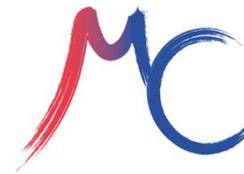




International
Muon Collider
Collaboration



MuCol

Muon Collider

D. Schulte

On behalf of the International Muon Collider Collaboration

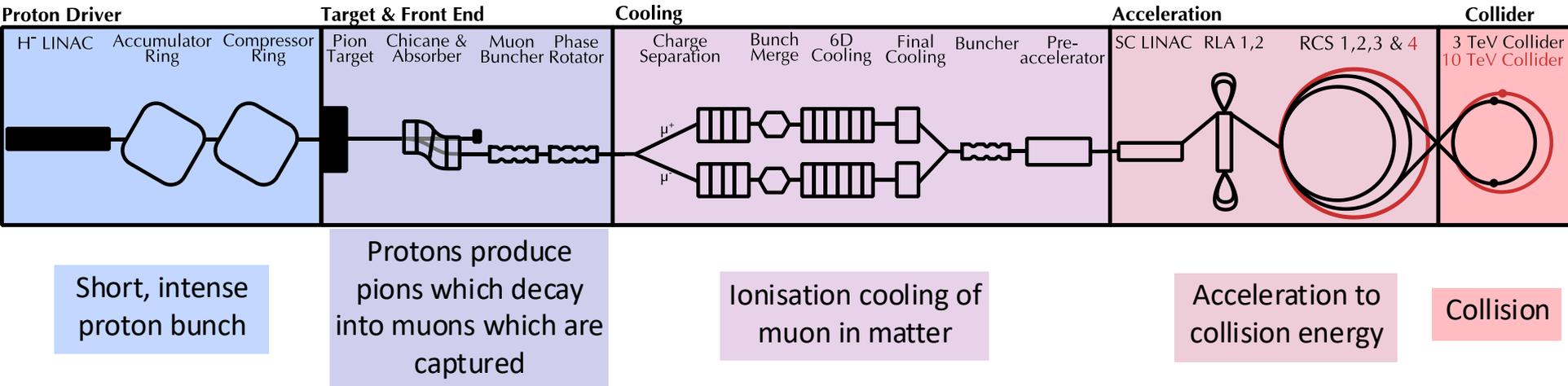
KET Meeting, DESY, November, 2024

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.



Muon Collider Overview

Would be easy if the muons did not decay
Lifetime is $\tau = \gamma \times 2.2 \mu\text{s}$ (e.g. 3100 turns in collider ring)



Muon Collider Promises

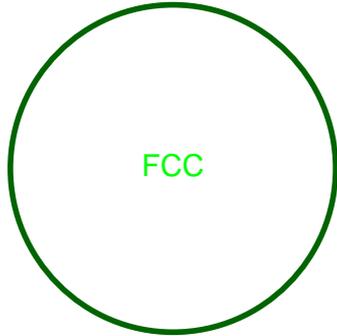


US Snowmass Implementation Task Force: Th. Roser, R. Brinkmann, S. Cousineau, D. Denisov, S. Gessner, S. Gourlay, Ph. Lebrun, M. Narain, K. Oide, T. Raubenheimer, J. Seeman, V. Shiltsev, J. Straight, M. Turner, L. Wang et al.

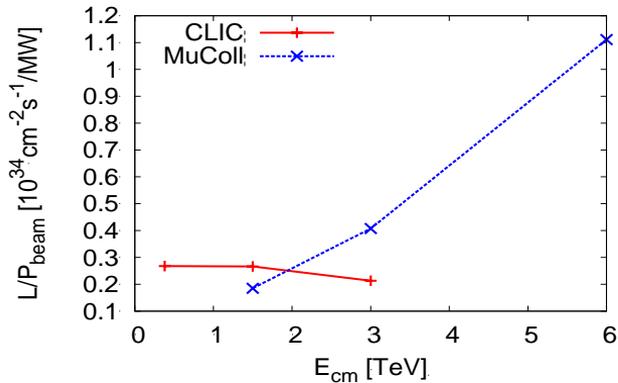
MC
10 TeV

MC
3 TeV

LHC



CLIC



	CME [TeV]	Lumi per IP [$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$]	Years to physics	Cost range [B\$]	Power [MW]
FCC-ee	0.24	8.5	13-18	12-18	290
ILC	0.25	2.7	<12	7-12	140
CLIC	0.38	2.3	13-18	7-12	110
ILC	3	6.1	19-24	18-30	400
CLIC	3	5.9	19-24	18-30	550
MC	3	1.8	19-24	7-12	230
MC	10	20	>25	12-18	300
FCC-hh	100	30	>25	30-50	560

Judgement by ITF, take it *cum grano salis*
Working on improved estimates

IMCC

International Muon Collider Collaboration



Develop high-energy muon collider as option for particle physics:

- Muon collider promises **sustainable** approach to the **energy frontier**
 - limited power consumption, cost and land use
- **Technology** and **design advances** in past years
- Reviews in Europe and US found **no unsurmountable obstacle**

Initial workplan in **LDG Accelerator R&D Roadmap**

Focus on **10 TeV feasibility**

- **Initial stage by 2050**, maybe around 3 TeV or 10 TeV with lower luminosity
- Could later consider other energies (above 10 TeV, 125 GeV, ...)

Goals for ESPPU is to provide document with

- **Assessment of muon collider** concept, technologies and work progress
- An **R&D plan** for the next 5 and 10 years
- **Implementation considerations** (including site, timeline, ...)

Label	Begin	End	Description	Aspirational		Minimal	
				[FTEy]	[kCHF]	[FTEy]	[kCHF]
MC.SITE	2021	2025	Site and layout	15.5	300	13.5	300
MC.NF	2022	2026	Neutrino flux mitigation system	22.5	250	0	0
MC.MDI	2021	2025	Machine-detector interface	15	0	15	0
MC.ACC.CR	2022	2025	Collider ring	10	0	10	0
MC.ACC.HE	2022	2025	High-energy complex	11	0	7.5	0
MC.ACC.MC	2021	2025	Muon cooling systems	47	0	22	0
MC.ACC.P	2022	2026	Proton complex	26	0	3.5	0
MC.ACC.COLL	2022	2025	Collective effects across complex	18.2	0	18.2	0
MC.ACC.ALT	2022	2025	High-energy alternatives	11.7	0	0	0
MC.HFM.HE	2022	2025	High-field magnets	6.5	0	6.5	0
MC.HFM.SOL	2022	2026	High-field solenoids	76	2700	29	0
MC.FR	2021	2026	Fast-ramping magnet system	27.5	1020	22.5	520
MC.FR.HE	2021	2026	High Energy complex RF	10.6	0	7.6	0
MC.FR.MC	2022	2026	Muon cooling RF	13.6	0	7	0
MC.FR.TS	2024	2026	RF test stand + test cavities	10	3300	0	0
MC.MOD	2022	2026	Muon cooling test module	17.7	400	4.9	100
MC.DEM	2022	2026	Cooling demonstrator design	34.1	1250	3.8	250
MC.TAR	2022	2026	Target system	60	1405	9	25
MC.INT	2022	2026	Coordination and integration	13	1250	13	1250
			Sum	445.9	11875	193	2445

Table 5.5: The resource requirements for the two scenarios. The personnel estimate is given in full-time equivalent years and the material in kCHF. It should be noted that the personnel contains a significant number of PhD students. Material budgets do not include budget for travel, personal IT equipment and similar costs. Colours are included for comparison with the resource profile Fig. 5.7.

<http://arxiv.org/abs/2201.07895>

The Collaboration

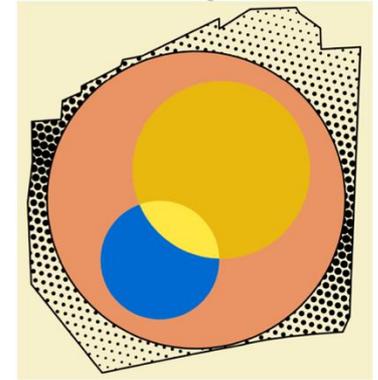


Collaboration currently **hosted by CERN**

New partners still joining (**58 signed**, more in the process)

- From different regions

EU co-funded design study MuCol started 2023



Strong recommendation from **P5 «This is our muon shot»**

- Interest in hosting at FNAL

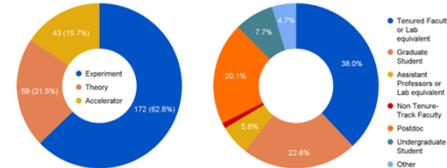
US partners are joining/plan to join

- **Strong interest** at US Muon Collider Inauguration Meeting in August at FNAL (about 300 participants)
- Addendum to **CERN-DoE agreement** in preparation

- In early August, held an open meeting of the US community
 - 274 (+25 virtual) participants

Strong US contribution to **IMCC R&D plan**

IMCC will carry out the R&D together and develop options to host the collider at CERN or at FNAL and potentially also other sites



IMCC Partners



IEIO	CERN	IT	INFN	SE	ESS	CA	Université Laval
FR	CEA-IRFU		INFN, Univ., Polit. Torino		University of Uppsala	US	Iowa State University
	CNRS-LNCMI		INFN, LASA, Univ. Milano	FI	Tampere University		University of Iowa
	<i>Mines St-Etienne</i>		INFN, Univ. Padova	LAT	Riga Technical University		Wisconsin-Madison
DE	DESY		INFN, Univ. Pavia	CH	PSI		University of Pittsburgh
	Technical University of Darmstadt		INFN, Univ. Bologna		University of Geneva		Old Dominion
	University of Rostock		INFN Trieste		EPFL		Chicago University
	KIT		INFN, Univ. Bari		HEIA-FR		Florida State University
UK	RAL		INFN, Univ. Roma 1	BE	Univ. Louvain		RICE University
	UK Research and Innovation		<i>ENEA</i>	AU	HEPHY		Tennessee University
	University of Lancaster		INFN Frascati		<i>TU Wien</i>		MIT Plasma science center
	University of Southampton		INFN, Univ. Ferrara	ES	I3M		Pittsburgh PAC
	University of Strathclyde		INFN, Univ. Roma 3		<i>CIEMAT</i>		Yale
	University of Sussex		INFN Legnaro		ICMAB		Princeton
	Imperial College London		INFN, Univ. Milano Bicocca	China	<i>Sun Yat-sen University</i>		Stony Brook
	Royal Holloway		INFN Genova		IHEP		Stanford/SLAC
	University of Huddersfield		INFN Laboratori del Sud		Peking University		...
	University of Oxford		INFN Napoli		Inst. Of Mod. Physics, CAS	DoE labs	FNAL
	University of Warwick	Mal	Univ. of Malta	KO	Kyungpook National University		LBNL
	University of Durham	EST	Tartu University		Yonsei University		JLAB
	University of Birmingham	PT	LIP		Seoul National University		BNL
	<i>University of Cambridge</i>	NL	University of Twente	India	<i>CHEP</i>	Brazil	CNPEN

Key Challenges

Environmental impact

- Neutrino flux mitigation
- Power, cost, CO₂, ...

