International MUON Collider Collaboration

MuCol

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CERN

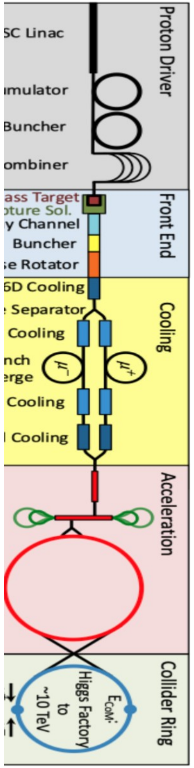
10 TeV Muon Collider: MDI – Machine-Detector and Beam Induced Background

D. Calzolari (CERN – SY/STI/BMI) on behalf of the IMCC

IMCC Annual Meeting 2024

March 2024

Outline



- **Machine-Detector Interface (MDI):**
  - Geometry of the interaction region
  - Conical nozzle to mitigate the background: nozzle
  - Workflow in IMCC
  - Software for simulations
- **Beam-Induced Background (BIB) from μ-decay at different energies**
  - Total number of BIB particles for different machines
  - Effect of the lattice at $\sqrt{s}$ = 10 TeV
  - Nozzle effect
- **Incoherent pair production**
- **Halo losses**
- **Radiation damage in the detectors**
- **Conclusions**

Interaction region: MDI

- MDI is a **difficult challenge** for the muon collider. First studies were done by the MAP collaboration (energies up to 6 TeV). So far, IMCC focused on studies for energies up to 10 TeV
- **Main objectives:**
  - Study the beam-induced background (BIB) and identify mitigation strategies for the **3 TeV** and **10(+) TeV** collider options.
  - Develop a credible **interaction region (IR) design** that yields background levels compatible with detector operation (1. enabling physics performance reach, 2. reducing radiation damage to acceptable levels)

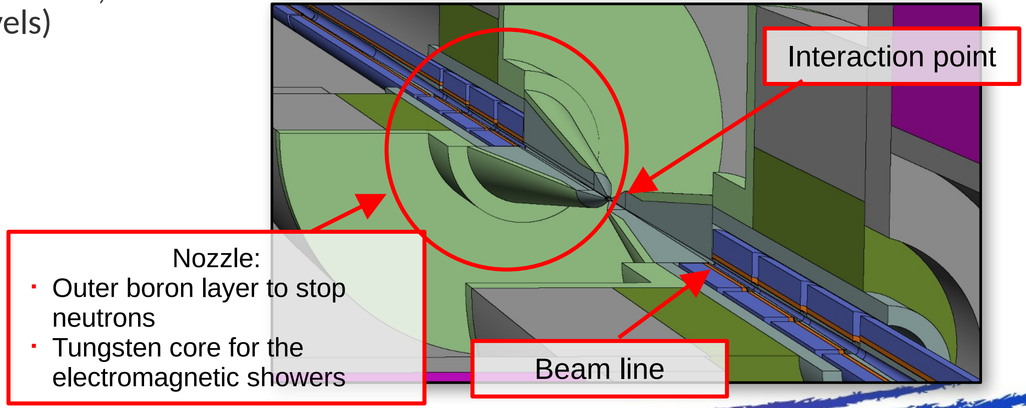
Tentative target parameters
Scaled from MAP parameters

Comparison:
CLIC at 3 TeV: 28 MW

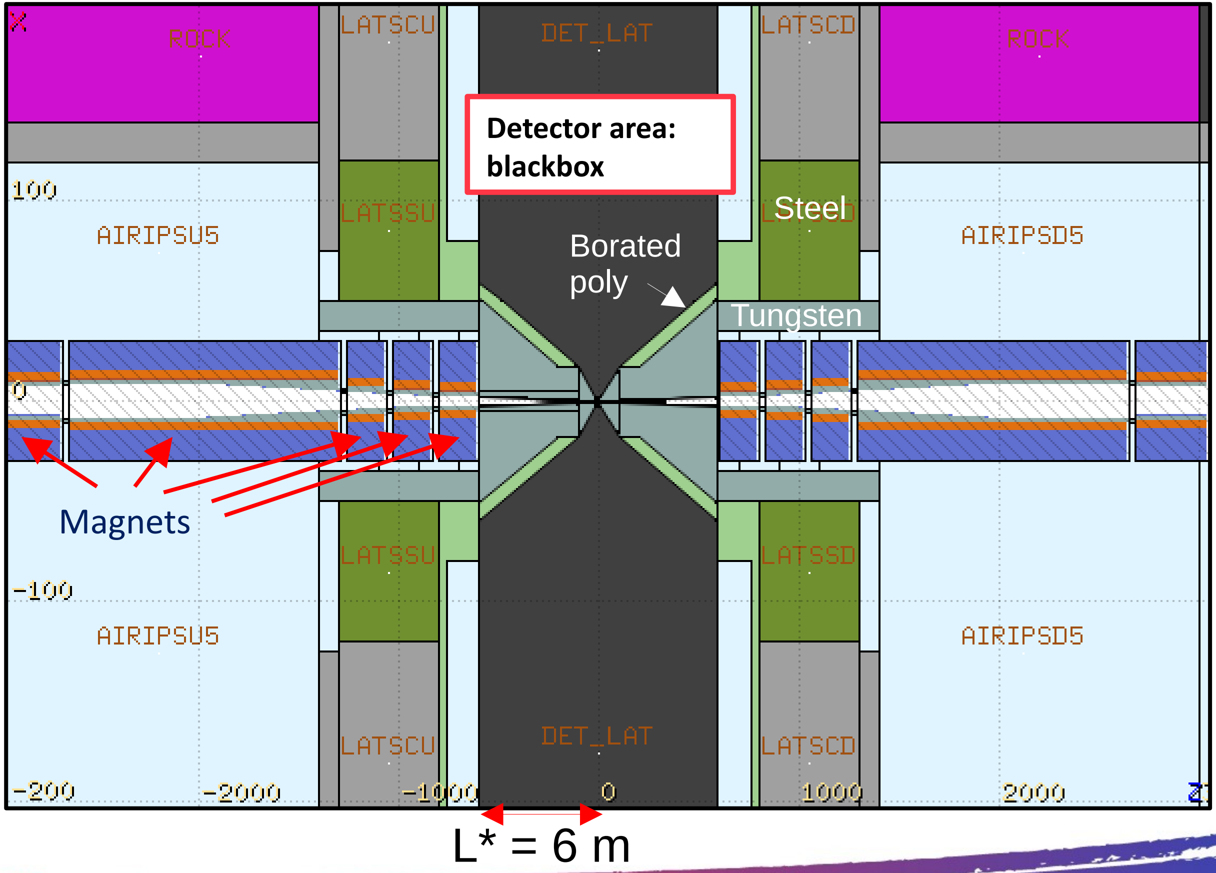
Parameter	Unit	3 TeV	10 TeV	14 TeV
L	10^{34} $cm^{-2}s^{-1}$	1.8	20	40
N	10^{12}	2.2	1.8	1.8
f_r	Hz	5	5	5
P_{beam}	MW	5.3	14.4	20
C	km	4.5	10	14

- **MDI Working Group**:
  - Formed last year in course of the Muon Collider Community meetings
  - Shall bring together expertise from different areas (lattice design, particle-matter interactions, detectors, magnets etc.)
  - Meetings every last Friday of a month (Indico event category)

