Physics prospects and detector design for a future multi-TeV muon collider

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35th Rencontres de Blois

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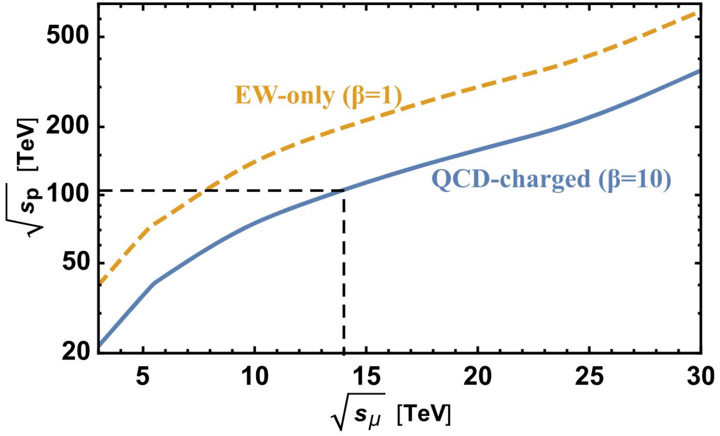
The case for a muon collider

A high-energy lepton collider: combining cutting edge discovery potential with precision measurements

Motivations

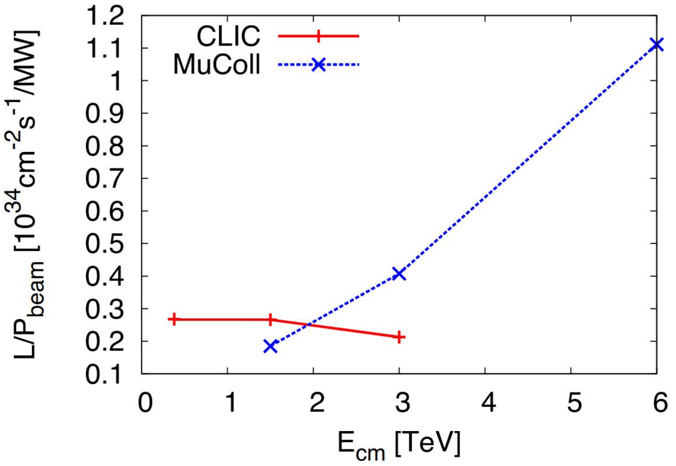
- No synchrotron radiation: **higher energy** reachable than e^+e^-
- **Point-like** particles: comparable physics reach at lower centre-of-mass than pp
- Good **luminosity** to beam power ratio: high s-channel cross sections at high energy



Comparison between muon and proton collider energy at same production cross-section of heavy particles

Physics reach

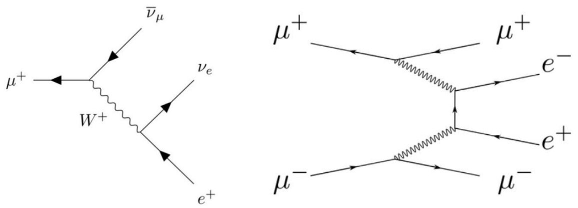
- Potential for new **discoveries**
- Precise **Higgs** studies
- Direct reach for physics coupled to **muons and neutrinos**



Normalized luminosity achievable with CLIC and Muon collider

[arXiv:2407.12450] Interim report for the International Muon Collider Collaboration (IMCC)

Muon collider challenges



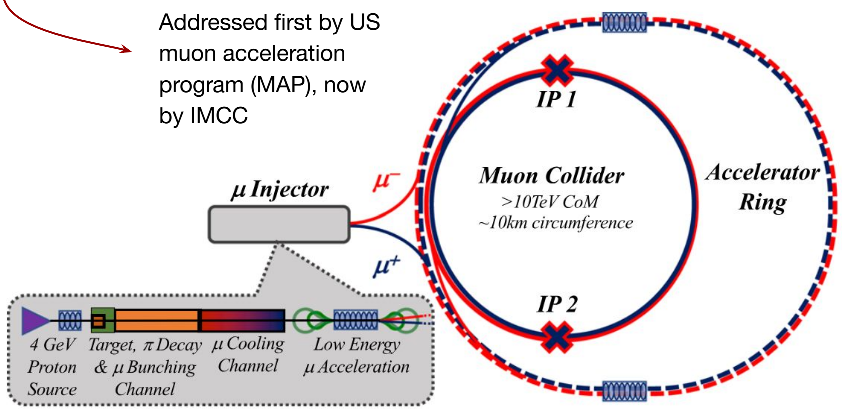
The muon lifetime is 2.2 μs

Short muon lifetime

Requires fast production, cooling and acceleration

- Ionization **cooling** under study
- Rapid **acceleration** by linac + 2 recirculating linacs
- Difficult to maintain small β and energy spread

