Workshop on Muon Driven Colliders

SnowMass Muon Collider Forum

January 27, 2022

Machine Detector Interface

status and plans

Nadia Pastrone

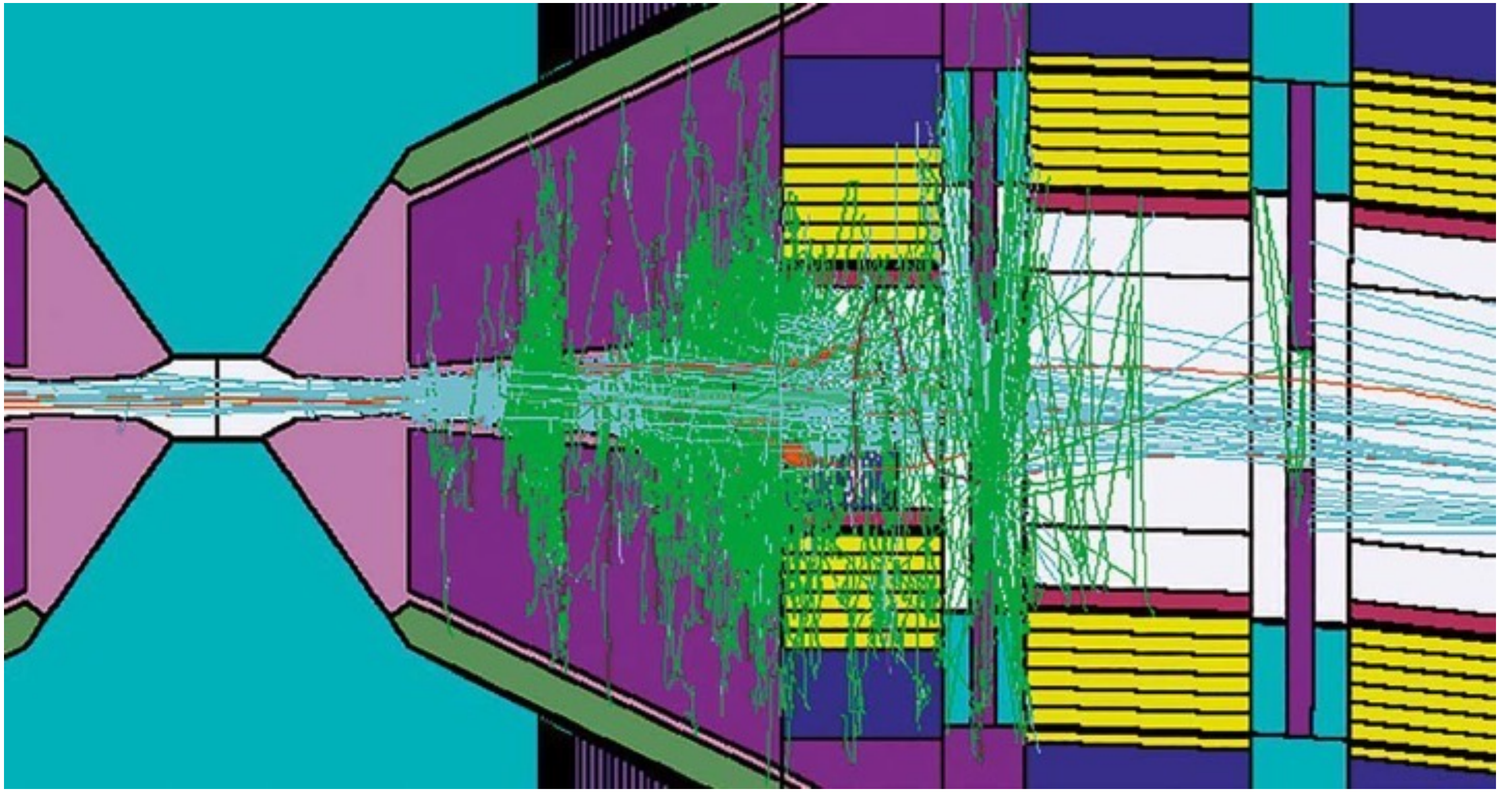
most recent reports from past/on-going studies at:

https://indico.cern.ch/category/14577/ *Community Meetings @ EU R&D Roadmap*
https://indico.cern.ch/category/14574/ *MDI Working Group meetings*
https://indico.fnal.gov/category/1267/ *SnowMass Muon Collider Forum*

Machine Detector Interface (MDI) Working Group

Donatella Lucchesi (University of Padova/INFN), Christian Carli (CERN), Anton Lechner (CERN), Nicolai Mokhov (FNAL), Nadia Pastrone (INFN), Sergo R Jindariani (FNAL)

MDI @ $\sqrt{s}$ = 125 GeV



Not discussed here

Accelerator R&D Roadmap
Bright Muon Beams and Muon Colliders

Panel members: **D. Schulte**,(Chair), **M. Palmer** (Co-Chair), T. Arndt, A. Chancé, J. P. Delahaye, A.Faus-Golfe, S.Gilardoni, P.Lebrun, K.Long, E.Métral, N.Pastrone, L.Quettier, T.Raubenheimer, C.Rogers, M.Seidel, D.Stratakis, A.Yamamoto
Associated members: A. Grudiev, R. Losito, D. Lucchesi

International Design Study Collaboration GOAL

In time for the next European Strategy for Particle Physics Update, aim to **establish whether the investment into a full CDR and a demonstrator is scientifically justified**

The Panel endorsed this ambition and concludes that:

- the MC presents enormous potential for fundamental physics research at the energy frontier

➔ it is the future direction toward high-energy, high-luminosity lepton collider

➔ it can be an option as next project after HL-LHC (i.e. operation mid2040s)

- at this stage the panel did not identify any showstopper in the concept and sees strong support of the feasibility from previous studies
- it identified important R&D challenges

ESPP Accelerator R&D Roadmap
arXiv:2201.07895 [physics.acc-ph]

The panel has identified a development path that can address the major challenges and deliver a 3 TeV muon collider by 2045

Baseline facility

- **Focus on two energy ranges:**

3 TeV technology ready for construction in 10-20 years

10+ TeV with more advanced technology

Proton driver production
Baseline @ International Design Study
Re-starting from well established MAP studies

ASSUMPTION/IP

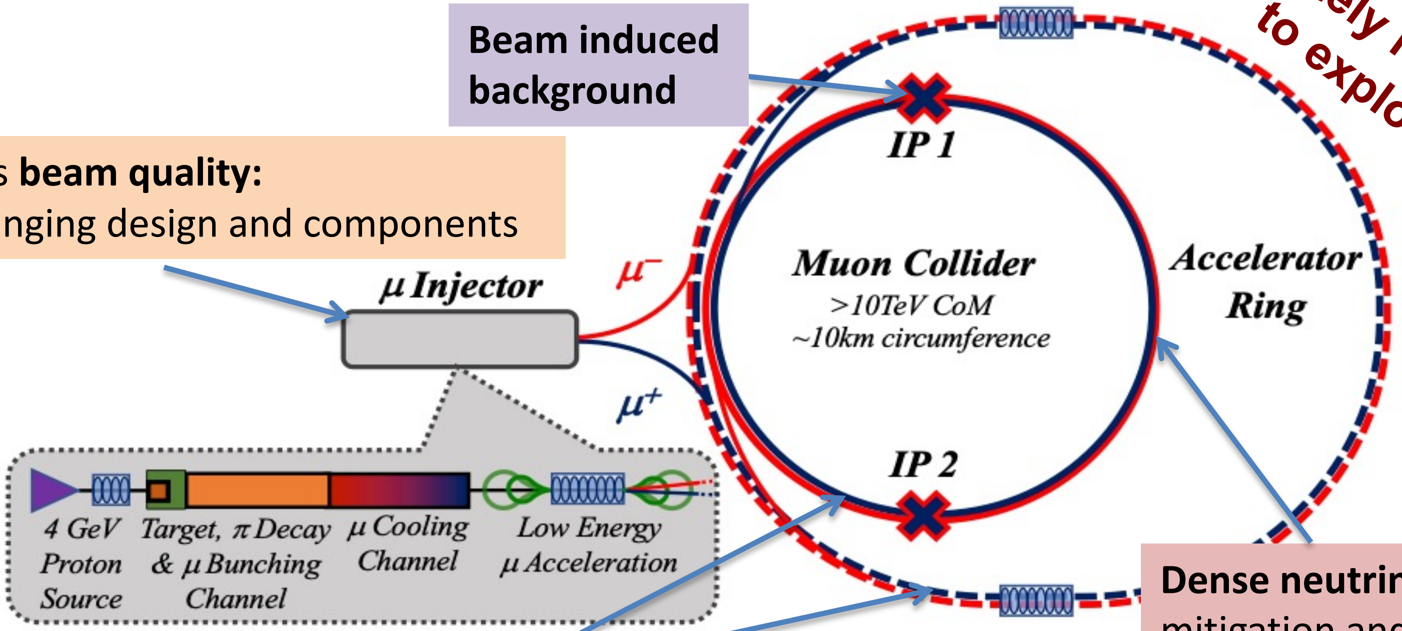
$\mathcal{L} = (E_{CM}/10\text{TeV})^2 \times 10\ \text{ab}^{-1}$

@ 3 TeV 1 ab^{-1} /5 years

@ 10 TeV 10 ab^{-1} /5 y

@ 14 TeV 20 ab^{-1} /5 y

10+ TeV completely new regime to explore!



Beam induced background

Drives **beam quality:**
challenging design and components

Dense neutrino flux
mitigation and site

Cost and **power** consumption drivers, limit energy reach
e.g. 30 km accelerator for 10/14 TeV, 10/14 km collider ring

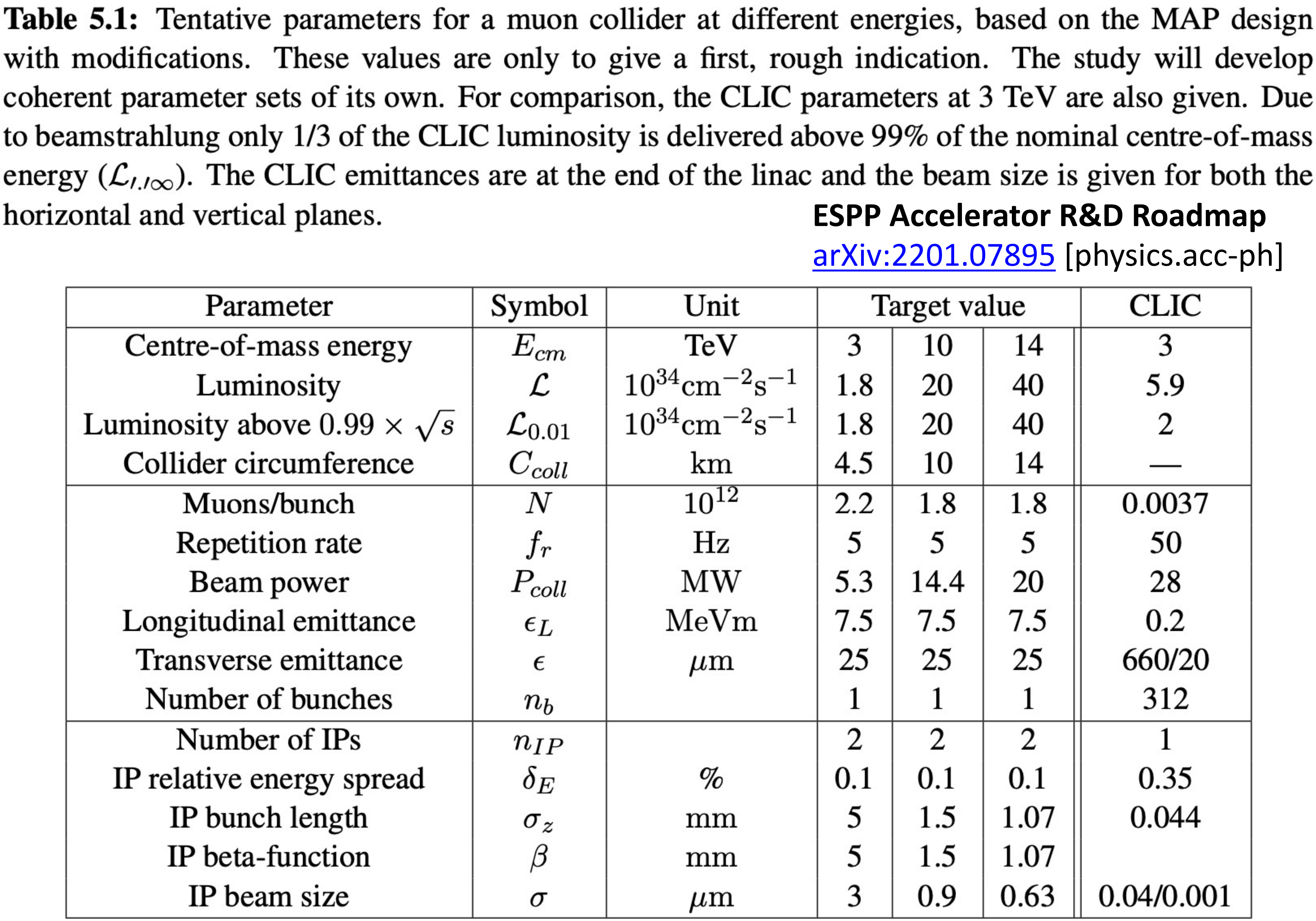


Table 5.1: Tentative parameters for a muon collider at different energies, based on the MAP design with modifications. These values are only to give a first, rough indication. The study will develop coherent parameter sets of its own. For comparison, the CLIC parameters at 3 TeV are also given. Due to beamstrahlung only 1/3 of the CLIC luminosity is delivered above 99% of the nominal centre-of-mass energy ($\mathcal{L}_{I.I\infty}$). The CLIC emittances are at the end of the linac and the beam size is given for both the horizontal and vertical planes.

