The path to the Muon Collider

Federico Meloni (DESY)

14/03/2025
FH Particle Physics Discussion

Co-funded by the European Union

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Overall goals and deliverables

International Muon Collider Collaboration goal:
Develop high-energy muon collider as option for particle physics:

- Focus on **10 TeV feasibility**
- **Initial stage as option by ~2050** as strongly recommended by Steering Board and Advisory Committee, with required compromises
- Could later consider other energies

LDG Roadmap deliverables (2026-2027):

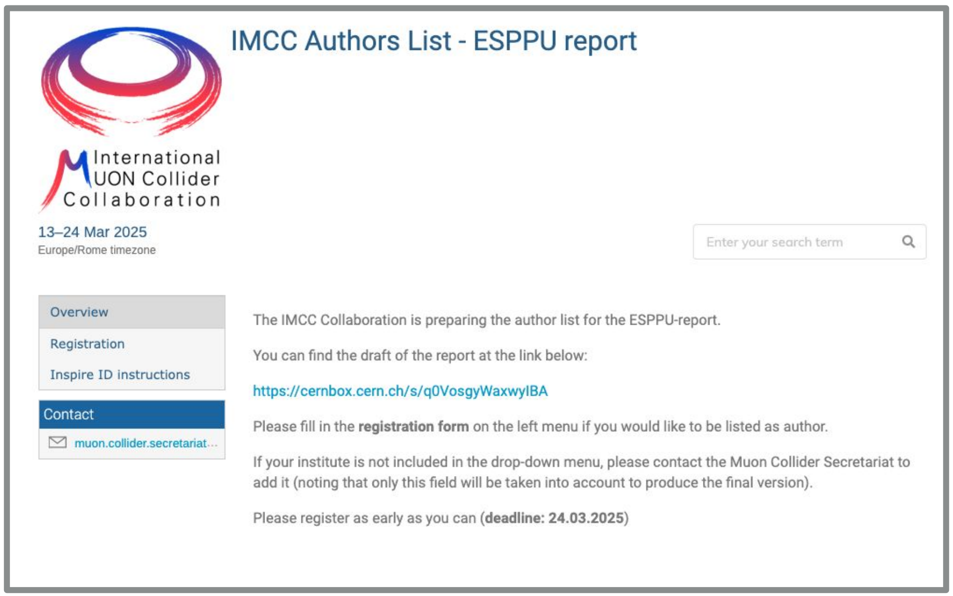
- A **Project Evaluation Report** that assesses key issues to motivate investment into a CDR;
- An **R&D Plan** that describes a path towards the collider;
- An **Interim Report** by the end of 2023 that documents progress (**done**)

Will deliver a **Project Evaluation Report** and a **tentative R&D Plan on March 31, 2025**
Final versions at the end of MuCol February 2027

European Strategy for Particle Physics

Prepared set on inputs for ESPPU submission

- 10 pages main submission
- 350+ pages addendum


IMCC Authors List - ESPPU report

International MUON Collider Collaboration

13–24 Mar 2025
Europe/Rome timezone

Enter your search term

Overview
Registration
Inspire ID instructions

Contact
muon.collider.secretariat...

The IMCC Collaboration is preparing the author list for the ESPPU-report.

You can find the draft of the report at the link below:

https://cernbox.cern.ch/s/q0VosgyWaxwyIBA

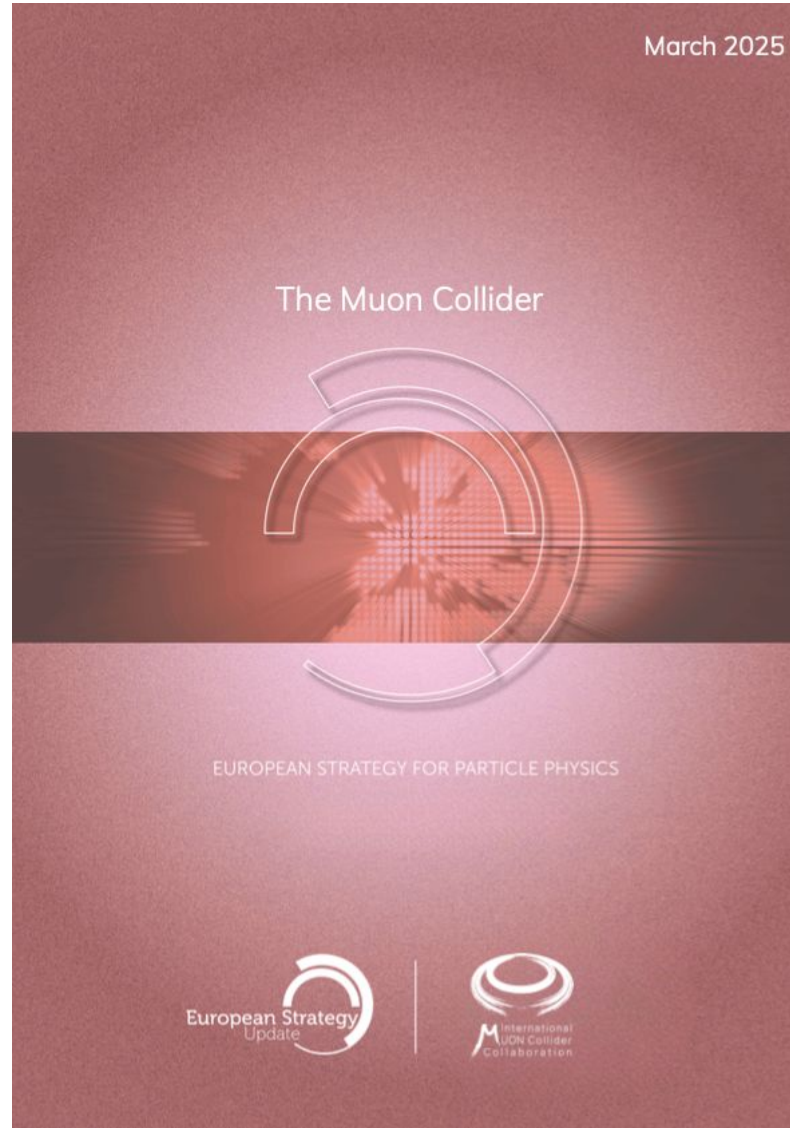
Please fill in the **registration form** on the left menu if you would like to be listed as author.

If your institute is not included in the drop-down menu, please contact the Muon Collider Secretariat to add it (noting that only this field will be taken into account to produce the final version).

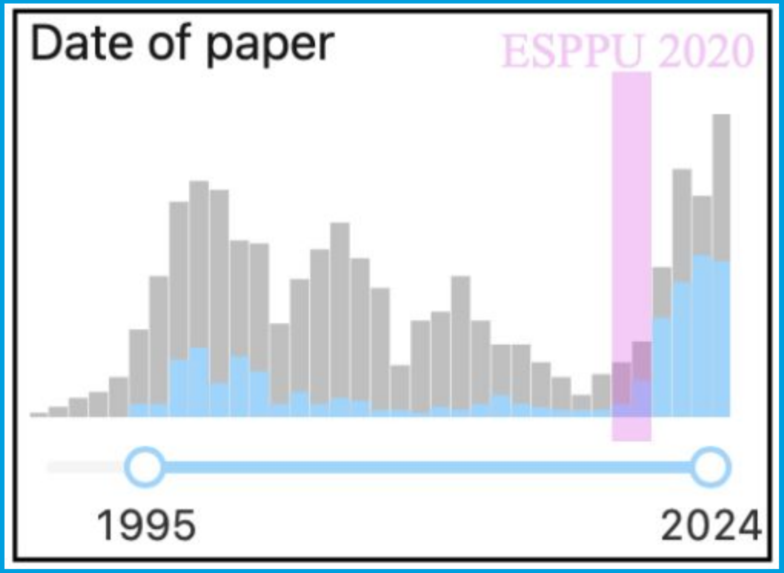
Please register as early as you can (**deadline: 24.03.2025**)

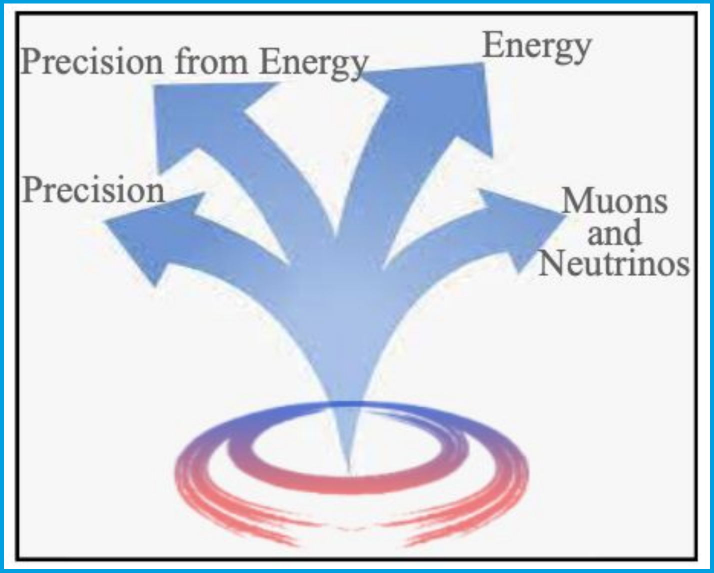
Sign-up if you support the project!

https://indico.cern.ch/event/1513450/



The physics programme





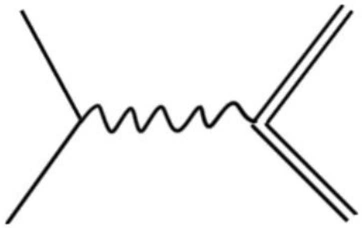
Why are we excited?

