Machine-detector interface design for a 10-TeV muon collider

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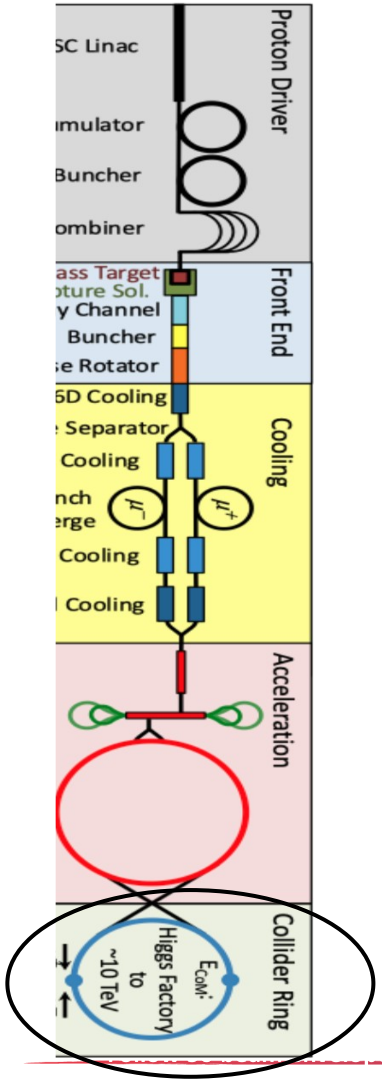
On behalf of the IMCC

