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Detector design for a multi-TeV Muon Collider

DIS 2022

The 22nd International Workshop
on Deep Inelastic Scattering and Related Subjects

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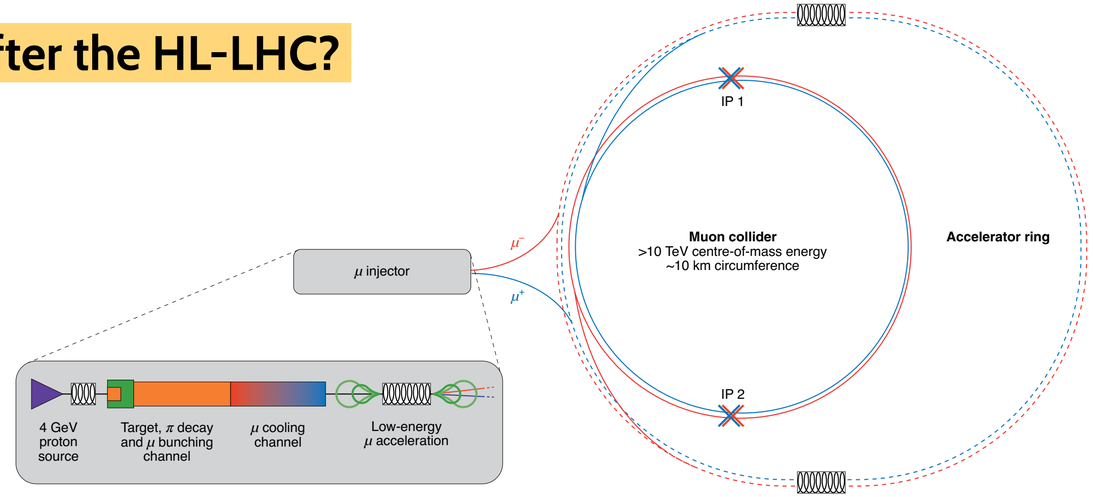
Muon Collider: unique machine

Big question for particle physics today: which collider to build after the HL-LHC?

Several important requirements have to be satisfied:

- energy reach exceeding the LHC by a large factor
- enable precision measurements of Standard Model
- environmentally friendly



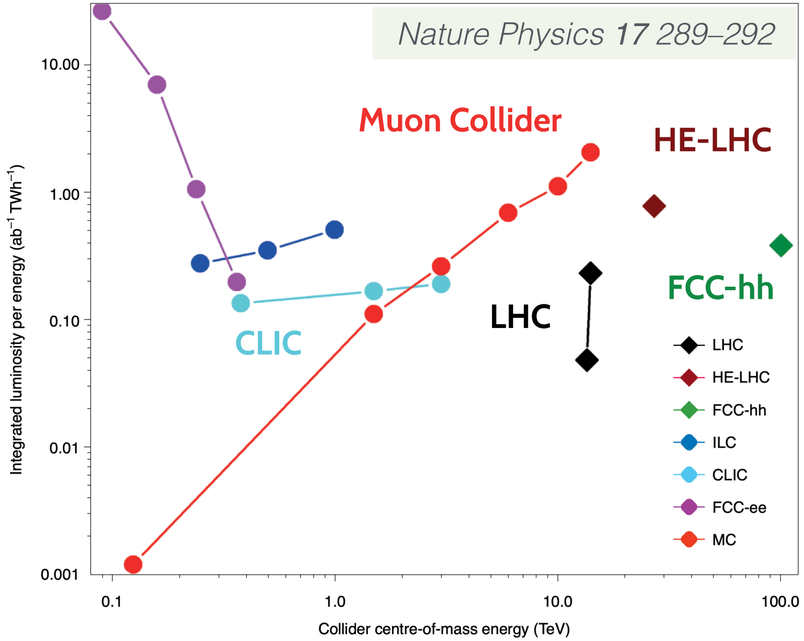
Typically two kinds of machines are considered:

- electron-positron collider (clean collisions vs limited luminosity/energy)
- proton-proton collider (high luminosity/energy vs uncertain kinematics)

Muon Collider combines the best features of the two classes of machines:

high precision of e^+e^- colliders + **high energy reach** of *pp* colliders

- like e^+/e^-, muons are elementary particles → creating *"clean"* collisions
- can be placed in fairly compact ring
- $\times$ 200 higher mass → $\times 10^4$ less synchrotron radiation losses



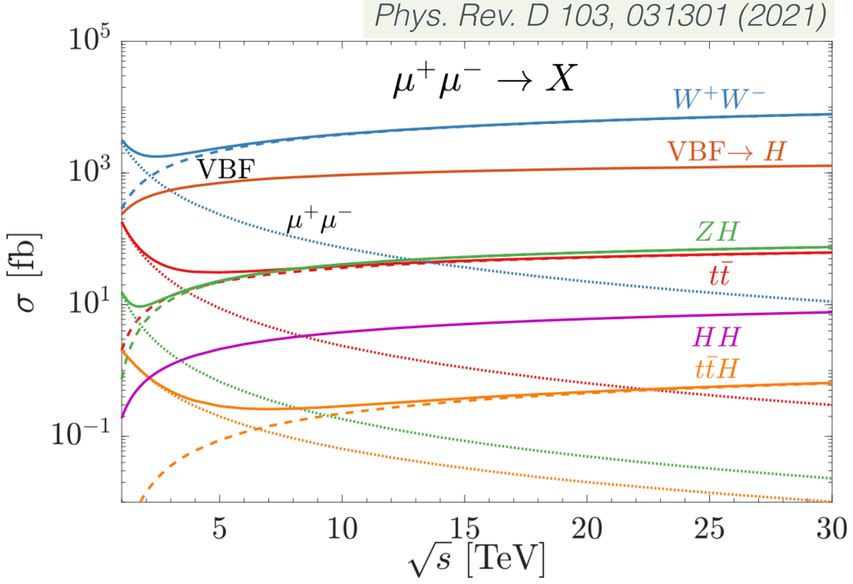
At $\sqrt{s} \geq 3$ TeV Muon Collider is the most energy efficient machine ▶

