Istituto Nazionale di Fisica Nucleare

Introduction to detector discussion and input to ESPPU

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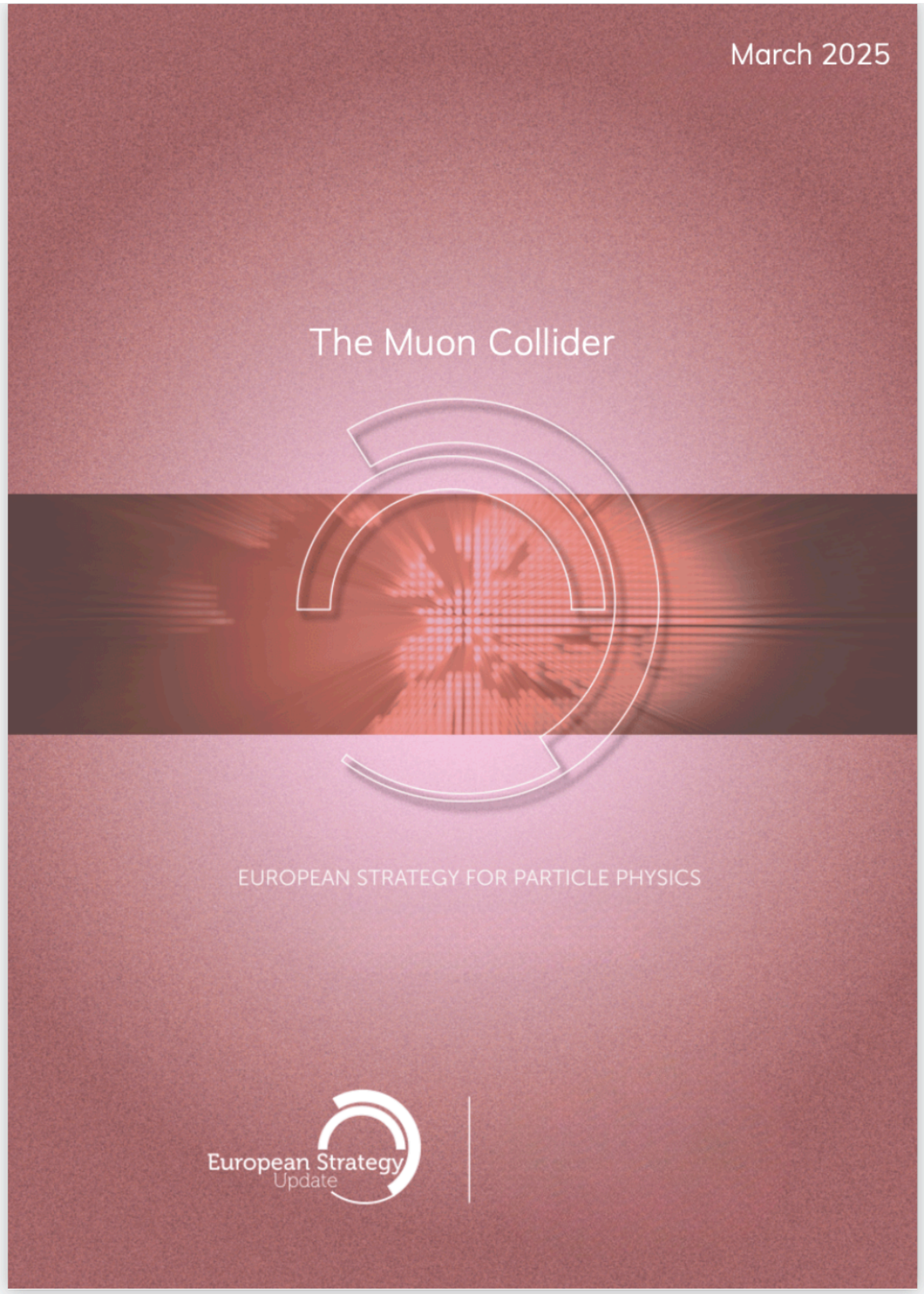
MuCol

