Seminar – February 6, 2023

The unique opportunity of a multi-TeV Muon Collider

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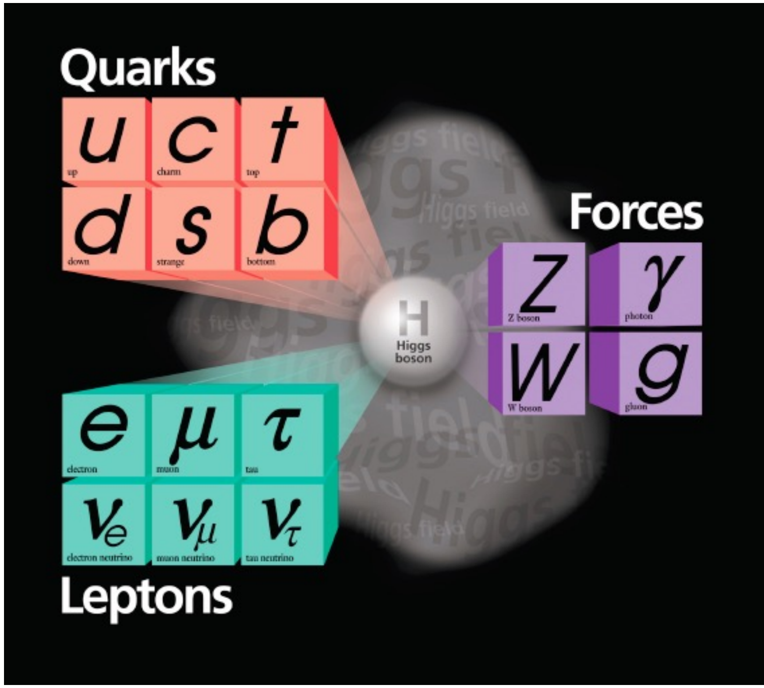
INFN TORINO

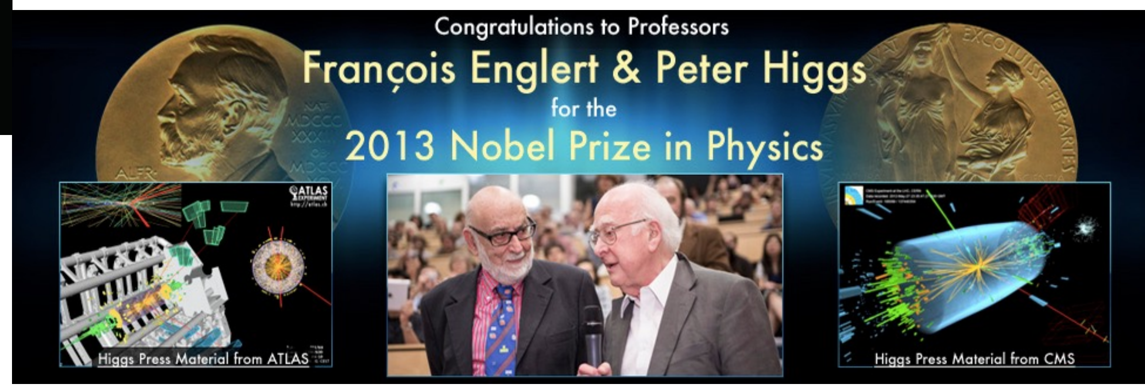
iFAST
Horizon 2020 Research and Innovation programme
under Grant Agreement No 101004730

International MUON Collider Collaboration

Standard Model of Particle Physics



- **Extremely precise measurements and confirmation of SM with great accuracy**
- **No signal of Beyond Standard Model evidence or SUSY**



after 10 years from the Higgs boson discovery

"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

Particle Physics: open questions

Several fundamental questions unexplained:

- ✓ the details of the evolution of the early universe
- ✓ the origin of the matter-antimatter asymmetry of the universe
- ✓ the nature of dark matter and dark energy
- ✓ the origin of neutrino masses
- ✓ the origin of the electroweak scale
- ✓ and the origin of flavor dynamics

The answers must lie in physics beyond the SM (BSM physics)

BSM physics quest

Two options for search and discovery:

✓ **direct search** for new phenomena in physics beyond the SM (BSM physics): many proposals for experiments to directly

✓ **precision measurements** of SM processes to reveal discrepancies between theory and experiment that can indicate BSM physics, potentially at even higher mass or energy scales than can be observed directly

➔ i.e. use the Higgs Boson as a Tool for Discovery

LHC Run3 just restarted in 2022

HL-LHC will be devoted to:

- precisely measure the properties of the Higgs Boson more precisely
- probe the boundaries of the SM further
- possibly observe new physics or point in a particular direction for discovery

Snowmass 2021 on HEP planning exercise

Report (2023)
of the 2021 U.S. Community Study
on the Future of Particle Physics
(Snowmass 2021)
organized by the APS Division of Particles and Fields
FERMILAB-CONF-23-008 SLAC-PUB-17717

Community Summer Study and Workshop
University of Washington in Seattle
July 17 – 26, 2022

New colliders: ultimate tools to extend Energy Frontier program into the next two decades
Combined strategy of precision measurements and high-energy exploration, exploiting future lepton colliders starting at energies as low as the Z-pole up to a few TeV

It will be crucial to find a way to carry out experiments at higher energy scales, directly probing new physics at the 10 TeV energy scale and beyond.

The EF supports a fast start for the construction of an **e^+e^- Higgs Factory** (linear or circular), and a **significant R&D program for multi-TeV colliders (hadron and muon).**
A Higgs Factory will require an immediate, vigorous, and targeted **accelerator and detector R&D program**, while the study towards multi-TeV colliders will need **significant and long-term investments in a broad spectrum of R&D programs for accelerators and detectors**.
Finally, the U.S. EF community has expressed renewed interest and ambition to develop options for an energy-frontier collider that could be sited in the U.S., while maintaining its international collaborative partnerships and obligations with CERN.

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

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

Input to EU Strategy of Particle Physics

European Strategy Update

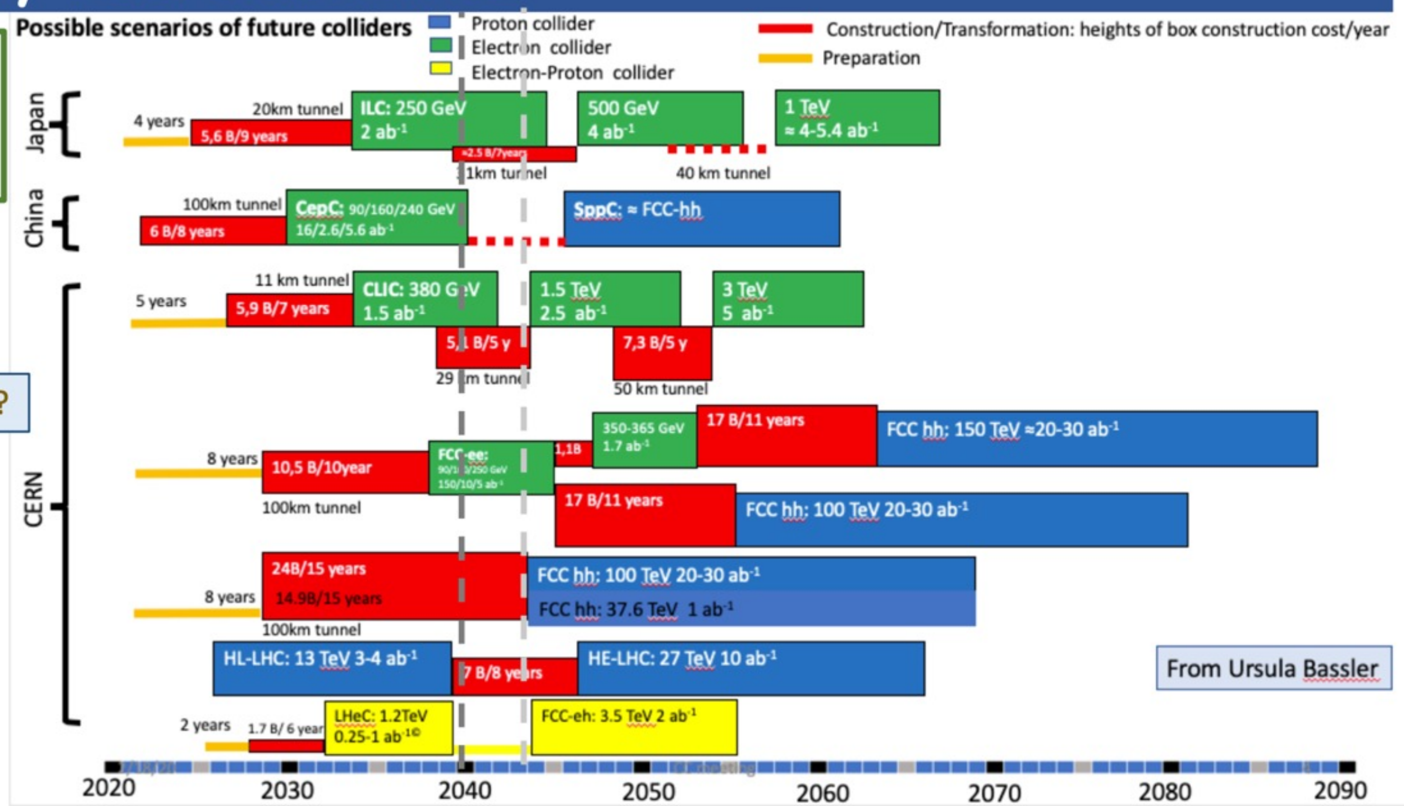
2020 Strategy Update

Halina Abramowicz

High-priority future initiatives

Map of possible future facilities submitted as input to the Strategy Update

Where is the muon collider?



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.

Long-term future: a multi-TeV collider

Snowmass 2021

- **For the next decade and beyond**
  - **2025-2030**:
    - Develop an initial design for a first stage TeV-scale Muon Collider in the US (pre-CDR)
    - Support critical detector R&D towards EF multi-TeV colliders
  - **2030-2035**: Demonstrate principal risk mitigation and deliver CDR for a first-stage TeV-scale Muon Collider
  - **After 2035**:
    - Demonstrate readiness to construct and deliver TDR for a first-stage TeV-scale Muon Collider
    - Ramp up funding support for detector R&D for EF multi-TeV colliders

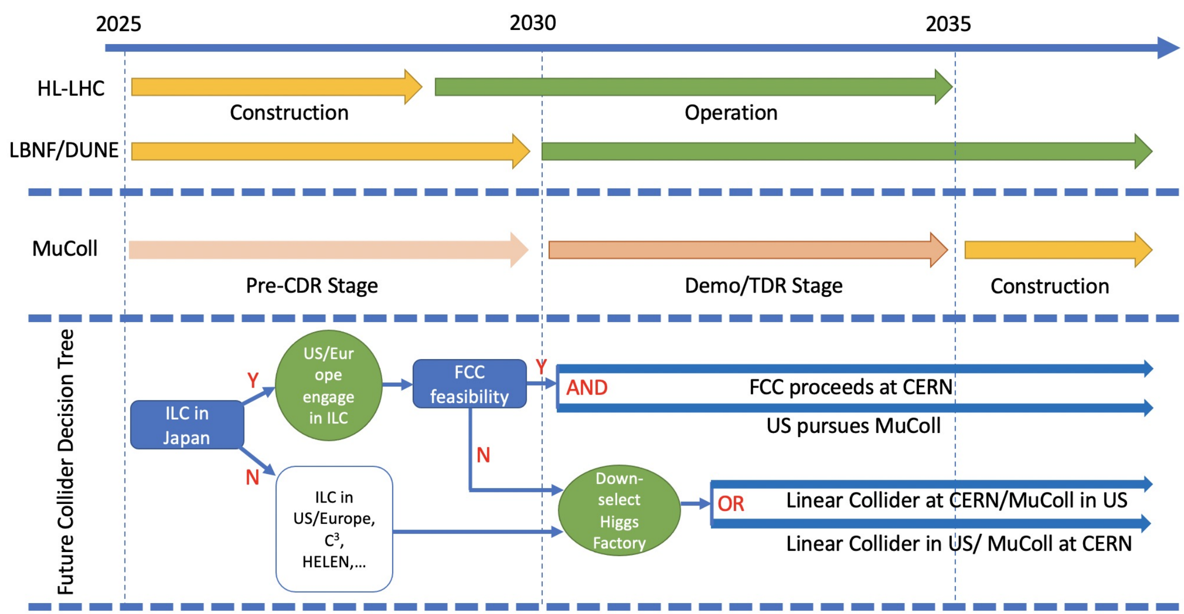
https://arxiv.org/abs/2203.07256

https://arxiv.org/abs/2203.07964

https://arxiv.org/abs/2203.07224

https://arxiv.org/abs/2203.08033

https://arxiv.org/abs/2203.07261



Muon Collider Forum Report

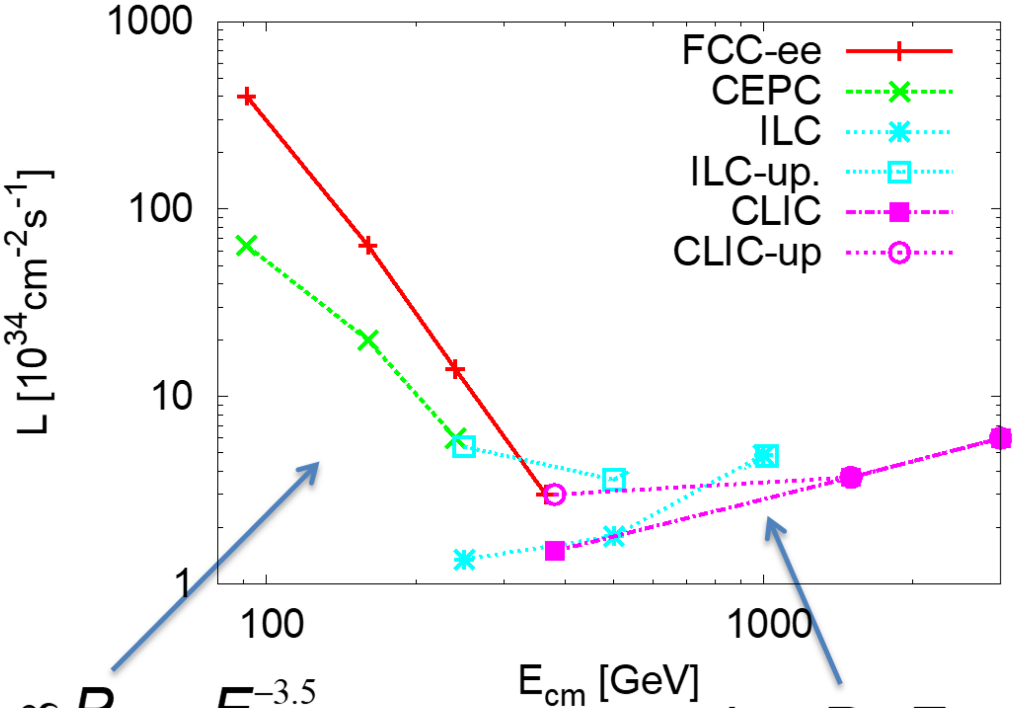
[arXiv:2209.01318](https://arxiv.org/abs/2209.01318) [hep-ex]

Forum Conveners:

K.M. Black, S. Jindariani, D. Li, F. Maltoni, P. Meade, D. Stratakis

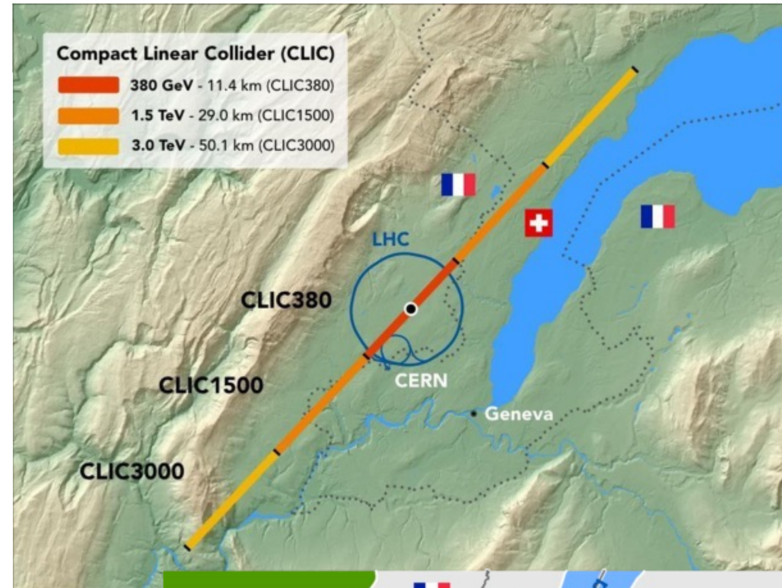
Linear vs Circular lepton e^+e^- collider