Muon Collider: rising interest

Extremely rich physics program provided by high-energy muon collisions

- **$\mu^+\mu^-$ + vector-boson fusion** *(increasing at higher energies)* ▶
- **unprecedented potential for precision measurements** including quartic Higgs self-coupling | J. High Energ. Phys. 2020, 98
- **increased interest to the muon sector of New Physics searches** thanks to anomalies in some B-physics and Muon g-2 measurements
- **discovery reach at 14 TeV comparable to FCC-hh at 100 TeV** for heavy particles pair production | arXiv:1901.06150

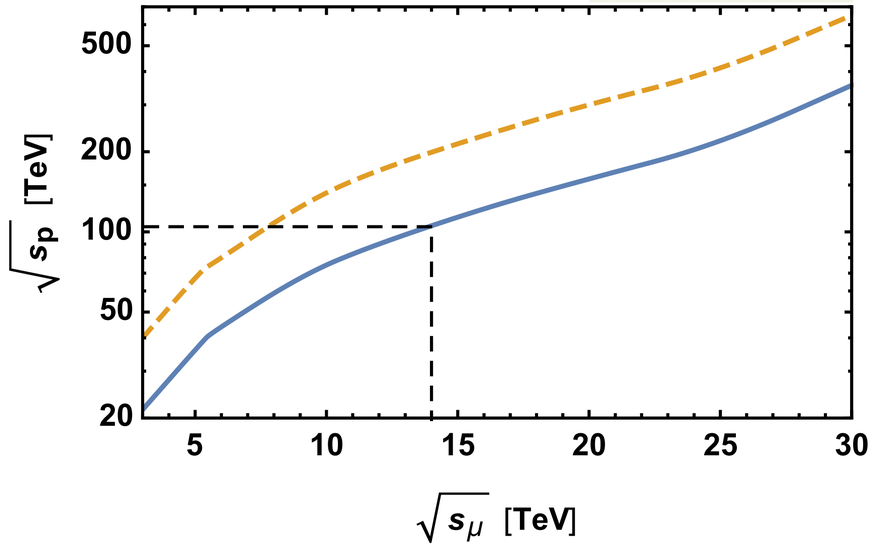
Phys. Rev. D 103, 031301 (2021)



Growing rate of theory publications exploring the Muon Collider physics considering a wide range of $\sqrt{s}$ = 126 GeV - 100 TeV

- The Muon Smasher's Guide | arXiv:2103.14043
- The physics case of a 3 TeV muon collider stage | arXiv:2203.07261

arXiv:2103.14043



First design studies started in 2010 by the Muon Accelerator Program (MAP)

New effort initiated in 2018 that led the establishment of the International Muon Collider Collaboration

Beam Induced Background: the critical challenge

Assuming the beam density of 2×10^{12} muons/bunch → **large number of decays in the collider ring**
e.g. for $\sqrt{s}$ = 1.5 TeV: 4.1×10^5 decays per meter of lattice

Secondary/tertiary particles interact with the accelerator lattice → **Beam Induced Background (BIB)**

- depends on the beam parameters *(energy, size, rate)*
- depends on the accelerator layout

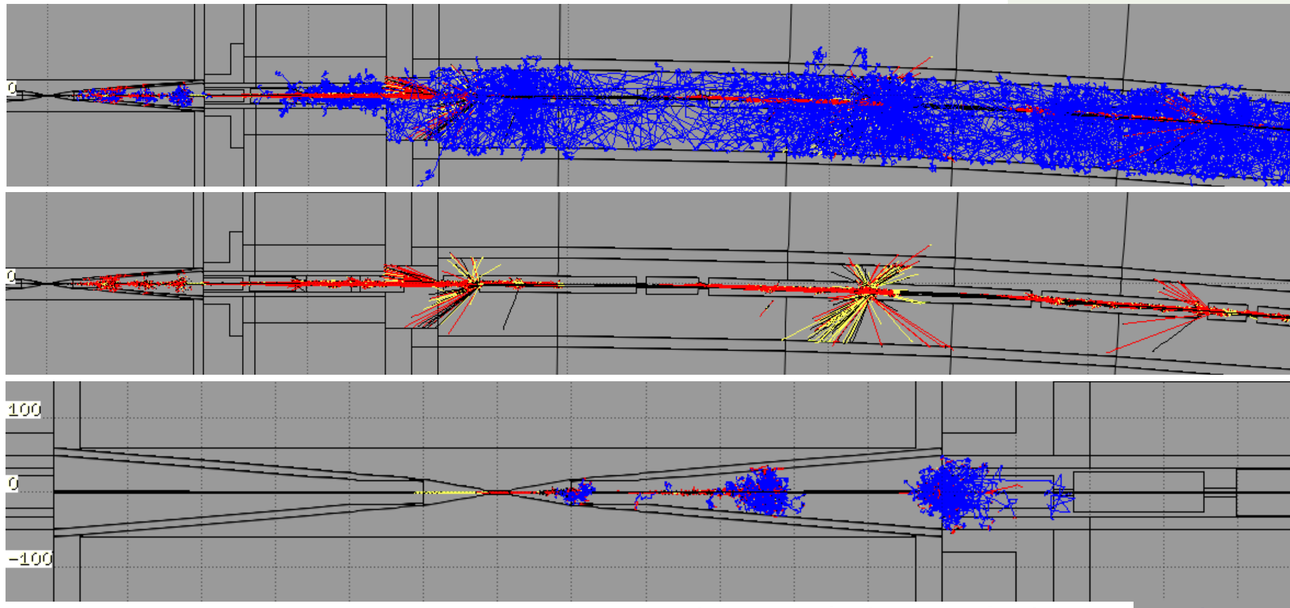
Machine-Detector Interface (MDI) becomes critical

- must be optimised for a specific collider design
- must be consistently included in the simulation

Dedicated MDI for a $\sqrt{s}$ = 1.5 TeV Muon Collider designed by the Muon Accelerator Program (MAP) ▶

- tungsten nozzles with BCH cladding
- 10° opening angle *(defining the forward acceptance)*

arXiv:2203.07964



FLUKA simulation

neutrons photons electrons positrons

MDI reduces the flux and energy of BIB particles reaching the detector by 2-3 orders of magnitude
but the remaining background still poses many experimental challenges