Addressed first by US muon acceleration program (MAP), now by IMCC



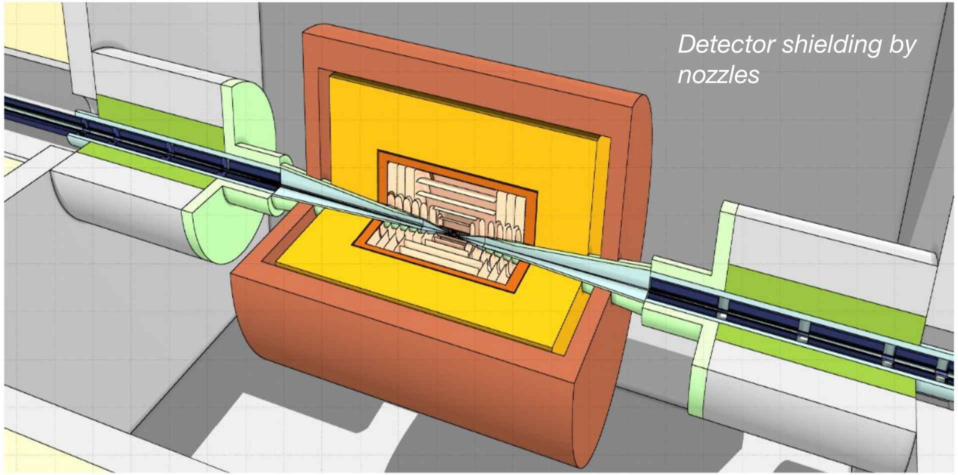
Muon accelerator and collider concept

Muon decay

Asynchronous **beam-induced background** (BIB) in experiments

1. Mostly photons, neutrons and electrons
2. Incoherent e^+e^- pairs produced at bunch crossing

Mitigation by **shielding** and choice of **detector** technologies



[arXiv:2105.09116] Advanced assessment of Beam Induced Background at a Muon Collider

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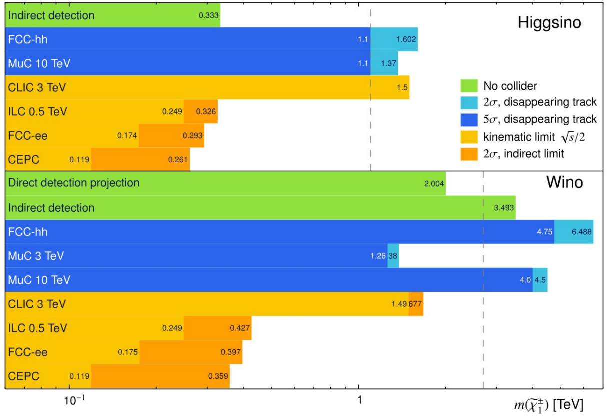
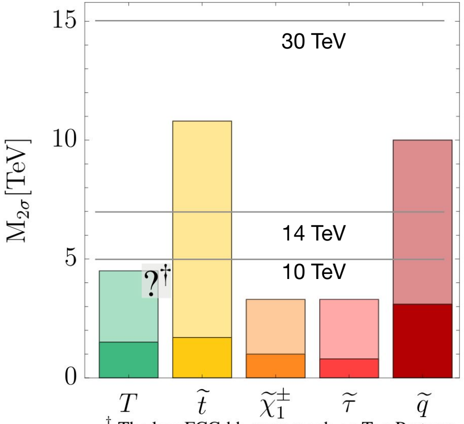
Physics reach

Towards a muon collider. *Eur. Phys. J. C* **83**, 864 (2023)

Discovery potential

Can access **thermal mass** for several minimal **WIMP** candidates





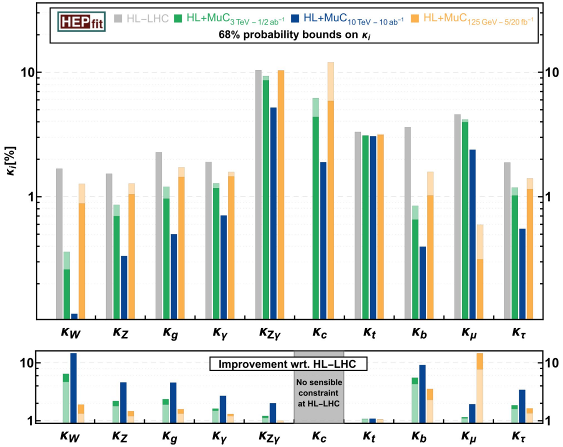
† The low FCC-hh mass reach on Top Partners could be due to a non-optimal analysis

Most sensitive to new **electroweak** charged states

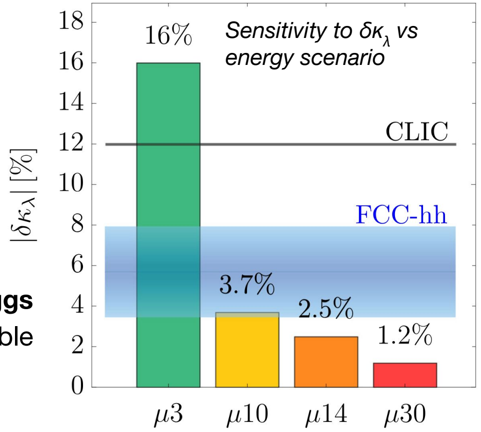
Precision Higgs & EW

A **Higgs factory**
10^7 at 10 ab^{-1}

Can measure **single-Higgs couplings** with precision < 1%



3 and 4-Higgs couplings accessible



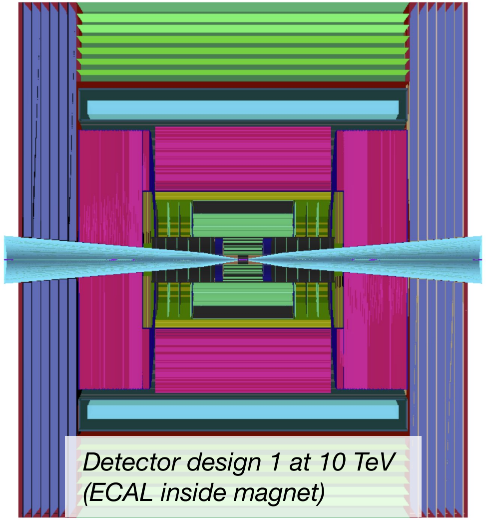
Detector design for 3 and 10 TeV

Design constrained by

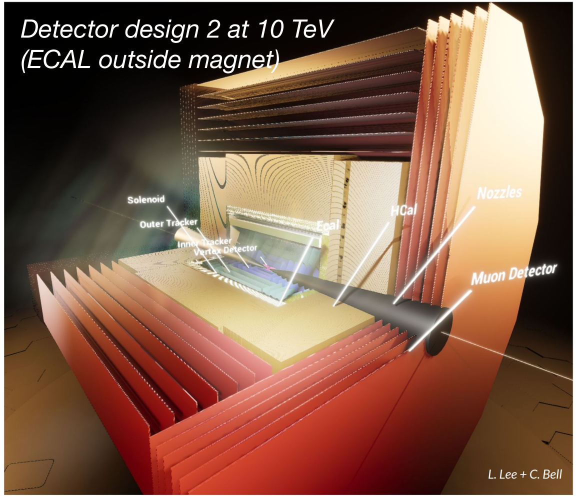
- **BIB** levels
- **Machine** design: focusing quadrupoles at **±6 m** from IP
- **Physics** requirements: detector has to be sensitive to
  - **Central** objects from massive particle decays
  - **Low-p_T** objects from standard model processes (e.g. Higgs decays)
  - **Non-standard** signatures (e.g. displaced vertices and jets)