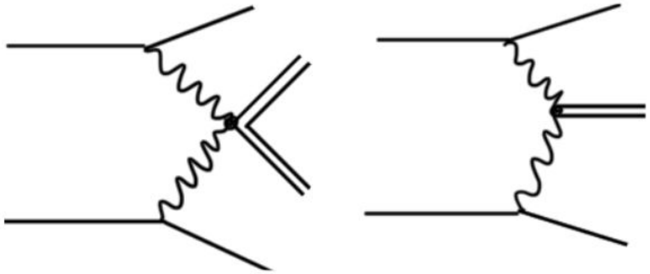
The muon collider combines *pp* and *ee* advantages:

- High available energy for new heavy particles production

Slide design credit: A. Wulzer

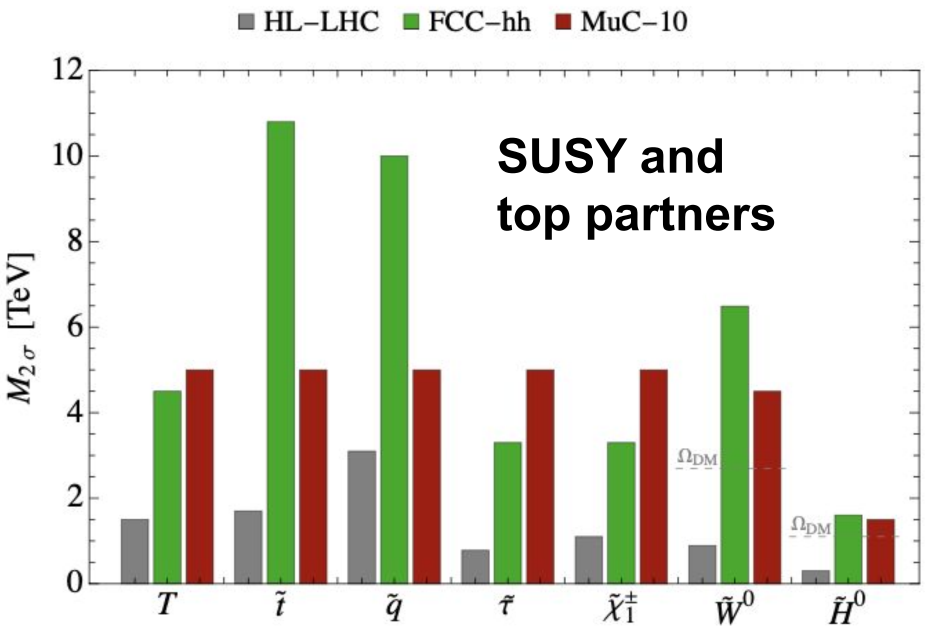
Direct mass reach

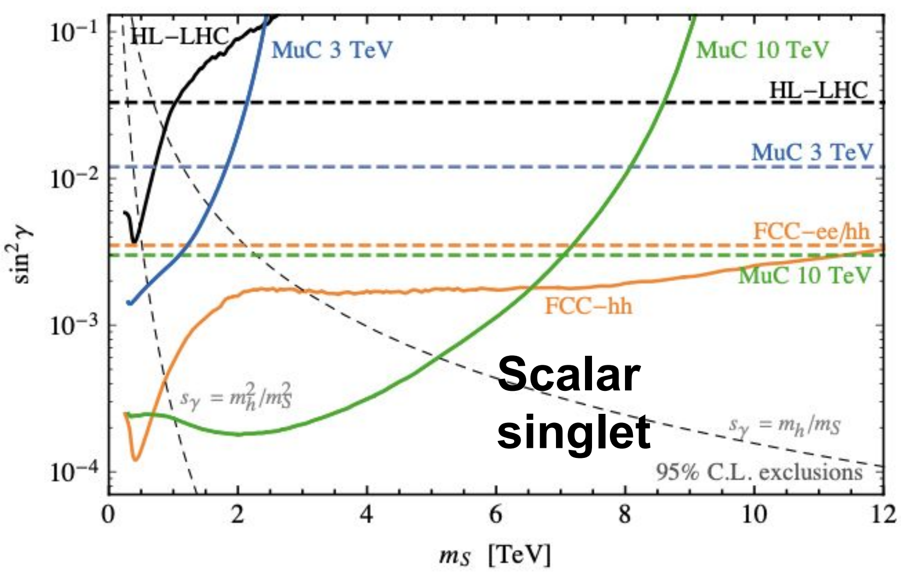




μμ annihilation
EW-charged particles up to $E_{cm}/2$

Vector Bosons Fusion
EW-neutral **Higgs-Portal** particles





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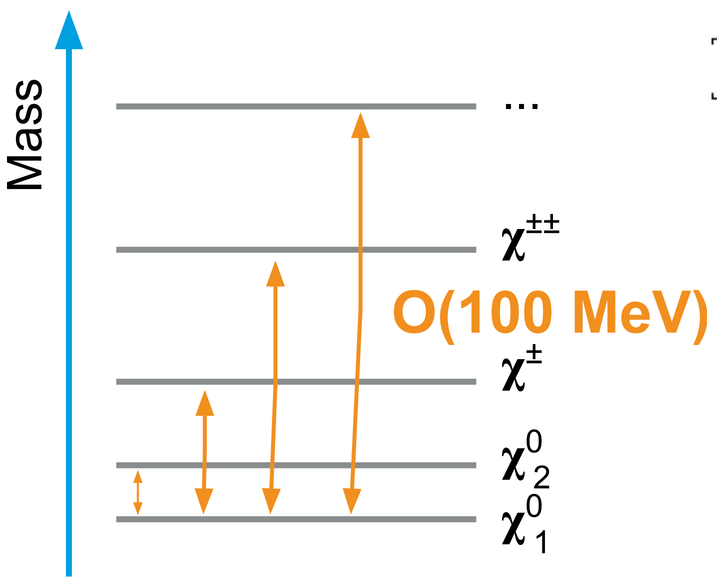
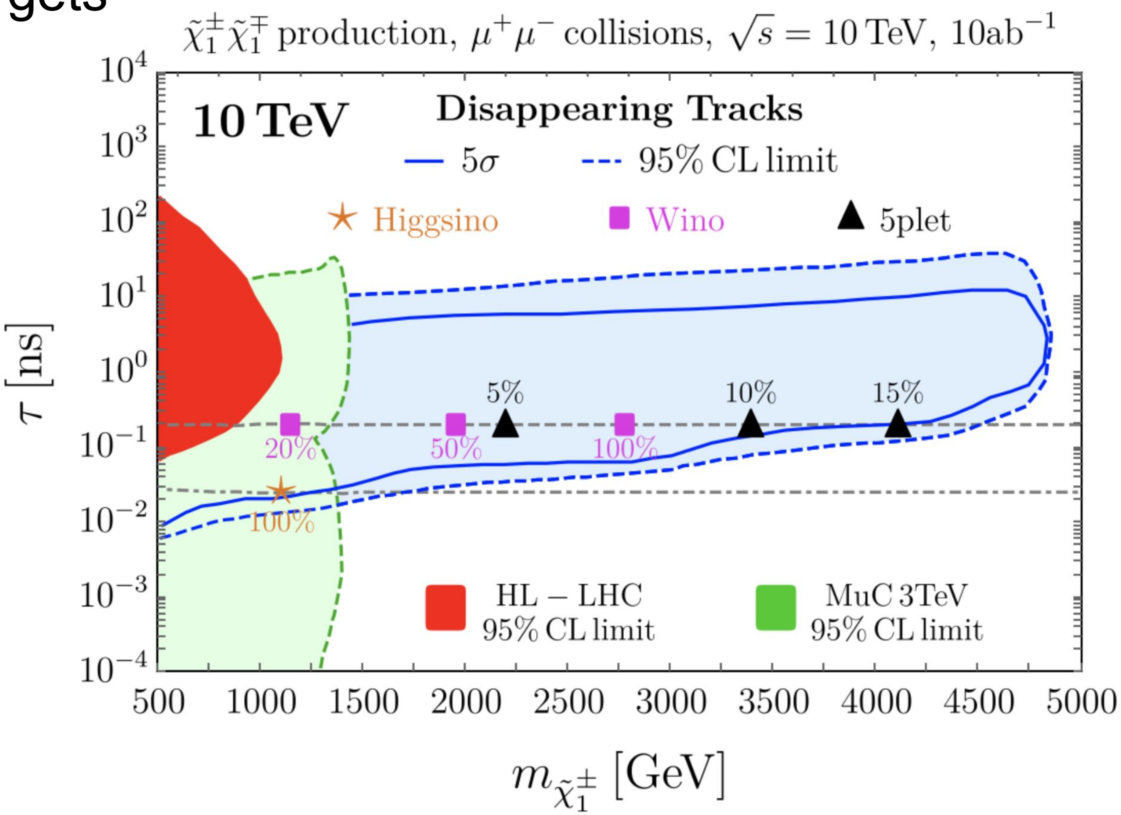
Minimal dark matter

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

Only collider able to discover both
Wino and Higgsino thermal targets





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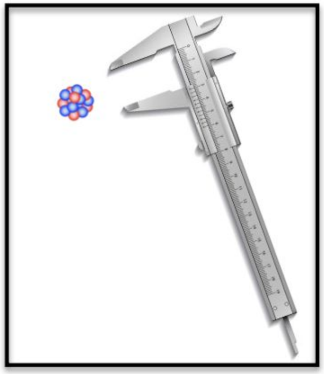
Why are we excited?

The 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)