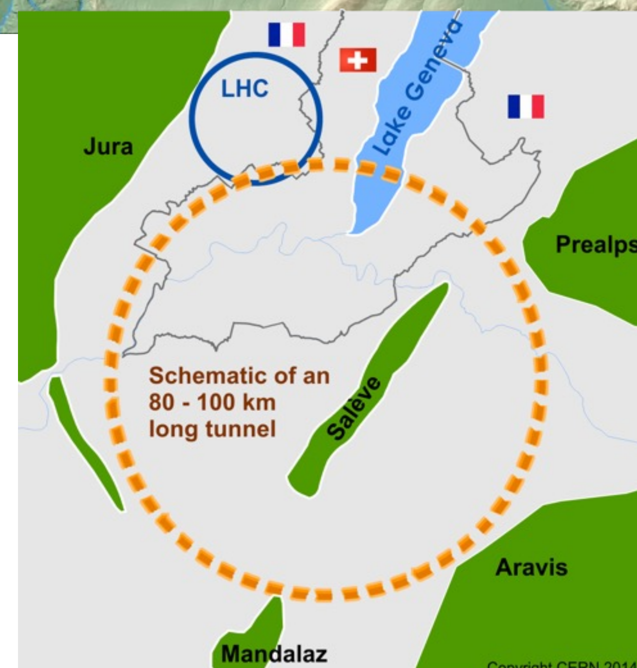
Luminosity per facility



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

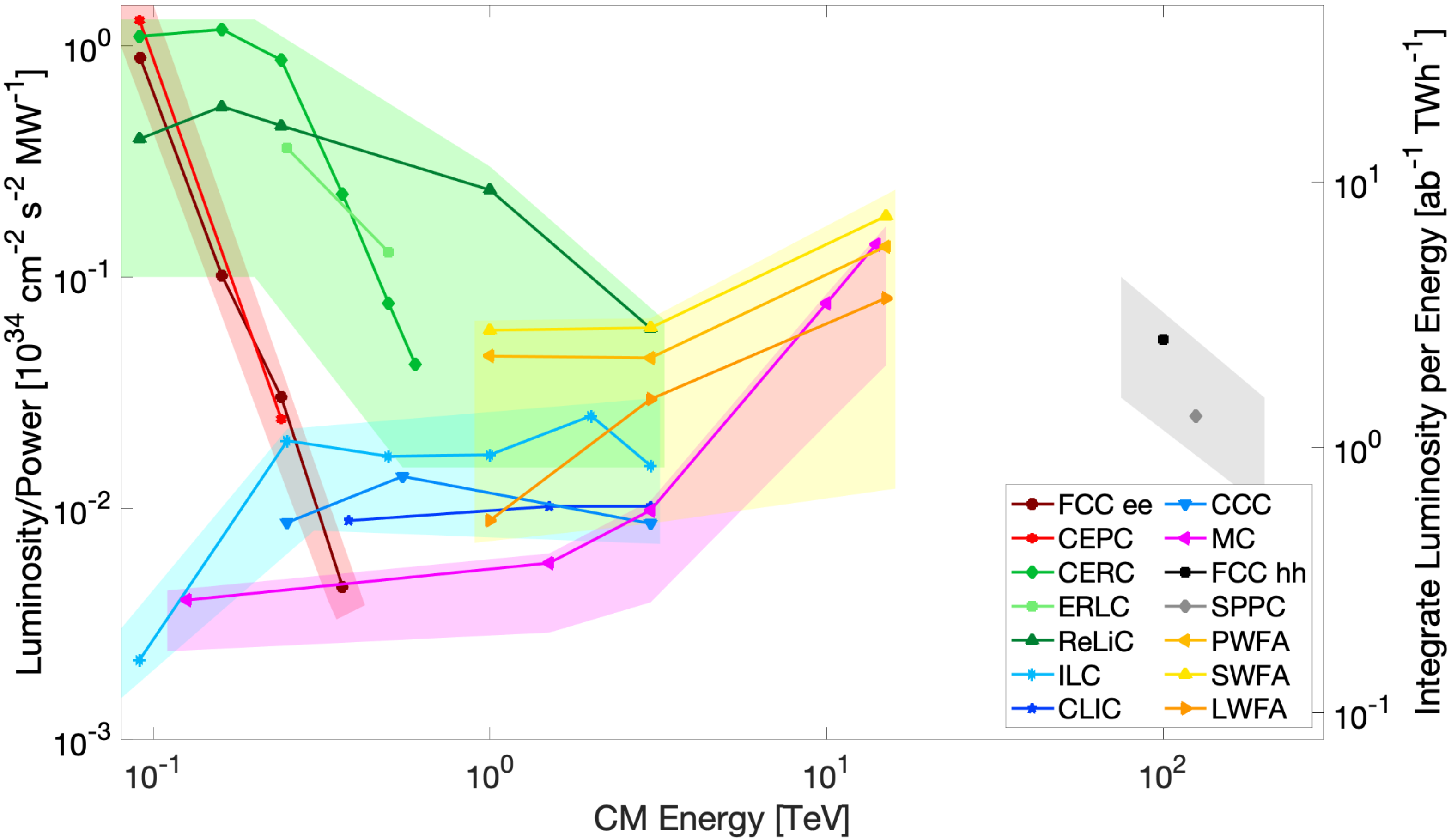
$L \propto P_{RF} E_{cm}$





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

Energy efficiency of present and future colliders



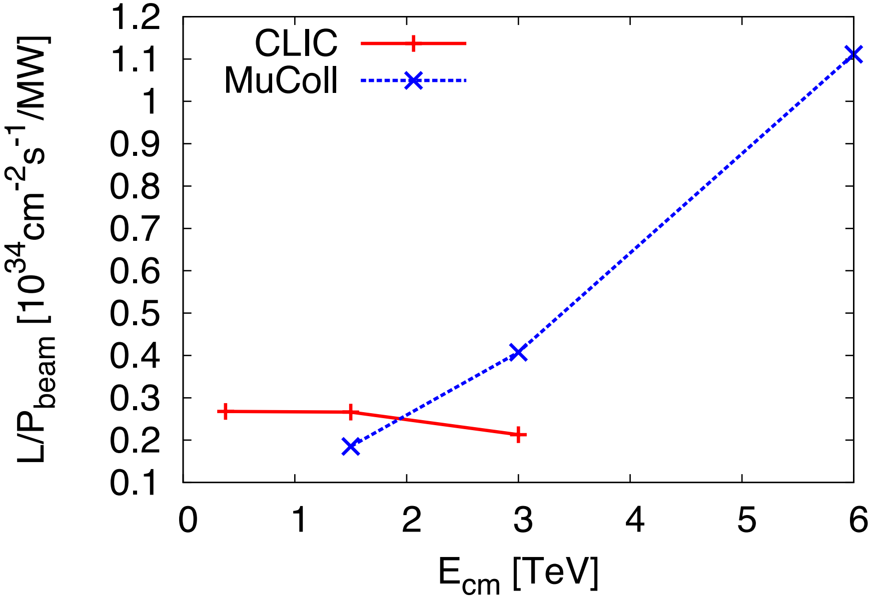
The effective energy reach of hadron colliders (LHC, HE-LHC and FCC-hh) is approximately a factor of seven lower than that of a lepton collider operating at the same energy per beam.

Why a multi-TeV Muon Collider?

cost-effective and unique opportunity

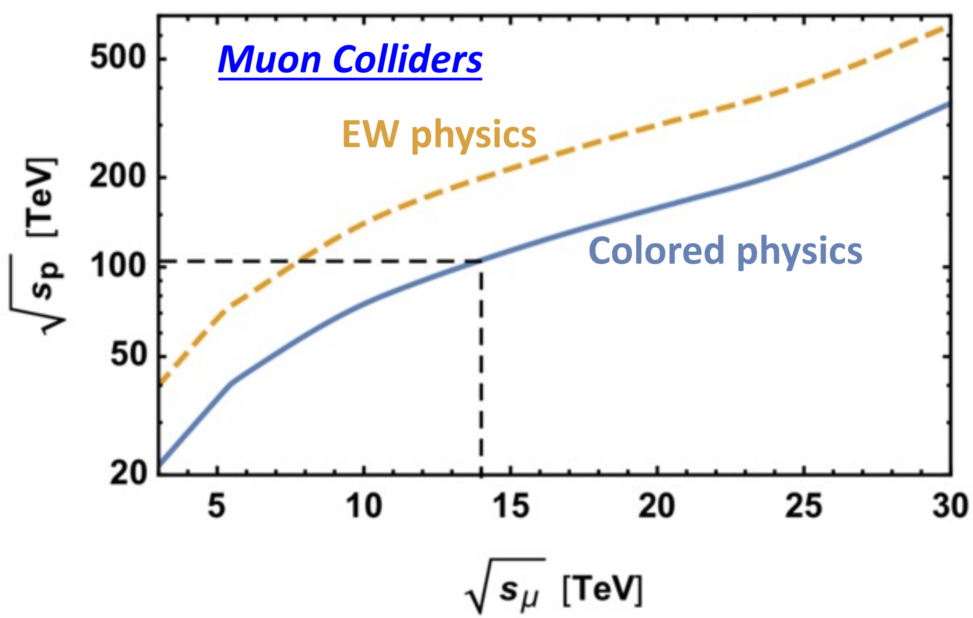
for lepton colliders @ Ecm > 3 TeV

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

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

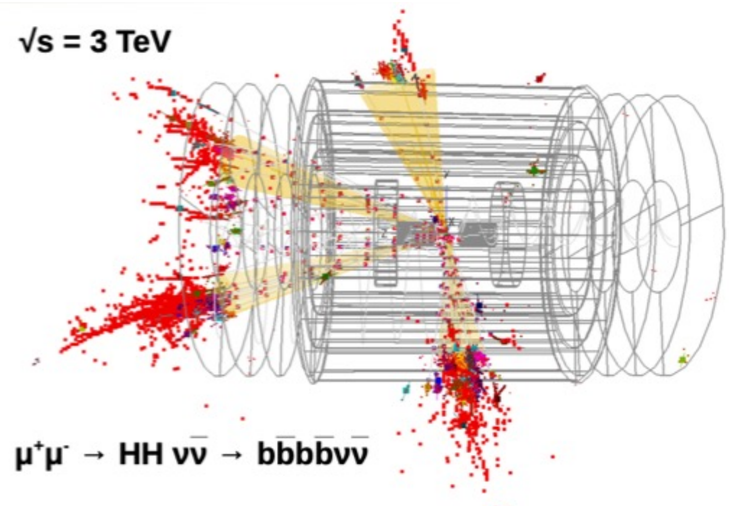
an idea over 50 years old has now the opportunity to become feasible

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**



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

Physics potential

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

Direct searches
Pair production, Resonances, VBF, Dark Matter, …

High-rate measurements
Single Higgs, self coupling, rare and exotic Higgs decays, top quarks, …

High-energy probes
Di-boson, di-fermion, tri-boson, EFT, compositeness, …

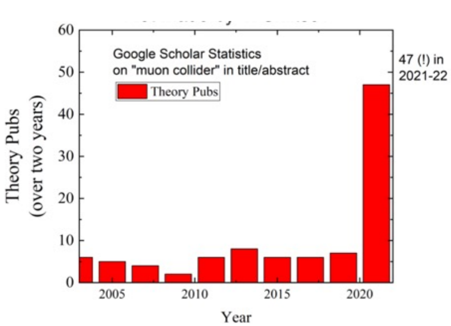
Muon physics
Lepton Flavor Universality, $b \to s\mu\mu$, muon g-2, …

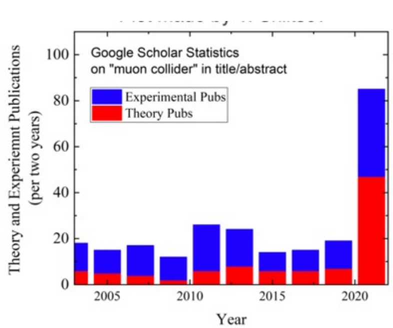
Muon Collider can be the game changer!

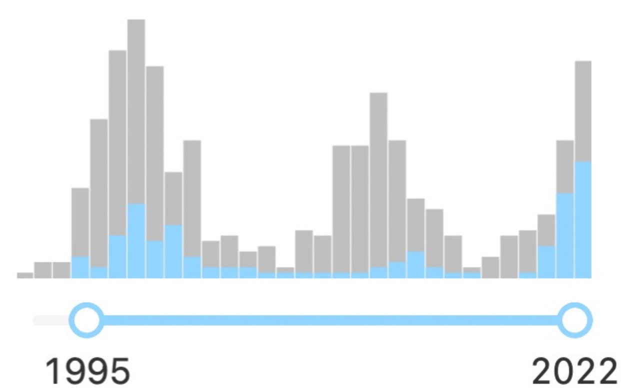
Great and growing interest in the theory community
➔ many papers recently published, as:

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**







Pheno Papers

Muon Collider interest

IMCC Annual Meeting 2022

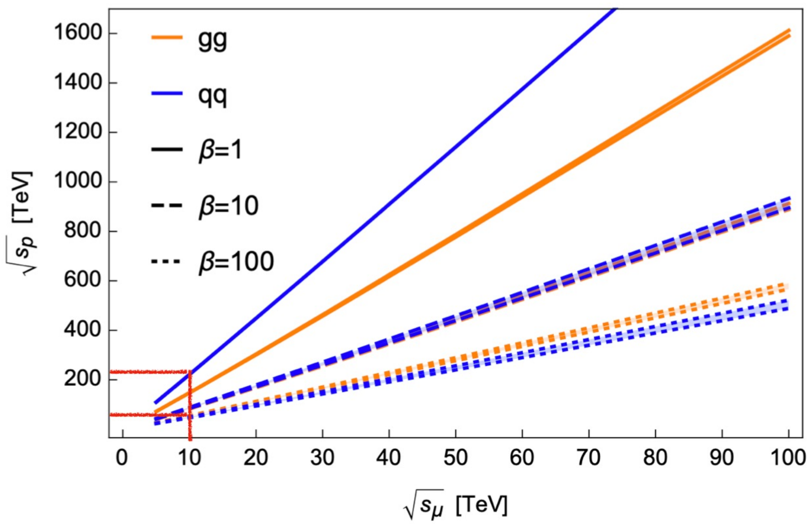
A new interest in a muon collider

2022 papers (including Snowmass)

