International MUON Collider Collaboration

MuCol

Higgs Prospects at Muon Collider

Donatella Lucchesi University and INFN of Padova, CERN

for the

International Muon Collider Collaboration

UK HEP Forum 2023: Completing the Higgs-saw puzzle

Cosener’s House

Abington Oxfordshire

Università degli Studi di Padova

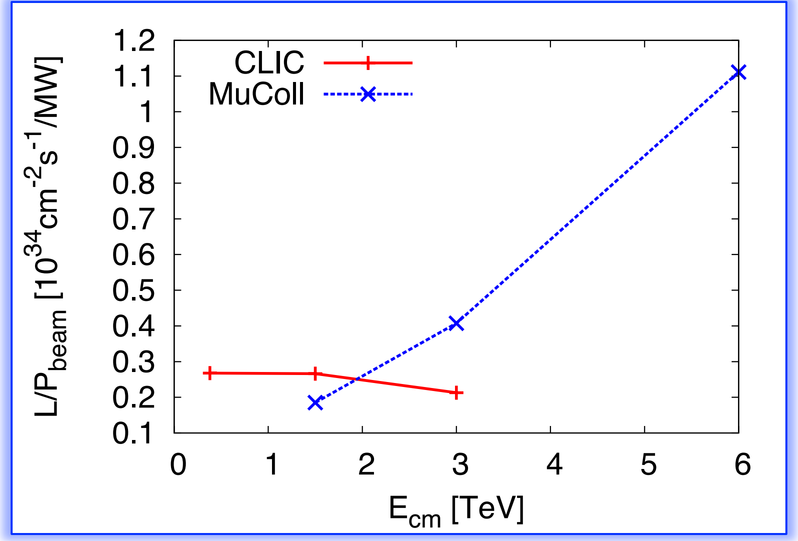
CERN

INFN
Istituto Nazionale di Fisica Nucleare

Advantages of multi-TeV muon collisions

$$P^{sync} \sim \frac{\alpha}{R^2}\left(\frac{E}{m}\right)^4$$ ➡ Possible to accelerate to very high energy

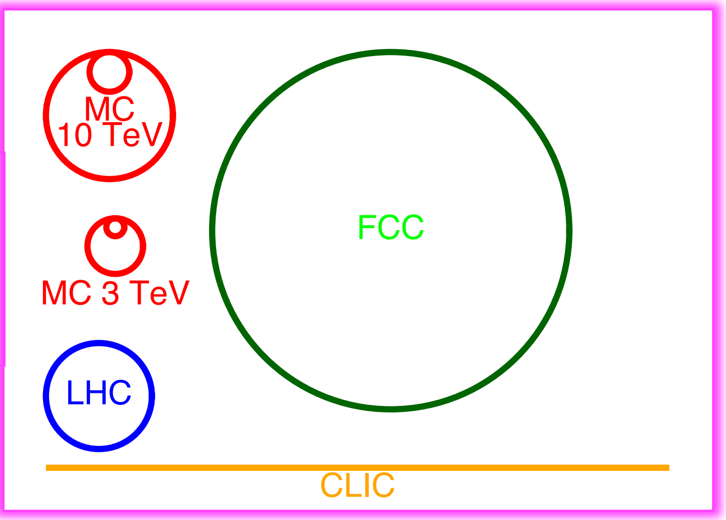
High center of mass energy & high luminosity & power efficient: luminosity increase per beam power



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

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



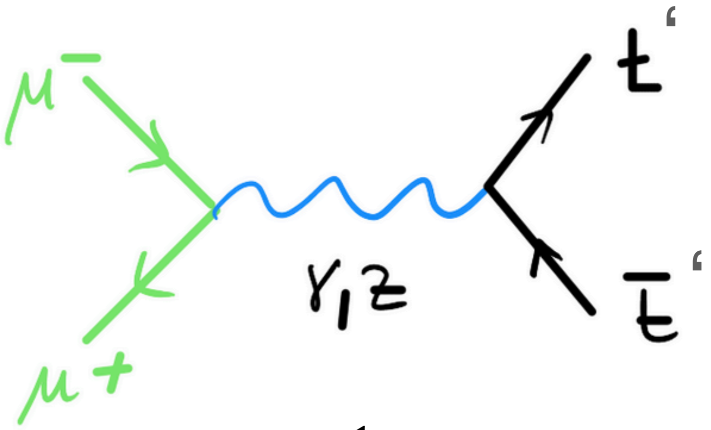
Integrated luminosity: $\sqrt{s}$ = 3 TeV 1 ab^{-1} 5 years one experiment

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

Advantages of multi-TeV muon collisions: two colliders in one

Multi-TeV muon collider opens a completely new regime :

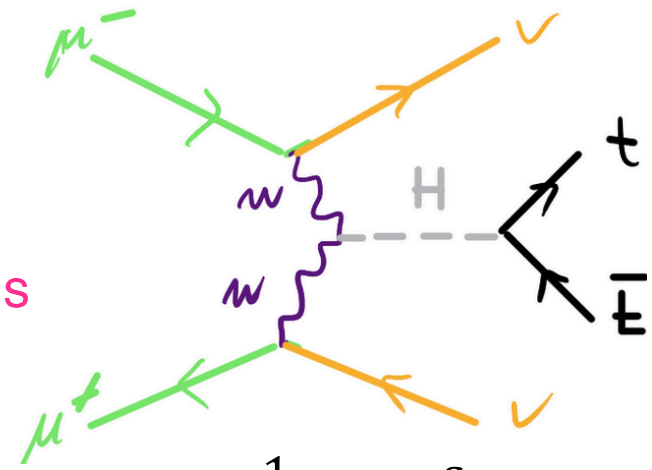
F. Maltoni
"Physics Overview" Annual Meeting IMCC



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

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

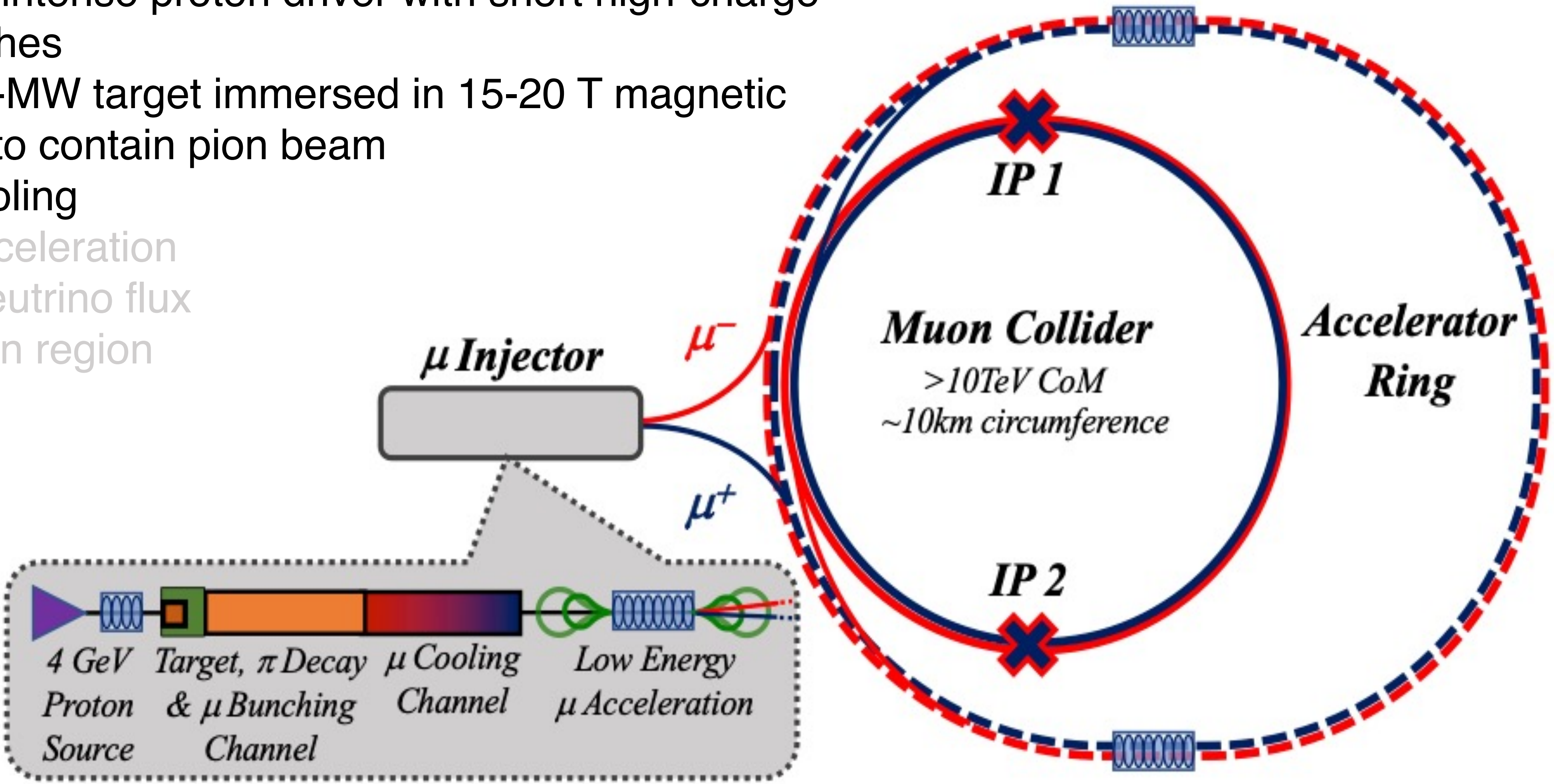
Muon Colliders, 1901.06150
The muon Smasher's guide, *Rept.Prog.Phys.* 85 (2022) 8, 084201 2103.14043
Muon Collider Forum Report, 2209.01318
Towards a Muon Collider, *Eur.Phys.J.C* 83 (2023) 9, 864, 2303.08533

Muon Collider Facility in a nutshell

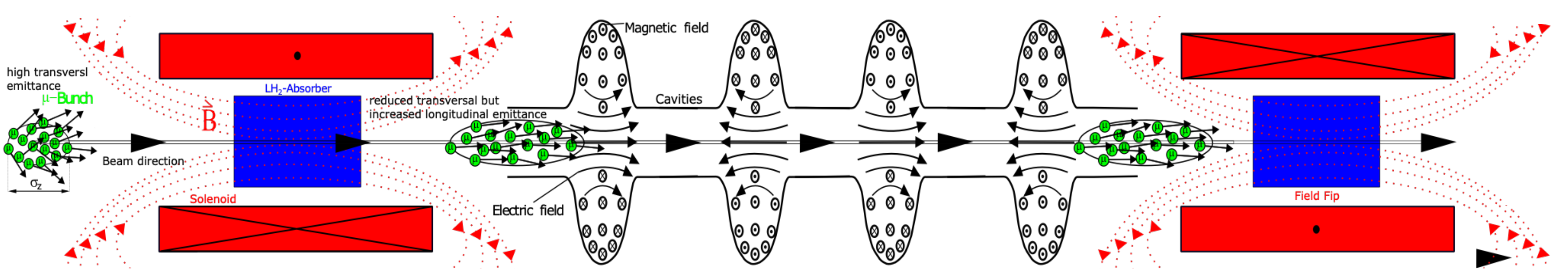
If not specified material is taken from
C. Accettura et al. "Towards a muon collider”

Key challenges

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



Muon ionization cooling principle



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

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

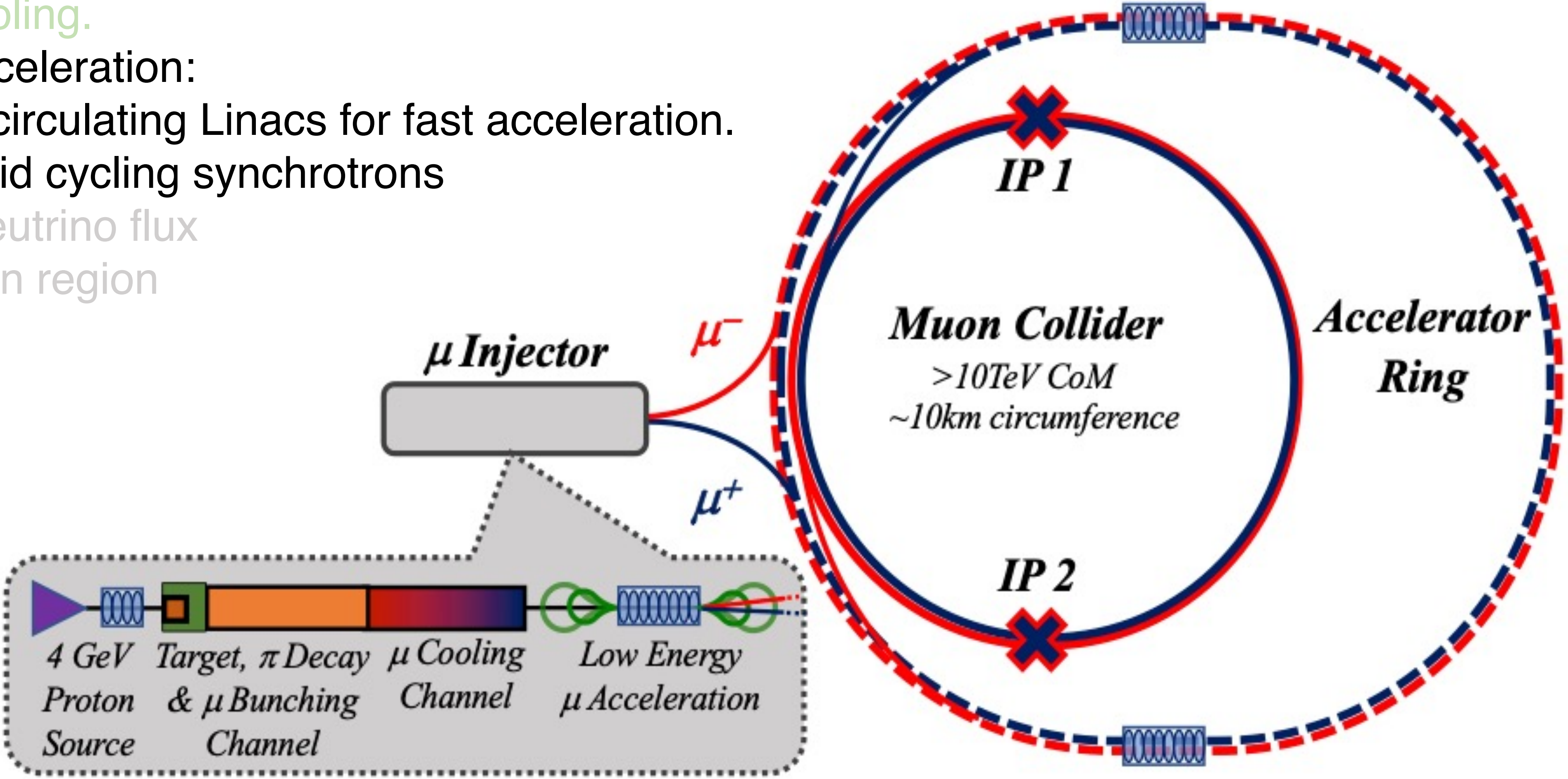
Two cooling stages:

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

Design baseline overview

Key challenges

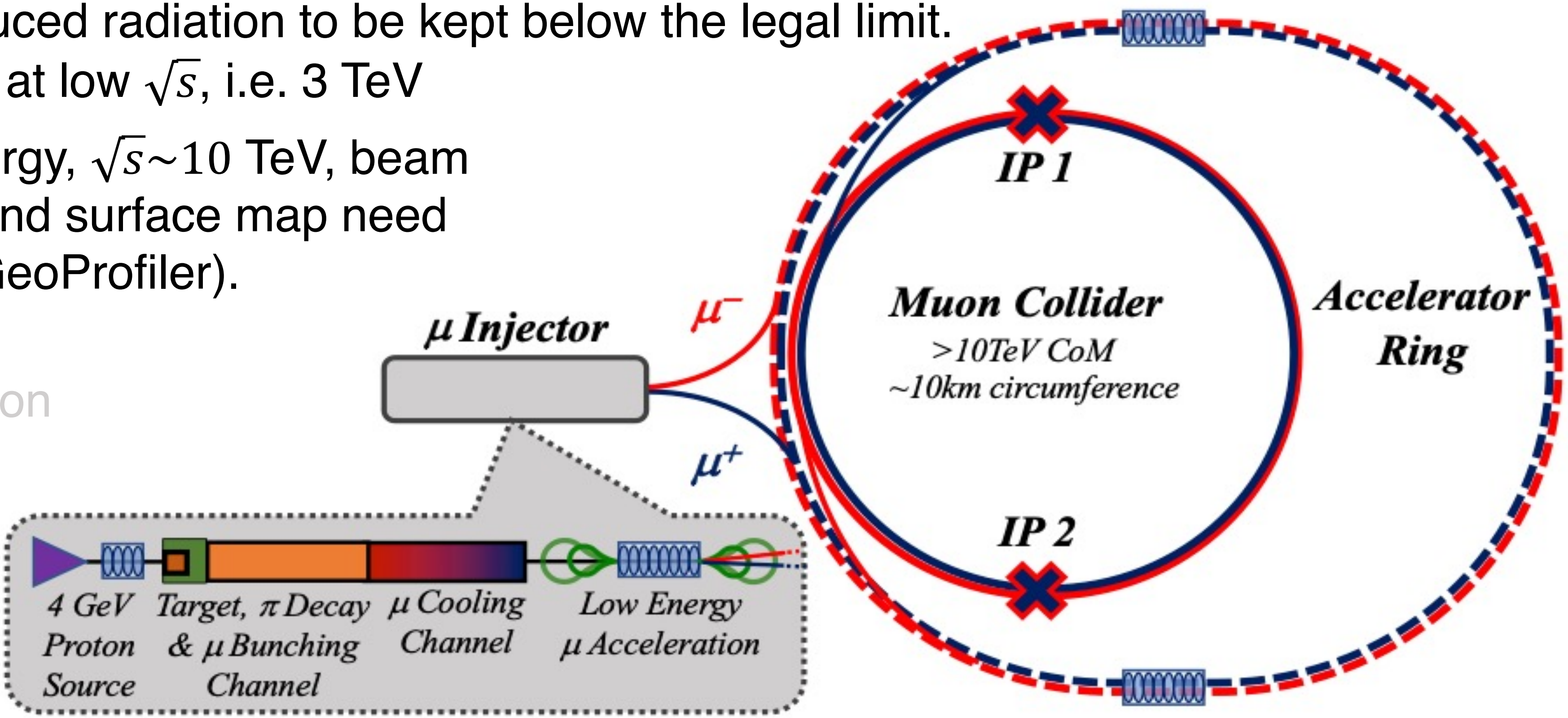
- Proton source.
- Muon cooling.
- Beam acceleration:
  1) Re-circulating Linacs for fast acceleration.
  2) Rapid cycling synchrotrons
- Dense neutrino flux
- Interaction region