International MUON Collider Collaboration

Co-funded by the European Union

RD_MUCOL meeting - Torino - 4/12/2024

ESPPU input


March 2025
The Muon Collider
EUROPEAN STRATEGY FOR PARTICLE PHYSICS
European Strategy
Update

Evaluation and R&D reports

iv

ESPPU Muon Collider Report – – December 4, 2024

Detector requirements

3.1 Physics and detector needs

P. MEADE, S. PAGAN-GRISO, F. MELONI, N. PASTRONE

Table 3.1.1: Preliminary summary of the "baseline" and "aspirational" targets for selected key metrics, reported separately for machines taking data at $\sqrt{s} = 3$ and 10 TeV. The reported performance targets refer to the measurement of the reconstructed objects in physics events after, for example, background subtraction and not to the bare detector performance.

Requirement	**Baseline**		**Aspirational**
	$\sqrt{s} = 3$ **TeV**	$\sqrt{s} = 10$ **TeV**	
Angular acceptance $\eta = -\log(\tan(\theta/2))$	$\lvert\eta\rvert < 2.5$	$\lvert\eta\rvert < 2.5$	$\lvert\eta\rvert < 4$
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 $\lvert\eta\rvert > 2.5$	~ 50 for $\lvert\eta\rvert > 2.5$	< 50 for $\lvert\eta\rvert > 2.5$
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

MDI

3.2 MDI

A. LECHNER, D. CALZOLARI

Expected updates for the MDI section:

- The sub-sections about Overview and Key Challenges are quite complete, but will be polished
- The sub-section about Recent Achievements needs to be updated wrt interim report
- The main updates will be:
  - Summary of present interaction region design for 10 TeV (plot already included below)
  - Brief description of the updated nozzle
  - Updated decay background distributions for the latest 10 TeV lattice (v0.8) and nozzle version (plots already included below)
  - Radiation damage estimates for the MUSIC and MAIA detectors (plots already included below, table with some key numbers to be added)

Table 3.2.1: Maximum values of the ionizing dose and the 1 MeV neutron-equivalent fluence (Si) in the two detector options. All values are per year of operation (10 TeV) and include only the contribution of muon decay.

Component	Dose [kGy]		1 MeV neutron-equivalent fluence (Si) [10^{14} n/cm^2]	
	MAIA	MUSIC	MAIA	MUSIC
Vertex (barrel)	1000		2.3	
Vertex (endcaps)	2000		8	
Inner trackers (barrel)	70		4.5	4
Inner trackers (endcaps)	30		11.5	10
ECAL	0.58	1.4	0.15	1

Luca Castelli contribution later

Detector concepts

Chapter 4

Detector concepts

4.1 Overview

D. Lucchesi, F. Meloni, S. Pagan-Griso, S. Jindariani

Possible structure: (0.5 page?)

- summary of the study of the detector at 3 TeV which demonstrates physics capabilities
- introduction to the challenges of the 10 TeV.

4.2 MUSIC

D. Lucchesi, L. Sestini, M. Casarsa, D. Zuliani

The MUSIC (MUon System for Interesting Collisions) detector concept is a multi-purpose collider detector featuring a cylindrical layout with a length of 11.4 m and a diameter of 12.8 m. It includes an all-silicon tracking system and an electromagnetic calorimeter, both housed within a superconducting solenoid that is surrounded by a hadronic calorimeter and muon detectors. The configuration of the MUSIC detector is shown in Fig. 4.2.1. In the following sections, the main features of the MUSIC sub-systems are briefly described.