BIB properties: $\sqrt{s} = 1.5$ TeV

BIB has several characteristic features to be exploited in the detector design

1. Predominantly very soft particles (~10 MeV) except for neutrons

fairly uniform spatial distribution → no isolated signal-like energy deposits

↳ conceptually different from pile-up contributions at the LHC

2. Significant spread in time (few ns + long tails up to a few μs)

$\mu^+\mu^-$ collision time spread: 30ps at $\sqrt{s}$ = 1.5 TeV | ≤20ps at $\sqrt{s}$ = 3 TeV

↳ strong handle on the BIB → requires state-of-the-art timing detectors

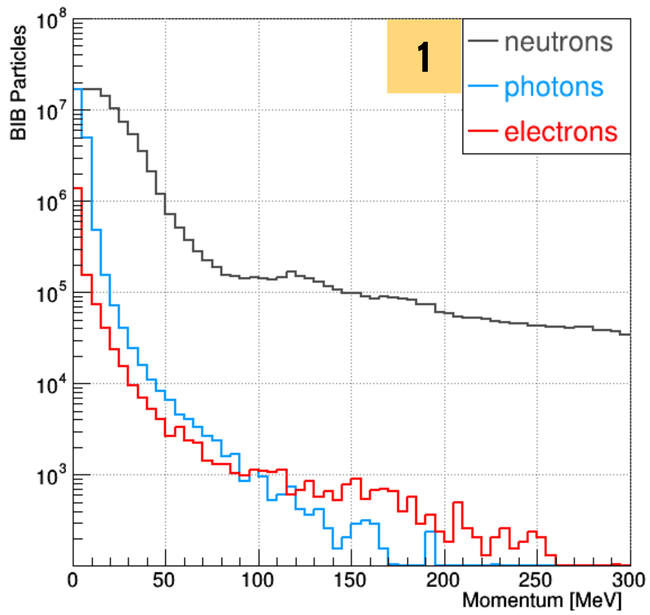
3. Strongly displaced origin along the beam

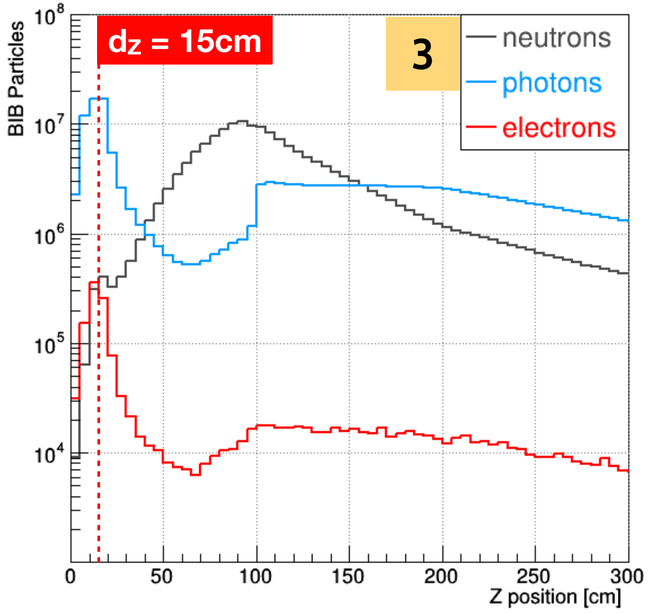
crossing detector surface at a shallow angle

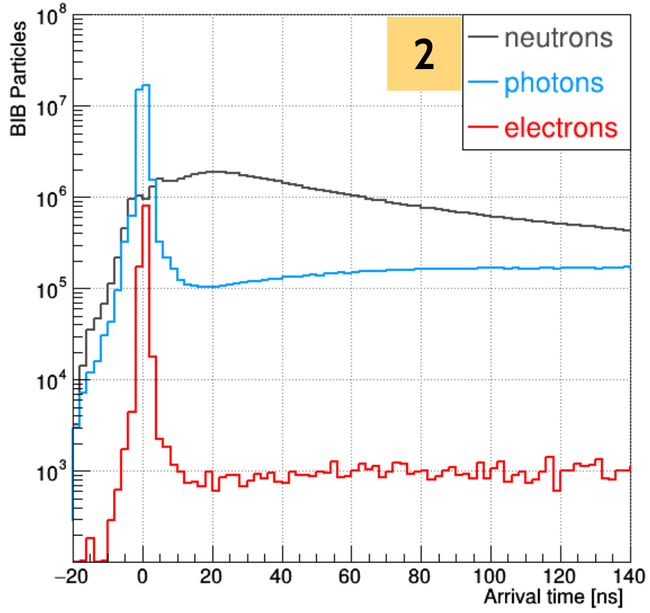
↳ affects charge distribution + time of flight

Each detector component needs to:

- be resistant to the BIB radiation
- enable effective BIB suppression through advanced readout and reconstruction algorithms exploiting the characteristic BIB features







Muon Collider detector

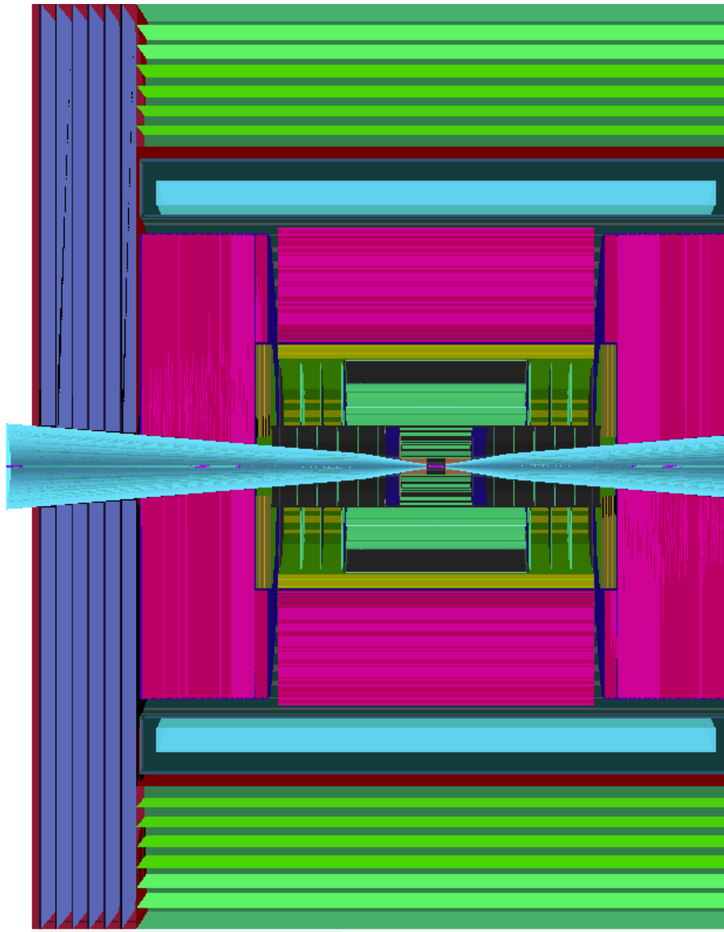
The extensive physics program at a Muon Collider requires a multipurpose detector