Has effects on

- detector design
- detector technologies
- software (e.g. reconstruction)



Detector design 1 at 10 TeV (ECAL inside magnet)



Detector design 2 at 10 TeV (ECAL outside magnet)

Experiment requirements

- Need **shielding** (nozzles) in forward region
- For BIB rejection:
  - High-**granularity** to handle high occupancy
  - Excellent **time resolution** to reject asynchronous BIB component
  - Good **energy resolution** to reject soft BIB spectrum by thresholds

Can be reached with technology available at HL-LHC

Two experimental designs

- **Two interaction points** allowed by the machine
- Generic detector design adapted **from CLIC**

  Several improvements moving to 10 TeV, also valid for 3 TeV design
- Main change from 3 to 10 TeV design: moving **solenoid inside calorimeters** (higher B field)

Detector design at 10 TeV

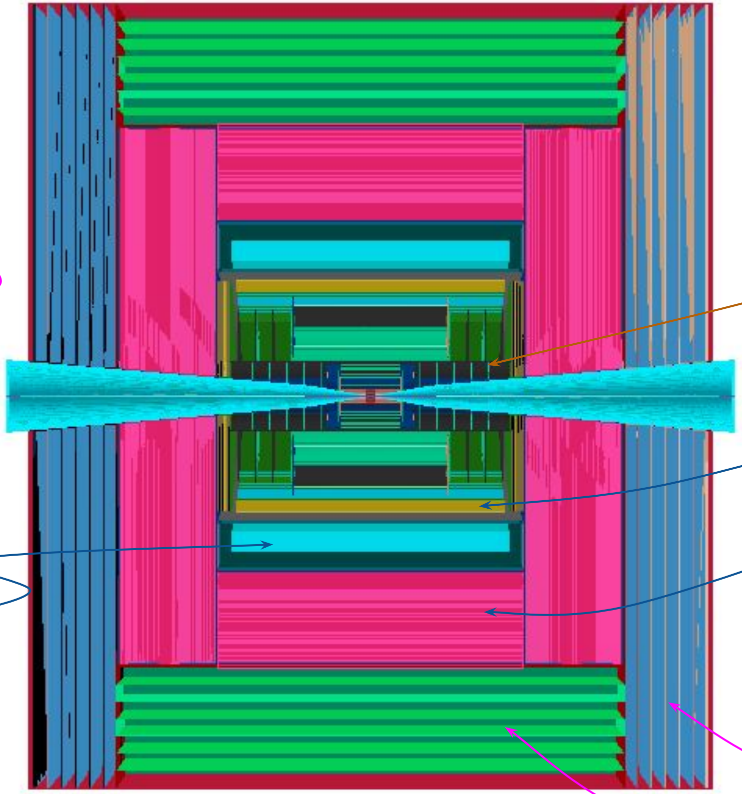
Towards a muon collider. *Eur. Phys. J. C* **83**, 864 (2023)

Shielding:

- Tungsten and borated polyethylene **nozzles**

Magnet:

- 5 T **superconducting solenoid**



Silicon detector:

- Micro-pixel **vertex** detector
- Strip inner and outer **trackers**

Calorimeters:

- **PbF_2 ECAL** with SiPM readout or silicon-tungsten ECAL
- **Iron** + scintillator **HCAL** (magnet return yoke)

Muon system:

- **Resistive plate chambers** or **triple-GEM** detectors + muon **timing** layer

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Tracker

BIB in tracker

- Up to 2000 hits/cm^2 per event

Detector requirements

- Doubled layers for stub reconstruction
- Time resolution < 100 ps to reject BIB

Detector technologies

- Vertex detector: 25x25 μm^2 Si **small-pixels** (30 ps time resolution)
- Inner tracker: 50 μm x 1 mm Si **macro-pixels** (60 ps time resolution)
- Outer tracker: same as inner

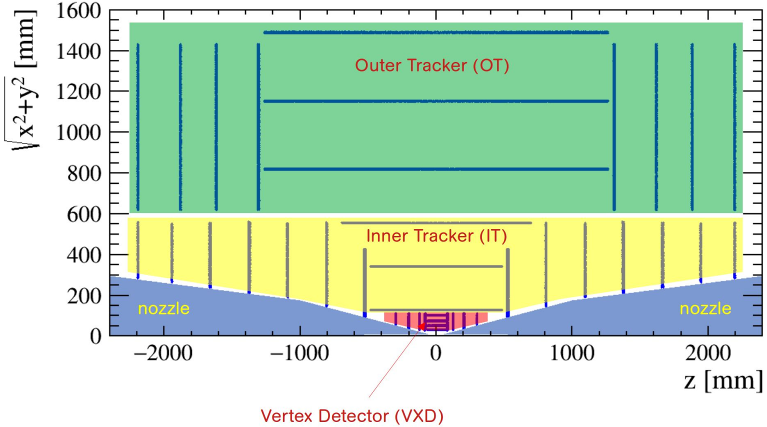
  Alternative layout: 50 μm x 10 mm Si **macro-strips**