Design baseline overview

Key challenges

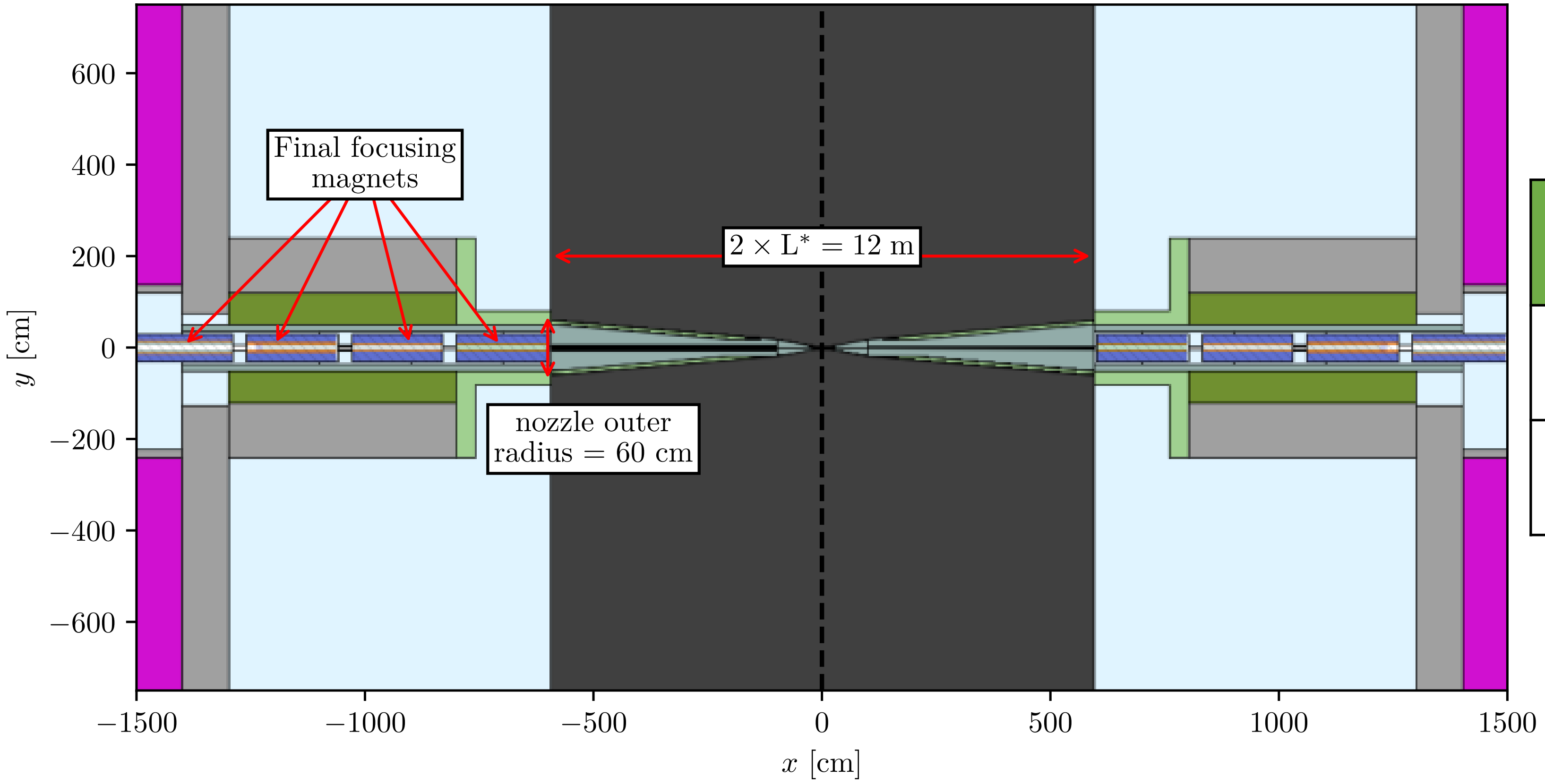
- ❊ Proton source.
- ❊ Muon cooling.
- ❊ Beam acceleration
- ❊ Dense neutrino flux
  - Possible induced radiation to be kept below the legal limit.
  - Not an issue at low $\sqrt{s}$, i.e. 3 TeV
  - At higher energy, $\sqrt{s}\sim 10$ TeV, beam parameters and surface map need to be used (GeoProfiler).
- ❊ Interaction region



Collider interaction region

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

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

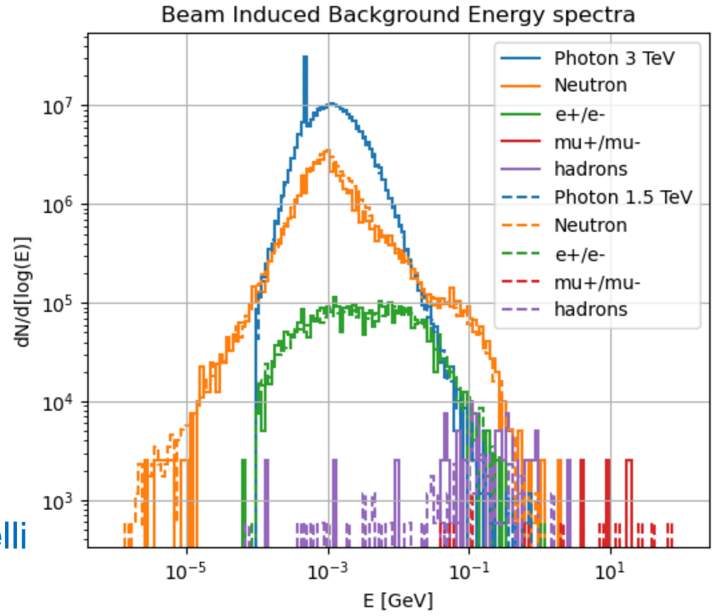


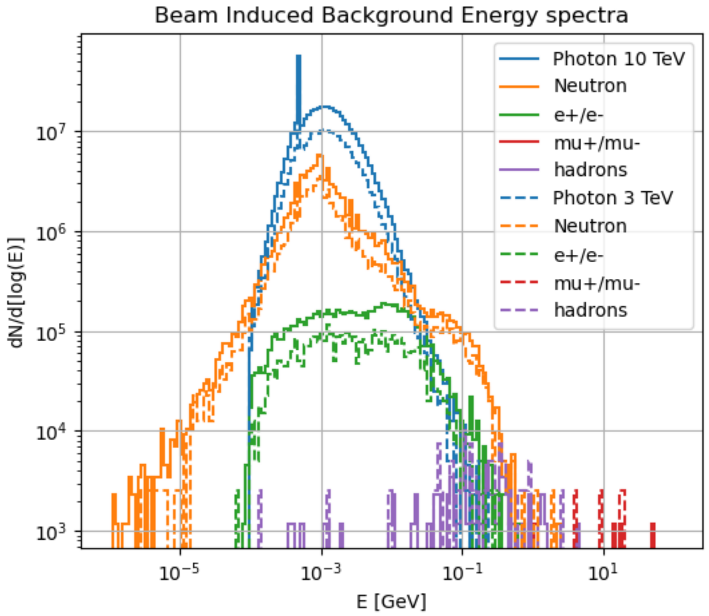
	LHC	MC $\sqrt{S} = 10$ TeV
bunch length σ_z	7.7 cm	1.5 mm
bunch size $\sigma_\perp$	16.7 μm	0.9 μm

Single bunch mode

Beam background sources in the detector region

- ✗ 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 electrons in collider magnetic field
  - ❋ electromagnetic showers from electrons and photons
  - ❋ hadronic component from photonuclear interaction with materials
  - ❋ Bethe-Heitler muon, $\gamma + A \to A' + \mu^+\mu^-$
- ✗ 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
- ✗ Beam halo: level of acceptable losses to be defined, not an issue now



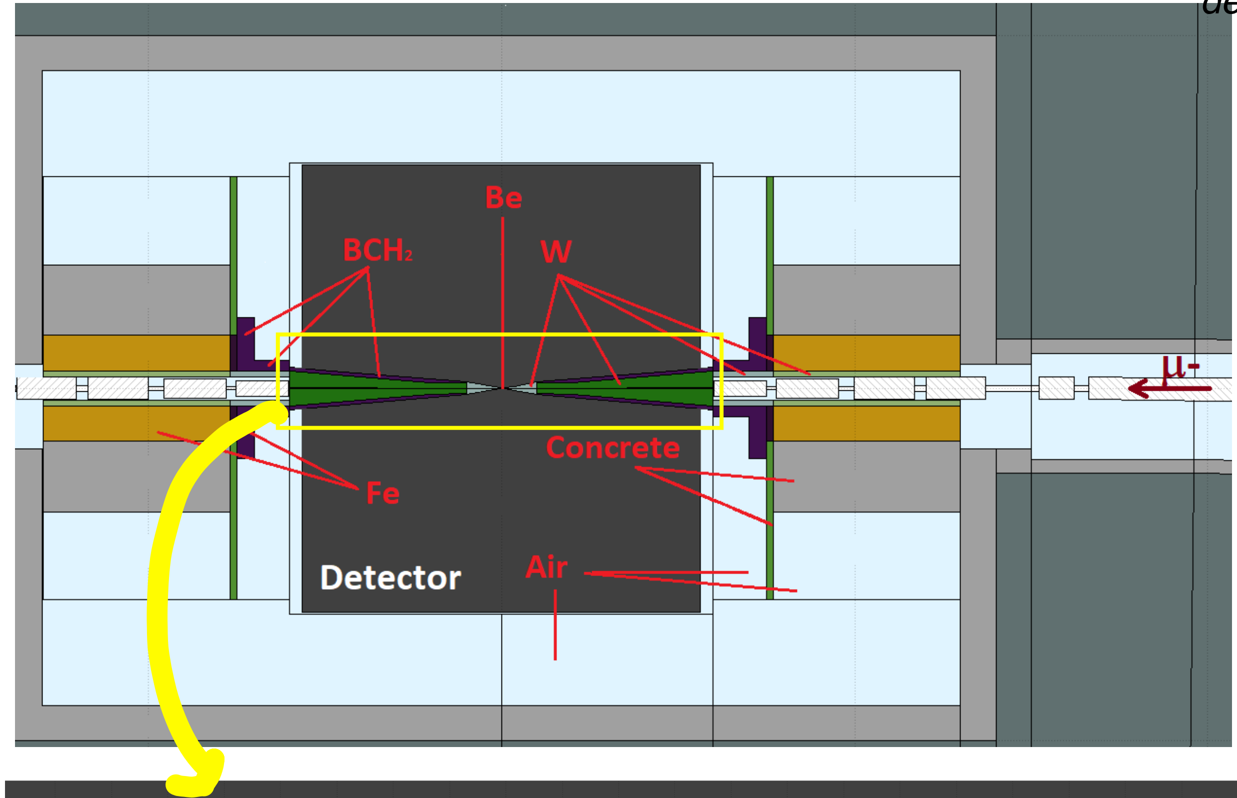


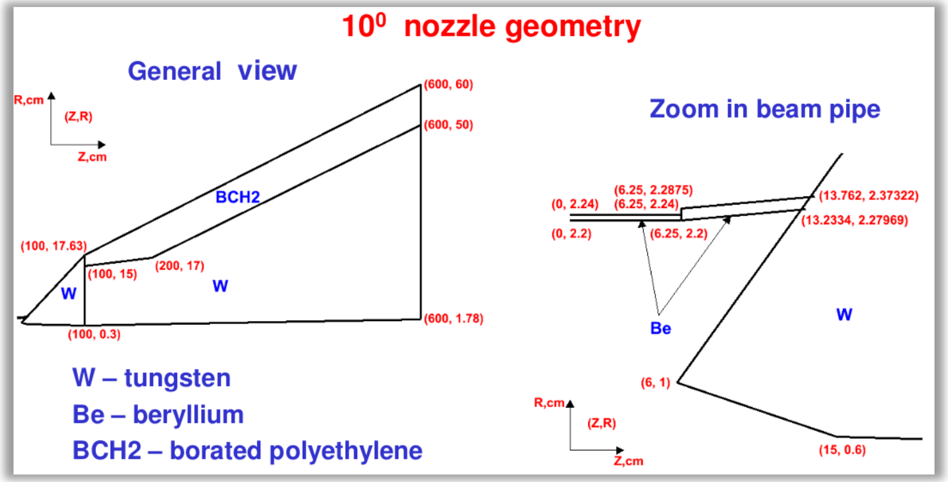
D. Calzolari, L. Castelli

Shielding structure: the nozzles

Designed by MAP (Muon Accelerator Program)

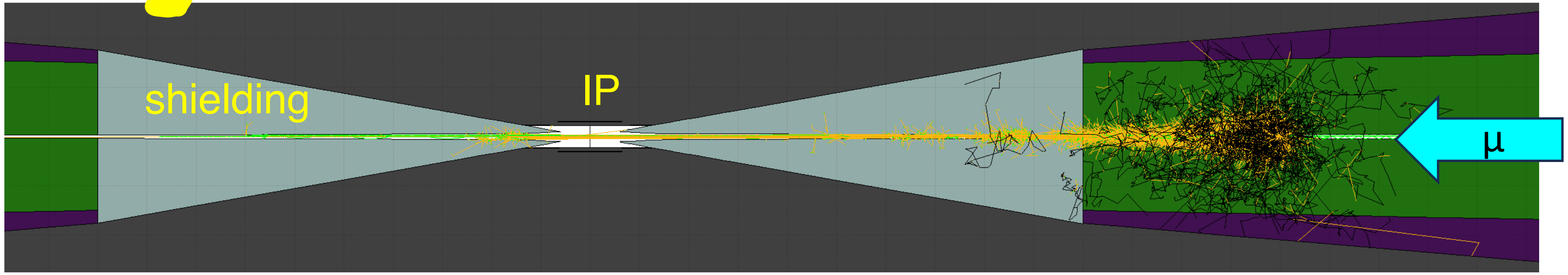
N.V. Mokhov et al. *Muon collider interaction region and machine-detector interface design* Fermilab-Conf-11-094-APC-TD





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

F. Collamati et al. 2021 JINST 16 P11009



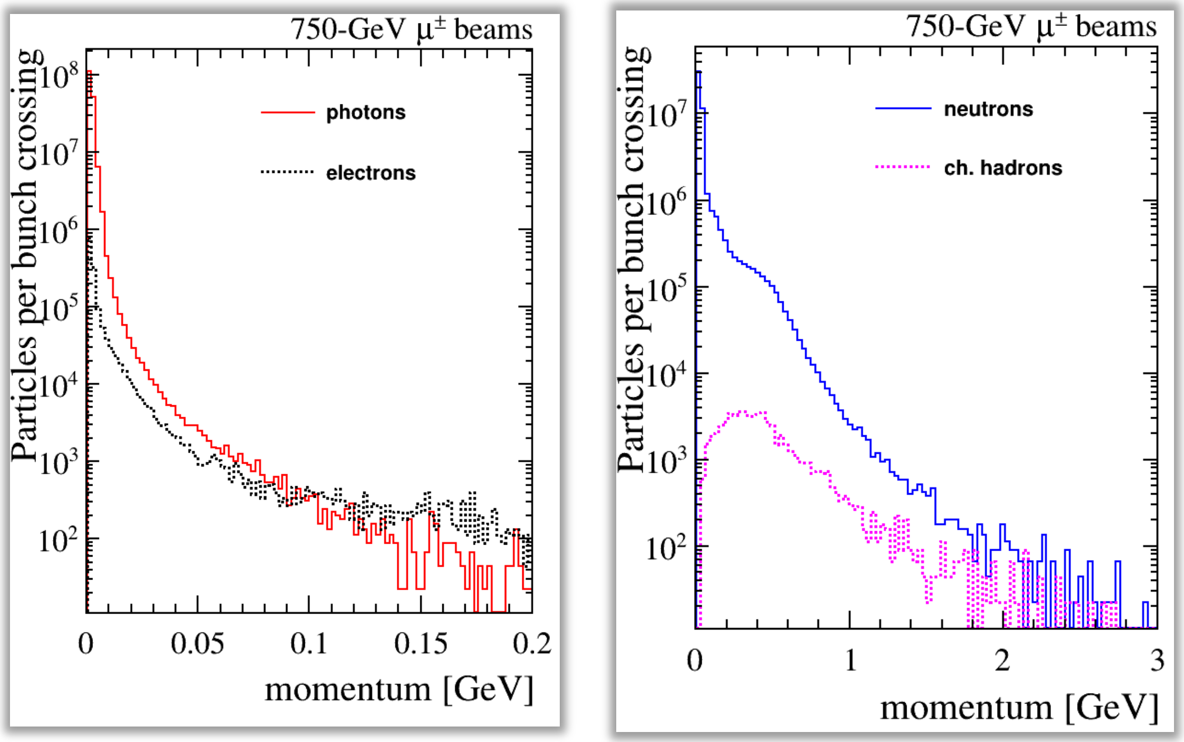
Single muon decay tracks

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

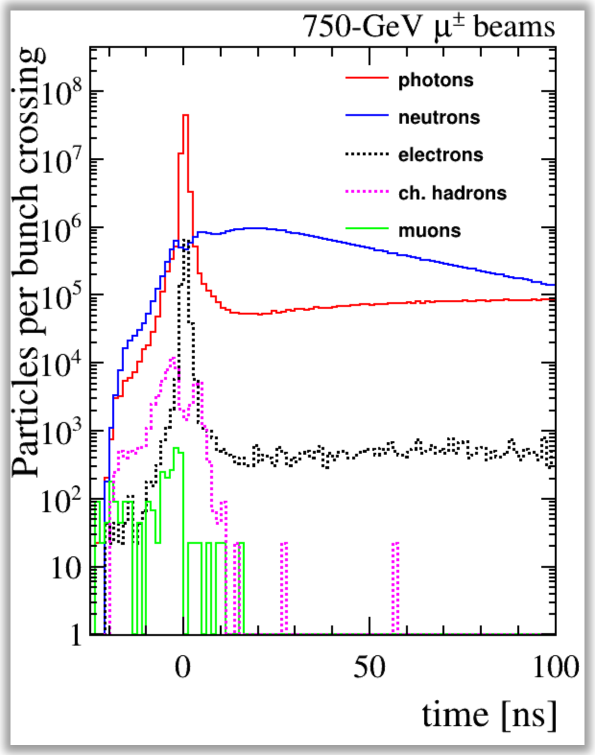
Survived beam-Induced background (BIB) properties

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 concept for multi-TeV muon collisions

It must cope with the beam-induced background:

- nozzles have to be part of the detector
- Sub-detector technologies need to be appropriate for large fluxes of low energy particles

$\sqrt{S} = 3$ TeV and $\sqrt{S} = 10$ TeV have different physics characteristics ⇒ different requirements:

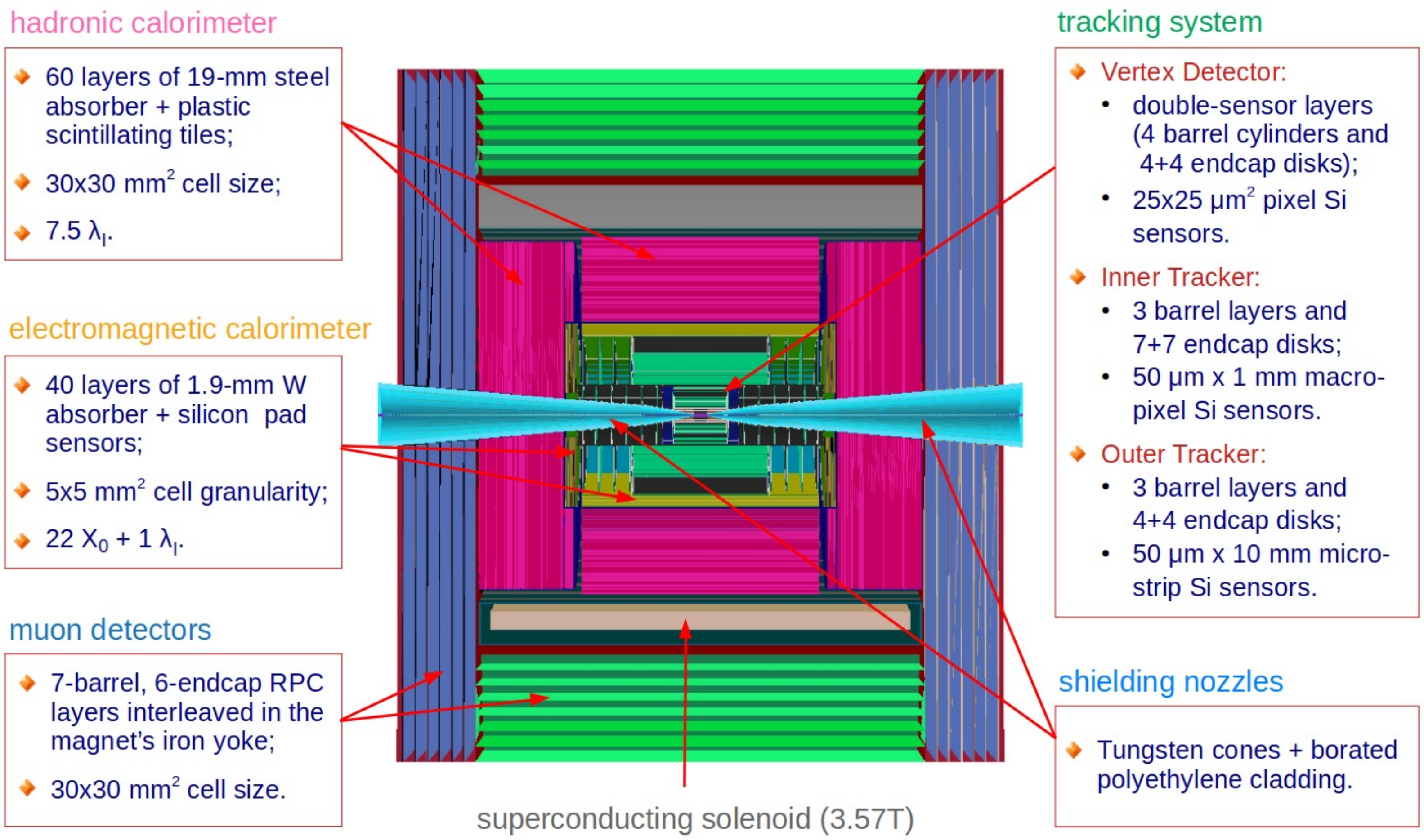
- $\sqrt{S} = 3$ TeV is well known thanks to CLIC's studies
- $\sqrt{S} = 10$ TeV study in progress

