Detector requirements and concepts for the future muon collider

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for the

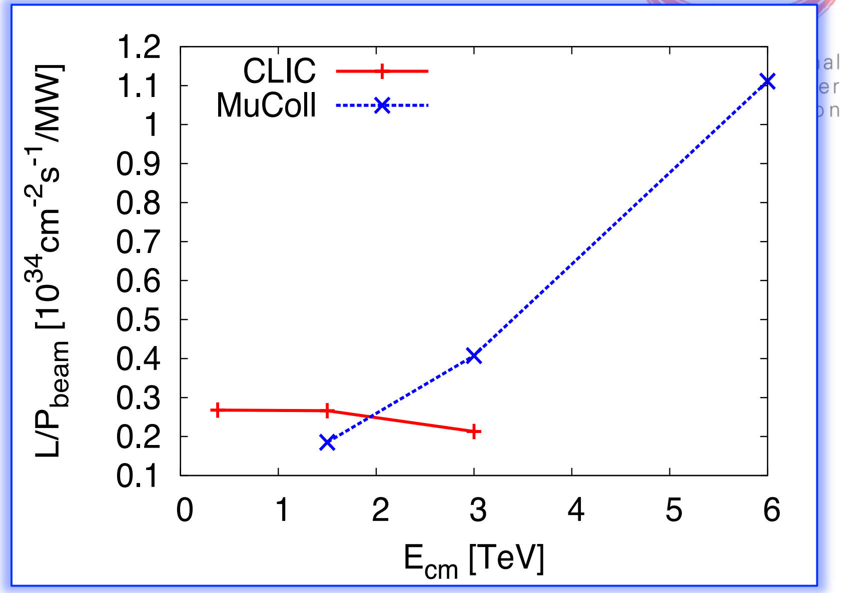
International Muon Collider Collaboration

CERN October 17, 2023

Muon Collider: a new concept facility

Muons do not suffer from synchrotron radiation in this energy range

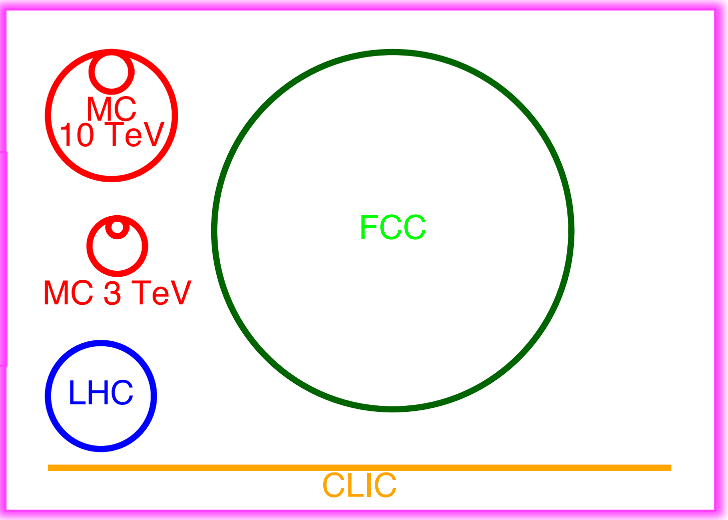
High center of mass energy & high luminosity & power efficient: luminosity increase per beam power



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

Parameter	Symbol	Unit	Target value		
Centre-of-mass energy	E_{cm}	TeV	3	10	14
Luminosity	$\mathfrak{L}$	1×10^{34} cm^{-2} 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 meaning of facility

Neutrino physics measurements, not discussed here

Experiments at a center of mass of

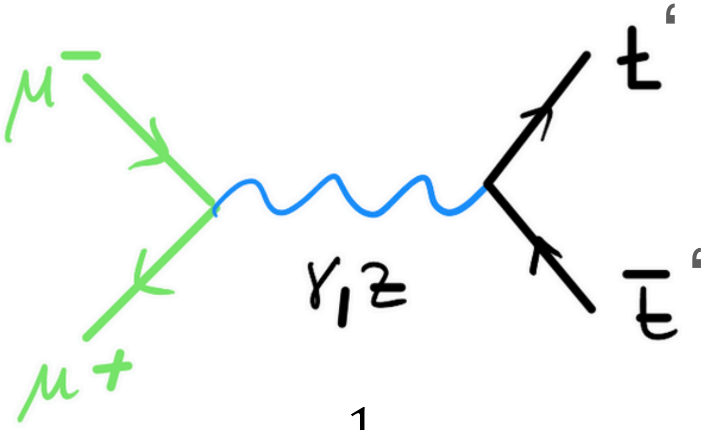
- ✗ few TeV, first stage of the collider
  $\sqrt{s} = 3$ TeV taken as working hypothesis
- ✗ 10-ish TeV, second stage of the collider
  $\sqrt{s} = 10$ TeV assumed in designing the first concept

Two cases, $\sqrt{s} = 3$ and $\sqrt{s} = 10$ TeV, will be discussed

Physic processes: two colliders in one

F. Maltoni
"Physics Overview" Annual Meeting IMCC

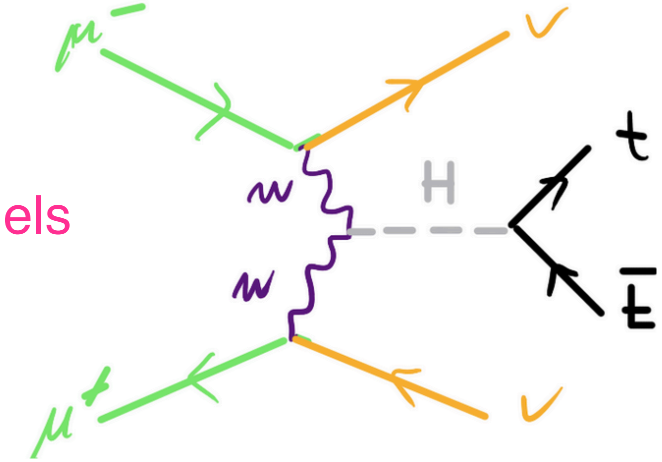
Multi-TeV muon collider opens a completely new regime :



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

Energetic final states
(heavy particle or very boosted)

Different physics can be probed in the two channels



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

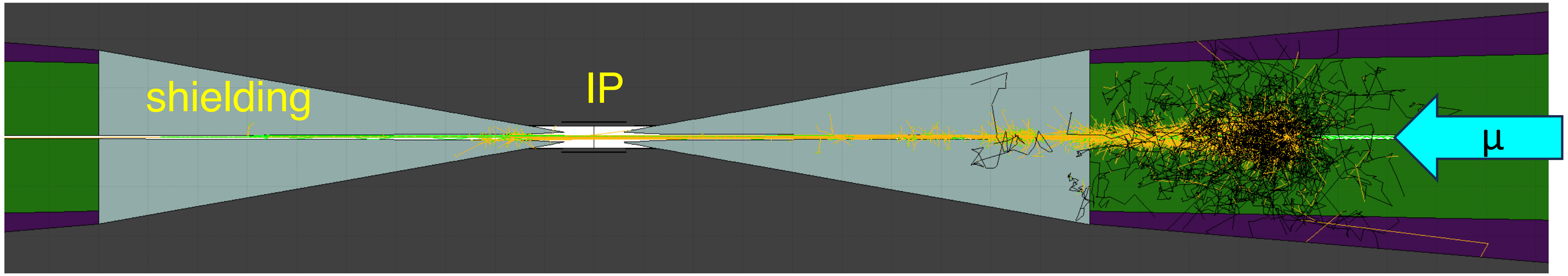
Standard Model coupling measurements
Discovery light and weakly interacting particles

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

Beam-induced background

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 ofμ 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

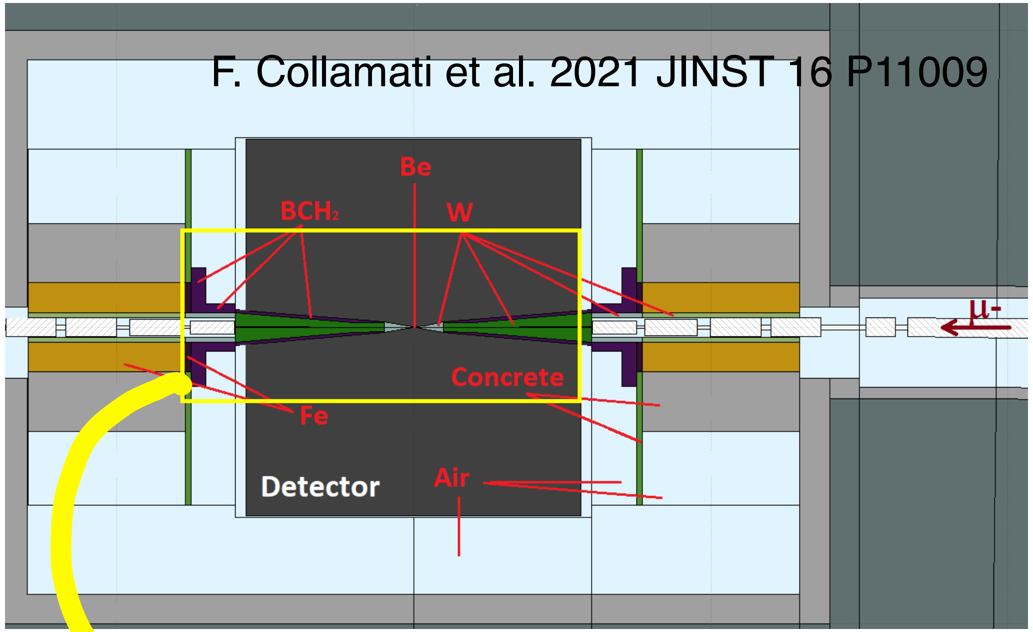


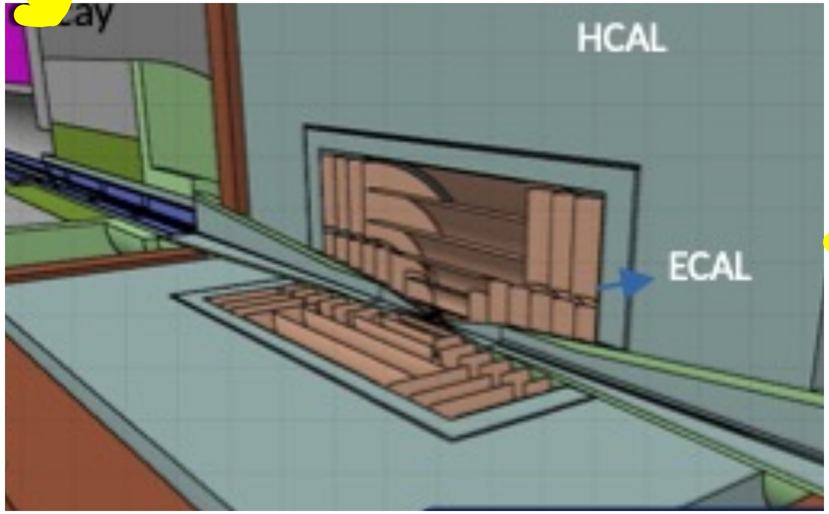
Single muon decay tracks

$N_\mu^\pm \sim 2x10^{12}$/bunch

F. Collamati et al. 2021 JINST 16 P11009

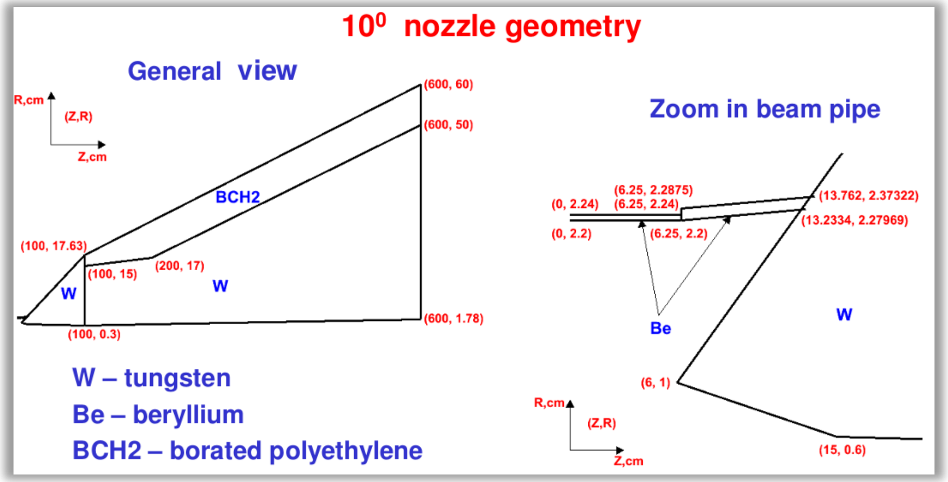
Shielding structure: the nozzles



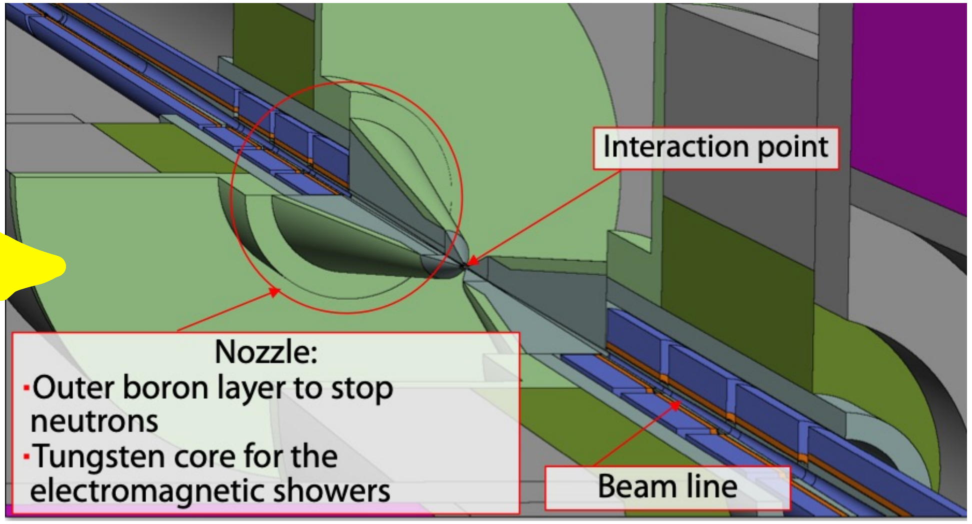


Designed by MAP (Muon Accelerator Program)

N.V. Mokhov et al. *Muon collider interaction region and machine-detector interface design* Fermilab-Conf-11-094-APC-TD



Optimized for $\sqrt{s} = 1.5$ TeV

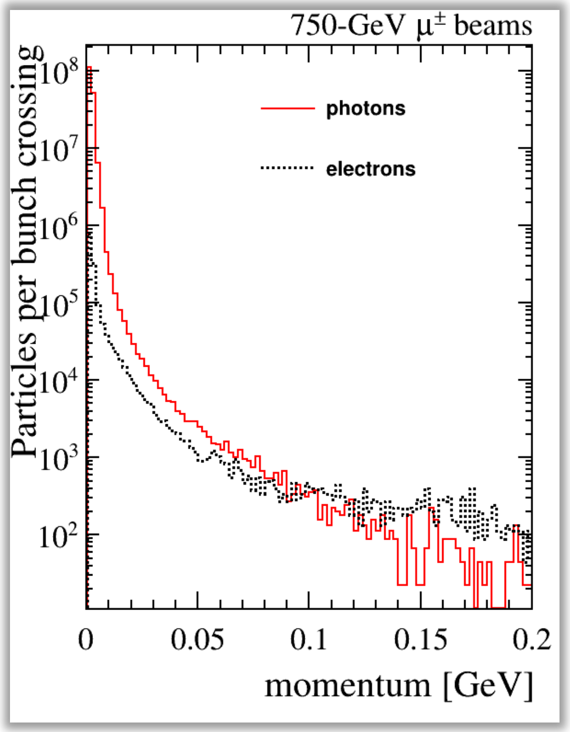


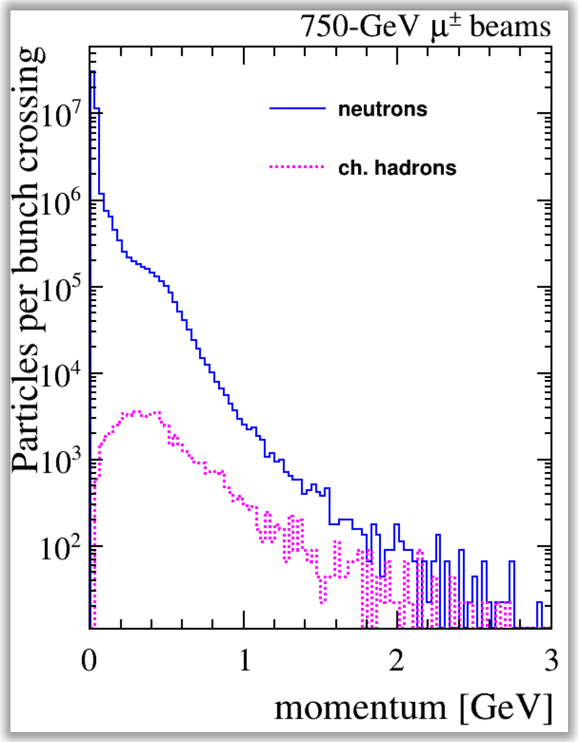
D. Calzolari [IMCC Ann. meeting Orsay 2023]