Energy



Precision

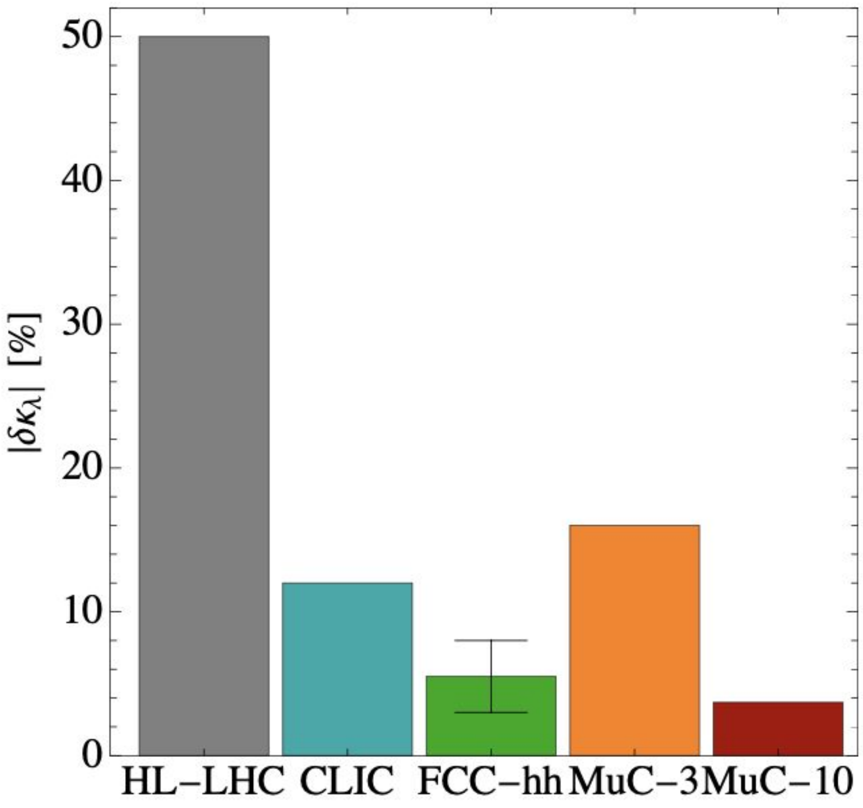
Slide design credit: A. Wulzer

Exploring the Higgs potential

At 10 TeV, 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

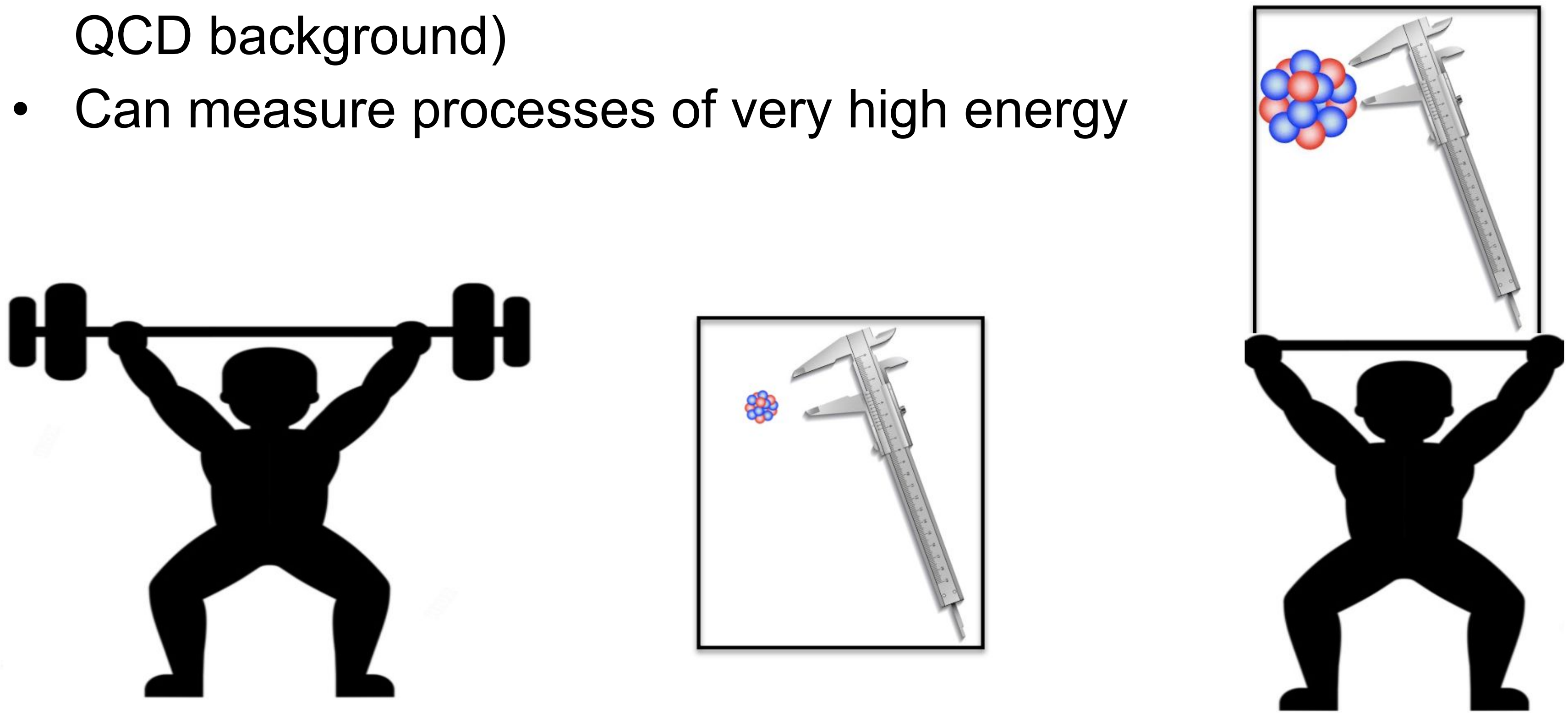


Total inclusive Higgs cross-section potentially accessible via Z-fusion processes

Why are we excited?

The 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**

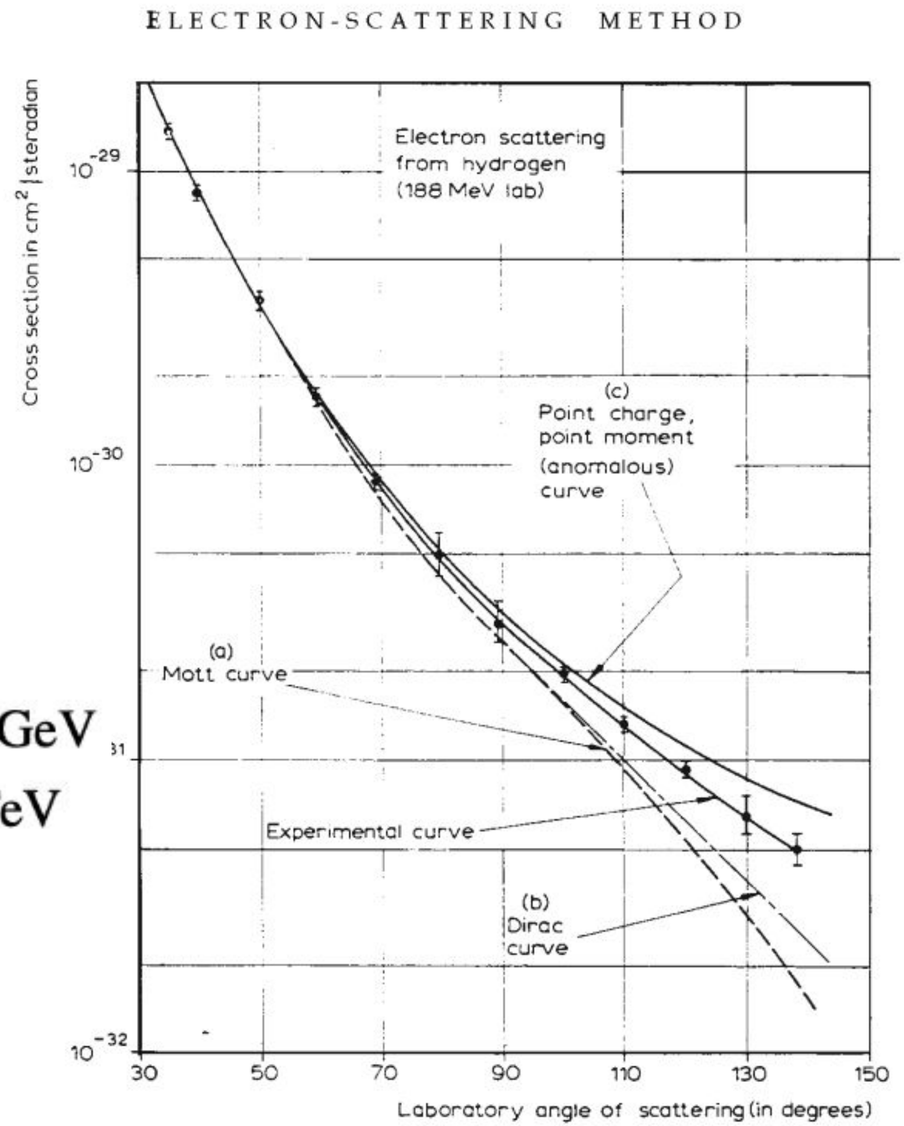
Slide design credit: A. Wulzer

Why are we excited?

Energy helps accuracy

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

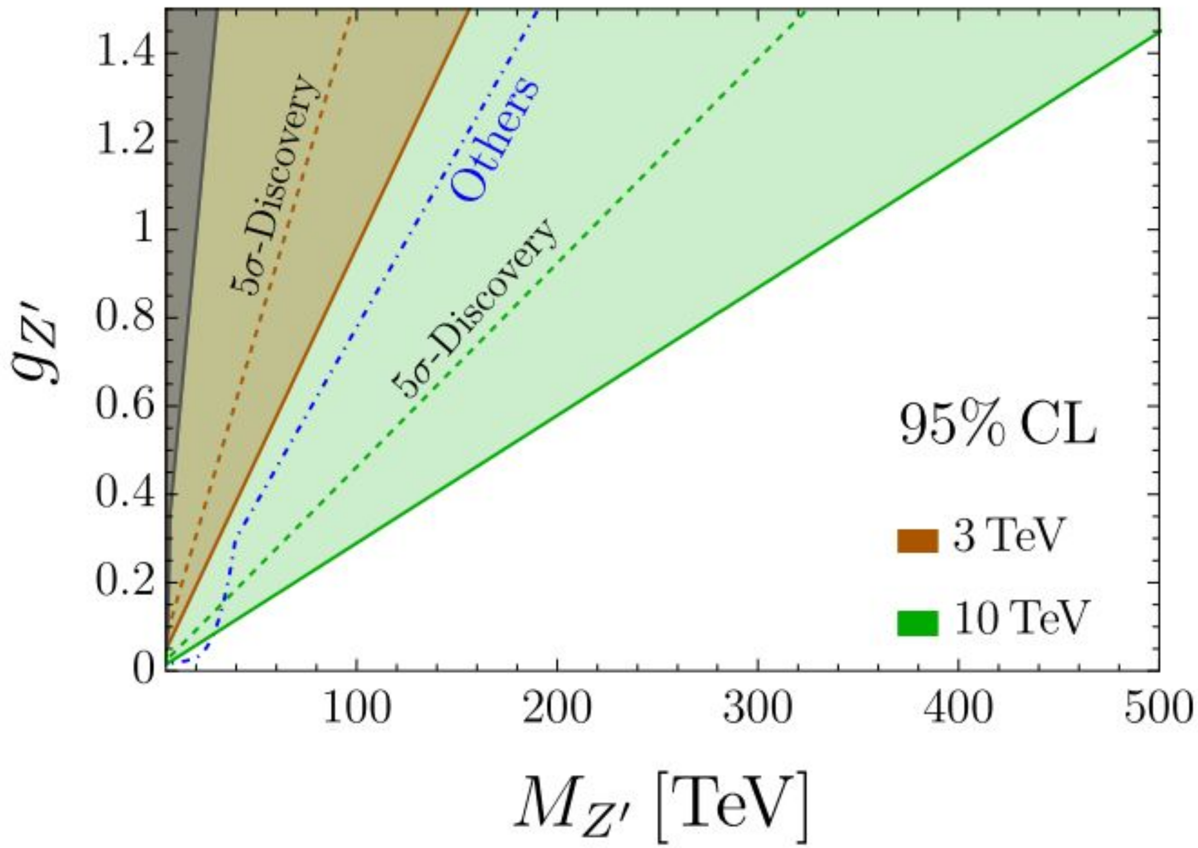
$$\frac{\Delta\sigma(E)}{\sigma_{SM}(E)} \propto \frac{E^2}{\Lambda^2_{BSM}} \approx \begin{cases} 10^{-6}, & E \sim 100\,\text{GeV} \\ 10^{-2}, & E \sim 10\,\text{TeV} \end{cases}$$



