Machine-detector interface studies for a 10 TeV muon collider

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On behalf of the International Muon Collider Collaboration

Outline

- **Muon collider (MC) radiation challenges**
- **Muon collider (MC) machine detector interface (MDI)**
  - Beam induced background (BIB): halo, muon decay and incoherent pair production by muons
  - Secondary electron losses on the aperture
  - Precedent work in the MAP collaboration
- **BIB for a 10 TeV machine**
  - Muon decay as main source of background and comparison with other machines
  - Incoherent pair production as a non negligible BIB
- **Lattice studies**
  - Lattice design influence on BIB
  - Muon decay in the chromaticity correction section
- **Nozzle design optimization**
- **Conclusions**

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

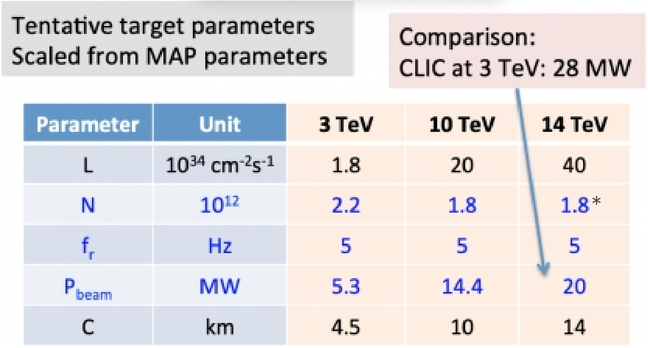
High energy **neutrinos** from the muon decay interact with the rock delivering **dose** to the **environment**.

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, 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

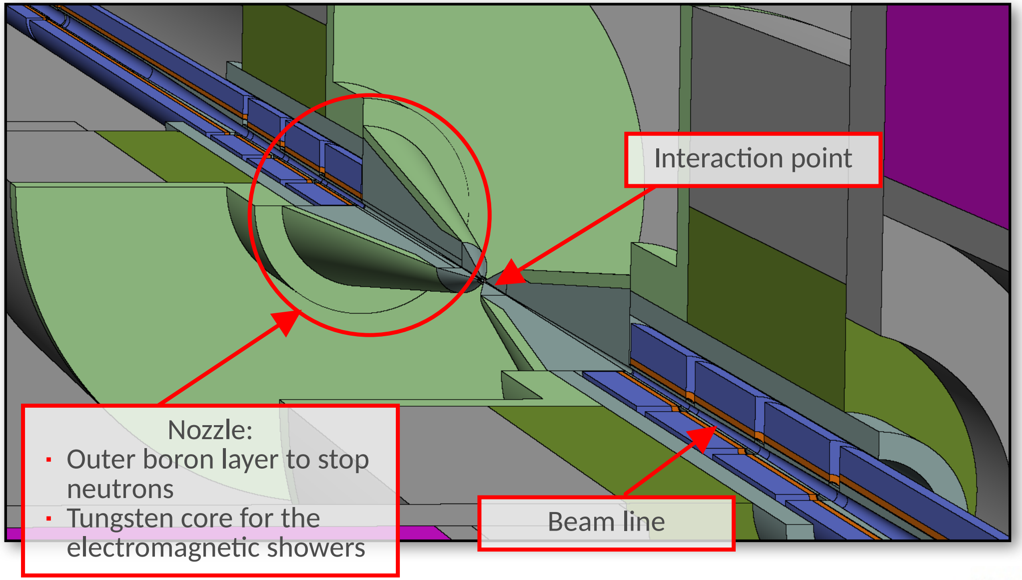


Tentative target parameters
Scaled from MAP parameters

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



Interaction point

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

Beam line

*The results presented here are referred to 1 bunch crossing containing 2E12 muons

MDI: radiation sources

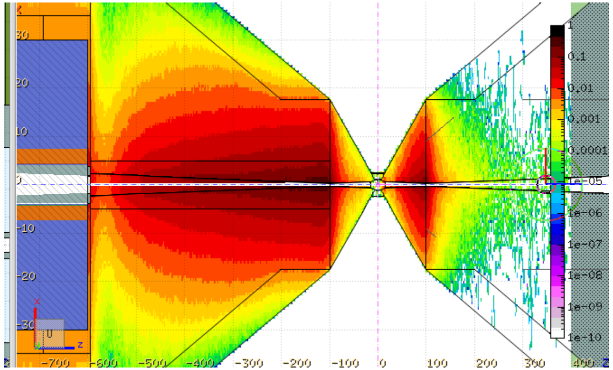
- **Main** source of detector **background** for all collider energy options.
- Main responsible for heat and radiation effects in the accelerator components.

- **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**)