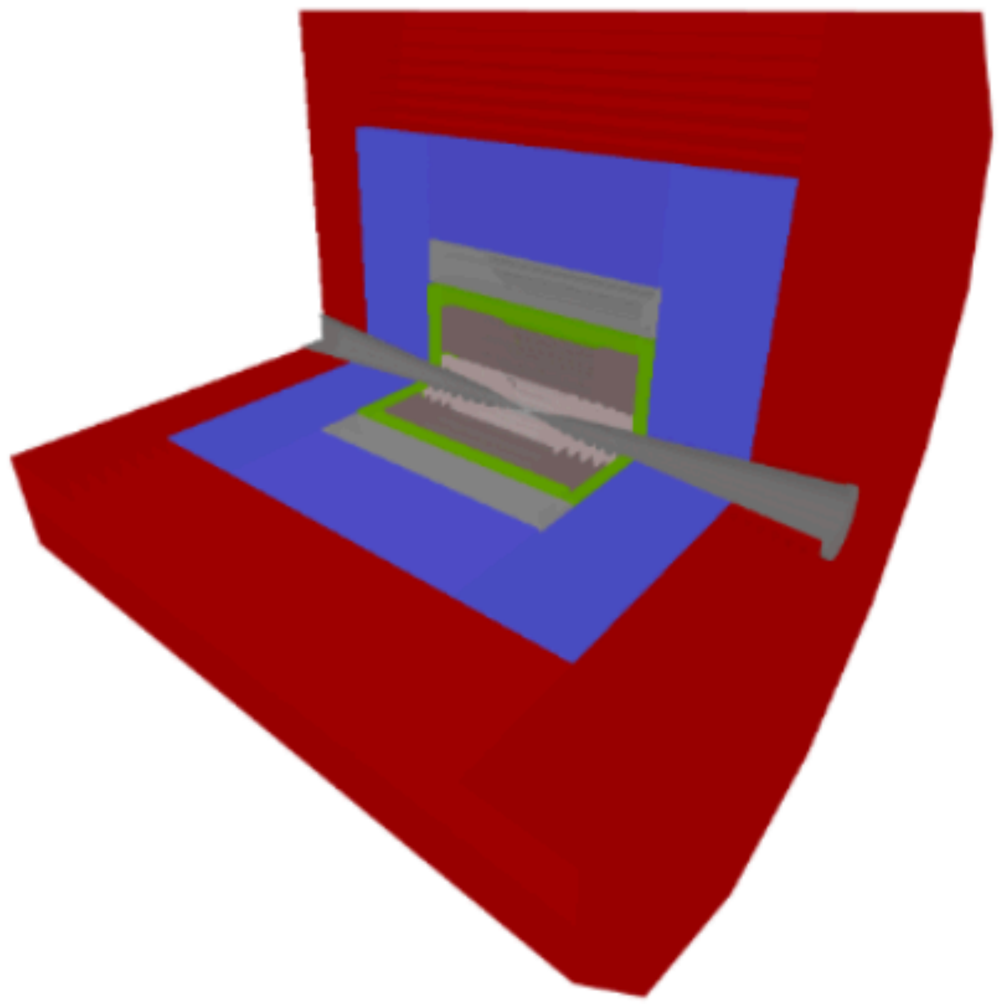


Fig. 4.2.1: Layout of the MUSIC detector concept: from the center to the outermost region, it includes a Vertex Detector and an Inner Tracker (light gray), an Outer Tracker (dark gray), an electromagnetic calorimeter (green), a superconducting magnet (gray), a hadronic calorimeter (blue), and muon detectors (red). The shielding nozzles, installed along the axis of the detector, are shown in dark gray.

Performance, technology, Software

4.4 Performance

D. LUCCHESI, L. SESTINI, M. CASARSA, D. ZULIANI, K. DI PETRILLO, T. HOLMES → **Massimo Casarsa today**
Leonardo Palombini tomorrow

4.5 Technologies

T. HEIM, A. APRESYAN, L. LONGO, N. BARTOSIK → **Ivano Sarra, Luigi Longo, Nazar Bartosik tomorrow**

4.6 Software & Computing

K. PEDRO, W. HOPKINS, K. KRIZKA, T. MADLENER → **Alessio Gianelle today**

+ Magnet discussion today (Andrea Bersani)

R&D

Chapter 9

Detector R&D

N. Pastrone, F. Meloni, S. Pagan-Griso, S. Jindariani

- Motivate why we need additional detector R&D.