Key technologies for timeline

- Magnet technology
- Muon cooling technology
- Detector

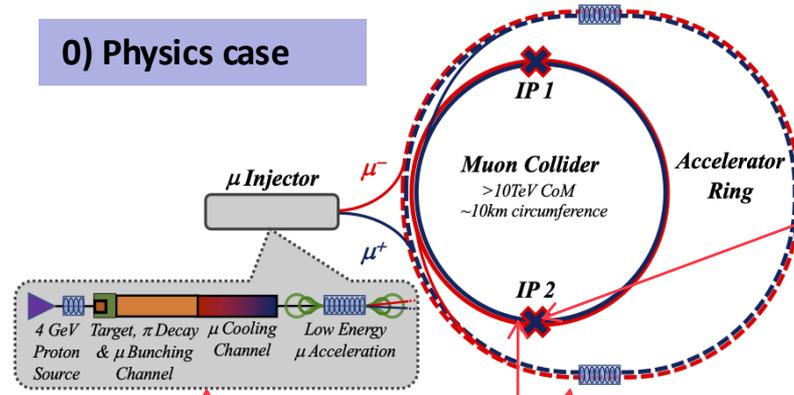
Other technologies are instrumental for performance, cost, power consumption and risk mitigation

- Accelerator physics, cryogenics, superconducting cavities, ...

Other important timeline considerations are

- Civil engineering
- Decision making

0) Physics case



2) Beam-induced background

4) Muon production and cooling drives the **beam quality**
MAP put much effort in design
optimise as much as possible

1) **Dense neutrino flux**
mitigated by mover system
and **site selection**

3) **Cost** and **power** consumption limit energy reach
e.g. 35 km accelerator for 10 TeV, 10 km collider ring
Also impacts **beam quality**

Environmental Impact

Limited study on CO₂ etc at this moment

Inherent muon collider benefits

- Compact size limits material use/CO₂ footprint
- Limited power consumption
- Limited land use, in particular if existing tunnels are reused

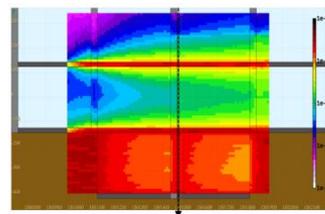
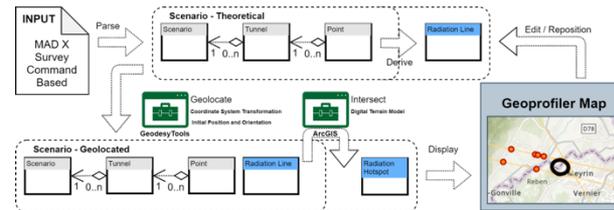
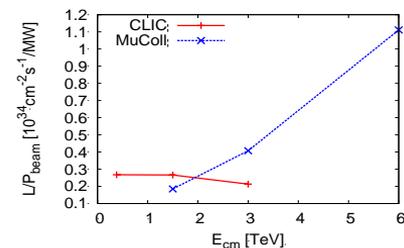
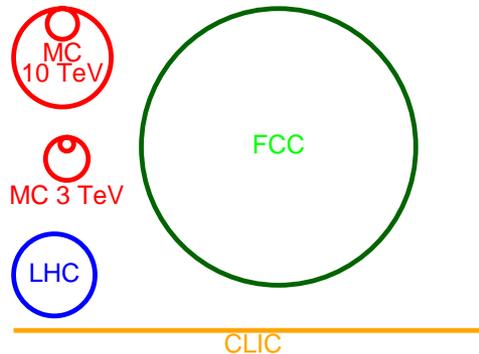
Aim at minimising neutrino flux

- Focus on collider ring for now
 - Need to expand later
- Working with **RP**
- Improved **geoprofiling tool** to place collider ring
- Mechanical system to avoid localized neutrino flux

First **promising site and orientation** identified

- Mitigates flux from experiments
- Arc flux likely negligible for 3 TeV
 - Approvable/negligible for 10 TeV

Further site optimization, detailed study, development of technical systems and beam study needed



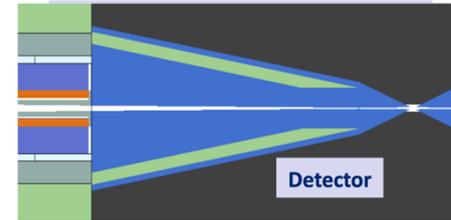
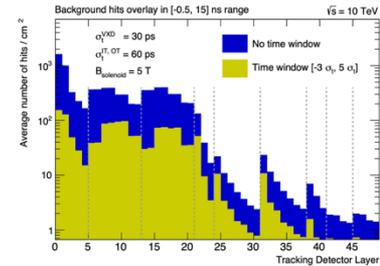
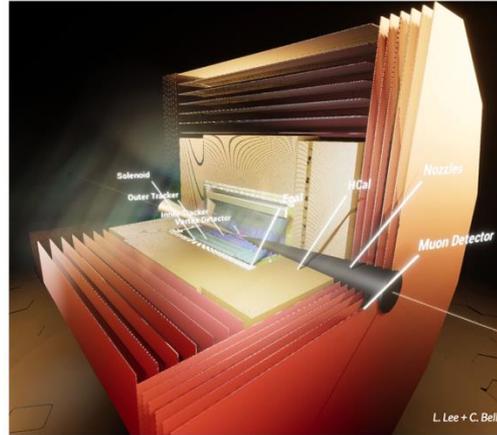
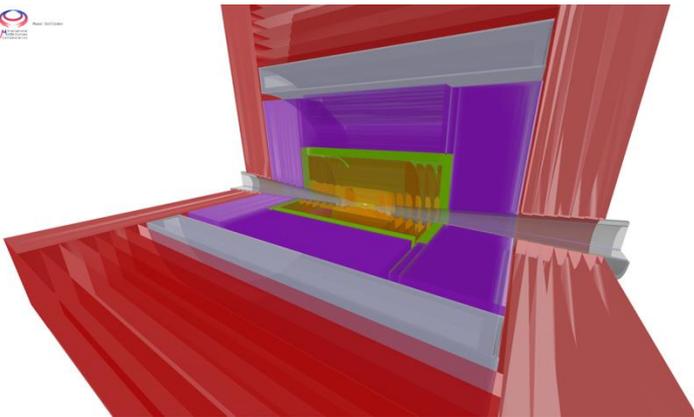
Physics and Detector Concepts

MUSIC

(MUon System for Interesting Collisions)

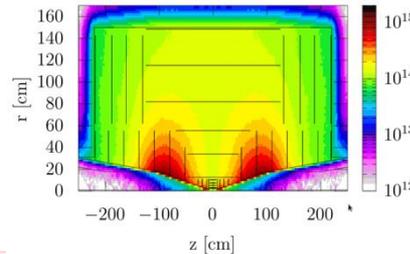
MAIA

(Muon Accelerator Instrumented Apparatus)



Two detector concepts are being developed

- Required resolutions
- MDI and background suppression
- ...



Can do the important physics with near-term technology also thanks to HL-LHC developments

Increasing effort to use available time for further improvements and exploiting **AI, ML** and **new technologies**

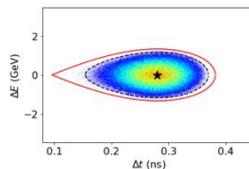
Closer **integration with ECFA detector R&D** highly welcome

Facility Design



Good progress in the different system designs

- Proton complex, muon production and cooling, acceleration and collider ring, collective effects, ...

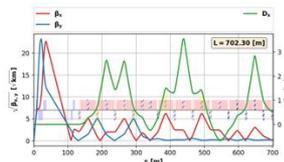


Preliminary design of cooling chain advanced

- 24 to 30 μm transverse emittance
- Goal 22.5 μm , MAP achieved 55 μm

Collider ring lattice design

- Achieve beta-function
- Need to improve energy acceptance (2-3 x)



Preliminary muon transmission estimate

- 1.5×10^{12} muons at IP (goal 1.8×10^{12})
 - Cooling transmission below target
 - High-energy complex is above (would like to reduce for cost)
- Need resources to improve system design
Will study higher power target (graphite or liquid metal)

Subsystem	Energy	Length	Achieved	Achieved	Target
	GeV	m	Transm. %	μ^-/bunch 10^{12}	μ^-/bunch 10^{12}
Proton Driver	5 (p^+)	1500	–	500 (p^+)	
Front End	0.17	150	9	45.0	
Charge Sep.	0.17	12	95	42.8	
Rectilinear A	0.14	363	50	21.4	
Bunch Merge	0.12	134	78	16.7	
Rectilinear B	0.14	424	32	5.3	
Final Cooling	0.005	100	60	3.2	
Pre-Acc.	0.25	140	86	2.8	4.0
Low-Energy Acc.	5	–	90*	2.5	
RLA2	62.5	$\circ 2430$	90	2.3	
RCS1	314	$\circ 5990$	90	2.1	
RCS2	750	$\circ 5990$	90	1.9	
RCS3	1500	$\circ 10700$	90	1.7	
3 TeV Collider	1500	$\circ 4500$	–	1.7	2.2
RCS4	5000	$\circ 35000$	90	1.5	
10 TeV Collider	5000	$\circ 10000$	–	1.5	1.8

Time to **increase design effort** to cover and integrate all systems (“**start-to-end simulation**”), improve codes, performances and consider alternatives

Magnets

Systematic **dipole performance prediction** for LTS and HTS

- Aperture, field, cost, stress, loadline, protection, ...

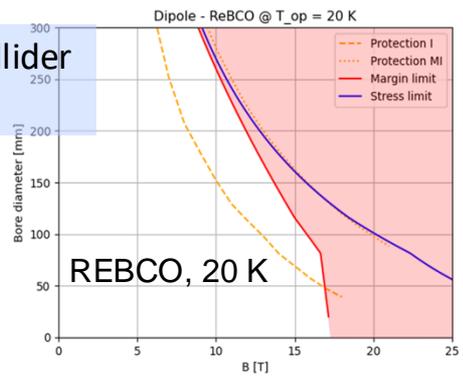
HTS solenoid designs (6D cooling, final cooling, target)

Normal-conducting **fast-pulsed dipoles** (HTS as alternative)

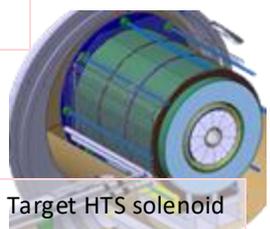
Technical timeline



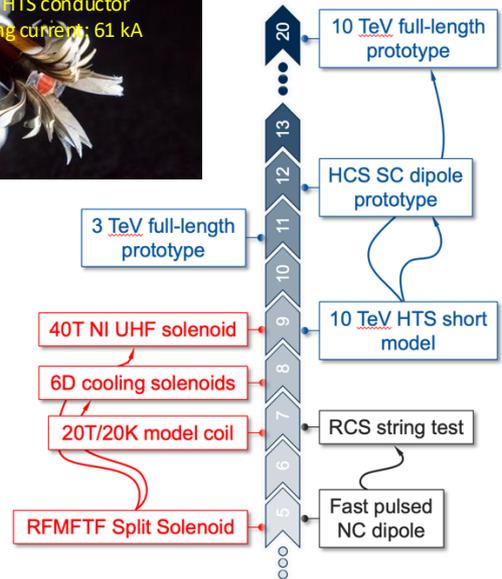
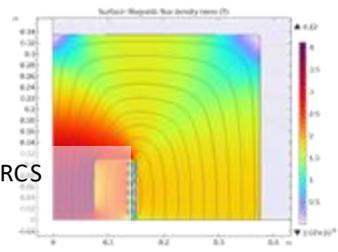
Will slightly adjust collider ring field for cost



HTS final cooling solenoid mechanical design



Normal-conducting RCS pulsed magnets



First HTS winding tests

Opportunity to **ramp up** effort

- Engineering designs
- Tests of cables, building models, ...