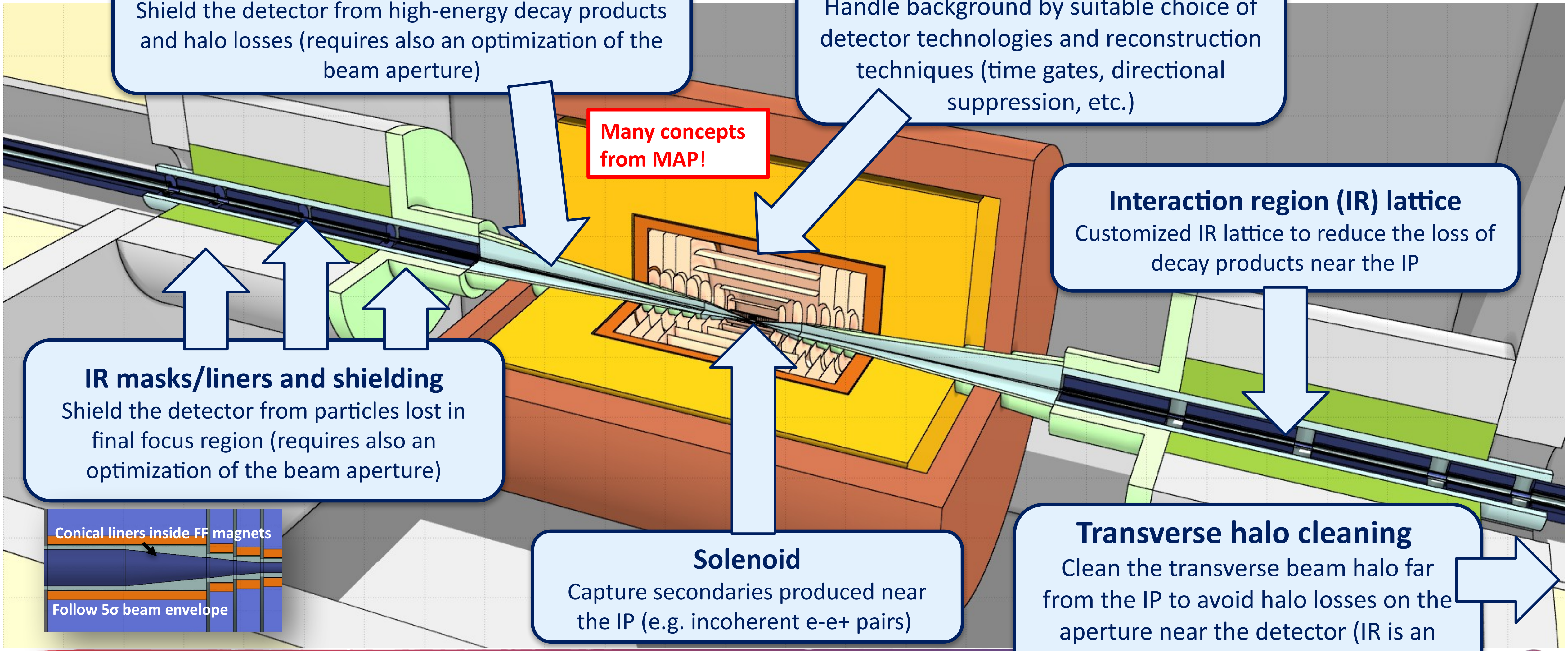
**Funded by
the European Union**

Outline



- **Machine-Detector Interface (MDI):**
  - Geometry of the interaction region
  - Lattice options and radiation load to the superconducting magnets
  - Workflow in the International Muon Collider Collaboration (IMCC)
- **Beam induced background**
  - Sources of BIB
  - Conical shielding for decay induced background: nozzle
- **Beam-Induced Background (BIB) from μ-decay**
- **Incoherent pair production in the IP and muon halo losses**
- **Detector radiation damage**
