aMUSE

International
MUON Collider
Collaboration

MuCol

International Muon Collider

April 20, Peking University 2024

Donatella Lucchesi University and INFN of Padova

for the

International Muon Collider Collaboration

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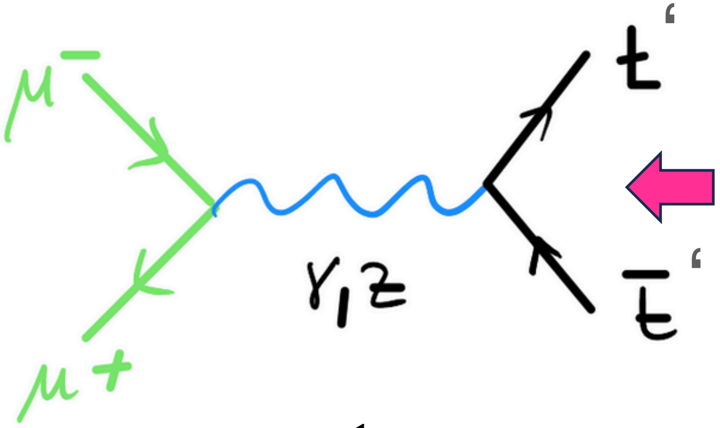
Università
degli Studi
di Padova

INFN
Istituto Nazionale di Fisica Nucleare

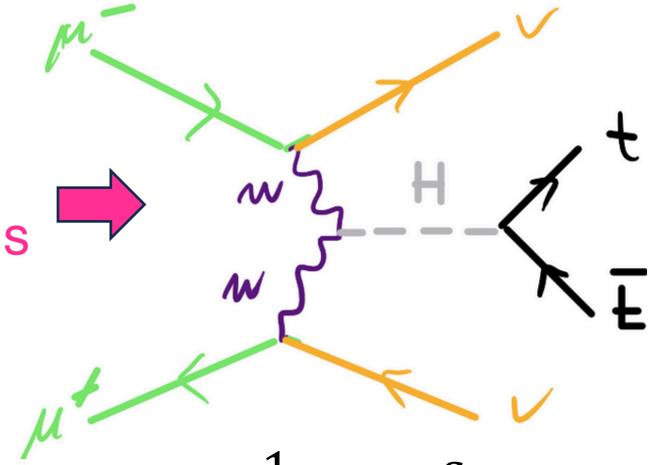
Physic processes: two colliders in one

F. Maltoni
"Physics Overview" Annual Meeting IMCC

Multi-TeV muon collider opens a completely new regime :



Different physics can be probed in the two channels



$$\sigma \sim \frac{1}{s}$$

Energetic final states
(heavy particle or very boosted)

$$\sigma \sim \frac{1}{M^2} log^n \frac{s}{M}$$

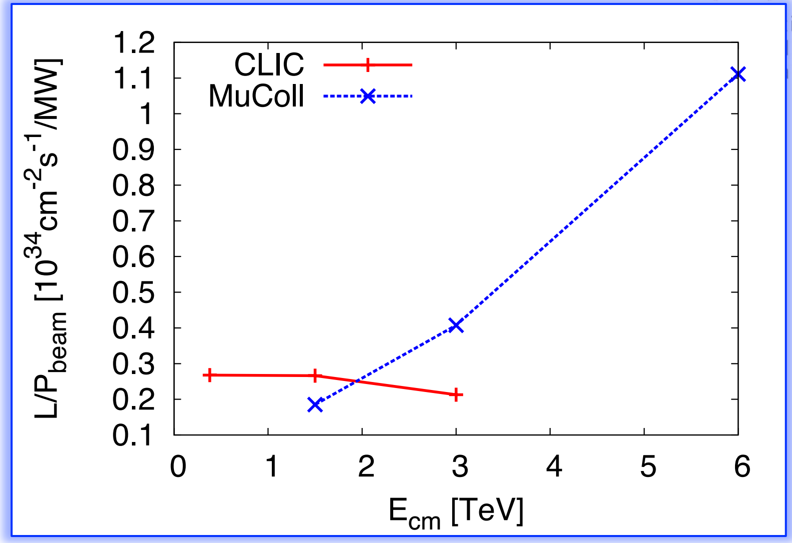
Standard Model coupling measurements
Discovery light and weakly interacting particles

Muon Colliders, 1901.06150
The muon Smasher's guide, *Rept.Prog.Phys.* 85 (2022) 8, 084201 2103.14043
Muon Collider Forum Report, 2209.01318
Towards a Muon Collider, *Eur.Phys.J.C* 83 (2023) 9, 864, 2303.08533

A “convenient” accelerator complex

Muons do not suffer from synchrotron radiation in this energy range

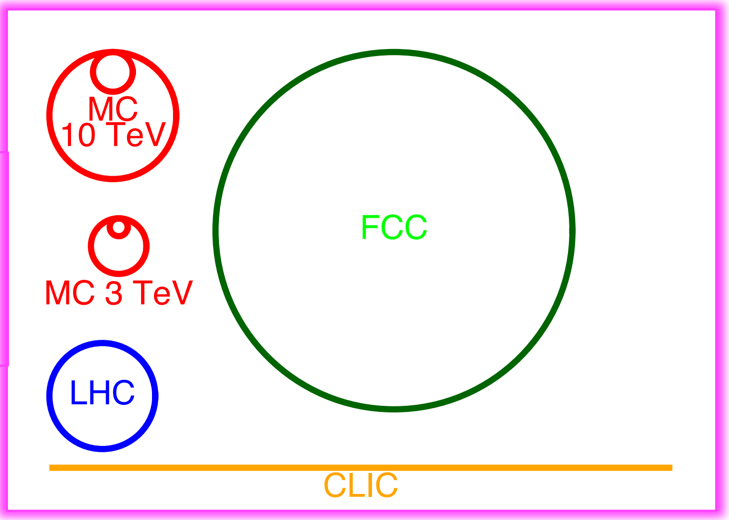
High center of mass energy & high luminosity & power efficient: luminosity increase per beam power



C. Accettura et al. "Towards a muon collider"

Parameter	Symbol	Unit	Target value		
Centre-of-mass energy	E_{cm}	TeV	3	10	14
Luminosity	$\mathfrak{L}$	$1 \times 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	2	20	40
Collider circumference	C_{coll}	km	4.5	10	14
Muons/bunch	$N_{\pm}$	1×10^{12}	2.2	1.8	1.8
Repetition rate	f_{r}	Hz	5	5	5
Total beam power	$P_{-} + P_{+}$	MW	5.3	14	20
Longitudinal emittance	ε_{l}	MeV m	7.5	7.5	7.5
Transverse emittance	$\varepsilon_{\perp}$	µm	25	25	25
IP bunch length	σ_z	mm	5	1.5	1.1
IP beta-function	$\beta^{*}_{\perp}$	mm	5	1.5	1.1
IP beam size	$\sigma_{\perp}$	µm	3	0.9	0.6

Compact: cost effective & sustainable



Integrated luminosity: $\sqrt{s} = 3$ TeV 1 ab^{-1} 5 years one experiment

$\sqrt{s} = 10$ TeV 10 ab^{-1} 5 years one experiment

The Facility

- Next generation of accelerator complex
- Neutrino physics experiments, not discussed here
- Experiments at $\sqrt{s}$ ranging from few TeV to 10-ish TeV

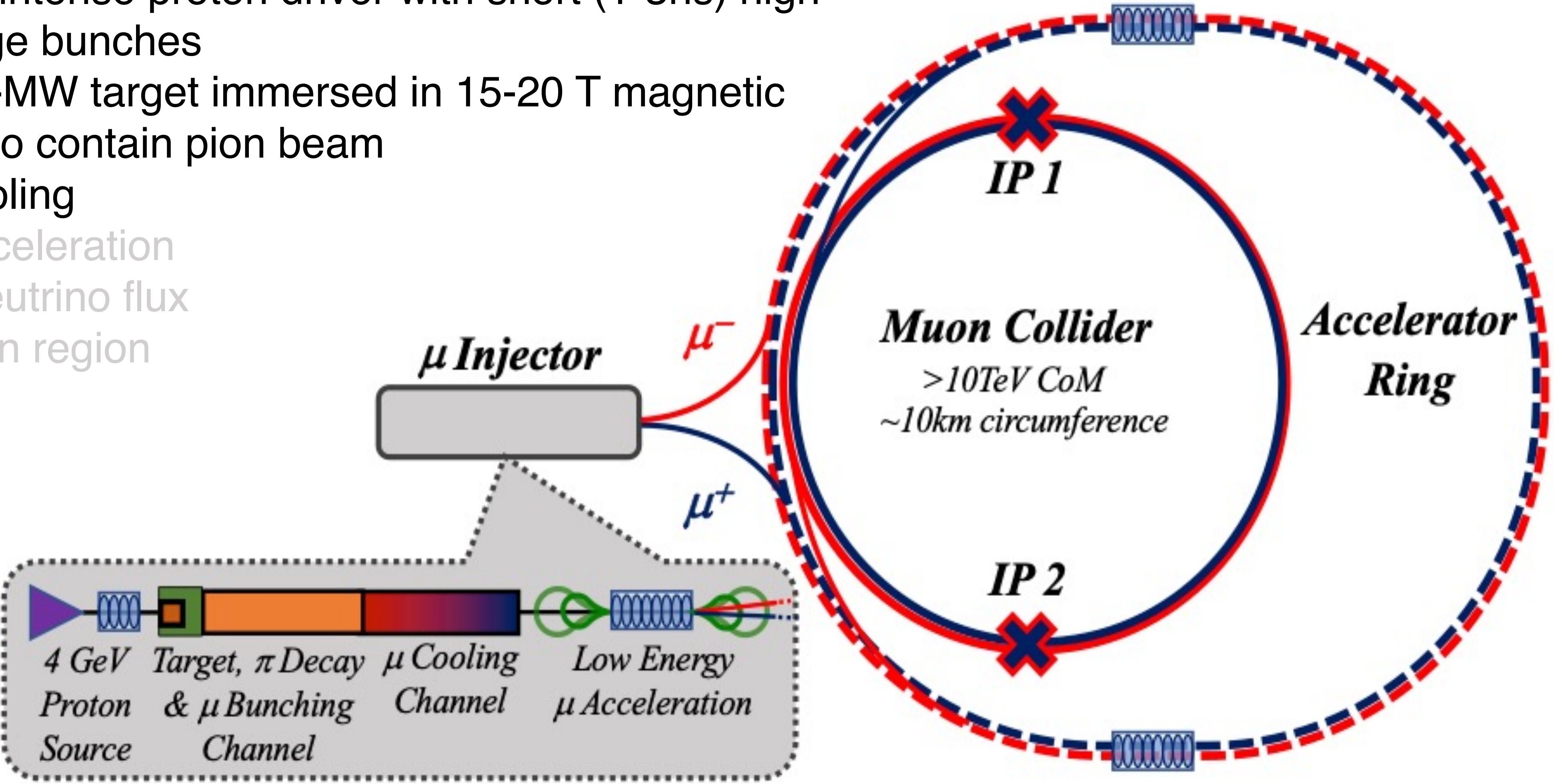
Accelerator complex

Muon Collider Facility in a nutshell

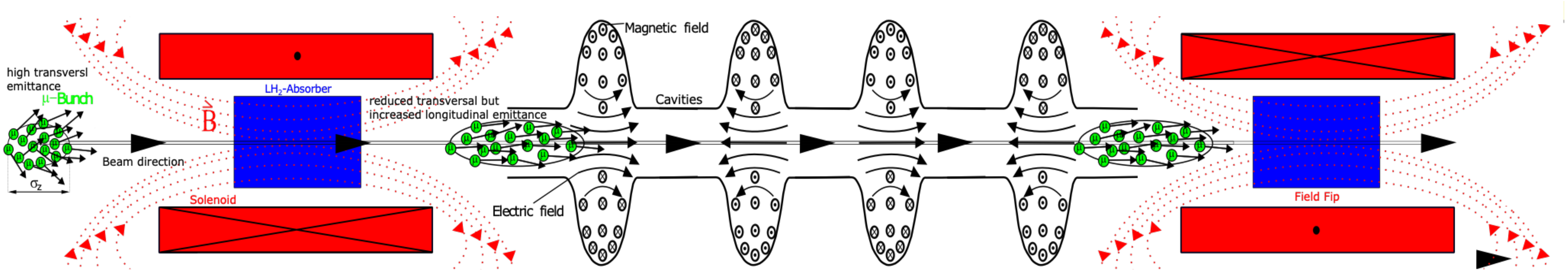
If not specified material is taken from
C. Accettura et al. "Towards a muon collider”