✗ ILCSoft is the simulation and reconstruction framework, initially forked from CLIC's software. Nowadays, quite well developed package MuonColliderSoftware. Transition to key4hep in progress. Recent tutorial in July 2023 (MuCol Project)

❊ Data taking in trigger-less mode

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

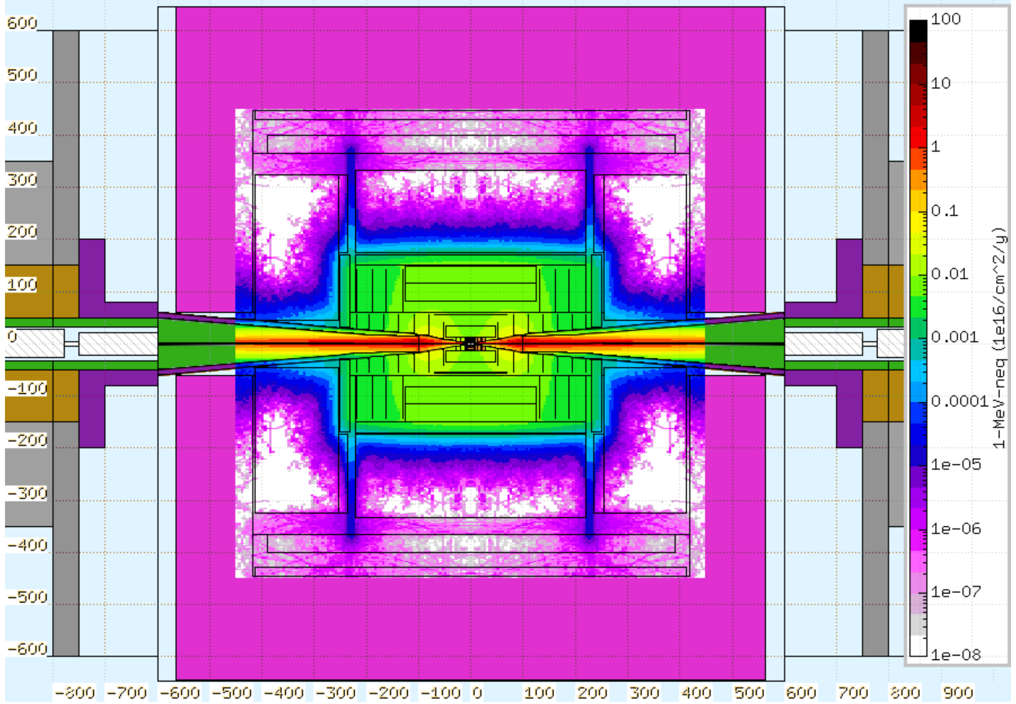
- Removed forward luminosity detectors
- Inserted nozzles
- Adapted tracker detector
- Magnetic field modified to cope with available beam-induced background



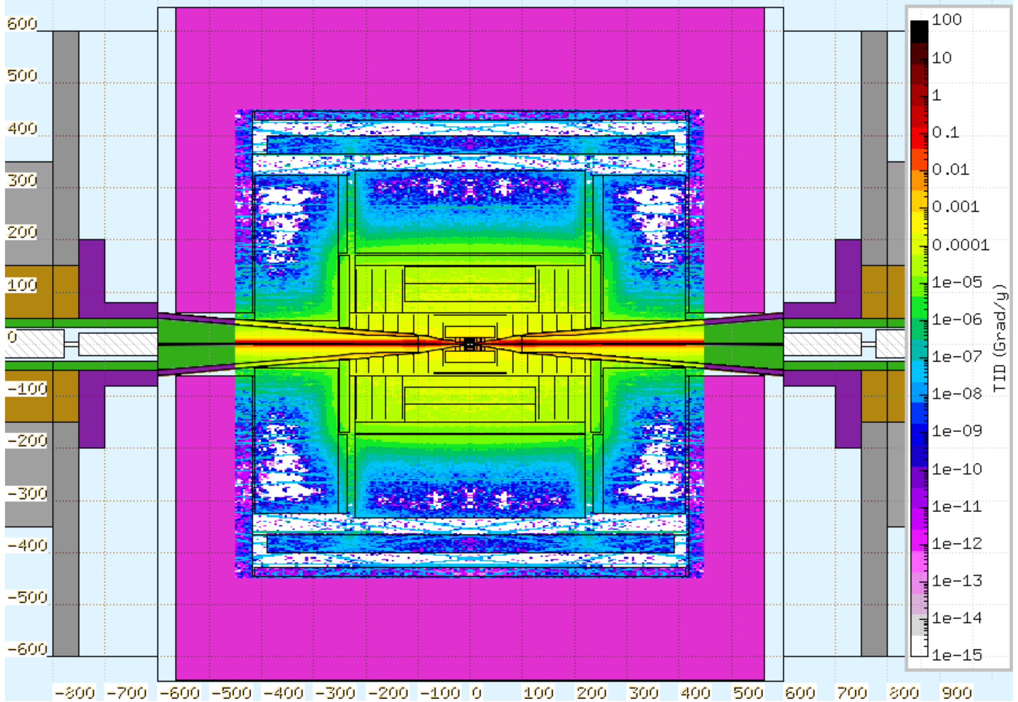
C. Accettura et al. "Towards a muon collider"
CLIC: H. Abramowicz et al., Eur. Phys. J. C 77, 475 (2017)

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

Expected Radiation hardness requirements like HL-LHC

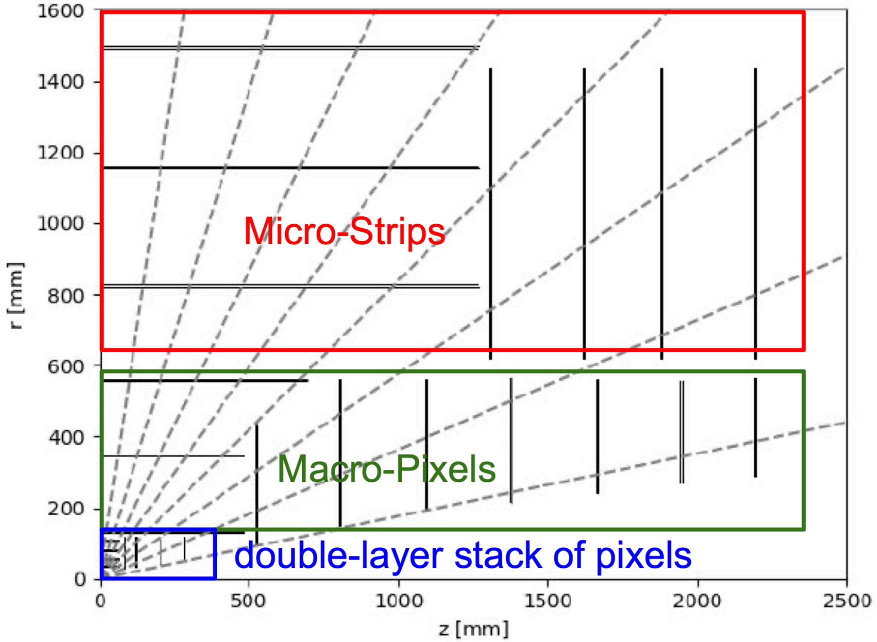
	Maximum Dose (Mrad)		Maximum Fluence (1 MeV-neq/cm^2)	
	R= 22 mm	R= 1500 mm	R= 22 mm	R= 1500 mm
Muon Collider	10	0.1	10^{15}	10^{14}
HL-LHC	100	0.1	10^{15}	10^{13}

K. Black, Muon Collider Forum Report

$\sqrt{S} = 3$ TeV and $\sqrt{S} = 10$ TeV similar values expected ⇒ dominated by BIB

Tracking system: full detector & BIB simulation

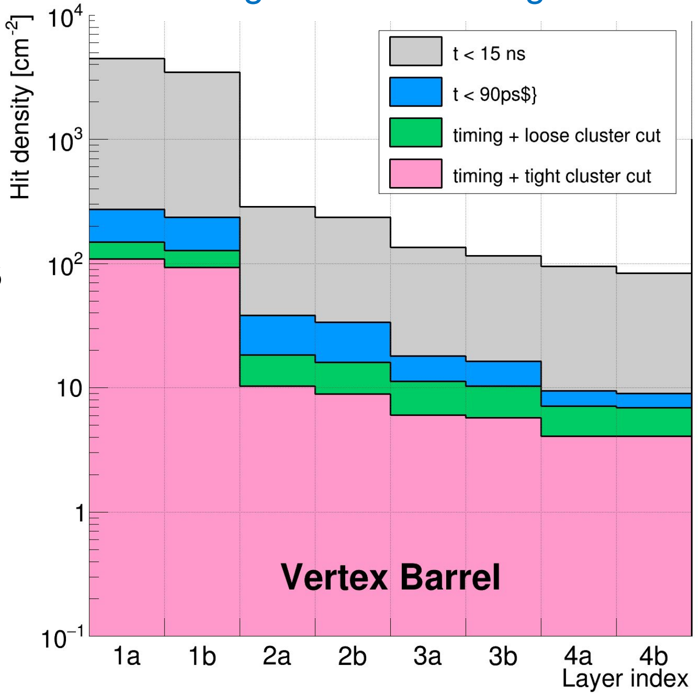
First layers of barrel vertex detector & forward disks highly impacted BIB



Tracker requirements

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

S. Pagan Griso C. Sellgren

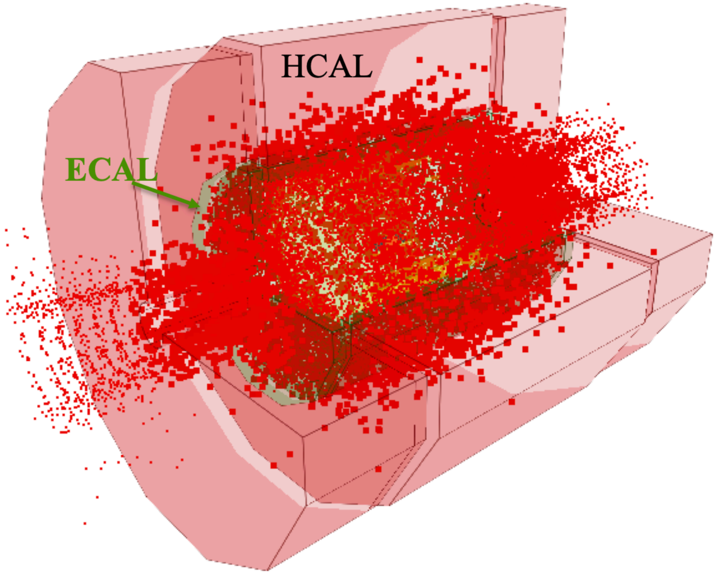


Higher occupancies with respect to LHC detectors crossing rate 100 kHz vs 40 MHz

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

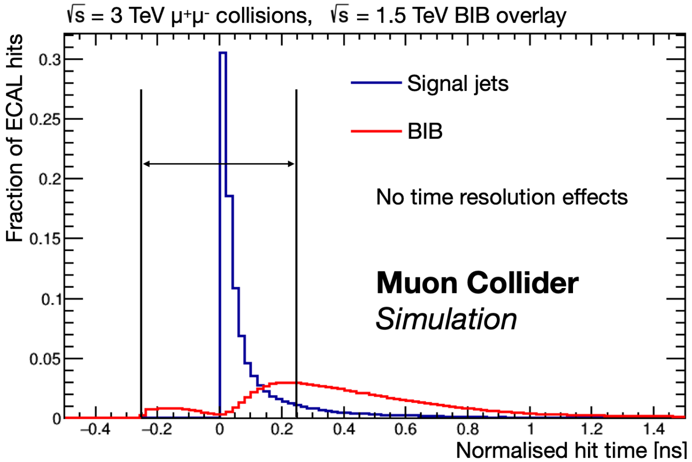


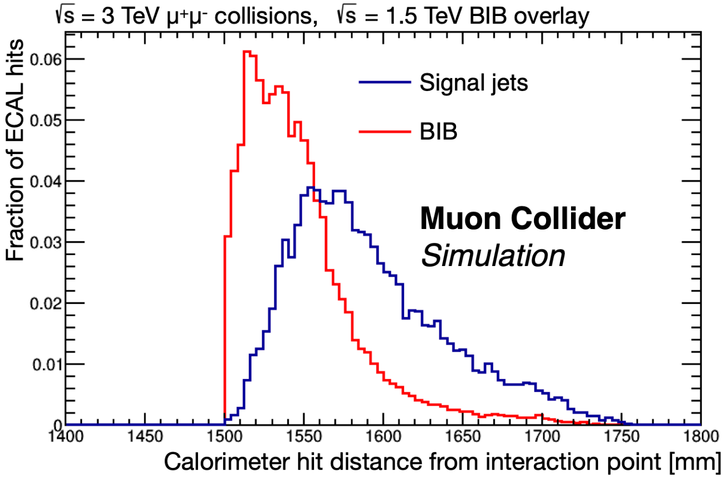
ECAL surface flux: 300 particle/cm^2

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

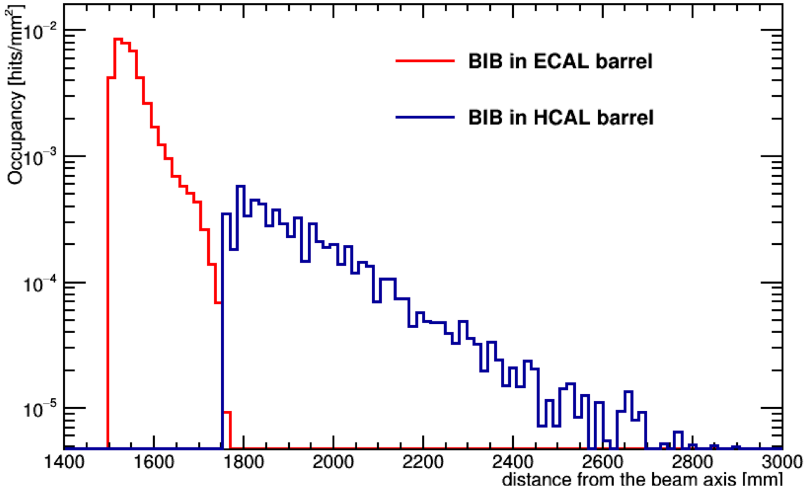
Calorimeter requirements

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





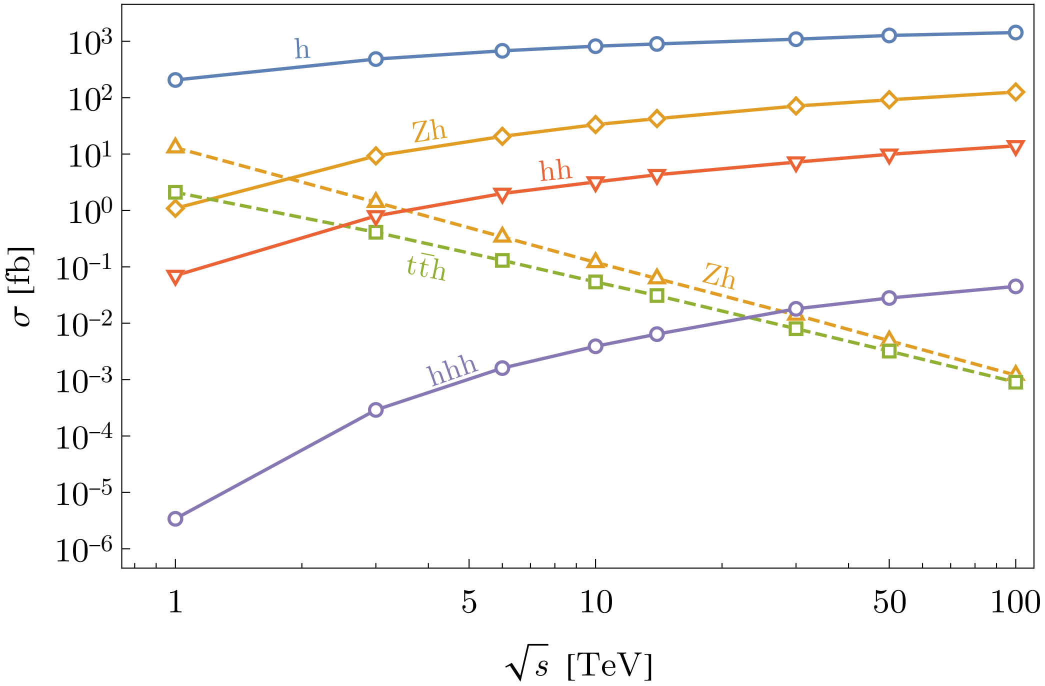
Occupancy: ECAL > 10 times HCAL



Dedicated ECAL R&D: **Crilin**
Each module: 5 layers of PbF_2 crystals (10x10x40 mm^3)
Cerenkov light detected with SiPMs
Dedicated HCAL proposal in progress.

Higgs Physics at Muon Collider

Ali HA et al.