Survived beam-Induced background (BIB) properties

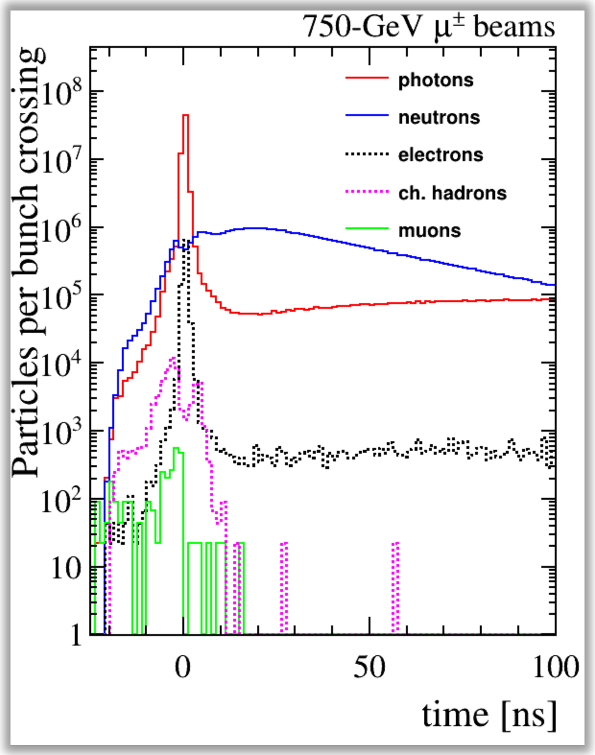
N. Bartosik *et al*
JINST **15** P05001

Despite the nozzles, huge number of particles arrives on the detector





Low momentum particles



Partially out of time vs beam crossing

Beam-induced background generated with FLUKA by using the interaction region layout.
Particles propagated into the detector with GEANT.

Detector for $\sqrt{s} = 3$ TeV

If not specified Muon Collider material is taken from
C. Accettura et al. "Towards a muon collider"
CLIC material from H. Abramowicz et al., Eur. Phys. J. C 77, 475 (2017)

First detector concept at $\sqrt{s} = 3$ TeV based on CLIC's detector concept

CLICdp-Note-2017-001

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

hadronic calorimeter

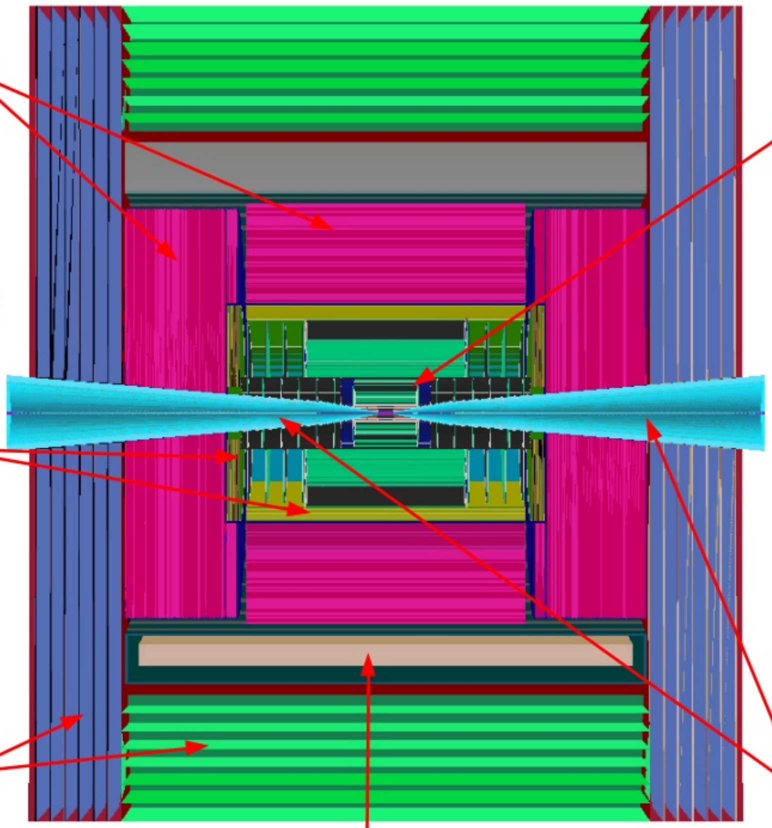
- 60 layers of 19-mm steel absorber + plastic scintillating tiles;
- 30x30 mm^2 cell size;
- 7.5 λ_I.

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.

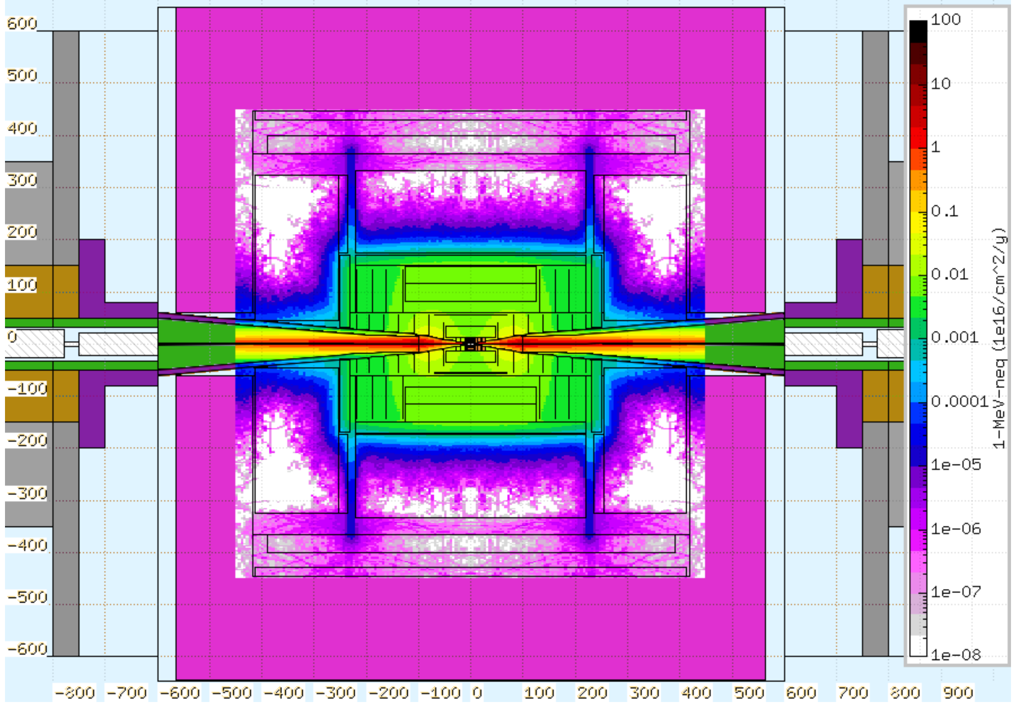
shielding nozzles

- Tungsten cones + borated polyethylene cladding.

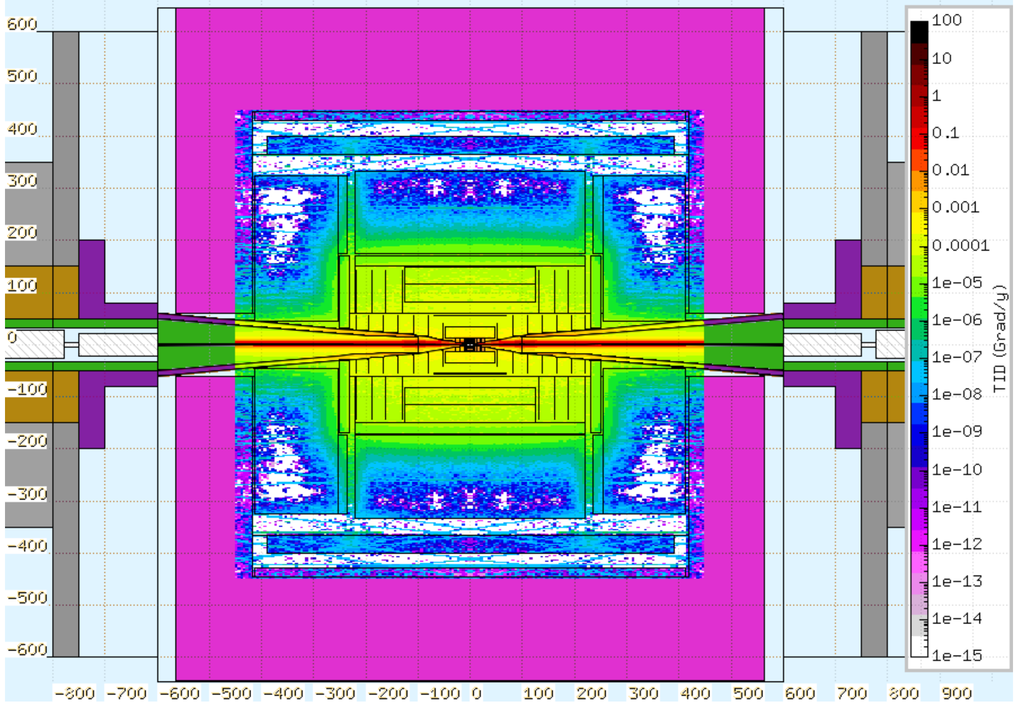
ILCSoft is the simulation and reconstruction framework, forked from CLIC's software.
Transition to key4hep in progress, timeline depending on person power.
Tutorial made in July 2023.

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
- Collision rate 100 kHz
- Beam injection frequency 5Hz
- Days of operation/year 200

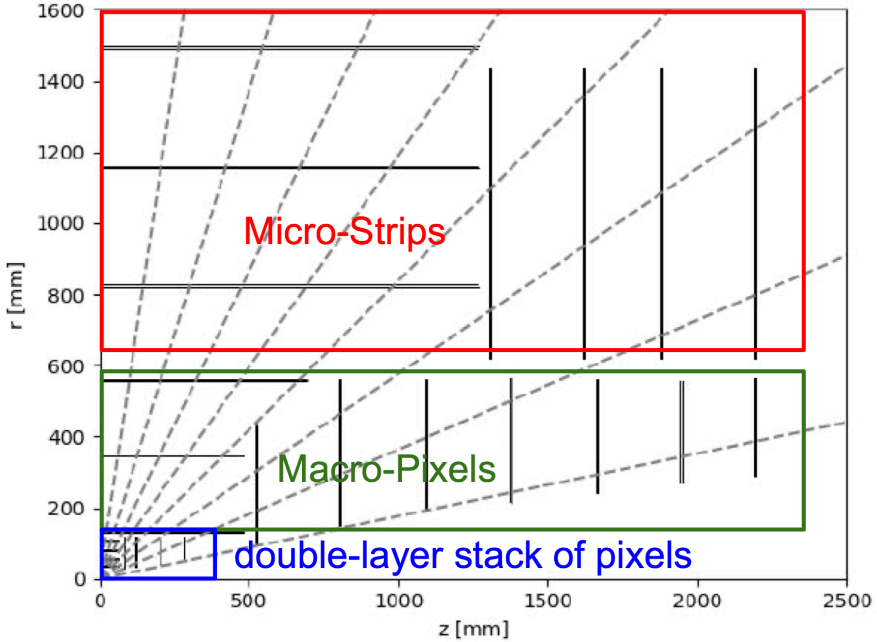
Radiation hardness requirements like HL-LHC (expected)

	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

Tracker system: full detector & BIB simulation

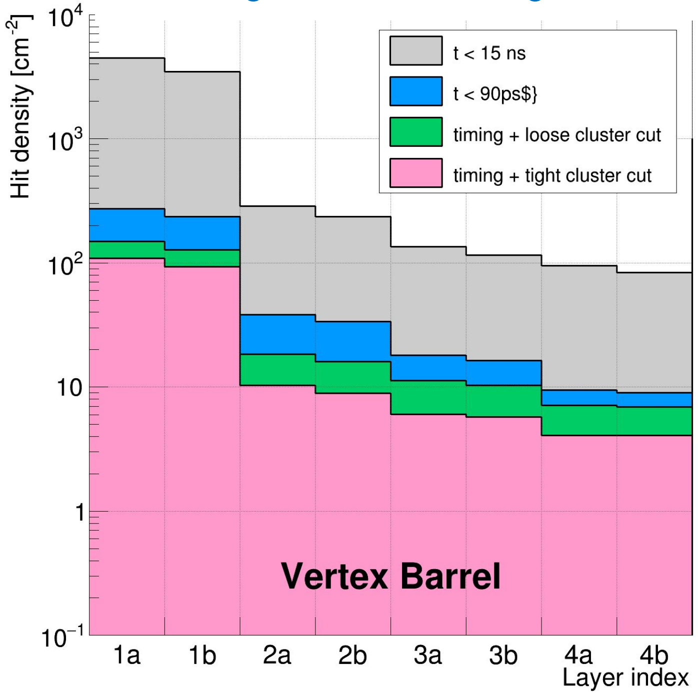
First layers of barrel vertex detector & forward disks highly impacted by BIB



Tracker requirements

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

S. Pagan Griso C. Sellgren

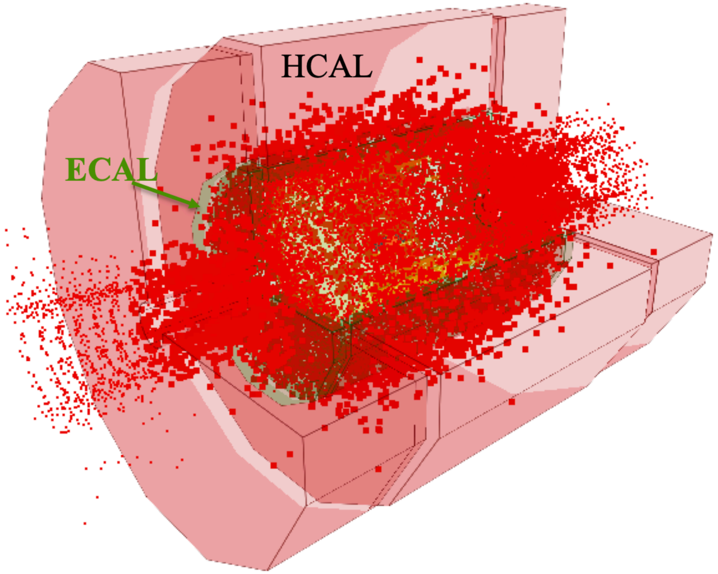


Higher occupancies respect to LHC detectors crossing rate 100 kHz vs 40 MHz

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 simulation

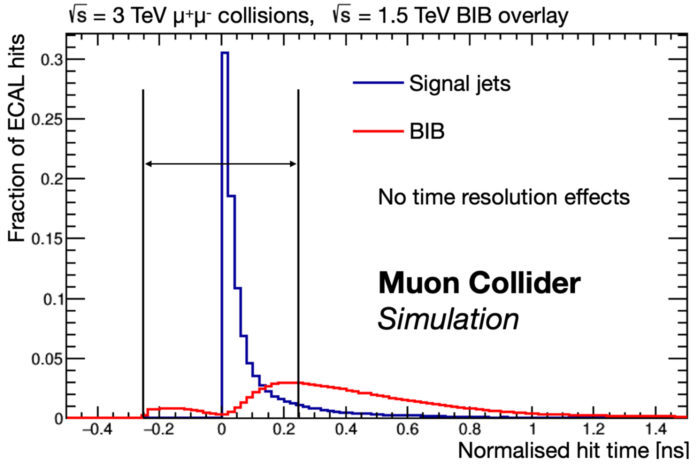


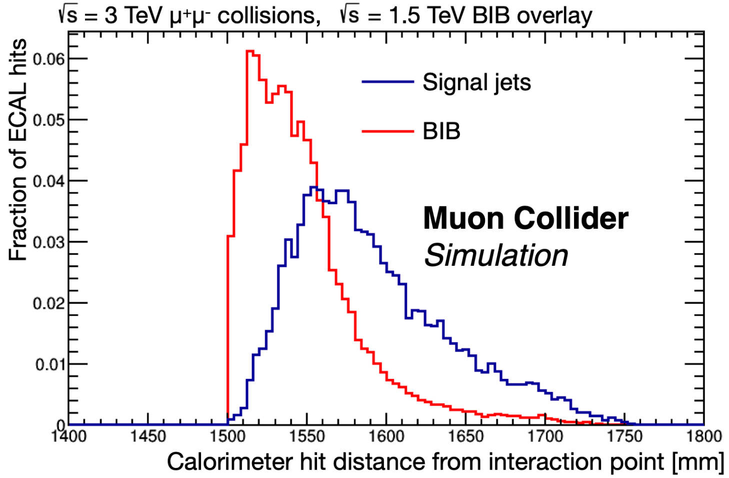
ECAL surface flux: 300 particle/cm^2

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

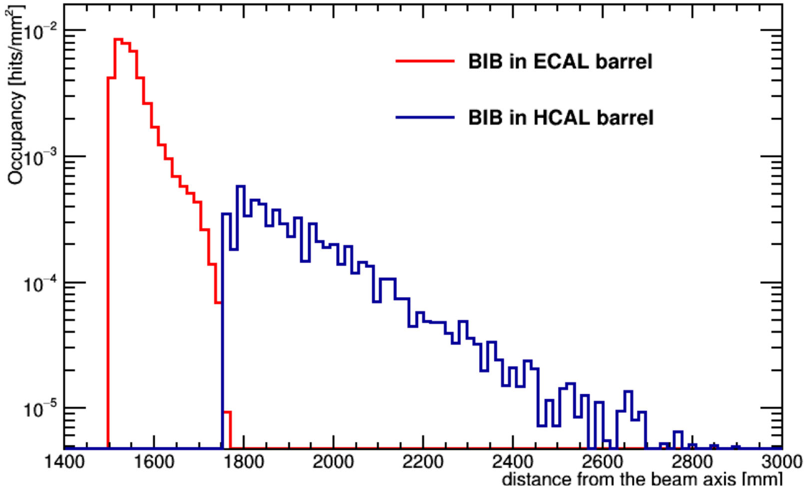
Calorimeter requirements

- 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 to avoid overlaps in the same cell