1. K.M. Black et al., "Muon Collider Forum Report," : 2209.01318 [hep-ex]
2. Arakawa et al. ,"Probing Muon $g-2$ at a Future Muon Collider et al. " e-Print: 2208.14464 [hep-ph]
3. Brendt et al. ,"NLO Electroweak Corrections to Multi-Boson Processes at a Muon Collider, e-Print: 2208.09438 [hep-ph]
4. Yang et al. ,"Shining light on the electroweak 't Hooft-Polyakov magnetic monopoles: the high-energy muon collider" , e-Print: 2208.02188 [hep-ph]
5. Lu et al.,"Unraveling the Scotogenic Model at Muon Collider", e-Print: 2207.07382 [hep-ph]
6. J. De Blas et al., "The physics case of a 3 TeV muon collider stage", arXiv:2203.07261 [hep-ph] (pdf).
7. Inan et al., "Probe of axion-like particles in vector boson scattering at a muon collider" 2207.03325 [hep-ph]
8. Chakraborty et al. " Searches f
9. Azatov et al., "New Physics in
10. Han et al. " BSM Higgs Produ
11. Senol et al. " Model-independ
12. Ji-Chang Yang et al., "Measur ... ep-ph]
13. Haghighat, Search for lepton-
14. S. Homiller et al. "Complemen
15. Aime et al. , "Muon Collider P
16. W. Altmannshofer et al, Snow
17. Bao et al., "Electroweak ALP
18. De Blas et al. ,"Higgs Precisio
19. L. Bottura, et al., " A Work Pro
20. S. Homiller et al., "Compleme
21. Yu. Alexahin et al., "Solving C ... physics.acc-ph]
22. Nazar Bartosiket al. ,"Simulated Detector Performance at the Muon Collider", 2203.07964 [hep-ex]
23. Brad Abbott et al., "Anomalous quartic gauge couplings at a muon collider", 2203.08135 [hep-ex]
24. Tao Han, Tong Li, Xing Wang. "Axion-Like Particles at High Energy Muon Colliders", arXiv:2203.05484 [hep-ph] (pdf).
25. Tao Han, Zhen Liu, Lian-Tao Wang, Xing Wang. "WIMP Dark Matter at High Energy Muon Colliders", arXiv:2203.07351 [hep-ph] (pdf).
26. D. Ally, L. Carpenter, T. Holmes, L. Lee, P. Wagenknecht. "Strategies for Beam-Induced Background Reduction at Muon Colliders", arXiv:2203.06773 [physics.ins-det] (pdf).
27. Sergo Jindariani, Federico Meloni, Nadia Pastrone, et al. "Promising Technologies and R&D Directions for the Future Muon Collider Detectors", arXiv:2203.07224 [physics.ins-det] (pdf).
28. D. Stratakis, N. Mokhov, M. Palmer, N. Pastrone, T. Raubenheimer, C. Rogers, D. Schulte, et al. "A Muon Collider Facility for Physics Discovery", arXiv:2203.08033 [physics.acc-ph] (pdf).
29. Nazar Bartosik, Karol Krizka, Simone Pagan Griso, Chiara Aimè, Aram Apyan, et al. "Simulated Detector Performance at the Muon Collider", arXiv:2203.07964 [hep-ex] (pdf).
30. K. Black, T. Bose, S. Dasu, H. Jia, S. Lomte, C. Vuosalo. et al. "Prospects for the Measurement of the Standard Model Higgs Pair Production at the Muon Colliders", arXiv:2203.08874 [hep-ex] (pdf).
31. Matthew Forslund, Patrick Meade. "High Precision Higgs from High Energy Muon Colliders", arXiv:2203.09425 [hep-ph] (pdf)
32. ……

Excitement building up on many innovative aspects from accelerators, to detectors, to an "unexpected" physics reach.
A growing interest in the community has allowed to put efforts in identifying the key
1] technologies that make a muon collider possible.
2] physics motivations that make a muon collider worth it

Muon Collider physics potential



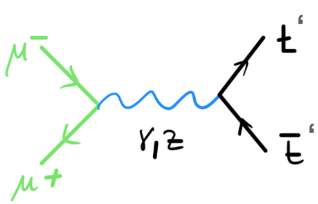
muC@10 TeV ~ pp@70 TeV

Simple/Naive/Rough estimate based on parton-parton luminosity for a generic $2 \rightarrow 2$ scattering.

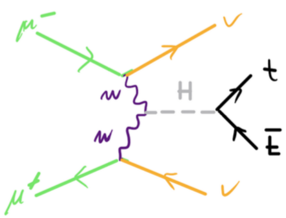
$EW : \beta \sim 1$

$QCD : \beta \sim (\alpha_S/\alpha)^2 \sim 100$

O(10) TeV muon collider energy allows to have two colliders in one:



$$\sigma_s \sim \frac{1}{s} \quad \Longleftrightarrow \quad \sigma_s \sim \frac{1}{M^2} \log^n \frac{s}{M}$$



Energetic final states (either heavy or very boosted)

Large production rates, SM coupling measurements Discovery light and weakly interacting

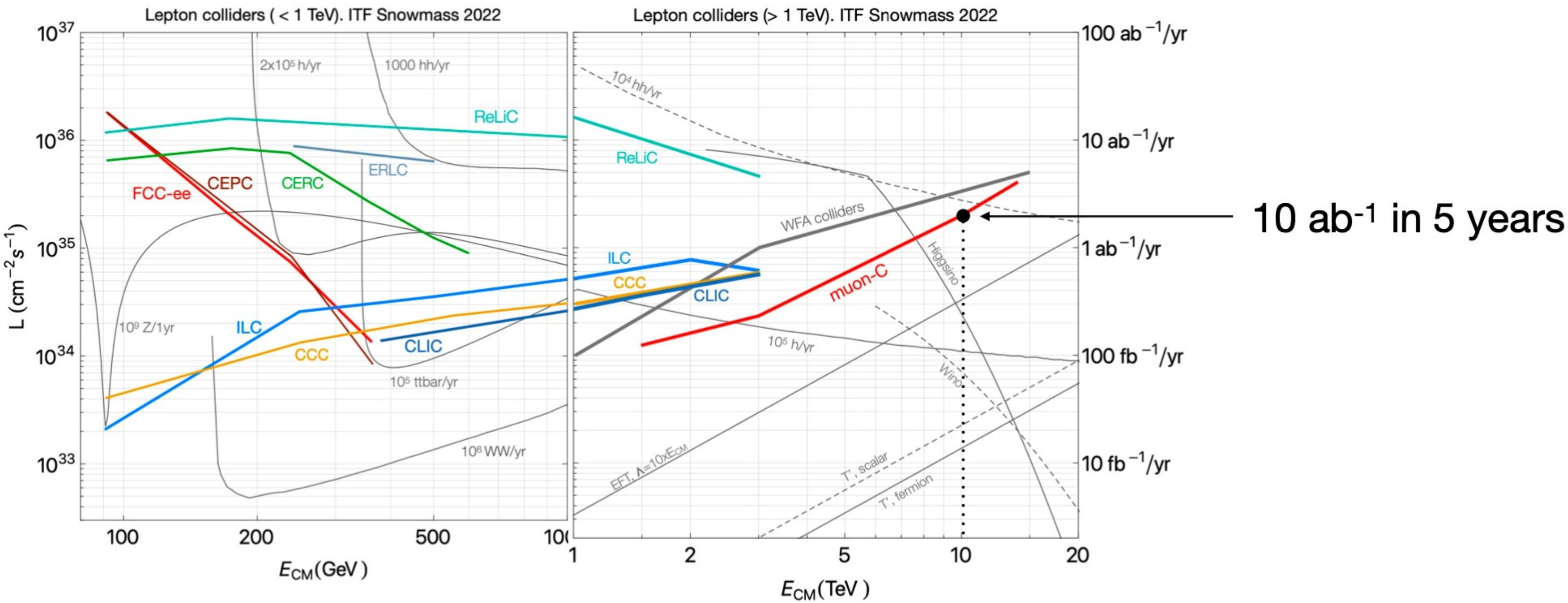
A completely new regime opening for a multi-TeV muon collider

Different physics being probed in the two channels

Luminosity vs Energy @ 10 TeV

Report of the Snowmass 2021 Collider Implementation Task Force

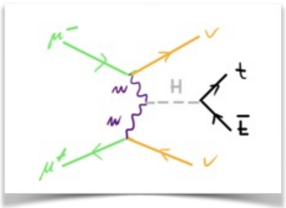
$$\widehat{\mathcal{L}} = 10\,\mathrm{ab}^{-1}\left(\frac{E_{\mathrm{cm}}}{10\,\mathrm{TeV}}\right)^2$$

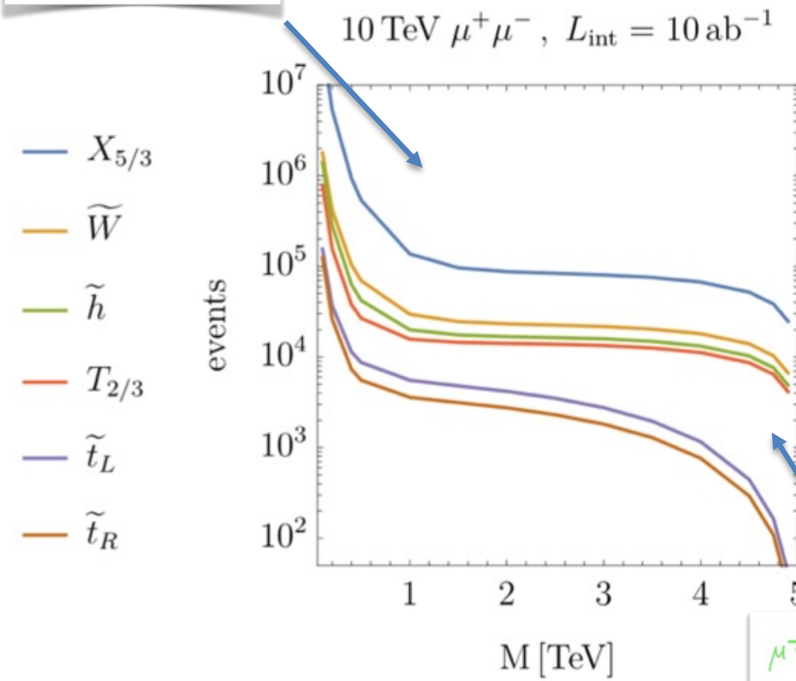


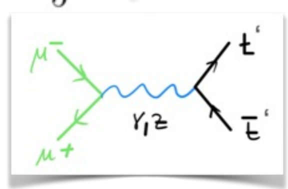
A O(10TeV) Muon Collider would radically change the way we do collider physics, opening the exploration of EW phenomena at higher scales through an hybrid direct/indirect approach in a clean environment

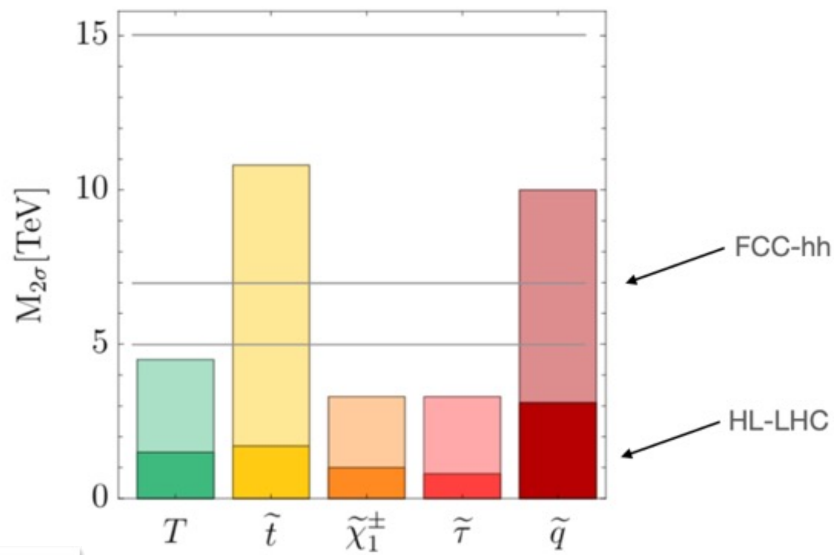
Direct rearch: s-channel pair production

[arXiv:2203.07256](https://arxiv.org/abs/2203.07256) **Muon Collider Physics Summary**
[arXiv:2203.07261](https://arxiv.org/abs/2203.07261) **The physics case of a 3 TeV muon collider stage**
[arXiv:2209.01318](https://arxiv.org/abs/2209.01318) **Muon Collider Forum Report**





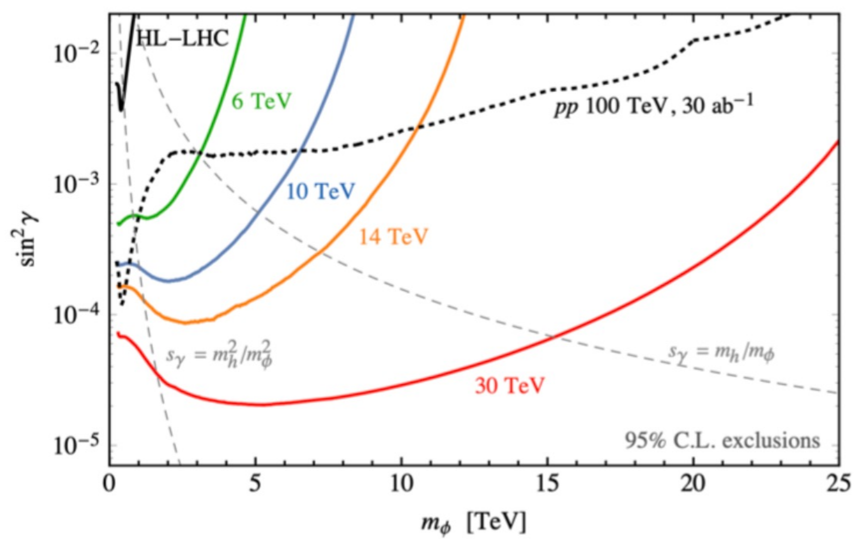




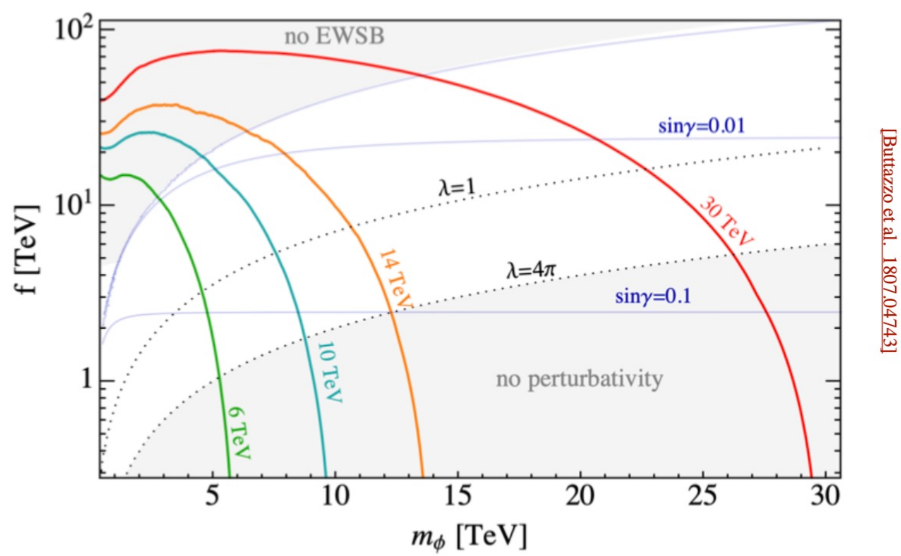
A few months of run could
be sufficient for a discovery

Direct rearch: VBF scalar singlet production

[arXiv:2203.07256] **Muon Collider Physics Summary**
[arXiv:2209.01318] **Muon Collider Forum Report**



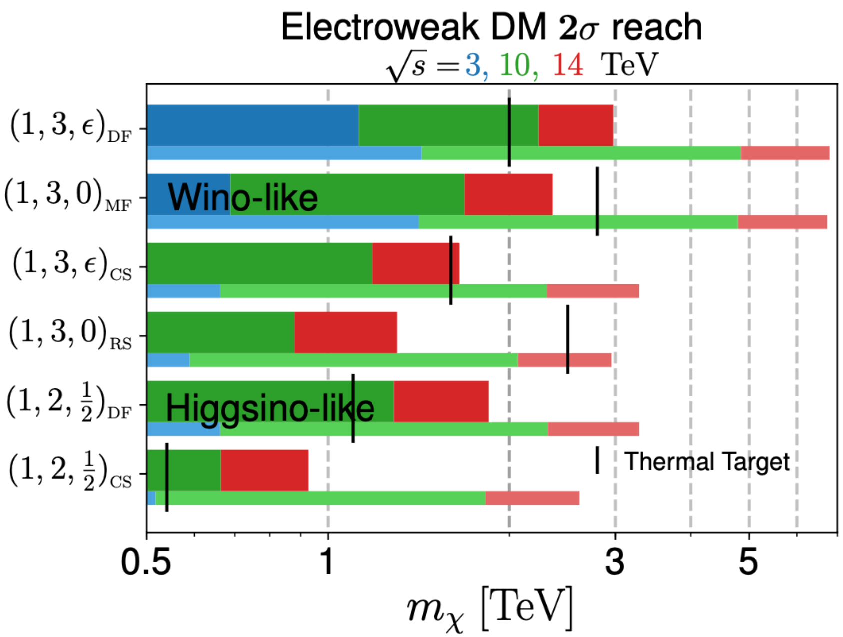
Exclusion contour for a scalar singlet of mass mφ mixed with the Higgs boson with strength sin γ.