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—— VBF

⇒

M. Casarsa et al. EPS-HEP2023 408

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

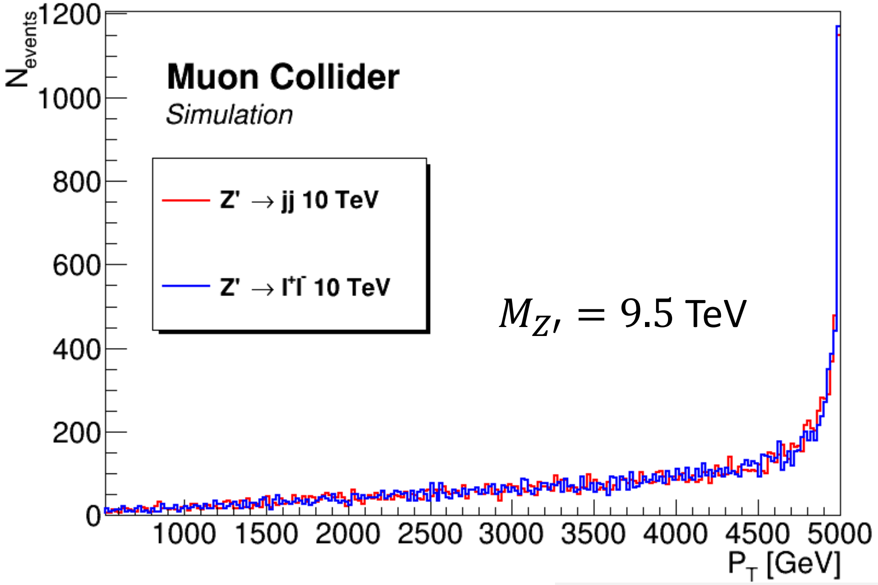
$\sqrt{s}$ = 3 TeV 1 ab^{-1} 5 years one experiment

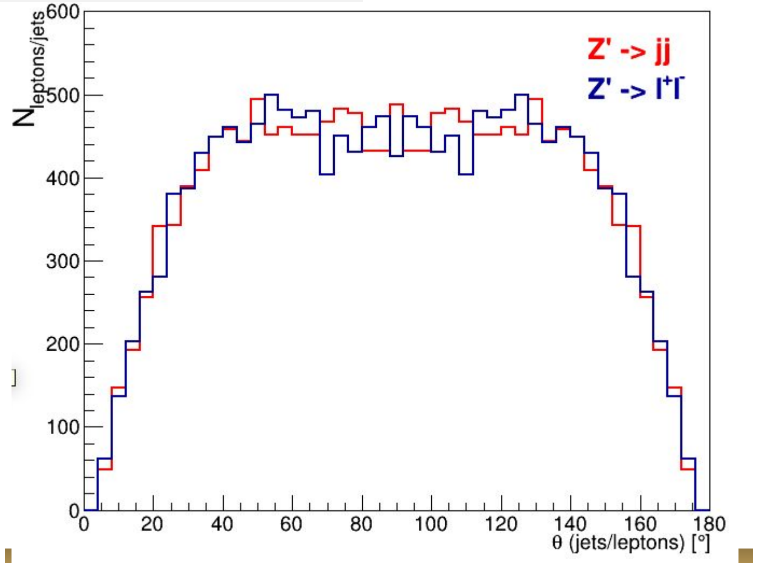
$\sqrt{s}$ = 10 TeV 10 ab^{-1} 5 years one experiment

Higgs kinematics

Heavy objects, Z', have high momentum and central decay products

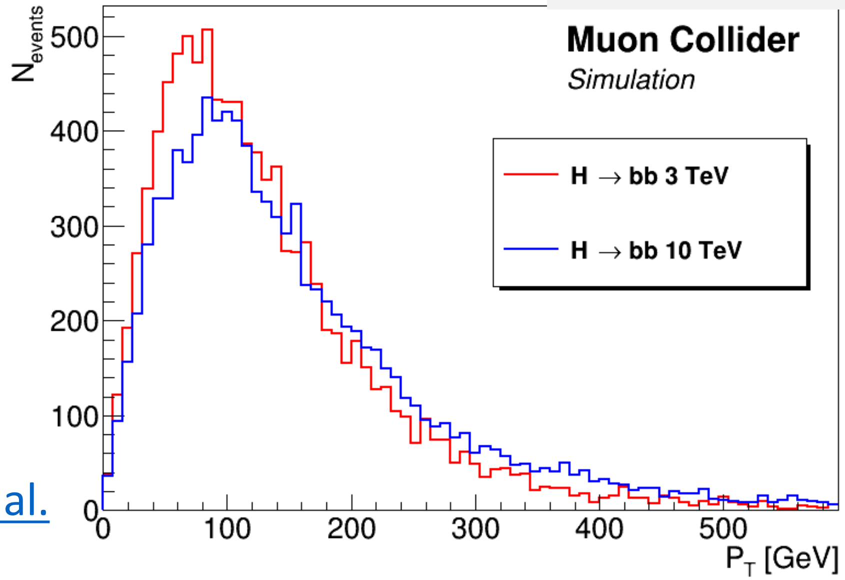
$\mu^+\mu^- \to Z'X \to jj/\ell\ell X\ \sqrt{s} = 10$ TeV

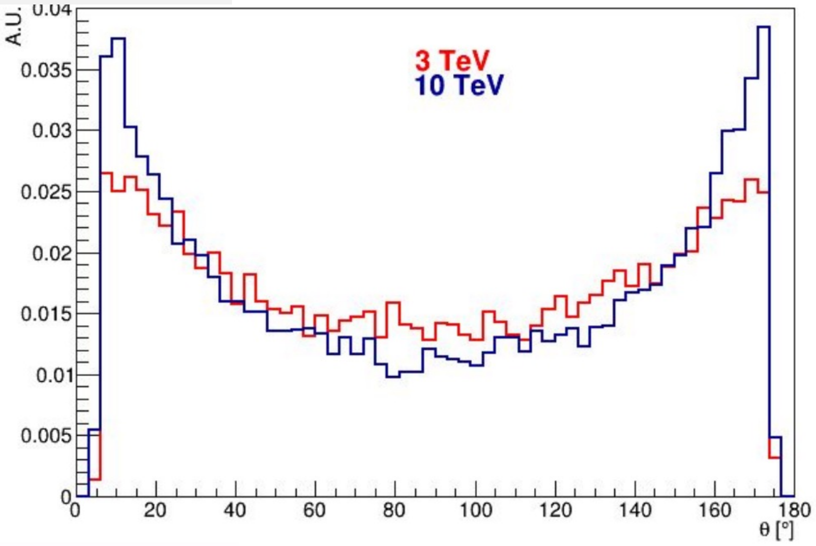




Higgs boson decay products are similar in momentum at $\sqrt{s} = 3$ TeV and $\sqrt{s} = 10$ TeV, more forward at high energy.

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





M. Casarsa et al.

Higgs study introduction

Higgs production mode: W bosons fusion
Higgs decay modes: $b\bar{b}, WW^*, ZZ^*, \gamma\gamma, \mu\mu$

Monte Carlo generators: Whizard and MadGraph5 aMC@NLO
Hadronization: Pythia8

Signal and physics background processed with detailed detector simulation including the beam-induced background

The results at $\sqrt{s} = 3$ TeV are compared to CLIC, not always with the same luminosity not always the same final states.

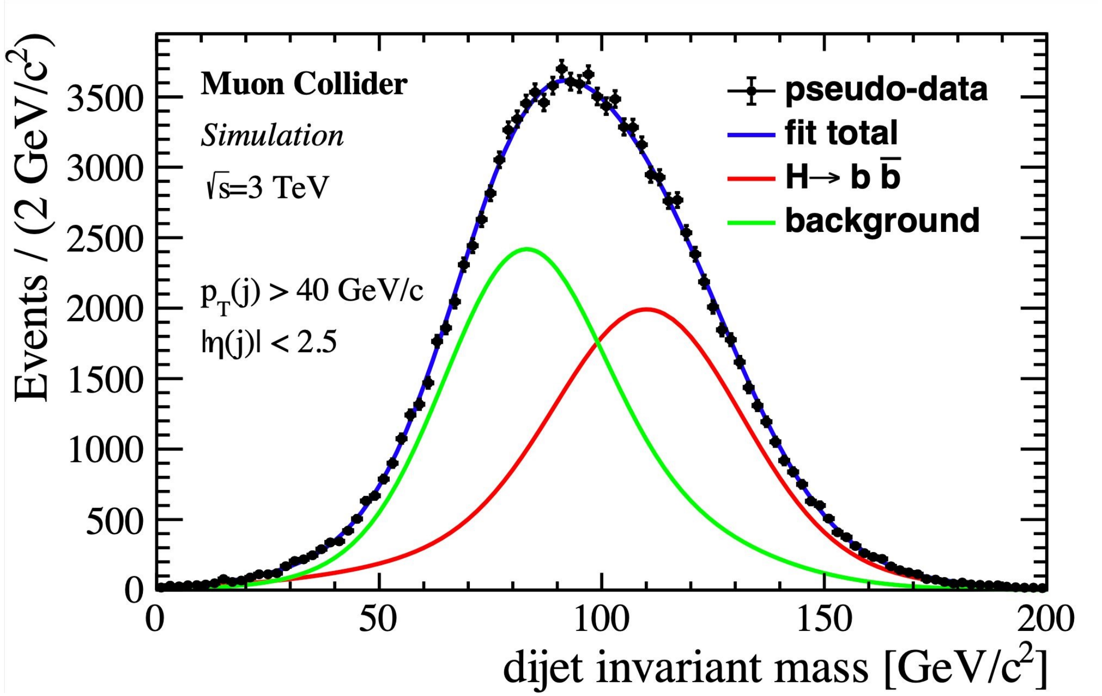
$\mu^+\mu^- \rightarrow H\nu\bar{\nu} \rightarrow b\bar{b}\nu\bar{\nu}$

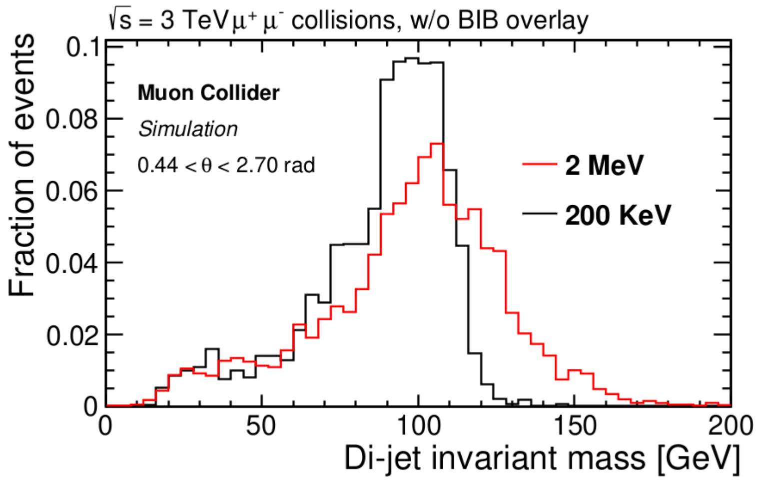
L. Buonincontri Master's thesis University of Padova

M. Casarsa et al.

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

- $P_T^{jet} > 40$ GeV, $|\eta^{jet}| < 2.5$





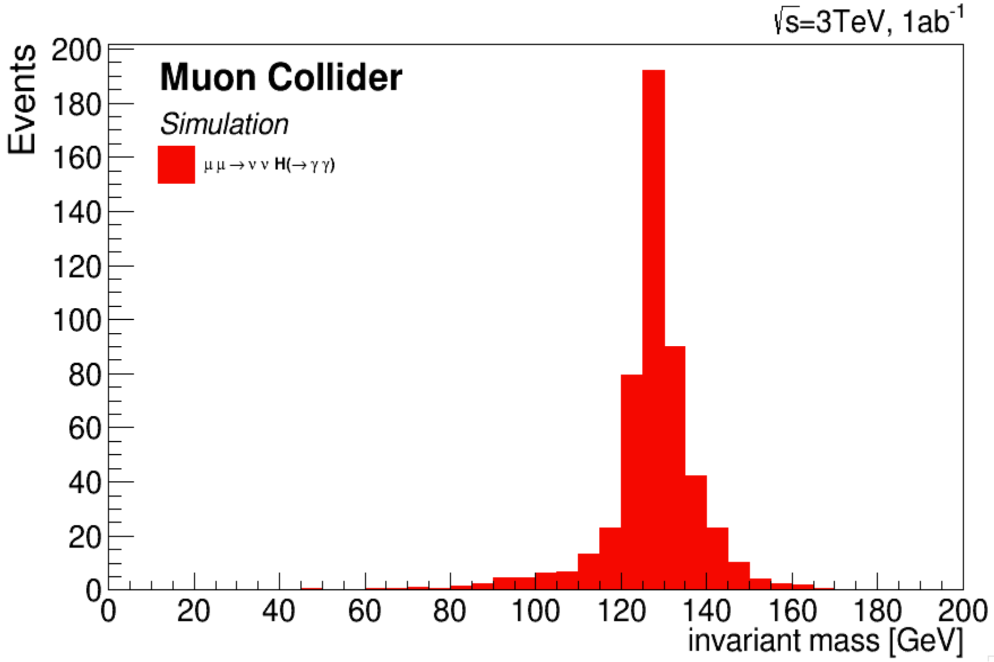
$\frac{\Delta\sigma_{H\rightarrow b\bar{b}}}{\sigma_{H\rightarrow b\bar{b}}} \sim 0.75\%$ 1 experiment 1 ab^{-1}

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

$\mu^+\mu^- \rightarrow H\nu\bar{\nu} \rightarrow \gamma\gamma\nu\bar{\nu}$ D. Zuliani et al.

- $E_\gamma > 15$ GeV
- $P_T^\gamma > 10$ GeV
- $10^o < \theta_\gamma < 170^o$

High energy photons reconstruction not significantly affected by beam-induced background.
Invariant mass resolution: 3.2 GeV



$$\frac{\Delta\sigma_{H\rightarrow\gamma\gamma}}{\sigma_{H\rightarrow\gamma\gamma}} = 7.6\%$$ 1 experiment 1 ab^{-1}

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

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

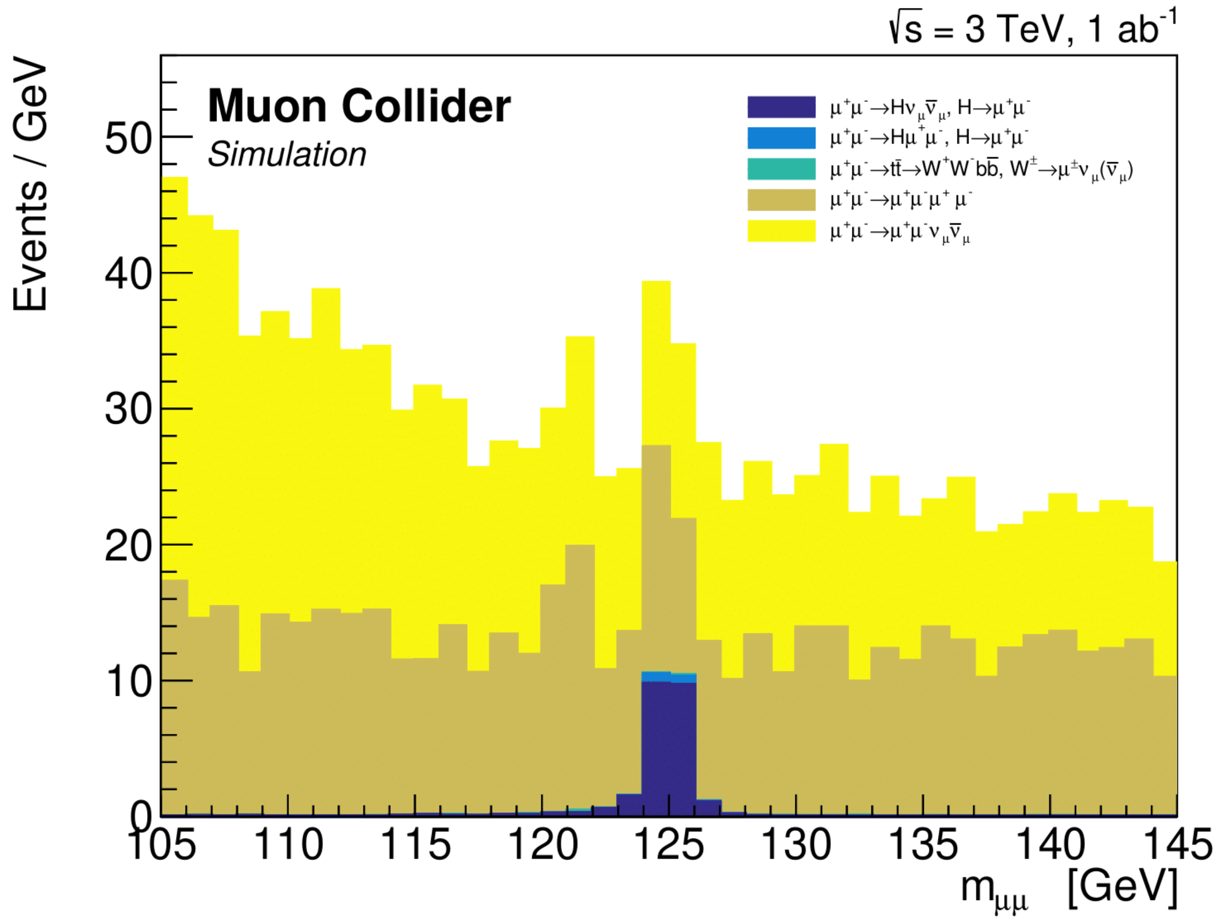
A. Montella et al.

- Two oppositely charged muons
- $P_T^\mu > 5$ GeV
- $10^o < \theta_\mu < 170^o$

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

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

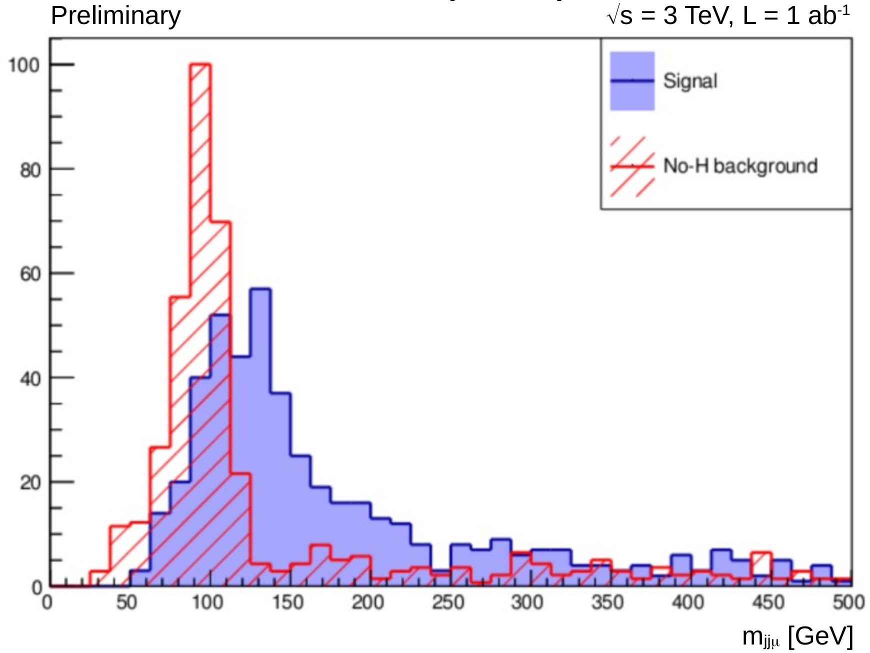
Muon Collider performance limited by the nozzles that prevent to tag forward muons and to measure missing energy with high resolution.