Occupancy: ECAL > 10 times HCAL



Engaged in DRD6 with dedicated ECAL R&D: **Crilin**

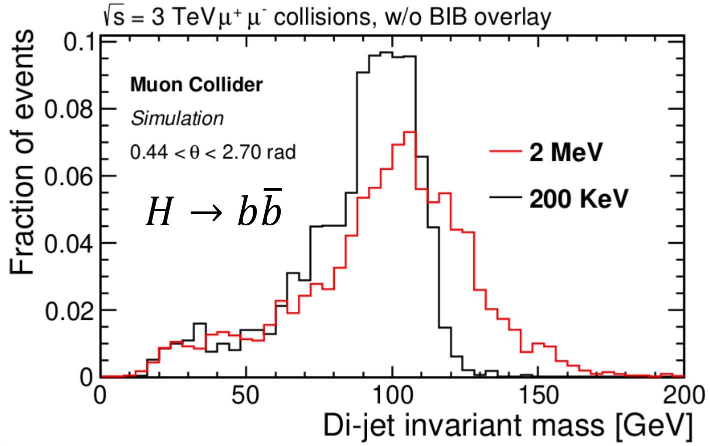
Module: 5 layers of PbF_2 crystals (10x10x40 mm^3) Cerenkov light detected with SiPMs

Dedicated HCAL proposal in progress.

Objects reconstruction performance

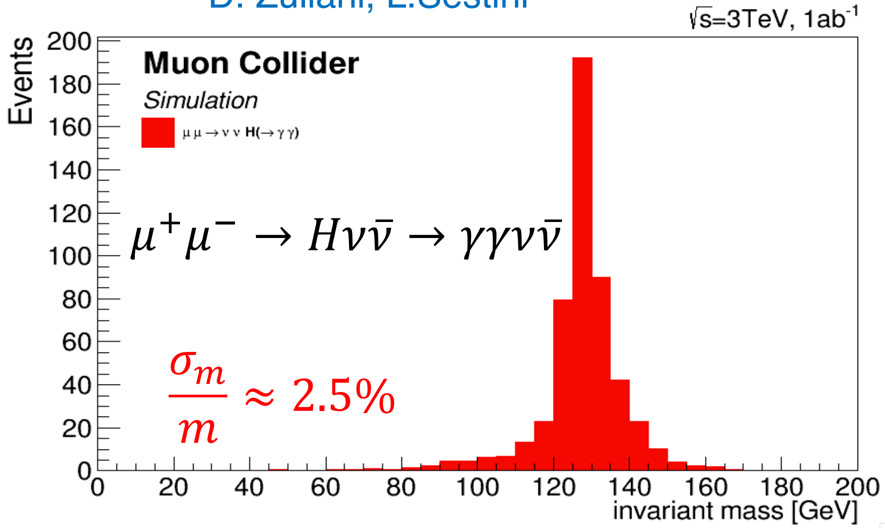
$E^{cell}_{threshold} \geq 2$ MeV for ECAL reconstruction

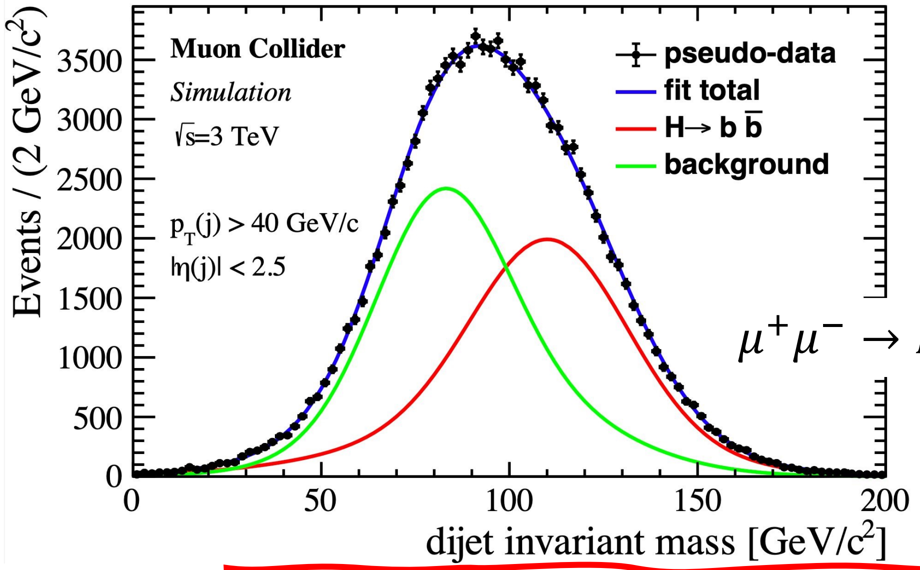
up to now, it dominates energy resolution



Despite BIB limitation quite good physics performance

D. Zuliani, L.Sestini





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

$\frac{\Delta\sigma_{H\to\gamma\gamma}}{\sigma_{H\to\gamma\gamma}} \sim 9\%$ 1 experiment 1 ab^{-1}

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

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

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

Jets reconstruction, even if not optimal, allows good performance on Higgs self coupling determination

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

$\sqrt{s} = 3$ TeV full detector and BIB simulation

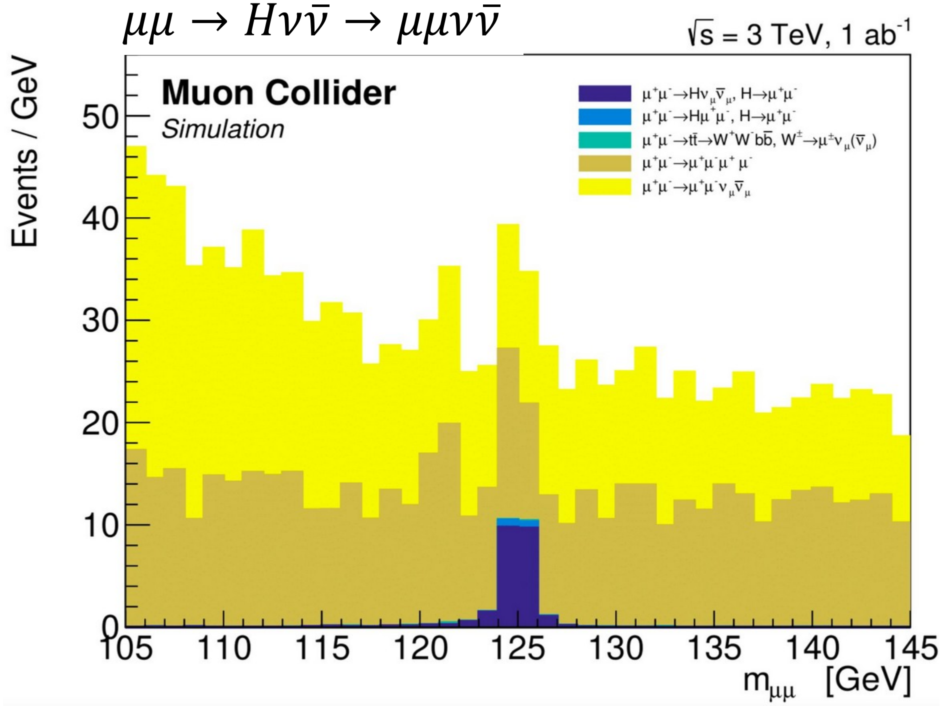
$\frac{\Delta\sigma_{HH\rightarrow b\bar{b}b\bar{b}}}{\sigma_{HH\rightarrow b\bar{b}b\bar{b}}} \sim 33\%$ $\frac{\Delta\lambda_3}{\lambda_3} \sim 20\%$ 1 experiment 1 ab^{-1}

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

$\frac{\Delta\lambda_3}{\lambda_3} \sim 4\%$ 1 experiment 10 ab^{-1}

Central muons do not suffer from BIB, forward detector more problematic.

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



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

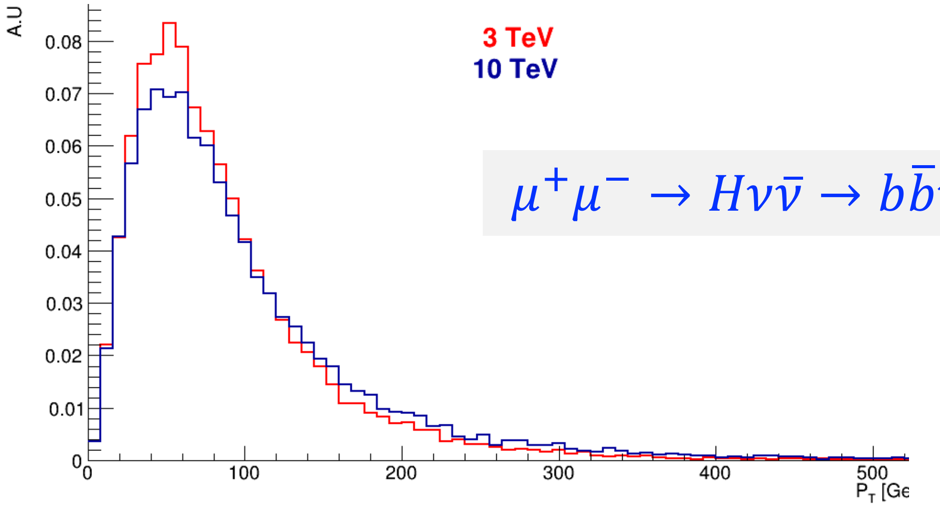
CLIC at 3 TeV 2 ab^{-1}: 25%

Engaged in DRD1 with dedicated R&D

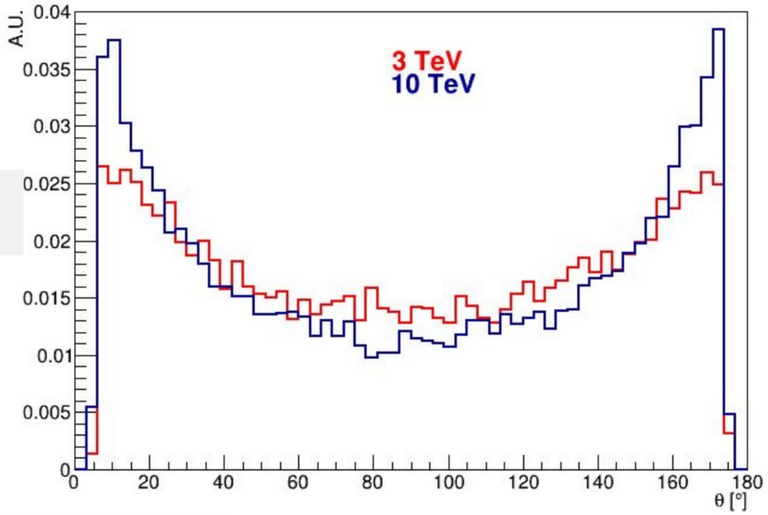
Detector for $\sqrt{s} = 10$ TeV: definition of requirements

Physics requirements: three classes of processes

Low momentum, forward-boosted phenomena,
ex. Higgs physics, double and triple Higgs production



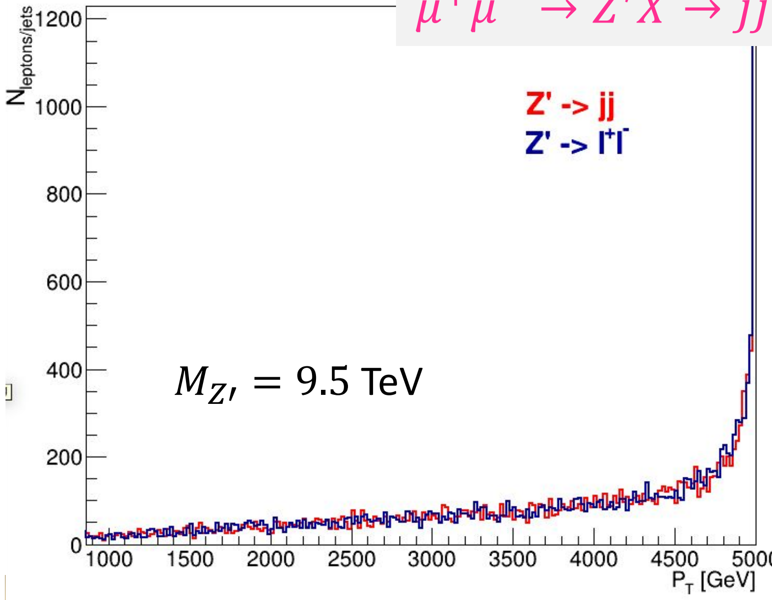
$\mu^+\mu^- \to H\nu\bar{\nu} \to b\bar{b}\nu\bar{\nu}$

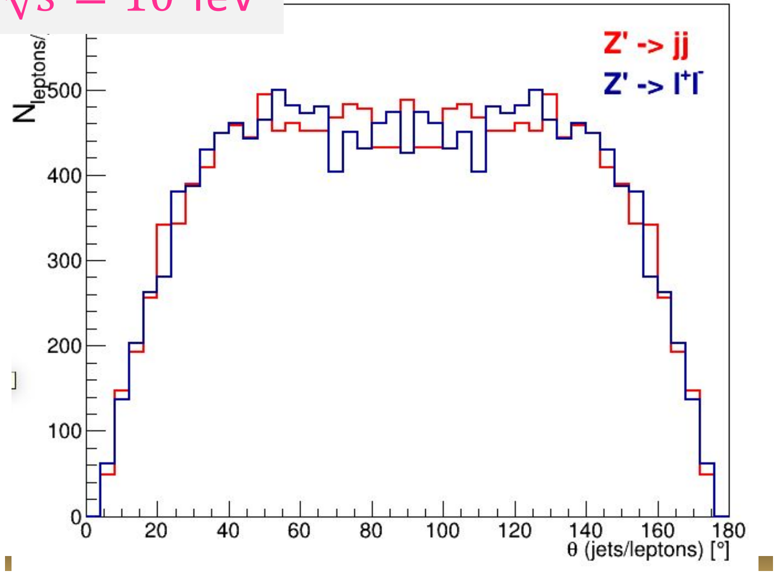


L. Buonincontri

High momentum central phenomena,
ex. Z'