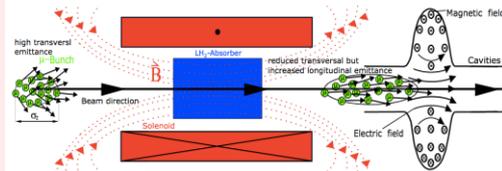
With sufficient resources **HTS solenoids** and **Nb₃Sn dipoles** could be **ready for decision in 10-15 years**

HTS dipoles likely take longer

Muon Production and Cooling

Muon cooling technology and demonstrator

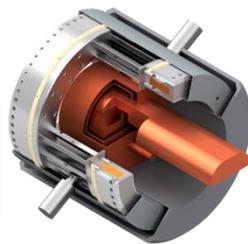
- Most integrated technology
- Operational demonstrator in O(10 years), with enough resources
- Allows to perform final optimization of cooling technology



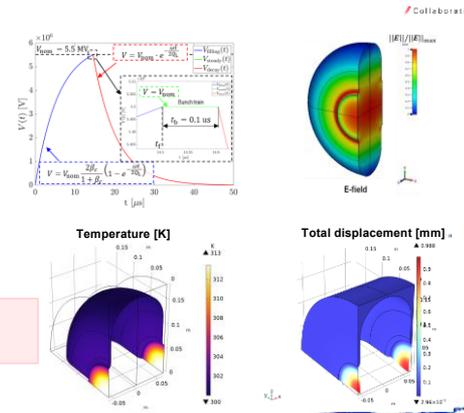
Very bright muon beam challenges **absorbers** and **windows**

- First tests of absorber windows performed
- Strong theoretical and experimental programme required

Engineering **module design** started
Including solenoid



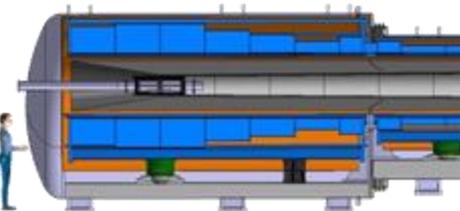
RF design ongoing



2 MW graphite target looks very promising

- Some work on windows remains
- Will study alternative higher power (4 MW) target
- Graphite, liquid metal, fluidized tungsten

Ready to **widen effort**, in particular beamdynamics, prototyping and experimental work



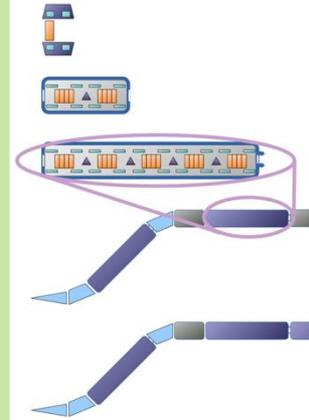
Demonstrator



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Ultimate 6D cooling technology integration

- Components: Magnets, RF systems, absorbers, vacuum, instrumentation, cryogenics, ...
- Integration, operation, performance with beam
- Gradual upgrades as cell design evolves, confidence grows
- Will be important part of commissioning preparation after the decision to build the muon collider



Staged implementation

- Components
- RF test stand (high magnetic field)
- Module test with power
- Module test with beam
- Improved module string



Detailed studies of site at CERN ongoing, considering TT7 tunnel
US plan to start detailed study at FNAL

Effort **ramp-up** in several stages

Modular plan will allow quickly moving forward

- adjust to developments in Europe and the US

Other R&D Programme

R&D on other technologies also needed

Power converter, high-field superconducting cavities, efficient RF power sources, cryogenics (e.g. **liquid hydrogen**), instrumentation, ...

Most important is training of **young people**

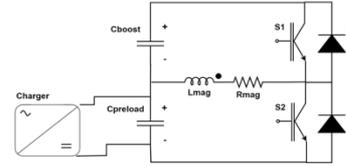
- Most important resource
- Strong interest by early career experts
 - e.g. <https://indico.cern.ch/event/1422393/>
- Motivating challenges

Exploit synergies with other fields (technology and physics)

- Strong **synergy** with **LDG HFM** and **RF**
- **HTS solenoids** have important potential
 - Fusion
 - Power generators for windmills and motors
 - Life sciences
 - Important step toward FCC-hh HTS dipoles
 - ...

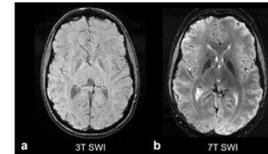
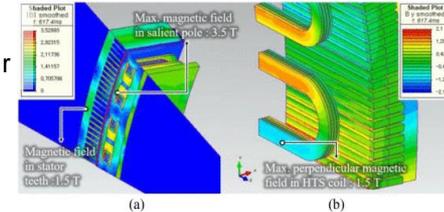
Detector technology development

- AI, ML, ...



RCS power converter
Synergy with MMC
For high-power transfer
e.g. off-shore windmills

Design of 10 MW HTS wind generator



Opportunities to profit from synergies

Attract young generation

R&D programme can be distributed world-wide

Staging

Expect to be ready for implementation in 15 years

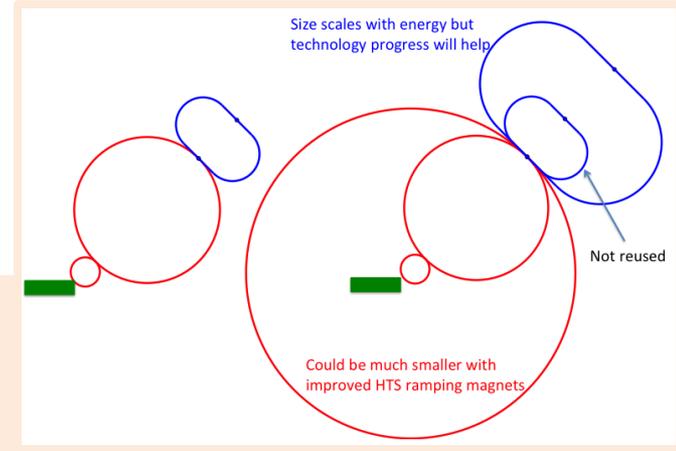
- **Detector**
- **Muon cooling technology**
- **HTS solenoid technology**
- **Nb₃Sn dipoles (11T)** for collider ring
- High-field HTS dipoles for second stage are likely later

Energy staging

- 3 TeV design takes lower dipole performance into account
 - HL-LHC type performances
- Cost split over two stages, little increase in integrated cost

Luminosity staging

- Longer collider ring arcs and less performant interaction region lead to less luminosity in first stage
- Can later upgrade interaction region (as in HL-LHC), remain at 2/3 of luminosity because of arcs
- Full cost at first stage



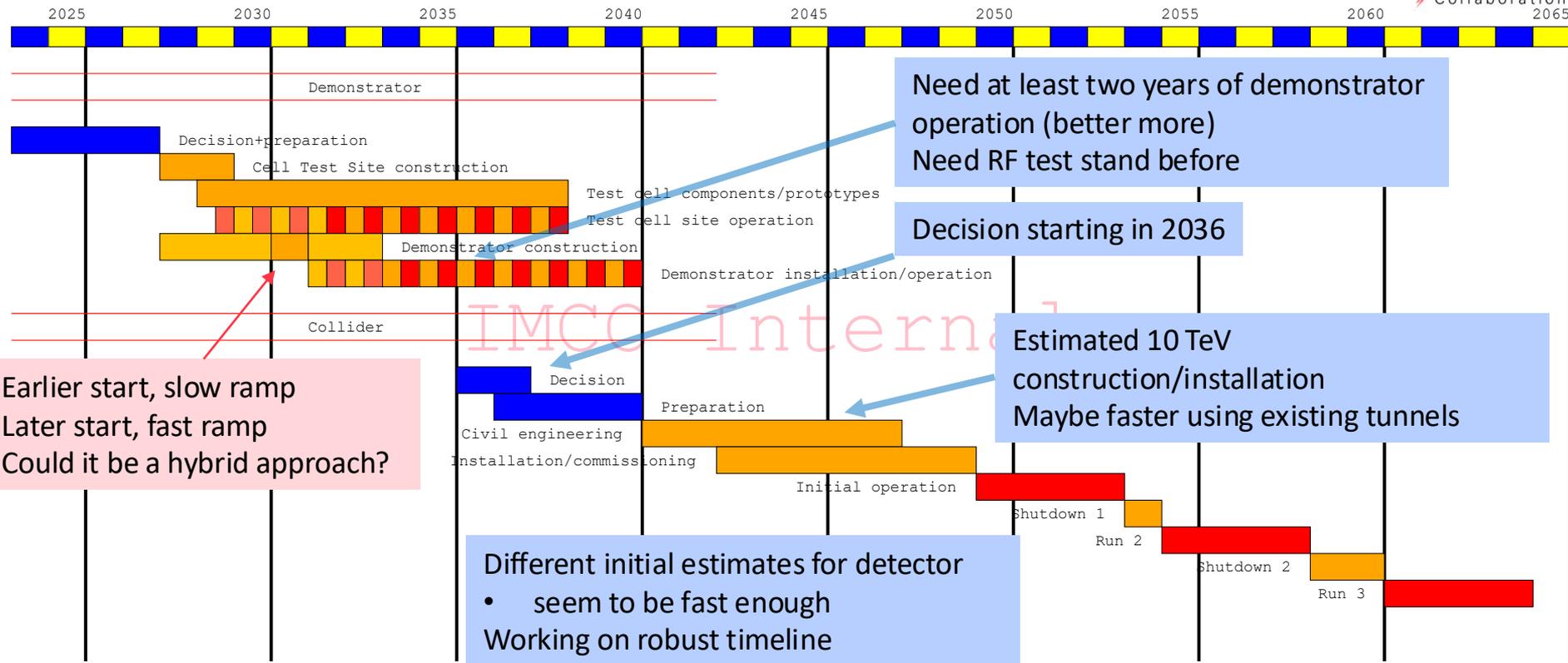
Parameter	Unit	3 TeV	10 TeV	10 TeV	10 TeV
L	$10^{34} \text{ cm}^{-2}\text{s}^{-1}$	1.8	20	tbd	13
N	10^{12}	2.2	1.8	1.8	1.8
f_r	Hz	5	5	5	5
P_{beam}	MW	5.3	14.4	14.4	14.4
C	km	4.5	10	15	15
	T	7	10.5	7	7

Potential Timeline (Fast-track 10 TeV)



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Only a basis to start the discussion, being reviewed



Earlier start, slow ramp
Later start, fast ramp
Could it be a hybrid approach?