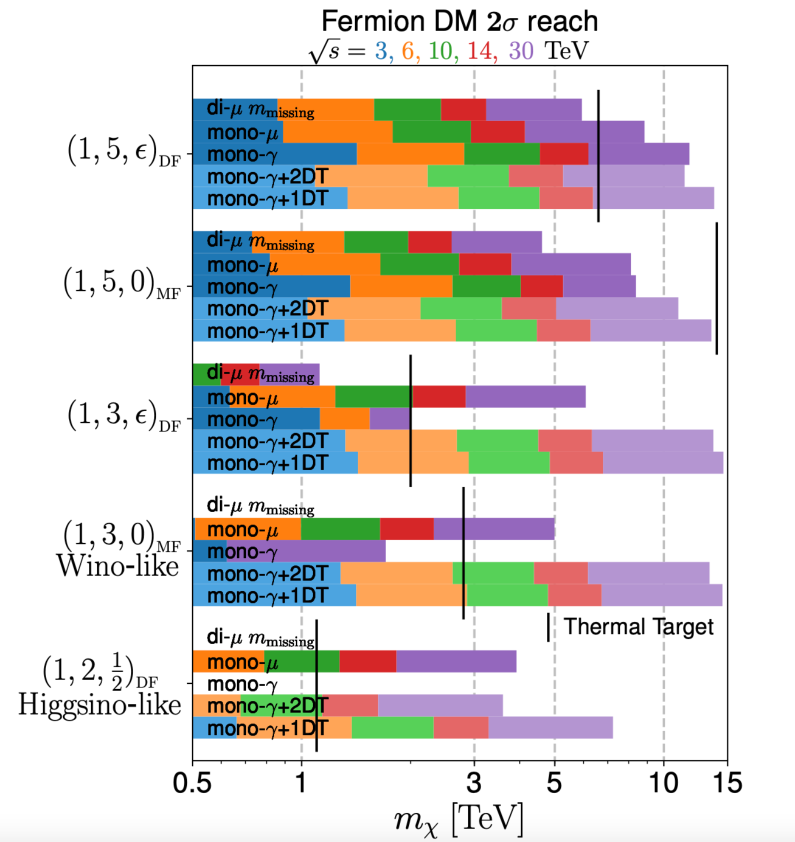
Reach in terms of the scale f in the Twin Higgs model

Direct rearch: minimal DM

arXiv:2209.01318 **Muon Collider Forum Report**



2σ exclusion of DM masses with horizontal (thick) bars for combined channels and various muon collider running scenarios by the different color codes. The thin bars are the estimation of the mono-photon plus one disappearing track search. The vertical bars indicate the thermal mass targets for the corresponding WIMP DM.

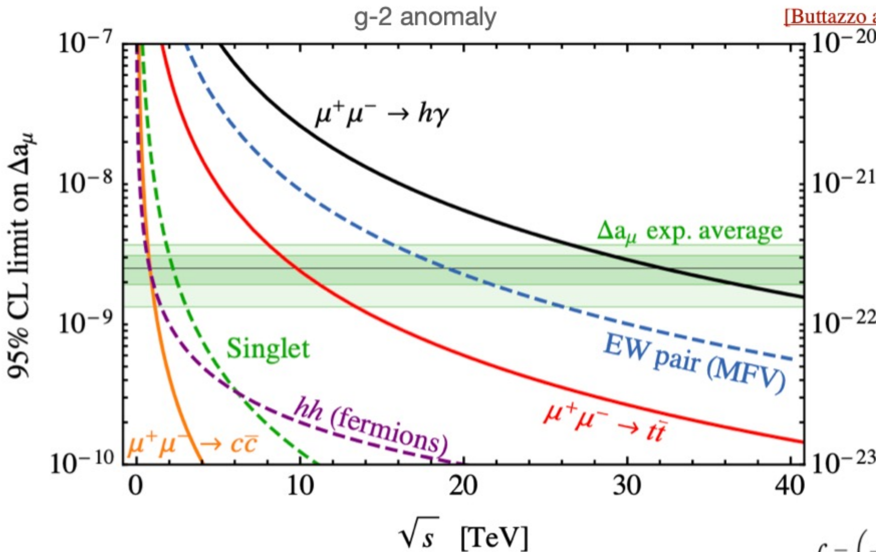


2σ exclusion of fermion DM masses with horizontal bars for individual search channels and muon collider energies by the different colors. The vertical bars indicate the thermal mass targets.

Anomalies: g-2 and B-anomalies: EFT scenarios

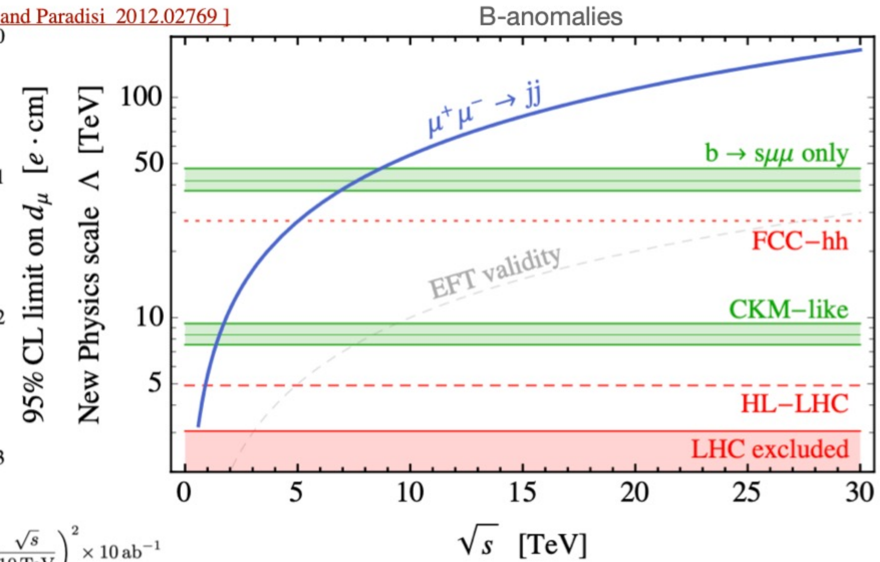
arXiv:2203.07256 **Muon Collider Physics Summary**

[Buttazzo and Paradisi 2012.02769]



Reach on the muon g-2 from high-energy measurements (solid lines), and from direct searches for new particles in explicit models (dashed lines).

$$\mathcal{L} = \left(\frac{\sqrt{s}}{10\,\mathrm{TeV}}\right)^2 \times 10\,\mathrm{ab}^{-1}$$



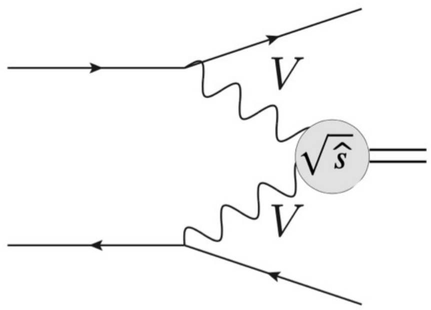
Reach from μμ → jj (solid line) on the scale Λ of semi-leptonic interactions that can account for the B-anomalies.

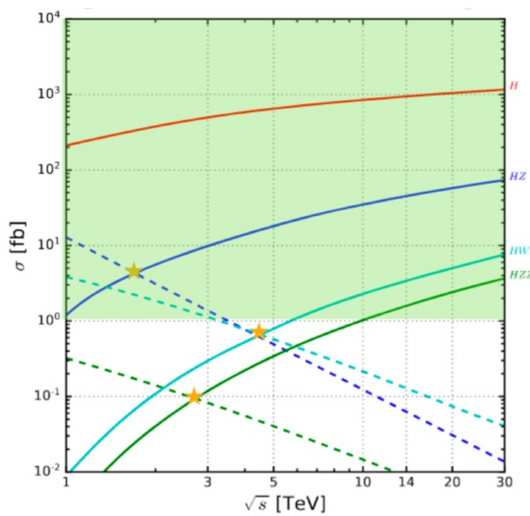
See also [Arakawa et al. 2208.14464]

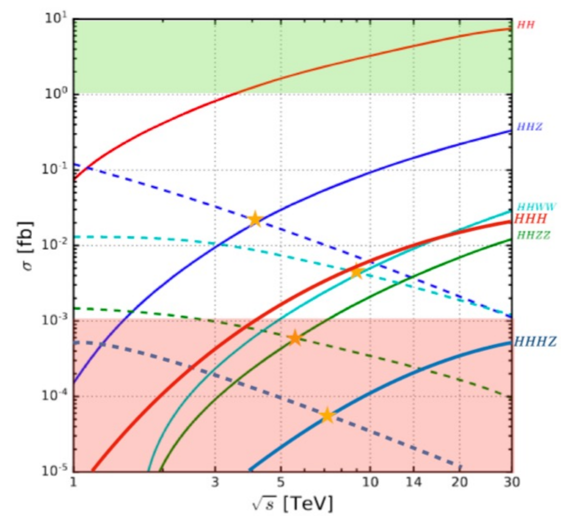
See also: [Azatov et al. 2205.13552]

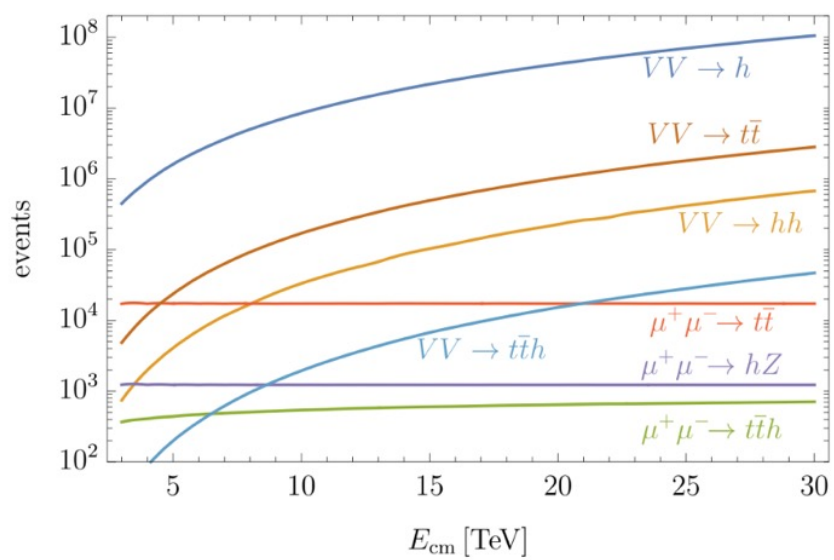
Precision physics: Vector Boson Collider

[arXiv:2203.07256](https://arxiv.org/abs/2203.07256) **Muon Collider Physics Summary**









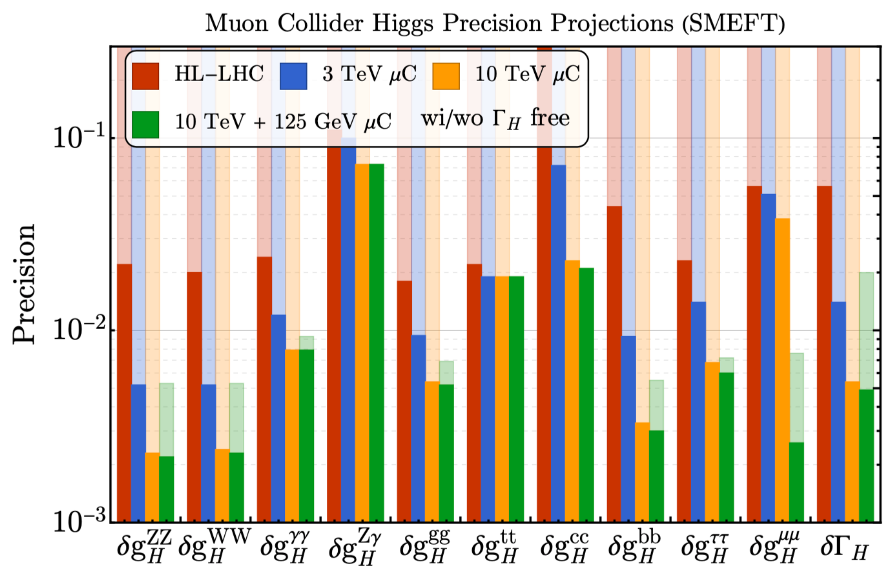
Higgs precision physics

arXiv:2203.07256 **Muon Collider Physics Summary**

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



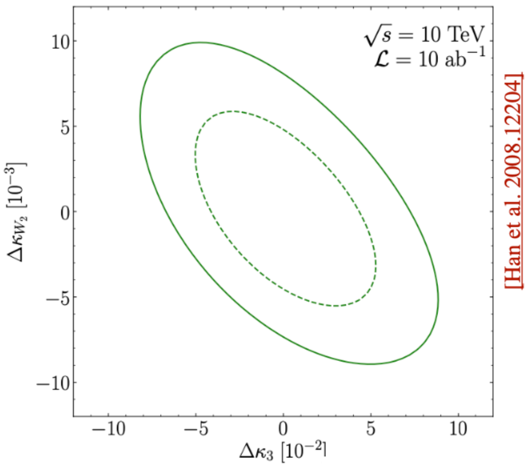
1σ sensitivities (in %) from a 10-parameter fit in the k- framework at a 10 TeV muon collider with 10 ab−1 , compared with HL-LHC. The effect of measurements from a 250 GeV e+e− Higgs factory is also reported.

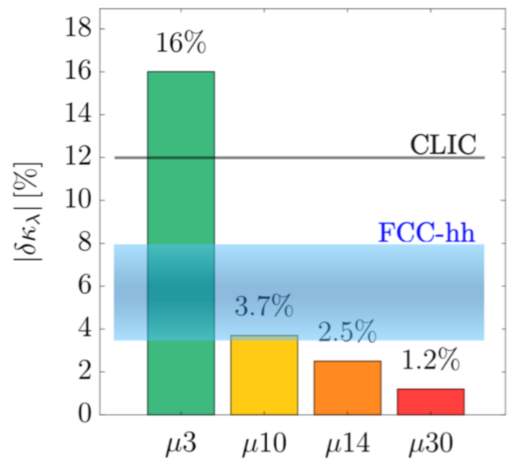
Higgs potential shape

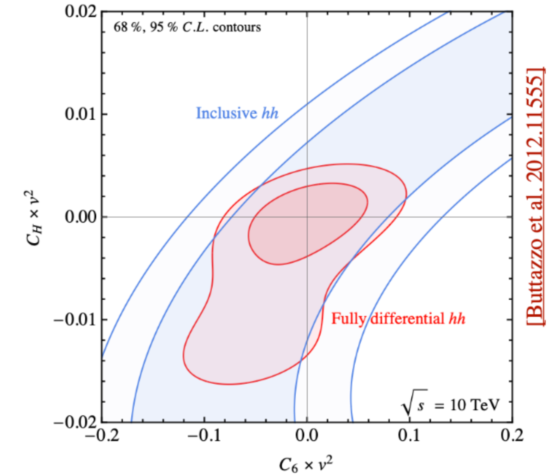
Reach on the trilinear coupling (and more) extremely competitive

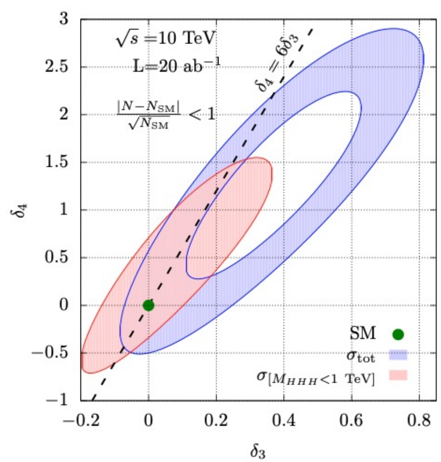
arXiv:2203.07256 **Muon Collider Physics Summary**

Higgs trilinear self-couplings



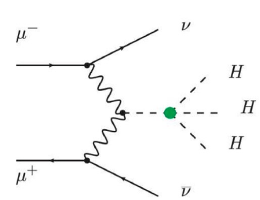


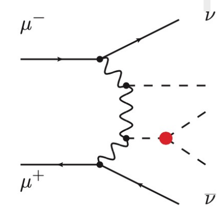




10 TeV $\quad \delta_4 \sim [-0.4, 0.7]$

3 Higgs final state





Quadrilinear determination extremely challenging at any collider, due to limited sensitivity.

