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

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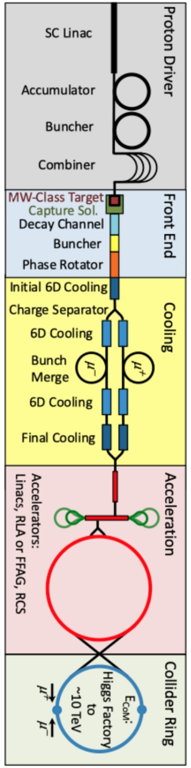
Colliders of Tomorrow: Muon Collider Beam Background

10 Aug 2023

International MUON Collider Collaboration

CERN

Outline



- **Muon collider (MC):**
  - Concept and motivations
  - Advantages and radiation challenges
- **Machine-Detector Interface (MDI):**
  - Geometry of the interaction region
  - Conical nozzle to mitigate the background: nozzle
  - Workflow in IMCC
  - Main aspects under study
- **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 background**
  - Secondary source of background important at high energy
- **Halo losses:** BIB first assessment
- **Long term detector damage**
- **Forward muons:** nozzle interference for high η
- **Conclusions**

Muon collider: concept and motivations

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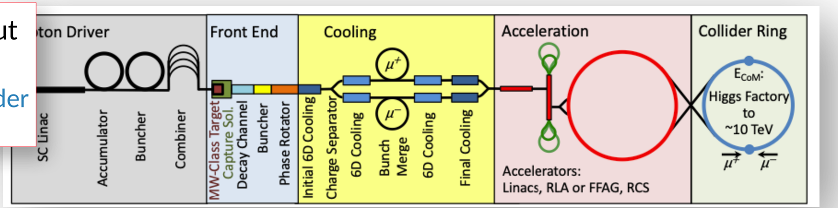
- Among various particles accelerated in colliders, muons have already been under consideration for a long time [1]. Very promising results were achieved in the contest of the **MAP collaboration** [2-3]. The following work is in the context and on behalf of the **International Muon Collider Collaboration (IMCC).**

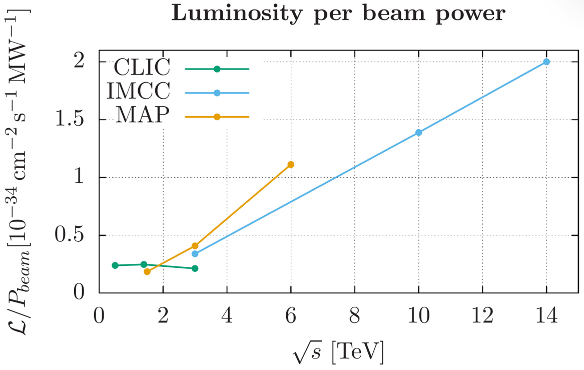
Why?

- A multi-TeV muon collider could investigate **Higgs properties** with an unprecedented precision. [2]
- With √s = 10 TeV we can explore **new physics at high energies**. [2]

Schematics layout from: https://muoncollider.web.cern.ch/



With a muon collider the **luminosity per beam power** increases with the collider energy!



$$\mathcal{L} \propto \gamma \langle B \rangle \sigma_\delta \frac{N_0}{\epsilon \epsilon_L} f_r N_0 \gamma$$

High energy

High field in collider ring

Large energy acceptance

Dense beam

High beam power

Muon collider: advantages

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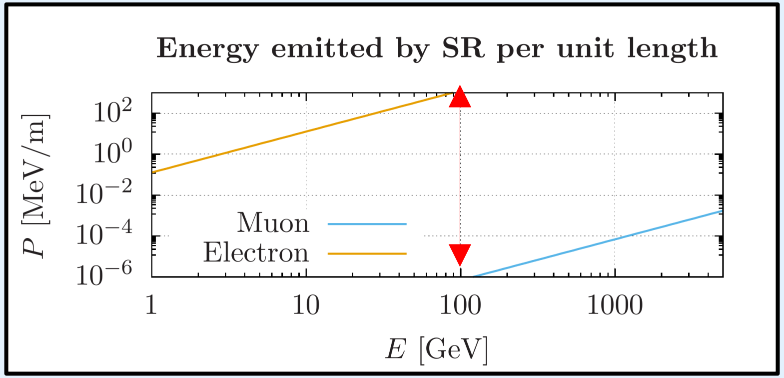
Synchrotron radiation*

$m_\mu = 105.7\ \text{MeV}/c^2$

- **Synchrotron radiation** (SR) is **not a limiting factor** for muon circular colliders.



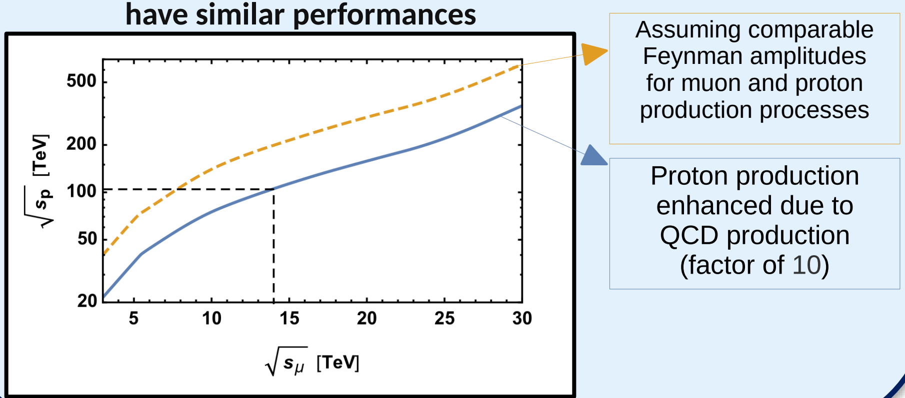
Muons emit $(m_\mu/m_e)^4$ = **1.6 · 10⁹** less synchrotron radiation than electrons

*of the primary muon beam

Lepton collisions

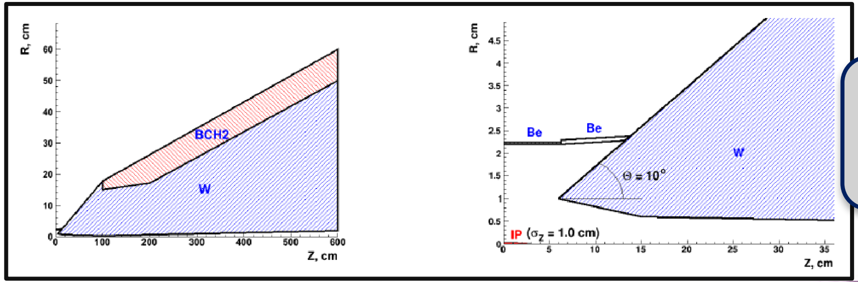
- Muons are elementary particles, and all the energy is involved in the collision. Instead, in protons, the energy is shared among constituents.
- **Same performance** of proton colliders, but with much **lower center of mass energy**! [2]

Energies at which proton/μ-colliders have similar performances



Previous studies in MAP

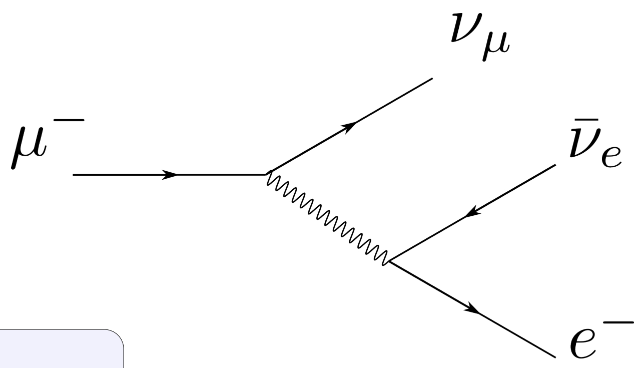
- The renewed efforts in the **International Muon Collider Collaboration (IMCC)** benefit from the previous work done in the **Muon Accelerator Program (MAP)**.
- Extensive work has been done in various field, among which:
  - Design of a muon production target handling ~MW proton sources
  - Exploration studies in the muon cooling
  - Magnet and shielding design to protect coils from decay products
  - **Interaction region design to mitigate the background to the detectors**
- To mitigate the BIB, particular attention has been devolved to the nozzles. This shielding equipment has been carefully optimized up to √s=1.5 TeV colliders



Nozzle detail: the boron layer stop thermal neutron, the tungsten shields from EM cascades (1807.00074)

Muon collider: radiation challenges

- **Muons** are **unstable particles**, with a rest lifetime of τ = 2.197 μs. They decay spontaneously into electron and positrons (depending on the muon original charge), which are the main contributors to the secondary radiation field.



Radiation challenges

Superconducting magnets
Secondary electrons impact on the beam chamber. Their energy induce **heat** and long term radiation **damage** in the **superconducting coils.**

MDI
The secondary field is a source of **background** to the experiment and induce radiation **damage** to the **detectors.**

Neutrino radiation
High energy **neutrinos** from the muon decay interact with the rock delivering **dose** to the **environment**.

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)

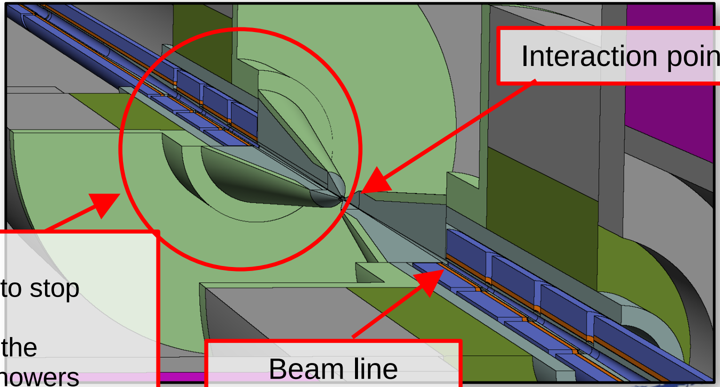
Tentative target parameters
Scaled from MAP parameters

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)

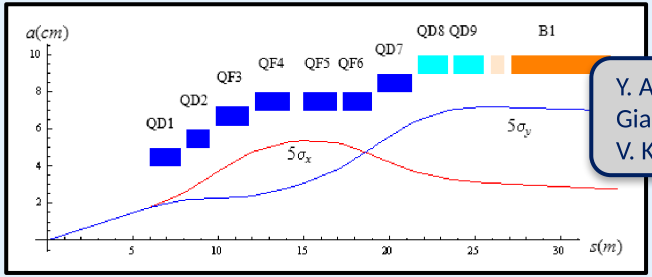
Geometry of the MDI



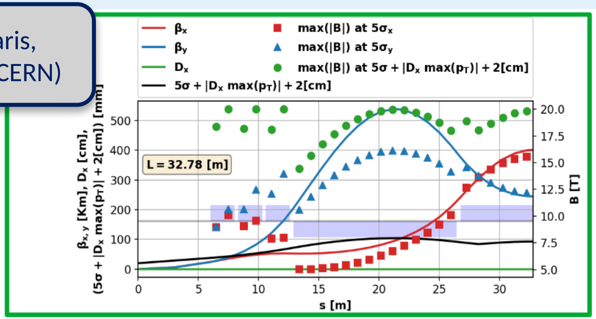
Nozzle:
- Outer boron layer to stop neutrons
- Tungsten core for the electromagnetic showers

MDI: lattices used for background studies

- √s = 3 TeV IR lattice taken from US-MAP (Y. Alexahin et al 2018 JINST 13 P11002):
  - L* = **6 m**
  - **Quadruplet** final focus with combined function magnets (ß* = **5 mm**)
  - Maximum field at inner bore is **12 T**
- **√s = 10 TeV IR lattice was developed from scratch within IMCC:**
  - L* = **6 m** as baseline
  - **Triplet layout** (ß* = **1.5 mm**), optionally with and without dipolar component
  - Max field at inner bore is **20 T**