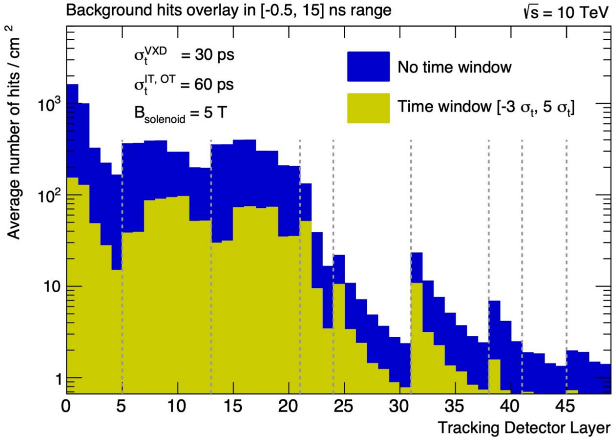
Performance studies

- Good **tracking efficiency** in the barrel (drop ~3.5% due to BIB)

  Ongoing studies in endcaps
- **Vertex resolution** ~3-5 μm with BIB, stable as a function of p_T and θ

Silicon detector layout





Number of hits in the tracker (detector design 2)

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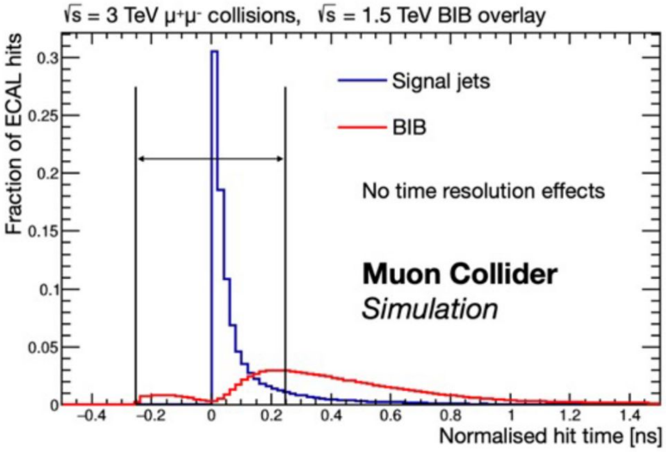
Electromagnetic calorimeter



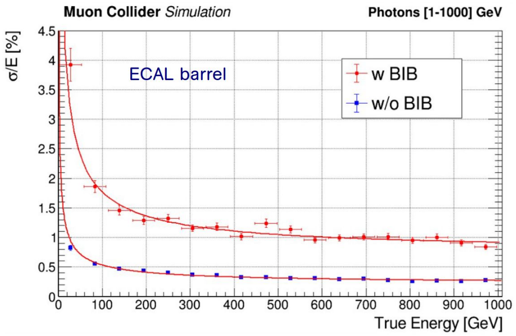
Arrival time distribution of ECAL hits for jets and BIB

BIB in electromagnetic calorimeter

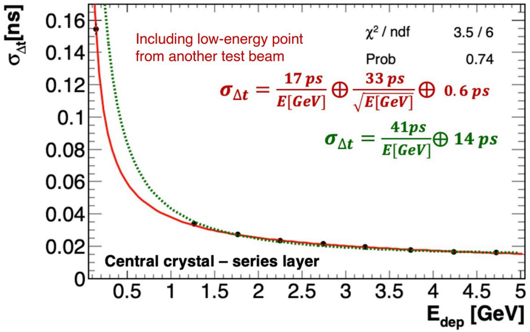
- Mostly **photons** (96%) and **neutrons** (4%)
- Occupancy: 300 hits / cm^2
- Can be excluded by ~240 ps time cut

Detector requirements

- Longitudinal **segmentation** for BIB "fake shower" rejection
- Timing < 100 ps
- Original baseline design: **silicon-tungsten**



Simulated CRILIN energy resolution



Measured CRILIN time resolution

Ongoing R&D: **semi-homogeneous** calorimeter made of PbF_2 crystals read out by SiPMs (CRILIN)

Baseline technology for design 1 at 10 TeV

- 5 layers with 45 mm length, 10✕10 mm^2 cell area (21.5 X_0)
- Excellent prototype **time resolution** measured in test beams
- Ongoing R&D for precise measurement of crystal & SiPM **radiation hardness**

[arXiv:2206.05838] Crilin: A CRystal calorImeter with Longitudinal InformatioN for a future Muon Collider

Hadronic calorimeter

Goal: 3-4 % jet energy resolution for hadronic Z decays
→ 60%/√E resolution for HCAL

BIB in hadron calorimeter

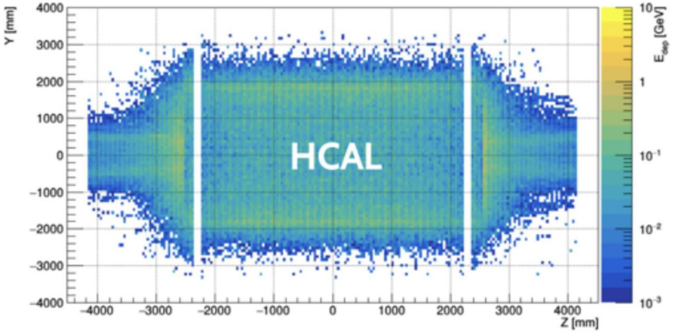
- Mostly **photons** (96%) and **neutrons** (4%)
- Large **asynchronous** component
- Occupancy: 0.06 hits / cm^2