Key challenges

- Proton source
  - High intense proton driver with short (1-3ns) high-charge bunches
  - Multi-MW target immersed in 15-20 T magnetic field to contain pion beam
- Muon cooling
- Beam acceleration
- Dense neutrino flux
- Interaction region



Muon ionization cooling principle



- Absorber: low Z material (Lithium hydride for first phase, liquid H for final cooling) in high magnetic filed to minimize the effect of multiple scattering
- RF cavities in magnetic field: accelerate the beam

Mice Coll. Demonstration of cooling by the Muon Ionization Cooling Experiment

Two cooling stages:

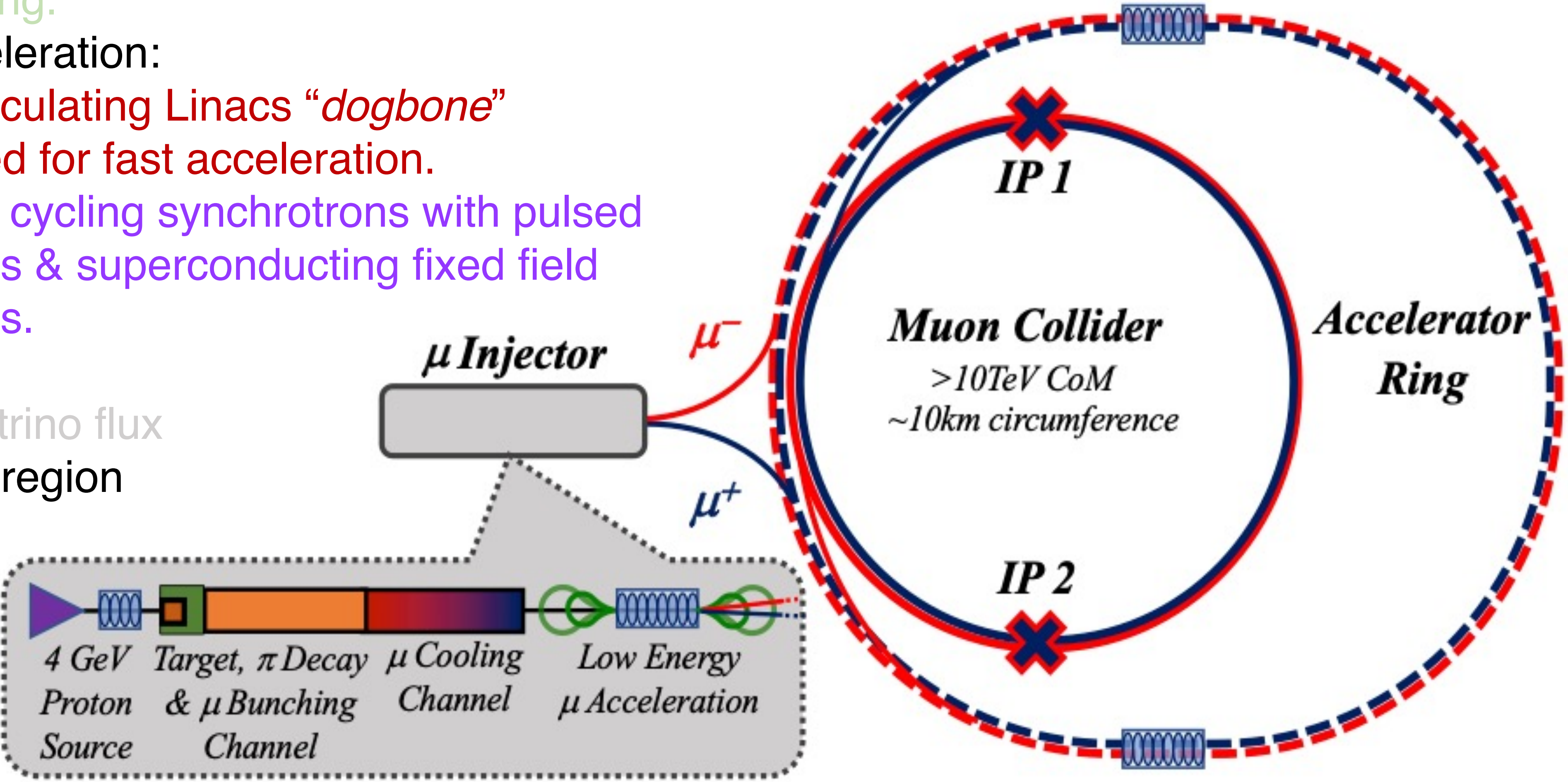
1) muons cooled both transversely and longitudinally, rectilinear cooling.
2) muons cooled transversely, final cooling.

Design baseline overview

Key challenges

- Proton source.
- Muon cooling.
- Beam acceleration:
  1) Re-circulating Linacs “*dogbone*” shaped for fast acceleration.
  2) Rapid cycling synchrotrons with pulsed dipoles & superconducting fixed field dipoles.

- Dense neutrino flux
- Interaction region

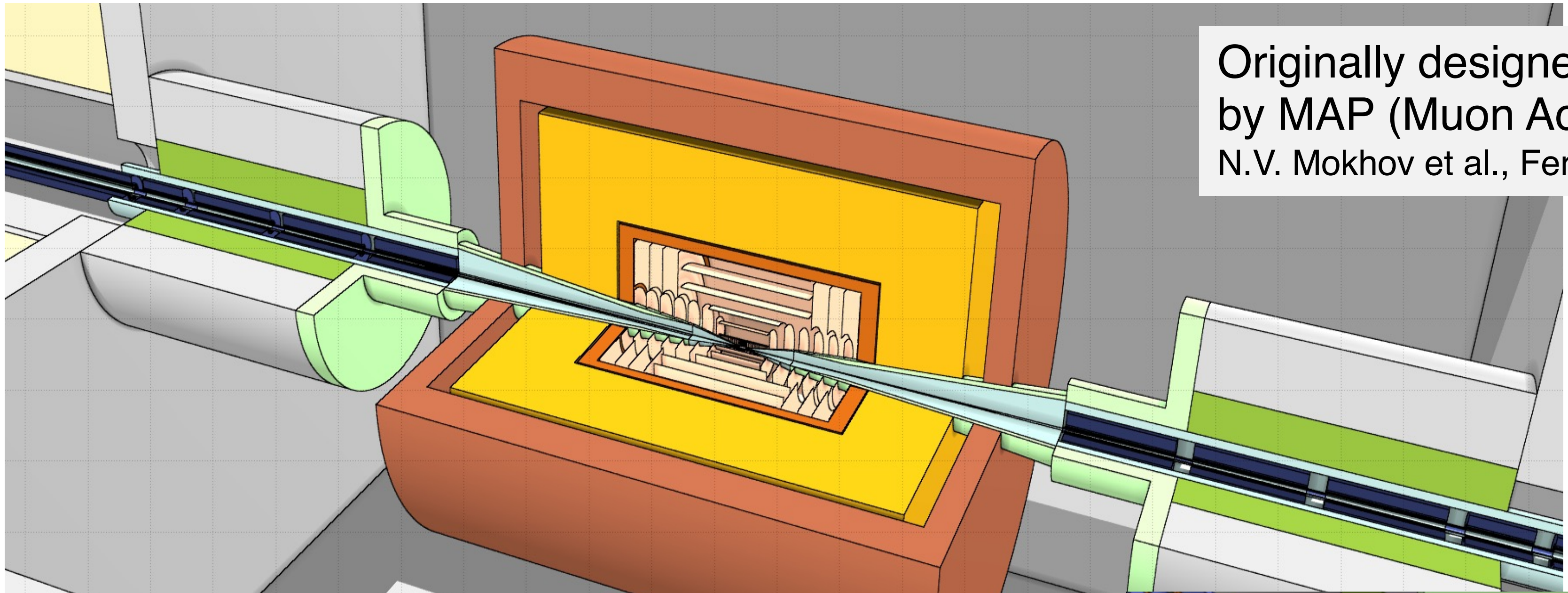


Beam background sources in the detector region

- ✗ Muon decay along the ring, $\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$: dominant process at all center-of-mass energies
  - ❈ photons from synchrotron radiation of energetic electrons in collider magnetic field
  - ❈ electromagnetic showers from electrons and photons
  - ❈ hadronic component from photonuclear interaction with materials
  - ❈ Bethe-Heitler muon, $\gamma + A \rightarrow A' + \mu^+\mu^-$
- ✗ Incoherent e^-e^+ production, $\mu^+\mu^- \rightarrow \mu^+\mu^-e^+e^-$: important at high $\sqrt{s}$
  - ❈ small transverse momentum $e^-e^+ \Longrightarrow$ trapped by detector magnetic field
- ✗ Beam halo: level of acceptable losses to be defined, not an issue now

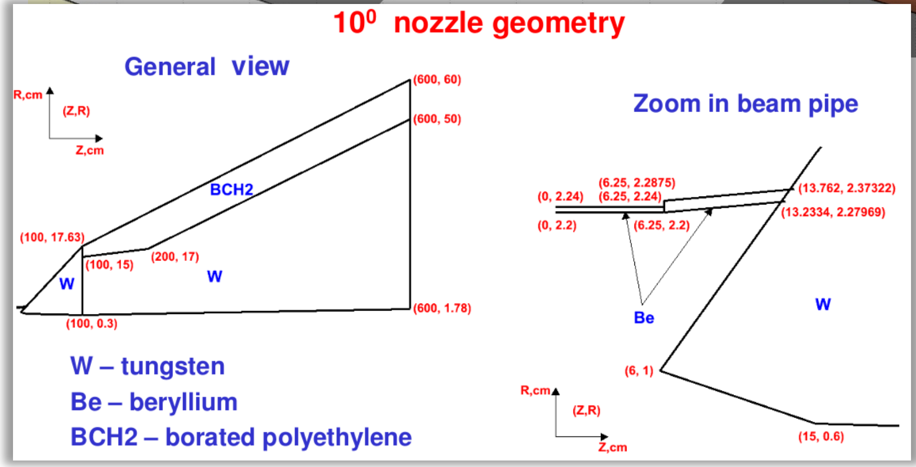
F. Collamati et al. 2021 JINST 16 P11009

Shielding structure: the nozzles



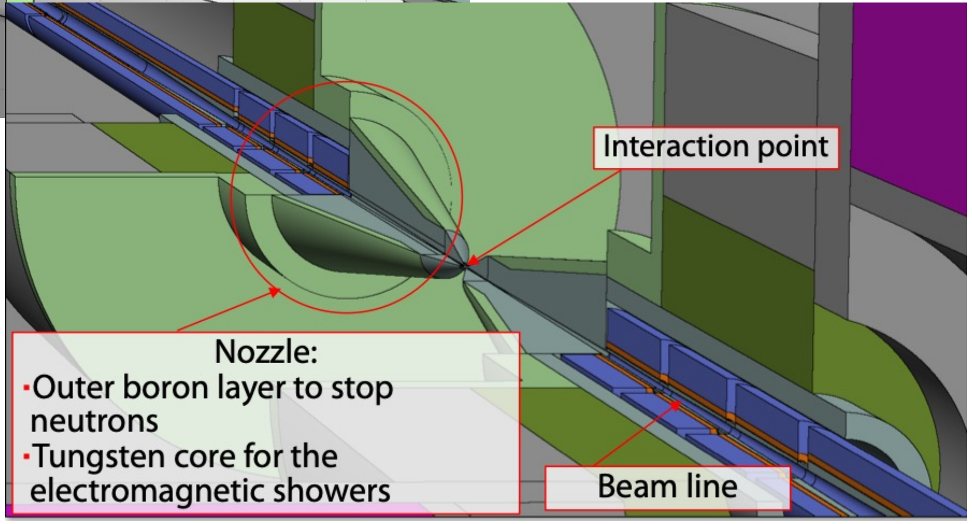
Originally designed for $\sqrt{s} = 1.5$ TeV
by MAP (Muon Accelerator Program)
N.V. Mokhov et al., Fermilab-Conf-11-094-APC-TD

