Online

LHCP2021

The Ninth Annual Conference on Large Hadron Collider Physics

7-12 June 2021 ~~Paris (France), Sorbonne Université (IN2P3/CNRS,IRFU/CEA)~~

June 9, 2021

Towards a multi-TeV Muon Collider

Nadia Pastrone INFN TORINO

on behalf of the

International MUON Collider Collaboration

A unique facility

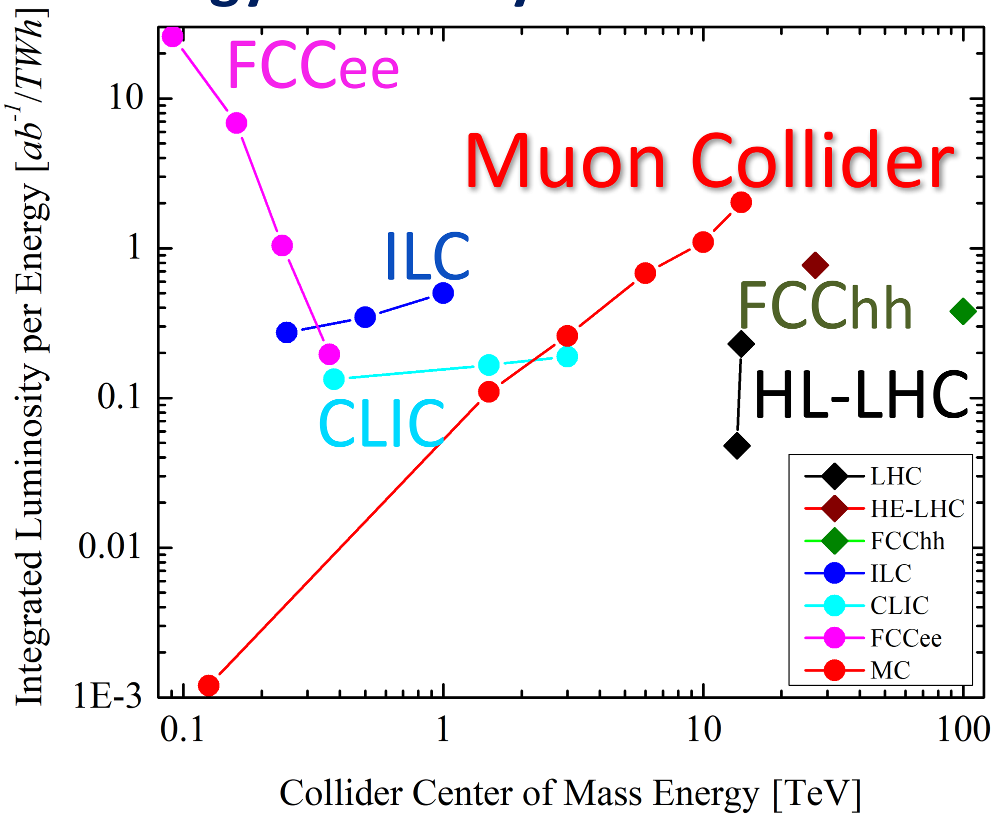
nature physics

[Muon colliders to expand frontiers of particle physics]

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

ESPP Input document: [Muon Colliders]

Energy Efficiency of Future Colliders



Overwhelming physics potential:

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

Challenging Facility Design:

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

Physics potential

[Muon Collider Physics and Detector Workshop]

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

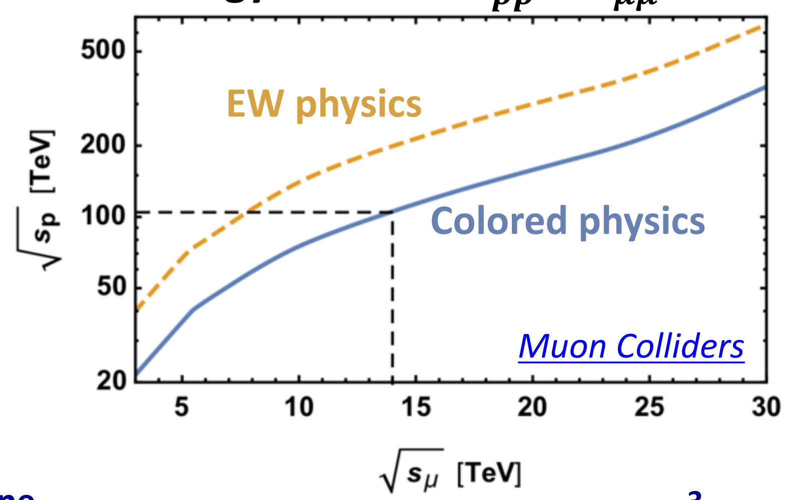
Direct searches	High-rate measurements	High-energy probes	Muon physics
Pair production, Resonances, VBF, Dark Matter, …	Single Higgs, self coupling, rare and exotic Higgs decays, top quarks, …	Di-boson, di-fermion, tri-boson, EFT, compositeness, …	Lepton Flavor Universality, b → sμμ, muon g-2, …

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

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

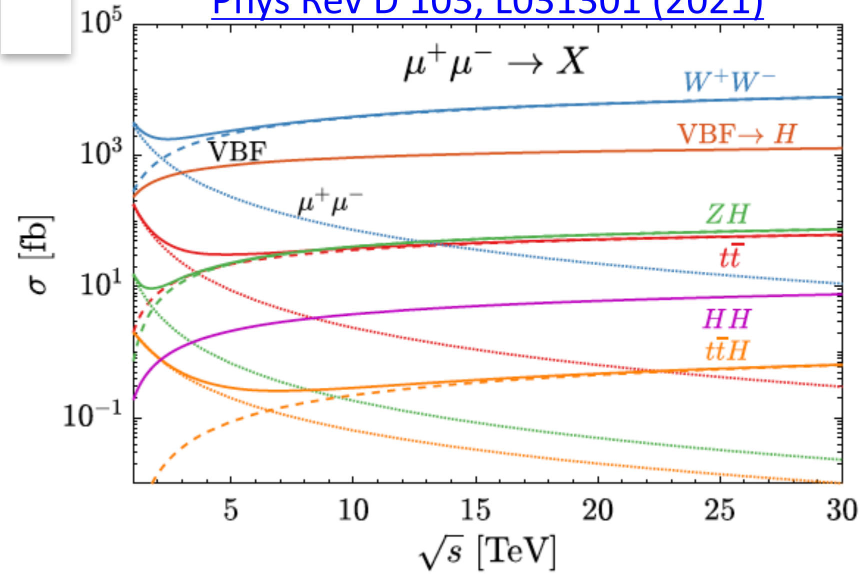
➔ Physics benchmarks steer machine parameters and experiment design

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



Searches and precise measurements

[Phys Rev D 103, L031301 (2021)](#)



Speculative high energy options (run plans specified here)

Muon (or electron colliders)

6 TeV 4/ab $\sim 3.2 \times 10^6$

10 TeV 10/ab $\sim 9.5 \times 10^6$

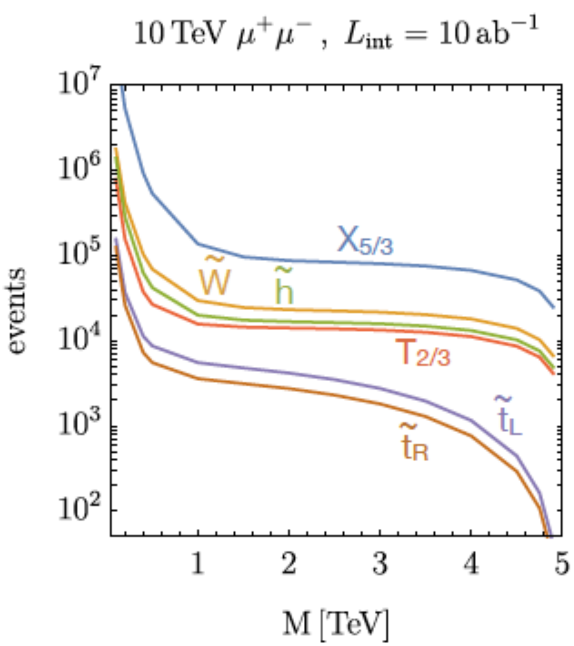
14 TeV 20/ab $\sim 22 \times 10^6$

30 TeV 90/ab $\sim .12 \times 10^9$

100 TeV 100/ab $\sim .18 \times 10^9$

Millions to 100s of millions

[The Muon Smasher's Guide](#)



First tentative comparisonon Higgs couplings

κ-0 fit	HL-LHC	LHeC	HE-LHC S2	HE-LHC S2′	ILC 250	ILC 500	ILC 1000	CLIC 380	CLIC 1500	CLIC 3000	CEPC	FCC-ee 240	FCC-ee 365	FCC-ee/eh/hh	$\mu^+\mu^-$ **10000**
κ_W [%]	1.7	0.75	1.4	0.98	1.8	0.29	0.24	0.86	0.16	0.11	1.3	1.3	0.43	0.14	0.06
κ_Z [%]	1.5	1.2	1.3	0.9	0.29	0.23	0.22	0.5	0.26	0.23	0.14	0.20	0.17	0.12	0.23
κ_g [%]	2.3	3.6	1.9	1.2	2.3	0.97	0.66	2.5	1.3	0.9	1.5	1.7	1.0	0.49	0.15
κ_γ [%]	1.9	7.6	1.6	1.2	6.7	3.4	1.9	98⋆	5.0	2.2	3.7	4.7	3.9	0.29	0.64
$\kappa_{Z\gamma}$ [%]	10.	–	5.7	3.8	99⋆	86⋆	85⋆	120⋆	15	6.9	8.2	81⋆	75⋆	0.69	1.0
κ_c [%]	–	4.1	–	–	2.5	1.3	0.9	4.3	1.8	1.4	2.2	1.8	1.3	0.95	0.89
κ_t [%]	3.3	–	2.8	1.7	–	6.9	1.6	–	–	2.7	–	–	–	1.0	6.0
κ_b [%]	3.6	2.1	3.2	2.3	1.8	0.58	0.48	1.9	0.46	0.37	1.2	1.3	0.67	0.43	0.16
κ_μ [%]	4.6	–	2.5	1.7	15	9.4	6.2	320⋆	13	5.8	8.9	10	8.9	0.41	2.0
κ_τ [%]	1.9	3.3	1.5	1.1	1.9	0.70	0.57	3.0	1.3	0.88	1.3	1.4	0.73	0.44	0.31