ESPP Accelerator R&D Roadmap

arXiv:2201.07895 [physics.acc-ph]

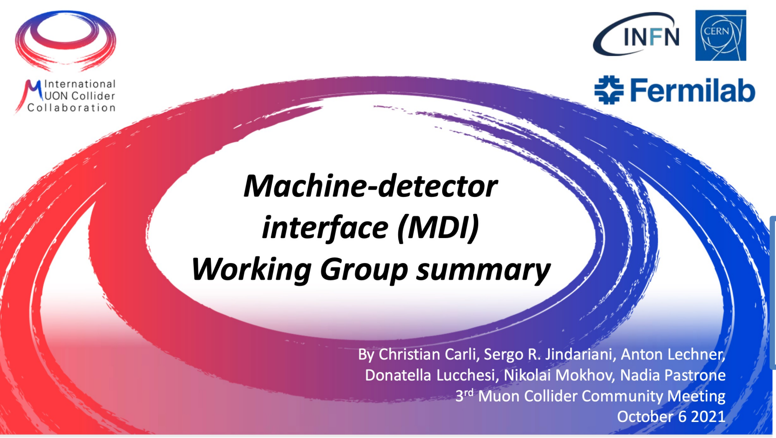
Parameter	Symbol	Unit	Target value			CLIC
Centre-of-mass energy	E_{cm}	TeV	3	10	14	3
Luminosity	$\mathcal{L}$	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.8	20	40	5.9
Luminosity above $0.99 \times \sqrt{s}$	$\mathcal{L}_{0.01}$	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.8	20	40	2
Collider circumference	C_{coll}	km	4.5	10	14	—
Muons/bunch	N	10^{12}	2.2	1.8	1.8	0.0037
Repetition rate	f_r	Hz	5	5	5	50
Beam power	P_{coll}	MW	5.3	14.4	20	28
Longitudinal emittance	ϵ_L	MeVm	7.5	7.5	7.5	0.2
Transverse emittance	ϵ	μm	25	25	25	660/20
Number of bunches	n_b		1	1	1	312
Number of IPs	n_{IP}		2	2	2	1
IP relative energy spread	δ_E	%	0.1	0.1	0.1	0.35
IP bunch length	σ_z	mm	5	1.5	1.07	0.044
IP beta-function	β	mm	5	1.5	1.07	
IP beam size	σ	μm	3	0.9	0.63	0.04/0.001

Key Challenge Areas

- **Physics potential** evaluation, including **detector concept and technologies**
- Impact on the environment
  - **Neutrino flux mitigation** and its impact on the site (first concept exists)
  - **Machine Induced Background** impact the detector, and might limit physics
- **High-energy systems** after the cooling (acceleration, collision, ...)
  - Fast-ramping magnet systems
  - High-field magnets (in particular for 10+ TeV)

High energy complex requires known components
➔ synergies with other future colliders

- **High-quality muon beam production**
  - Special RF and high peak power
  - Superconducting solenoids
  - Cooling string demonstration (cell engineering design, demonstrator design)
- **Full accelerator chain**
  - e.g. proton complex with H- source, compressor ring ➔ test of target material



Machine-detector interface (MDI) Working Group summary

By Christian Carli, Sergo R. Jindariani, Anton Lechner,
Donatella Lucchesi, Nikolai Mokhov, Nadia Pastrone
3rd Muon Collider Community Meeting
October 6 2021

MDI WG Summary

Can base the new studies on the valuable experience gained within MAP (N. Mokhov et al.)

- Study the beam-induced background and identify mitigation strategies
- Develop a **(conceptual) interaction region (IR) design** that yields background levels compatible with detector operation, i.e. show that
  - the desired physics performance can be reached
  - the cumulative radiation damage in the detector remains acceptable
- Address **different centre-of-mass energies**, with particular attention to:
  - **3TeV**
  - **10TeV** (IR design to be scaled up further to **14TeV** if needed)

✓ By end of 2022, aim to have a **first level IR optimization**

3 TeV option: start optimizing the IR design starting from MAP layout

10 TeV option: obtain a first IR design, first quantification of background

✓ By 2025, aim to have a **mature IR design**

Demonstrate feasibility of reaching detector performance goals for both collider options

✓ Meetings with common discussions inviting contact persons from other WPs

✓ Interface with Snowmass is important

Recap of background sources

N. Mokhov 1st Muon Collider community meeting

- Certainly a **main background source** for all collider options

Muon decay around the ring

Major contribution comes from decays in IR
Bethe-Heitler muons also from further away

Incoherent e^-/e^+ pair production during bunch crossing in IP

e^-/e^+ trajectories influenced by solenoid field can impact on nozzle and detector vacuum chamber

Beam-halo losses at aperture bottlenecks

- Was found not to be an issue at energy of $\sqrt{s}$=2 TeV* (with a solenoid field of a few T)
- **Nevertheless to be studied for the $\sqrt{s}$=10+ TeV collider option**

- Halo losses near detector can yield non-negligible background contribution
- **Acceptable halo loss levels to be defined (halo cleaning)**

Links with other accelerator WPs

List of topics is not complete (and not all have same priority)

Strong ties needed with:
High-energy complex
Magnets
Beam dynamics
Radiation protection

- Iterate on **lattice design**, converge on **L***
- Explore **background mitigation techniques** (e.g. combined-function magnets, chicanes, sweeping magnets)

- Estimate achievable **magnet apertures**
- Integrate shielding/masks (*synergies with heat load/radiation damage studies for magnets*)
- Quantify affordable **minimum beam clearance**

- Model **beam halo**
- Define requirements **for halo cleaning system** for background reduction (in addition to injection scraping)

- Quantify impact of **neutrino hazard mitigation techniques** (e.g. movers) on detector background

MDI WP depends on resource allocation in other WPs to address the different topics

Links with detector community

List of topics is not complete!

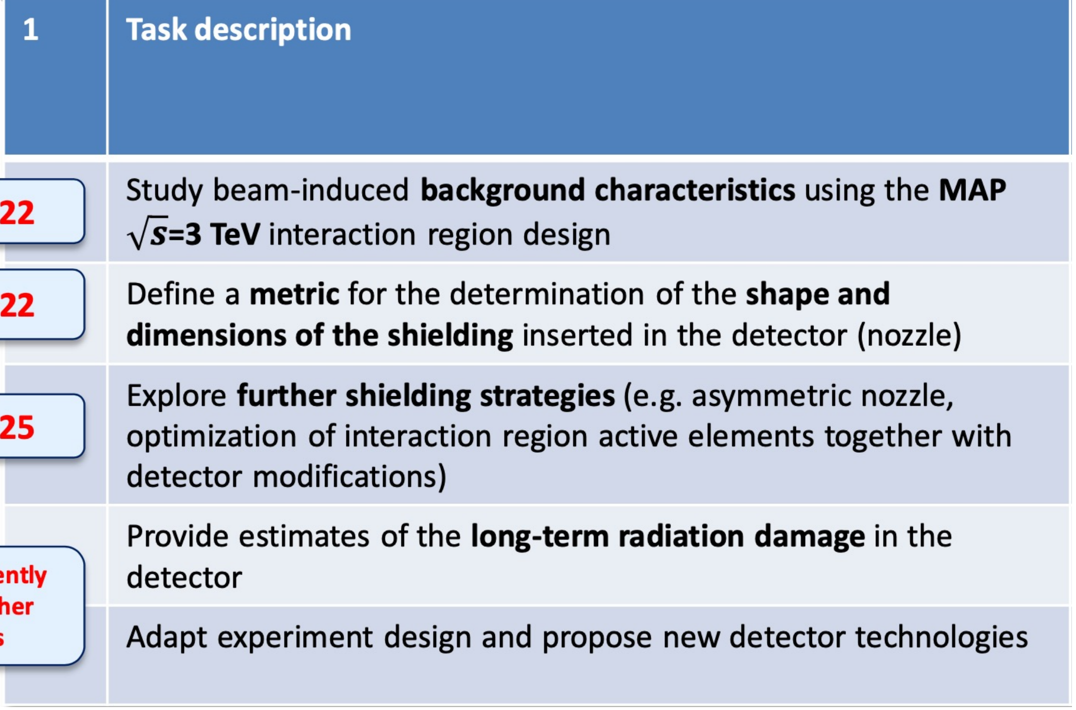
Detector experts

- Iteration concerning **detector envelope** (compromise between shielding requirements and detector acceptance)
- Define metric for envelope optimization

- Define (simple) figure-of-merit for first shielding optimization
- Later full detector simulation

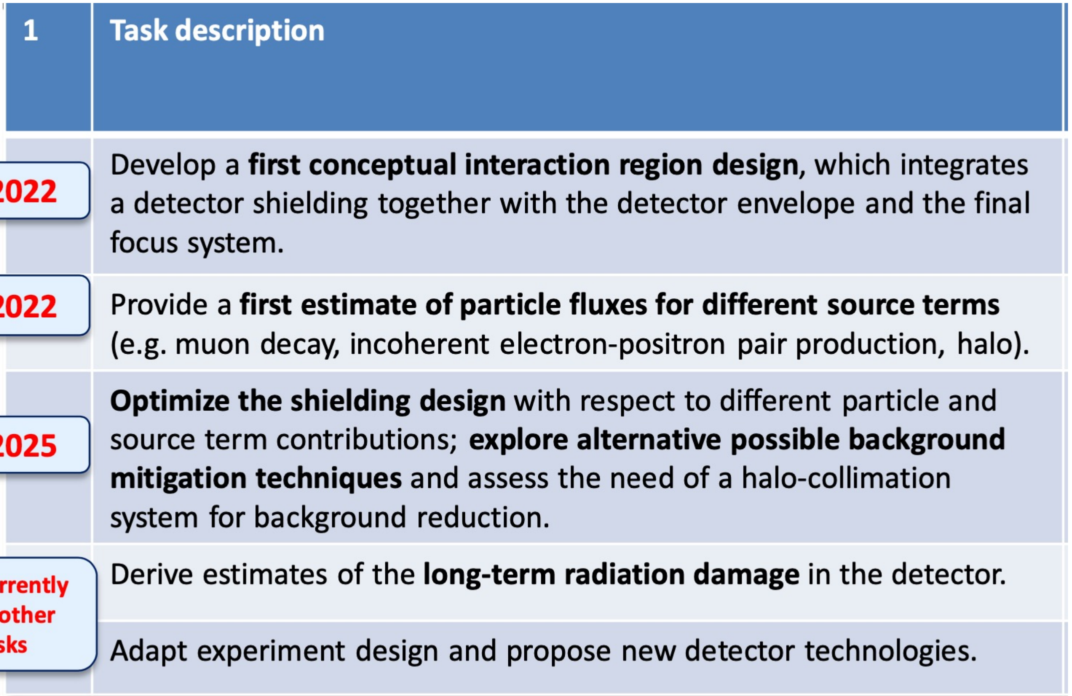
- Develop **active background mitigation techniques**, for example:
  - Time gates
  - Smart shielding (instrumented)
  - Directional suppression (e.g. BH muons)

The MDI work shall help to define the detector specs



	1	Task description
By 2022		Study beam-induced **background characteristics** using the **MAP $\sqrt{s}$=3 TeV** interaction region design
By 2022		Define a **metric** for the determination of the **shape and dimensions of the shielding** inserted in the detector (nozzle)
By 2025		Explore **further shielding strategies** (e.g. asymmetric nozzle, optimization of interaction region active elements together with detector modifications)
Concurrently with other tasks		Provide estimates of the **long-term radiation damage** in the detector
		Adapt experiment design and propose new detector technologies

TOTAL
15 FTEy/5 years

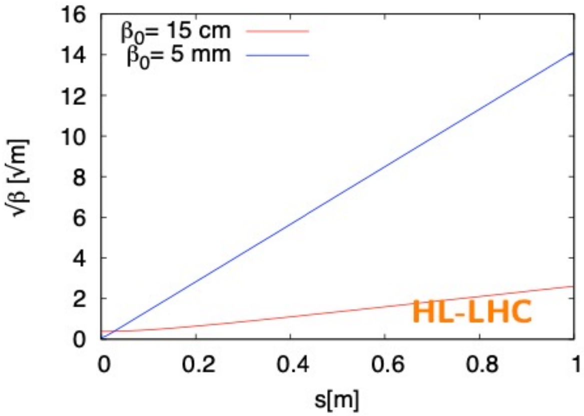


	1	Task description
By 2022		Develop a **first conceptual interaction region design**, which integrates a detector shielding together with the detector envelope and the final focus system.
By 2022		Provide a **first estimate of particle fluxes for different source terms** (e.g. muon decay, incoherent electron-positron pair production, halo).
By 2025		**Optimize the shielding design** with respect to different particle and source term contributions; **explore alternative possible background mitigation techniques** and assess the need of a halo-collimation system for background reduction.
Concurrently with other tasks		Derive estimates of the **long-term radiation damage** in the detector.
		Adapt experiment design and propose new detector technologies.

Lattice challenges

Eliana Gianfelice-Wendt (FNAL)

- Low β^* (few mm):
  - Strong IR quadrupoles and large $\hat{\beta}$:
    - $*$ large chromaticity;
    - $*$ large sensitivity to misalignments and field errors.
- Small circumference, particularly important for short living particles!
- High density: $N \approx 2\times10^{12}$ per bunch.
- Neutrinos hotspots limit the length of field-free regions at beam energy $\gtrsim$1.5 TeV
- Protection of magnets and detectors.
- $\sigma_\ell \leq \beta^*$ to avoid hour-glass effect.



- Expected large momentum spread ($\approx$ 0.1%) requires
  - small $|\alpha_p|$ ($\approx 1\times10^{-5}$) over the momentum range to achieve short bunches with reasonable RF voltage;
  - sufficient Dynamic Aperture ($\gtrsim 3\sigma$) in presence of strong sextupoles and large dp/p.