↳ **the latest design of the CLIC experiment taken as a starting point** *(e^+e^- collider)*

LHC experiments have demonstrated the great power of the Particle Flow approach which relies on high-granularity calorimeter data and high-quality track reconstruction

The main components of the baseline detector:

- **Tungsten nozzles** extending over 6cm → 6m from the interaction point (IP)
- **All-silicon tracker** with double-layer structure in the Vertex Detector
- **High-granularity sampling calorimeters**
  - **ECAL** 40 layers of **W + Si**
  - **HCAL** 60 layers of **Fe + scintillator + SiPM**
- **Superconducting solenoid:** B = 3.57T magnetic field
- **Muon spectrometer:** 7 layers of **Fe + RPC**



MuColl_v1 geometry

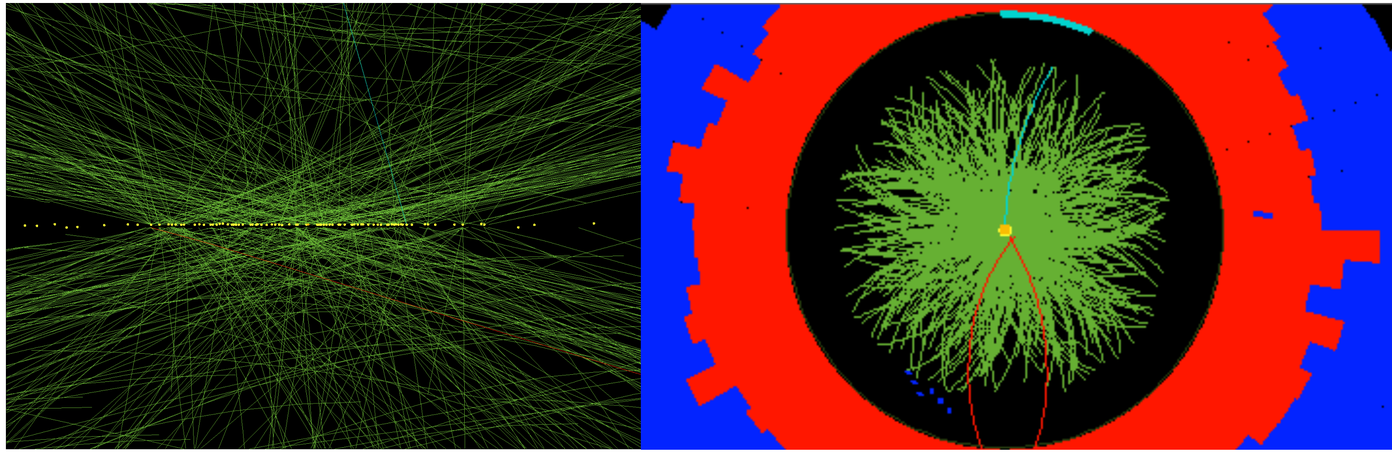
Almost all the detector technologies developed by CLIC are reused in the baseline setup of the Muon Collider simulations (using GEANT4)

Tracking detector: BIB environment

At the LHC we are used to backgrounds primarily from pile-up *pp* collisions

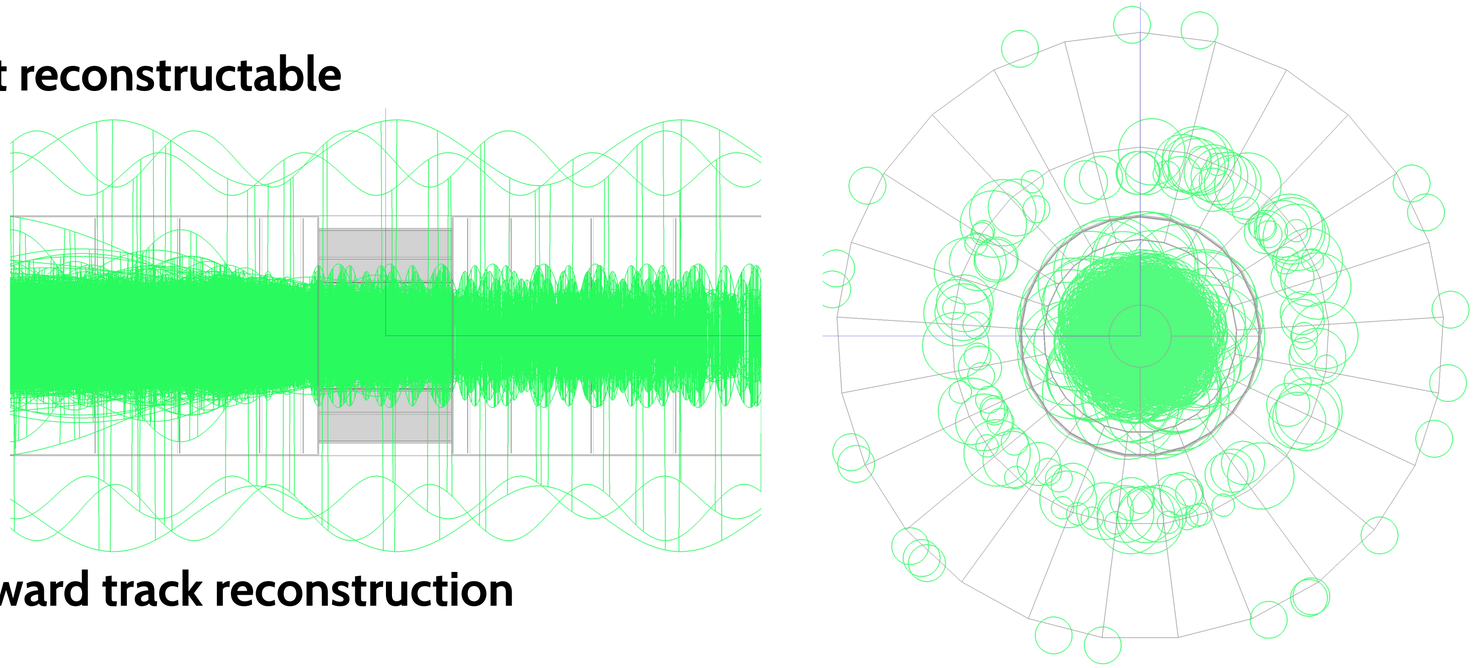
↳ **distinctive tracks pointing at displaced vertices**