Nozzles reduce background particle flux by 2-3 orders of magnitude



10^0 nozzle geometry

W – tungsten
Be – beryllium
BCH2 – borated polyethylene



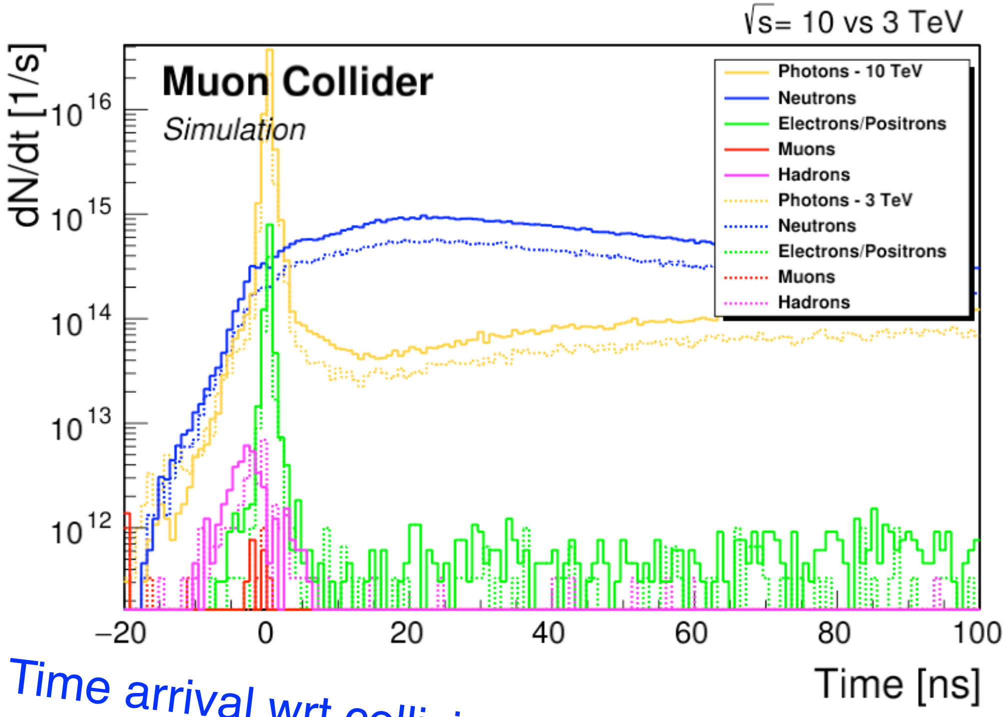
Interaction point

Nozzle:
- Outer boron layer to stop neutrons
- Tungsten core for the electromagnetic showers

Beam line

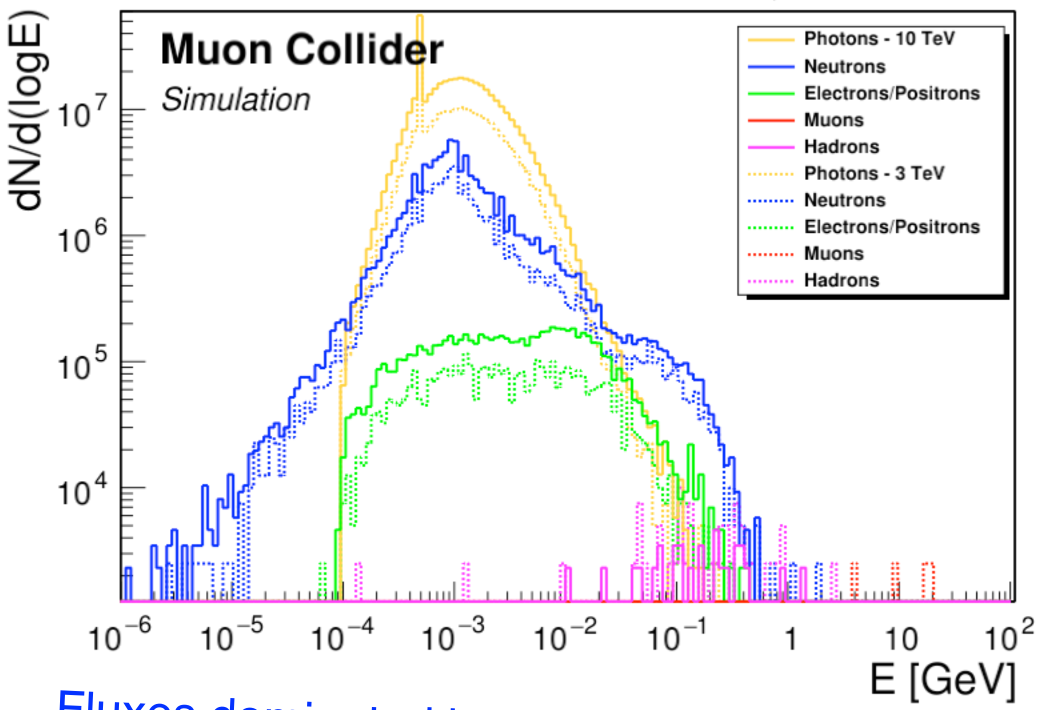
D. Calzolari
[IMCC Ann. meeting Orsay 2023]

Survived beam-Induced background (BIB) properties



Time arrival wrt collision time

[-1, 15] ns wrt t_0



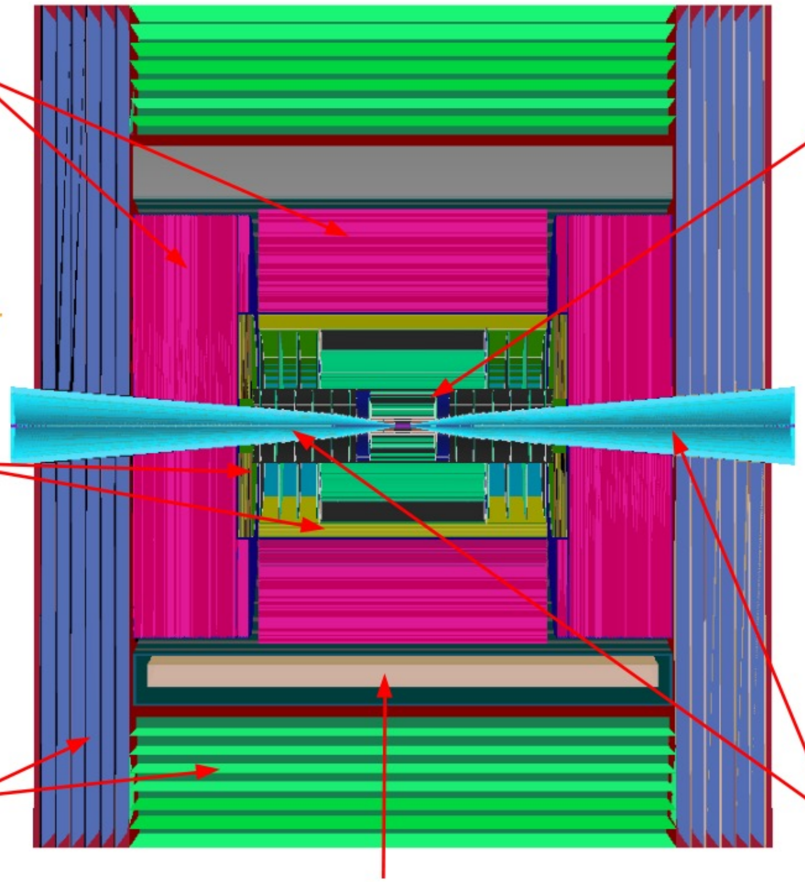
Fluxes dominated by low momentum particles

- Use the same nozzle structure of $\sqrt{s} = 1.5$ TeV $\Longrightarrow$ optimization for $\sqrt{s} = 3$ TeV and $\sqrt{s} = 10$ TeV in progress
- Fluxes at $\sqrt{s} = 3$ and $\sqrt{s} = 10$ TeV quite similar $\Longrightarrow$ beam-induced background characteristics determined by the nozzles

Detector and physics performance

Detector concept at $\sqrt{S} = 3$ TeV evolved from CLIC's detector design CLICdp-Note-2017-001

- Removed forward luminosity detectors
- Inserted nozzles
- Adapted tracker detector
- Magnetic field modified to cope with available beam-induced background



hadronic calorimeter

- 60 layers of 19-mm steel absorber + plastic scintillating tiles;
- 30x30 mm^2 cell size;
- 7.5 λ_I.

electromagnetic calorimeter

- 40 layers of 1.9-mm W absorber + silicon pad sensors;
- 5x5 mm^2 cell granularity;
- 22 X_0 + 1 λ_I.

muon detectors

- 7-barrel, 6-endcap RPC layers interleaved in the magnet's iron yoke;
- 30x30 mm^2 cell size.

superconducting solenoid (3.57T)

tracking system

- Vertex Detector:
  - double-sensor layers (4 barrel cylinders and 4+4 endcap disks);
  - 25x25 µm^2 pixel Si sensors.
- Inner Tracker:
  - 3 barrel layers and 7+7 endcap disks;
  - 50 µm x 1 mm macro-pixel Si sensors.
- Outer Tracker:
  - 3 barrel layers and 4+4 endcap disks;
  - 50 µm x 10 mm micro-strip Si sensors.

shielding nozzles

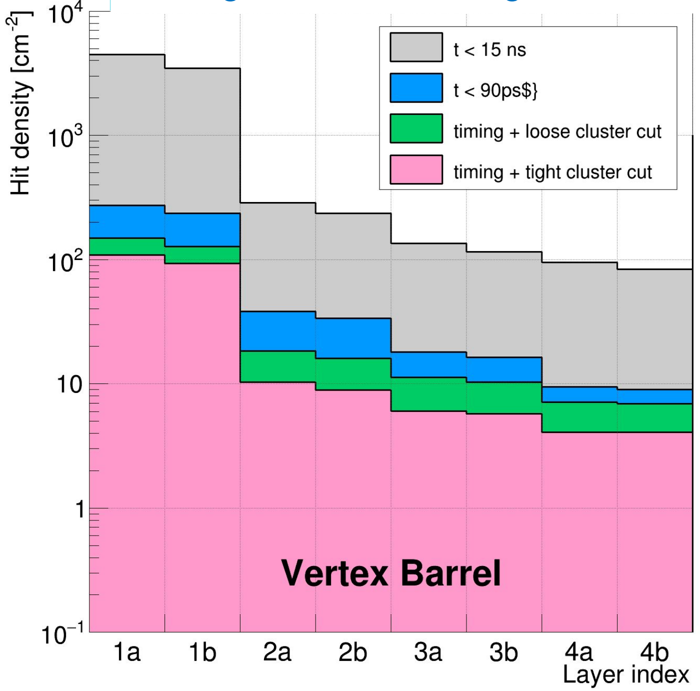
- Tungsten cones + borated polyethylene cladding.

ILCSoft is the simulation and reconstruction framework, implemented starting from CLIC's software. Transition to key4hep in progress. Tutorial available if interested to play with.