E. Gianfelice-Wendt

Interaction Region @ $\sqrt{s}$ = 1.5 and 3 TeV

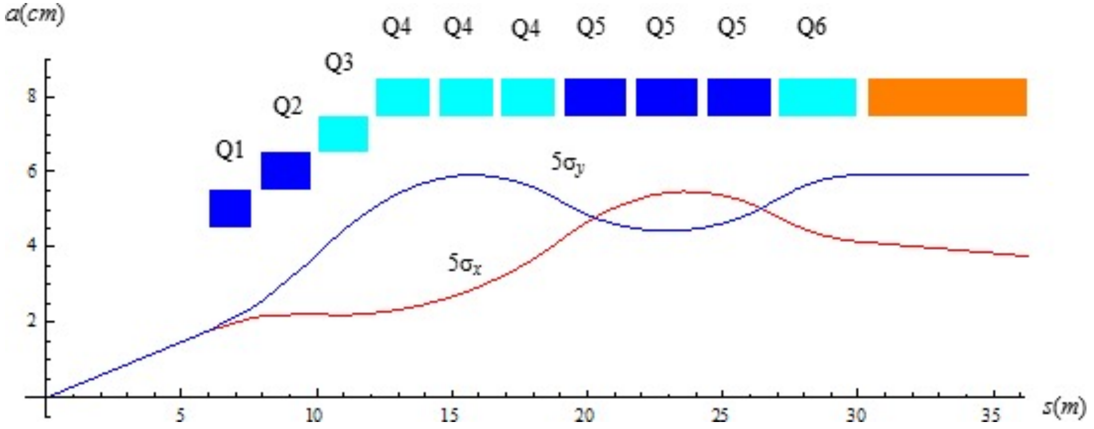
Muon Collider Lattice Concepts

Y. Alexahin *et al* 2018 *JINST* **13** P11002

Name	Q_1	Q_2	Q_3, Q_4	Q_5	B_1
Rc_{int} (cm)	4	5.5	8	8	8
Rc_{out} (cm)	8	9.5	12	12	12
Ri_{out} (cm)	20	25	30	30	30
Length (m)	1.5	1.76	1.7	1	6

$\sqrt{s}$ = 1.5 TeV

**The machine elements, MDI and interaction region must be properly designed and optimized
@ each collider energy**



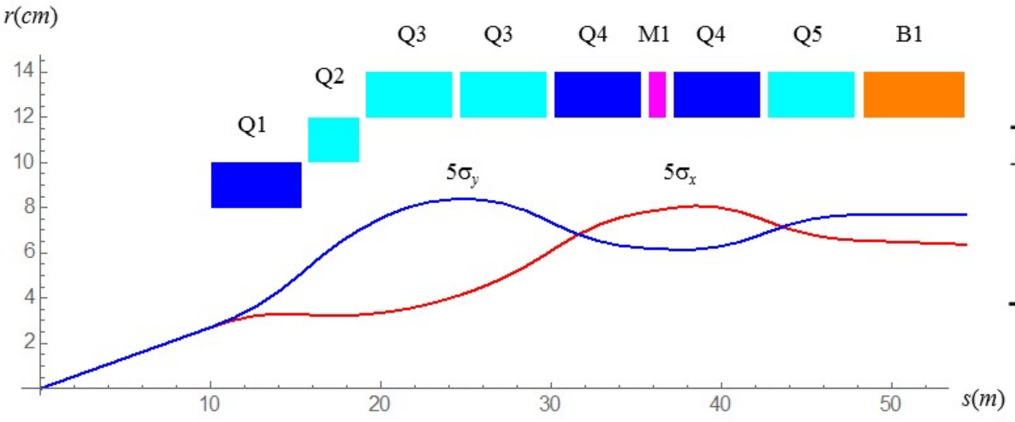
Final Focus quadrupoles

$\sqrt{s}$ = 3 TeV

in cyan: defocusing quadrupoles
with up to 2 T dipole component

Preliminary IR design @ $\sqrt{s}$ = 6 TeV

assumed available Nb_3Sn magnet technology



Muon Collider Lattice Concepts

[Y. Alexahin *et al* 2018 *JINST* **13** P11002](#)

Final Focus quadrupoles

Parameter	*Q1*	*Q2*	*Q3*	*Q4*	*Q5*
ID (mm)	160	200	240	240	240
G (T/m)	200	-125	-100	103	-78
B_{dipole} (T)	0	3.5	4.0	3.0	6.0
L (m)	5.3	3.0	5.1	5.1	5.1

in cyan: defocusing quadrupoles with up to 5 T dipole component

Design goals:

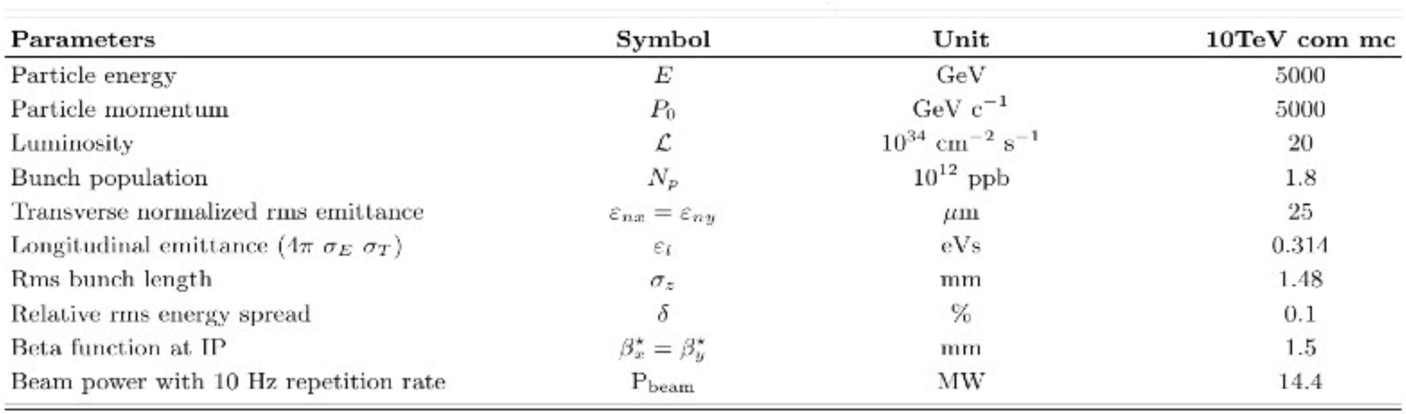
- β^* = 3 mm
- 10 m distance from IP to the first quad
- $\geq$ 3 T dipole component in quads (not Q1) to sweep away charged secondaries
- magnet inner bore radius constrained by IR > $5\sigma_{\perp}^{(max)}$ + 3 cm ➔ good field quality
- magnets cut in pieces shorter than 6 m to insert protecting masks

Preliminary IR design @ $\sqrt{s}$ = 10 TeV

Kyriacos Skoufaris - Christian Carli (CERN)

Design requirements:

- ✓ **the ring length should be as small as possible**
  - to reach design luminosity with given β* and intensity
  - use of the maximum allowed magnetic field for all the lattice magnets, 20T for the final focusing quads and 16T for the rest of the magnets
- ✓ **to mitigate Neutrino radiation issue (avoid local high doses)**
  - extensive use of dipoles and combined function magnets (dipole+multipole), with only exception the final focusing quads and the magnets in the straight section
  - the free space between magnets is 0.3m
- ✓ **good control of the lattice optics, errors, fringe field and the particle dynamics needed**
  - the chromatic phenomena such as linear/non-linear chromaticity, Montague functions, second order dispersion and higher order momentum compaction should be compensate/controlled

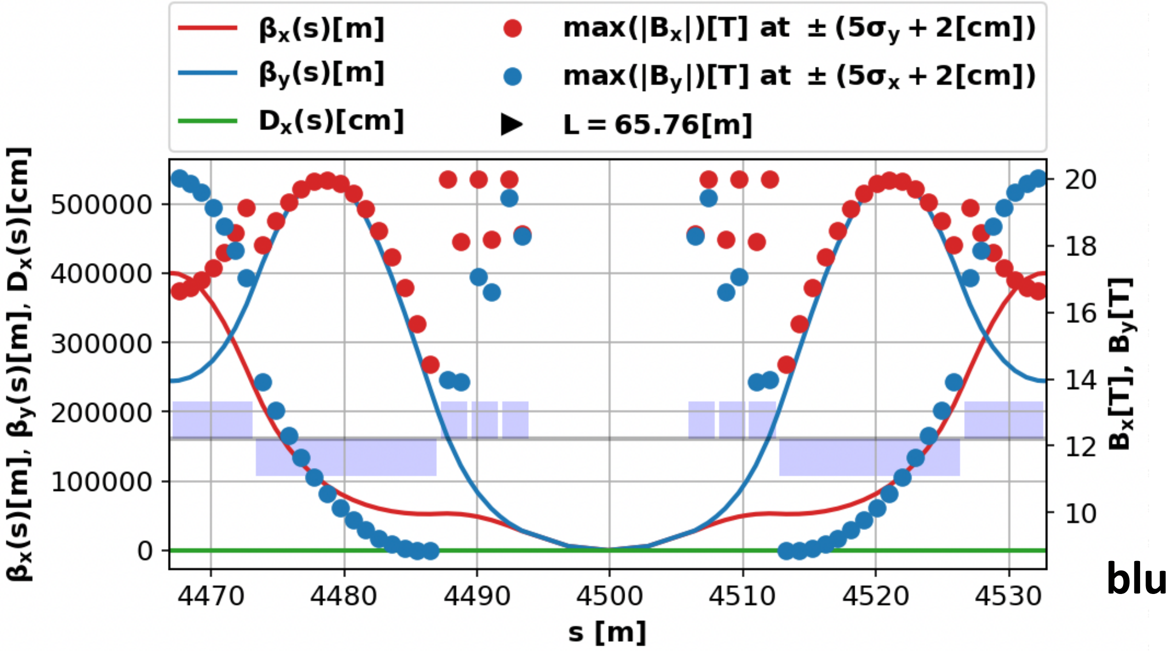


Parameters	Symbol	Unit	10TeV com mc
Particle energy	E	GeV	5000
Particle momentum	P_0	GeV c^{-1}	5000
Luminosity	$\mathcal{L}$	10^{34} cm^{-2} s^{-1}	20
Bunch population	N_p	10^{12} ppb	1.8
Transverse normalized rms emittance	$\varepsilon_{nx} = \varepsilon_{ny}$	μm	25
Longitudinal emittance ($4\pi\ \sigma_E\ \sigma_T$)	ε_l	eVs	0.314
Rms bunch length	σ_z	mm	1.48
Relative rms energy spread	δ	%	0.1
Beta function at IP	$\beta_x^* = \beta_y^*$	mm	1.5
Beam power with 10 Hz repetition rate	P_{beam}	MW	14.4

FF scheme with CCS @ $\sqrt{s}$ = 10 TeV

- The interaction region (IR) consists of the final focusing (FF) quadrupole triplet and the chromatic correction scheme (CCS)
- Strong chromatic effects from FF quads with strength depending on particle energy is compensated in CCS by dipole-sextupoles and dipole-quadrupole combined function magnets
- The magnetic field at the FF quads is close to 20T and for the rest elements in the CCS is close to the 16T (maximum allowed one)

This is a first version without dipolar magnetic fields to understand BIB

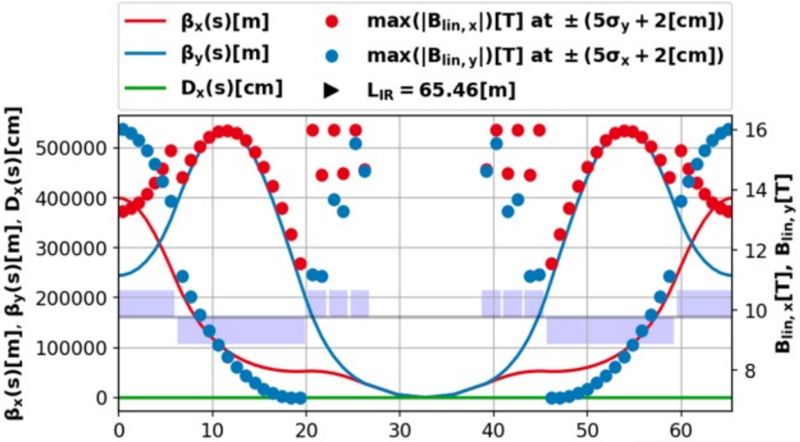


blue boxes quadrupole

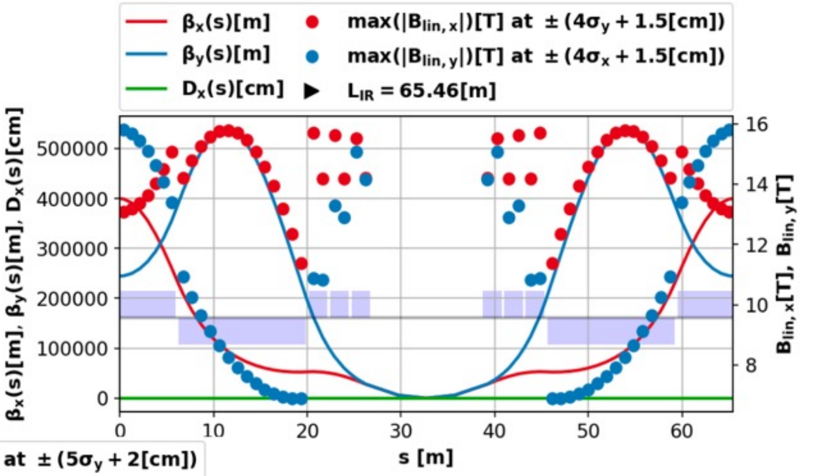
Options if only 16T magnets available

Interaction region – FF scheme

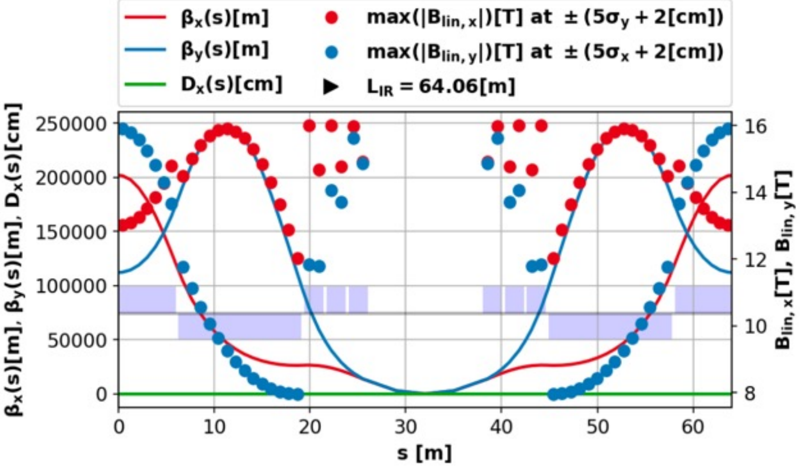
Reduction of the com energy to 8TeV



Reduction of the beam envelope to 4σ+1.5cm



Increase of the β*
by a factor (10/7)^2



Beam Induced Background @ 1.5 TeV

N.V. Mokhov - S.I. Striganov (FNAL)