Geometry of the MDI



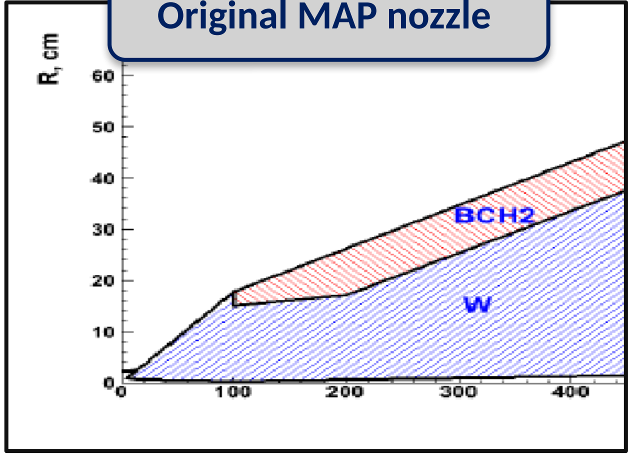
MDI: geometry of a 10 TeV collider



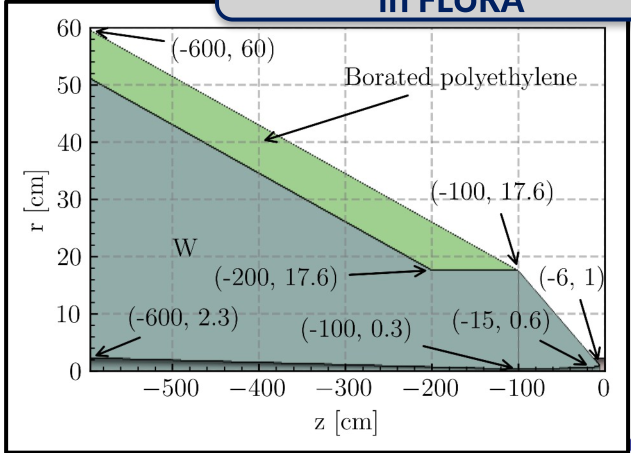
MDI: nozzle geometry

- Our implementation of the nozzle follows the original design from MAP collaboration
- The scope of the solid **tungsten** layer is to have a dense material to **stop electromagnetic cascades**
- The **boron polyethylene** layer acts as moderator (the hydrogen atoms), while the boron content is **capturing** the thermalized **neutrons**

Original MAP nozzle



Nozzle implementation in FLUKA



Workflow in the IMCC

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Machine-Detector Interface: MDI

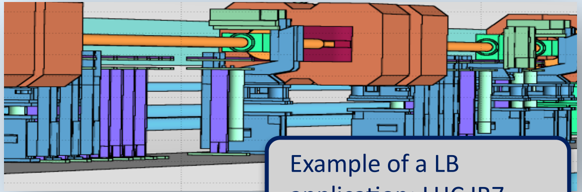
1. Lattice design

The magnet optics is computed via dedicated codes (e.g. MAD-X).

The output is a twiss file, containing the machine elements in a sequence

2. FLUKA geometry model

Via LineBuilder (LB), complex geometries are assembled in a FLUKA input file



Example of a LB application: LHC IR7

3. BIB simulation

With the built geometry, a FLUKA simulation is run.

The position and momentum of the decay muons are sampled from the matched phase-space

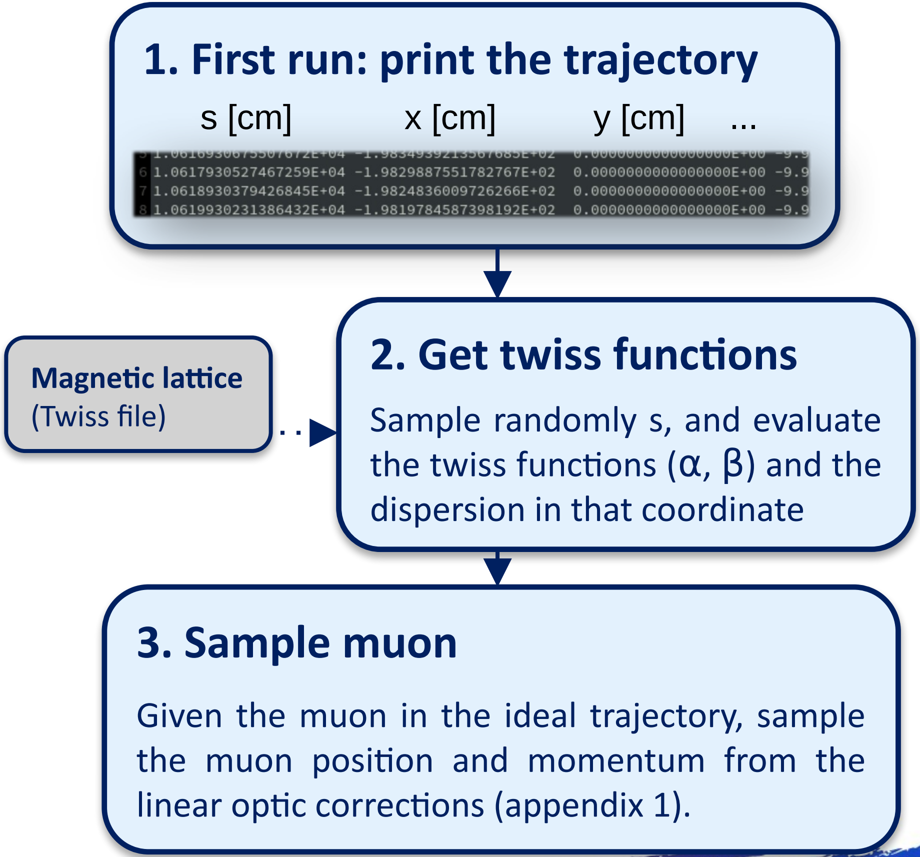
Iteration with lattice design experts to mitigate the BIB

BIB data to detector experts

CERN STI/BMI is currently responsible for the geometry built at √s = 3 and 10 TeV

µ decay: sampling procedure

- For an accurate description, I propose to sample the muon decays position and momentum from a **matched phase-space distribution**
- Once the position and momentum of the muons are known, the **muon decay is forced**
- Results are naturally expressed per muon decay
- Muons do not need to be tracked in the machine (+ save CPU time & + no tracking inaccuracy)



How to read BIB data: FLUKA output

1. Fluka simulation output

It contains a long list of particles. To save storage space and speed up the analysis, a binary format is preferred

Particle informations

Position, momentum, energy, time of arrival

Particle list to feed the detector simulation with

Additional information

Ancestor informations

How to read BIB data: data format

- Question: are these variables descriptive (and sufficient) to understand the BIB sources?

What is a "parent"? Are there any insightful variables for the detector studies?
Currently is the first position of impact

Id particle	Id parent	Energy	x/y/z	$p_x/p_y/p_z$	Time of crossing	x/y/z sampling	Energy parent	x/y/z parent	$p_x/p_y/p_z$ parent
Integer	Integer	Double	Double (x 3)	Double (x 3)	Double	Double (x 3)	Double	Double (x 3)	Double (x 3)