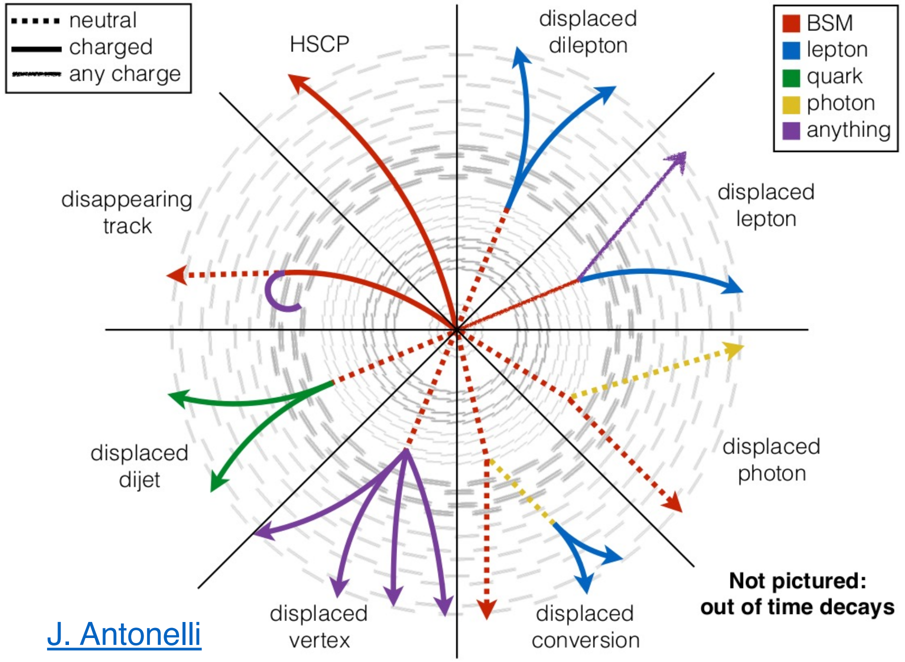
$\mu^+\mu^- \to Z'X \to jj/\ell\ell X \;\sqrt{s} = 10$ TeV





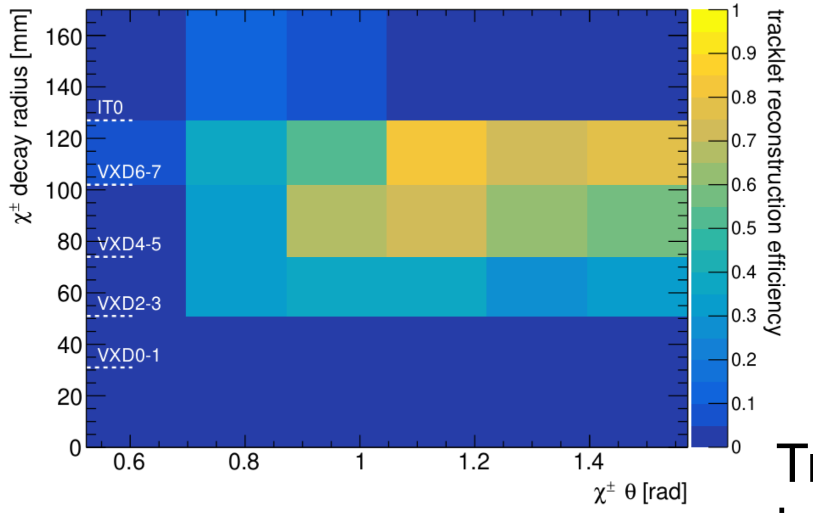
Physics requirements: three classes of processes cont'd

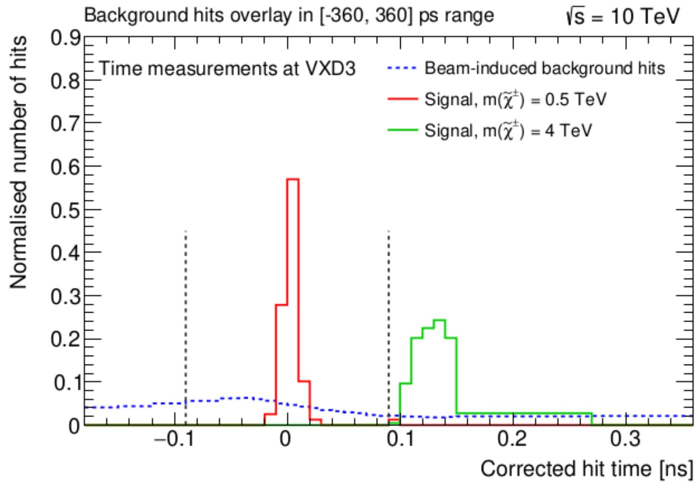
Less conventional signatures from BSM processes, ex. Disappearing Track



J. Antonelli

R. Capdevilla et al.,. JHEP 06, 133 (2021)



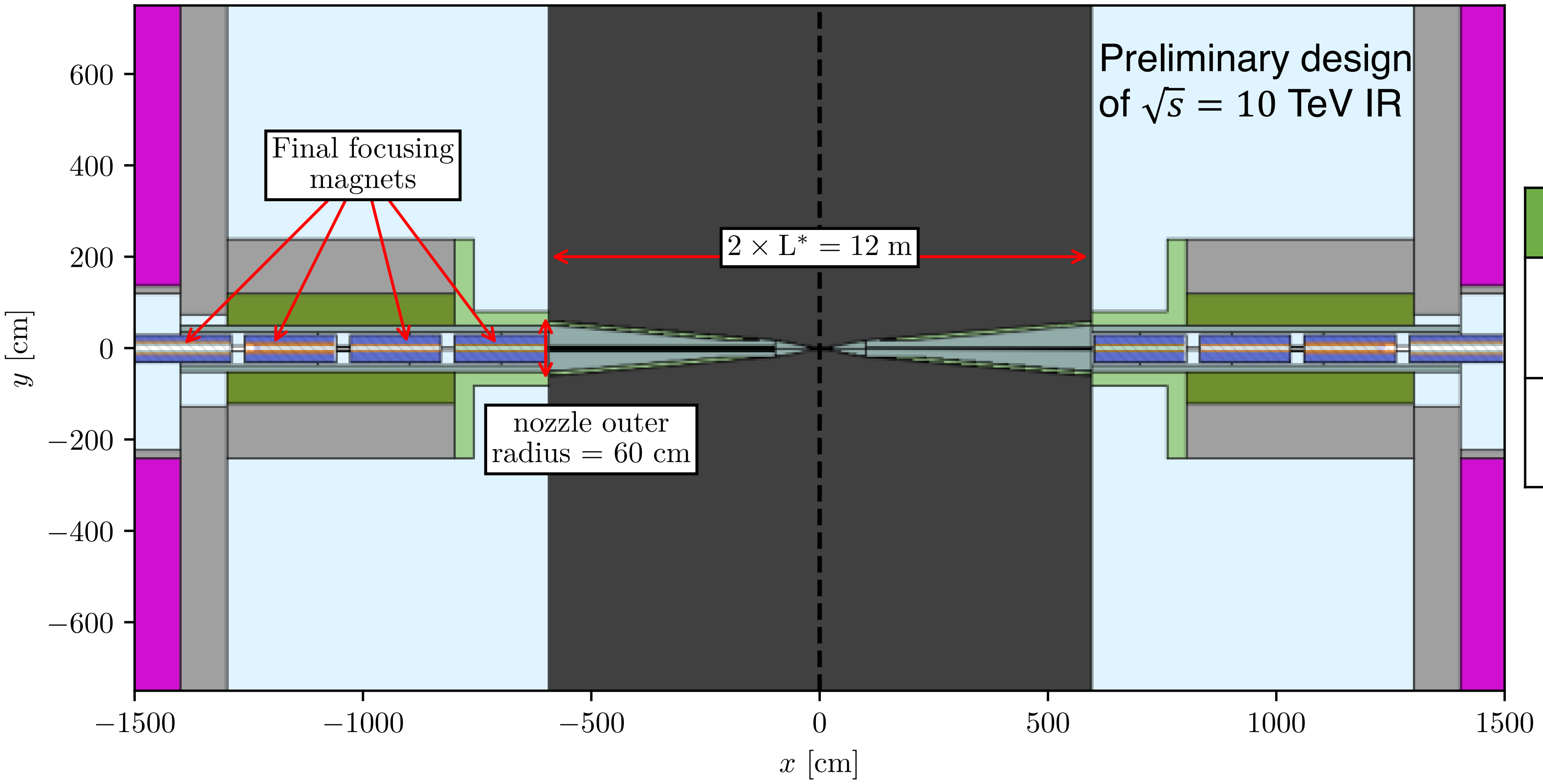


Tracker design important to avoid limitation of performance

Collider interaction region requirements

Longitudinal size of the detector determined by position of final focusing magnets. At $\sqrt{s} = 10$ TeV it would be very difficult from the lattice point of view to have more than ± 6 m

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



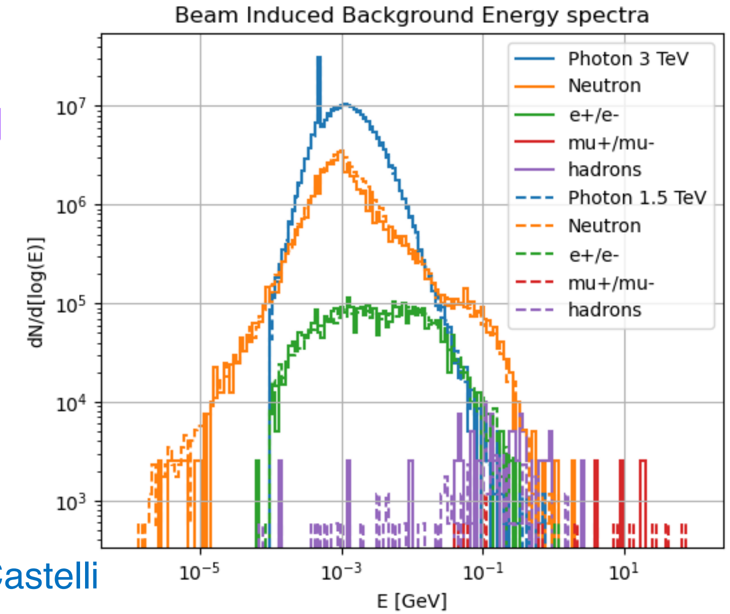
Beam dimension at IP

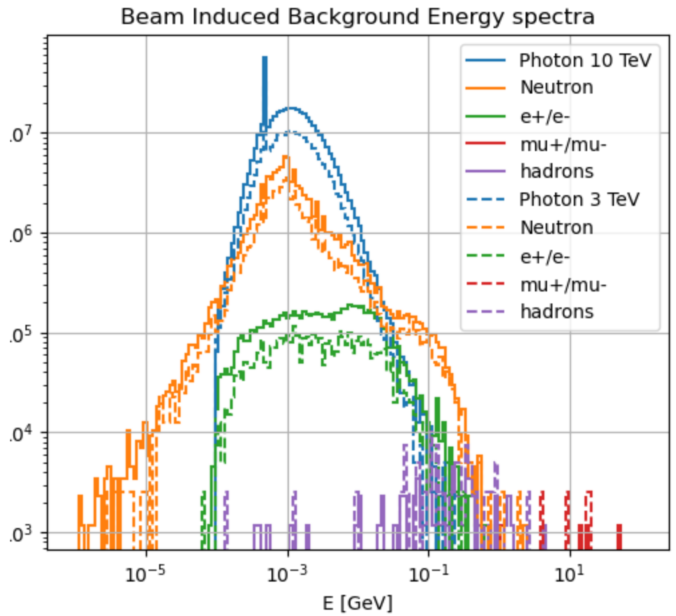
	LHC	MC
bunch length σ_z	7.7 cm	1.5 mm
bunch size $\sigma_\perp$	16.7 μm	0.9 μm

Beam background sources in the detector region

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

1) Muon decay along the ring fluxes arriving on detector dominated by shape, material, dimensions of nozzles

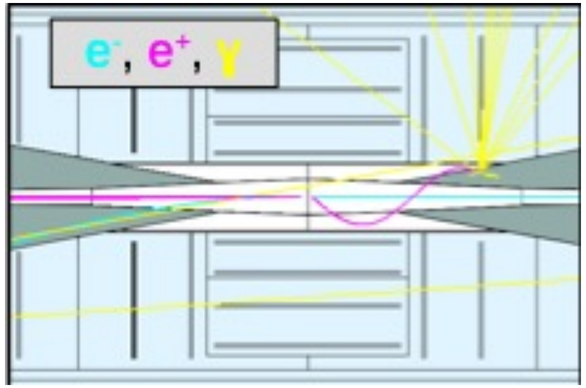




D. Calzolari, L. Castelli

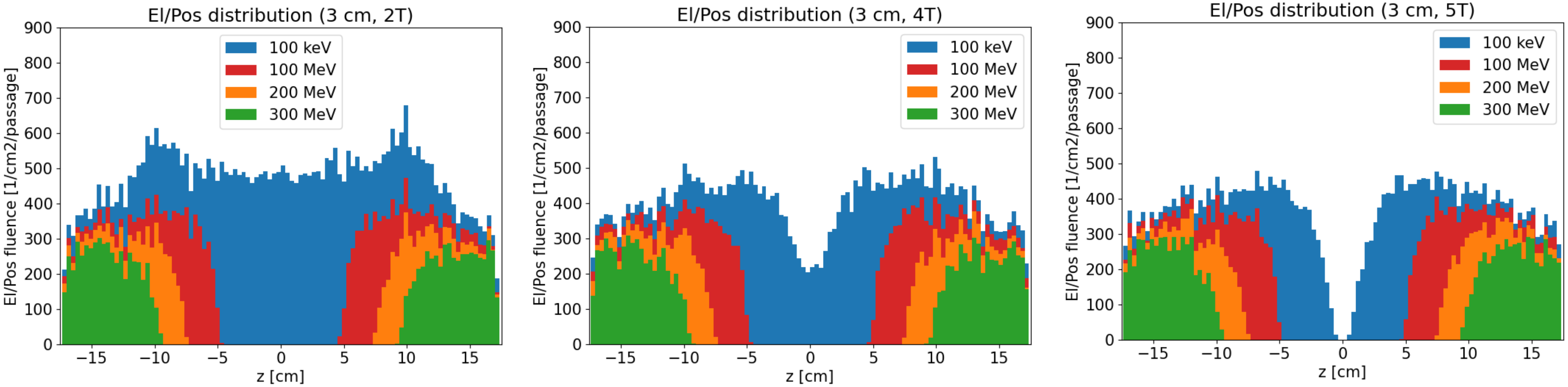
2) Incoherent e^-e^+ production $\mu^+\mu^- \rightarrow \mu^+\mu^- e^+e^-$

- Study in progress by using *Guinea-Pig* program
- Incoherent e^+e^-
  - produced in time with bunch crossing at interaction point
  - very energetic



- Study focuses on reducing the component arriving on the detector by trapping it through solenoidal field

D. Calzolari, Magnet for 10 TeV Detector



Magnetic field needed to reduce beam-induced background

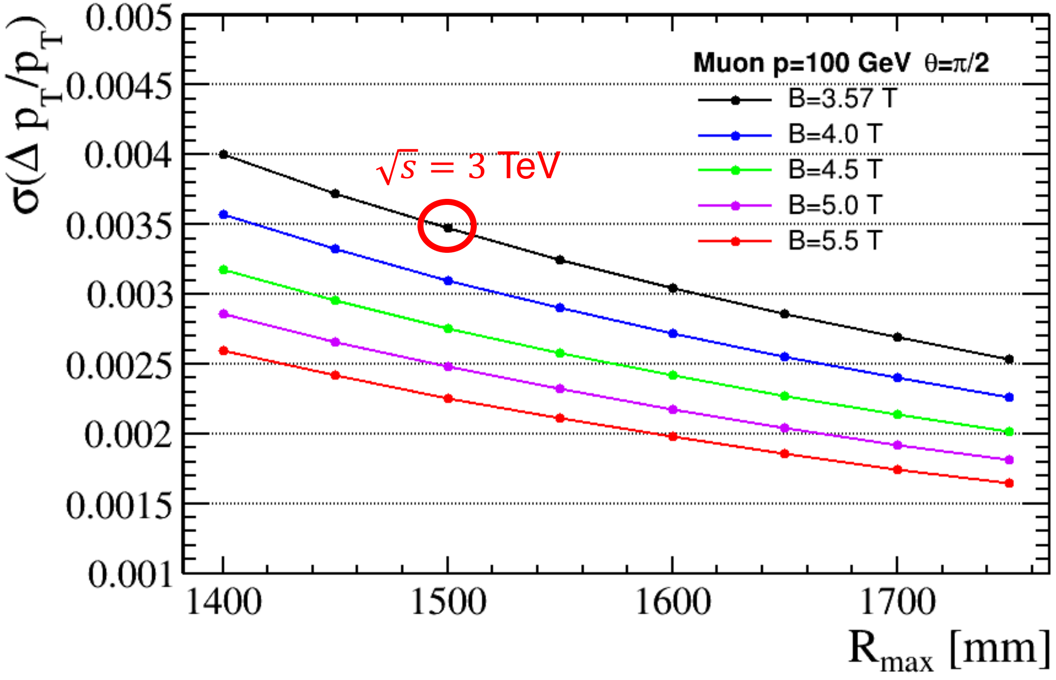
Which magnetic field for the detector?