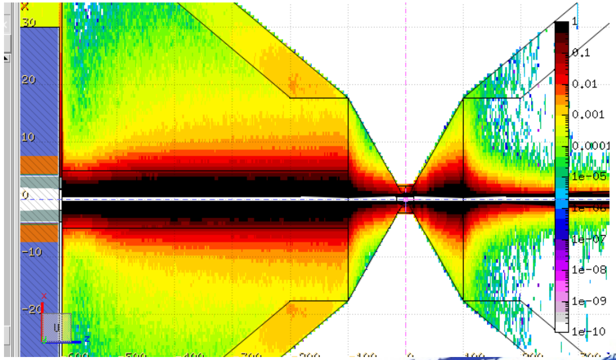
Neutron fluence



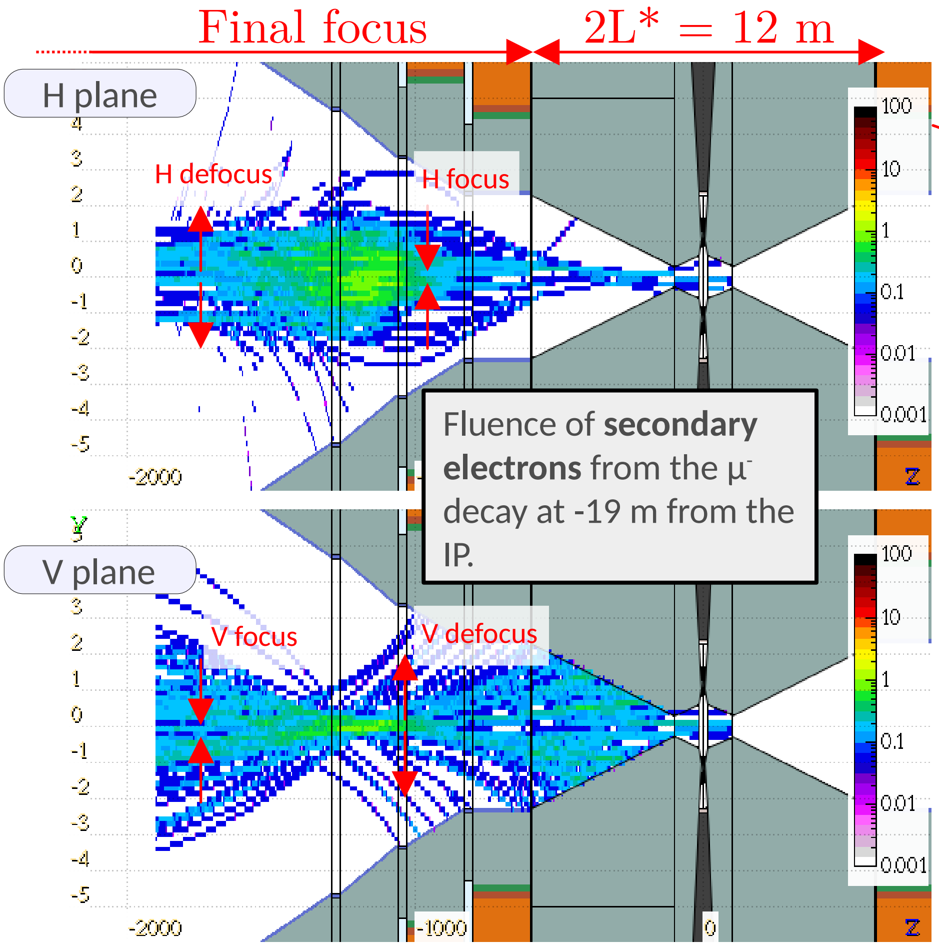
Effects

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

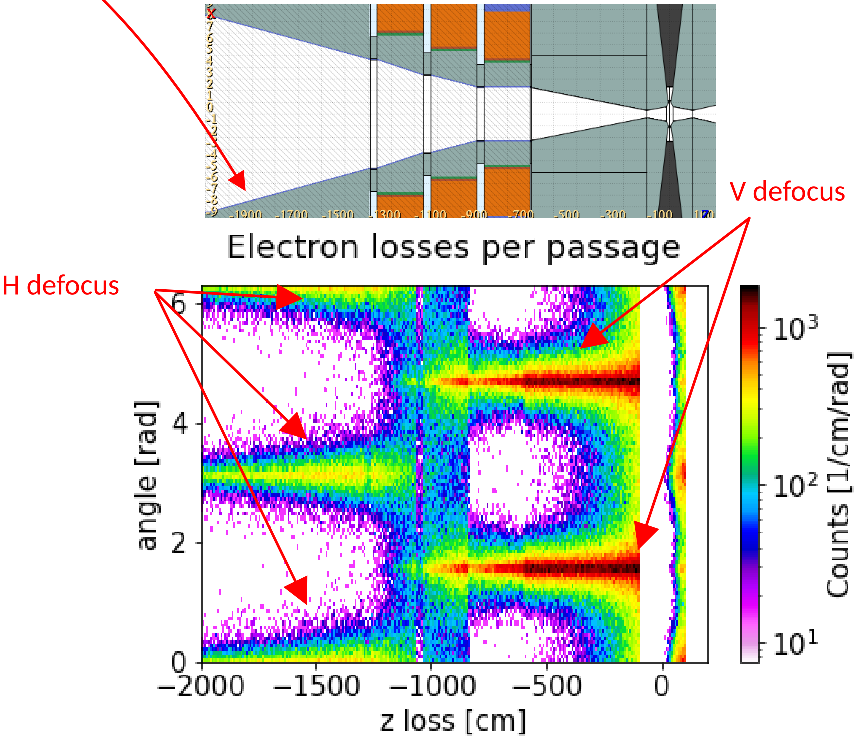


e^+/e^- impact on aperture: qualitative view



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

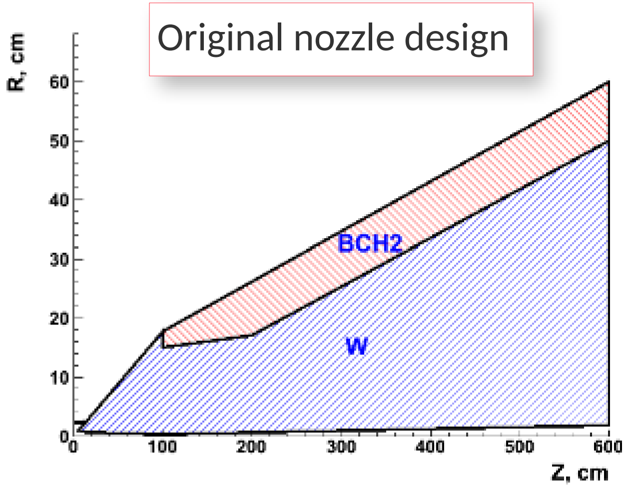
- Final focusing fields induce peaks in the azimuthal distribution of the e^-/e^+ impact position.
- (but!)The azimuthal dependence is diluted to negligible levels by the W nozzle.



