FONDAZIONE BRUNO KESSLER
ECT*
EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS
LFC22: Strong interactions from QCD to new strong dynamics at LHC and Future Colliders

August 29, 2022

Muon Collider: status and perspectives

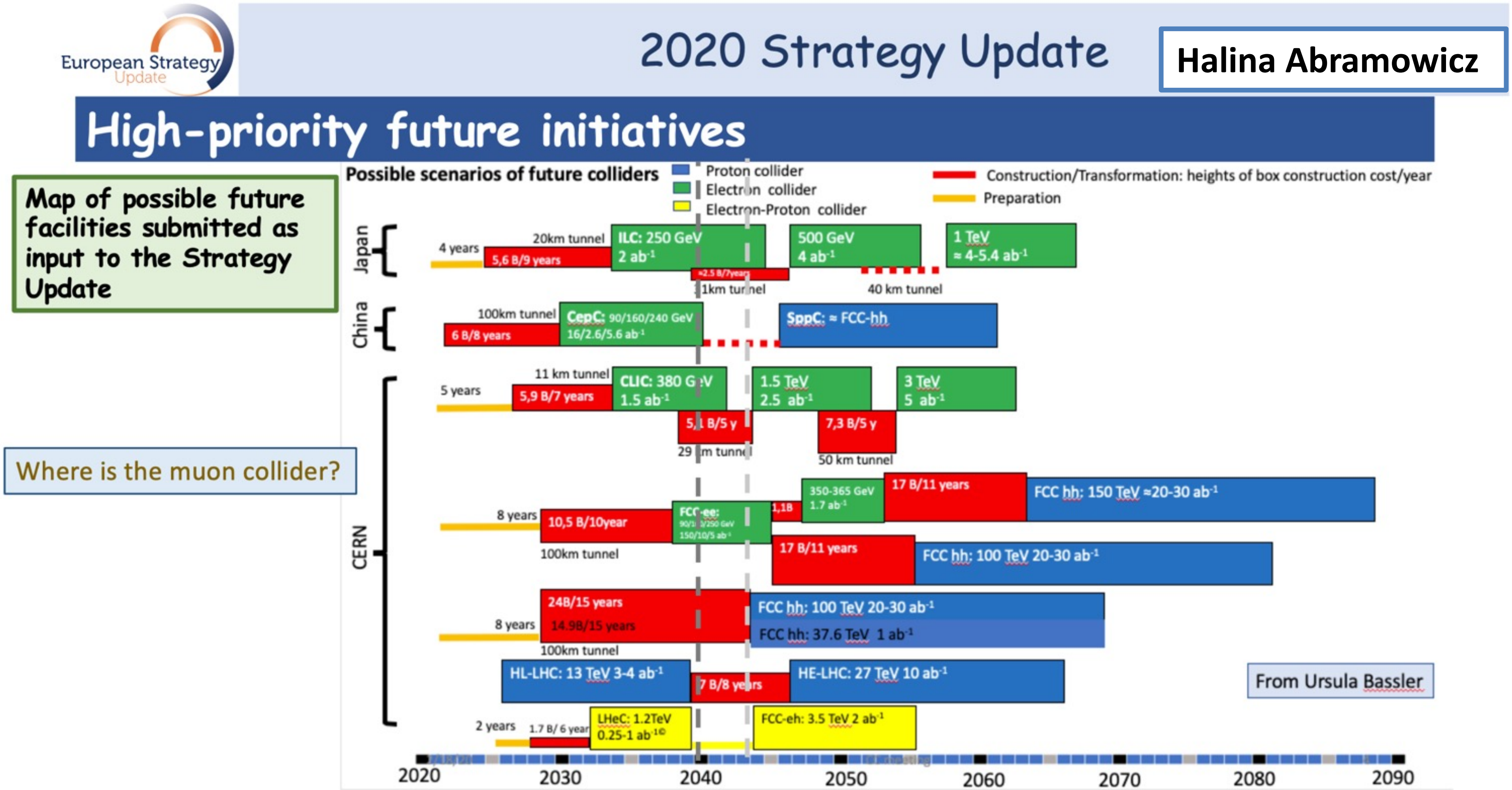
Nadia Pastrone
INFN TORINO

Thanks to many colleagues in Italy, EU, USA

International MUON Collider Collaboration

Acknoledgement to the European
Horizon 2020 Research and Innovation programme
under Grant Agreement No 101004730
iFAST

Input to EU Strategy of Particle Physics



Input Document to EU Strategy Update - Dec 2018:

"Muon Colliders," [arXiv:1901.06150](https://arxiv.org/abs/1901.06150)

by *CERN-WG on Muon Colliders*

J.P. Delahaye et al.

2020 Update of the European Strategy for Particle Physics

19 June 2020 10.17181/CERN.JSC6.W89E

- Ensure Europe's continued **scientific and technological leadership**
- **Strengthen the unique ecosystem of research centres in Europe**

3 High-priority future initiatives

- **An electron-positron Higgs factory is the highest-priority next collider**.
  For the longer term, the European particle physics community has the **ambition to operate a proton-proton collider** at the highest achievable energy.
  These compelling goals will require **innovation and cutting-edge technology:**
  - ✓ ramp up R&D on advanced accelerator technologies, in particular **high-field superconducting magnets**, **including high-temperature superconductors**
  - ✓ investigate the **technical and financial feasibility of a future hadron collider at CERN** with a centre-of-mass energy of at least **100 TeV** and **with an electron-positron Higgs and electroweak factory as a possible first stage**
  - ✓ the ILC in Japan would be compatible with this strategy
- The European particle physics community must **intensify accelerator R&D** and sustain it with adequate resources. **A roadmap should prioritise the technology**

EU Strategy → Accelerator R&D Roadmap

European **Strategy Update – June 19, 2020**:

3 | High-priority future initiatives

High-priority future initiatives [..]

In addition to the high field magnets the **accelerator R&D roadmap** could contain:

[..] an **international design study** for a **muon collider**, as it represents a **unique opportunity** to achieve a ***multi-TeV energy domain*** *beyond the reach of* e^+e^- *colliders*, and potentially within a *more compact circular tunnel* than for a hadron collider. The **biggest challenge** remains to produce an intense beam of cooled muons, but *novel ideas are being explored.*

CERN Laboratory Directors Group (LDG) established an Accelerator R&D roadmap

to define a route towards implementation of the goals of the 2020 ESPPU bringing together the capabilities of CERN and the LNLs to carry out R&D and construction and operation of demonstrators

The compelling physics reach justifies establishment of an international collaboration to develop fully the muon collider design study and to pursue R&D priorities, according to an agreed upon work plan.

To facilitate implemention of the European Strategy LDG decided (July 2 2020) to:

Agree to start building the collaboration for international muon collider design study

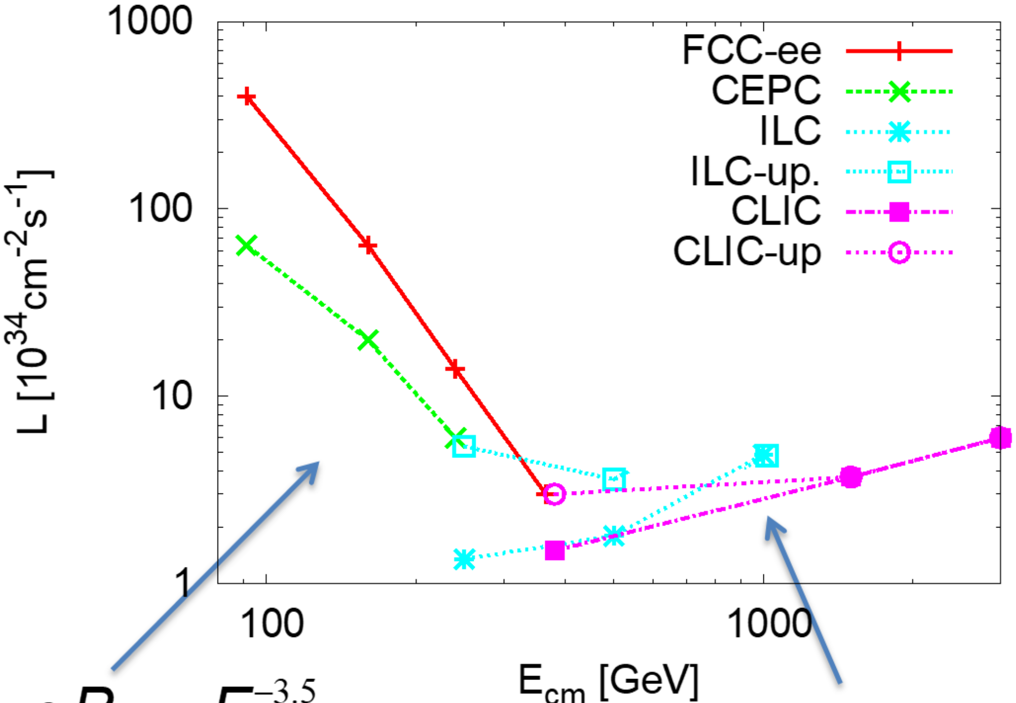
→ **International Muon Collider Collaboration kick-off virtual meeting**

(>260 participants) https://indico.cern.ch/event/930508/

July 3rd, 2020

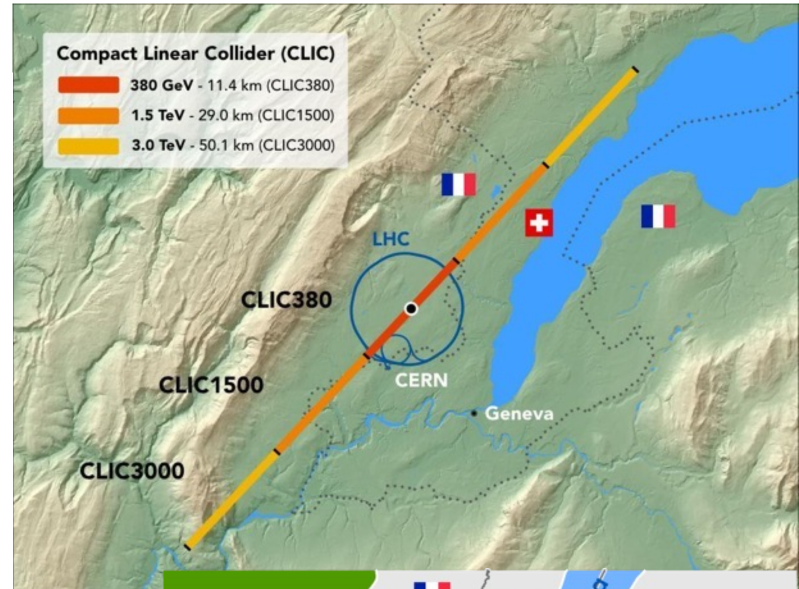
Linear vs Circular lepton e^+e^- collider

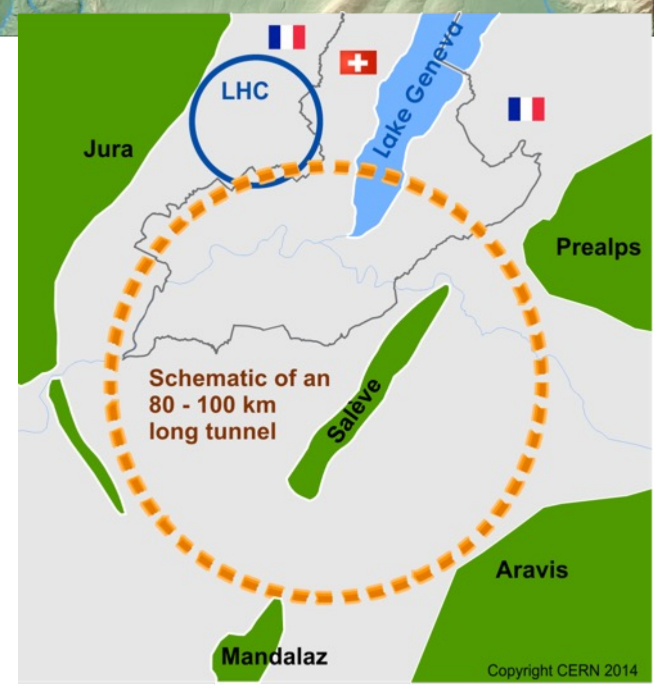
Luminosity per facility



$L \propto P_{synrad} E_{cm}^{-3.5}$

$L \propto P_{RF} E_{cm}$





CLIC at 3 TeV has been optimised over decades:
18 GCHF, 590 MW power consumption

Muon beams specific properties

Muons are leptons with mass (105.7 MeV/c^2) 207 times larger than $e^{\pm}$

➔ Negligible synchrotron radiation emission ($\propto m^{-4}$)

- **Multi-pass collisions (1000 turns) in collider ring:**

☺
- **High luminosity with reasonable beam power and wall plug power needs**
  - **relaxed beam emittances & sizes, alignment & stability**
- **Multi-detectors supporting broad physics communities**
- **Large time (15 ms) between bunch crossings**

☺
- **No beam-strahlung at collision:**
- **narrow luminosity spectrum**

☺
- **Multi-pass acceleration in rings or RLA:**
- **Compact acceleration system and collider**
- **Cost effective construction & operation**

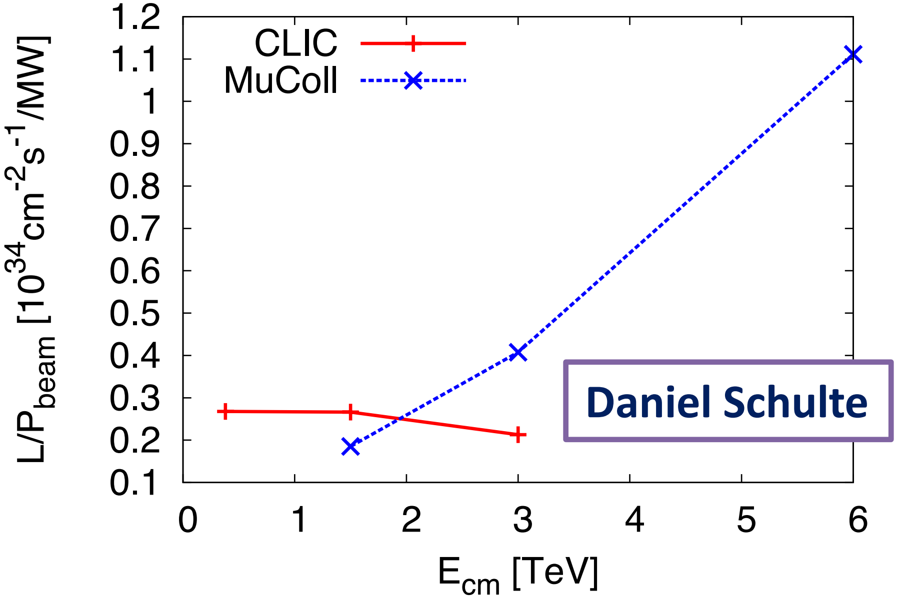
☹
- **No cooling by synchrotron radiation in standard damping rings**
- **Requires development of novel cooling method**

Why a multi-TeV Muon Collider?

cost-effective and unique opportunity

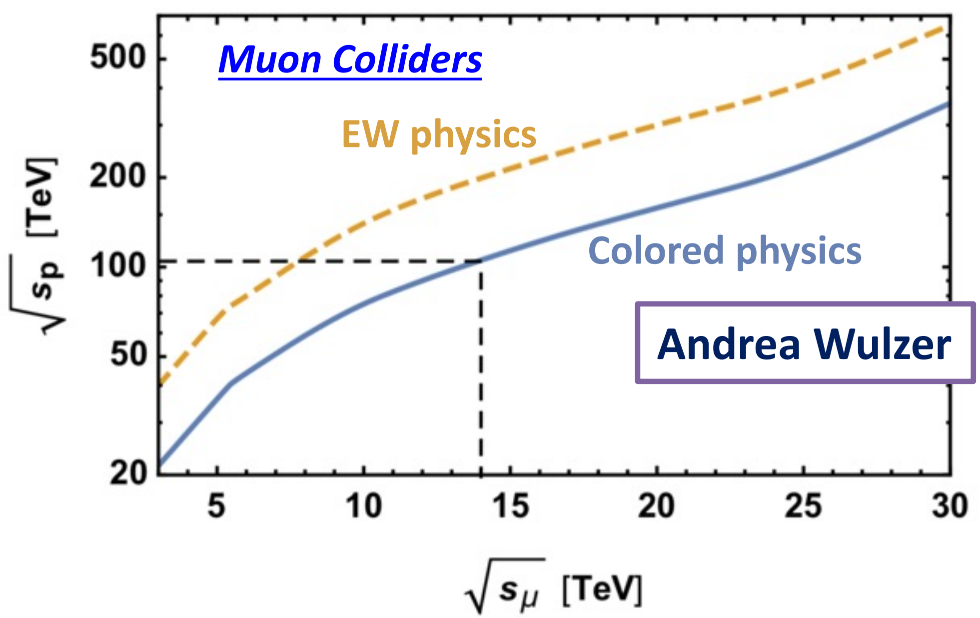
for lepton colliders @ Ecm > 3 TeV

Energy Efficiency



sufficient luminosity required

Energy at which $\sigma_{pp} = \sigma_{\mu\mu}$



Strong interest to reuse existing facilities and infrastructure (i.e. LHC tunnel) in Europe

Muons: Issues & Challenges

- **Limited lifetime: 2.2 μs at rest**
  - **Race against death: fast generation, acceleration & collision before decay**
  - ☹ **Muons decay in accelerator and detector**
    - **Physics feasibility with large background?**
    - **Shielding of detector and facility irradiation**
  - **Decays in neutrinos:**
    - **Ideal source of well defined electron and muons neutrinos in equal quantities :**

☺

$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$

$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$

The neutrino factory concept

☹ » **Limitation in energy reach by neutrino radiation**

- **Generated as tertiary particles in large emittances**
  - **powerful MW(s) driver**
  - ☹ **novel cooling method (6D 10^6 emittance reduction)**

☺ **Development of novel ideas and technologies with key accelerator and detector challenges!**

A unique facility

Jan 2021 nature physics

[Muon colliders to expand frontiers of particle physics](#)

K.Long, **D.Lucchesi**, M.Palmer, **N.Pastrone**, D.Schulte, V. Shiltsev

an idea over 50 years old has now the opportunity to become feasible

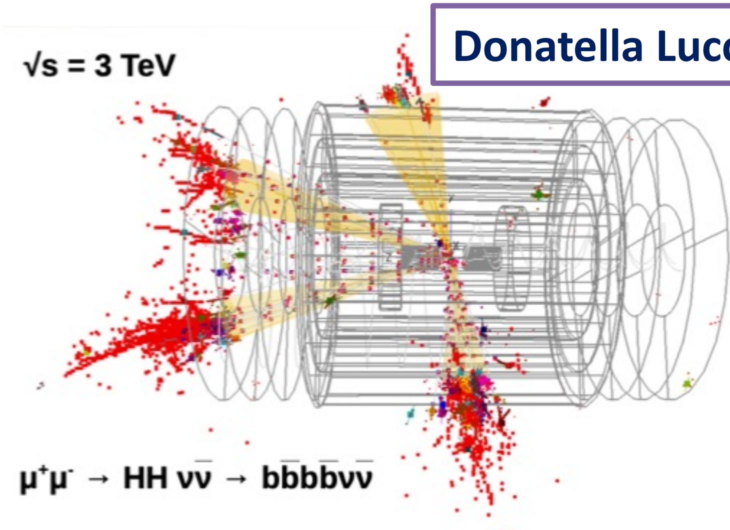
ESPP Input document: [Muon Colliders](#)

Muons – fundamental particles –
leptons ~ 200 times heavier than electron
decay with lifetime at rest of 2.2 μs

Overwhelming physics potential:

- **Precision measurements**
- **Discovery searches**

Donatella Lucchesi et al.



