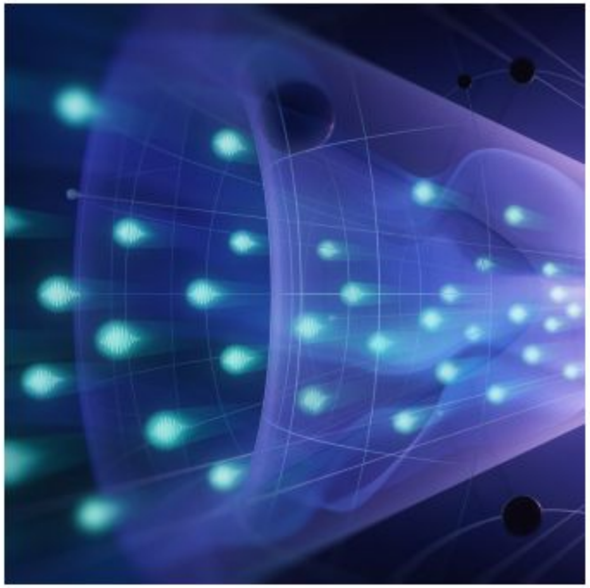
IMCC highlights and news

Federico Meloni (DESY)

FC@DESY
12/04/2024

Co-funded by the European Union

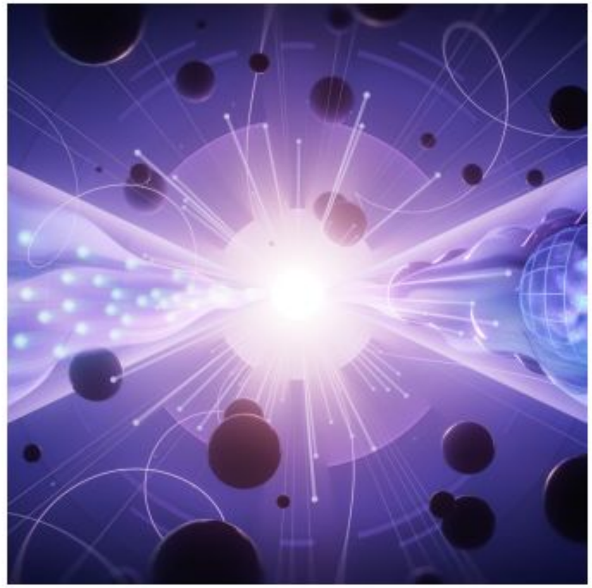
The Muon Shot



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

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

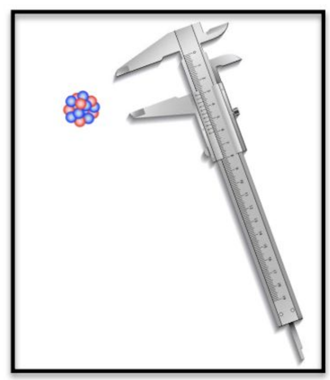
2203.07256
2103.14043

Why are we excited about muon colliders?

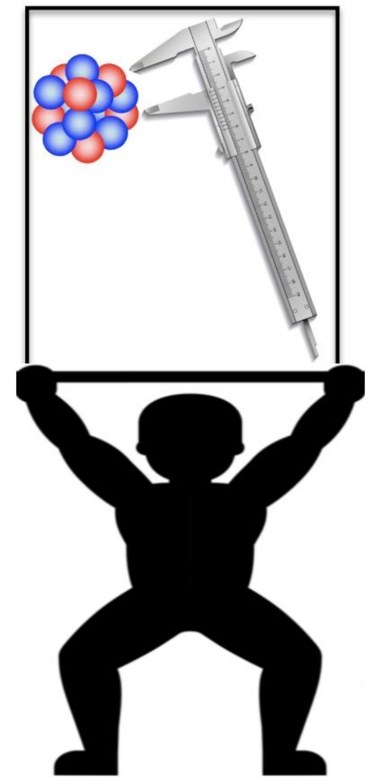
A muon collider combines *pp* and *ee* advantages:

- High available energy for new heavy particles production
- High available statistics for precise measurements (and no QCD background)
- Can measure processes of very high energy

Energy



Precision



High-energy Precision

Slide design credit: A. Wulzer

IMCC week 2024 @ CERN

~200 people, 3.5 days, ~100 talks

Evolution of mindset

Actually an important change toward the end of the Interim Report preparation

In **European Accelerator Roadmap** main goal has been to be back into the field

- Focus on justifying our existence
- Focus on the ESPPU allowing us to continue

Several developments since

- With the **progress of work** are gaining confidence that collider can keep its promises
- Are becoming a **global effort**
  - **US expresses strong interest** in the collider
  - Also **interest in Asia,** might well increase
  - Are becoming less dependent on decisions in Europe

So we need to **focus on the longer term** and prepare the R&D programme

D. Schulte

Roadmap

Initial tentative findings (to be reviewed now):

- Expect detector and muon production and cooling can meet the required timeline
- Magnets are main limitation:

Consensus of magnet experts (review panel):

- Anticipated **mature magnet technology in O(15 years):**
  - **HTS solenoids** in muon production target, 6D cooling and final cooling
    - HTS tape can be applied more easily in solenoids
    - Strong synergy with society, e.g. fusion reactors
  - **Nb_3Sn 11 T magnets** for collider ring (or HTS if available): 150mm aperture, 4K
  - This corresponds to 3 TeV design
- Still under discussion:
  - Timescale for HTS/hybrid collider

First Parameter Report submitted in October 2023

The first parameter document has been important progress

- The teams took ownership of their parameters
- Now need to consolidate and update the parameters

Feel that we are in a position to start making trade-offs

- Cannot not at this moment make the final parameter set
- But consider different options

D. Schulte

Staging options

Staging Approaches

MuCol

International MUON Collider Collaboration

Assumptions:

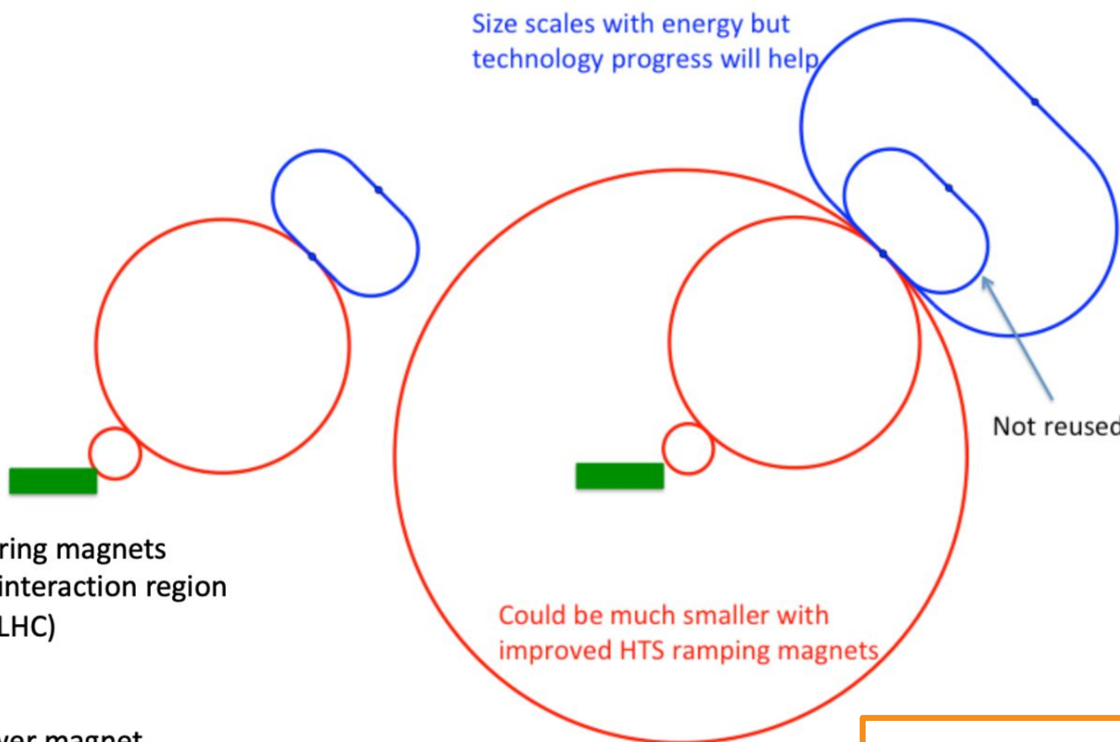
- In O(15 years):
    - HTS technology available for solenoids
    - Nb_3Sn available for collider ring
- In O(25 years):
    - HTS available for collider ring

Scenario 1: Energy staging

- Start at lower energy (e.g. 3 TeV)
- Build additional accelerator and collider ring later
- Requires less budget for first stage
- 3 TeV design takes lower performance into account

Scenario 2: Luminosity staging

- Start at with full energy, but less performant collider ring magnets
- Main sources of luminosity loss are collider arcs and interaction region
    - Can recover interaction region later (as in HL-LHC)
    - But need full budget right away
    - Some luminosity loss remains (O(1.5))
    - More power for the collider ring required (lower magnet temperature)