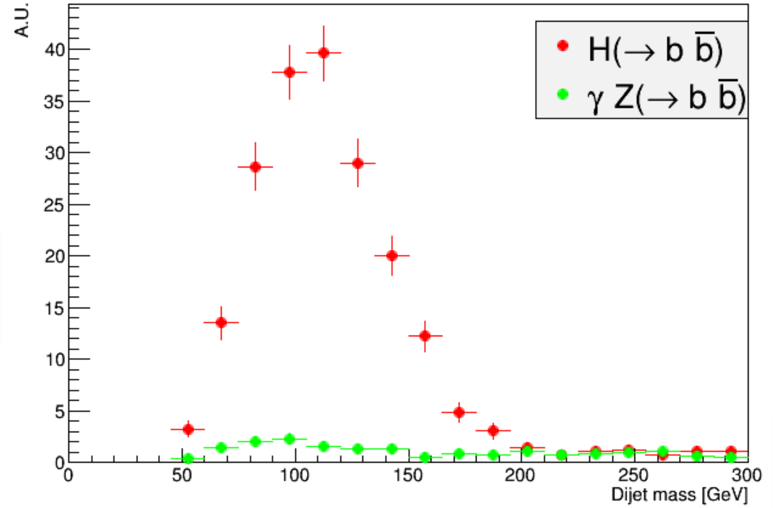
$$\text{ILC} \sim [-10, 10]$$
$$\text{CLIC} \sim [-5, 5]$$
$$\text{FCC} \sim [-2, 4]$$

Very preliminary study points to the possibility of setting competitive bounds at a muon collider.

$H \to bb$ @ 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.

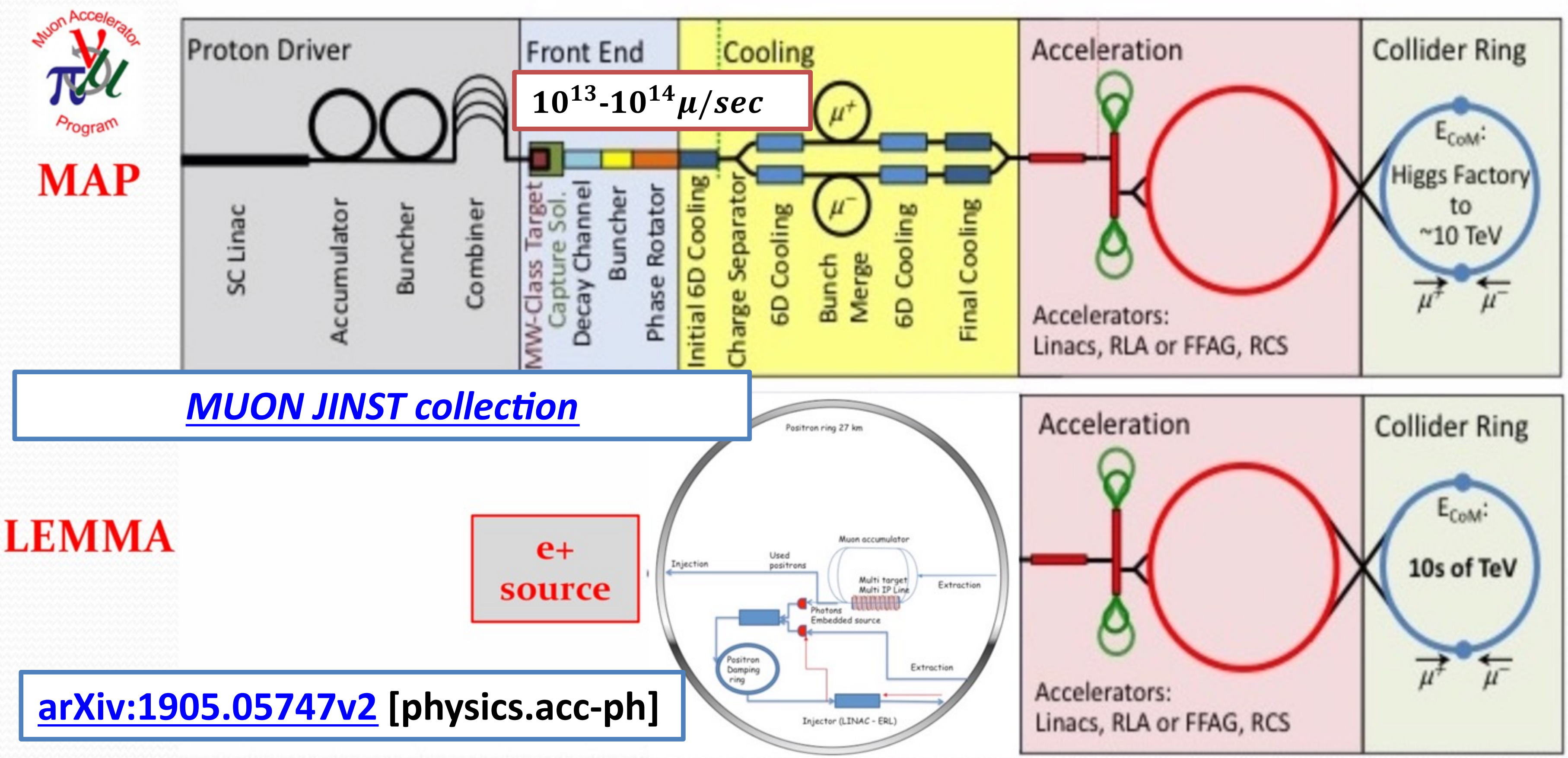
$\sqrt{s}$ [TeV]	A [%]	ϵ [%]	$\mathcal{L}$ [cm^{-2}s^{-1}]	$\mathcal{L}_{int}$ [ab^{-1}]	σ [fb]	N	B	$\frac{\Delta\sigma}{\sigma}$ [%]	$\frac{\Delta g_{Hbb}}{g_{Hbb}}$ [%]
1.5	35	15	$1.25 \cdot 10^{34}$	0.5	203	5500	6700	2.0	1.9
3.0	37	15	$4.4 \cdot 10^{34}$	1.3	324	33000	7700	0.60	1.0
10	39	16	$2 \cdot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

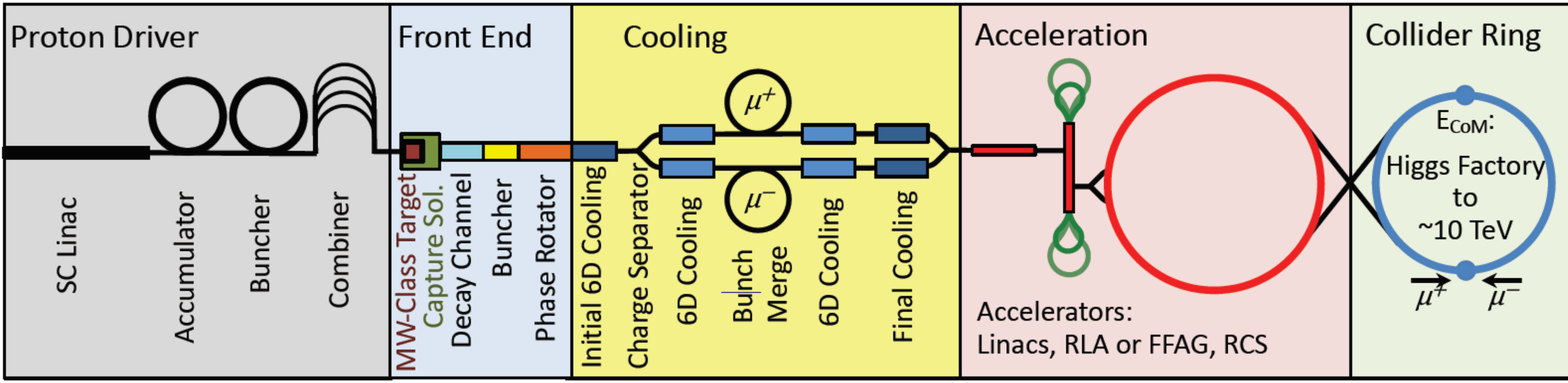
proton (MAP) vs positron driven muon source



[*MUON JINST collection*]

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

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:**

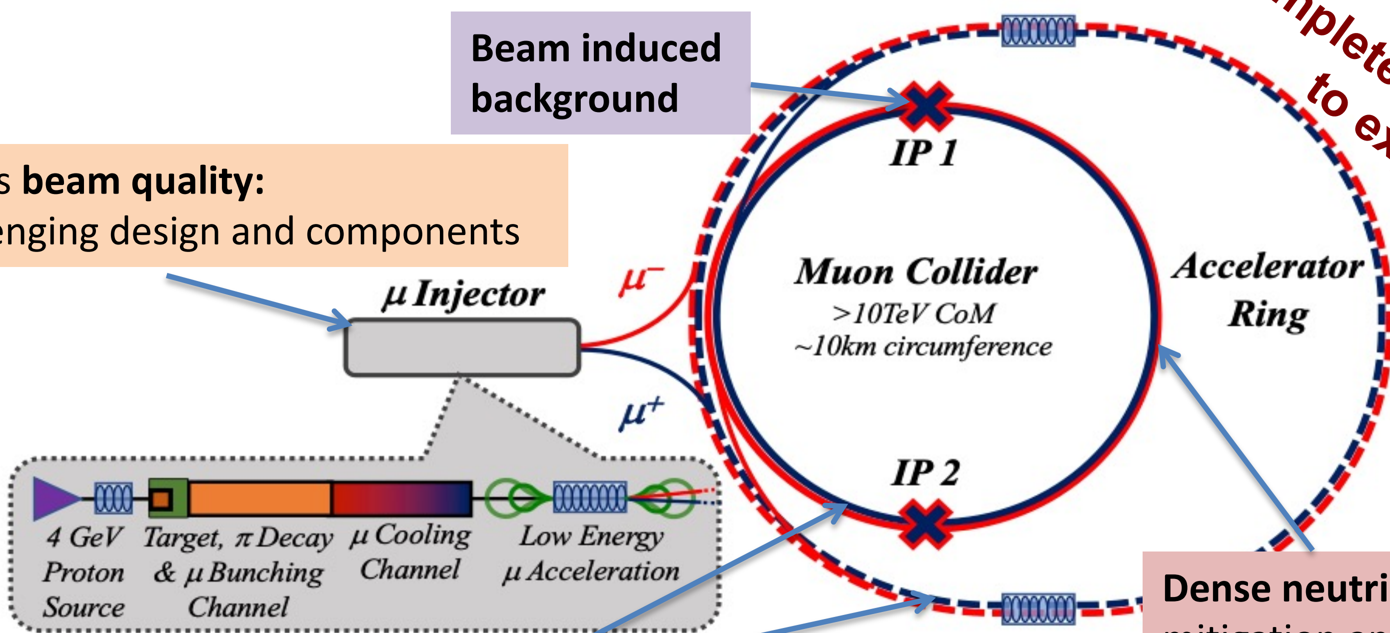
3 TeV technology ready for construction in 10-20 years

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

Luminosity and parameters goals

Target integrated luminosities

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

@ 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

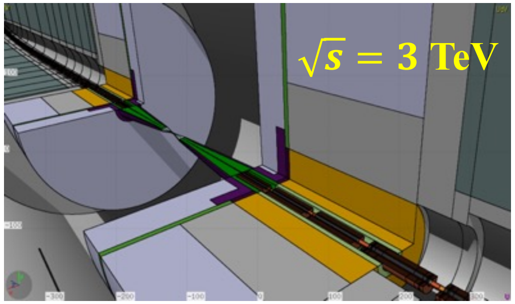
Comparison:
CLIC at 3 TeV: 28 MW

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

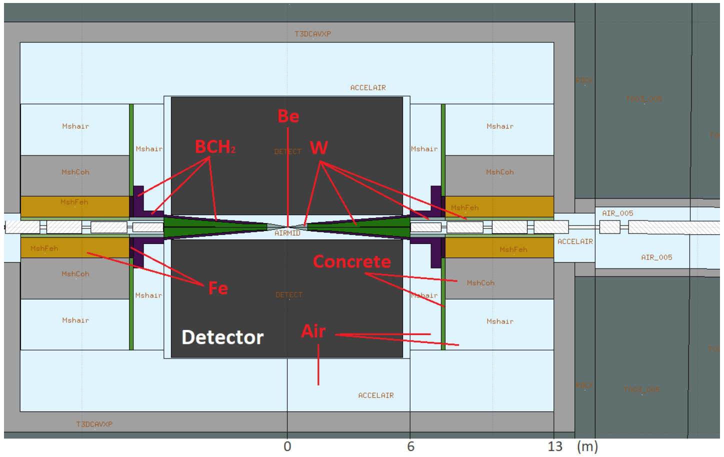
Machine Detector Interface

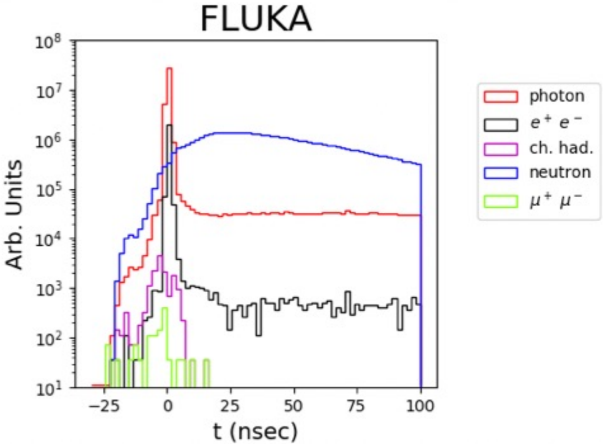
Advanced assessment of beam-induced background at a muon collider
F. Collamati, C. Curatolo, D. Lucchesi, A. Mereghetti, P. Sala *et al.* 2021 *JINST* **16** P11009