9.1 Detector concept and performance

K. Di Petrillo, T. Holmes, L. Sestini, M. Casarsa, D. Zuliani

Tracking system

- Study on full 4D track reconstruction
- Optimized tracker layout, in particular the endcaps
- Optimized track fit and quality selection requirements
- Study on technical specifications of tracker sensors
- Improved realistic digitization algorithm for tracker cells
- Optimized algorithm for primary/secondary vertex reconstruction

Magnet

- Study on the magnetic field return yoke
- Implementation of a realistic map of the magnetic field

Calorimeter system

- Improved realistic digitization algorithm for calorimeters cells
- Optimized BIB subtraction and calibration techniques
- Optimized clustering and fake rejection algorithms
- Optimized calorimeters endcap layout and reconstruction
- Investigation on alternative technologies for HCAL

Muon Detector design

- Study on magnetic field configurations for the muon detector
- Optimized layout of the muon detector (dependent also on the technology choice)
- Development of a muon reconstruction algorithm

Potential forward detector systems - in partnership with MDI

- Development of forward muon detector for tagging and momentum estimation
- Study on luminosity measurement (this has some overlap with MDI - check with Daniele/Donatella)

Cross system

- Optimized particle flow reconstruction for higher level physics objects
- Development of a robust flavour tagging algorithm, considering also machine learning techniques

9.2 Detector technologies

T. Heim, A. Apresyan, I. Vai, I. Sarra, S. Ricciardi

9.3 Software & computing for detectors

K. Pedro, W. Hopkins, K. Krizka, T. Madlener

PPG benchmarks

Benchmark measurements / processes for PPG Groups

1. Electroweak physics, incl. Higgs
   - Higgs (mH, single-Higgs couplings via SMEFT and kappas)
   - HH and Higgs potential (Higgs self-coupling)
   - Precision EW (mW, Z width, sin2thetaW; EW couplings via SMEFT)
   - Longitudinal scattering
   - Top benchmarks: top mass and SMEFT

   Co-convener: Jorge de Blas, Monica Dunford

2. Strong Interactions
   - Precision QCD
     - Precision and accuracy on alpha_s;
   - Inner structure of protons and nuclei
     - Precision on (longitudinal) PDF(x,Q^2);
     - Precision on nuclear PDF(x,Q^2);
   - Hot and dense QCD
     - Heavy-flavour hadron production (rare states, kinematic coverage); QGP transport coefficients (heavy quarks, jets);
     - QGP thermal radiation / temperature;
   - QCD connections with hadronic, nuclear and astro(particle) physics
     - Constraints on nature of exotic hadrons from spectroscopy and h-h correlations;
     - Precision on anti-nuclei production and absorption relevant for cosmic-ray physics;

   Co-convener: Andrea Dainese, Cristinel Diaconu

PPG benchmarks

3. Flavour physics

$B \to K^{(*)} \tau\tau$

$B \to K^{(*)} \nu\nu$

$B_d \to \mu\mu$

$\tau \to 3\mu$

τ lifetime and $B(\tau \to \mu\nu\nu)$ (τ universality tests)

CP violation in neutral D-meson mixing

4. BSM physics

- New gauge forces (Z', W'...)
- Compositeness (indirectly from EFT fits)
- Extension of the minimal real scalar sector giving 1st order EW phase transition and possibly stability.
- Minimal dark matter (WIMP) global
- High-energy aspects of flavour, e.g. exotic top decays
- SUSY (direct only collider)
- Portals (dark photon, dark higgs, HNLs, axions, ALPs)

Co-convener: Fabio Maltoni, Rebeca Gonzales Suarez

5. Dark matter and dark sector

Ultralight DM: ALPs, Z'.
Light DM: ALPs, Z', Freeze-In
Heavy DM: Wino & Higgsino, Simplified Models, ALPs, Z', Dark Showers
Note: Cannot compare benchmark processes across collider/direct/indirect detection. Only models.

