



Muon Collider: A Challenging Opportunity

Donatella Lucchesi University and INFN of Padova, CERN

for the

International Muon Collider Collaboration

University of Geneva October 18, 2023

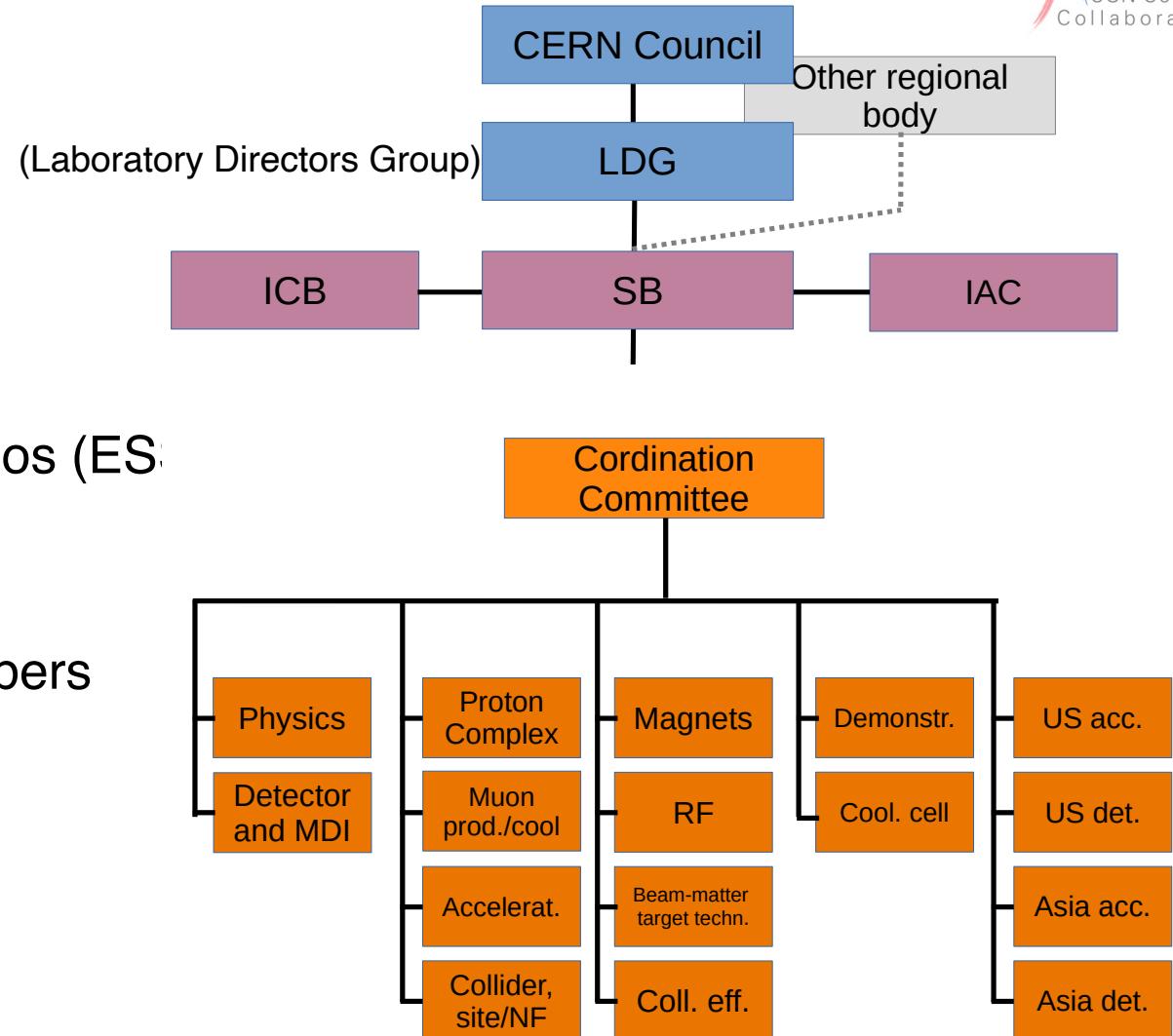


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International Muon Collider Collaboration

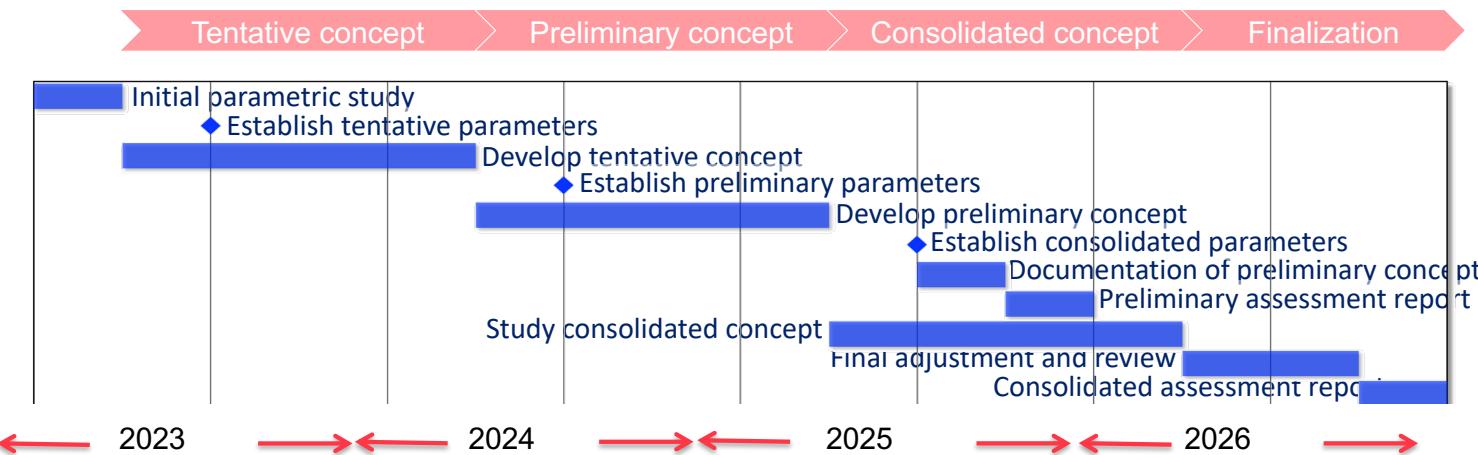
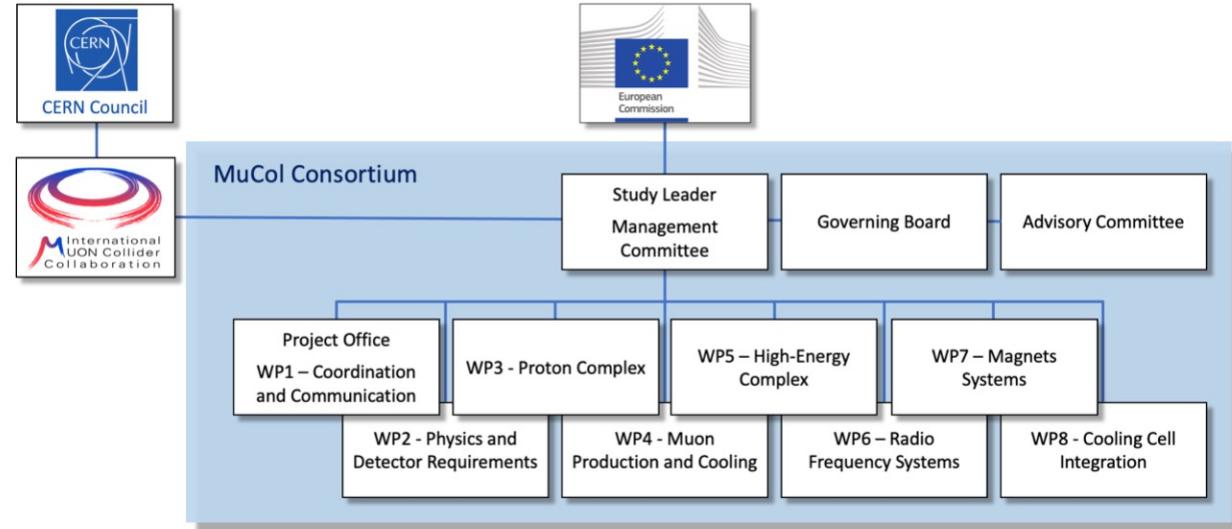
- **Collaboration Board (ICB)**
 - Elected chair: [Nadia Pastrone](#)
- **Steering Board (SB)**
- Chair [Steinar Stapnes](#)
- CERN members: M. Lamont, G. Arduini
- ICB members: D. Newbold (STFC), M. Lindroos (ESF), P. Vedrine (CEA), N. Pastrone (INFN)
- Study members: SL and deputies
- Will add US but wait for US decision on members
- **Advisory Committee:** To be defined
- **Coordination committee (CC)**
 - Study Leader: [Daniel Schulte](#)
 - Deputies: [A. Wulzer](#), [D. Lucchesi](#), [C. Rogers](#)



European design study and funds

MuCol:

- European project started in March 2023
- It provides 3 MEUR from the European Commission.
- Additional funds from UK and Switzerland.
- Additional dedicated funds from Italy, INFN.





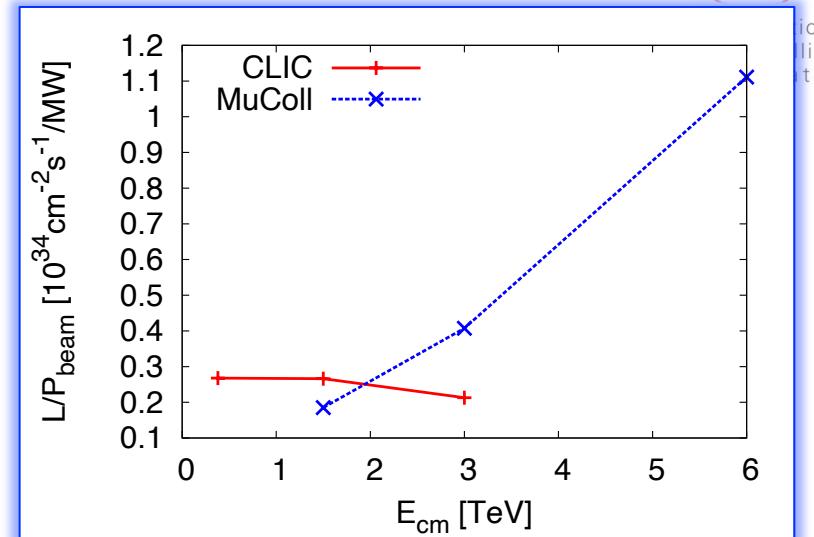
Muon Collider: a new concept facility

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	\mathcal{L}	$1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$	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_1	MeV m	7.5	7.5	7.5
Transverse emittance	ε_{\perp}	μm	25	25	25
IP bunch length	σ_z	mm	5	1.5	1.1
IP beta-function	β_{\perp}^*	mm	5	1.5	1.1
IP beam size	σ_{\perp}	μm	3	0.9	0.6

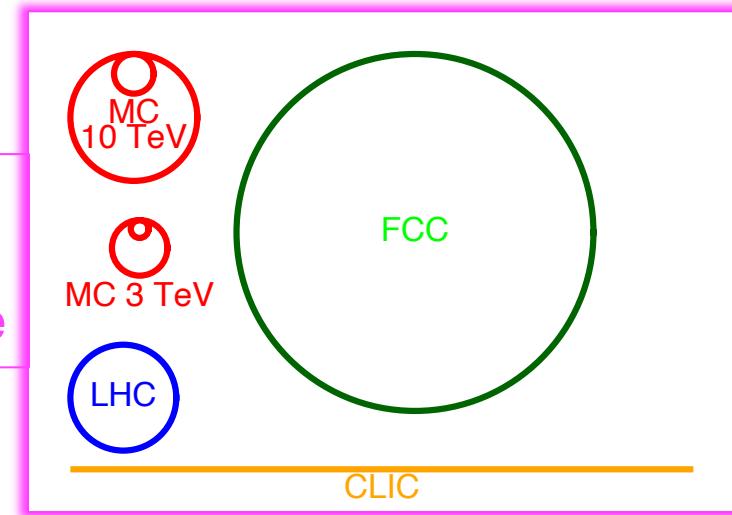


Compact:
cost effective
& sustainable

Integrated luminosity:

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

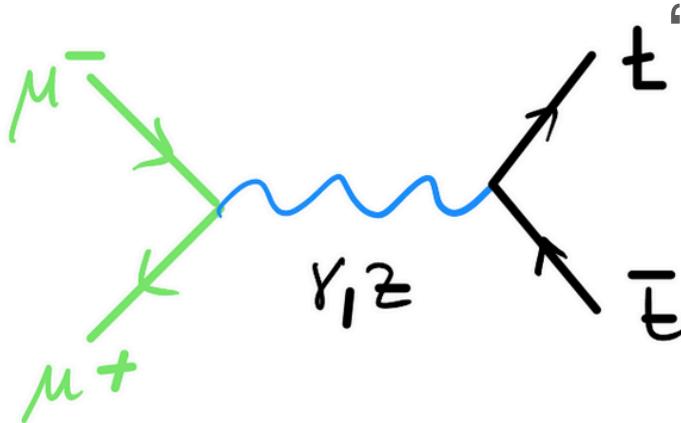
$\sqrt{s} = 10 \text{ TeV } 10 \text{ ab}^{-1} 5 \text{ years one experiment}$



Physic processes: two colliders in one

F. Maltoni
["Physics Overview" Annual Meeting IMCC](#)

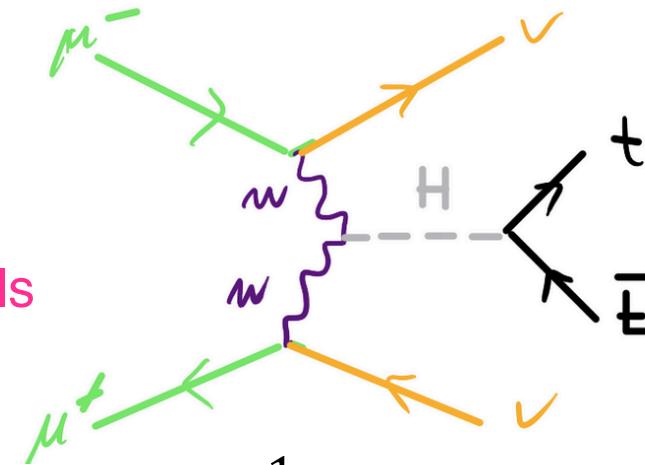
Multi-TeV muon collider opens a completely new regime :



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

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

The facility

Next generation of accelerator complex

Neutrino physics measurements, not discussed here

Experiments at a center of mass of

X few TeV, first stage of the collider
 $\sqrt{s} = 3$ TeV taken as working hypothesis

X 10-ish TeV, second stage of the collider
 $\sqrt{s} = 10$ TeV assumed in design the first concept

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

Accelerator complex

Design baseline overview

Key challenges

* Proton source

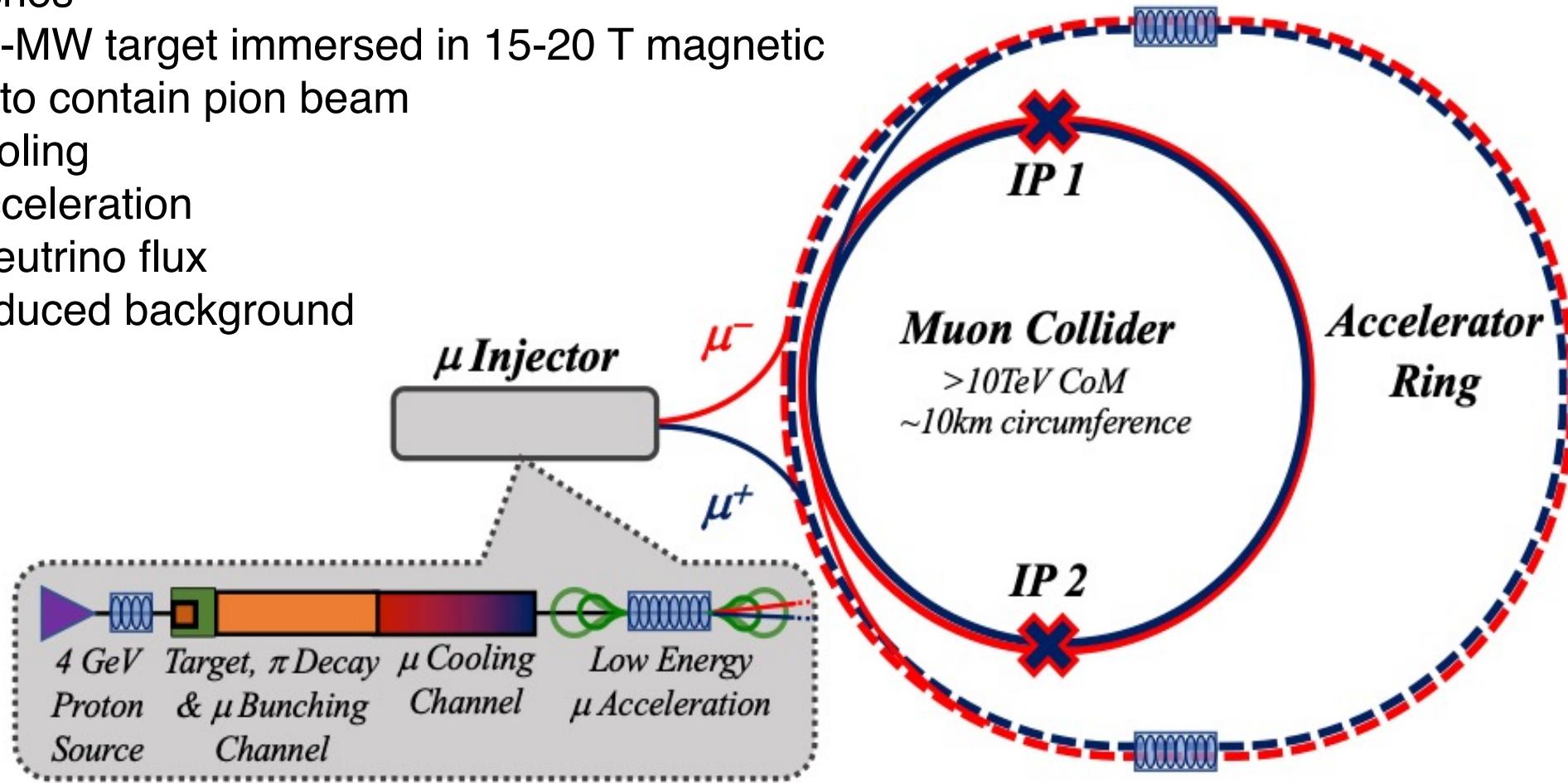
- High intense proton driver with short high-charge bunches
- Multi-MW target immersed in 15-20 T magnetic field to contain pion beam

* Muon cooling

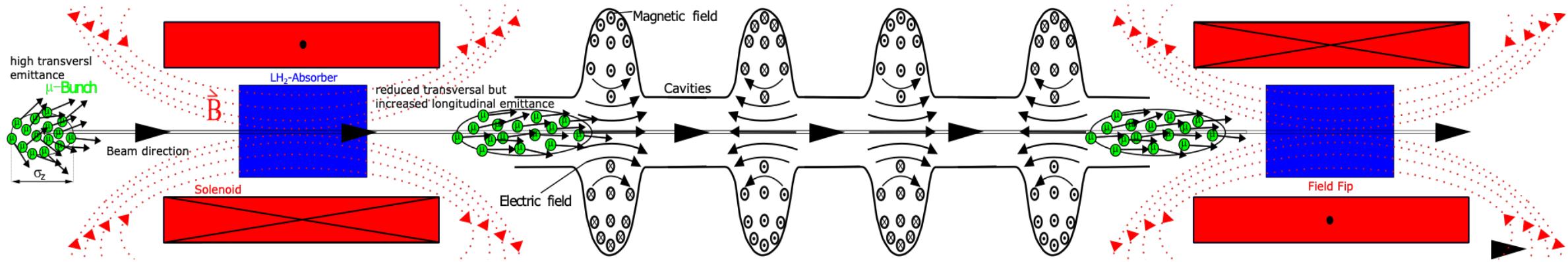
* Beam acceleration

* Dense neutrino flux

* Beam-induced background



Muon ionization cooling principle



- Absorber: low Z material (Lithium hydride for first phase, liquid H for final cooling) in high magnetic field 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](#)