Event at the CMS experiment with 78 reconstructed vertices ▶



At the Muon Collider background tracks are not reconstructable

A cloud of looping tracks from soft electrons: $\langle p_T \rangle$ = 3.5 MeV ▶

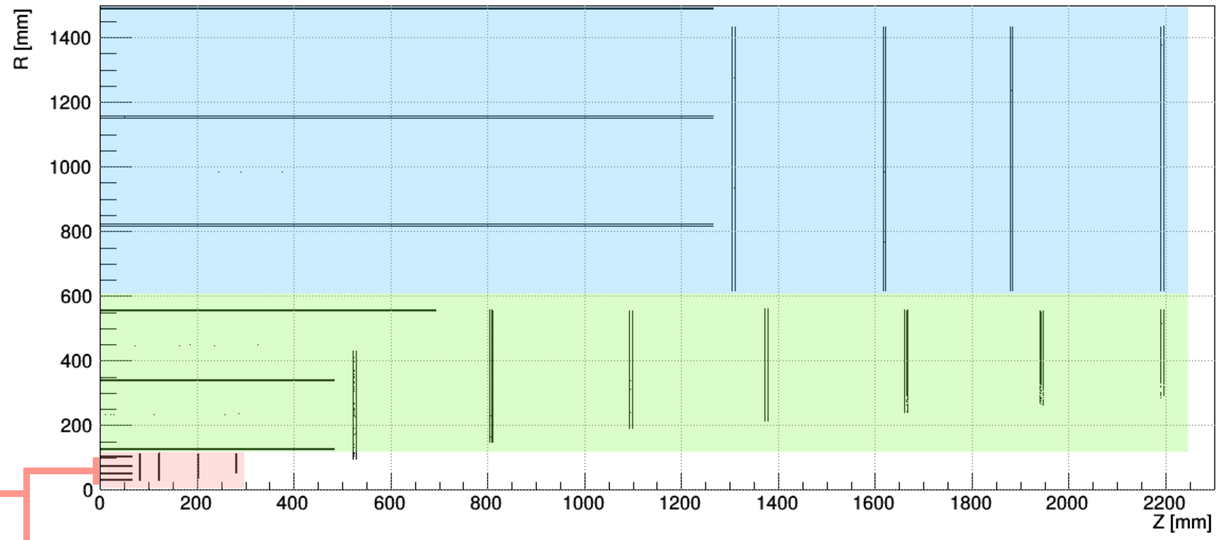


Tremendous combinatorics for the classical outward track reconstruction

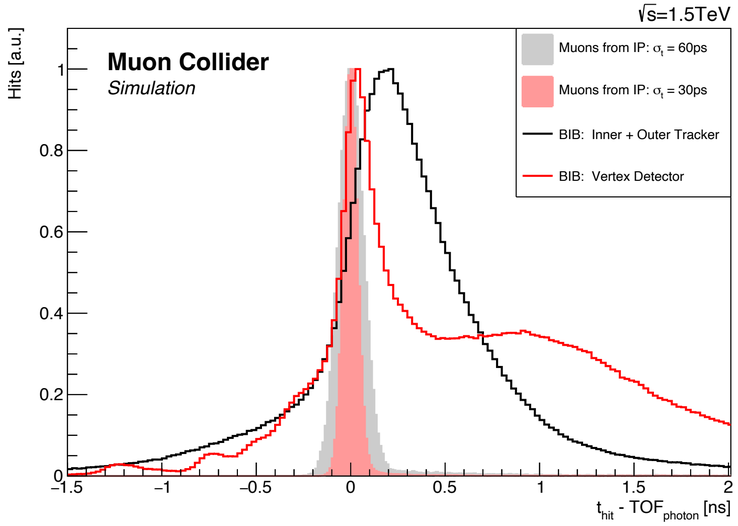
Tracking detector: baseline layout

Silicon sensors with high spatial and timing resolution

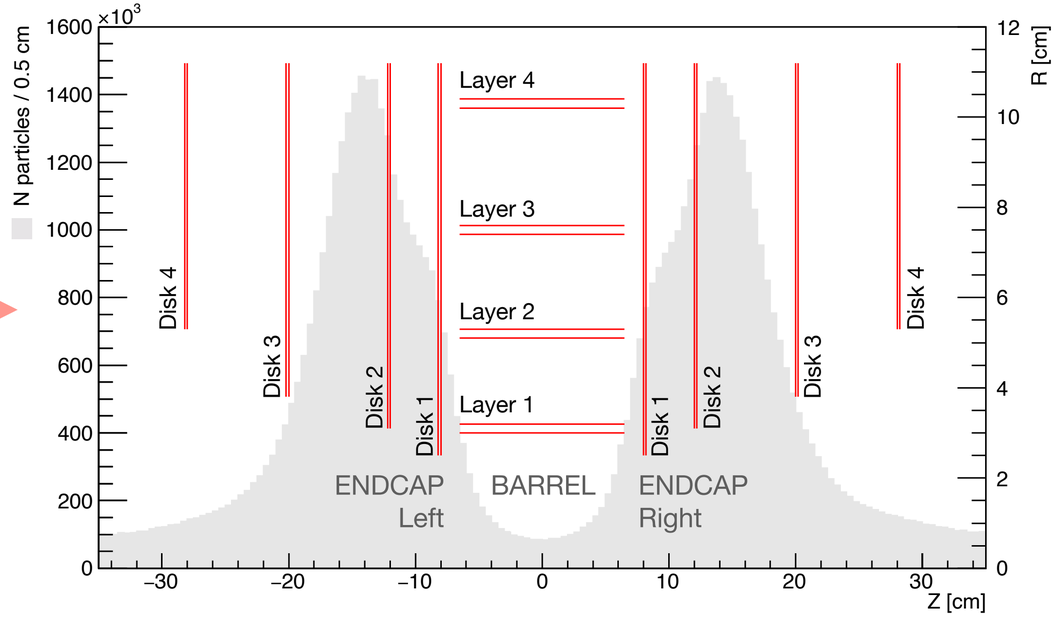
- **Outer Tracker** 50μm × 1mm σ_t = 60ps
- **Inner Tracker** 50μm × 10mm σ_t = 60ps
- **Vertex Detector** 50μm × 50μm σ_t = 30ps
  - double layers with 2mm spacing
  - forward disks placed outside of the regions with highest BIB flux to minimize occupancy