Co-convener: Mathew McCullough, Jocelyn Monroe

PPG benchmarks

6. **Detector instrumentation**

In general, scalability, time scales, Technology Readiness Levels (TRLs) of the proposed technologies and a discussion on existing/missing coverage in ECFA/CERN DRD collaborations is requested.

For collider experiments, in addition, requirements on:

- Vertex: Impact parameter resolution, single hit resolution on detector plane, material budget limits, power consumption, cooling
- Tracking: Momentum resolution, timing requirements (4D tracking), material budget, occupancy
- Calorimeter: energy resolution, granularity for FPA, dual readout
- PID: required particle separation capabilities over p range
- DAQ: data rate, latency, is a hardware trigger required?
- MDI: integration aspects, especially on last focussing magnet inside experiment volume

Co-convener: Thomas Bergauer, Ulrich Husemann

Discussions

Today

Introduction to detector discussion and input to ESPPU	*Lorenzo Sestini*	*Sala Riunioni DIMEAS P3, Politecnico di Torino*	16:10 - 16:20
Detector performance studies	*Massimo Casarsa*	*Sala Riunioni DIMEAS P3, Politecnico di Torino*	16:20 - 16:40
Magnet discussion	*Andrea Bersani*	*Sala Riunioni DIMEAS P3, Politecnico di Torino*	16:40 - 16:55
Machine Detector Interface developments	*Luca Castelli*	*Sala Riunioni DIMEAS P3, Politecnico di Torino*	16:55 - 17:10
Simulation software discussion	*Alessio Gianelle*	*Sala Riunioni DIMEAS P3, Politecnico di Torino*	17:10 - 17:25
Discussion		*Sala Riunioni DIMEAS P3, Politecnico di Torino*	17:25 - 17:45

17:00

Tomorrow

R&D TPC for demonstrator		*Sala Riunioni DIMEAS P3, Politecnico di Torino*	17:30 - 17:40
Electron reconstruction and particle flow	*Leonardo Palombini*	*Sala Riunioni DIMEAS P3, Politecnico di Torino*	17:40 - 17:50
ECAL R&D	*Ivano Sarra*	*Sala Riunioni DIMEAS P3, Politecnico di Torino*	17:50 - 18:00
HCAL R&D	*Luigi Longo*	*Sala Riunioni DIMEAS P3, Politecnico di Torino*	18:00 - 18:10
Tracking sensors R&D	*Nazar Bartosik*	*Sala Riunioni DIMEAS P3, Politecnico di Torino*	18:10 - 18:20
Muon detector R&D		*Sala Riunioni DIMEAS P3, Politecnico di Torino*	18:20 - 18:30