$\mu\mu \to H\nu\bar{\nu} \to WW^* \to \mu\nu_\mu q\bar{q}'$

L. Castelli, Master's Thesis, Univ. of Padua

- $P_T^\mu > 10$ GeV, $10^o < \theta_\mu < 170^o$
- $P_T^{jet} > 20$ GeV, $|\eta^{jet}| < 2.5$



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

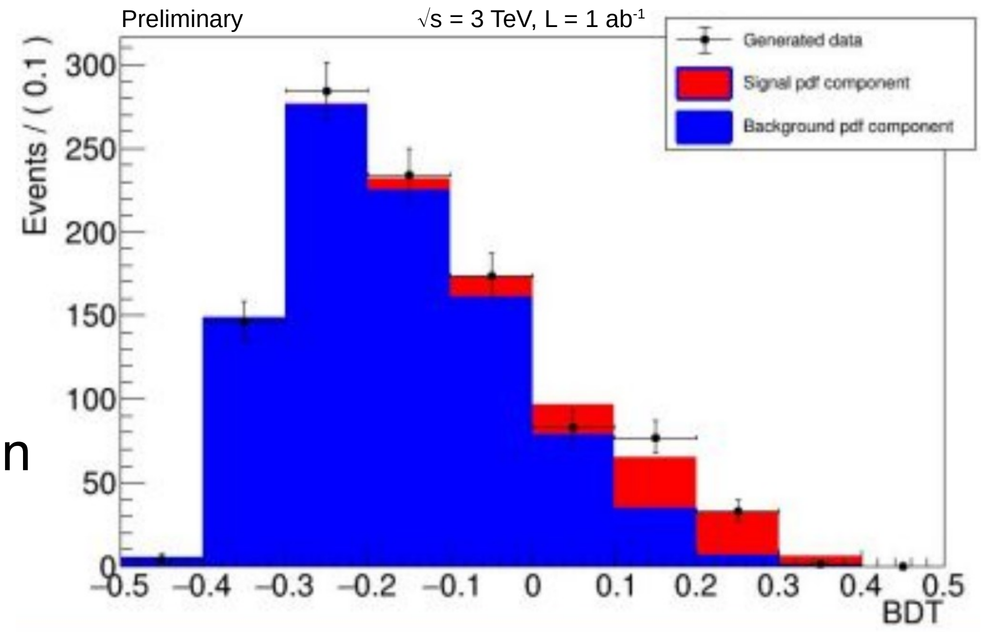
CLIC at 3 TeV 2 ab^{-1} ($\ell\nu_\ell q\bar{q}'$ $+q\bar{q}'q\bar{q}'$): 0.7%

Jet reconstruction limited by BIB

$\mu\mu \to H\nu\bar{\nu} \to ZZ^* \to \mu\mu q\bar{q}'$

M. Casarsa et al.

- $P_T^\mu > 10$ GeV, $10^o < \theta_\mu < 170^o$
- $P_T^{jet} > 15$ GeV, $30^o < \theta_{jet} < 150^o$



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

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

Higgs couplings determination

David A, et al., arXiv:1209.0040

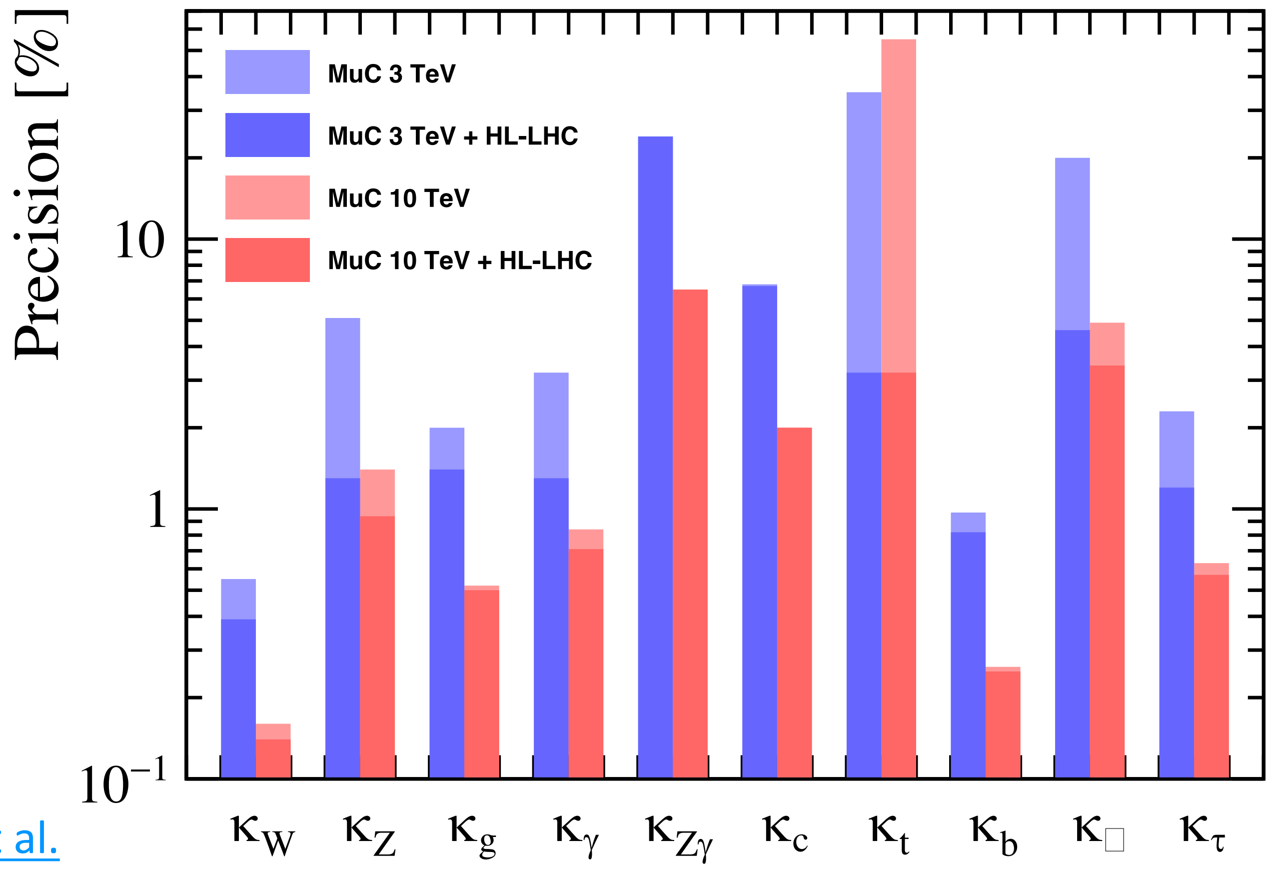
Measurement of $\sigma_H \times BR(H \to f)$ allows determination of H to f coupling in the k-framework
k_i coupling modifiers: ratio between the measured and the standard model values.

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

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

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

M. Casarsa et al.



Higgs potential: trilinear coupling

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

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

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

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

M. Casarsa et al.

$$\frac{\Delta\sigma_{HH\to b\bar{b}b\bar{b}}}{\sigma_{HH\to b\bar{b}b\bar{b}}} \sim 33\%$$

$\frac{\Delta\lambda_3}{\lambda_3} \sim 20-30\%\ (25\%)$ parametric study

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

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

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

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

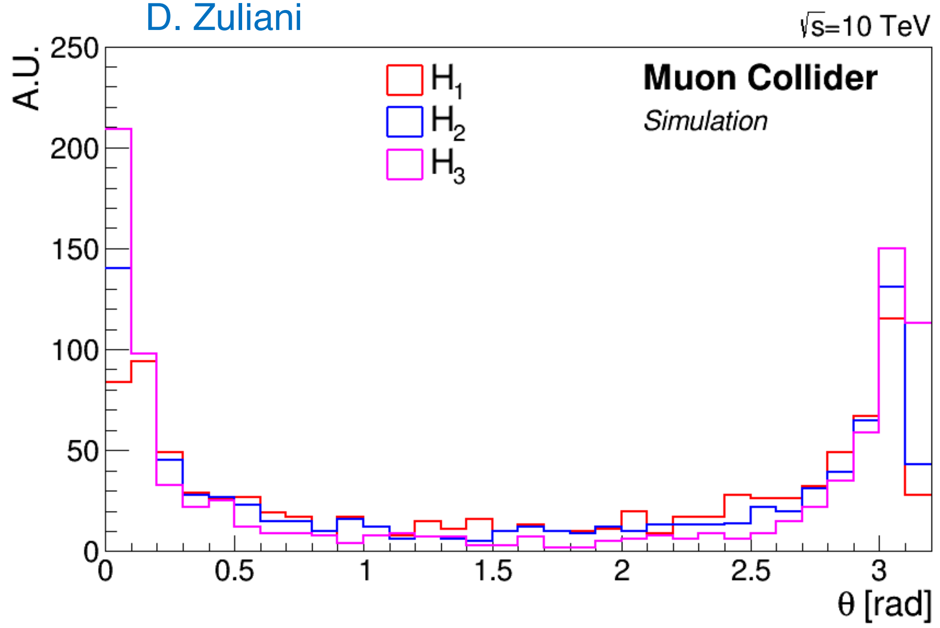
1 experiment
10 ab^{-1}

Higgs potential: quadrilinear coupling

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

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

D. Zuliani



Dedicated jets reconstruction and tagging algorithm must be developed

Parametric study

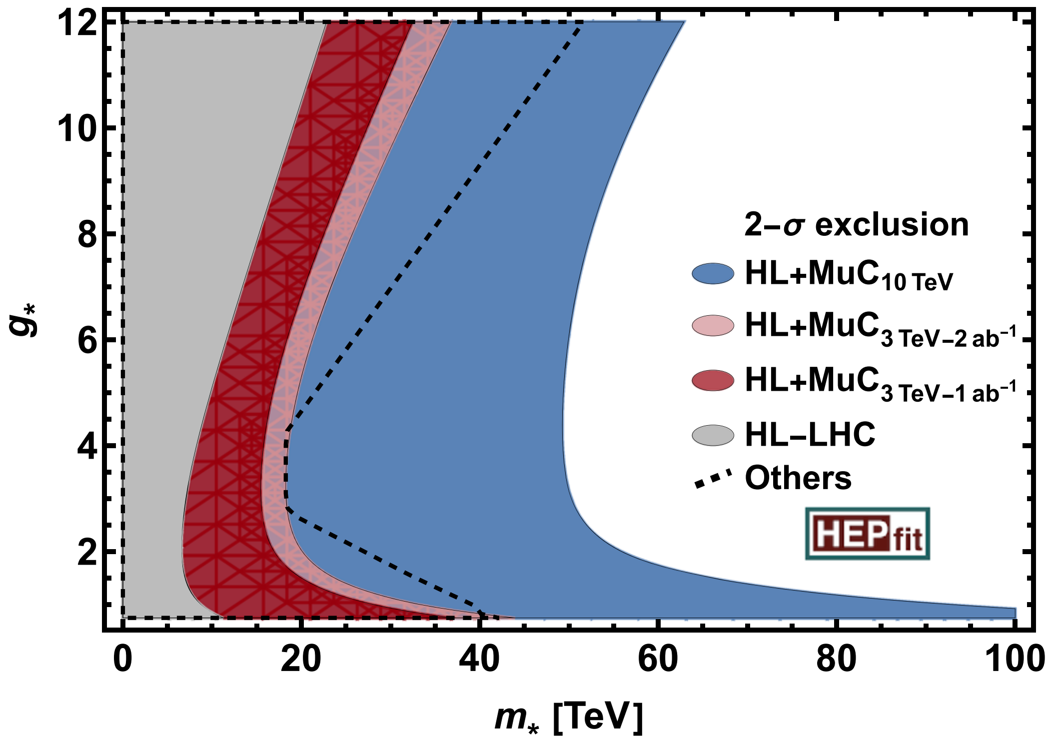
Chiesa M, et al. J. High Energ. Phys. 2020:98 (2020)

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

Accuracy of ~10% with 20 ab^{-1}

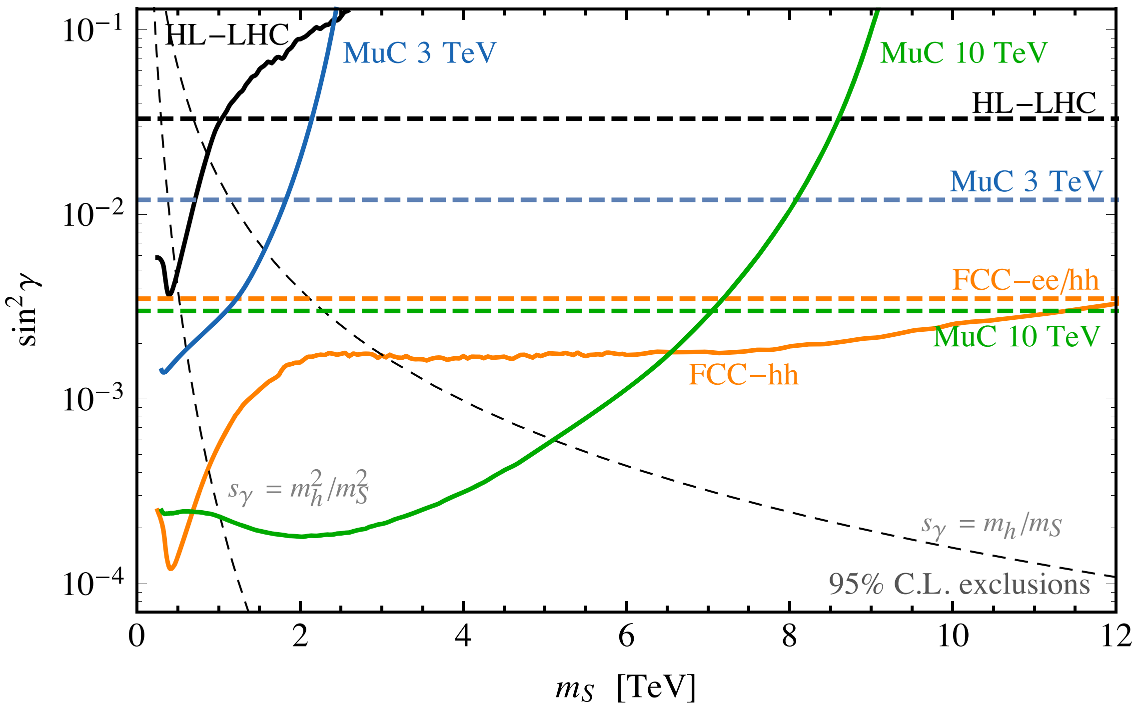
The power of $\sqrt{s} = 10$ TeV muon collisions for BSM searches

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



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

Higgs portal: new scalar field with no color



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

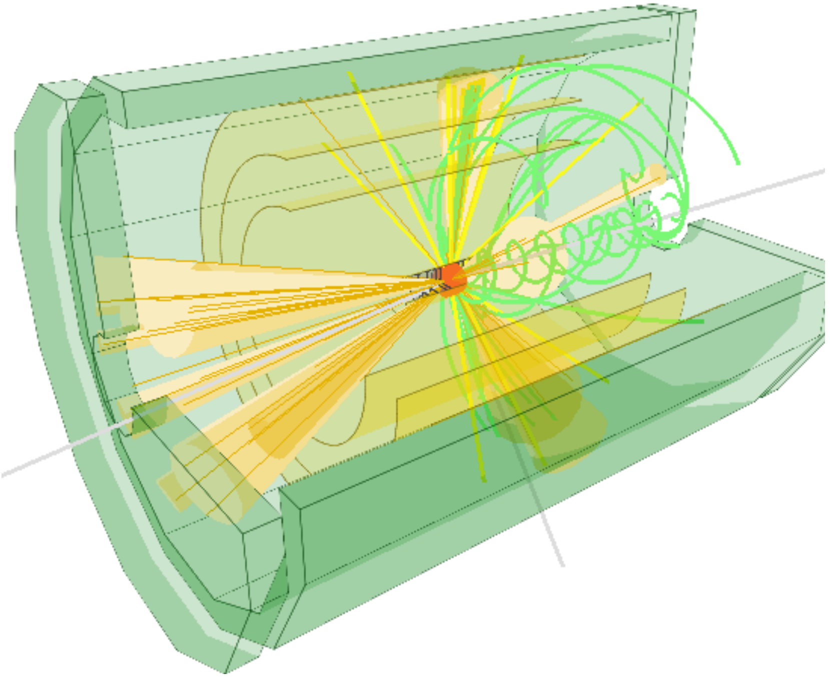
—— direct sensitivity ----- indirect sensitivity

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

Outlook

The design of Multi-TeV muon collider facility is progressing with no fundamental showstoppers.

Detector concept at $\sqrt{S} = 3$ TeV works and has very good performance even if not fully optimized. The $\sqrt{S} = 10$ TeV detector concept in progress.



Higgs physics performance determined with detailed detector simulation including beam-induced background. Parametric and pheno studies used to determine the couplings reach.

Possible to determine Higgs potential parameters up to the quartic term!

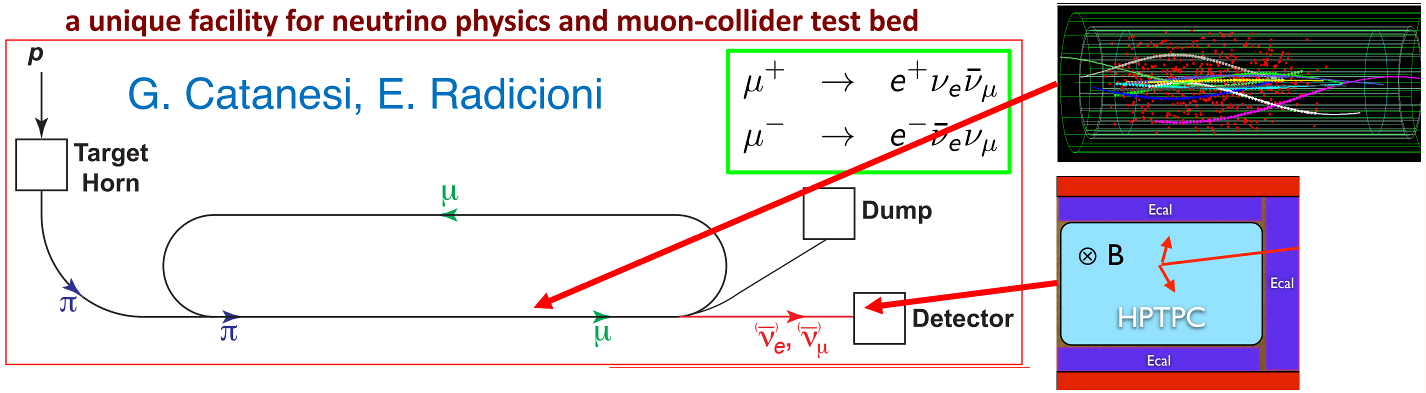
Open uncharted areas of BSM…

On a short time scale: muon collider demonstrator

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.

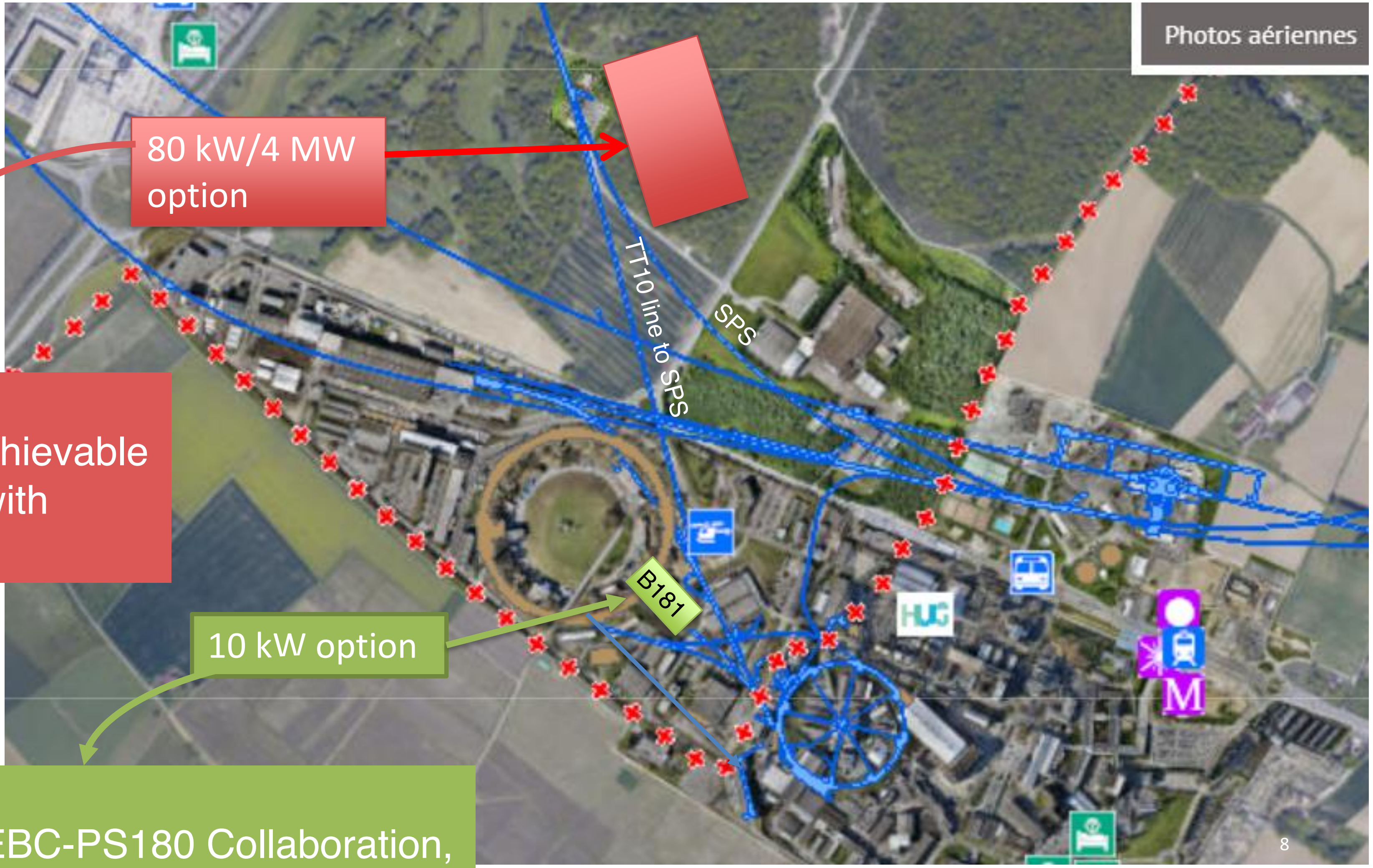
- Design physics experiment with the relative detectors:
  - nuSTORM and ENUBET could be branched.
  - Possible physics studies…