Challenging Facility Design:

- **Key issues/risks**
- **R&D plan - synergies**

cost effective ➔ need real study to confirm cost
power efficient ➔ need a more detailed study
compact site ➔ more with better ramping magnets

Different phyiscs benchmark simulated with Beam-Induced Background at 3 TeV to demonstrate feasibility and physics potential reach

International Collaboration

International MUON Collider Collaboration

Project Leader: *Daniel Schulte*

Objective:
In time for the next European Strategy for Particle Physics Update, the Design Study based at CERN since 2020 aims to **establish whether the investment into a full CDR and a demonstrator is scientifically justified**.
It will **provide a baseline concept**, well-supported performance expectations and assess the associated key risks as well as cost and power consumption drivers.
It will also **identify an R&D path to demonstrate the feasibility of the collider**.

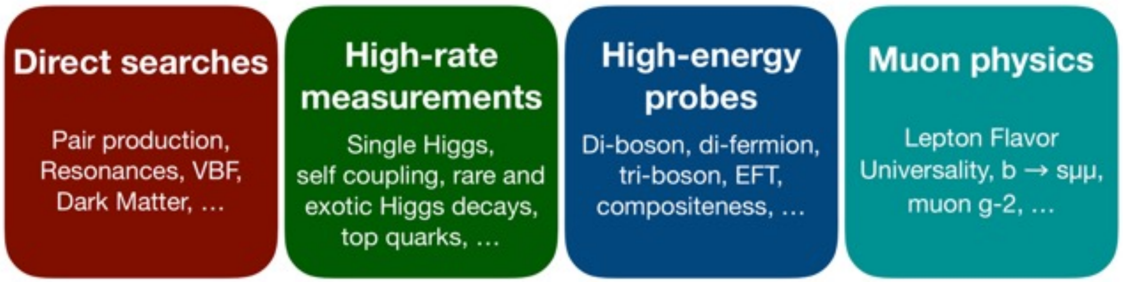
Scope:

- Focus on the high-energy frontier and two energy ranges:
  - **3 TeV** if possible with technology ready for construction in 10-20 years
  - **10+ TeV** with more advanced technology, **the reason to choose muon colliders**
- Explore synergies with other options (neutrino/higgs factory)
- Define **R&D path**

Web page:
http://muoncollider.web.cern.ch

Physics potential

A dream machine to probe unprecedented energy scales and many different directions at once!



Muon Collider can be the game changer!

Great and growing interest in the theory community

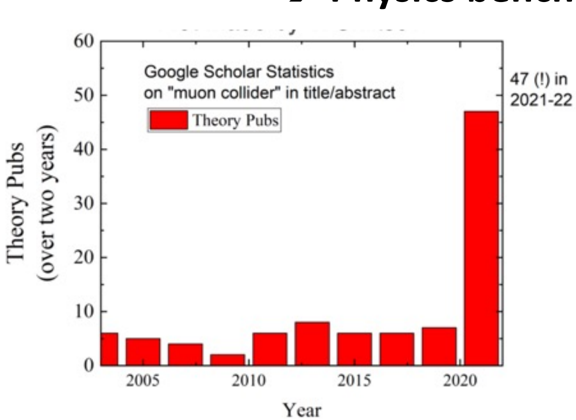
➔ many papers recently published, as:

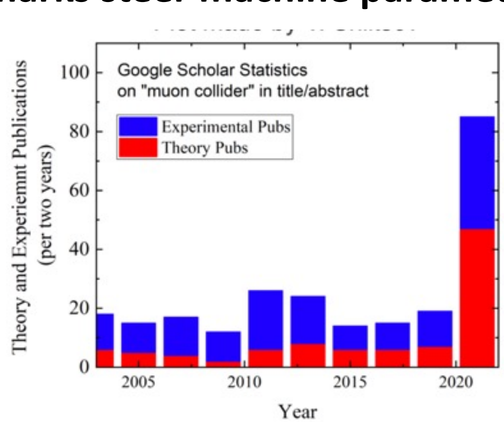
The Muon Smasher's Guide,

https://doi.org/10.48550/arXiv.2103.14043

Strong and crucial synergies to design the machine and the experiment to reach the physics goals with energy and luminosity allowing % precision measurements

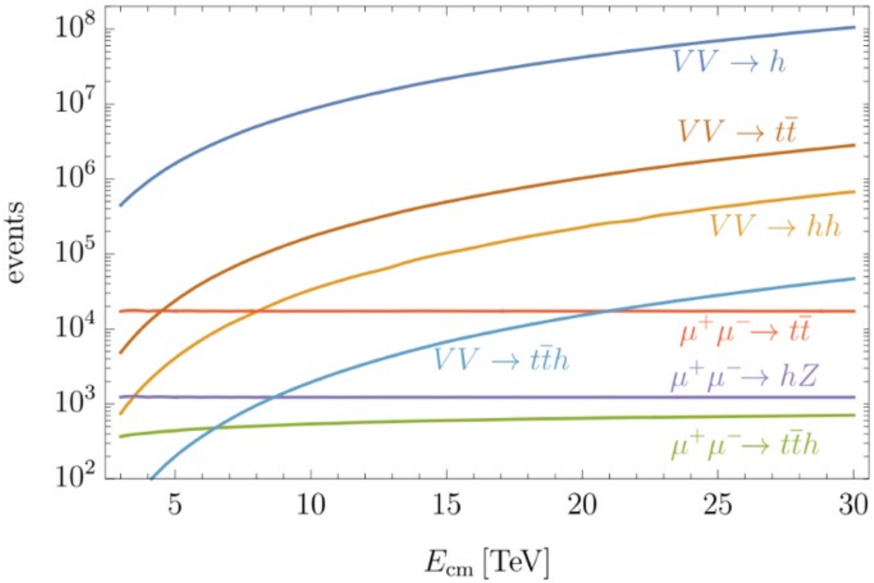
➔ **Physics benchmarks steer machine parameters and experiment design**





Higgs physics

arXiv:2203.07256 **Muon Collider Physics Summary**
arXiv:2203.07261 **The physics case of a 3 TeV muon collider stage**



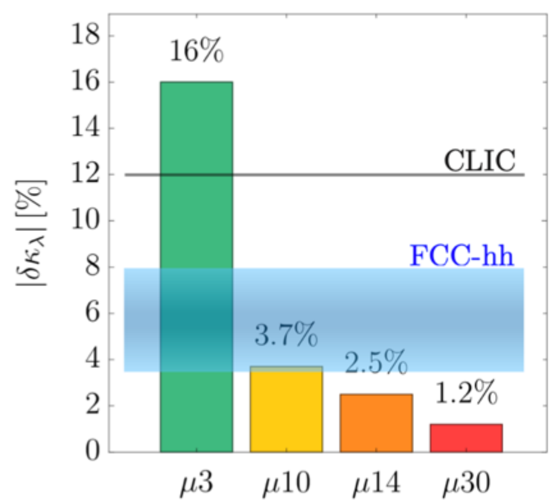
https://snowmass21.org/energy/muon_forum

Higgs coupling sensitivities k-framework

	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
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
$\kappa^*_{Z\gamma}$	10	10	10
κ^*_t	3.3	3.1	3.1

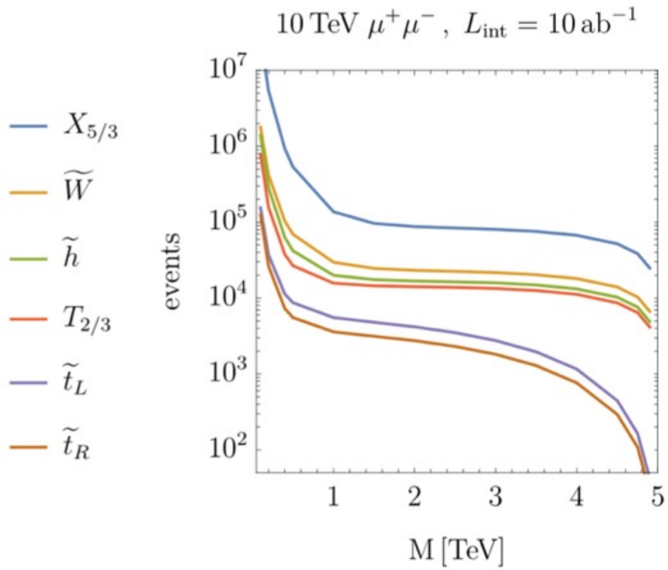
* No input used for μ collider

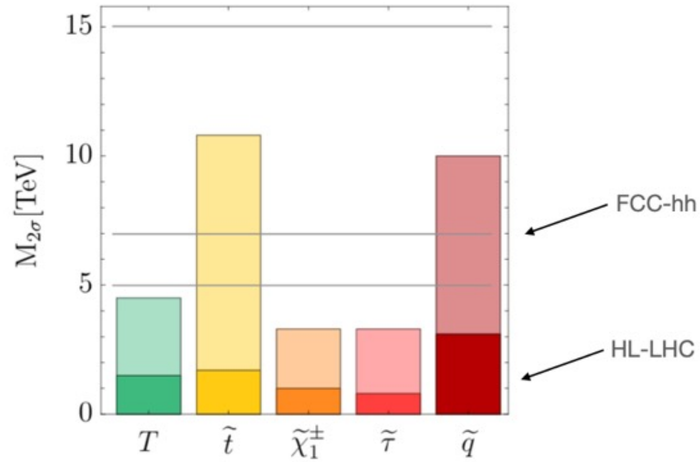
Higgs trilinear self-couplings



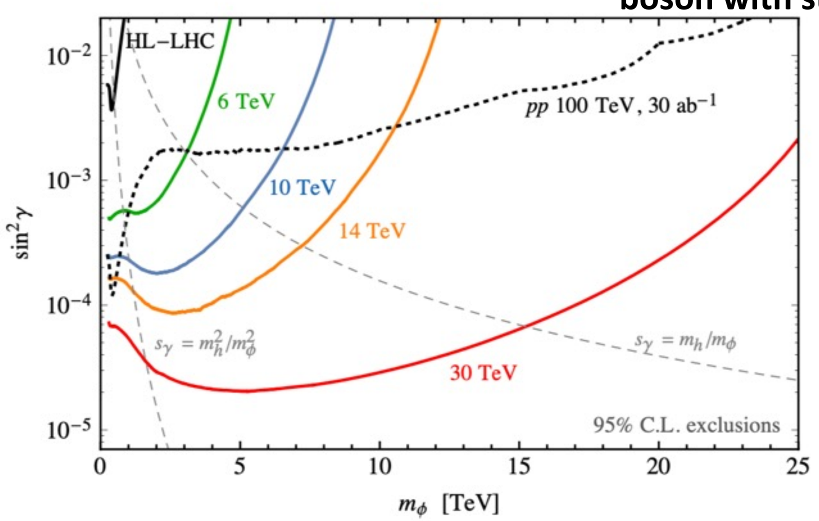
Physics reach in a nutshell

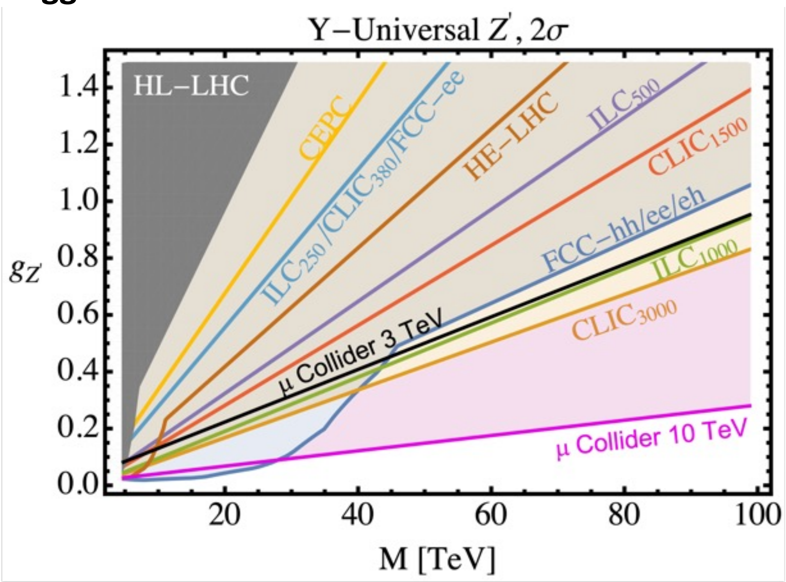
arXiv:2203.07256 **Muon Collider Physics Summary**
arXiv:2203.07261 **The physics case of a 3 TeV muon collider stage**





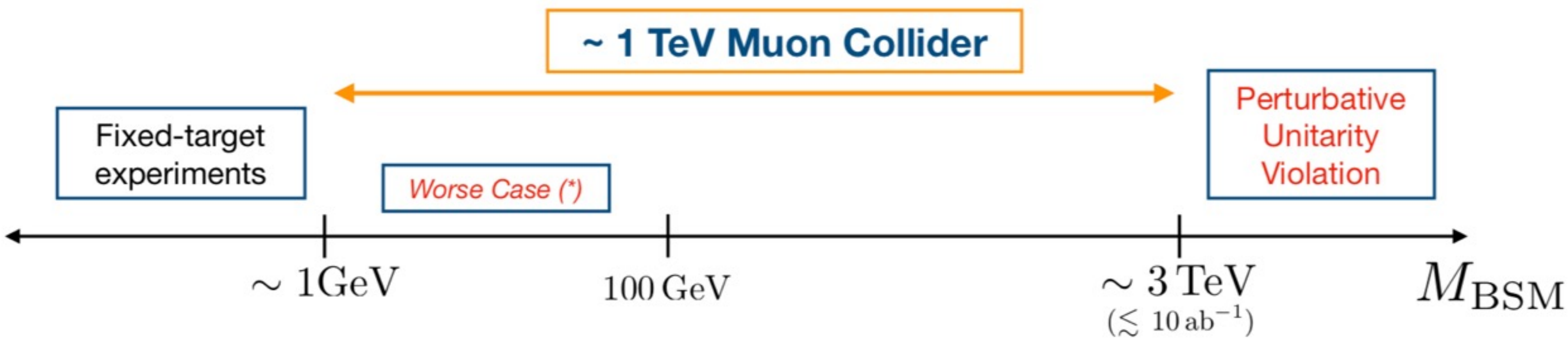
Exclusion contour for a scalar singlet of mass mϕ mixed with the Higgs boson with strength sin γ



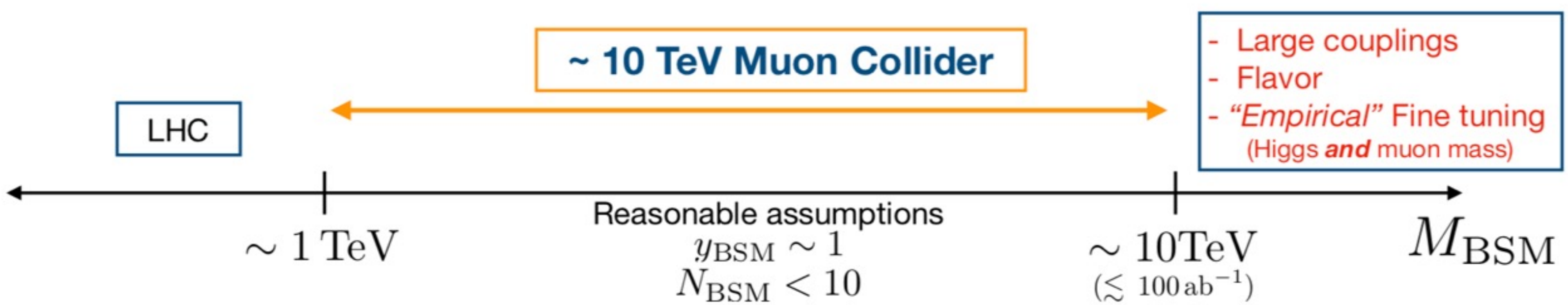


g-2 @ Muon Collider

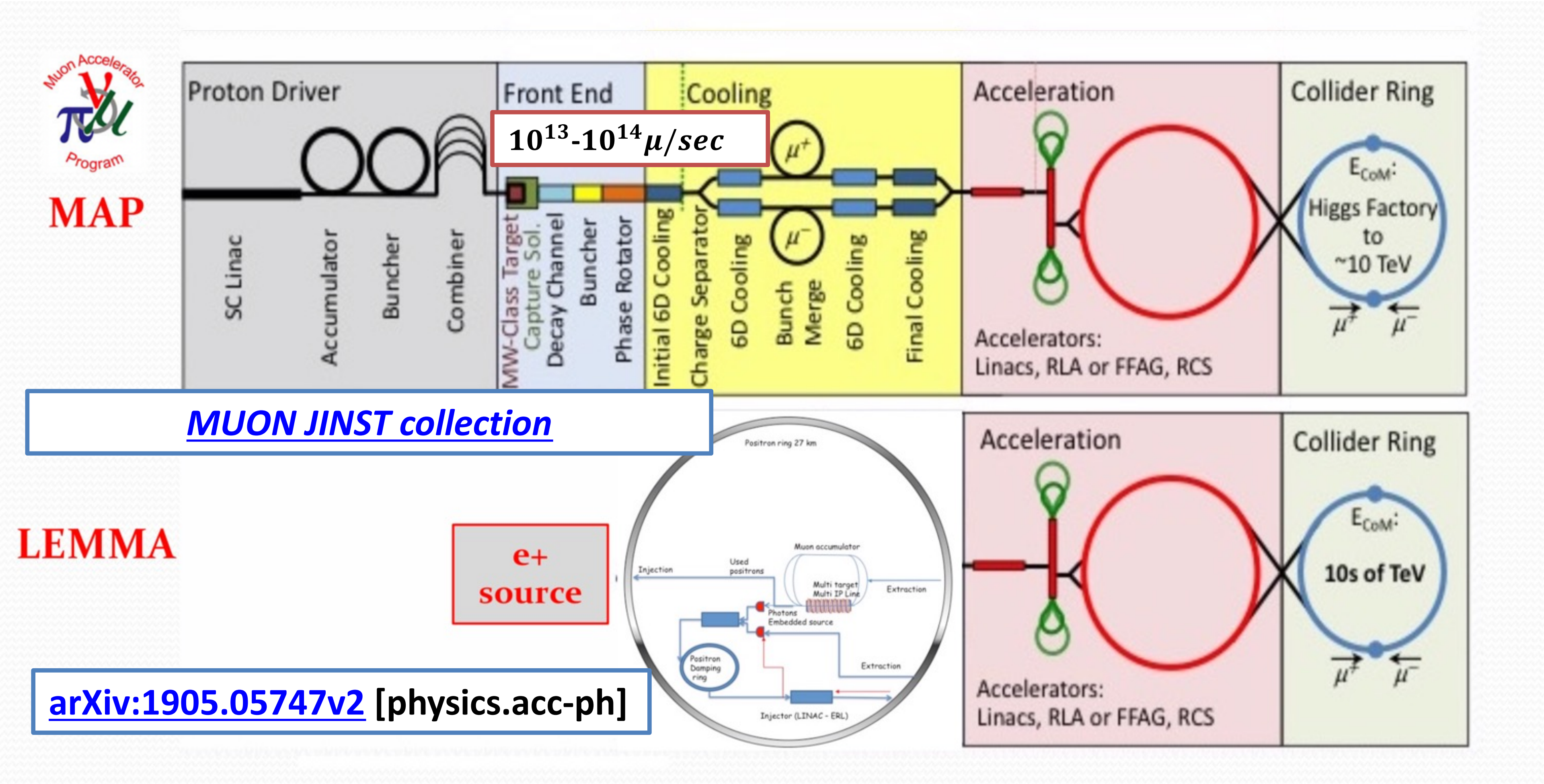
- Singlet Models



- High-Scale EW Models



proton (MAP) vs positron driven muon source



[*MUON JINST collection*]