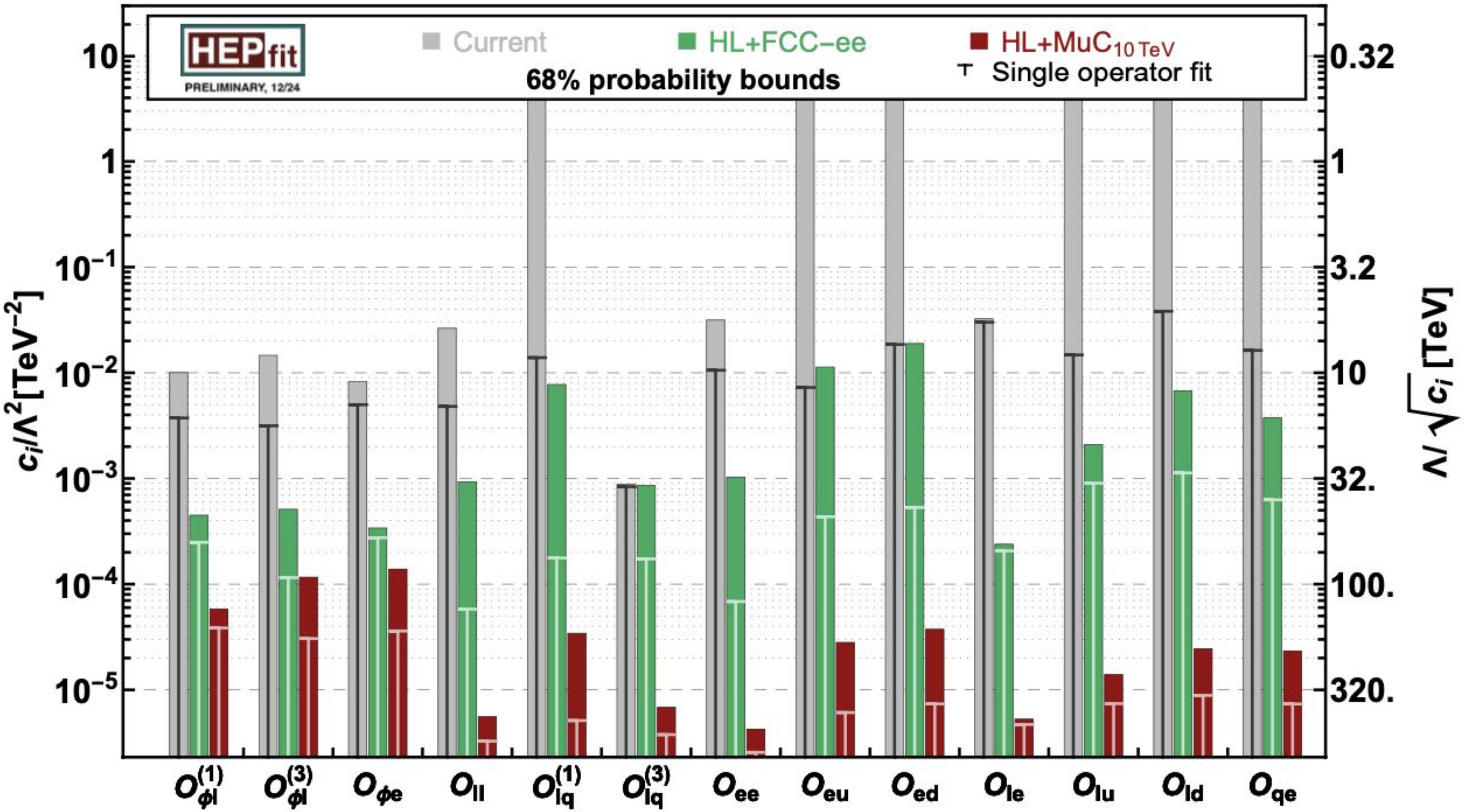
Heavy resonances

Reach on a new neutral current interaction mediated by a heavy Z′

- Discovery up to 100 TeV for SM-like EW gauge couplings
- Exclusion up to 500 TeV for the maximal value of the $g_{Z'}$ coupling

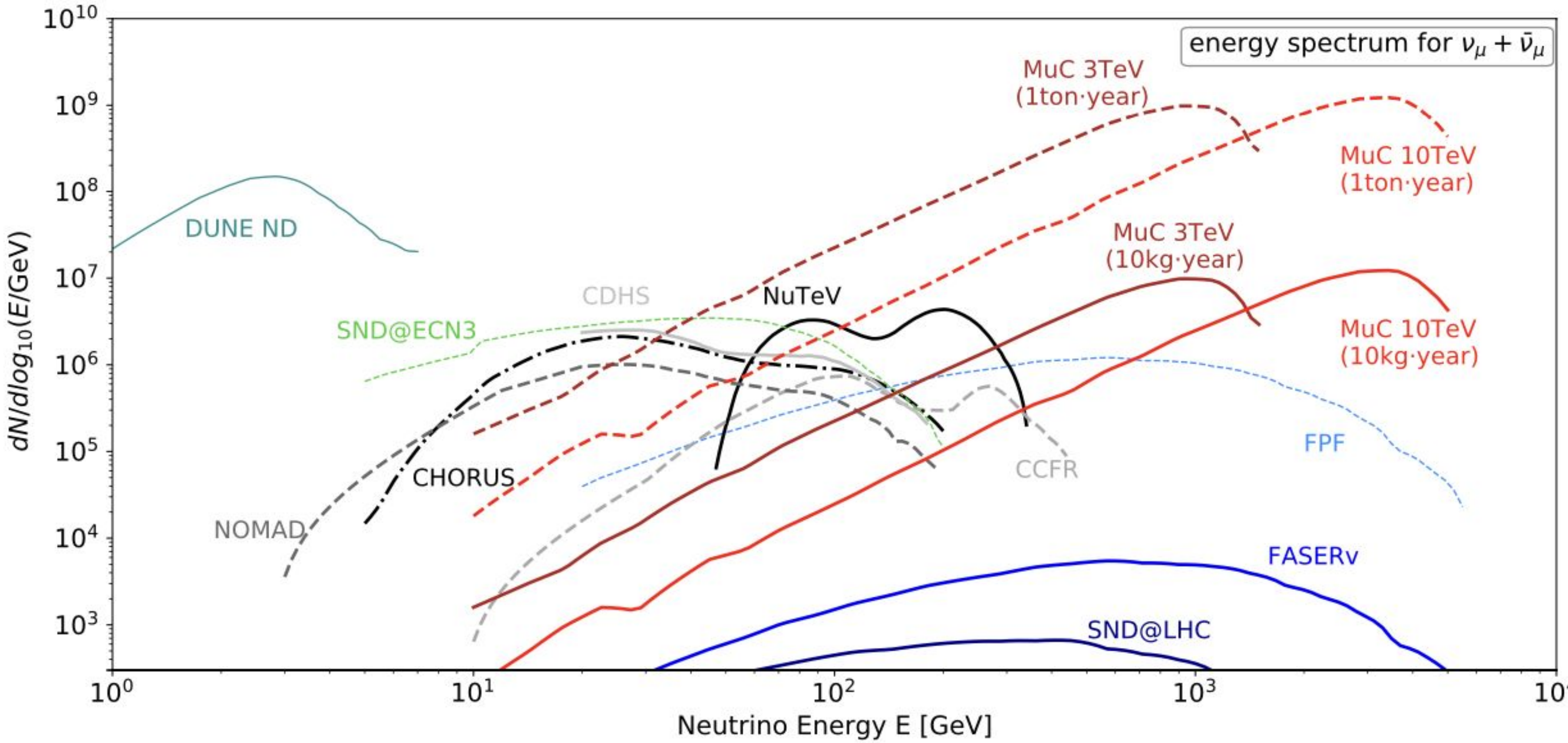


EFT



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

Neutrinos!


energy spectrum for $\nu_\mu + \bar{\nu}_\mu$
MuC 3TeV (1ton·year)
MuC 10TeV (1ton·year)
MuC 3TeV (10kg·year)
MuC 10TeV (10kg·year)
DUNE ND
CDHS
NuTeV
SND@ECN3
CHORUS
NOMAD
CCFR
FPF
FASERν
SND@LHC
$dN/dlog_{10}(E/\mathrm{GeV})$
Neutrino Energy E [GeV]

The R&D path

Core muon collider technologies

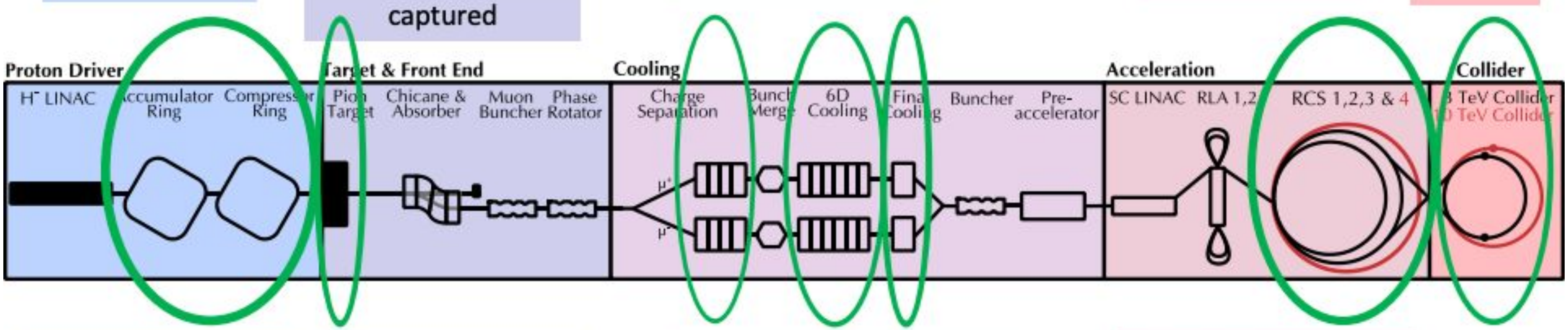
Short, intense proton bunch

Protons produce pions which decay into muons which are captured

Ionisation cooling of muon in matter

Acceleration to collision energy

Collision



- Proton driver bunch compression

- Graphite target
- Target solenoid

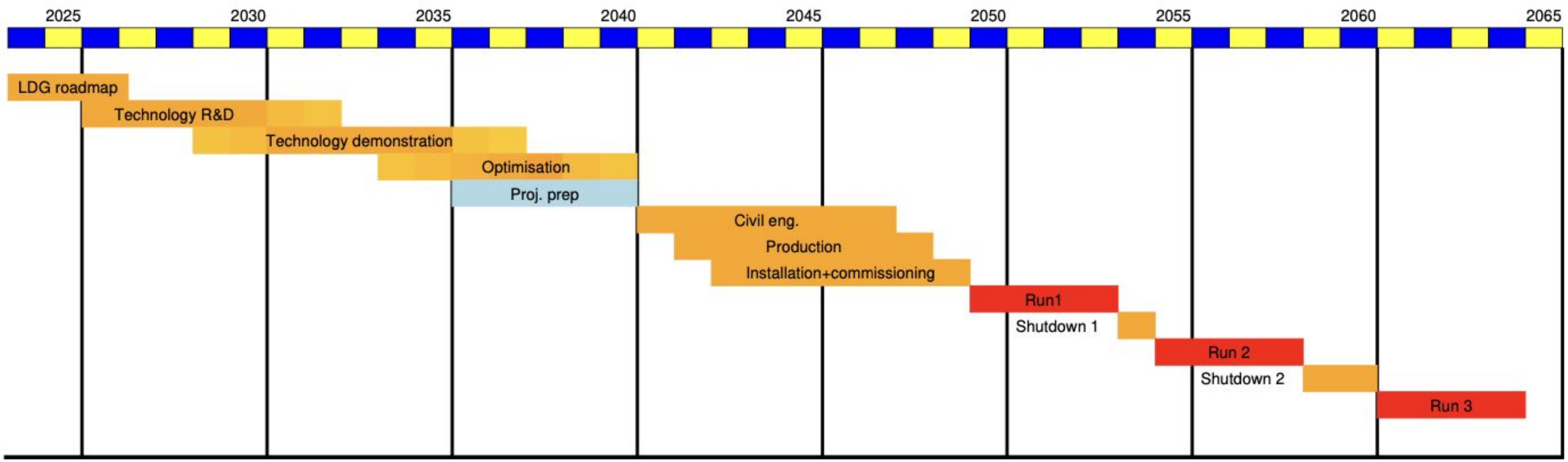
- Muon cooling design
- 6D cooling solenoids
- 6D cooling RF cavities
- Final cooling solenoids