International Muon Collider Collaboration

International MUON Collider Collaboration

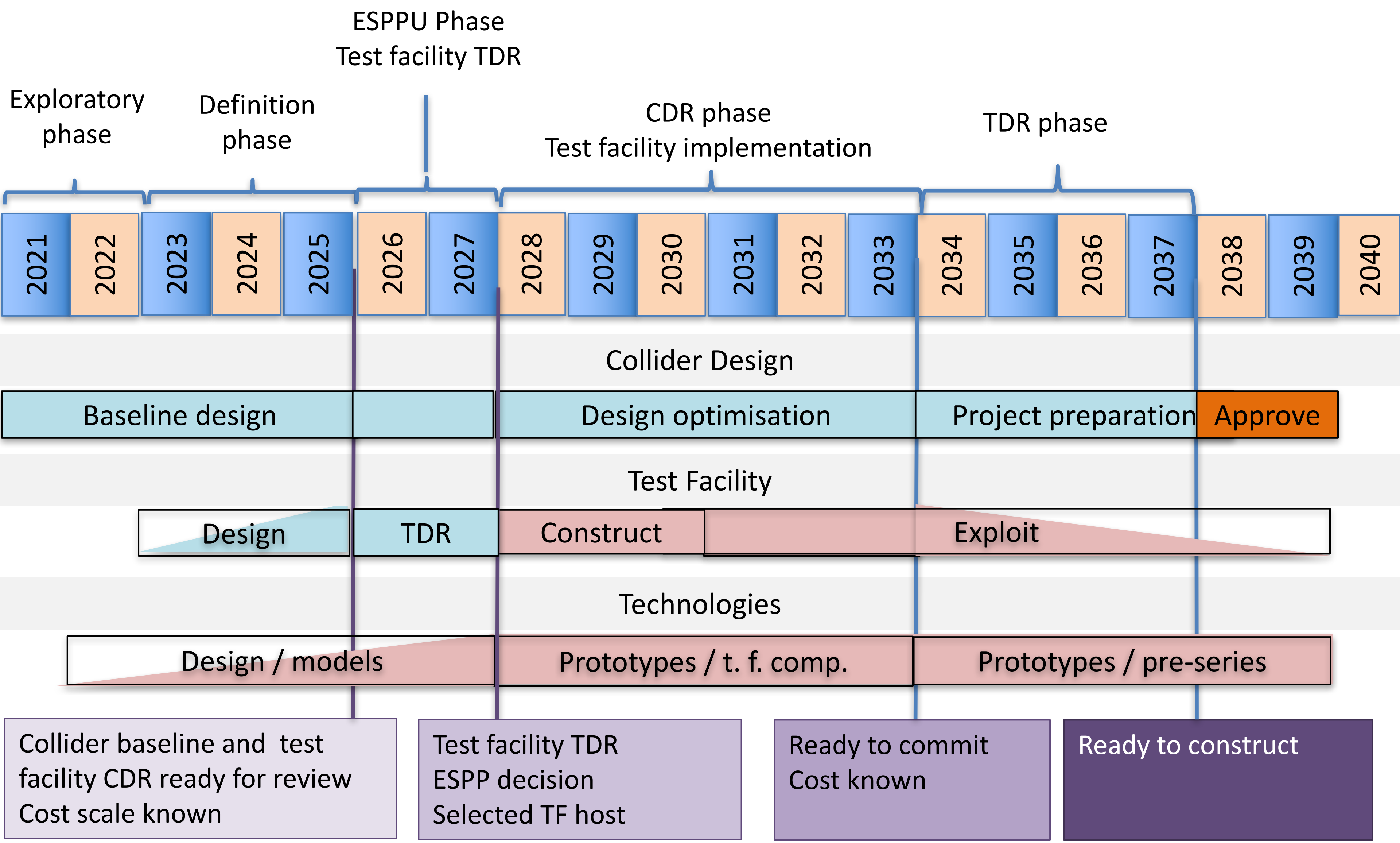
Project Leader: *Daniel Schulte*

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 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**

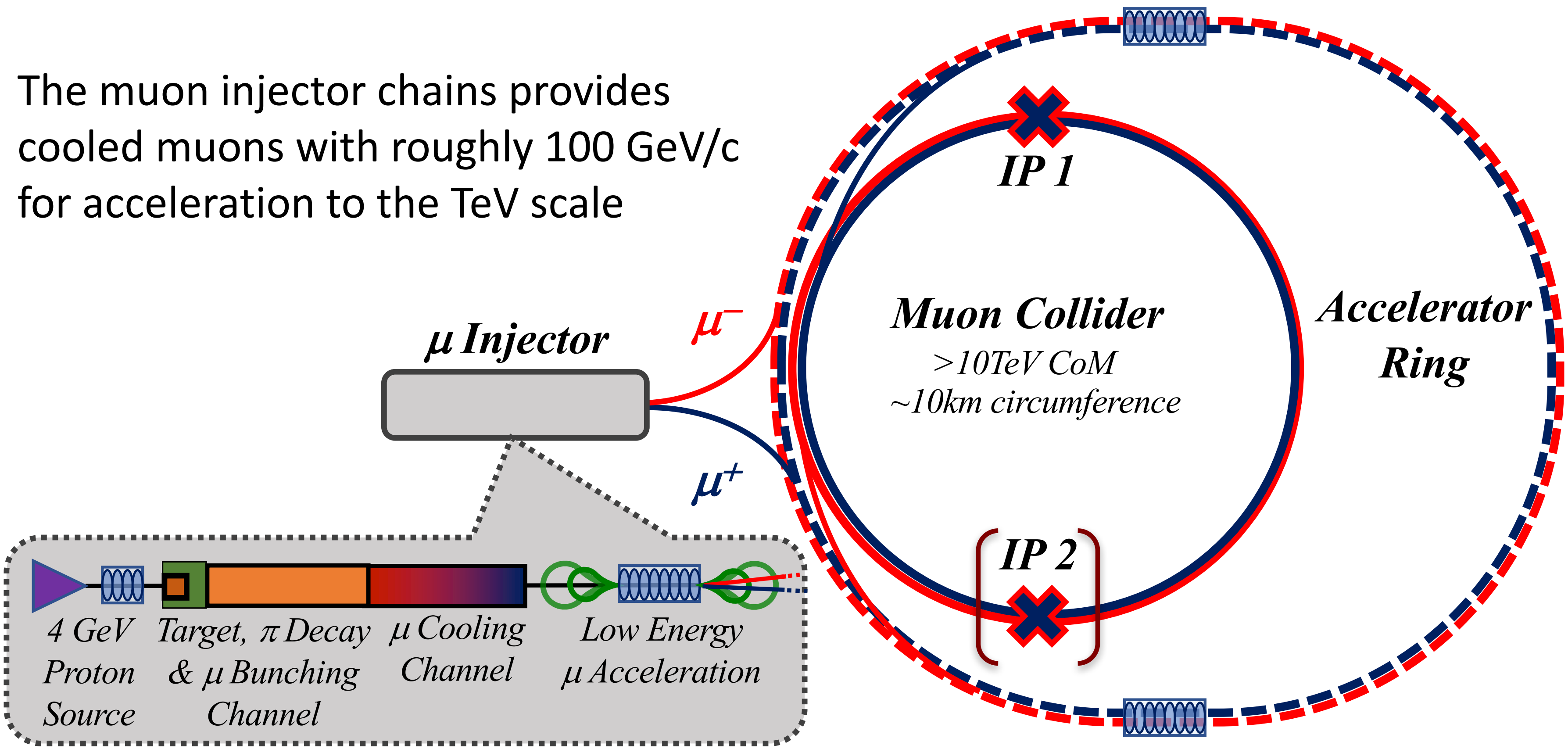
Web page: http://muoncollider.web.cern.ch

Technically Limited Long-Term Timeline



Sketch of the multi-TeV facility

The muon injector chains provides cooled muons with roughly 100 GeV/c for acceleration to the TeV scale



Alternative Muon production Sources, such as LEMMA, could be also considered

~ $2\times10^{12}\mu/bunch$
1 bunch/beam colliding each 20-30 μs
➔ max 2 Interaction Points - IP
ONLY 1 EXPERIMENT CONSIDERED at present

Luminosity and Parameters Goals

Target integrated luminosities

$\sqrt{s}$	$\int \mathcal{L}dt$
3 TeV	$1\ \mathrm{ab}^{-1}$
10 TeV	$10\ \mathrm{ab}^{-1}$
14 TeV	$20\ \mathrm{ab}^{-1}$

Note: currently no staging
Would only do 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