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.

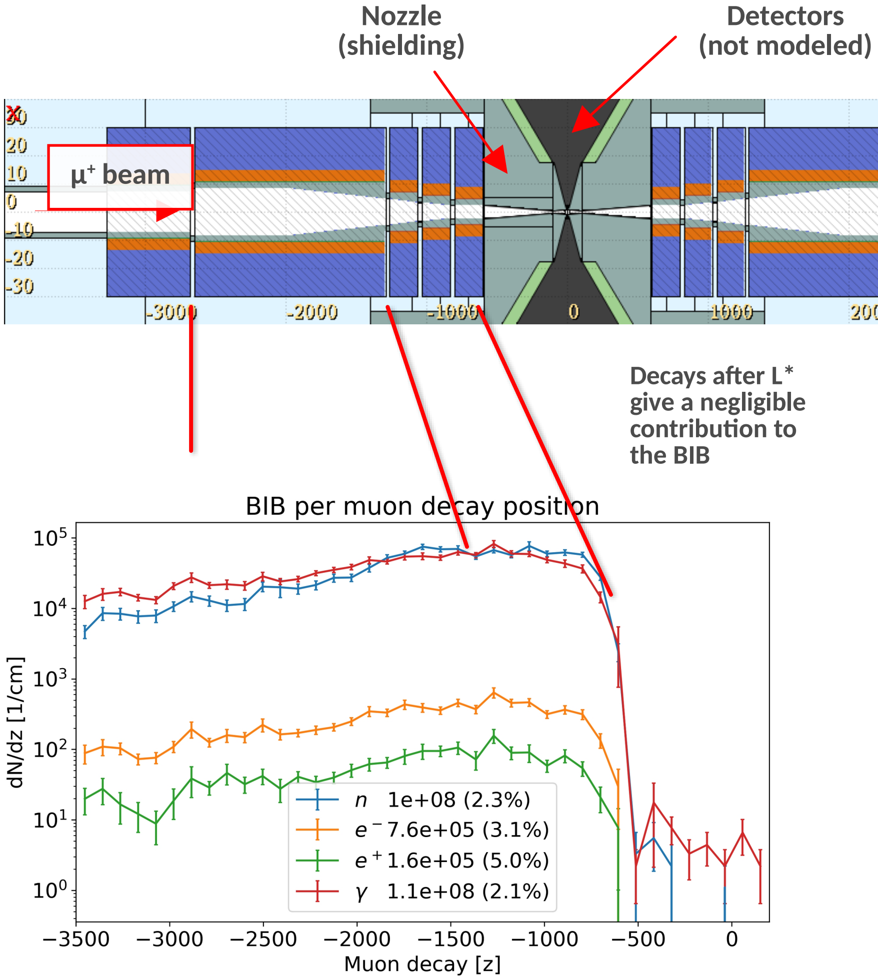
Original nozzle design



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)	$1.5\ 10^3$	$1\ 10^3$

10 TeV: BIB from muon decay (Final focusing)



Decays after L* give a negligible contribution to the BIB

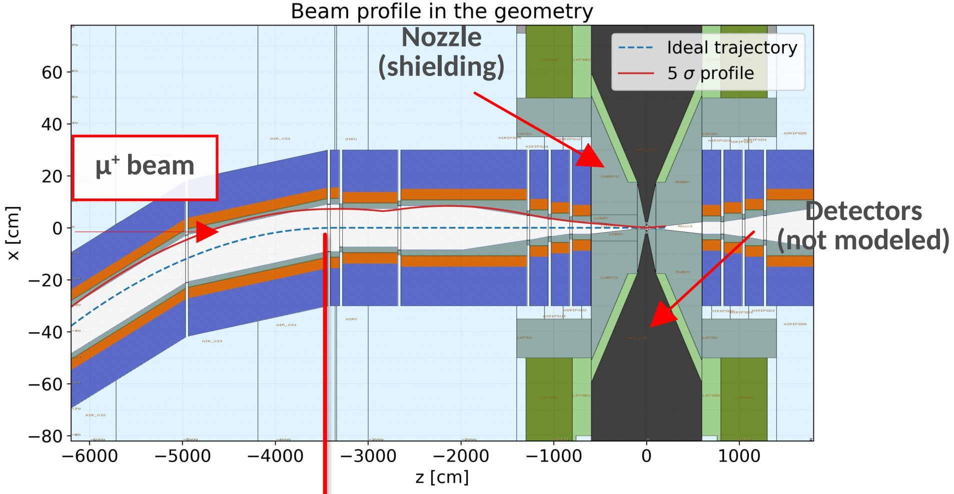
- The 10 TeV geometry **has to be extended** to fully collect the BIB from decay position further away from the IP.
- The total number of particles entering into the detector is **not significantly worse** than the lower energy results!

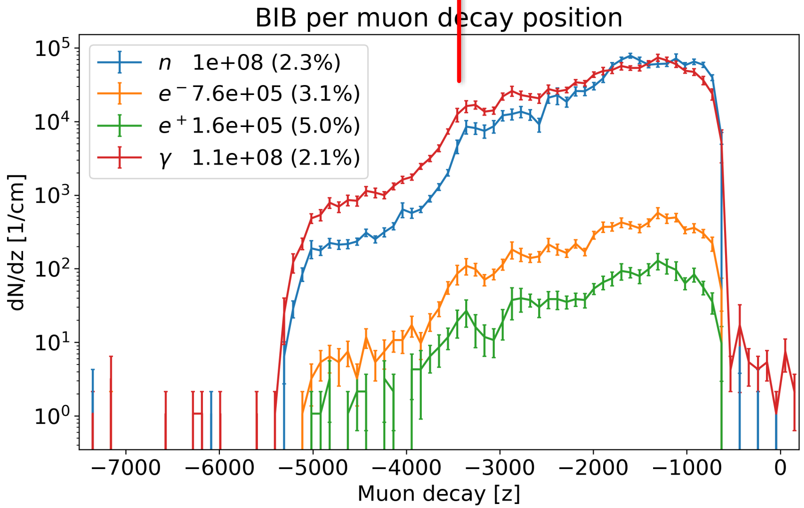
Total particle number: comparison with different collider energies

Collider energy	1.5 TeV	3 TeV	10 TeV Updated!
Photons	7.1E+7	9.6E+7	1.07E+8
Neutron	4.7E+7	5.8E+7	1.01E+8
e^+/e^-	7.1E+5	9.3E+5	9.6E+5
Ch. hadrons	1.7E+4	2.0E+4	4.3E+4
Muons	3.1E+3	3.3E+3	4.8E+3

Non optimized [14-15]

10 TeV: BIB from muon decay (Final focusing and chromaticity correction)


Beam profile in the geometry

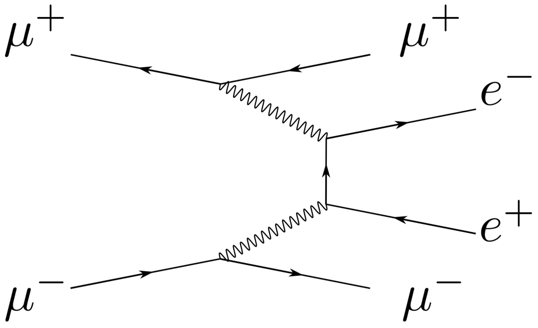

BIB per muon decay position

- The total number of particles entering into the detector is **not significantly worse** than the lower energy results!
- Before the final focusing magnet, there is a sharp decrease in the signal for what concerns most of the produced particles

Muon production still not statistically significant!

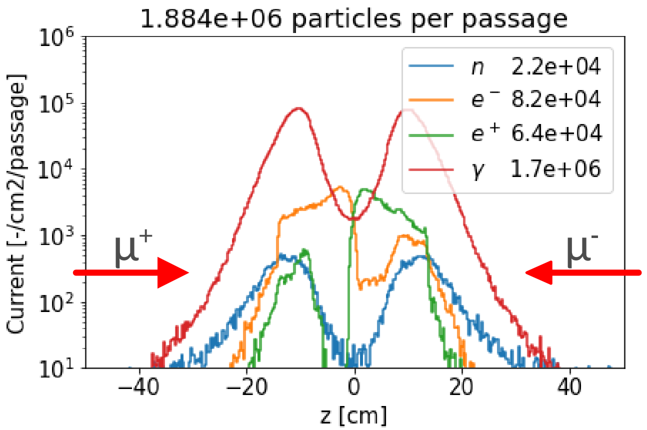
10 TeV: BIB from incoherent pair production

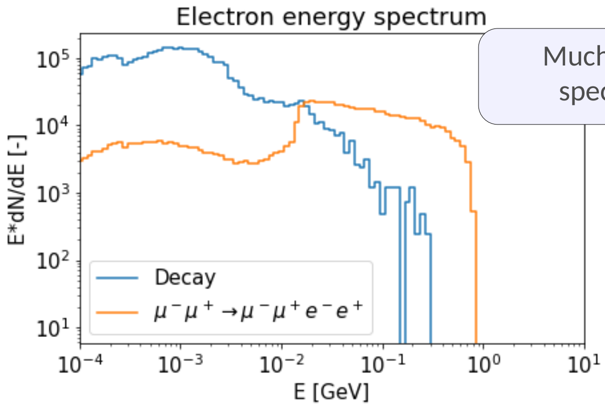
- At very high beam energies, beam-beam effects are not negligible. The most important phenomenon is due to the **incoherent beam-beam pair production μ+μ-→μ+μ-e+e-**.
  - The incoherent pair production e^+/e^- are provided by D. Schulte and are obtained by a **Guinea-Pig simulation**
- The **total number**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

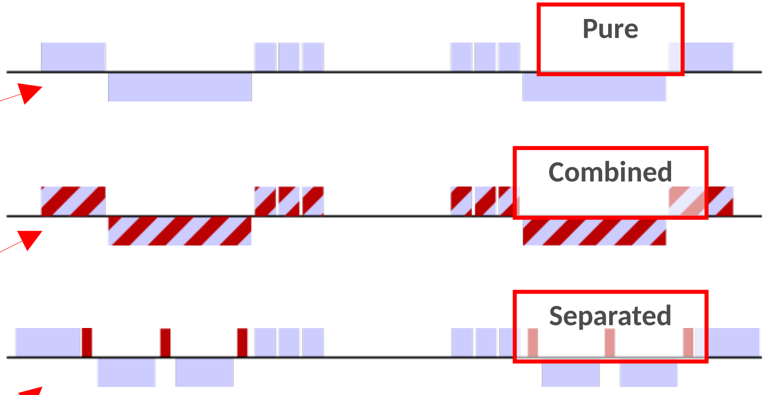




Much harder spectrum!

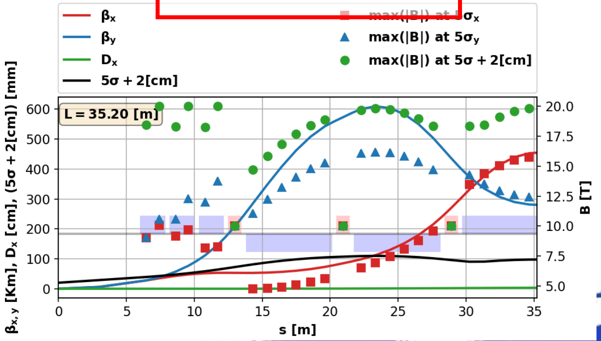
10 TeV: possible lattice design choices

- 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.



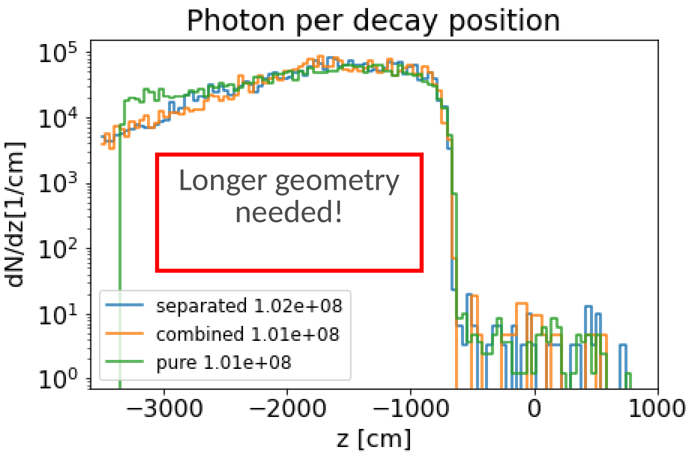
- We considered three possibilities (from K. Skoufaris and C. Carli) for the lattice in the final focusing:
  - Only quadrupoles, with no dipoles and no dipole component (**pure**).
  - Combined function magnets, where there are no dipole magnet, but each quadrupole contains a 2T dipolar component (**combined**).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

Twiss parameters of the separated lattice

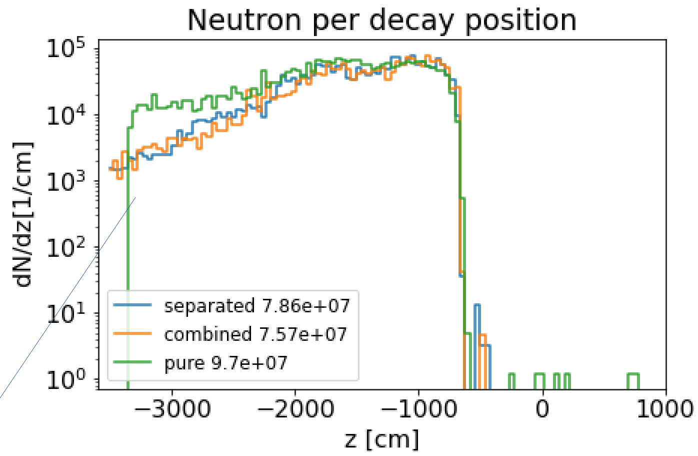


10 TeV: lattice effects on BIB

- 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** is limited. Even if we **reduce slightly** the BIB from **far away**, other optimization means have to be found.



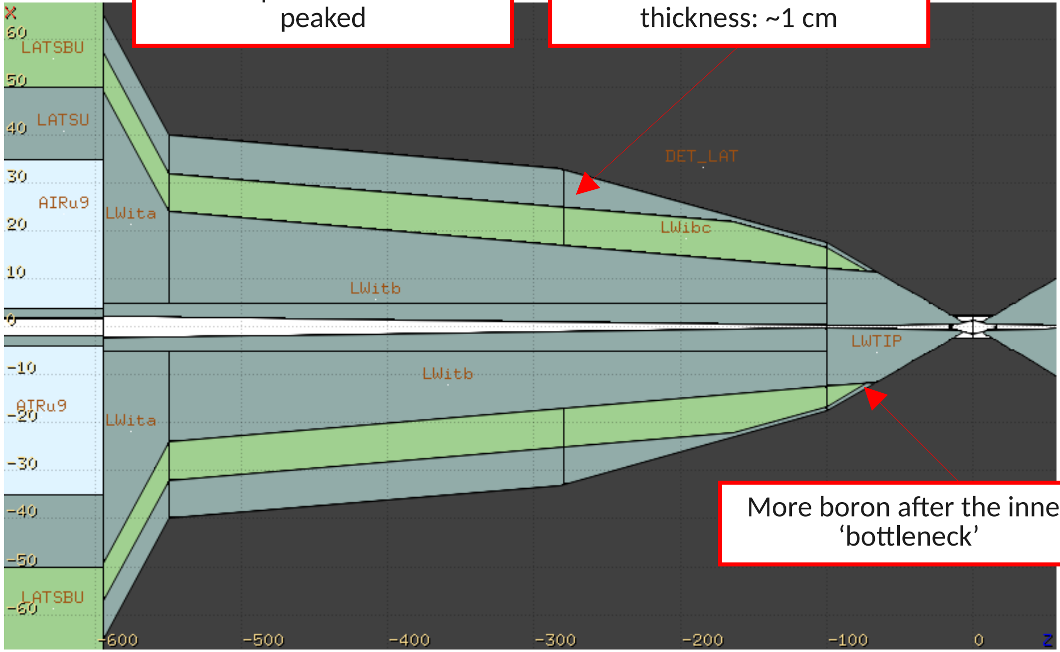
Longer geometry needed!



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.

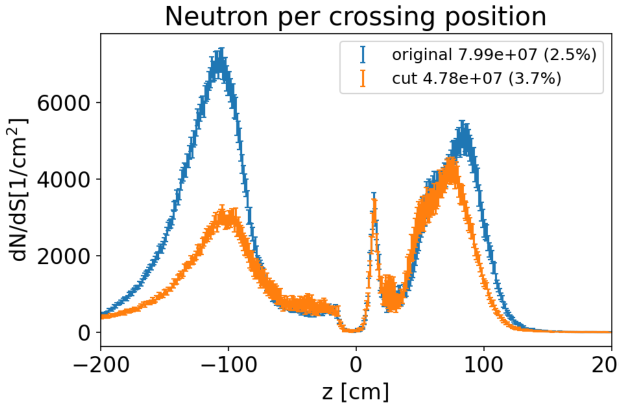


Lateral tungsten shaven off from the lateral side. The photon fluence is already small, the EM shower development is forward peaked

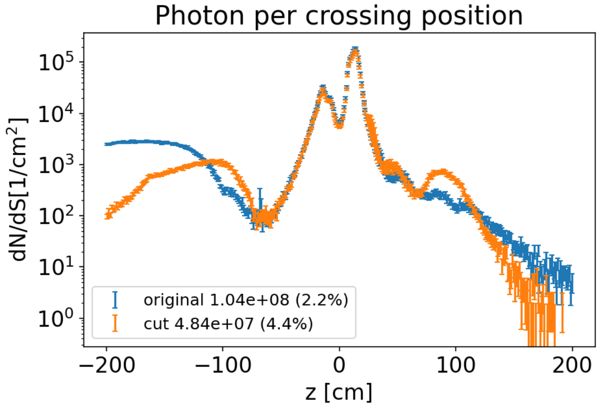
Tungsten layer after the boron one. Smallest thickness: ~1 cm

More boron after the inner ‘bottleneck’

Neutron per crossing position

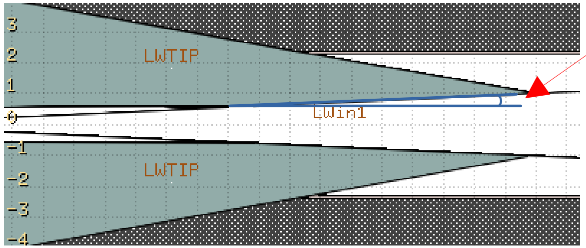


Photon per crossing position

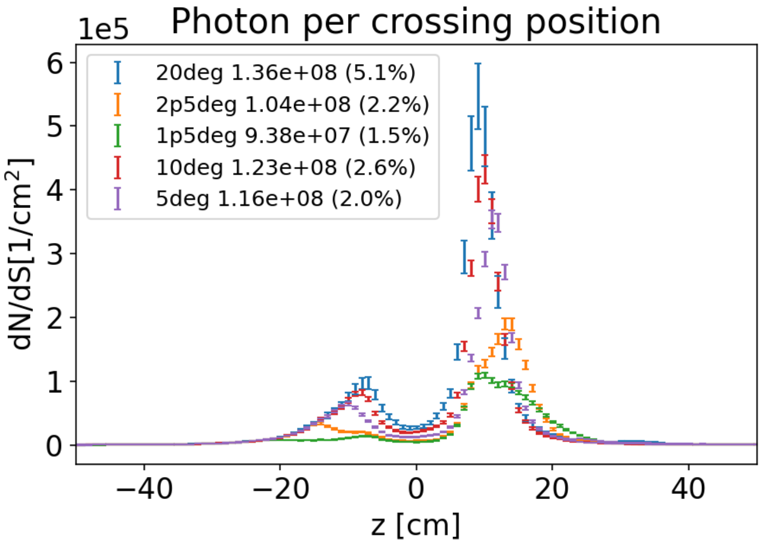


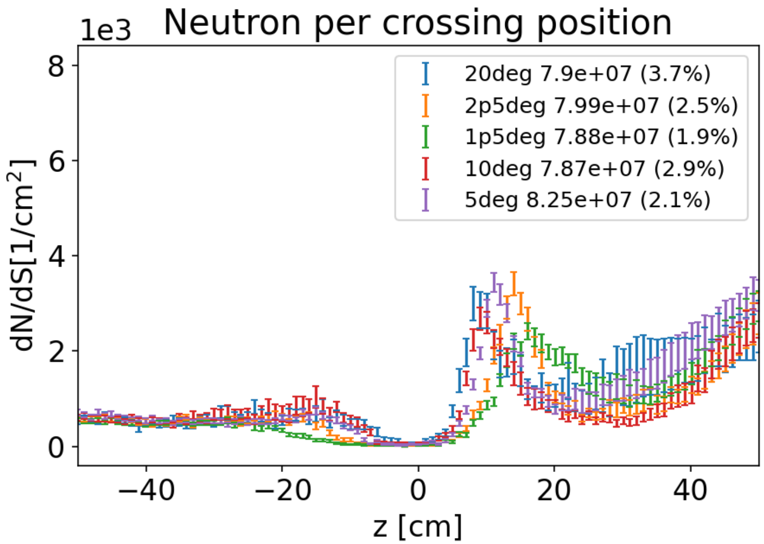
Current nozzle optimization: angle tip

- 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.

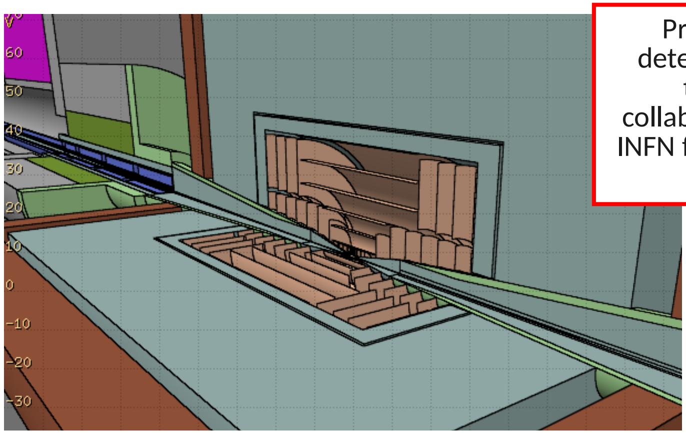

Photon per crossing position


Neutron per crossing position

Conclusions

- **Muons decay** induces an intense secondary radiation field in all component of the muon collider. The MDI 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 alters the background in a more substantial way.
- Contributions from decay further away from the final focus region are not significant.
- 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:**
  - Simulate the BIB in the case of longer L* (10 m instead of presently 6 m)
  - 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

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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- [4] Berg, A Cost-Effective Design for a Neutrino Factory (doi: 10.1103/PhysRevSTAB.9.011001)
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- [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
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- [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

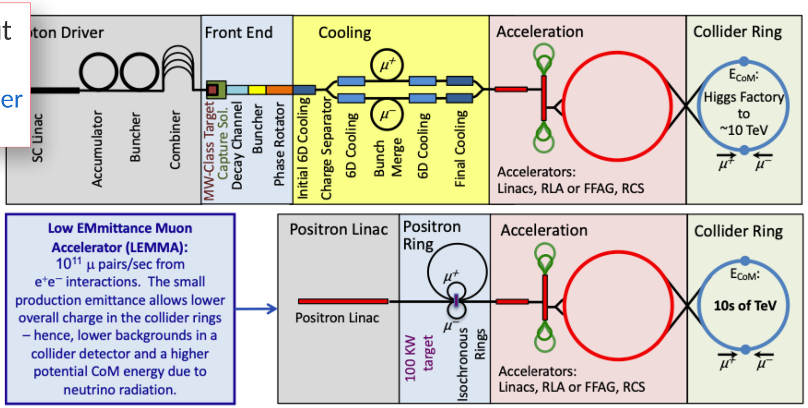
Muon collider: concept and motivations

- 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?

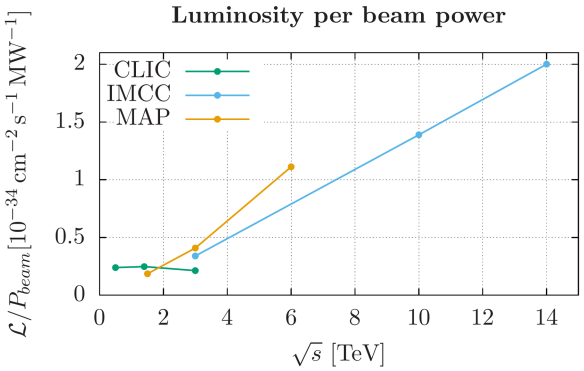
- A multi-TeV muon collider could investigate **Higgs properties** with an unprecedented precision. [2]
- With √s = 10 TeV we can explore **new physics at high energies**. [2]

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



Low EMmittance Muon Accelerator (LEMMA): 10^{11} μ pairs/sec from e^+e^- interactions. The small production emittance allows lower overall charge in the collider rings – hence, lower backgrounds in a collider detector and a higher potential CoM energy due to neutrino radiation.

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

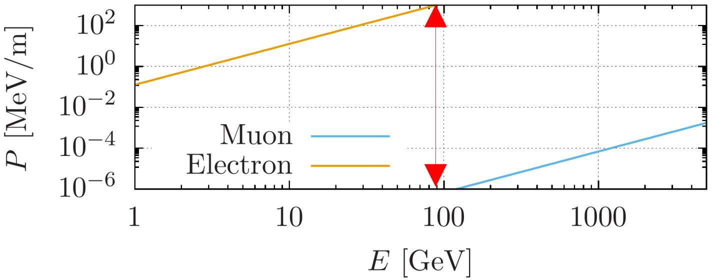
High beam power

Muon collider: advantages

Synchrotron radiation*

- The muon mass: **105.7 MeV/c^2. Synchrotron radiation** (SR) is **not a limiting factor** for muon circular colliders.

