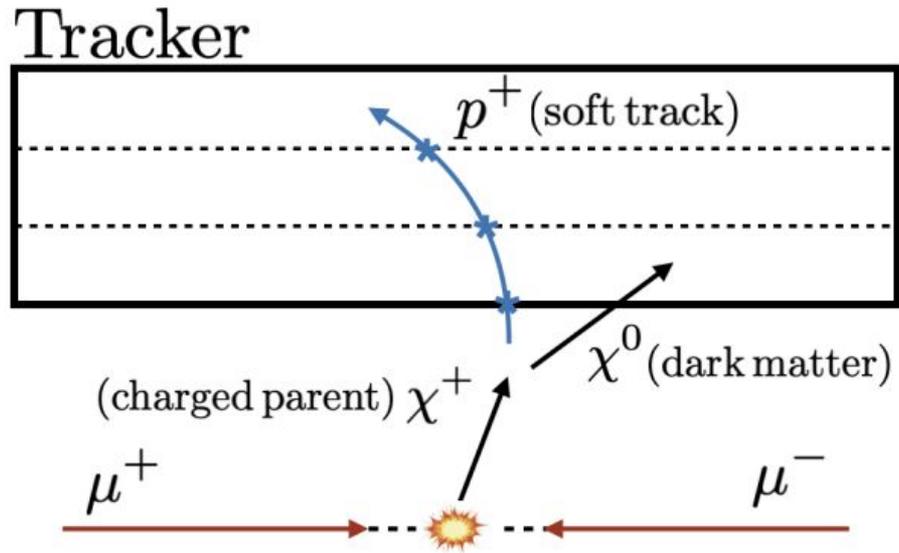
SUSY

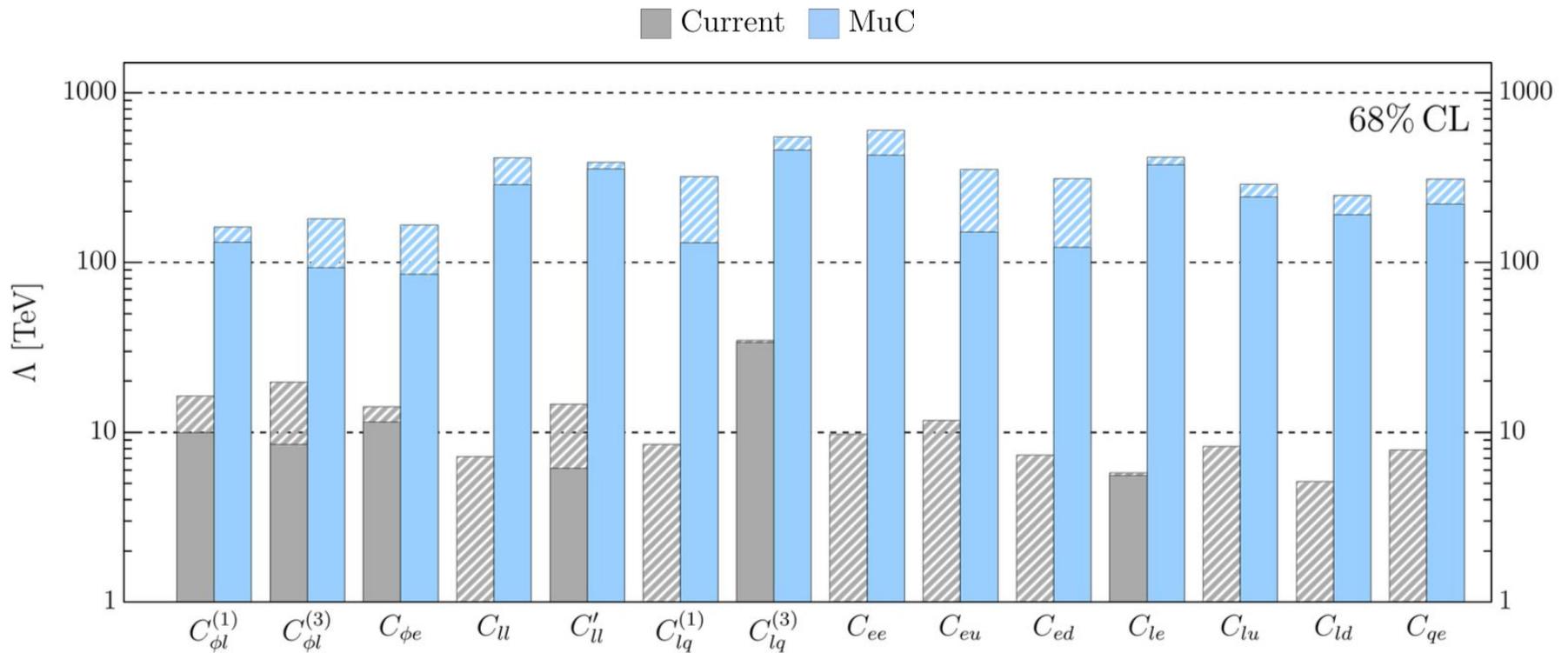


Scalar singlet



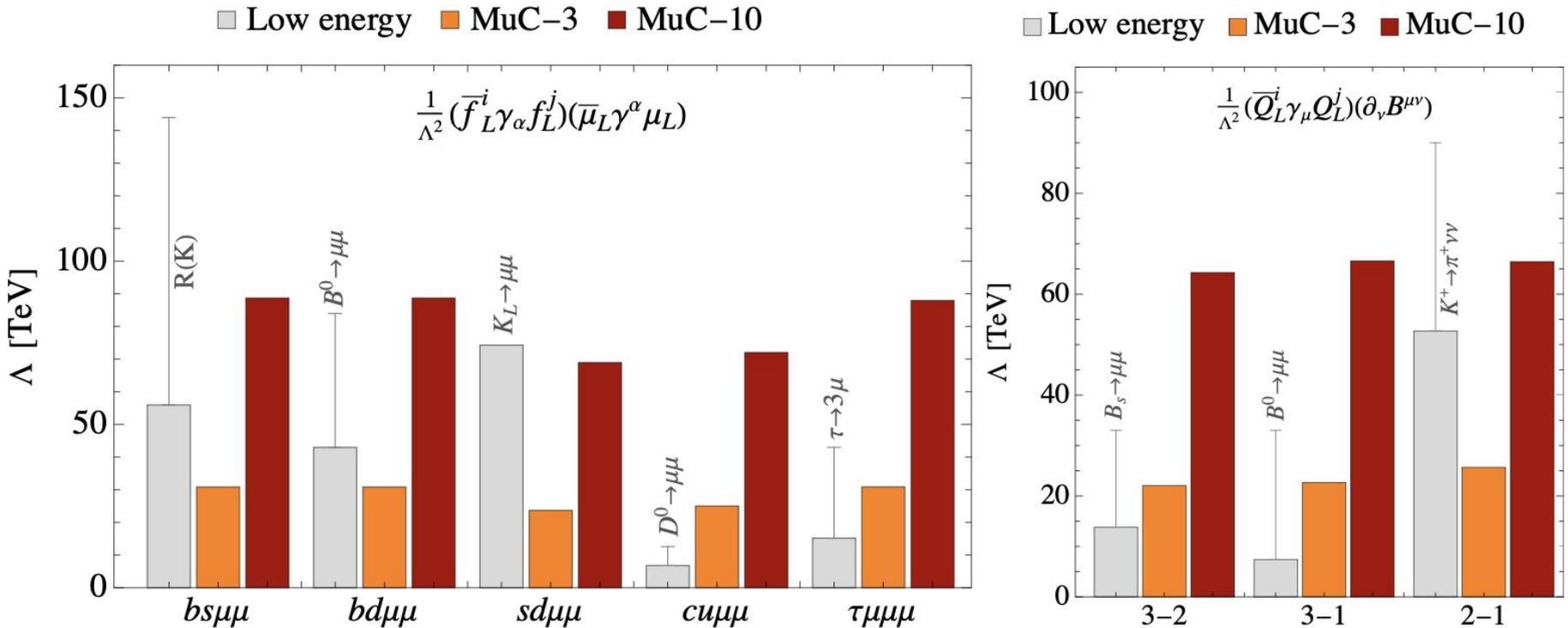
Soft tracks





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