Major detector challenges: occupancy

First layers of barrel vertex detector & forward disks highly impacted BIB

S. Pagan Griso C. Sellgren



ECAL surface flux: 300 particle/cm^2

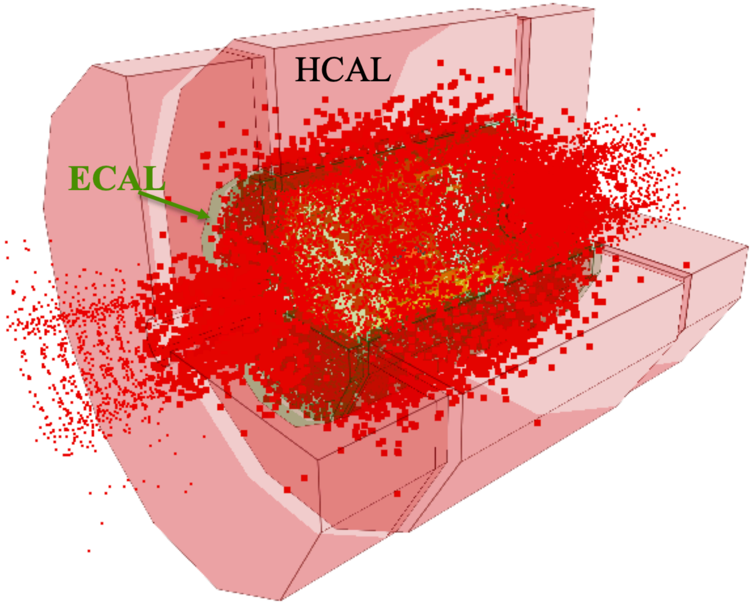
- 96% photons, 4% neutrons
- $E_{\gamma}^{Ave.} \sim 1.7$ MeV

Detector requirements

- Timing: high resolution to suppress out of time BIB. Tracking ~ 30ps, ECAL ~100ps
- High granularity

+

- Double layers on vertex
- Longitudinal segmentation ECAL



- Hadronic calorimeter and barrel muon detector almost not affected by BIB
- Forward muon affected as the tracker system

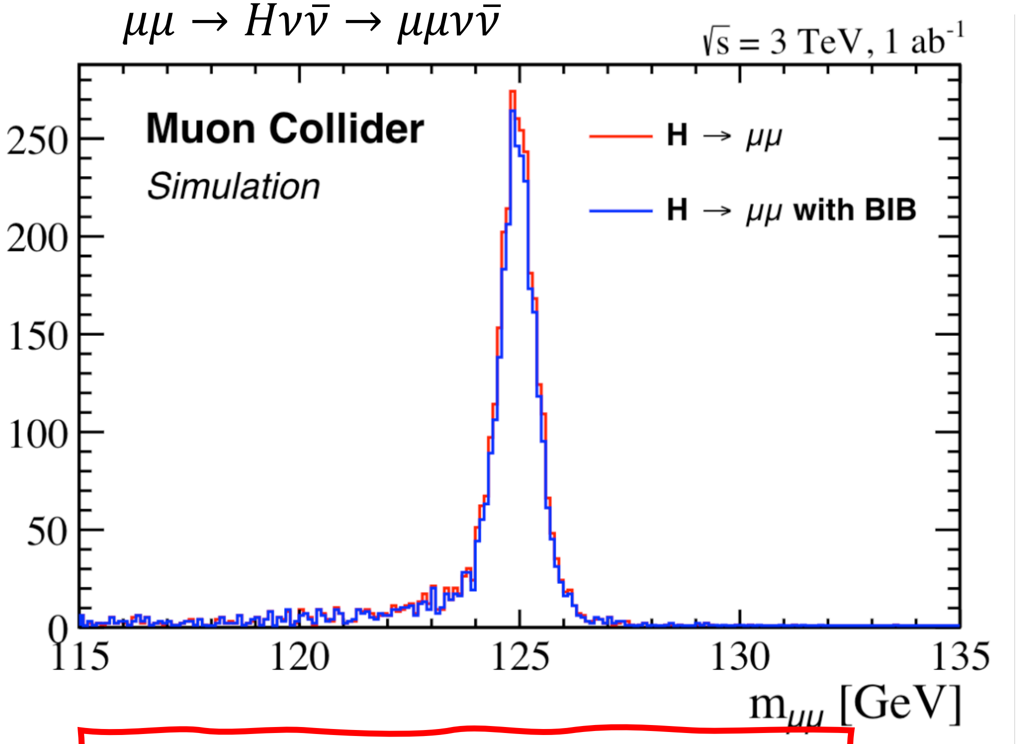
Radiation hardness requirements like expected HL-LHC

Tracks & muon reconstruction

Need to cover a momentum range from few GeV up to TeV

Usual methods for “low” momentum

$\mu\mu \rightarrow H\nu\bar{\nu} \rightarrow \mu\mu\nu\bar{\nu}$



$$\frac{\Delta\sigma_{H\rightarrow\mu\mu}}{\sigma_{H\rightarrow\mu\mu}} \sim 38\%$$ 1 experiment 1 ab^{-1}

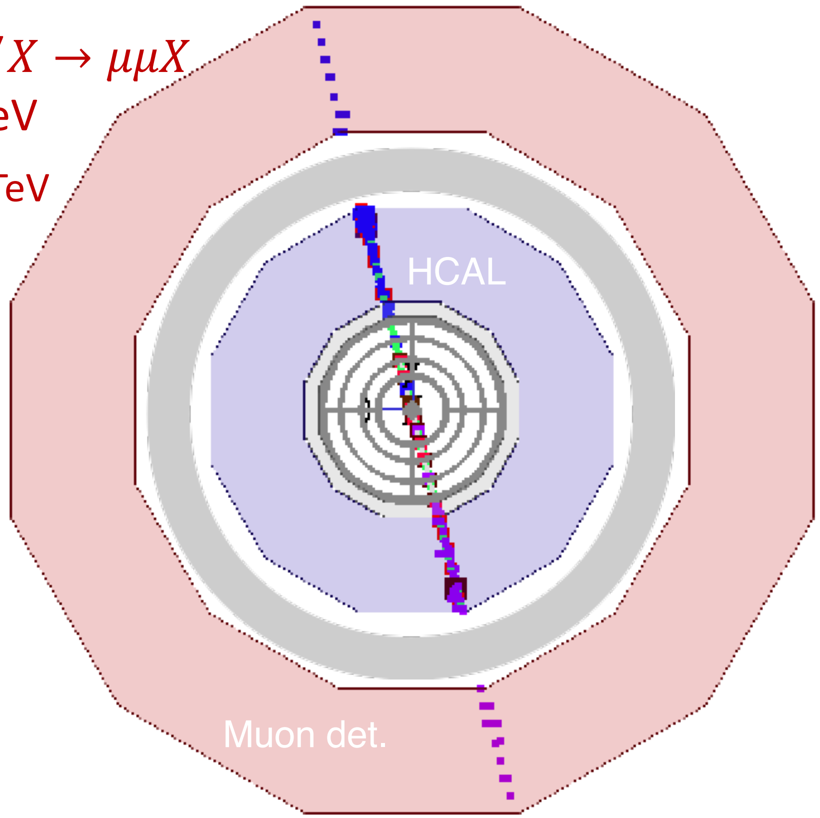
CLIC at 3 TeV 2 ab^{-1}: 25%

Jet-like structure: combine information from muons detector, tracker and calorimeter

$\mu^+\mu^- \rightarrow Z'X \rightarrow \mu\mu X$

$\sqrt{s}$ = 10 TeV

$M_{Z'}$ = 9.5 TeV



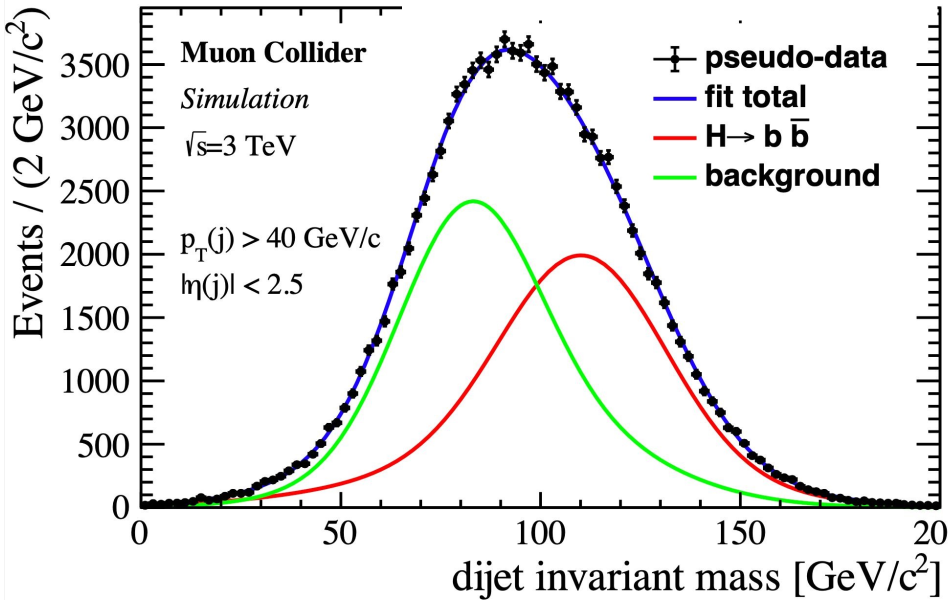
Jet reconstruction performance

- $E_{th} \geq 2$ MeV EM calorimeter cells to mitigate BIB effect
- efficiency: $80 \div 90\%$
- Negligible fake rate

b-jet identification:

- Simple algorithm, secondary vertex
- Efficiency:45% (20 GeV) 70% (120 GeV)
- c-jet mis-identification ~20%
- light jets mis-identification few %

$\mu^+\mu^- \to H\nu\bar{\nu} \to b\bar{b}\nu\bar{\nu}$



Invariant mass resolution: 18%

$\frac{\Delta\sigma_{H\to b\bar{b}}}{\sigma_{H\to b\bar{b}}} \sim 0.75\%$ 1 experiment 1 ab^{-1}

CLIC at 3 TeV 2 ab^{-1}: 0.3%

No major issues with photon reconstruction

The $\mu^+\mu^- \to H\nu\bar{\nu} \to \gamma\gamma\nu\bar{\nu}$ reconstructed obtaining

$\frac{\sigma_m}{m} \approx 2.5\%$ $\frac{\Delta\sigma_{H\to\gamma\gamma}}{\sigma_{H\to\gamma\gamma}} = 7.6\%$ 1 experiment 1 ab^{-1}

CLIC at 3 TeV 2 ab^{-1}: 10%

Two Examples of Expected Physics Performance: Higgs & Z' Bosons

Sensitivity on Higgs potential parameters

$$V(h) = \frac{1}{2}m_H^2 h^2 + \lambda_3 v h^3 + \frac{1}{4}\lambda_4 h^4$$

Good performance on Higgs trilinear self coupling determination, even if not optimal

Process: $\mu^+\mu^- \to HH\nu\bar{\nu} \to b\bar{b}b\bar{b}\nu\bar{\nu}$ only

Han T, Liu D, Low I, Wang X.
Phys. Rev. D 103:013002 (2021)

$\sqrt{s} = 3$ TeV full detector and BIB simulation,1 experiment 1 ab^{-1}

$$\frac{\Delta\sigma_{HH\to b\bar{b}b\bar{b}}}{\sigma_{HH\to b\bar{b}b\bar{b}}} \sim 33\% \qquad \frac{\Delta\lambda_3}{\lambda_3} \sim 20-30\%\ (25\%)$$

parametric study

CLIC at 3 TeV 2 ab^{-1}+ final states: 22%

$\sqrt{s} = 10$ TeV parametric studies

$$\frac{\Delta\lambda_3}{\lambda_3} = 5.6\%$$

1 experiment 10 ab^{-1} 5 years

M. Casarsa et al.

Chiesa M, et al. J. High Energ.
Phys. 2020:98 (2020)

Parametric study on quartic self coupling

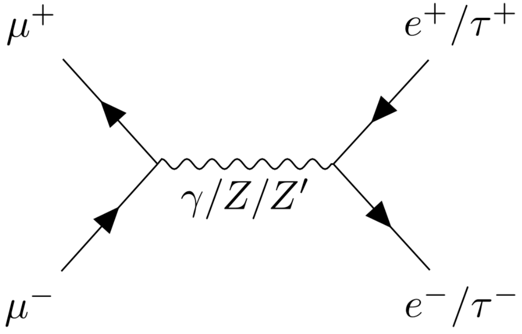
- Only $\mu^+\mu^- \to HHH\nu\bar{\nu} \to b\bar{b}b\bar{b}b\bar{b}\nu\bar{\nu}$
- No background considered
- No BR applied
- No selections optimization