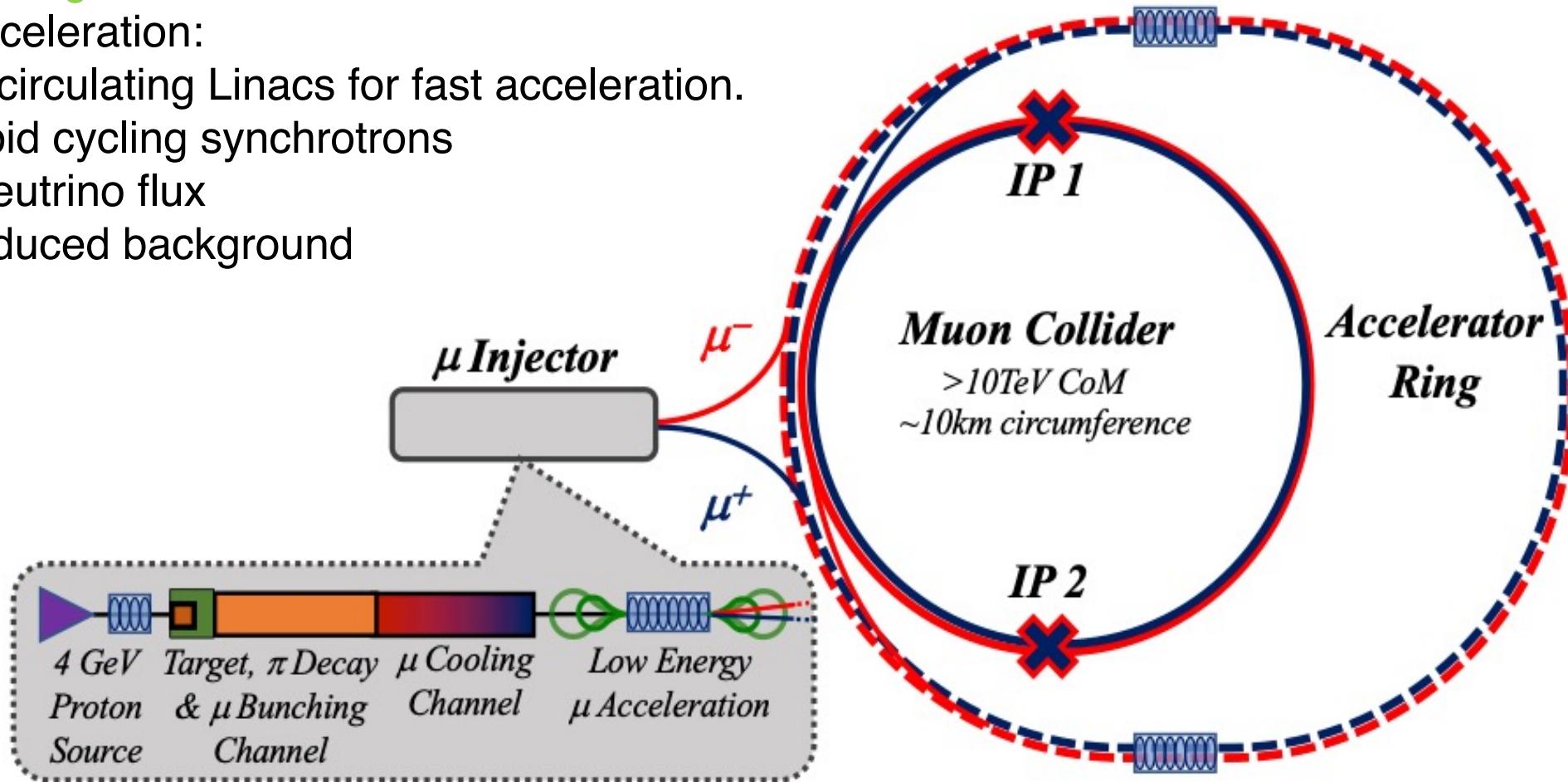
Two cooling stages:

- 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 for fast acceleration.
 - 2) Rapid cycling synchrotrons
- * Dense neutrino flux
- * Beam-induced background

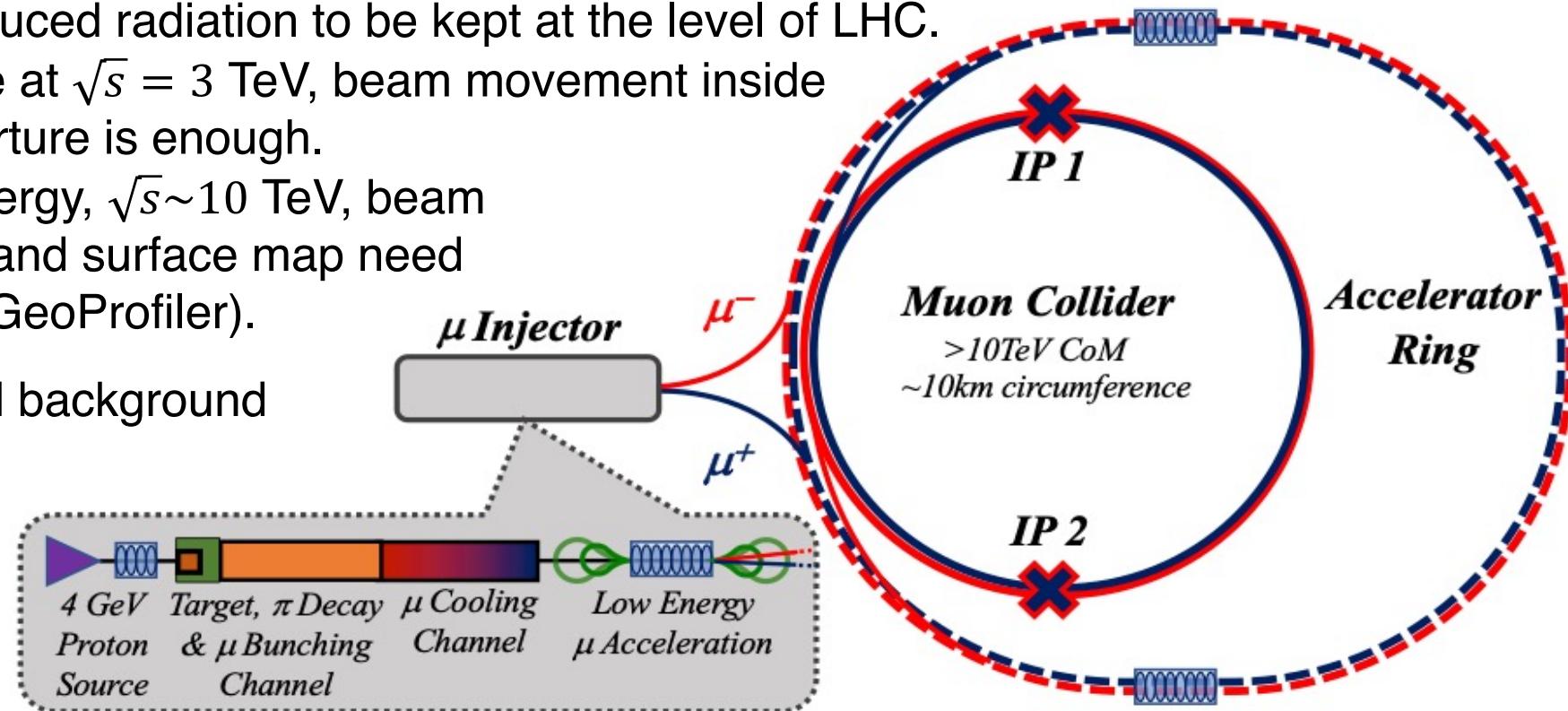


Design baseline overview

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- * Proton source.
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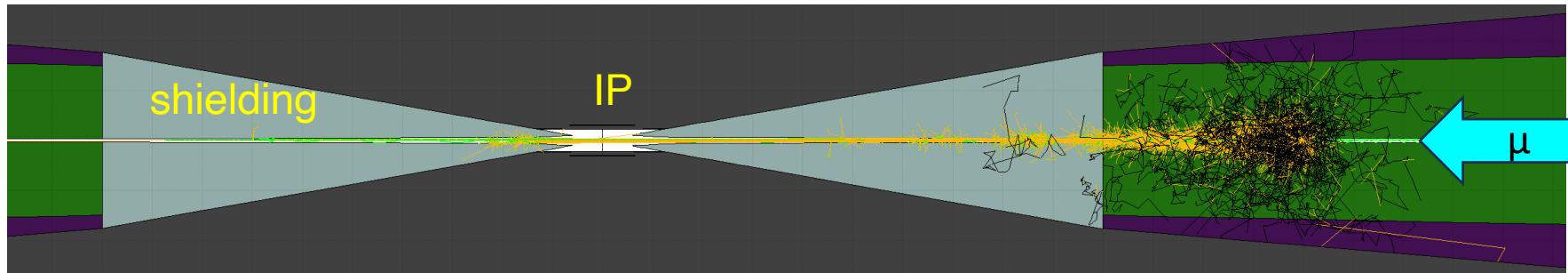
- Possible induced radiation to be kept at the level of LHC.
- Not an issue at $\sqrt{s} = 3 \text{ TeV}$, beam movement inside magnet aperture is enough.
- At higher energy, $\sqrt{s} \sim 10 \text{ TeV}$, beam parameters and surface map need to be used (GeoProfiler).
- * Beam-induced background



Beam-induced background

Beam background sources in the detector region

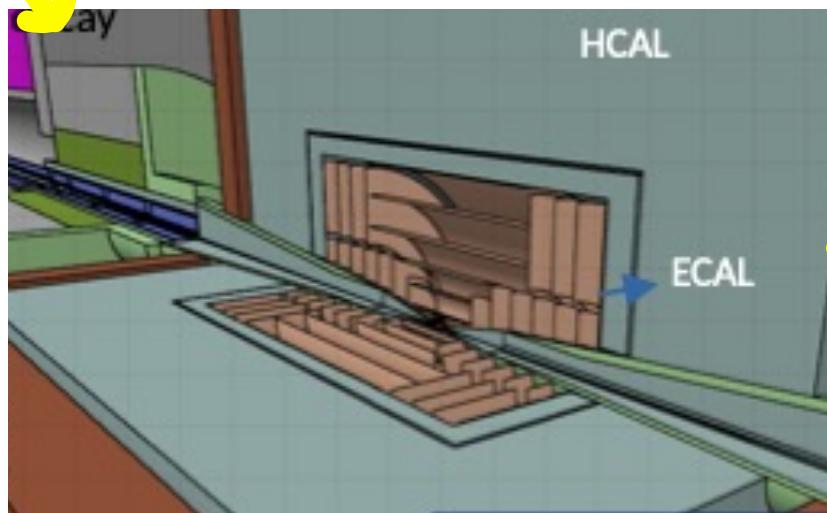
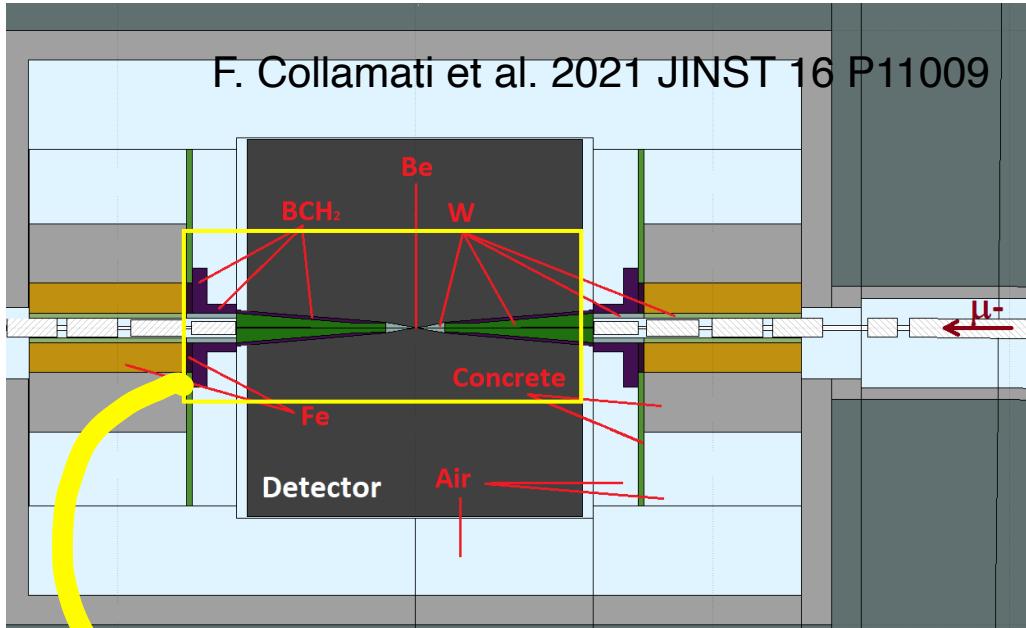
- ✗ Muon decay along the ring, $\mu^- \rightarrow e^-\bar{\nu}_e\nu_\mu$: dominant process at all center-of-mass energies
 - * photons from synchrotron radiation of energetic electrons in collider magnetic field
 - * electromagnetic showers from electrons and photons
 - * hadronic component from photonuclear 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 $e^-e^+ \Rightarrow$ trapped by detector magnetic field
- ✗ Beam halo: level of acceptable losses to be defined, not an issue now



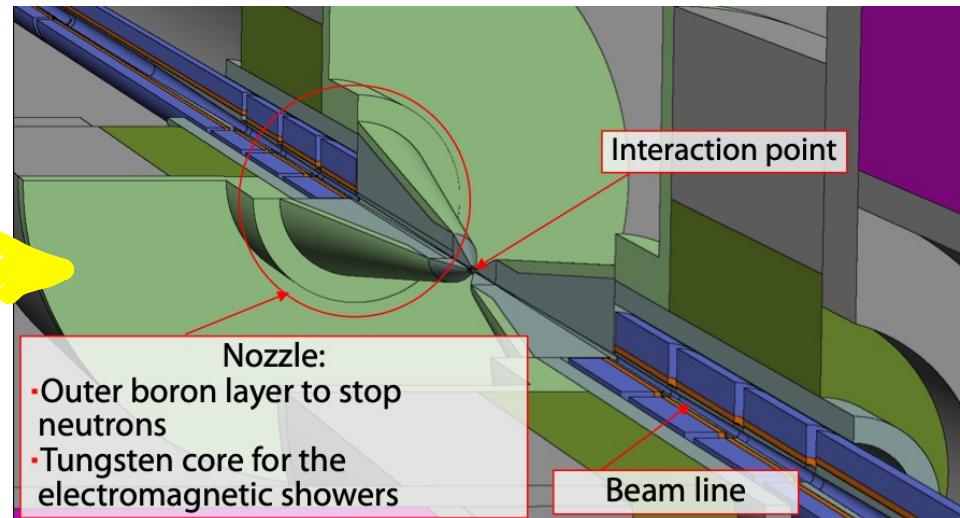
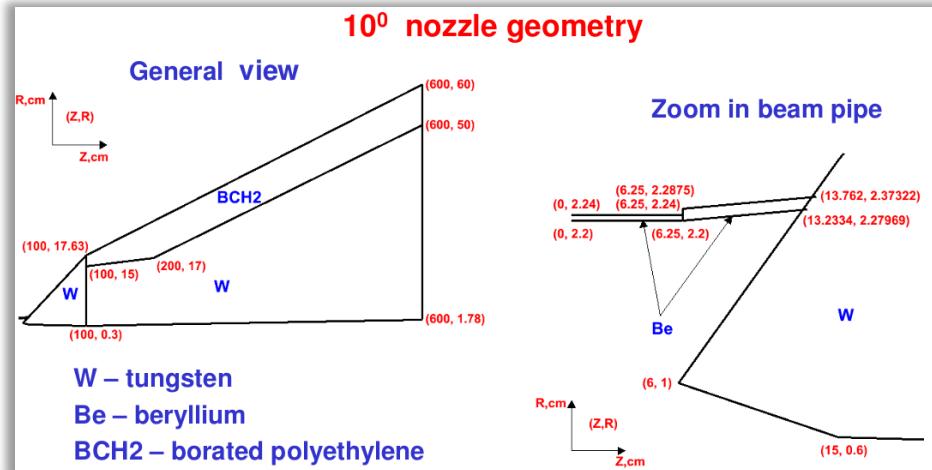
F. Collamati et al. 2021 JINST 16 P11009

Donatella Lucchesi

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



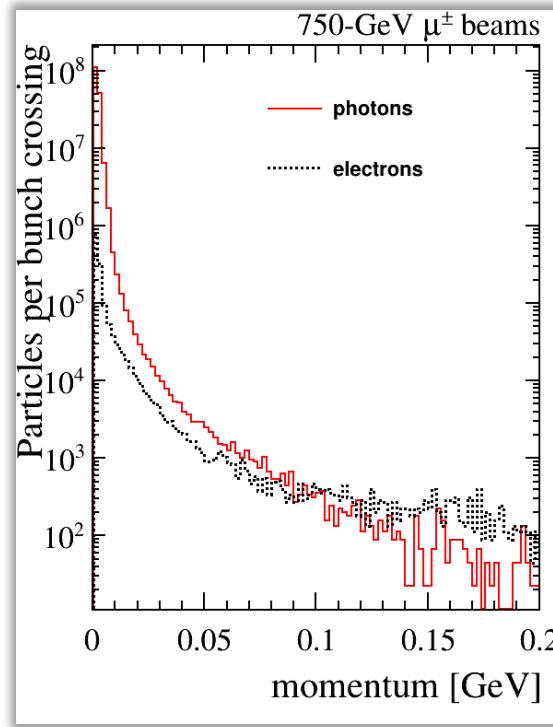
Optimized for $\sqrt{s} = 1.5$ TeV

D. Calzolari
[IMCC Ann. meeting](#)
Orsay 2023

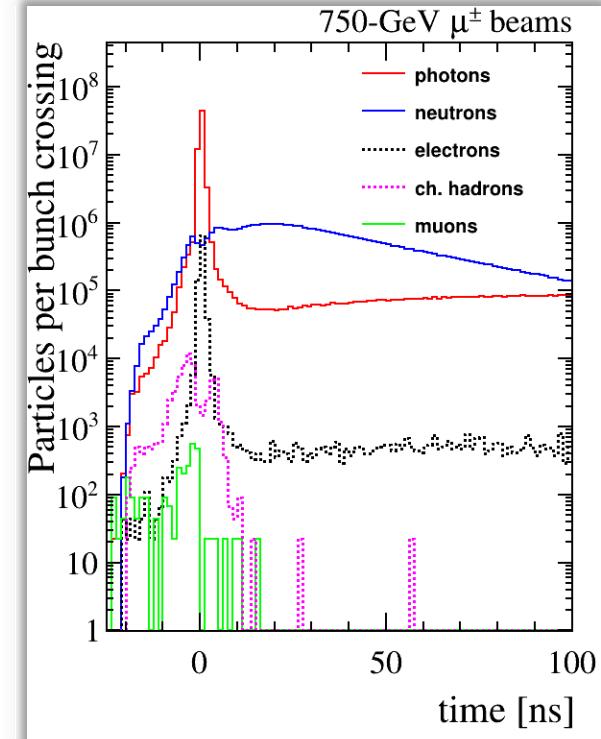
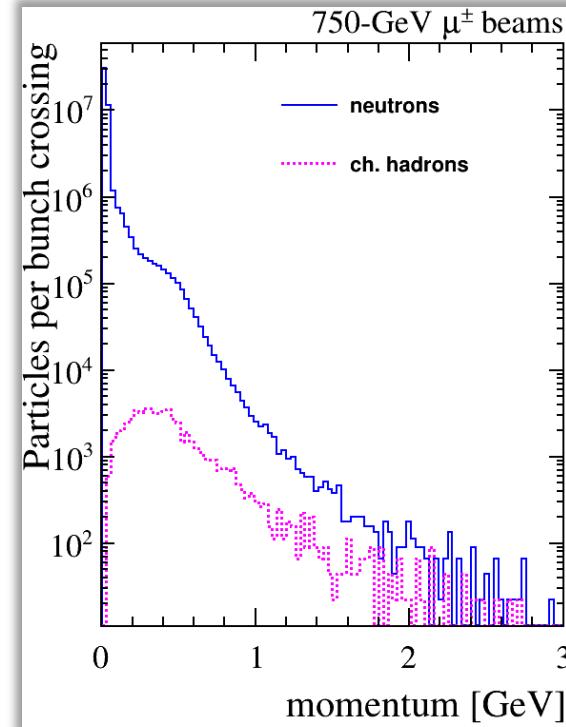
Survived beam-Induced background (BIB) properties