18:00

Detector proposals for 10 TeV

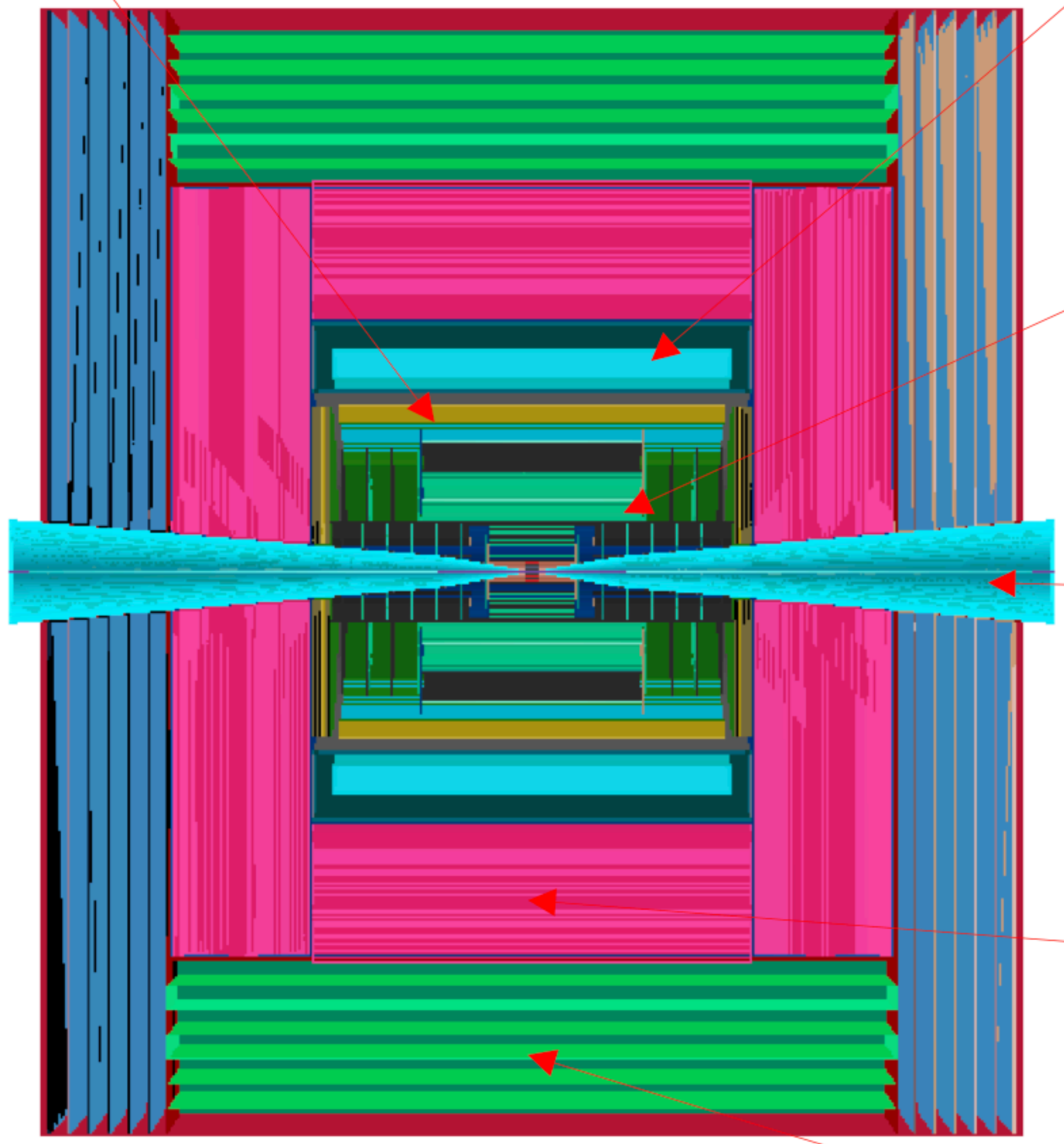
International MUON Collider Collaboration

INFN Istituto Nazionale di Fisica Nucleare

MUSIC (MUon System for Interesting Collisions)

PbF$_2$-crystal electromagnetic calorimeter (inside the solenoid)