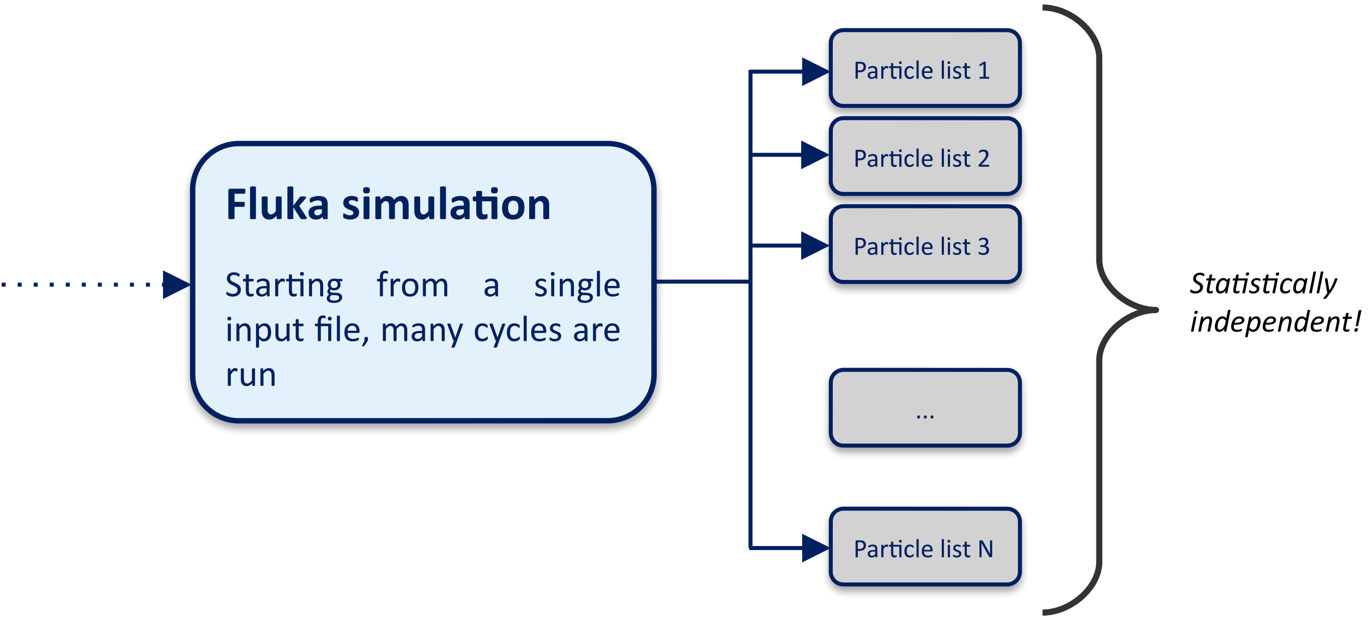
```
00000000: 0700 0000 0000 0000 fbb2 9397 b9db 353f
00000010: 0a7e 778f 357b f4bf 72da e775 b03d 0040
00000020: a467 dd2a 1c5c 27c0 0f5f a698 d8de e8bf
     030: b001 93bf 6ed9 d83f d0c7 8226 ffb0 dfbf
00000040: 77e1 7cc9 f9b3 723e fa58 4ded e8b9 a43e
00000050: e06b 1731 2ea7 d03f 5a23 1df7 850b 01c0
```

Little endian

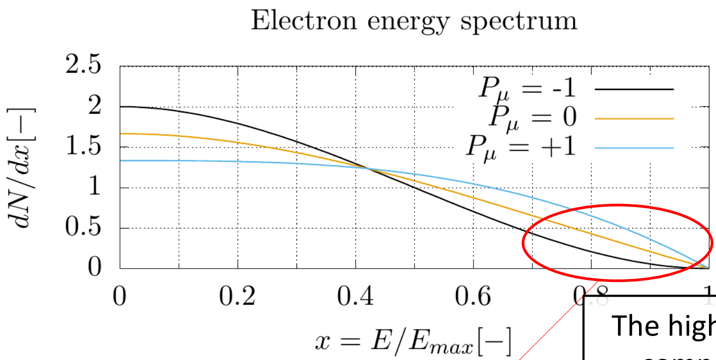
Example: a photon (particle id = 7), with energy 0.710383952 GeV, is crossing in the detector area in (-1.91, 2.00, -2.61)

How to read BIB data: data organization

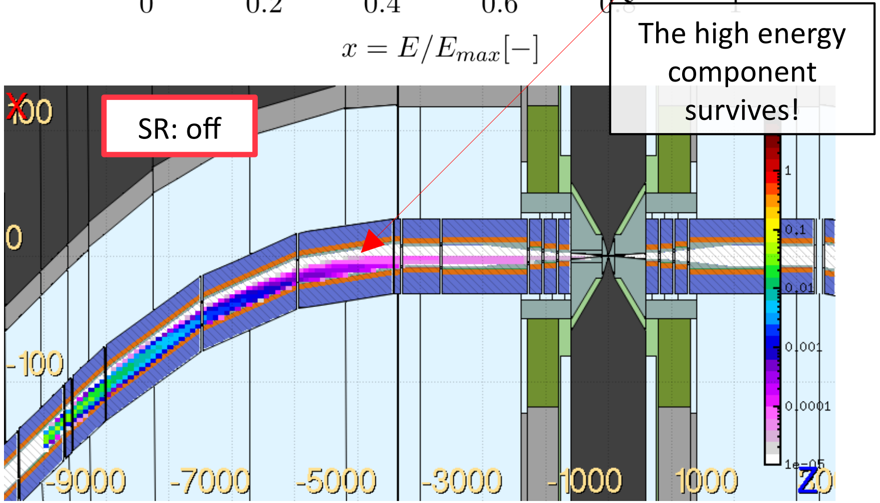
- Each simulation is run in parallel in many cycles. To estimate the uncertainty, I do a batch statistical analysis.

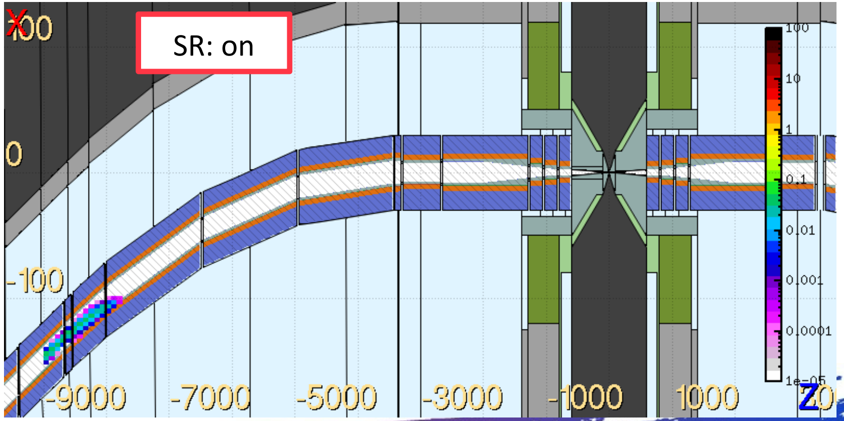


Relevant FLUKA capability: synchrotron radiation



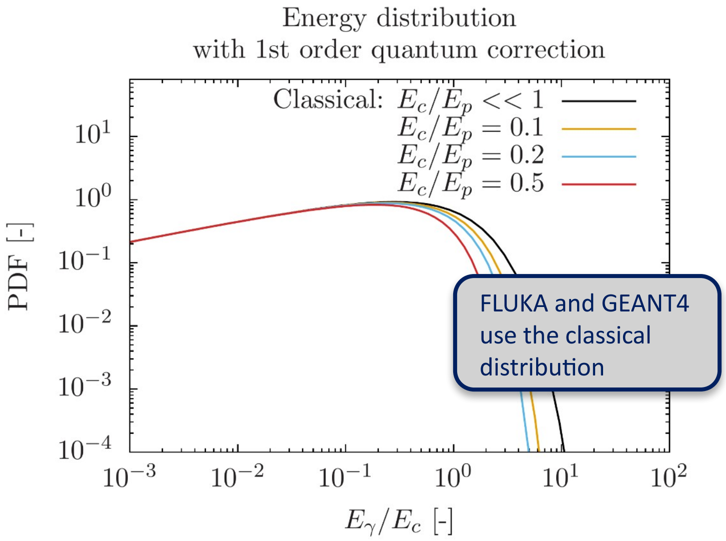
- The synchrotron radiation has a leading role in suppressing the BIB coming from far away (in particular for the v0.4 @10 TeV and all lattices at other energies)
- The mechanism is simple: the high energy electrons lose energy and the dispersion effects are enhanced.