Need at least two years of demonstrator operation (better more)
Need RF test stand before

Decision starting in 2036

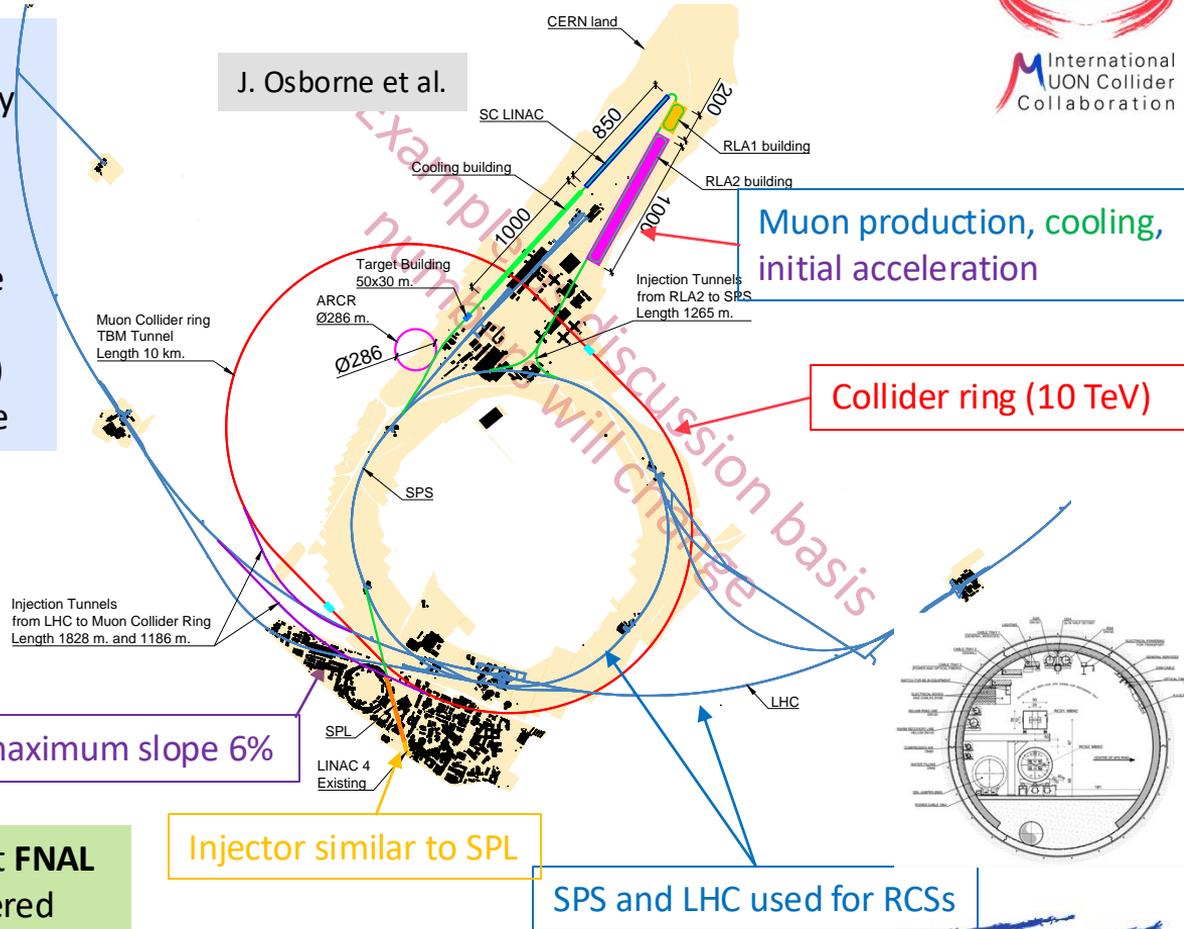
Estimated 10 TeV construction/installation
Maybe faster using existing tunnels

Different initial estimates for detector
• seem to be fast enough
Working on robust timeline

Exploratory Site Studies

At CERN, first look is promising:

- First collider ring site identified that largely **mitigates neutrino flux from experiments**
 - Some more work required
- SPS and LHC tunnels reused
- All construction on CERN land (maybe one experiment not)
- Energy stages maybe 2.5-3 and 8 TeV (tbc)
- More studies will be required in the future



Maturity, Cost, Power, Land Use



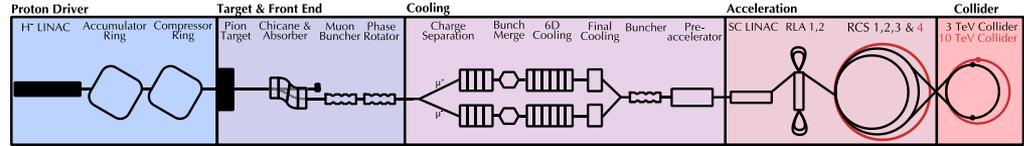
Maturity

The moment to commit depends on many factors

- Important for society
- Willingness to take risk
- ...

Feel that we need a decade more R&D

- Further and optimize overall design
- Address challenges



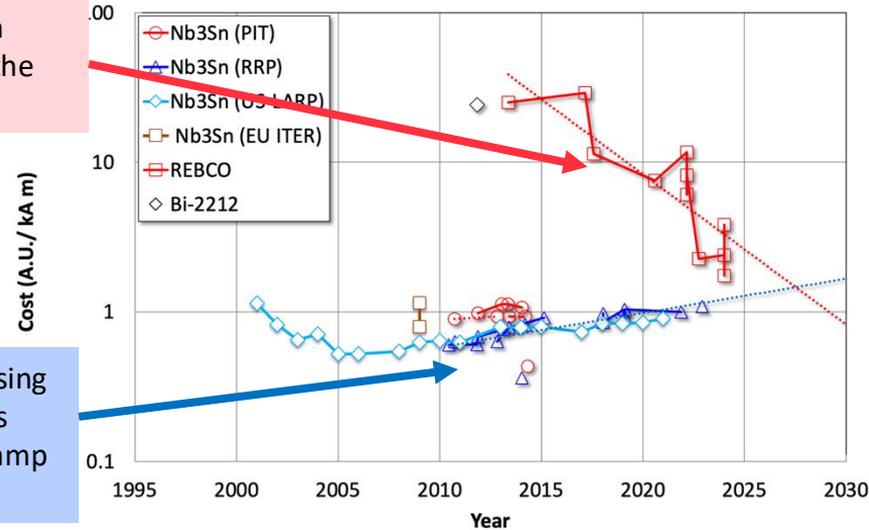
Cost and Power

Are collecting cost and power information (Carlo Rossi is also leading the CLIC costing), at this moment

- Remaining uncertainties exist
- Important magnet cost uncertainty
- Are asked to adjust to FCC-hh costing methodology

Land Use looks promising

HTS cost is coming down
How much depends on the overall use of HTS



Nb3Sn cost slowly increasing
We may be the only users
Industry would have to ramp up just for us

German Considerations



Muon collider is high-energy **Particle Physics** option

- Important option as **next flagship after HL-LHC** in Europe, if higgs factory were not in Europe
- Important **option for the US** as high-energy frontier particle physics project
- Important option as **flagship after a higgs factory** in Europe, no matter what the geometry
- There can be facilities on the way
 - Proton linac, neutrino facilities, ...

Muon collider provides **exciting R&D opportunities**, can exploit synergies and German strengths:

- Physics and detector expertise (DESY)
 - Technologies, AI, ML
- RF expertise (Rostock)
- Particle-matter interaction
- Magnet expertise (Darmstadt, KIT)
- Exciting accelerator physics
- Environmental impact

Obviously, current involvement level should be increased

Very motivating for the **young generation**, can bring new people to the field

- Strong synergy with **societal applications**
 - E.g. very active magnet R&D (wind generators, fusion, ...)
 - Links to liquid hydrogen, power converter, ...

Conclusion



The status

Interest in Muon collider is rising and collaboration is growing

- EU co-funding, contributions from increasing number of partners
- Very strong interest in the US

Made important progress addressing identified challenges but still on our way

- Identified some additional challenges
- Moved much closer to our target

First exploration of CERN site motivates more detailed studies

- FNAL is also exploring their site

The future

Timeline with focus on fast scenario with physics starting around 2050

Will provide an R&D plan to ESPPU

- Identifying priorities for the next five and ten years

Excellent opportunity for Europe to maintain muon collider as option

- Magnets, cooling technology, detector, accelerator physics, ...
- Profit from synergies and contribute to society
- Engage young generation

Many thanks to the collaboration for all the work
To join contact muon.collider.secretariat@cern.ch

Reserve



Muon Collider Physics Case

A. Wulzer

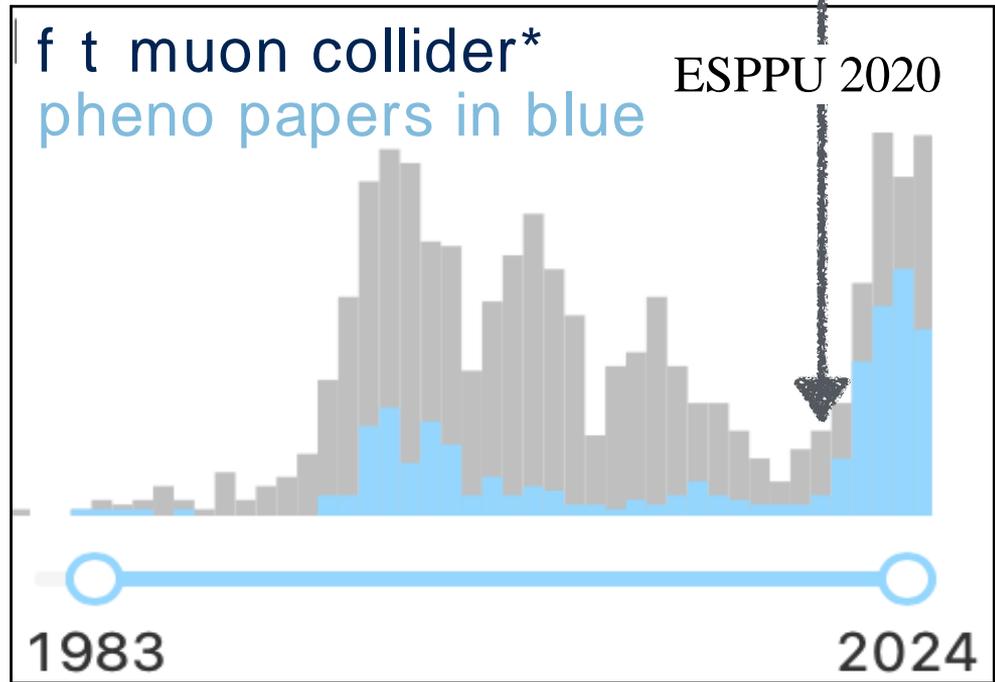


A Physics-Driven Collider



Past:
limited ph response to ACC advances

Present: hep-ph is dominant
component of MuC papers



Why this enthusiasm?