Detector Backgrounds at Muon Colliders

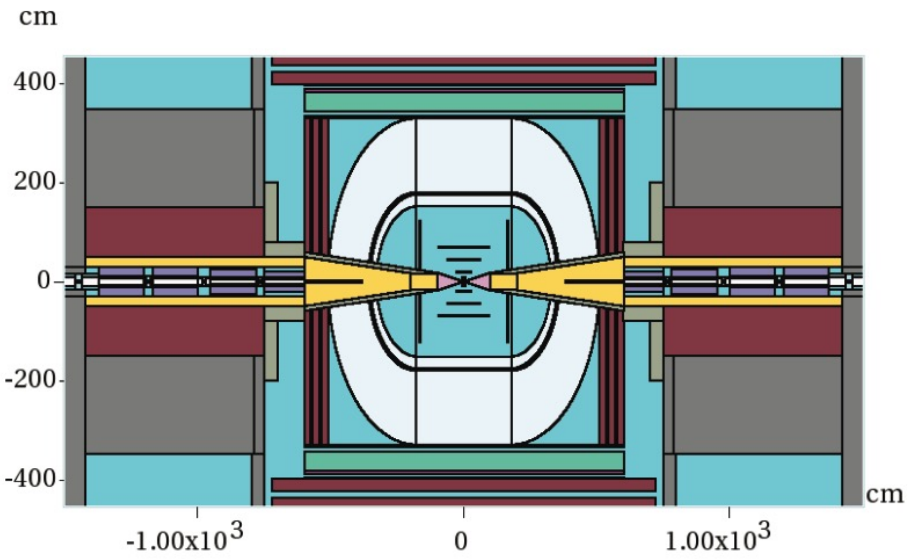
[Physics Procedia 37 (2012),2015]

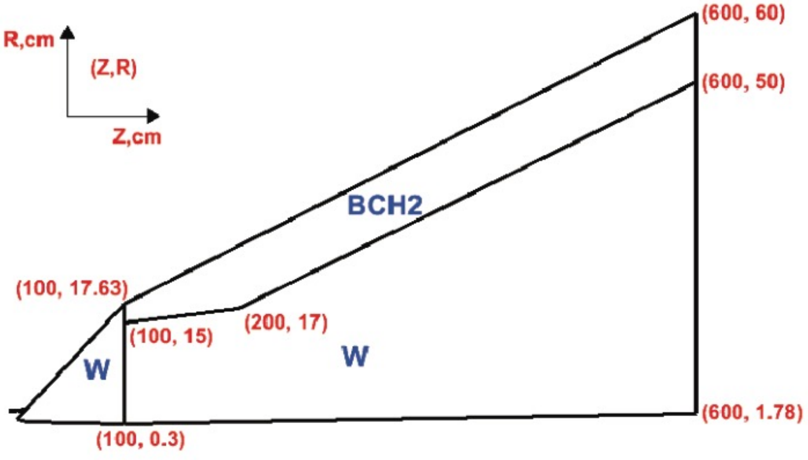
0.75 TeV muon ➔ decay length 4.7×10^{6} m

2×10^{12} muons/bunch ➔ 4.28×10^{5} decays per meter of the lattice in a single pass

1000-turn stores with 15 stores per second

➔ 1.28×10^{10} decays/meter/sec for two 0.75-TeV muon beams

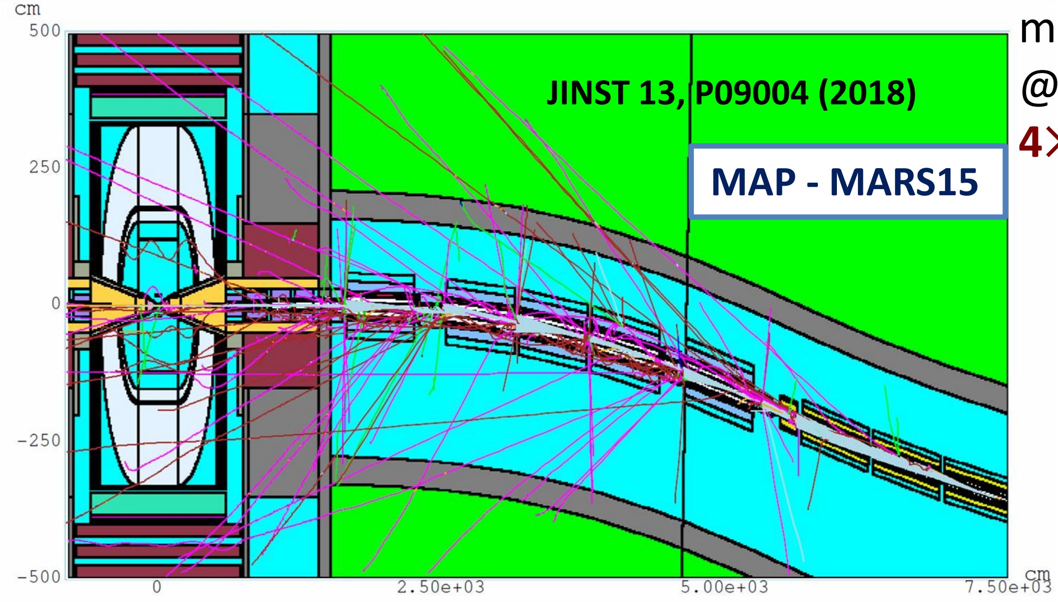




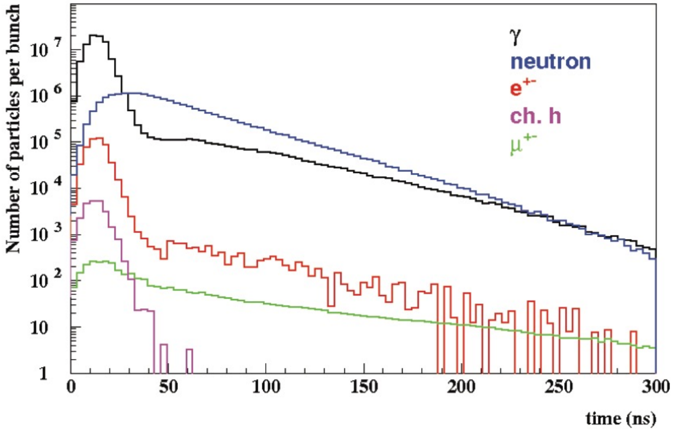
Machine Detector Interface @1.5

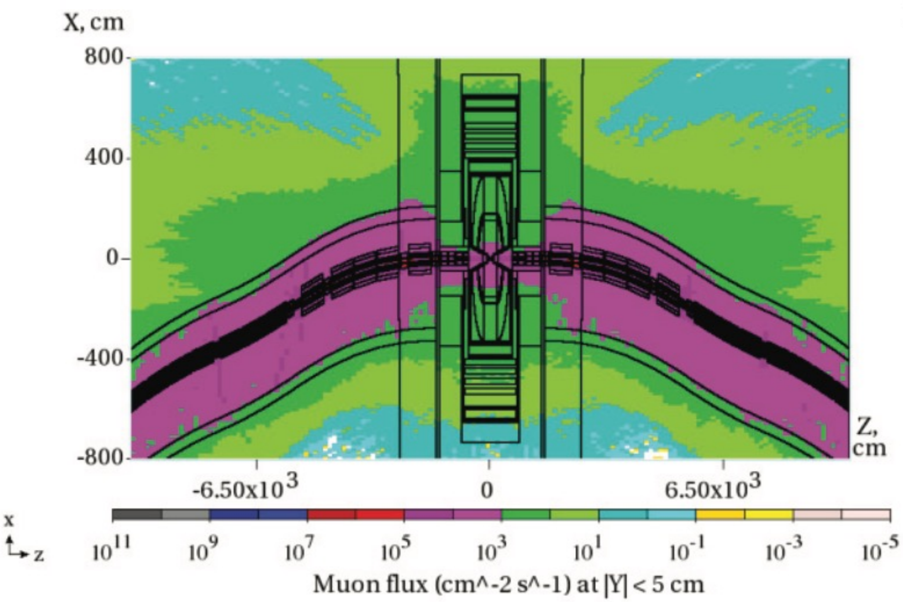
muon beams

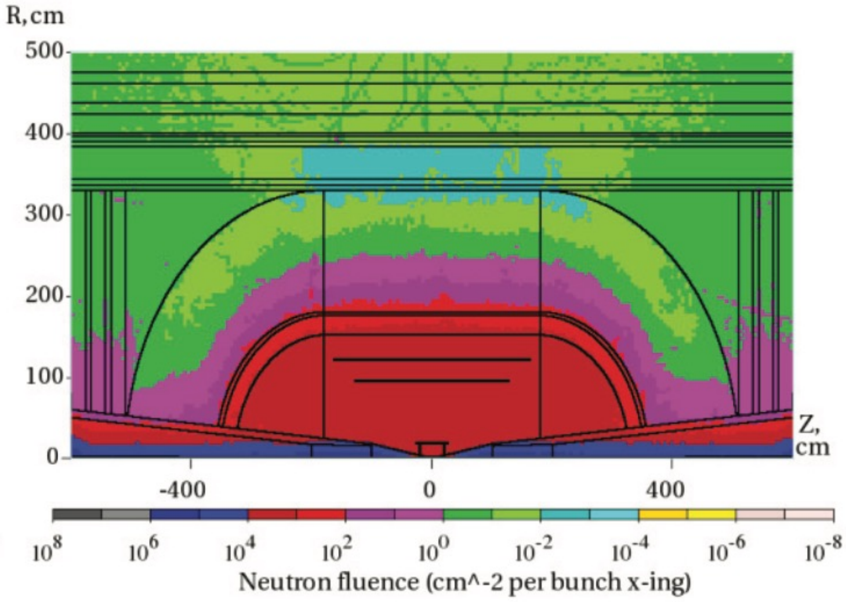
@ **0.75 TeV** with **2×10^{12}muons/bunch** ➔ **4×10^{5} muon decays/m** single bx


JINST 13, P09004 (2018)