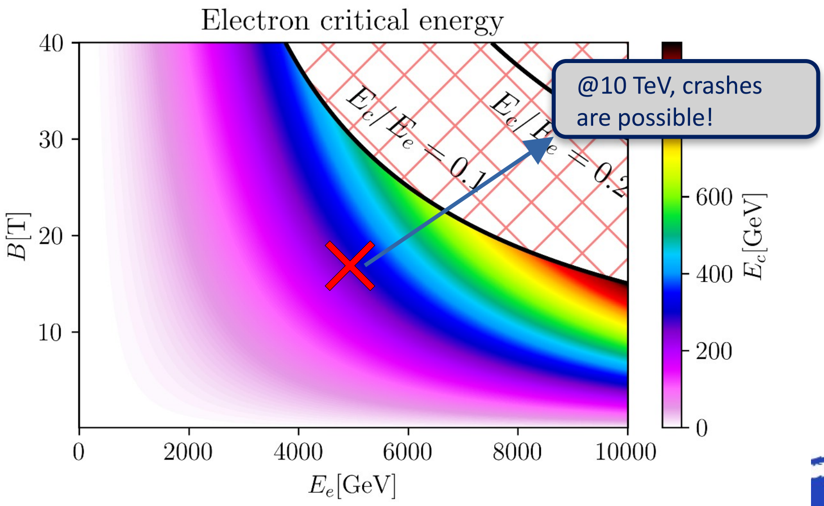




Relevant FLUKA capability: synchrotron radiation

- Current implementation: the synchrotron radiation is sampled from the classical distribution.
- If the critical energy is comparable with the electron energy, the classical description fails (it predicts that the photon energy could be higher than the original electron one)

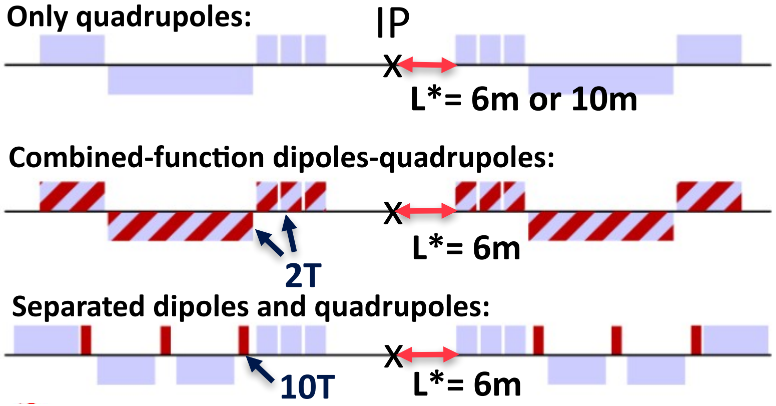




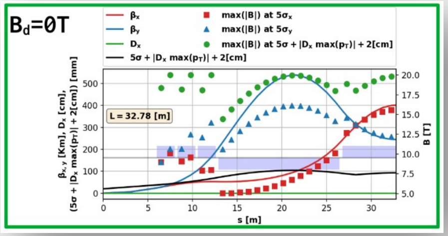
μ decay @ √s = 10 TeV: past lattice design choices

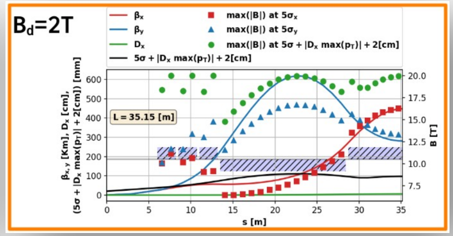
- *Can the decay-induced background be reduced by adjusting the lattice design?*
- Two key aspects were investigated:
  - Dipolar component in the final focus triplet (combined function magnets or separate dipoles)
  - Distance between IP and final focus magnets (L*)

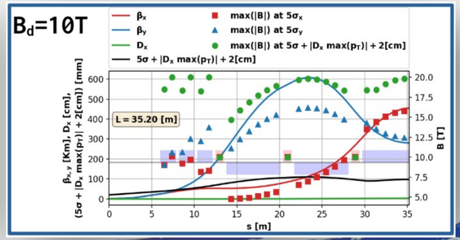
Layouts considered for the BIB studies:



Lattices with and without dipolar component (L=6m):*



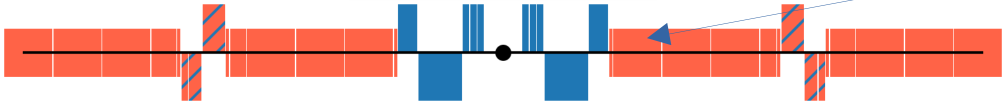




K. Skoufaris

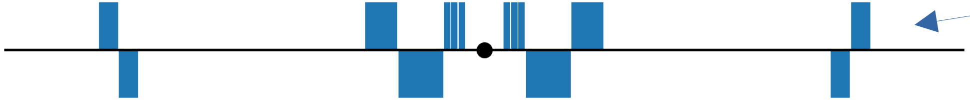
Lattices for a 10 TeV muon collider

Version 0.4



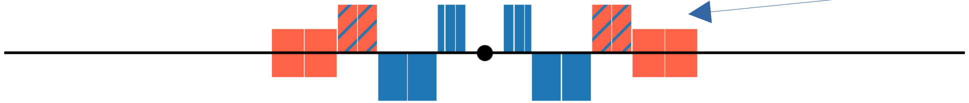
Dipolar component suppress BIB outside of the final focus. The BIB sample distributed (and considered baseline)

Version 0.6



All the muon decays in ~200 meters from the IP give a non negligible contribution to the BIB

Version 0.7

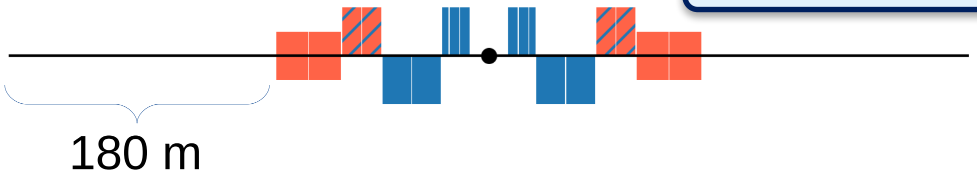


A chicane is added to partially clean the line from the secondary electrons before they reach the nozzle

Long drift sections: decay $e^{+/-}$ build-up

Version 0.7

- In the collider ring, the muons generate decay $e^{+/-}$ that carry a power of 500 W/m
- In bending magnets, these electrons are continuously directed towards the magnet aperture, and the power is locally dissipated
- Whit this novel lattice versions, all the electrons produced in the straight section will accumulate. The energy builds up.