Accuracy of ~50% with 20 ab^{-1}

Z' boson mass reach

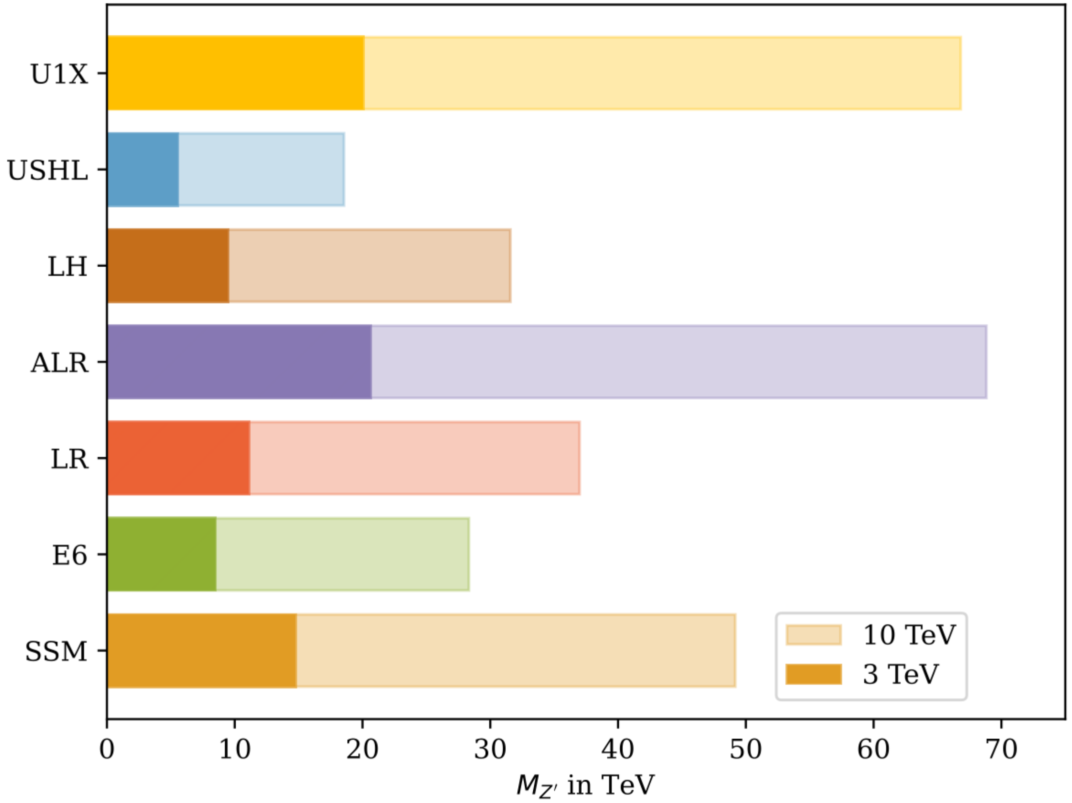
K. Korshynska et al.
https://doi.org/10.48550/arXiv.2402.18460

Effective Z'-model with new gauge boson couplings to the SM fermions



Observables of fermion final states $f = e, \tau$ for off-peak analysis combine in a χ^2:

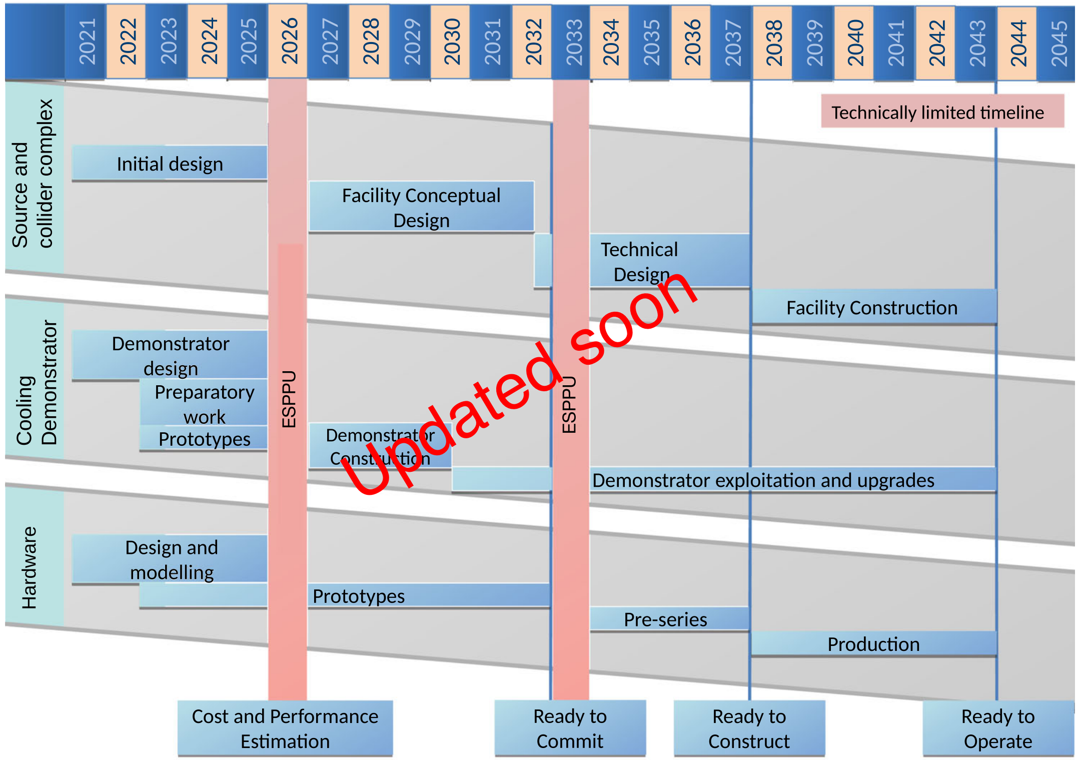
- Total cross section σ_f
- Forward-backward asymmetry $A_{FB}^f = \frac{\sigma_F^f - \sigma_B^f}{\sigma_f}$
- Left-right asymmetry $A_{LR}^f = \frac{\sigma_{LR}^f - \sigma_{RL}^f}{\sigma_f}$
- Polarization asymmetry $A_{pol}^\tau = \frac{\sigma_{LR}^\tau - \sigma_{RL}^\tau}{\sigma_\tau}$



Masses up to 70 TeV can be excluded @95% CL depending on the model

Mass limit:
LHC: 5 TeV, HL-LHC: 8 TeV
Future e^+e^-: 20 TeV

You may think that the muon collider is far in time…
… true, but the activities on the facility can start with a *demonstrator* on a short time scale!



A technically limited timeline for the muon collider R&D program.

Demonstrator facility can:

- Test muon cooling cells and, later, muon cooling functionalities for 6D cooling principle at low emittance including re-acceleration.
- Study high gradients and relatively high-field solenoid magnets for the machine.
- Develop and test high-power production target.
- Identify and construct detectors to measure beam emittances.
- Perform physics measurements

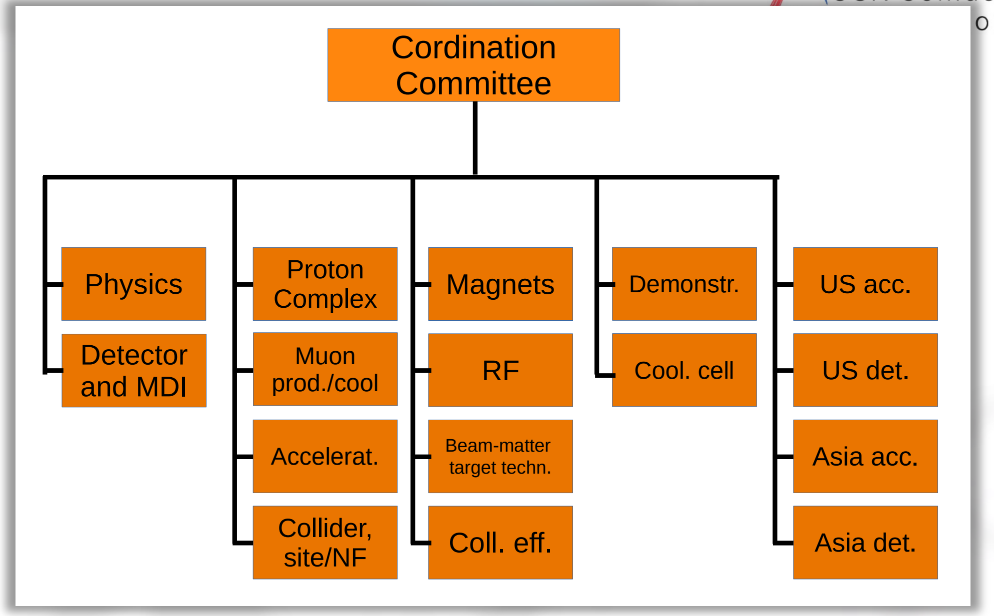
Where:

Several possibilities: CERN, Fermilab, JPARC, …

Summary

The International Muon Collider Collaboration has working groups that are making progress on

- Facility complex design:
  - Muon production
  - Muon cooling
  - Muon acceleration and collision
- Detector design and performance:
  - First detector concept for a $\sqrt{s} = 3$ TeV exhibits performance sufficiently robust
  - A $\sqrt{s} = 10$ TeV detector is being designed with new approach to cope with very high energy
- Design of demonstrator facility

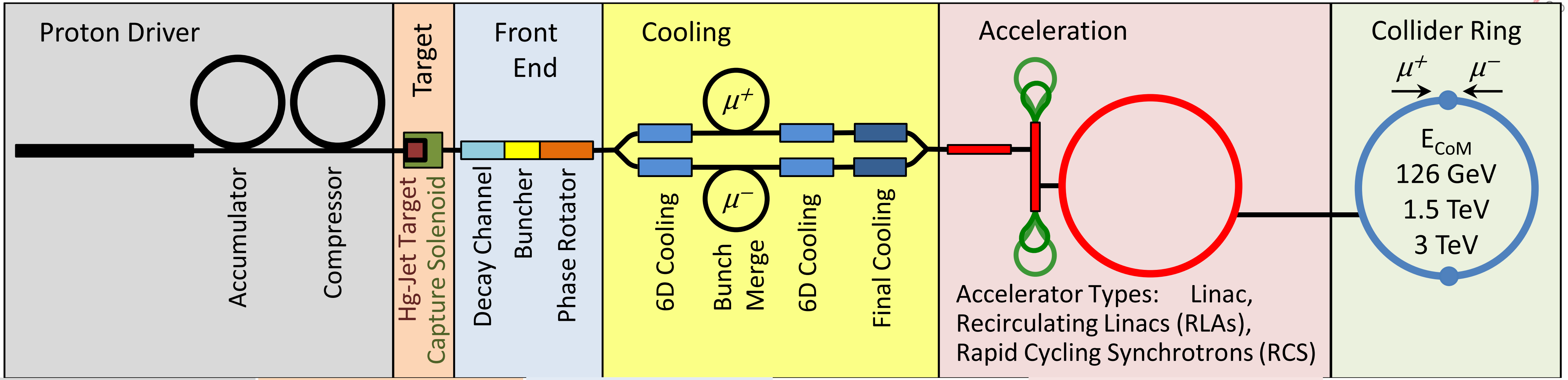


If interested contact:
Study Leader: D. Schulte
Deputies: A. Wulzer, D. Lucchesi, C. Rogers
CB chair: N. Pastrone