Analytic formula to relate magnetic field and track momentum resolution

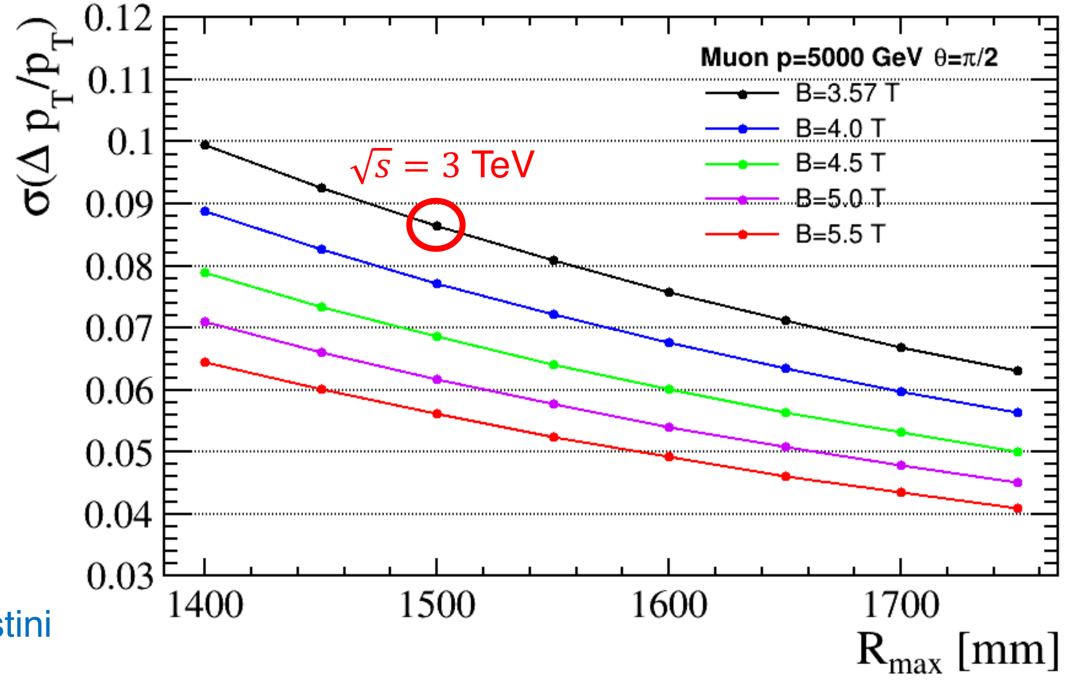
$$\frac{\sigma_{p_T}}{p_T} \cong \frac{12\sigma_{r\varphi} p_T}{0.3BL^2}\sqrt{\frac{5}{N+5}}$$

Z. Drasal and W. Riegler, NIM A 910 (2018) 127

p_μ = 100 GeV at θ_μ = 90°



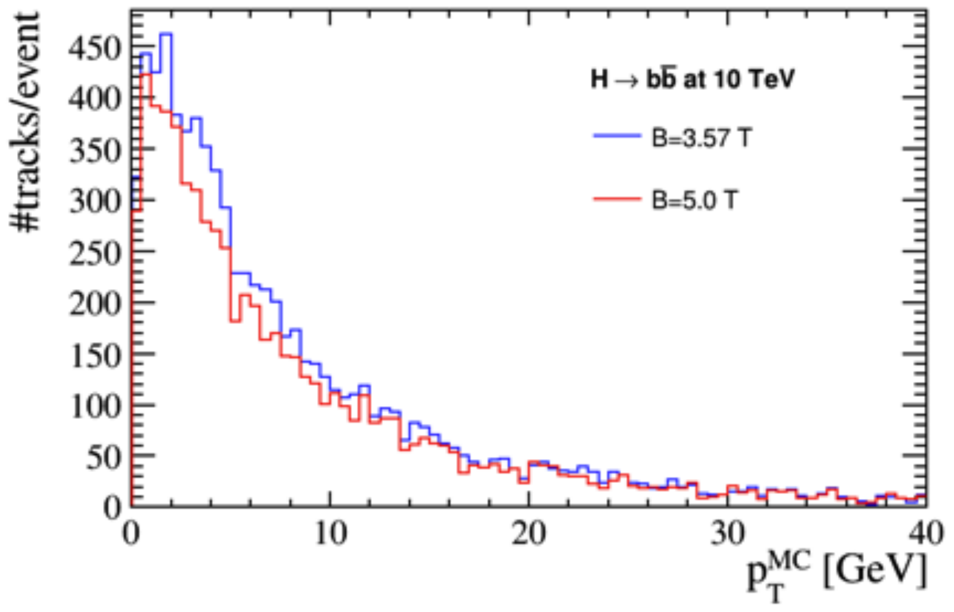
p_μ = 5000 GeV at θ_μ = 90°



L. Sestini

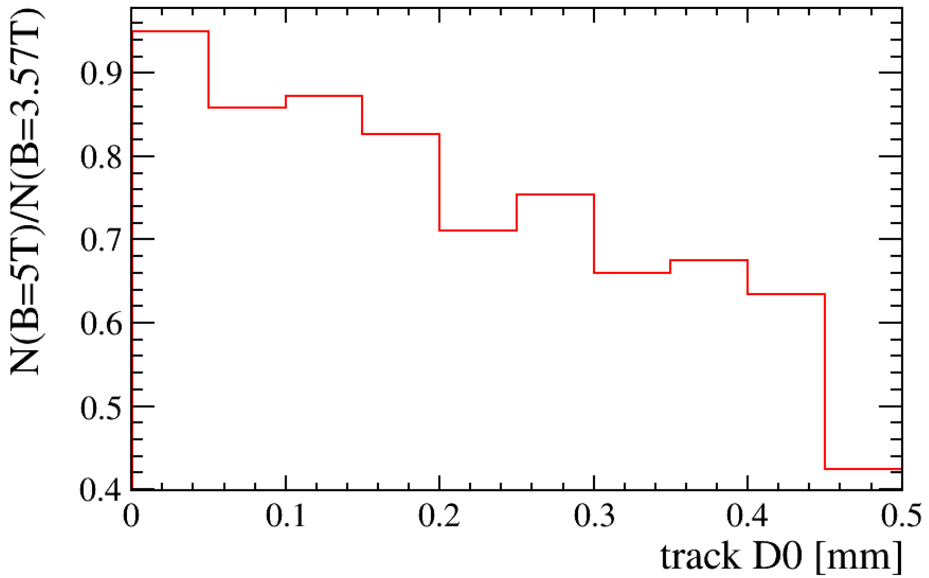
Tracking and magnetic field

generator-level p_T of reconstructed tracks



L. Sestini

N_{tracks}(B=5 T)/N_{tracks}(B=3.57 T) vs track impact parameter



Study of track efficiency with B= 5 T vs. B = 3.57 T by using $H \rightarrow b\bar{b}$ generated at $\sqrt{s} = 10$ TeV:

- inefficiency ~ 15%
- mainly due to displaced tracks

A magnetic field of about 4 T or 5 T is needed
Magnet should not be a problem, but…

Detector magnet meeting

Detector magnet for 10 TeV MuC

https://indico.cern.ch/event/1324236

5 October 2023
CERN
Europe/Zurich timezone

Enter your search term

- Overview
- Timetable
- Contribution List
- Registration
- Participant List
- Videoconference

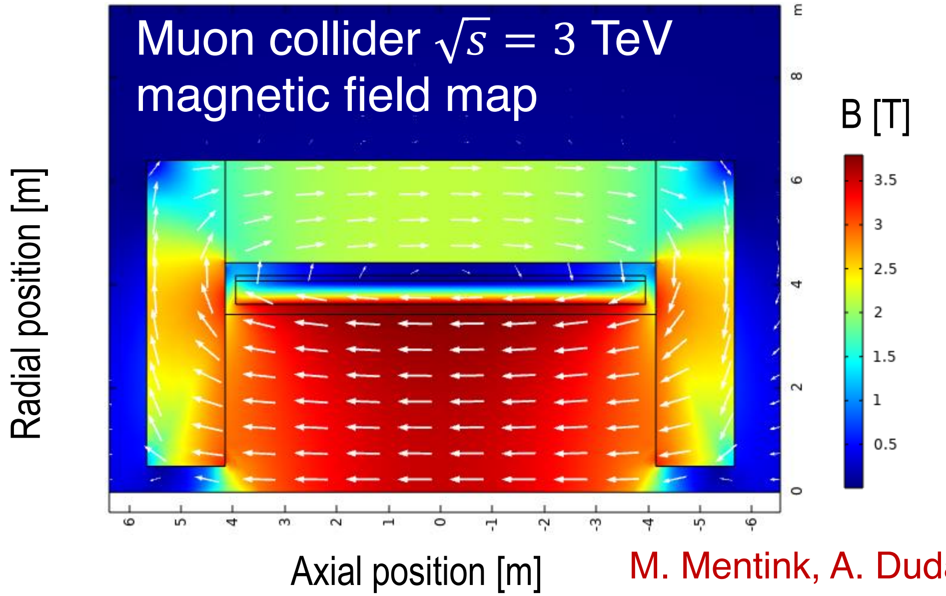
Contacts
donatella.lucchesi@cern...

The design of a possible detector for a 10 TeV center of mass energy muon collider requires the definition of possible detector magnet configurations and technologies . The presence of the beam-induced background shielding structure complicates the magnet design. This meeting brings together detector, machine-detector interface and magnet experts to start the discussion on possible configurations of the complete interaction region.

MuCol

iFAST

Funded by the European Union



M. Mentink, A. Dudarev, B. Cure

CERN organization for Detector Magnets

B. Cure

Steering committee set up at CERN in March 2023

Decision taken by AT and RC CERN Directors and Department Heads EN, EP & TE, on a cooperation between the Accelerator and the Research sector on experiments magnets.

Co-leaders: Said Atieh (EN/MME), Benoit Curé (EP/CMX)

Cooperation at CERN between the Accelerator and the Research sectors on experiments magnets.

It concerns in particular the issue of non-availability of Alu-stab SC.

Working Group (initiated following the SDMW)

Members from: - **CERN** EN, EP, TE departments.

- **KEK.**

The WG is now working on establishing a program on coextrusion
with institutional and industrial

Message conveyed by magnet experts attending the meeting

We need to action it, NOW ?

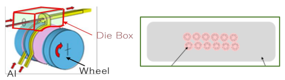
A. Yamamoto

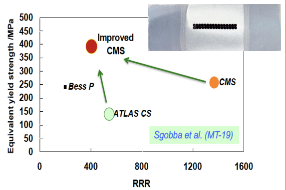
Urgent Action Required:

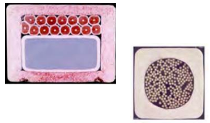
- **Al-stabilized superconductor technology** needs to be resumed,
  - **"Co-extrusion technology"** of Al-stabilizer to be resumed, and
  - "Hybrid-structure technology" by using electron beam welding (EBW)
  - **Laboratory's leading effort very important** to advance the technology
- CERN is now working for establishing a program on coextrusion process for Al-stab SC with institutional and industrial partners.

Remarks:

- It will be **needed** to investigate **backup solutions** such as:
  - soldering technology of NbTi/Cu conductor with Cu-coated Al-stabilizer, and/or CICC. ,,,
- It will be encouraged to investigate Al-stabilized HTS for specofoc applications

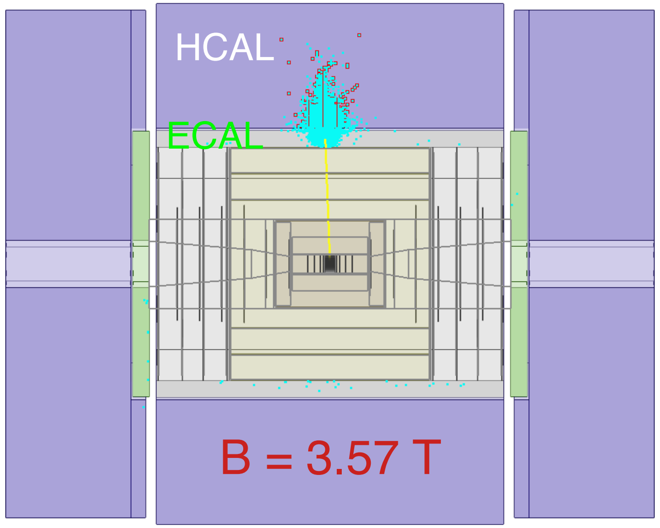




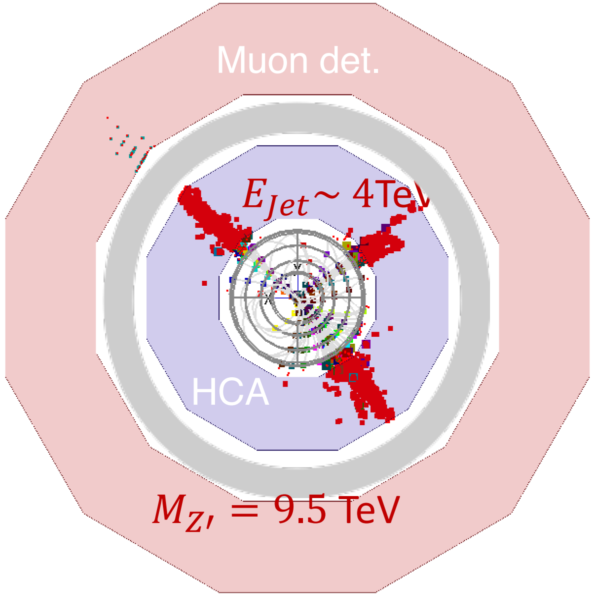


Photon and jet reconstruction

central 5 TeV photon M. Casarsa

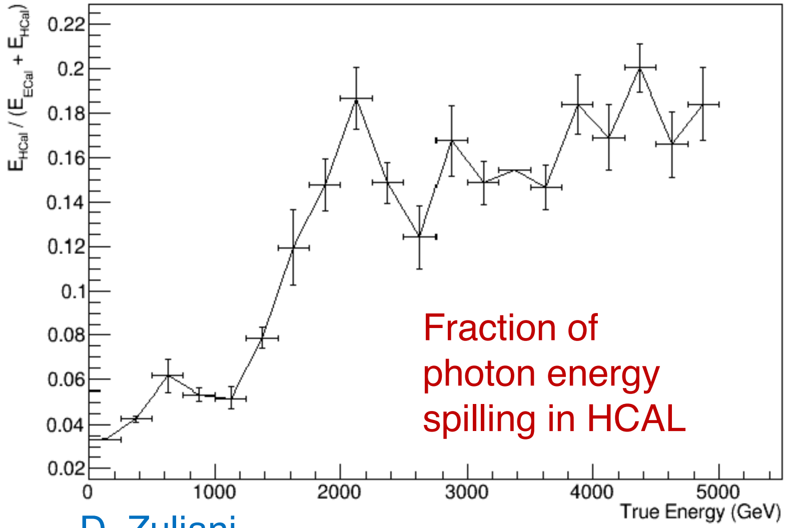


$\mu^+\mu^- \rightarrow Z'X \rightarrow jjX$ $\sqrt{s} = 10$ TeV



Desired ECAL :

- Deep: ~25X_0
- High granularity
- Longitudinal segmentation
- Timing ~100 ps
- CRILIN @10 TeV under study



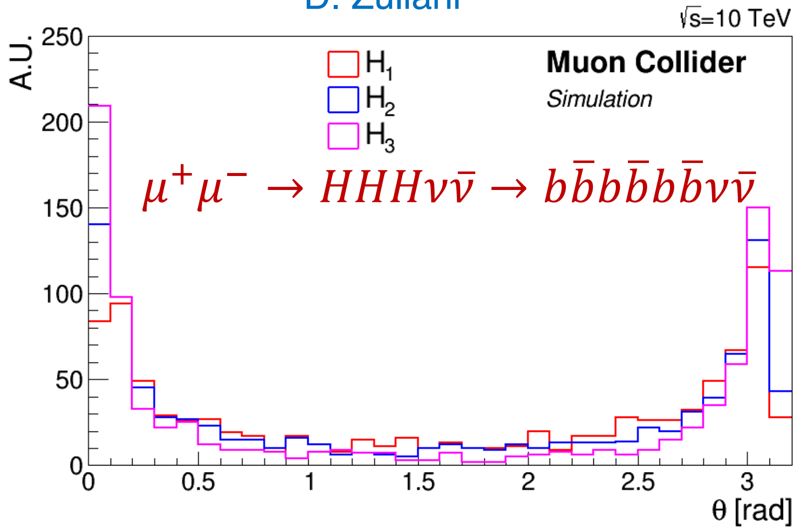
D. Zuliani

E_γ[GeV]

Desired HCAL :

- Deep: ~8.5λ_i
- Good forward coverage
- Sufficient granularity to be used in particle flo

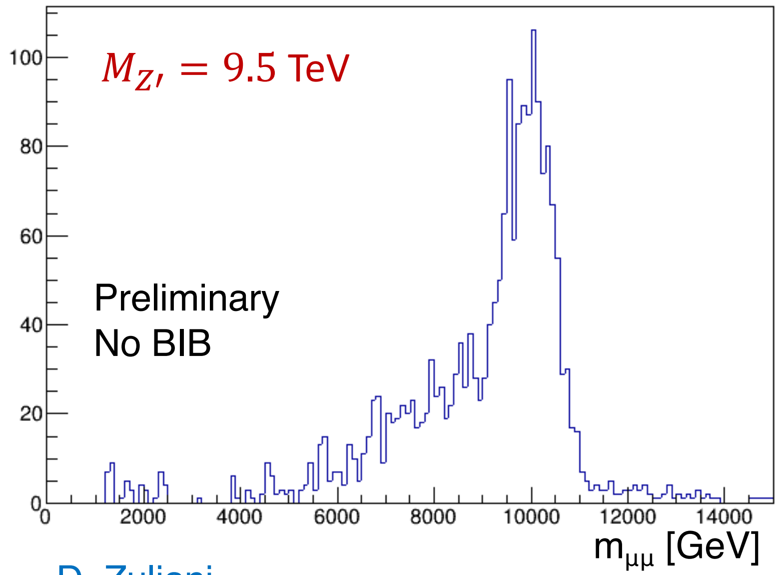
D. Zuliani



Muon reconstruction

- Need to cover a momentum range from few GeV up to TeV
- New approach needed:
  - usual methods for low momentum;
  - combine information from muons detector, tracker and calorimeter information, jet-like structure.