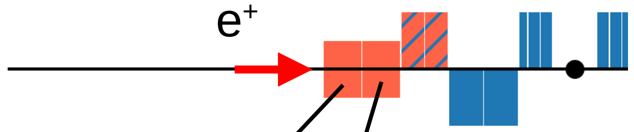
Average power to electrons per unit length [W/m]	Length straight section [m]	Total power accumulated [W]
505	180	90800

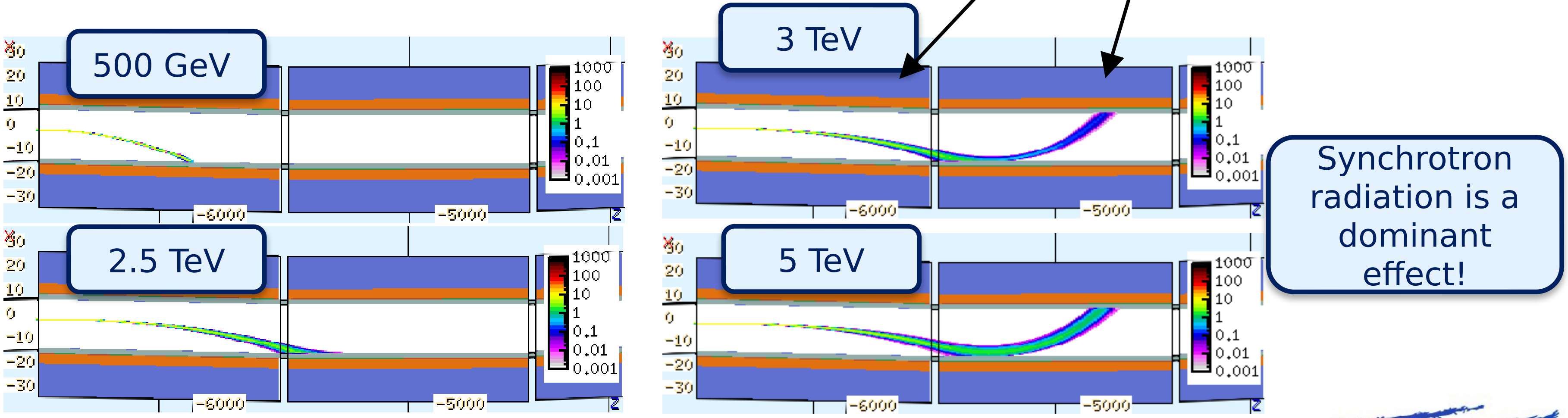
Almost 100kW in → On the nozzle (causing BIB)

→ To the final focusing magnets

Decay products trajectory in lattice v 0.7

- Considering a pencil beam positrons along the ideal trajectory, the path in the first two magnets is reported.
- Two hotspots are generated in the first and second magnets

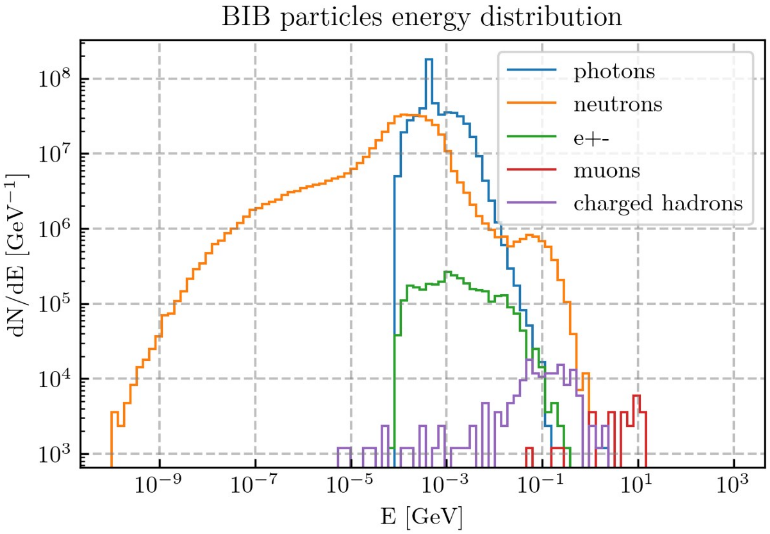




Lattice v0.7: particle spectra

Length of the trajectory [m]	Bunch intensity	Momentum [GeV]	Relativistic gamma	Lab lifetime	Decay per unit length	Total number of decays
210	1.8E12	5000	47322.32516	0.104	57800	7.05E+06

- The energy spectrum is similar in all lattice versions
- Neutrons at thermal energies are captured and killed by the boron content
- Electrons and positrons are the dominant contribution for the tracker occupancy
- Photons are the most abundant particles



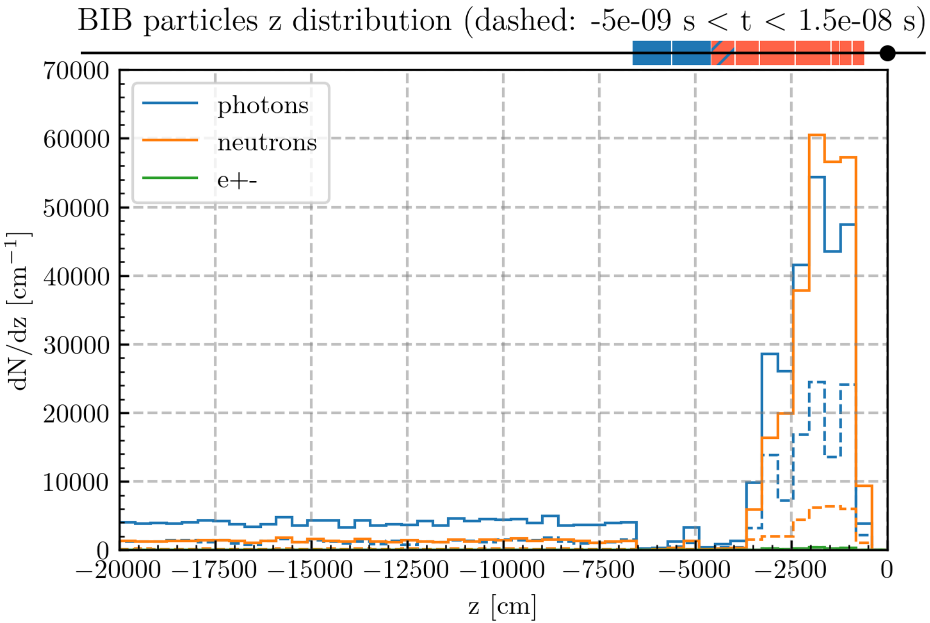
Lattice v0.7: differences with past

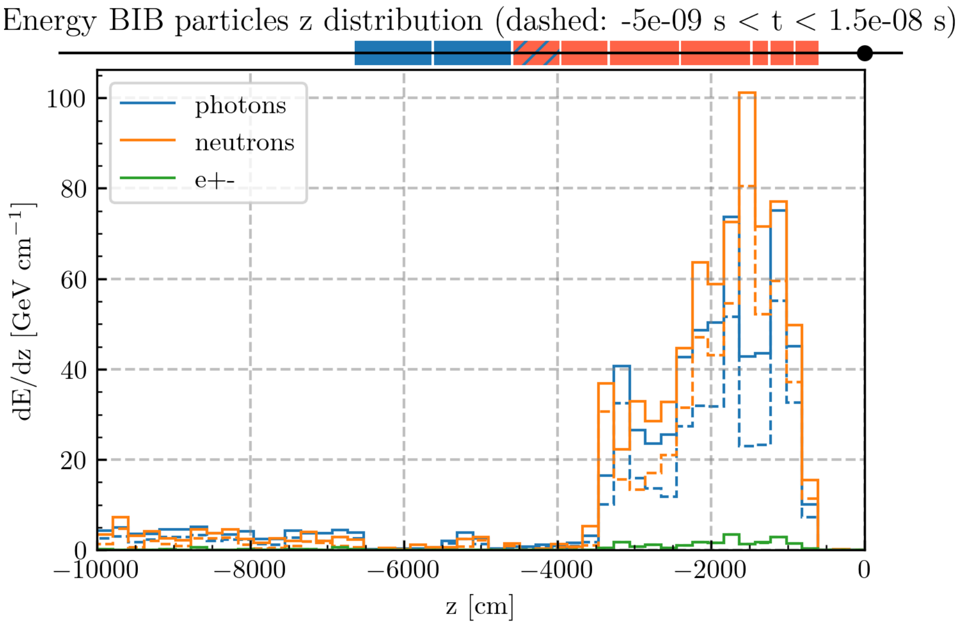
- The general trend is the same, the BIB increases sligthly with the energy
- A longer final focusing scheme is always worse for the BIB. The v 0.7 is slightly better in comparison with the v 0.6