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

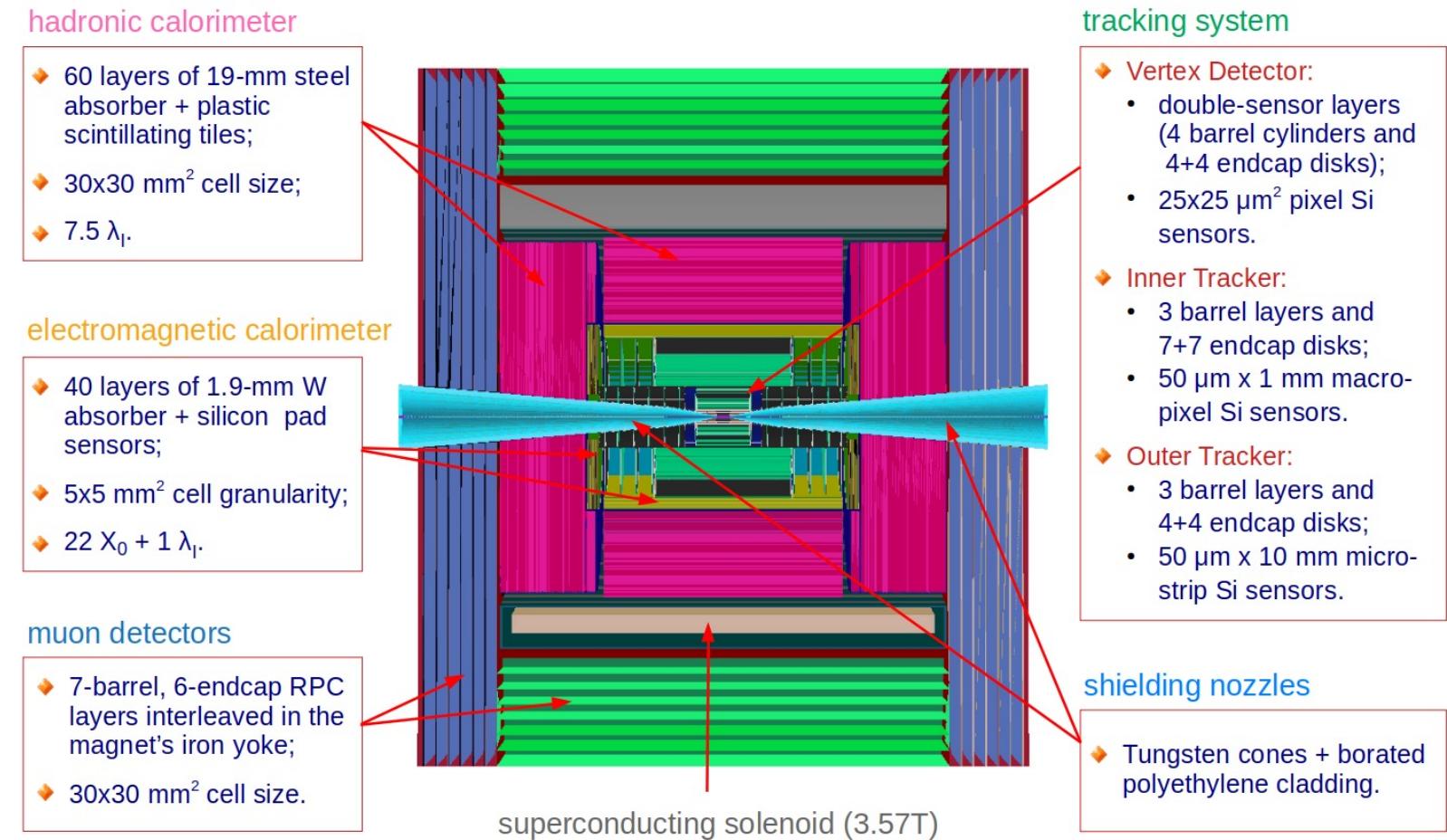
Beam-induced background generated with FLUKA by using the interaction region layout.
Particles propagated into the detector with GEANT.

Detector and physics performance at $\sqrt{s} = 3 \text{ TeV}$

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 $\sqrt{S} = 3 \text{ TeV}$ based on CLIC's detector concept CLICdp-Note-2017-001

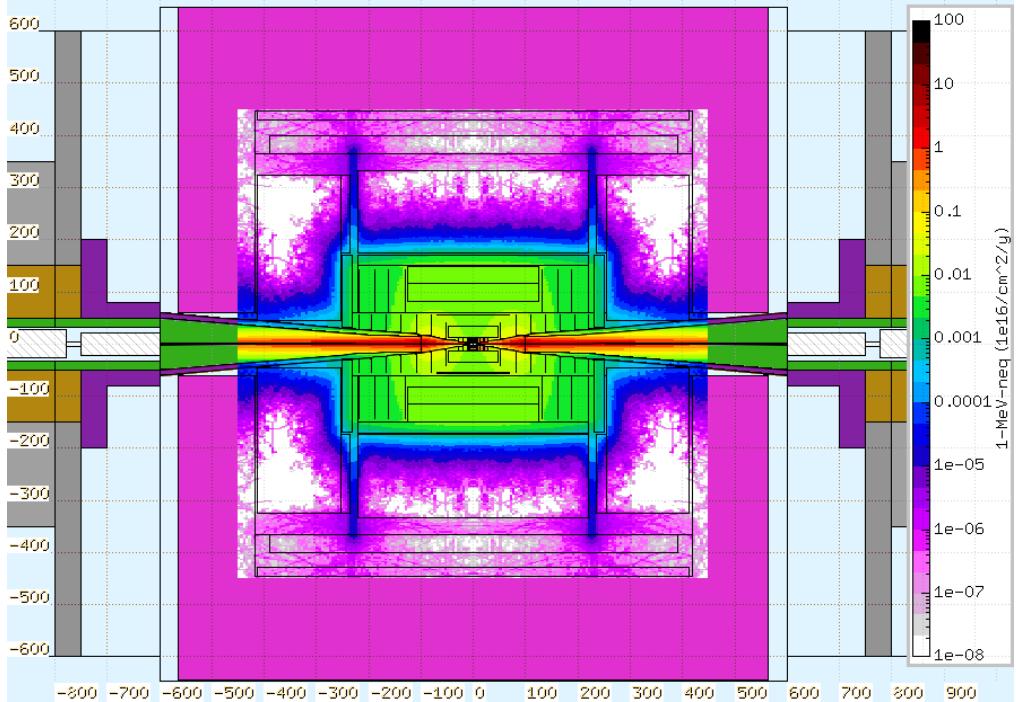
- Removed forward luminosity detectors
- Inserted nozzles
- Adapted tracker detector
- Magnetic field modified to cope with available beam-induced background



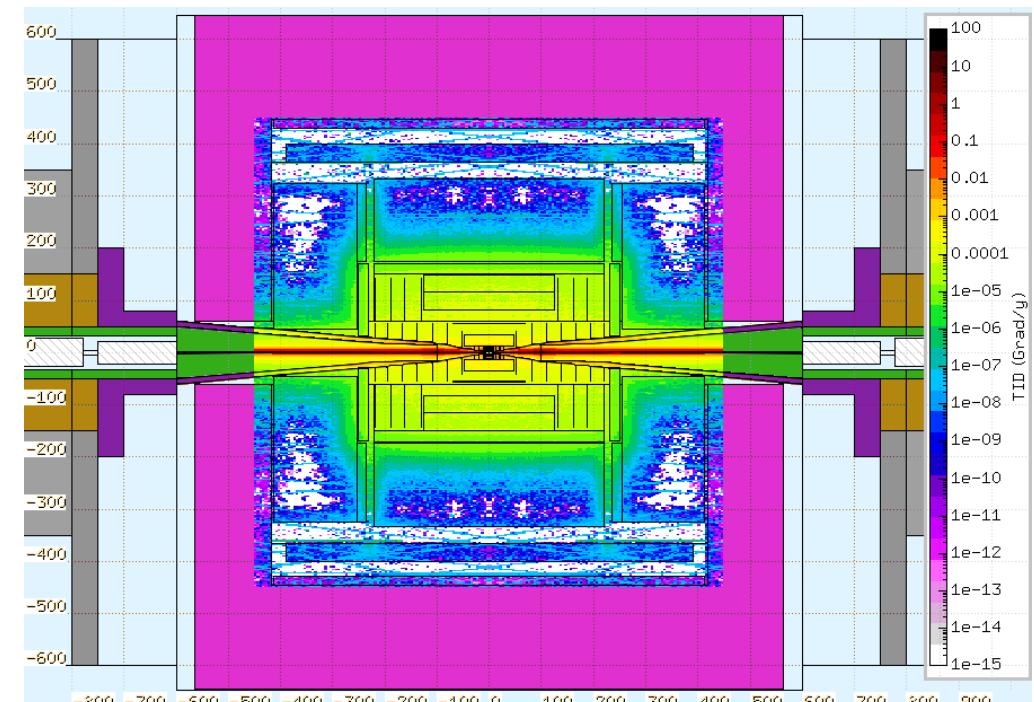
ILCSoft is the simulation and reconstruction framework, forked from CLIC's software.
 Transition to key4hep in progress, timeline depending on person power.
Tutorial made in July 2023.

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
- Beam injection frequency 5Hz
- Days of operation/year 200

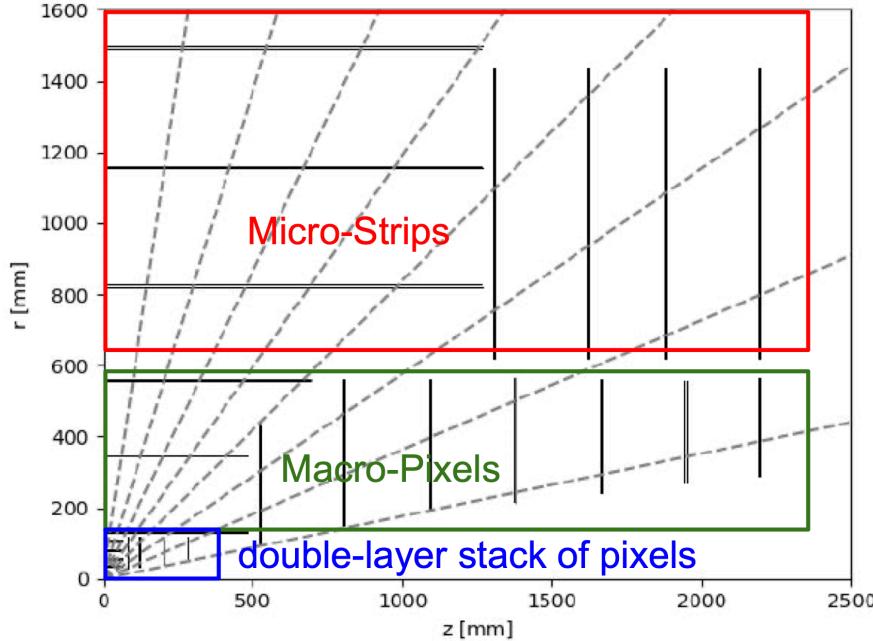
Radiation hardness requirements like HL-LHC (expected)

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

K. Black, Muon Collider Forum Report

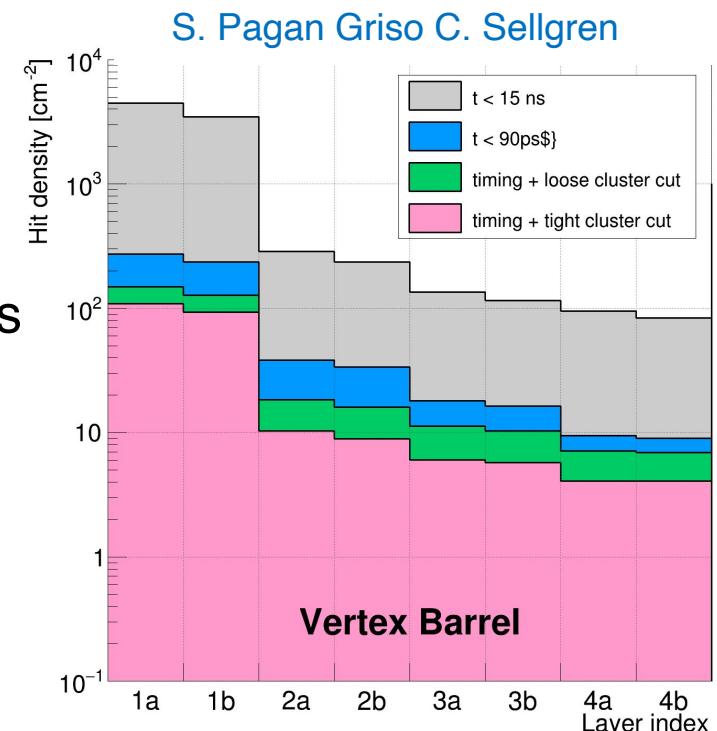
Tracker system: full detector & BIB simulation

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



Tracker requirements

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

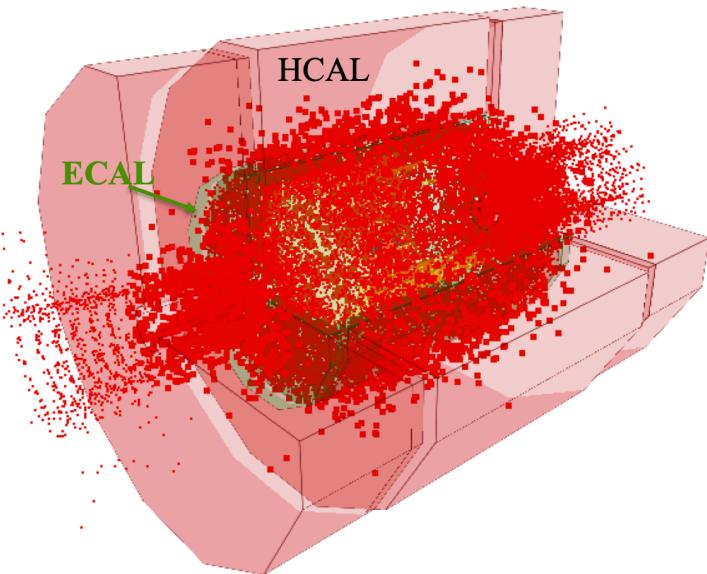


Higher occupancies respect to LHC detectors
 crossing rate 100 kHz vs 40 MHz

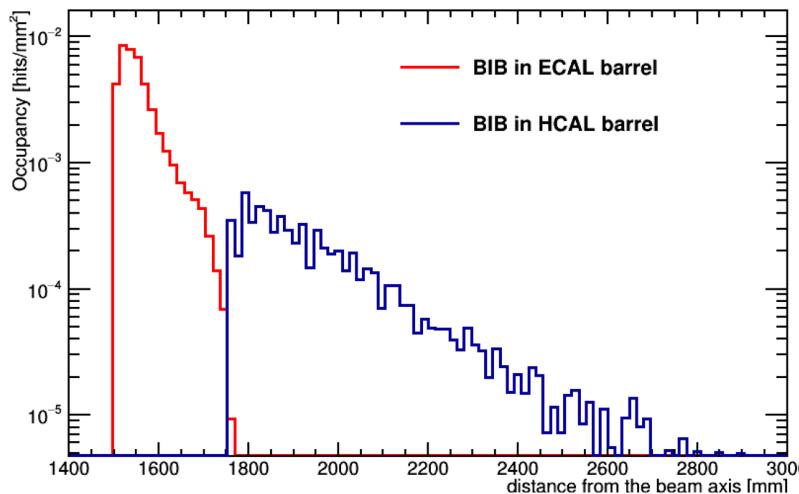
Fully engaged in ECFA DRD silicon tracker

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



Occupancy: ECAL > 10 times HCAL



ECAL surface flux: 300 particle/cm²

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

Calorimeter requirements

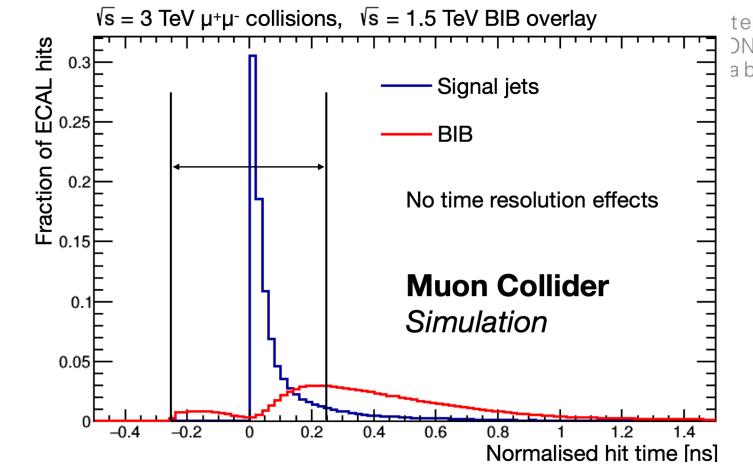
- time-of-arrival: resolution ~100 ps to reject out-of-time particles.
- Longitudinal segmentation: different profile signal vs. BIB.
- High granularity: to separate BIB particles from signal avoiding overlaps in the same cell.

Dedicated ECAL R&D: **Crilin**

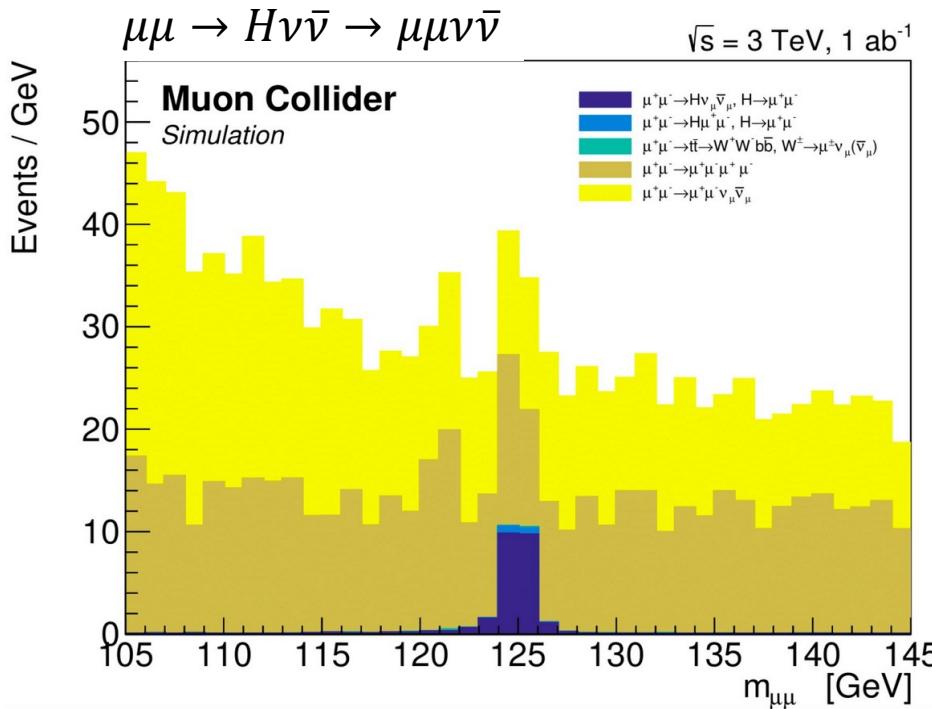
Each module: 5 layers of PbF₂ crystals ($10 \times 10 \times 40$ mm³)

Cerenkov light detected with SiPMs

Dedicated HCAL proposal in progress.