1. **Higgs-Electroweak** interplay at very high energy (AKA, the SM) is new frontier, as well as the origin or the solution to SM/BSM mysteries.
→ Need **high-energy leptonic** collisions
2. **Physicists need** the truly **novel** challenges/opportunities offered by a radically new type of particle collider

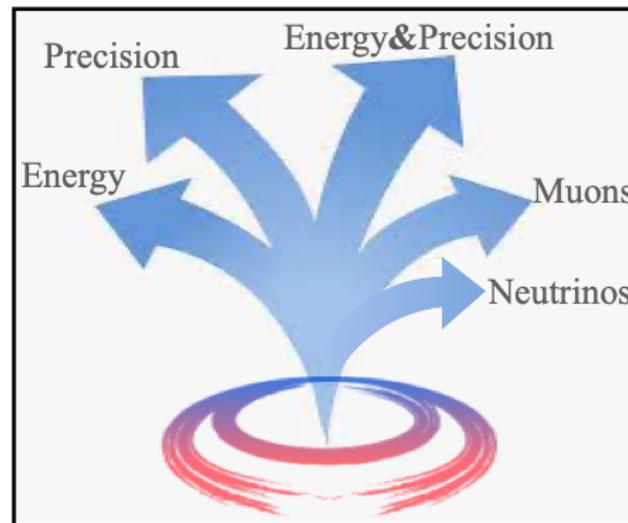
Physics case in short:

– *discover new particles with presently inaccessible mass, including WIMP dark matter candidate*

– *discover cracks in the SM by the precise study of the Higgs boson, including the precise direct measurement of triple Higgs coupling.*

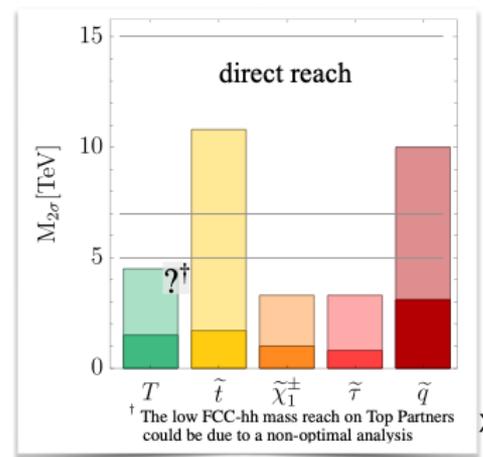
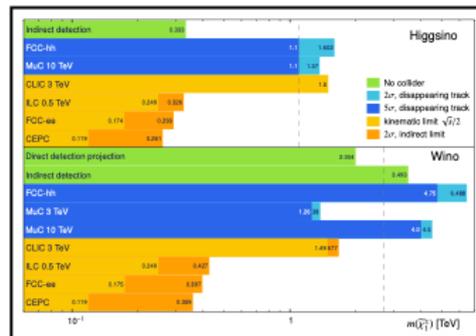
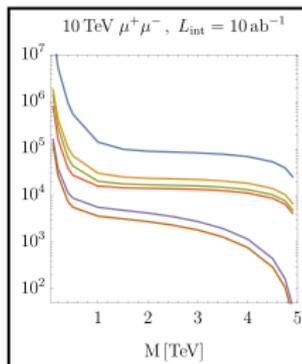
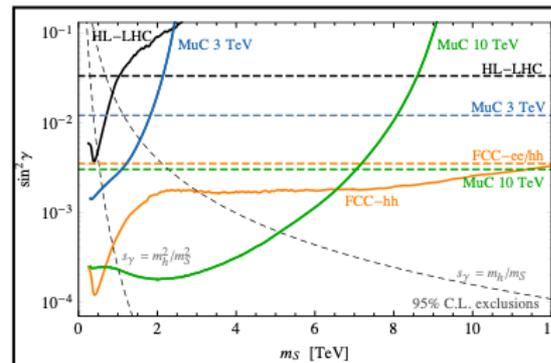
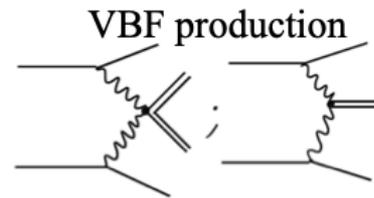
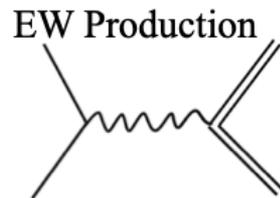
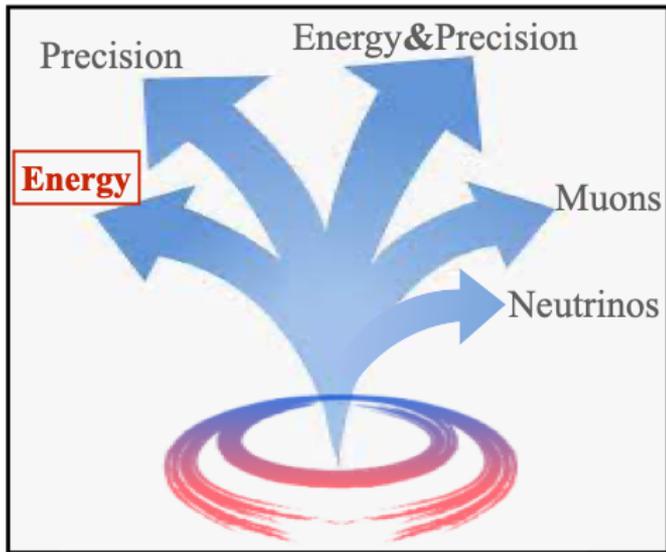
– *uniquely pursue the quantum imprint of new phenomena in novel observables by combining precision with energy.*

– *unique access to new physics coupled to muons and delivers beams of neutrinos with unprecedented properties from muons decay.*

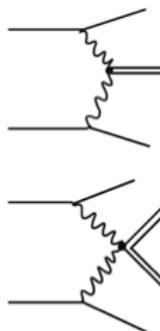
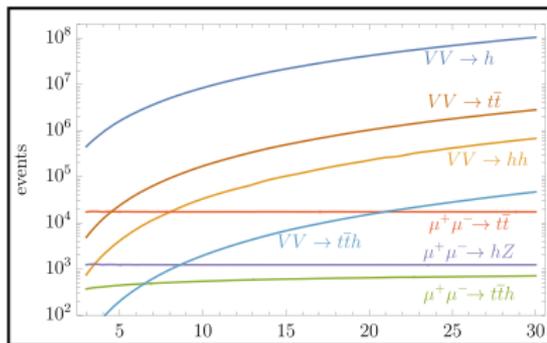
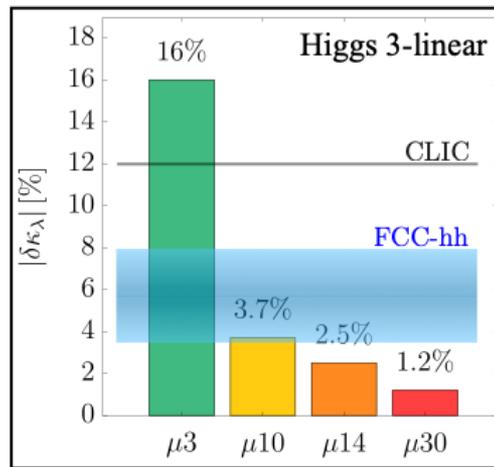
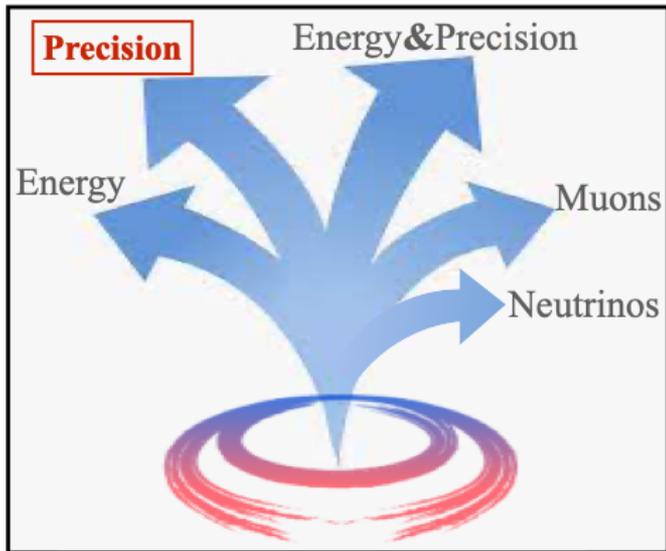


Even shorter

– *unique probe of EW+Higgs in novel high-energy regime.*



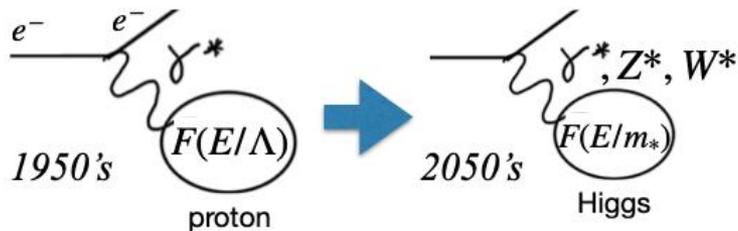
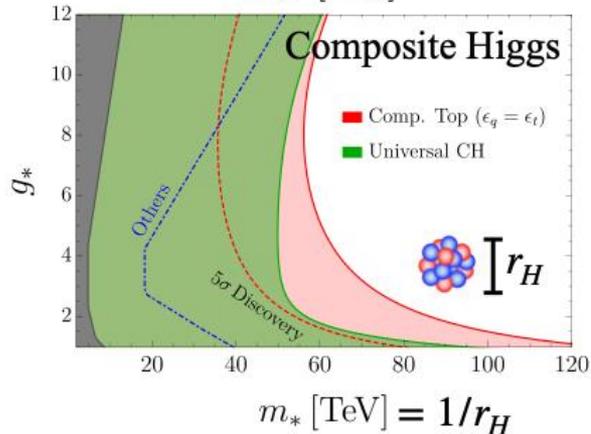
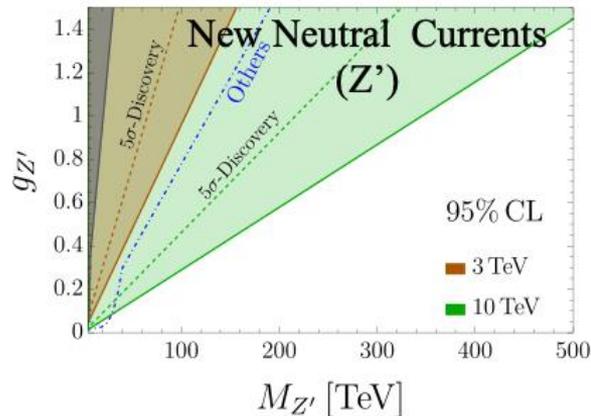
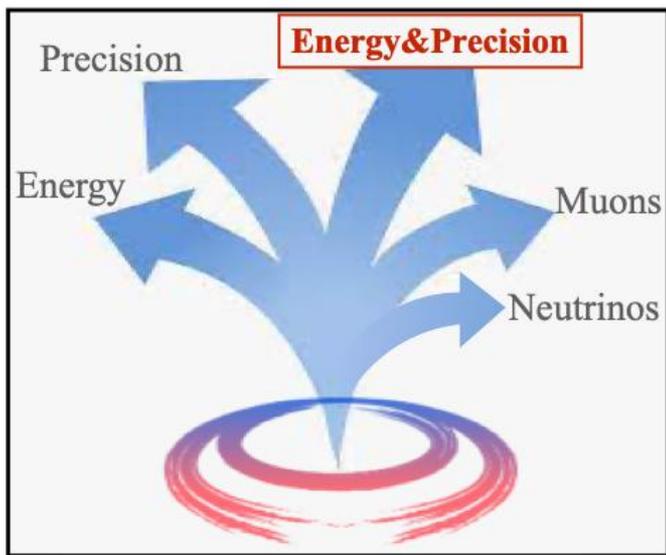
Discover new heavy particles ... such as long-sought WIMP dark matter candidates