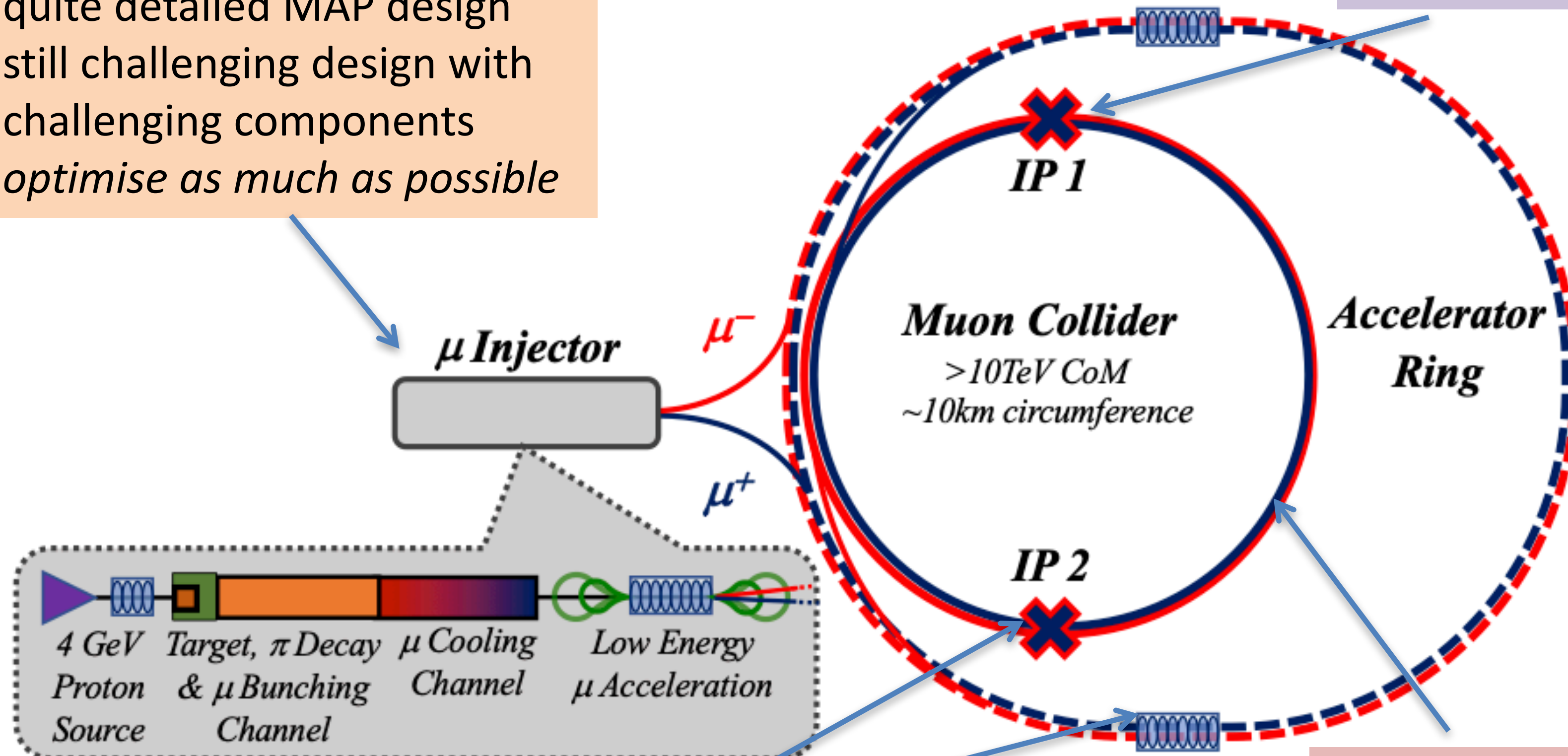
Comparison:
CLIC at 3 TeV: 28 MW

Parameter	Unit	3 TeV	10 TeV	14 TeV
L	$10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$	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

Key Challenges

Drives the **beam quality**
quite detailed MAP design
still challenging design with
challenging components
optimise as much as possible

Beam induced background

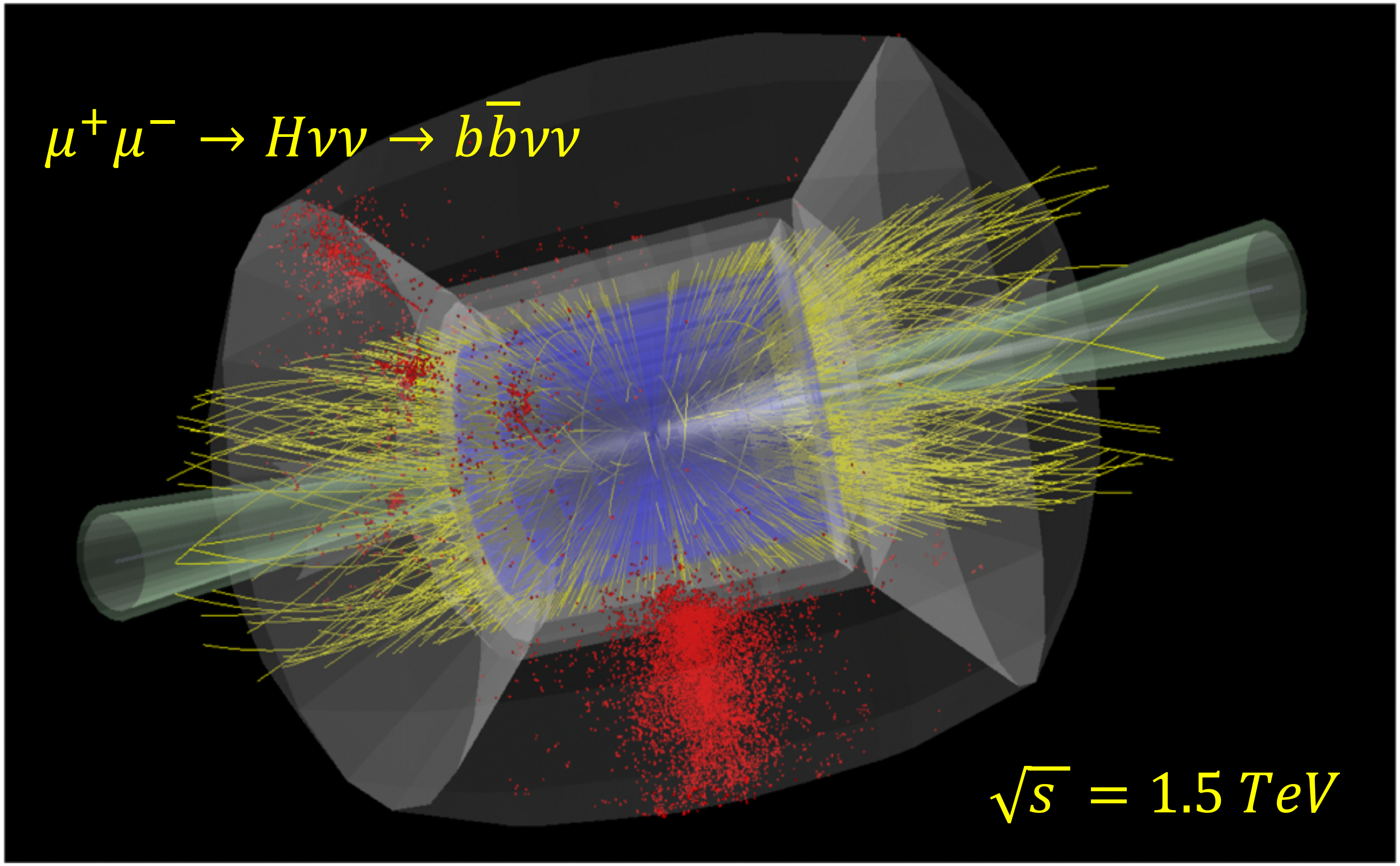


Dense neutrino flux
mitigated by mover system
and site selection

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

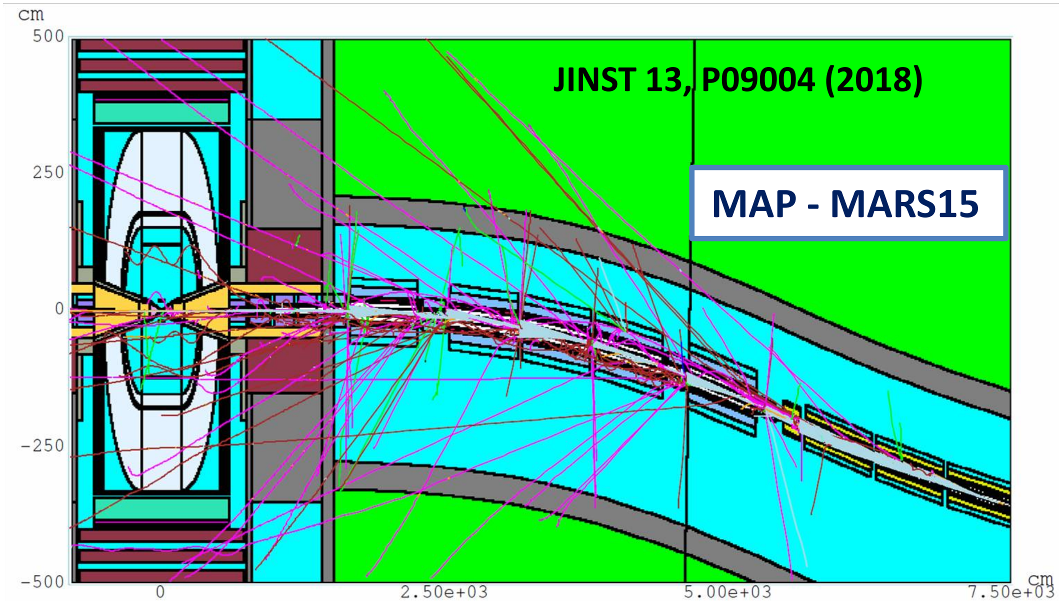
Accelerator R&D Roadmap
Muon Beam Panel
Community Meeting

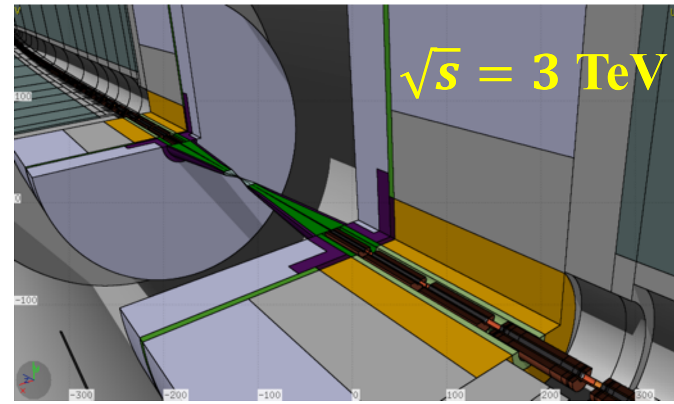
$H \rightarrow b\bar{b}$ + muon beams induced backgound