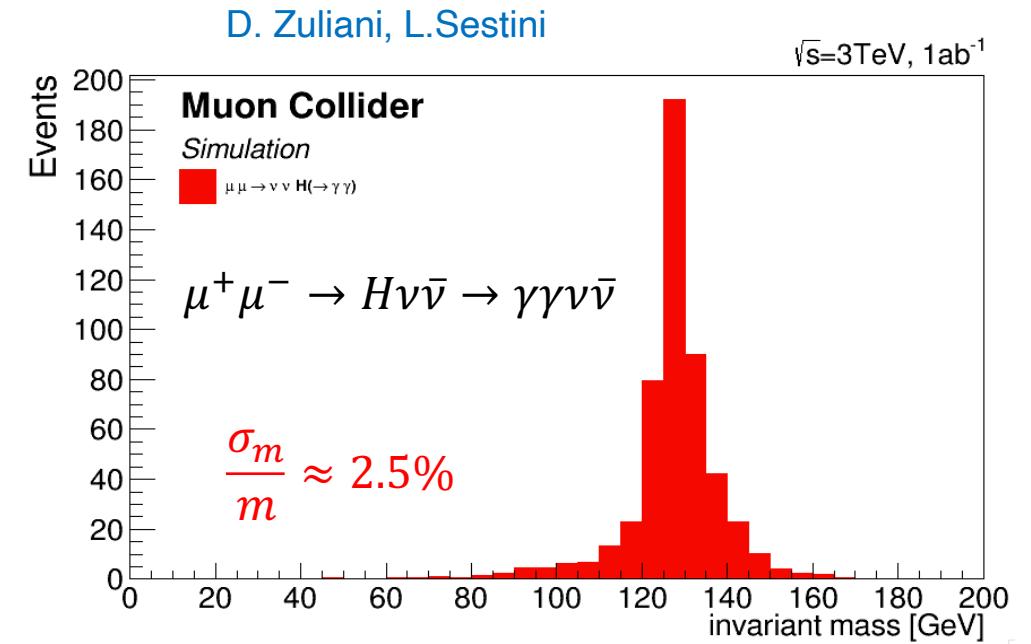


Central muons do not suffer from BIB,
it is concentrated in the end-cap.



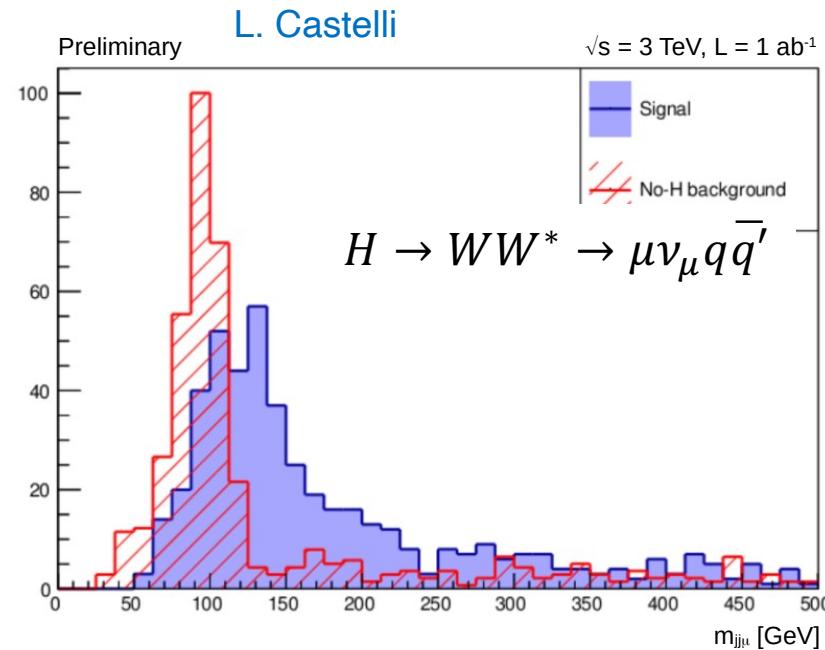
$\frac{\Delta\sigma_{H \rightarrow \mu\mu}}{\sigma_{H \rightarrow \mu\mu}} \sim 38\% \text{ 1 experiment } 1 \text{ ab}^{-1}$
 $\text{CLIC at 3 TeV } 2 \text{ ab}^{-1}: 25\%$

Good performance in high energy
photon reconstruction



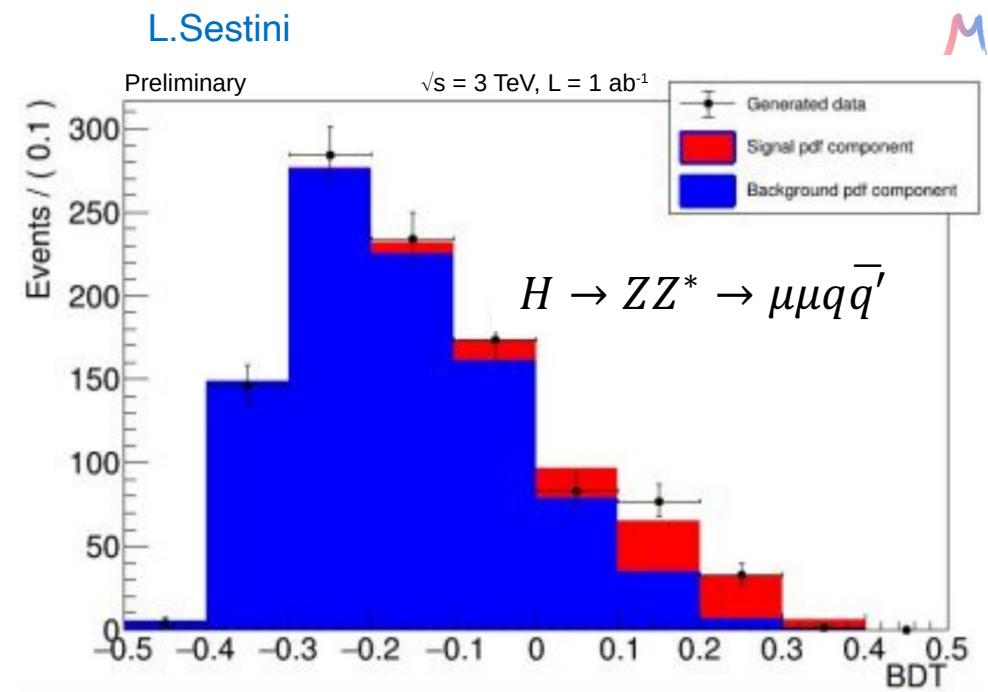
$\frac{\Delta\sigma_{H \rightarrow \gamma\gamma}}{\sigma_{H \rightarrow \gamma\gamma}} \sim 9\% \text{ 1 experiment } 1 \text{ ab}^{-1}$
 $\text{CLIC at 3 TeV } 2 \text{ ab}^{-1}: 10\%$

$H \rightarrow WW^*$ and $H \rightarrow ZZ^*$ performance



$$\frac{\Delta\sigma_{H \rightarrow WW^*}}{\sigma_{H \rightarrow WW^*}} \sim 3\% \quad 1 \text{ experiment } 1 \text{ ab}^{-1}$$

CLIC at 3 TeV 2 ab⁻¹ ($\ell\nu_\ell q\bar{q}' + q\bar{q}' q\bar{q}'$): 0.7%

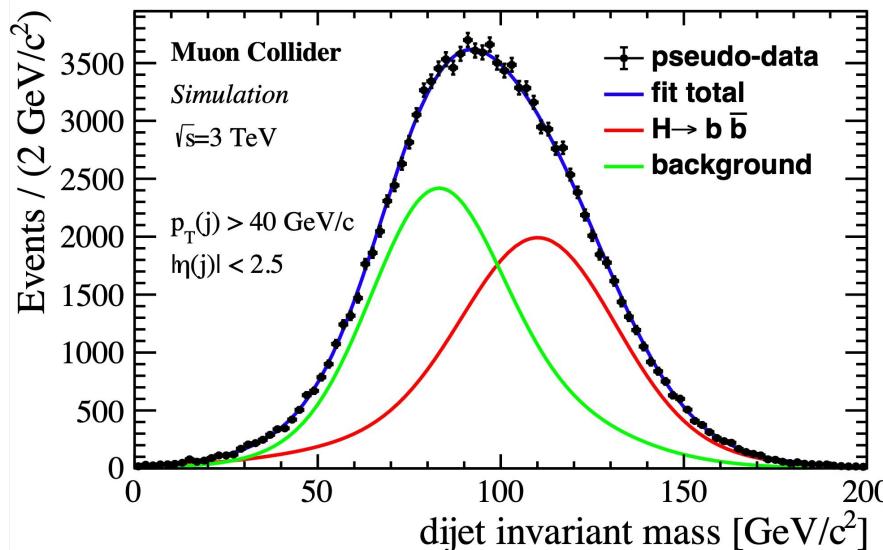


$$\frac{\Delta\sigma_{H \rightarrow ZZ^*}}{\sigma_{H \rightarrow ZZ}} \sim 17\% \quad 1 \text{ experiment } 1 \text{ ab}^{-1}$$

CLIC at 3 TeV 2 ab⁻¹ ($\ell\ell q\bar{q}'$): 4%

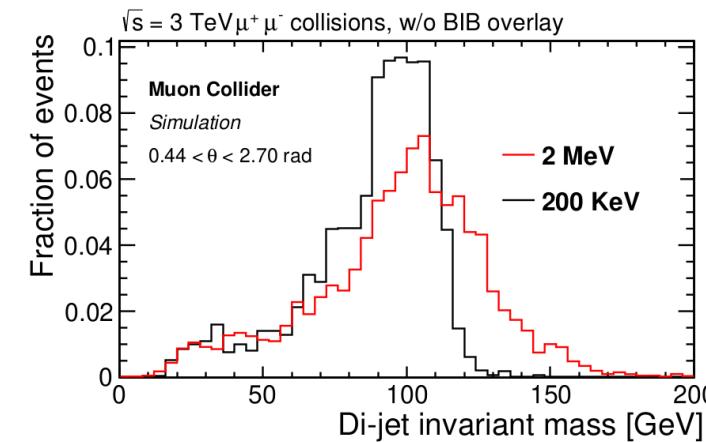
Jet reconstruction performance

$E_{threshold}^{cell} \geq 2$ MeV for ECAL reconstruction
up to now, it dominates energy resolution



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

CLIC at 3 TeV 2 ab⁻¹: 0.3%



Jets reconstruction, even not optimal, allows good performance on Higgs self coupling determination
Process: $\mu^+ \mu^- \rightarrow H H v \bar{v} \rightarrow b \bar{b} b \bar{b} v \bar{v}$

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

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

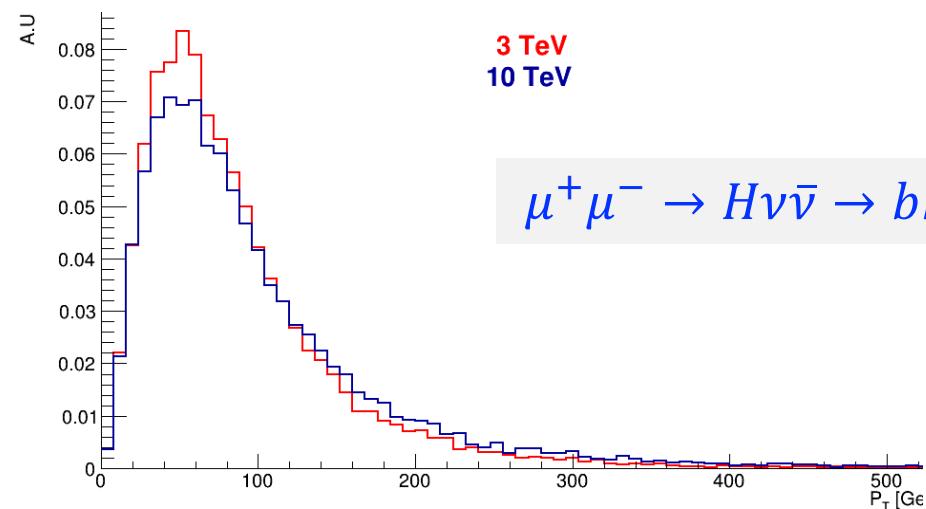
$\sqrt{s} = 10$ TeV parametric studies

$$\frac{\Delta\lambda_3}{\lambda_3} \sim 4\% \quad \begin{matrix} 1 \text{ experiment} \\ 10 \text{ ab}^{-1} \end{matrix}$$

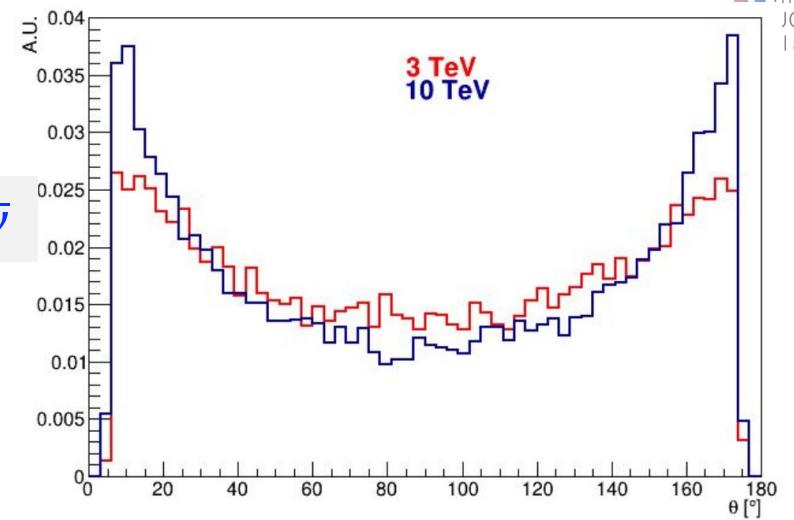
Detector for $\sqrt{s} = 10 \text{ TeV}$: definition of requirements

Physics requirements: three classes of processes

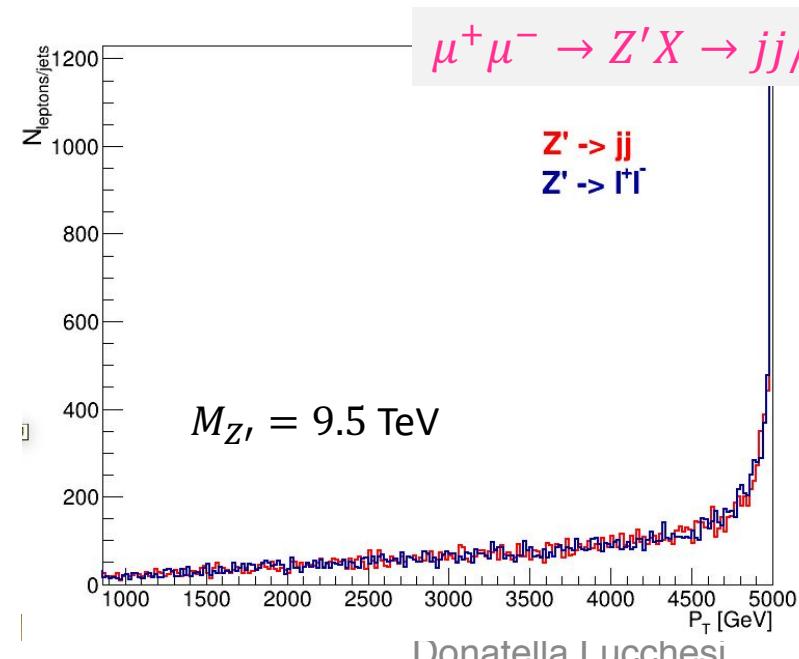
Low momentum,
forward-boosted
phenomena,
ex. Higgs boson.



$$\mu^+ \mu^- \rightarrow H v\bar{v} \rightarrow b\bar{b} v\bar{v}$$



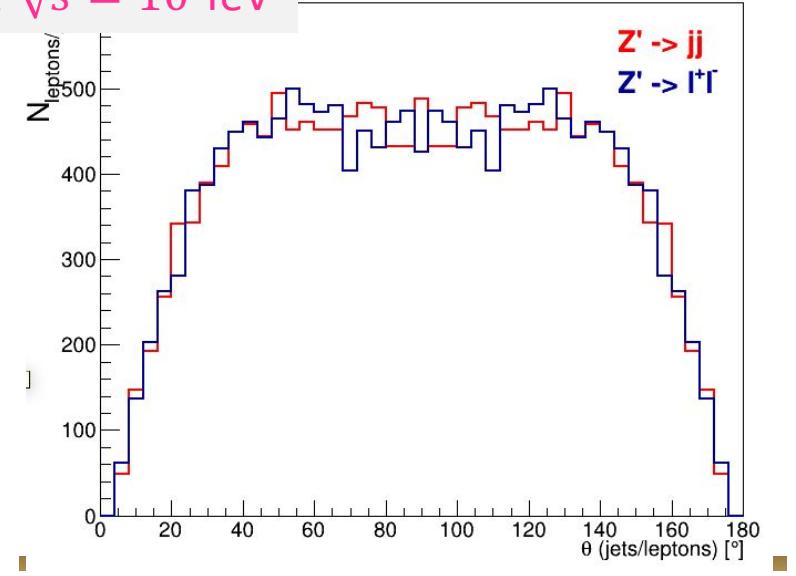
High momentum
central phenomena,
ex. Z'



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

October 18, 2023

Donatella Lucchesi



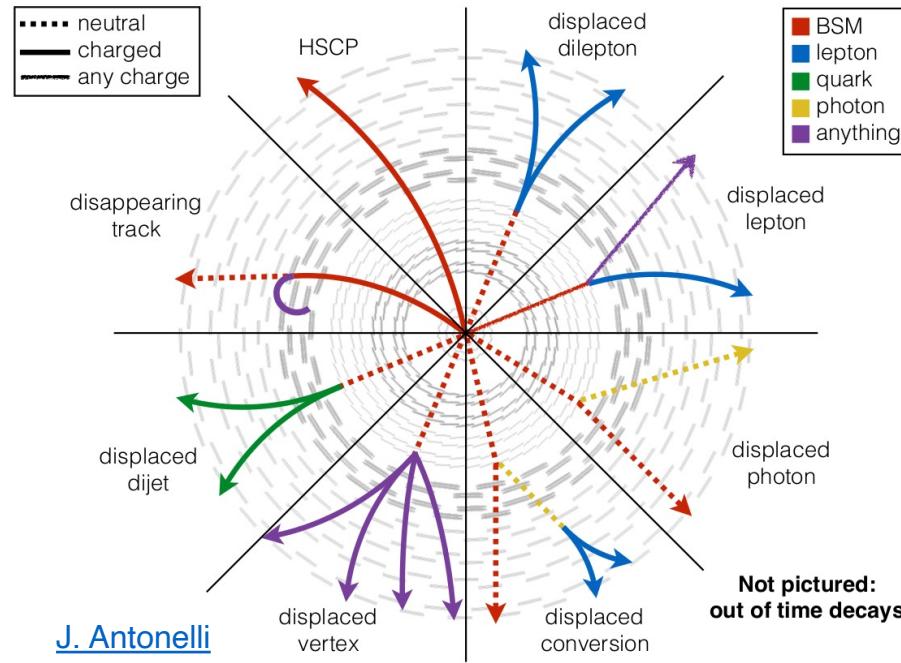
$$Z' \rightarrow jj$$

$$Z' \rightarrow \ell^+\ell^-$$

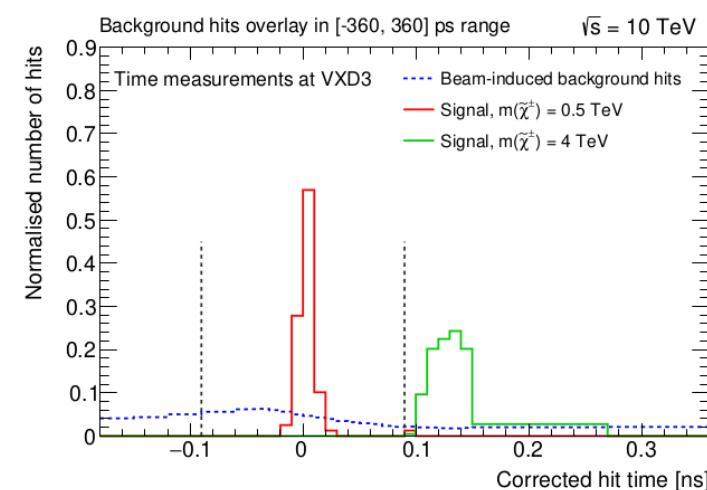
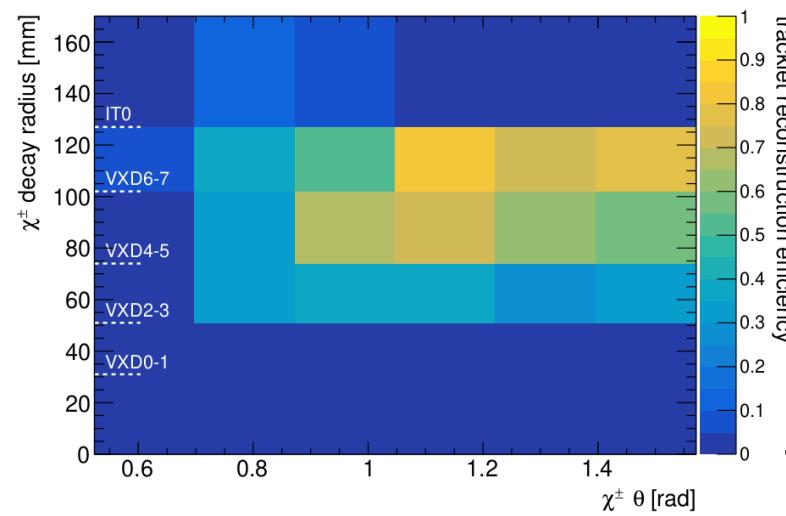
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Physics requirements: three classes of processes cont'd