Precise timing enables very narrow readout time windows to reject BIB hits on detector → minimized bandwidth



◀ inline with ongoing R&D on 4D tracking for HL-LHC



Tracking detector: design considerations

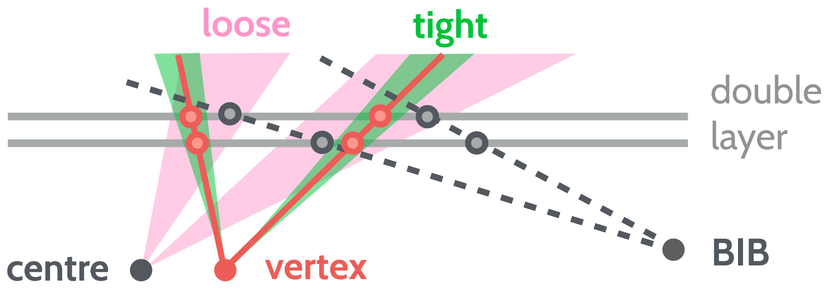
Raw hit density in the Vertex Detector is unsustainable (≤ 1K hits/cm²)

More than 50% of BIB hits can be rejected by narrow time windows ▶

↳ **requires state-of-the-art time resolution and small pixels**
to avoid pile-up pulses from different BIB particles

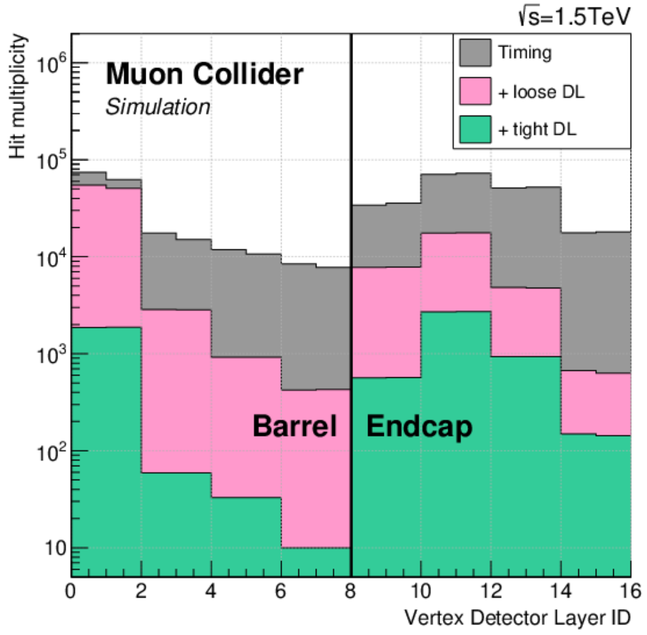
On-detector identification of shallow-angle tracks is even more powerful

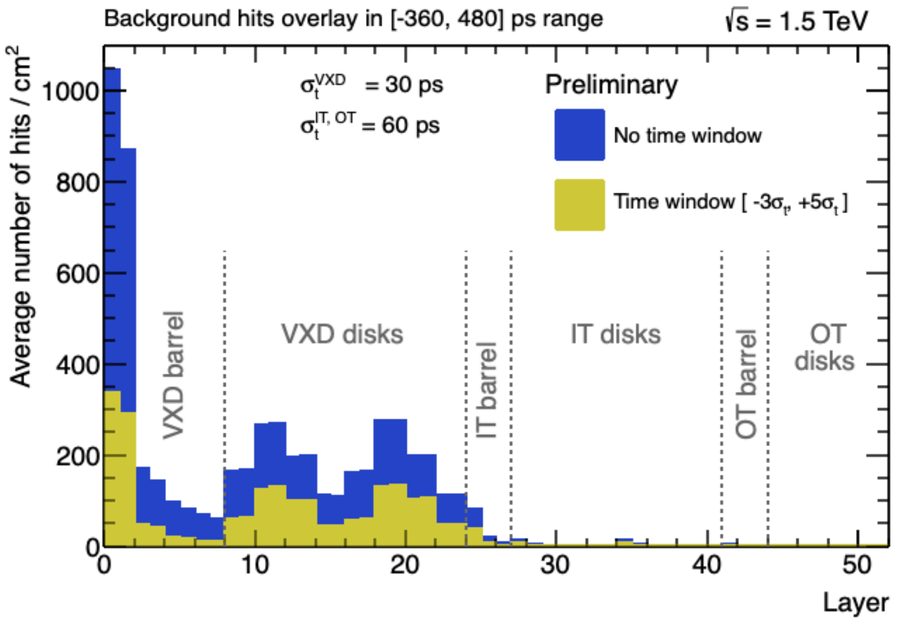
Currently angular information is obtained from stubs in double layers