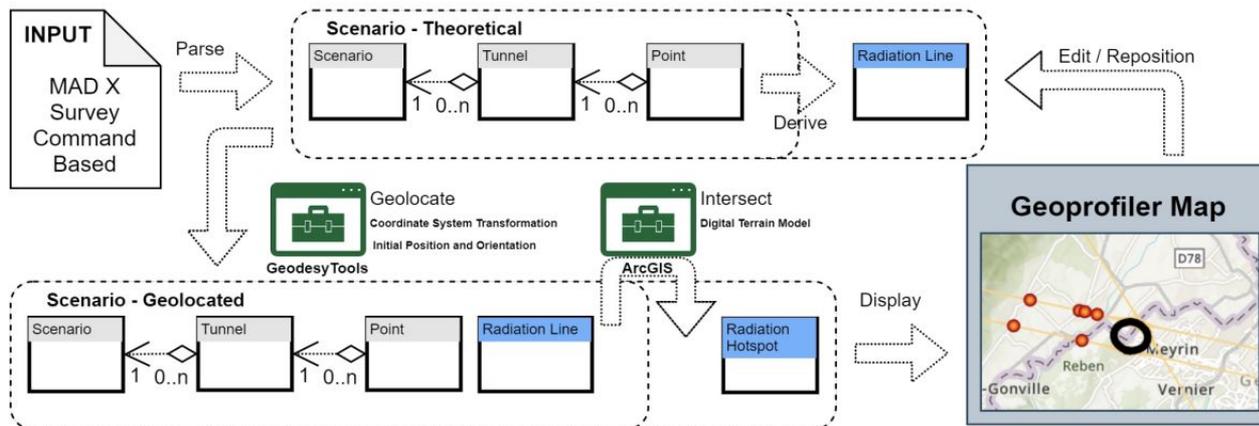
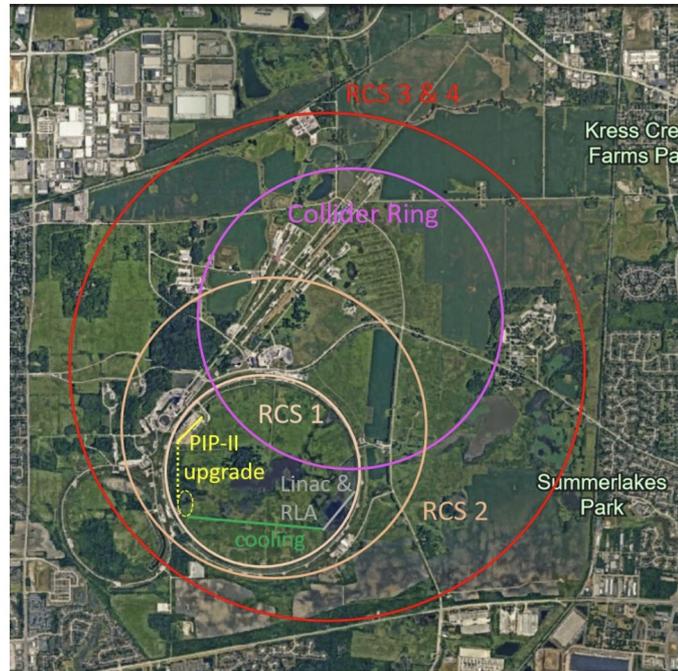
Flavour



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.

FNAL Siting

Preliminary
Fermilab siting
study



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 ₃ Sn 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 $O(\pm 1\text{mradian})$
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