Status of existing and on-going studies at 1.5 and 3 TeV center-of-mass energy
Future steps towards 10 TeV and higher center-of-mass energy to exploit physics reach

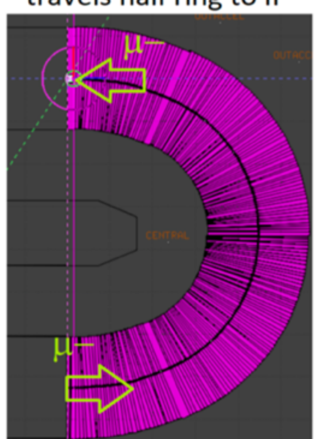
Machine Detector Interface @1.5 - 3 TeV





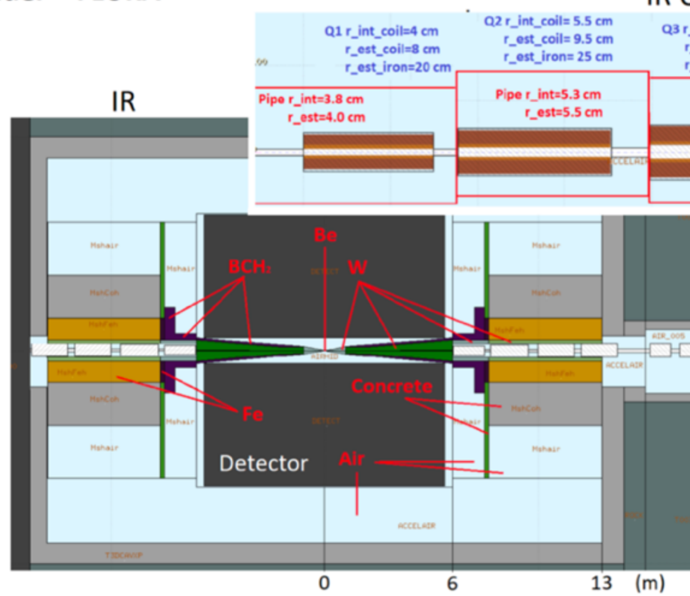
Simulation tool: **LineBuilder + FLUKA**
Data analysis: **Python**

750 GeV muon beam travels half ring to IP

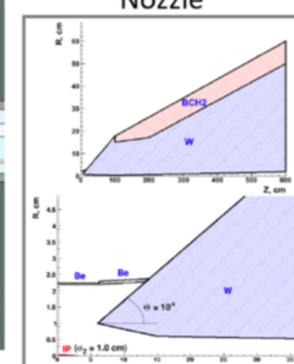


IR

IR Quadrupoles

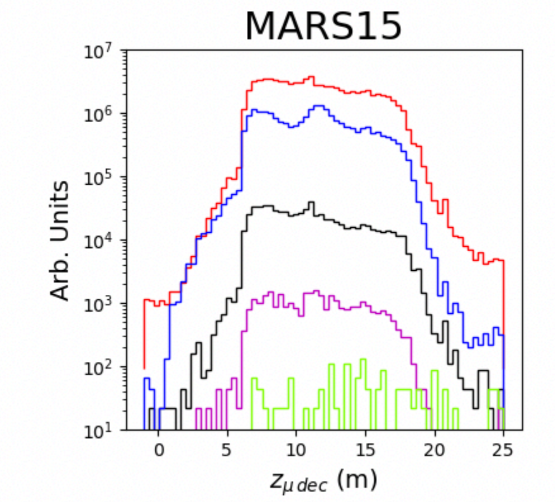


Nozzle



LHCP2021

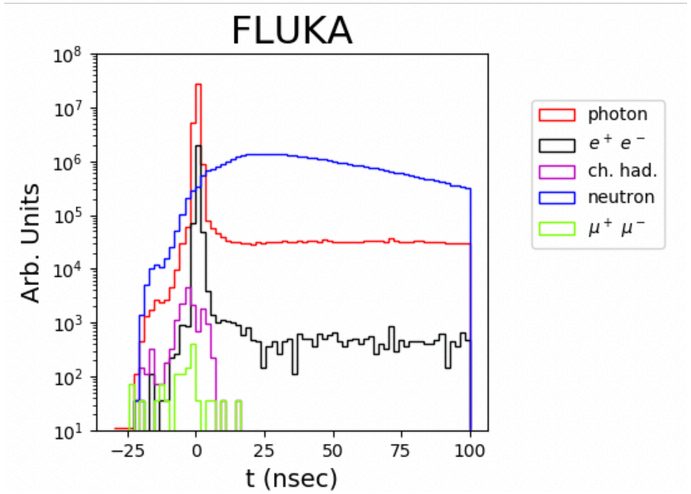
Beam Induced background distributions

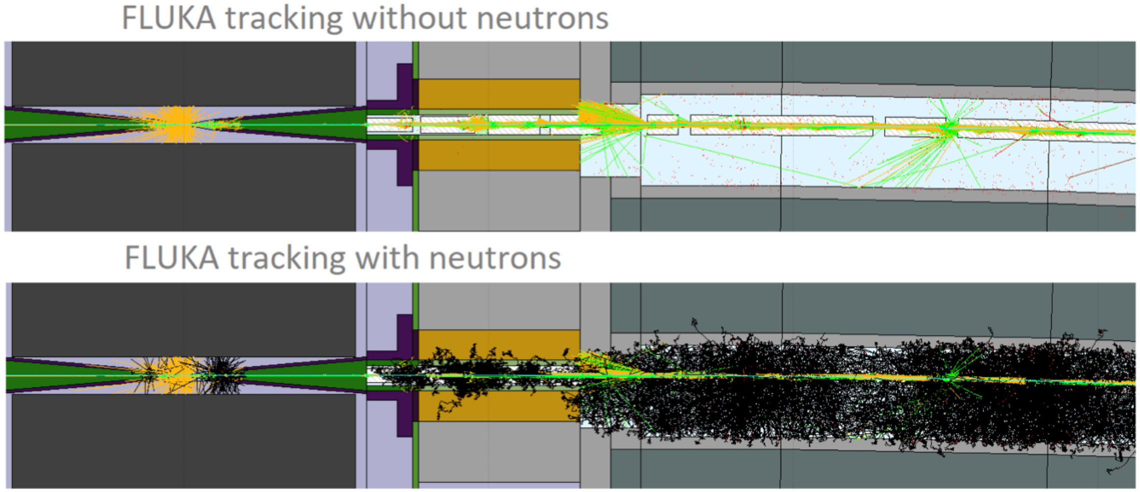


[Advanced assessment of Beam Induced Background at a Muon Collider]

muon beams
@ **0.75 TeV** with **2×10^{12}muons/bunch** ➔
4×10^5 muon decays/m single bx

BIB @ 10 TeV to be studied ex novo

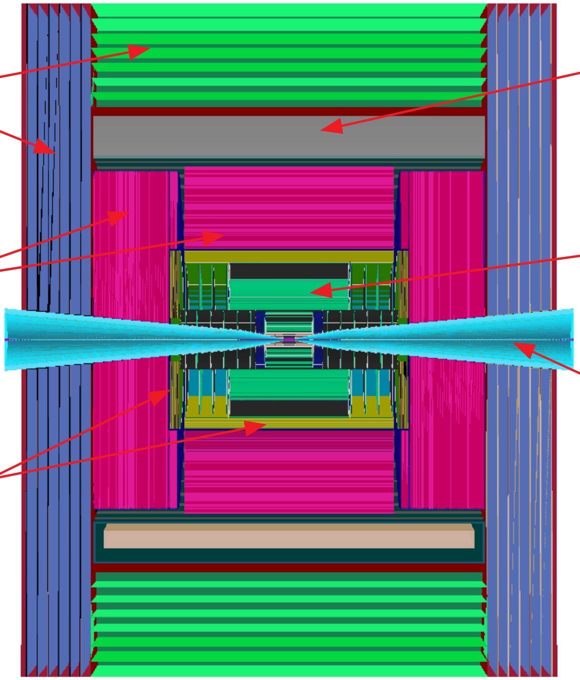




For each collider energy the machine elements, the MDI and interaction region have to be properly designed and optimized

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

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



B = 3.57 T to be studied and tuned

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

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

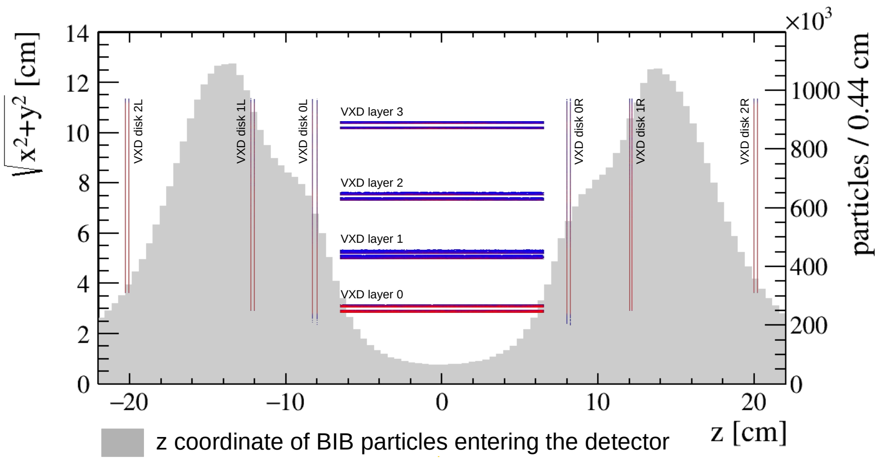
Hadron Calorimeter (HCAL)
- 60 layers steel absorber & plastic scintillating tiles, 30x30 mm^2