Tighter angular filtering requires the vertex position to be known in advance

↳ possible only at the reconstruction level but reduces combinatorial background tremendously *(by ×20-×1000)* ▶





Angular sensitivity from single hits could be possible also by cluster-shape or pulse-shape analysis

Can be implemented on detector further reducing bandwidth requirements

↳ but requires more computing power compromising the material budget (electronics, cooling)

Calorimeters: BIB environment

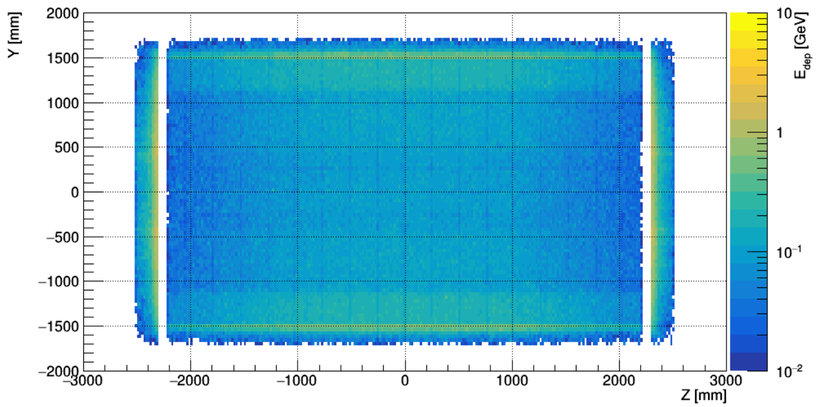
Similarly to the Tracker, very diffused energy deposits from BIB across ECAL (photons) **and HCAL** (neutrons)

ECAL

5×5 mm² cells

40 sensitive layers

W absorber (1.9mm)
+ **Si** sensor pads

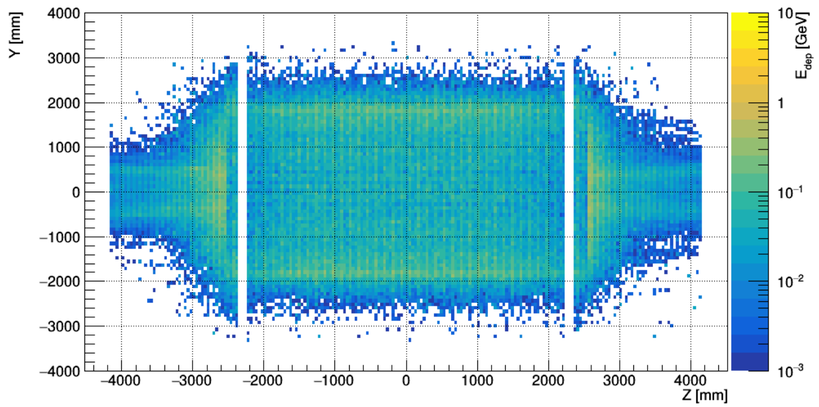


HCAL

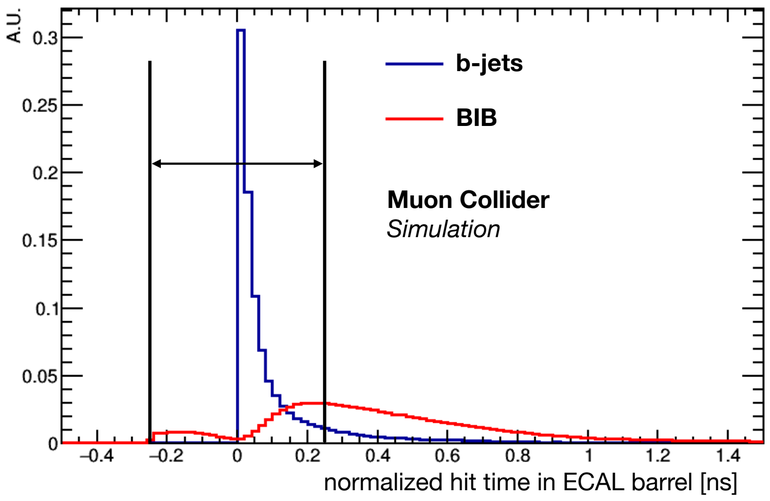
30×30 mm² cells

60 sensitive layers

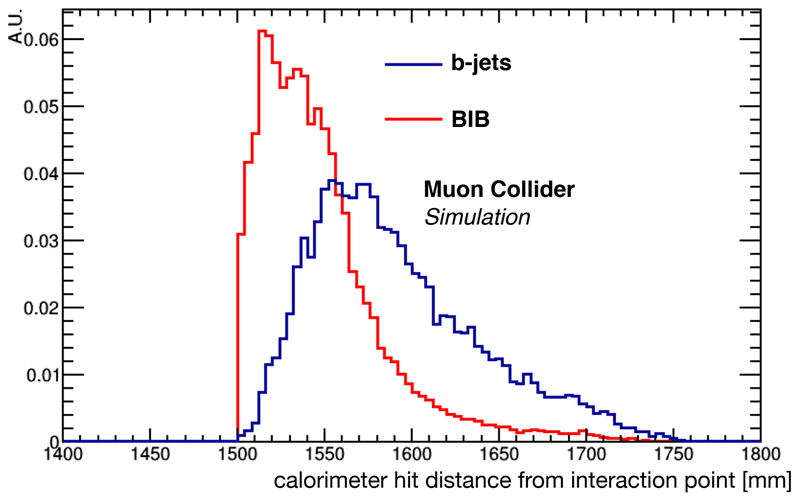
Fe absorber (19mm)
+ plastic scintillator



Distinctive out-of-time BIB contribution in ECAL



Smaller penetration depth of the soft BIB radiation



R&D directions

Ultra-fast Si sensors for the Tracking detector: high spatial granularity (≤50μm) and time resolution (≤30ps)

↳ LGAD, RSD, MAPS, 3D integrated circuits

Sensor requirements very much overlap with the ones of HL-LHC → good synergy with ongoing R&D efforts

On-detector hit filtering is more unique to Muon Collider → requires dedicated R&D