MAP - MARS15



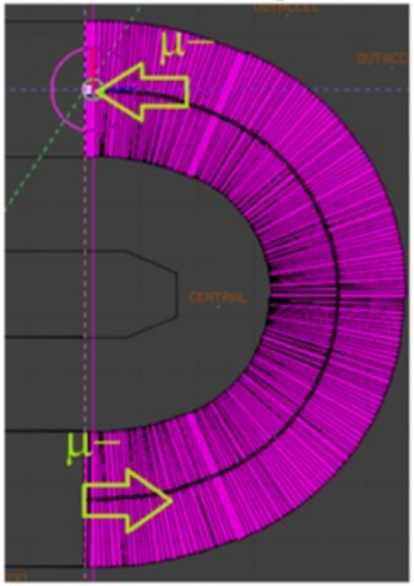




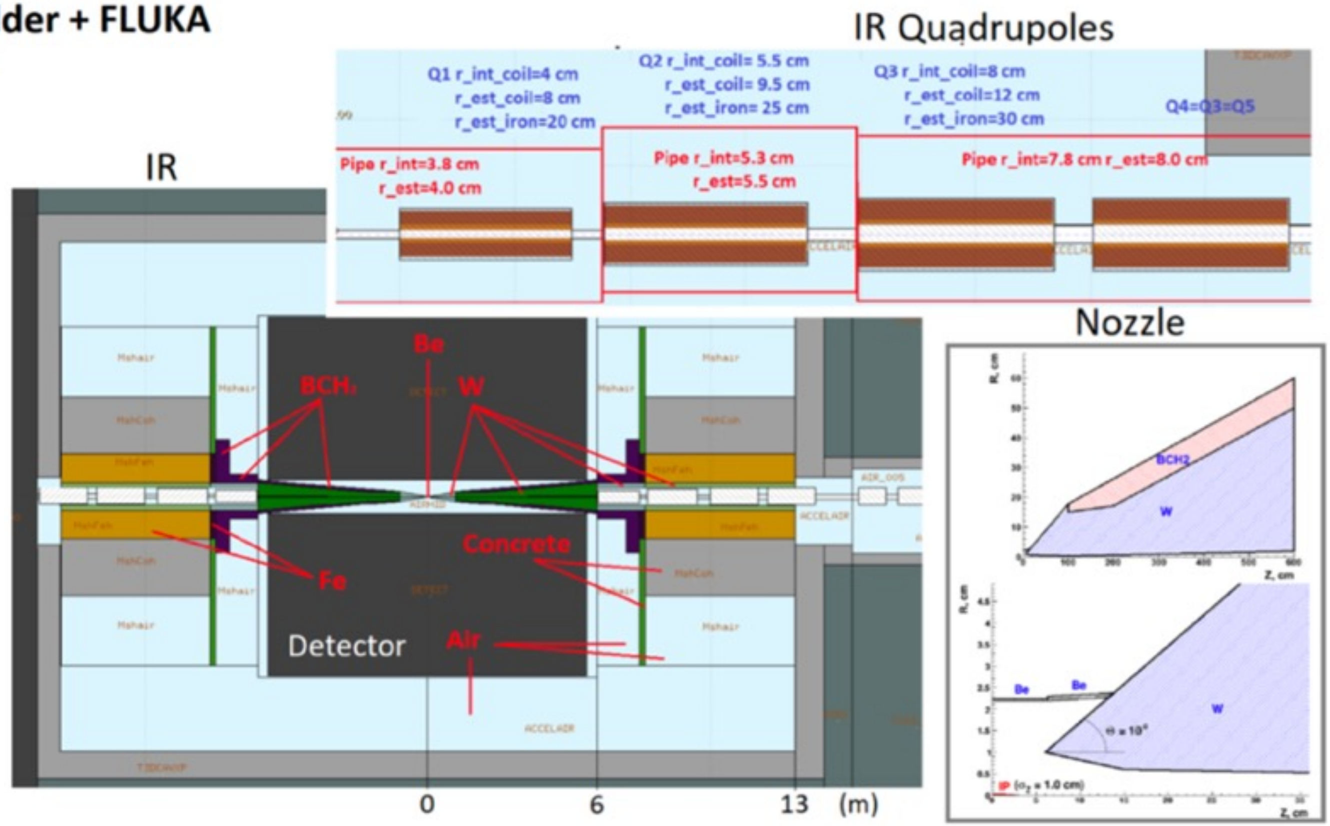
Machine Detector Interface @1.5 – 3 TeV

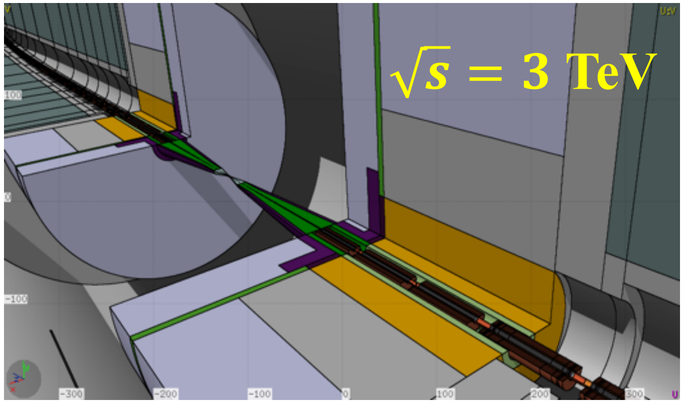
Simulation tool: **LineBuilder + FLUKA**
Data analysis: **Python**

750 GeV muon beam travels half ring to IP



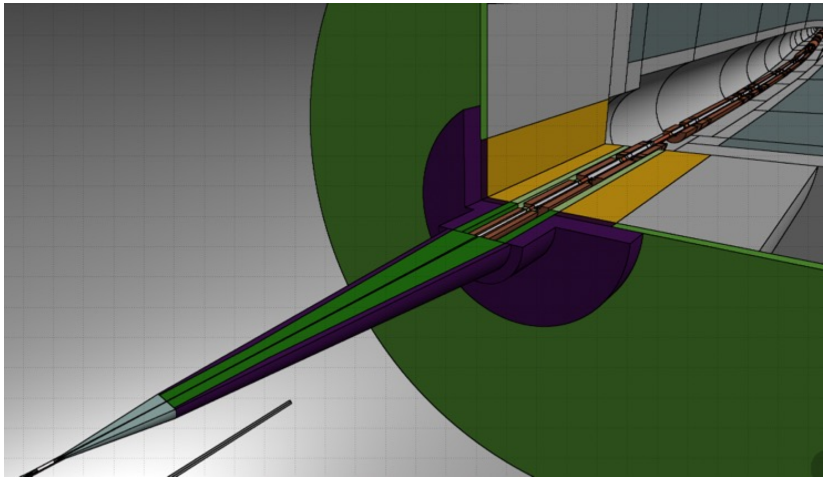
IR

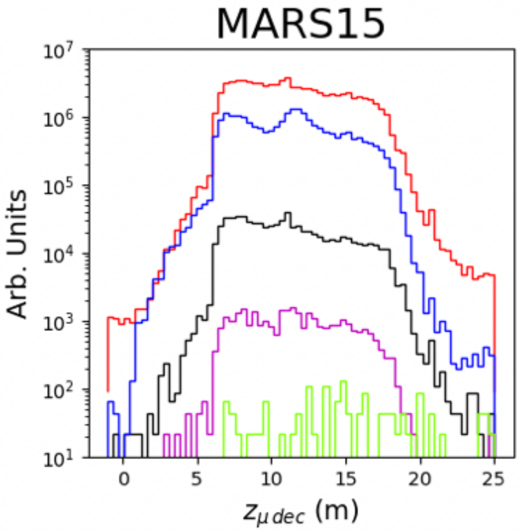




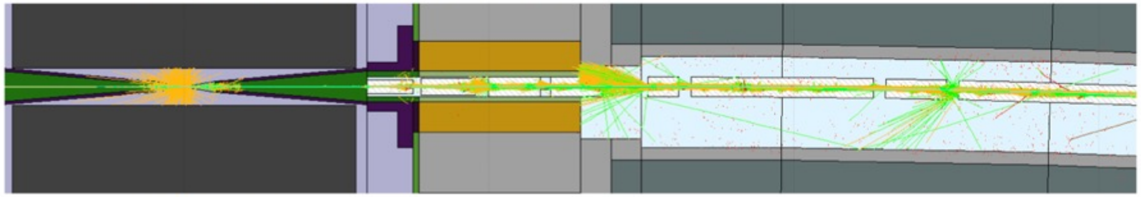
Beam Induced Background distributions

Advanced assessment of beam-induced background at a muon collider
F. Collamati *et al* 2021 *JINST* **16** P11009

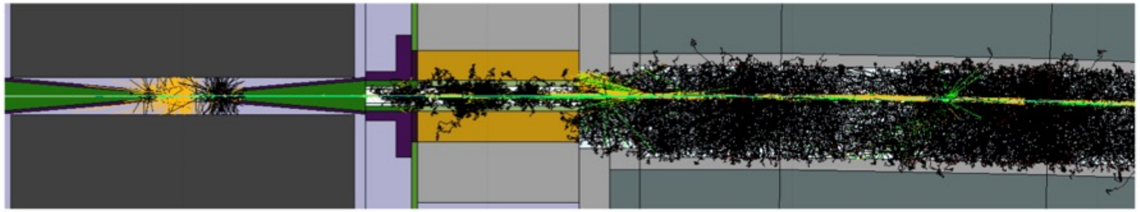


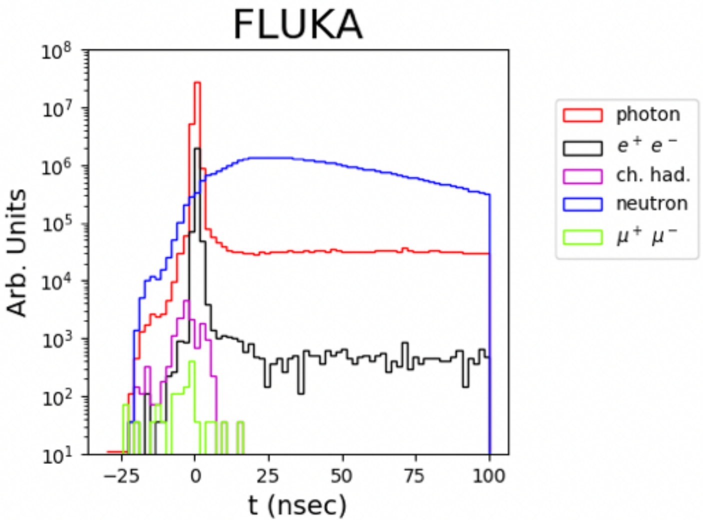


FLUKA tracking without neutrons



FLUKA tracking with neutrons

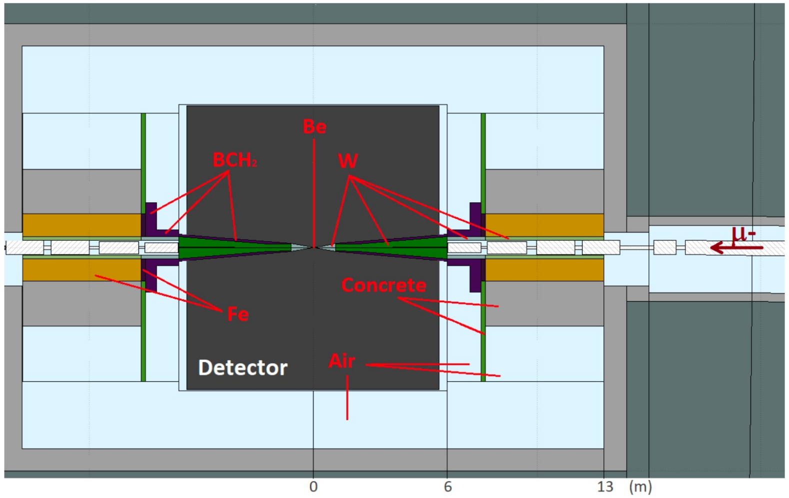


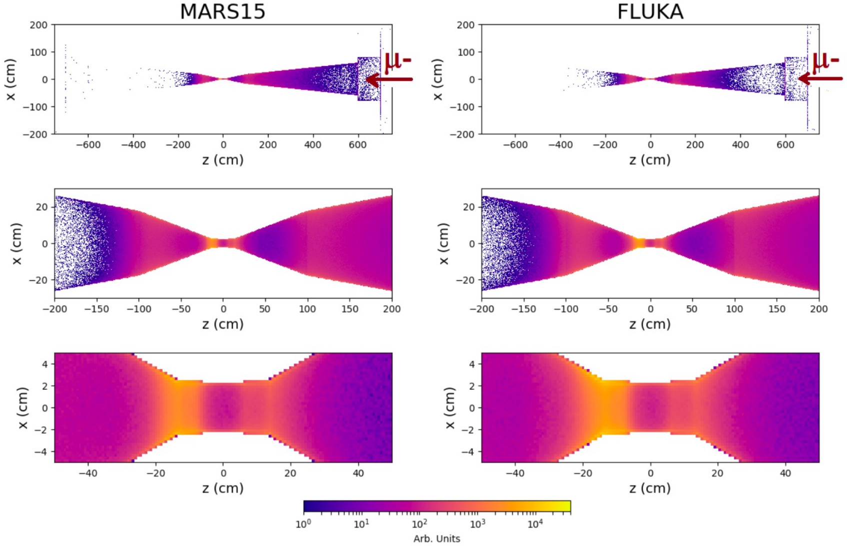


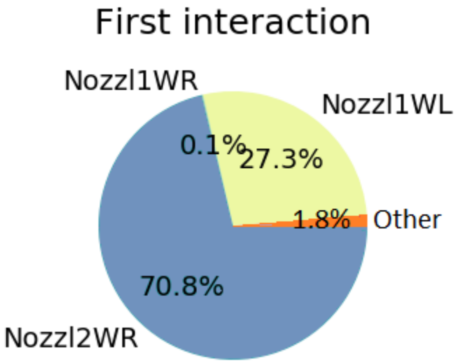
MARS15 – FLUKA Comparisons

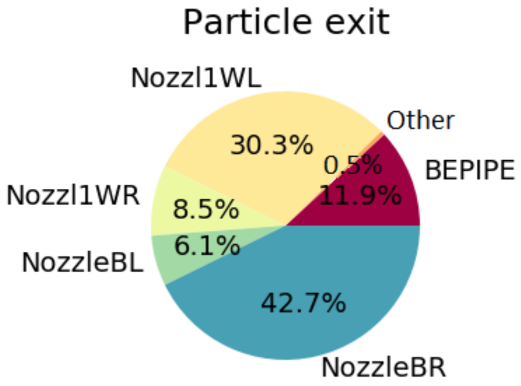
Advanced assessment of beam-induced background at a muon collider

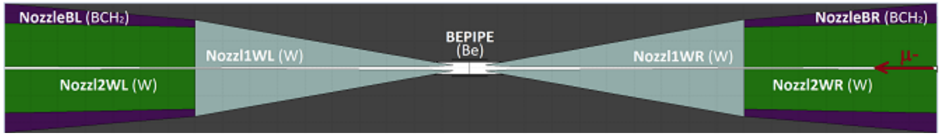
F. Collamati *et al* 2021 *JINST* **16** P11009











Comparisons of BIB at different energies

Massimo Casarsa et al. (INFN ++)

three colliders operating at:

125 GeV 1.5 TeV 3 TeV

a single μ^- beam arriving from the right

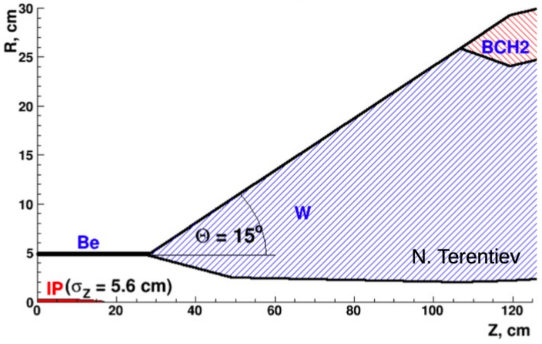
BIB samples not uniform: some generated with MARS15, some with FLUKA

results at 3 TeV are very preliminary: there is still no optimized MID and ideal beam