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



LineBuilder + FLUKA simulation



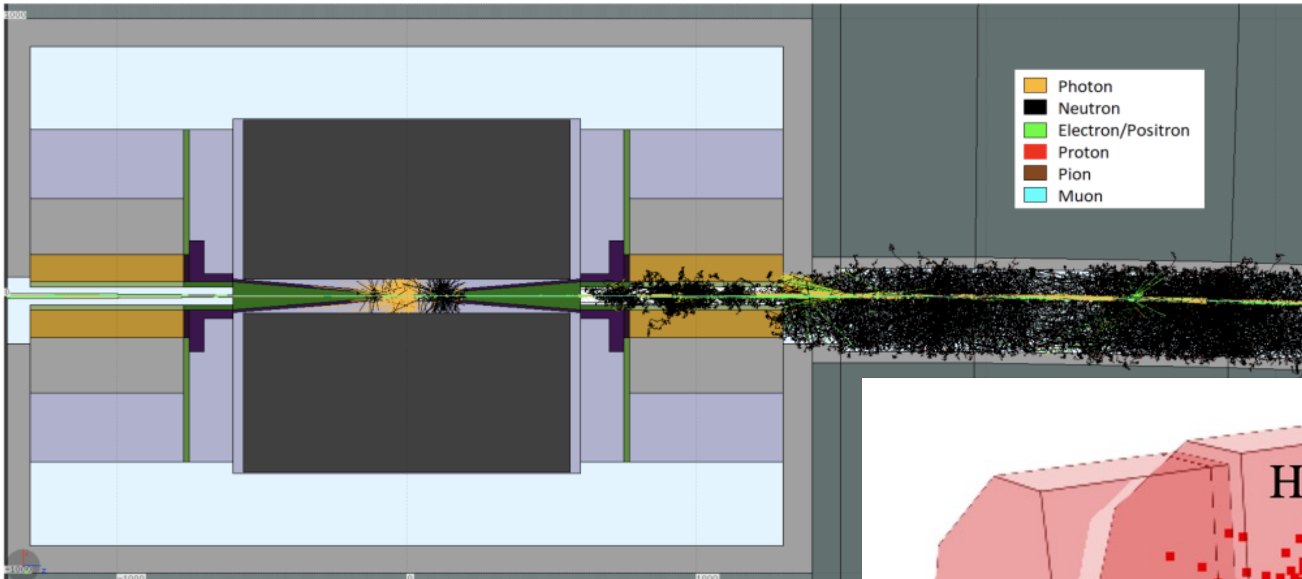


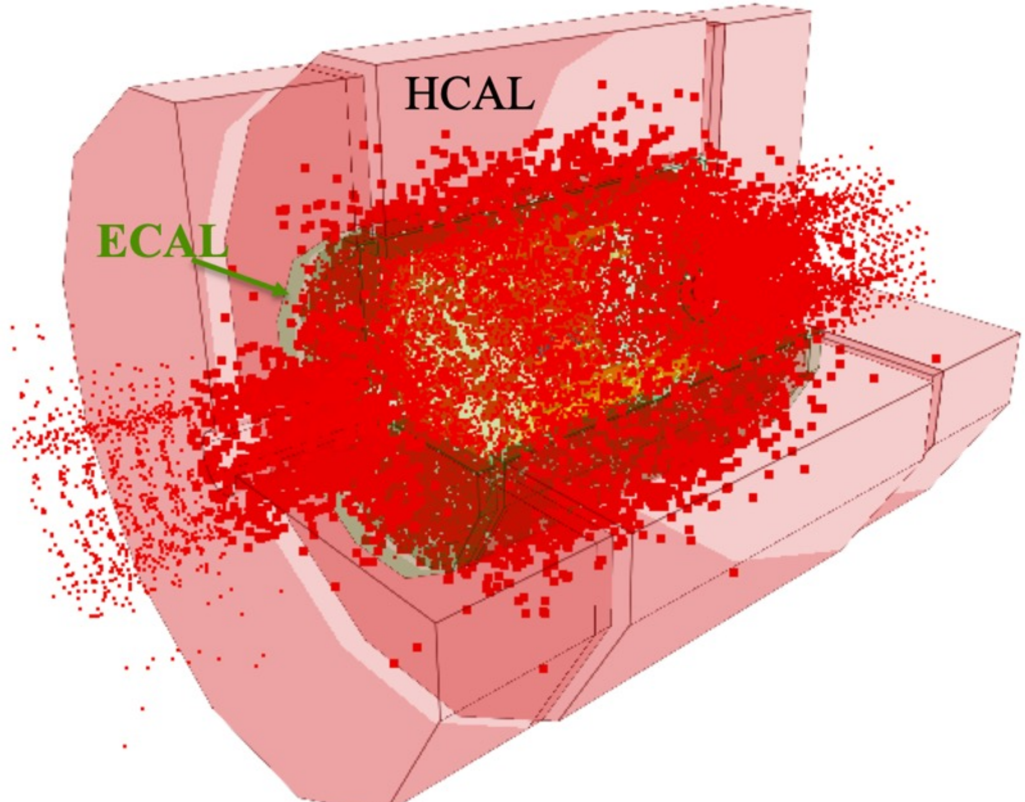
➔ **first lattice and MDI studies @ 10 TeV by CERN**

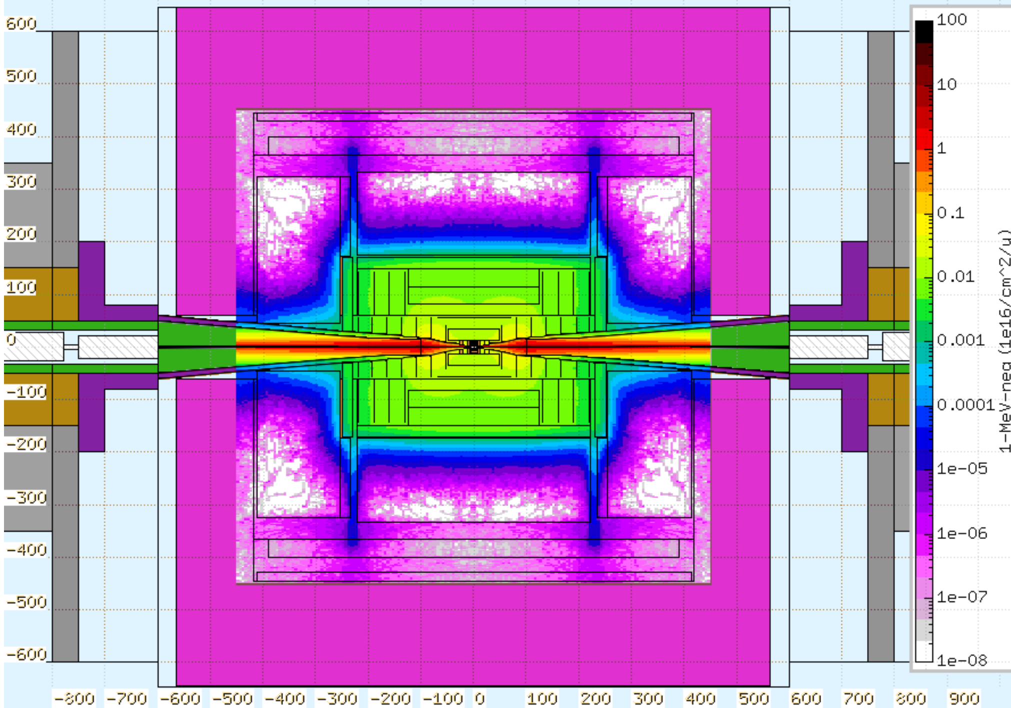
The machine elements, MDI and interaction region must be properly designed and optimized
@ each collider energy

Beam Induced Background

FLUKA simulation

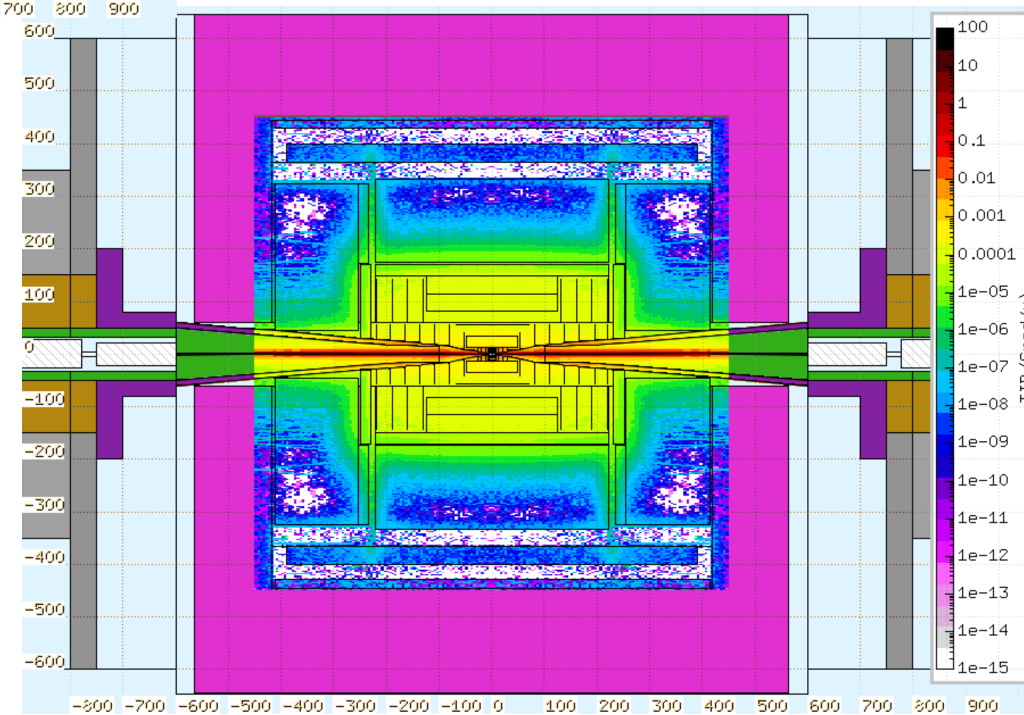






1 MeV n_{eq} fluence/year @ 3 TeV

TID/year @ 3 TeV

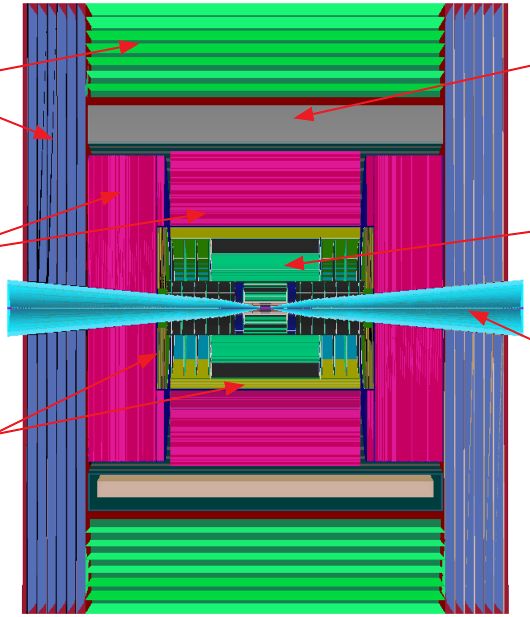


Detector studies @ $\sqrt{s}$ =1.5 TeV

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 25x25μm²
- 4+4 double-sensor disks 25x25μm²

Inner Tracker (IT)
- 3 barrel layers 50x50μm²
- 7+7 disks "

Outer Tracker(OT)
- 3 barrel layers 50x50μm²
- 4+4 disks "

Electromagnetic Calorimeter (ECAL)
- 40 layers W absorber and silicon pad sensors, 5x5 mm²

Hadron Calorimeter (HCAL)
- 60 layers steel absorber & plastic scintillating tiles, 30x30 mm²

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

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

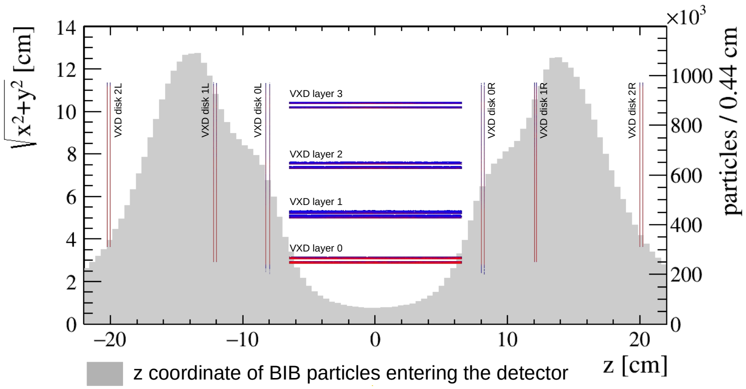
B = 3.57 T to be studied and tuned

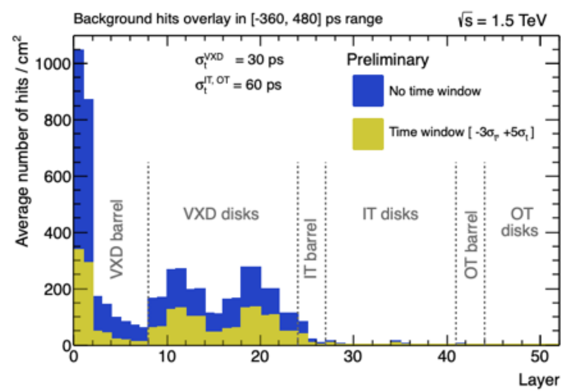
Full simulation available on public repository

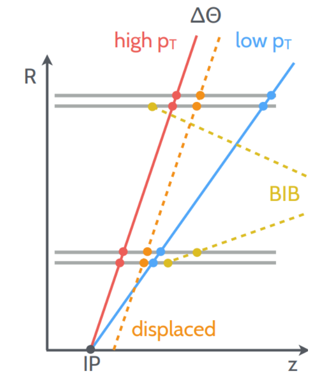
Quite advanced conceptual design for 1.5 TeV and 3 TeV
➔ More R&D on technologies required @ 10+ TeV

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

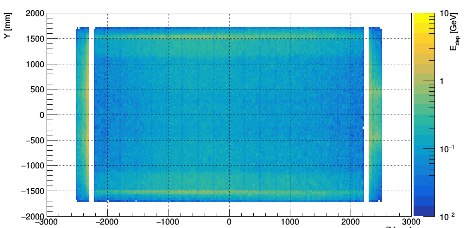
Calorimeters and Muon detectors

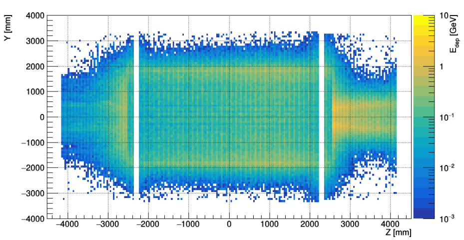
timing and longitudinal measurements play a key role in the BIB suppression

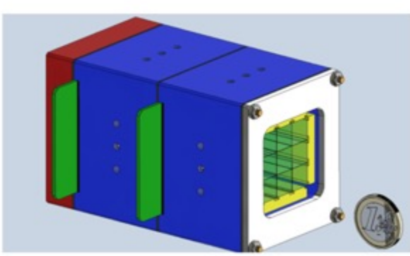
Muon System
Low BIB contribution, concentrated in the low-radius endcap region

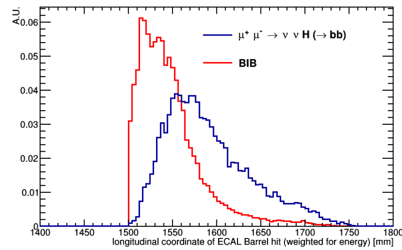
Calorimeters

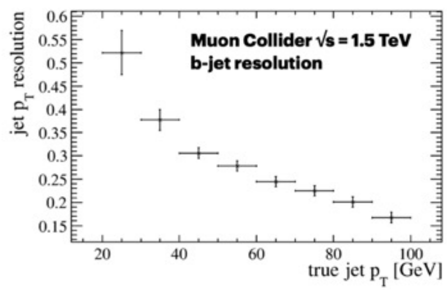
BIB deposits large amount of energy in both ECAL and HCAL