[arXiv:1905.05747v2] [physics.acc-ph]

LEMMA: main idea
Low EMittance Muon Accellerator

M. Antonelli and P. Raimondi, Snowmass Report (2013) - INFN-13-22/LNF Note

POSITRON DRIVEN MUON SOURCE : direct μ pairs production

Muons produced from $e^+e^- \rightarrow \mu^+\mu^-$ at the $\mu^+\mu^-$ threshold @ $\sqrt{s} \approx$ **0.212 GeV**

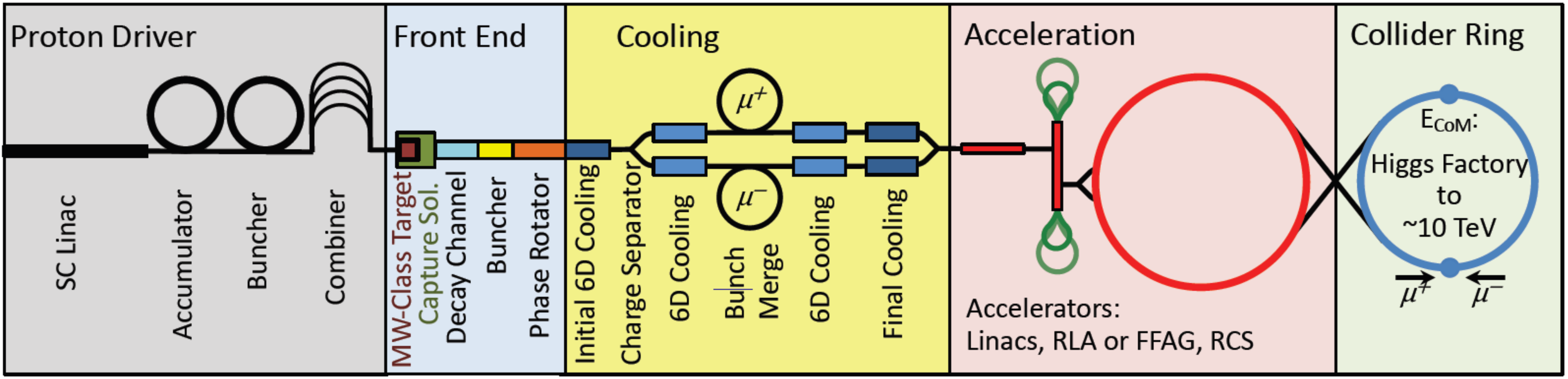
Asymmetric collisions maximize the $\mu^+\mu^-$ pairs production cross section and minimize the $\mu^+\mu^-$ beam angular divergence and energy spread

➔ **45 GeV positron beam impinging on a target** (e^- at rest)

➔ $\mu^+\mu^-$ produced **@ ~22 GeV** with low transverse emittance with $\gamma(\mu) \approx$ **200** and μ laboratory **lifetime** of about **500 μs**

Aimed at obtaining high luminosity with relatively small $\mu^\pm$ fluxes thus reducing background rates and activation problems due to high energy $\mu^\pm$ decays

Proton-driven Muon Collider Concept



Short, intense proton bunches to produce hadronic showers

Pions decay into muons that can be captured

Muon are captured, bunched and then cooled

Acceleration to collision energy

Collision

MICE ionization cooling experiment

U.S. Muon Accelerator Program (MAP)

http://map.fnal.gov/

- Recommendation from 2008 Particle Physics Project Prioritization Panel (P5)
- Approved by DOE-HEP in 2011 ➔ Ramp down recommended by P5 in 2014

AIM: to assess feasibility of technologies to develop muon accelerators for the Intensity and Energy Frontiers

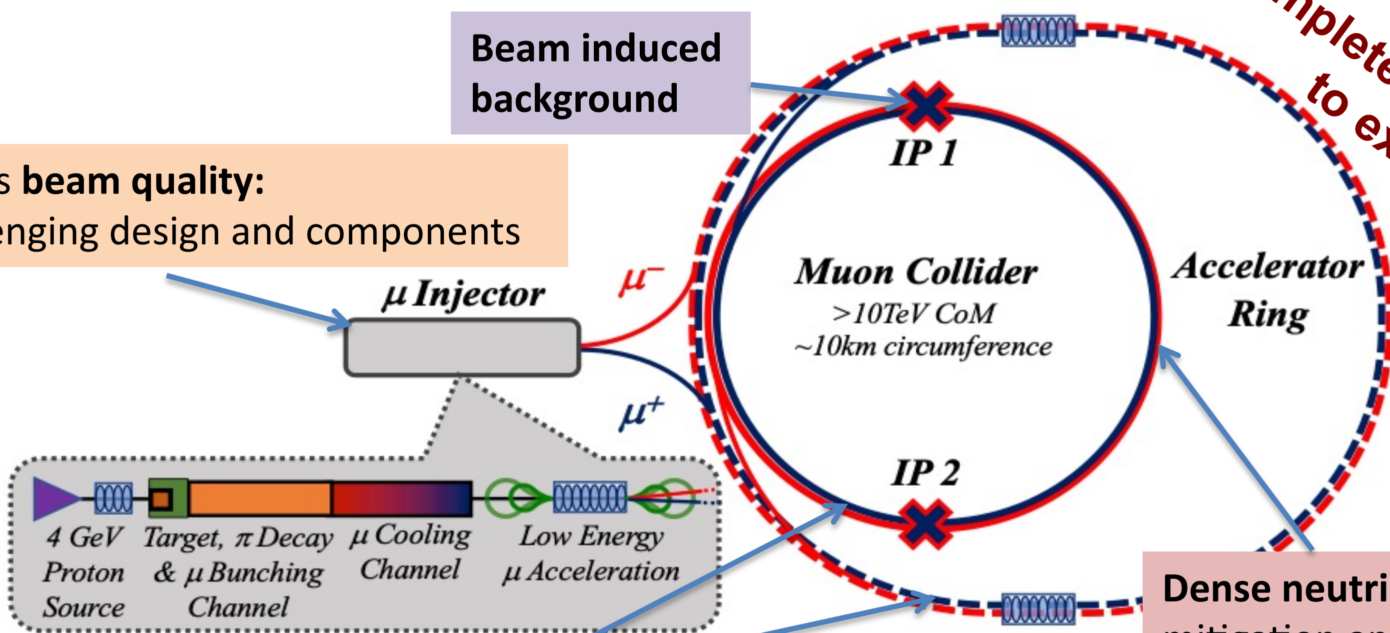
International Design Study facility

Proton driver production as baseline

- **Focus on two energy ranges:**

3 TeV technology ready for construction in 10-20 years

10+ TeV with more advanced technology



10+ TeV completely new regime to explore!

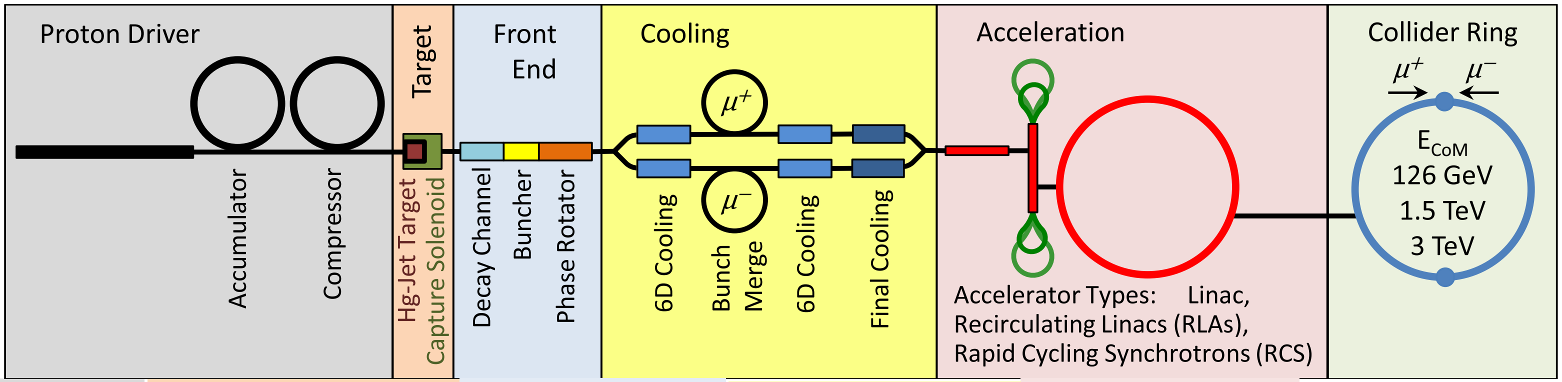
Beam induced background

Drives **beam quality:** challenging design and components

Dense neutrino flux mitigation and site

Cost and **power** consumption drivers, limit energy reach
e.g. 30 km accelerator for 10/14 TeV, 10/14 km collider ring

MAP to International Design Study



- Based on 6-8 GeV Linac Source
- H- stripping requirements similar to neutrino ones

- high power target
- π production in high-field solenoid

- RF cavities bunch & phase rotate $\mu^{\pm}$ into bunch train

- Ionization cooling 6D
- MICE

- Fast acceleratio n
- Use RF and SC

- $\mu^{\pm}$ decay background
- Critical Machine Detector Interface

Luminosity and parameters goals

Target integrated luminosities

$\mathcal{L} = (E_{CM}/10\text{TeV})^2 \times 10\ ab^{-1}$

@ 3 TeV ~ 1 ab^{-1} 5 years

@ 10 TeV ~ 10 ab^{-1} 5 years

@ 14 TeV ~ 20 ab^{-1} 5 years

Note: currently consider 3 TeV and either 10 or 14 TeV

- Tentative parameters achieve goal in 5 years
- FCC-hh to operate for 25 years
- Might integrate some margins
- Aim to have two detectors

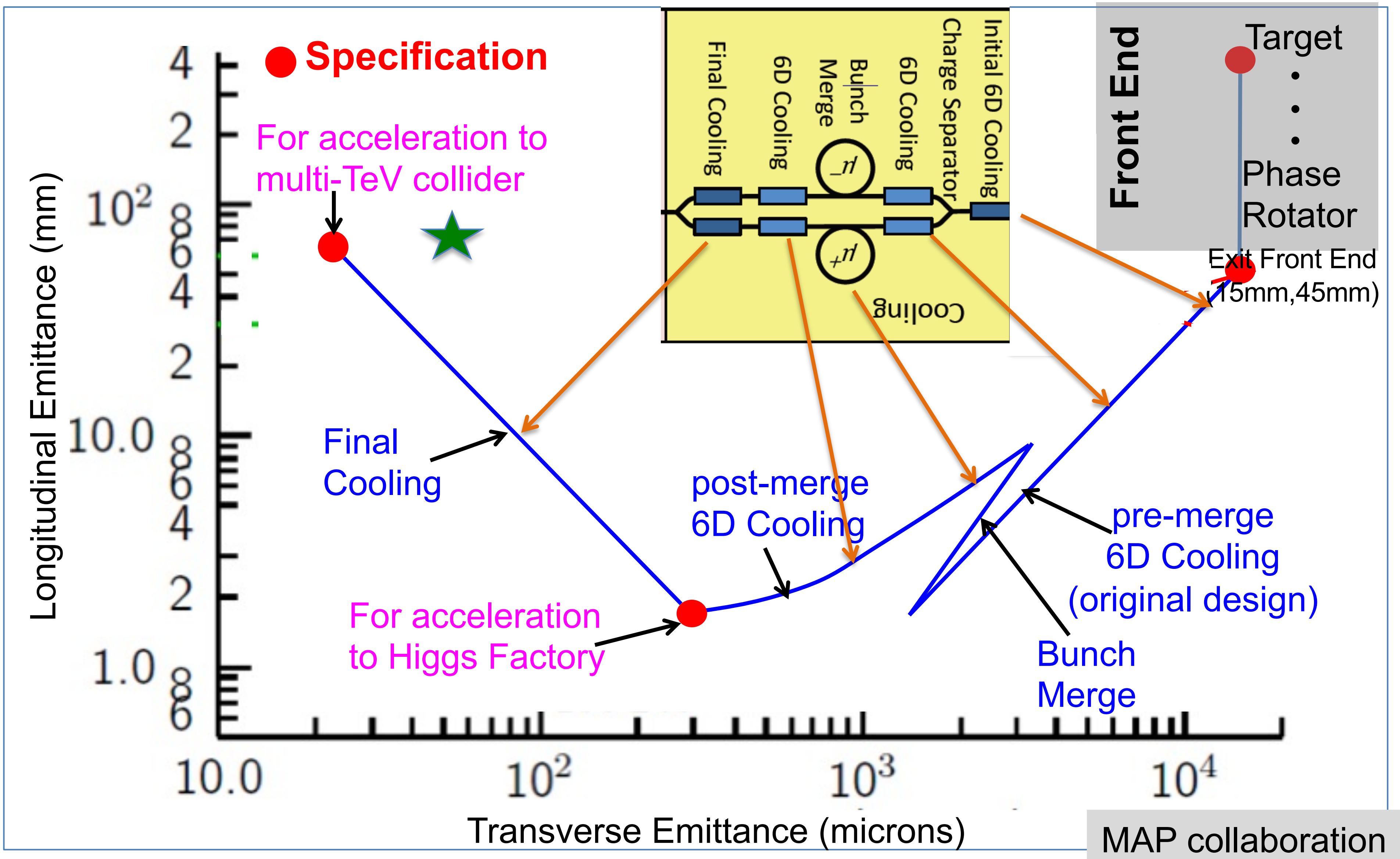
Now study if these parameters lead to realistic design with acceptable cost and power

Tentative target parameters
Scaled from MAP parameters

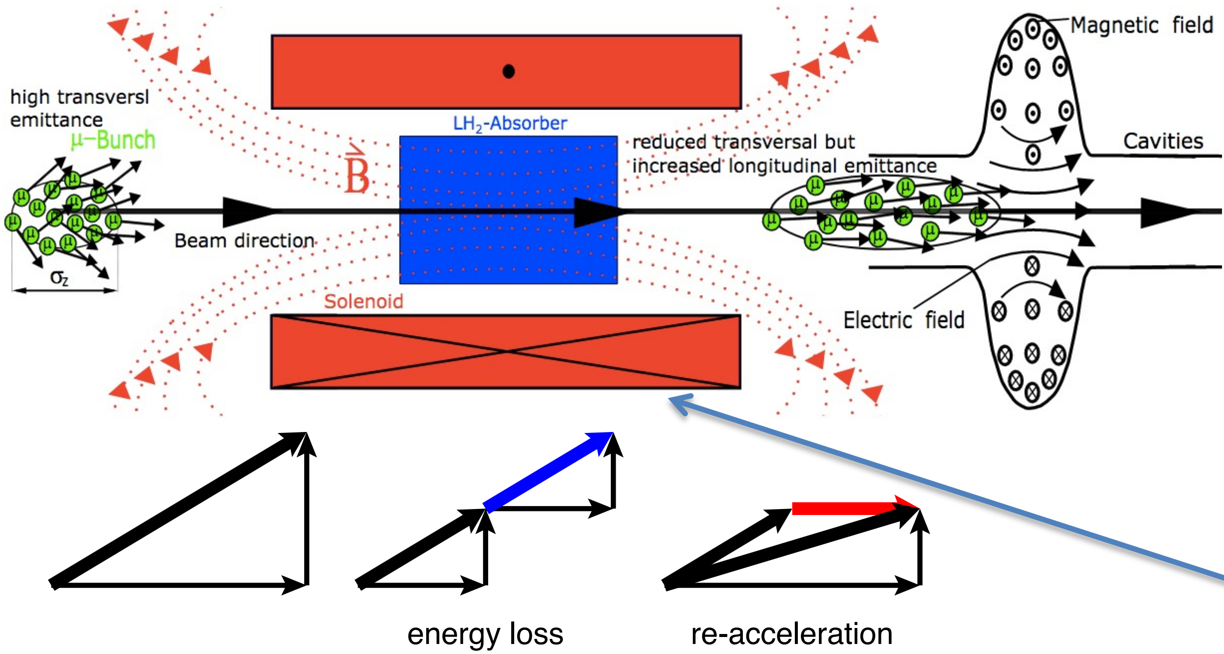
Comparison:
CLIC at 3 TeV: 28 MW

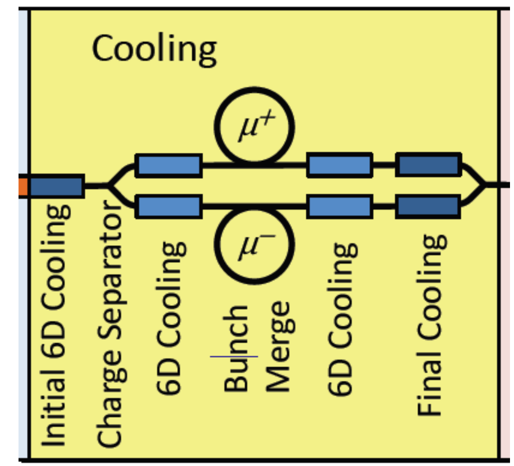
Parameter	Unit	3 TeV	10 TeV	14 TeV
L	$10^{34}\ cm^{-2}s^{-1}$	1.8	20	40
N	10^{12}	2.2	1.8	1.8
f_r	Hz	5	5	5
P_{beam}	MW	5.3	14.4	20
C	km	4.5	10	14
<B>	T	7	10.5	10.5
ε_L	MeV m	7.5	7.5	7.5
σ_E / E	%	0.1	0.1	0.1
σ_z	mm	5	1.5	1.07
β	mm	5	1.5	1.07
ε	µm	25	25	25
$\sigma_{x,y}$	µm	3.0	0.9	0.63