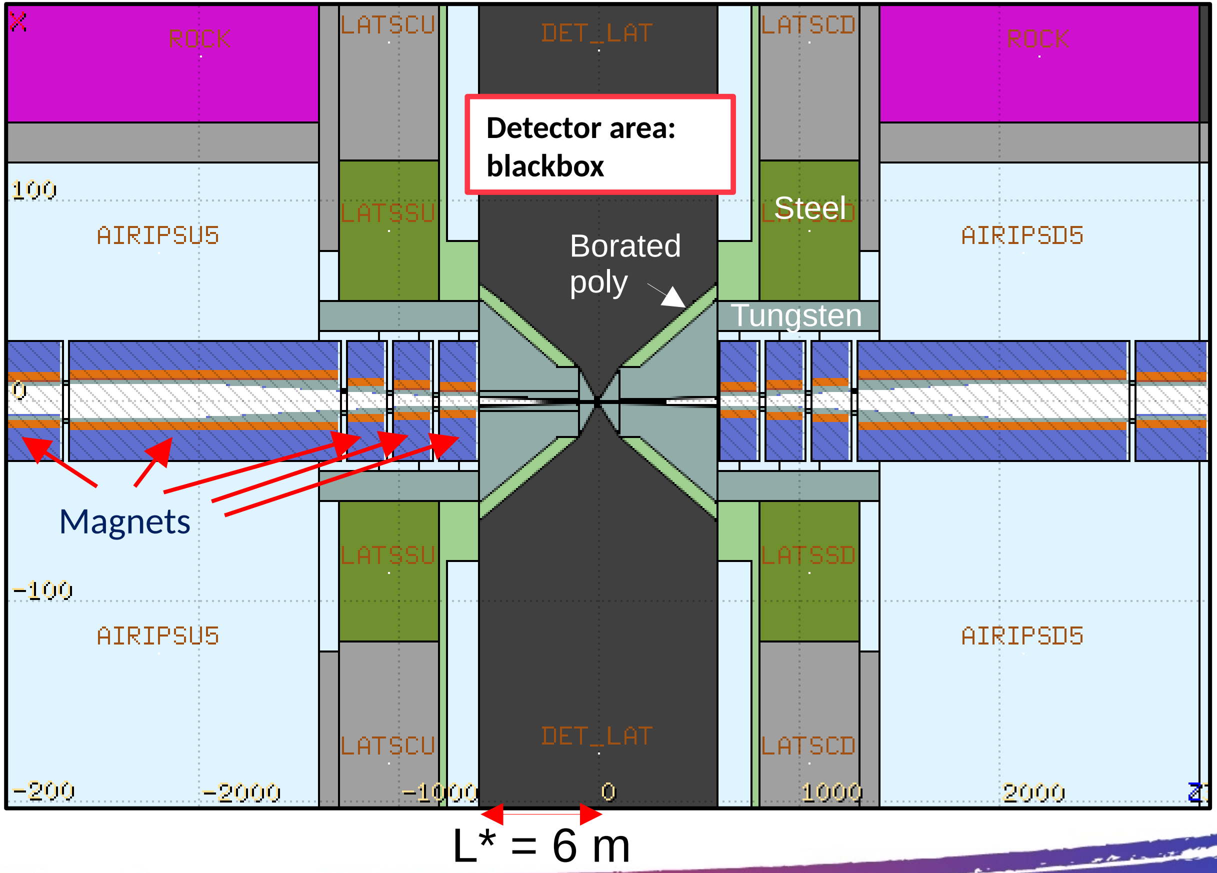


Y. Alexahin, E. Gianfelice-Wendt, V. Kapin (Fermilab)



K. Skoufaris, C. Carli (CERN)

MDI: geometry of a 10 TeV collider



MDI: nozzle geometry

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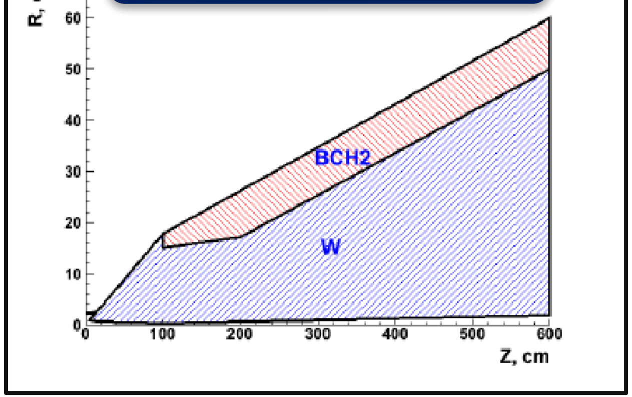
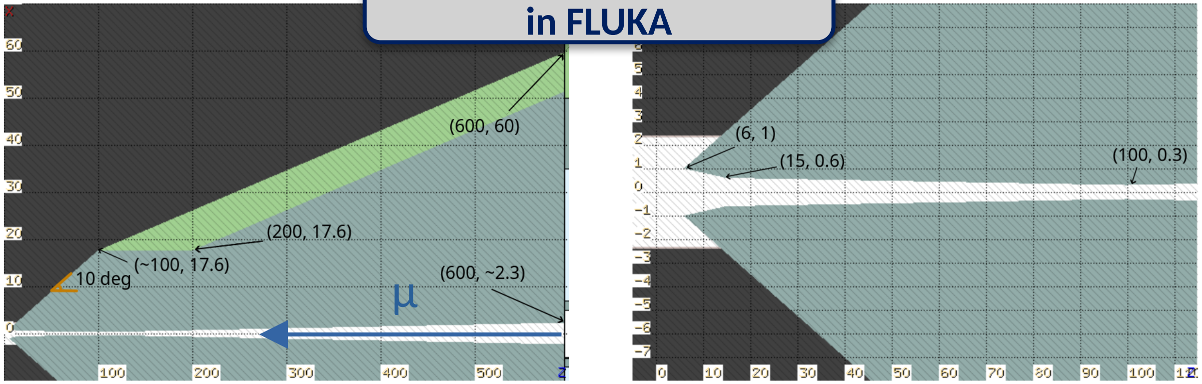
- Our implementation of the nozzle follows the original design from MAP collaboration
- The scope of the solid **tungsten** layer is to have a dense material to **stop electromagnetic cascades**
- The **boron polyethylene** layer acts as moderator (the hydrogen atoms), while the boron content is **capturing**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

Original MAP nozzle



Nozzle implementation in FLUKA



(a) Nozzle shape

(b) Tip details

Workflow in the IMCC

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Collaboration

Machine-Detector Interface: MDI

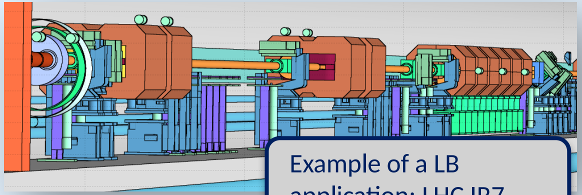
1. Lattice design

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

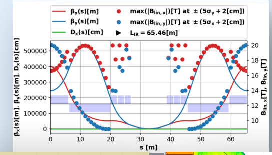
BIB data to detector experts

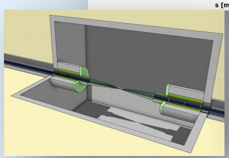
CERN STI/BMI is currently responsible for the geometry built at $\sqrt{s}$ = 3 and 10 TeV

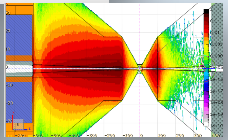
MDI: main aspects under study

Background and radiation damage in detector*

Develop a credible **interaction region (IR) design** that yields background levels compatible with detector operation

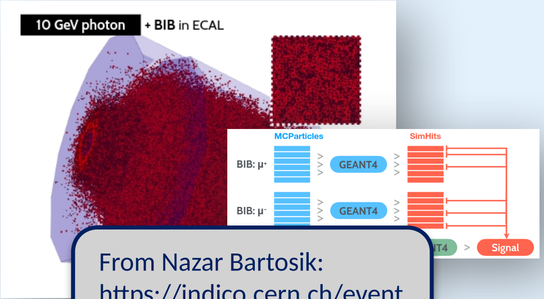






BIB data handling in collaboration with detector simulation

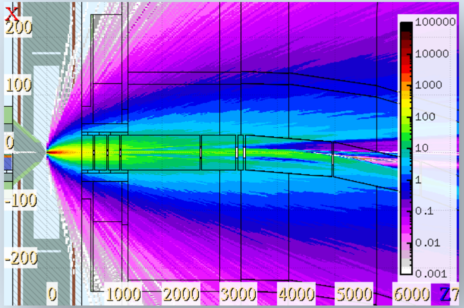
Establish a coherent framework to share the simulated background for the signal reconstruction



From Nazar Bartosik: https://indico.cern.ch/event/1175126/contributions/5024030/

MDI design for forward muon detection

Incorporate forward muon detection needs in the design choices.

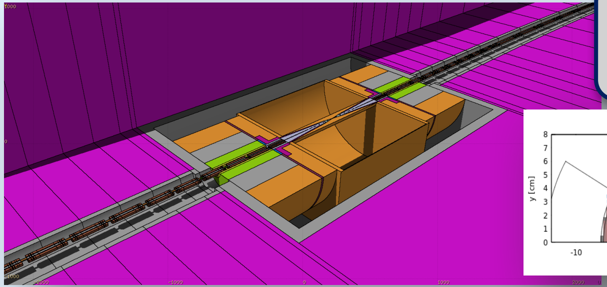


*Most relevant point, and this presentation will focus mostly on this

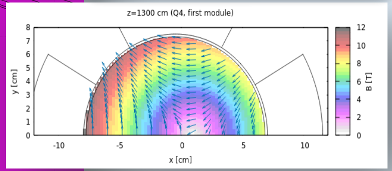
Status of the background studies for the √s = 3 TeV collider

- √s = 3 TeV BIB studies with FLUKA:
  - The procedure used to verify the beam-induced background at = 1.5 TeV (F. Collamati et al 2021 JINST 16 P11009) is being used to study background at = 3 TeV
  - Nozzle inspired by 1.5 TeV MAP design (N. Mokhov)
  - Particle distributions were used for first detector studies
  - Dose/neutron fluence maps for detector
  - Renewed effort in assessing the background reported in L. Castelli presentation during 2023 IMCC annual meeting

FLUKA model of 3 TeV interaction region:



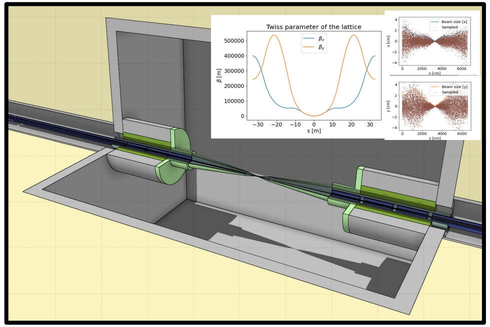
A. Mereghetti (CNAO),
C. Curatolo (INFN),
F. Collamati (INFN) et al.



See presentation of D. Lucchesi in the IMCC Accelerator meeting Nov 14, 2022

Status of the background studies for the √s = 10 TeV collider

- Simulation model (FLUKA):
  - Started with a nozzle inspired by 1.5 TeV MAP design (N. Mokhov)
  - Conical W liners in magnets which follow **5σ beam envelope**
  - Muon decay sampling → fully matched beam phase space distr.



- Topics addressed so far for the 10 TeV collider:
  - Is the decay-induced background worse than in a 3 TeV collider?
  - **Impact of lattice design choices on the decay background**
  - Assessment of the nozzle optimization potential for 10 TeV
  - Assessment of the contribution of incoherent electron-positron pair production
  - Estimate of the cumulative radiation damage in the detector
  - First study of forward muons from IP (muon tagging)

See next slides

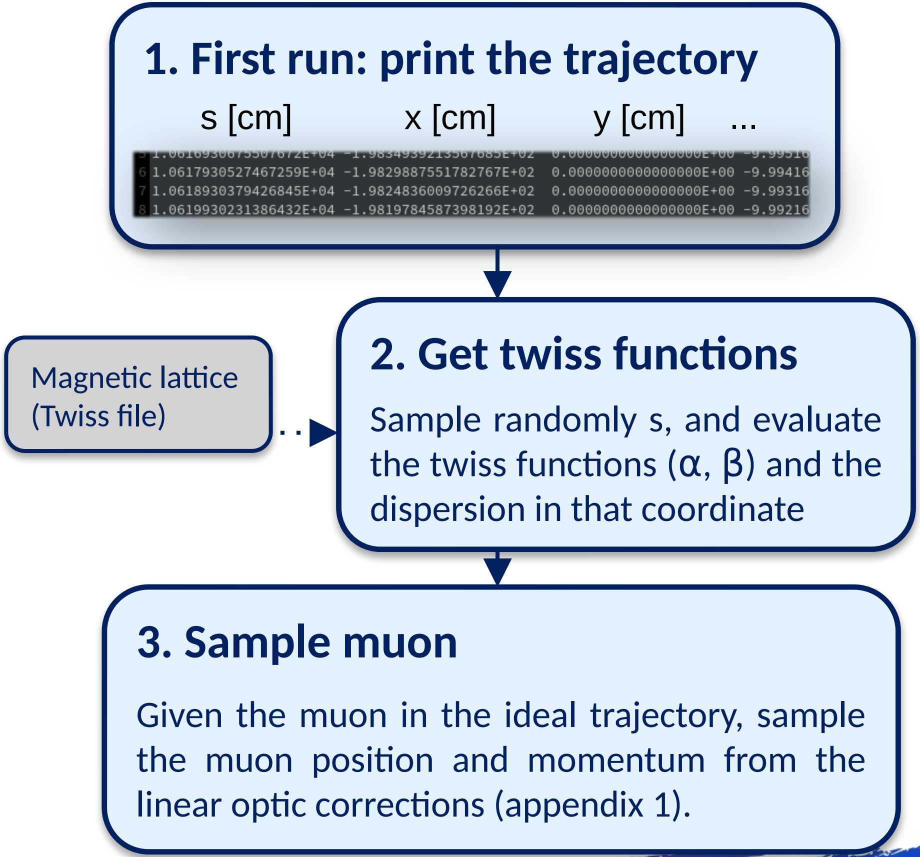
Results with MAP-like nozzle yield similar number of particles entering detector for 3 TeV and 10 TeV:

Monte Carlo simulator	FLUKA	FLUKA
Beam energy [GeV]	1500	5000
μ decay length [m]	$93.5 \cdot 10^5$	$311.7 \cdot 10^5$
μ decay/m/bunch	$2.1 \cdot 10^5$	$0.64 \cdot 10^5$
Photons ($E_\gamma > 0.1$ MeV)	$70 \cdot 10^6$	$107 \cdot 10^6$
Neutrons ($E_n > 1$ MeV)	$91 \cdot 10^6$	$101 \cdot 10^6$
Electrons & positrons ($E_{e^\pm} > 0.1$ MeV)	$1.1 \cdot 10^6$	$0.92 \cdot 10^6$
Charged hadroms ($E_{h^\pm} > 0.1$ MeV)	$0.020 \cdot 10^6$	$0.044 \cdot 10^6$
Muons ($E_{\mu^\pm} > 0.1$ MeV)	$0.0033 \cdot 10^6$	$0.0048 \cdot 10^6$

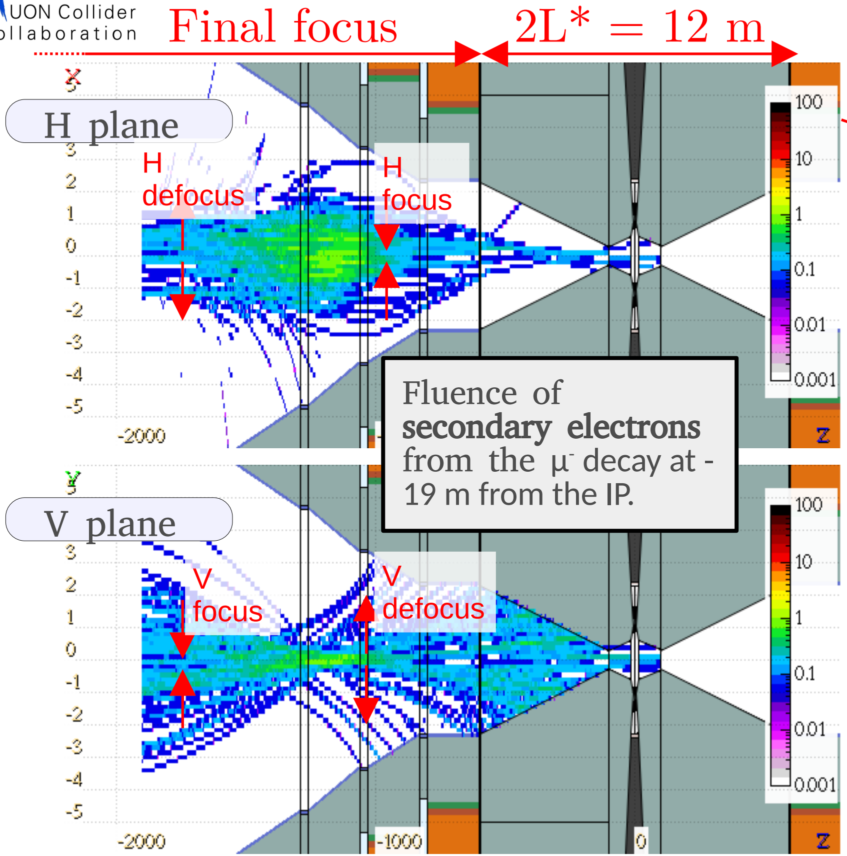
From Snowmass white paper.

μ decay: sampling procedure

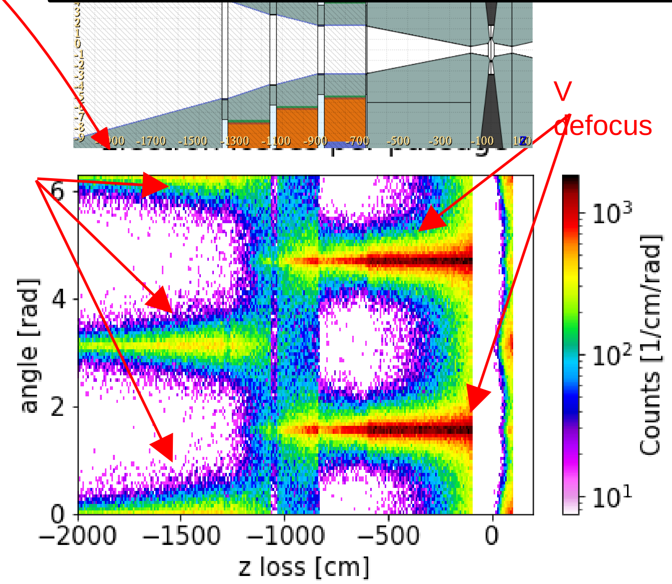
- For an accurate description, I propose to sample the muon decays position and momentum from a **matched phase-space distribution.**
- Once the position and momentum of the muons are known, the **muon decay is forced**.
- Results are naturally expressed per muon decay.
- Muons do not need to be tracked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



μ decay: $e^{+/-}$ impact on aperture

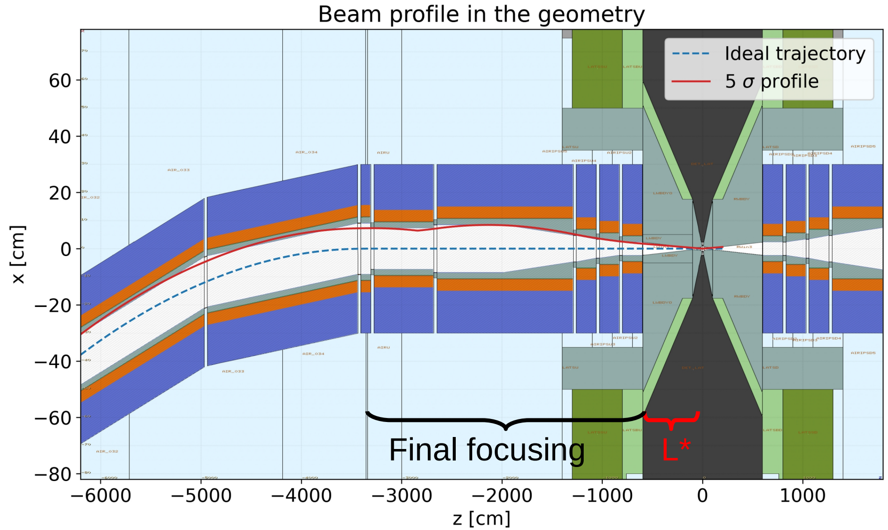


- Final focusing fields induce peaks in the azimuthal distribution of the e^-/e^+ impact position.
- (but!)The azimuthal dependence is diluted to negligible levels by the W nozzle.



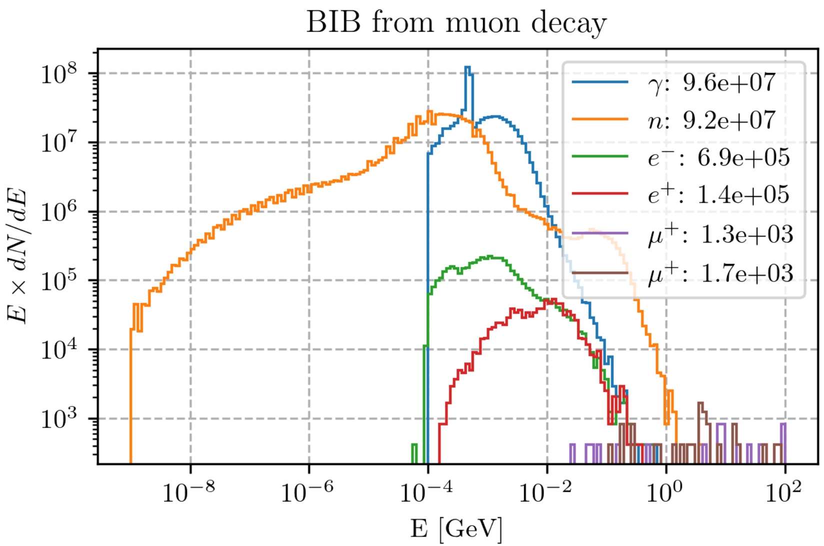
μ decay: original lattice

- The original preliminary lattice consisted of a L* = 6m, followed by the final focusing scheme. This consisted of a straight section containing quadrupoles up to ~35 m from the IP.
- The contribution coming from the bent section is proven negligible



μ decay @ √s = 10 TeV: particle spectra

- Considering the starting simplified lattice, the BIB particle multiplicity has been evaluated.



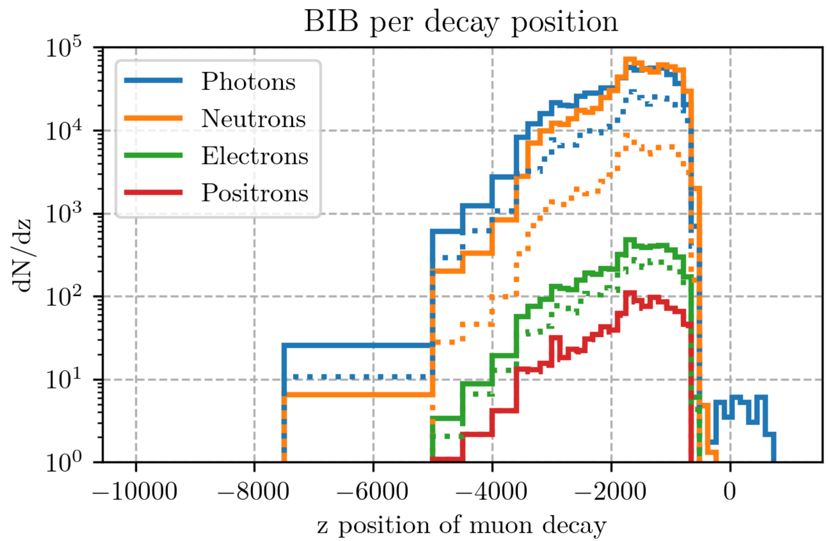
Updated!

Collider energy	1.5 TeV	3 TeV	10 TeV
Photons	7.1E+7	9.6E+7	9.6E+7
Neutron	4.7E+7	5.8E+7	9.2E+7
e^+/e^-	7.1E+5	9.3E+5	8.3E+5
Ch. hadrons	1.7E+4	2.0E+4	3.0E+4
Muons	3.1E+3	3.3E+3	2.9E+3

Data from: https://arxiv.org/pdf/2209.01318.pdf

μ decay @ √s = 10 TeV: particle origin

- Considering the starting simplified lattice, the BIB particle multiplicity has been evaluated.



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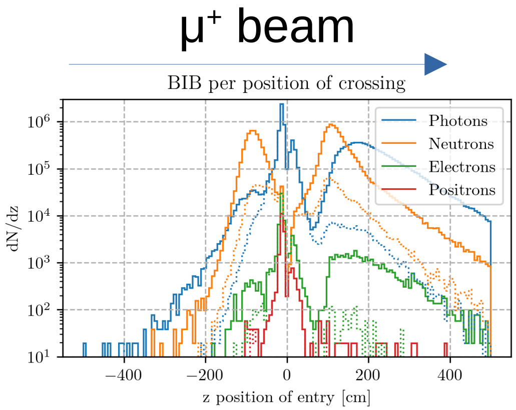
Ch. hadrons	1.7E+4	2.0E+4	3.0E+4
Muons	3.1E+3	3.3E+3	2.9E+3

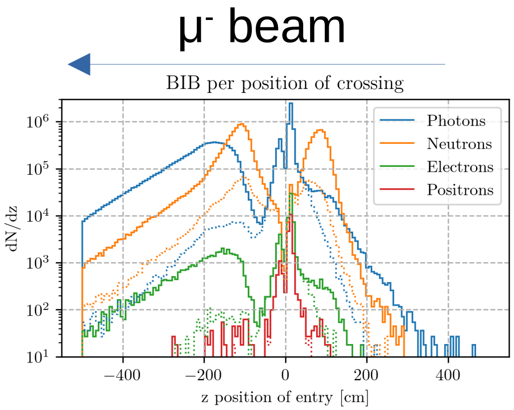
Dashed line for particles arriving in the time window of [-5, 15] ns

Data from:
https://arxiv.org/pdf/2209.01318.pdf

μ decay @ √s = 10 TeV: different beams contribution

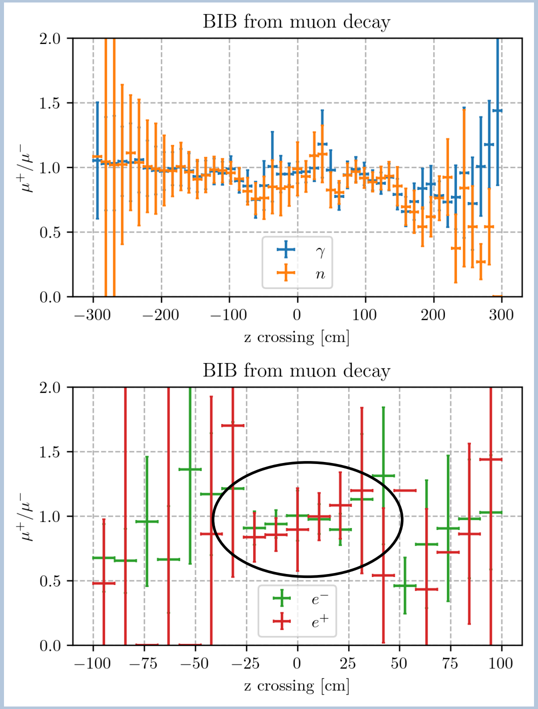
- Most of the 10 TeV simulations are conducted with a μ^+ beam. To confirm that the contribution from the opposite beam is the same, a comparison has been done.
- The simulations (comparing also energy spectra) **do not show any systematic difference!**





Dashed line for particles arriving in the time window of [-5, 15] ns

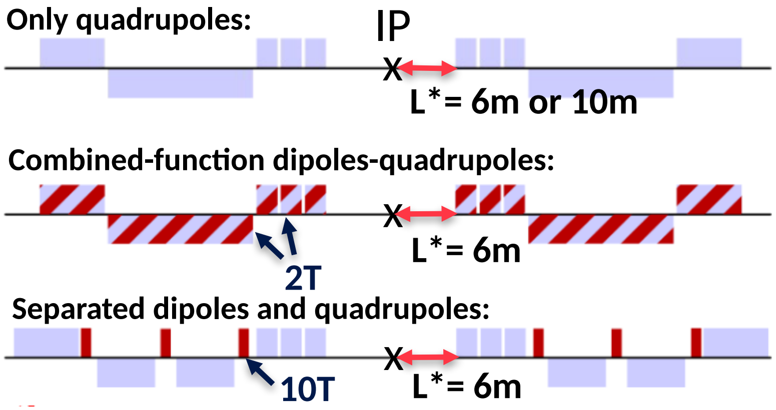
Ratio of BIB from different beams



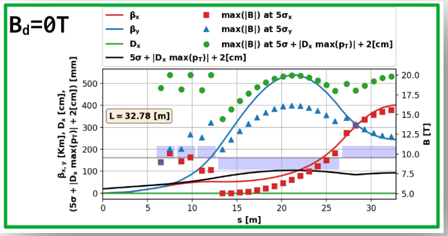
μ decay @ √s = 10 TeV: lattice design choices

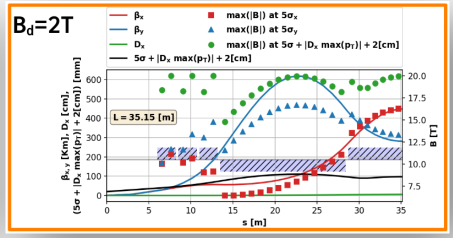
- *Can the decay-induced background be reduced by adjusting the lattice design?*
- Two key aspects were investigated:
  - Dipolar component in the final focus triplet (combined function magnets or separate dipoles)
  - Distance between IP and final focus magnets (L*)

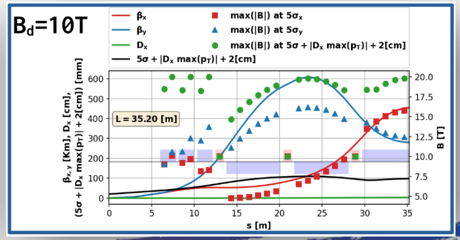
Layouts considered for the BIB studies:



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







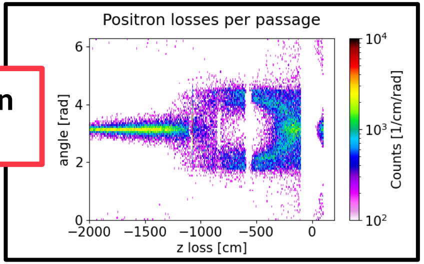
K. Skoufaris

μ decay @ √s = 10 TeV: dipolar component

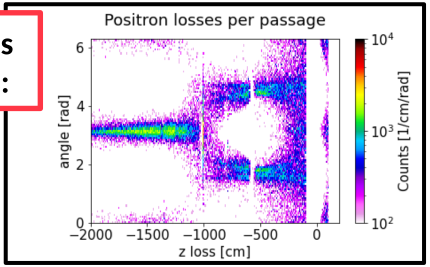
- The presence of a dipolar component changes the loss distribution of decay-e^-/e^+ on the aperture
- Some reduction of the contribution from distant decays
- However, the overall benefits are limited

Only quadrupoles

Combined-function dipoles-quad.

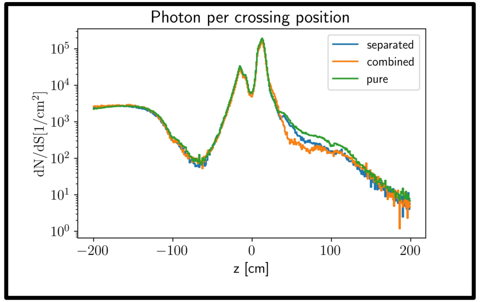


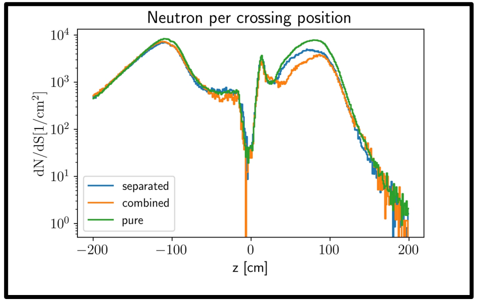
Separated dipoles and quadrupoles:



20m

IP



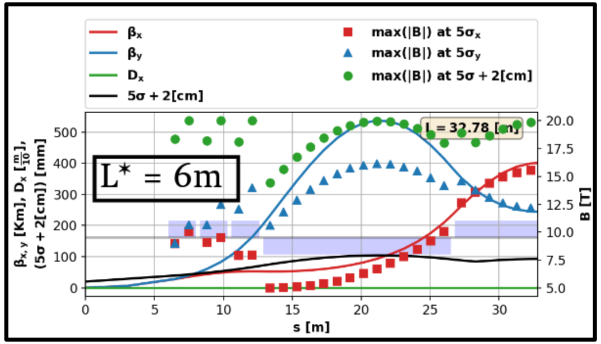


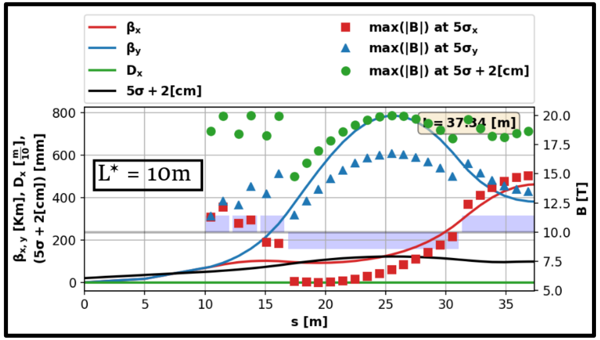
Particles crossing into the detector around the IP (with and without dipolar component):

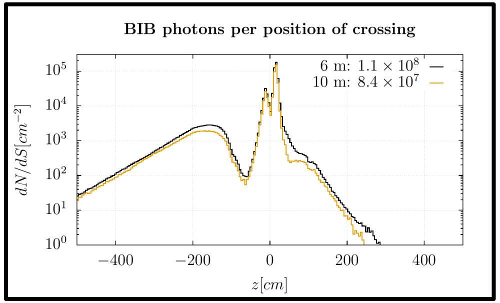
MDI meeting #5, 29/05/2022

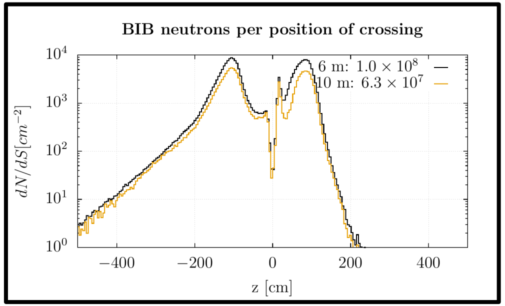
μ decay @ √s = 10 TeV: different L*

- The 10 TeV MDI studies show that μ-decays between IP and first quad contribute little to the BIB – is it beneficial to increase L*?
- With **L*= 10 m**, some reduction of the particle fluence is found around the IP compared to **L*= 6 m**
- Nevertheless, the gain is not large enough to justify the increase of L*









K. Skoufaris

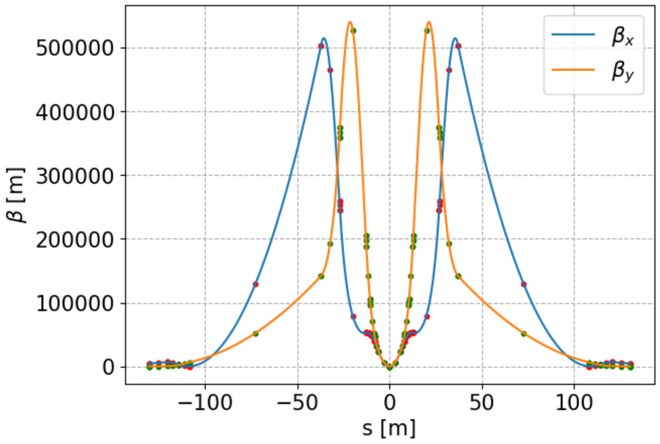
MDI meeting #7, 09/12/2022

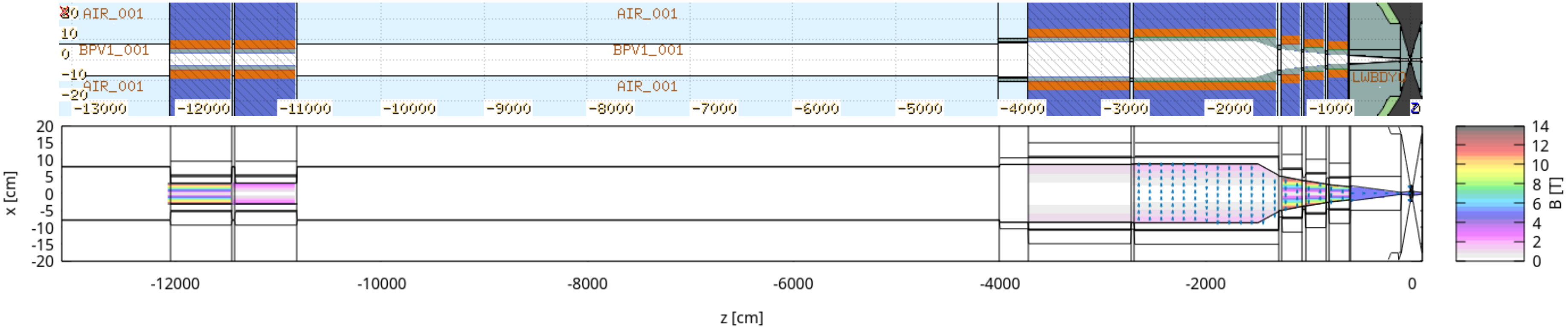
μ decay @ √s = 10 TeV: new lattice (v.06)

International MUON Collider Collaboration

- For a realistic machine, the final focusing schemes studied so far do not represent a satisfactory scenario.
  - A new lattice was provided by K. Skoufaris containing a very long straight section before the nozzle
  - Electrons produced in the drift section are not overbent or deflected by strong quadrupoles nor dipoles!

Betatron function

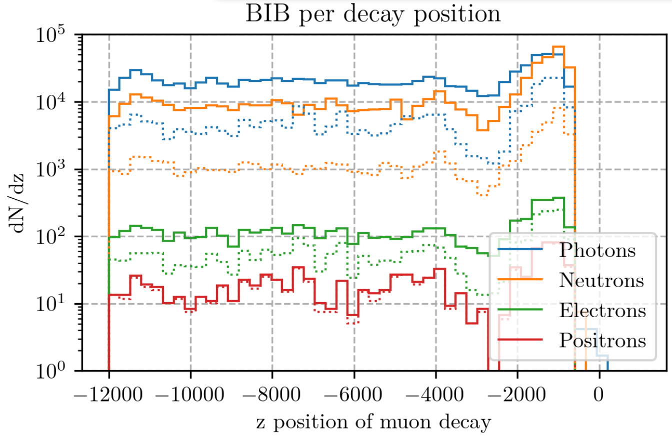


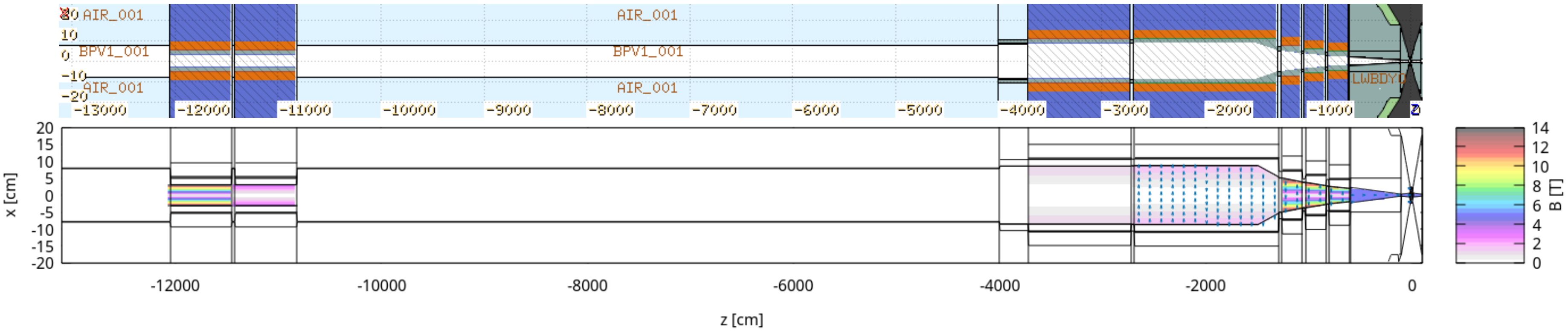


μ decay @ √s = 10 TeV: new lattice (v.06)

- For a realistic machine, the final focusing schemes studied so far do not represent a satisfactory scenario.
  - A new lattice was provided by K. Skoufaris containing a very long straight section before the nozzle
  - Electrons produced in the drift section are not overbent or deflected by strong quadrupoles nor dipoles!

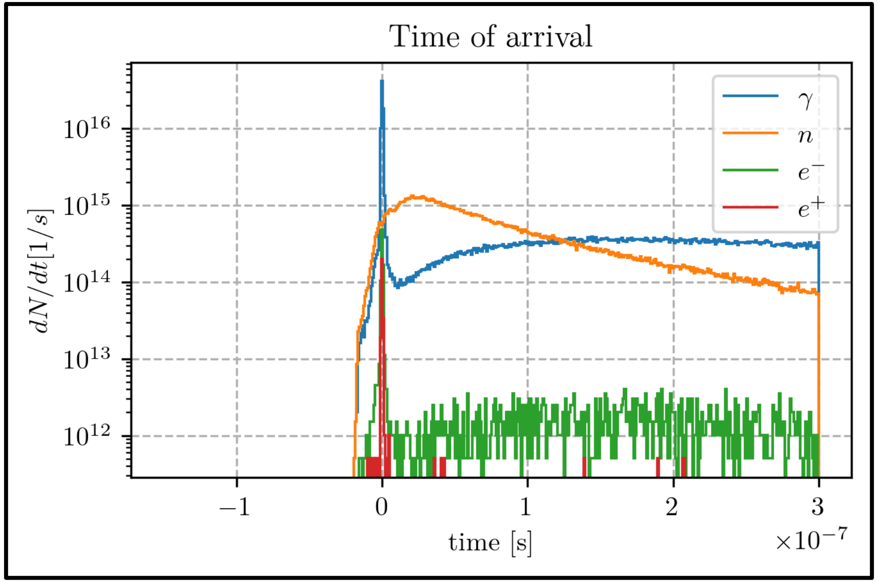
Dashed line: with time cut



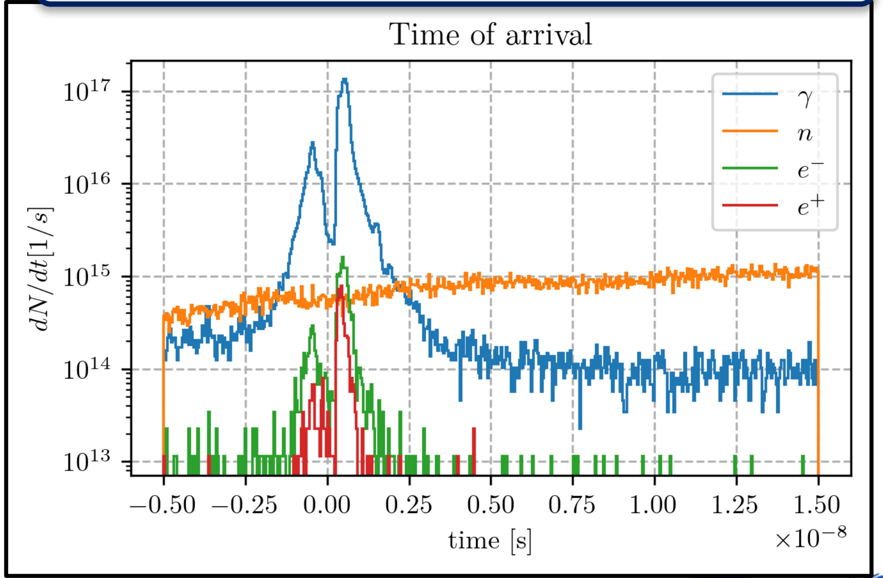


μ decay @ √s = 10 TeV: new lattice (v.06) time distribution

- Part of the BIB arrives with delayed times in comparison with the bunch crossing. Applying a time cut offers the possibility to strongly reduce this background.

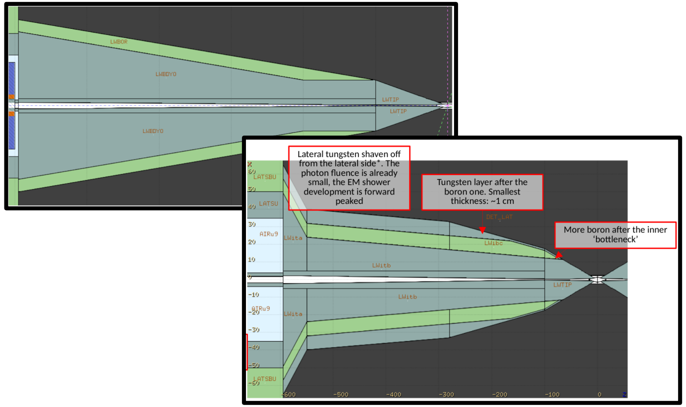


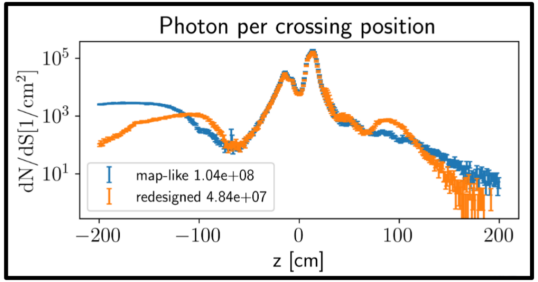
Particles arriving in the time window of [-5, 15] ns

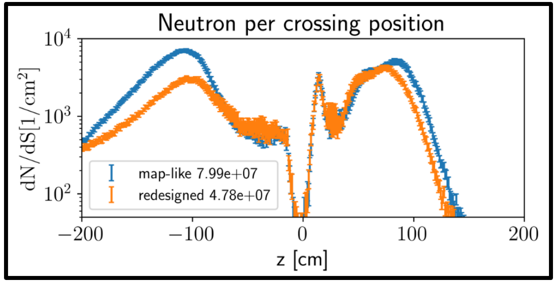


μ decay @ √s = 10 TeV: nozzle optimization (1)

- So far, a proof of concept for the nozzle optimization has been conducted.
- The next step will be to start from scratches and perform a nozzle optimization for the 10 TeV machine, having in mind the detector performance
- Room for improvement!



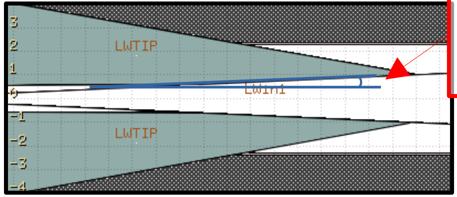




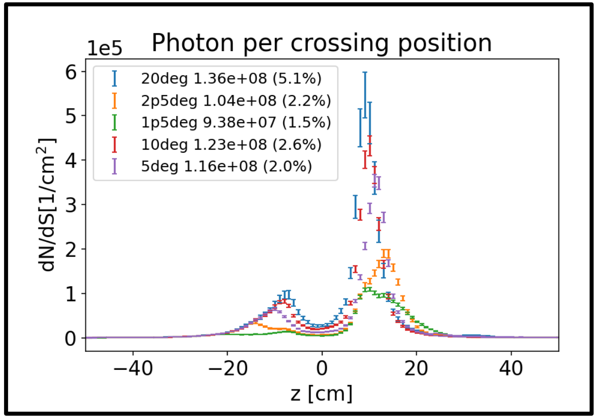
MDI meeting #6, 29/06/2022

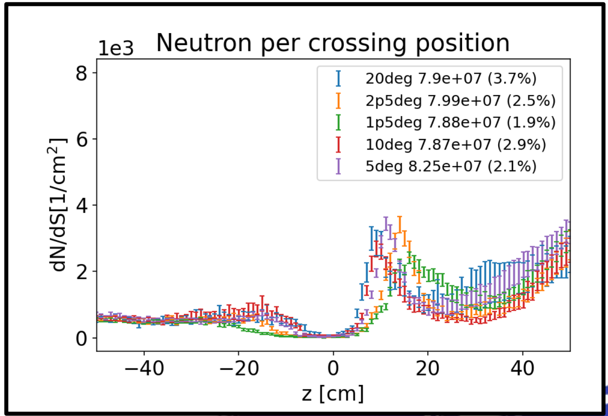
μ decay @ √s = 10 TeV: nozzle optimization (2)

- So far, a proof of concept for the nozzle optimization has been conducted.
- The next step will be to start from scratches and perform a nozzle optimization for the 10 TeV machine, having in mind the detector performance
- Room for improvement!

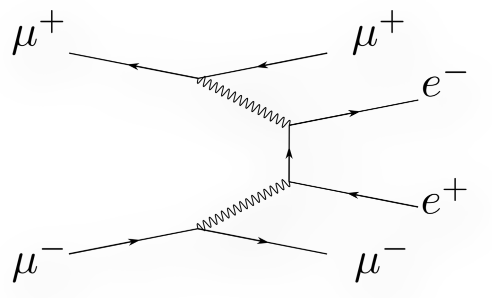


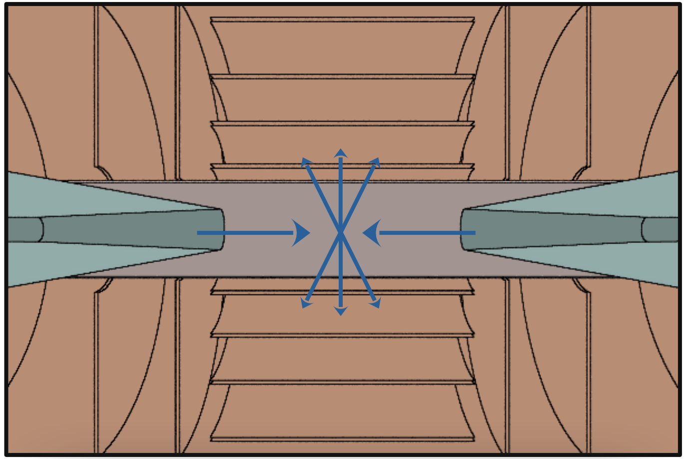
Starting from 2.5 deg, we modify this angle.

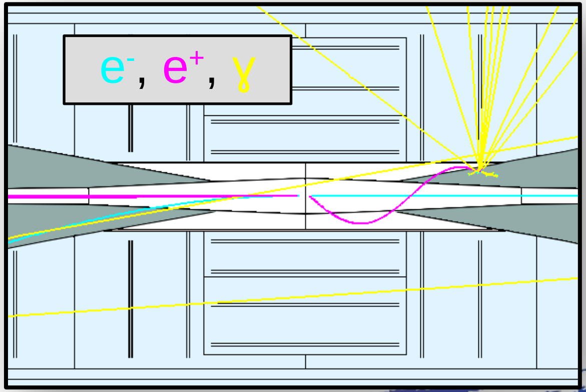




Incoherent pair production: phenomenon





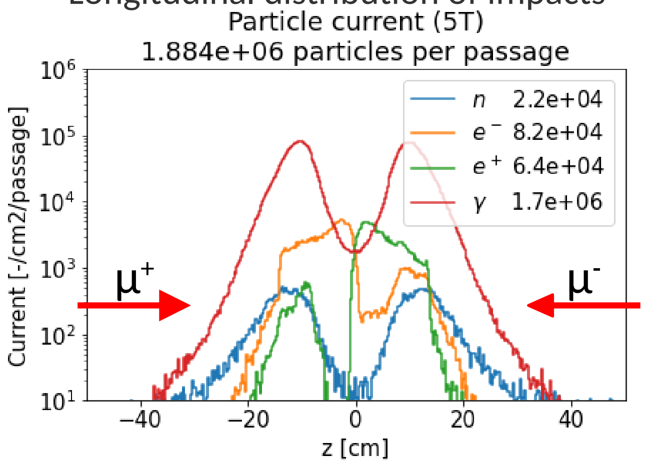


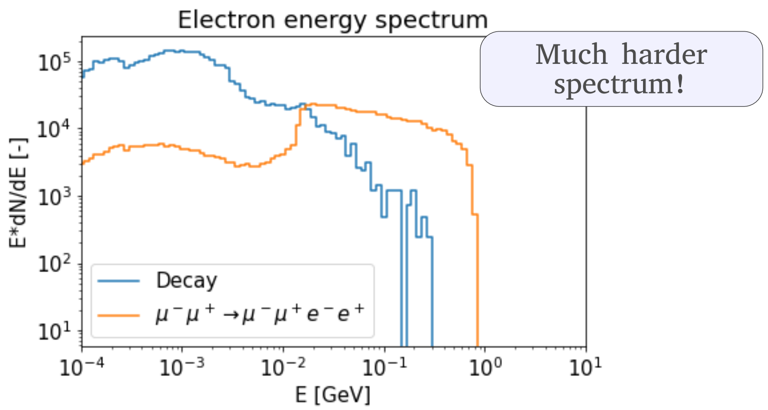
- At very high beam energies, beam-beam effects are not negligible. The most important phenomenon is due to the **incoherent beam-beam pair production μ+μ-→μ+μ-e+e-**.
  - The incoherent pair production e^+/e^- are provided by D. Schulte and are obtained by a **Guinea-Pig simulation**
- The **total number** 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.

Incoherent pair production: space distribution

- The trajectory of the pairs is curved by the solenoidal 5 T magnetic field.
- Most of the particles enter in the detector area as photons produced in the nozzle

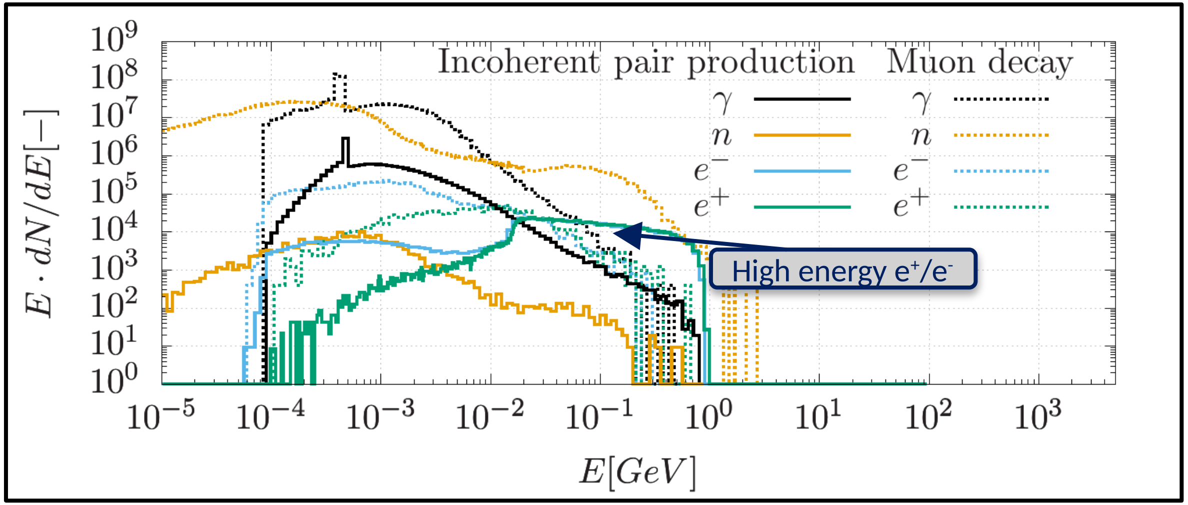
Longitudinal distribution of impacts





Incoherent pair production: spectra

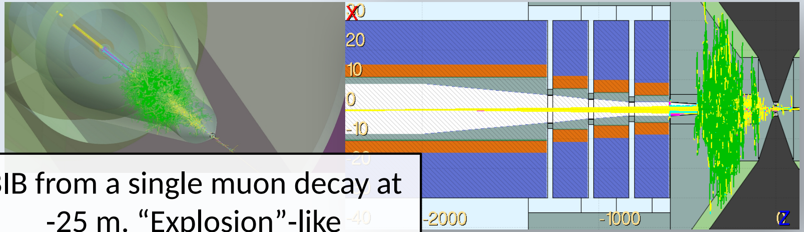
- The total BIB multiplicity is much smaller than the one coming from the muon decay
- However, the spectrum is significantly harder, and the BIB is in time with the signal



Halo losses: spectra

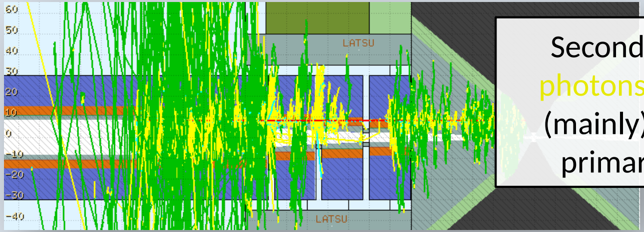
- The halo losses gives a significantly different contribution to the BIB: the particles are generated close to the IP due to the muon interaction with the nozzle.
- As a preliminary simulation, we considered a muon beam going in the magnet at 0 degrees with the z axis

Muon decay



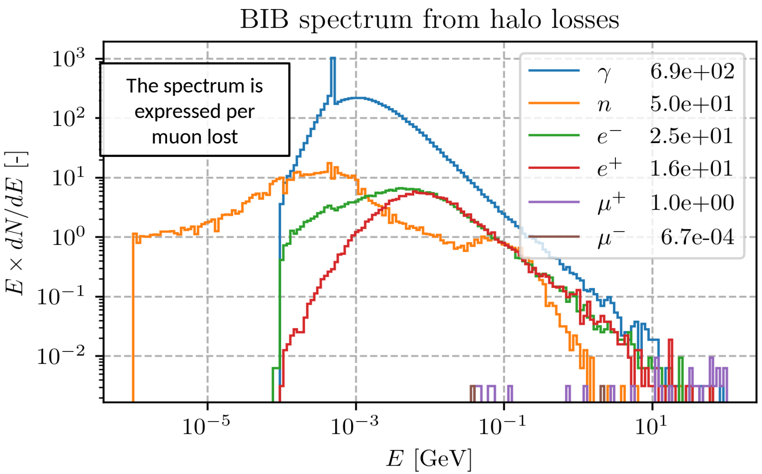
BIB from a single muon decay at -25 m. “Explosion”-like secondary distribution

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.



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? Suggestions are well accepted

What is a “parent”? Are there any insightful variables for the detector studies?

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

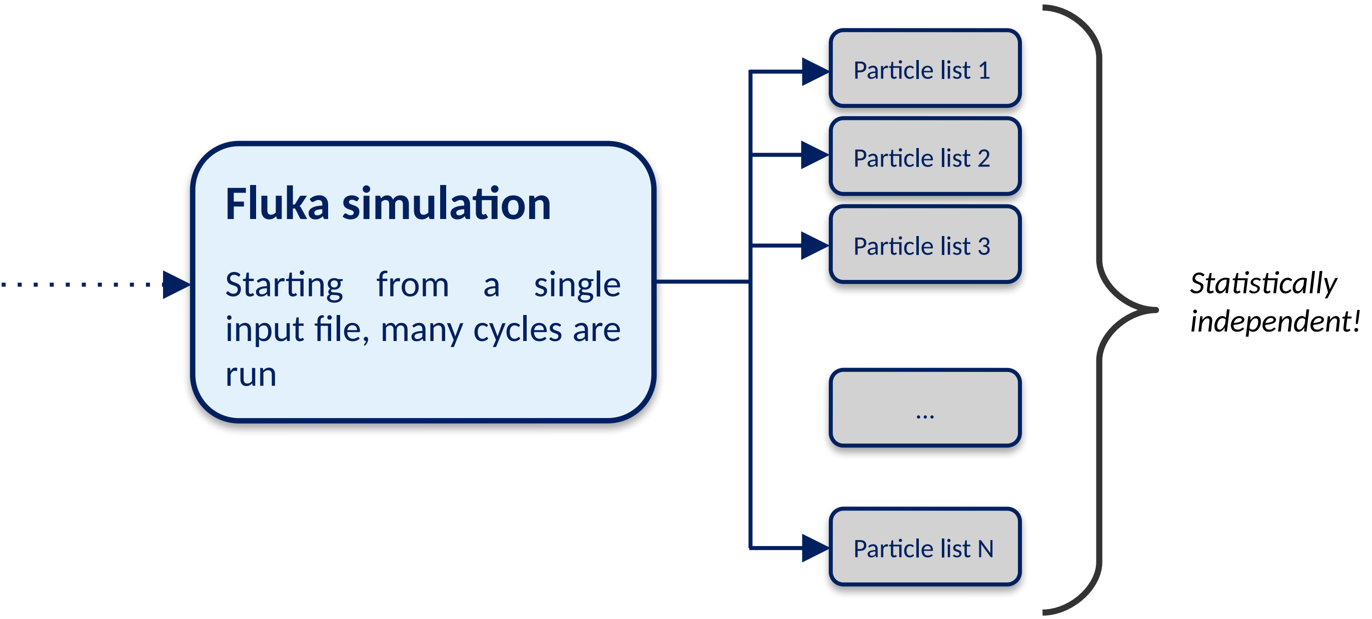
```
00000000: 0700 0000 0000 0000 fbb2 9397 b9db 353f
00000010: 0a7e 778f 357b f4bf 72da e775 b03d 0040
00000020: a467 dd2a 1c5c 27c0 0f5f a698 d8de e8bf
     030: b001 93bf 6ed9 d83f d0c7 8226 ffb0 dfbf
00000040: 77e1 7cc9 f9b3 723e fa58 4ded e8b9 a43e
00000050: e06b 1731 2ea7 d03f 5a23 1df7 850b 01c0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

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)

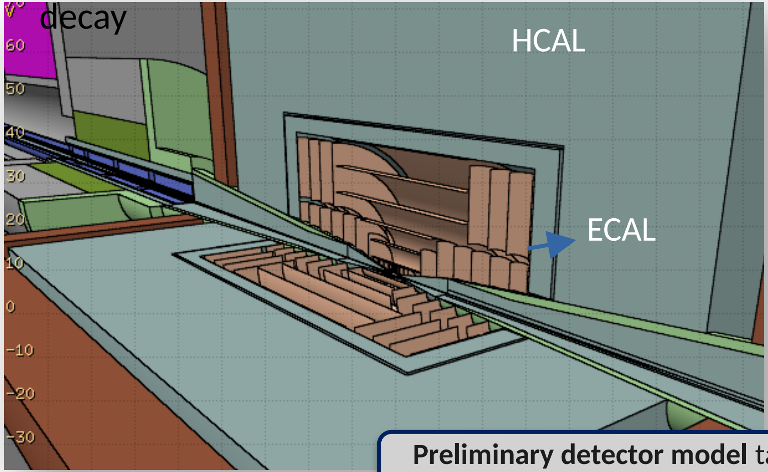
How to read BIB data: data organization

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



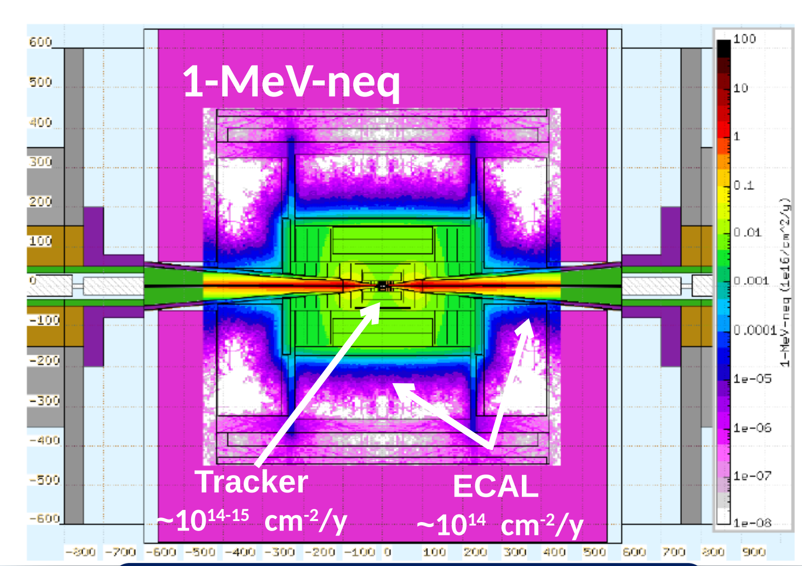
Long term detector damage: FLUKA detector implementation

- 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



Preliminary detector model taken from the CLIC layout

√s = 3 TeV neutron equivalent fluence

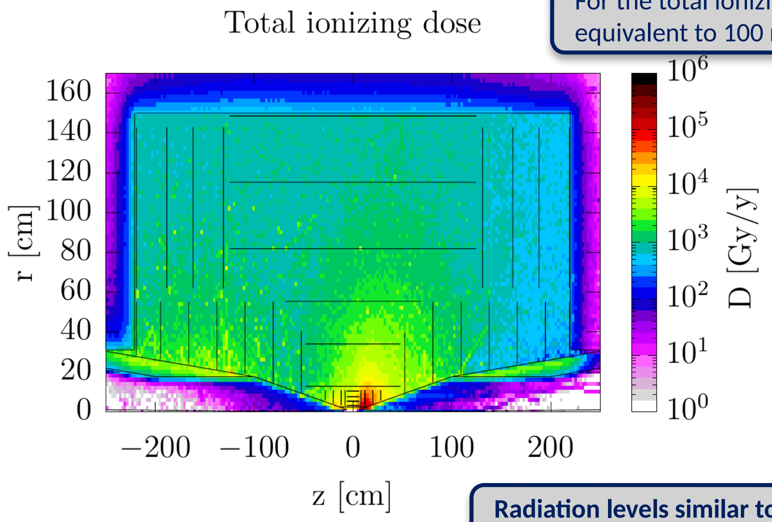


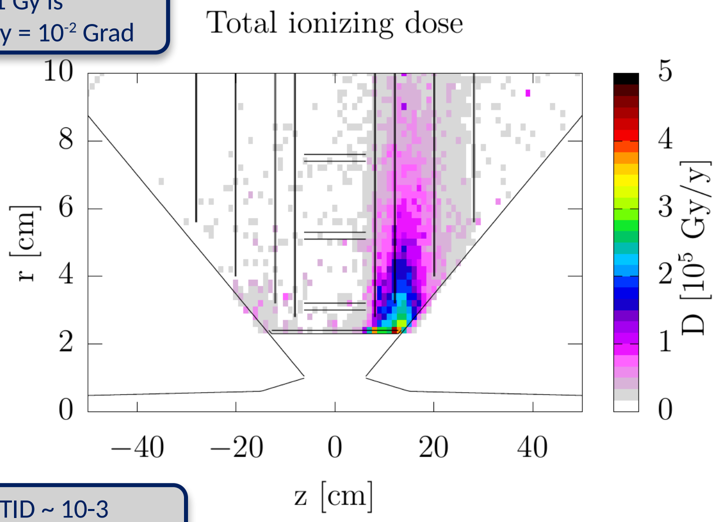
Radiation levels similar to HL-LHC (TID ~ 10^{-3} Grad/y on tracker and ~10^{-4} Grad/y ECA)
(10.1088/1748-0221/16/11/P11009 and 10.3390/instruments6040062)

Long term detector damage: √s = 10 TeV total ionizing dose

- As operational lifetime, we assume to work for 5 years. Each year, we assume to work for 1.2E7 seconds (139 days). In comparison with the nominal luminosity and the target integrated luminosity, we have a 20% safety factor.
- In the plots, the effects of one beam (left to right) are shown

For the total ionizing dose, 1 Gy is equivalent to 100 rad: 10^5 Gy = 10^{-2} Grad

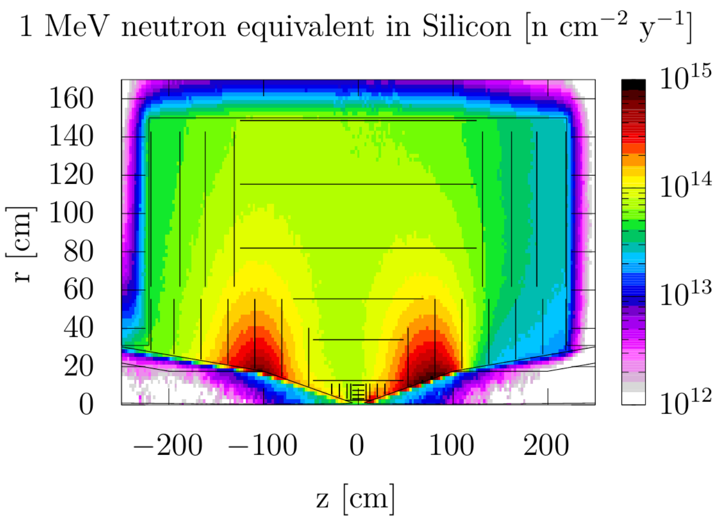


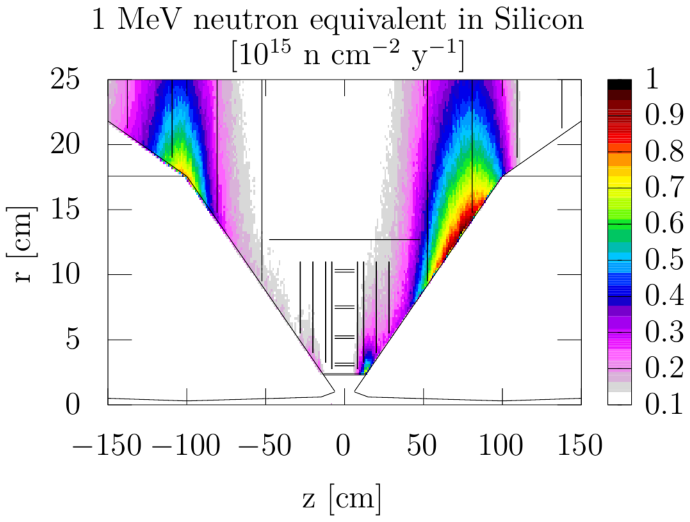


Radiation levels similar to HL-LHC (TID ~ 10-3 Grad/y on tracker and ~10-4 Grad/y ECA)

Long term detector damage: √s = 10 TeV total displacement damage

- As operational lifetime, we assume to work for 5 years. Each year, we assume to work for 1.2E7 seconds (139 days). In comparison with the nominal luminosity and the target integrated luminosity, we have a 20% safety factor.
- In the plots, the effects of one beam (left to right) are shown



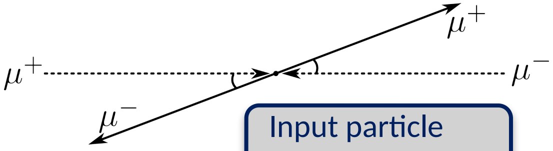


Forward muon detection: introduction

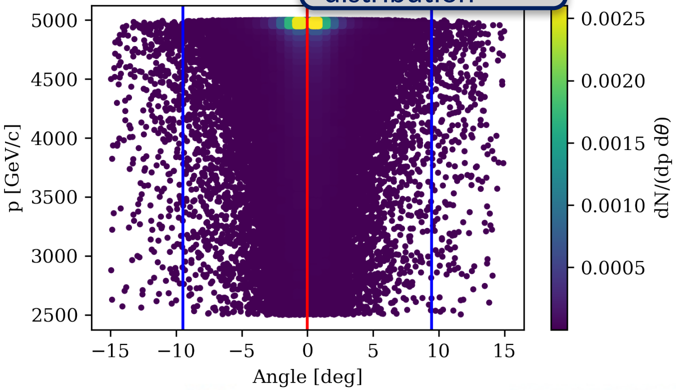
- During the annual meeting, **Maximilian Ruhdorfer** clearly shown the physics interest in tagging forward directed muons (this talk). *'Coverage of very forward muons is crucial'*.
- For a full coverage, η above 6. At η = 2.44 (**ϑ = 10°**), all the **signal is removed**.
- The muon collider requires **thick nozzles** to **mitigate** the enormous **BIB** to the detectors generated by the decaying beams.
- The a part of the forward muons crosses the shielding and machine components before it can be detected.
- In this study, I simulated the **propagation of very forward muons** in the machine. We want to understand *if*, *how* and *where* these muons can be detected.
- All results here are **preliminary**

Forward muon detection: first test case

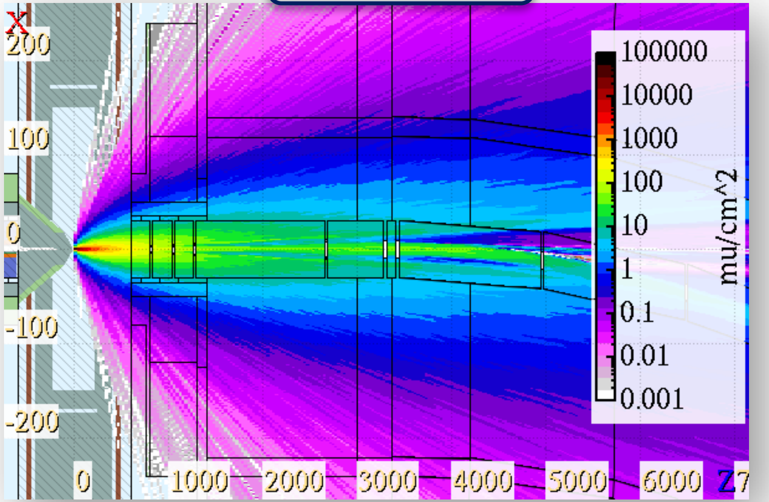
- **Matthew Forslund** generated and **Massimo Casarsa** provided us a muon list containing both μ^+ and μ^- in case of a VBF possible process.



Input particle distribution



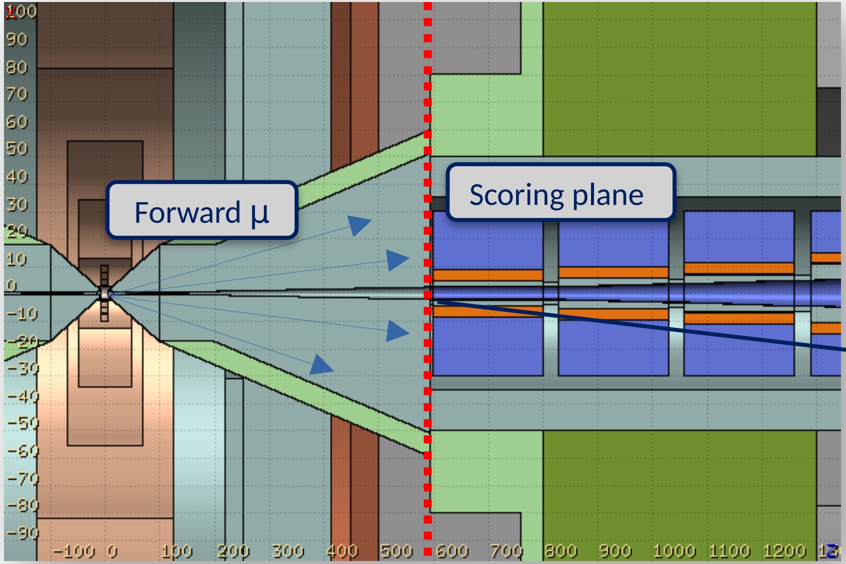
Muon fluence in the machine

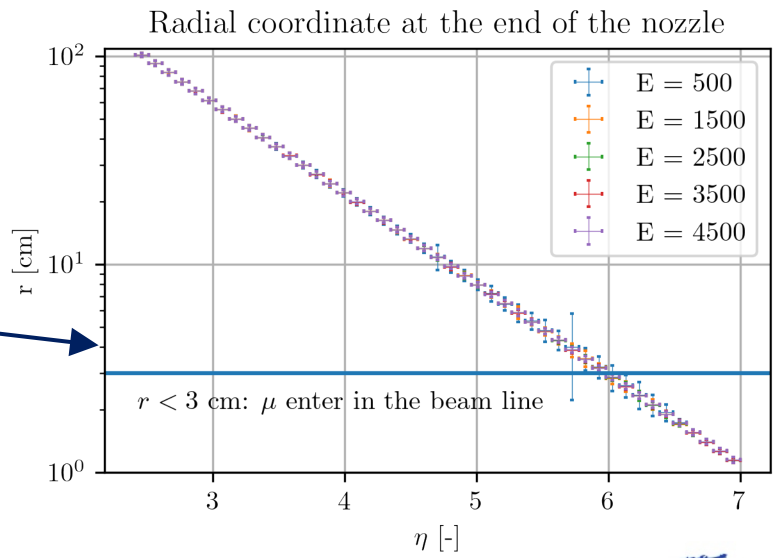


Forward muon detection: general case

- Assuming isotropy in the φ angle, I made some simulation for the forward muons emitted at various energies and angles in the interaction point.

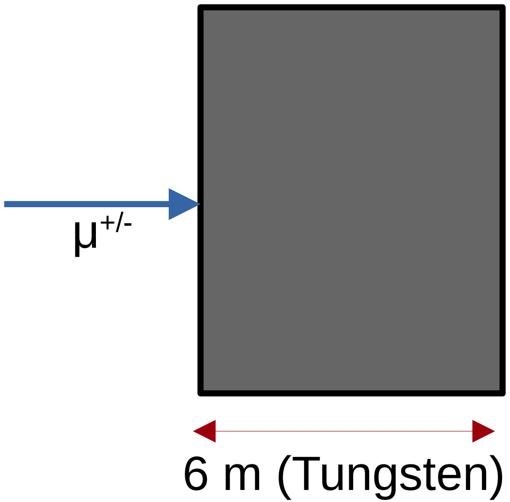
$$\eta \equiv -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$



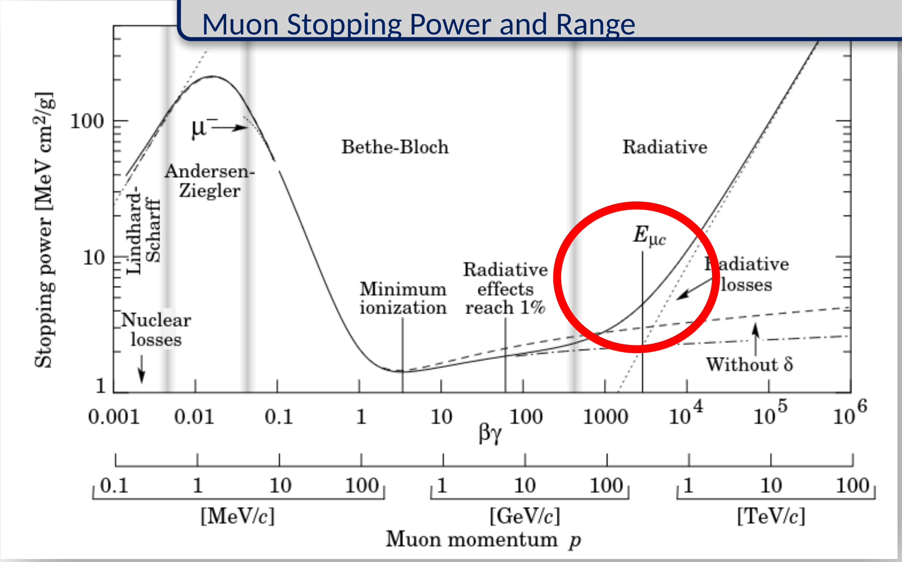


Forward muon detection: general case

- Within a large pseudo-rapidity range, muons will cross a large portion of the tungsten nozzle. They lose energy in it!

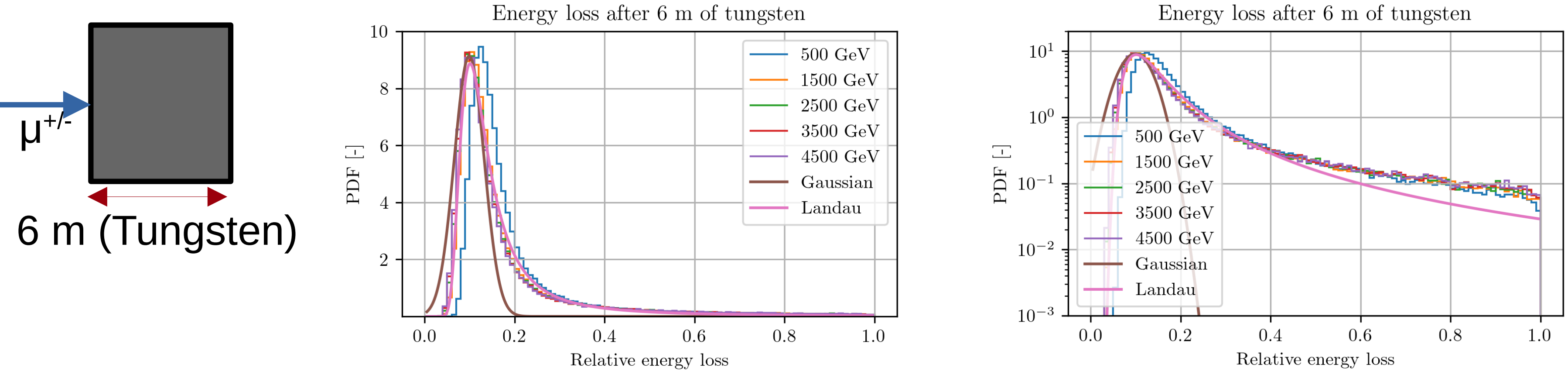


D. E. GROOM, N. V. MOKHOV, and S. STRIGANOV
Muon Stopping Power and Range



Forward muon detection: general case

- The energy loss distribution depends on the interaction mechanism (energy straggling). The energy loss follows the Landau distribution.

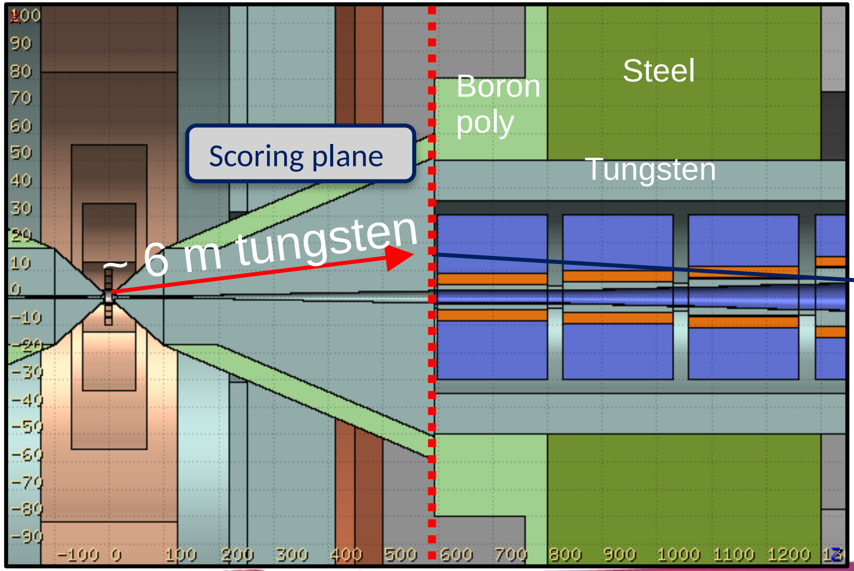


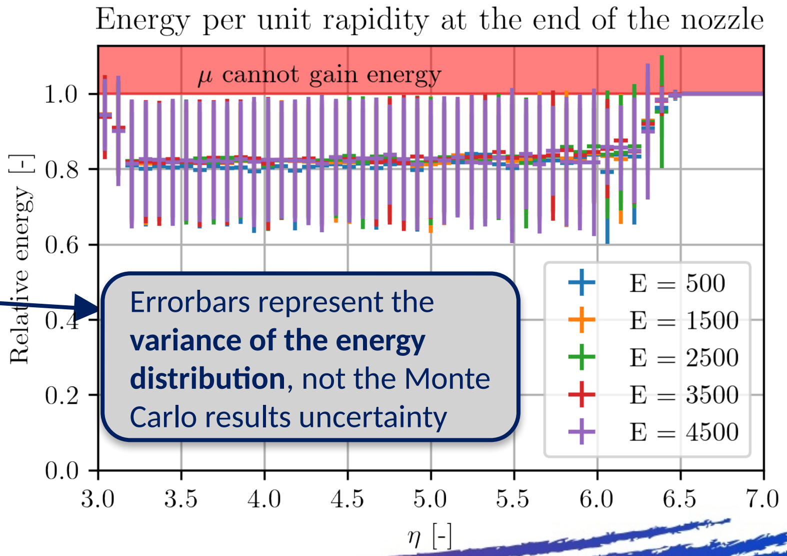
$$p(x;\mu,c) = \frac{1}{\pi c}\int_0^\infty e^{-t}\cos\left(t\left(\frac{x-\mu}{c}\right)+\frac{2t}{\pi}\log\left(\frac{t}{c}\right)\right)dt$$

Fit:
$\mu = 0.185$
$c = 0.032$

Forward muon detection: general case

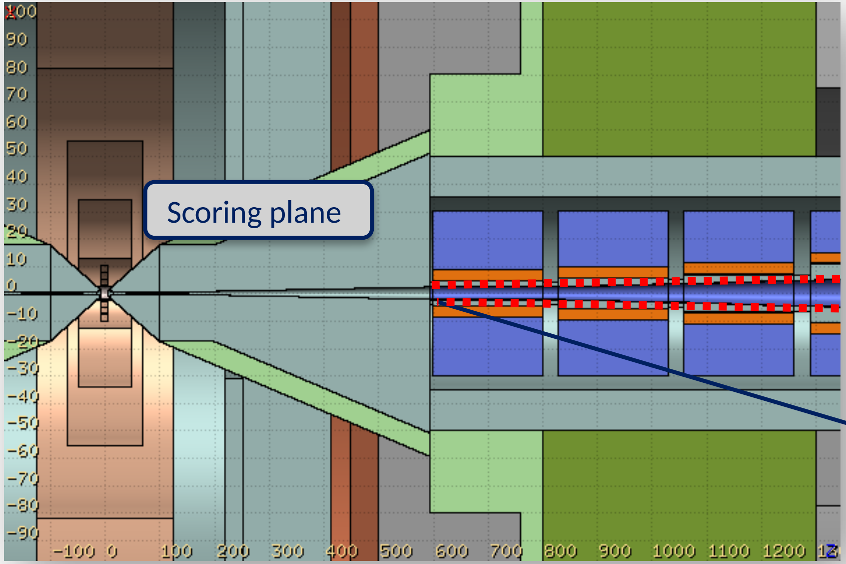
- As expected, the energy loss distibution is similar for all the η values.
- Behind the nozzle there are **machine elements** (η > 3.7) and further **lateral shielding** (η < 3.7) → potentially higher energy straggling
- Forward muons were not a primary MDI requirement. We can include them in future shielding design.

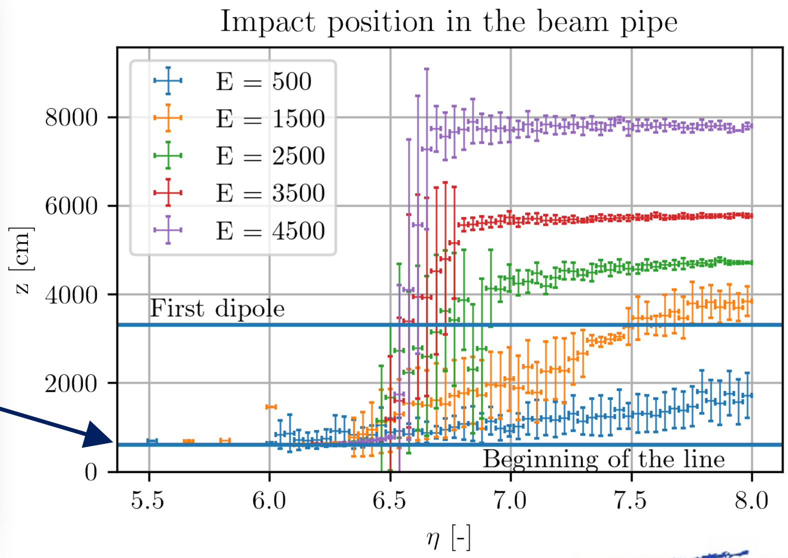




Forward muon detection: general case

- When the pseudorapidity is large enough (~6.5) the muons do not touch the tungsten and go directly in the beam pipe. There, they cross the magnet and leave the line





Conclusions

- **BIB from muon decay** has been assessed with various configuration:
  - A dipolar component offers only a slight beneficial contribution to the BIB mitigation
  - The new lattice with a l**ong drift increases the BIB** multiplicity of a factor 2
- The **negative muon beam and the positive one have the same effect** for what concerns the BIB from muon decay
- **Incoherent pair production is a non negligible background at high energies**. This should be included with the BIB from muon decay in the detector design
- The halo losses could pose a threat only if a large fraction of the beam is lost at the final focusing. A tracking study could be necessary to better assess this contribution
- 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
- The long term radiation damage has been assessed. From preliminary simulation, the **damage** is **comparable with the Hi-Lumi LHC upgrade**
- **Tracking** and **measuring forward muons can be challenging**. Nevertheless, we should keep these in thought during the MDI design process

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Thank you
for your attention!

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- [14] https://indico.cern.ch/event/1134938/contributions/4765158/attachments/2402421/4117427/BIB_CCuratolo_4mar2022.pdf
- [15] https://indico.fnal.gov/event/51315/contributions/225846/attachments/148314/190521/casarsa_BIBcomparison.pdf

Particle sampling in linear optics

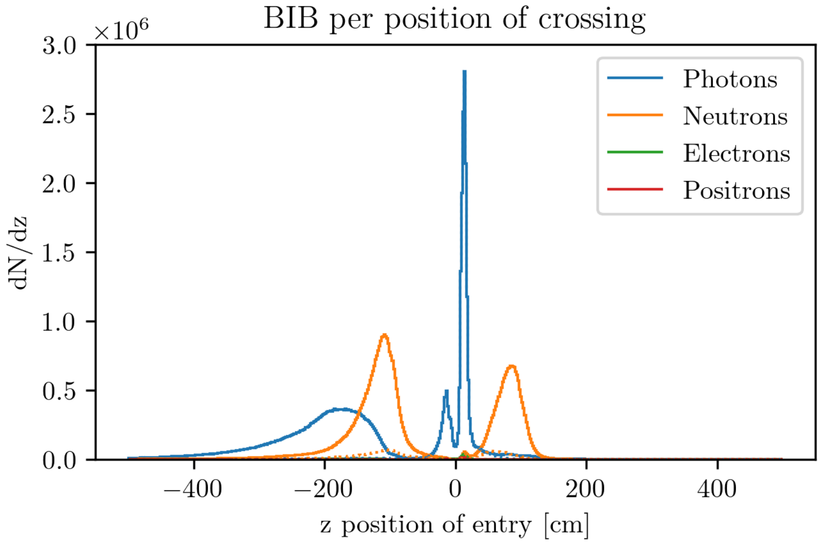
- Sample the **s-coordinate** (curvilinear arc length) uniformly across the particle trajectory.
- Sample the beam **energy** from a gaussian distribution
- Sample from the matched phase-space the correction to the ideal trajectory (this formula is applied performing the Cholensky matrix decomposition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

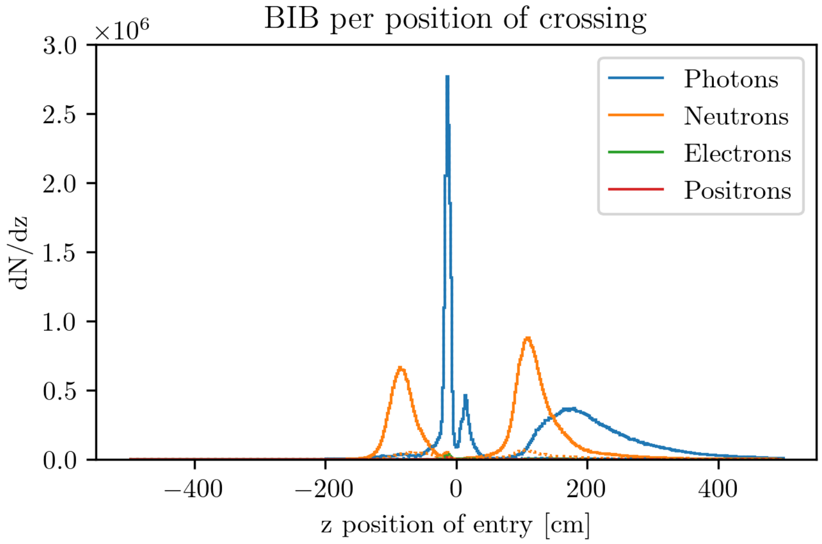
$$\begin{cases} \Delta_x = \mathrm{Rand}_x \cdot \sqrt{\epsilon_x \beta_x} \\ \Delta_{x'} = (\mathrm{Rand}_{x'} - \mathrm{Rand}_x \cdot \alpha_x)\sqrt{\epsilon_x / \beta_x} \end{cases}$$

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

10 TeV muon collider: position of crossing

μ+ beam → ← μ- beam





10 TeV muon collider: new and original lattice