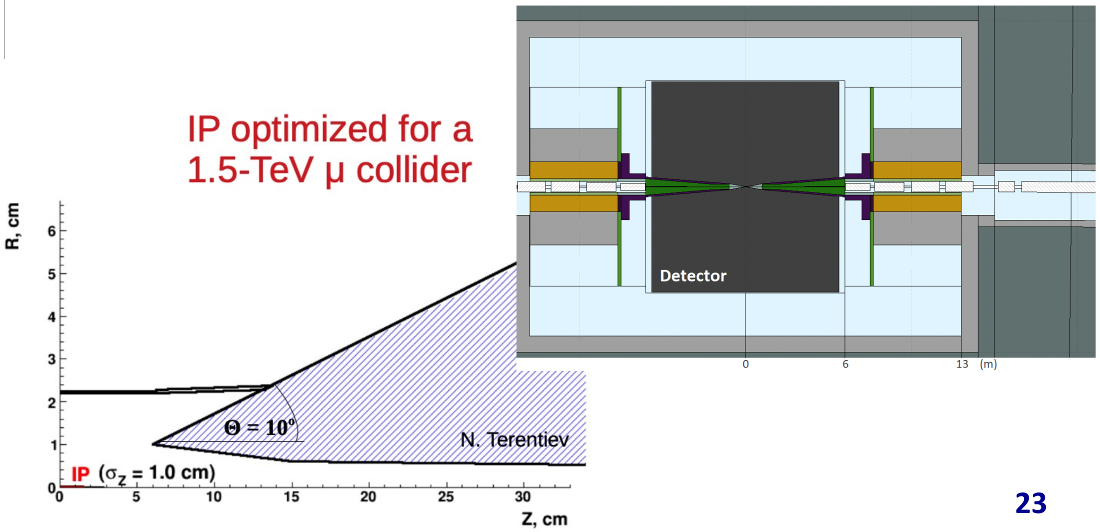
beam energy [GeV]	63	750	1500
average inst. lum. [cm^2 s^{-1}]	0.008 x 10^{34}	1.25 x 10^{34}	4.6 x 10^{34}
number of muons/bunch	4 x 10^{12}	2 x 10^{12}	2 x 10^{12}
number of bunches	1	1	1
repetition rate [Hz]	15	15	12
β* [cm]	1.7	1	0.5
normalized ε_T [π mm rad]	0.2	0.025	0.025
normalized ε_L [π mm rad]	1.5	70	70
bunch length [cm]	6.3	1	0.5
bunch size at IP [μm]	75	6	3
momentum spread [%]	0.004	0.1	0.1

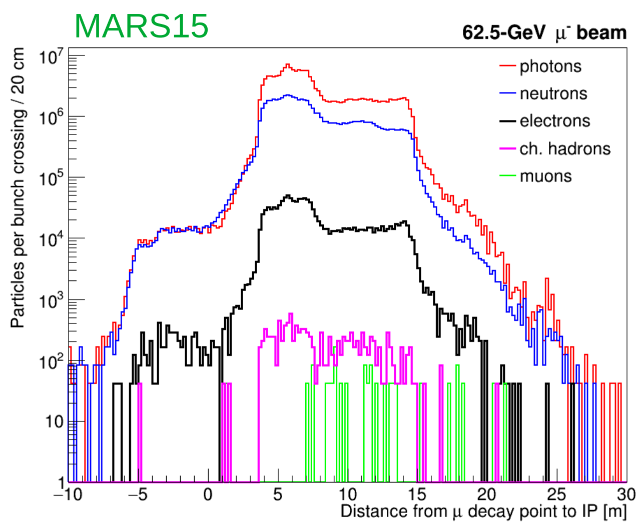
Both MARS15 and FLUKA simulate the interaction of the muon decay products with the machine elements and transport the BIB particles up to the detector envelop

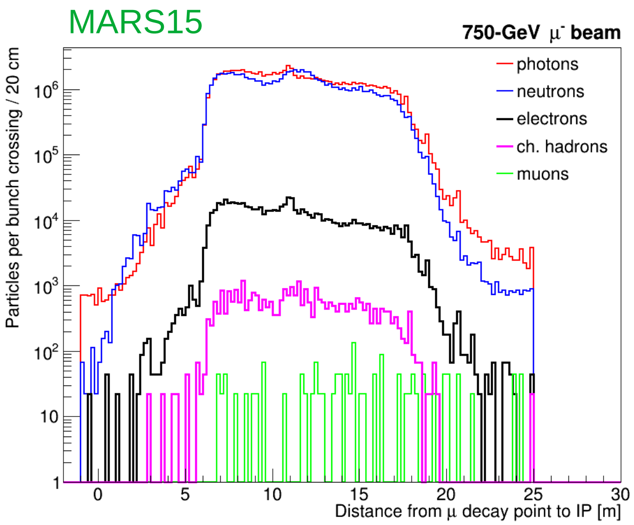
IP optimized for a 125-GeV μ collider

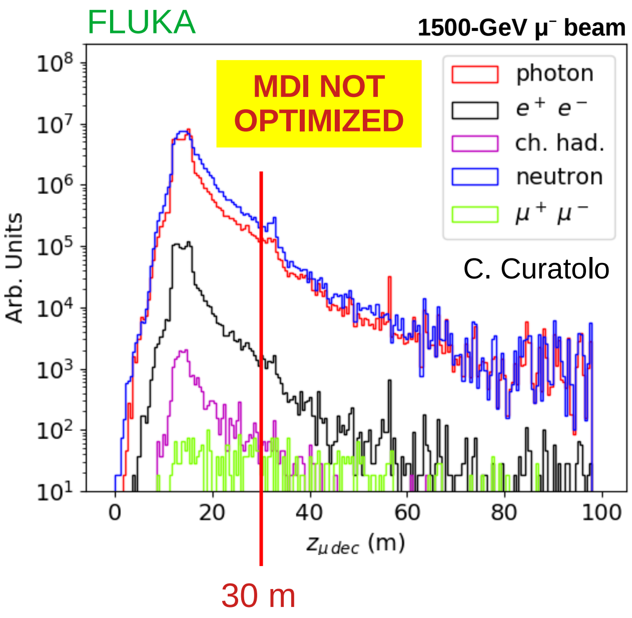


IP optimized for a 1.5-TeV μ collider





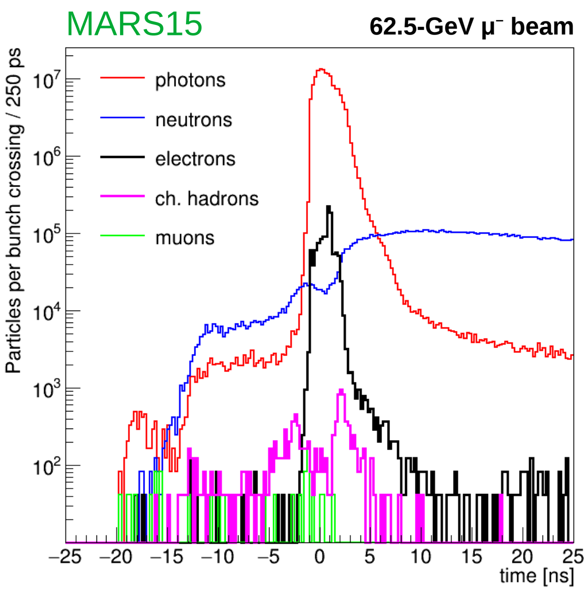


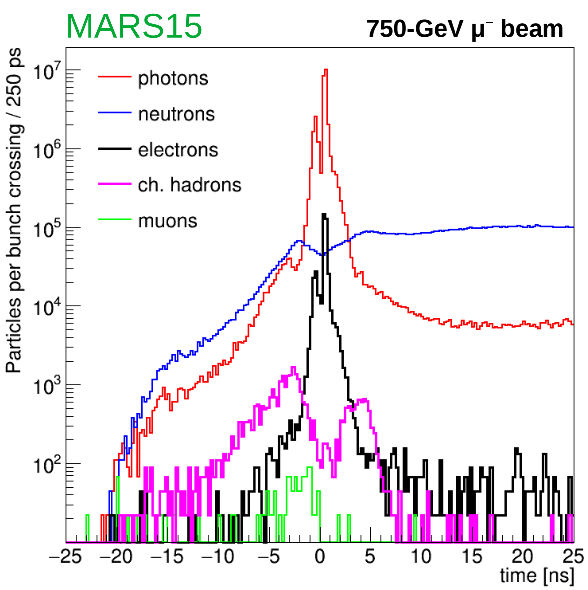


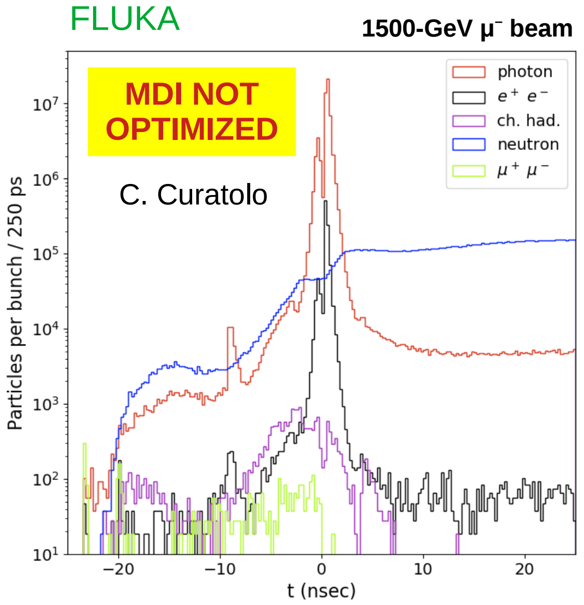
MDI NOT OPTIMIZED

C. Curatolo

Muon Decay point







MDI NOT OPTIMIZED

C. Curatolo

Time of arrival

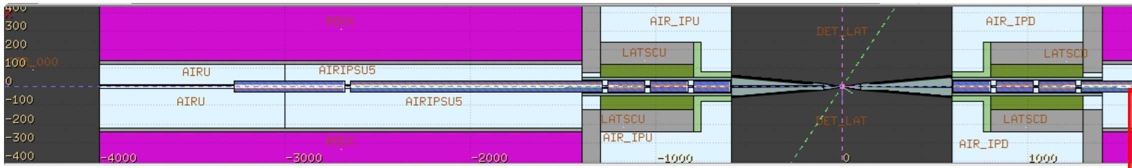
BIB yields

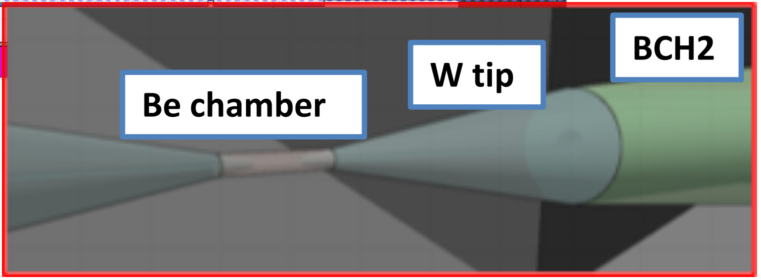
	MARS15	MARS15	FLUKA	FLUKA
beam energy [GeV]	62.5	750	750	1500 **MDI NOT OPTIMIZED**
μ decay length [m]	3.9 x 10^5	46.7 x 10^5	46.7 x 10^5	93.5 x 10^5
μ decays/m per beam (for 2x10^{12} μ/bunch)	51.3 x 10^5	4.3 x 10^5	4.3 x 10^5	2.1 x 10^5
simulation z range [m]	[-10, 30]	[-1, 25]	[0, 100]	[0, 100]
photons/BX (E_γ > 0.1 MeV)	170 x 10^6	86 x 10^6	51 x 10^6	70 x 10^6
neutrons/BX (E_n > 1 meV)	65 x 10^6	76 x 10^6	110 x 10^6	91 x 10^6
$e^\pm$/BX (E_e > 0.1 MeV)	1.3 x 10^6	0.75 x 10^6	0.86 x 10^6	1.1 x 10^6
charged hadrons/BX (E_h > 0.1 MeV)	0.011 x 10^6	0.032 x 10^6	0.017 x 10^6	0.020 x 10^6
muons/BX (E_h > 0.1 MeV)	0.0012 x 10^6	0.0015 x 10^6	0.0031 x 10^6	0.0033 x 10^6

MDI @ $\sqrt{s}$ = 10 TeV – first study

Daniele Calzolari et al.(CERN)

The quantities are normalized to the single passage, assuming a bunch containing $2{\cdot}10^{12}$ muons.





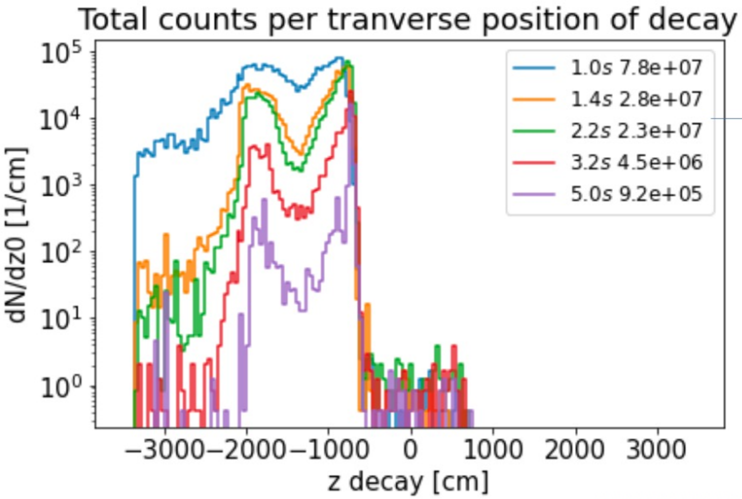
Electron, positrons and photons cutoffs are at **100 keV**.
SR photons are produced down to 100 keV.
Neutrons are simulated down to thermal energies (~meV) (less than 10% will have energies below 10^{-5} GeV).
Photonuclear reactions are activated at all energy ranges.
Muon pair production by photons and bremsstrahlung by muons are activated.

BIB mainly due to **decays** which happens **around** the **beam core**.
Decays further away in the transverse plane give less contribution.

The **tunnel** simulated length is **±35 m**.
Only pure quadrupole magnets are present in the lattice.
The **detector area** is modeled as a **blackbox**, and the particle crossing its surface are scored.
It is considered as the region outside of the nozzle (and the beryllium chamber) inside two planes at ±6m.
In the nozzle, there is a solenoidal magnetic field of 5 T.