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

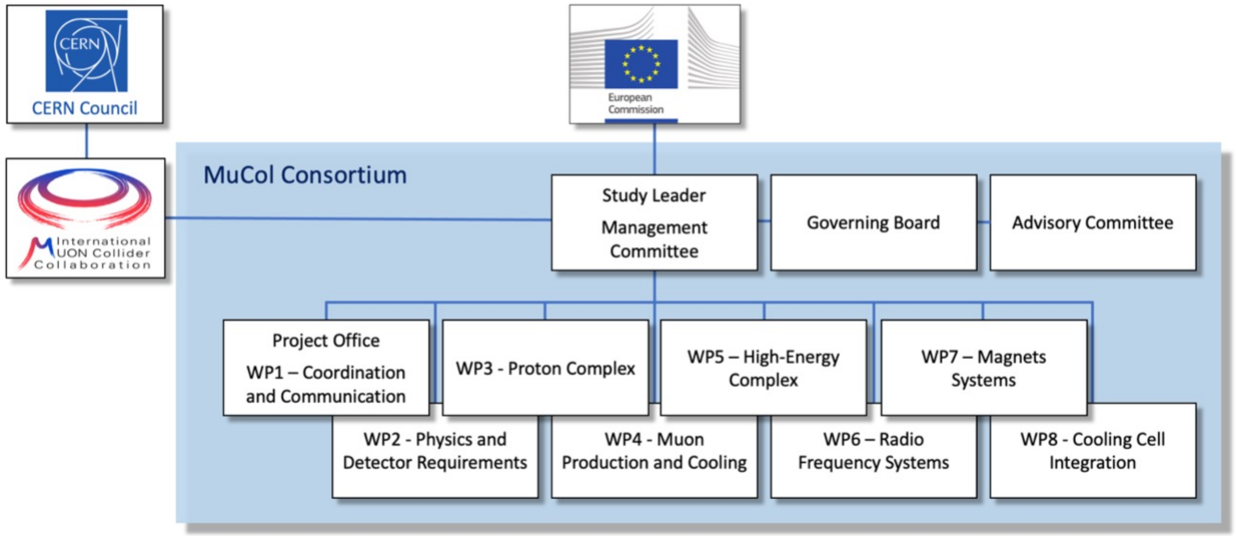
Low power:
Reuse line of BEBC-PS180 Collaboration, decommissioned, extending it towards B181 (now magnet factory)

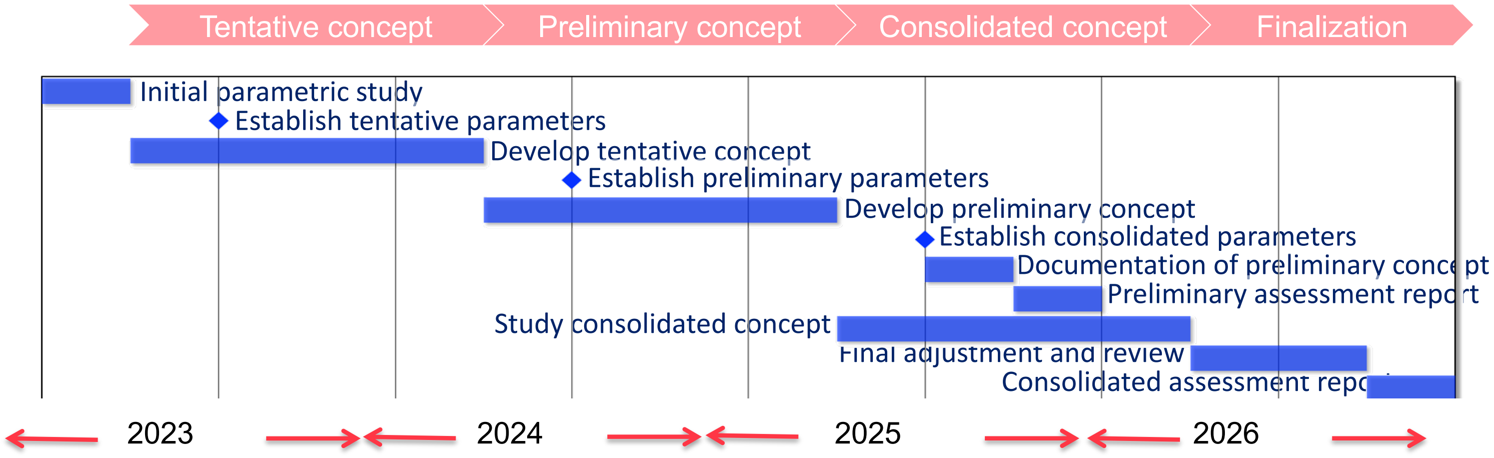
Additional material

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.



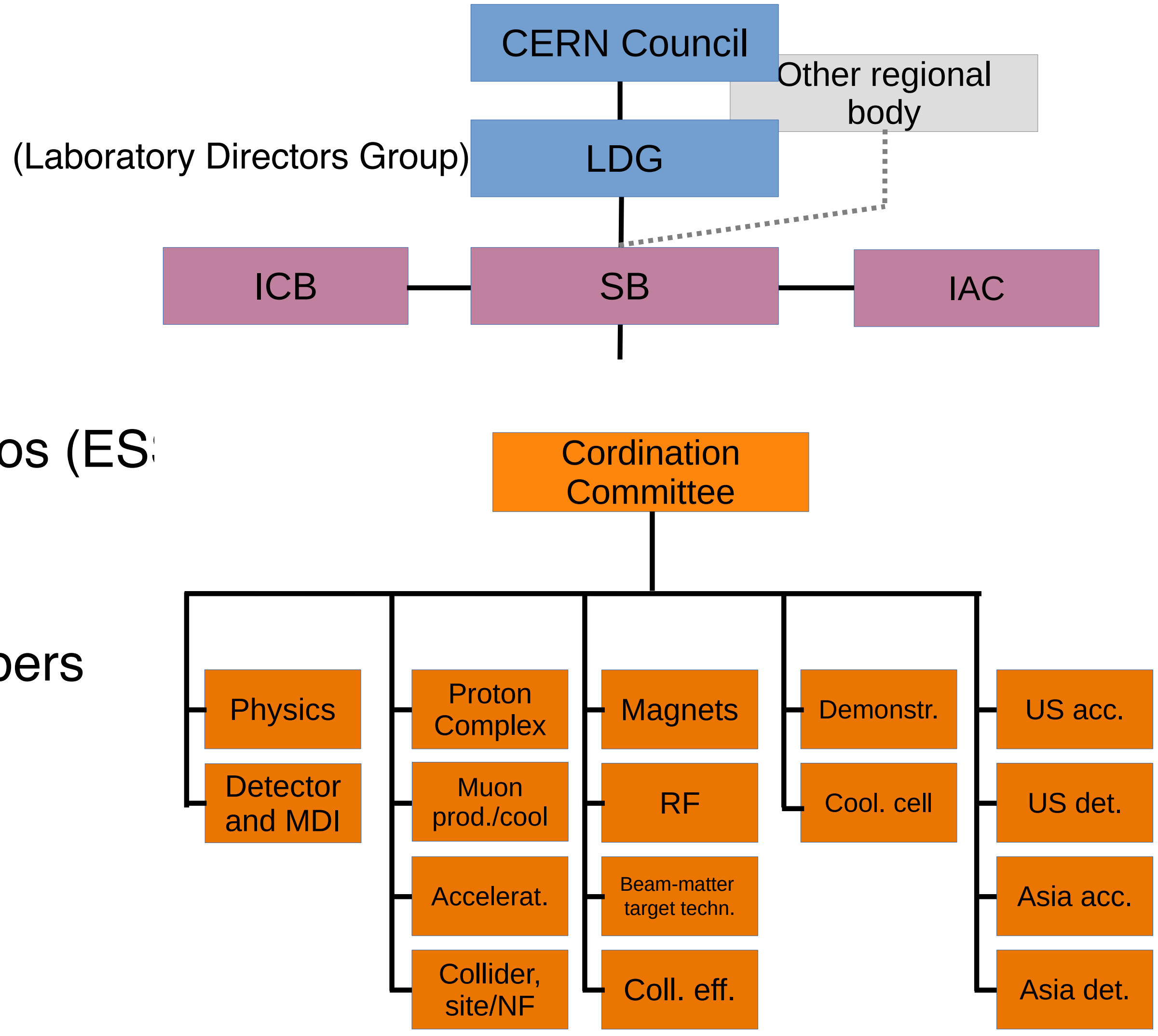


International Muon Collider Collaboration

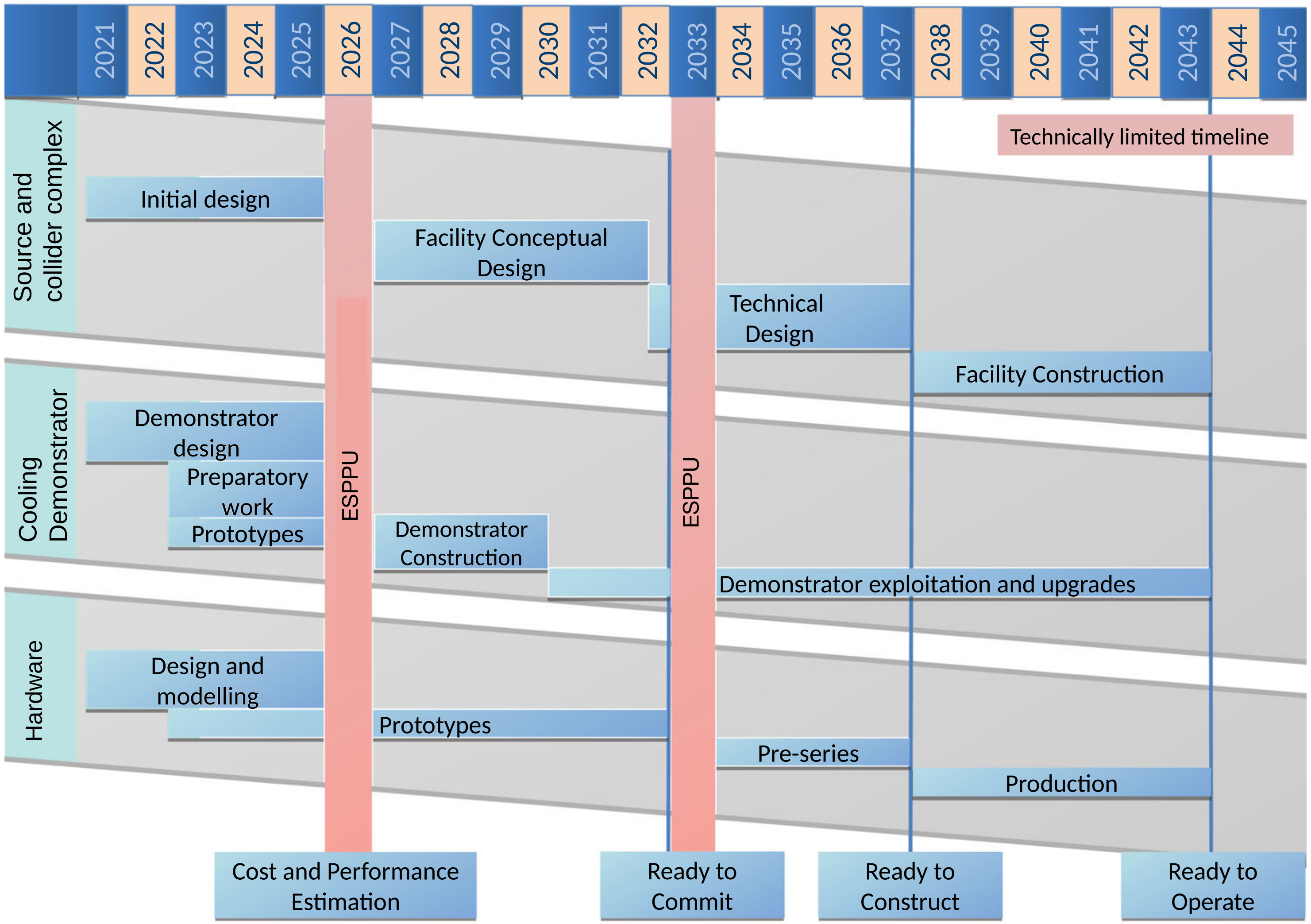
- **Collaboration Board (ICB)**
  - Elected chair: Nadia Pastrone

- **Steering Board (SB)**
- Chair Steinar Stapnes
- CERN members: M. Lamont, G. Arduini
- ICB members: D. Newbold (STFC), M. Lindroos (ES
  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

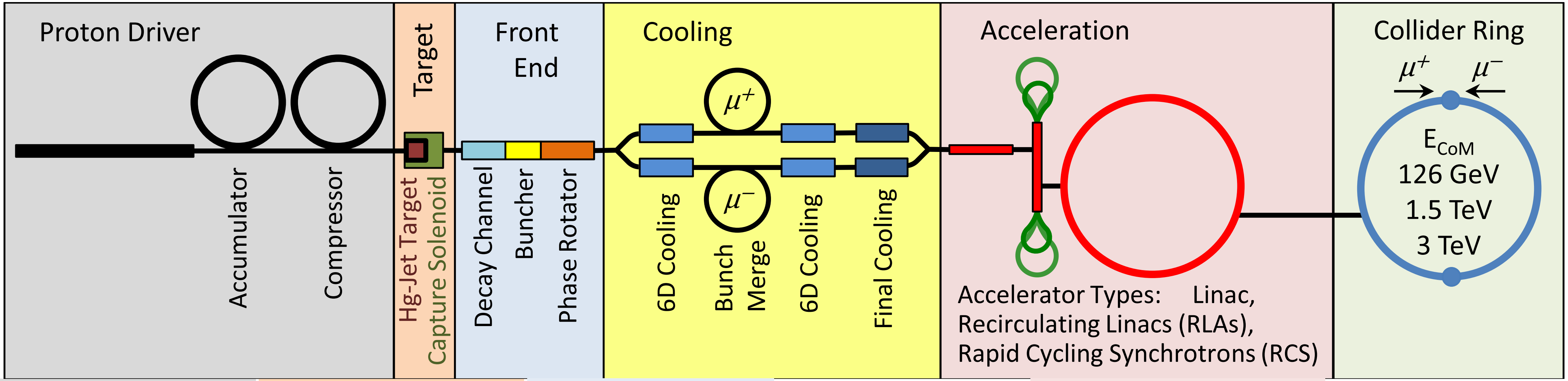


A technically limited timeline for the muon collider R&D programme that would see a 3 TeV muon collider constructed in the 2040s



Proton-driven Muon Collider Concept

Muon Accelerator Program (MAP)



- Based on 6-8 GeV Linac Source
- H- stripping requirements similar to neutrino ones

- high power target
- π production in high-field solenoid

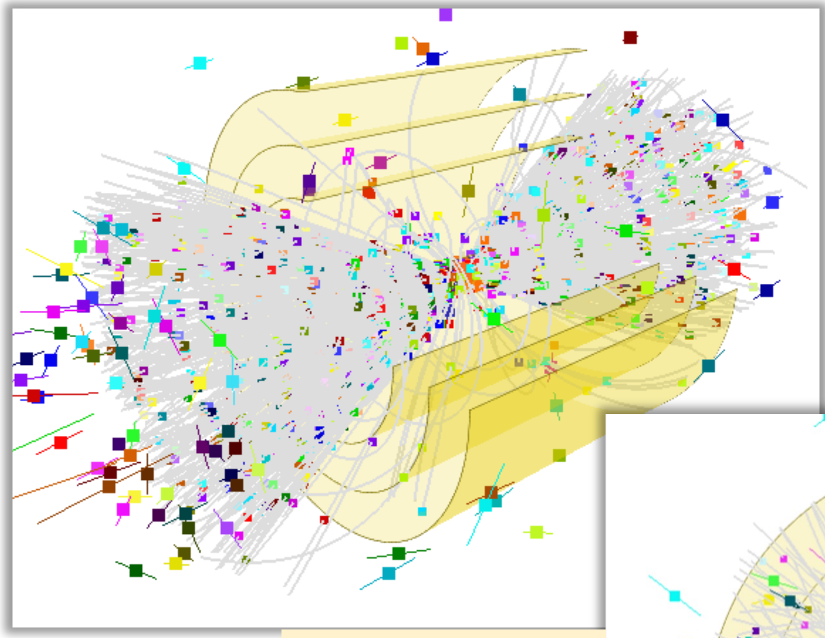
- RF cavities bunch & phase rotate $\mu^\pm$ into bunch train

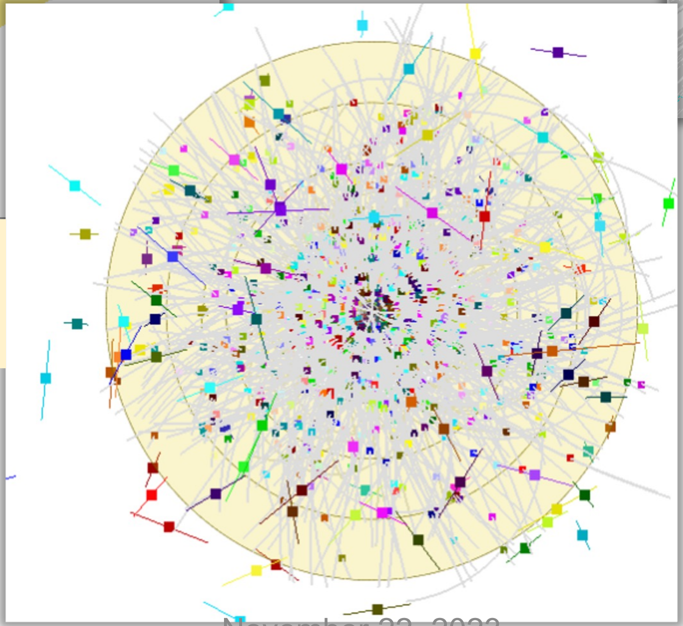
- Ionization cooling 6D
- MICE

- Fast acceleration
- Use RF and SC

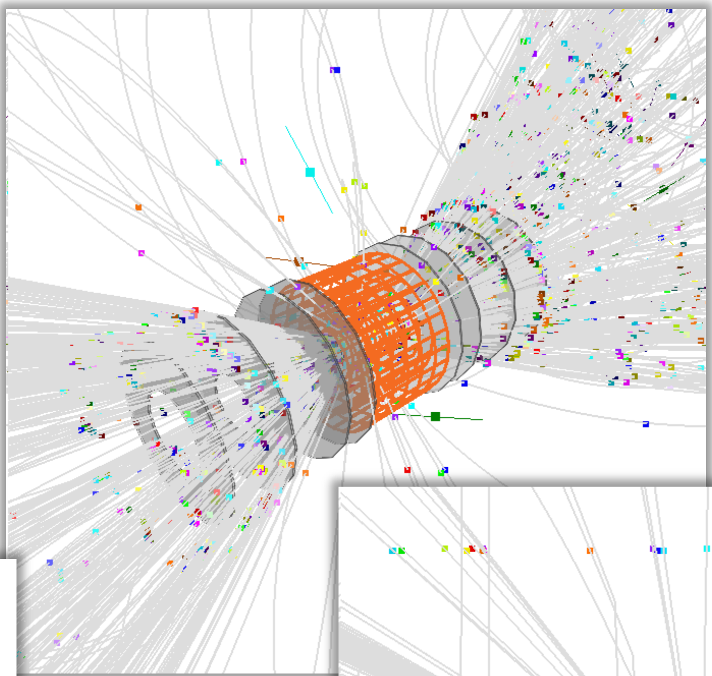
- $\mu^\pm$ decay background
- Critical Machine Detector Interface