Cooling: Emittance Path



Final Cooling Challenge





High field solenoids minimise beta-function and impact of multiple scattering

Energy loss = cooling

Multiple scattering = heating

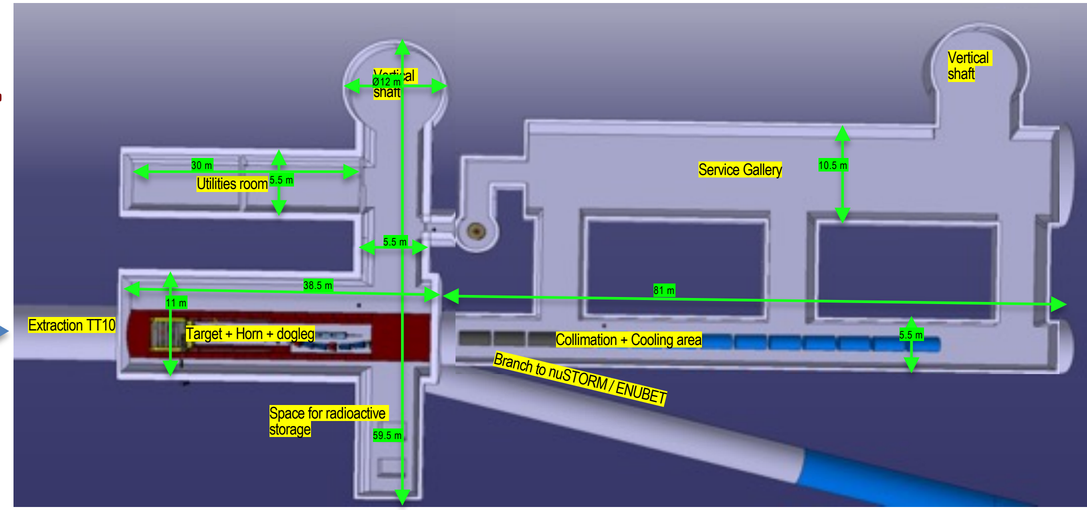
$$\frac{d\epsilon_\perp}{ds} = -\frac{1}{(v/c)^2}\frac{dE}{ds}\frac{\epsilon_\perp}{E} + \frac{1}{2}\frac{1}{(v/c)^3}\left(\frac{14\,\mathrm{MeV}}{E}\right)^2\frac{\beta\gamma}{L_R}$$

Demonstrator and test facilities

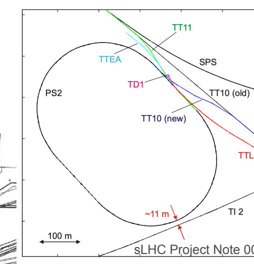
(Muon production) and Cooling Demonstrator @ CERN

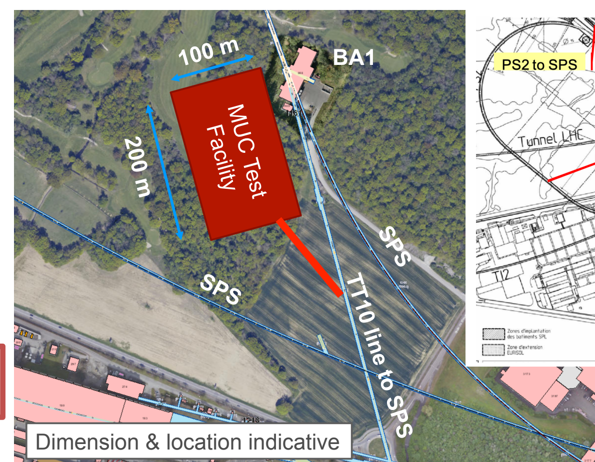
Strong synergies with nuSTORM and ENUBET

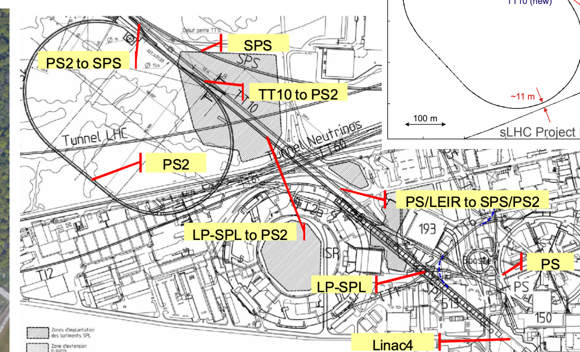
First attempt to design a site
Great opportunity to contribute



It could be close to TT10, and inject beam from PS
It would be on molasse,
no radiation to ground water







M. Benedikt, LHC Performance Workshop, Chamonix 2010
CERN-AB-2007-061

Test facilities for enabling tecnologies:
RF, Magnets, Target materials…..

Strong synergies with other future projects

Accelerator R&D Roadmap
Bright Muon Beams and Muon Colliders

International Design Study Collaboration GOAL

In time for the next European Strategy for Particle Physics Update, aim to **establish whether the investment into a full CDR and a demonstrator is scientifically justified**

The Panel endorsed this ambition and concludes that:

- the MC presents enormous potential for fundamental physics research at the energy frontier

➔ it is the future direction toward high-energy, high-luminosity lepton collider

➔ it can be an option as next project after HL-LHC (i.e. operation mid2040s)

- at this stage the panel did not identify any showstopper in the concept and sees strong support of the feasibility from previous studies

- it identified important R&D challenges

The panel has identified a development path that can address the major challenges and deliver a 3 TeV muon collider by 2045

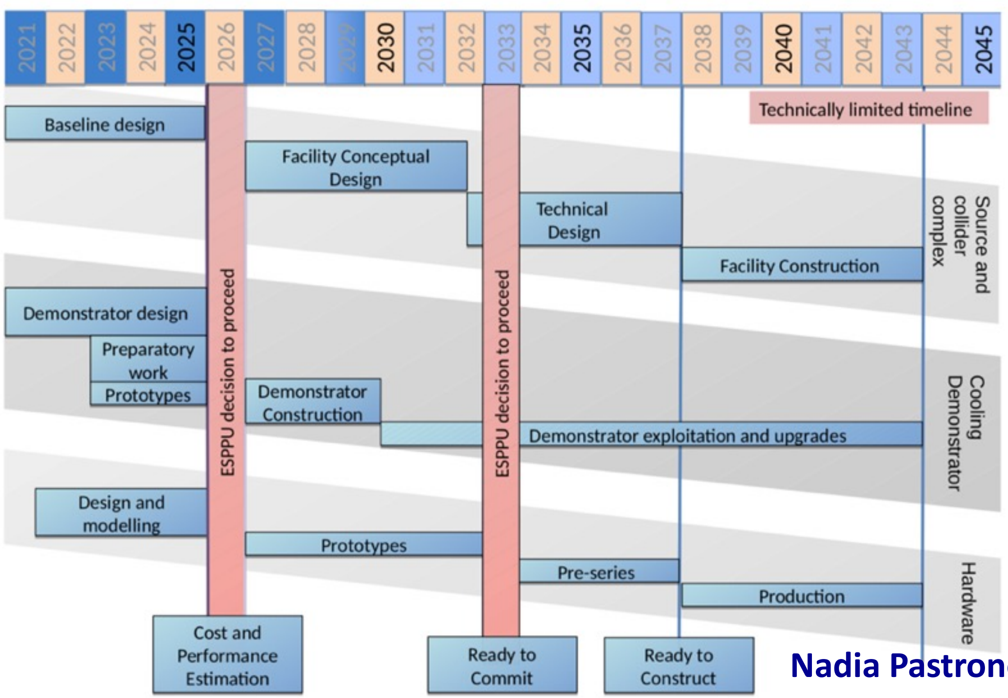
Accelerator R&D Roadmap

Bright Muon Beams and Muon Colliders

Panel members: **D. Schulte**,(Chair), M. Palmer (Co-Chair), T. Arndt, A. Chancé, J. P. Delahaye,
A.Faus-Golfe, S.Gilardoni, P.Lebrun, K.Long, E.Métral, N.Pastrone, L.Quettier, T.Raubenheimer,
C.Rogers, M.Seidel, D.Stratakis, A.Yamamoto
Associated members: A. Grudiev, R. Losito, D. Lucchesi

Intense preparation and review activities in 2021:
3 Community Meetings (May, July, October) and
a dedicated Muon Collider Physics and Detector Workshop

presented to CERN Council in December and
published https://arxiv.org/abs/2201.07895
now under implementation by LDG + Council…



Technically limited timeline

A 3 TeV muon collider could be ready by 2045, as reviewed by the Roadmap

Plan

The panel has identified a development path that can address the major challenges and deliver a 3 TeV muon collider by 2045

Label	Begin	End	Description	Aspirational [FTEy]	Aspirational [kCHF]	Minimal [FTEy]	Minimal [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.RF.HE	2021	2026	High Energy complex RF	10.6	0	7.6	0
MC.RF.MC	2022	2026	Muon cooling RF	13.6	0	7	0
MC.RF.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

Scenarios

Aspirational		Minimal	
[FTEy]	[kCHF]	[FTEy]	[kCHF]
445.9	11875	193	2445

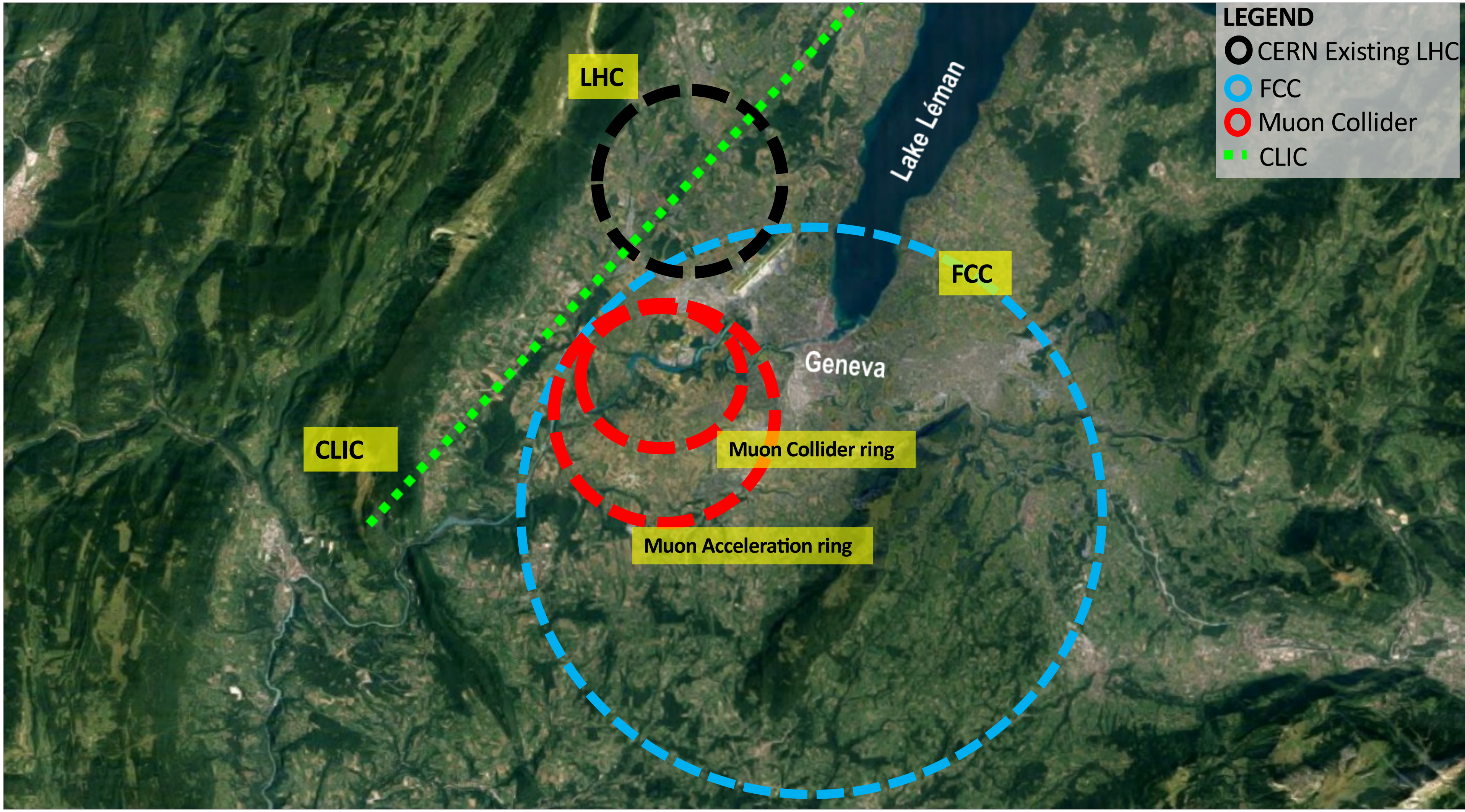
~70 Meu/5 years

International Community

CONTEXT:

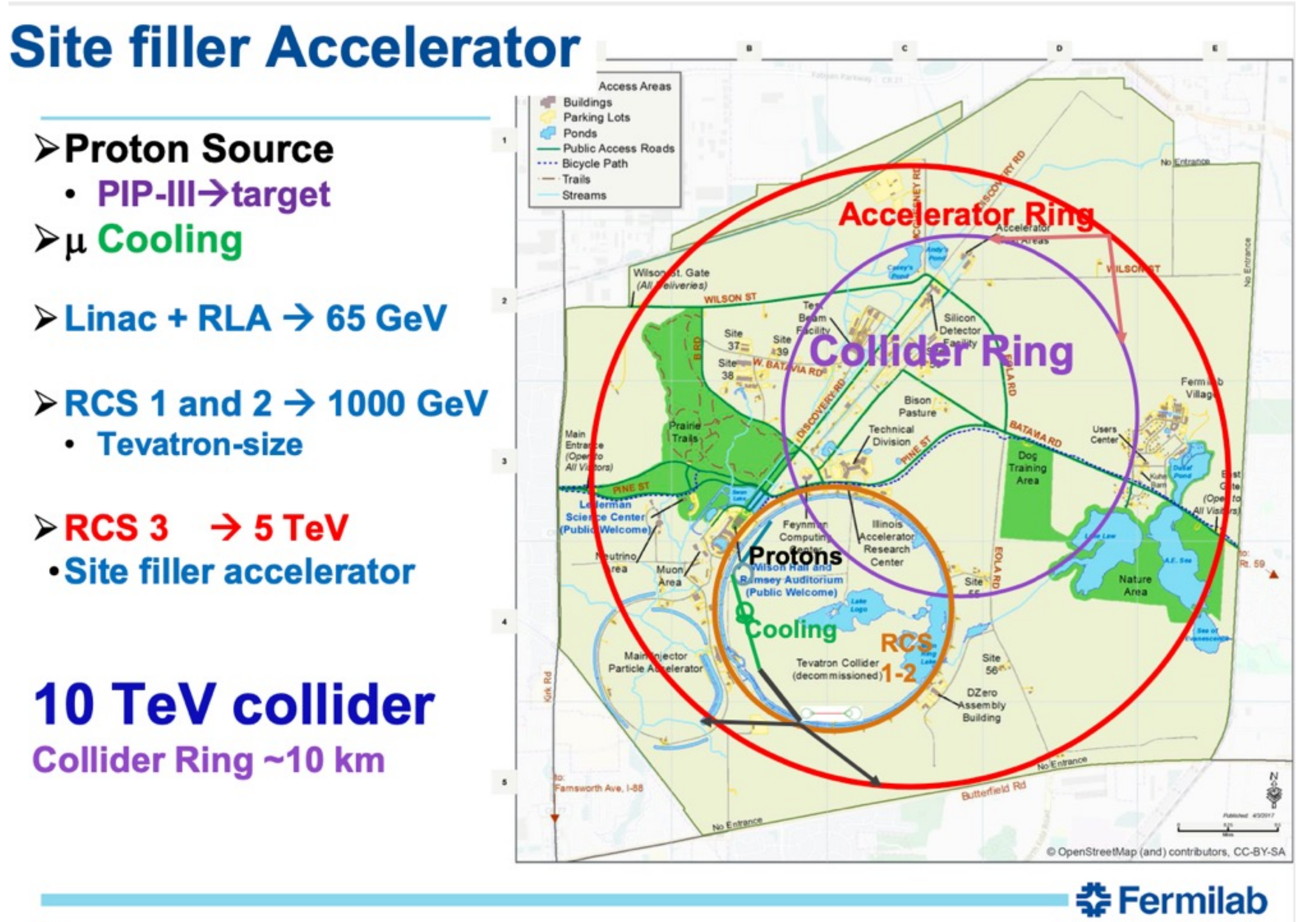
- **Laboratory Directors' Group (LDG) initiated a muon collider collaboration July 2, 2020**
- CERN Medium Term Plan 2021-2025 - dedicated budget line – 2MCHF/year
- **International Design Study based at CERN → MoC signed by INFN July 2021**
  the project encompasses physics, machine, detector and Machine Detector Interface
- European LDG **Accelerator R&D Roadmap → presented to December Council 2021**
  dedicated Muon Beams Panel - but also synergies in High field magnets, RF and ERL
- European ECFA **Detector R&D Roadmap → presented to December Council 2021**
  Muon collider @ 10 TeV is one of the targeted facilities emerging from the EPPSU
- US SnowMass Muon Collider Forum **since 2021** *share ideas and studies across frontiers*
- Snowmass/P5 process in the US → **ready by 2023**
- HORIZON-INFRA-2022-DEV-01-01 EU project for Design Study approved **July 2022**
  Research infrastructure concept development → **supported by TIARA**