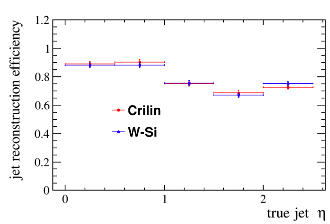


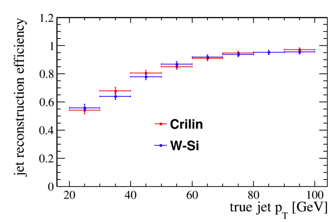


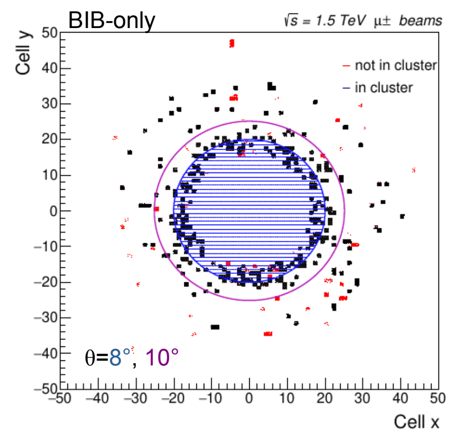




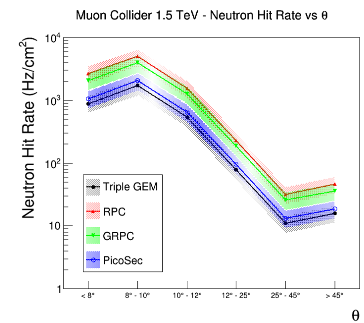


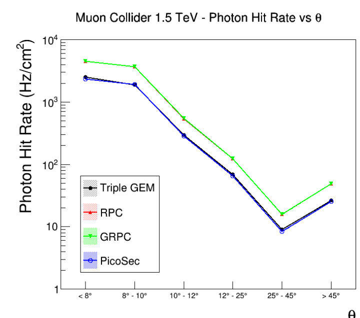






Investigating new technologies for R&D



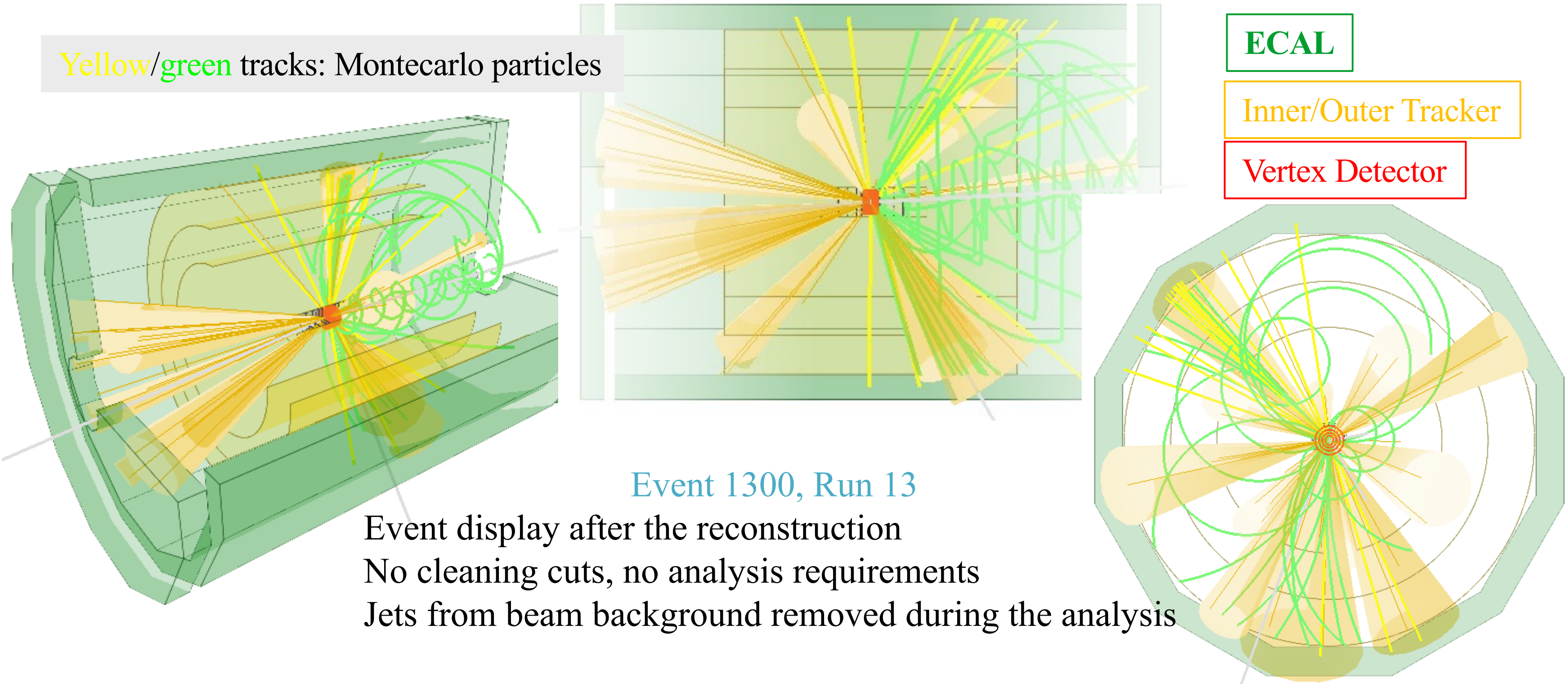


Innovative and computationally efficient event-reconstruction approaches are needed

High Precision Measurements

Donatella Lucchesi et al.

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



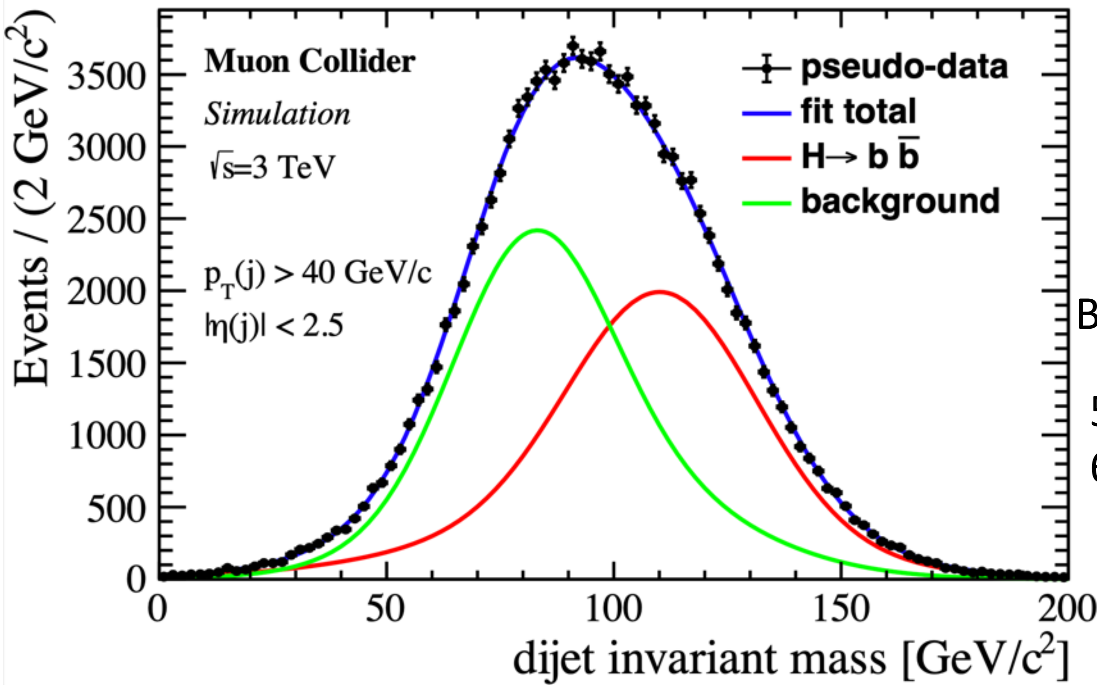
Event display after the reconstruction
No cleaning cuts, no analysis requirements
Jets from beam background removed during the analysis

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

μ+μ-→ H(→ bb̄)+X

@ 3 TeV - 1 ab^{-1}



relative statistical uncertainty on H→ bb̄ cross section of 0.75% found

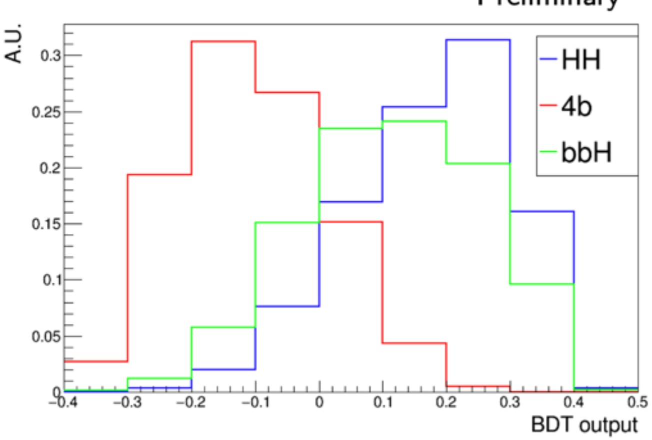
Background μ+μ- → qq + X (with q=b or c)

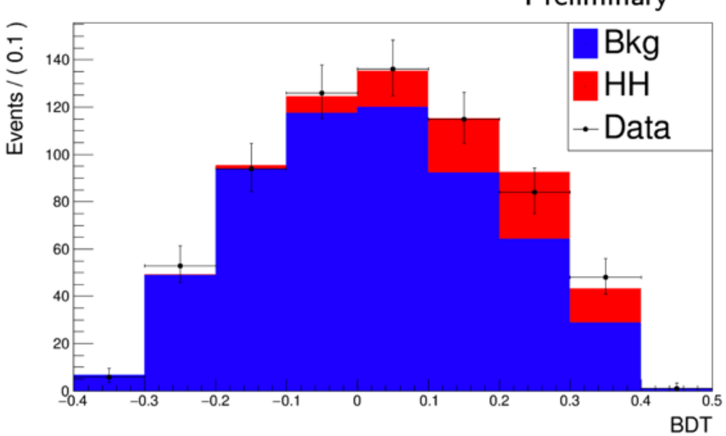
59.5k signal events and
65.4k background events expected

WHIZARD+Pythia8 simulation @ 3 TeV

Uncertainty on HH → bb̄bb̄ cross section of about 30% found

50 HH and 432 background





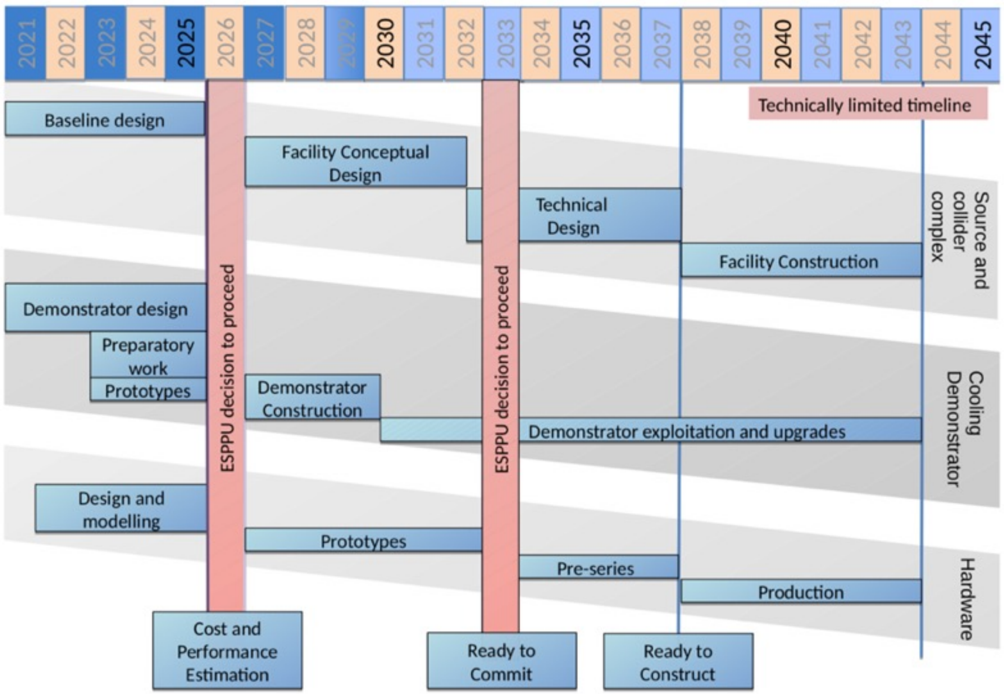
Accelerator R&D Roadmap

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

International Context

- **Laboratory Directors' Group (LDG)** **initiated a muon collider collaboration July 2, 2020**

Project Leader:
Daniel Schulte

- **CERN Medium Term Plan** 2021-2025 - dedicated budget line – ~2MCHF/year
  mainly to cover machine up to MDI activities
- **International Design Study based at CERN** ➔ **MoC signed by Funding Agencies/several Institutes**
  the project encompasses physics, machine, detector and Machine Detector Interface
- European LDG **Accelerator R&D Roadmap** ➔ **implementation after Council Dec 2021**
  dedicated Muon Beams Panel - but also synergies in High field magnets, RF and ERL
- European ECFA **Detector R&D Roadmap** ➔ **implementation after Council Dec 2021**
  Muon collider @ 10 TeV is one of the targeted facilities emerging from the EPPSU
- US Snowmass'21 Muon Collider Forum **since 2021 – Muon Collider Forum Report Sept 2022**
- Snowmass/P5 process in the US ➔ **ready by Fall 2023**
- HORIZON-INFRA-2022-DEV-01-01 EU project **MuCol** approved **July 2022 and January 2023**
  Research infrastructure concept development for design study ➔ **supported by TIARA**

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

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

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)

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

- **Full accelerator chain**
  - e.g. proton complex with H- source, compressor ring ➔ test of target material

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

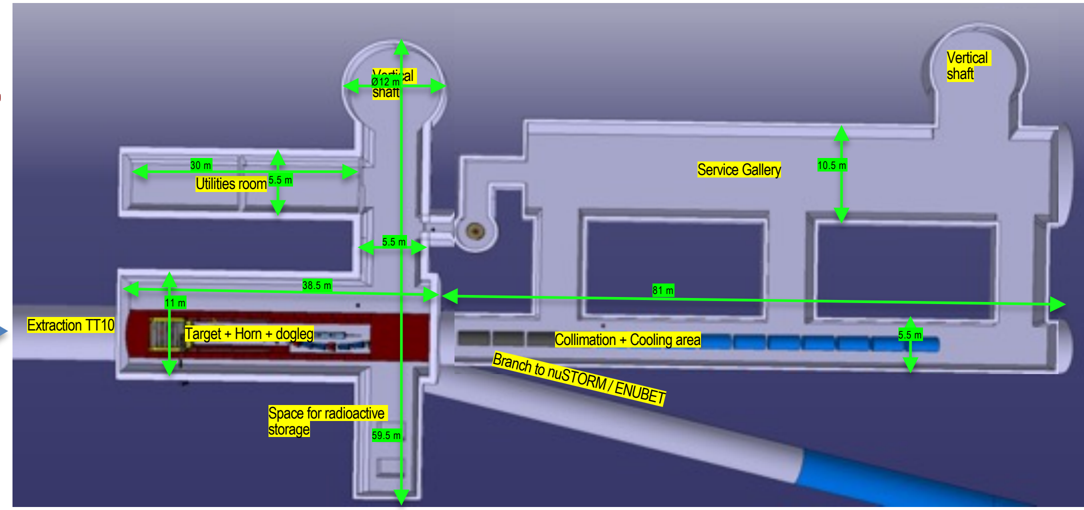
~70 Meu/5 years

Demonstrator and test facilities

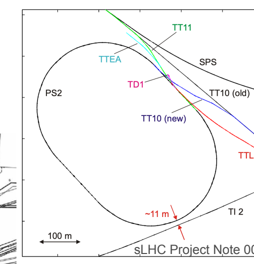
(Muon production) and Cooling Demonstrator @ CERN

Strong synergies with nuSTORM and ENUBET

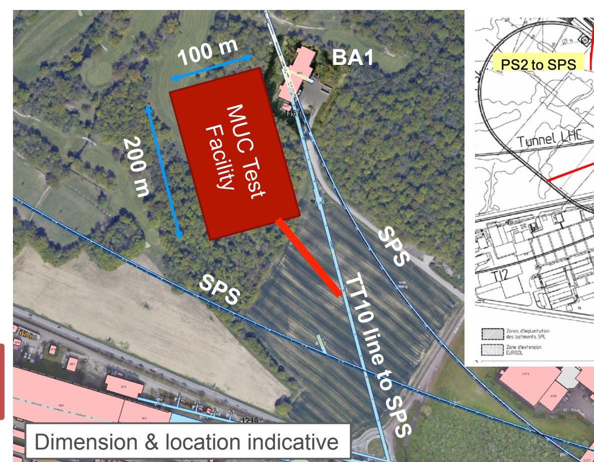
First attempt to design a site
Great opportunity to contribute

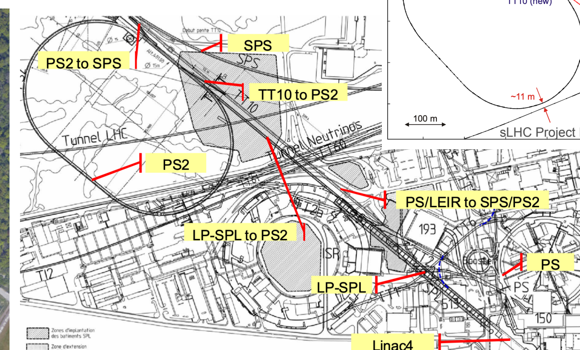


It could be close to TT10, and inject beam from PS
It would be on molasse,
no radiation to ground water