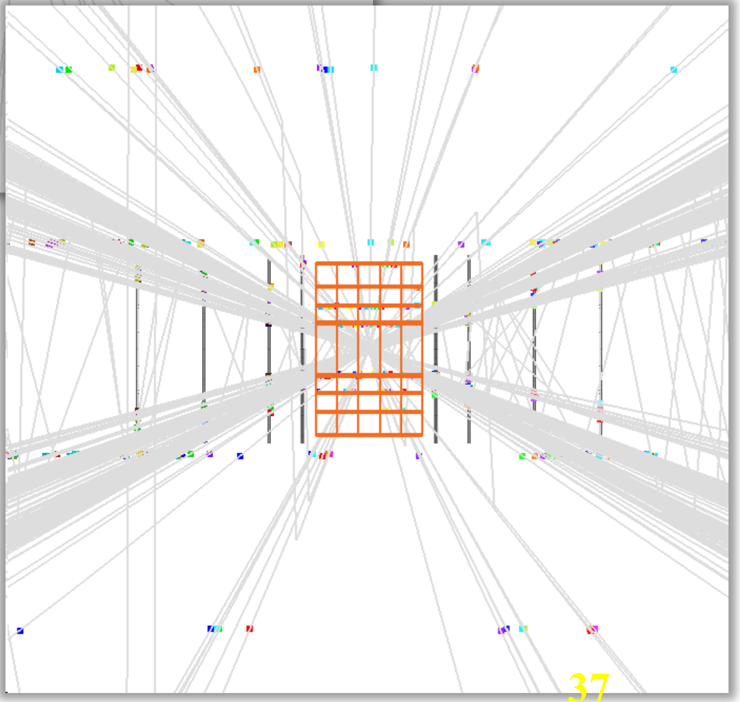
Beam-Induced Background in the tracker





Inner/Outer Tracker

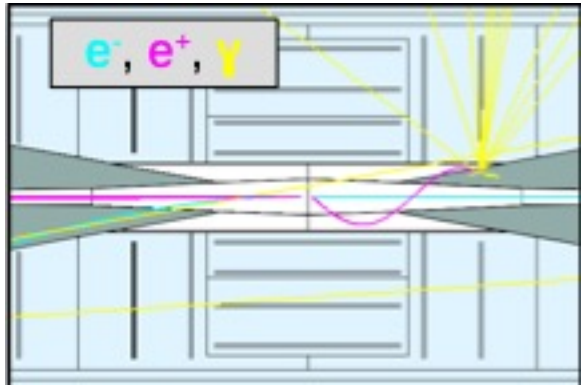




Vertex Detector

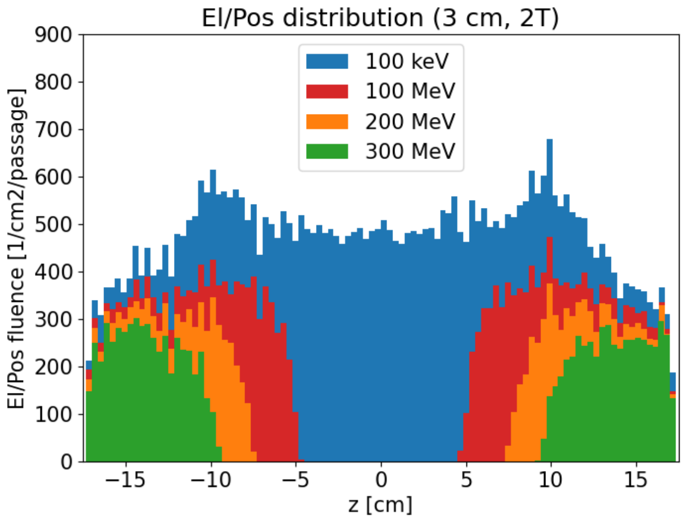
Incoherent e^-e^+ production $\mu^+\mu^- \rightarrow \mu^+\mu^-e^+e^-$

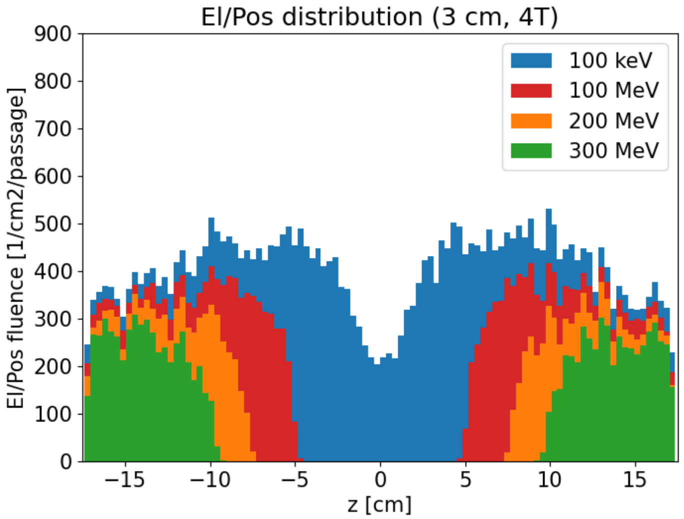
- Study in progress by using *Guinea-Pig* program
- Incoherent e^+e^-
  - produced in time with bunch crossing at interaction point
  - very energetic

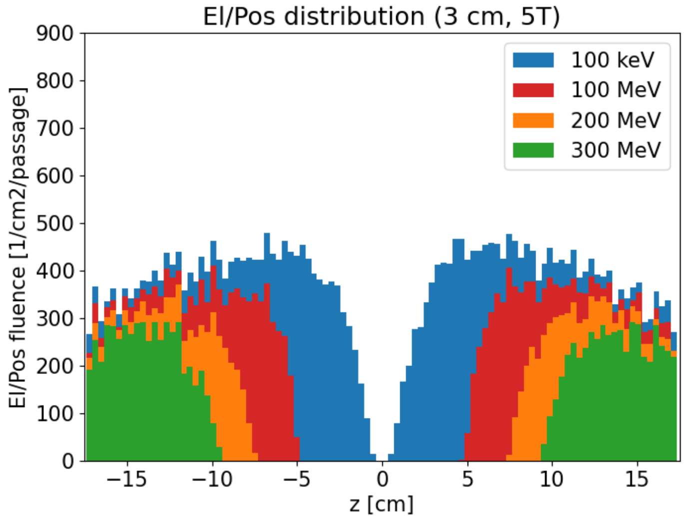


- Study focuses on reduce the component arriving on the detector by trapping it through solenoidal field

D. Calzolari, Magnet for 10 TeV Detector







Magnetic field needed to reduce beam-induced background

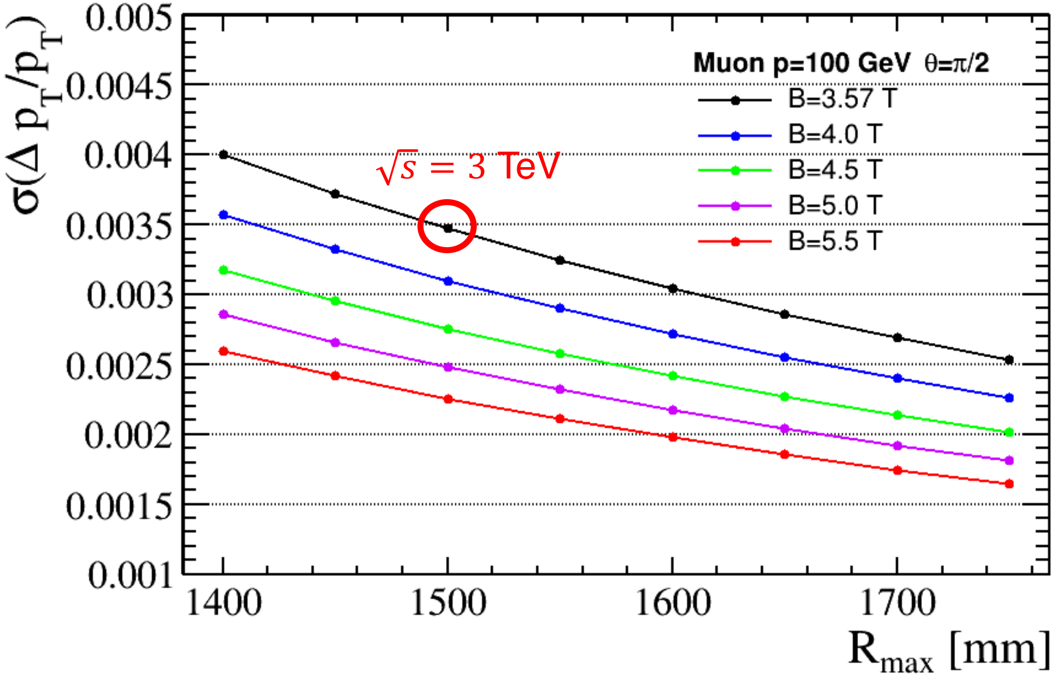
Which magnetic field for the detector?

Analytic formula to relate magnetic field and track momentum resolution

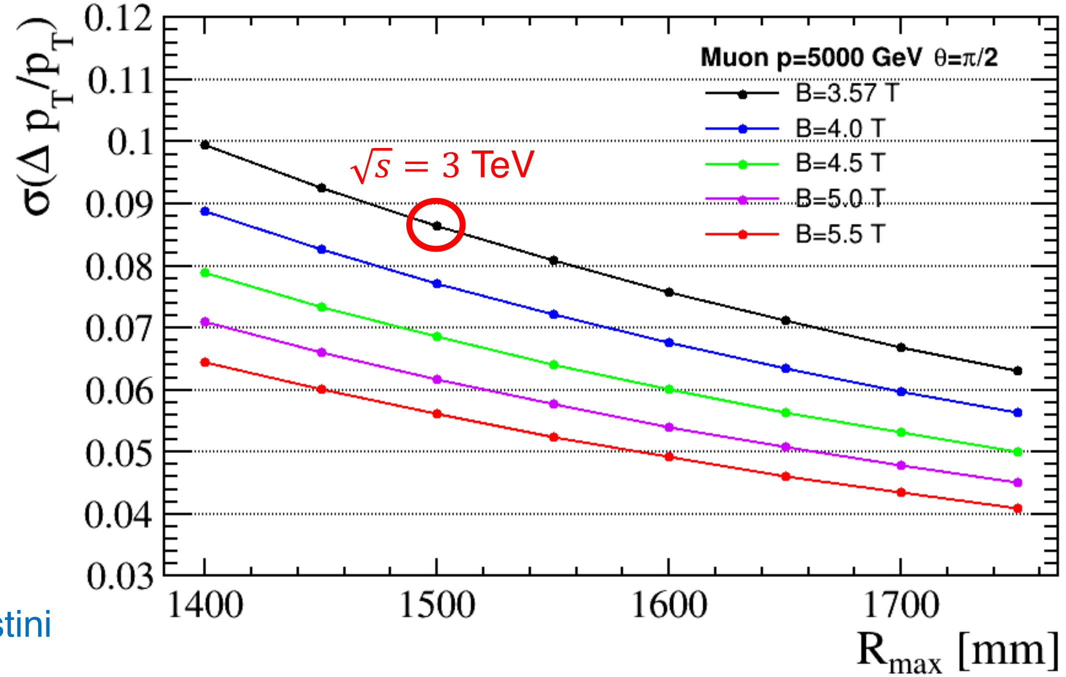
$$\frac{\sigma_{p_T}}{p_T} \cong \frac{12\sigma_{r\varphi}p_T}{0.3BL^2}\sqrt{\frac{5}{N+5}}$$

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

p_μ = 100 GeV at θ_μ = 90°

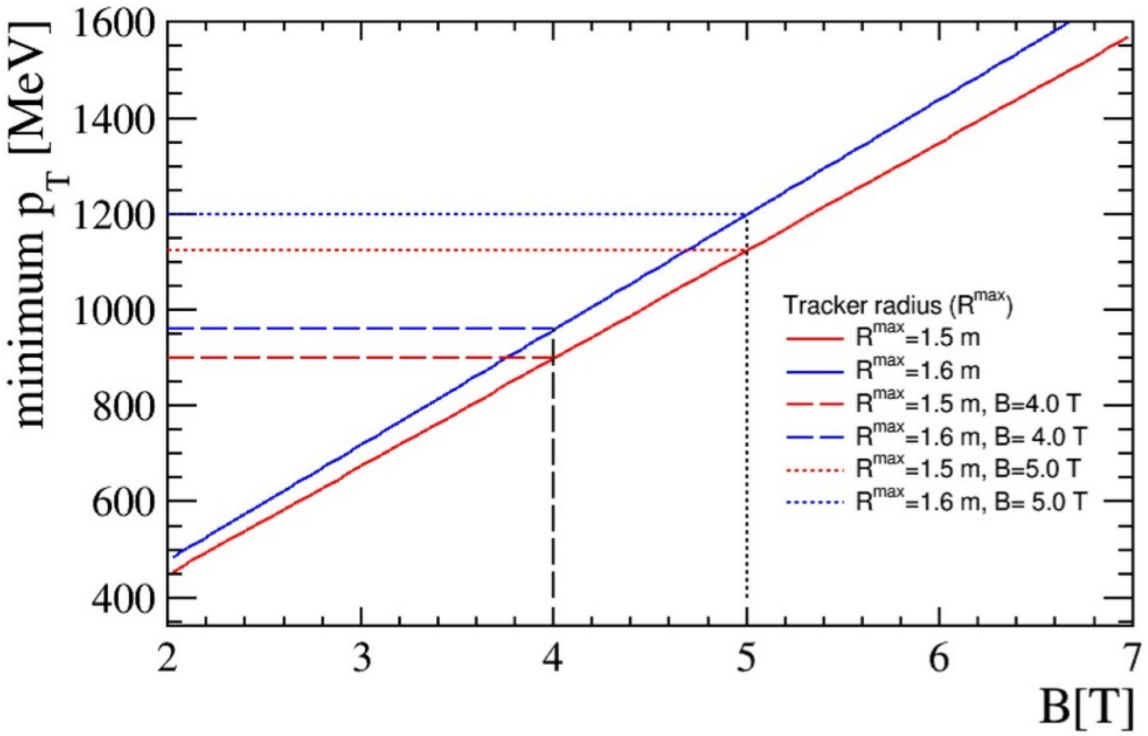


p_μ = 5000 GeV at θ_μ = 90°



L. Sestini

Higgs requirements at $\sqrt{s} = 10$ TeV



A magnetic field of about 4 T or 5 T is needed

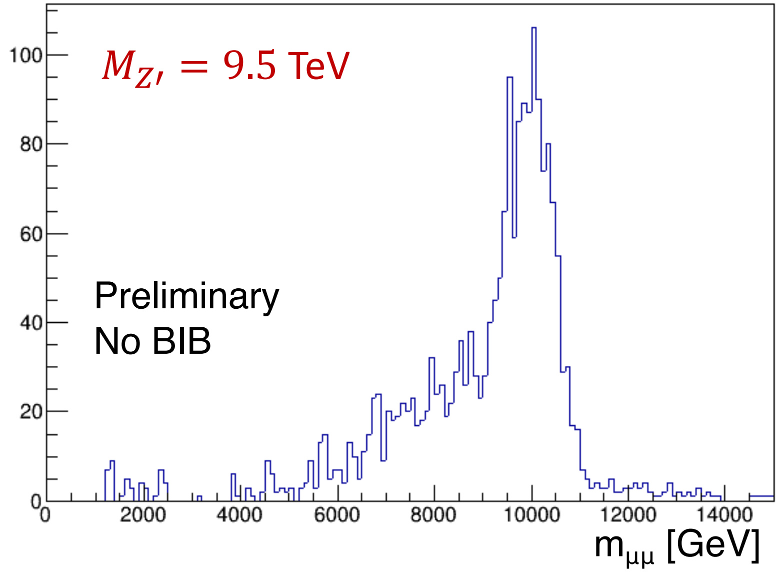
Study of track efficiency with B= 5 T vs. B = 3.57 T by using $H \rightarrow b\bar{b}$ generated at $\sqrt{s} = 10$ TeV:

- inefficiency ~ 15%
- mainly due to displaced tracks

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.

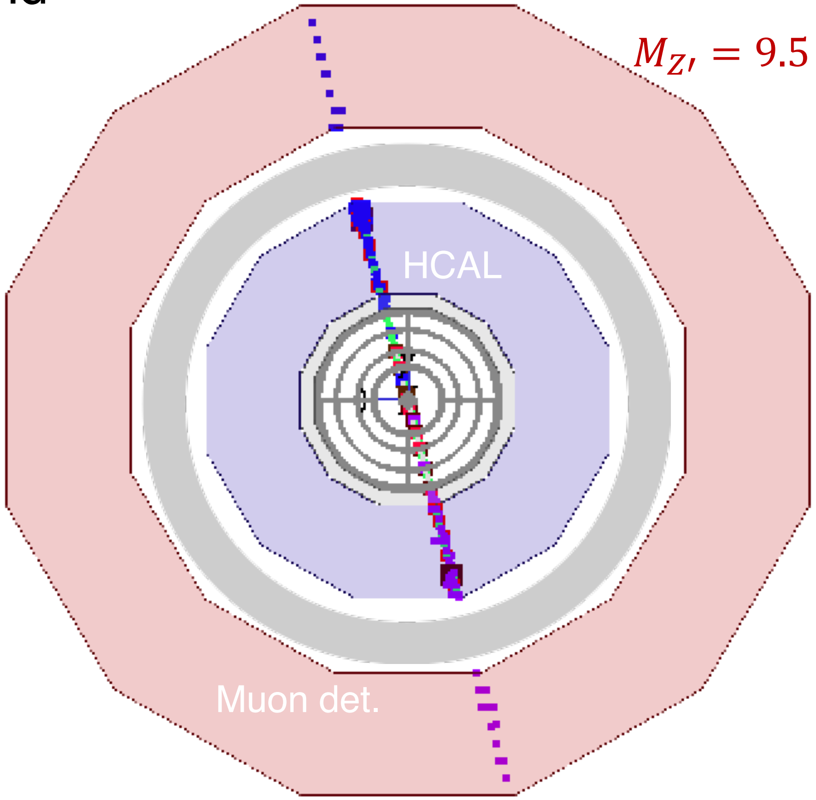
$\mu^+\mu^- \to Z'X \to \mu\mu X$ $\sqrt{s} = 10$ TeV



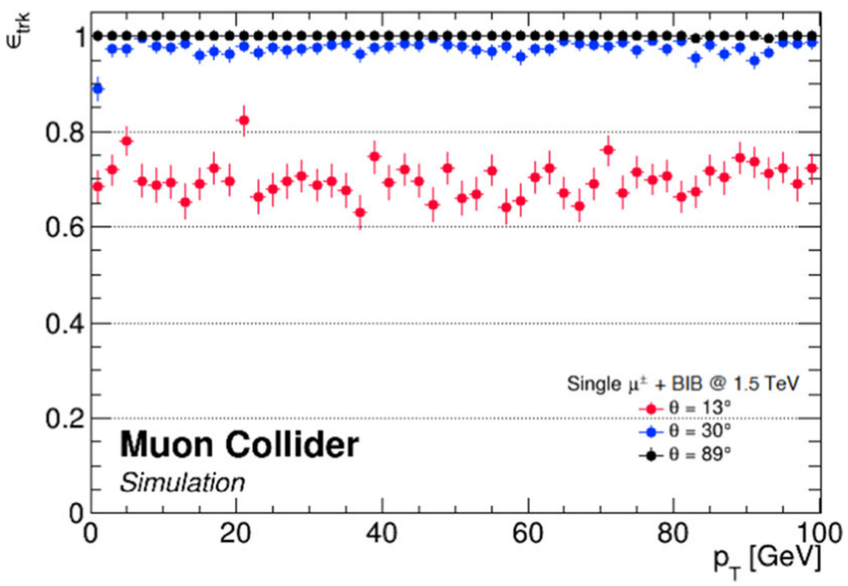
B = 5 T

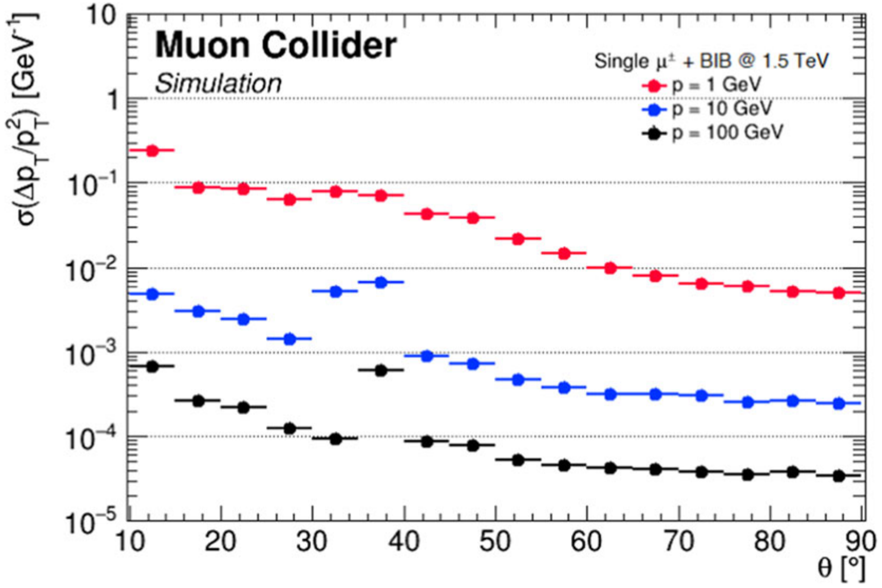
$\mu^+\mu^- \to Z'X \to \mu\mu X$ $\sqrt{s} = 10$ TeV