Footprint of future colliders @ CERN



Muon Collider @ FNAL option

10 TeV collider
requires ~16 T dipoles
in RCS scenarios
With rapid-cycling
2-4 T magnets



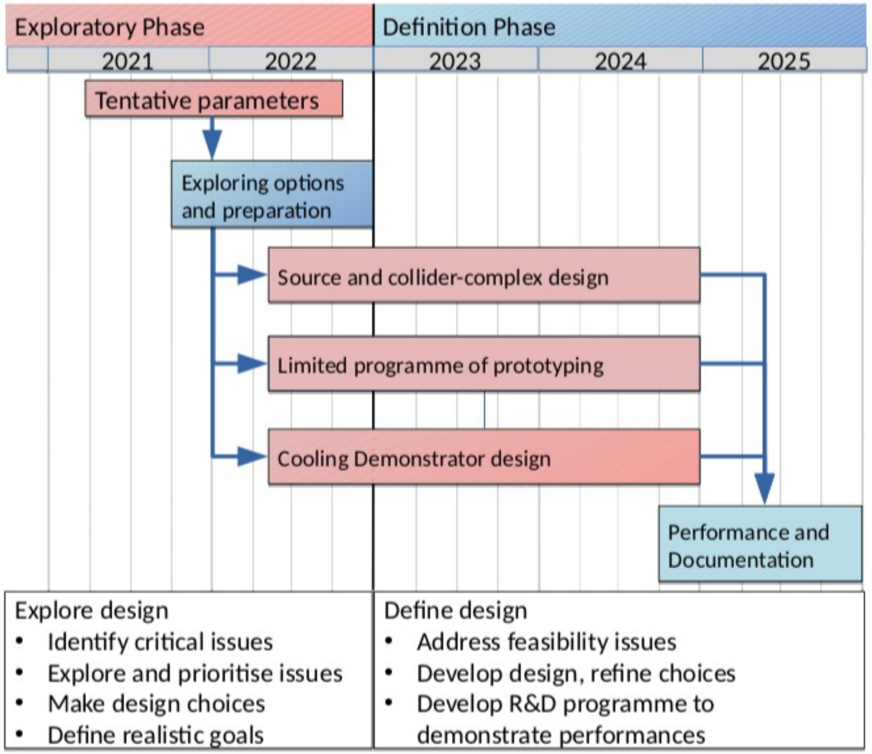
Fermilab new formed
Future Colliders Group
is actively exploring filler option

Key Challenge Areas

- **Physics potential** evaluation, including **detector concept and technologies**
- Impact on the environment
  - **Neutrino flux mitigation** and its impact on the site (first concept exists)
  - **Machine Induced Background** impact the detector, and might limit physics
- **High-energy systems** after the cooling (acceleration, collision, ...)
  - Fast-ramping magnet systems
  - High-field magnets (in particular for 10+ TeV)
- **High-quality muon beam production**
  - Special RF and high peak power
  - Superconducting solenoids
  - Cooling string demonstration (cell engineering design, demonstrator design)
- **Full accelerator chain**
  - e.g. proton complex with H- source, compressor ring ➔ test of target material

High energy complex requires known components
➔ synergies with other future colliders

Plan for next 5 years



- **End-to-end design with all systems**
- **Key performance specifications**
- **Evidence to achieve luminosity goal:**
  - beam parameters, collective effects, tolerances …
- **Evidence that the design is realistic:**
  - performance specification supported by technology
  - key hardware performances
  - radiation protection, impact and mitigation of losses
  - cost and power scale, site considerations
- **A path forward**
  - Test facility
  - Component development
  - Beam tests
  - System optimisation

Key R&D challenges

Mark Palmer

Key R&D Challenges

	Issues	Status
Target	• Multi-MW Targets • High Field, Large Bore Capture Solenoid	• Ongoing >1 MW target development • Challenging engineering for capture solenoid
Front End	• Energy Deposition in FE Components • RF in Magnetic Fields (see Cooling)	• Current designs handle energy deposition
Cooling	• RF in Magnetic Field • High and Very High Field SC Magnets • Overall Ionization Cooling Performance	• MAP designs use 20 MV/m → 50 MV/m demo • >30 T solenoid demonstrated for Final Cooling • Cooling design that achieves most goals
Acceleration	• Acceptance • Ramping System • Self-Consistent Design	• Designs in place for accel to 125 GeV CoM • Magnet system development needed for TeV-scale • Self-consistent design needed for TeV-scale
Collider Ring	• Magnet Strengths, Apertures, and Shielding • High Energy Neutrino Radiation	• Self-consistent lattices with magnet conceptual design up to 3 TeV • > ~5 TeV – ν radiation solution required
MDI/Detector	• Backgrounds from μ Decays • IR Shielding	• Further design work required for multi-TeV • Initial physics studies at 1.5 TeV promising

Design Study activities: EU project MuCol

Total EU budget 3 Meu - 48 months - 18(+14) beneficiaries (associated)

HORIZON-INFRA-2022-DEV-01-01: Research infrastructure concept development

The MuCol study will produce a coherent description of a novel particle accelerator complex that will collide muons of opposite charge at the energy frontier. The study will target a centre-of-mass energy (ECM) of 10 TeV with 3 TeV envisaged as a first stage.

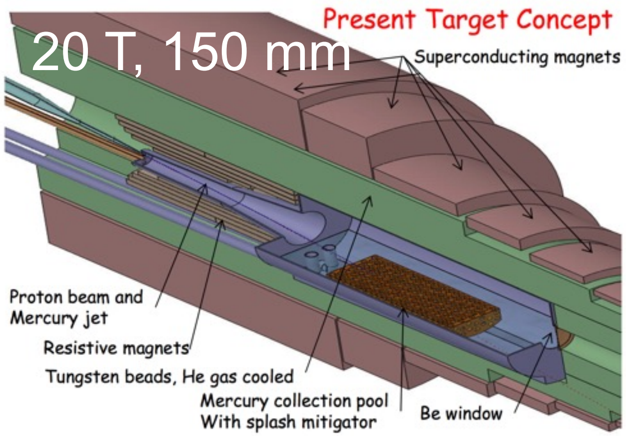
The main outcome of MuCol will be a report documenting the facility design that should demonstrate that:

- the physics case of the muon collider is sound and detector systems can yield sufficient resolution and rejection of backgrounds;
- there are no principle technology showstoppers that will prevent the achievement of a satisfactory performance from the accelerator or from the detectors side;
- the muon collider provides a highly sustainable energy frontier facility as compared to other equivalent colliders;
- exploiting synergies with other scientific and industrial R&D projects, a valuable platform to provide Europe a leading edge not only in terms of discovery potential, but also for the development of associated technologies.

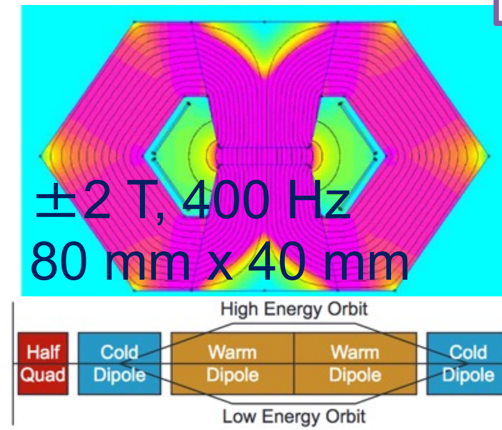
The final report will include a thorough assessment of benefits and risks of the accelerator and detector complex, including an evaluation of the scientific, industrial and societal return beyond high-energy physics, the cost scale and sustainability of the complex and the impact arising from an implementation on the CERN site.

Magnet Demands

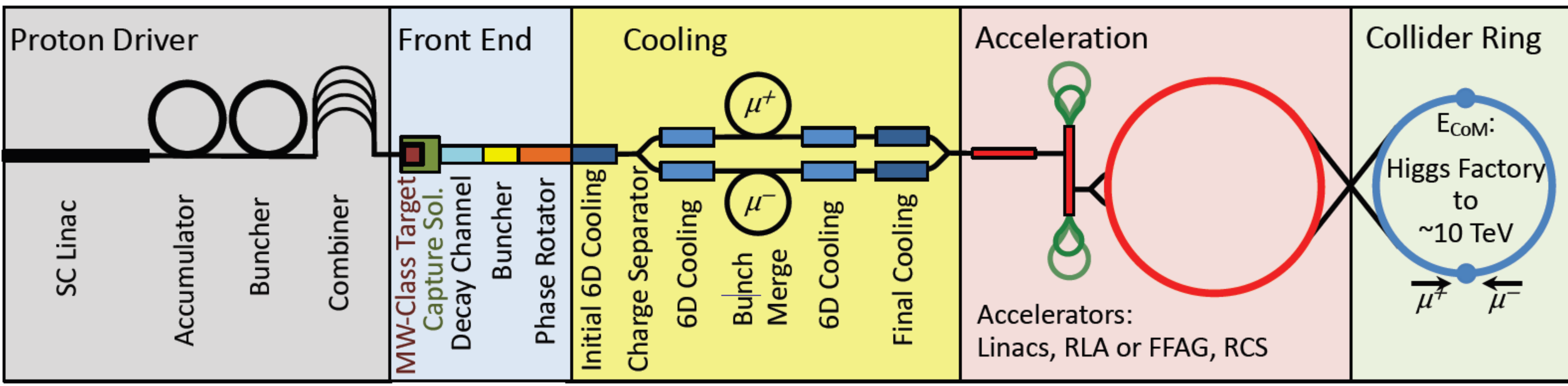
Luca Bottura



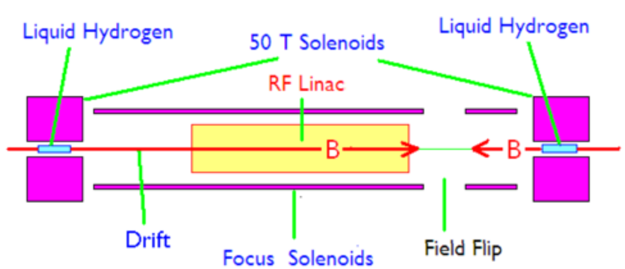
High-field and large aperture target solenoid with heavy shielding to withstand heat (100 kW/m) and radiation loads



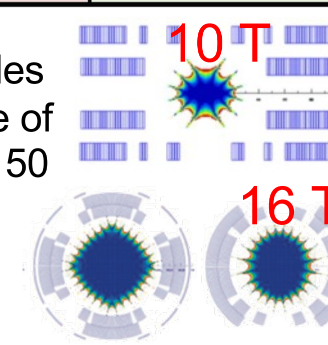
Combination of DC SC magnets (10 T) and AC resistive magnets (±2T)



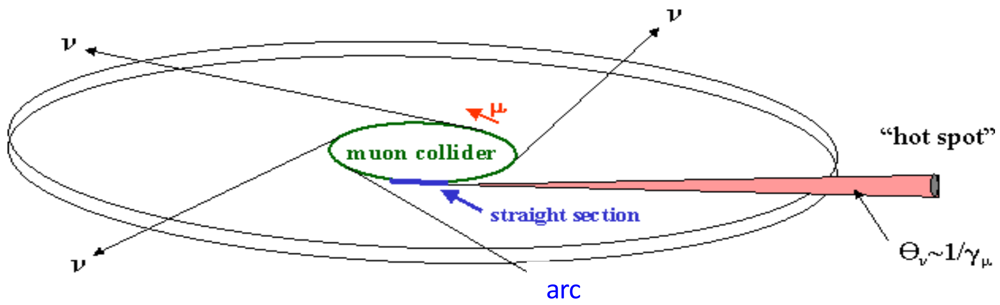
Ultra-high-field solenoids (40…60 T) to achieve desired muon beam cooling



Open midplane or large dipoles and quadrupoles in the range of 10…16 T, bore in excess of 150 mm to allow for shielding against heat (500 W/m) and radiation loads



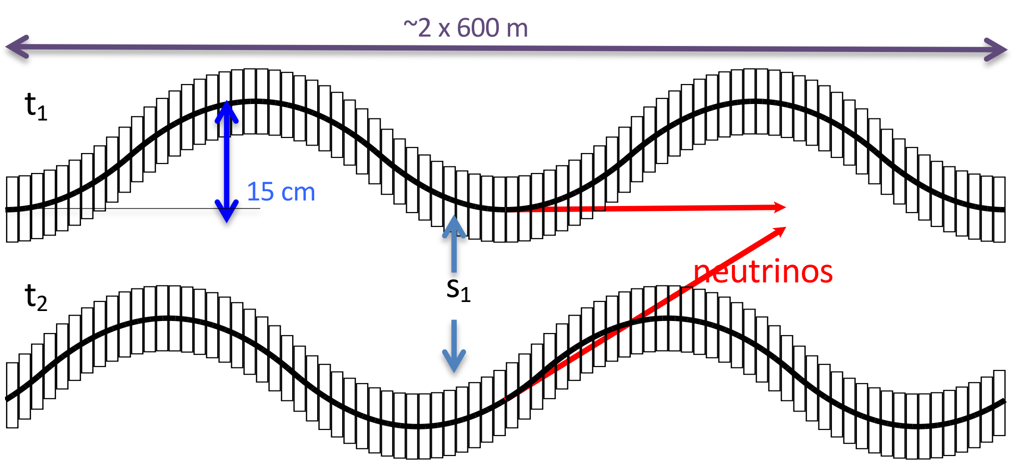
Neutrino Flux Mitigation



Legal limit 1 mSv/year
MAP goal < 0.1 mSv/year
Our goal: arcs below threshold for legal procedure < 10 μSv/year
LHC achieved < 5 μSv/year

3 TeV, 200 m deep tunnel is about OK

Need mitigation of arcs at 10+ TeV:
idea of Mokhov, Ginneken to move beam in aperture
our approach: move collider ring components, e.g. vertical bending with 1% of main field



Opening angle ± 1 mradiant

14 TeV, in 200 m deep tunnel comparable to LHC case

Need to study mover system, magnet, connections and impact on beam

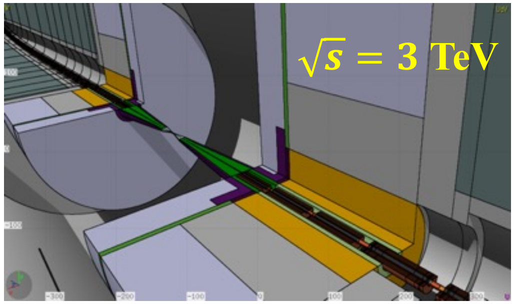
Working on different approaches for experimental insertion

Machine Detector Interface

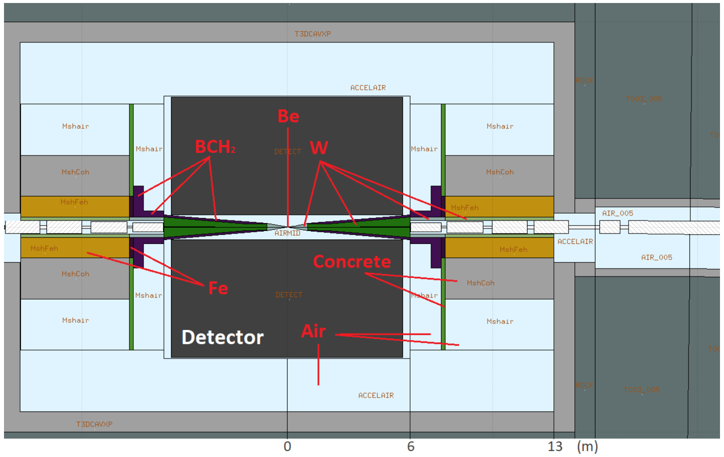
Advanced assessment of beam-induced background at a muon collider

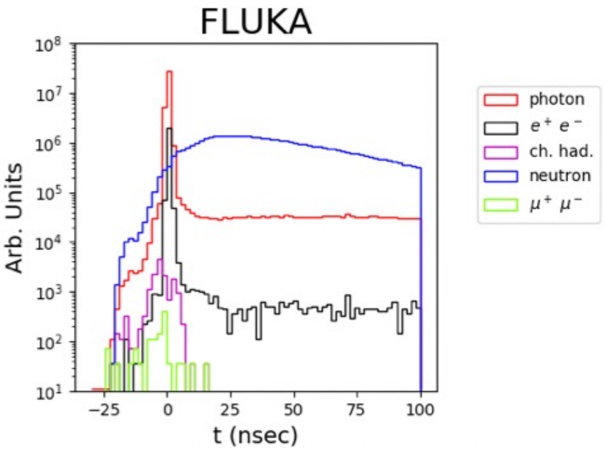
F. Collamati, C. Curatolo, D. Lucchesi, A. Mereghetti, P. Sala *et al.* 2021 *JINST* **16** P11009

Study Beam-Induced Background @ $\sqrt{s} = 1.5$ and 3 TeV, using MAP lattice –
nozzle optimized at 1.5 TeV



LineBuilder + FLUKA simulation

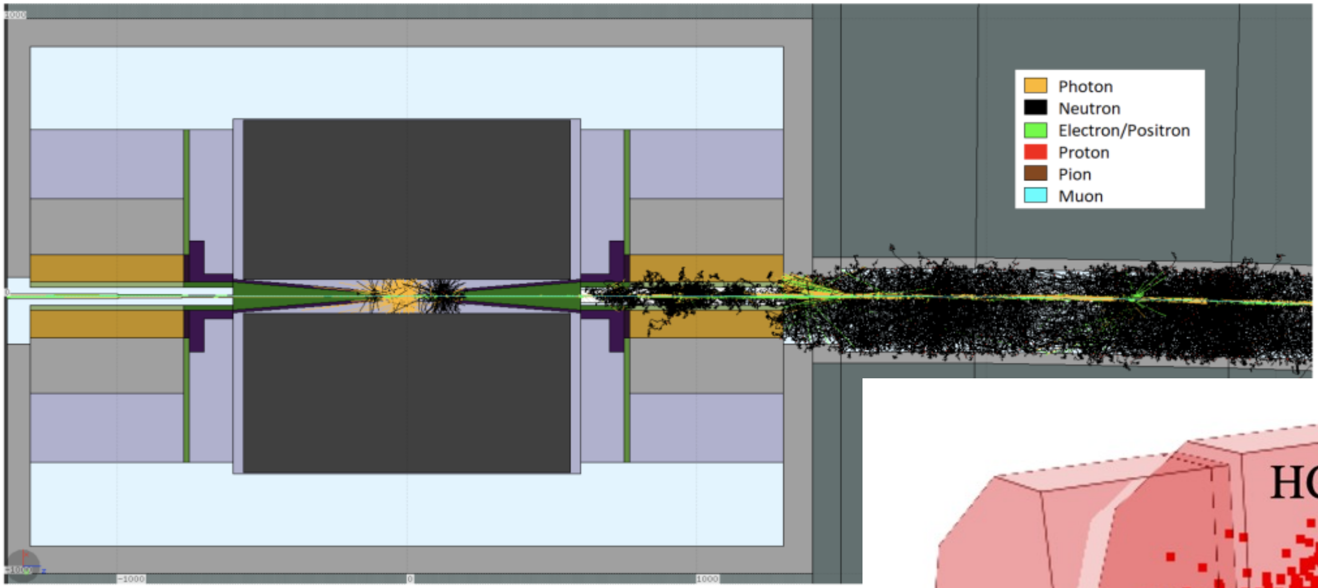




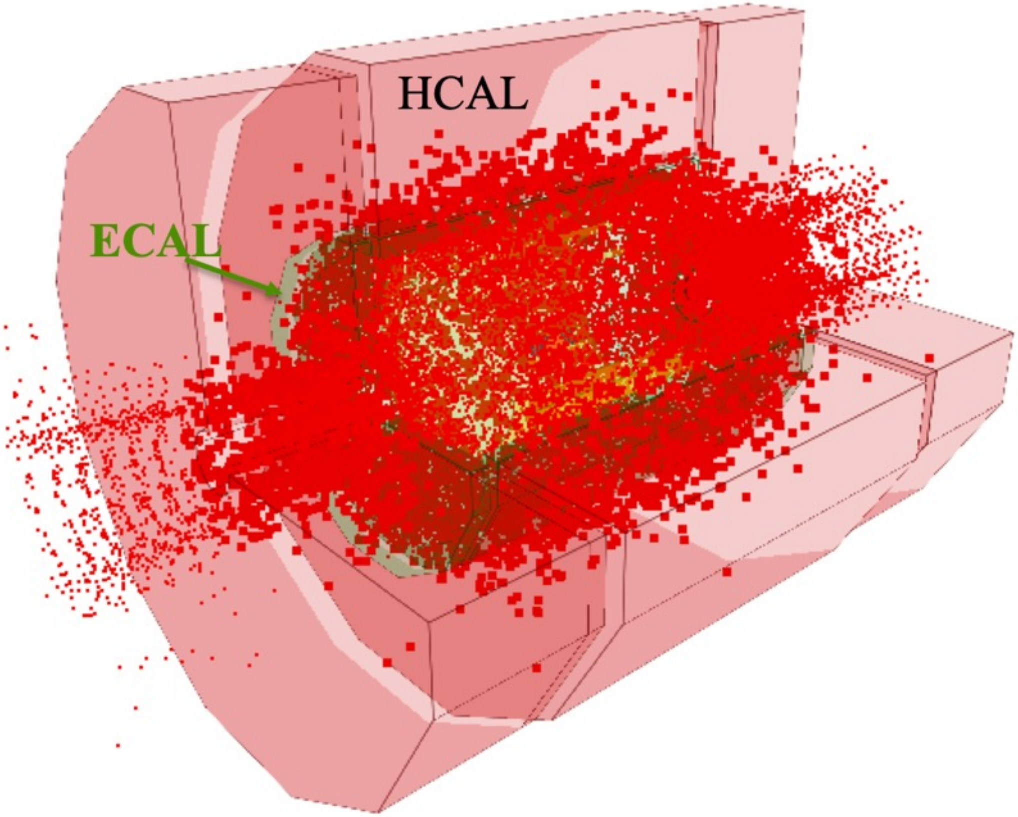
➔ **first lattice and MDI studies @ 10 TeV by CERN**