κ [%]	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

10 M Higgs bosons produced

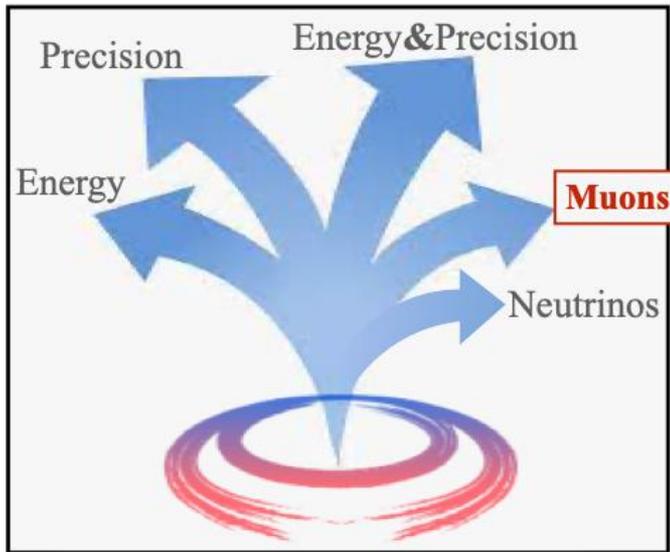
Permille-level precision
 on Higgs couplings



Higher-energy observables are more sensitive to heavy physics:

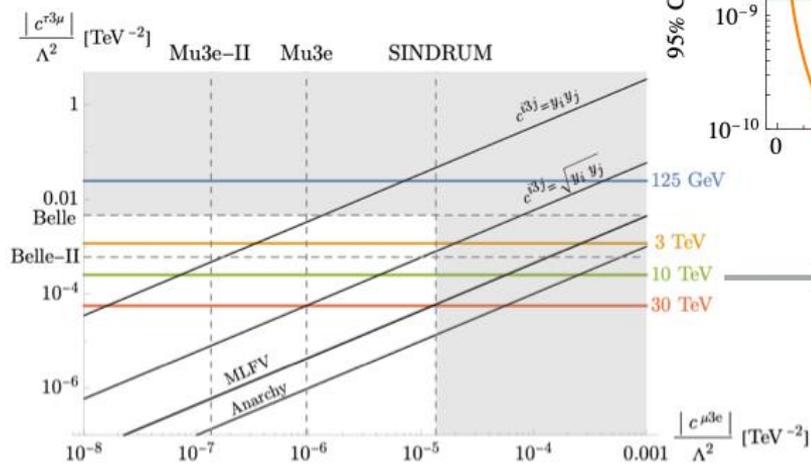
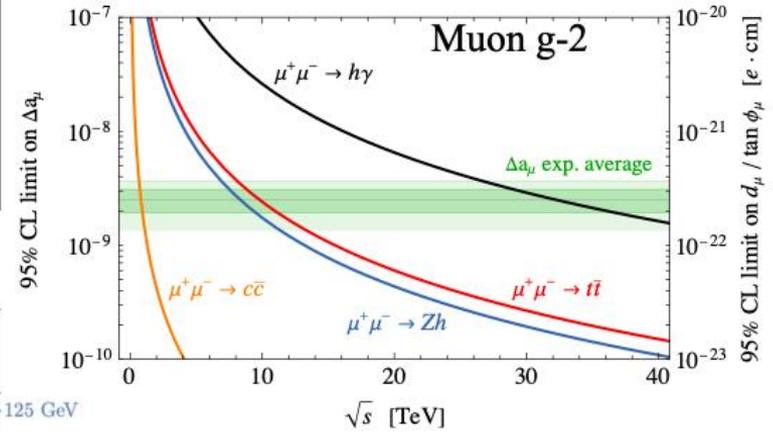
$$\frac{\Delta\sigma(E)}{\sigma_{\text{SM}}(E)} \propto \frac{E^2}{\Lambda_{\text{BSM}}^2} \quad [\text{say, } \Lambda_{\text{BSM}} = 100 \text{ TeV}]$$

$\rightarrow 10^{-6}$ at EW [FCC-ee] energies
 $\rightarrow 10^{-2}$ at muon collider energies

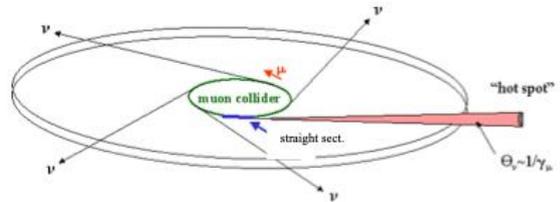
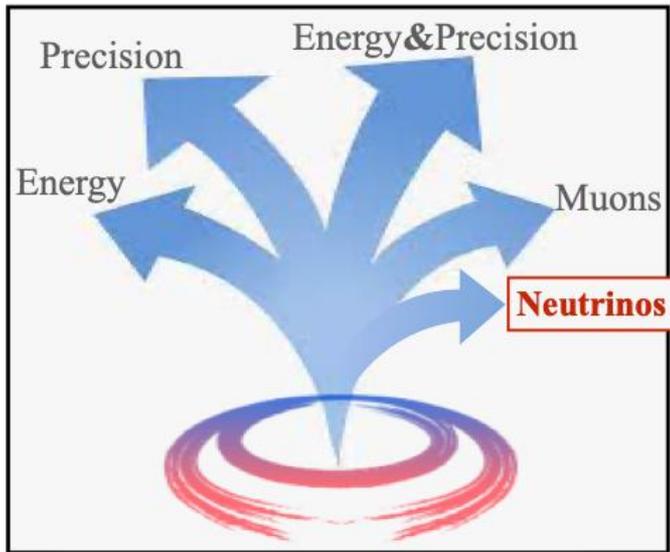


NP might couple primarily to muons because:

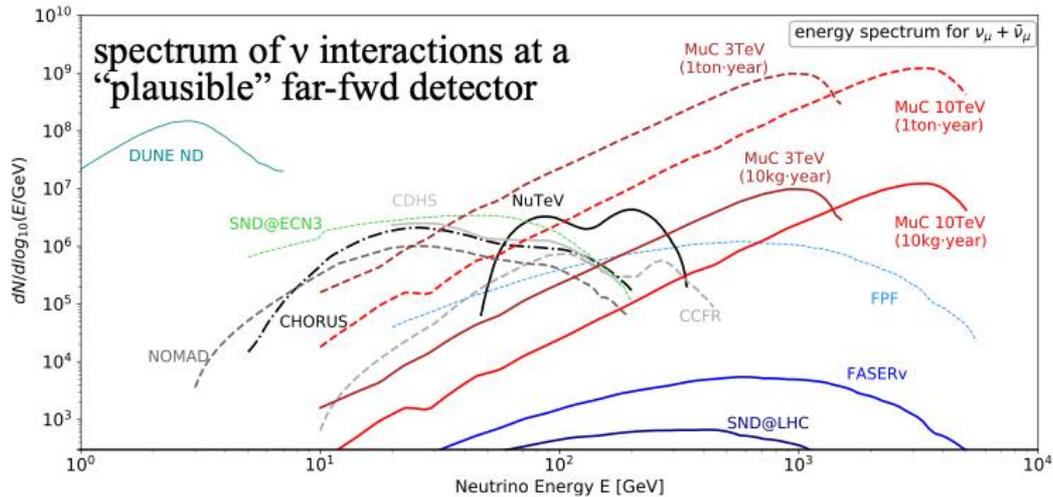
1. The Higgs does (so maybe NP in EWSB as well)
2. Possible connection with flavour
3. And because we haven't checked!



Complementarity with low-energy Lepton Flavour Violation probes



Muons decay to neutrinos:
 Collimated, perfectly known, TeV-
 energy neutrino beams
 First flux estimate with IMCC MuC
 beam appears in Interim Report
 Still unexplored physics opportunities



Muon Collider Experiment Status

D. Lucchesi, F. Meloni



Reminder of target parameters

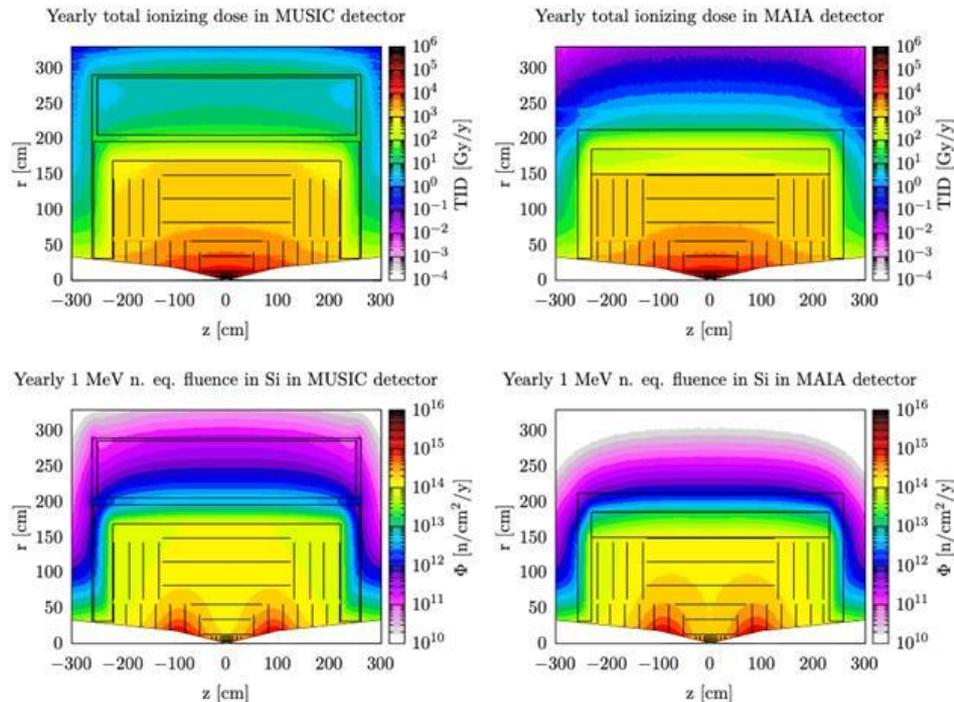
From interim report

Requirement	Baseline		Aspirational
	$\sqrt{s} = 3 \text{ TeV}$	$\sqrt{s} = 10 \text{ TeV}$	
Angular acceptance ($\eta = -\log(\tan(\theta/2))$)	$ \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

Status: radiation environment

BIB sets the requirements for radiation hardness of detector technologies.

- Expected in line with HL-LHC



Status: tracking 1/2

BIB and incoherent pairs affect reconstruction performance via hit multiplicity.

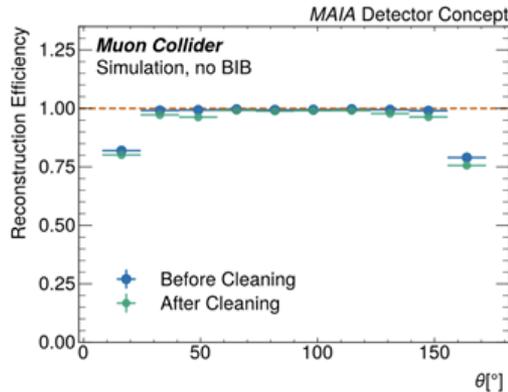
Tracking performance well under control (using LHC CKF reconstruction)

The main bottleneck in algorithmic execution time

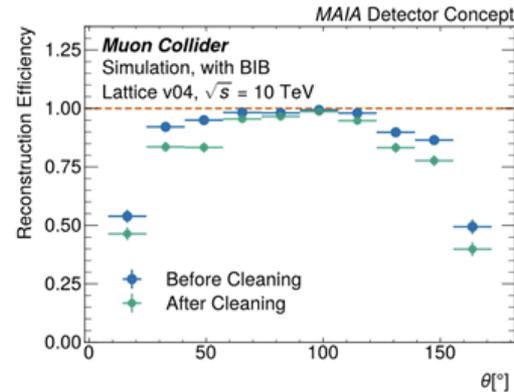
- The O(5%) inefficiencies present in the current reconstruction are caused by the need of keeping the CPU time within O(minutes) per event.