Collider energy	1.5 TeV	3 TeV	10 TeV v 0.4	10 TeV: v 0.6	10 TeV: v 0.7
Photons	7.1E+7	9.6E+7	9.6E+7	2.5E8	1.7E8
Neutron	4.7E+7	5.8E+7	9.2E+7	1.4E8	1.2E8
e^+/e^-	7.1E+5	9.3E+5	8.3E+5	1.7E6	9.7E5
Ch. hadrons	1.7E+4	2.0E+4	3.0E+4	6.9E4	7.9E3
Muons	3.1E+3	3.3E+3	2.9E+3	7.3E3	5.0E3

Lattice v0.7: particle origin

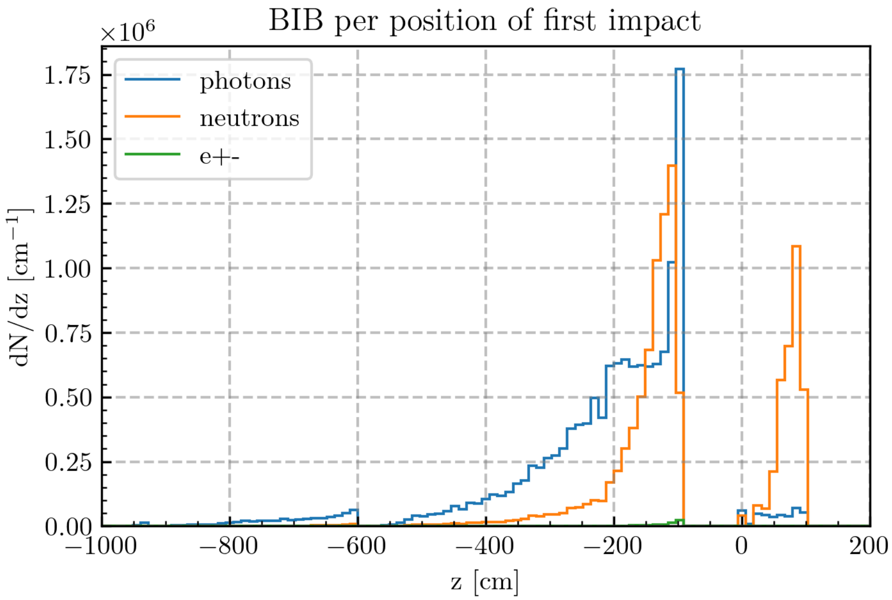
- The chicane offers partial mitigation for the BIB coming from far away position, but the muon decaying from further away still have a non zero contribution





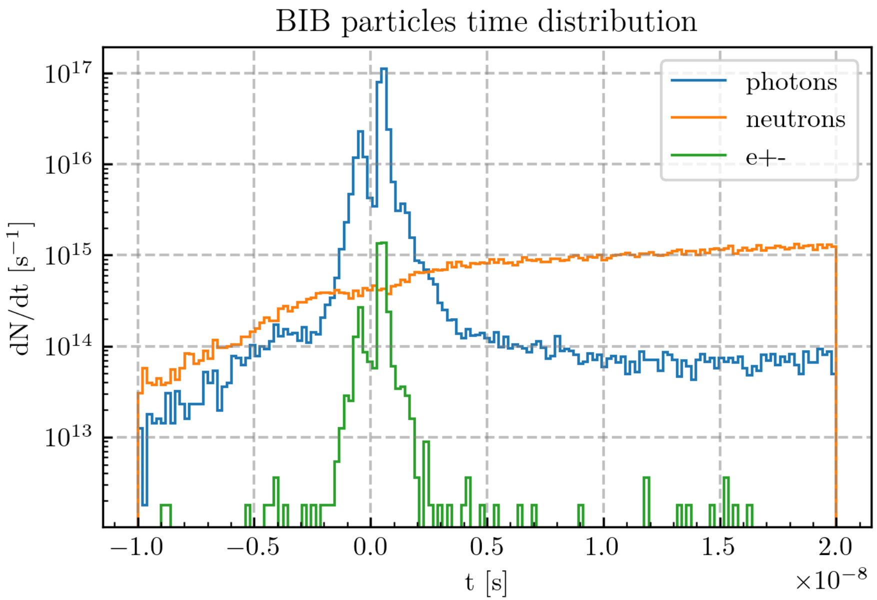
Lattice v0.7: first position of impact

- Most of the BIB is coming from electron/positrons that impacted directly on the nozzle
- If a particle is intercepted before, no BIB arrives to the detector area



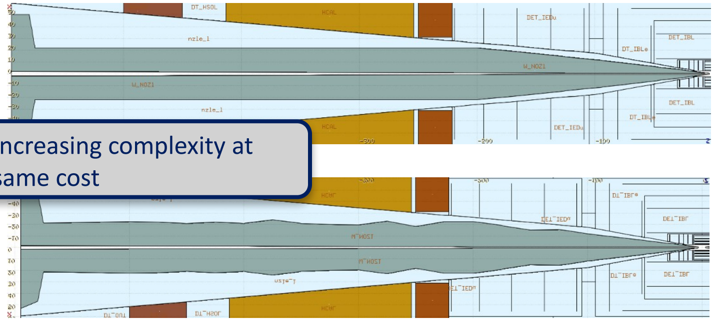
Lattice v0.7: time distribution

- The time distribution is equivalent in all lattice versions
- It is strongly peaked around 0, with a long tail for the neutron time of arrival distribution



Nozzle optimization procedure: detector description

- Nozzle design starting with a simple approach, considering just **one layer** of tungsten to shield the contribution from electromagnetic showers.
- The neutron absorber will be added in a second stage.



Increasing complexity at same cost

...via ad-hoc python script

1. json nozzle description

This simplified description allows a human-readable format for the nozzle geometry.

2. FLUKA inputfile

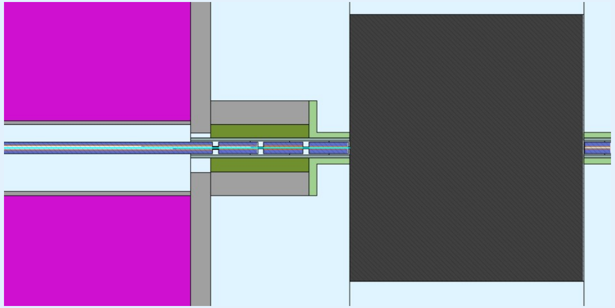
Hard to interpret, the inputfile can be only inspected with flair

Nozzle optimization procedure: two step procedure

- Simulating all the processes from the muon decay to the background entering in the detector area is **expensive**.
- Another more useful strategy is to adopt a 2 step simulation: all the particles are simulated in the line, and reloaded for the nozzle and detector simulations