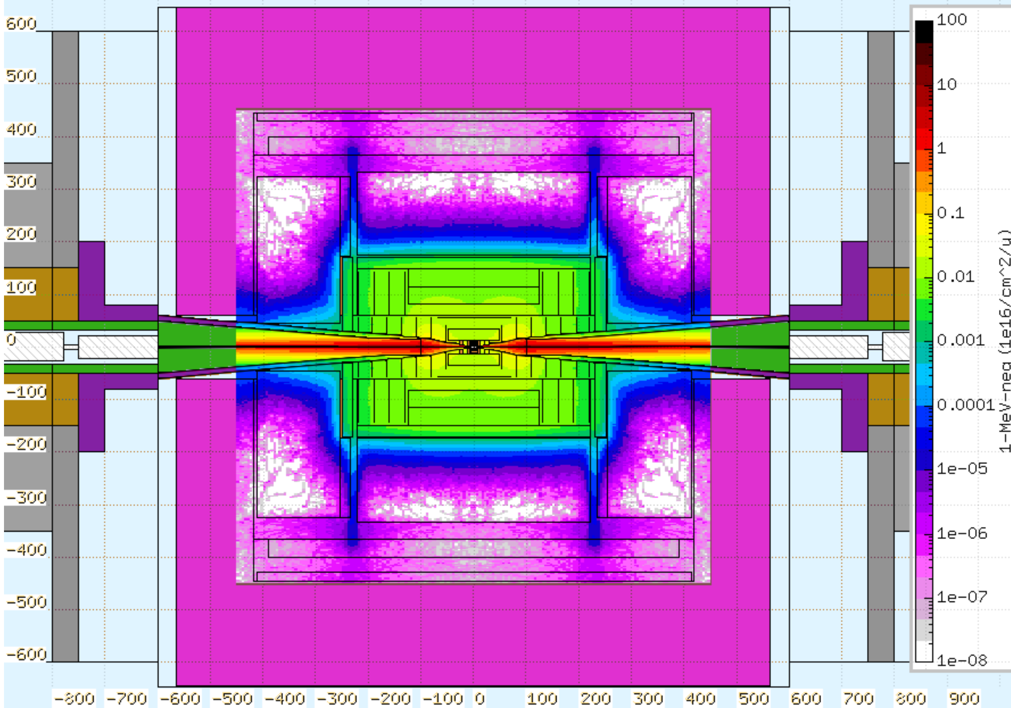
**The machine elements, MDI and interaction region must be properly designed and optimized
@ each collider energy**

Beam Induced Background



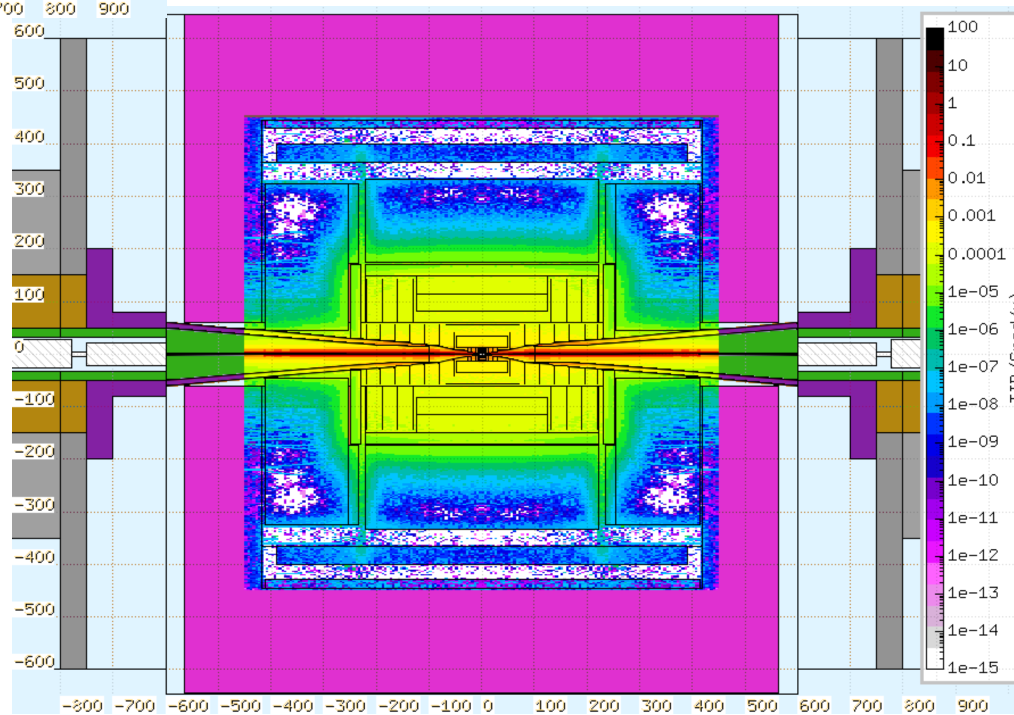
FLUKA simulation





1 MeV n_{eq} fluence/year @ 3 TeV

TID/year @ 3 TeV

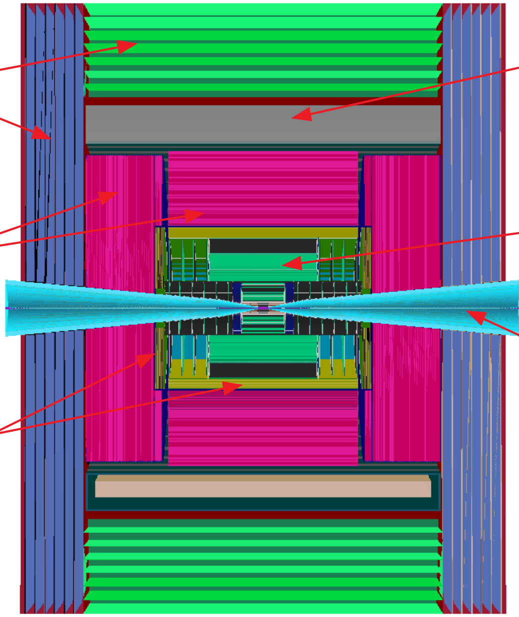


Detector studies @ $\sqrt{s}$ =1.5 TeV

arXiv:2203.07964 Simulated Detector Performance at the Muon Collider
arXiv:2203.07224 Promising Technologies and R&D Directions for the Future Muon Collider Detectors

Synergies with AIDAinnova EU project

- CLIC Detector technologies adopted with important tracker modifications to cope with BIB
- Detector design optimization at $\sqrt{s}$=1.5 (3) TeV



Vertex Detector (VXD)
- 4 double-sensor barrel layers 25x25μm^2
- 4+4 double-sensor disks 25x25μm^2

Inner Tracker (IT)
- 3 barrel layers 50x50μm^2
- 7+7 disks ”

Outer Tracker(OT)
- 3 barrel layers 50x50μm^2
- 4+4 disks ”

Electromagnetic Calorimeter (ECAL)
- 40 layers W absorber and silicon pad sensors, 5x5 mm^2

Hadron Calorimeter (HCAL)
- 60 layers steel absorber & plastic scintillating tiles, 30x30 mm^2

R&D Detector
LGAD
ECAL PbF2 CRILIN
HCAL-gas
mu_picosec

TO BE IMPROVED
TUNED at higher $\sqrt{s}$

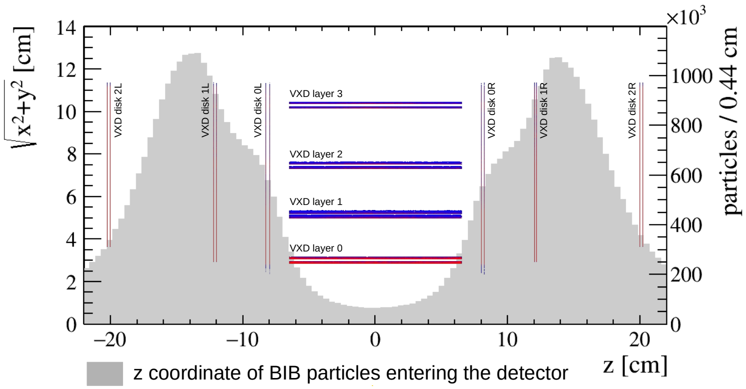
B = 3.57 T to be studied and tuned

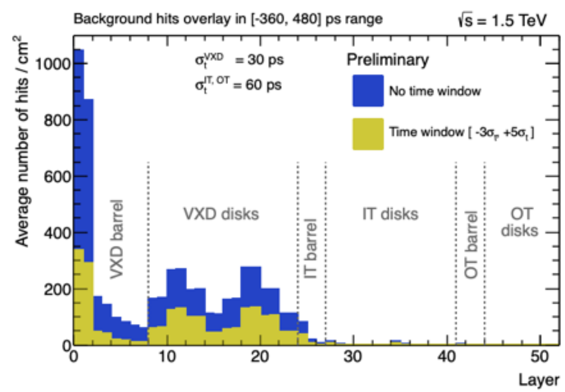
Full simulation available on public repository

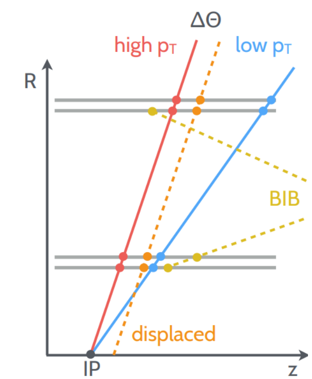
Quite advanced conceptual design for 1.5 TeV and 3 TeV
➔ More R&D on technologies required @ 10+ TeV

Tracker detector @ 1.5 TeV

Max radiation tolerance NIEL: 0.5x 10^{16} neq/cm^2/year
Max radiation tolerance TID: 300 Mrad/year







- Vertex detector properly designed to not overlap with the BIB hottest spots around IR
- Timing window applied to reduce hits from out-of-time BIB
- Granularity optimized to ensure $\lesssim$ 1% occupancy
- Realistic digitization in progress ➔ BIB suppression based on cluster shape
- If primary vertex could be known before ➔ effective angular matching of hit doublets
- To be tuned in presence of secondary vertices or long-lived particles

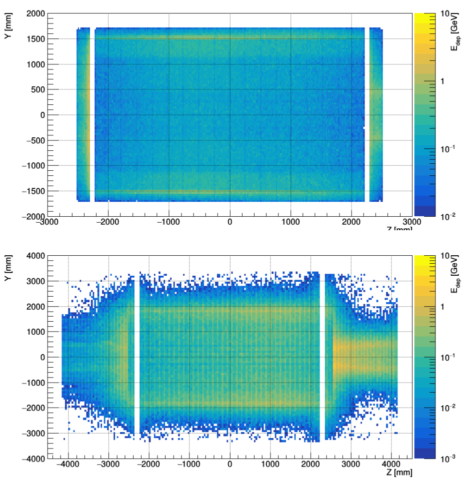
Calorimeters and Muon detectors

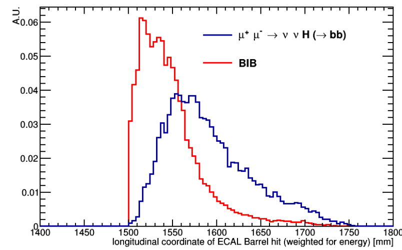
timing and longitudinal measurements play a key role in the BIB suppression

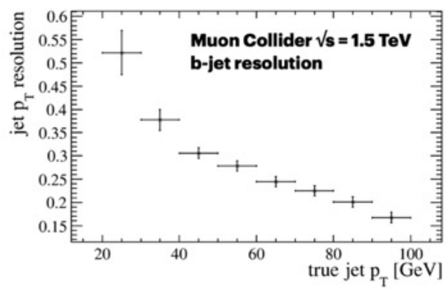
Muon System
Low BIB contribution, concentrated in the low-radius endcap region

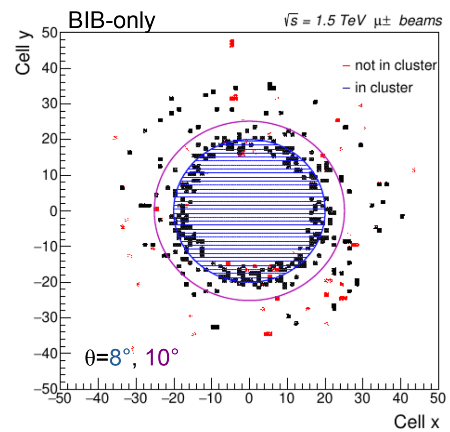
Calorimeters

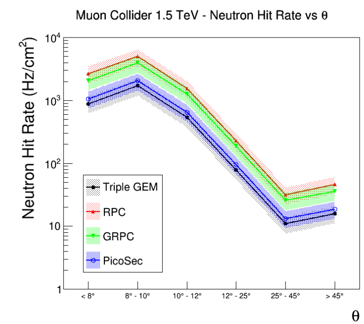
BIB deposits large amount of energy in both ECAL and HCAL



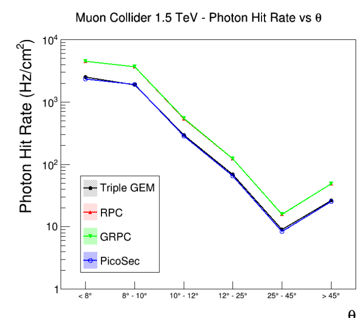


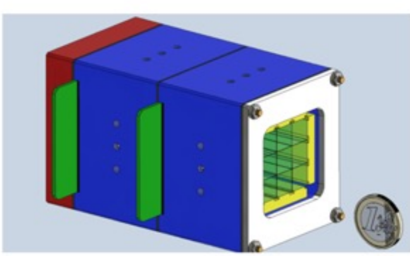


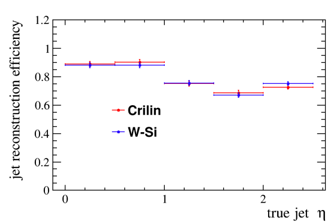


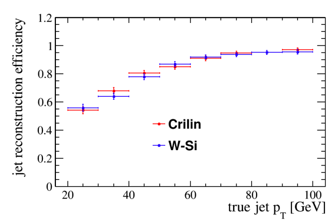


Investigating new technologies for R&D







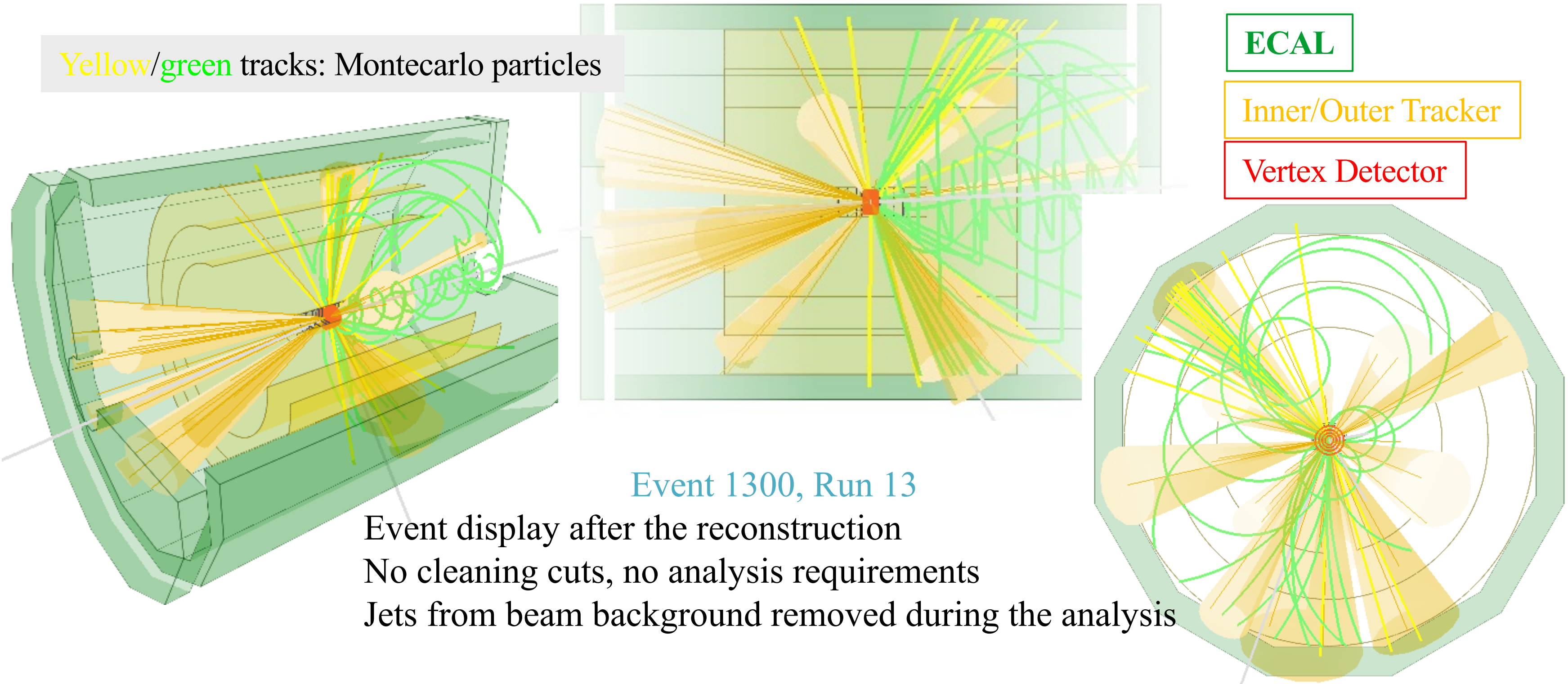


Innovative and computationally efficient event-reconstruction approaches are needed

High Precision Measurements

Donatella Lucchesi et al.