BIB decay origin @ 10 TeV

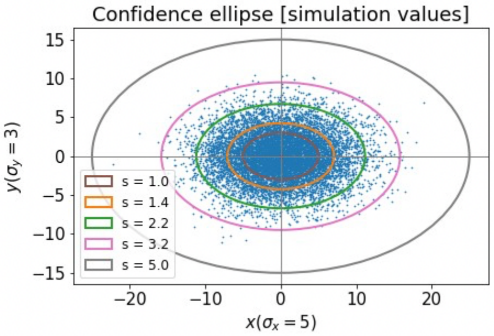
- The **longitudinal decay position** is a very important indicator to understand the contribution of decays at large distances.
  - Most of the particles come from the region where there is the largest variation of the beam size.
  - Secondary muons and charged hadrons are not yet included. (The number of counts is still not enough for a satisfactory statistics)
  - The main contributions are always due to decays happening near to the ideal trajectory.



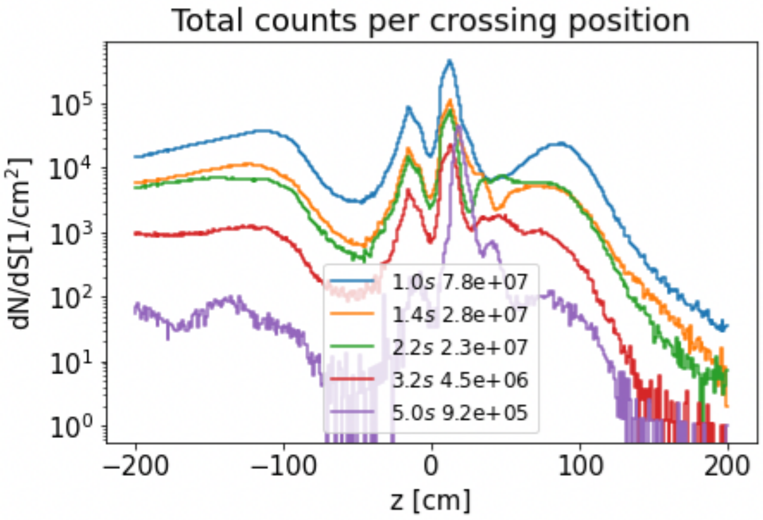
$P(s^2 \in (0,1))$	0.393
$P(s^2 \in (1,2))$	0.239
$P(s^2 \in (2,5))$	0.286
$P(s^2 \in (5,10))$	0.075
$P(s^2 \in (10,25))$	0.0067

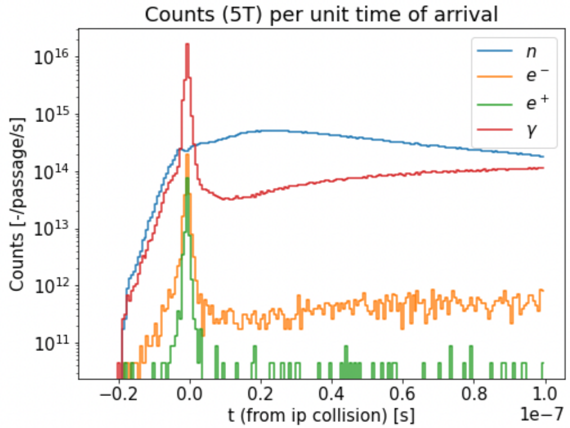
Normalization of the number of crossing for each probability to decay at a certain distance from the beam core

Interval	Crossing per decay in interval
$s \in (0,1)$	1.98×10^8
$s \in (1,1.4)$	1.19×10^8
$s \in (1.4,2.2)$	8.17×10^7
$s \in (2.2,3.2)$	5.97×10^7
$s \in (3.2,5)$	1.37×10^8

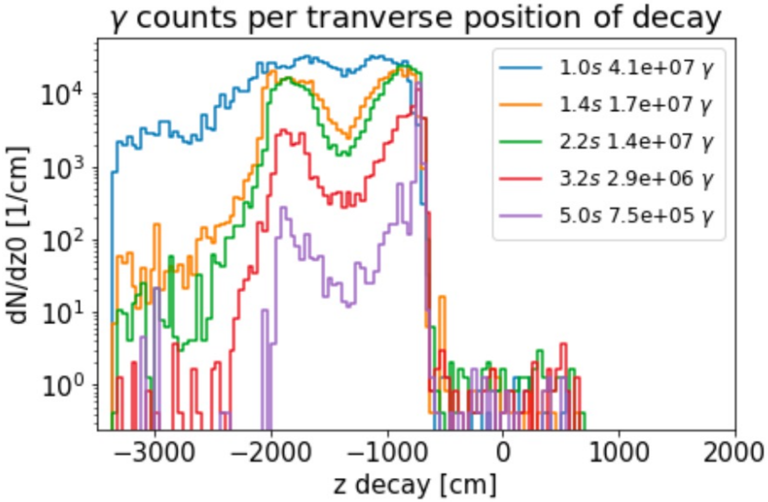


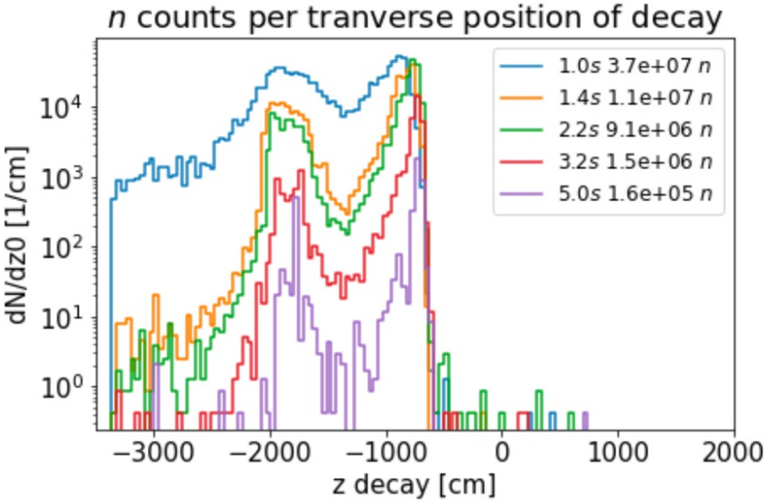
BIB distributions @ 10 TeV





ollaboration

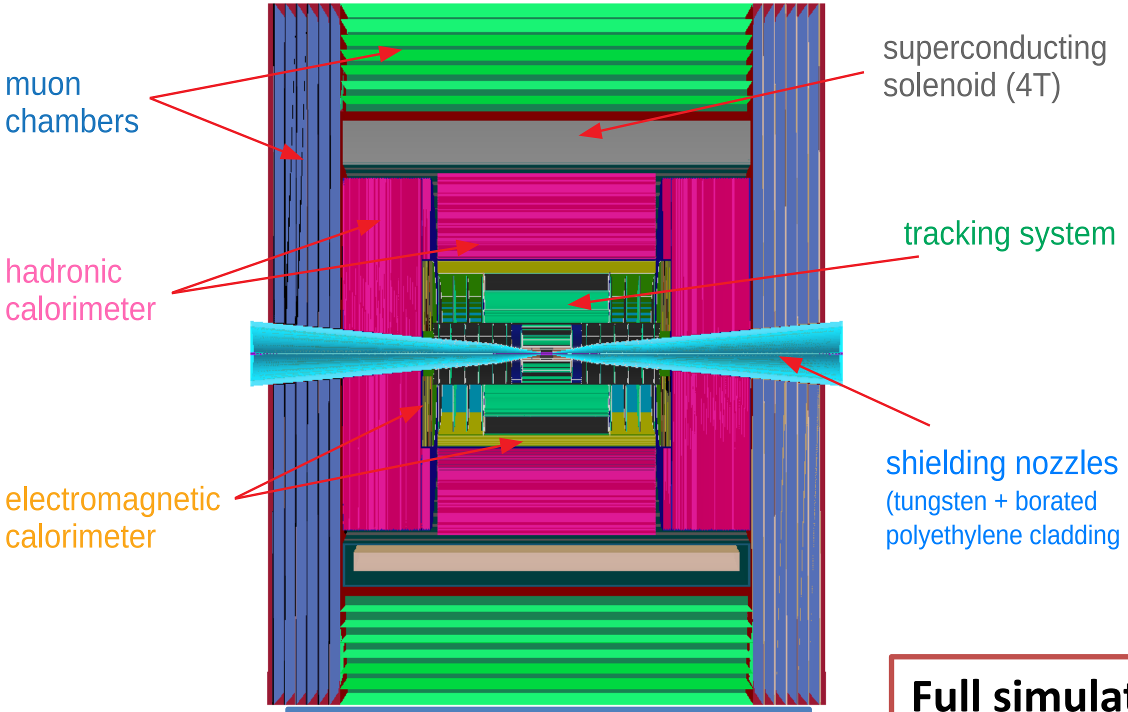




- Both the photons and the neutrons show the same behavior. Far away from the IP, only the muons decaying around the beam core give a significant contribution.
- Near to the beginning of the nozzle, the tails become more important since the corresponding secondary electrons have to travel for less distance in the materials.

Detector studies @ $\sqrt{s}$ =1.5 TeV

- CLIC Detector technologies adopted with important tracker modifications to cope with BIB
- Detector design optimization at $\sqrt{s}$=1.5 (3) TeV



B = 3.57 T to be studied and tuned

TO BE IMPROVED

TUNED at higher $\sqrt{s}$

Vertex Detector (VXD)

- 4 double-sensor barrel layers 25x25μm^2
- 4+4 double-sensor disks 25x25μm^2

Inner Tracker (IT)

- 3 barrel layers 50x50μm^2
- 7+7 disks ”

Outer Tracker(OT)

- 3 barrel layers 50x50μm^2
- 4+4 disks ”

Electromagnetic Calorimeter (ECAL)

- 40 layers W absorber and silicon pad sensors, 5x5 mm^2

Hadron Calorimeter (HCAL)

- 60 layers steel absorber & plastic scintillating tiles, 30x30 mm^2

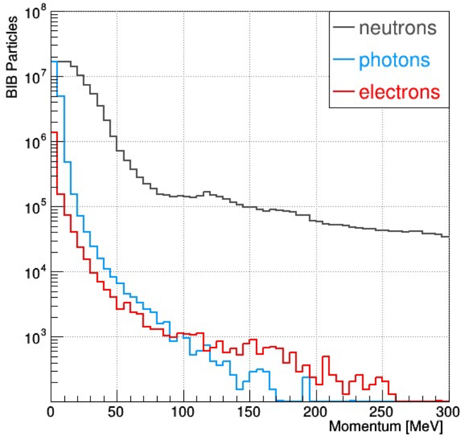
Full simulation available on public repository

Quite advanced conceptual design for Higgs factory, 1.5 TeV and 3 TeV

Properties of BIB contribution

BIB has several characteristic features → crucial for its effective suppression

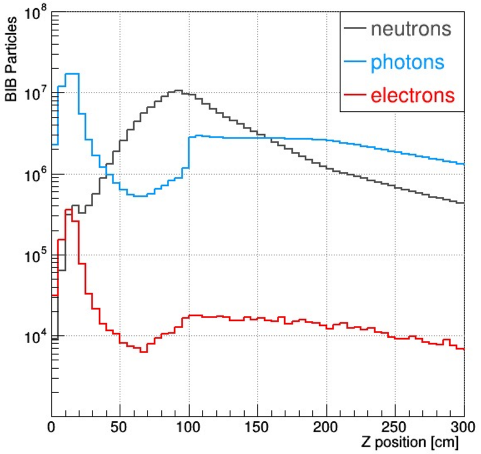
1. **Predominantly very soft particles** (p << 250 MeV) except for neutrons
   fairly uniform distribution in the detector → no isolated signal-like deposits
   ↳ conceptually different from pile-up contributions at the LHC

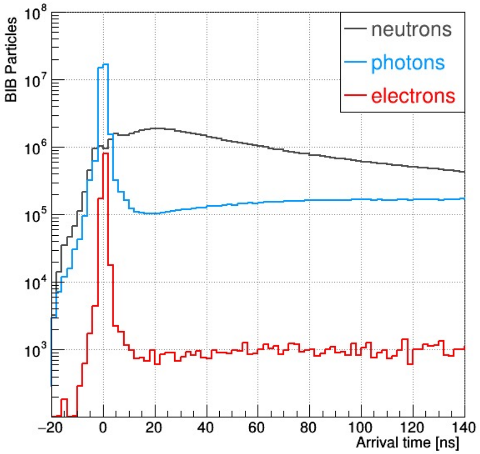


2. **Significant spread in time** (few ns + long tails up to a few μs)
   $\mu^+\mu^-$ collision time spread: 30ps (defined by the muon-beam properties)
   ↳ strong handle on the BIB → requires state-of-the-art timing detectors

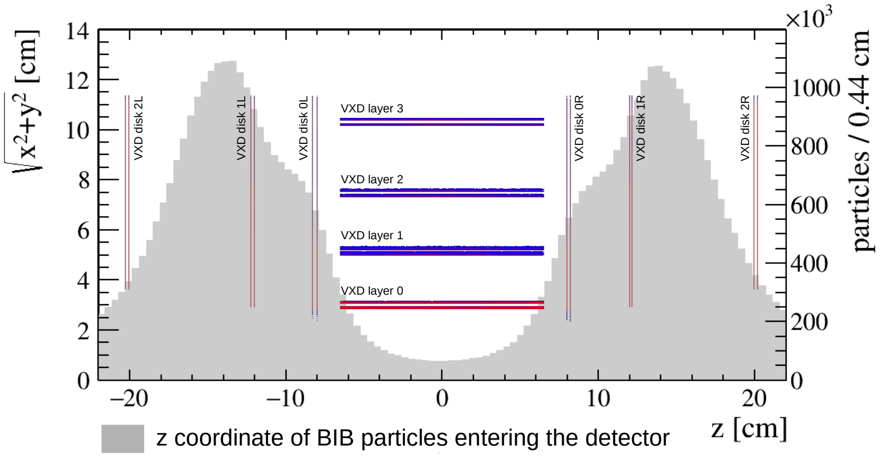
3. **Large spread of the origin along the beam**
   different azimuthal angle wrt the detector surface
   + affecting the time of flight to the detector
   ↳ relevant for position-sensitive detectors