Less conventional signatures from BSM processes, ex. Disappearing Track



R. Capdevilla et al., [JHEP 06, 133 \(2021\)](#)

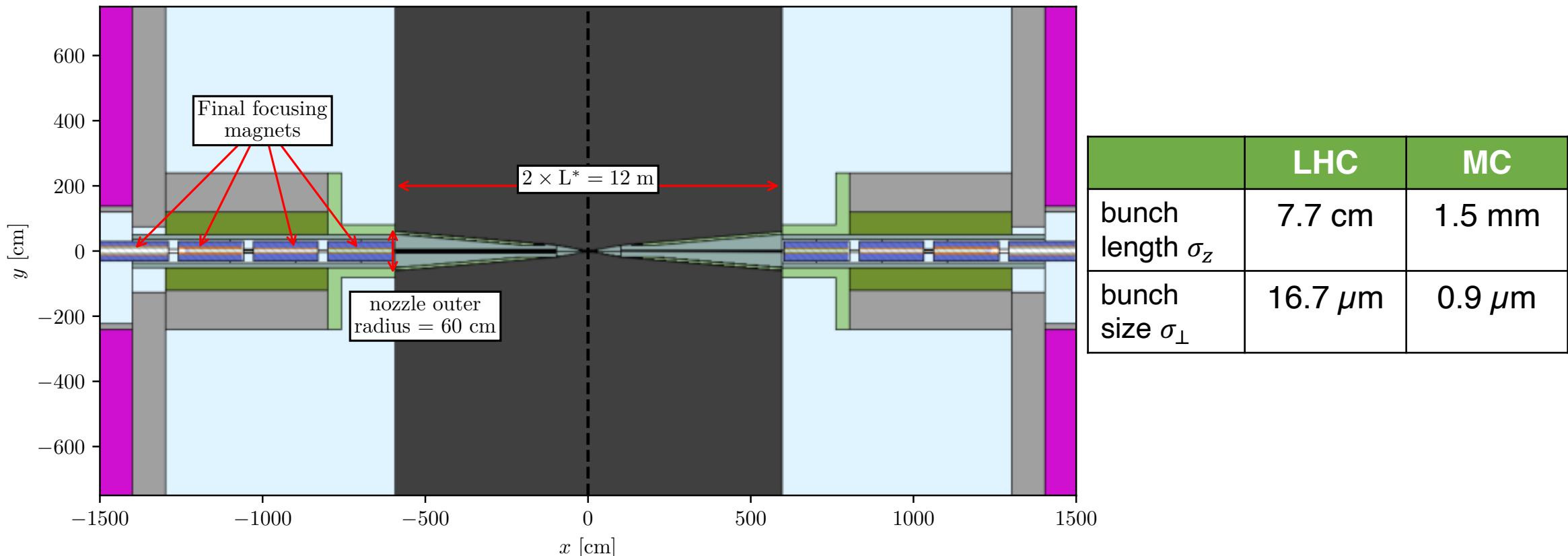


Tracker design important to avoid limitation of performance

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 the lattice point of view to have more than ± 6 m

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

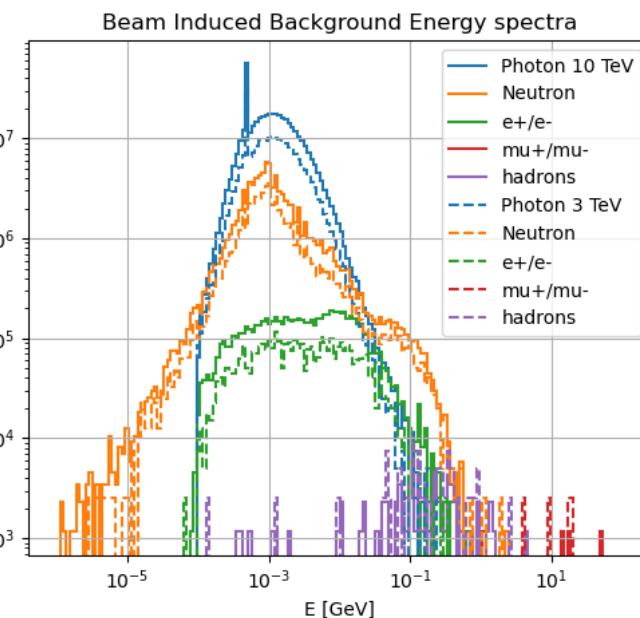
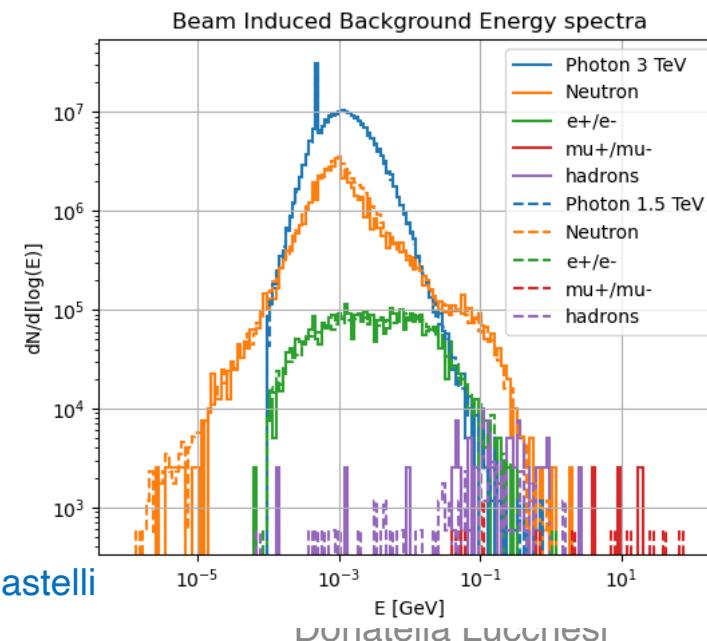


Beam background sources in the detector region



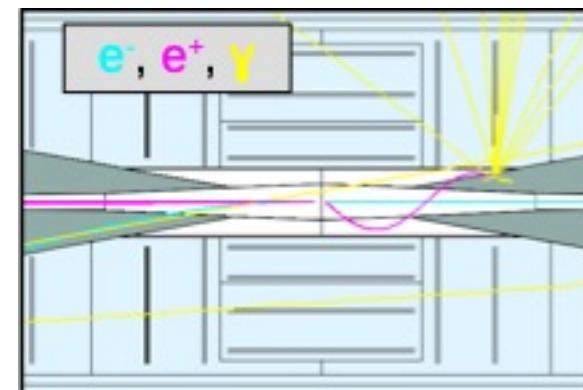
- 1) Muon decay along the ring, $\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$: dominant process at all center-of-mass energies
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 - * Bethe-Heitler muon, $\gamma + A \rightarrow A' + \mu^+ \mu^-$
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 - * small transverse momentum $e^- e^+ \Rightarrow$ 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

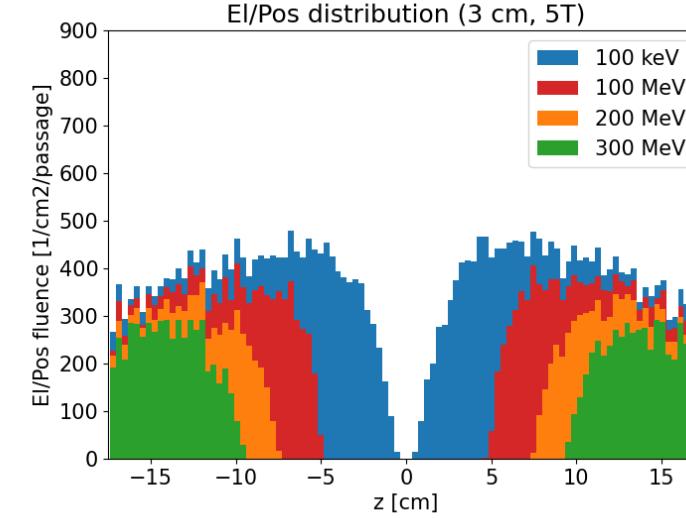
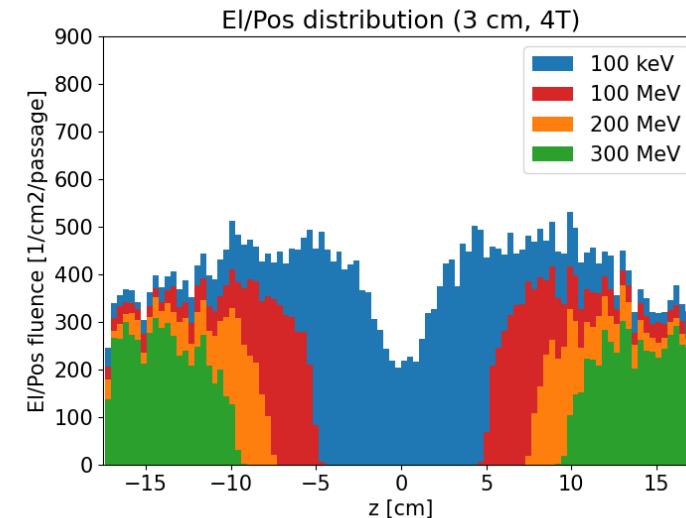
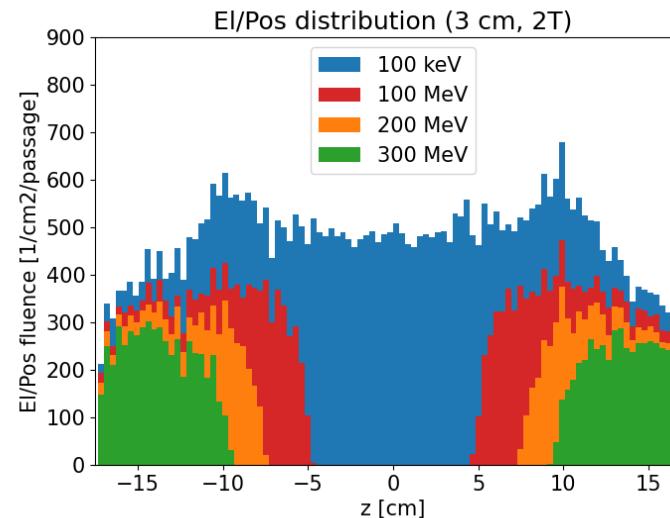


2) Incoherent e^-e^+ production $\mu^+\mu^- \rightarrow \mu^+\mu^- e^+e^-$

- * 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 reduce the component arriving on the detector by trapping it through solenoidal field



[D. Calzolari, Magnet for 10 TeV Detector](#)



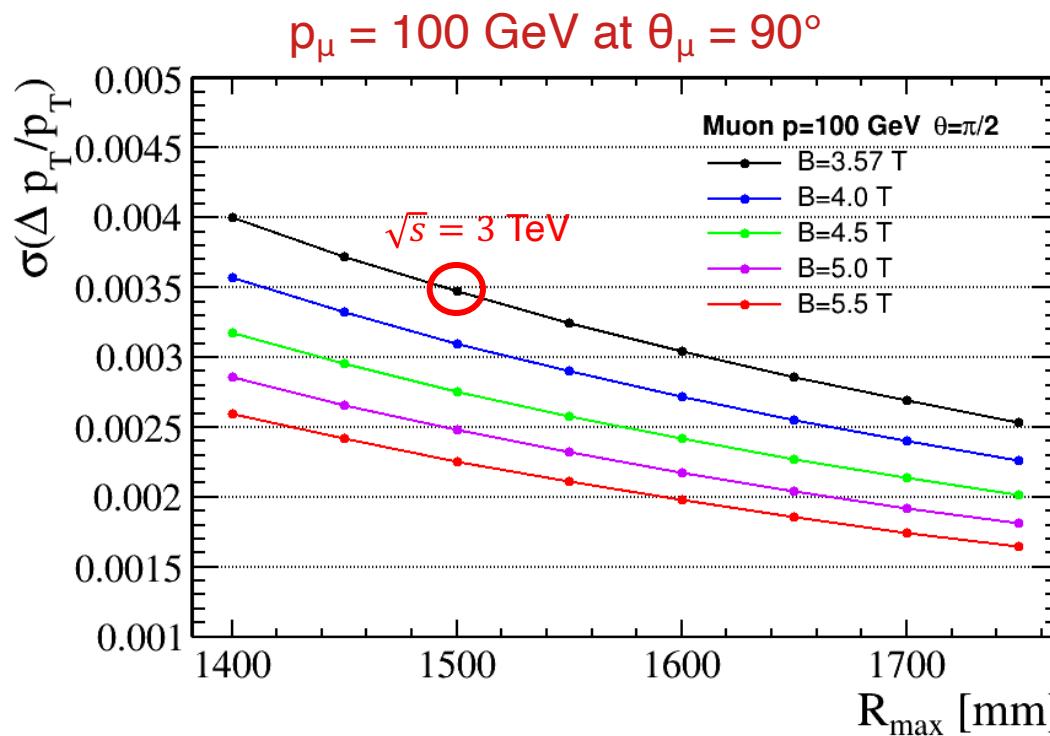
Magnetic field needed to reduce beam-induced background

Which magnetic field for the detector?

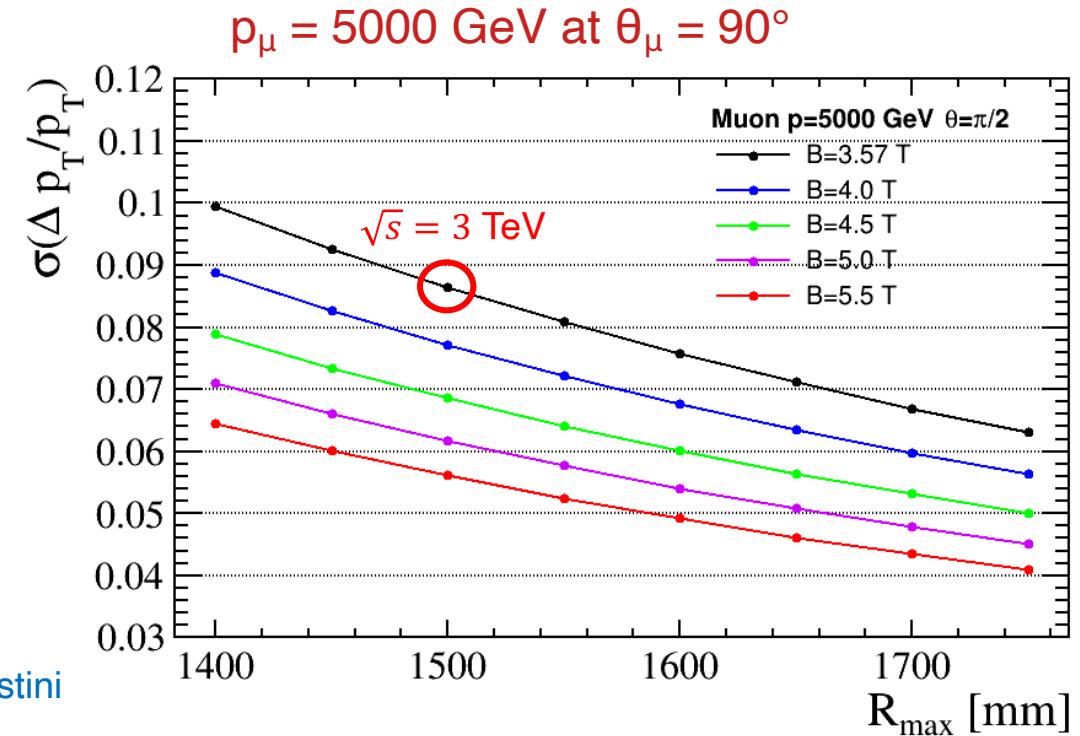
Analytic formula to relate magnetic field and track momentum resolution

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

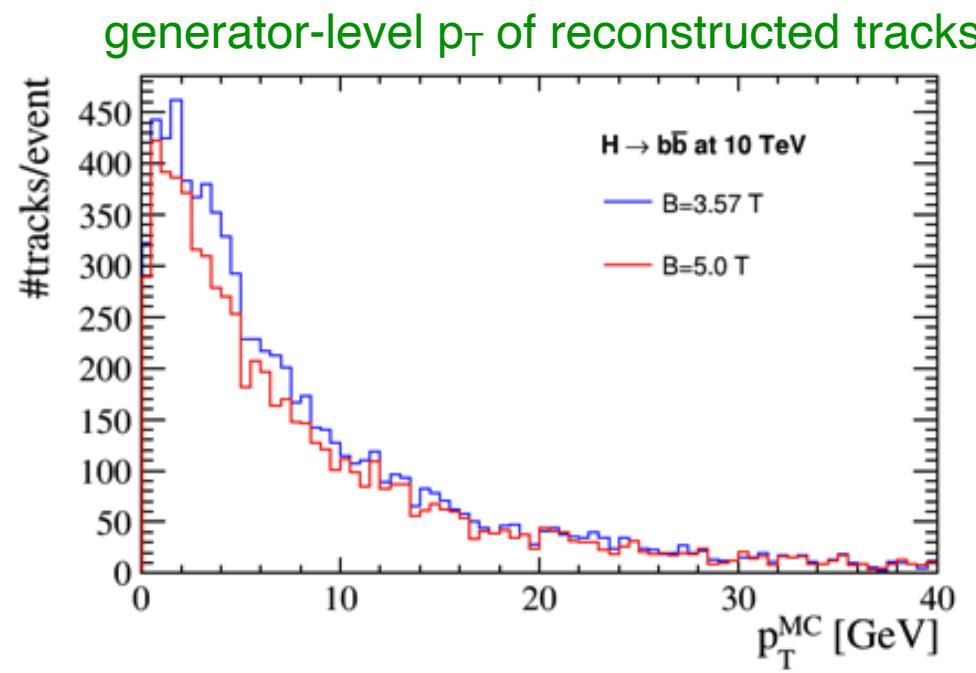
Z. Drasal and W. Riegler,
NIM A 910 (2018) 127



L. Sestini

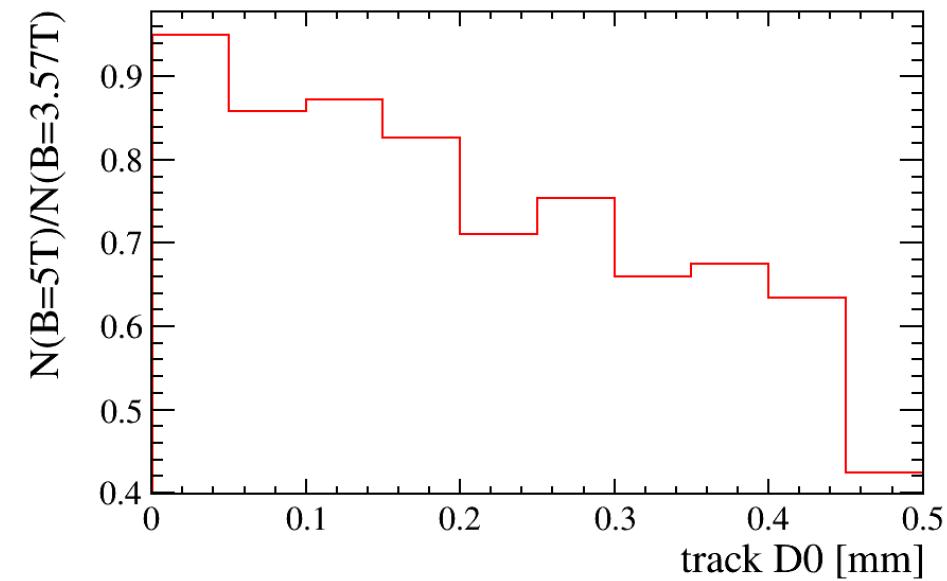


Tracking and magnetic field



L. Sestini

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



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

- inefficiency $\sim 15\%$
- 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

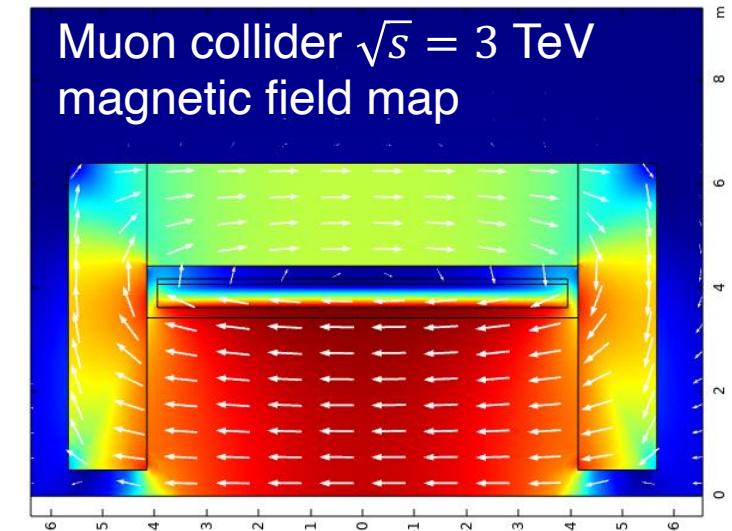
<https://indico.cern.ch/event/1324236>

5 October 2023
CERN
Europe/Zurich timezone

Enter your search term

- Overview
 - Timetable
 - Contribution List
 - Registration
 - Participant List
 - Videoconference
- Contacts
donatella.lucchesi@cern.ch

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.