Additional material

Proton-driven Muon Collider Concept

Muon Accelerator Program **(MAP)**



- 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

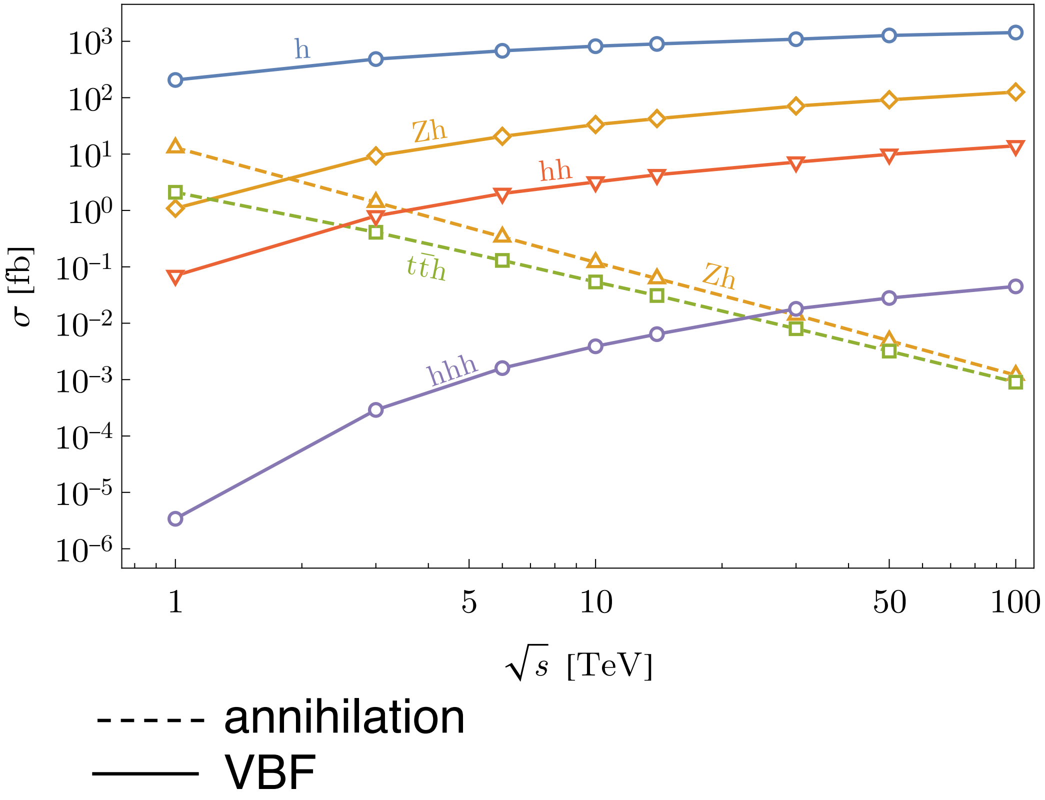
- Ionization cooling 6D
- MICE

- Fast acceleration
- Use RF and SC

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

Higgs Physics at Muon Collider

Ali HA et al.



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M. Casarsa et al. EPS-HEP2023 408

	cross section [fb]		expected events	
	3 TeV	10 TeV	1 ab^{-1} at 3 TeV	10 ab^{-1} at 10 TeV
H	550	930	5.5×10^{5}	9.3×10^{6}
ZH	11	35	1.1×10^{4}	3.5×10^{5}
$t\bar{t}H$	0.42	0.14	420	1.4×10^{3}
HH	0.95	3.8	950	3.8×10^{4}
HHH	3.0×10^{-4}	4.2×10^{-3}	0.30	42

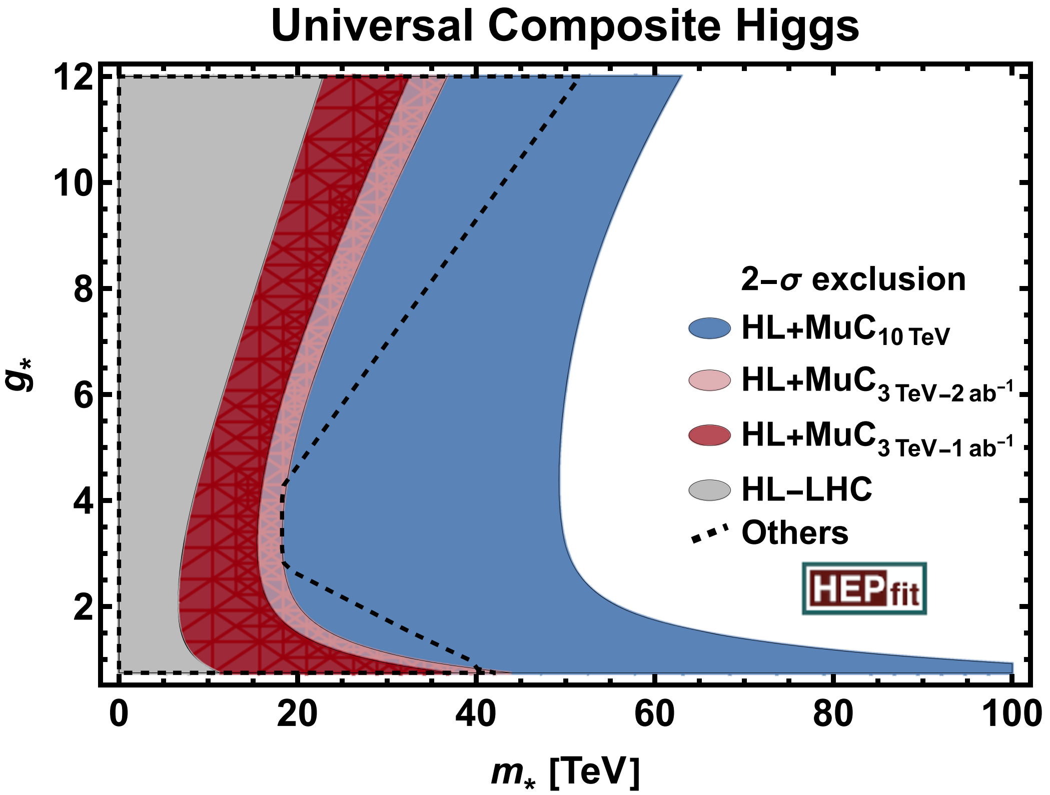
$\sqrt{s}$ = 3 TeV 1 ab^{-1} 5 years one experiment

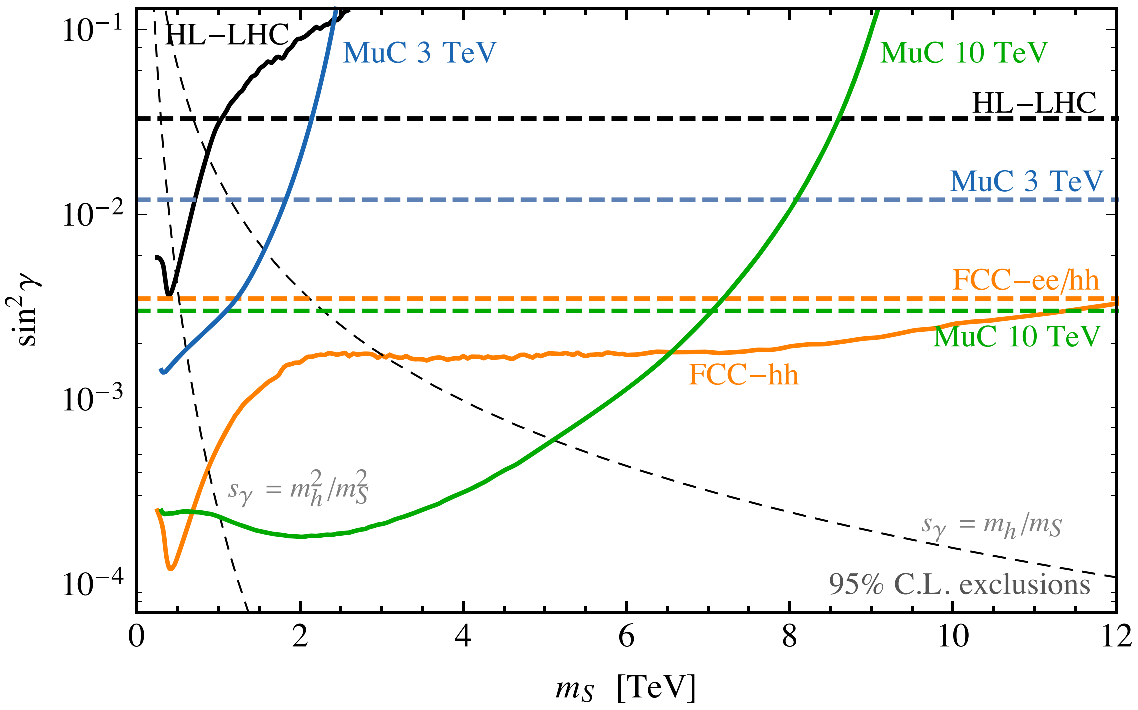
$\sqrt{s}$ = 10 TeV 10 ab^{-1} 5 years one experiment

The power of $\sqrt{s} = 10$ TeV muon collisions for BSM searches

SM EFT including HL-LHC + MuC Higgs @10 TeV

Higgs portal: new scalar field with no color





Composite Higgs: dynamics parameterised in terms of single coupling, g_*, and mass, m_*

Scalar field singlets, mass: m_s mixing parameter: $\sin\gamma$

— direct sensitivity - - - - indirect sensitivity

C. Accettura et al. "Towards a muon collider"

Dense neutrino flux

Muons per bunch: 1.8×10^{12} → N° decay per meter of lattice:

2×10^{5} at $\sqrt{S}=3$ TeV

6×10^{4} at $\sqrt{S}=10$ TeV

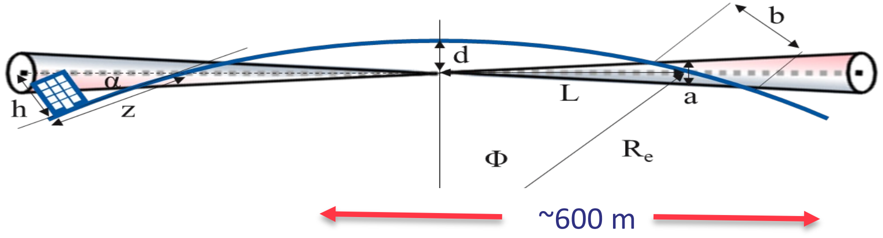
Hadronic/electromagnetic showers produced by high-energy neutrinos interacting with the underground environment can induce radiation when exiting.

Collider arcs:

- Keep induced radiation at the level of LHC
  - Not an issue at $\sqrt{s}=3$ TeV if at 200 m.
  - At $\sqrt{s}=10$ TeV, beam movement inside magnet aperture should be enough.

Straight sessions, interaction points:

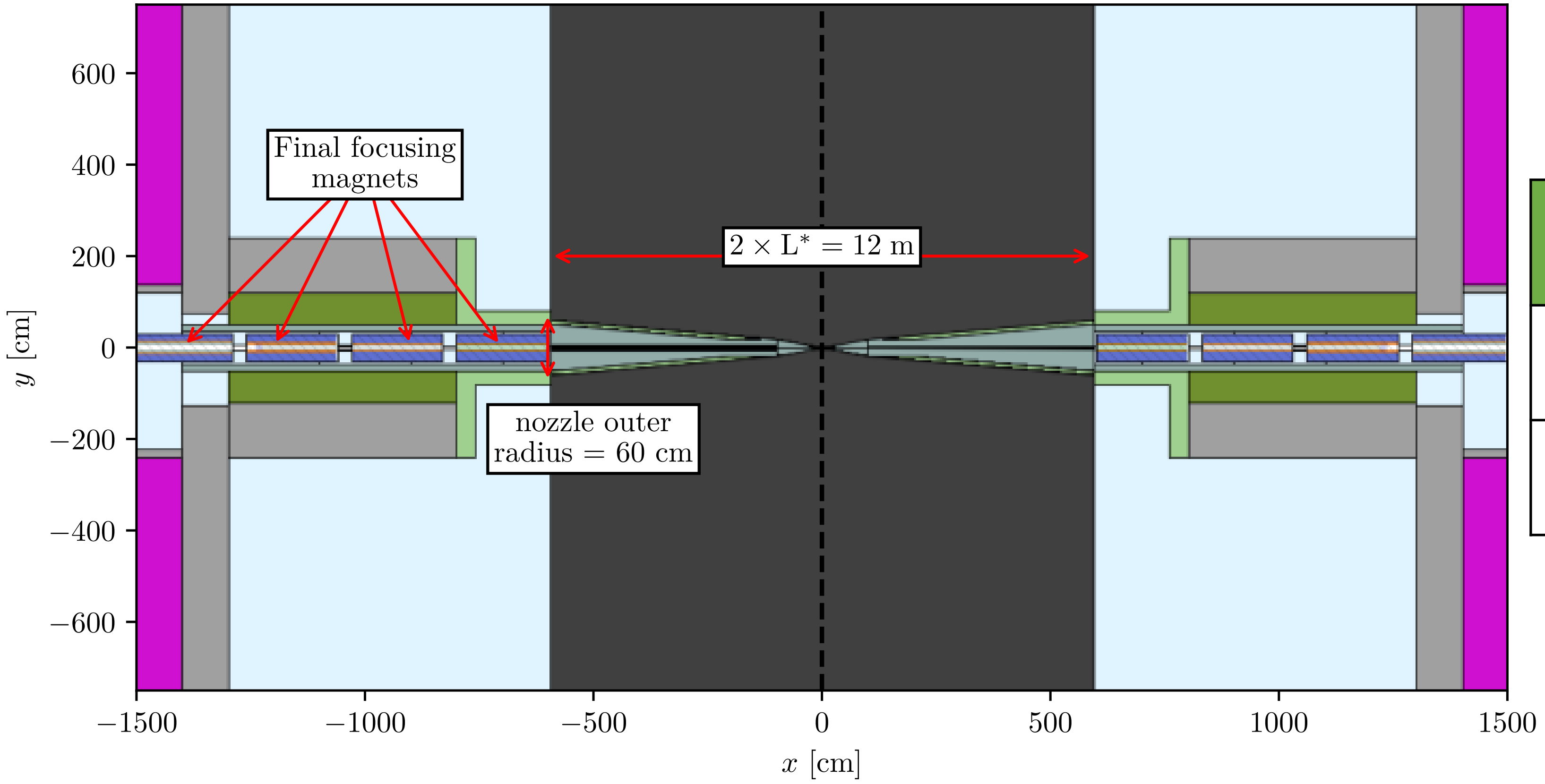
At higher energy, $\sqrt{s}\sim10$ TeV, beam parameters and surface map need to be used (GeoProfiler) to determine the effects of fluxes.



Collider interaction region

Longitudinal size of the detector determined by position of final focusing magnets.
it would be very difficult from the the lattice point of view to have more than ±6 m

C. Carli, A. Lechner, **D. Calzolari**, K. Skoufaris

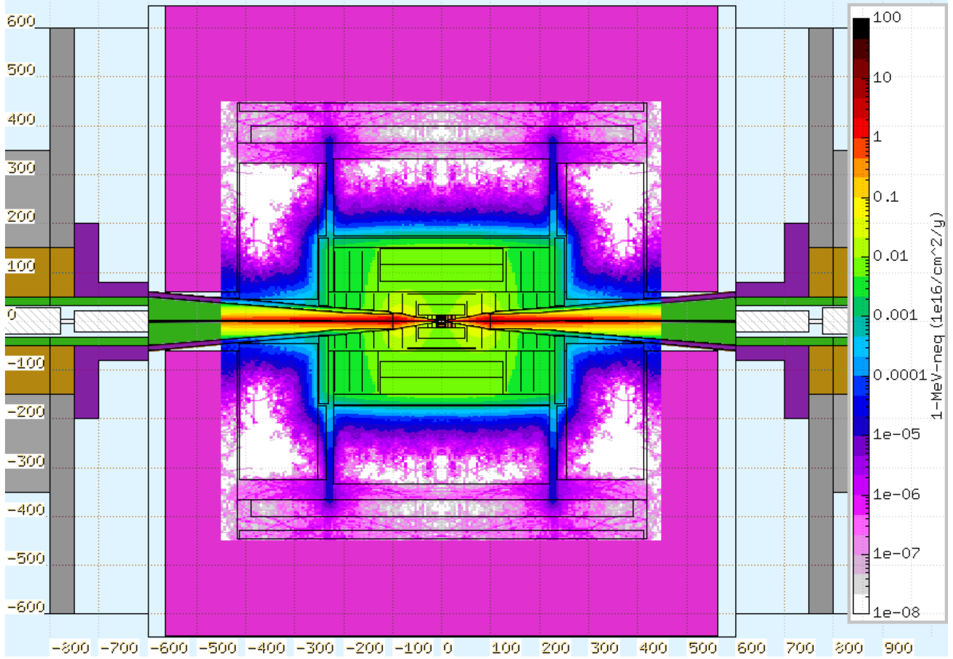


	LHC	**MC** $\sqrt{S} = 10$ TeV
bunch length σ_z	7.7 cm	1.5 mm
bunch size $\sigma_\perp$	16.7 μm	0.9 μm

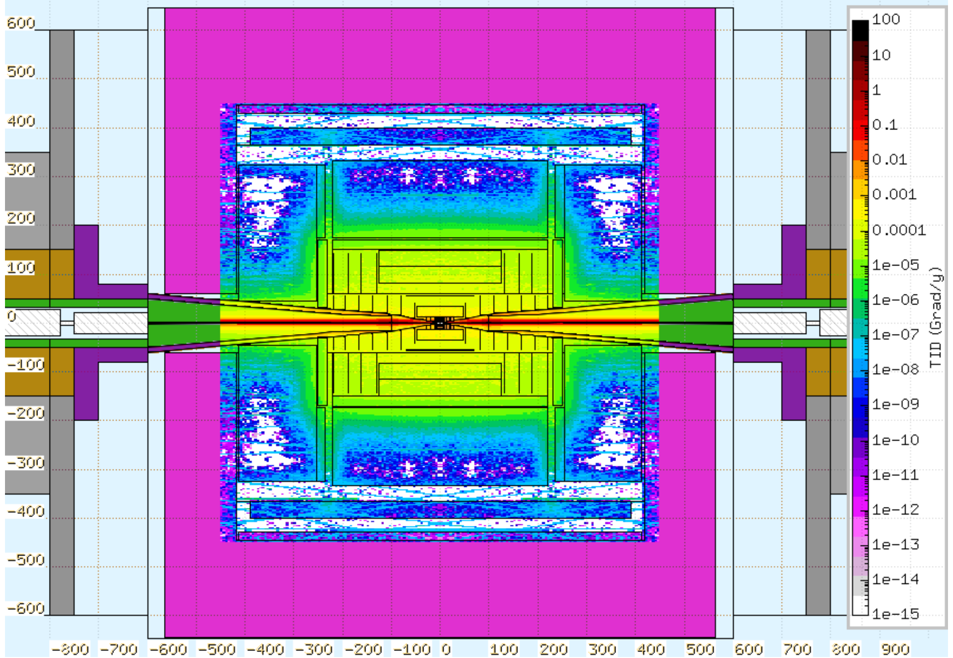
Single bunch mode

Radiation environment

1-MeV neutron equivalent fluence per year



Total ionizing dose per year



Assumptions:

- Collision energy 1.5 TeV
- Collider circumference 2.5 km
- Beam injection frequency 5Hz
- Days of operation/year 200

Radiation hardness requirements like HL-LHC (expected)

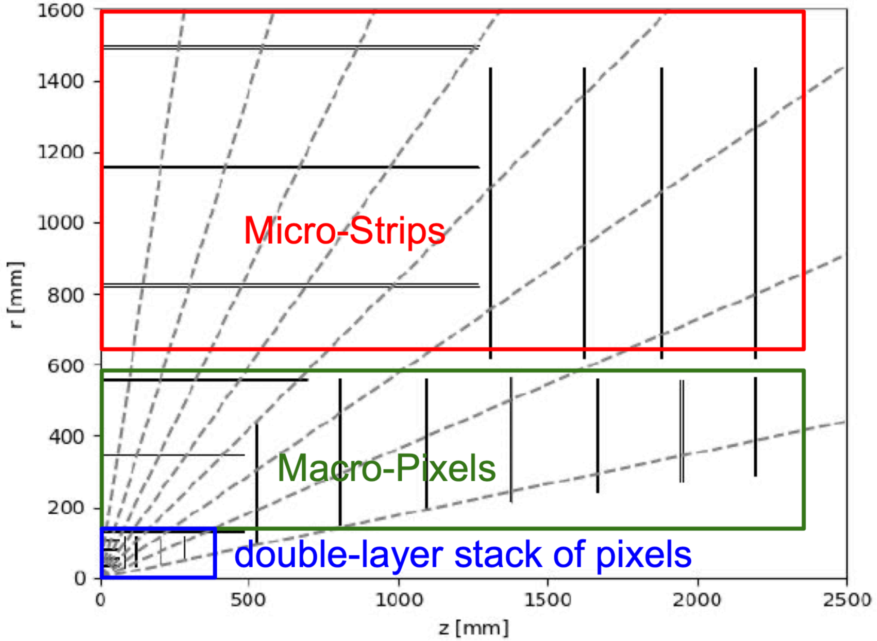
	Maximum Dose (Mrad)		Maximum Fluence (1 MeV-neq/cm^2)	
	R= 22 mm	R= 1500 mm	R= 22 mm	R= 1500 mm
Muon Collider	10	0.1	10^{15}	10^{14}
HL-LHC	100	0.1	10^{15}	10^{13}

K. Black, Muon Collider Forum Report

$\sqrt{S} = 3$ TeV the same, $\sqrt{S} = 10$ TeV under study, expected similar since dominated by BIB

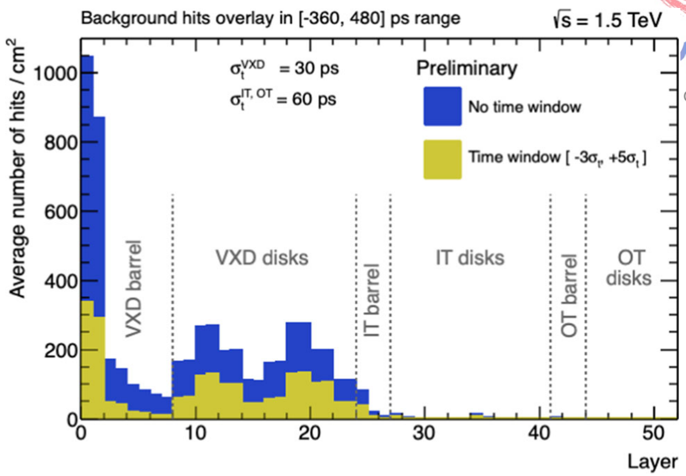
Tracker system: full detector & BIB simulation

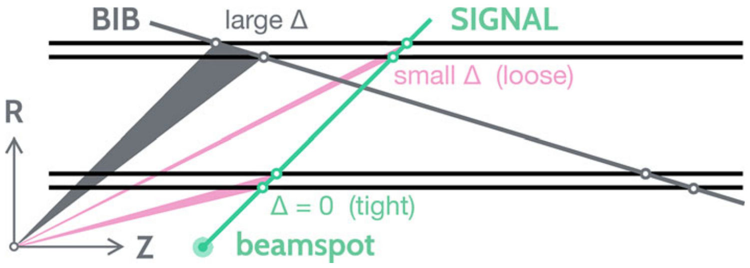
First layers of barrel vertex detector & forward disks highly impacted by BIB



Tracker requirements

- Timing: high resolution to suppress out of time BIB.
- Double layers: apply directional filtering.
- Energy deposition: exploit different cluster shapes.