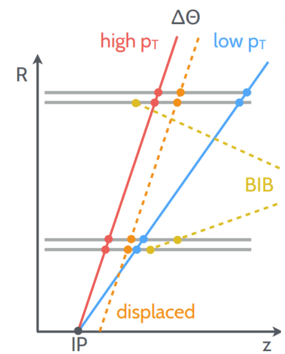
Full simulation available on github

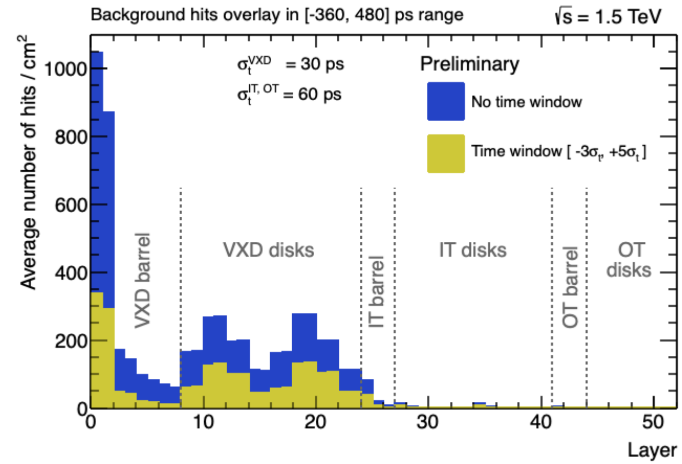
Luminosity measurement at Muon Collider
Poster by Laura Buonincontri et al.

Quite advanced conceptual design for Higgs factory, 1.5 TeV and 3 TeV

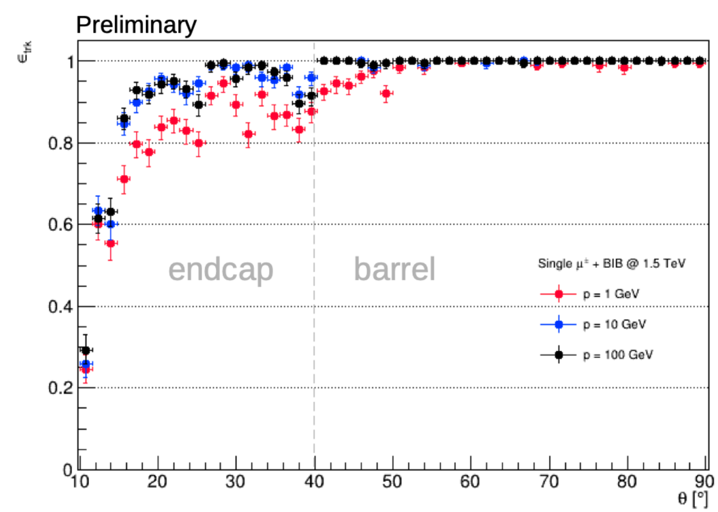
Tracker detector considerations







- Timing window applied to reduce out-of-time BIB's hits
- Granularity optimized to ensure ≲ 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

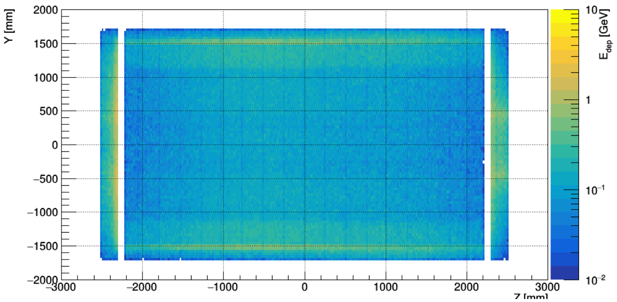


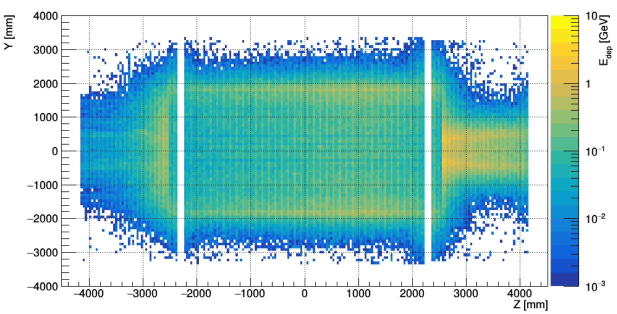
Calorimeters and Muon detectors

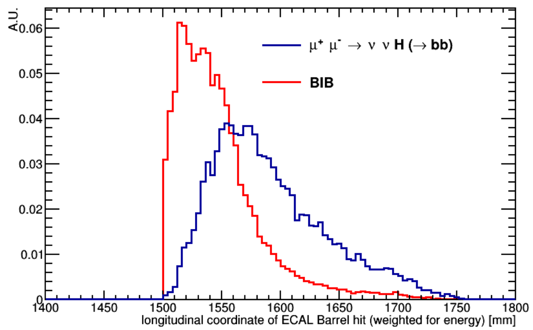
Calorimeters

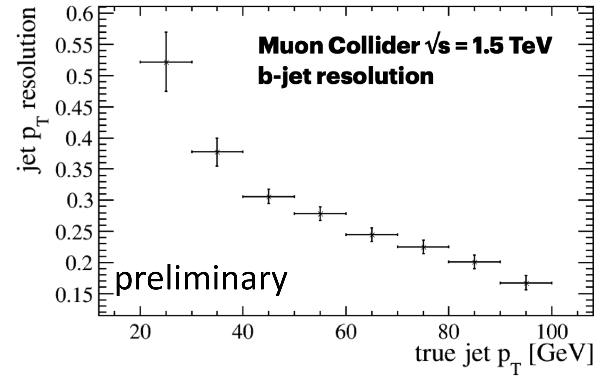
BIB deposits large amount of energy in both ECAL and HCAL

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



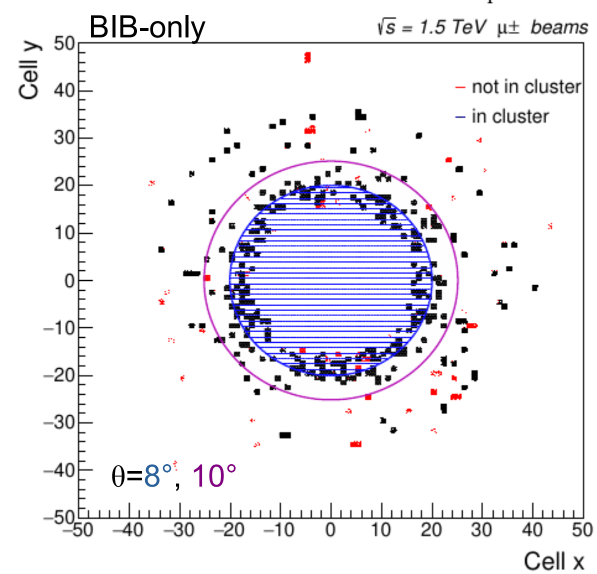






Muon System

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



Innovative and computationally efficient event-reconstruction approaches are needed

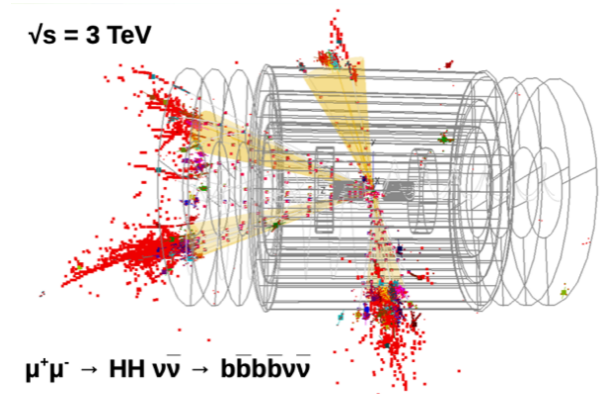
Double Higgs in full simulated detector

$\mu^+\mu^- \to HH\nu\bar{\nu} \to b\bar{b}b\bar{b}\nu\bar{\nu}$ @ $\sqrt{s} = 3$TeV under study by using the full detector simulation

✦ Reach on Higgs trilinear coupling: hh → 4b

B, Franceschini, Wulzer 2012.11555
Costantini et al. 2005.10289
Han et al. 2008.12204

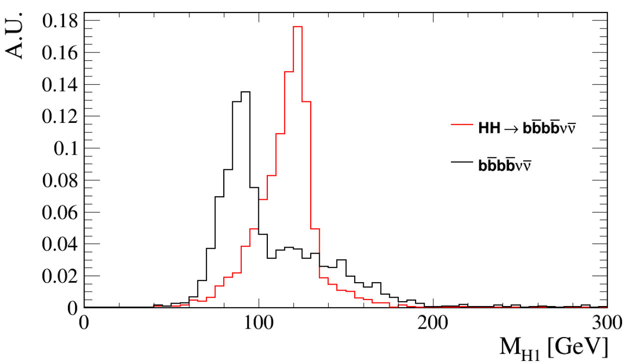
E [TeV]	$\mathscr{L}$ [ab^{-1}]	N_{rec}	$\delta\sigma \sim N_{rec}^{-1/2}$	$\delta\kappa_3$
3	5	170	~ 7.5%	~ 10%
10	10	620	~ 4%	~ 5%
14	20	1340	~ 2.7%	~ 3.5%
30	90	6'300	~ 1.2%	~ 1.5%