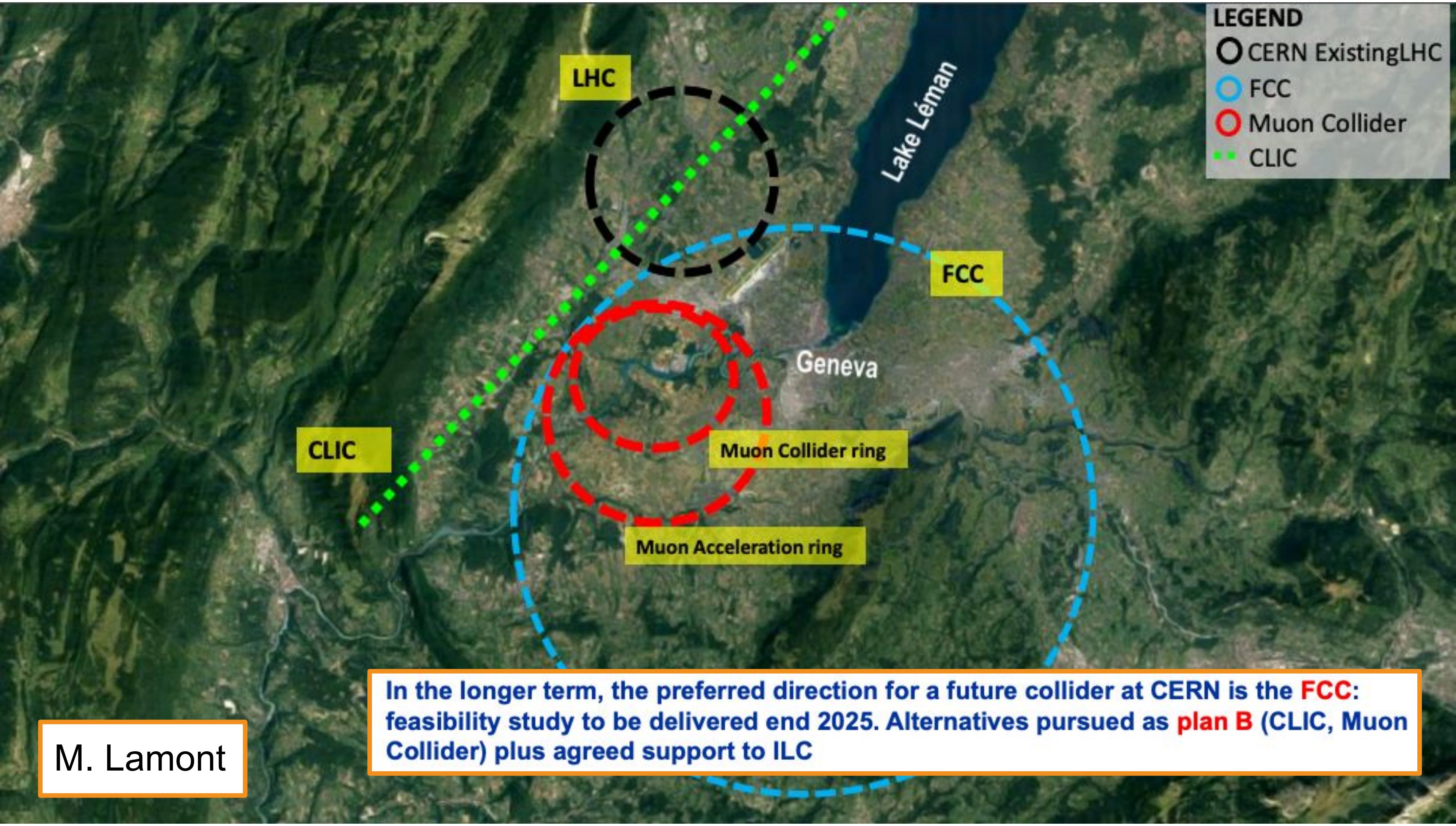


D. Schulte

D. Schulte Muon Collider, CERN, March 2024

Facility updates and demonstrator programme(s)

News from CERN

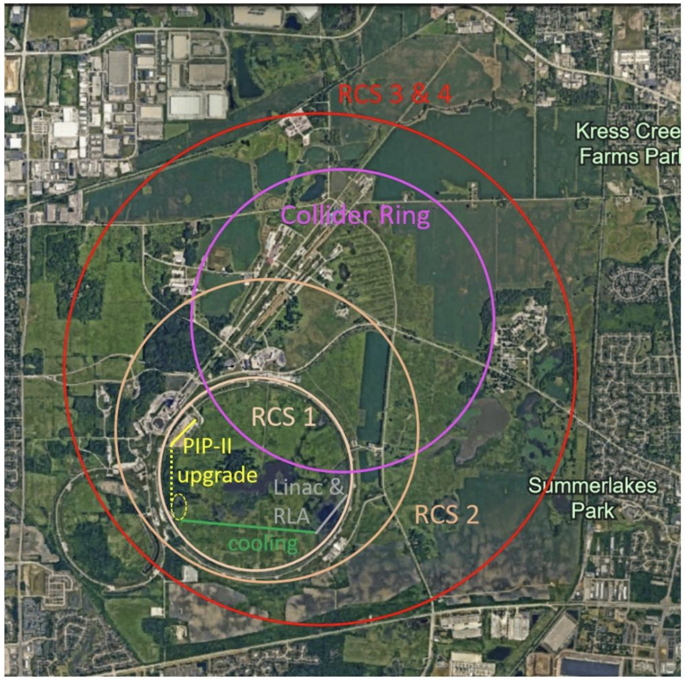


In the longer term, the preferred direction for a future collider at CERN is the FCC: feasibility study to be delivered end 2025. Alternatives pursued as plan B (CLIC, Muon Collider) plus agreed support to ILC

M. Lamont

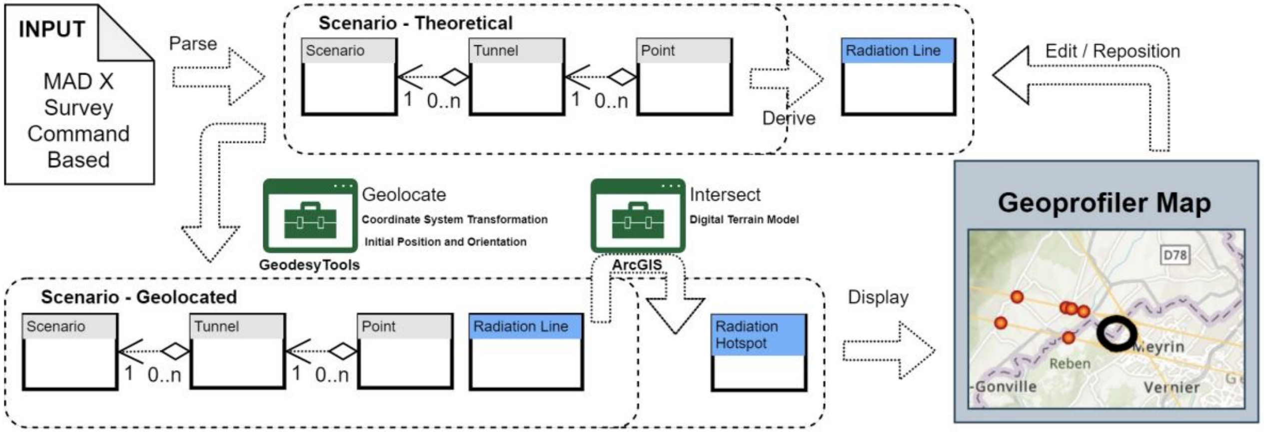
Siting details

Preliminary Fermilab siting study



Potential site next to CERN identified

- Mitigates neutrino flux
  - Points toward mediterranean and uninhabited area in Jura

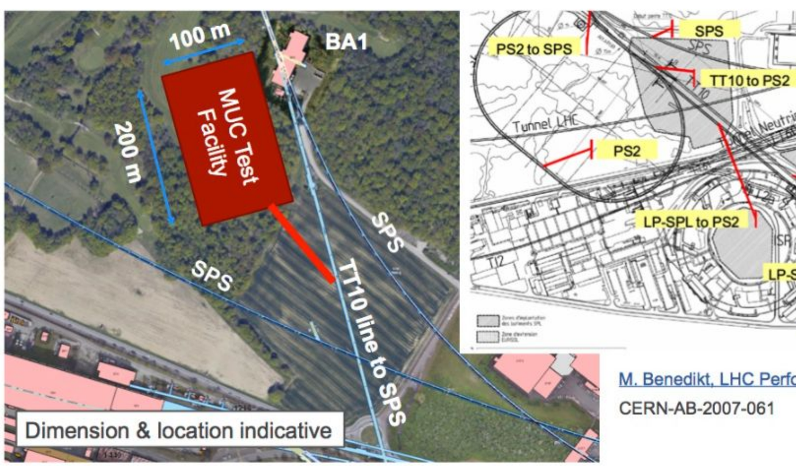


Demonstrator programme(s)

Planning demonstrator facility with muon production target and cooling

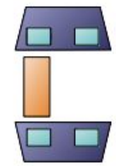
- Intensity below real collider (e.g. 10 kW target)