$\mu^+\mu^- \to Hx \to b\bar{b}x$ with Beam-Induced Background at 3 TeV



Event 1300, Run 13

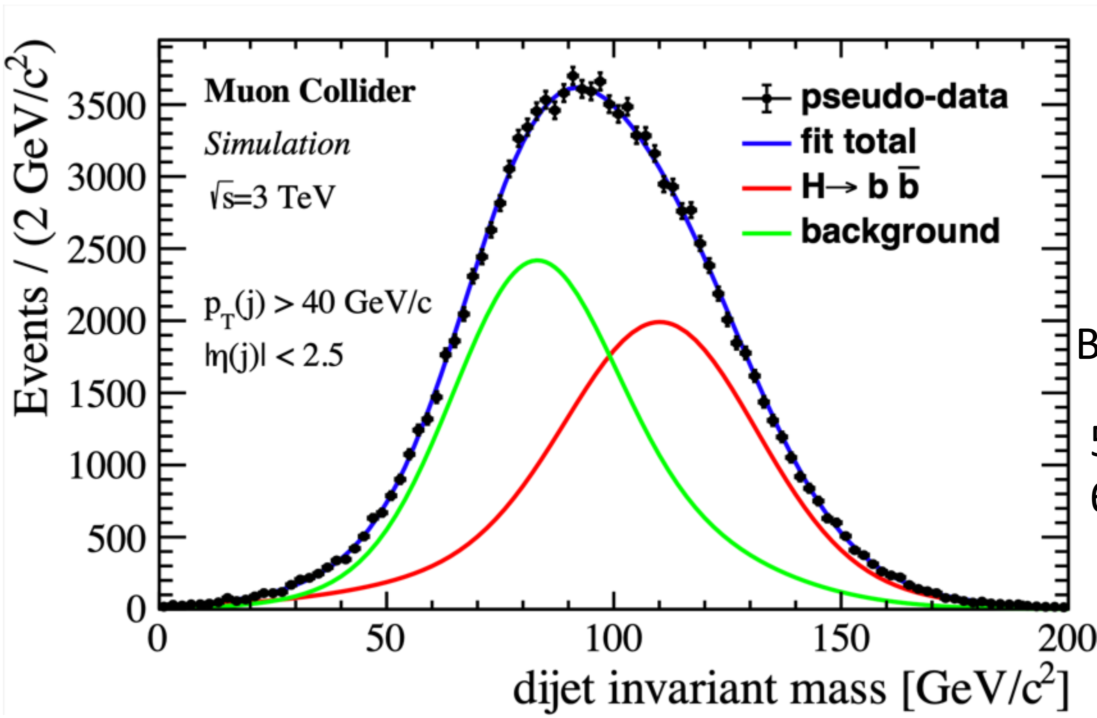
Event display after the reconstruction
No cleaning cuts, no analysis requirements
Jets from beam background removed during the analysis

Different phyiscs benchmark simulated with Beam-Induced Background at 3 TeV to demonstrate feasibility and physics potential reach

arXiv:2203.07261 The physics case of a 3 TeV muon collider stage
arXiv:2203.07964 Simulated Detector Performance at the Muon Collider

$\mu^+\mu^- \rightarrow H(\rightarrow b\bar{b})+X$

@ 3 TeV - 1 ab^{-1}



relative statistical uncertainty on $H \rightarrow b\bar{b}$ cross section of 0.75% found

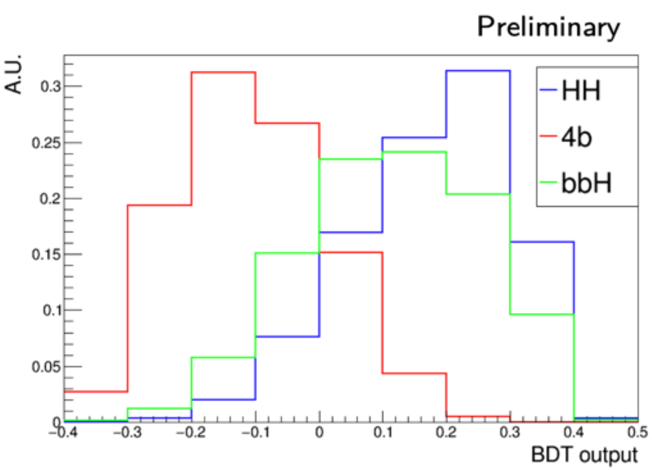
Background $\mu^+\mu^- \rightarrow qq + X$ (with q=b or c)

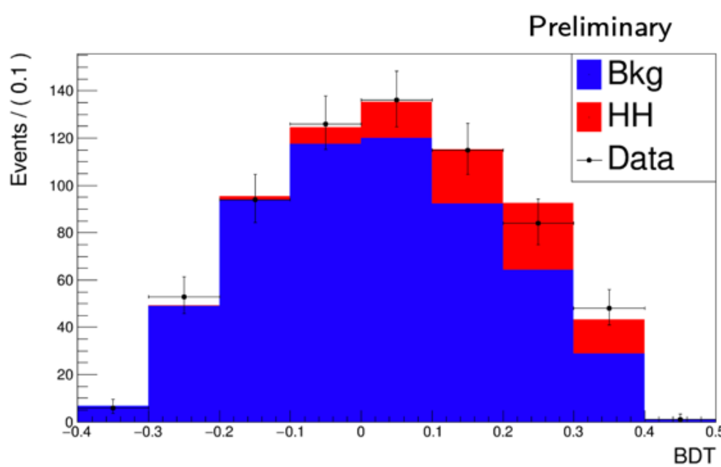
59.5k signal events and
65.4k background events expected

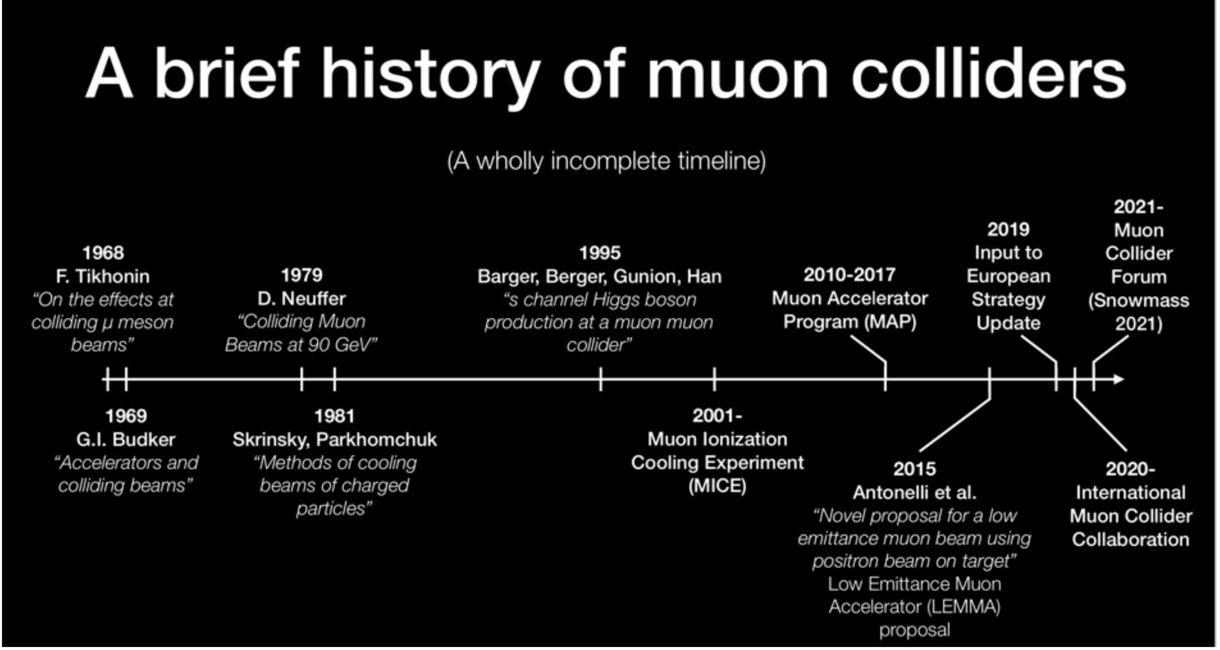
WHIZARD+Pythia8 simulation @ 3 TeV

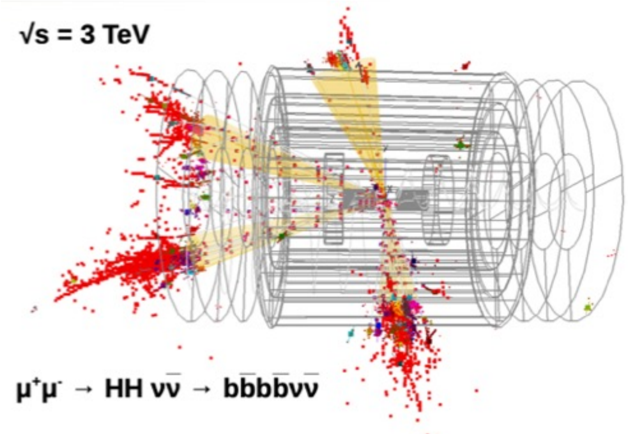
Uncertainty on $HH \rightarrow b\bar{b}b\bar{b}$ cross section of about 30% found

50 HH and 432 background









- New key technologies are becoming available
  ➔ Time scale is becoming realistic for a multi-TeV collider
- New Physics opportunities
  ➔ Higher energy = Higher luminosity
  ➔ Direct searches+precision – reach physics program

Advances in detector and accelerator pair with the opportunities of the physics case

Collaboration Meeting of the Muon Collider Study @ CERN
October 11-14, 2022 https://indico.cern.ch/event/1175126/

Thanks for the attention!

- **CERN website**
  https://muoncollider.web.cern.ch/
- **INFN Confluence website: full simulation**
  https://confluence.infn.it/display/muoncollider
- **International Design Study Indico @ CERN**
  https://indico.cern.ch/category/11818/
- **Muon Collider SnowMass Forum USA**
  https://indico.fnal.gov/event/47038/

Please subscribe at the

CERN e-group "muoncollider":

MUONCOLLIDER-DETECTOR-PHYSICS

MUST-phydet@cern.ch

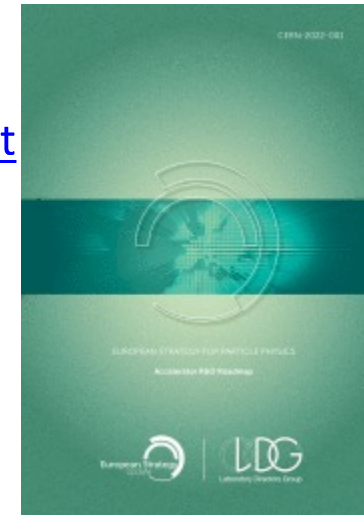
MUONCOLLIDER-FACILITY

MUST-mac@cern.ch

extras

International Design Study facility

- ✓ IMCC started officially on July 3rd 2020: Web site
- ✓ Several institutions are collaborating, US via the Snowmass process
- ✓ Muon collider is part of European Accelerator R&D Roadmap Yellow Report
- ✓ A lot of contributions submitted to the Snowmass process



https://arxiv.org/abs/2203.07256

International MUON Collider Collaboration

March 15, 2022
https://muoncollider.web.cern.ch

Muon Collider Physics Summary

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

https://arxiv.org/abs/2203.07964

International MUON Collider Collaboration

March 16, 2022
https://muoncollider.web.cern.ch

Simulated Detector Performance at the Muon Collider

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

https://arxiv.org/abs/2203.07224

International MUON Collider Collaboration

March 15, 2022
https://muoncollider.web.cern.ch

Promising Technologies and R&D Directions for the Future Muon Collider Detectors

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

https://arxiv.org/abs/2203.08033

International MUON Collider Collaboration

April 1, 2022
https://muoncollider.web.cern.ch

A Muon Collider Facility for Physics Discovery

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

https://arxiv.org/abs/2203.07261

International MUON Collider Collaboration

March 15, 2022
https://muoncollider.web.cern.ch

The physics case of a 3 TeV muon collider stage

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

MUon collider STrategy network – MUST

INFN – CERN (+BINP) – CEA – IJCLAB – KIT – PSI – UKRI – (USA not beneficiary)

May 1, 2021 – April 30, 2024

Task 5.1

....

It will serve as the common ground for a growing international muon-collider collaboration

MUST will support to establish an international collaboration and develop an optimized R&D roadmap towards a future muon collider, including the definition of optimum test facilities and possible intermediate steps

1 January 2022 - 31 December 2025 EU RISE project

aMUSE further provides an excellent platform for an ambitious EU-US network to advance the development of muon beams.

Objectives WP3 – leader: Donatella Lucchesi

- Study techniques of unstable particles beam cooling muon beams at different energies, aiming to validate the simulation with experimental tests
- High energy muon beams: determine the optimal interaction region configuration by studying the beam induced background and new detector technologies able to handle it
- Design and simulate detector for different centre of mass energies
- Evaluate the radiation hazards related to the neutrino flux emitted by the muon beams.

EU project: WP

WP 2: Physics and Detector Requirements

Leader D. Lucchesi Univ. PD + INFN (M. Casarsa) + many + + Univ. PV associated

Link to the physics and detector studies, to provide a database with Beam-Induced Background (BIB) to the physics community and maintain a simplified model of the detector for physics studies. Based on feedback from the physics community, it will provide feedback and guidance to the accelerator design.

WP 3: The Proton Complex

Leader ESS-CERN-UU

key challenge of the proton complex design, the accumulation of the protons in very high-charge bunches and determine the required basic parameters of the complex.

WP 4: The Muon Production and Cooling

Leader STFC-CERN+ UK

Production of the muons by the proton beam hitting a target and the subsequent cooling

WP 5: The High-energy Complex

Leader CEA(Antoine Chance)-CERN-STFC-INFN (F. Collamati – RM1-TO) only MDI

Acceleration and collision complex of the muons. Interaction Region and Machine Detector Interface.

EU project: WP

WP 6: Radio Frequency Systems

Leader CEA(C. Marchand)+INFN(D. Giove- MI - LNL)-CERN++++

Radio Frequency (RF) systems of the muon cooling and the acceleration complex.

WP 7: Magnet Systems

Leader CERN(L. Bottura)-CERN+++ INFN(GE, MI, BO) + Univ. BO associated

Most critical magnets of the muon collider. In particular focus on the solenoids of the muon production and cooling, which are specific to the muon collider. The fast-ramping magnet system, which has ambitious requirements on power flow and power efficiency and limits the energy reach of the collider,

WP 8: Cooling Cell Integration

Leader CERN(R. Losito)+Univ. MI (L. Rossi)-STFC-INFN(M. Statera – mag. e D. Giove – RF)

Design of the muon cooling cell, which is a unique and novel design and which faces integration challenges: interact to address the challenges of the muon collider concept.

Magnet R&D impact on Science and Society

Luca Bottura

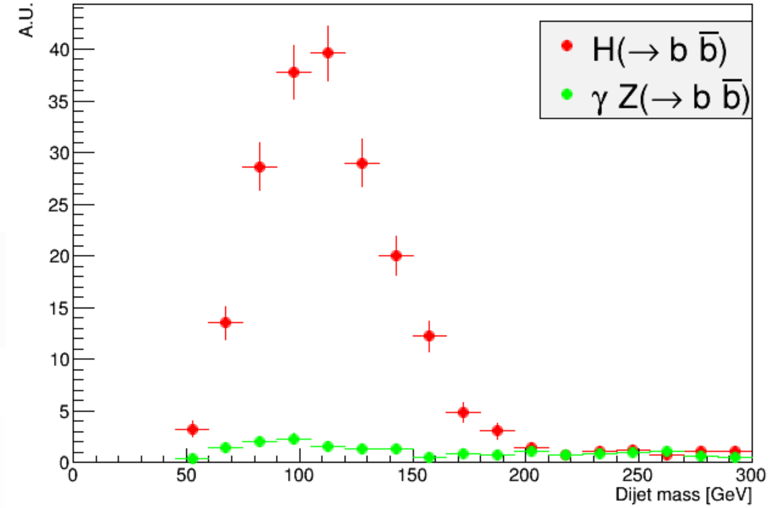
- R&D on the magnet technology necessary for a muon collider has multiple implications for other fields of science, industry and society. Below some relevant examples:
  - The *target solenoid* requires large fields (15 T) in a large bore (2 m), in the range of field and geometry relevant for a full-body MRI of the next generation[1], or solenoid magnets for fusion[2]
  - Ultra-high field solenoids (40…60 T) with modest bore (50 mm) as required by the *final cooling stage* share the challenges of magnets for high-field science[3-5], as well as solenoids for NMR spectroscopy [6]
  - The fast-ramped magnets planned in the acceleration stage (4 T field swing, 400 Hz) are relevant to the development of rapid cycled synchrotrons for intense beams, nuclear physics, medical applications, and accelerator-driven reactors and transmutation systems [7]
  - Energy and power management for the fast ramped magnets in the accelerator complex, typically tens of MJ on the time scale of 1 ms, i.e. tens of GW, share challenges with pulsed power conversion for high-field magnets, as well as energy storage and power management for the power grid
  - Large aperture dipoles and quadrupoles for the collider will profit from the stress-management techniques developed for High-Field Magnets

H→bb @ 1.5 TeV

JINST 15 (2020) 05, P05001

D. Lucchesi et al.

$\mu^+\mu^- \to H\nu\bar{\nu} \to b\bar{b}\nu\bar{\nu}$ + beam-induced background fully simulated



Higgs $b\bar{b}$ Couplings Results

- The instantaneous luminosity, $\mathcal{L}$, at different √s is taken from MAP.
- The acceptance, A, the number of signal events, N, and background, B, are determined with simulation.