- **Conclusions**

Machine-detector interface



Conical absorber inside detector (nozzle)
Shield the detector from high-energy decay products and halo losses (requires also an optimization of the beam aperture)

Many concepts from MAP!

Detector
Handle background by suitable choice of detector technologies and reconstruction techniques (time gates, directional suppression, etc.)

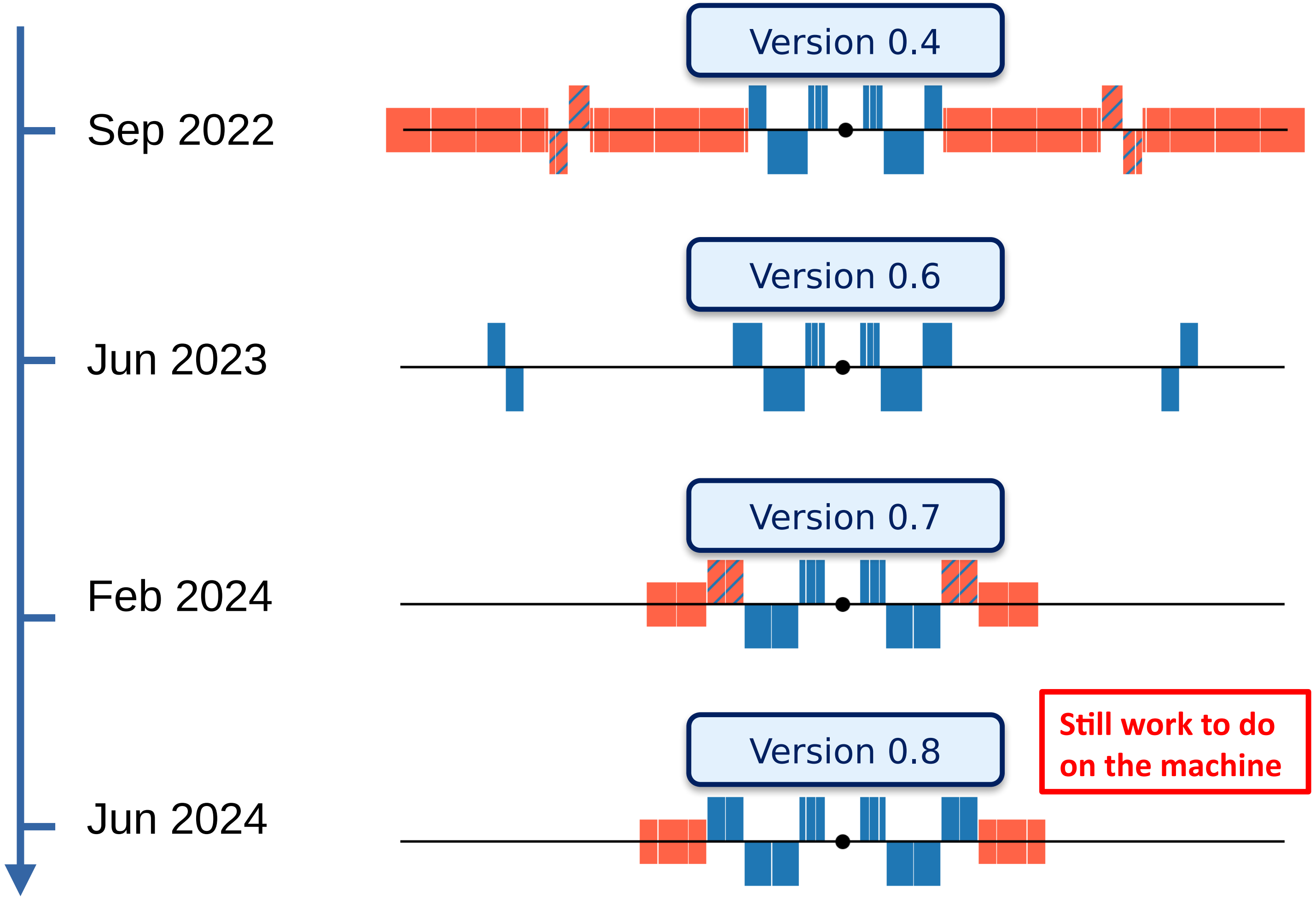
Interaction region (IR) lattice
Customized IR lattice to reduce the loss of decay products near the IP