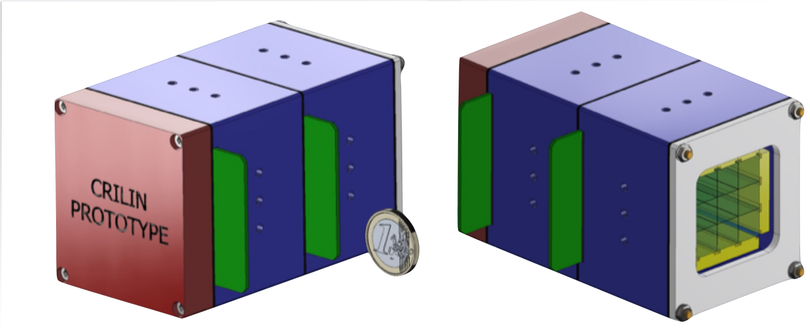
In Calorimeters BIB can't be completely excluded → it has to be subtracted as precisely as possible

↳ high spatial granularity in 3D + good time resolution (≤100ps)

No conceptual showstoppers except for the cost (W+Si)

R&D on a more cost-effective ECAL concept is ongoing: Crilin ▶

↳ homogenous design with Cherenkov crystals + SiPM readout



No major issues in the Muon system

- most of the BIB contained within Tracker + Calorimeters
- BIB muons contribute only in the very forward region and are easily removable

Developments on high-bandwidth data links for HL-LHC are highly relevant for DAQ at the Muon Collider

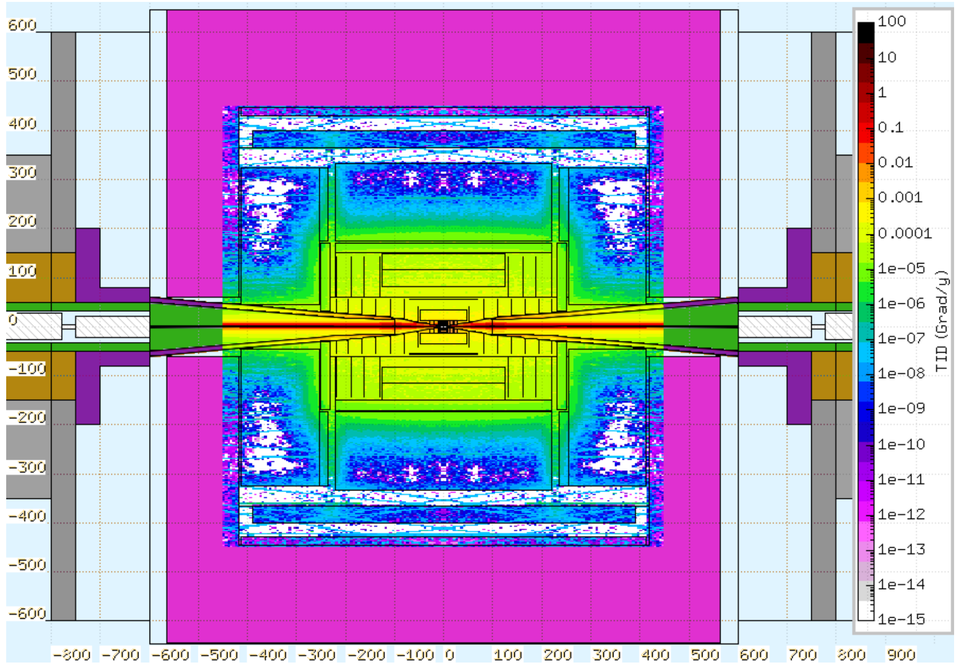
Further information

Up to now most studies performed on the √s = 1.5 TeV case
for a connection with the previous MAP studies

Realistic Muon Collider designs foresee √s = 3 TeV and √s ≥ 10 TeV
but no dramatic changes in BIB characteristics are expected

Muon Collider will operate at ~100 KHz bunch-crossing rate
leaving plenty of time for data-processing (10μs)

Radiation levels do not exceed those at HL-LHC



Dedicated publications on physics and detector prepared as part of the Snowmass '21 process:

- Muon Collider Physics Summary | arXiv:2203.07256
- Simulated Detector Performance at the Muon Collider | arXiv:2203.07964
- Promising Technologies and R&D Directions for the Future Muon Collider Detectors | arXiv:2203.07224

Technical side of detector simulations for the Muon Collider | Comput.Softw.Big Sci. 5 (2021) 1, 21

Special JINST issue on Muon Accelerators for Particle Physics

Summary

Muon Collider is a unique machine for both discoveries and precision measurements
gaining a lot of attention from the theoretical and experimental communities

Feasibility study under way within the International Muon Collider Collaboration
with a dedicated group working on detector and physics simulations

Beam Induced Background is pushing detector requirements to the limits
in terms of time resolution, granularity, data rates, ...

Baseline detector geometry revealed the main performance bottlenecks
and primary targets for detector R&D

Large overlap with ongoing efforts towards HL-LHC experiments
with no obvious showstoppers considering ~10 years ahead

Muon Collider accelerator parameters

Parameter	$\sqrt{s} = 1.5$ TeV	$\sqrt{s} = 3$ TeV	$\sqrt{s} = 10$ TeV
Beam momentum [GeV]	750	1500	5000
Beam momentum spread [%]	0.1	0.1	0.1
Bunch intensity	$2 \cdot 10^{12}$	$2.2 \cdot 10^{12}$	$1.8 \cdot 10^{12}$
$\beta^*_{x,y}$ [cm]	1	0.5	0.15
ϵ_{TN} normalised transverse emittance [π μm rad]	25	25	25
ϵ_{LN} normalised longitudinal emittance [MeV m]	7.5	7.5	7.5
$\sigma_{x,y}$ beam size [μm]	6	3	0.9
σ_z beam size [mm]	10	5	1.5

Integrated luminosity targets: 10 ab^{-1} at $\sqrt{s}$ = 10 TeV + potentially 1 ab^{-1} at $\sqrt{s}$ = 3 TeV
with instantaneous luminosity of ~10^{34} - 10^{35} cm^{-2} s^{-1}