$\sqrt{s}$ [TeV]	A [%]	ϵ [%]	$\mathcal{L}$ [cm^{-2}s^{-1}]	$\mathcal{L}_{int}$ [ab^{-1}]	σ [fb]	N	B	$\frac{\Delta\sigma}{\sigma}$ [%]	$\frac{\Delta g_{Hbb}}{g_{Hbb}}$ [%]
1.5	35	15	$1.25 \cdot 10^{34}$	0.5	203	5500	6700	2.0	1.9
3.0	37	15	$4.4 \cdot 10^{34}$	1.3	324	33000	7700	0.60	1.0
10	39	16	$2 \cdot 10^{35}$	8.0	549	270000	4400	0.20	0.91

	$\sqrt{s}$ [TeV]	$\mathcal{L}_{int}$ [ab^{-1}]	$\frac{\Delta g_{Hbb}}{g_{Hbb}}$ [%]
Muon Collider	1.5	0.5	1.9
	3.0	1.3	1.0
	10	8.0	0.91
CLIC	0.35	0.5	3.0
	1.4	+1.5	1.0
	3.0	+2.0	0.9

CLIC numbers are obtained with a model-independent multi-parameter fit performed in three stages, taking into account data obtained at the three different energies.

Results published on JINTST as Detector and Physics Performance at a Muon Collider

Extremely promising

1) muon produced with low emittance ➔ “no/low cooling” needed
2) muon produced already boosted with low energy spread

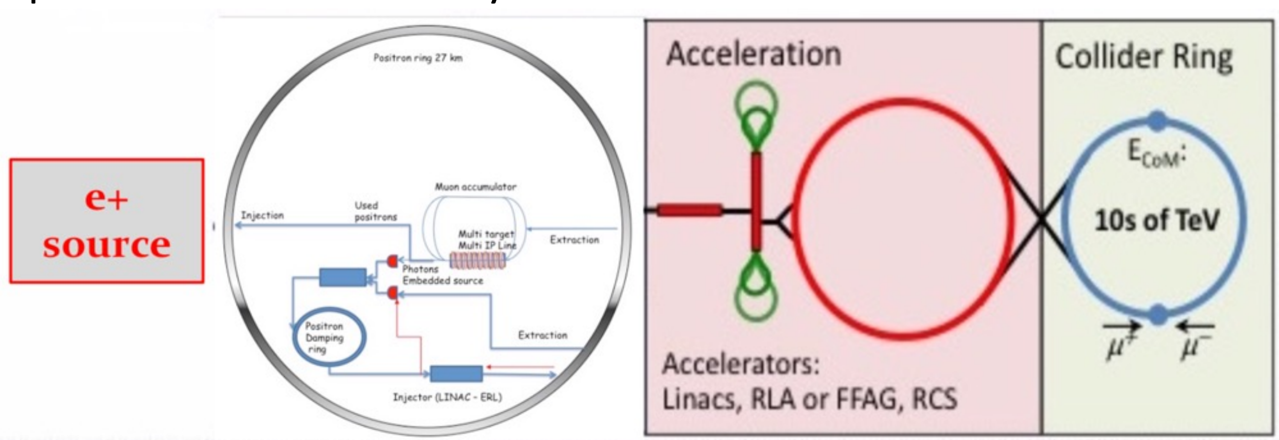
But difficult

1) **Low** production **cross section**: maximum $\sigma(e^+e^- \to \mu^+\mu^-) \sim 1\ \mu$b
2) **Low** prodution **efficiency** ($\sim 9{\times}10^{-8}$ μ per e^+ using a 3 mm Be target)
3) **Bremsstrahlung** (high Z → Z^2) & **multiple scattering** ($\sqrt{X_0}$) in production target
4) **High heat load** and **stress** in μ production target
5) **Synchrotron power** O(100 MW) 🡐 available 45 GeV positron sources

➔ **need consolidation** to overcome technical limitations to reach higher muon intensities
➔ **LEMMA pre-CDR plan** presented to INFN GE by Alessandro Variola October 2019

LEMMA

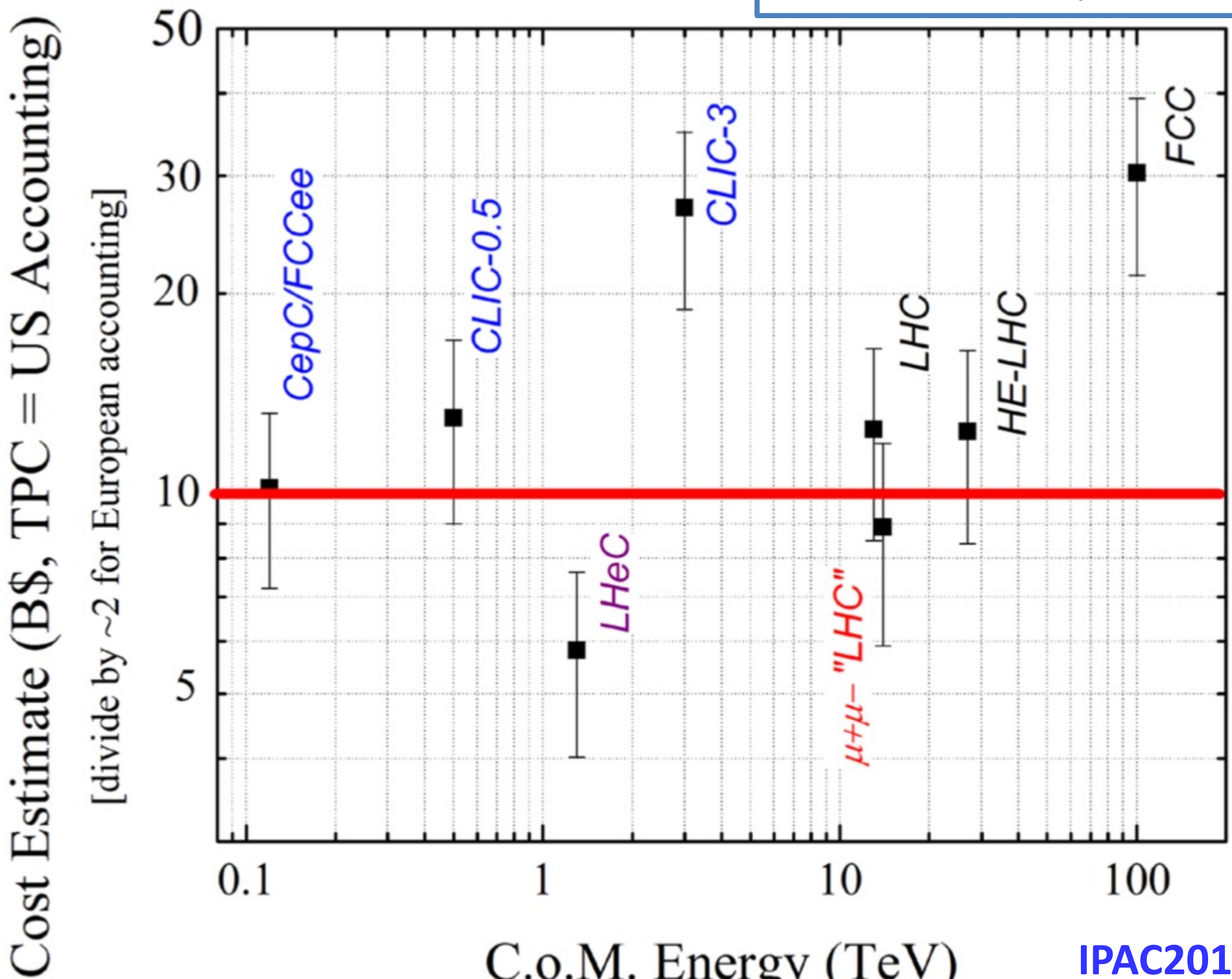
arXiv:1905.05747



Very rough cost estimate

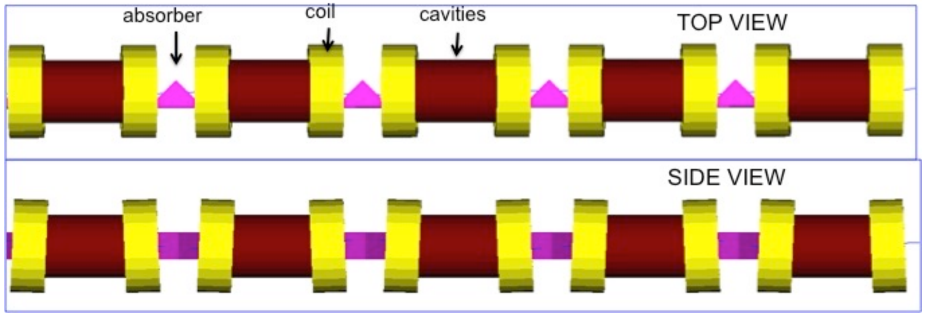
NB: all $$ - "US Accounting" (divide by 2-2.4 at CERN)

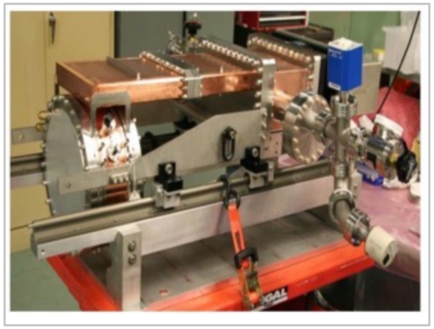
Vladimir SHILTSEV, David NEUFFER (Fermilab)



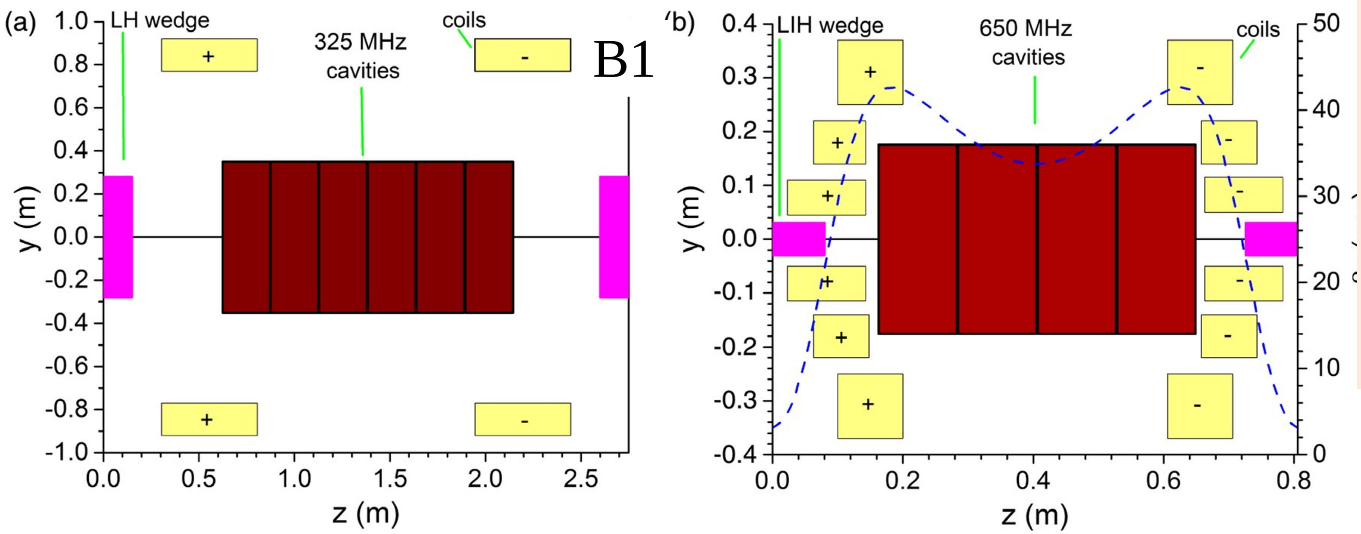
IPAC2018 - MOPMF072

6D Cooling Cell Design





MuCool: >50 MV/m in 5 T
Two solutions
- H2-filled copper cavities
- Cavities with Be end caps

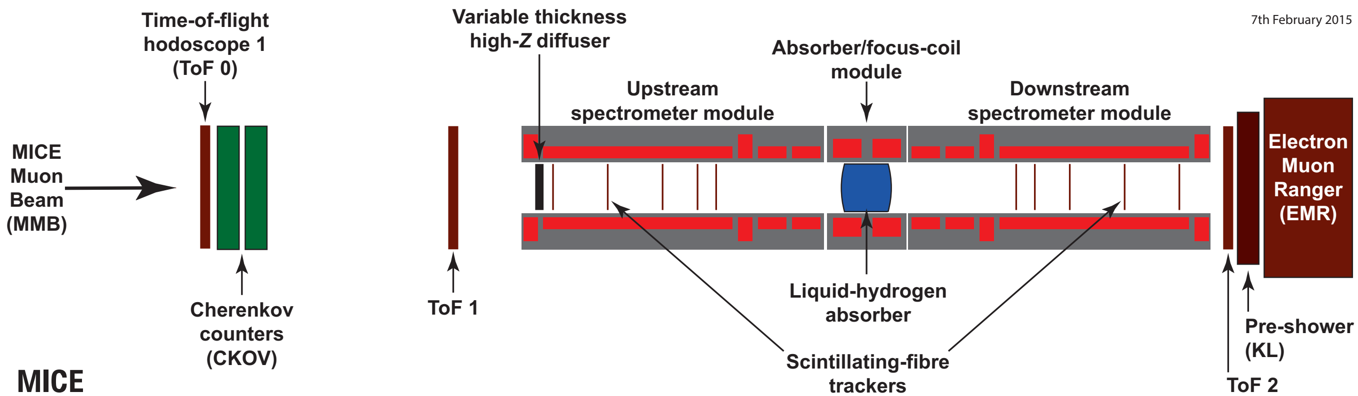


High-gradient cavities in high magnetic field

Tight integration of solenoids, RF, absorbers, instrumentation, cooling, vacuum, alignment, …

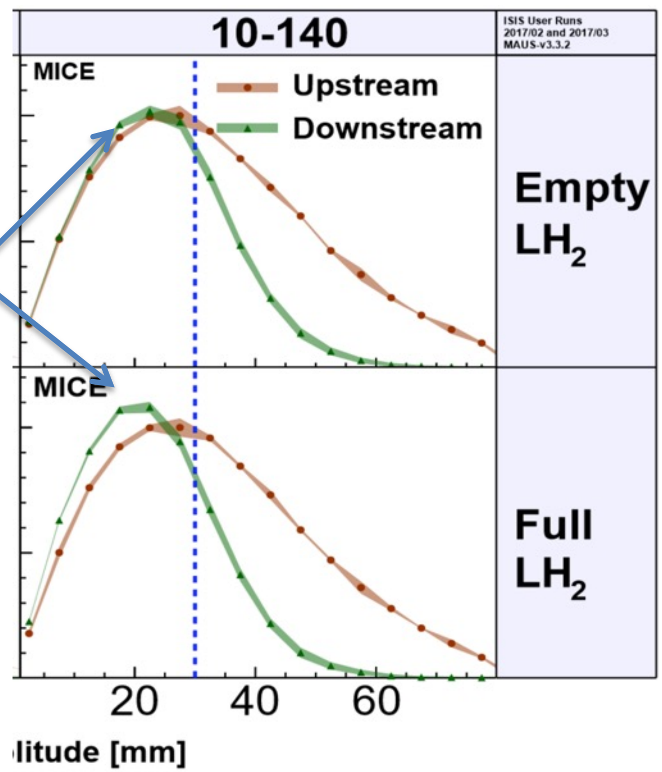
Will aim for further optimisation
This is the **unique** and **novel** system of the muon collider
Will need a **test facility**

MICE (in the UK)



Nature volume 578, pages 53-59 (2020)

More particles at smaller amplitude after absorber is put in place



Principle of ionisation cooling has been demonstrated

More complete experiment with higher statistics, more than one stage required

Integration of magnets, RF, absorbers, vacuum is engineering challenge

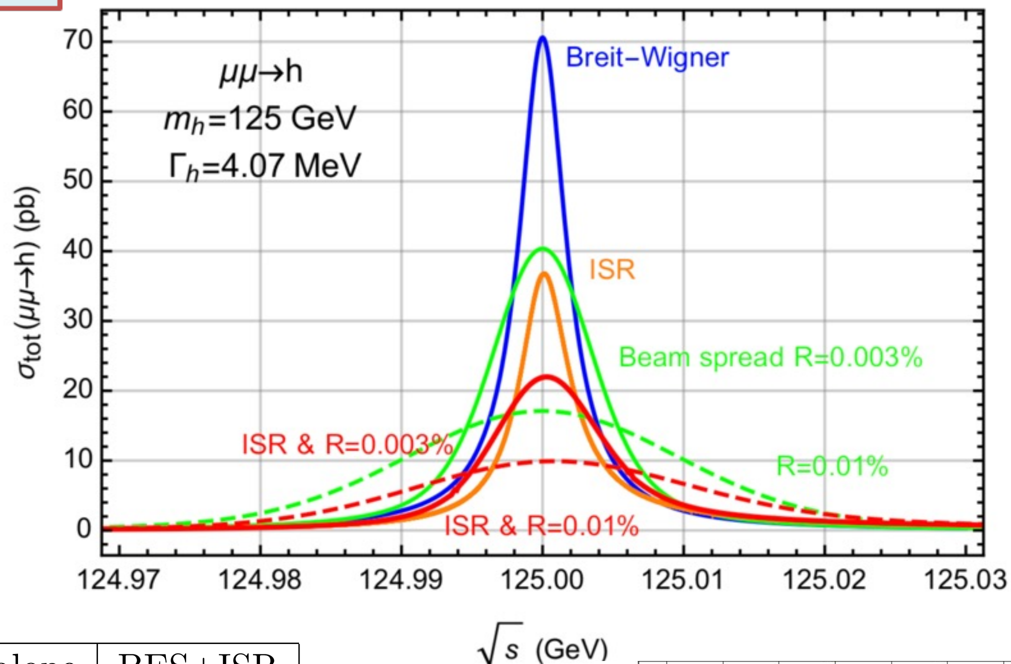
Lepton Colliders: μ vs e @ $\sqrt{s}$=125 GeV

Back on the envelope calculation:

$$\sigma(\mu^+\mu^- \to H) = \left(\frac{m_\mu}{m_e}\right)^2 \times\sigma(e^+e^- \to H) = \left(\frac{105.7MeV}{0.511\,MeV}\right)^2 \times\sigma(e^+e^- \to H)$$

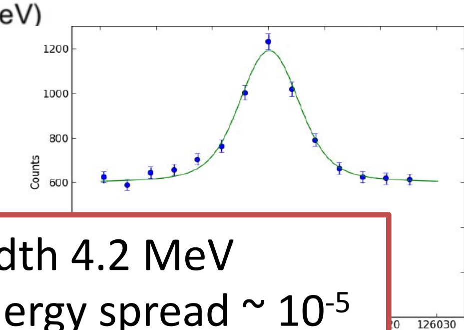
$$\sigma(\mu^+\mu^- \to H) = 4.3\times10^4\times\sigma(e^+e^- \to H)$$

More precise determination
by M. Greco et al. [arXiv:1607.03210v2]



R: percentage beam energy resolution, key parameter

σ(BW)	ISR alone	R (%)	BES alone	BES+ISR
$\mu^+\mu^-$: 71 **pb**	37	0.01	17	10
		0.003	41	22
e^+e^-: 1.7 **fb**	0.50	0.04	0.12	0.048
		0.01	0.41	0.15



Higgs width 4.2 MeV
Beam energy spread ~ 10^{-5}