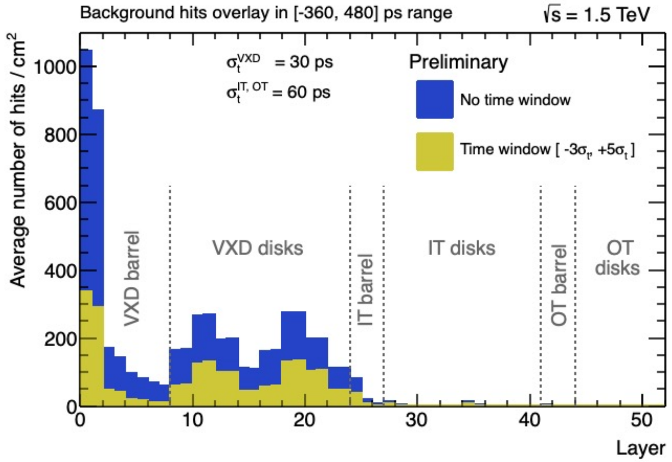
An overview of the main optimisation steps and their impact presented in a [recent paper]()

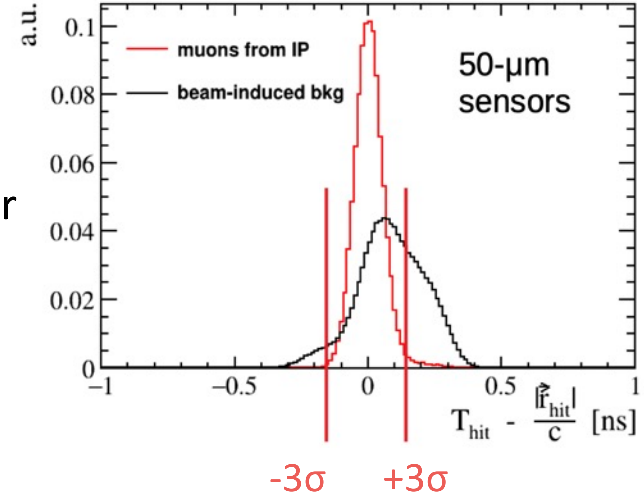




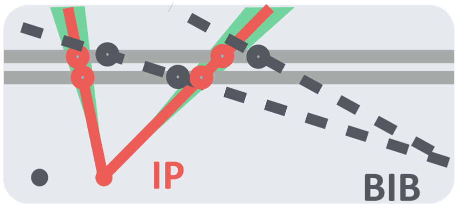
Tracker detector requirements







- Timing window applied to reduce out-of-time BIB’s hits
- Granularity optimized to ensure $\lesssim$ 1% occupancy
- BIB suppression based on cluster shape
- If primary vertex could be known before ➔ effective angular matching of hit doublets
- To be tuned in presence of secondary vertices or long-lived particles



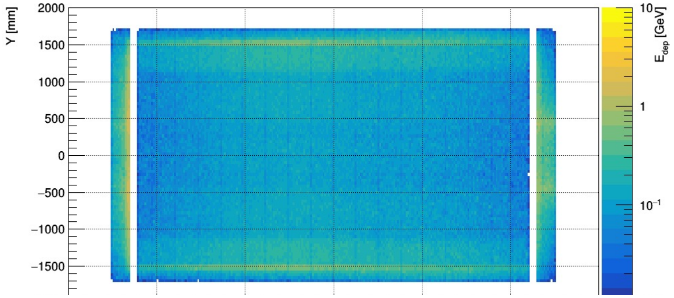
Reconstruction of tracks suffers from large combinatorial background

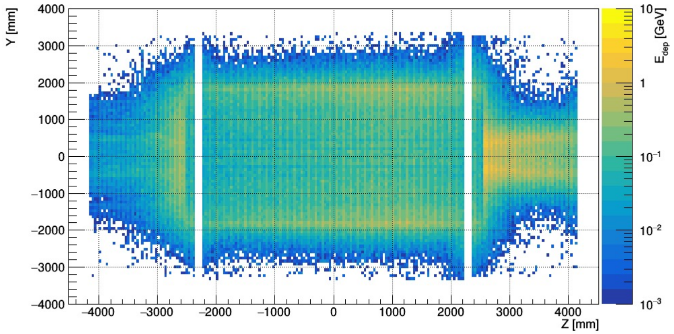
↳ need suppression of BIB hits + efficient tracking strategies/algorithms

Calorimeters

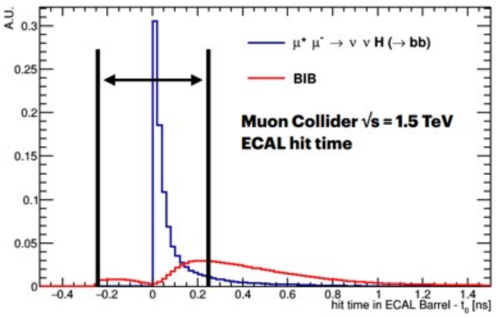
Calorimeters

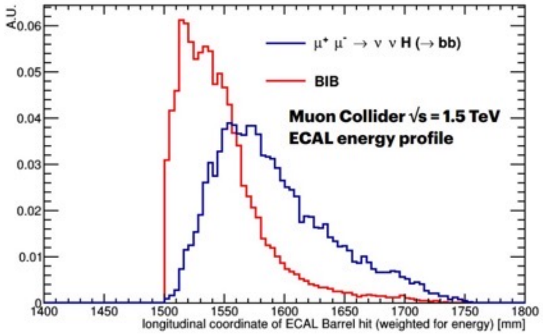
BIB deposits large amount of energy in both ECAL and HCAL





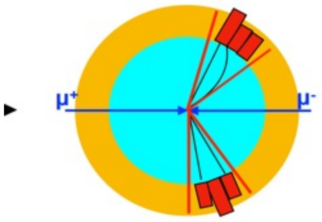
timing and longitudinal measurements play a key role in the BIB suppression

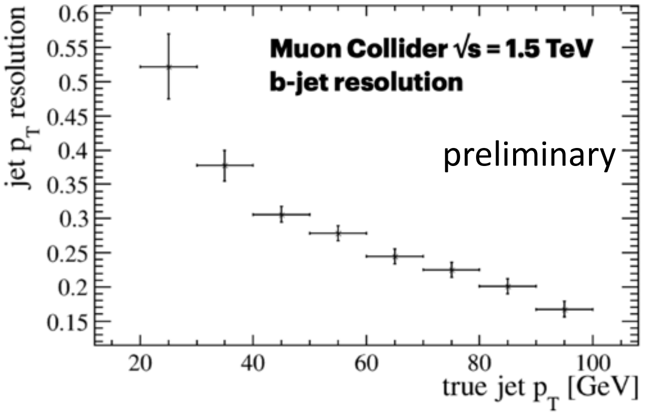




Remaining BIB is removed by subtraction

Step 3: final jet clustering
using calorimeter clusters and tracks
with PandoraPFA and kt (R=0.5)





Experiment design steps forward

- Beam Induced Background requires an optimized interaction region design to mitigate the unique harsh environment limiting detector acceptance

  ➔ Luminosity measure proposed via $\mu\mu \rightarrow \mu\mu$ scattering ($m_{\mu\mu} \sim \sqrt{s}$)

- A baseline detector for full simulation studies @ 3 TeV is available to be optimized
- New design and studies still missing @ 10+ TeV

  ➔ **ECFA Roadmap Detector R&D**

- Tracker design and Tracking: biggest challenge is pattern recognition
- Calorimeter: huge diffuse background
- Muons: no major problems seen

A few comments and next steps

- Is a Muon Collider a more affordable alternative to hadron and lepton colliders both at the energy frontier?

First MDI Kick-off meeting @ November 2021

➔first lattice and MDI studies @ 10 TeV by CERN

Next tomorrow https://indico.cern.ch/event/1121610/

NEXT STEPS:

- Optimize the nozzle geometry with systematic design process @ 3 and 10 TeV
- Produce Fluence and TID maps to address proper detector R&Ds

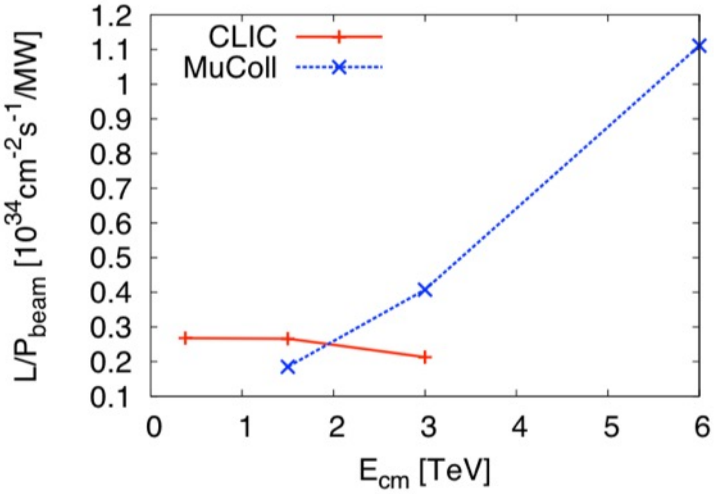
Many thanks to all the community who contributed!!!

extras

multi-TeV Muon Collider

European Strategy Update – June 19, 2020:

High-priority future initiatives [..]
In addition to the high field magnets the **accelerator R&D roadmap** could contain:
[..] an **international design study** for a **muon collider**, as it represents a **unique opportunity** to achieve a *multi-TeV energy domain beyond the reach of* e^+e^-*colliders*, and potentially within a *more compact circular tunnel* than for a hadron collider. The biggest challenge remains to produce an intense beam of cooled muons, but *novel ideas are being explored.*



International Design Study Collaboration
established in July 2020
Project Leader**: Daniel Schulte**

International
MUON Collider
Collaboration

nature physics

[Muon colliders to expand frontiers of particle physics]()

K.Long, D.Lucchesi, M.Palmer, N.Pastrone, D.Schulte, V. Shiltsev

Label	Begin	End	Description	Aspirational		Minimal	
				[FTEy]	[kCHF]	[FTEy]	[kCHF]
MC.SITE	2021	2025	Site and layout	15.5	300	13.5	300
MC.NF	2022	2026	Neutrino flux mitigation system	22.5	250	0	0
MC.MDI	2021	2025	Machine-detector interface	15	0	15	0
MC.ACC.CR	2022	2025	Collider ring	10	0	10	0
MC.ACC.HE	2022	2025	High-energy complex	11	0	7.5	0
MC.ACC.MC	2021	2025	Muon cooling systems	47	0	22	0
MC.ACC.P	2022	2026	Proton complex	26	0	3.5	0
MC.ACC.COLL	2022	2025	Collective effects across complex	18.2	0	18.2	0
MC.ACC.ALT	2022	2025	High-energy alternatives	11.7	0	0	0
MC.HFM.HE	2022	2025	High-field magnets	6.5	0	6.5	0
MC.HFM.SOL	2022	2026	High-field solenoids	76	2700	29	0
MC.FR	2021	2026	Fast-ramping magnet system	27.5	1020	22.5	520
MC.RF.HE	2021	2026	High Energy complex RF	10.6	0	7.6	0
MC.RF.MC	2022	2026	Muon cooling RF	13.6	0	7	0
MC.RF.TS	2024	2026	RF test stand + test cavities	10	3300	0	0
MC.MOD	2022	2026	Muon cooling test module	17.7	400	4.9	100
MC.DEM	2022	2026	Cooling demonstrator design	34.1	1250	3.8	250
MC.TAR	2022	2026	Target system	60	1405	9	25
MC.INT	2022	2026	Coordination and integration	13	1250	13	1250
			Sum	445.9	11875	193	2445

Community Meeting WG

Radio-Frequency (RF): *Alexej Grudiev (CERN), Jean-Pierre Delahaye (CERN retiree), Derun Li (LBNL), Akira Yamamoto (KEK)*

Magnets: *Lionel Quettier (CEA), Toru Ogitsu (KEK), Soren Prestemon (LBNL), Sasha Zlobin (FNAL), Emanuela Barzi (FNAL)*

High-Energy Complex (HEC): *Antoine Chance (CEA), J. Scott Berg (BNL), Alex Bogacz (JLAB), Christian Carli (CERN), Angeles Faus-Golfe (IJCLab), Eliana Gianfelice-Wendt (FNAL), Shinji Machida (RAL)*

Muon Production and Cooling (MPC): *Chris Rogers (RAL), Marco Calviani (CERN), Chris Densham (RAL), Diktys Stratakis (FNAL), Akira Sato (Osaka University), Katsuya Yonehara (FNAL)*

Proton Complex (PC): *Simone Gilardoni (CERN), Hannes Bartosik (CERN), Frank Gerigk (CERN), Natalia Milas (ESS)*

Beam Dynamics (BD): *Elias Metral (CERN), Tor Raubenheimer (SLAC and Stanford University), Rob Ryne (LBNL)*

Radiation Protection (RP): *Claudia Ahdida (CERN)*

Parameters, Power and Cost (PPC): *Daniel Schulte (CERN), Mark Palmer (BNL), Philippe Lebrun (CERN retiree and ESI), Mike Seidel (PSI), Vladimir Shiltsev (FNAL), Jingyu Tang (IHEP)*

Machine Detector Interface (MDI): *Donatella Lucchesi (University of Padova and INFN), Christian Carli (CERN), Anton Lechner (CERN), Nicolai Mokhov (FNAL), Nadia Pastrone (INFN), Sergo R Jindariani (FNAL)*

Synergy: *Kenneth Long (Imperial College), Roger Ruber (Uppsala University), Koichiro Shimomura (KEK)*

Test Facility (TF): *Roberto Losito (CERN), Alan Bross (FNAL), Tord Ekelof (Uppsala University)*

Physics & Detector:
Donatella Lucchesi *(Univ. Padova - INFN)*

WG 1: **Physics Potential:** Andrea Wulzer (EPFL&CERN) et al.
WG 2: **Detector performance (with several focus areas)**
WG 3: **Detector R&D and Software & Computing development**