Detector requirements

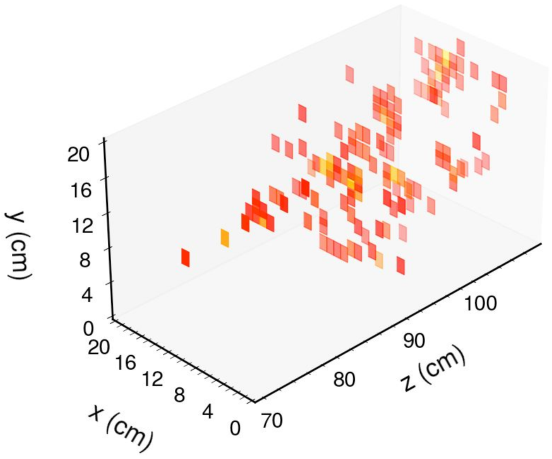
- Longitudinal **segmentation** for BIB rejection
- High **granularity** (< 3x3 cm^2)
- Single layer **timing** of few ns

Baseline technology: iron absorber (also B field return yoke) + pad scintillators

Ongoing R&D: micro-pattern gaseous detectors (MPGDs) as active layer
→ higher radiation resistance



Energy deposited by BIB in HCAL for a single bunch crossing



Pion shower in MPGD-HCAL prototype in test beam

Studies on a hadronic calorimeter with MPGD technology for a future Muon Collider experiment, 2024 JINST 19 C05037

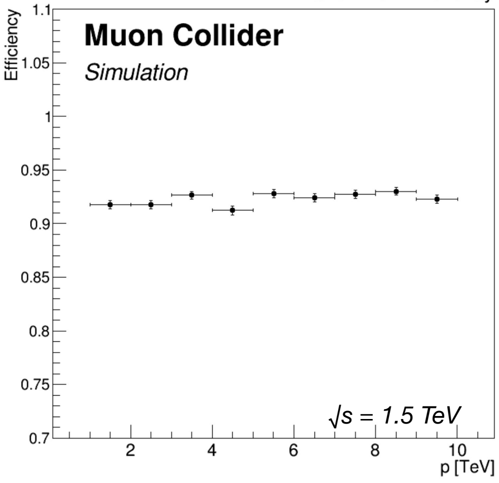
Muon system

No technological **choice yet**: low B-field and high momentum make p_T measurement difficult

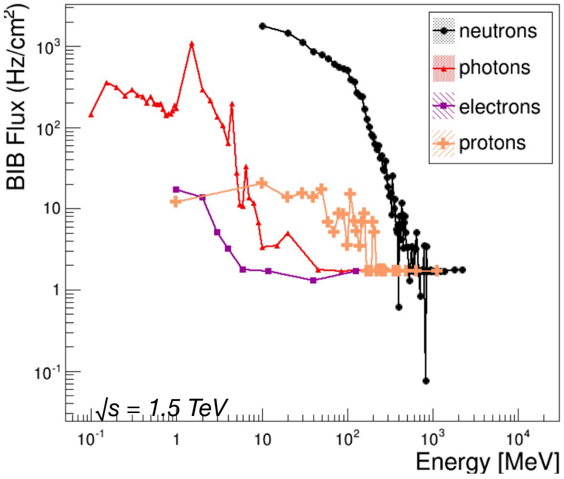
Possible candidates

- 6-7 layers of resistive plate chambers (**RPC**)
- 6 layers of triple-**GEMs** + 1 timing layer made of **Picosec-MicroMegas**

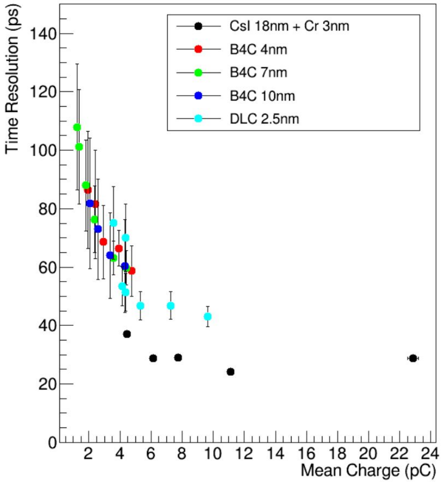
  Ongoing R&D to optimize detector gas mixtures, radiators and photocathodes for large scale



Simulated detection efficiency in muon barrel



Simulated BIB energy spectrum



Picosec time resolution measured in test beam with different photocathodes

Simulation and R&D studies for the muon spectrometer at a 10 TeV Muon Collider

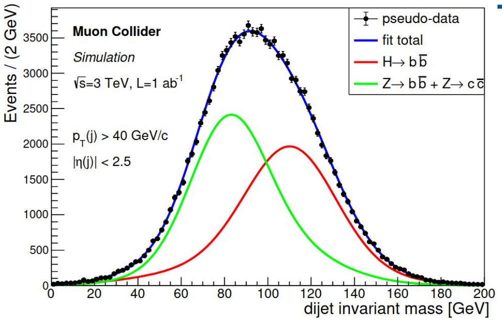
Higgs couplings

[arXiv:2405.19314] Higgs Physics at a $\sqrt{s}$=3 TeV Muon Collider with detailed detector simulation

Several cases of Higgs coupling studied in Muon collider **full software simulations** at 3 TeV

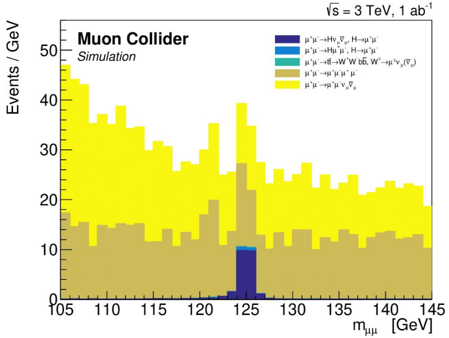
H → bb

- Main background: Z→bb and Z→cc
- Uncertainty on production cross-section **0.75%** (dominated by signal yield uncertainty)



H → $\mu^+\mu^-$

- Production from ZZ or WW fusion
- Two BDTs for background rejection
- Statistical sensitivity **38%**
- Sensitivity could be enhanced by tagging ZZ fusion