- Pulsed magnets and power converters
- RCS RF system

- Collider ring dipoles
- Final focus quadrupoles

Identified and prioritized with community
Other areas need now also to be addressed (some work started)

Technically limited timeline



“Don’t give us another collider in the 2070s”

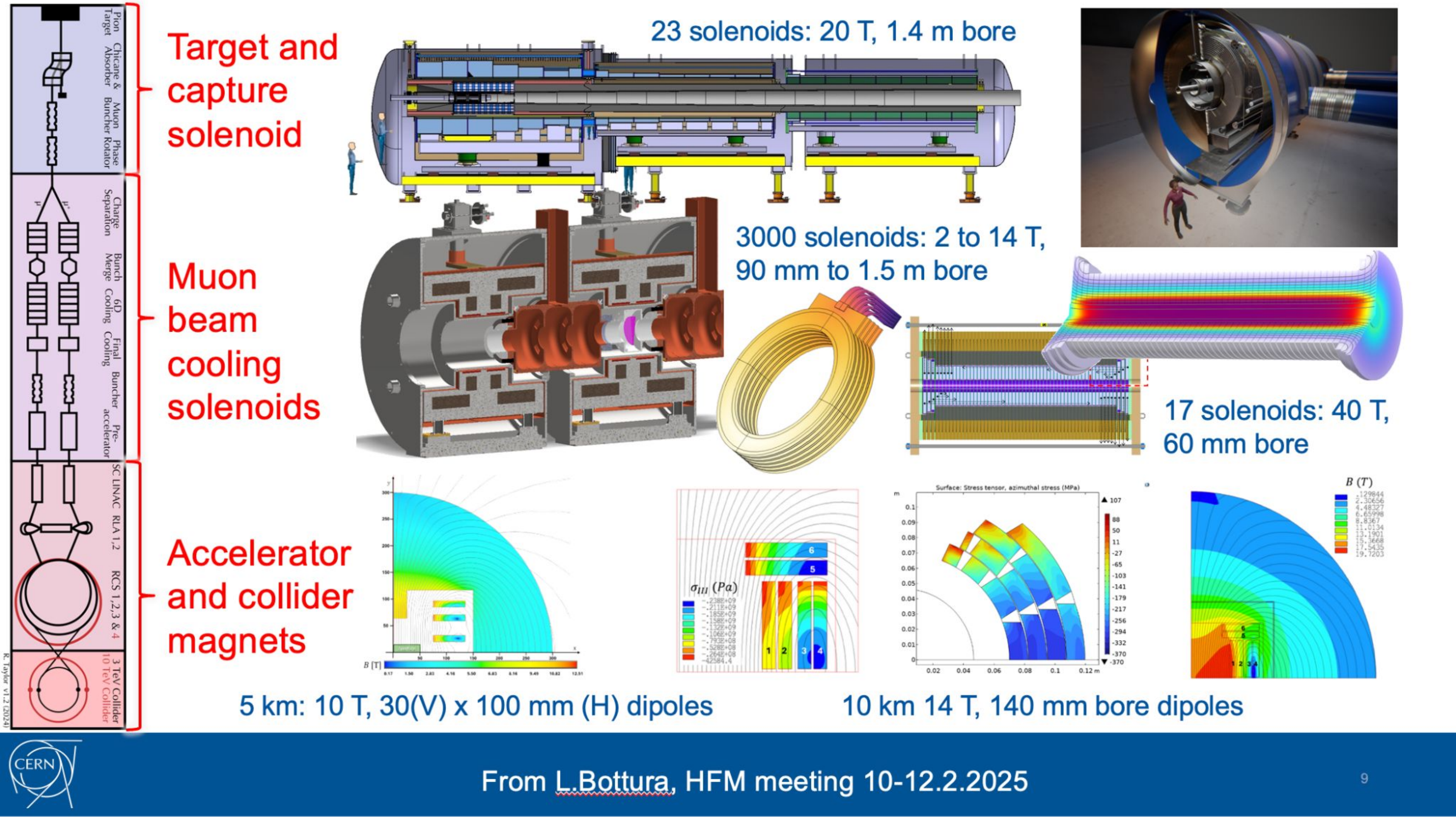
Slide from S. Stapnes

R&D key technical challenges

Challenges	TRL today	TRL goals 2036
Target solenoid (HTS)	5	6-7
Final cooling solenoid (HTS)	3	6
Cooling cell RF Cooling cell solenoid (HTS) Integrated in cell w/absorbers	3 3 4	6-7 for the three
Demonstrator	To provide relevant conditions for cooling HW system tests, TDR by 2028-2030	
Pulsed magnets (NC) Integrated w/power converter SC magnets (HTS)*	7 4 3	7 6-7 5-6
Collider ring NbTi Collider ring Nb3Sn Collider ring (HTS)*	7 6 3	7 6-7 5
Acc. Design – S/E simulation, lattices** Acc. Design – Imperfections, Collective effects**	4 4	7-8*** 7***

* Not needed for 3 TeV, ** To address performance (E/L), backgrounds, collective effects, ***After 5 years

Magnets



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

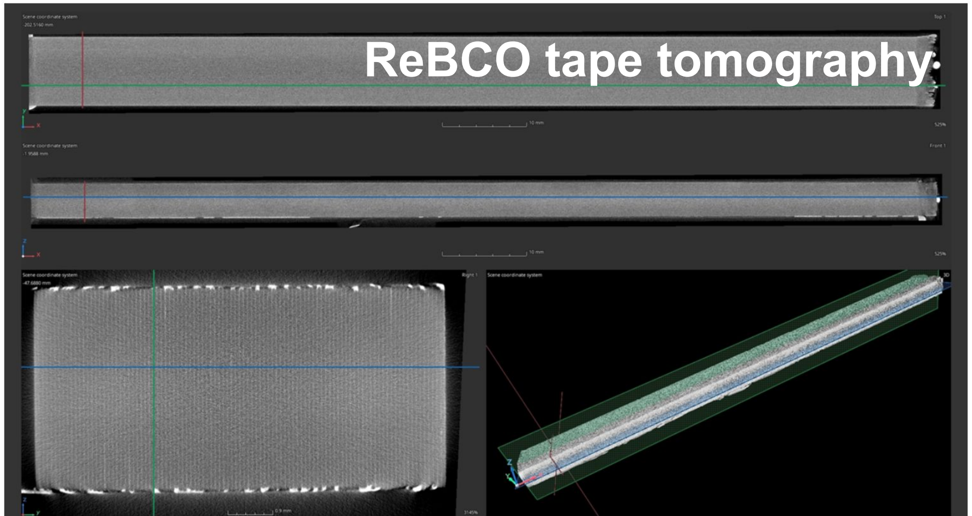


Fig. 4 – ReBCO Tape merged – quad view – section 1.

- **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)

Slide from D. Schulte

Muon beam cooling

Key conclusions:

- Muon cooling is much improved

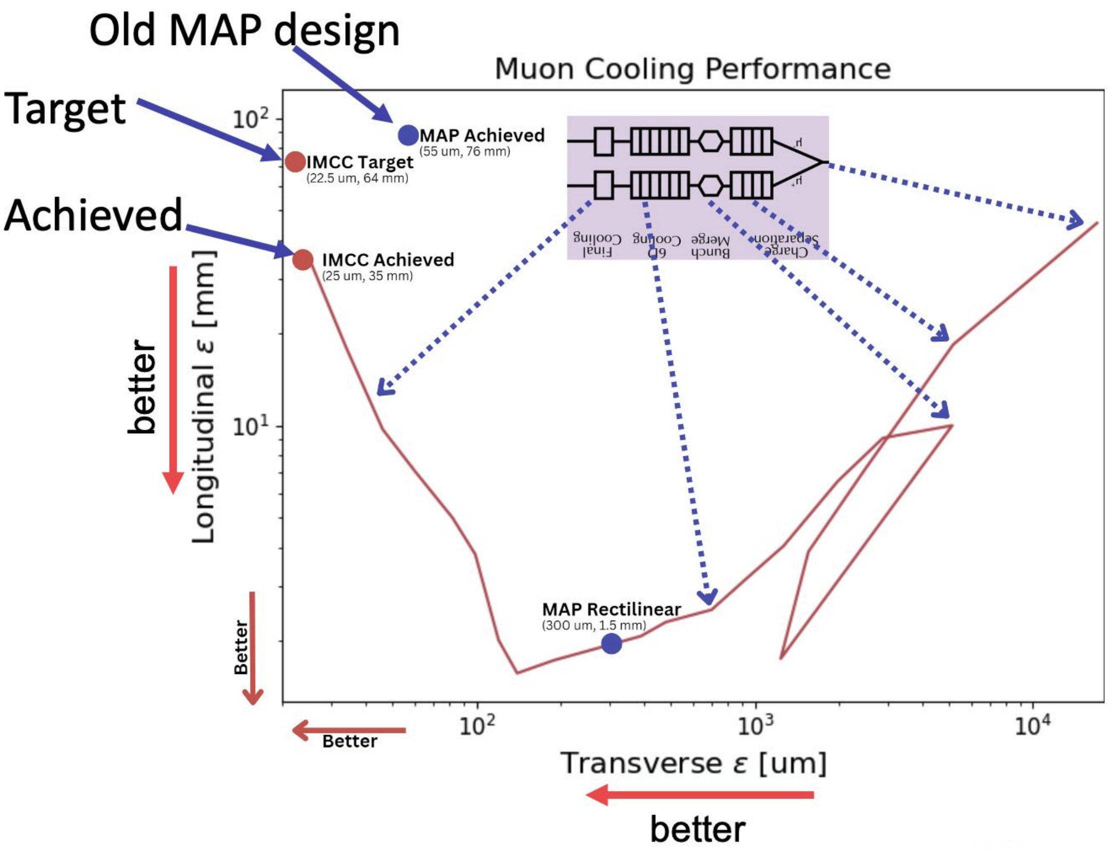
Parameter	MAP	goal	est.
Long. emitt [meVs]	26.7	<22.5	12.3
Transv. emitt [um]	55	<22.5	24