Suitable sites exist on CERN and Fermilab land

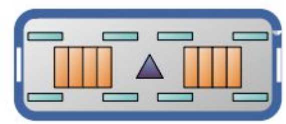


M. Benedikt, LHC Performance Workshop, (

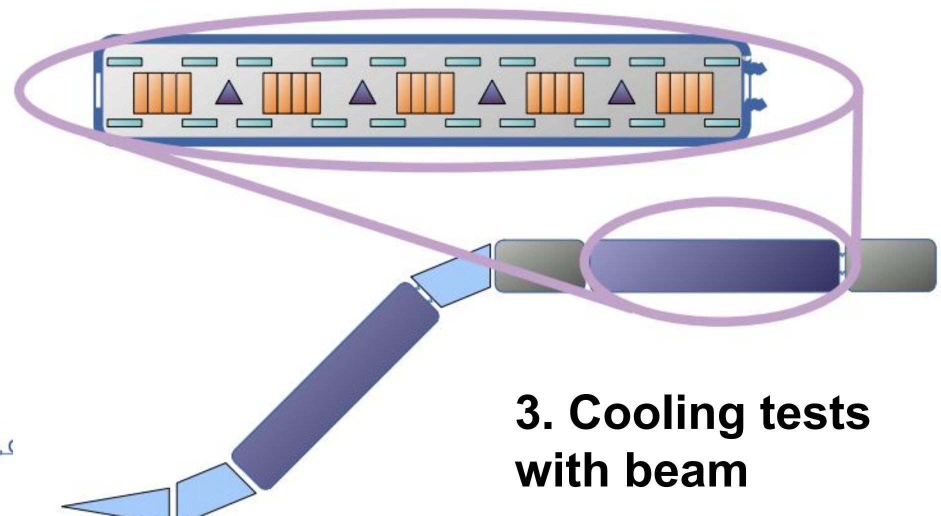
CERN-AB-2007-061



1. RF tests



2. Prototype cooling vacuum vessel



3. Cooling tests with beam

RF Magnetic field test facility

Magnetic fields induce sparking in RF

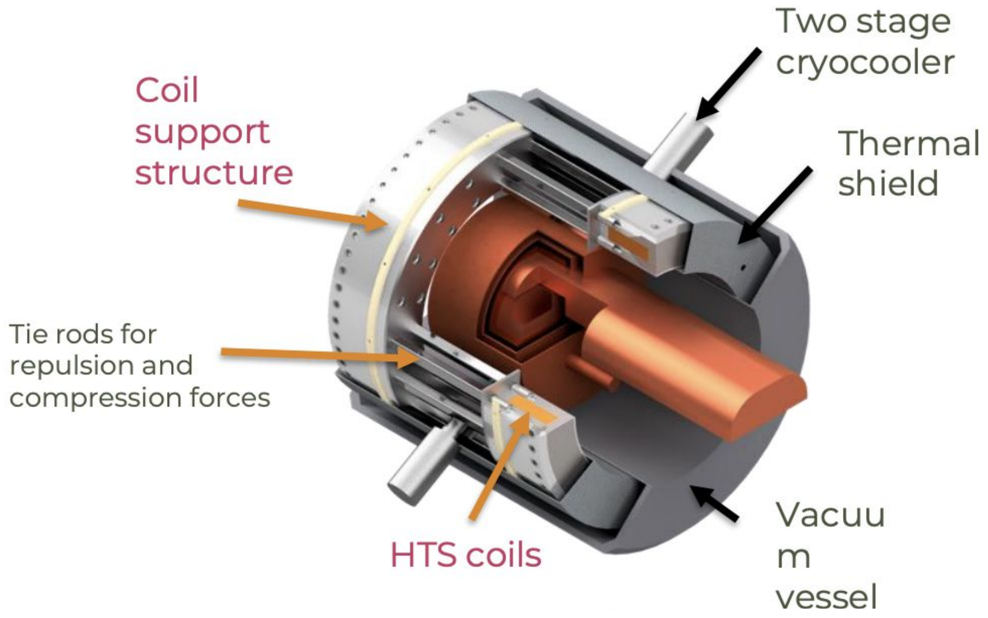
Preliminary mitigations exist

- Novel materials
- Surface preparations
- Gas insulation
- Cavity management

Need full design

- Experimental demonstration
- Needs to happen before cooling demonstrator construction

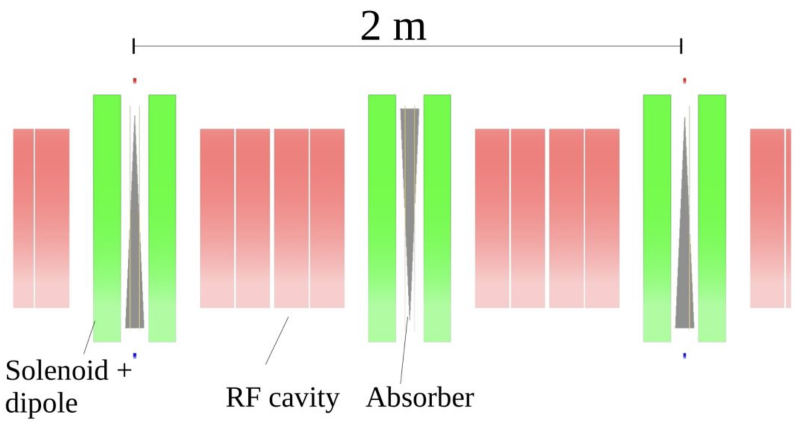
Test stands proposed in **Milan, Daresbury, CEA Saclay**



Muon cooling

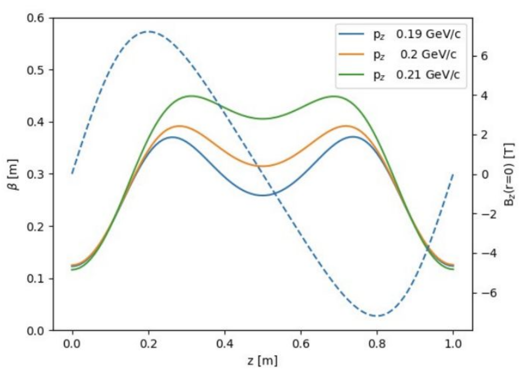
Cooling cell design independent of the site,
but muon beam production and preparation may not be

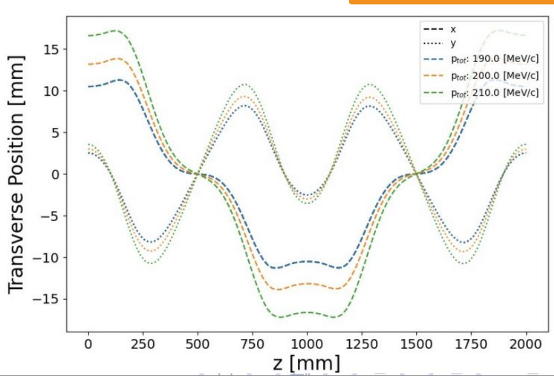
- Ongoing studies on the implementation of a demo facility in CERN TT7
- Preliminary cooling lattice design done



Cooling System	
Cell length	2 m
Peak solenoid field on-axis	7.2 T
Dipole field	0.2 T
Dipole length	0.1 m
RF real estate gradient	22 MV/m
RF nominal phase	20°
RF frequency	704 MHz
Wedge thickness on-axis	0.0342 m
Wedge apex angle	5°
Wedge material	LiH