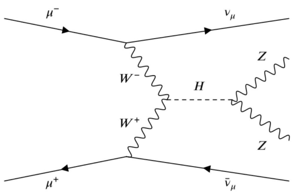
H → WW*

- Analyzed in semileptonic final state
- Kinematic requirements: central muon and jets
- Two BDTs for background rejection
- Statistical sensitivity **2.9%**

In all cases **agreement** within few % between full simulation and **parametric** (Delphes) **simulations**

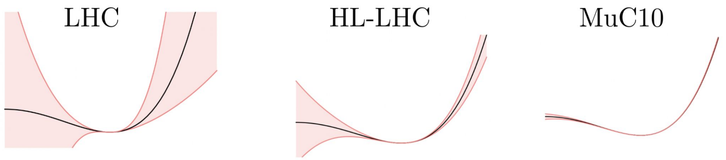
Higgs width measurement

- Can be measured from on-shell and off-shell H → WW* and H → ZZ* processes
- **3.4%** precision from 10 TeV projections
- Would be improved by muon forward tagging



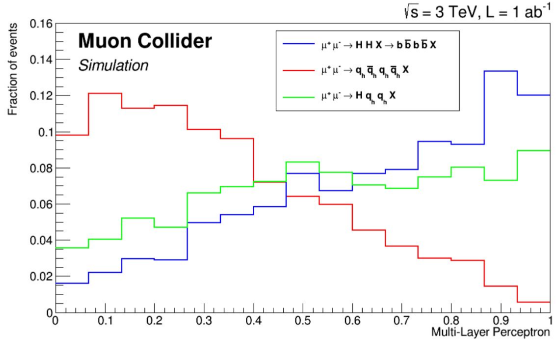
Higgs trilinear coupling

$$V(h) \supset \lambda_3 v h^3 + \frac{\lambda_4}{4} h^4$$



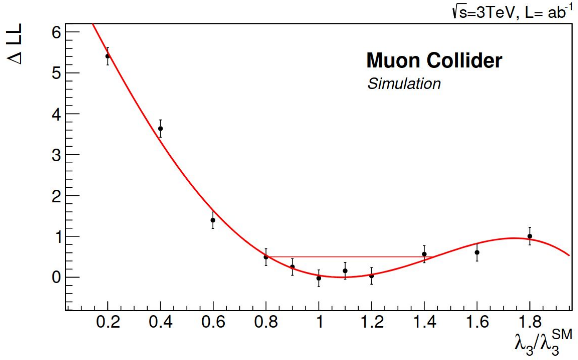
HH → bbbb: a first step in the trilinear coupling measurement

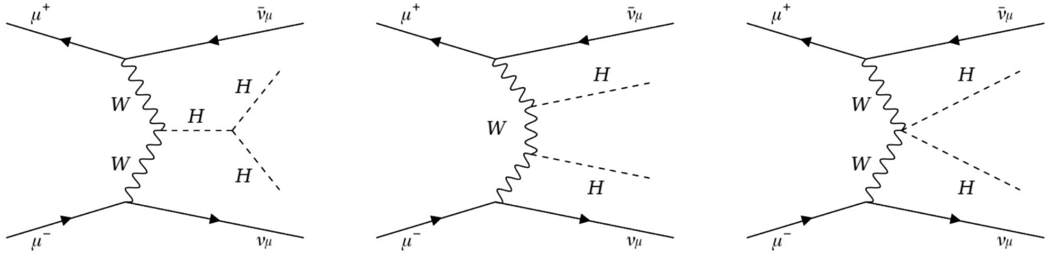
- Channel with highest statistics
- Four jets in final states, paired to minimize $(m_{12}-m_H)^2+(m_{34}-m_H)^2$
- Multi-layer perceptron (MLP) to discriminate **w/ and w/o Higgs** backgrounds
- Statistical uncertainty **33%**



Precision trilinear coupling measurement

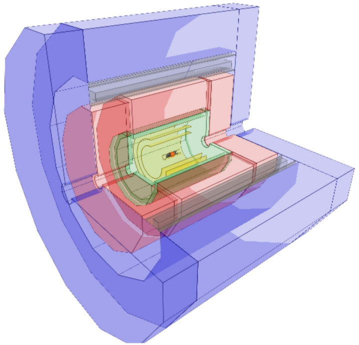
- One MLP to **distinguish from non-Higgs** background
- A second MLP to **discriminate off-shell production** (sensitive to trilinear coupling) from other HH production processes
- Expected **$0.81 < \kappa_{\lambda 3} < 1.44$ at 68% CL**, but optimizations ongoing





[arXiv:2308.02633] Precision Higgs Width and Couplings with a High Energy Muon Collider

Outlook



The Muon collider has a strong case for Higgs physics and BSM searches.

- **Advantages**: $m_\mu \gg m_e \rightarrow$ high-energy, entirely available in collisions
- **Main challenges**: τ_μ = 2.2 μs → fast acceleration, shielding, BIB rejection

Detector and physics activities

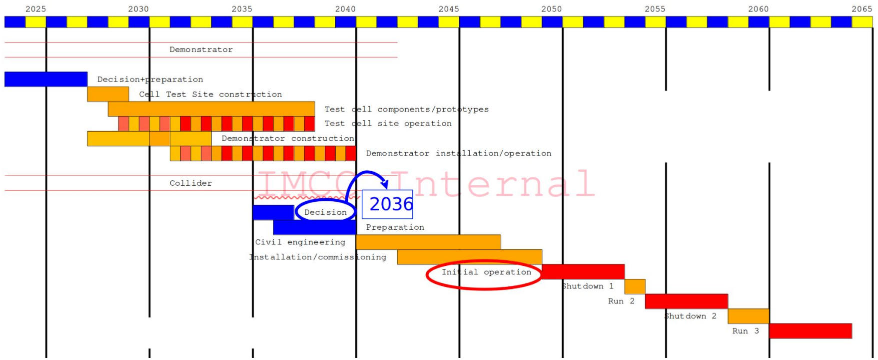
- Physics studies completed in 3 TeV detector design
- Software implementation of 10 TeV design ongoing