- Muon transmission should be improved

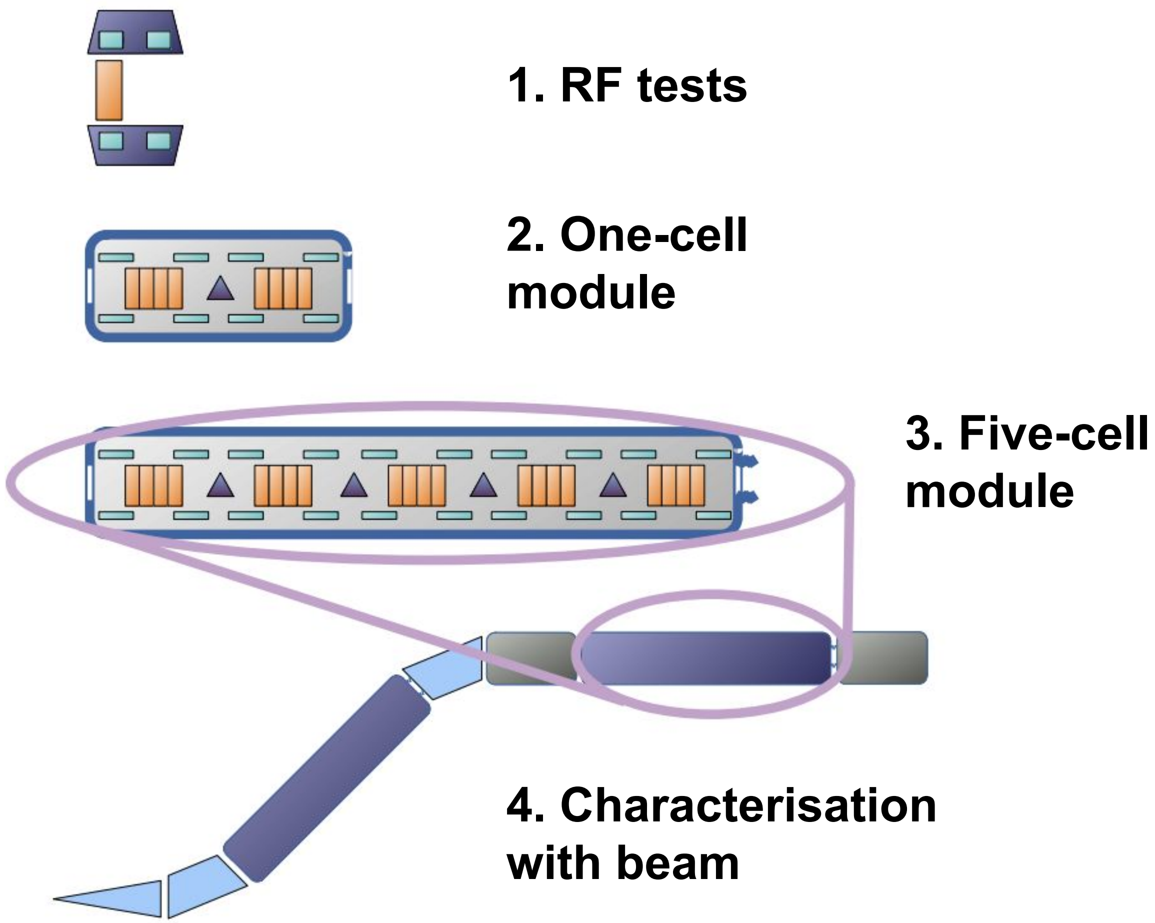
System	goal	estim.
End of cooling	4×10^{12}	2.8×10^{12}
Collider	1.8×10^{12}	1.5×10^{12}

(Compensated by high-energy complex, could increase target power, mu+ could be 30% more)

- Identified final cooling absorber as CTE, solved by using hydrogen gas
- Collective effects and imperfections need to be addressed



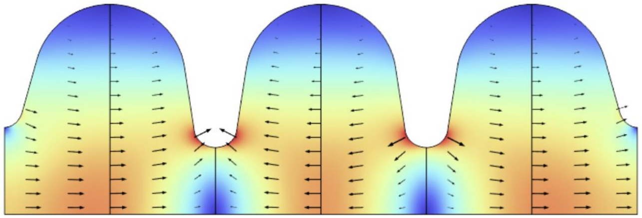
Muon Cooling Demonstrator Programme



RF tests

Parameters defined (32 MV/m at 704 MHz)

- Started RF cavity designs
- Beam loading needs to be controlled



High-field RF gradients in solenoid field have been demonstrated at FNAL, test stand no longer exists

- **Need new RF test stand urgently**

Several hosts interested: CERN, INFN, Daresbury Laboratory, and SLAC

- INFN LASA started some funding
- **SLAC is preparing test stand for 3 to 1.3 GHz**

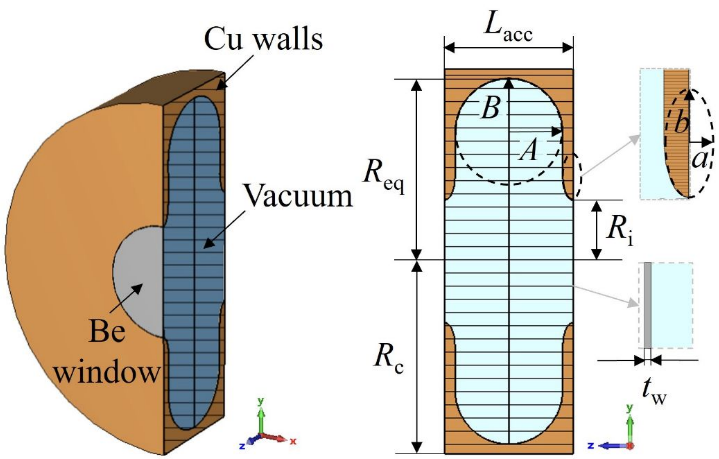


Fig. 6.3.1: Design of the 704 MHz cavity for muon cooling.

Cooling Cells

One-cell module

Test the operation of RF cavities in an operational magnetic environment

Five-cell module

Demonstrate integration of the solenoids, RF and other equipment

- Include weak dipoles to couple longitudinal and transverse emittances
- Thermal insulation

Fig. 6.6.2: Preliminary design of the MuCol Cooling cell

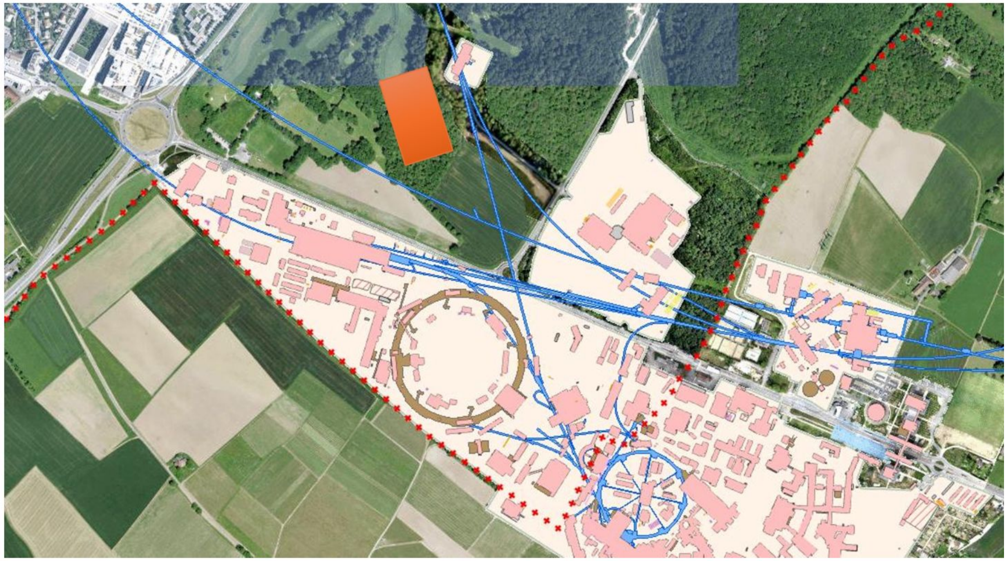
Demonstrator with beams

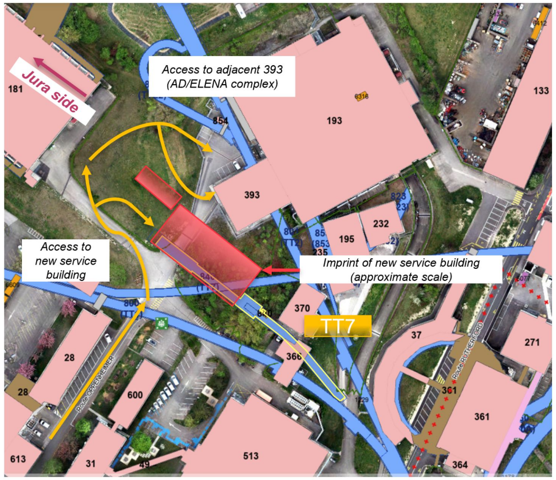
Tests with beam in **order to demonstrate commissioning and operation**

Demonstrator TDR for 2028-2030 (Infrastructure TRL 7)

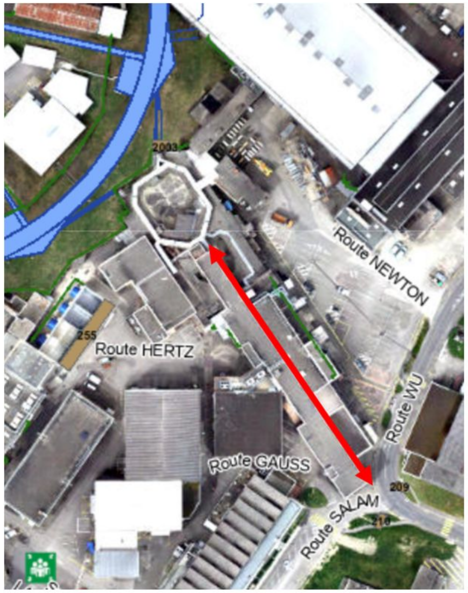
Add more modules to optimise technologies and performance