M. Mentink, A. Dudarev,
B. Cure

October 18, 2023

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)

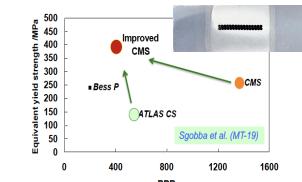
Members from:
 - CERN EN, EP, TE departments.
 - KEK.

The WG is now working on establishing a program on coextrusion process for Alu-stab SC with institutional and industrial partners.

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.

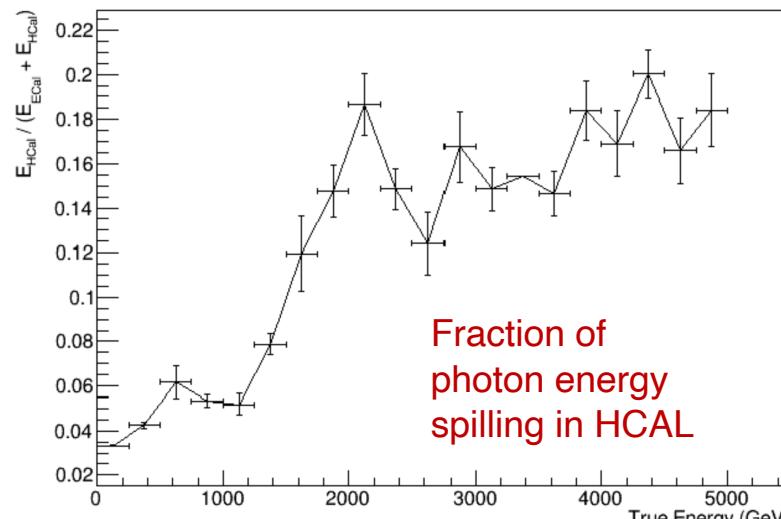
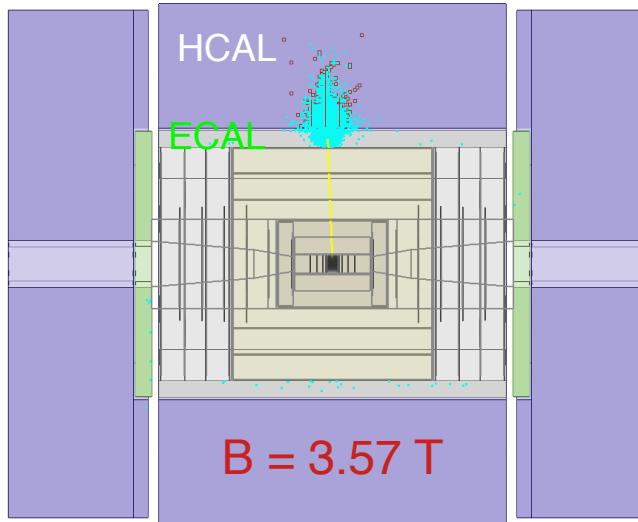
Remarks:

- 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

Donatella Lucchesi

Photon and jet reconstruction

central 5 TeV photon M. Casarsa



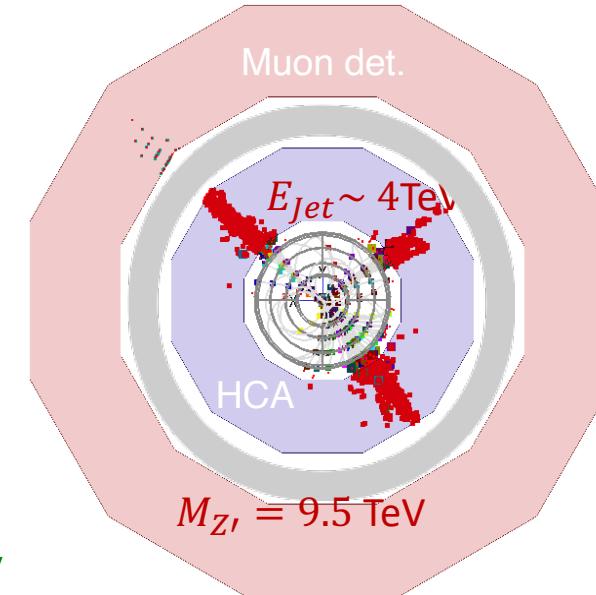
October 17, 2023

E_γ [GeV]

Desired ECAL :

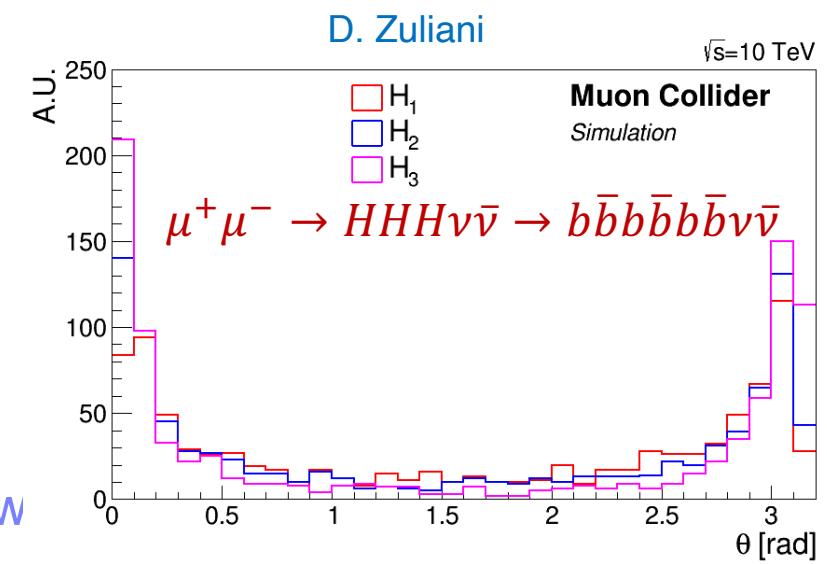
- Deep: $\sim 25X_0$
- High granularity
- Longitudinal segmentation
- Timing ~ 100 ps
- CRILIN @10 TeV under study

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



Desired HCAL :

- Deep: $\sim 8.5\lambda_i$
- Good forward coverage
- Sufficient granularity to be used in particle flow

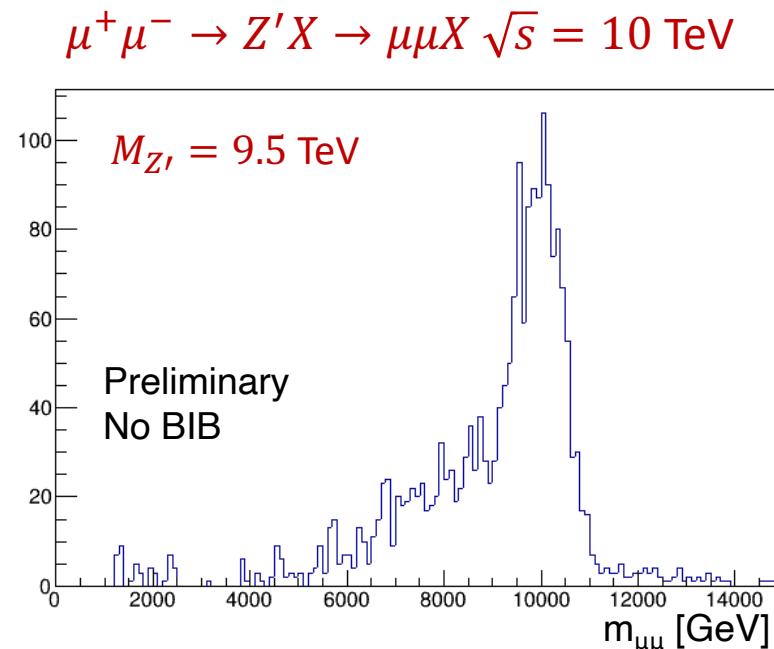


Donatella Lucchesi

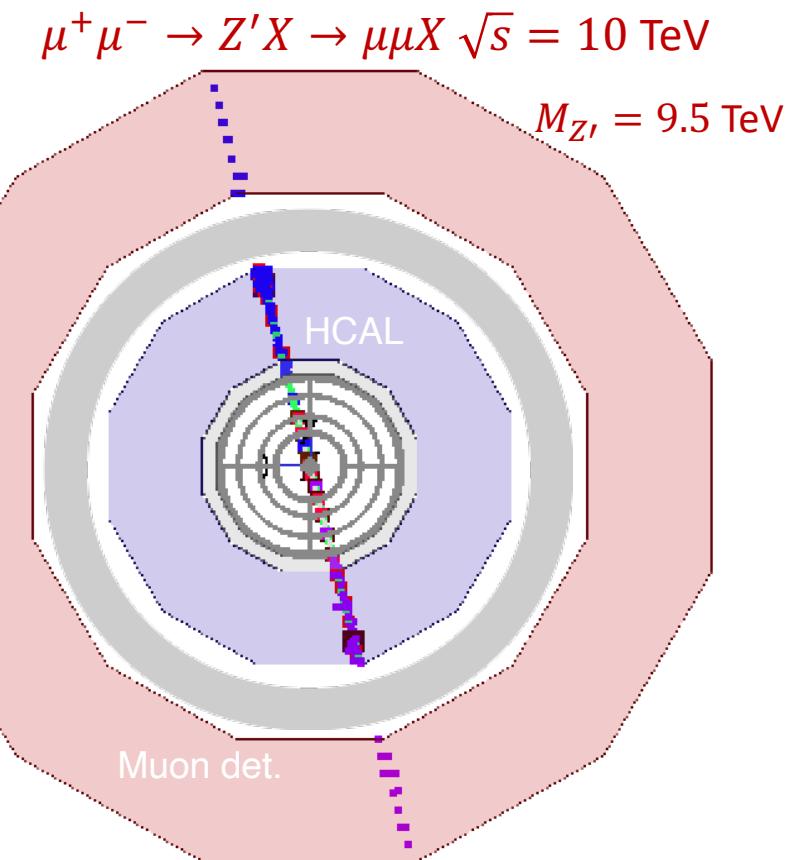
33

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.



$B = 5 \text{ T}$



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

- X few TeV, first stage of the collider
 $\sqrt{s} = 3$ TeV taken as working hypothesis
- X 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

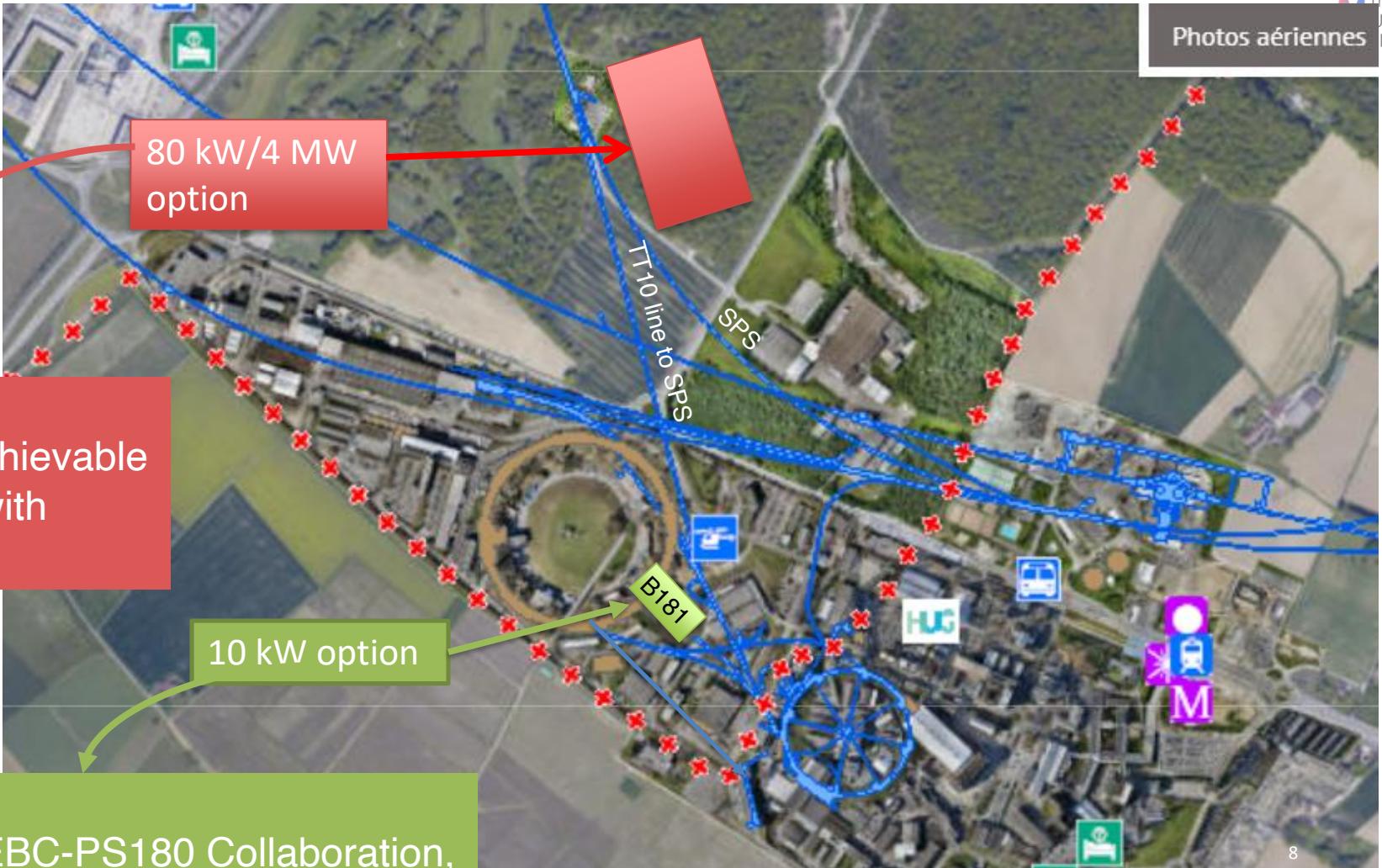
[R. Losito IMCC-2023](#)

Both use maximum intensity per pulse $\sim 10^{13}$ ppp (or more) in pulses of few ns at 20+ GeV.

Different repetition rate:

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

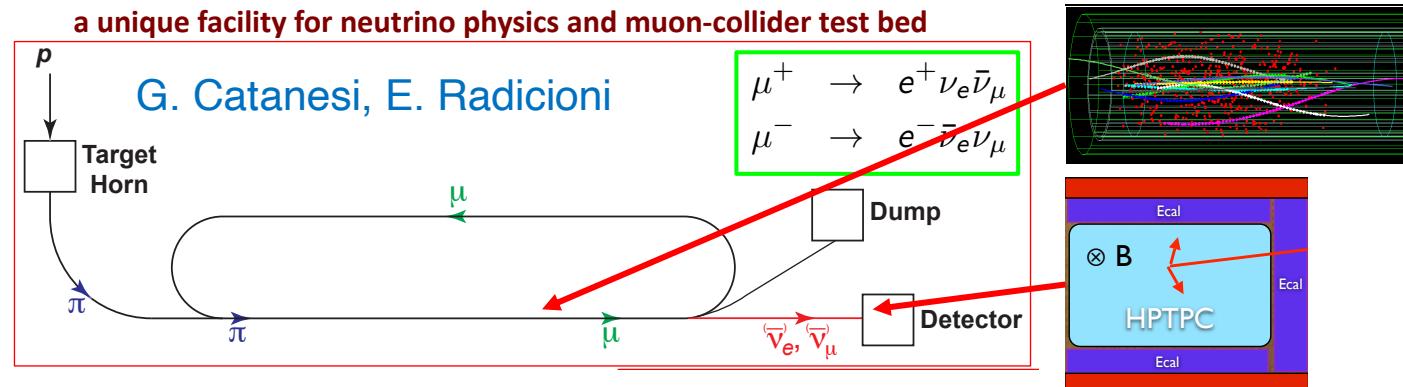
High power
 $O(80\text{ kW})$ on target easily achievable
 No showstopper for 4 MW with beam at a depth of 40 m



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.



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

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.

Summary

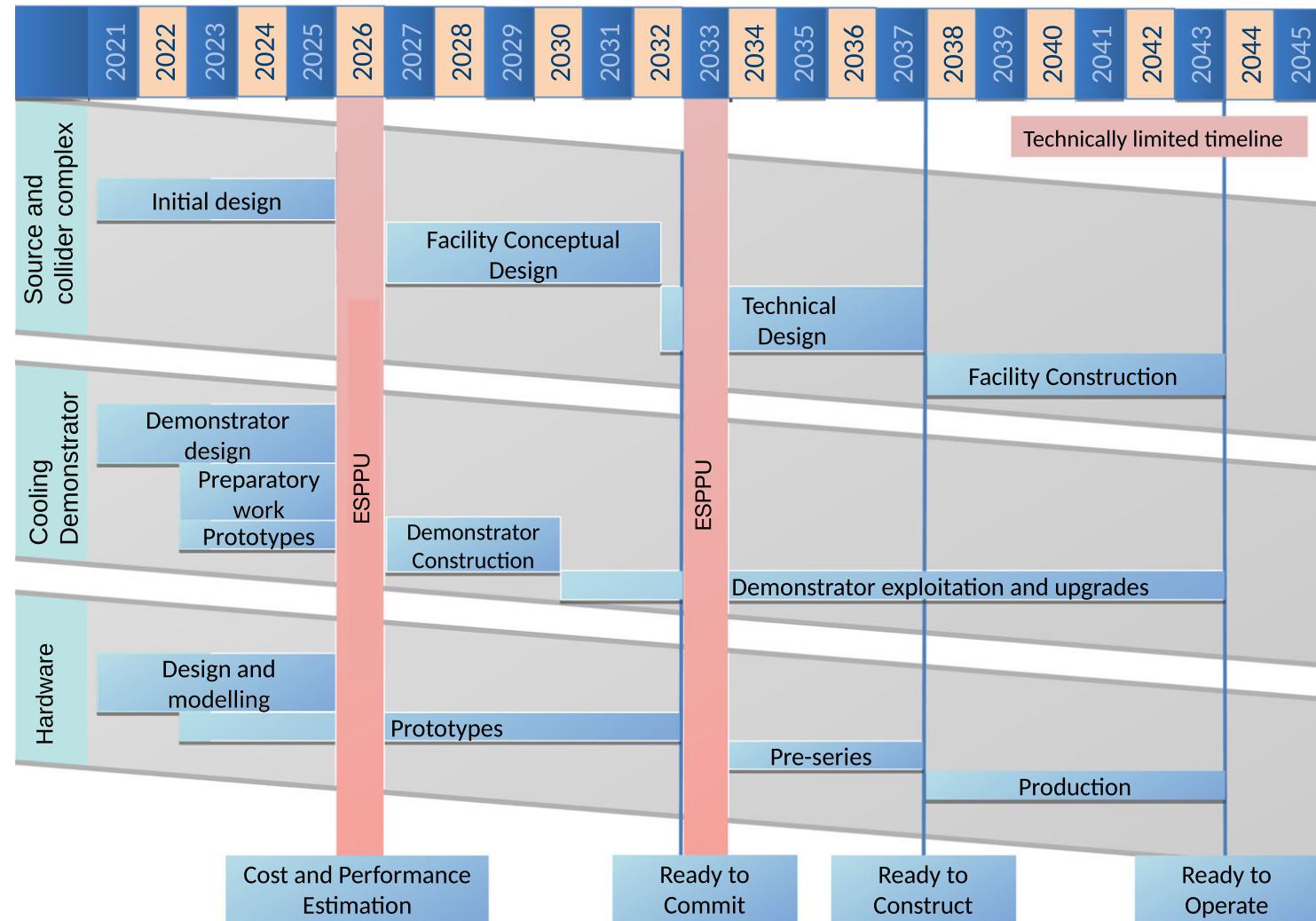
The first detector concept for a $\sqrt{s} = 3$ TeV Muon Collider already exhibits physics objects reconstruction performance that is sufficiently robust for high-precision measurements and searches for new physics.