$\mu^+\mu^- \to Z'X \to \mu\mu X \; \sqrt{s} = 10$ TeV

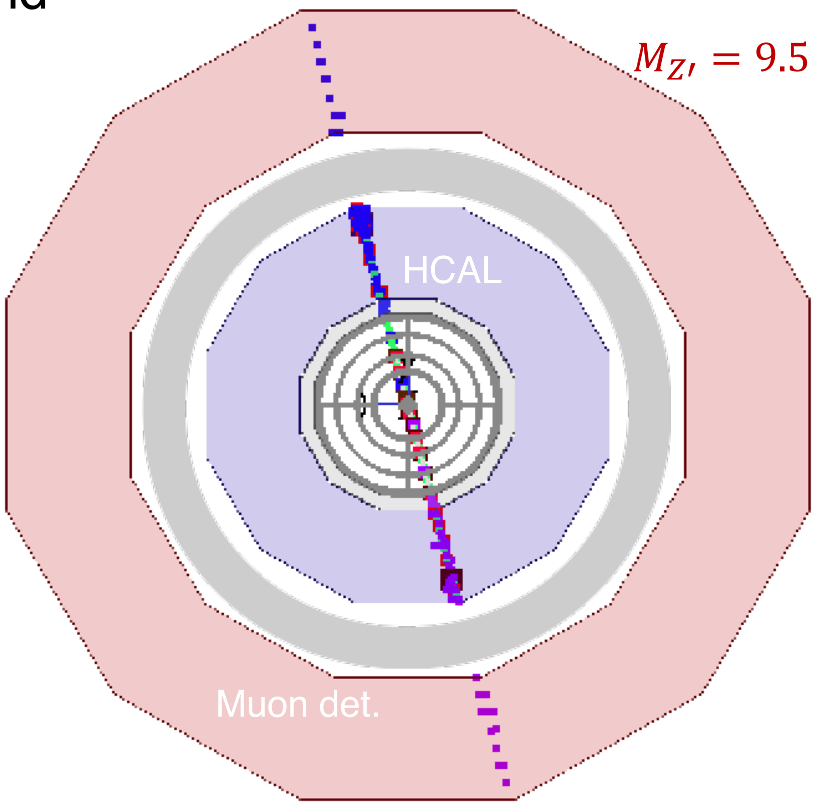


D. Zuliani

B = 5 T

$\mu^+\mu^- \to Z'X \to \mu\mu X \; \sqrt{s} = 10$ TeV

$M_{Z'} = 9.5$ TeV



The long-term muon collider facility has been presented so far

The meaning of facility

Neutrino physics measurements, not discussed here

Experiments at a center of mass of

- ✗ few TeV, first stage of the collider
  $\sqrt{s} = 3$ TeV taken as working hypothesis
- ✗ 10-ish TeV, second stage of the collider
  $\sqrt{s} = 10$ TeV assumed in design the first concept

Two cases, $\sqrt{s} = 3$ and $\sqrt{s} = 10$, TeV will be discussed

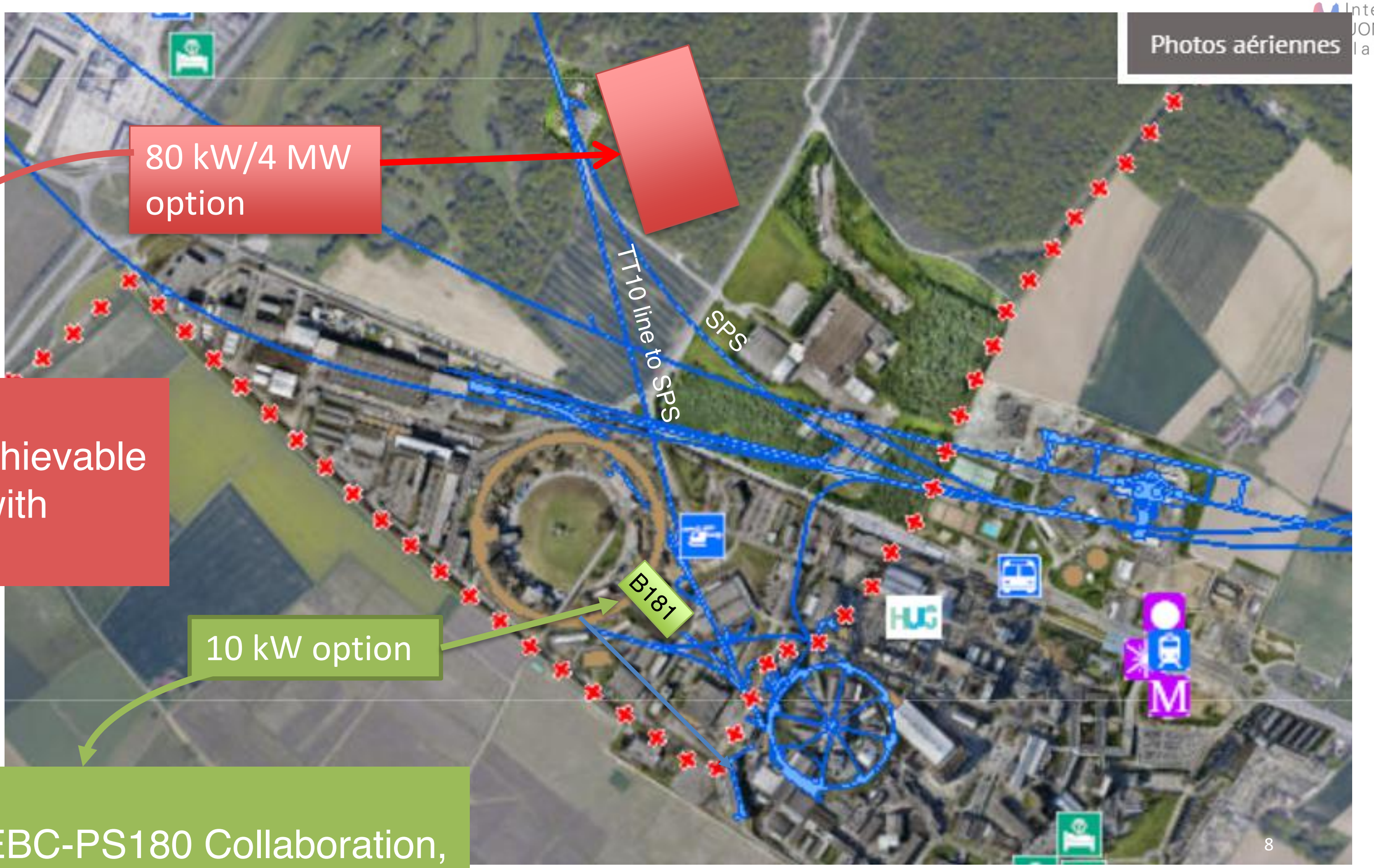
and may think that the muon collider, even at $\sqrt{s} = 3$ TeV is far in time…
… true, but the facility can start with the demonstrator on a very short time scale!

CERN option, other solutions could be possible

R. Losito IMCC-2023

Both use maximum intensity per pulse ~10^{13} ppp (or more) in pulses of few ns at 20+ GeV.
Different repetition rate:

- 1 pulse/few second
- 1÷2 pulse/per minute



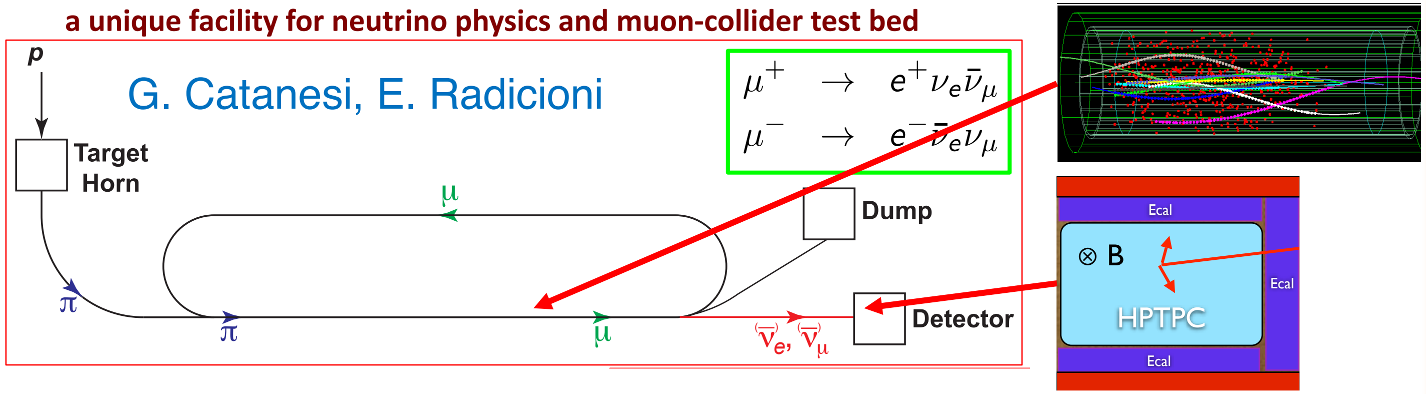
High power
O(80kW) on target easily achievable
No showstopper for 4 MW with beam at a depth of 40 m

Low power:
Reuse line of BEBC-PS180 Collaboration, decommissioned, extending it towards B181 (now magnet factory)

Demonstrator facility will allow:

- Test muon cooling cell 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.



Light atmospheric-pressure TPC: excellent tracker for precision emittance study.
High-pressure TPC: ideal active target for precise ν cross-section measurement on a range of target nuclei in a very much needed energy range.
In both cases, the optical readout is an enabling technology, (R&D in DRD1) to access low background and excellent energy resolution.

- Design physics experiment with the relative detectors:
  - nuSTORM and ENUBET could be branched.
  - Possible physics studies…

Summary

The first detector concept for a $\sqrt{s} = 3$ TeV Muon Collider already exhibits physics objects reconstruction performance that is sufficiently robust for high-precision measurements and searches for new physics.

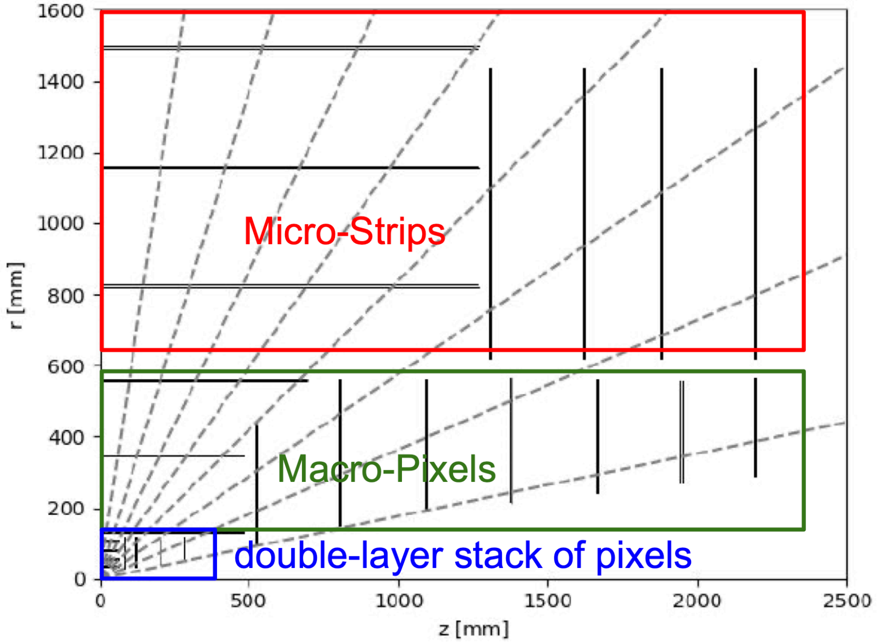
A detector for a $\sqrt{s} = 10$ TeV muon collider is beginning to be designed, with physics requirements identified and configuration possibilities ready for implementation.

The Demonstrator Facility, besides enabling numerous measurements, will actively engage the community in experimental activities, preventing the loss of valuable expertise and knowledge.