BA1-TT10 @ CERN





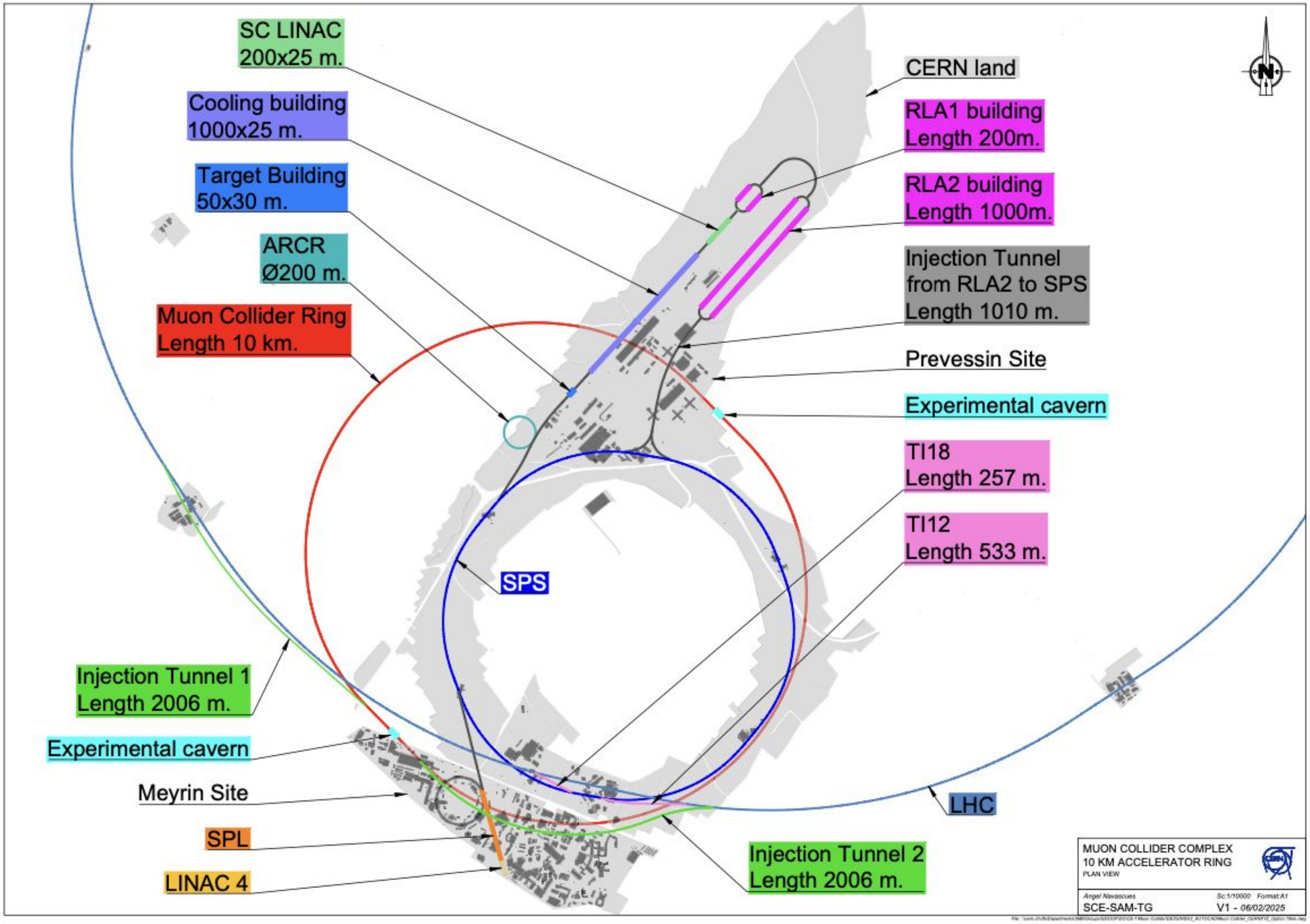
TT7 @ CERN



CTF3 @ CERN

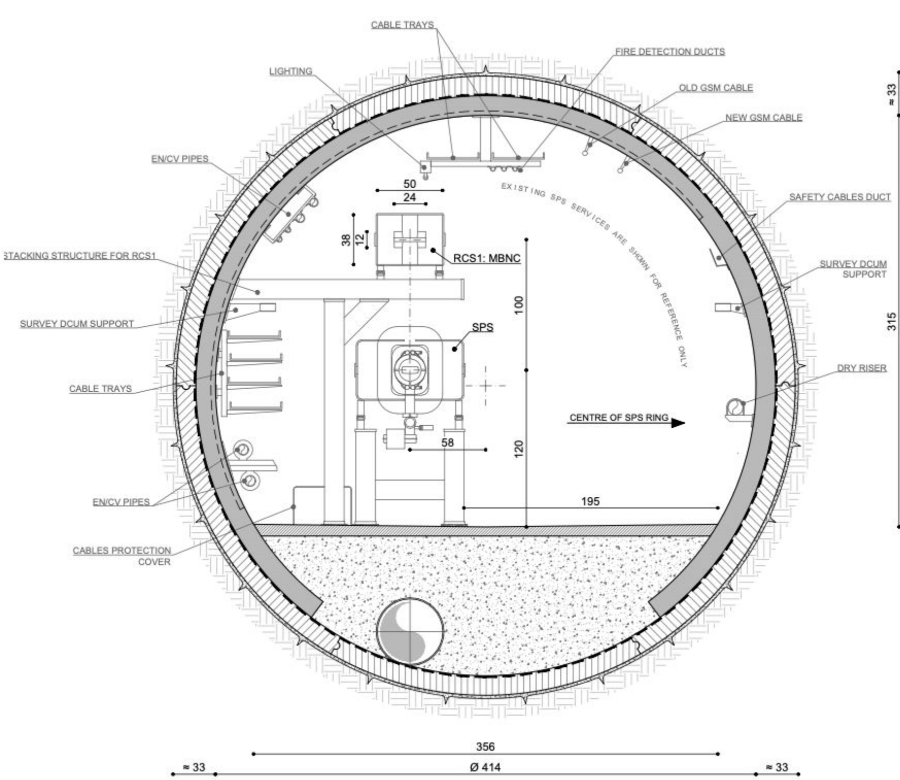
Implementation

Collider implementation

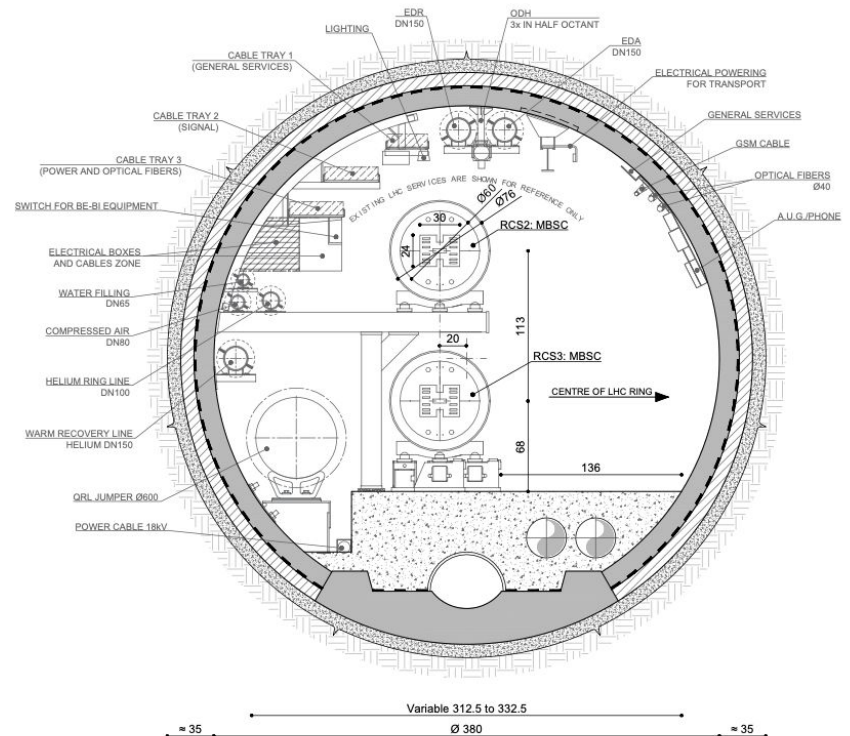


FNAL site also being investigated

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

Summary

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

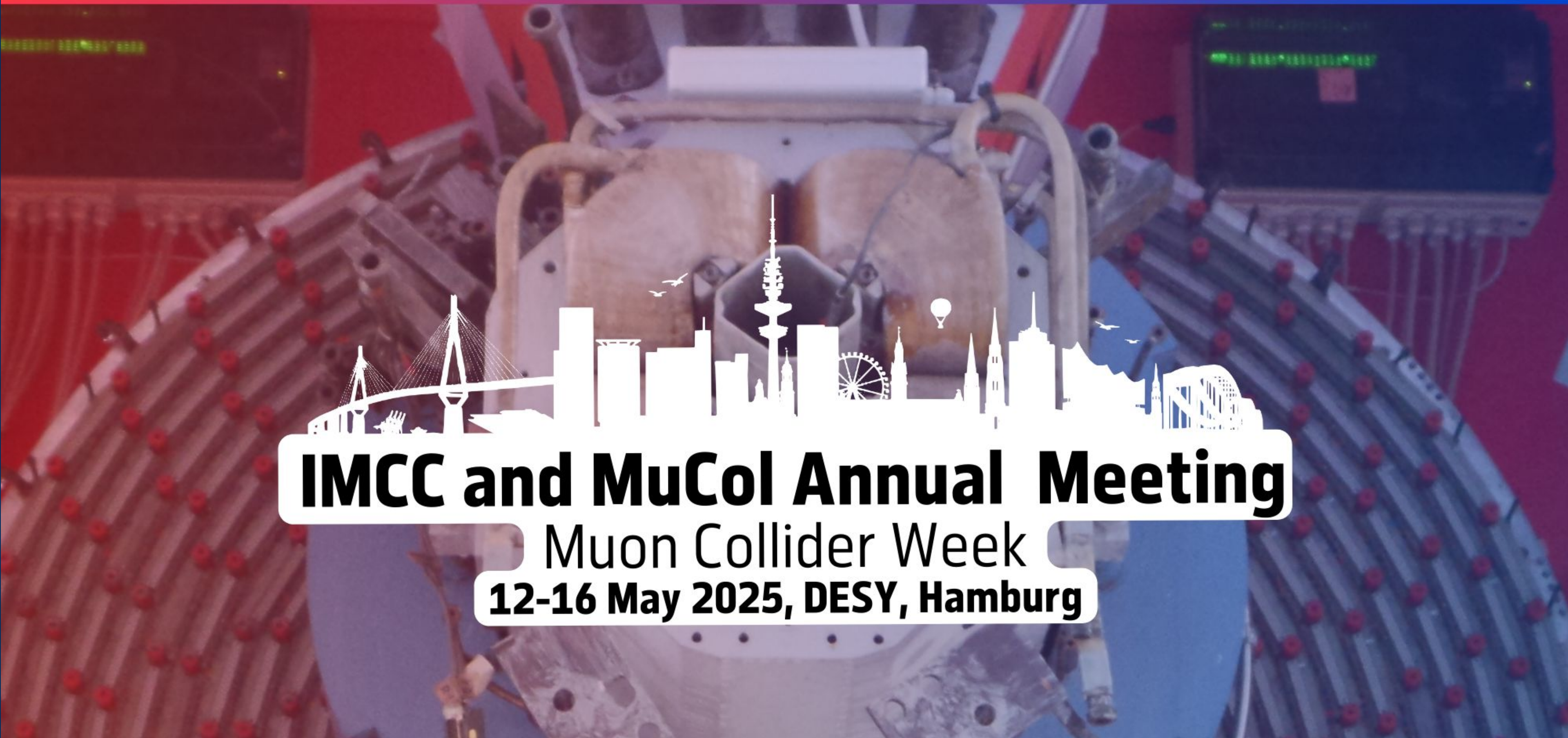
- F. Maltoni

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!**

Support the R&D programme in Venice!