IR masks/liners and shielding
Shield the detector from particles lost in final focus region (requires also an optimization of the beam aperture)

Solenoid
Capture secondaries produced near the IP (e.g. incoherent e-e+ pairs)

Transverse halo cleaning
Clean the transverse beam halo far from the IP to avoid halo losses on the aperture near the detector (IR is an aperture bottleneck)

Evolution of the optics



Sep 2022

Version 0.4

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

Jun 2023

Version 0.6

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

Feb 2024

Version 0.7

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

Jun 2024

Version 0.8

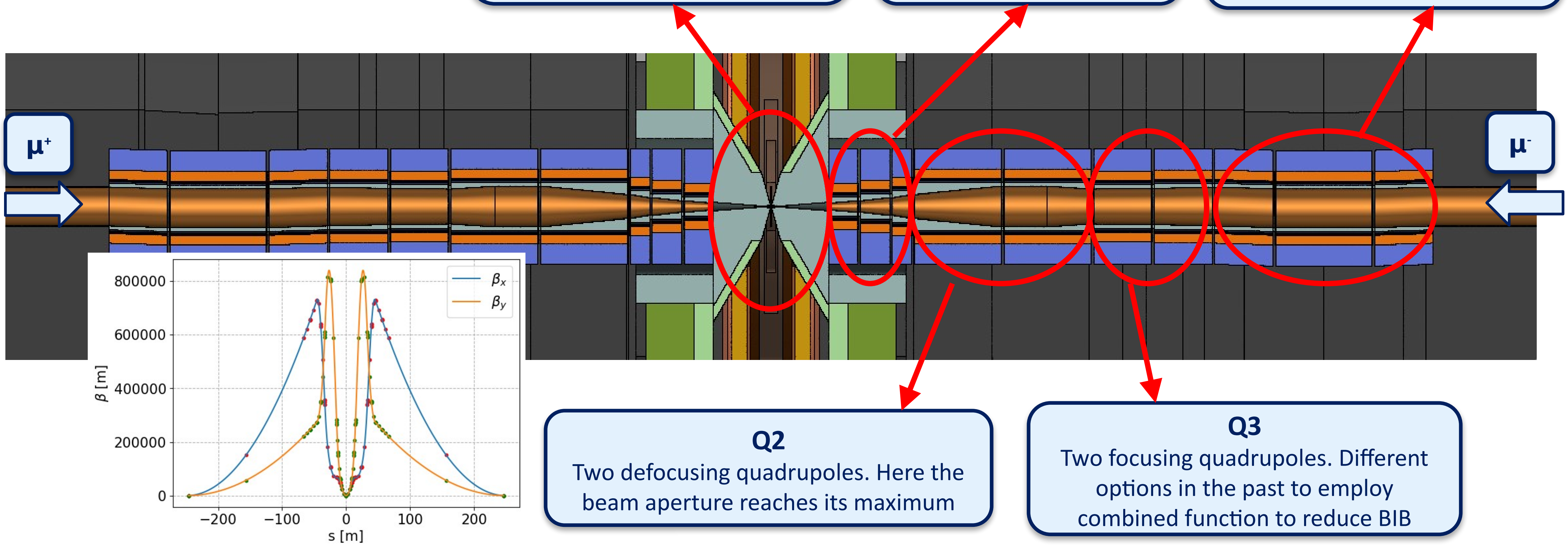
Still work to do on the machine

The chicane concludes with 0 angle, and the magnet aperture is increased in the dipoles

Many details on the challenges here: https://indico.cern.ch/event/1402725/contributions/6013054/

Final focus optics

Overview of the lattice version 0.8. The novel approach does not leave a residual angle and does not require combined function magnets



Interaction point (IP) & nozzle
Reduce the amount of decay-induced background by several order of magnitude

Q1
Three focusing quadrupoles to control the beam size in the IP

Chicane
Three dipoles that remove the electrons coming from the line

Q2
Two defocusing quadrupoles. Here the beam aperture reaches its maximum

Q3
Two focusing quadrupoles. Different options in the past to employ combined function to reduce BIB

Radiation load on the final focus

- In all magnets, the limiting quantity is the total **ionizing dose (TID)** in organic materials (insulation, spacers etc.)
- The current limitation assumed for the yearly TID is around **5-10 MGy/y** → **50 MGy** during the collider lifetime.
- We assume an **operational time of 1.2E7 second per year**, with 5 to 10 years of operation.
- The **damage is cumulative**. In case of extended collider use lower limits must be taken.

Table: radial build for superconducting magnets

Shield radial build	Thickness (mm)
beam screen	0.01
shield	2.53
shield support +thermal insulation	1.1
cold bore	0.3
insulation (kapton)	0.05
clearance + liquid helium	0.01
Sum	4