C. Rogers

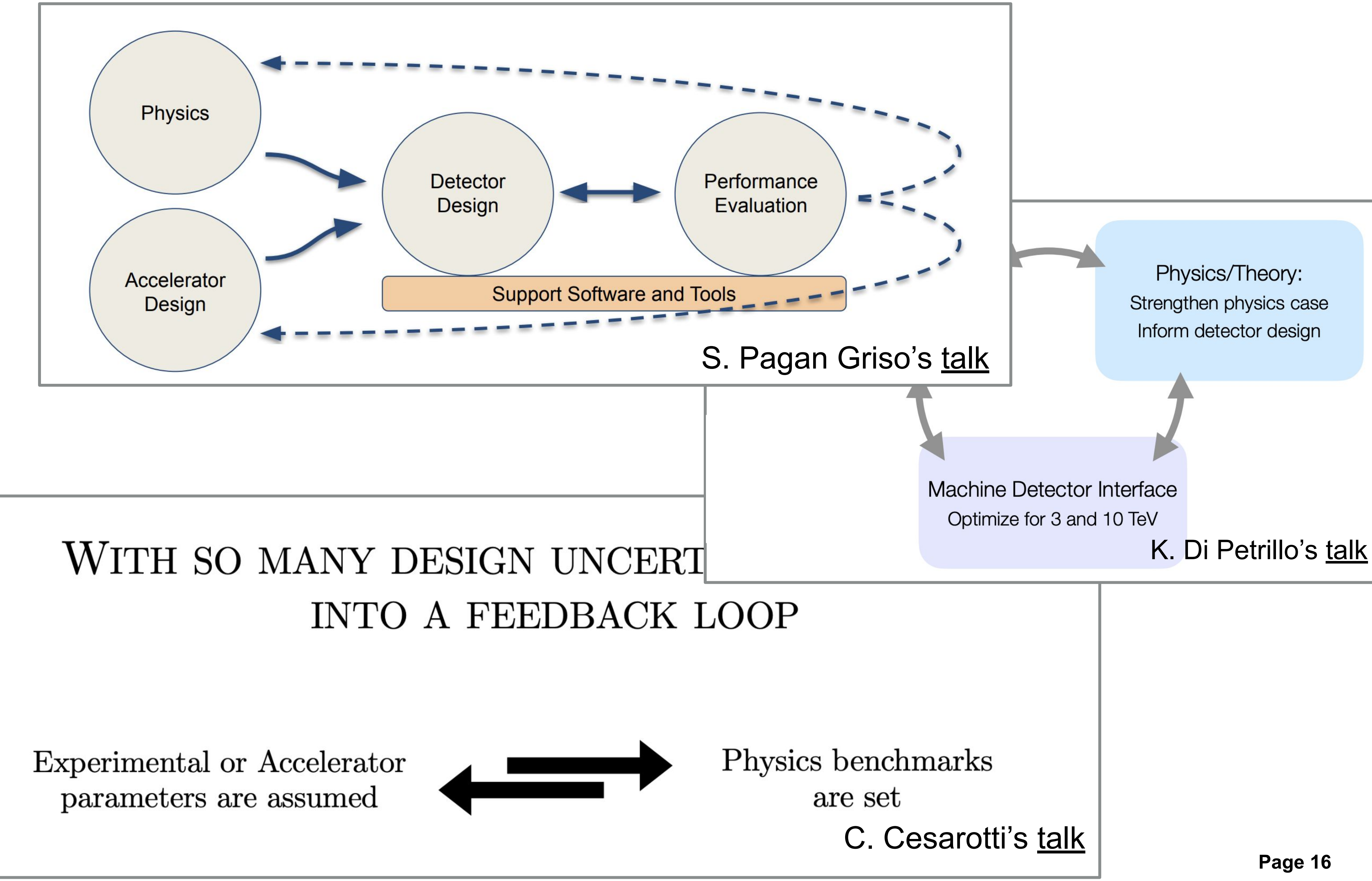




Transmission losses	2.00%
Decay losses	4.00%
Trans ε in	1.95 mm
Trans ε out	1.57 mm
Long ε in	3.61 mm
Long ε out	2.99 mm
6D ε in	12.7 mm^3
6D ε out	6.3 mm^3

Detector requirements

A feedback loop



Interim report requirements

Requirement	Baseline		Aspirational
	$\sqrt{s} = 3$ **TeV**	$\sqrt{s} = 10$ **TeV**	
Angular acceptance	$\|\eta\| < 2.5$	$\|\eta\| < 2.5$	$\|\eta\| < 4$
Minimum tracking distance [cm]	~ 3	~ 3	< 3
Forward muons ($\eta > 5$)	–	tag	$\sigma_p/p \sim 10\%$
Track σ_{p_T}/p_T^2 [GeV^{-1}]	4×10^{-5}	4×10^{-5}	1×10^{-5}
Photon energy resolution	$0.2/\sqrt{E}$	$0.2/\sqrt{E}$	$0.1/\sqrt{E}$
Neutral hadron energy resolution	$0.5/\sqrt{E}$	$0.4/\sqrt{E}$	$0.2/\sqrt{E}$
Timing resolution (tracker) [ps]	$\sim 30 - 60$	$\sim 30 - 60$	$\sim 10 - 30$
Timing resolution (calorimeters) [ps]	100	100	10
Timing resolution (muon system) [ps]	~ 50 for $\|\eta\| > 2.5$	~ 50 for $\|\eta\| > 2.5$	< 50 for $\|\eta\| > 2.5$
Flavour tagging	b vs c	b vs c	b vs c, s-tagging
Boosted hadronic resonance ID	h vs W/Z	h vs W/Z	W vs Z

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Driven by BIB rejection

Physics opportunities arise as byproduct: s-tagging? Massive long-lived particles?

Need to quantify!

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Flavou			ging
Booste			

	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}	
HL-LHC	100	0.1	10^{15}	
Muon Collider (10 TeV)	20	0.2	3×10^{14}	10^{14}

B. Rosser's talk

The detector should not break down!

- The technological readiness might impact our final performance

Interim report requirements

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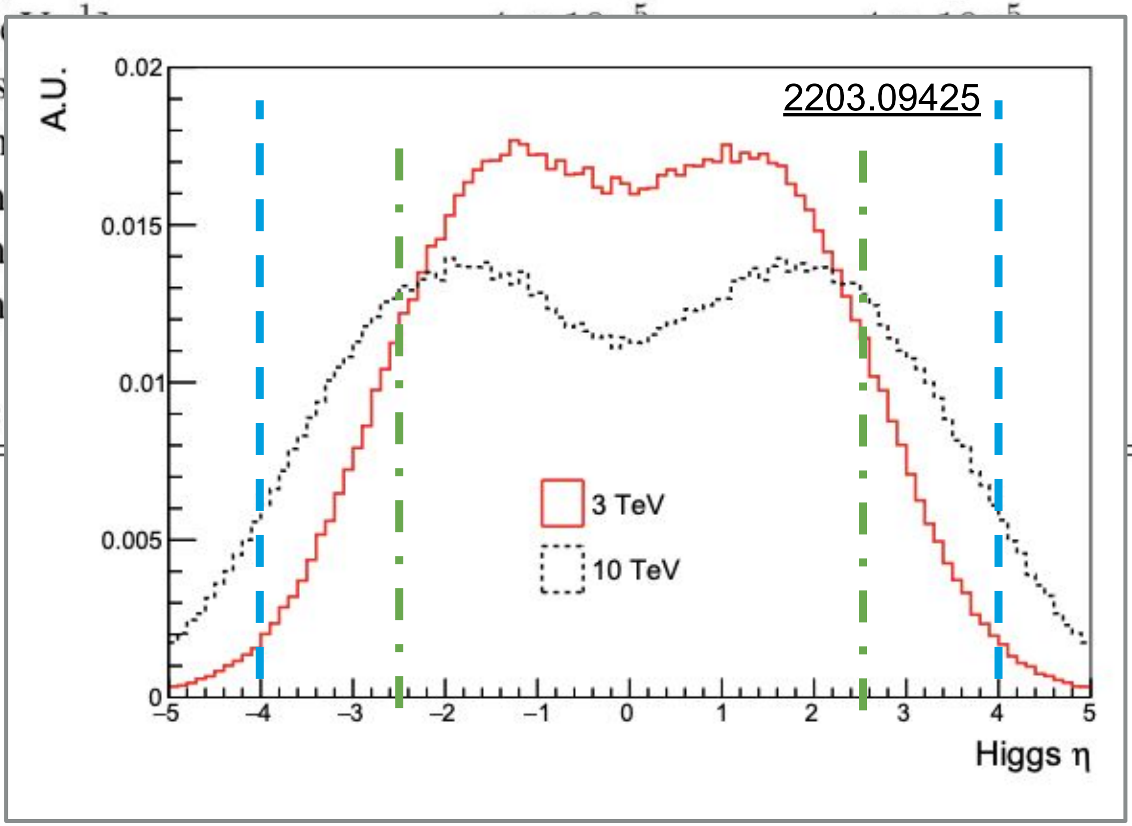

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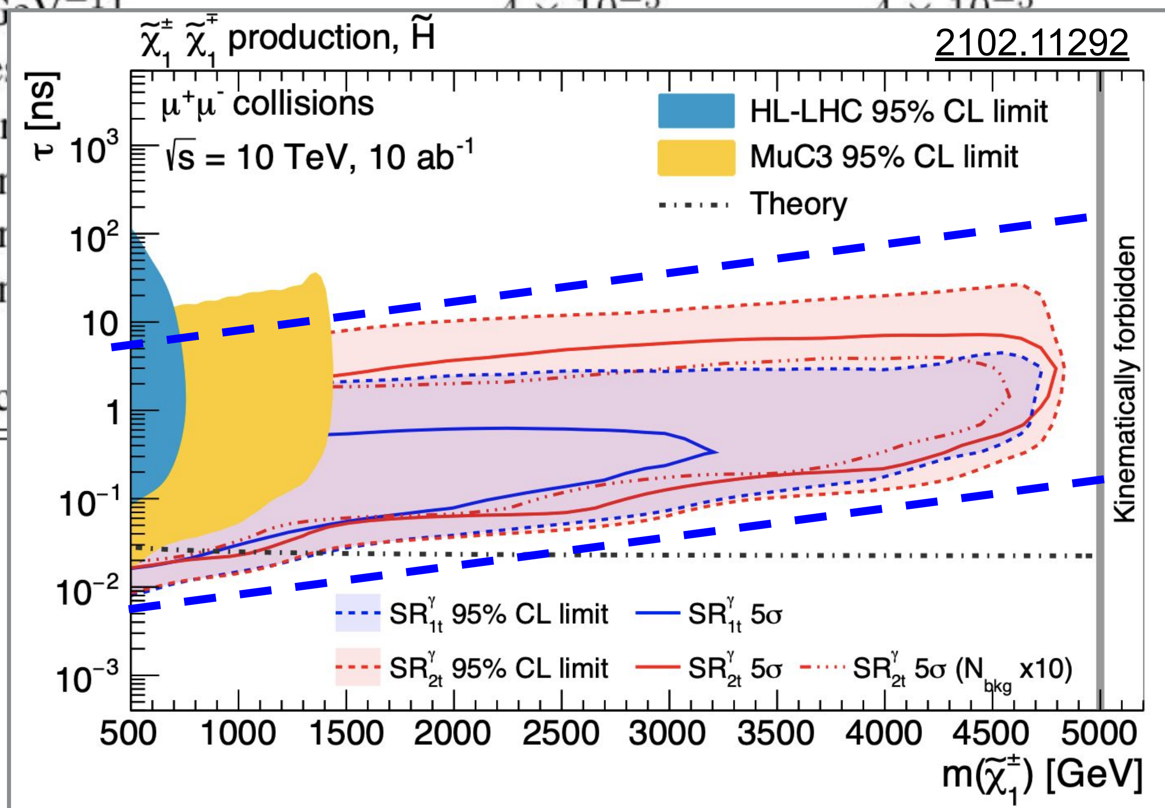