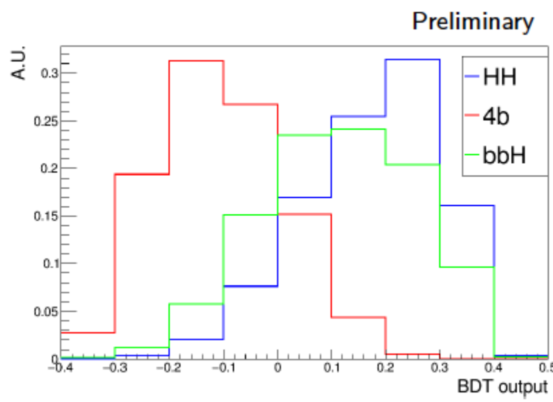


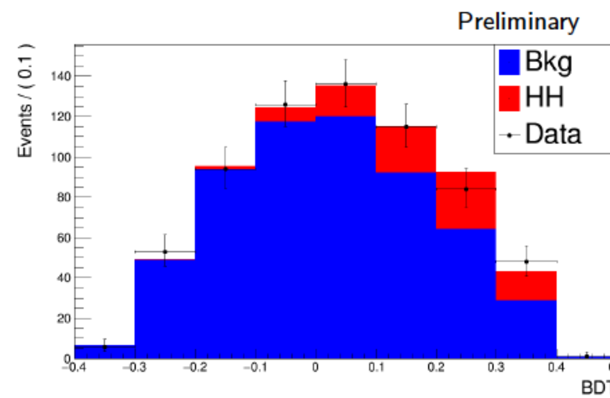
b-tagging efficiency with BIB: ~ 60% with a mis-tag ~ 1% @ 1.5 TeV used to weight events 2020 JINST 15 P05001

Classification of signal and background events with Machine Learning technique (BDT

Invariant mass of the leading Higgs







Physics & Detector Group

1.3 ab^{-1} (4 years) @ 3 TeV 65 HH events expected and 561 background events with 30% BDT uncertainty

Looking forward

AMBITION: successful implementation of an **international plan** to address all studies and key issues towards the design of a muon collider capable to reach multi-TeV collision energies with an adequate luminosity for high-precision measurements and new discoveries

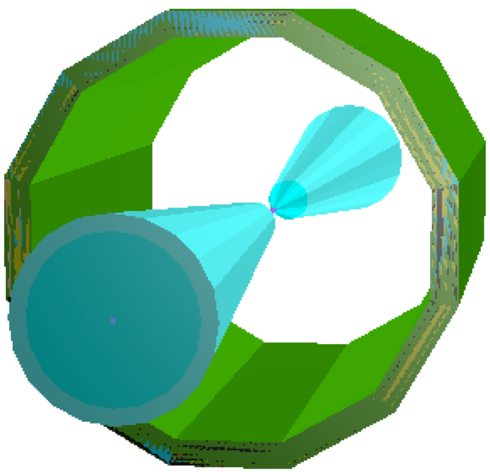
CHALLENGES: establish an organized international collaboration to address key issues and plan future steps. Evaluate reuse of existing infrastructures taking into account neutrino radiation hazards. Design of needed **test facilities** to address **final feasibility**

Many new papers in preparation addressing the facility, the demonstrator and synergies and the possible detector R&D and reconstruction tools to mitigate Beam Induced Background

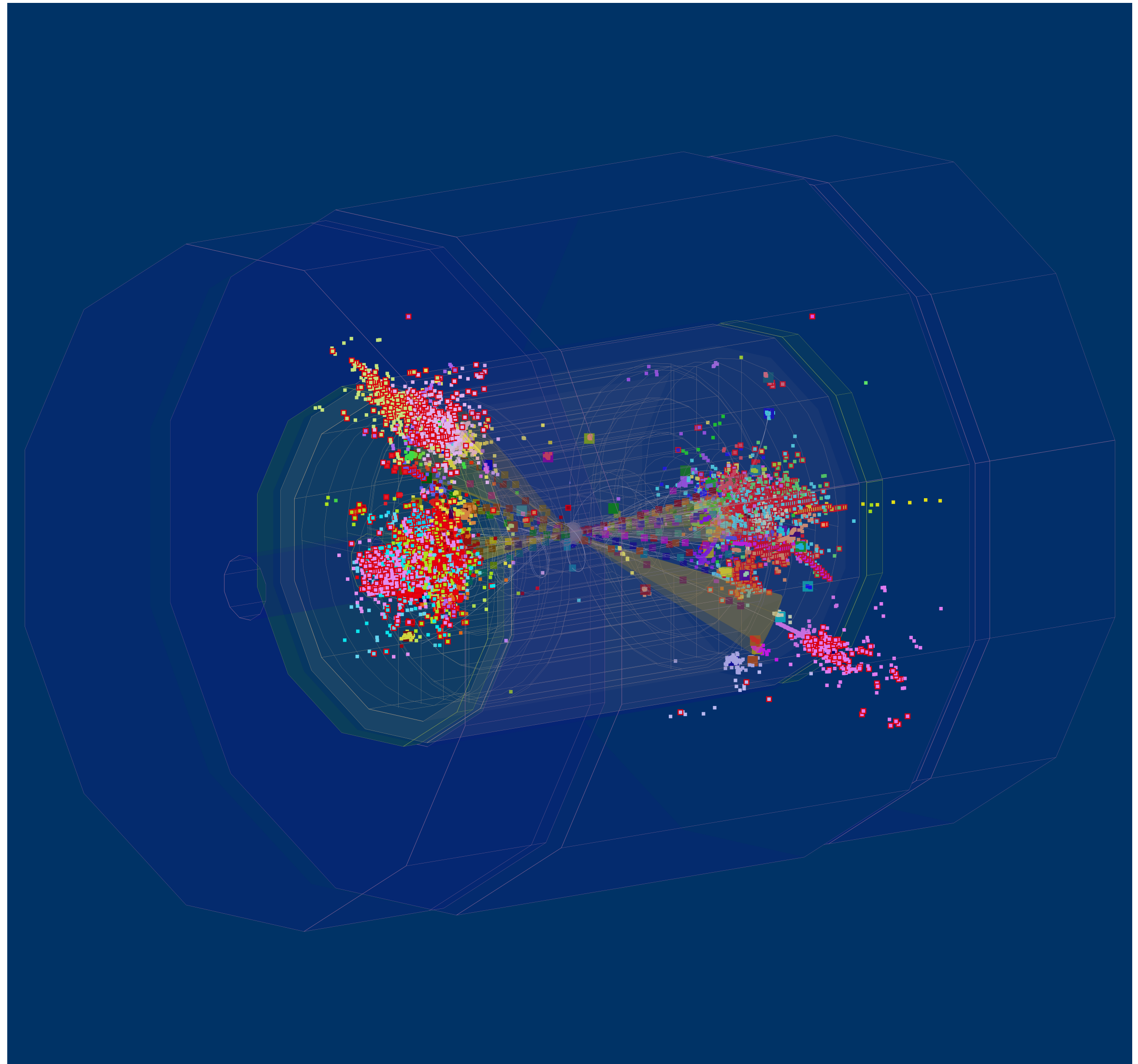
- **CERN website**
  https://muoncollider.web.cern.ch/
- **INFN Confluence website: full simulation**
  https://confluence.infn.it/display/muoncollider
- **International Design Study Indico @ CERN**
  https://indico.cern.ch/category/11818/
- **Muon Collider SnowMass Forum USA**
  https://indico.fnal.gov/event/47038/

Please subscribe at the
CERN e-group “muoncollider”
if you are interested to follow

Thanks to all the colleagues and for your attention!



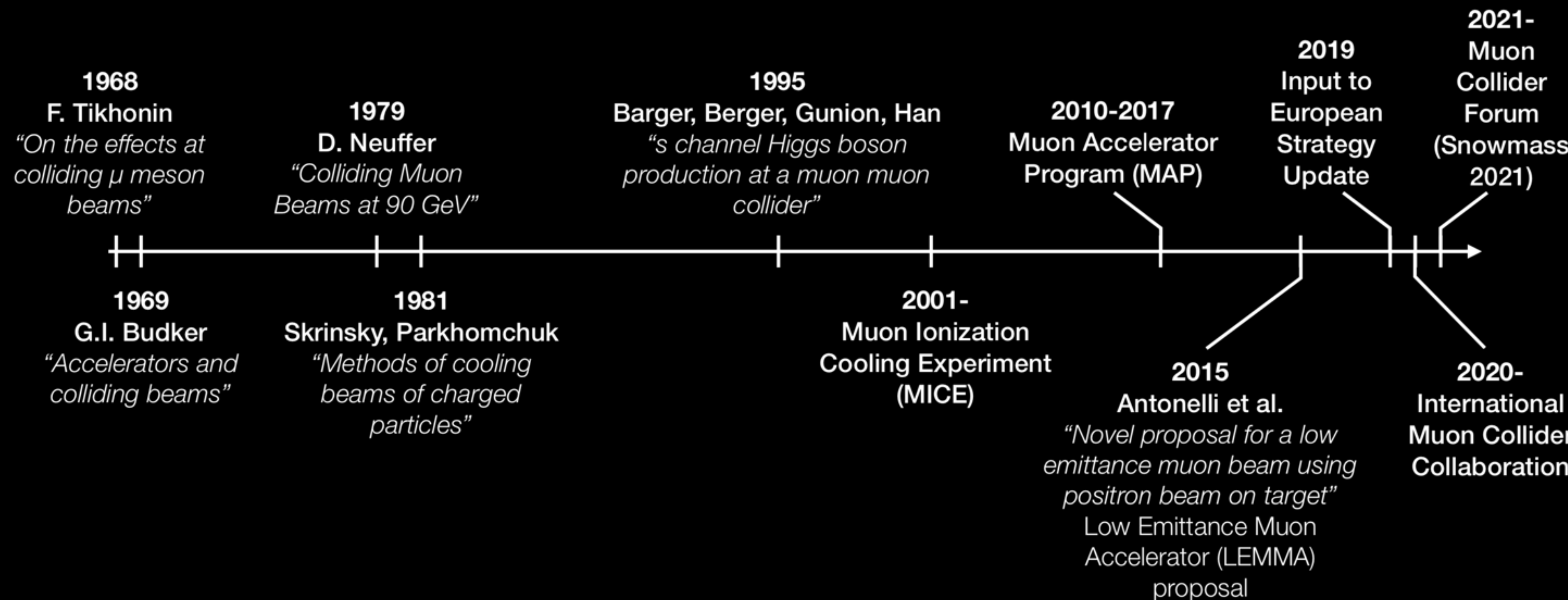
First new dedicated detector R&D: Crilin, a crystal calorimeter with longitudinal information under study