Background image credit: L. Lee



Scientific Program Committee - Chairs: K. Kennedy (Princeton) & R. Taylor (CERN)

Members: C. Ahdida (CERN) , L. Bottura (CERN), C. Carli (CERN), A. Chance (CEA) ,S. Pagan Griso (LBNL), A. Grudiev (CERN), T. Holmes (UTK), S. Jindariani (FNAL), A. Lechner (CERN), R. Losito (CERN), D. Lucchesi (INFN), T. Luo (LBNL), P. Meade (SBU), E. Metral (CERN), N. Milas (ESS), E. A. Nanni (SLAC), M. Palmer (BNL), N. Pastrone (INFN), C. Rogers (STFC), L. Rossi (INFN), D. Schulte (CERN), L. Sestini (INFN), D. Stratakis (FNAL), J. Tang (USTC), A. Wulzer (IFAE/ICREA)

With thanks to A. Auger and M. Lancellotti

DESY Organising Committee: F. Meloni, J. List, I. Melzer-Pellmann, P. Pani, J. Reuter With thanks to B. Breetzke, A. Gerhardt and C. Groetzinger

MuCol: Funded by the European Union (EU). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the EU or European Research Executive Agency (REA). Neither the EU nor the REA can be held responsible for them.

https://indico.desy.de/event/45968/

Thank you!

Contact

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Background image credit: L. Lee

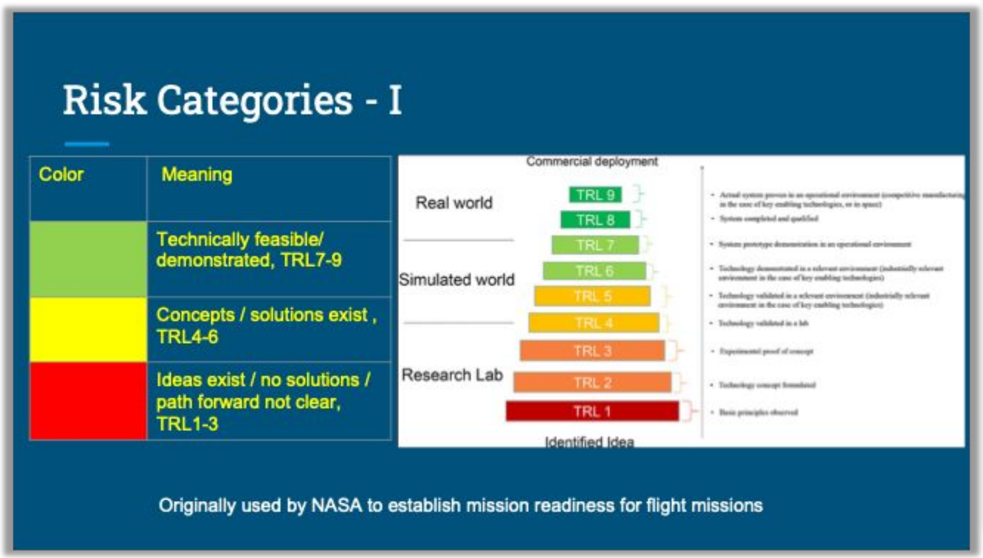
TRL definitions

Below , the one the one proposed by the review committee - from NASA

On the right - also from NASA, more explanations, and includes SW

Next slide, DOE version, consulted
EU version (LINK), consulted

Consistency good



Technology Readiness Level Definitions

TRL	Definition	Hardware Description	Software Description	Exit Criteria
1	Basic principles observed and reported.	Scientific knowledge generated underpinning hardware technology concepts/applications.	Scientific knowledge generated underpinning basic properties of software architecture and mathematical formulation.	Peer reviewed publication of research underlying the proposed concept/application.
2	Technology concept and/or application formulated.	Invention begins, practical application is identified but is speculative, no experimental proof or detailed analysis is available to support the conjecture.	Practical application is identified but is speculative, no experimental proof or detailed analysis is available to support the conjecture. Basic properties of algorithms, representations and concepts defined. Basic principles coded. Experiments performed with synthetic data.	Documented description of the application/concept that addresses feasibility and benefit.
3	Analytical and experimental critical function and/or characteristic proof of concept.	Analytical studies place the technology in an appropriate context and laboratory demonstrations, modeling and simulation validate analytical prediction.	Development of limited functionality to validate critical properties and predictions using non-integrated software components.	Documented analytical/experi-mental results validating predictions of key parameters.
4	Component and/or breadboard validation in laboratory environment.	A low fidelity system/component breadboard is built and operated to demonstrate basic functionality and critical test environments, and associated performance predictions are defined relative to the final operating environment.	Key, functionally critical, software components are integrated, and functionally validated, to establish interoperability and begin architecture development. Relevant Environments defined and performance in this environment predicted.	Documented test performance demonstrating agreement with analytical predictions. Documented definition of relevant environment.
5	Component and/or breadboard validation in relevant environment.	A medium fidelity system/component brassboard is built and operated to demonstrate overall performance in a simulated operational environment with realistic support elements that demonstrates overall performance in critical areas. Performance predictions are made for subsequent development phases.	End-to-end software elements implemented and interfaced with existing systems/simulations conforming to target environment. End-to-end software system, tested in relevant environment, meeting predicted performance. Operational environment performance predicted. Prototype implementations developed.	Documented test performance demonstrating agreement with analytical predictions. Documented definition of scaling requirements.
6	System/sub-system model or prototype demonstration in an operational environment.	A high fidelity system/component prototype that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate operations under critical environmental conditions.	Prototype implementations of the software demonstrated on full-scale realistic problems. Partially integrate with existing hardware/software systems. Limited documentation available. Engineering feasibility fully demonstrated.	Documented test performance demonstrating agreement with analytical predictions.
7	System prototype demonstration in an operational environment.	A high fidelity engineering unit that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate performance in the actual operational environment and platform (ground, airborne, or space).	Prototype software exists having all key functionality available for demonstration and test. Well integrated with operational hardware/software systems demonstrating operational feasibility. Most software bugs removed. Limited documentation available.	Documented test performance demonstrating agreement with analytical predictions.
8	Actual system completed and "flight qualified" through test and demonstration.	The final product in its final configuration is successfully demonstrated through test and analysis for its intended operational environment and platform (ground, airborne, or space).	All software has been thoroughly debugged and fully integrated with all operational hardware and software systems. All user documentation, training documentation, and maintenance documentation completed. All functionality successfully demonstrated in simulated operational scenarios. Verification and Validation (V&V) completed.	Documented test performance verifying analytical predictions.
9	Actual system flight proven through successful mission operations.	The final product is successfully operated in an actual mission.	All software has been thoroughly debugged and fully integrated with all operational hardware/software systems. All documentation has been completed. Sustaining software engineering support is in place. System has been successfully operated in the operational environment.	Documented mission operational results.

TRL from DOE

Table 1. Technology Readiness Levels

Relative Level of Technology Development	Technology Readiness Level	TRL Definition	Description
System Operations	**TRL 9**	Actual system operated over the full range of expected mission conditions.	The technology is in its final form and operated under the full range of operating mission conditions. Examples include using the actual system with the full range of wastes in hot operations.
System Commissioning	**TRL 8**	Actual system completed and qualified through test and demonstration.	The technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental testing and evaluation of the system with actual waste in hot commissioning. Supporting information includes operational procedures that are virtually complete. An Operational Readiness Review (ORR) has been successfully completed prior to the start of hot testing.
	TRL 7	Full-scale, similar (prototypical) system demonstrated in relevant environment	This represents a major step up from TRL 6, requiring demonstration of an actual system prototype in a relevant environment. Examples include testing full-scale prototype in the field with a range of simulants in cold commissioning[1]. Supporting information includes results from the full-scale testing and analysis of the differences between the test environment, and analysis of what the experimental results mean for the eventual operating system/environment. Final design is virtually complete.
Technology Demonstration	**TRL 6**	Engineering/pilot-scale, similar (prototypical) system validation in relevant environment	Engineering-scale models or prototypes are tested in a relevant environment. This represents a major step up in a technology's demonstrated readiness. Examples include testing an engineering scale prototypical system with a range of simulants.[1] Supporting information includes results from the engineering scale testing and analysis of the differences between the engineering scale, prototypical system/environment, and analysis of what the experimental results mean for the eventual operating system/environment. TRL 6 begins true engineering development of the technology as an operational system. The major difference between TRL 5 and 6 is the step up from laboratory scale to engineering scale and the determination of scaling factors that will enable design of the operating system. The prototype should be capable of performing all the functions that will be required of the operational system. The operating environment for the testing should closely represent the actual operating environment.
Technology Development	**TRL 5**	Laboratory scale, similar system validation in relevant environment	The basic technological components are integrated so that the system configuration is similar to (matches) the final application in almost all respects. Examples include testing a high-fidelity, laboratory scale system in a simulated environment with a range of simulants[1] and actual waste[2]. Supporting information includes results from the laboratory scale testing, analysis of the differences between the laboratory and eventual operating system/environment, and analysis of what the experimental results mean for the eventual operating system/environment. The major difference between TRL 4 and 5 is the increase in the fidelity of the system and environment to the actual application. The system tested is almost prototypical.
Technology Development	**TRL 4**	Component and/or system validation in laboratory environment	The basic technological components are integrated to establish that the pieces will work together. This is relatively "low fidelity" compared with the eventual system. Examples include integration of ad hoc hardware in a laboratory and testing with a range of simulants and small scale tests on actual waste[2]. Supporting information includes the results of the integrated experiments and estimates of how the experimental components and experimental test results differ from the expected system performance goals. TRL 4-6 represent the bridge from scientific research to engineering. TRL 4 is the first step in determining whether the individual components will work together as a system. The laboratory system will probably be a mix of on hand equipment and a few special purpose components that may require special handling, calibration, or alignment to get them to function.
Research to Prove Feasibility	**TRL 3**	Analytical and experimental critical function and/or characteristic proof of concept	Active research and development (R&D) is initiated. This includes analytical studies and laboratory-scale studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative tested with simulants.[1] Supporting information includes results of laboratory tests performed to measure parameters of interest and comparison to analytical predictions for critical subsystems. At TRL 3 the work has moved beyond the paper phase to experimental work that verifies that the concept works as expected on simulants. Components of the technology are validated, but there is no attempt to integrate the components into a complete system. Modeling and simulation may be used to complement physical experiments.
Basic Technology Research	**TRL 2**	Technology concept and/or application formulated	Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are still limited to analytic studies. Supporting information includes publications or other references that outline the application being considered and that provide analysis to support the concept. The step up from TRL 1 to TRL 2 moves the ideas from pure to applied research. Most of the work is analytical or paper studies with the emphasis on understanding the science better. Experimental work is designed to corroborate the basic scientific observations made during TRL 1 work.
	TRL 1	Basic principles observed and reported	This is the lowest level of technology readiness. Scientific research begins to be translated into applied R&D. Examples might include paper studies of a technology's basic properties or experimental work that consists mainly of observations of the physical world. Supporting Information includes published research or other references that identify the principles that underlie the technology.