Track parameter resolutions (pT, d0, z0) are unaffected by BIB.

- Expected to improve with future computing hardware and seeding strategies

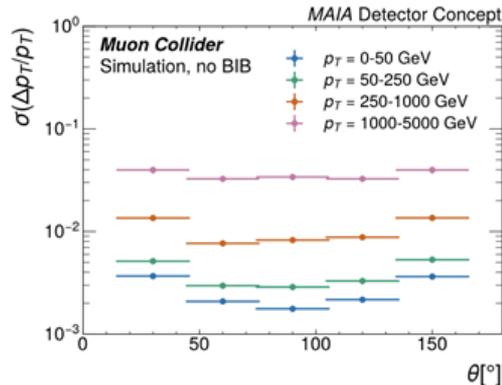


(a) No BIB

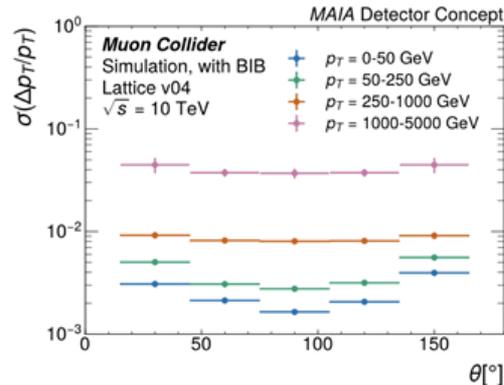


(b) BIB

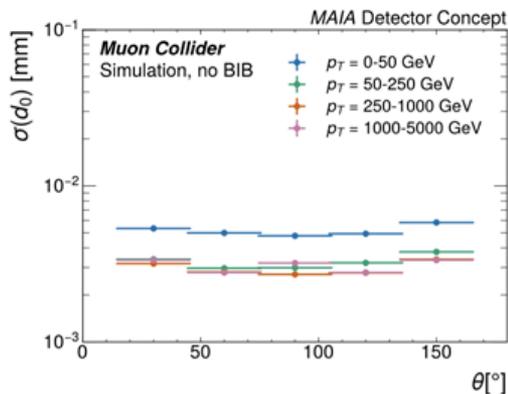
Status: tracking 2/2



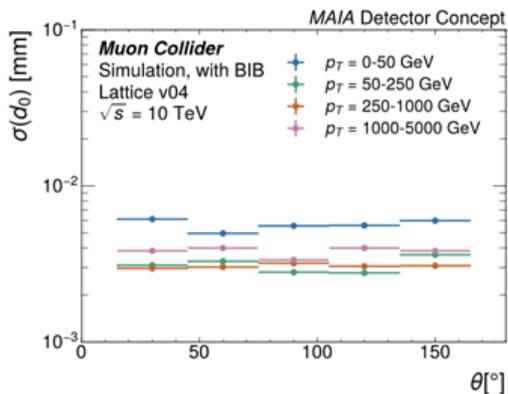
(a) No BIB



(b) BIB



(a) No BIB



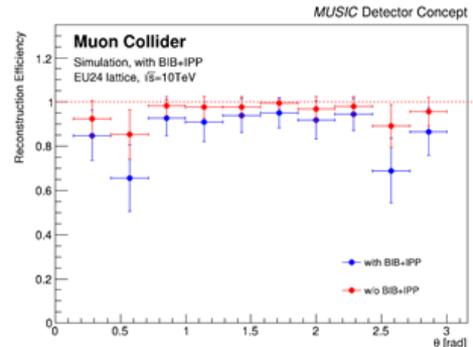
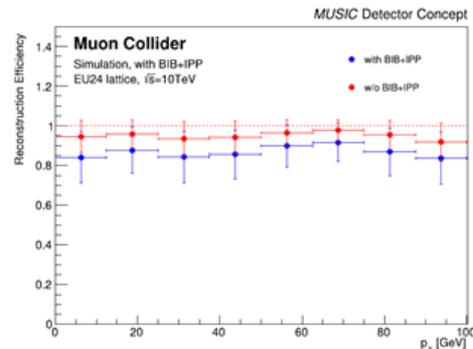
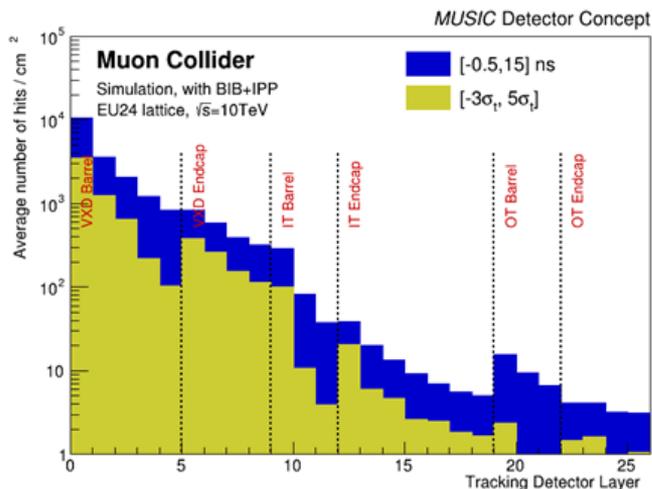
(b) BIB

Status: MUSIC tracking efficiency

Tracking system optimized for a better coverage up to the nozzle angle.

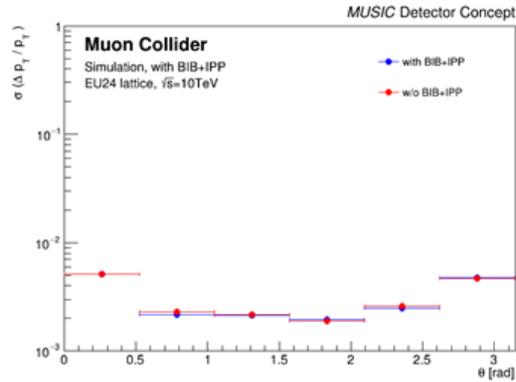
Performance evaluated with **BIB** and **incoherent pair production (IPP)** events produced with Interaction Region version EU24 frozen for ESPPU.

Despite the high occupancy, track reconstruction optimized (not fully) to reach high performance.



Status: MUSIC tracking performance

The resolution on track parameters are not impacted by the BIB presence.

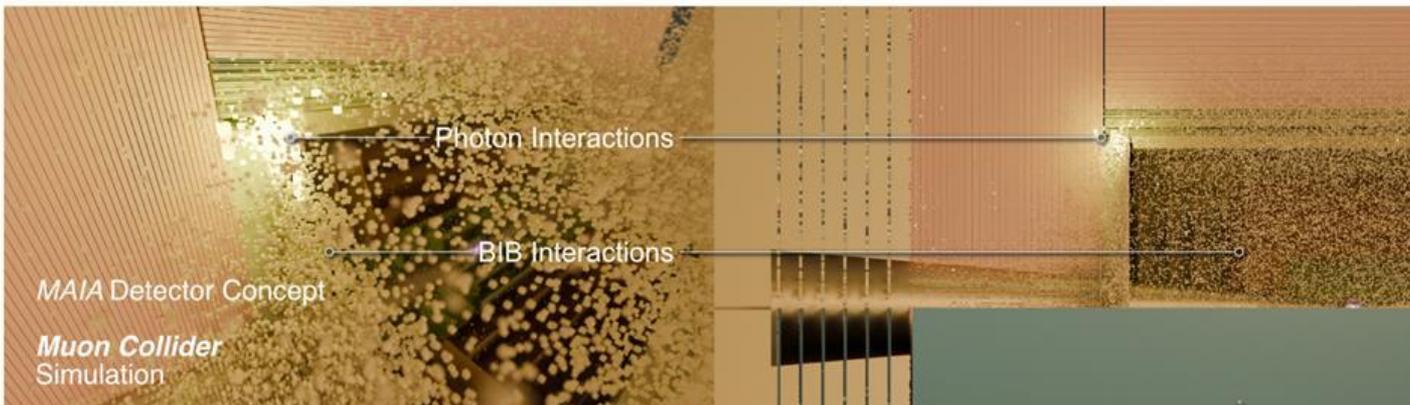
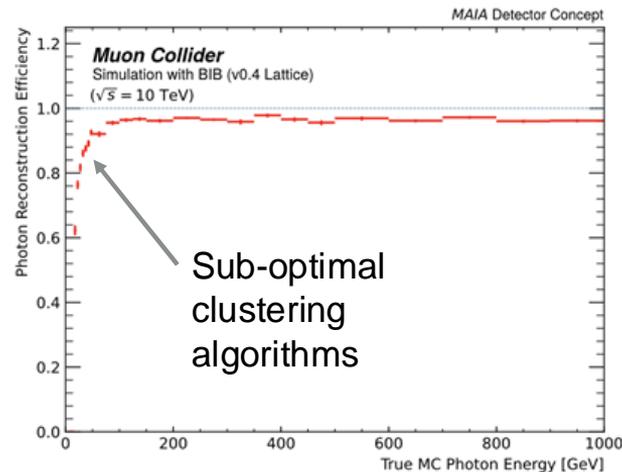


Status: Calorimetry 1/3

BIB impact on calorimetry more different across 10 TeV detector concepts

- Solenoid placement
- Technological choices - semi-homogeneous (MUSIS) vs sampling (MAIA)

Performance close to minimal targets, limited by reconstruction algorithms (most notably clustering and background subtraction)



Status: Calorimetry 2/3

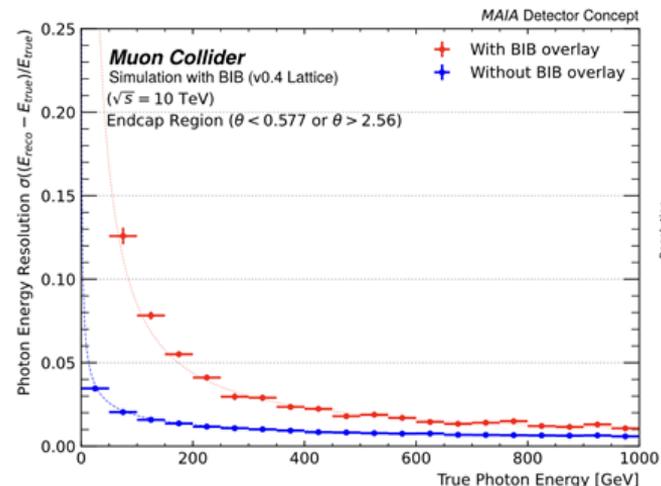
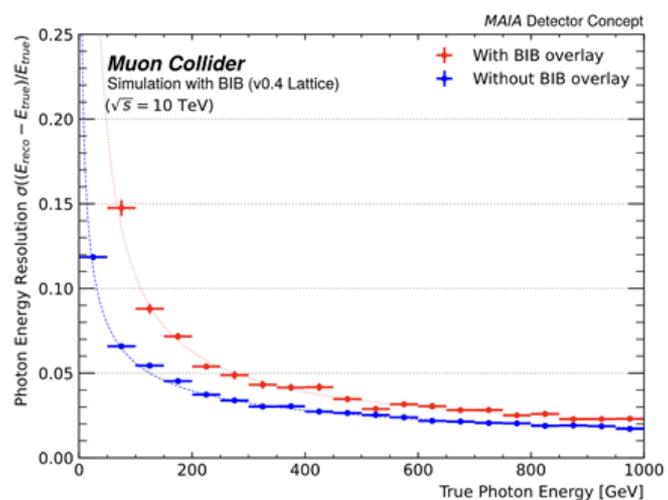
Lack of BIB subtraction (a-la-PUPPI) affect energy resolution.