extras

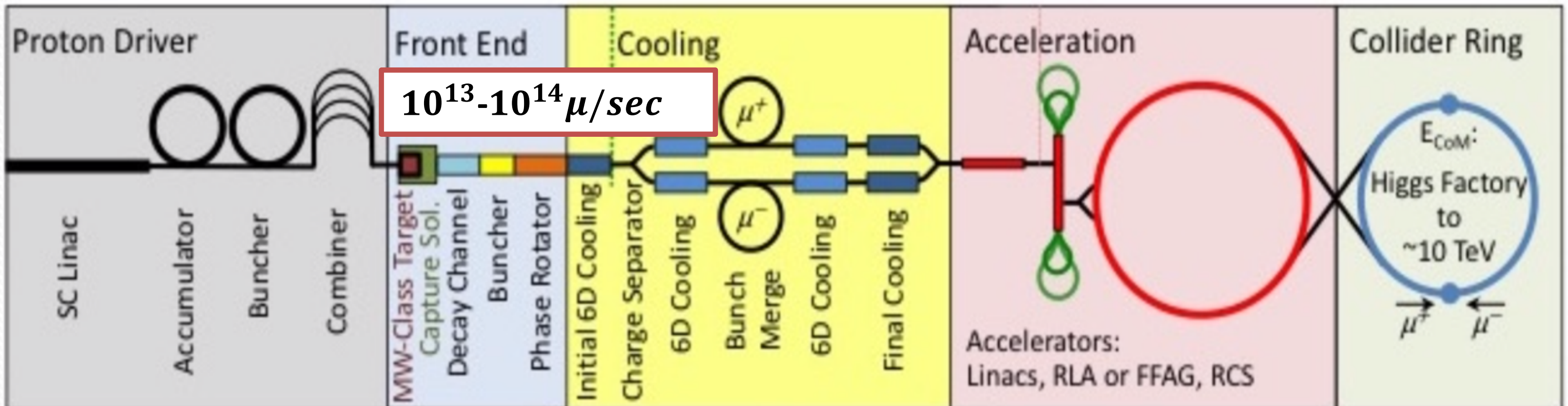
A brief history of muon colliders

(A wholly incomplete timeline)



proton (MAP) vs positron (LEMMA) driven muon source

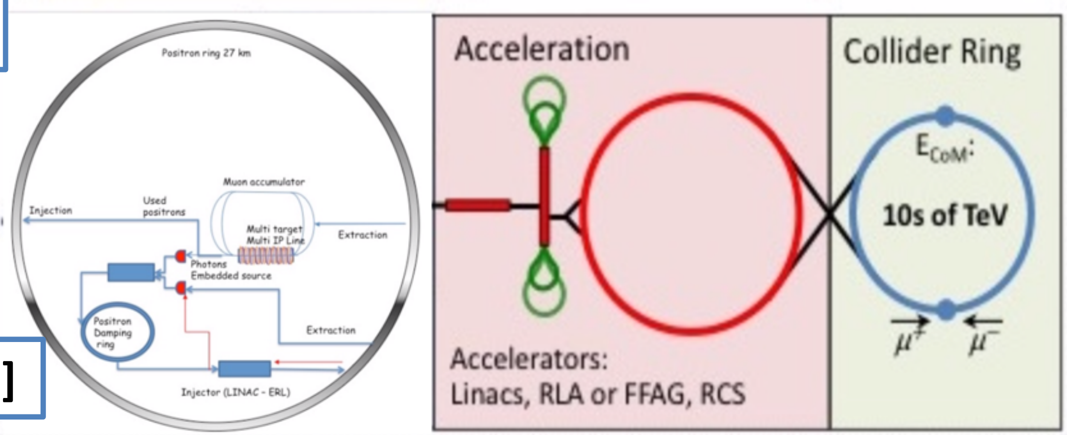
MAP



MUON JINST, shorturl.at/kxKU7

LEMMA

e+ source

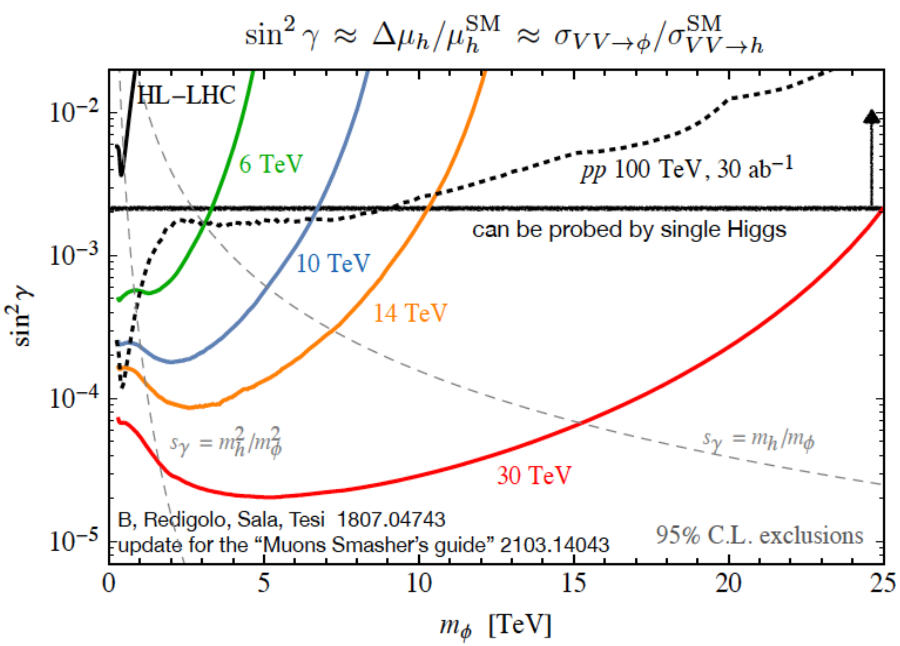


arXiv:1905.05747v2 [physics.acc-ph]

➔ **need consolidation** to overcome technical limitations to reach higher muon intensities

Other searches and precise measurements

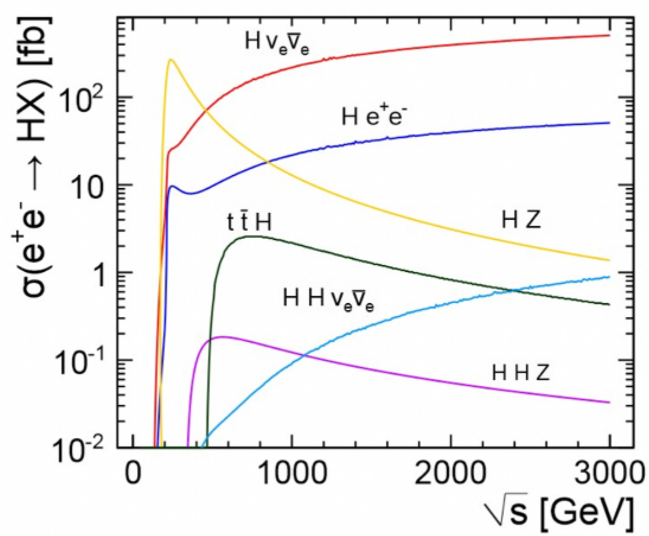
The Muon Smasher's Guide



$\sqrt{s}$ (TeV)	3	6	10	14	30
benchmark lumi (ab^{-1})	1	4	10	20	90
σ (fb): $WW \to H$	490	700	830	950	1200
$ZZ \to H$	51	72	89	96	120
$WW \to HH$	0.80	1.8	3.2	4.3	6.7
$ZZ \to HH$	0.11	0.24	0.43	0.57	0.91