Proposal from INFN

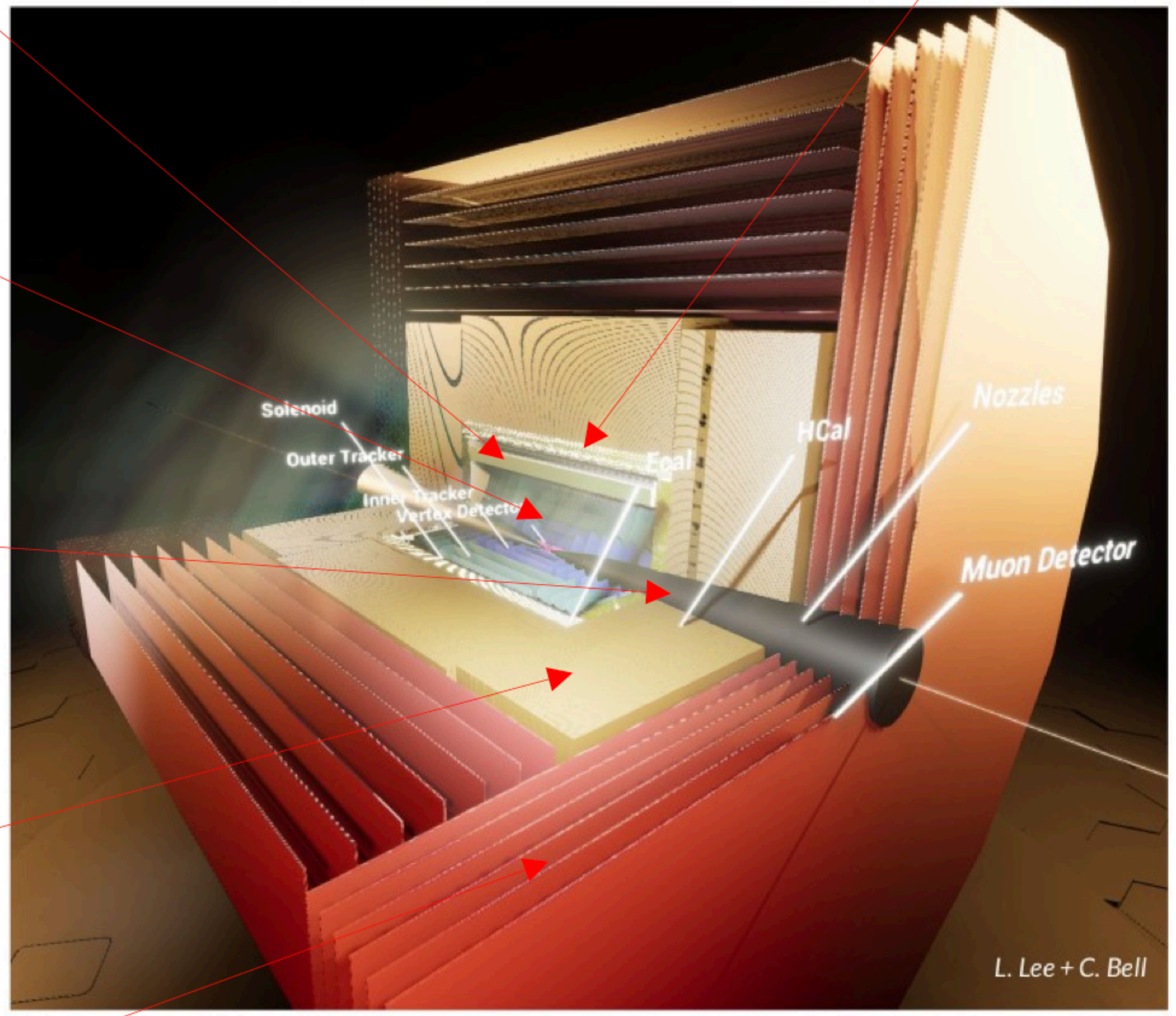


ALEPH-like detector

MAIA (Muon Accelerator Instrumented Apparatus)

Si-W electromagnetic calorimeter (ouside the solenoid)

Proposal from USA+DESY



ATLAS-like detector

superconducting solenoid (B = 5 T)

full silicon tracking system

tungsten shielding nozzles

Fe-scintillator hadronic calorimeter (serves as B field return yoke)

muon detectors

Software framework (branched from ILCSoft) https://github.com/MuonColliderSoft

ICHEP 2024: Detector performance for low- and high-momentum particles in √s = 10 TeV muon collisions

Thanks for your attention!

Backup