Additional material

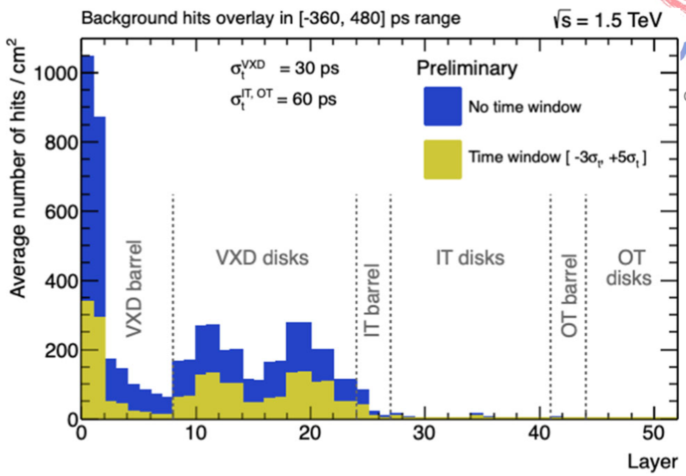
Tracker system: full detector & BIB simulation

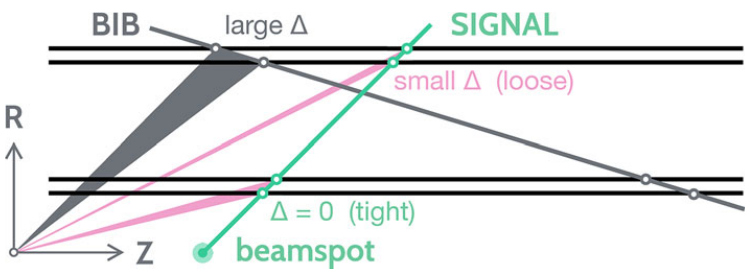
First layers of barrel vertex detector & forward disks highly impacted by BIB



Tracker requirements

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



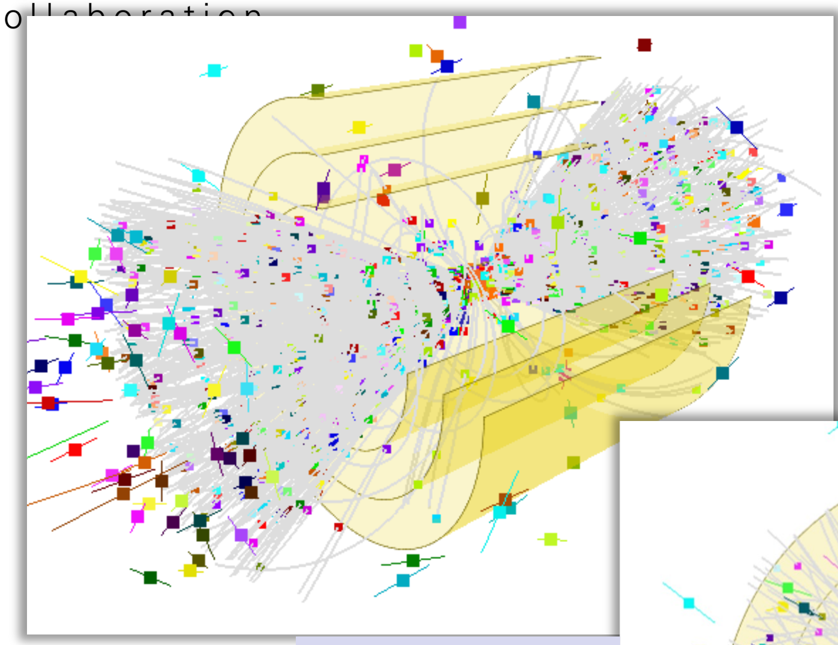


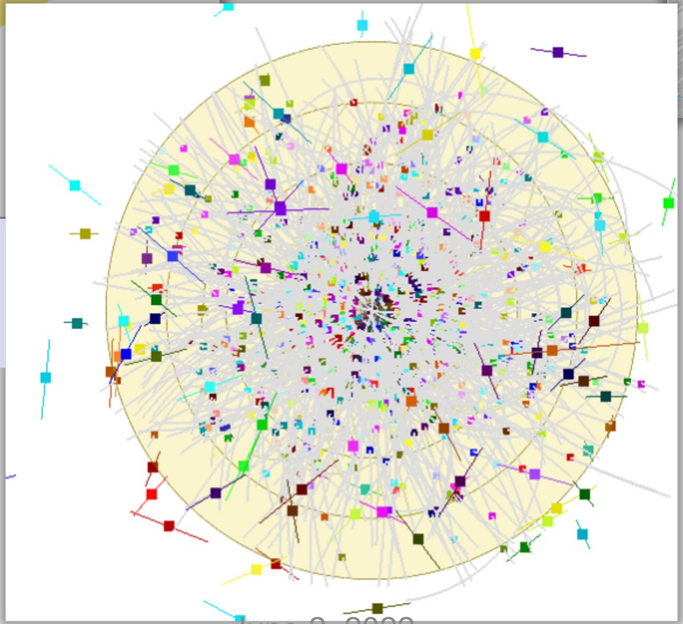
Higher occupancies respect to LHC detectors crossing rate 100 kHz vs 40 MHz

Engaged in ECFA DRD3: silicon vertex and tracker

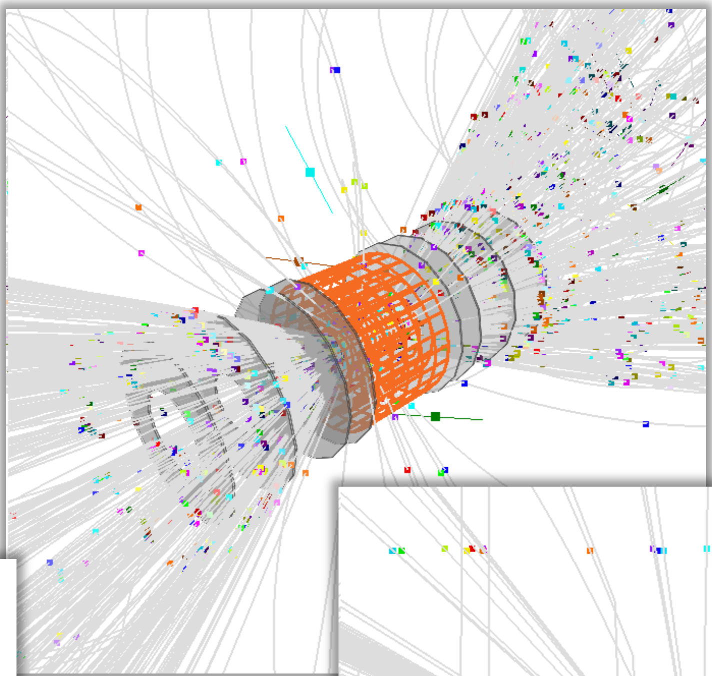
Detector reference	Hit density [mm^{-2}]		
	MCD	ATLAS ITk	ALICE ITS3
Pixel Layer 0	3.68	0.643	0.85
Pixel Layer 1	0.51	0.022	0.51

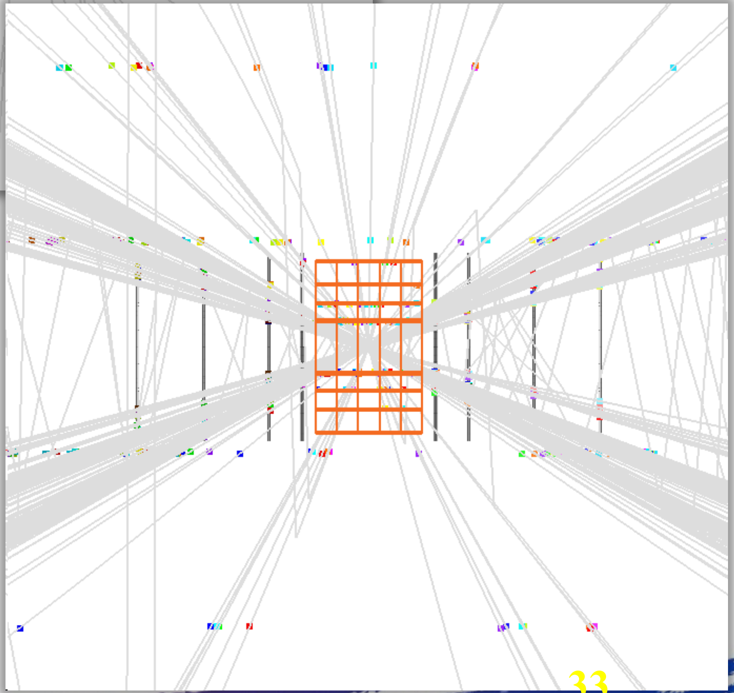
Beam-Induced Background in the tracker





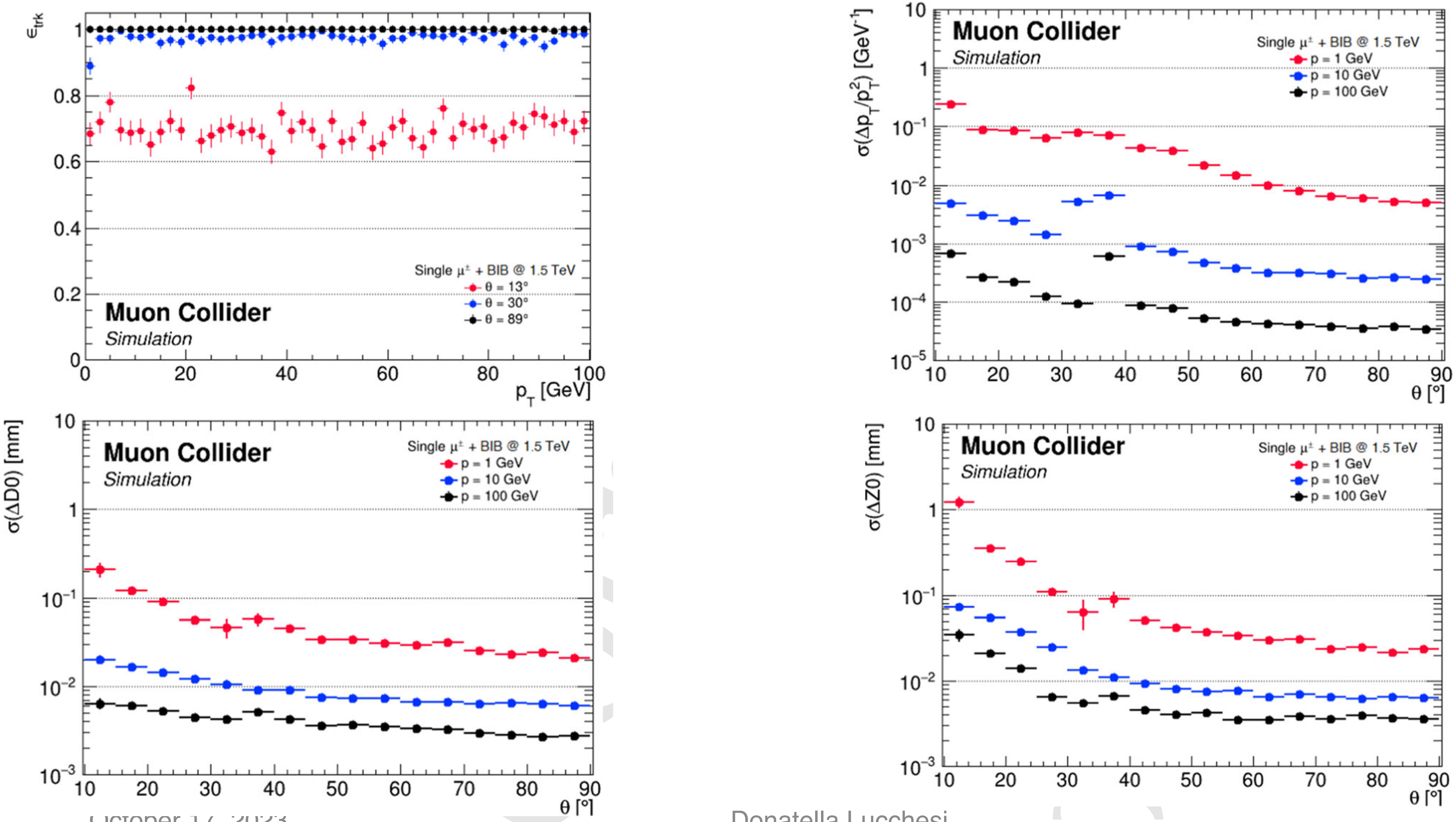
Inner/Outer Tracker





Vertex Detector

Track reconstruction performance



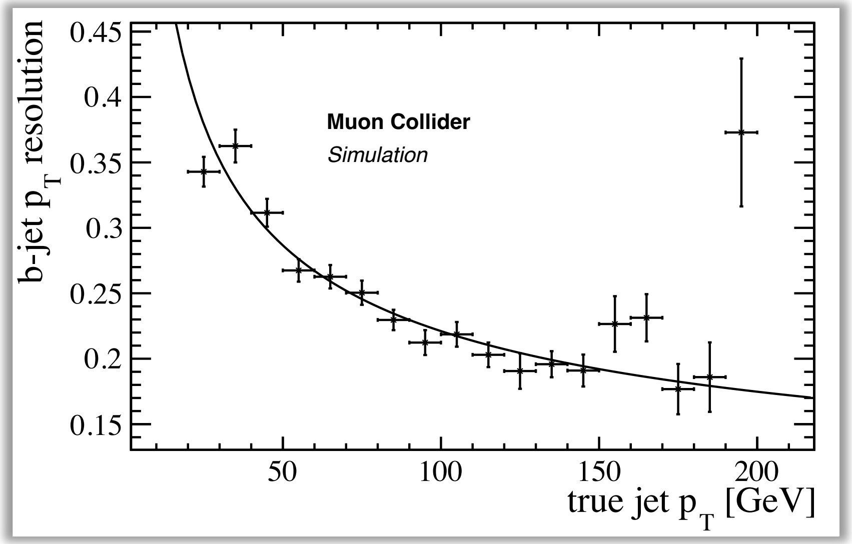
Jets reconstruction performance

International MUON Collider Collaboration

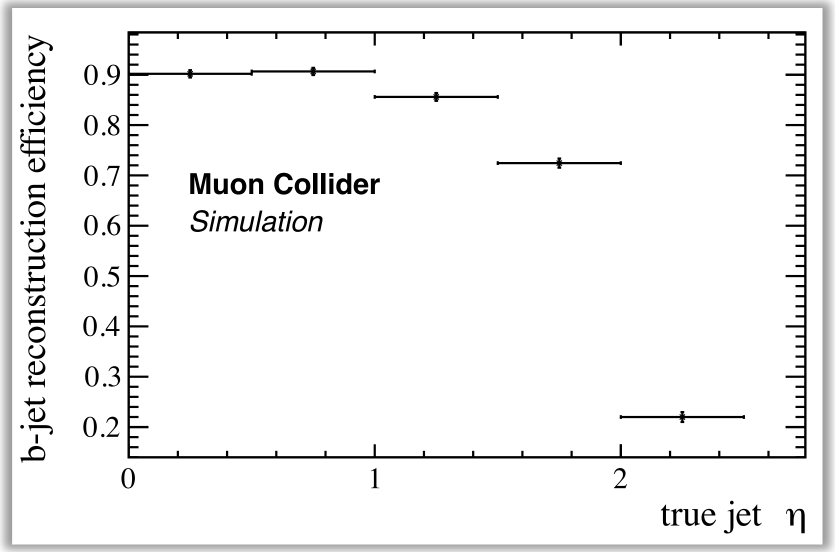
Jets reconstruction proceeds:

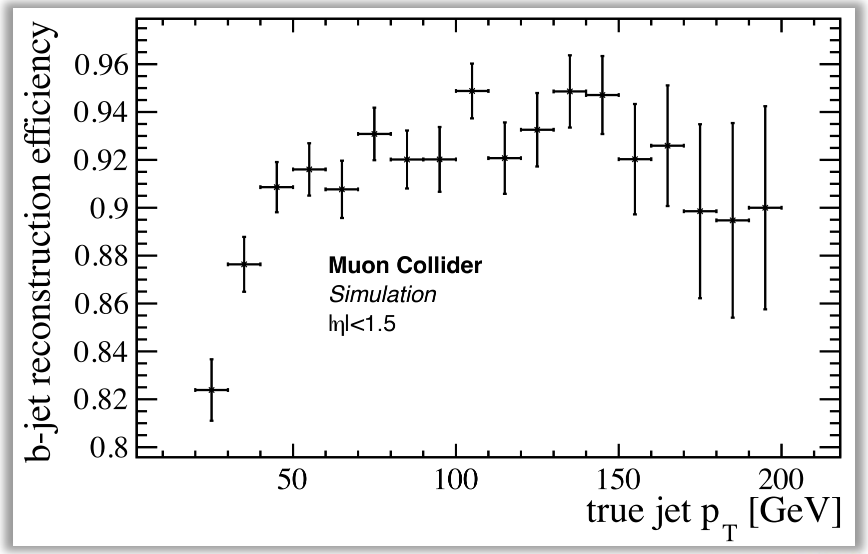
- Filter ”on time” calorimeter hits
- Combine track and calorimeter information to reconstruct particles
- Use k_T algorithm to cluster particles in jets
- Apply requirements to remove fake jets (max 0.7%)
- Correct energy