- Cell thresholds raised to counterbalance BIB effects, de facto decreasing the sampling fraction

Achieved performance close to baseline goals

- Expect to improve once advanced algorithms are implemented

Fit Params	Stochastic	Noise	Constant
No BIB	0.184	0.0	0.0
BIB	0.213	8.219	0.0

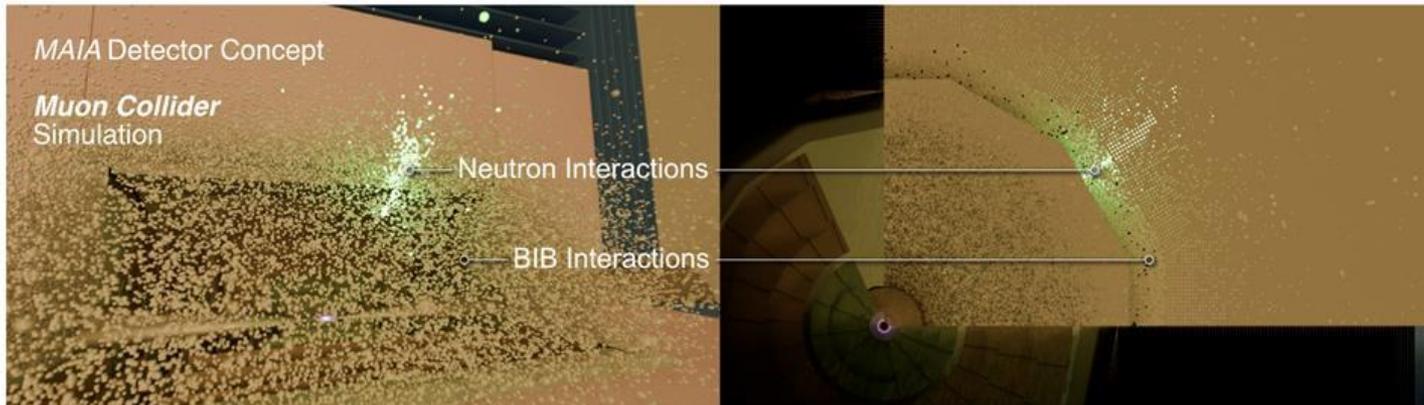
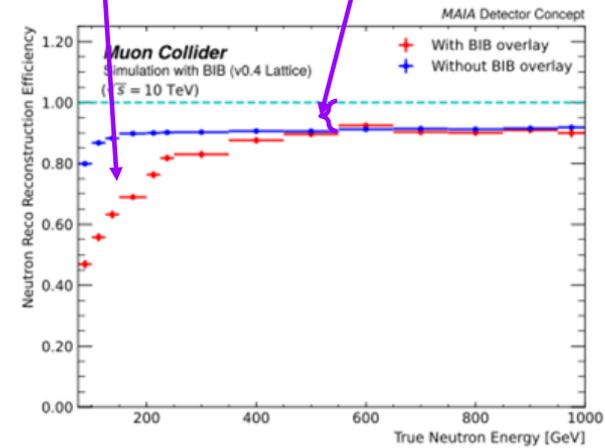


Status: Calorimetry 3/3

Neutral PFO reconstruction affected by same algorithmic limitations

- Forward region particularly challenging

Sub-optimal clustering
Acceptance at large theta

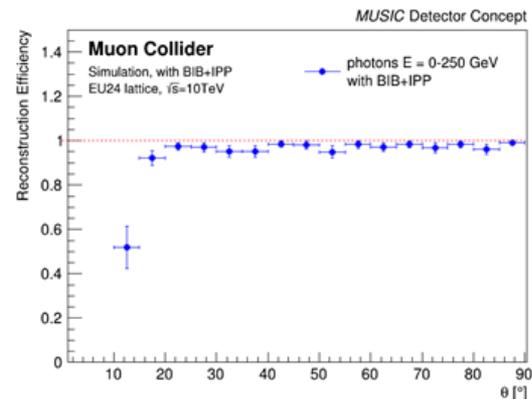
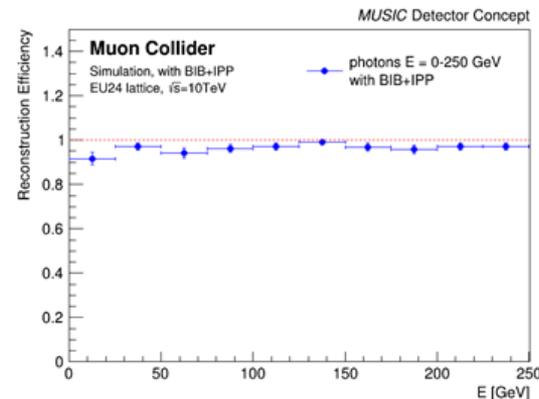
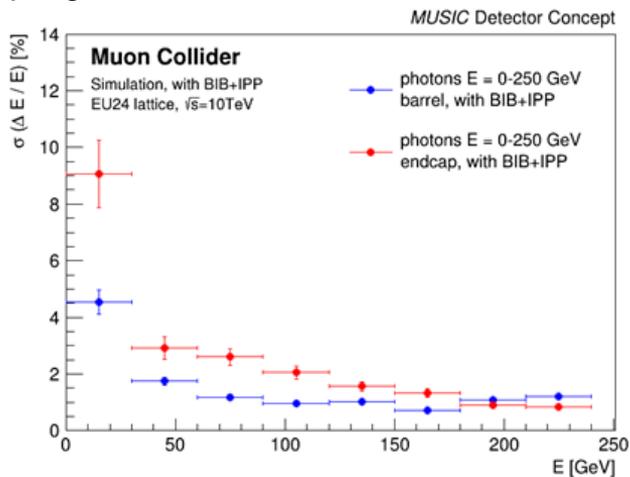


Status: MUSIC Calorimeter

MUSIC calorimeter system:

- ECAL: CRILIN, *CRystal calorimeter with Longitudinal INformation* designed for MuC
- HCAL: Iron-scintillator sampling calorimeter common to other detectors

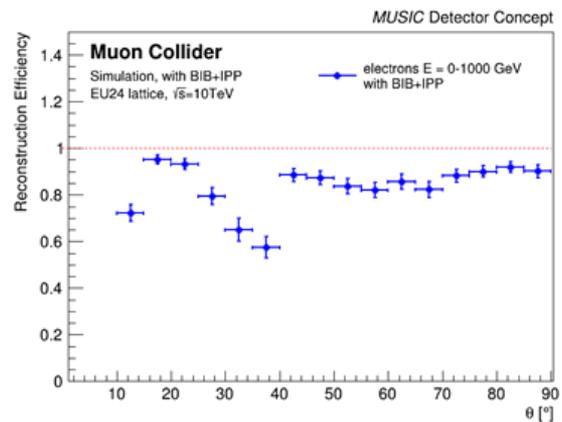
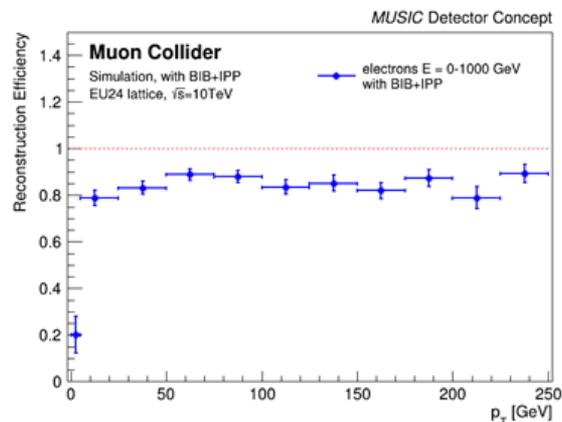
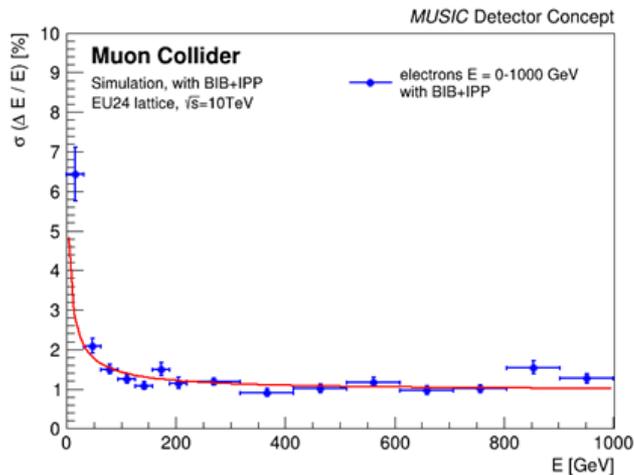
So far reconstructed: photons and electrons, jets in progress.



Status: MUSIC Calorimeter

The electron are reconstructed for the first time in muon collisions at 10 TeV CoM

Tracks reconstructed with ACTS are matched to a ECAL cluster by using PandoraPFA. The results show that even if not optimized (there is no Bremsstrahlung recovery yet) the MUSIC detector performs very well also for electrons



Status: muons and forward

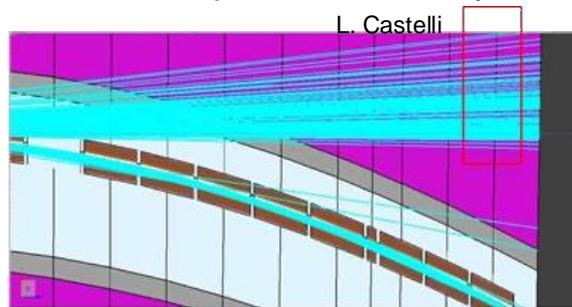
Muon systems are almost free from BIB contributions

- Performance at 10 TeV not yet studied in detail, as it is not expected to be a challenging task

Both concepts don't foresee a dedicated muon spectrometer but rather rely on inner detector tracks with a PID match from a barebones muon system placed beyond the HCAL

- Choice motivated by track resolution being dominated by inner tracker measurement across p_T spectrum

Forward (~ 10 deg) and very forward (5 deg) regions require dedicated studies and development of detector concepts for which only initial studies have been performed.



Plans

Ongoing work to update to latest collider lattice for ESPPU.

- ⑩ BIB expected to have a harder energy spectrum, but final performance comparable (at the cost of a larger stress on computing resources)

Over the next several years, migrate reconstruction algorithms to fully exploit LHC know-how.

For example:

- ⑩ CMS HGCal clustering (CLUE)
- ⑩ Local pile-up subtraction -> BIB subtraction
- ⑩ Multivariate/AI approaches to flavour tagging (for which we demonstrated only basic inputs)