Also:
track impact parameters

Interim report requirements

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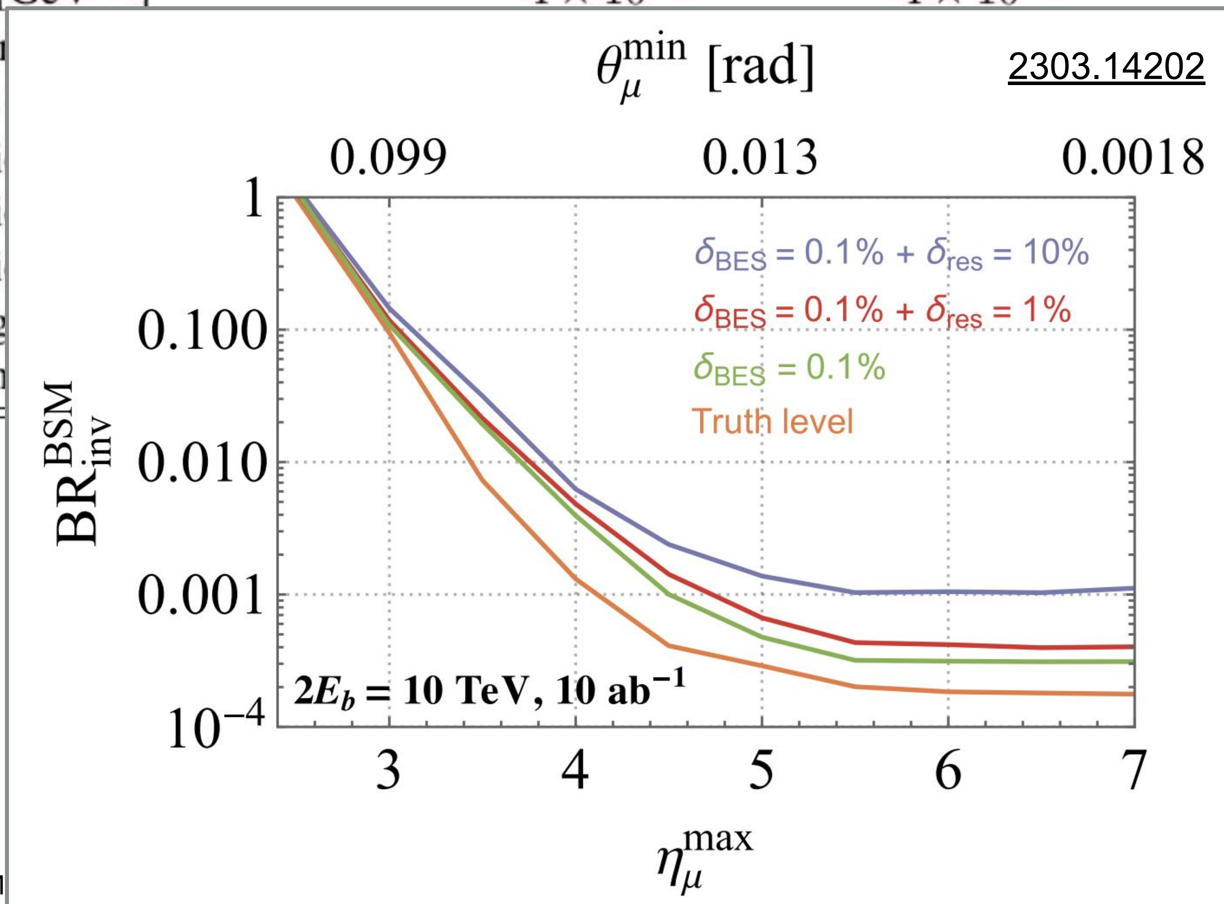

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From a mix of parametric studies, “LHC-like”, “already achieved” and “Higgs-factory-like”

Plan to use high-priority physics benchmarks to understand what the actual minimum requirements are and support choices

High priority benchmarks

To make our physics results as robust as possible in view of the next ESPPU, we have to agree on a restricted set of high-priority benchmarks to dissect in detail.

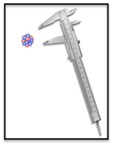
- Substantial work in this direction done within the physics, detector and dedicated workshops

Current proposals:

1) Search for high-mass states (HVT-like)

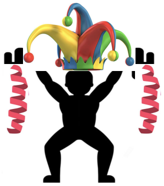
Energy

2) Measurement of di-Higgs coupling



Precision

3) Disappearing tracks



Unconventional

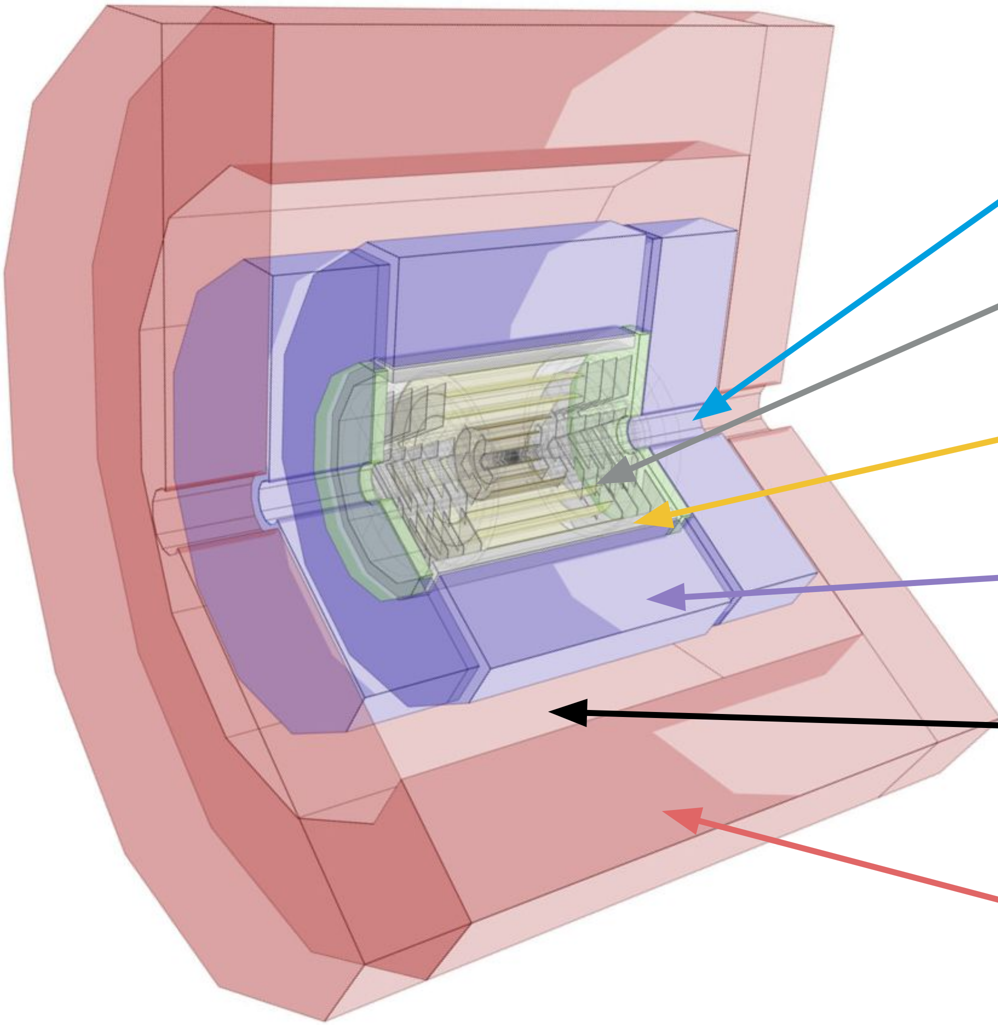
Producing the final number is not enough

- Demonstrate **robustness of fast-simulation**
- Validate **distributions** of key quantities and **efficiencies** of selection cuts

Novel detector designs

Reminder: 3 TeV detector layout

The detector model is based on the CLIC concept



Nozzles

All-silicon tracker

ECAL (Tungsten+Silicon)