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.

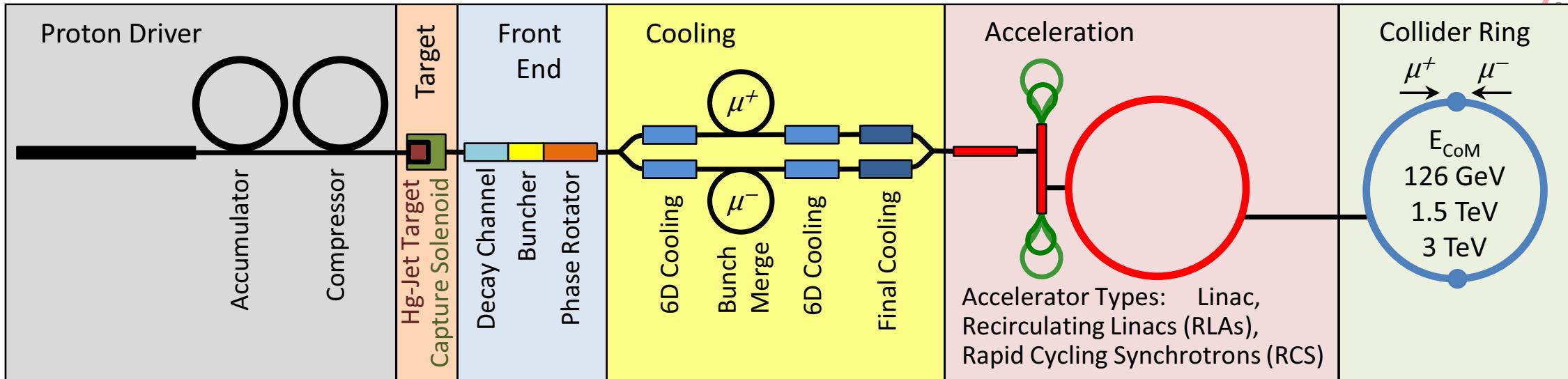
Additional material

A technically limited timeline for the muon collider R&D programme that would see a 3 TeV muon collider constructed in the 2040s



Proton-driven Muon Collider Concept

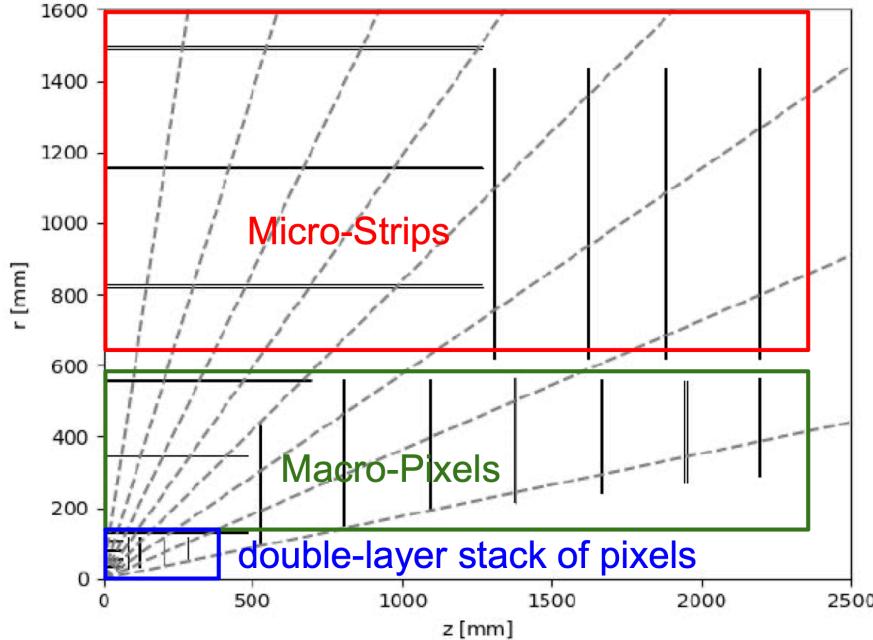
Muon Accelerator Program (MAP)



- | | | | | | |
|---|---|--|---|--|--|
| <ul style="list-style-type: none"> Based on 6-8 GeV Linac Source H- stripping requirements similar to neutrino ones | <ul style="list-style-type: none"> high power target π production in high-field solenoid | <ul style="list-style-type: none"> RF cavities bunch & phase rotate μ^\pm into bunch train | <ul style="list-style-type: none"> Ionization cooling 6D MICE | <ul style="list-style-type: none"> Fast acceleration Use RF and SC | <ul style="list-style-type: none"> μ^\pm decay background Critical Machine Detector Interface |
|---|---|--|---|--|--|

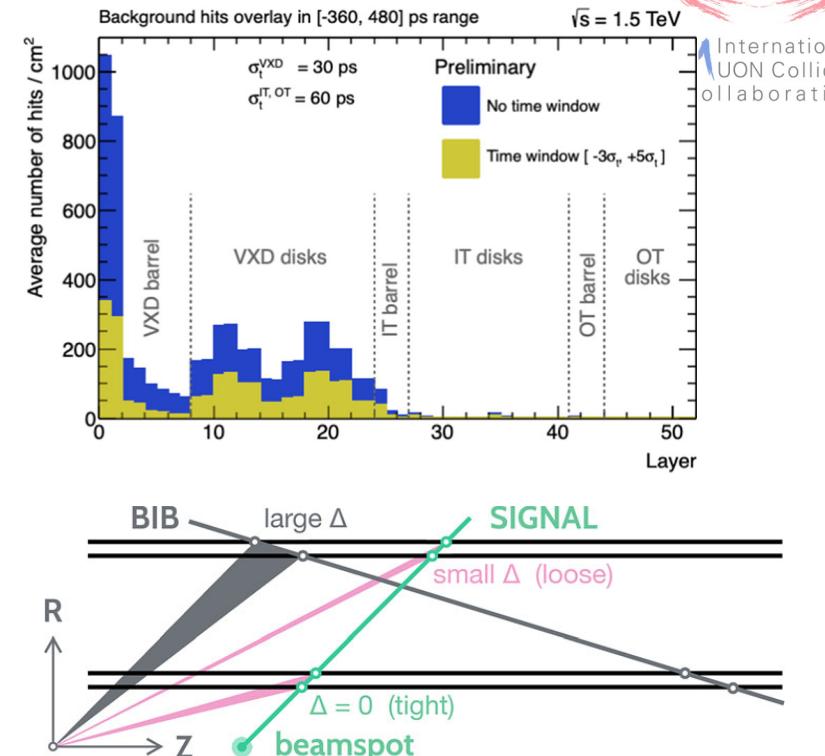
Tracker system: full detector & BIB simulation

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

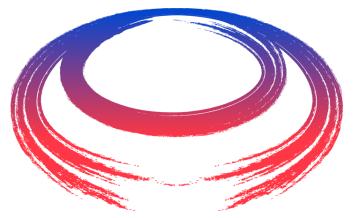
0.85

Pixel Layer 1

0.51

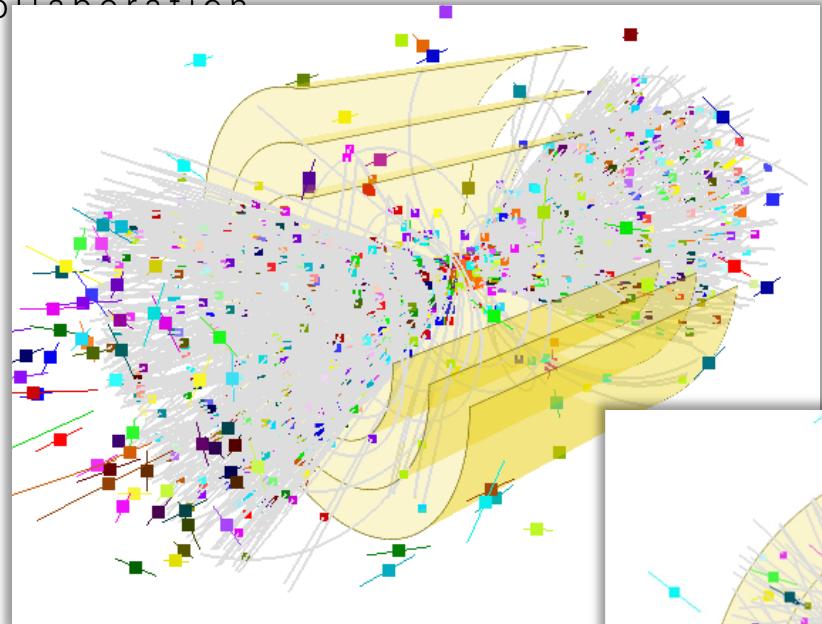
0.022

0.51

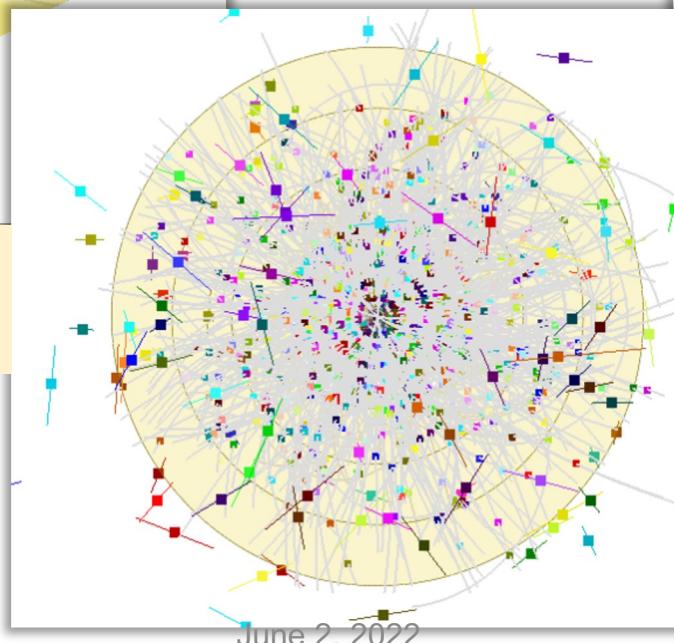


International
MUON Collider
Collaboration

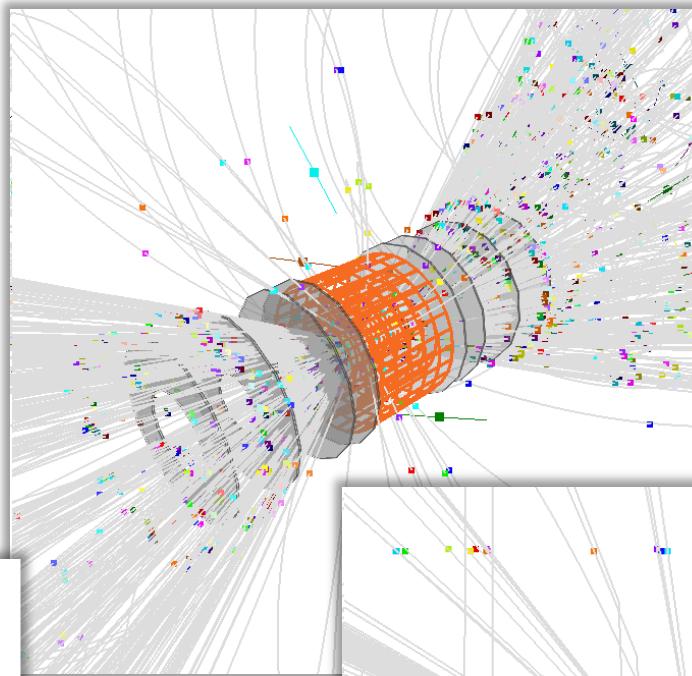
Beam-Induced Background in the tracker



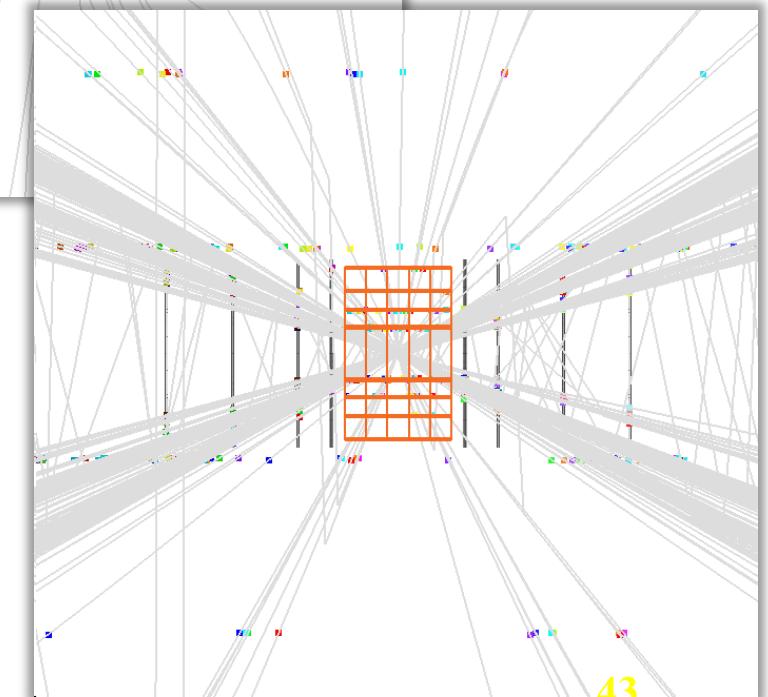
Inner/Outer
Tracker



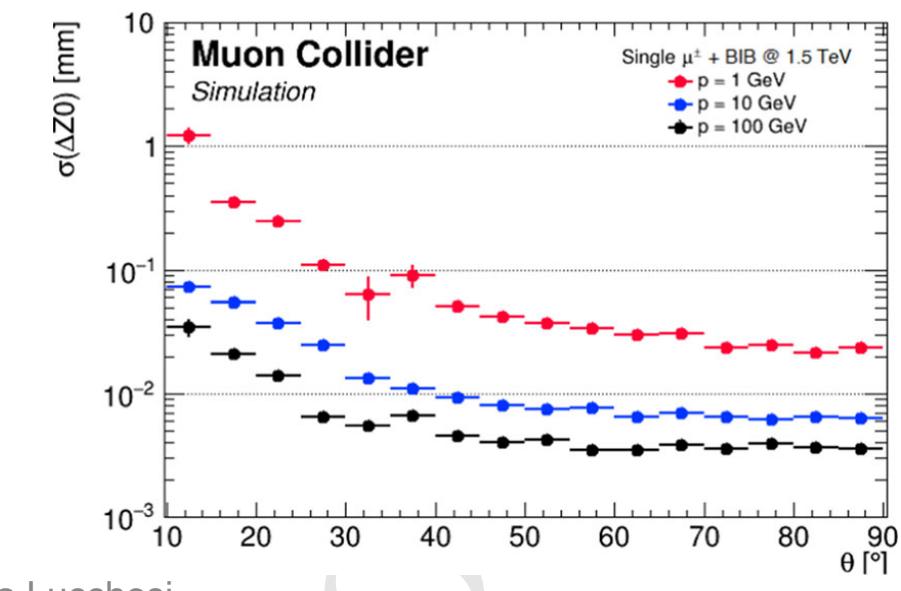
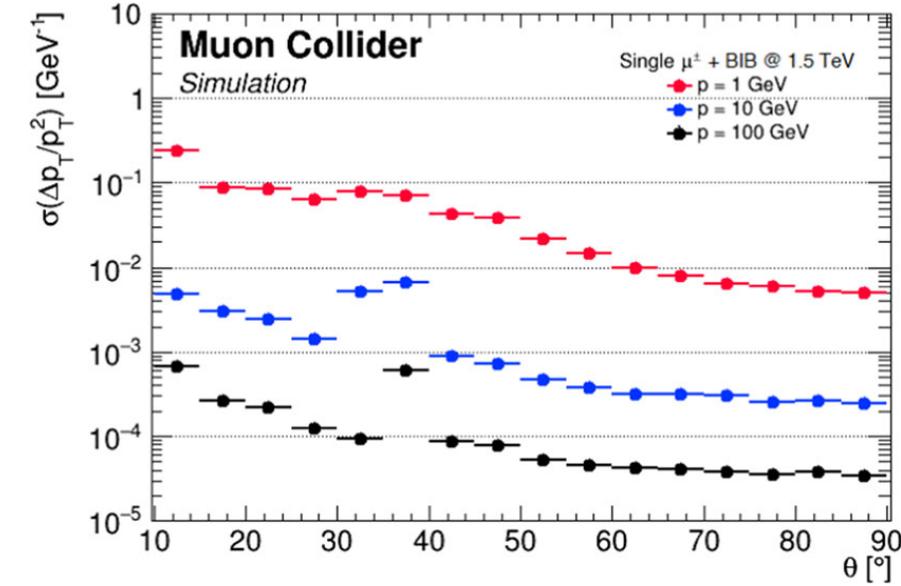
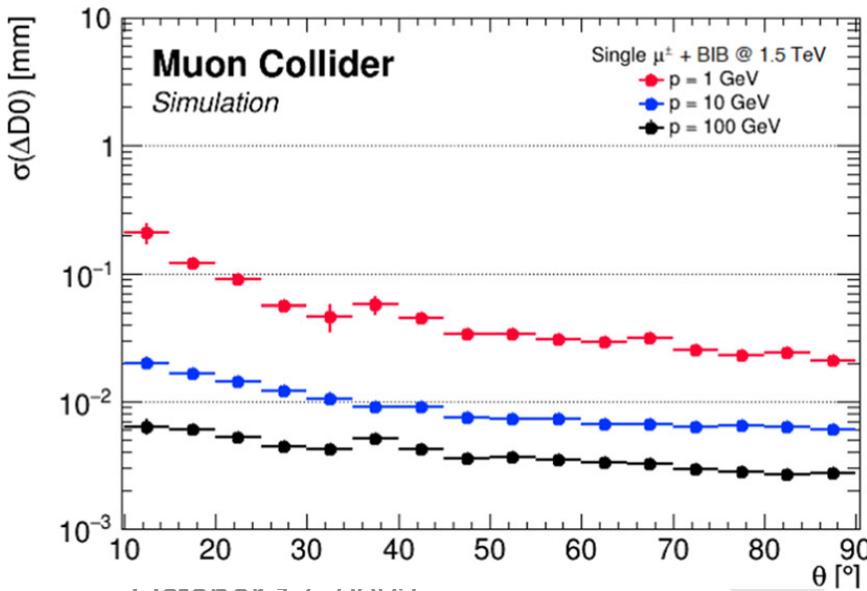
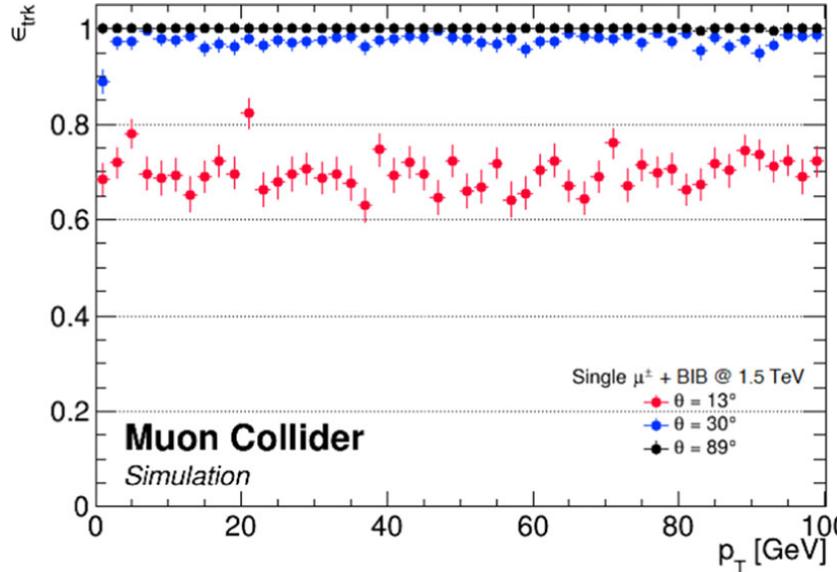
June 2, 2022