Possible project implementation

Plans mentioned here are from IMCC interim report, but still evolving

Two possible scenarios:

1. Energy staging: from 3 to 10 TeV
2. **Luminosity staging: 10 TeV up to 10 ab^{-1}**



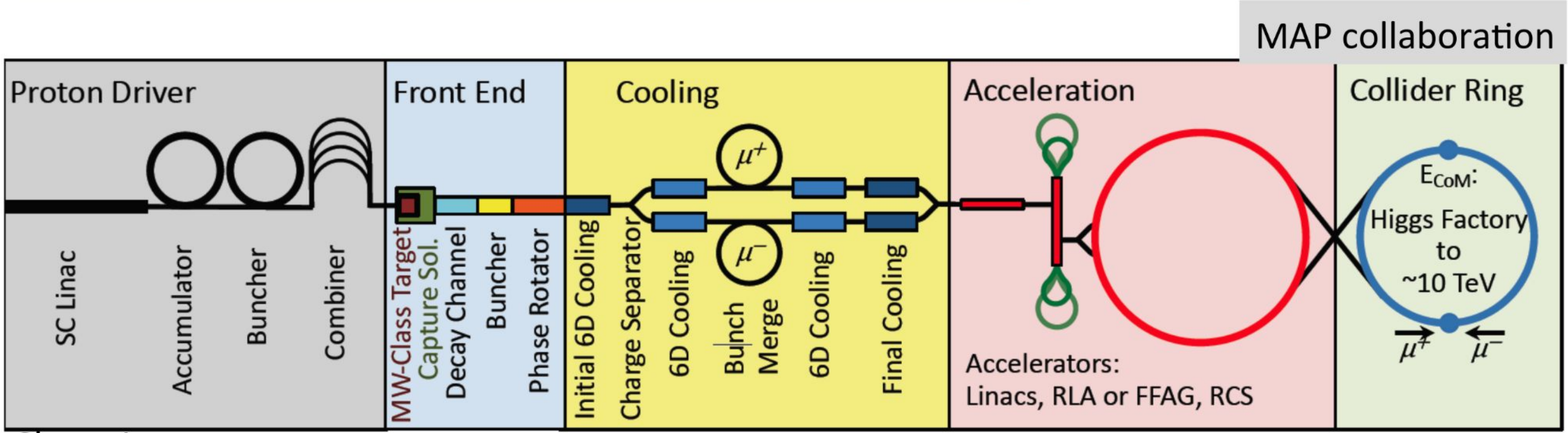
Efforts coordinated by the International Muon Collider Collaboration since 2020

Muon Collider progress - ICHEP 2024

Thank you

Backup

Proton-driven muon collider



Short, intense proton bunches to produce hadronic showers

Muon are captured, bunched and then cooled by ionisation cooling in matter

Collision

Acceleration to collision energy

Protons produce pions

BIB composition

	Description	Relevance as background
Muon decay	**Decay of stored muons around the collider ring**	**Dominating source**
Synchrotron radiation by stored muons	Synchrotron radiation emission by the beams in magnets near the IP (including IR quads → large transverse beam tails)	**Small**
Muon beam losses on the aperture	Halo losses on the machine aperture, can have multiple sources, e.g.: • Beam instabilities • Machine imperfections (e.g. magnet misalignment) • Elastic (Bhabha) μμ scattering • Beam-gas scattering (Coulomb scattering or Bremsstrahlung emission) • Beamstrahlung (deflection of muon in field of opposite bunch)	**Can be significant** (although some of the listed source terms are expected to yield a small contribution like elastic μμ scattering, beam-gas, Beamstrahlung)
Coherent e^-e^+ pair production	Pair creation by real* or virtual photons of the field of the counter-rotating bunch	**Expected to be small** (but should nevertheless be quantified)
Incoherent e^-e^+ pair production	Pair creation through the collision of two real* or virtual photons emitted by muons of counter-rotating bunches	**Significant**