HCAL (Steel+Scintillators)

3.57 T Solenoid

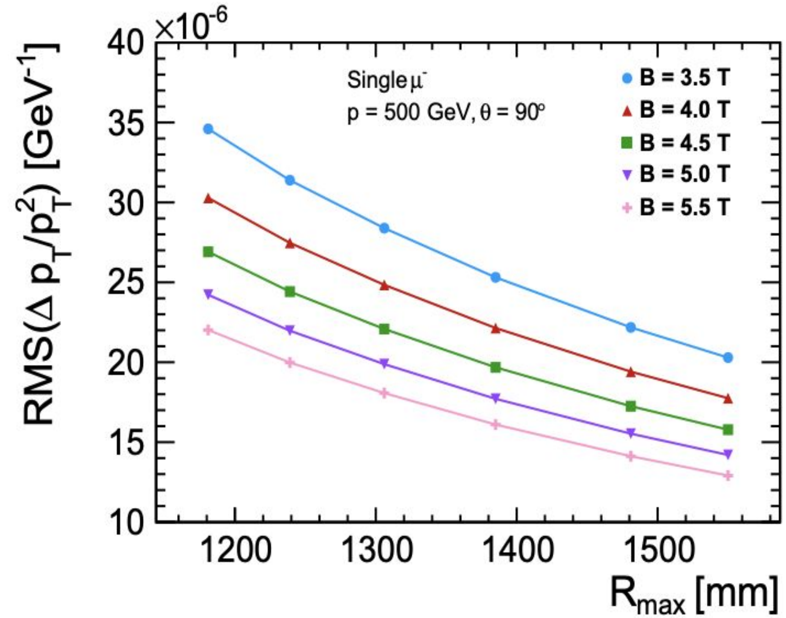
Muon chambers (RPC) in magnet yoke

CLICdp-Note-2017-001
CERN-FCC-PHYS-2019-0003

Designing a 10 TeV detector

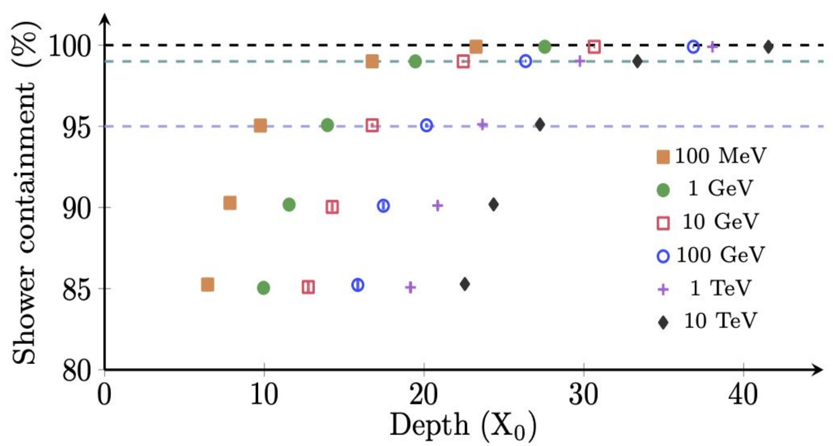
Update the tracker

- Optimise position and granularity
- Reconsider double layers
- Re-design endcap region



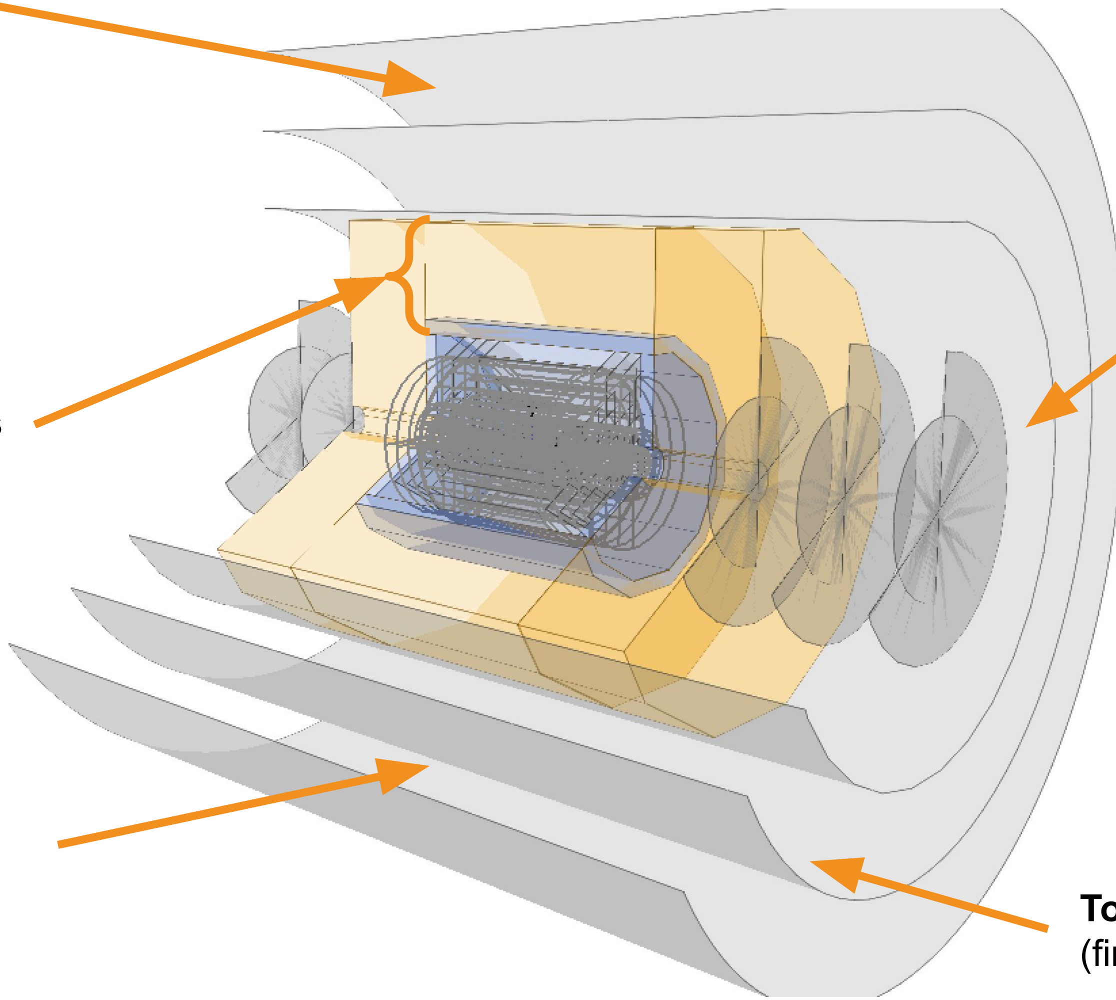
Make the calorimeters thicker

- More radiation/interaction-lengths for containment
- Revisit cell energy thresholds, or think about some level of “BIB shielding”



Verify feasibility of streaming operation

Fast evolution from concept (March '23) …



No need for a Yoke

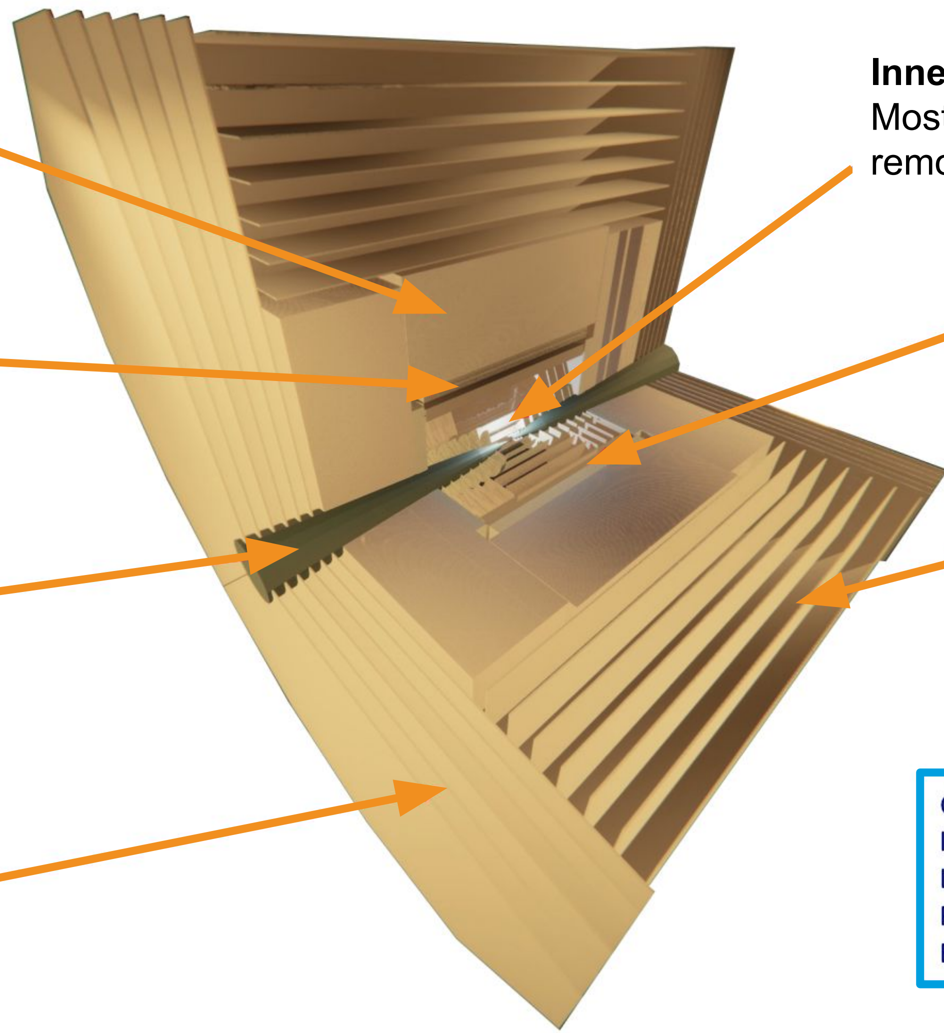
Calorimeter depth optimised with photon and pion gun samples (changed both sampling fraction and N_{layers})