Resolution



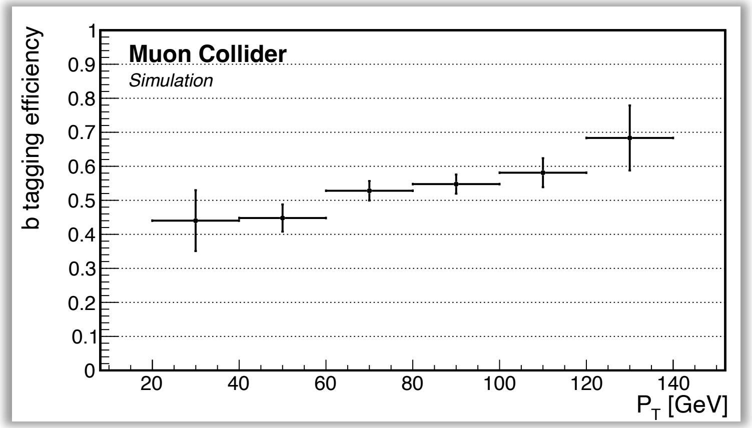
Efficiency



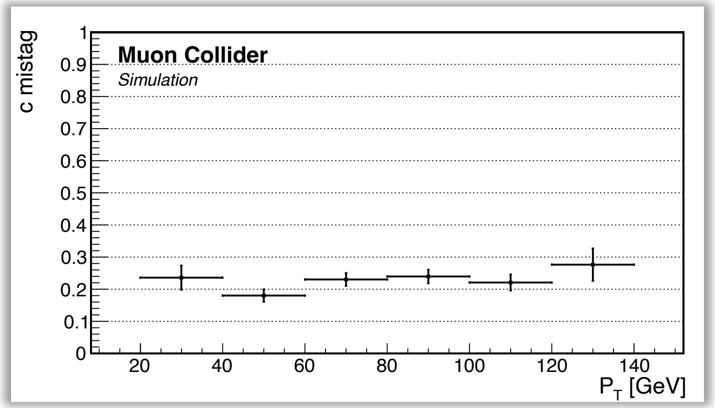


Heavy Flavor Jets Identification Performance

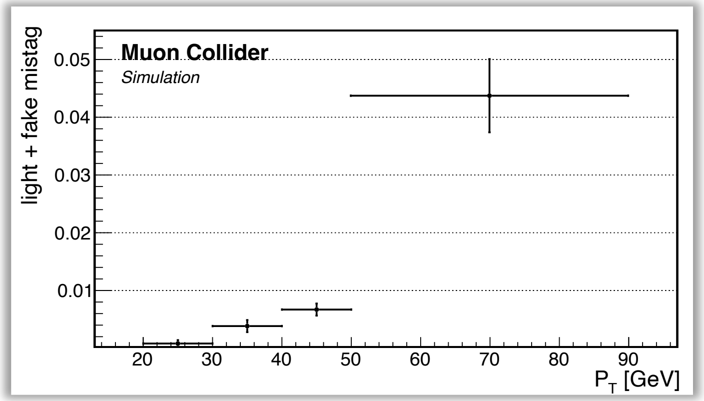
b-quark

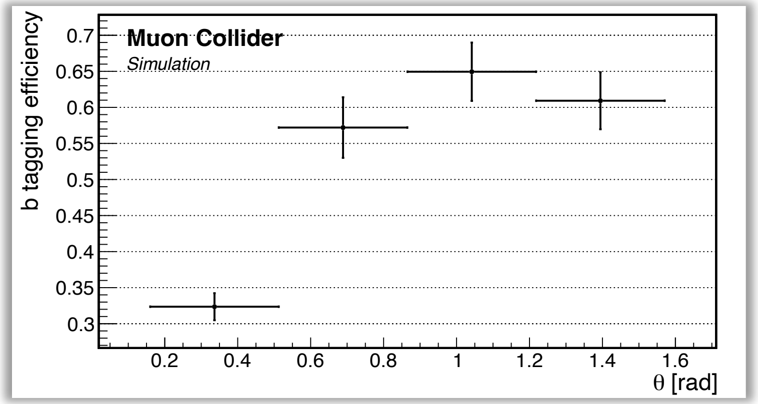


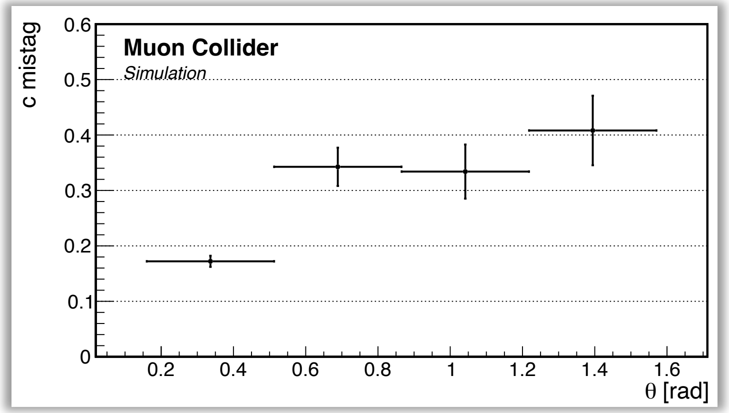
c-quark

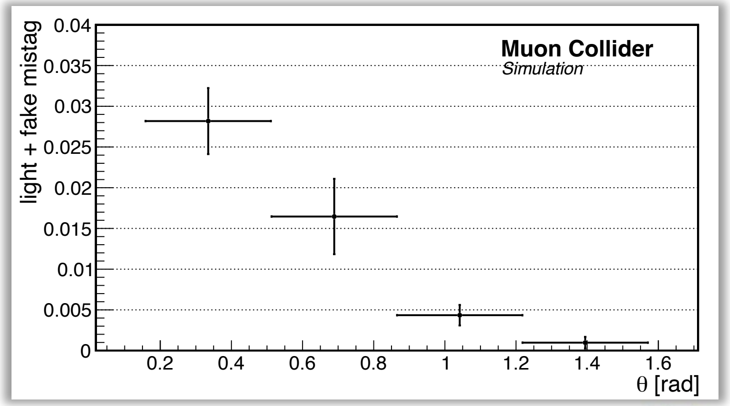


light-quark/fake jets



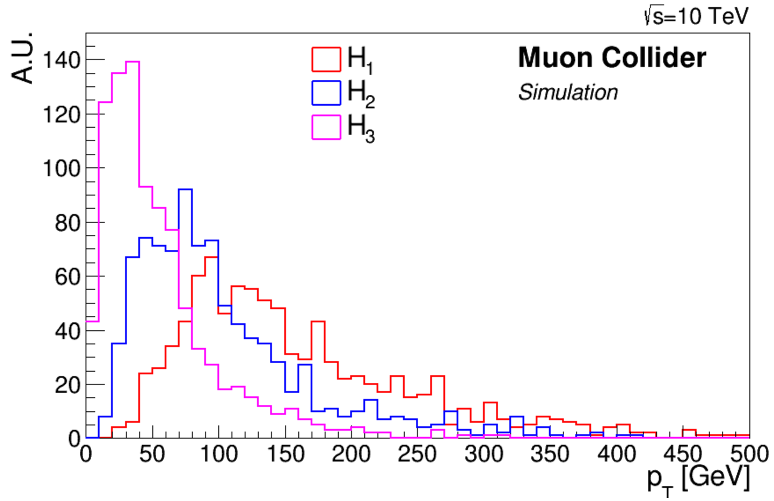


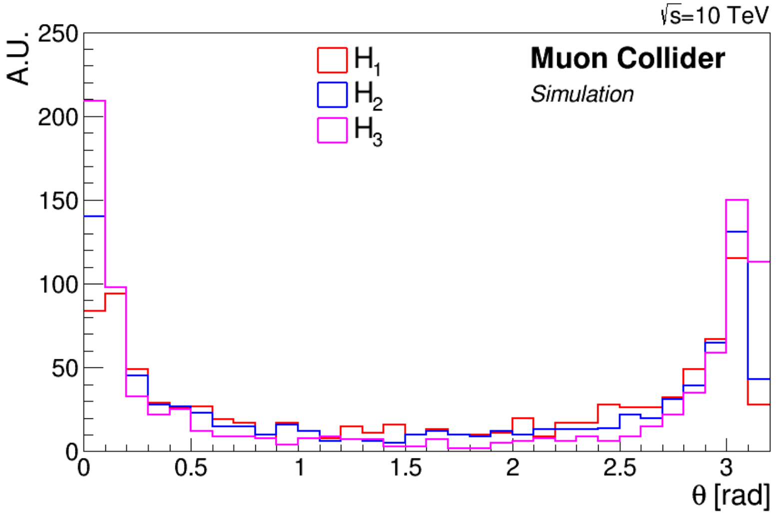




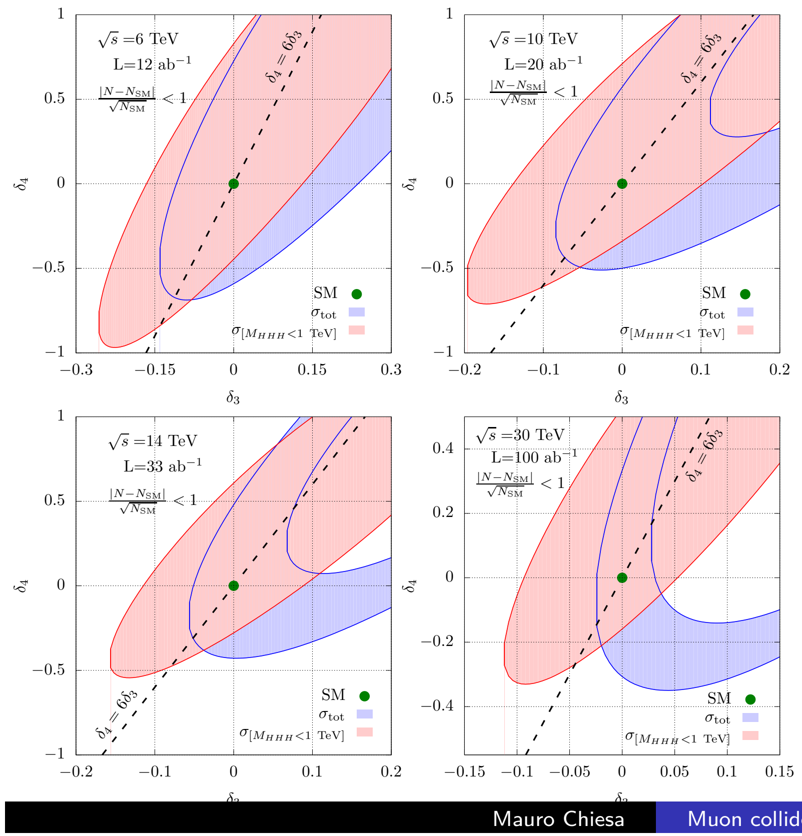
Triple Higgs

$$\mathcal{L} = -\frac{1}{2} M_H^2 H^2 - (1+\delta_3)\frac{M_H^2}{2v} H^3 - (1+\delta_4)\frac{M_H^2}{8v^2} H^4$$





One sigma exclusion plots



- no cuts
- $M_{HHH} < 1$ TeV

$\delta_3 = 0$

6 TeV $\delta_4 \sim [-0.45, 0.8]$

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

14 TeV $\delta_4 \sim [-0.35, 0.6]$

30 TeV $\delta_4 \sim [-0.2, 0.5]$

Sensitivity evaluated in term of standard deviation from standard model

$$\frac{|N - N_{SM}|}{\sqrt{N_{SM}}}$$

- ☆ No background considered
- ☆ No BR applied
- ☆ No selections optimization

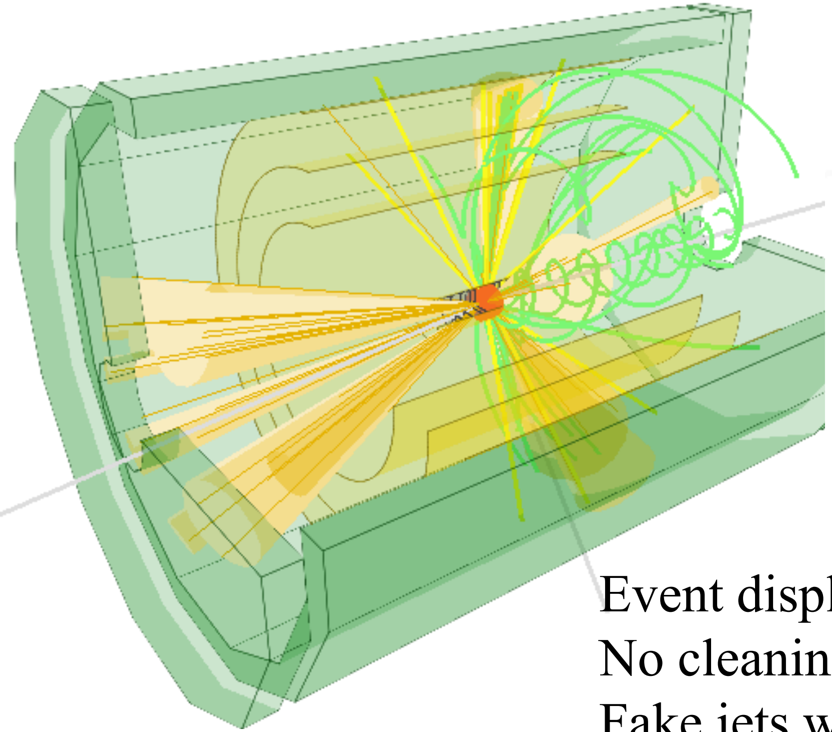
$\mu^+\mu^- \to Hx \to b\bar{b}x$ with Beam-Induced Background at 3 TeV

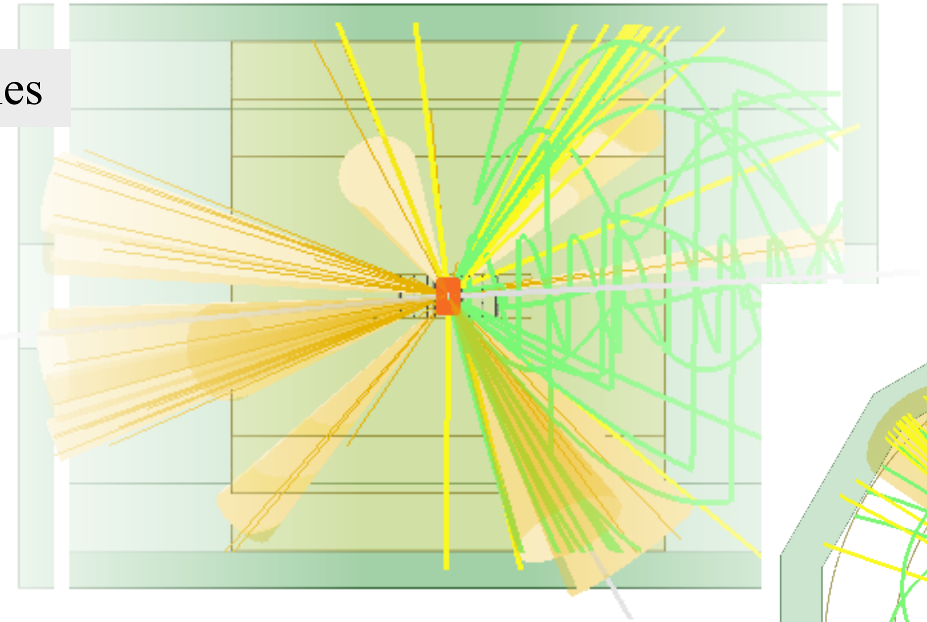
Yellow/green tracks: Montecarlo particles

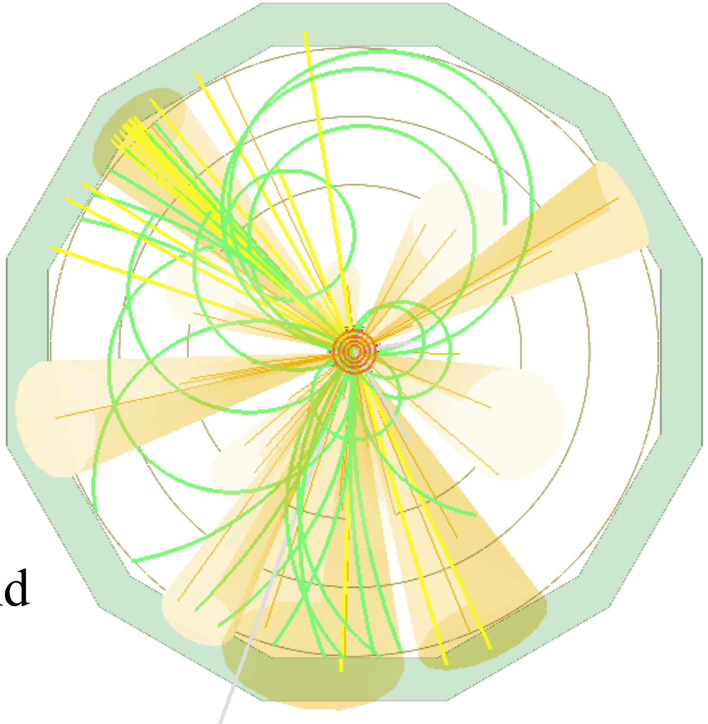
ECAL

Inner/Outer Tracker

Vertex Detector







Event 1300, Run 13

Event display after the reconstruction
No cleaning cuts, no analysis requirements
Fake jets with contributions of beam background removed during the analysis

ILCSoft software stack: | **Key4hep software stack:**

1. LCIO → **TO BE DONE** → long term → EDM4hep
2. DD4hep — DD4hep
3. Marlin — Gaudi
4. ILCSoft — Spack

used only by us → no other maintainers | **used and maintained by other experiments**

NO multithreading support | **built with multithreading in mind**

All EDM4hep data classes defined in a single YAML file: edm4hep.yaml → generates actual C++ code

Switching from LCIO → EDM4hep will change input for all our simulation code

↳ each processor has to be adapted to the new data format → **substantial amount of work**