Machine-detector interface studies for a multi-TeV muon collider

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Outline

- **Muon collider (MC) characteristics:**
  - Concept and advantages
  - Radiation effect challenges
- **Interaction region: machine detector interface (MDI)**
  - Beam induced background (BIB): halo, muon decay and incoherent pair production by muons
  - Secondary electron/positron trajectories
- **1.5 TeV results:**
  - Precedent work in the MAP collaboration
  - Comparison between MARS and FLUKA
- **10 TeV results:**
  - Muon decay as main source of background and comparison with other machines
  - Incoherent pair production as a non negligible BIB
  - Lattice design influence on BIB
  - Toward a 10 TeV nozzle design
- **Conclusions**

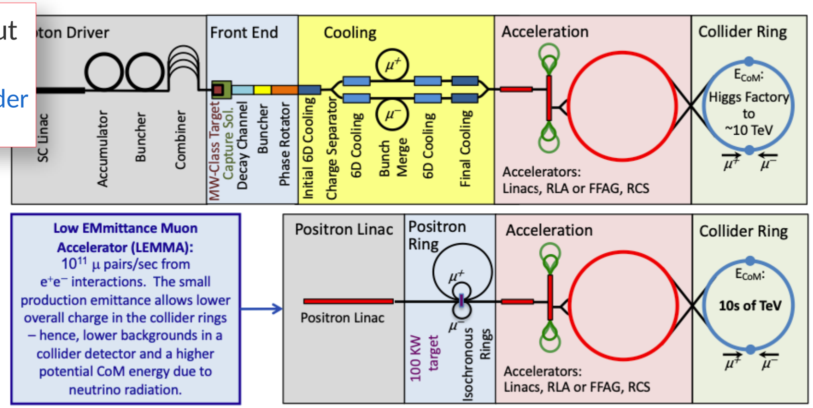
Muon collider: concept and motivations

- 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).**

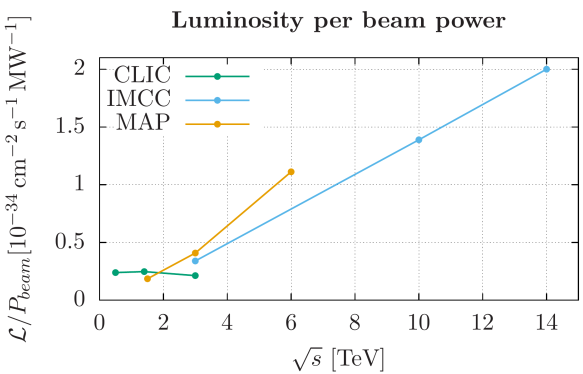
Why?

- 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: 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 up** 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, no studies were performed for a 10 TeV collider.
- Objectives of the new studies within the IMCC:
  - 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.

- Starting from the **geometry** of the nozzle devised by the **MAP collaboration** [5], first MDI studies for colliders up to 10 TeV have been conducted.

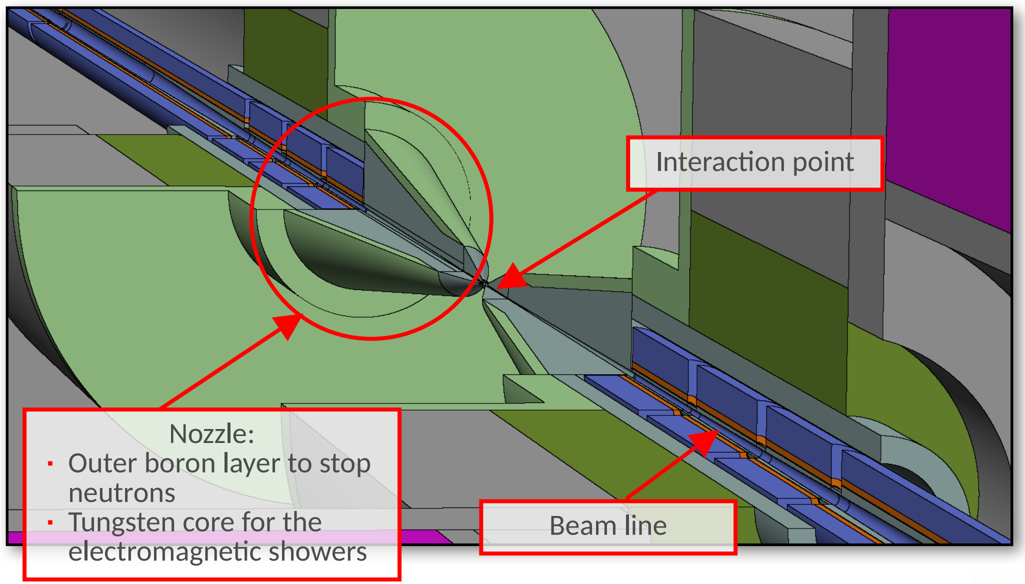
Parameters table

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



MDI: radiation sources

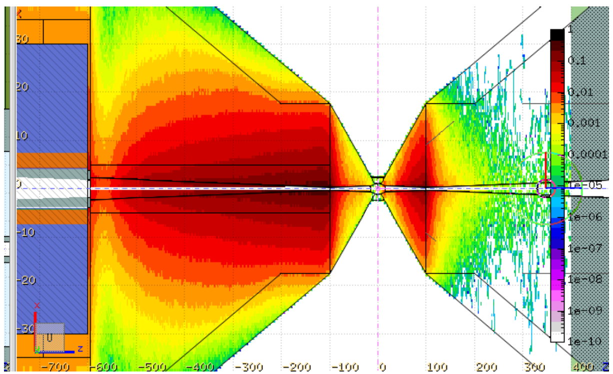
- **Muon decay** around the ring
- **Incoherent e^-/e^+ pair production** during bunch crossing in IP
- **Beam-halo losses** at aperture bottlenecks

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

Incoherent e^-/e^+ pair production:
- 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.

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

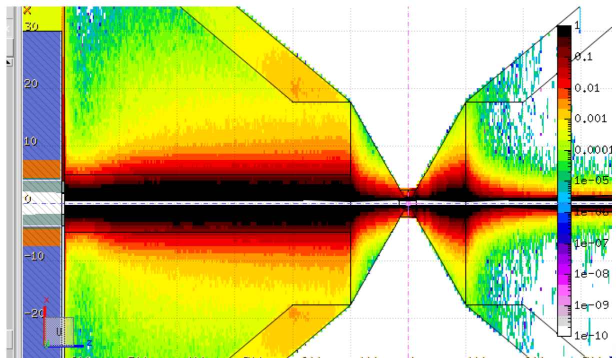
Neutron fluence



Effects

Secondaries will **interact** with the **machine components** and with the detectors. In figure, a thick **nozzle** shielding **protects** the **detector area** by the strong fluences arising from the muon decay.

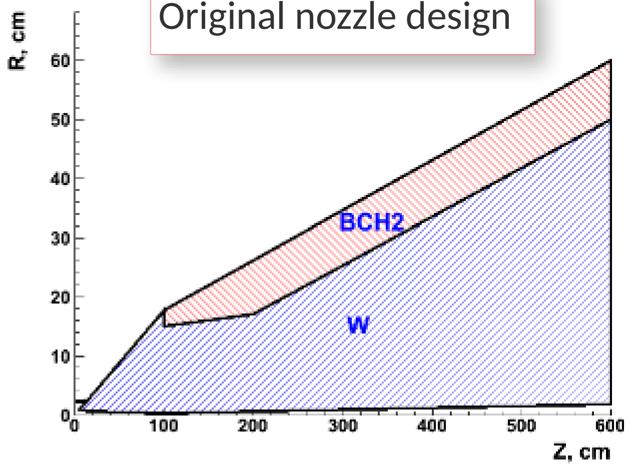
Photon fluence



MDI past results (MAP)

- 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 **good agreement** with the past studies.

Original nozzle design



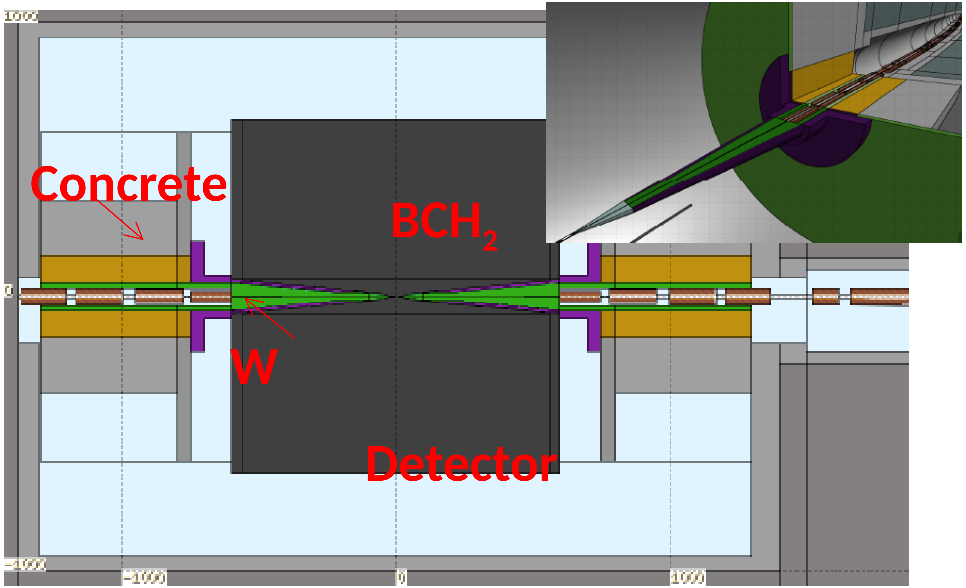
FLUKA/MARS15 results for the BIB of a 1.5 TeV muon collider from [9]

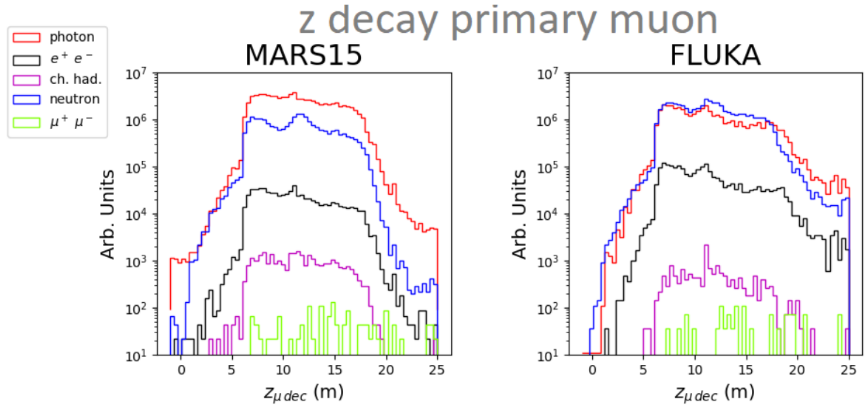
Particle (E_{th})	MARS15	FLUKA
Photon (100 keV)	$8.6\ 10^7$	$5\ 10^7$
Neutron (1 meV)	$7.6\ 10^7$	$1.1\ 10^8$
Electron/positron (100 keV)	$7.5\ 10^5$	$8.5\ 10^5$
Ch. Hadron (100 keV)	$3.1\ 10^4$	$1.7\ 10^4$
Muon (100 keV)	$1.5\ 10^3$	$1\ 10^3$

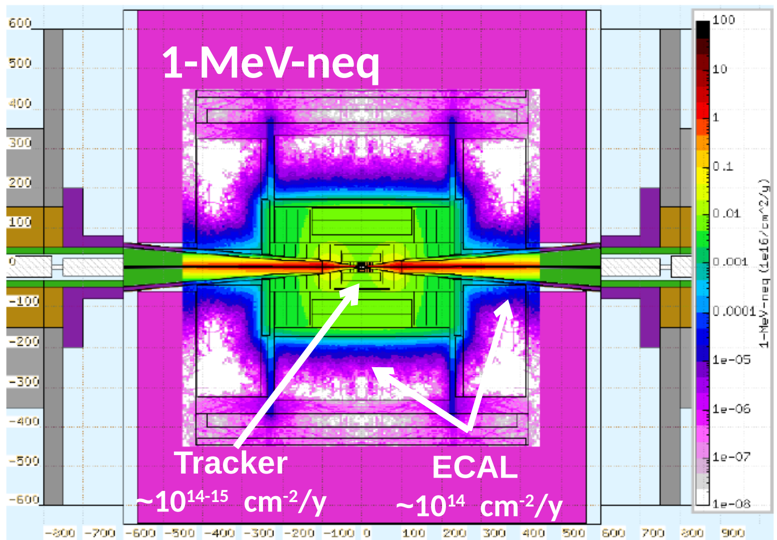
1.5 TeV: results

- From the MAP collaboration, the results at 1.5 TeV are reported. In the former case, a comparison with FLUKA code shows a good agreement for all the particle spectra.

1.5 TeV geometry and comparison with MARS from [13]

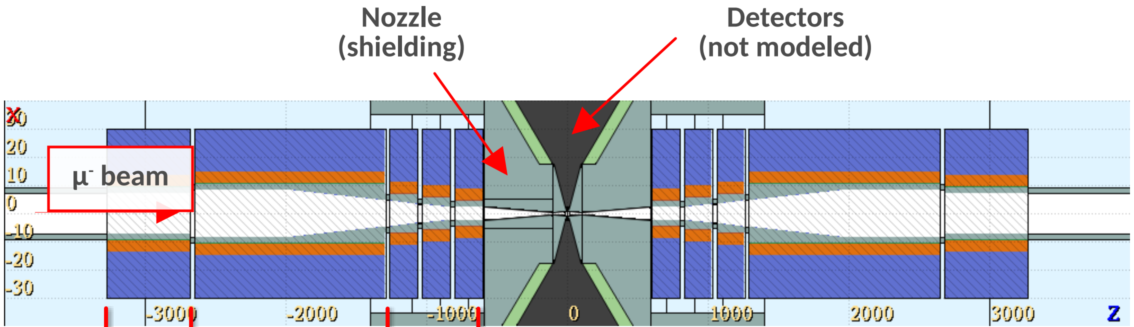




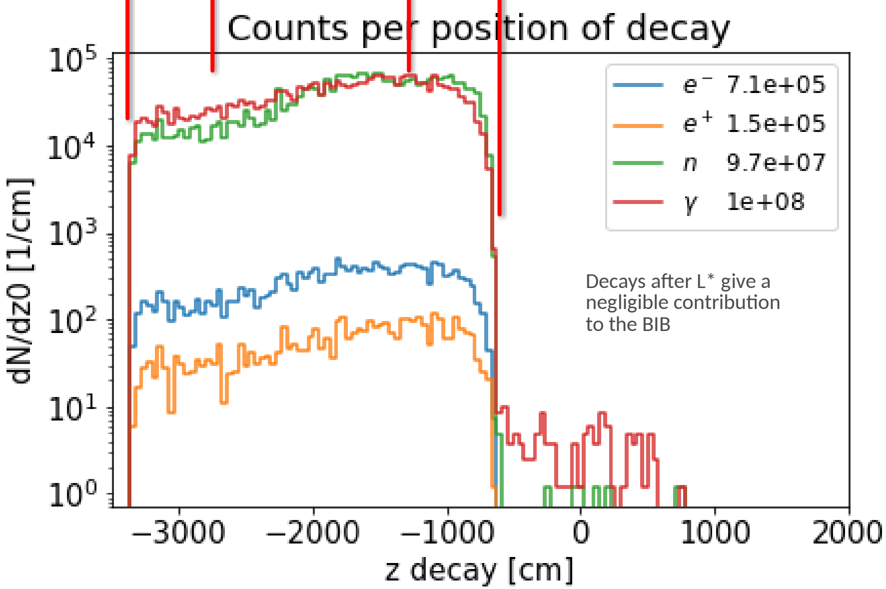


- **Radiation maps**: 2×10^{12} m/bunch, C=2.5 km, 5 Hz rate, 200 days/y
- Preliminary simulations show **comparable BIB** also with **3 TeV colliders**.
- **Radiation levels similar to HL-LHC** (TID ~ 10^{-3} Grad/y on tracker and ~10^{-4} Grad/y ECA)

10 TeV: BIB from muon decay



- The 10 TeV geometry **has to be extended** to fully collect the BIB from decay position further away from the IP.
- The total number of particles entering into the detector is **not significantly worse** than the lower energy results!



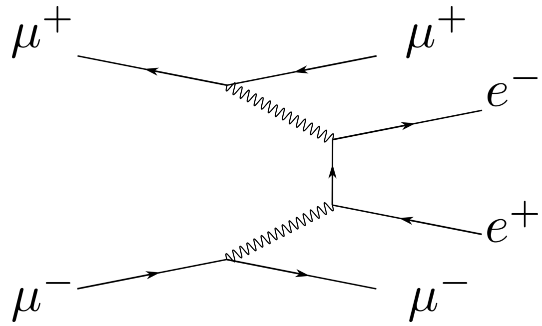
Total particle number: comparison with different collider energies

Collider energy	1.5 TeV	3 TeV	10 TeV
Photons	7.1E+7	9.6E+7	1.16E+8
Neutron	4.7E+7	5.8E+7	8.88E+7
e^+/e^-	7.1E+5	9.3E+5	9.49E+5
Ch. hadrons	1.7E+4	2.0E+4	3.37E+4
Muons	3.1E+3	3.3E+3	2.99E+3

Non optimized [14-15]

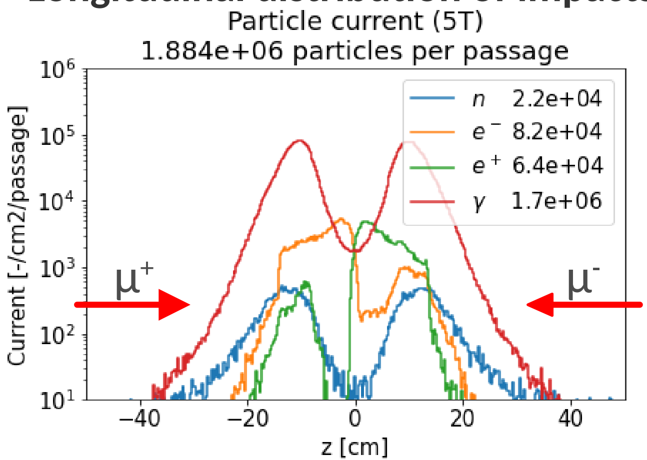
10 TeV: BIB from incoherent pair production

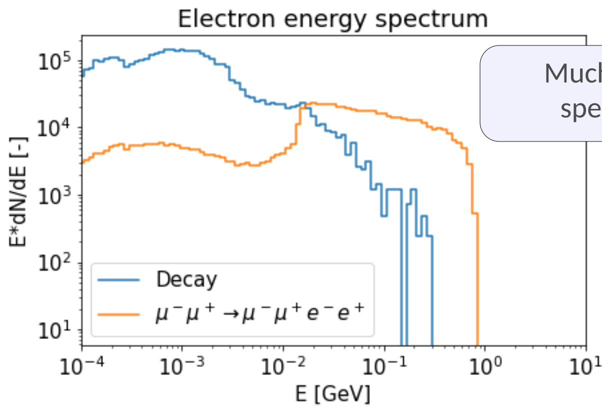
- At very high beam energies, beam-beam effects are not negligible. The most important phenomenon is due to the **incoherent beam-beam pair production μ+μ-→μ+μ-e+e-**.
  - The incoherent pair production e^+/e^- are provided by D. Schulte and are obtained by a **Guinea-Pig simulation**
- The **total number**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



Landau-Lifshitz-like pairs [10]

Longitudinal distribution of impacts

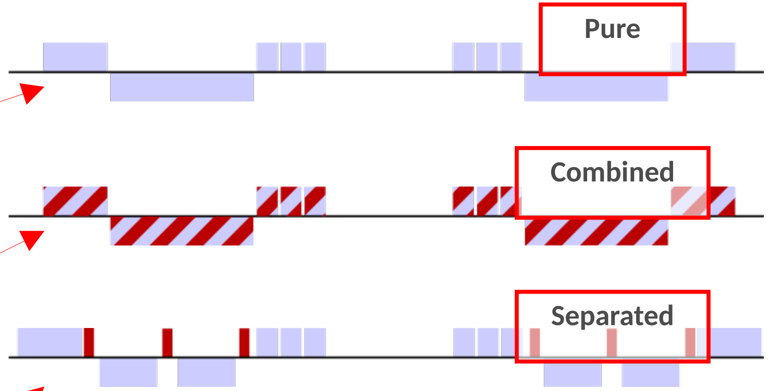


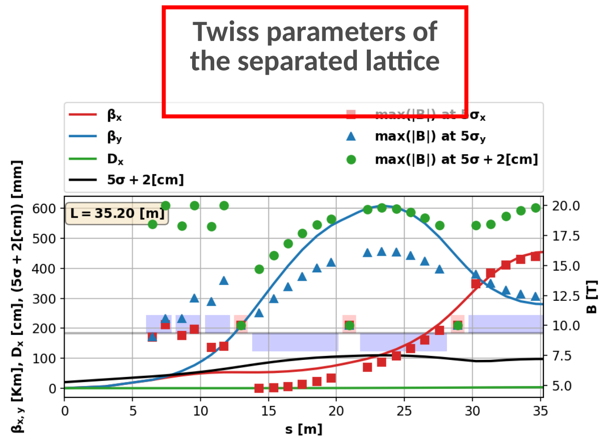


10 TeV: possible lattice design choices

- A first attempt to reduce the BIB is conducted working on the **lattice** just before the IP. In principle, having a **dipolar component** in the lattice is **beneficial**, since all the low energy electrons are forced to impact on the magnet sides.

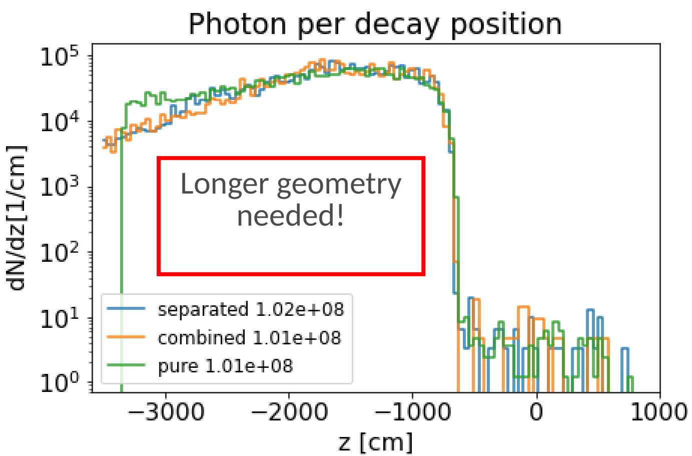
- We considered three possibilities (from K. Skoufaris and C. Carli) for the lattice in the final focusing:
  - Only quadrupoles, with no dipoles and no dipole component (**pure**).
  - Combined function magnets, where there are no dipole magnet, but each quadrupole contains a 2T dipolar component (**combined**).
  - 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**).

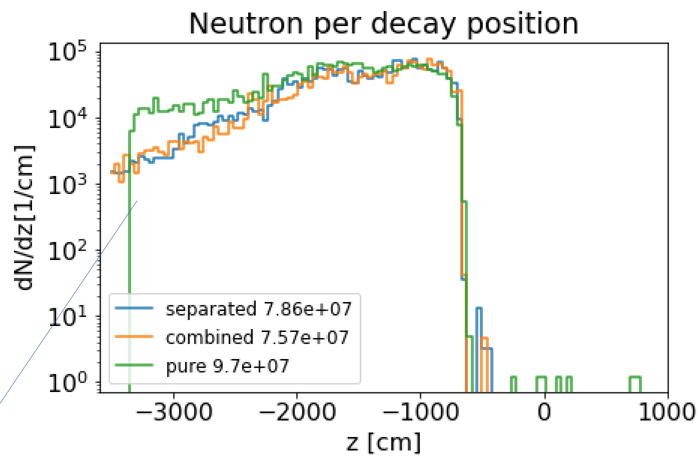




10 TeV: lattice design week BIB suppression

- The **contribution** of **different decay position** to the BIB for a positive muon beams is reported. As expected, the further away the decay occurs, the less background will arrive to the detector area.
- The overall capability to suppress BIB with **lattice design choices** does not seem to provide optimistic results. Even if we **reduce slightly** the BIB from **far away**, other optimization means have to be found.





With a dipole component in the final focusing, small reduction far away from IP

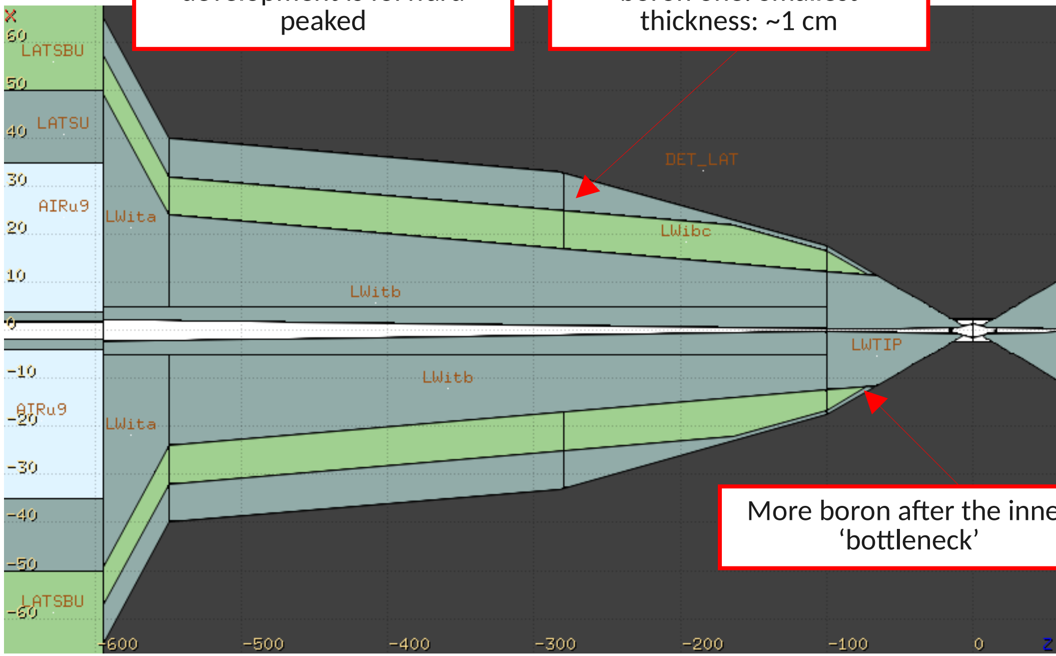
Current nozzle optimization: nozzle shape

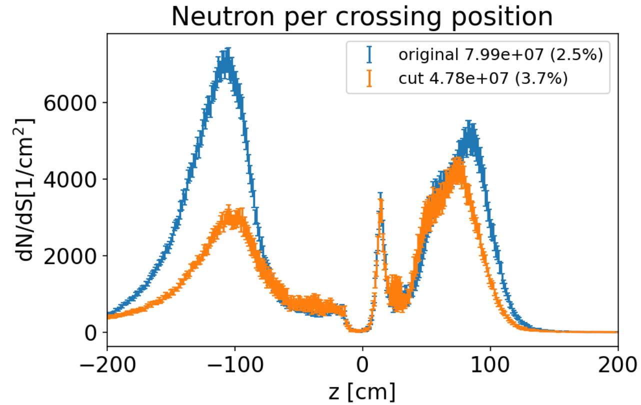
- Considering the particle fluences in the **nozzle**, a tentative nozzle geometry reshaping has been conducted.

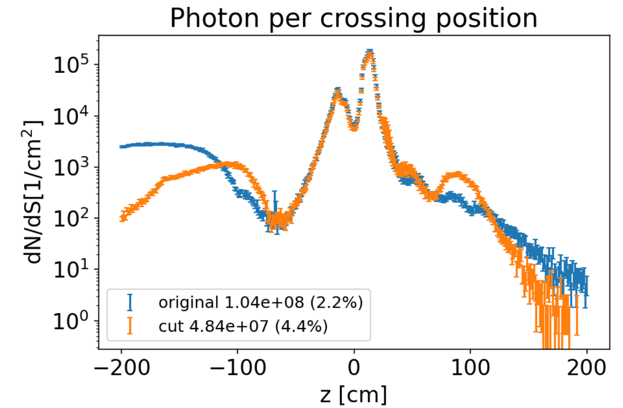
Lateral tungsten shaven off from the lateral side. The photon fluence is already small, the EM shower development is forward peaked

Tungsten layer after the boron one. Smallest thickness: ~1 cm

More boron after the inner 'bottleneck'







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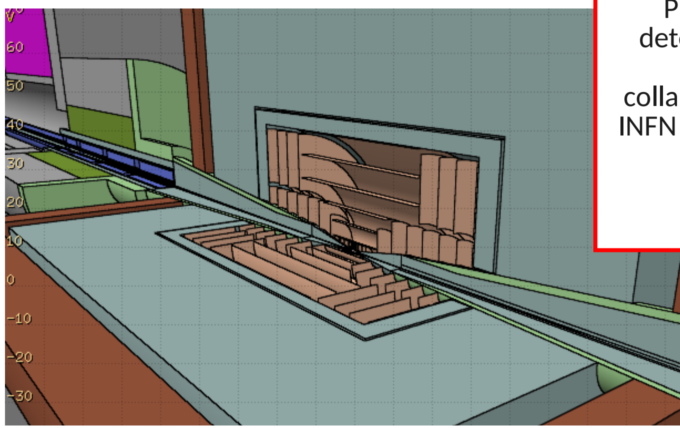
Conclusions

- **Muons decay** induces an intense secondary radiation field in all component of the muon collider. A detailed design is vital to mitigate the phenomenon.
- The situation with the **high energy option** (10 TeV) is **not significantly worse** in comparison with the 3 TeV collider.
- Different lattices do not significantly alter the BIB from muon decay in close proximity with the final focusing, while changing the nozzle shape alter the background profile in a more substantial way.
- At 10 TeV the incoherent pair production from muon is a non negligible source of radiation, while with lower energies this phenomenon is mitigated by the solenoidal magnetic field.

- **Next steps**:
  - Continue the optimization of the nozzle design at different energies
  - Detectors response and radiation damage shall be studied



Preliminary detector design taken in collaboration with INFN from the CLIC layout

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Thank you for the attention!

References

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- [2] Franceschini, R. and Greco, M., 2021. Higgs and BSM physics at the future muon collider. Symmetry, 13(5), p.851.
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- [5] N. V. Mokhov, (2009, November). Muon Collider Detector Backgrounds and Machine Detector Interface.
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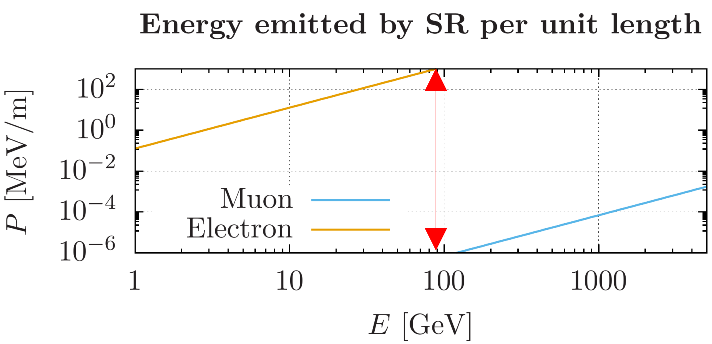
- [8] N. V. Mokhov, Detector Background at Muon Colliders. (arXiv:1204.6721)
- [9] Collamati, F. et al, Advanced assessment of beam-induced background at a muon collider. (arXiv:2105.09116)
- [10] Strong field processes in beam-beam interactions at the Compact Linear Collider, J. Esberg et al., doi: 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

Muon collider: advantages

Synchrotron radiation*

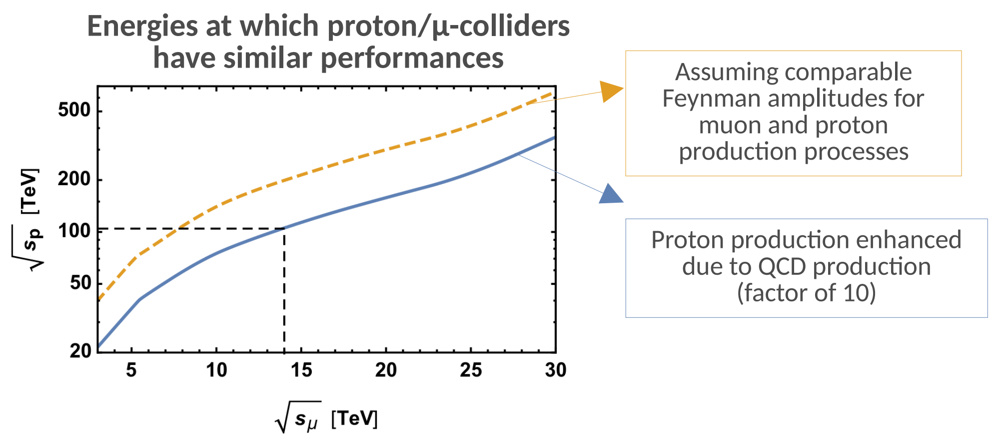
- The muon mass: **105.7 MeV/c². Synchrotron radiation** (SR) is **not a limiting**



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

Lepton collisions

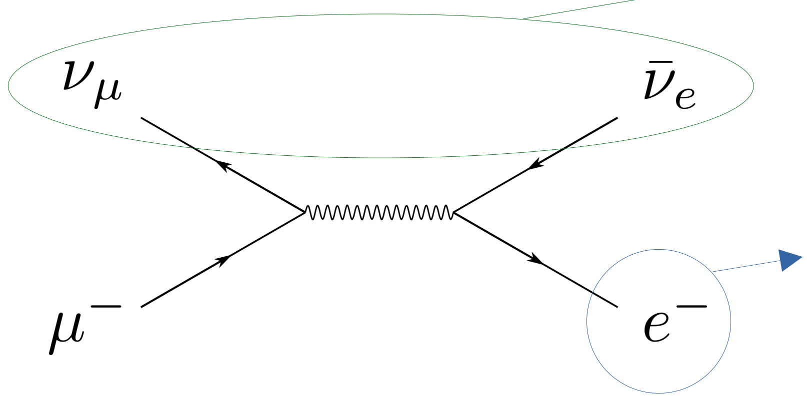
- Muons, as leptons, are elementary particles, and they allow collision where the entire center of mass energy is involved (in proton collision the energy is shared among constituents)
- **Same performance** of proton colliders, but with much **lower center of mass energy**! [2]



*of the primary muon beam

Muon collider: radiation challenges

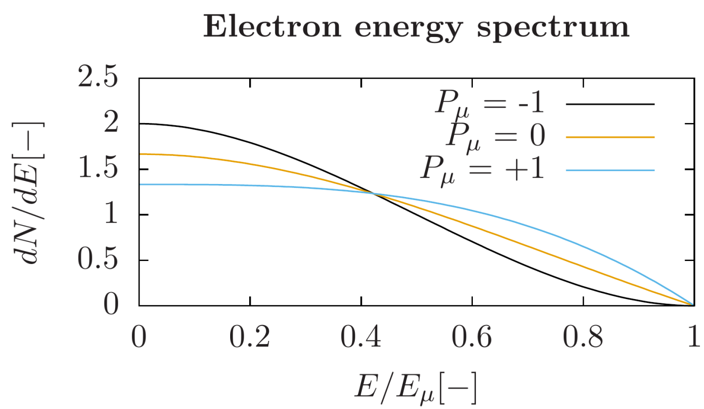
- **Muons** are **unstable particles**, with a rest lifetime of τ = 2.197 μs. They decay spontaneously into electron and positrons (depending on the muon original charge).



Neutrinos: they hardly interact with the accelerator component, therefore little concern for the beam-machine interaction. The only concern is due to **dose delivered** to the **environment** outside the surface.

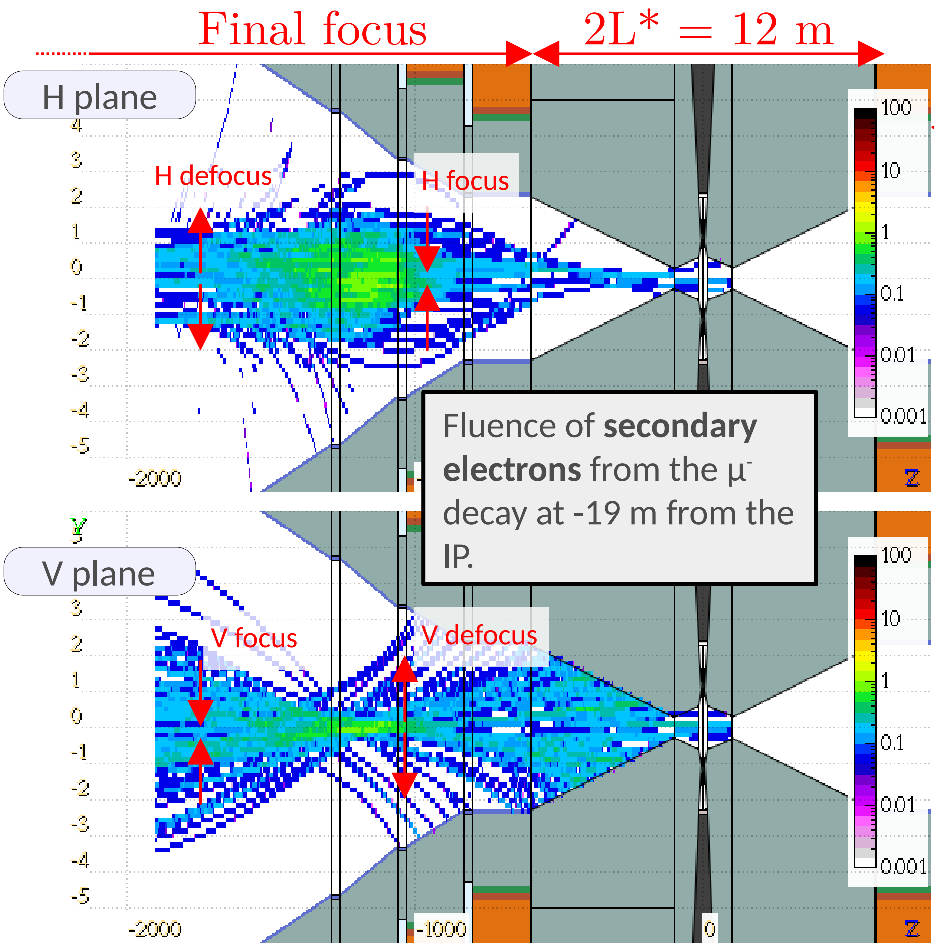
e⁻/e⁺: they carry **around 1/3 of the original muon energy** and they are responsible for the heat load and the **radiation damage** of the **accelerator components**.

Original muon: thanks to the Lorentz boos, it will survive for γτ. In any case, the muon production/acceleration/collision must be **extremely fast**.

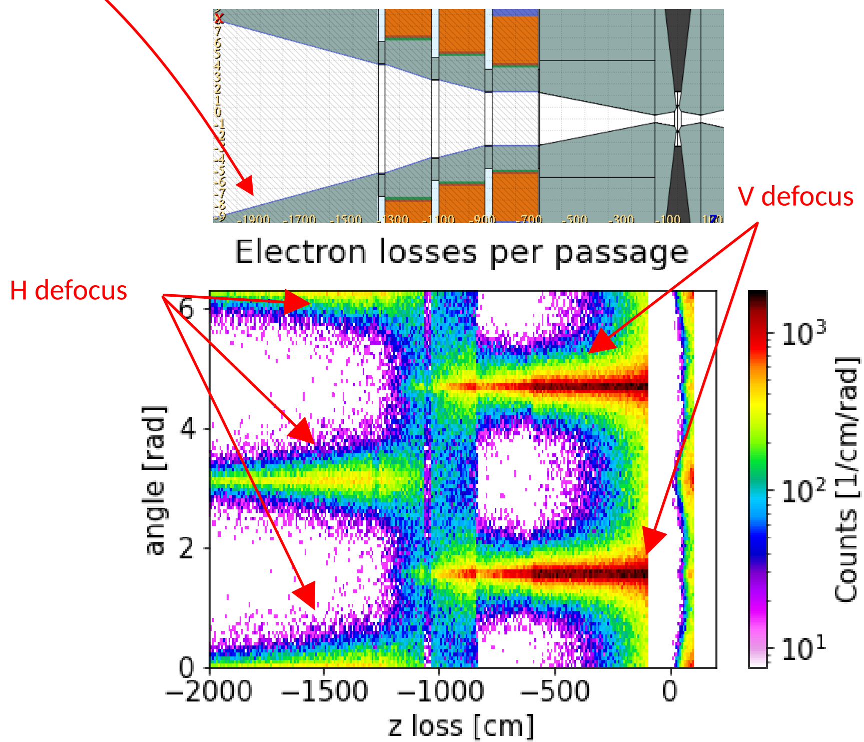


e^+/e^- impact on aperture: qualitative view

- 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.

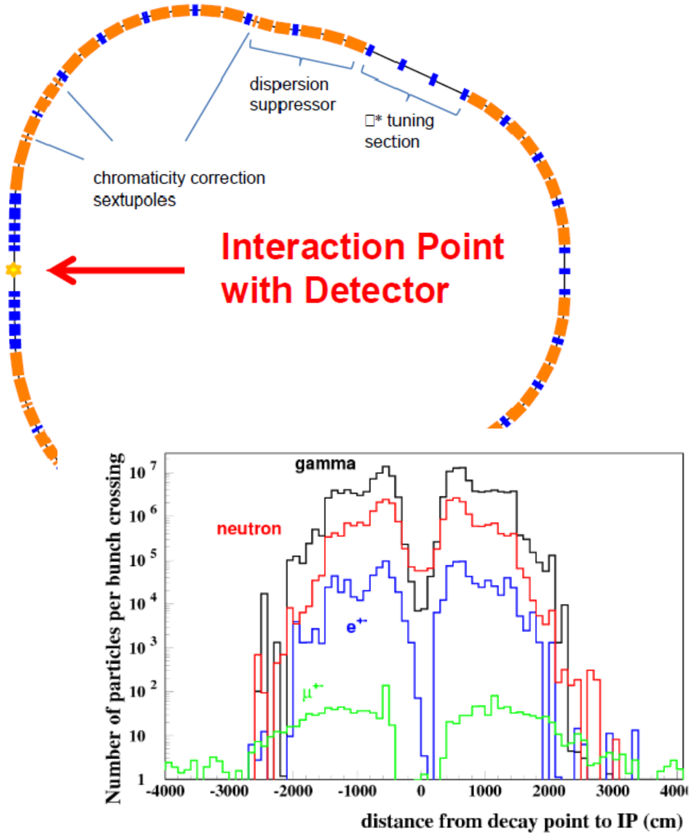


Fluence of **secondary electrons** from the μ^- decay at -19 m from the IP.

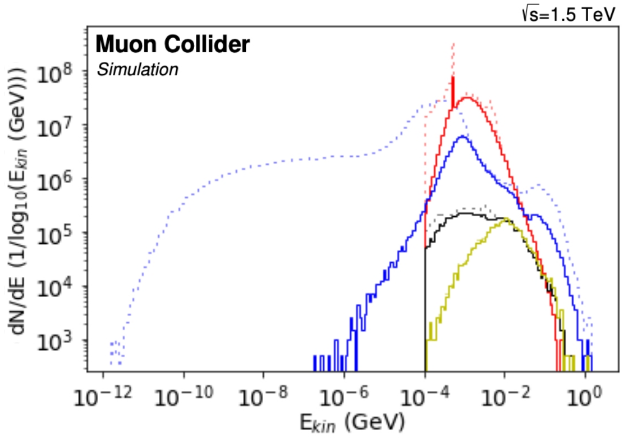


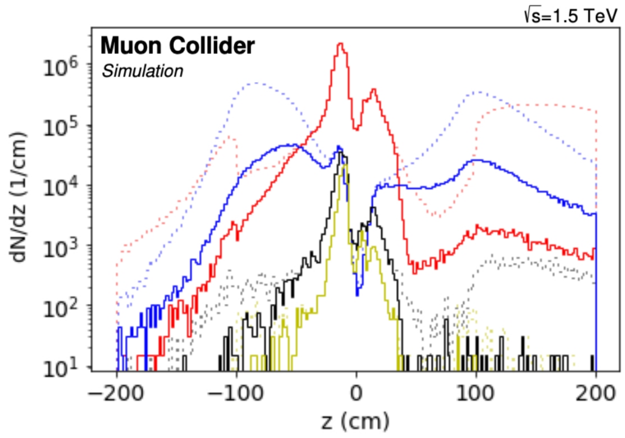
Higgs factory

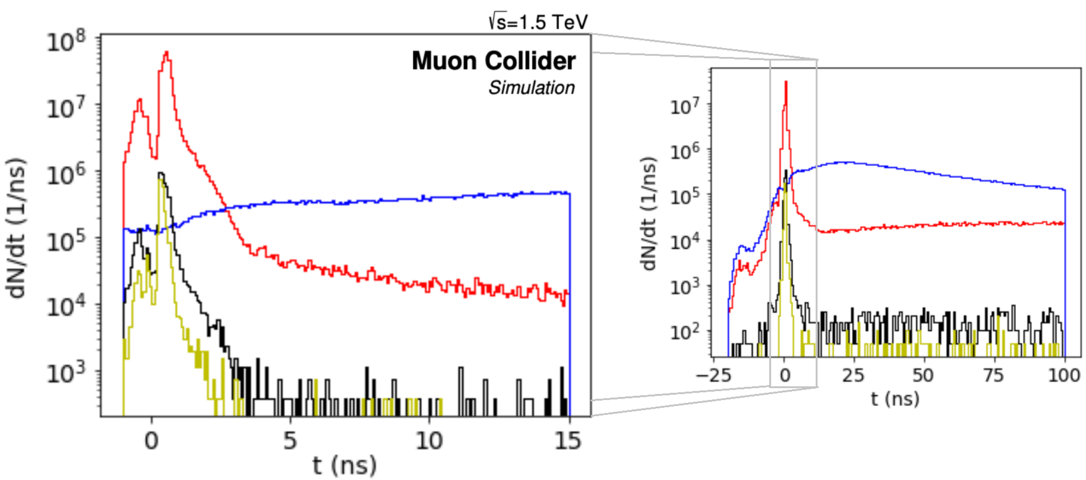
125 GeV: Higgs' factory [11,12]

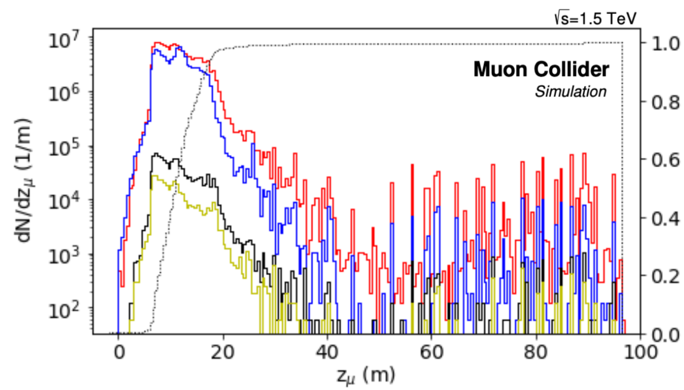


1.5 TeV spectra



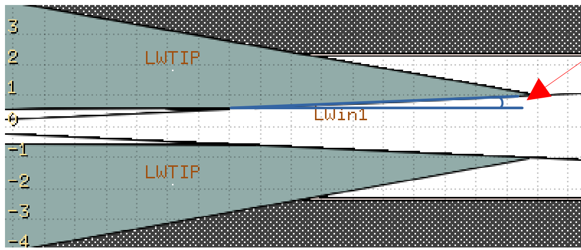






Current nozzle optimization: angle tip

- Considering the aperture of the **nozzle**, various **angles** have been tested. The scope of the optimization of these parameters, is not to reduce the overall number of particles going into the detectors, but to **reduce** their **peaks**.
- The results shows a clear advantage to **reduce the tip angle** down to very small values.



Starting from 2.5 deg, we modify this angle.