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

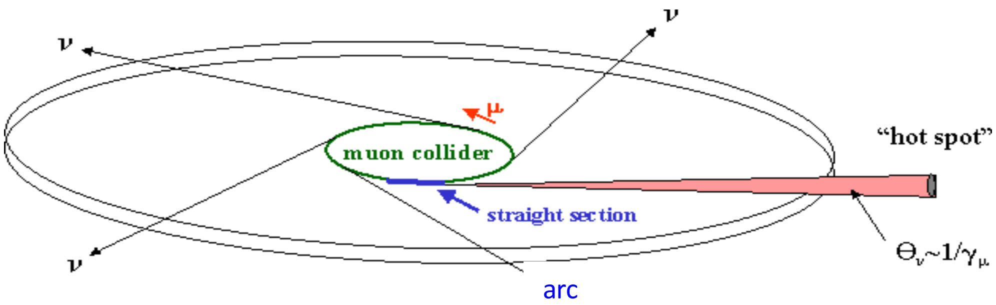




Strong synergies with other future projects

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

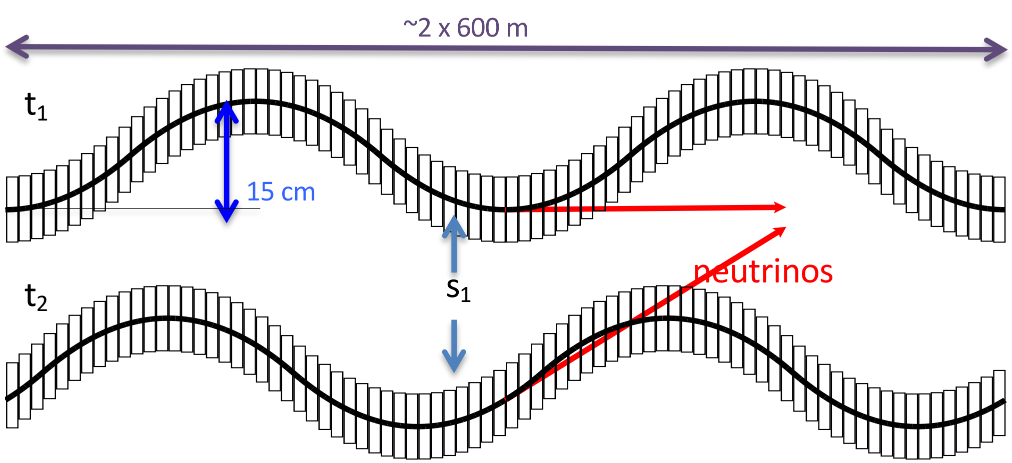
Neutrino Flux Mitigation



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



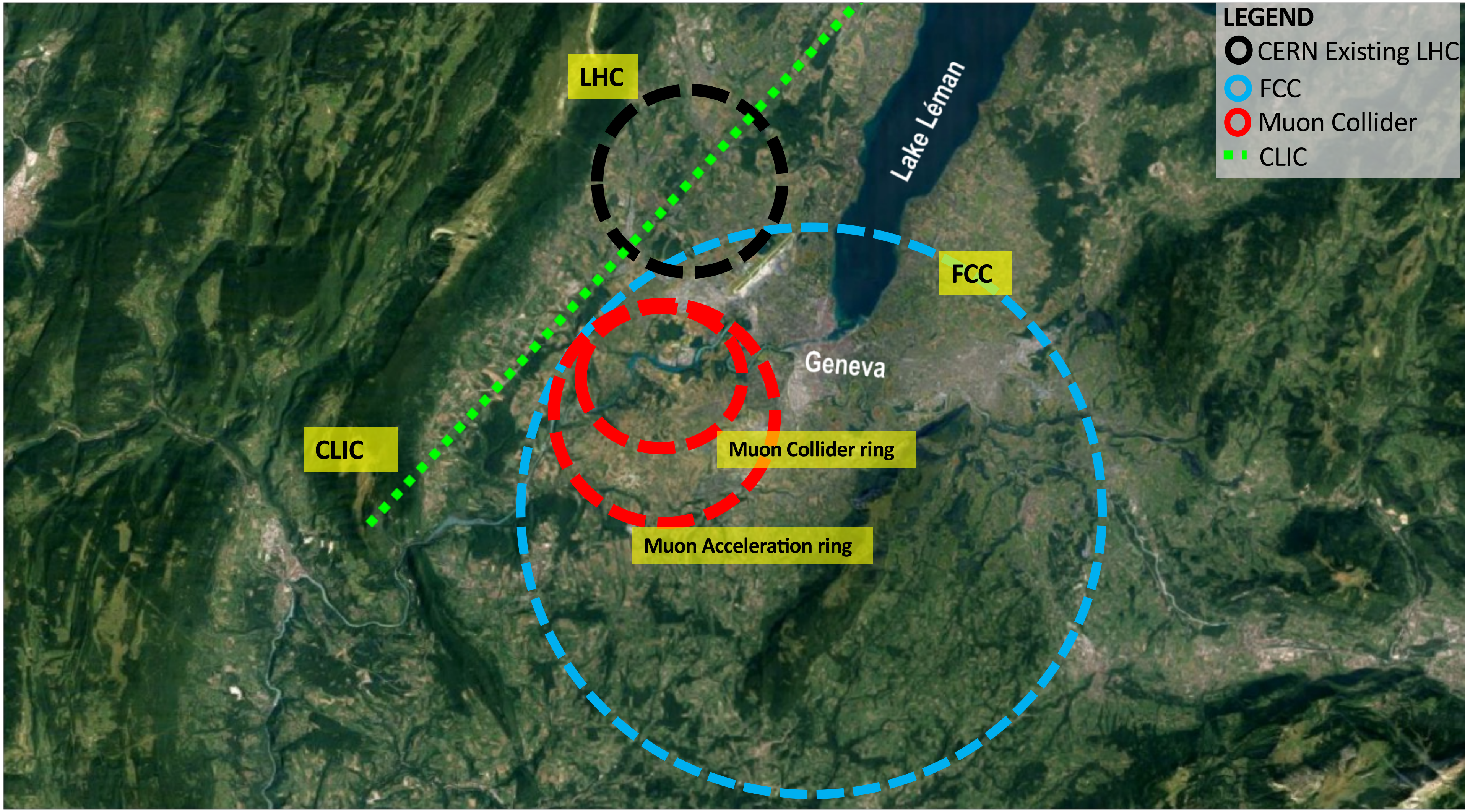
Opening angle ± 1 mradiant

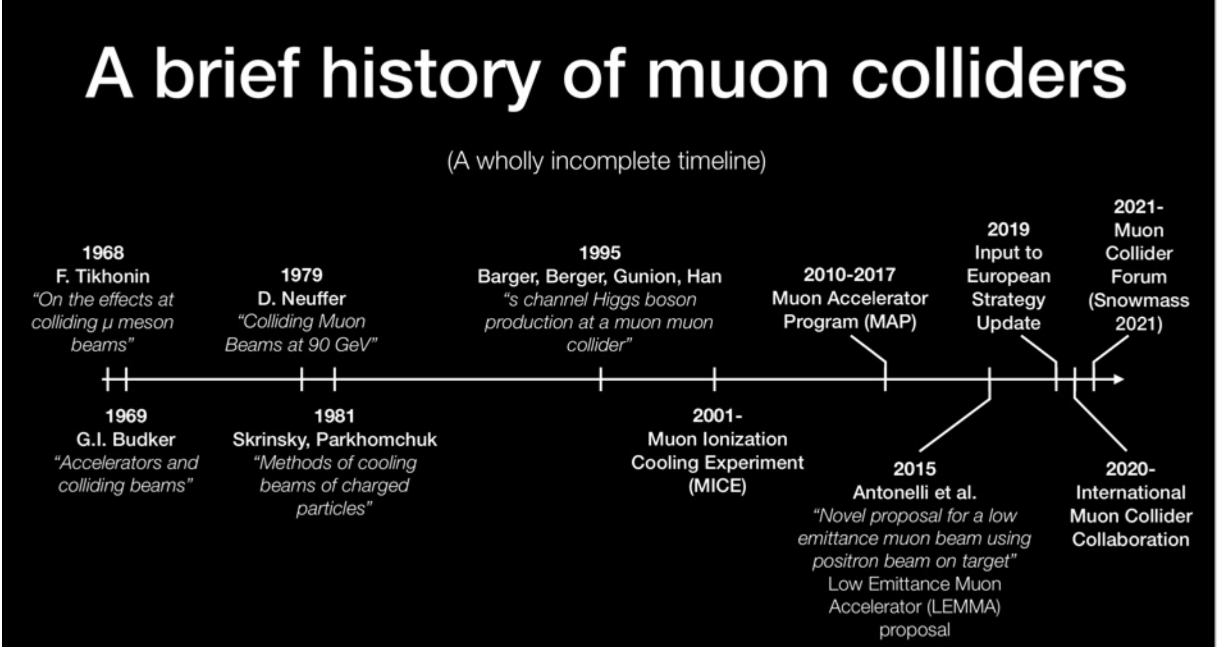
14 TeV, in 200 m deep tunnel comparable to LHC case

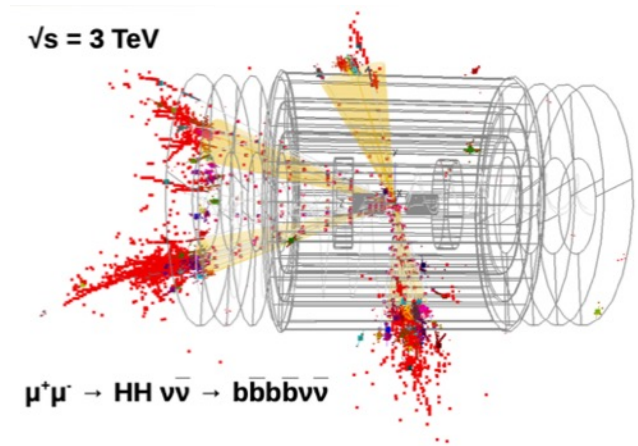
Need to study mover system, magnet, connections and impact on beam

Working on different approaches for experimental insertion

Footprint possible future colliders @ CERN







- 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

A growing collaboration

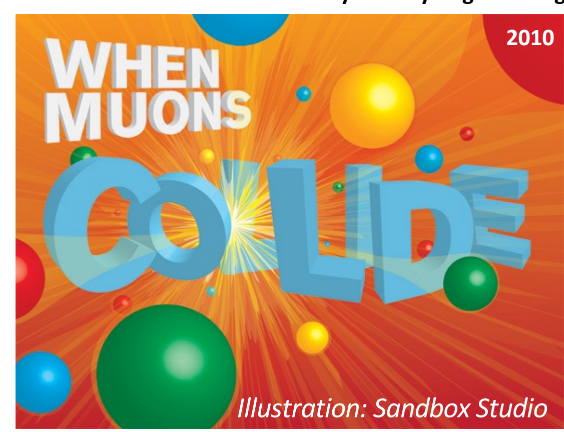
http://map.fnal.gov/

U.S. Muon Accelerator Program (MAP)

participants

	Participants
Padova July 2018	
CERN April 2019	56
CERN October 2019	85
Remote March 2020	165
Remote July 2020	272
Remote Community May-Oct 2021	153-113
CERN October 2022	187

www.symmetrymagazine.org



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":

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MUST-phydet@cern.ch

MUONCOLLIDER-FACILITY

MUST-mac@cern.ch

extras

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

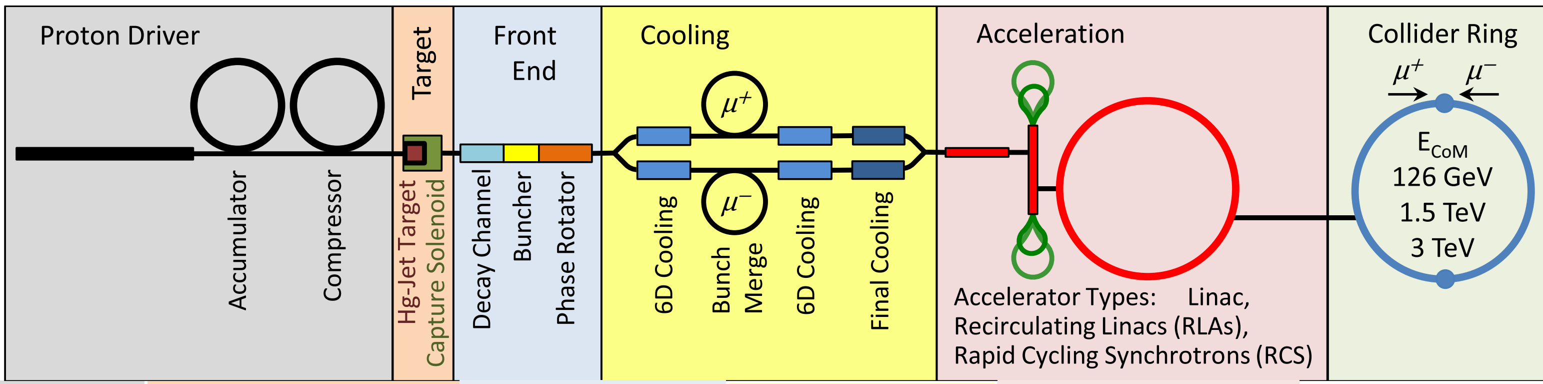
The MuCol study will produce a coherent description of a novel particle accelerator complex that will collide muons of opposite charge at the energy frontier. The study will target a centre-of-mass energy (ECM) of 10 TeV with 3 TeV envisaged as a first stage.

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.

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

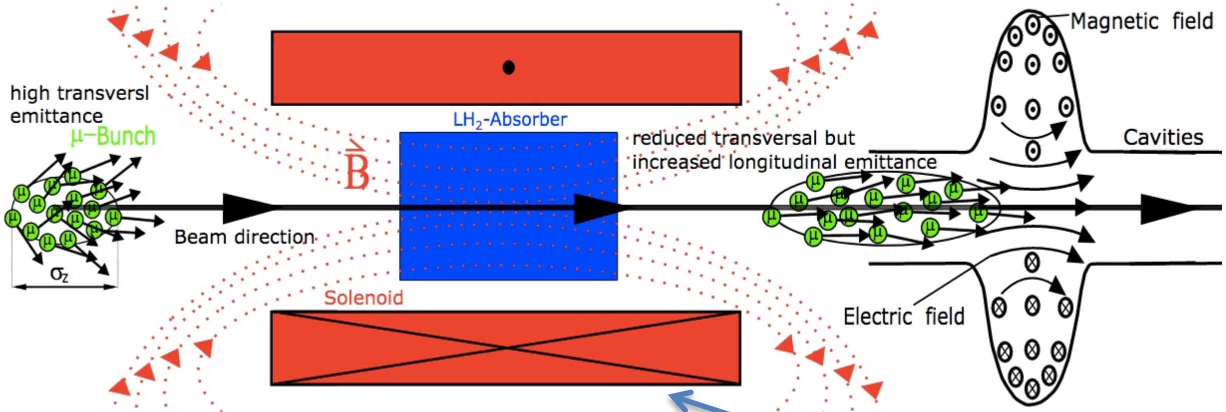
- RF cavities bunch & phase rotate $\mu^{\pm}$ into bunch train

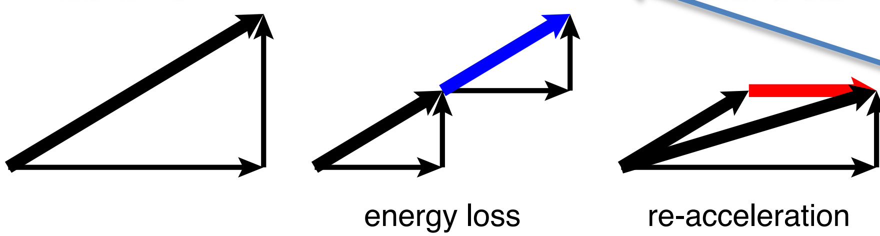
- Ionization cooling 6D
- MICE

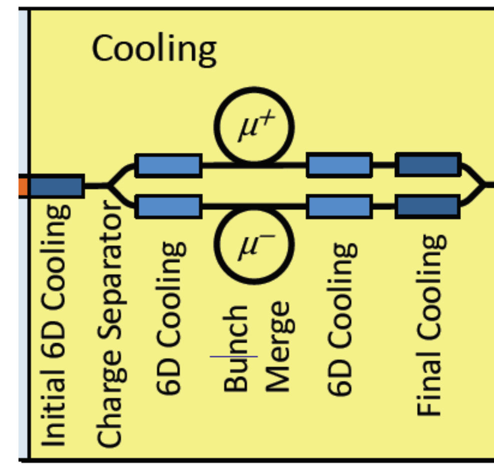
- Fast acceleration
- Use RF and SC

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

Final Cooling Challenge







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

Energy loss = cooling

Multiple scattering = heating

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

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

Site filler Accelerator

- ➢ **Proton Source**
  - **PIP-III→target**
- ➢ μ **Cooling**
- ➢ **Linac + RLA → 65 GeV**
- ➢ **RCS 1 and 2 → 1000 GeV**
  - **Tevatron-size**
- ➢ **RCS 3 → 5 TeV**
  - **Site filler accelerator**

10 TeV collider

Collider Ring ~10 km

Fermilab