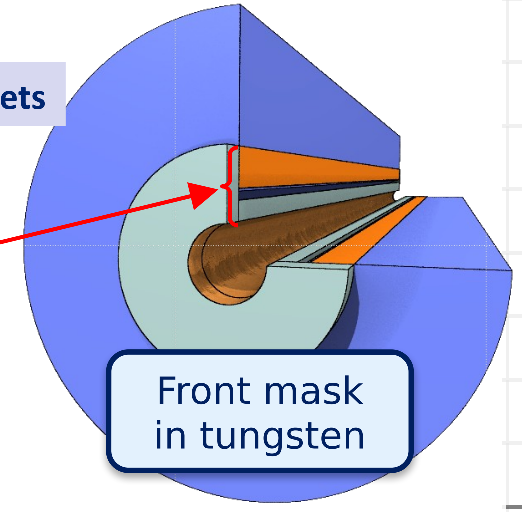
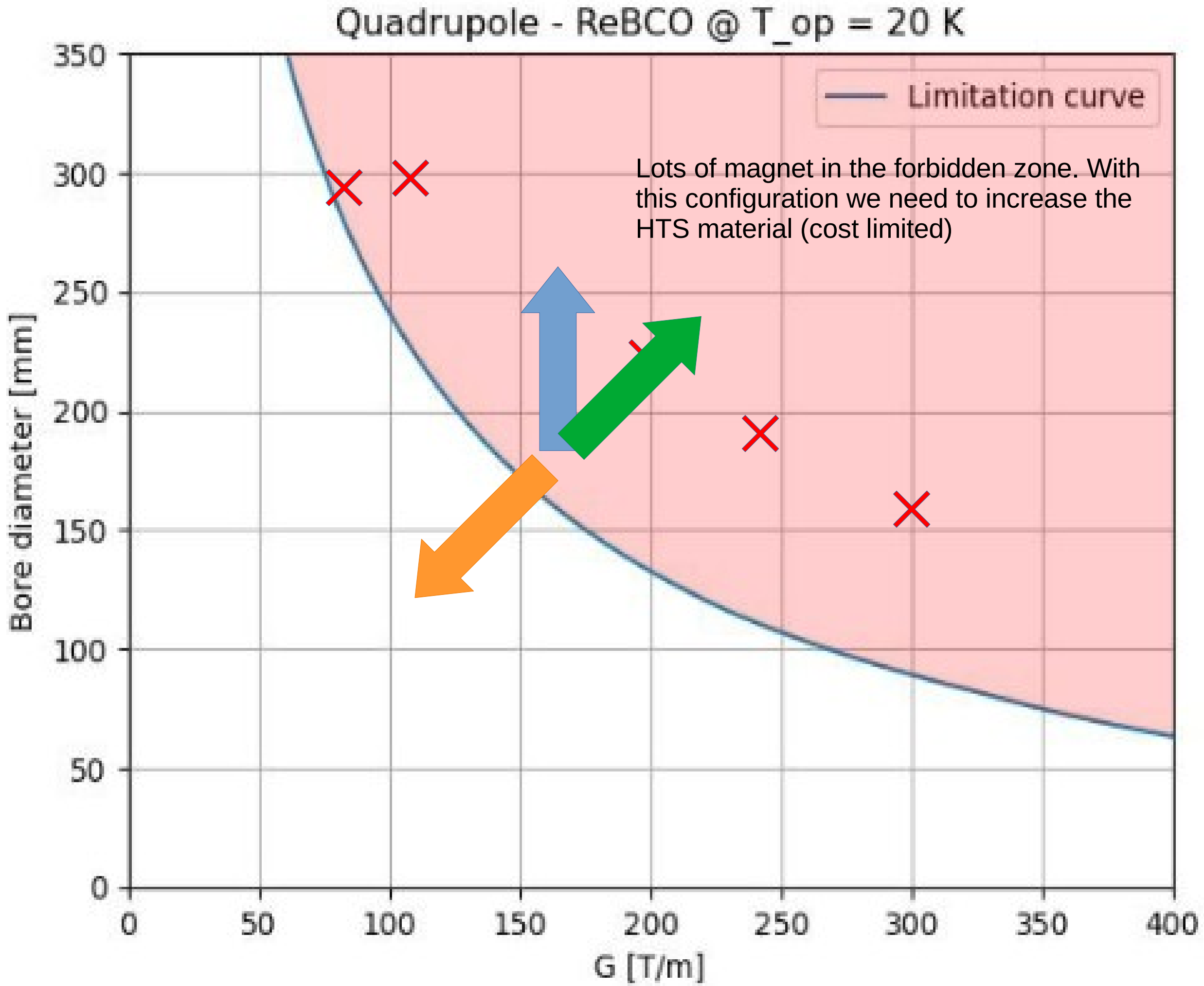

Front mask in tungsten

Table: radiation load for each magnet in the final focus

Name	L [m]	Shield thickness [cm]	Coil aperture (radius) [cm]	Peak TID [MGy/y]
IB2	6	6	16	1.3
IB1	10	6	16	3.1
IB3	6	6	16	4.9
IQF2	6	4	14	7.7
IQF2_1	6	4	13.3	4.6
IQD1	9	4	14.5	1.1
IQD1_1	9	4	14.5	3.7
IQF1B	2	4	10.2	6.4
IQF1A	3	4	8.6	3.6
IQF1	3	4	7	3.5