Vertex
Detector



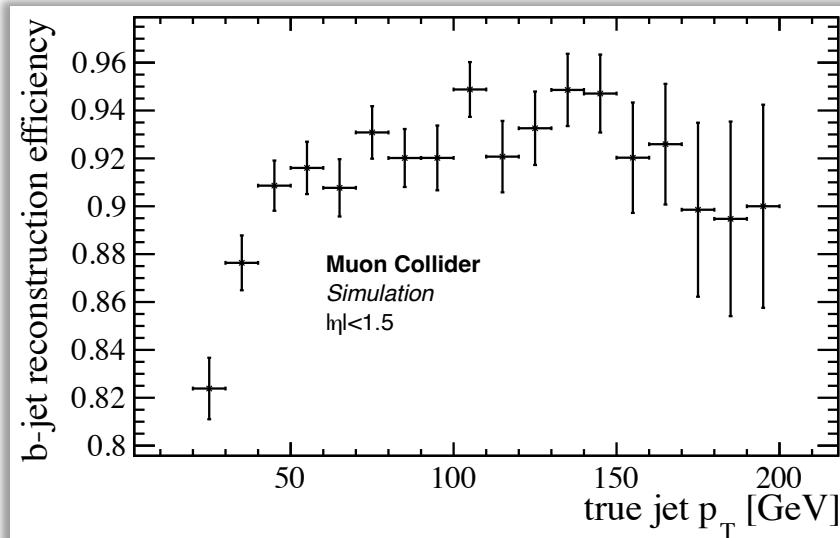
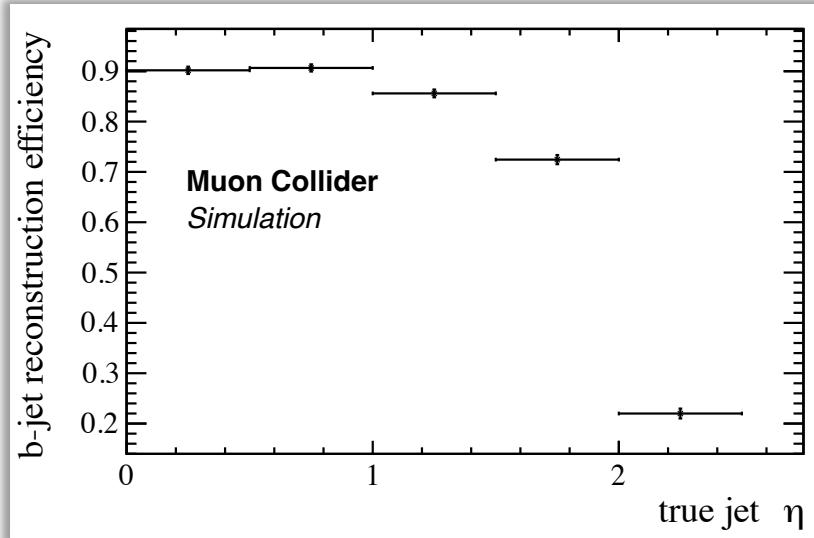
Track reconstruction performance



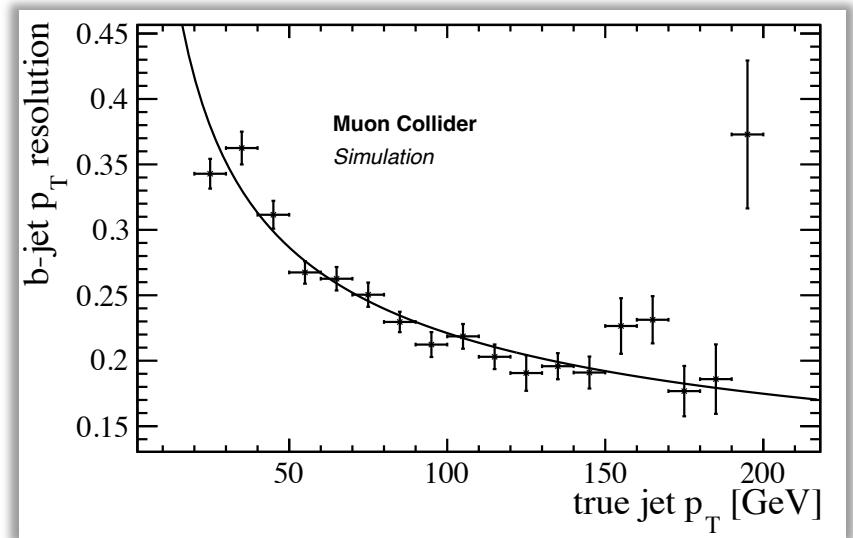
Jets reconstruction performance

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

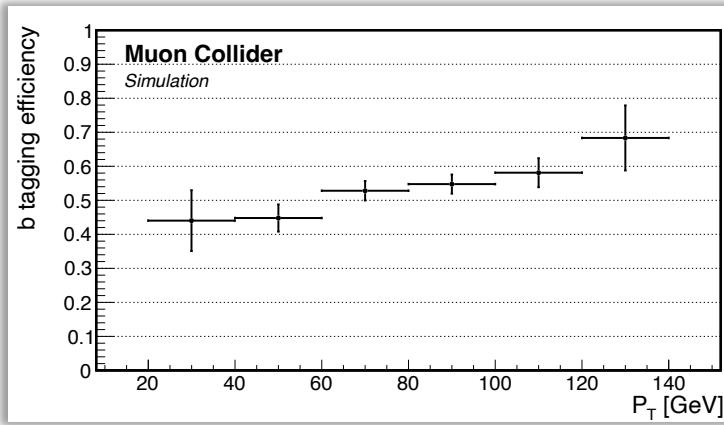


Resolution

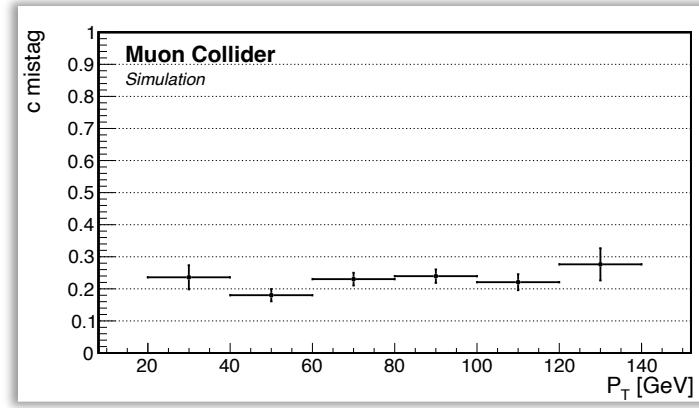


Heavy Flavor Jets Identification Performance

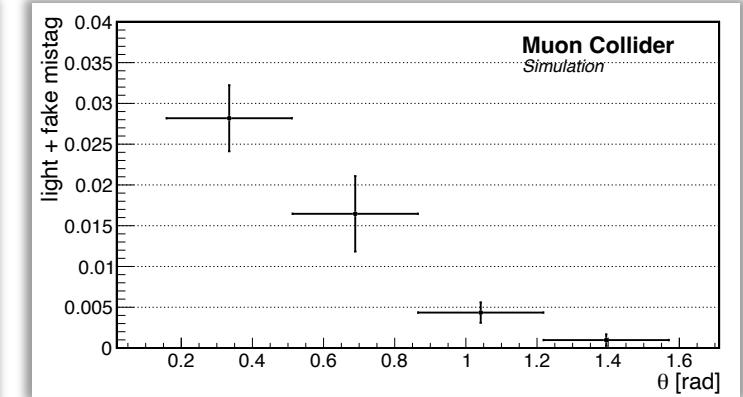
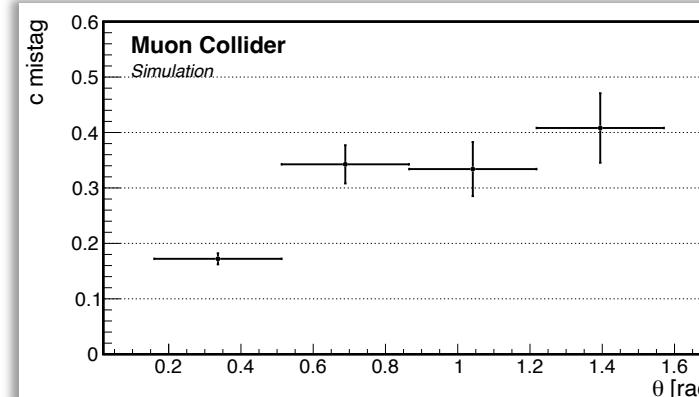
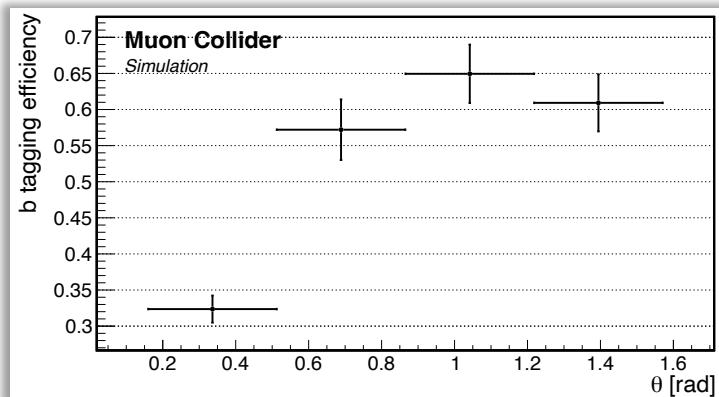
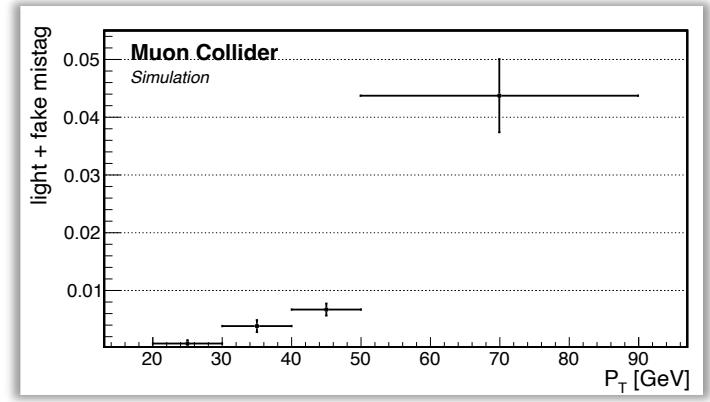
b-quark



c-quark



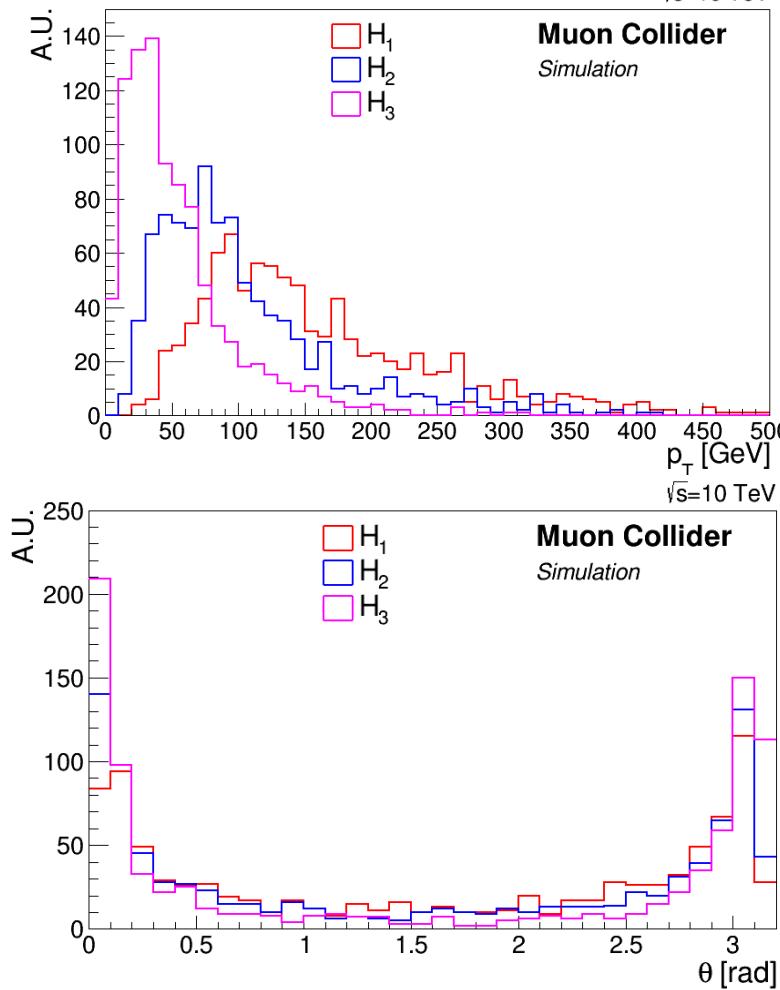
light-quark/fake jets



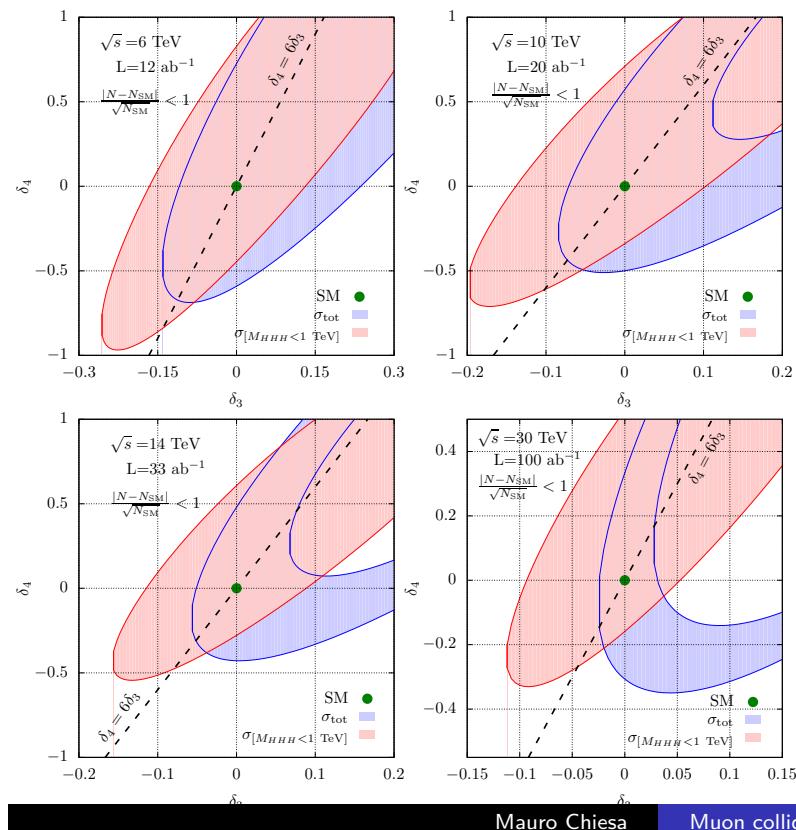
Triple Higgs

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

$\sqrt{s}=10 \text{ TeV}$



One sigma exclusion plots



$\delta_3 = 0$

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

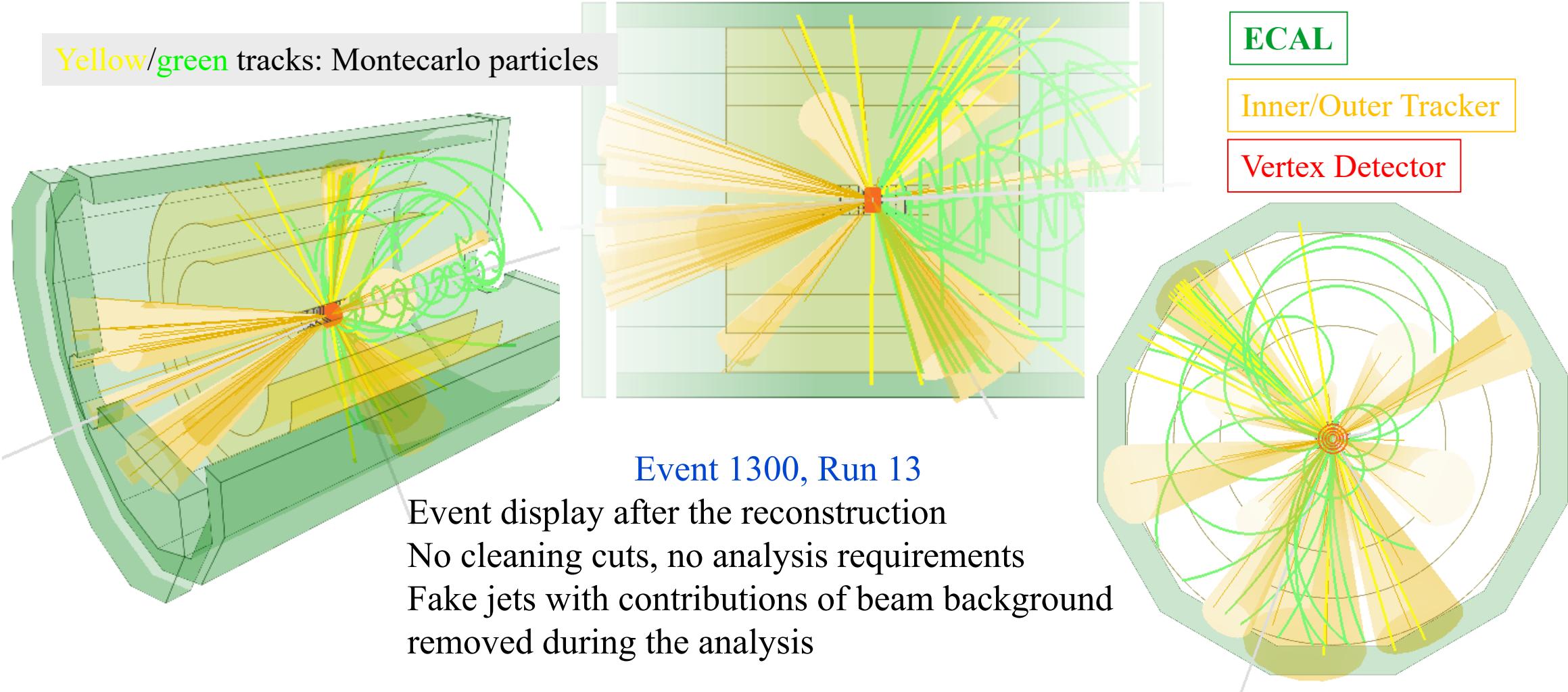
$$\frac{|N - N_{SM}|}{\sqrt{N_{SM}}}$$

Mauro Chiesa

Muon collider: quartic Higgs coupling

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

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



ILCSoft software stack:

1. LCIO
2. DD4hep
3. Marlin
4. ILCSoft

TO BE DONE

→ long term

Key4hep software stack:

- EDM4hep
- DD4hep
- Gaudi
- Spack

used only by us → no other maintainers

NO multithreading support

used and maintained by other experiments

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**