Simplified muon system

Visualisation glitch **(extend up to the barrel)**

Toroidal field (first time in key4hep)

… to design (October ‘23)



HCAL
Fe+Scillator
Return B field

ECAL
Si+W

Shielding nozzle
Dimensions to be optimised

In-air muon system
RPC-based

Inner tracker
Most double layers removed

Solenoid
5 T
3m diameter

Toroidal field could be added

C. Bell, D. Calzolari, K. DiPetrillo, M. Hillman, I. Hirsch, T. Holmes, S. Jindariani, B. Johnson, L. Lee, T. Madlener, F. Meloni, I. Ojalvo, P. Pani, S. Pagan Griso, K. Pedro, R. Powers, B. Rosser, L. Rozanov, A. Vendrasco, J. Zhang

DESY manuscript review incoming…

… to de

HCAL
Fe+Scillator
Return B field

ECAL
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Shielding nozzle
Dimensions to be optimised

In-air muon system
RPC-based

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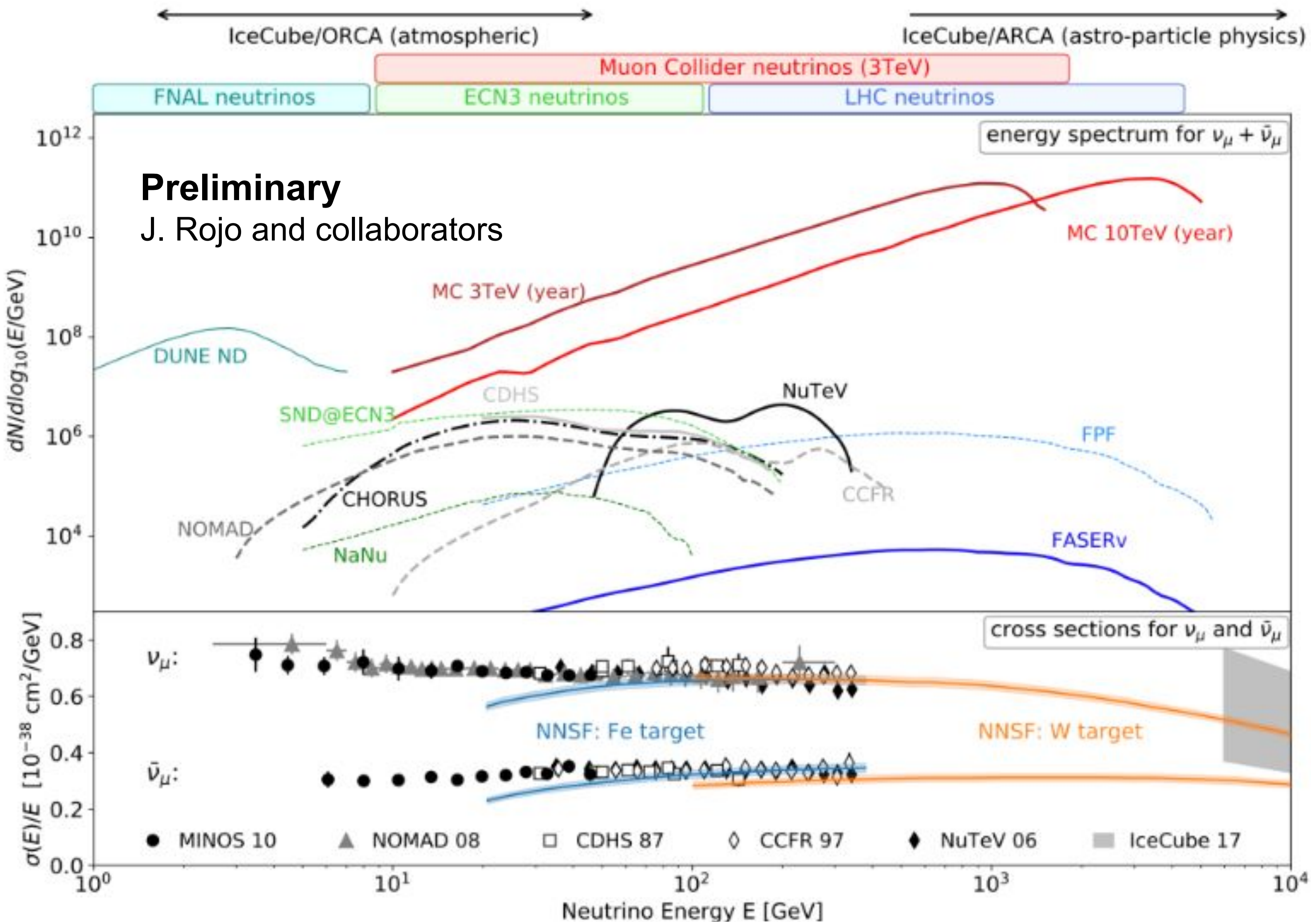
n Griso, K. Pedro, R. Powers,
zanov, A. Vendrasco, J. Zhang

view incoming…

Physics potential highlights

Neutrino synergies



WIMPs with soft tracks

i.e. more shameless self-promotion

FERMILAB-PUB-23-0832-T APS/123-QED

Discovering Electroweak Interacting Dark Matter at Muon Colliders using Soft Tracks

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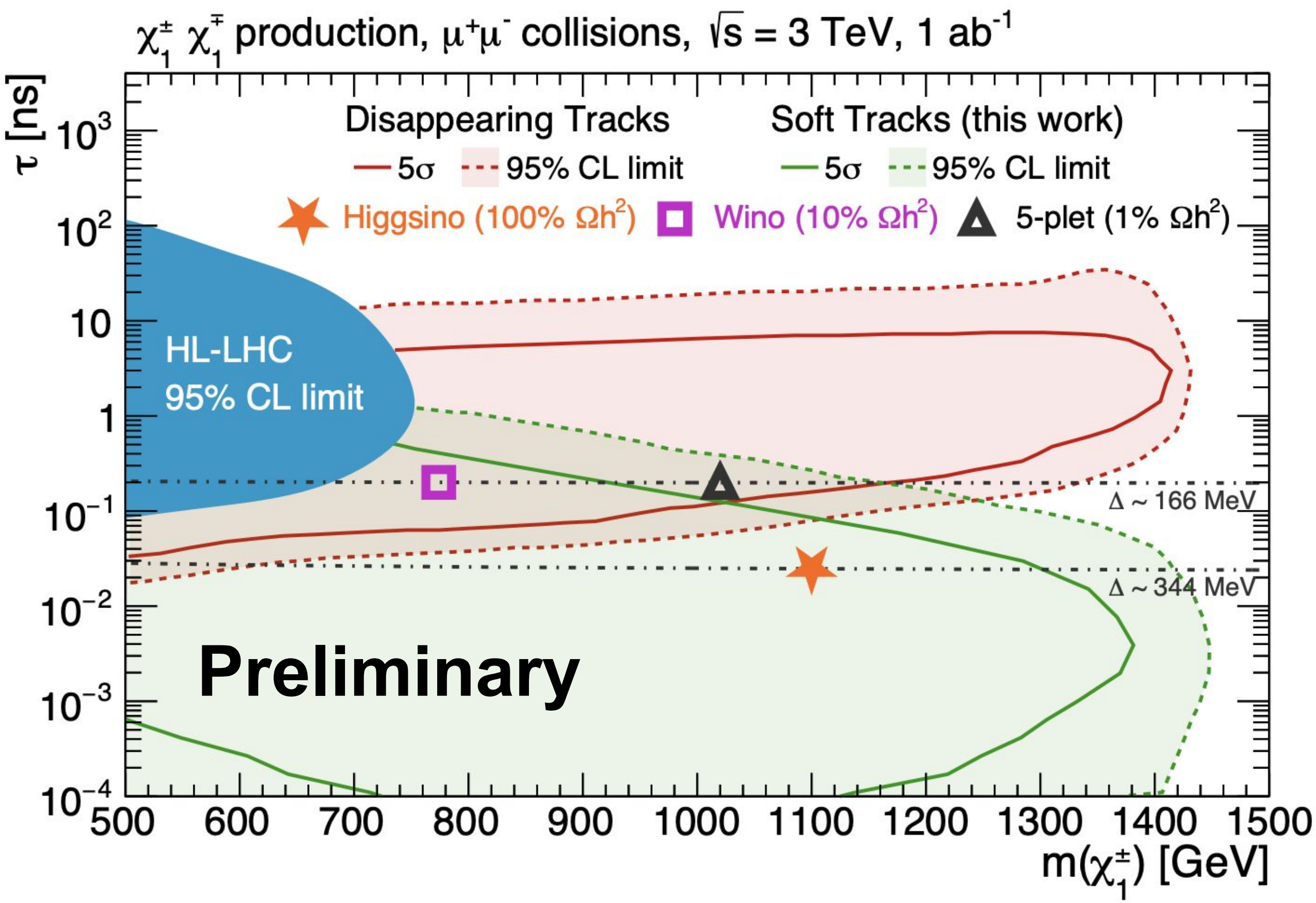
[1] *Particle Theory Department, Fermi National Accelerator Laboratory, Batavia, IL 60510, USA*[*]
[2] *Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany*[†]
[3] *Instituto de Física Corpuscular, CSIC-Universitat de València, Valencia, Spain*[‡]
(Dated: March 26, 2024)