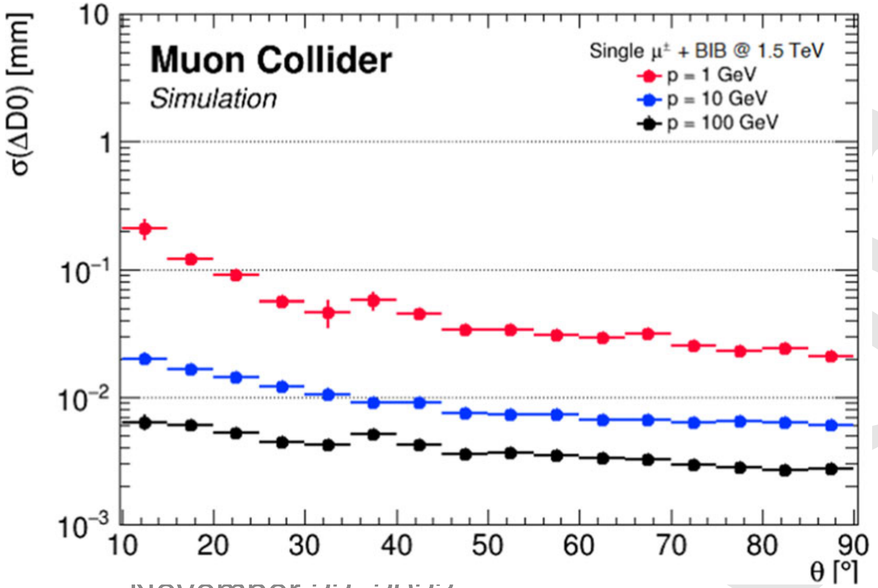
$M_{Z'} = 9.5$ TeV

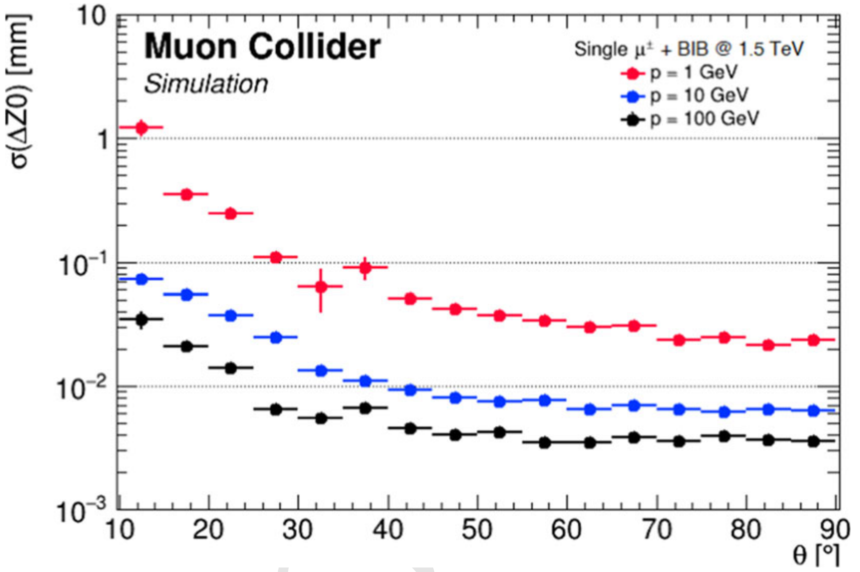


Track reconstruction performance







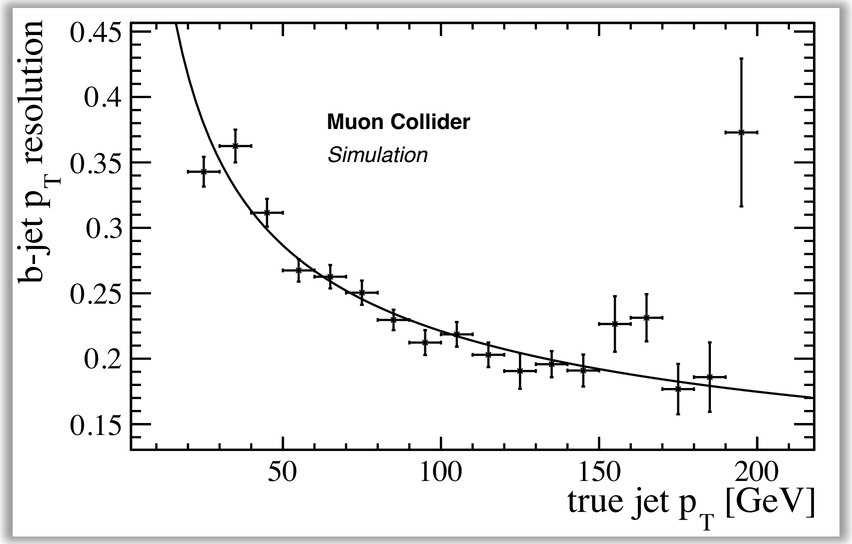


Jets reconstruction performance

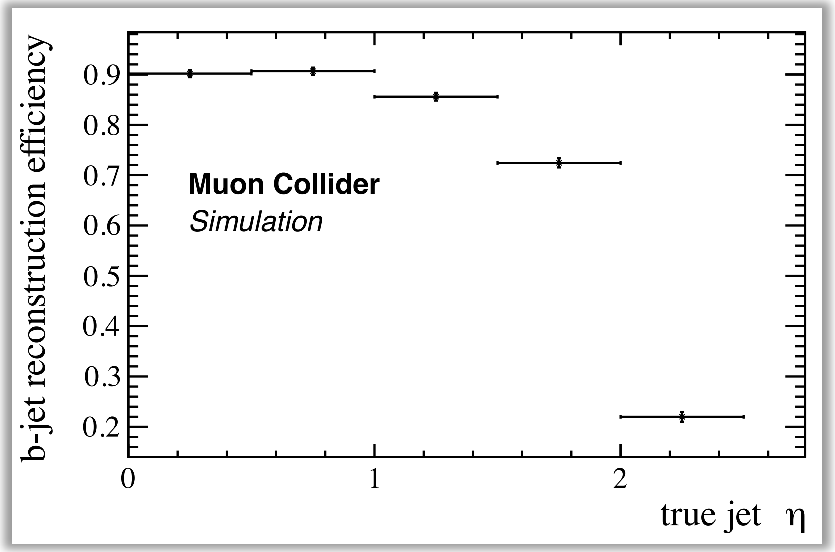
Jets reconstruction proceeds:

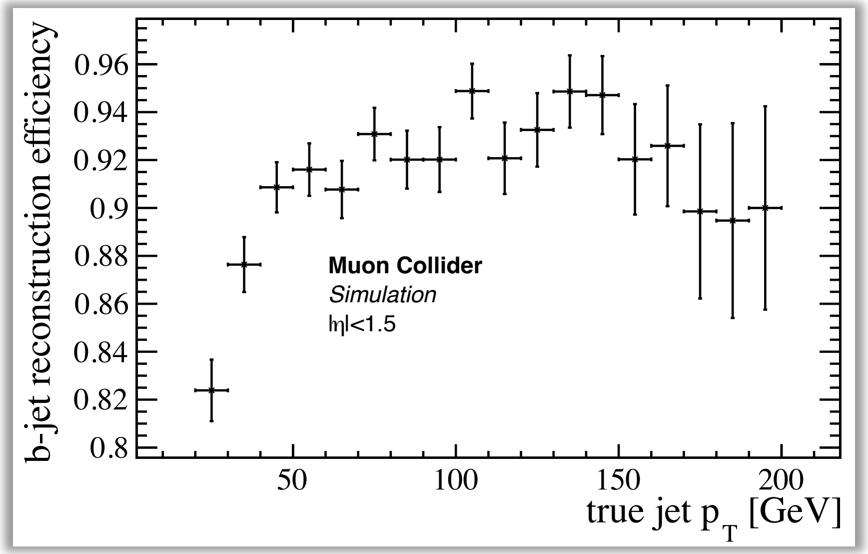
- Filter "on time" calorimeter hits
- Combine track and calorimeter information to reconstruct particles
- Use k_T algorithm to cluster particles in jets
- Apply requirements to remove fake jets (max 0.7%)
- Correct energy

Resolution



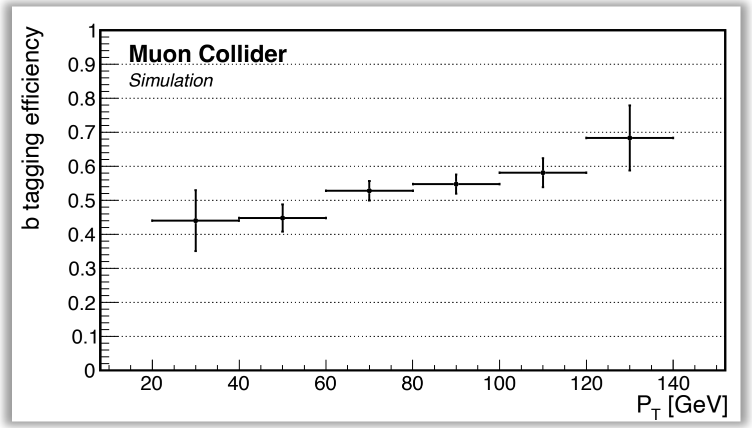
Efficiency

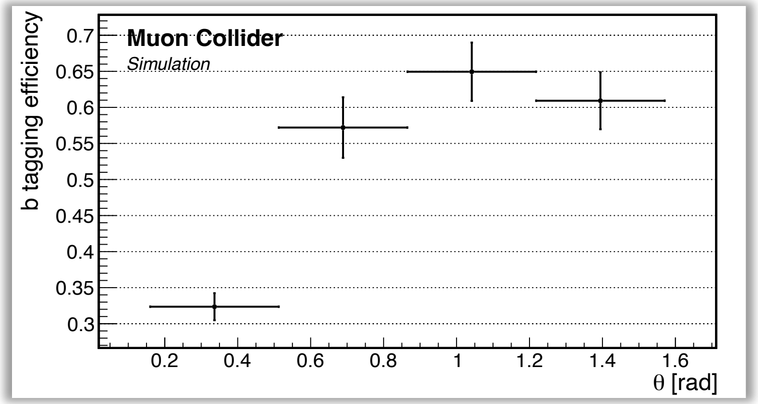




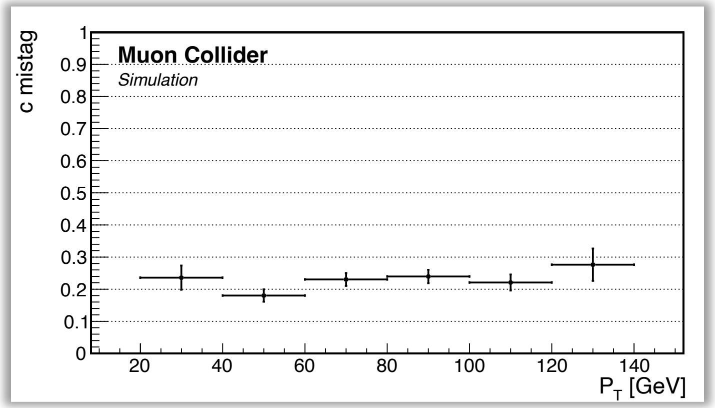
Heavy Flavor Jets Identification Performance

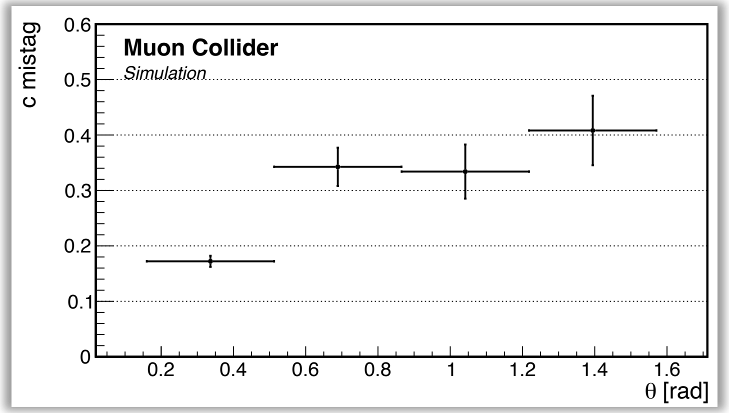
b-quark



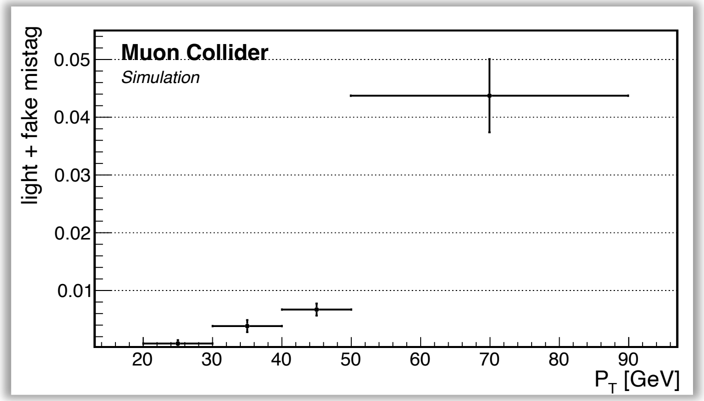


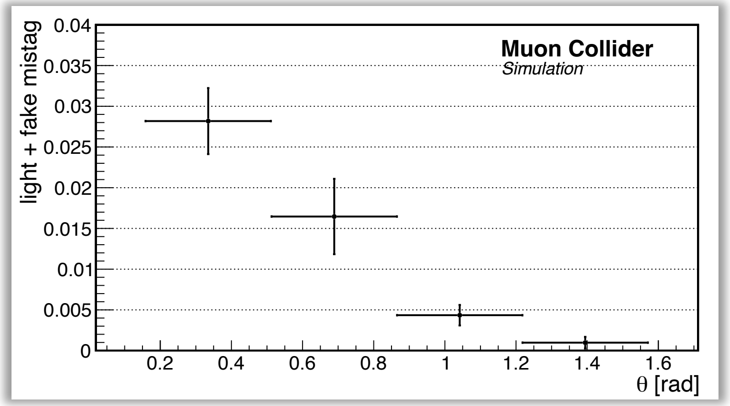
c-quark





light-quark/fake jets

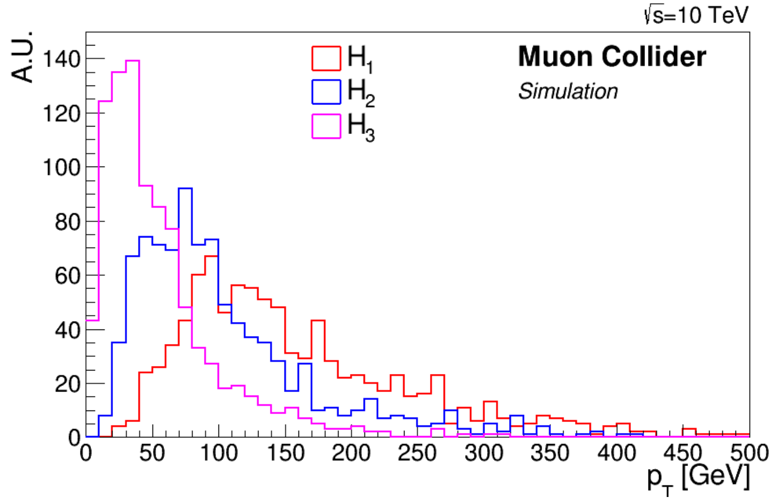


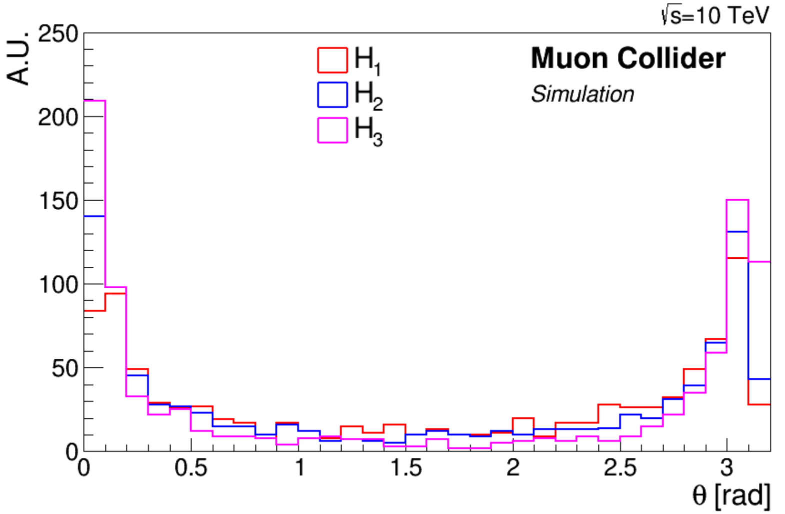


[M. Chiesa et al. JHEP 98, 2020](#)

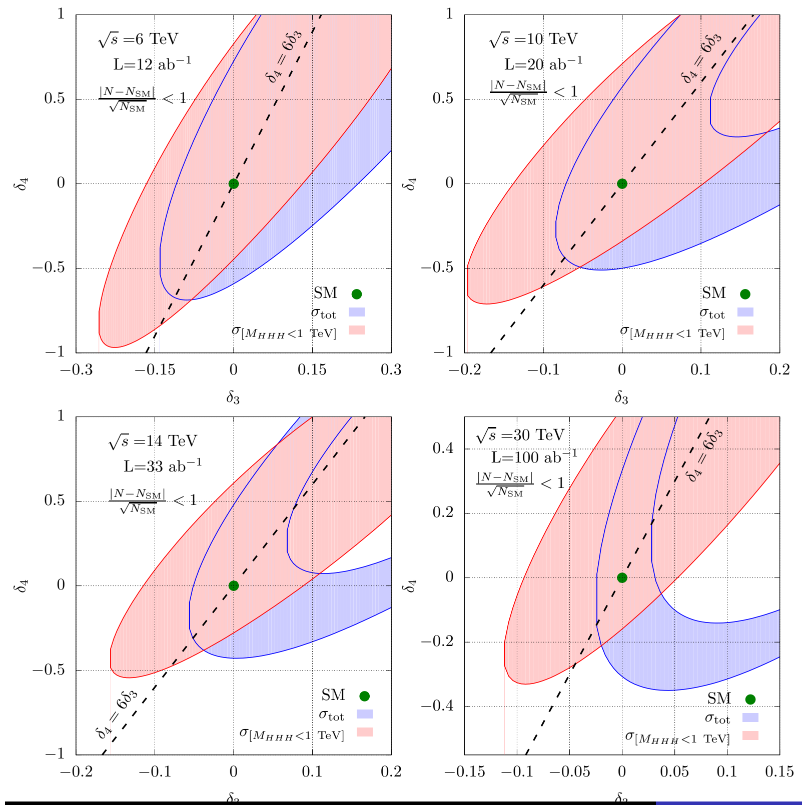
Triple Higgs

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





One sigma exclusion plots



Mauro Chiesa | Muon collider: quartic Higgs coupling

- 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

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

TO BE DONE → long term

1. LCIO → EDM4hep
2. DD4hep — DD4hep
3. Marlin — Gaudi
4. ILCSoft — 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**