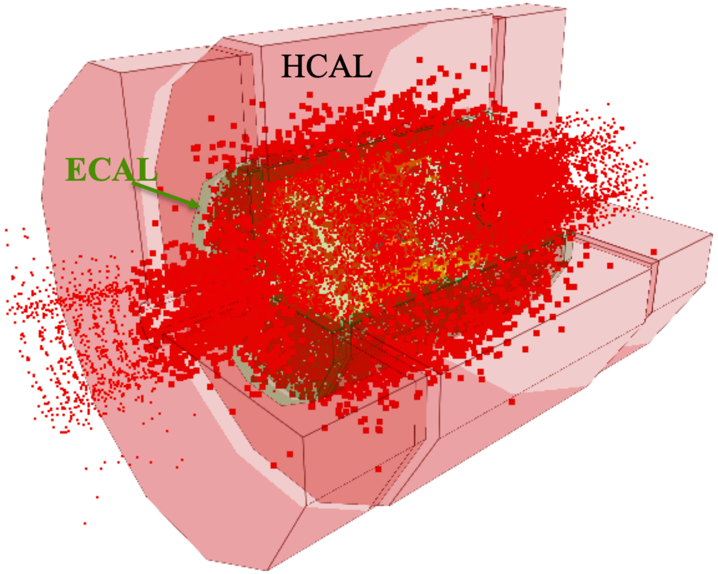


Higher occupancies respect to LHC detectors crossing rate 100 kHz vs 40 MHz

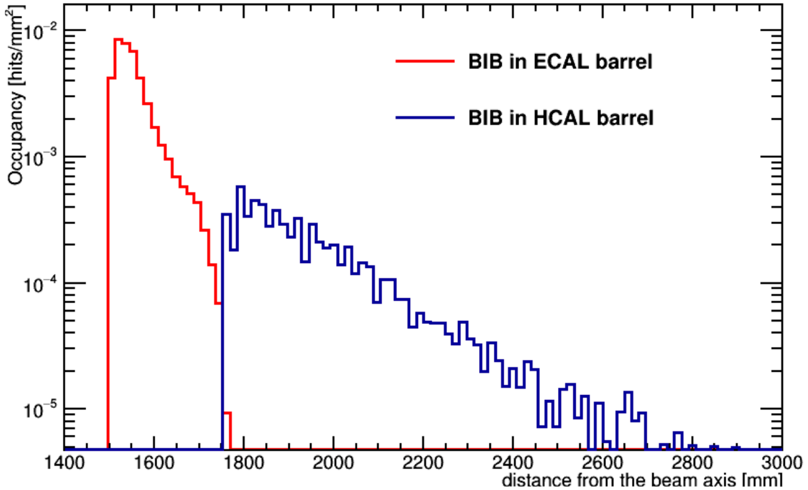
Engaged in ECFA DRD3: silicon vertex and tracker

Detector reference	Hit density [mm^{-2}]		
	MCD	ATLAS ITk	ALICE ITS3
Pixel Layer 0	3.68	0.643	0.85
Pixel Layer 1	0.51	0.022	0.51

Calorimeter system: full detector & BIB simulations



Occupancy: ECAL > 10 times HCAL

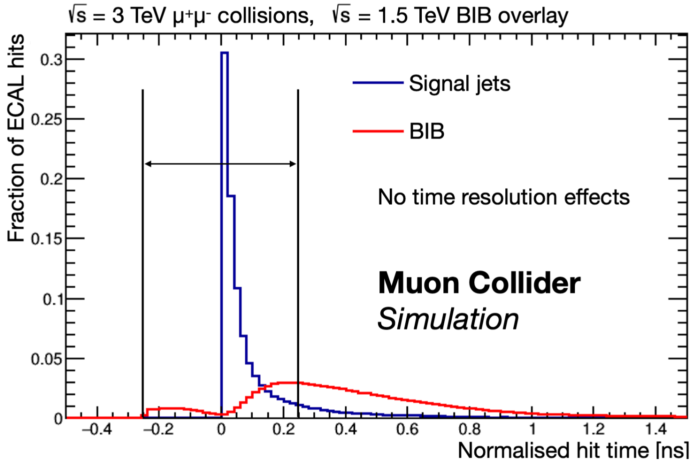


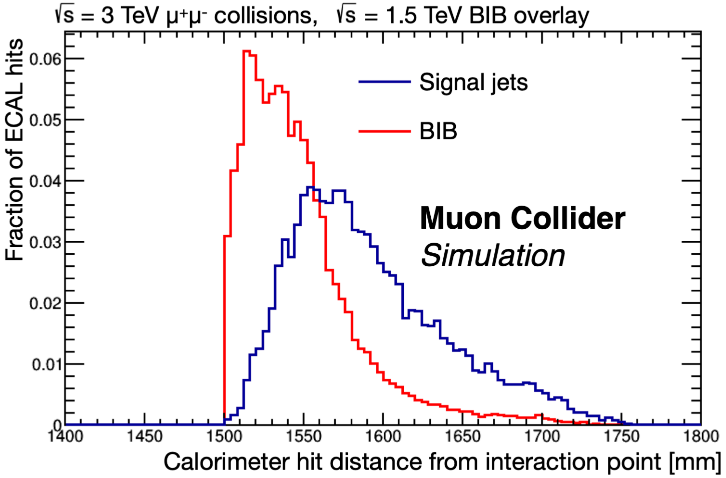
ECAL surface flux: 300 particle/cm^2

- 96% photons, 4% neutrons
- $E_{\gamma}^{Ave.} \sim 1.7$ MeV

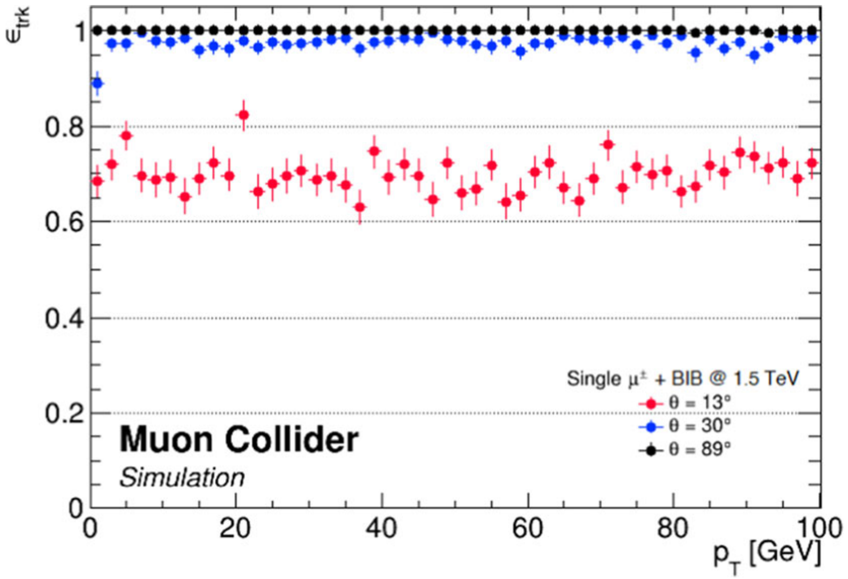
Calorimeter requirements

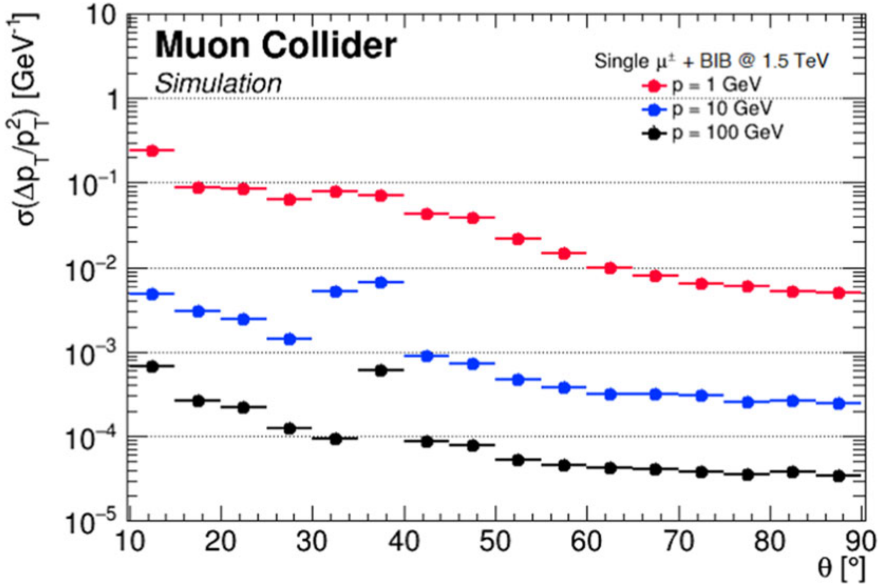
- time-of-arrival: resolution ~100 ps to reject out-of-time particles.
- Longitudinal segmentation: different profile signal vs. BIB.
- High granularity: to separate BIB particles from signal avoiding overlaps in the same cell.

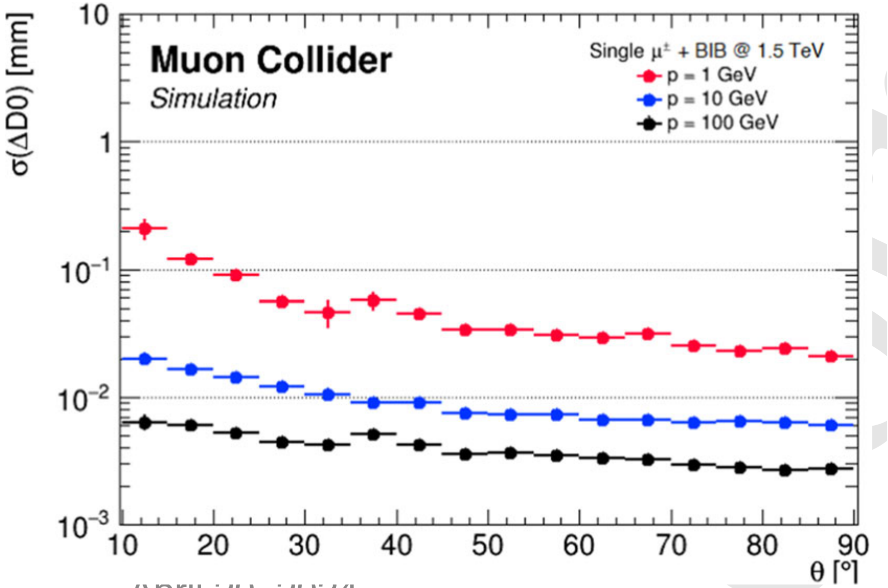


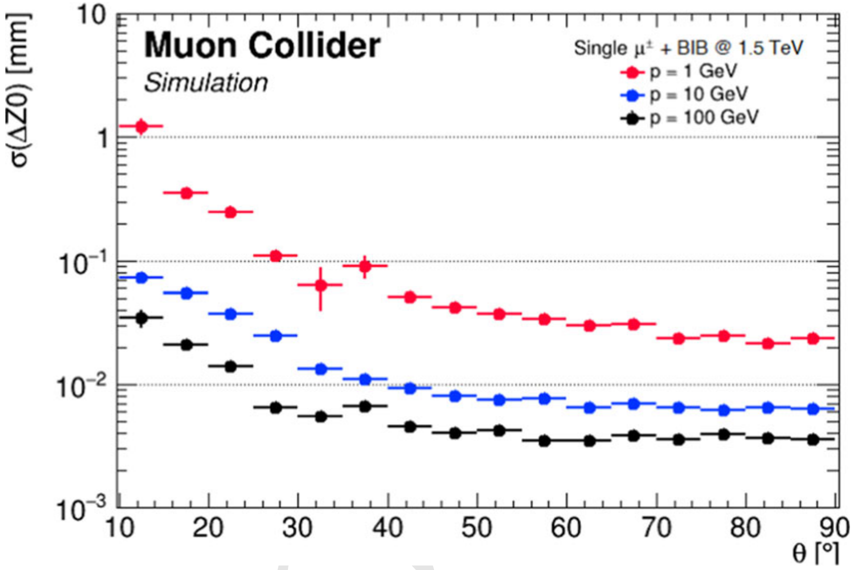


Track reconstruction performance









Expectations in Higgs physics: determination of couplings

David A, et al., arXiv:1209.0040

Measurement of $\sigma_H \times BR(H \rightarrow f)$ allows determination of H to f coupling in the k-framework
k_i coupling modifiers: ratio between the measured and the standard model values.

Studied performed so far do not cover all the relevant H decay modes

Exercises benchmark parametric studies at $\sqrt{s} = 3$ TeV and $\sqrt{s} = 10$ TeV

Forslund M, Meade P. J. High Energ. Phys. 2022:185 (2022)

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