Minimal Dark Matter models feature one neutral particle that serves as a thermal relic dark matter candidate, as well as quasi-degenerate charged states with TeV masses. When the charged states are produced at colliders, they can decay into dark matter and a low-momentum (soft) charged particle, which is challenging to reconstruct at hadron colliders. We demonstrate that a 3 TeV Muon Collider is capable of detecting these soft tracks, enabling the discovery of thermal Higgsinos and similar dark matter candidates which constitute highly motivated scenarios for future collider searches.



Summary

The progress of work is **increasing the confidence** that the collider can keep its promises

The **worldwide engagement** in the project boomed during Snowmass, and is still growing

An initial **set of requirements** spelled out for the interim report should be refined and supported with more studies

Plenty of work to do before the next ESPPU!

Exploring the energy frontier with muon beams

June 23 to July 24, 2025 Event page

Galileo Galilei Institute, Florence

Organizing committee: Scott Berg, Dario Buttazzo, Roberto Franceschini, Tova Holmes, Fabio Maltoni, Patrick Meade, Federico Meloni

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

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.

2201.07895
Nature Phys. 8 (2012) 243-247

Accelerator ring

Ramp magnets to follow E_{beam}

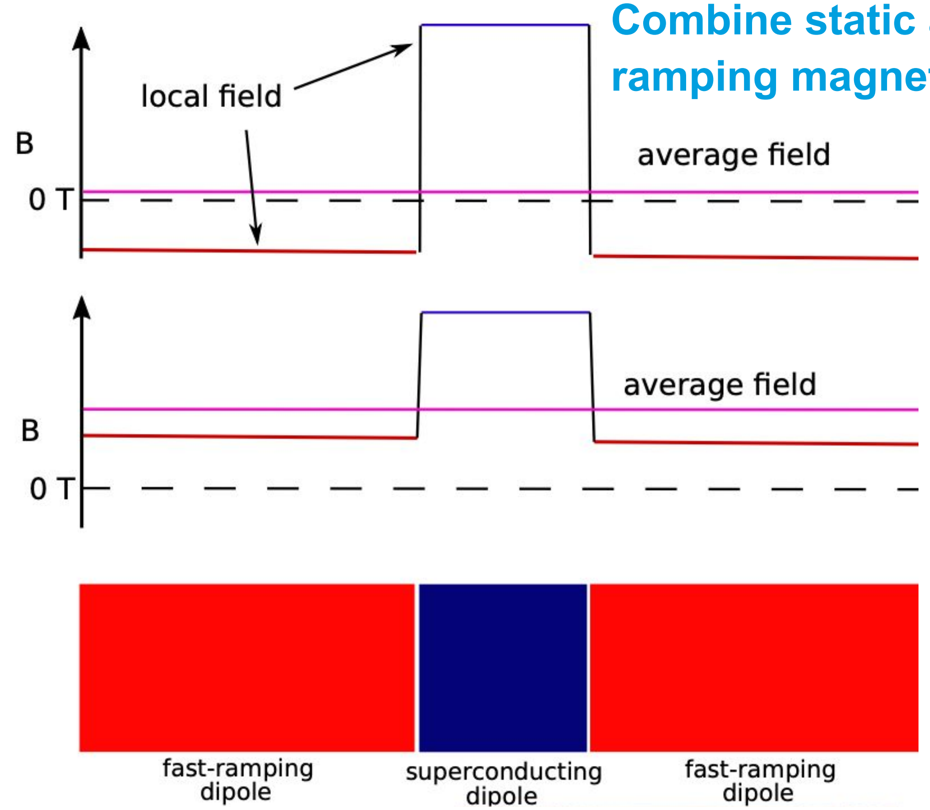
- **Fast-ramping synchrotron magnets** (−2T to 2T in 2 ms)

Demonstrated:

- Normal-conducting magnets (2.5 T/ms with peak of 1.81 T)
- HTS (12 T/ms, peak of 0.24 T)

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

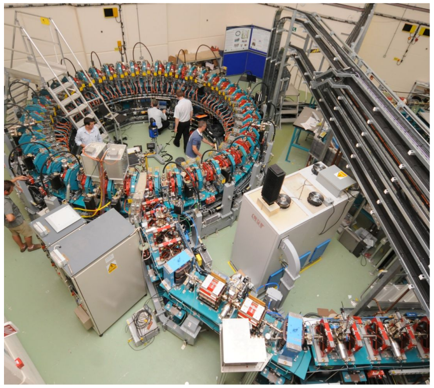
Combine static and ramping magnets



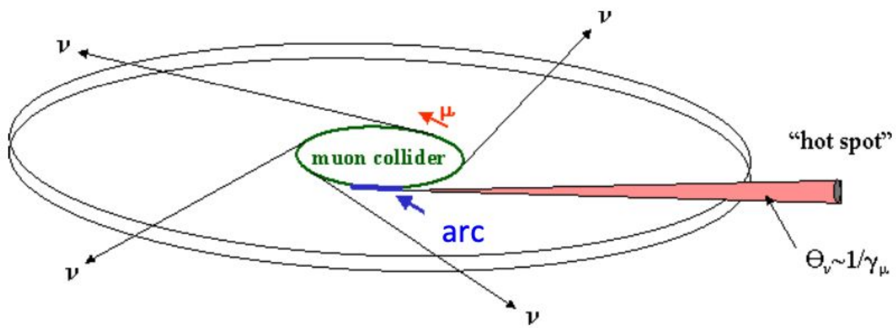
Fixed-Field alternating gradient Accelerator (alternative)

- Complex high-field magnets
- Challenging beam dynamics

EMMA proof of FFA principle



Neutrino flux



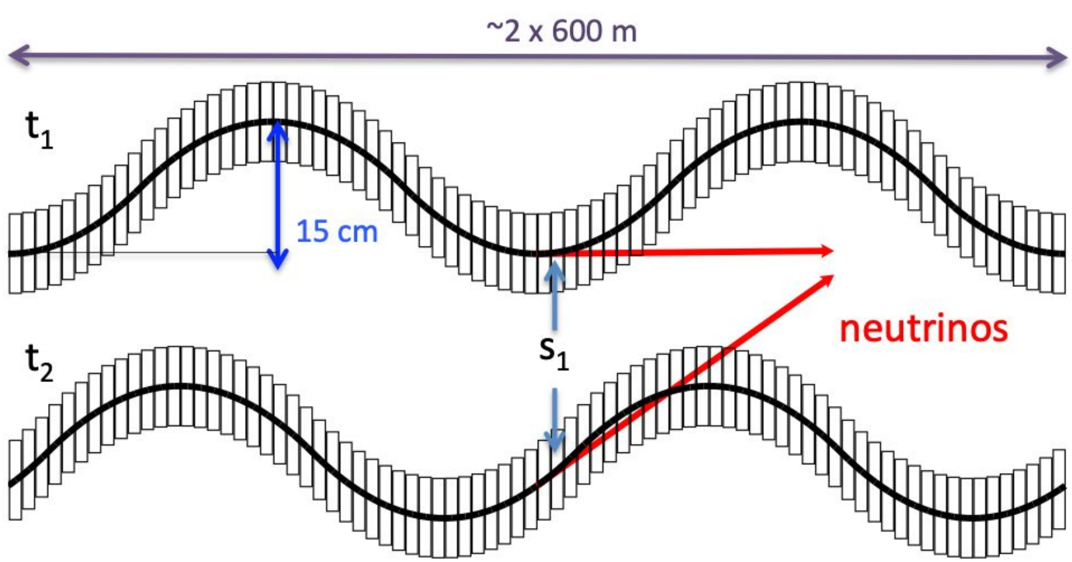
Legal limit: 1 mSv/year
MAP goal: < 0.1 mSv/year

IMCC goal: arcs below threshold for legal procedure < 10μSv/year
LHC achieved: < 5 μSv/year

3 TeV, 200 m deep tunnel ~ OK

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

Example: vertical bending



Sketch credit: D. Schulte

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

Need to engineer mover system and study impact on beams