Energy emitted by SR per unit length

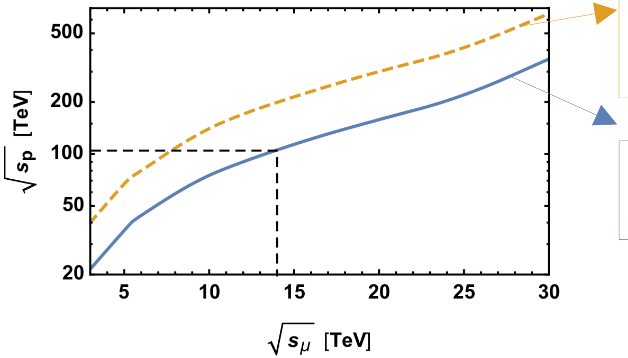


Muons emit $(m_\mu/m_e)^4$ = **$1.6 \cdot 10^9$** less synchrotron radiation than electrons

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]

Energies at which proton/μ-colliders have similar performances



Assuming comparable Feynman amplitudes for muon and proton production processes

Proton production enhanced due to QCD production (factor of 10)

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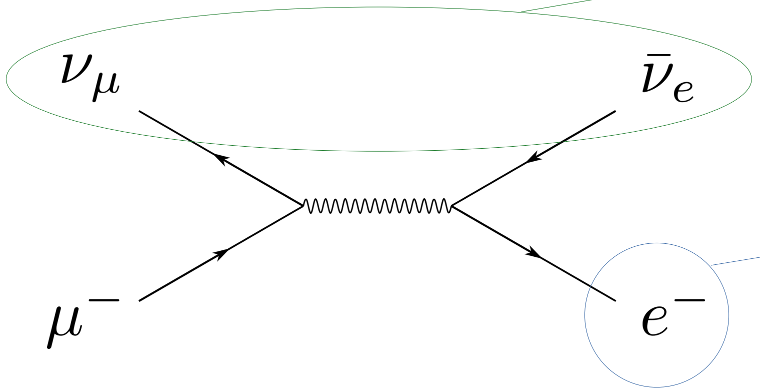
*of the primary muon beam

Muon collider: radiation challenges

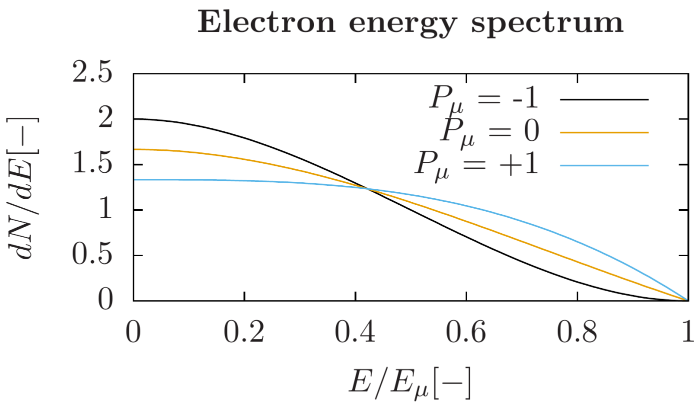
- **Muons** are **unstable particles**, with a rest lifetime of τ = 2.197 μs. They decay spontaneously into electron and positrons (depending on the muon original charge).



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.

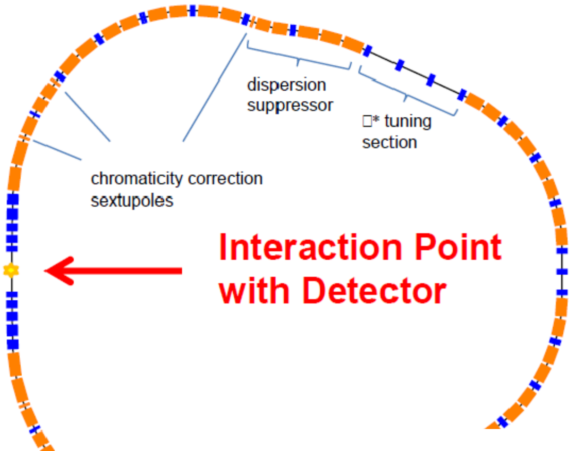
e^-/e^+: they carry **around 1/3 of the original muon energy** and they are responsible for the heat load and the **radiation damage** of the **accelerator components**.

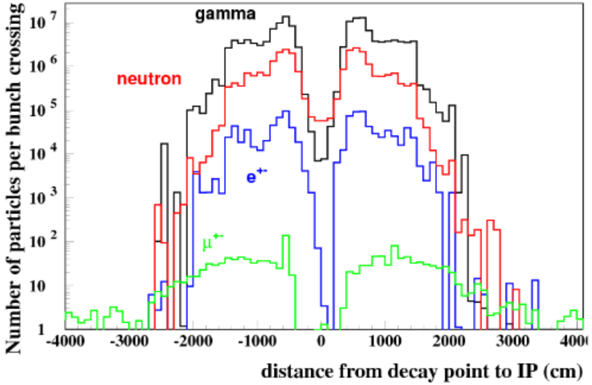
Original muon: thanks to the Lorentz boos, it will survive for γτ. In any case, the muon production/acceleration/collision must be **extremely fast**.



Higgs factory

125 GeV: Higgs’ factory [11,12]





1.5 TeV spectra