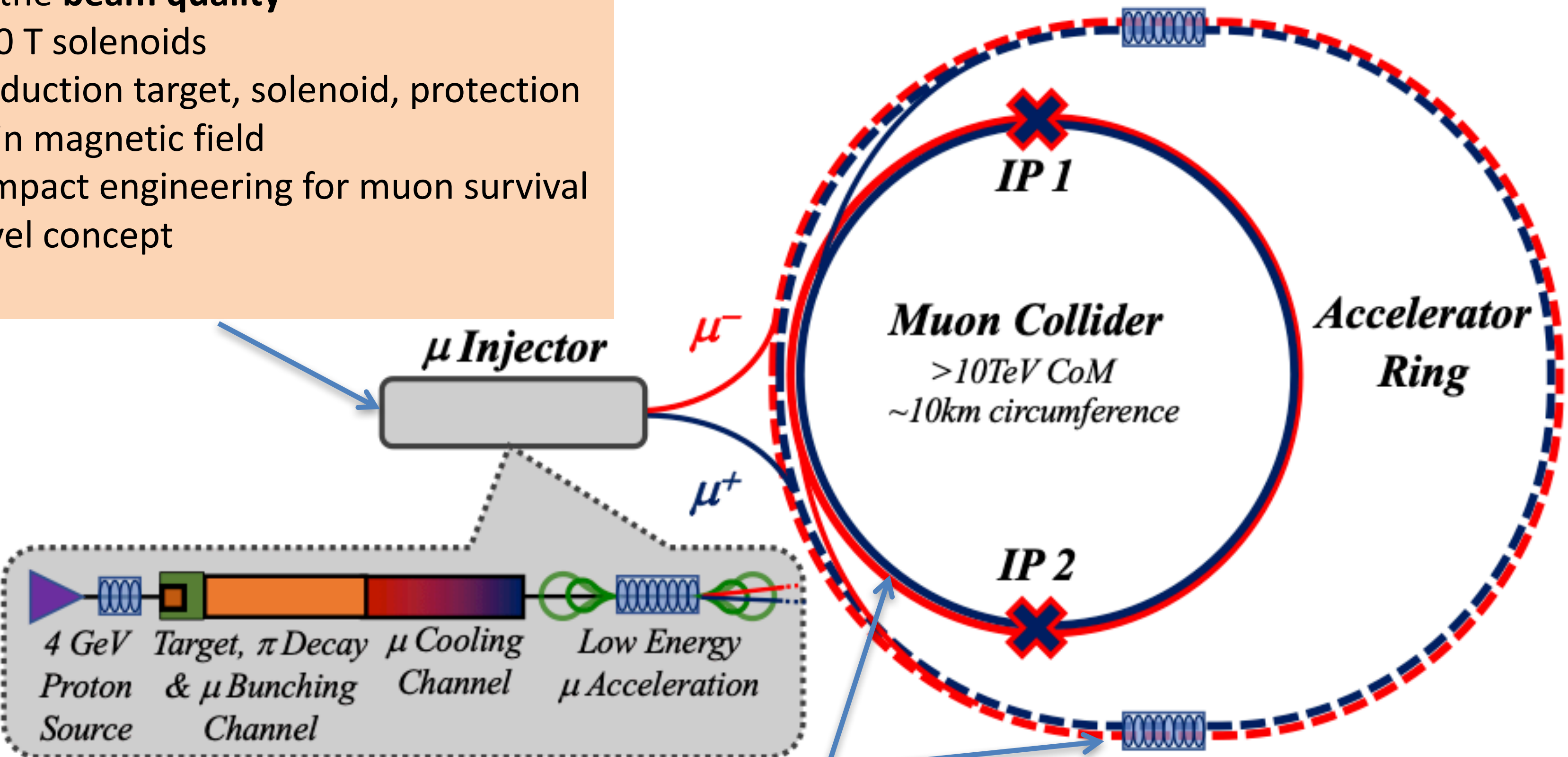
$\mathcal{O}(10^6 - 10^8)$ Higgs $\Rightarrow \mathcal{O}(10^{-3} - 10^{-4})$ precision

$\mathcal{O}(10^3 - 10^5)$ di-Higgs $\Rightarrow \mathcal{O}(10^{-2} - 10^{-3})$ precision



R&D Challenges

Drives the **beam quality**
- > 30 T solenoids
- Production target, solenoid, protection
- RF in magnetic field
- Compact engineering for muon survival
- novel concept
- …

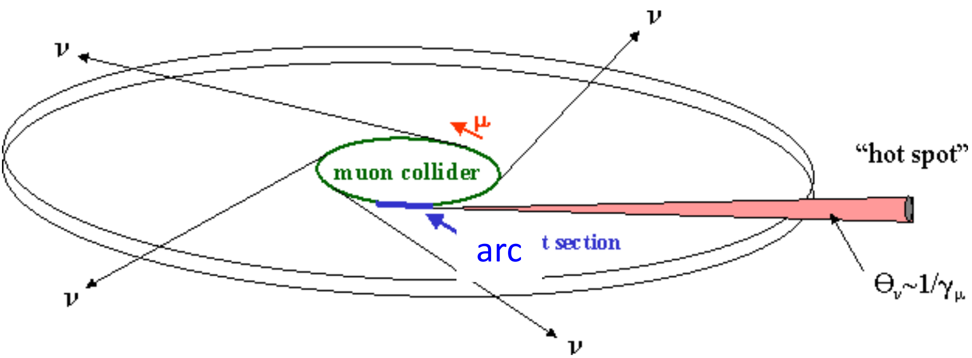


Cost and **power** consumption limit energy reach
- Superconducting collider ring magnets
- Protection of collider (and other) magnets from muon decays
- Fast ramping magnets with energy recovery
- Efficient RF for high bunch charge
- FFA

Neutrino flux on Earth surface limits energy and site choice
MDI might limits energy reach

Integrated coherent concept/parameters

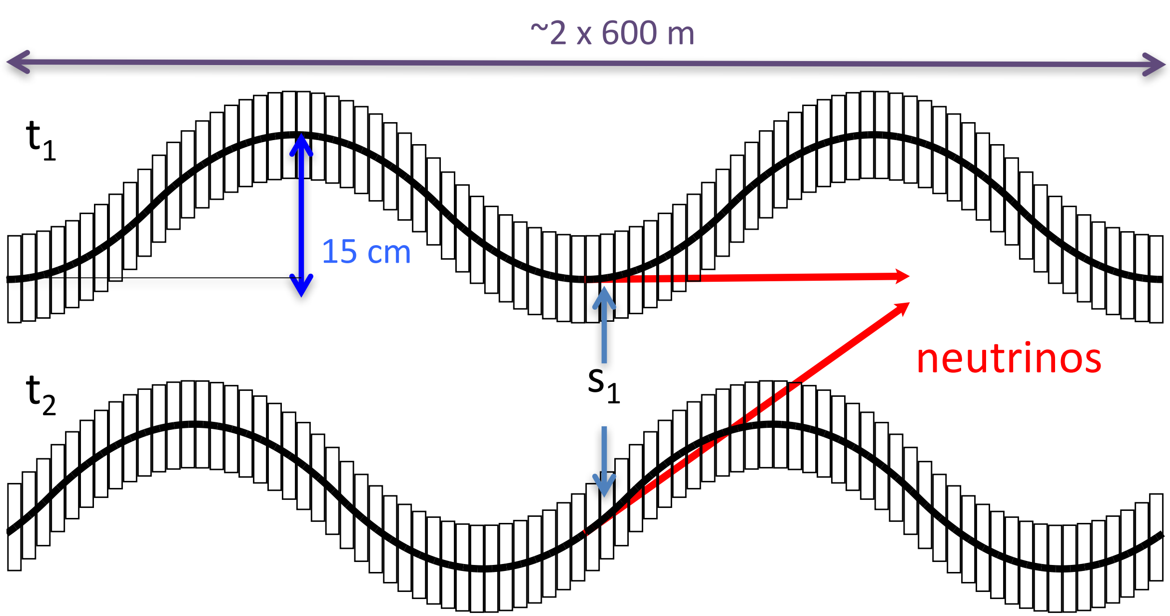
Neutrino Flux Mitigation



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 mradian

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

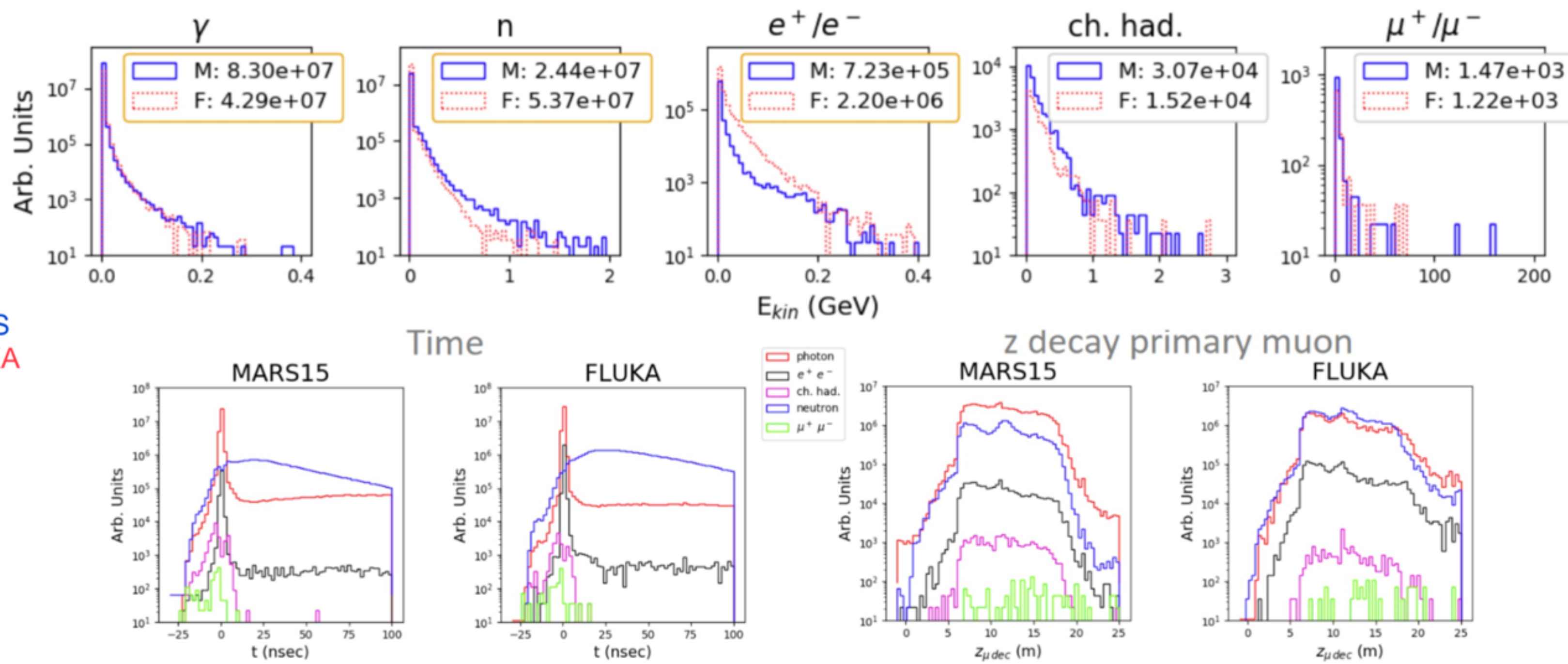
MAR15 – FLUKA BIB comparison

International MUON Collider Collaboration

The 1.5TeV case benchmark

MARS-FLUKA Results Comparison

MARS
FLUKA



Residual discrepancies in **particles time and energy distribution**:

- Minor layout differences (passive elements, absorbers)
- Intrinsic differences between codes

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