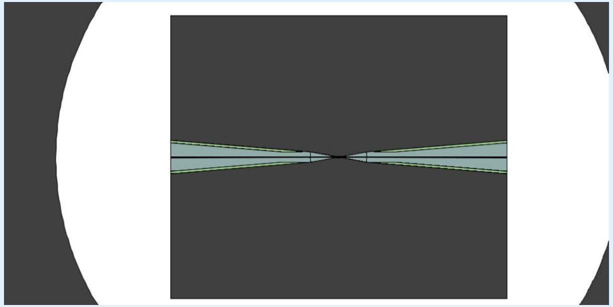
1. From muon decay to nozzle area

Machine dependent



2. Nozzle area to detectors

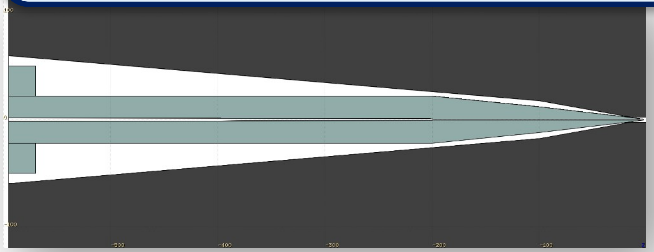
Nozzle dependent

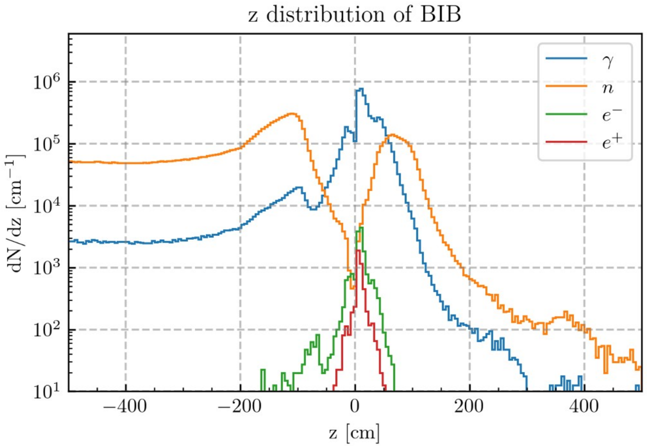


Nozzle optimization procedure: current approaches

- The objective is to achieve a **realistic design**, possible to build in terms of engineering requirements and minimizing BIB
- Among the conflicting objectives: **minimize mass, increase angular acceptance, reduce BIB**

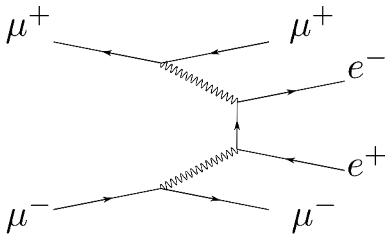
Tentative novel approaches in progress, results still below satisfactory levels

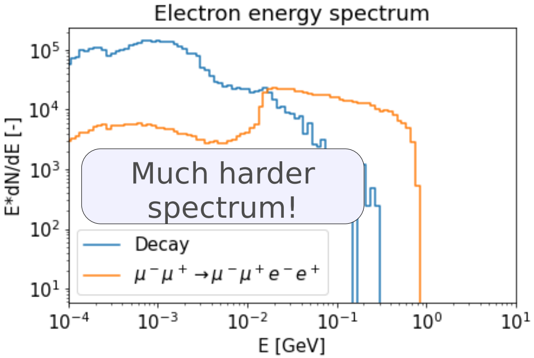




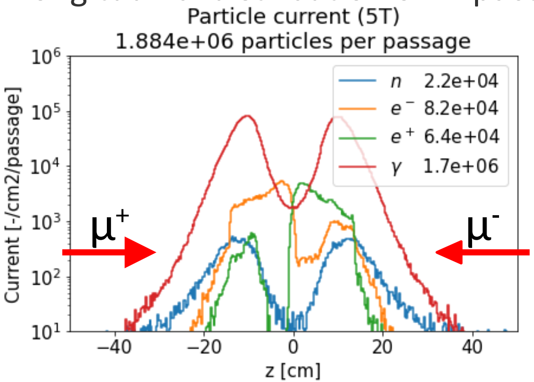
Incoherent pair production

- At very high beam energies, beam-beam effects are not negligible. The most important phenomenon is due to the **incoherent beam-beam pair production μ+μ-→μ+μ-e+e-**.
  - The incoherent pair production e^+/e^- are provided by D. Schulte and are obtained by a **Guinea-Pig simulation**
- The **total number** of crossing is much **lower** than the muon **decay** case.
- The produced electrons are **energetic** and they **impact** directly on the **detectors**, since are generated in the IP, hence they might be dangerous despite the low total number.





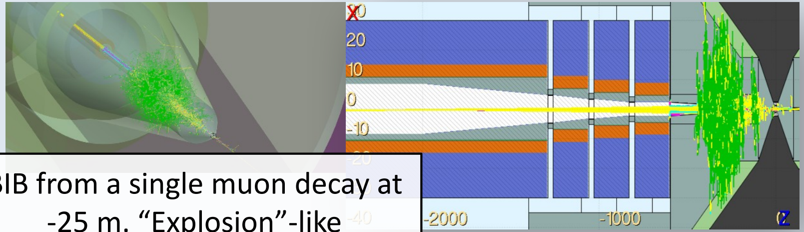
Longitudinal distribution of impacts



Halo losses

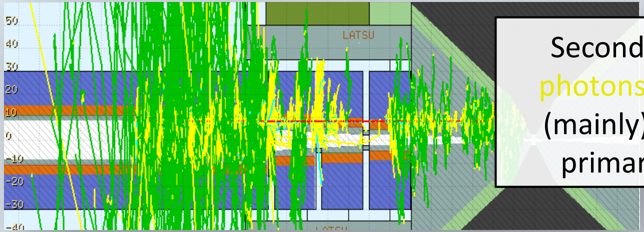
- The halo losses gives a significantly different contribution to the BIB: the particles are generated close to the IP due to the muon interaction with the nozzle.
- As a *preliminary* simulation, we considered a muon beam going in the magnet at 0 degrees with the z axis

Muon decay



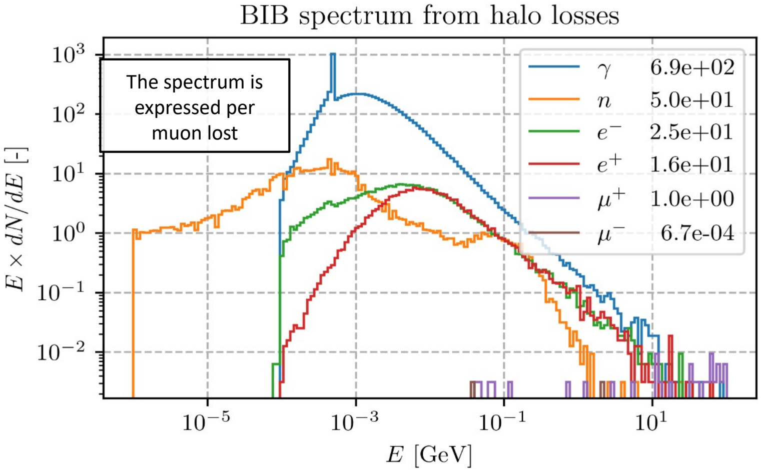
BIB from a single muon decay at -25 m. "Explosion"-like secondary distribution

Halo losses



Secondary neutrons, photons and electrons (mainly) surround the primary muon lost.

- In terms of n and ɣ, the muon decay produces ~10^8 particle per bunch crossing. To have the same contribution here, we would need to lose ~2E5 muons in the final focusing.

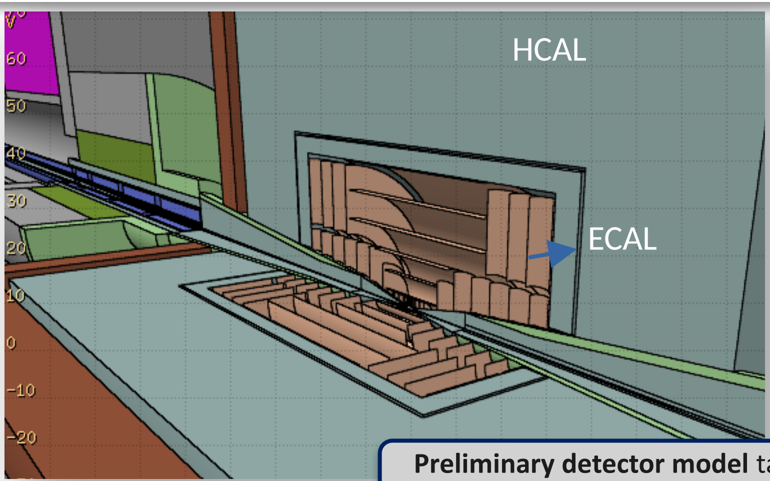


The spectrum is expressed per muon lost

Long term detector damage: lattice v 0.4

- The first detector FLUKA implementation follows the CLIC models.
- In the context of BIB studies, the detector damage is studied.
- The only source of detector damage considered are the secondary particles coming from the **muon decay**
- The quantity scored are:
  - **Total ionizing dose**
  - **1 MeV neutron equivalent fluence in Si**

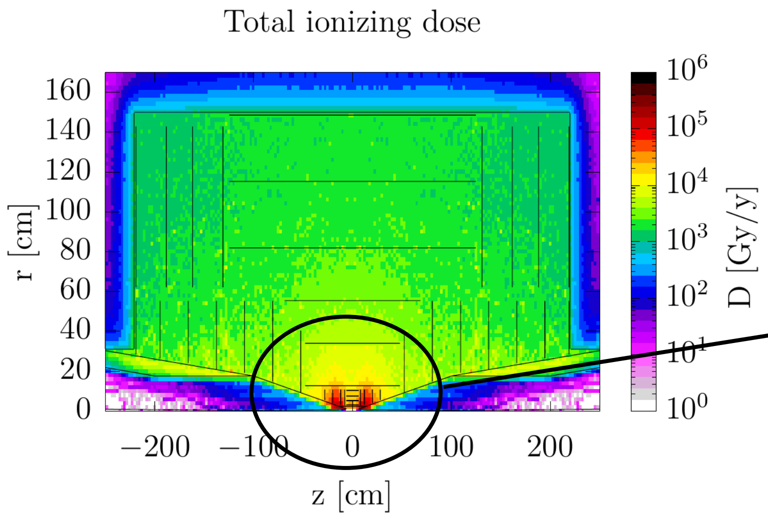
Per year of operation (140d)	Ionizing dose	Si 1 MeV neutron-equiv. fluence
Vertex detector	200 kGy	3×10^{14} n/cm^2
Inner tracker	10 kGy	1×10^{15} n/cm^2
ECAL	2 kGy	1×10^{14} n/cm^2

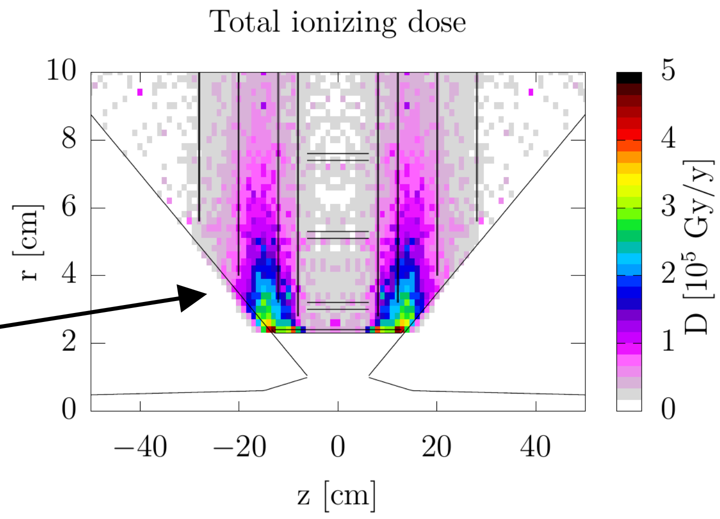


Preliminary detector model taken from the CLIC layout

Long term detector damage: lattice v 0.4

*Radiation damage estimates for 10 TeV (**MAP nozzle, CLIC-like detector**)*
Includes only contribution of decay-induced background!





Long term detector damage: lattice v 0.4

*Radiation damage estimates for 10 TeV (**MAP nozzle, CLIC-like detector**)*
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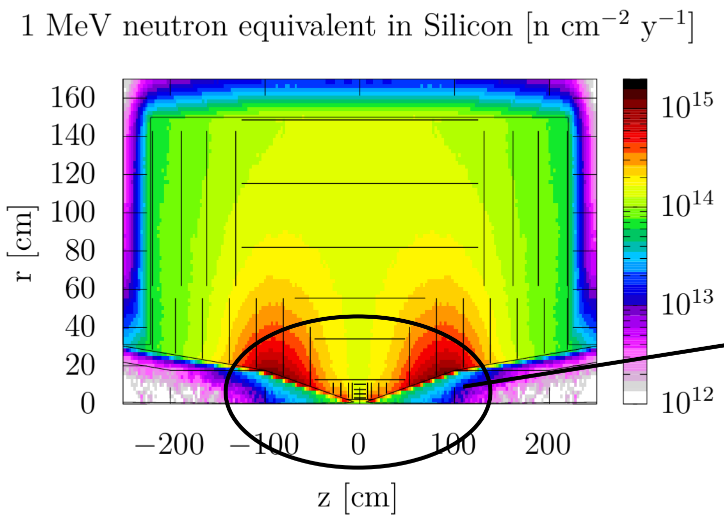

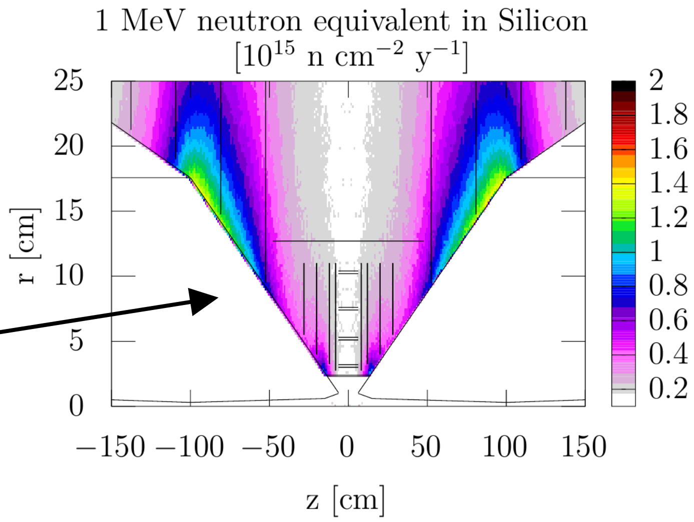

Conclusions

- Software for the BIB generation is reported
- **BIB from muon decay** has been assessed with various configuration:
  - A dipolar component offers only a slight beneficial contribution to the BIB mitigation
  - The lattice v0.6 with a **long drift increases the BIB** multiplicity of a factor 2
  - The novel v0.7 has intermediate performances, with only a slight increase in BIB
- The **negative muon beam and the positive one have the same effect** for what concerns the BIB from muon decay
- The **nozzle** still remains the **most important element in the MDI**. A systematic optimization is necessary, once an agreement is reached for the final focusing lattice

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Thank you
for your attention!

Particle sampling in linear optics

- Sample the **s-coordinate** (curvilinear arc length) uniformly across the particle trajectory.
- Sample the beam **energy** from a gaussian distribution
- Sample from the matched phase-space the correction to the ideal trajectory (this formula is applied performing the Cholensky matrix decomposition for the beam matrix)

$$\begin{cases} \Delta_x = \mathrm{Rand}_x \cdot \sqrt{\epsilon_x \beta_x} \\ \Delta_{x'} = (\mathrm{Rand}_{x'} - \mathrm{Rand}_x \cdot \alpha_x)\sqrt{\epsilon_x / \beta_x} \end{cases}$$

$$\begin{cases} \Delta_x = D_x \delta_p \\ \Delta_{x'} = D_{x'} \delta_p \end{cases}$$

Lattice v0.7: spatial distribution