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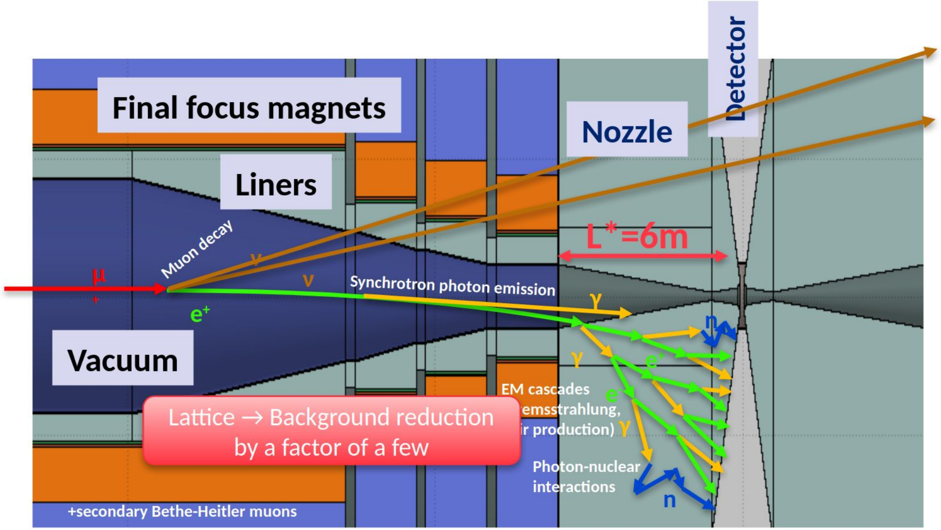
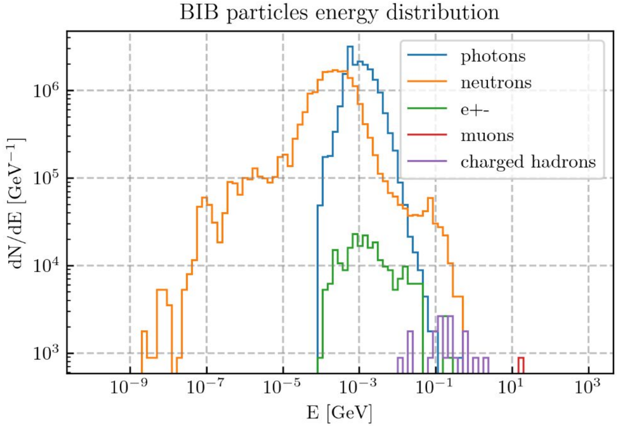
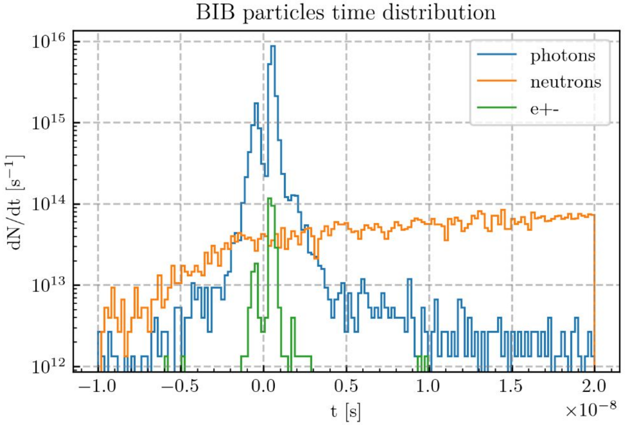
Effect of nozzles on detector

- Shielding of the background coming from the muon decay
- It reduces the background by several order of magnitude
- Design optimization ongoing





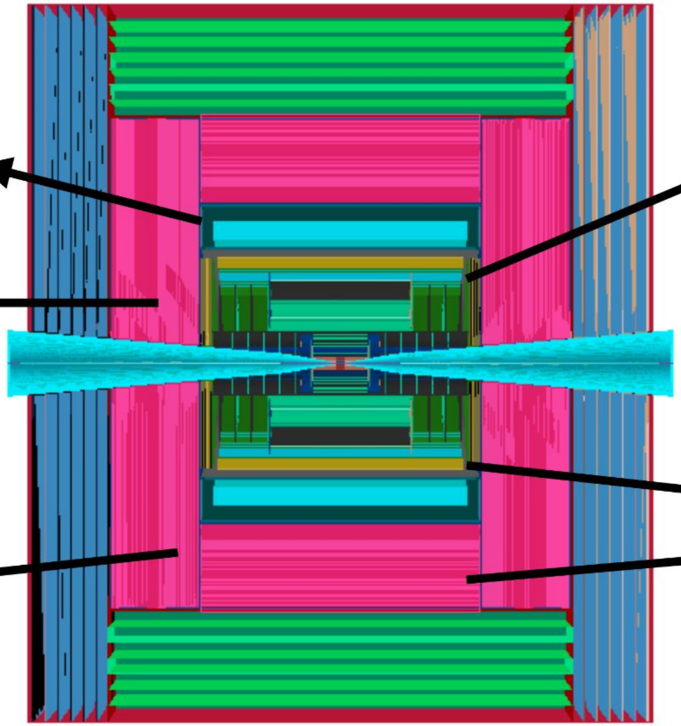


Changes from 3 to 10 TeV

4-5 T solenoid in between calorimeters

Magnetic flux closed by iron in HCAL

Removed HCAL ring (not necessary)



Increased dimension of tracker (1500 → 1700 mm)

Increased dimension of calorimeters:

ECAL (40 → 51 layers)

HCAL (60 → 70 layers)

Project staging

Parameter	Symbol	unit	Scenario 1		Scenario 2	
			Stage 1	Stage 2	Stage 1	Stage 2
Centre-of-mass energy	E_{cm}	TeV	3	10	10	10
Target integrated luminosity	$\int \mathcal{L}_{\mathrm{target}}$	ab^{-1}	1	10	10	
Estimated luminosity	$\mathcal{L}_{\mathrm{estimated}}$	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	2.1	21	tbc	14
Collider circumference	C_{coll}	km	4.5	10	15	15
Collider arc peak field	B_{arc}	T	11	16	11	11
Luminosity lifetime	N_{turn}	turns	1039	1558	1040	1040
Muons/bunch	N	10^{12}	2.2	1.8	1.8	1.8
Repetition rate	f_{r}	Hz	5	5	5	5
Beam power	P_{coll}	MW	5.3	14.4	14.4	14.4
RMS longitudinal emittance	$\varepsilon_{\parallel}$	eVs	0.025	0.025	0.025	0.025
Norm. RMS transverse emittance	$\varepsilon_{\perp}$	µm	25	25	25	25
IP bunch length	σ_z	mm	5	1.5	tbc	1.5
IP betafunction	β	mm	5	1.5	tbc	1.5
IP beam size	σ	µm	3	0.9	tbc	0.9
Protons on target/bunch	N_{p}	10^{14}	5	5	5	5
Protons energy on target	E_{p}	GeV	5	5	5	5
BS photons	$N_{\mathrm{BS,0}}$	per muon	0.075	0.2	tbc	0.2
BS photon energy	$E_{\mathrm{BS,0}}$	MeV	0.016	1.6	tbc	1.6
BS loss/lifetime (2 IP)	$E_{\mathrm{BS,tot}}$	GeV	0.002	1.0	tbc	0.67