Conflicting requirement for magnet shielding

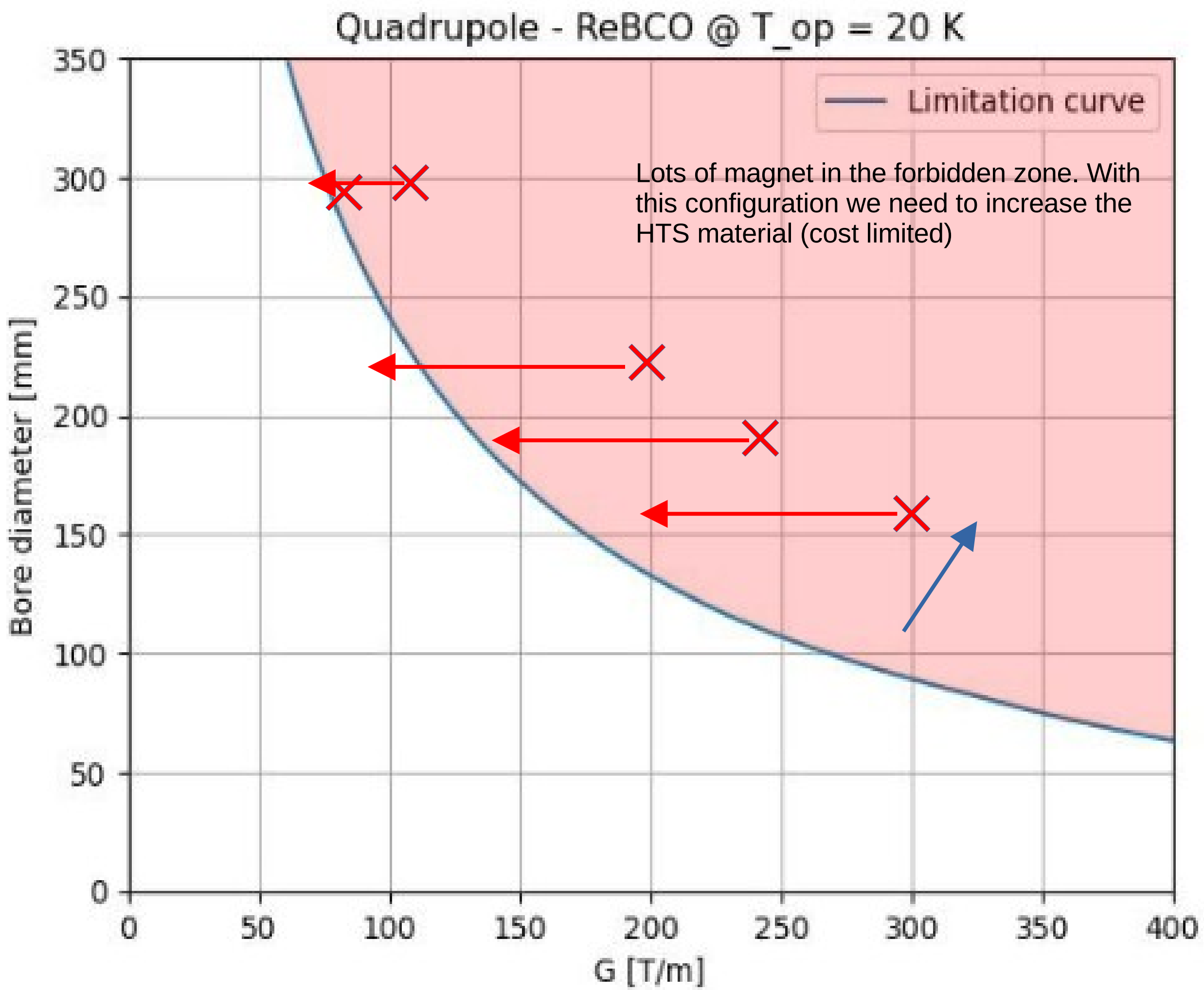


Lots of magnet in the forbidden zone. With this configuration we need to increase the HTS material (cost limited)

From: Samuele Mariotto, Barbara Caiffi, Daniel Novelli, Tiina Salmi
https://indico.cern.ch/event/1325963/contributions/5798926/

- Radiation load requirement: larger aperture allows for more shielding
- Magnets requirements: small aperture and field intensities. Depending on the technology there are different limitations.
- