MDI – Machine-Detector Interface studies for a 10 TeV muon collider

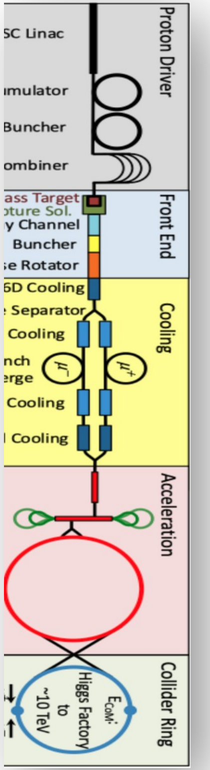
D. Calzolari (CERN – SY/STI/BMI)* on behalf of the IMCC,

special thanks to N. Bartosik, C. Carli, M. Casarsa, F. Collamati, C. Curatolo, S. Jindariani A. Lechner, D. Lucchesi, F. Meloni, N. Mokhov, N. Pastrone, D. Schulte, K. Skoufaris, A. Wulzer and many others

April 2023

**speaker*

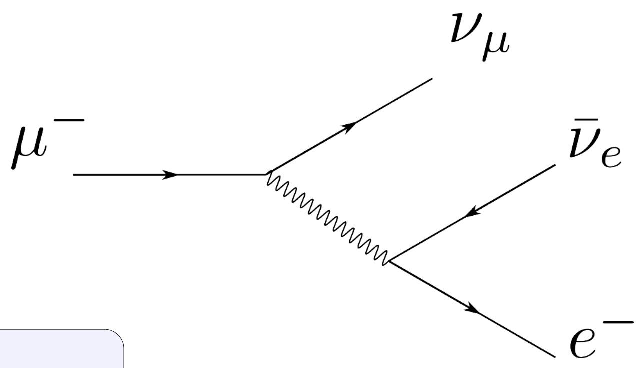
Outline



- **Muon collider (MC) radiation challenges for the MDI:**
  - Secondary electron losses on the aperture
  - Beam induced background (BIB): halo, muon decay and incoherent pair production by muons
- **Workflow in the IMCC**
- **BIB for a 10 TeV machine**
  - Muon decay as main source of background and comparison with other machines
- **Lattice studies**
  - Lattice design influence on BIB
  - Muon decay in the chromaticity correction section
  - BIB in case of a long drift section
- **Conclusions**

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

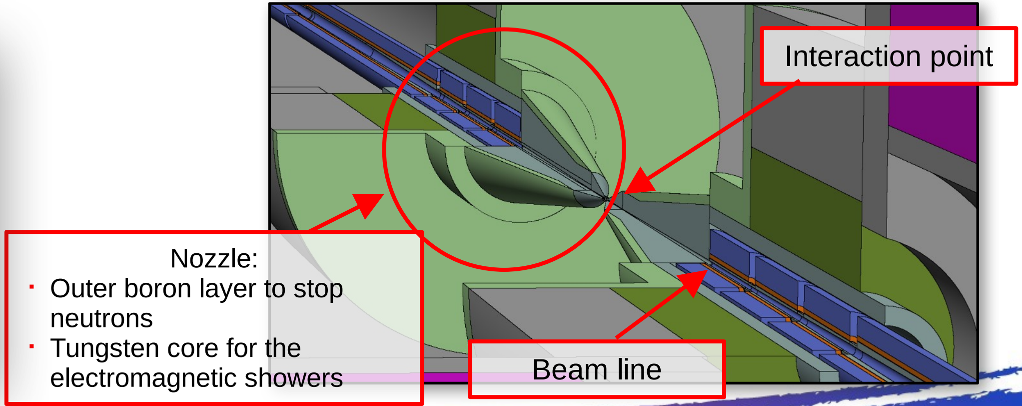
- MDI is a **difficult challenge** for the muon collider. First studies were done by the MAP collaboration (energies up to 6 TeV). So far, IMCC focused on studies for energies up to 10 TeV.
- Objectives of the new studies:
  - Devise a conceptual IP design achieving **background** levels **compatible** with **detector operation**, both in terms of physics performance and acceptable cumulative radiation damage.
  - The focus energies are 3 TeV and 10 TeV.

Tentative target parameters
Scaled from MAP parameters

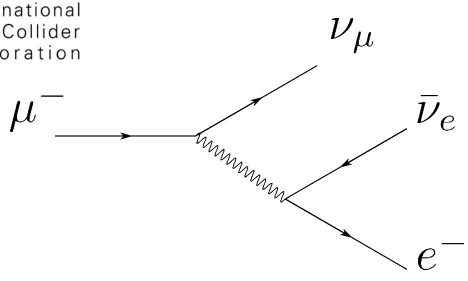
Comparison:
CLIC at 3 TeV: 28 MW

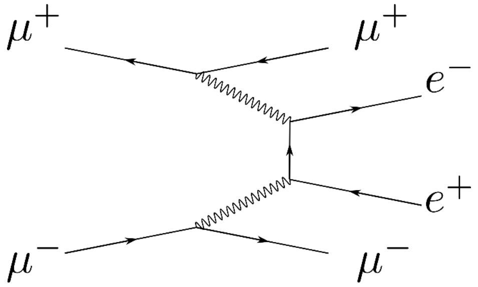
Parameter	Unit	3 TeV	10 TeV	14 TeV
L	10^{34} $cm^{-2}s^{-1}$	1.8	20	40
N	10^{12}	2.2	1.8	1.8
f_r	Hz	5	5	5
P_{beam}	MW	5.3	14.4	20
C	km	4.5	10	14

Geometry of the MDI



Radiation sources for the MDI





- **Main** source of detector **background** for all collider energy options.
- Main responsible for heat and radiation effects in the accelerator components.

- **Muon decay** around the ring
- **Incoherent e⁻/e⁺ pair production** during bunch crossing in IP
- **Beam-halo losses** at aperture bottlenecks

- Potential problem for the detector **background**.
- Proven not to be an issue for low energy colliders, providing a **solenoid field** of ~1s T. [5].
- Under study in the 10 TeV collider.

- Potential contribution to the BIB and damage on accelerator components.
- Levels of acceptable halo losses to be defined. (**halo cleaning**)

Workflow in the IMCC

Machine-Detector Interface: MDI

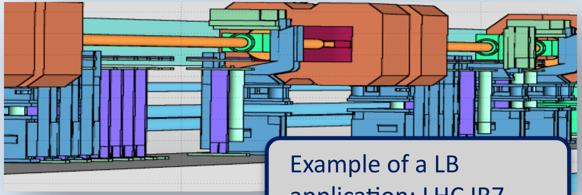
1. Lattice design

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

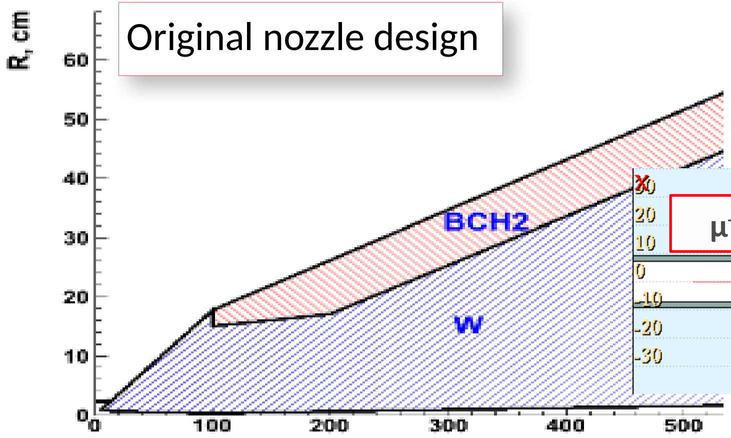
MDI: past results and geometry

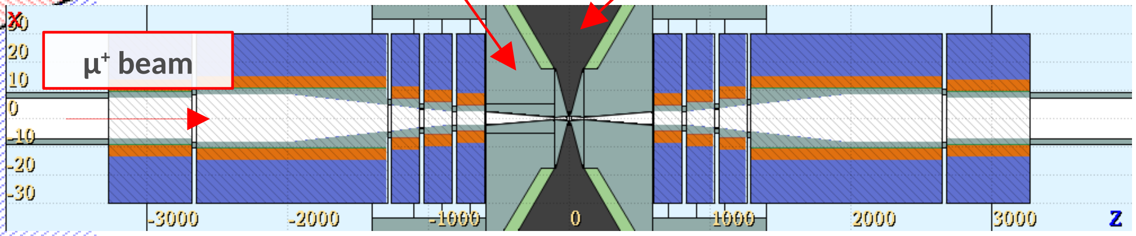
- In the context of the **MAP collaboration**, the muon collider detector background and Machine-detector interface has been thoroughly studied [5-8].
- They observed that most **background** particles are generated in the last **25 m straight section**, except **muons** that can be produced **further away**.
- The MAP collaboration optimized **nozzles** for colliders up to 1.5 TeV (with MARS code).
- Recent **FLUKA** results are in a **eccellent agreement** with the past studies.

FLUKA/MARS15 results for the BIB of a 1.5 TeV muon collider from [9]

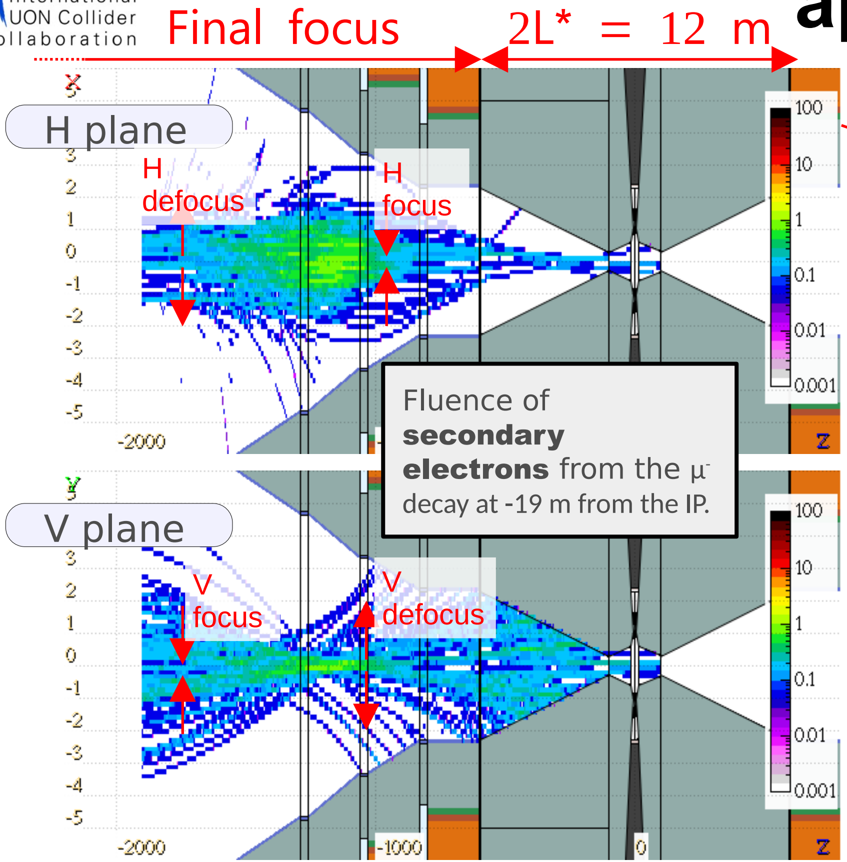
Particle (E_{th})	MARS15	FLUKA
Photon (100 keV)	$8.6\ 10^7$	$5\ 10^7$
Neutron (1 meV)	$7.6\ 10^7$	$1.1\ 10^8$
Electron/positron (100 keV)	$7.5\ 10^5$	$8.5\ 10^5$
Ch. Hadron (100 keV)	$3.1\ 10^4$	$1.7\ 10^4$
Muon (100 keV)	$1.5\ 10^3$	$1\ 10^3$

Original nozzle design



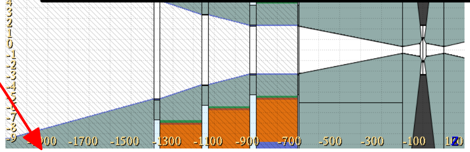


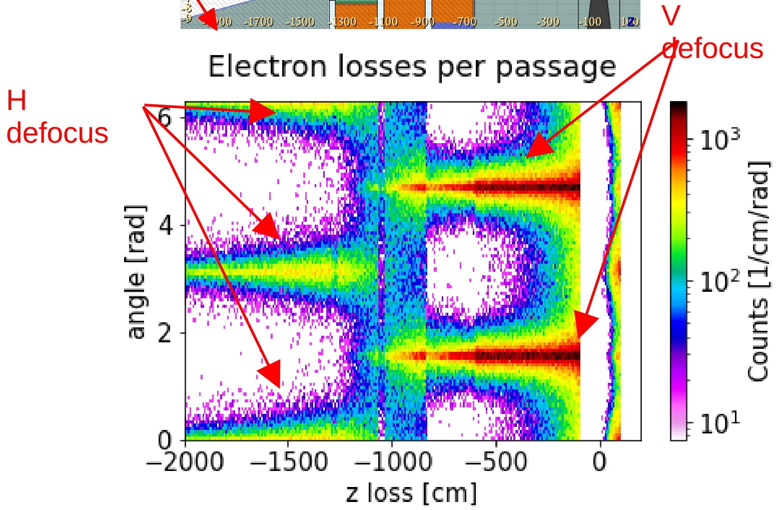
BIB @ √s = 10 TeV: e+/e- impact on aperture



Fluence of **secondary electrons** from the μ⁻ decay at -19 m from the IP.

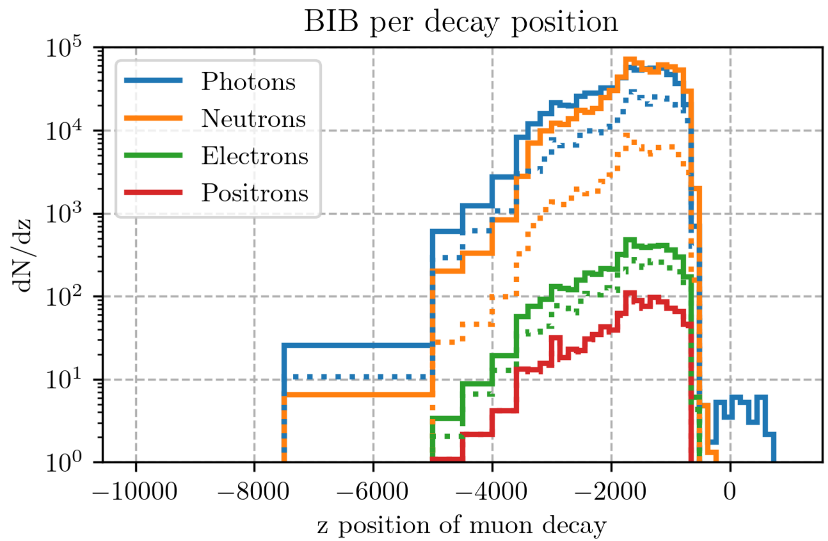
- Final focusing fields induce peaks in the azimuthal distribution of the e⁻/e⁺ impact position.
- (but!)The azimuthal dependence is diluted to negligible levels by the W nozzle.





BIB @ √s = 10 TeV: original lattice

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



Updated!

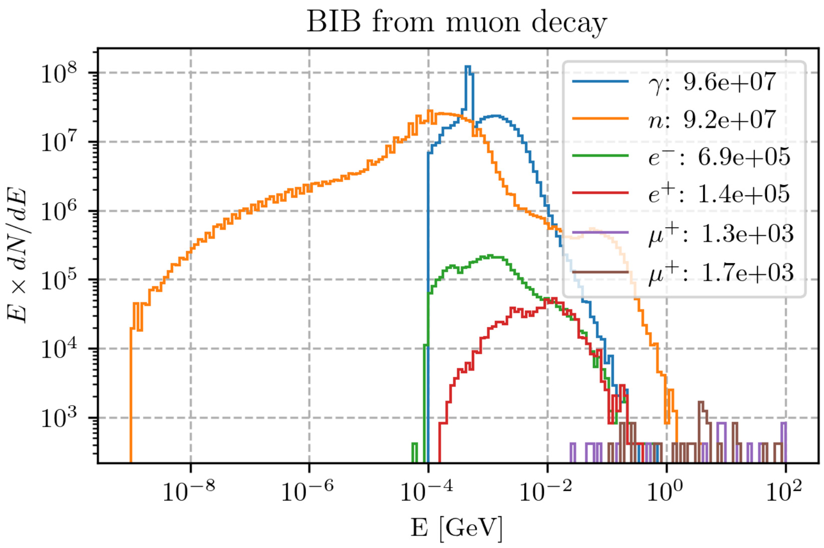
Collider energy	1.5 TeV	3 TeV	10 TeV
Photons	7.1E+7	9.6E+7	9.6E+7
Neutron	4.7E+7	5.8E+7	9.2E+7
e^+/e^-	7.1E+5	9.3E+5	8.3E+5
Ch. hadrons	1.7E+4	2.0E+4	3.0E+4
Muons	3.1E+3	3.3E+3	2.9E+3

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

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

BIB @ √s = 10 TeV: particle spectra

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



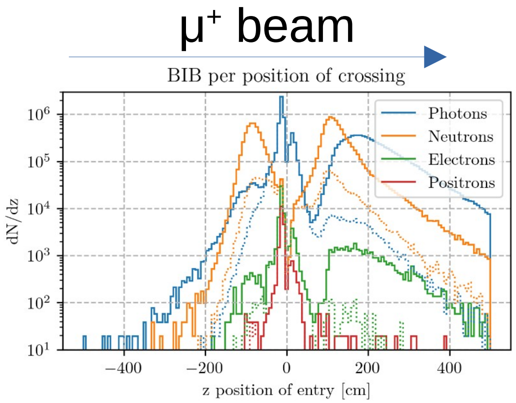
Updated!

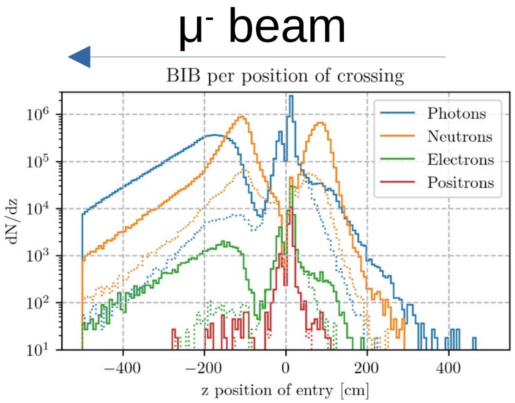
Collider energy	1.5 TeV	3 TeV	10 TeV
Photons	7.1E+7	9.6E+7	9.6E+7
Neutron	4.7E+7	5.8E+7	9.2E+7
e^+/e^-	7.1E+5	9.3E+5	8.3E+5
Ch. hadrons	1.7E+4	2.0E+4	3.0E+4
Muons	3.1E+3	3.3E+3	2.9E+3

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

BIB @ √s = 10 TeV: different beams contribution

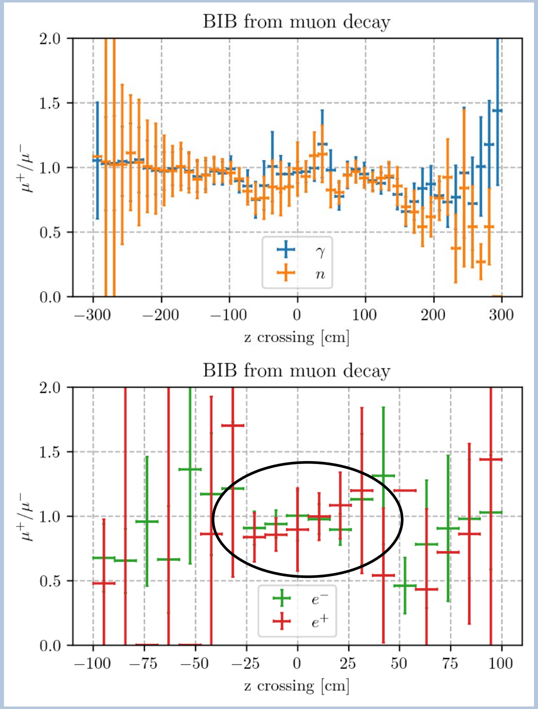
- Most of the 10 TeV simulations are conducted with a μ^+ beam. To confirm that the contribution from the opposite beam is the same, a comparison has been done.
- The simulations (comparing also energy spectra) **do not show any systematic difference!**





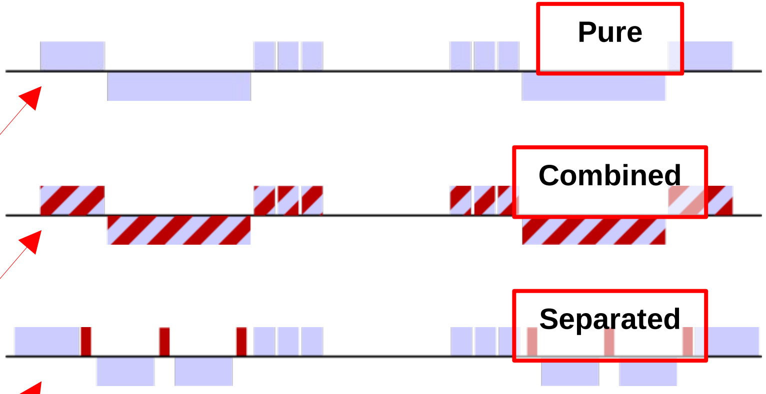
Dashed line for particles arriving in the time window of [-5, 15] ns

Ratio of BIB from different beams

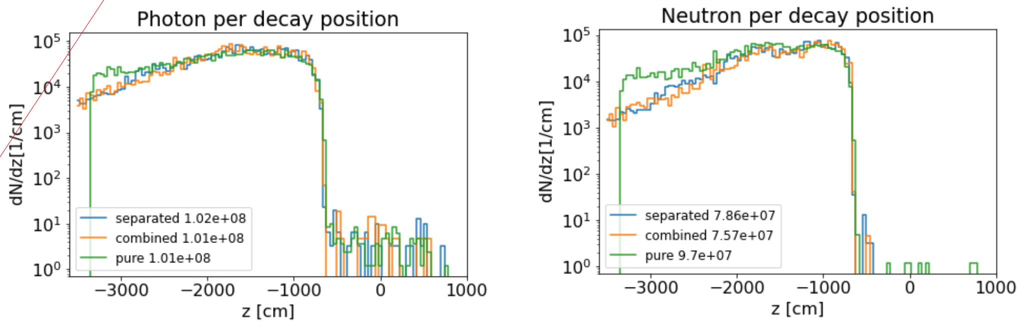


BIB @ √s = 10 TeV: dipolar component

- We considered three possibilities (from K. Skoufaris and C. Carli) for the lattice in the final focusing:
  - Only quadrupoles, with no dipoles and no dipole component (**pure**).
  - Combined function magnets, where there are no dipole magnet, but each quadrupole contains a 2T dipolar component (**combined**).
  - Having both dipoles and quadrupoles in the final triplet, but without exploiting combined function magnets. In this case we “separate” the dipolar component in short 10 T dipole magnets (**separated**).



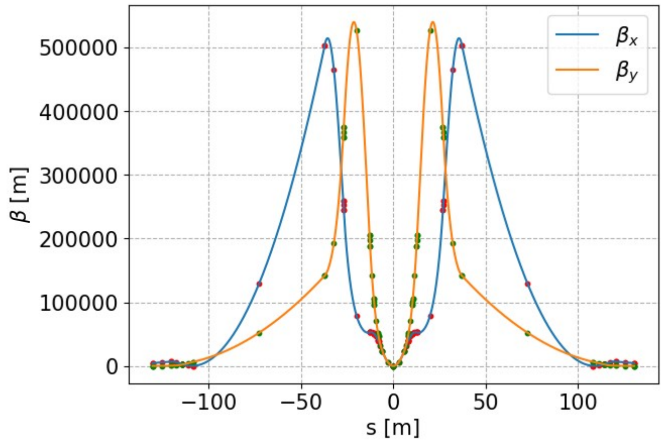
*Lattice design offers only **marginal** mitigation*

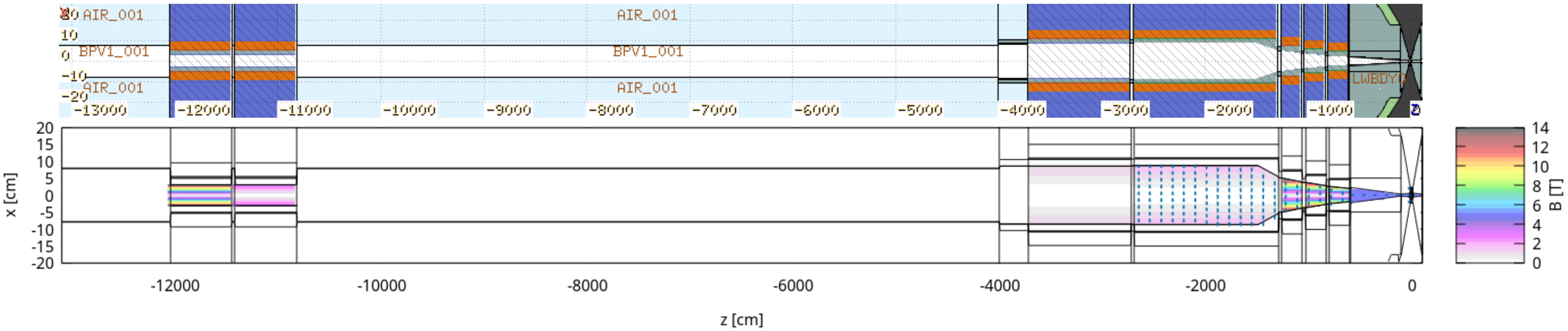


BIB @ √s = 10 TeV: new lattice

- For a realistic machine, the final focusing schemes studied so far do not represent a satisfactory scenario.
- A new lattice was provided by Kyriacos 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

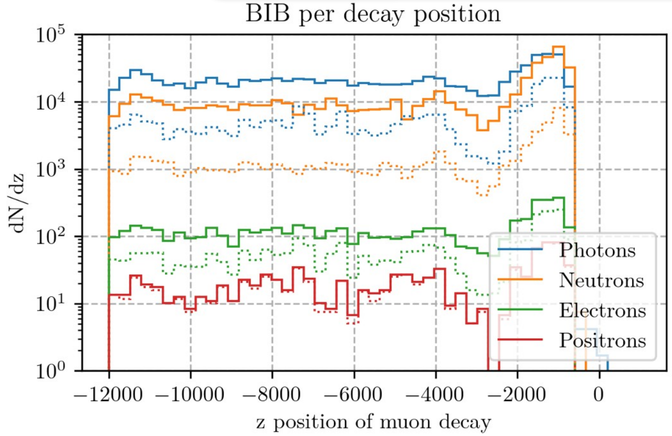


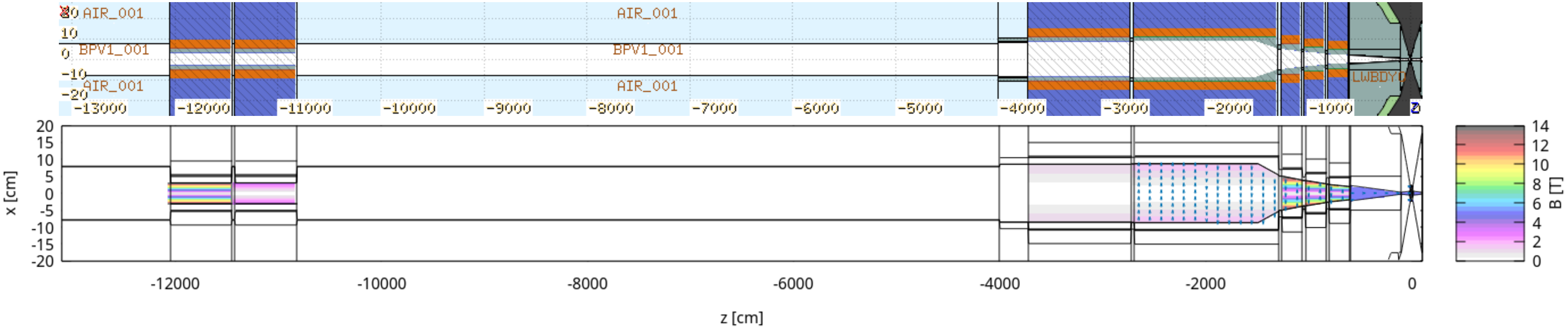


BIB @ √s = 10 TeV: new lattice

- For a realistic machine, the final focusing schemes studied so far do not represent a satisfactory scenario.
- A new lattice was provided by Kyriacos 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



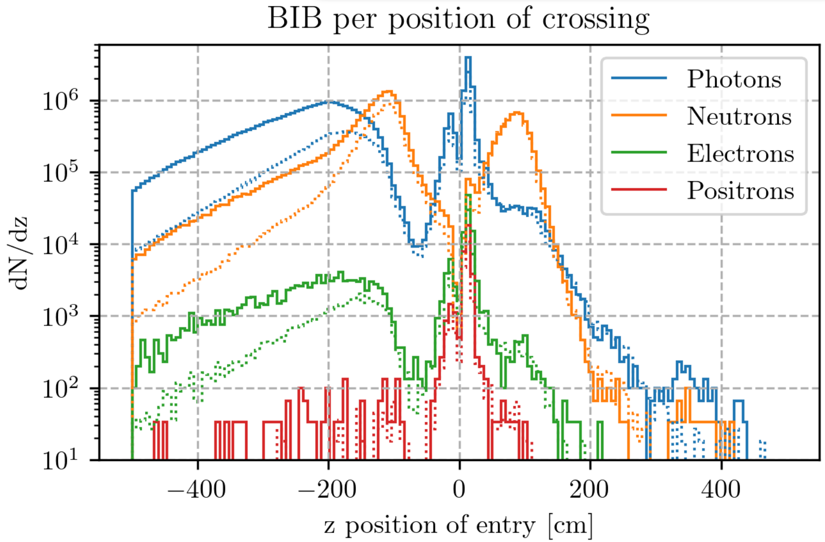


BIB @ √s = 10 TeV: new lattice

- The total particle number change significantly (a factor 2), but the energy spectrum and the spatial distribution of the BIB particles are still the same

Dashed line: original lattice

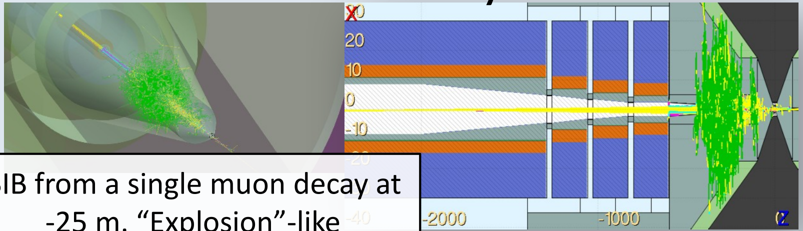
Collider energy	1.5 TeV	3 TeV	10 TeV	10 TeV: long drift
Photons	7.1E+7	9.6E+7	9.6E+8	2.5E8
Neutron	4.7E+7	5.8E+7	9.2E+8	1.4E8
e^+/e^-	7.1E+5	9.3E+5	8.3E+5	1.7E6
Ch. hadrons	1.7E+4	2.0E+4	3.0E+4	6.9E4
Muons	3.1E+3	3.3E+3	2.9E+3	7.3E3



BIB @ √s = 10 TeV: halo losses

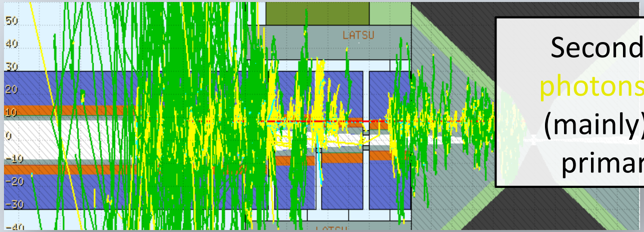
- The halo losses gives a significantly different contribution to the BIB: the particles are generated close to the IP due to the muon interaction with the nozzle.
- As a preliminary simulation, we considered a muon beam going in the magnet at 0 degrees with the z axis

Muon decay



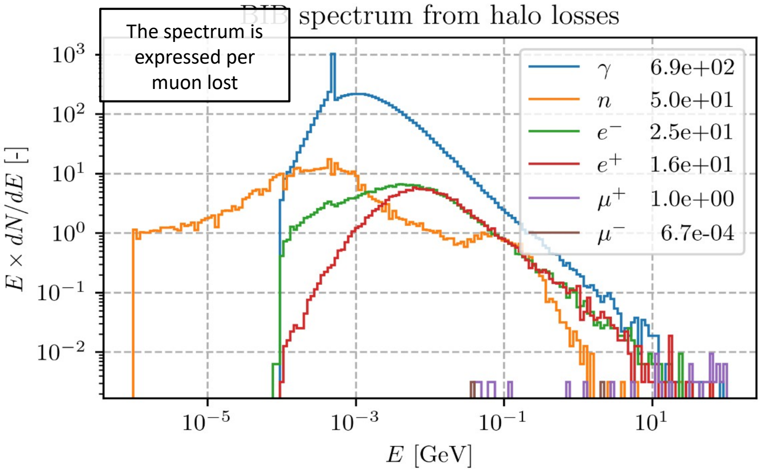
BIB from a single muon decay at -25 m. "Explosion"-like secondary distribution

Halo losses



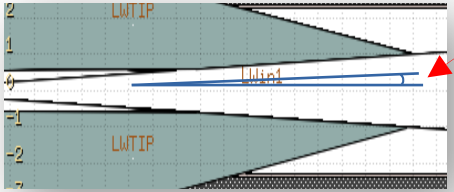
Secondary neutrons, photons and electrons (mainly) surround the primary muon lost.

- 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.

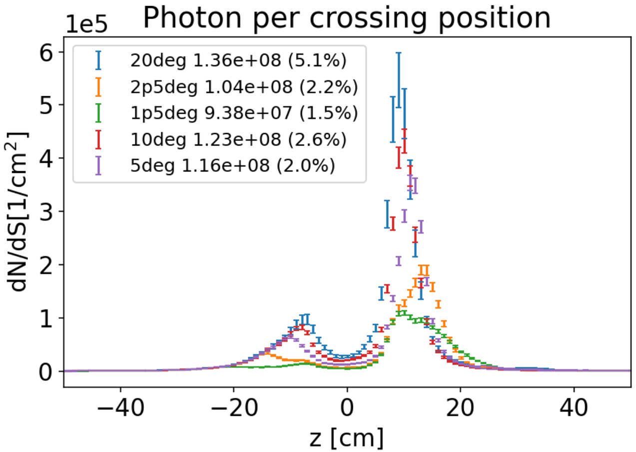


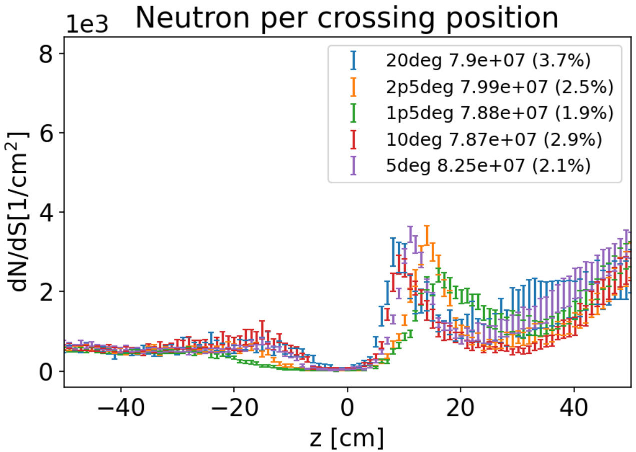
BIB @ √s = 10 TeV: nozzle optimization

- The nozzle is the most important element in the BIB mitigation
- A simple parametric scan proved effective in altering the nozzle shape to mitigate the BIB multiplicity
- In collaboration with Physics and Detector performance working group, we need to identify fundamental parameters to perform a systematic study



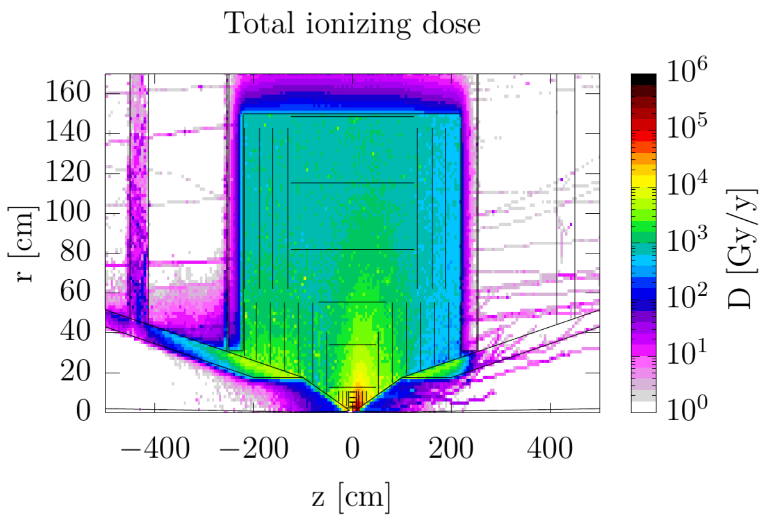
Starting from 2.5 deg, we modify this angle.

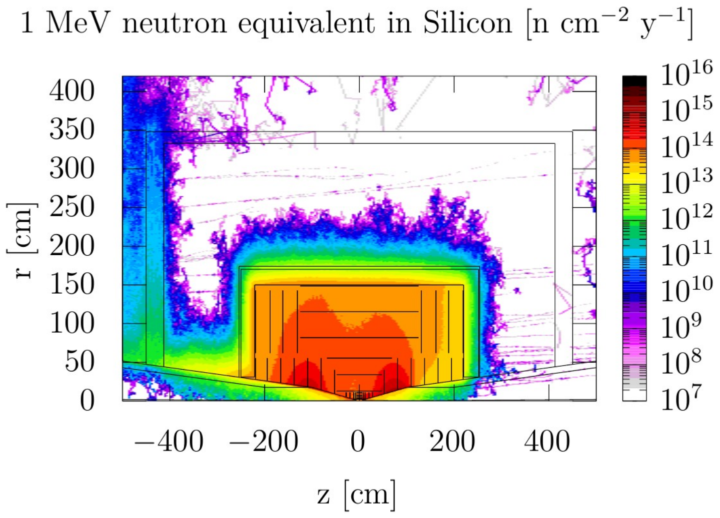




Long term detector damage

- After years of operation, the background will affect detector performance due to radiation effects
- Long term radiation damage presents in two forms:
  - Total ionizing dose, which is the cause of degradation of organic components
  - Displacement damage, often expressed as 1 MeV neutron equivalent fluence in Silicon.





As conservative assumption, we took 139 days per year → 2.4 ab^{-1}/y at nominal luminosity
Originally we started with 200, too conservative.

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 long drift increases the BIB multiplicity of more than a factor 2
- The negative muon beam and the positive one have the same effect for what concerns the BIB from muon decay.
- 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

International
MUON Collider
Collaboration

CERN

Thank you
for your attention!

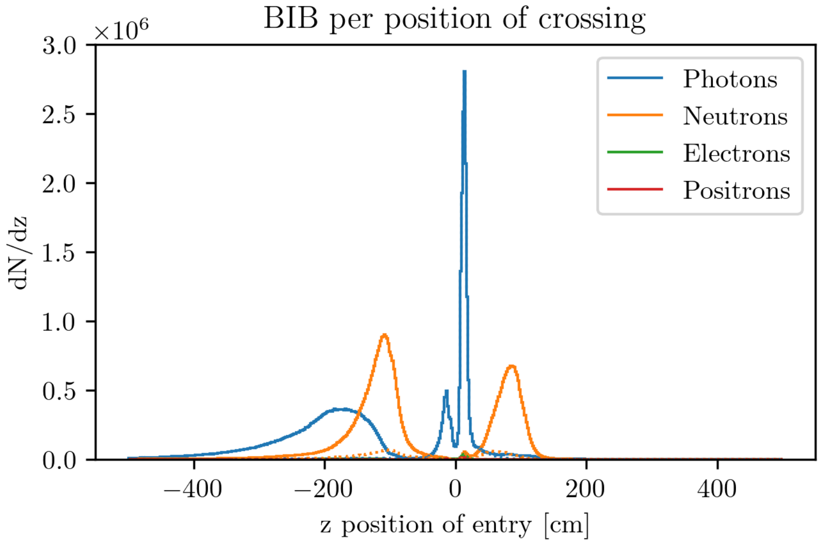
References

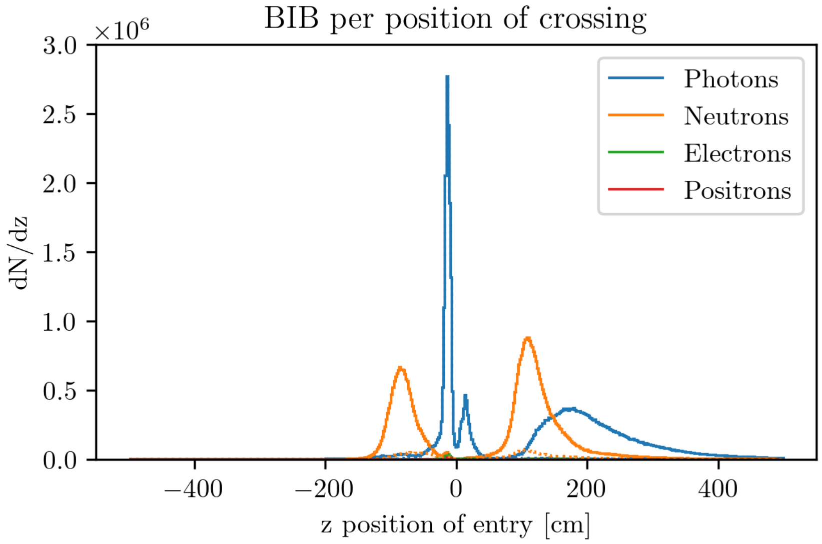
- [1] R. Palmer et al, Muon collider design. (https://doi.org/10.1016/0920-5632(96)00417-3)
- [2] Franceschini, R. and Greco, M., 2021. Higgs and BSM physics at the future muon collider. Symmetry, 13(5), p.851.
- [2] J. P. Delahaye, Muon Colliders (arXiv:1901.06150)
- [4] Berg, A Cost-Effective Design for a Neutrino Factory (doi: 10.1103/PhysRevSTAB.9.011001)
- [5] N. V. Mokhov, (2009, November). Muon Collider Detector Backgrounds and Machine Detector Interface.
- [6] V. Di Benedetto et al., “A study of muon collider background rejection criteria in silicon vertex and tracker detectors (arXiv:1807.00074)
- [7] N. V. Mokhov, Muon Collider interaction region and machine-detector interface design. (arXiv:1202.3979)
- [8] N. V. Mokhov, Detector Background at Muon Colliders. (arXiv:1204.6721)
- [9] Collamati, F. et al, Advanced assessment of beam-induced background at a muon collider. (arXiv:2105.09116)
- [10] Strong field processes in beam-beam interactions at the Compact Linear Collider, J. Esberg et al., doi: 10.1103/PhysRevSTAB.17.051003
- [11] D. Neuffer et al, A muon collider as a Higgs factory (arXiv:1502.02042)
- [12] N. V. Mokhov, Reducing backgrounds in the higgs factory muon collider detector (arXiv:1409.1939)
- [13] https://agenda.infn.it/event/26948/contributions/136379/attachments/81308/106480/IPAC_Curatolo.pdf
- [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

10 TeV muon collider: position of crossing

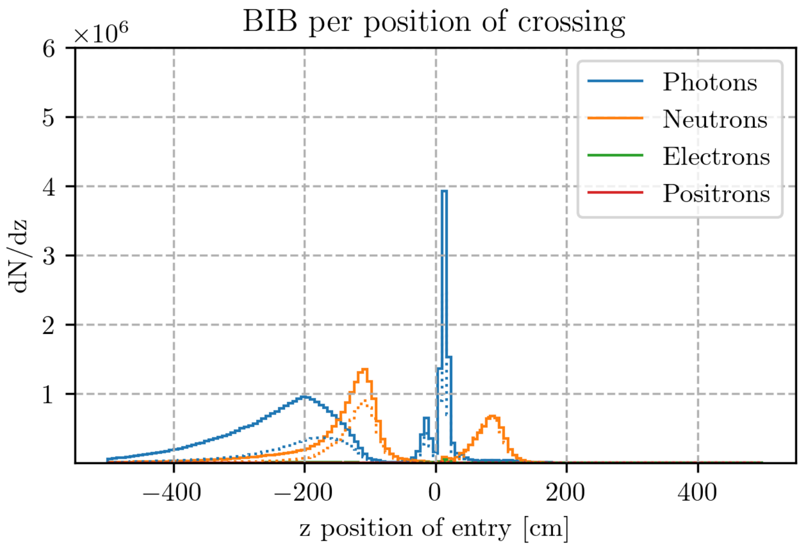
μ⁺ beam →

← μ⁻ beam



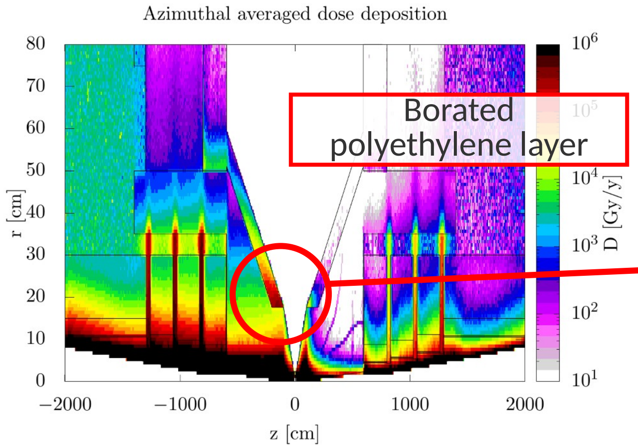


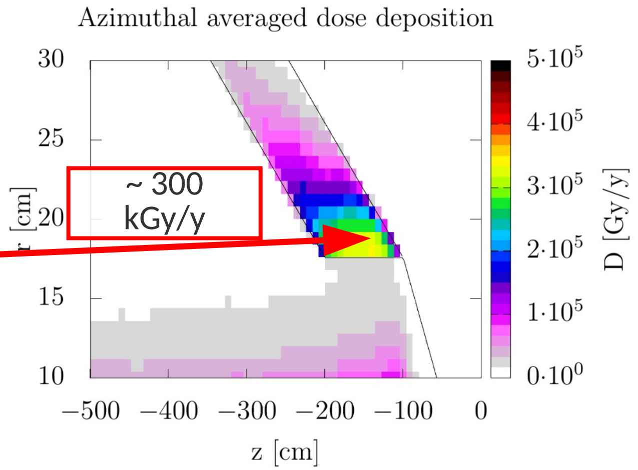
10 TeV muon collider: new and original lattice



Polyethylene radiation damage

- Assuming 200 days of irradiation per year, with a 2E12 muons per bunch, the **TID** in the polyethylene is ~10^5 Gy per year.
- In the context of preliminary exploration, a relatively high Boron-10 content is considered (25% atoms in the material). The nuclear industry offer a vast know-how in this field, however most applications work with natural Boron*
- Under the assumption of 10 years of operation, we might be **over the limit of the possible material degradation**.
- Do we have any studies for the lower energy cases (?)

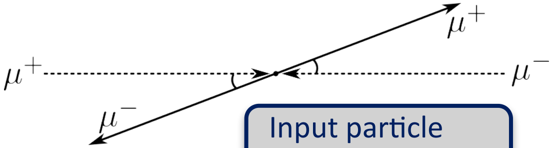




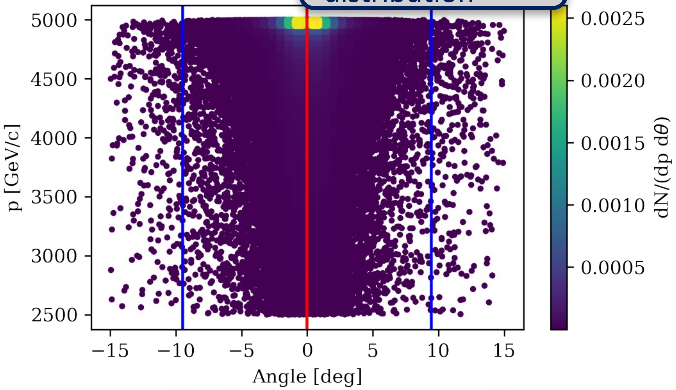
* (i.e. https://www.shieldwerx.com/poly-based-shielding.html, https://inis.iaea.org/search/search.aspx?orig_q=RN:49021962)

Forward muon detection: first test case

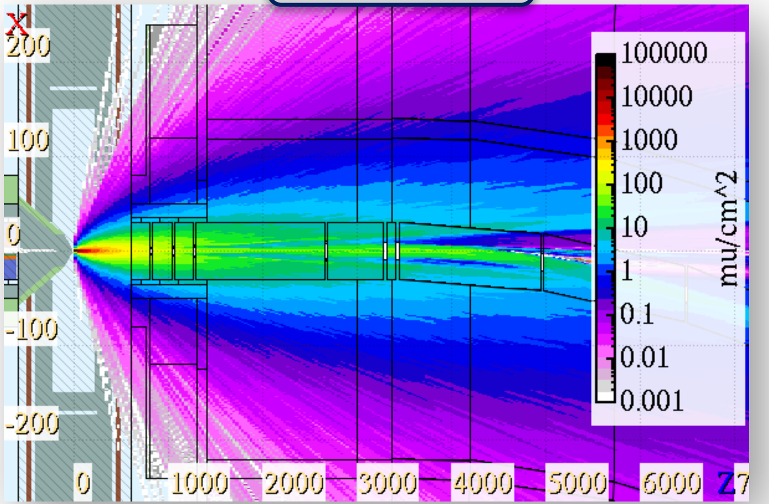
- **Matthew Forslund** generated and **Massimo Casarsa** provided us a muon list containing both μ^+ and μ^- in case of a VBF possible process.



Input particle distribution

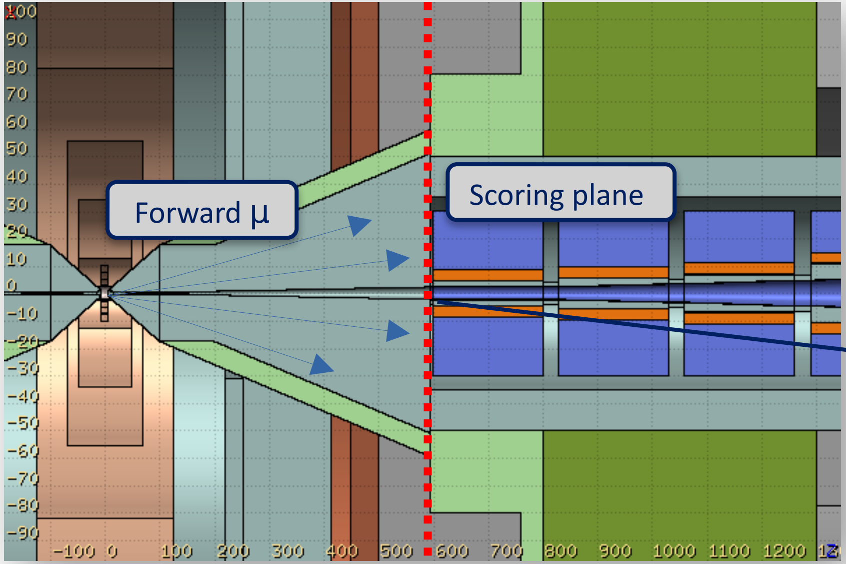


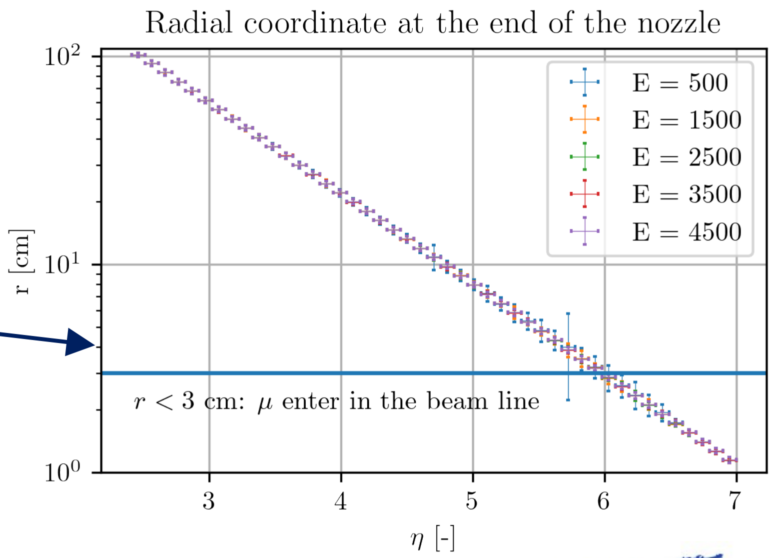
Muon fluence in the machine



Forward muon detection: general case

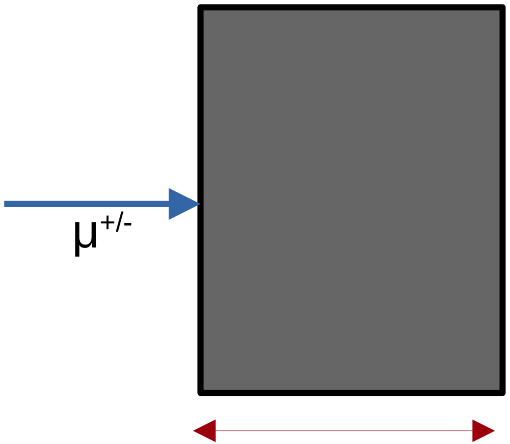
- Assuming isotropy in the φ angle, I made some simulation for the forward muons emitted at various energies and angles in the interaction point.



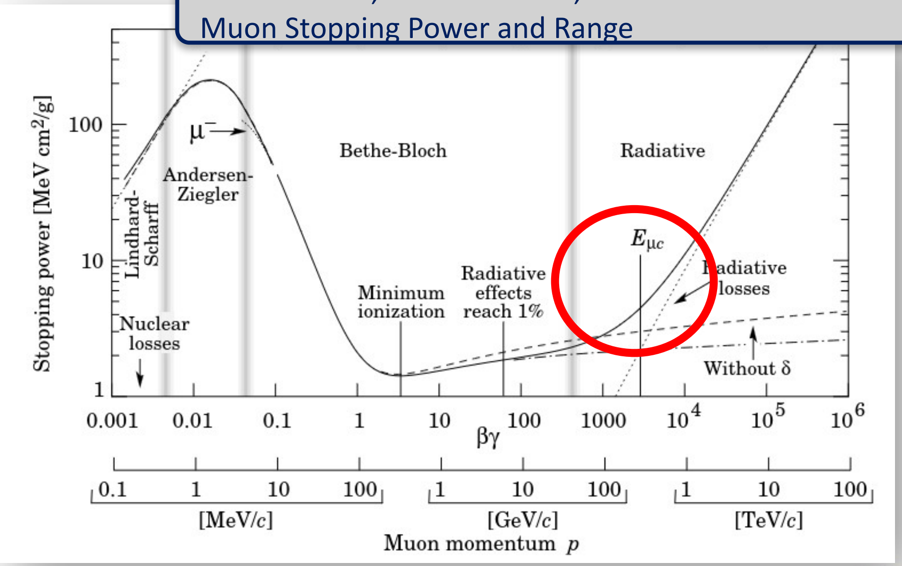


Forward muon detection: general case

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

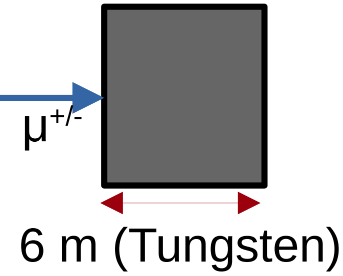


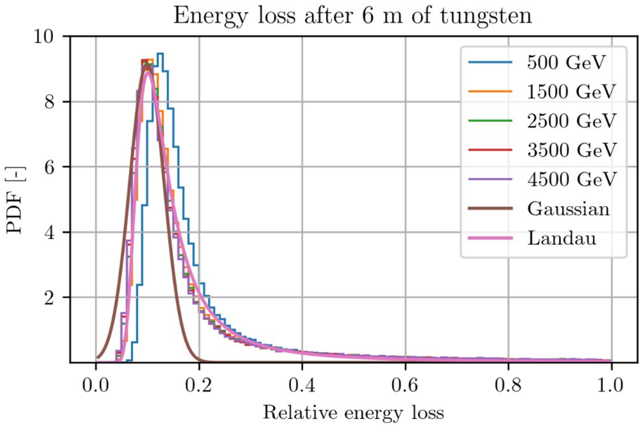
D. E. GROOM, N. V. MOKHOV, and S. STRIGANOV
Muon Stopping Power and Range

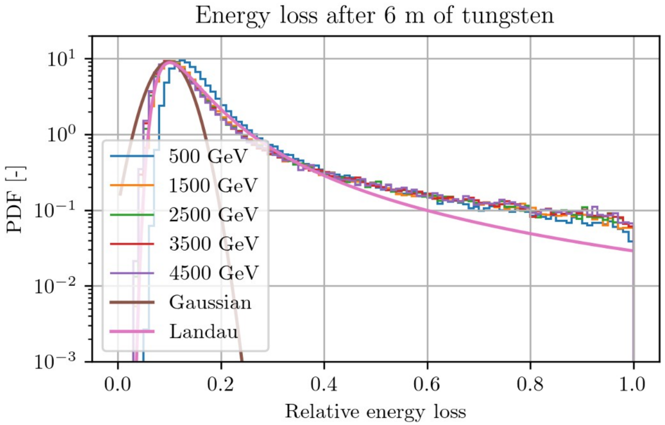


Forward muon detection: general case

- 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:
μ = 0.185
c = 0.032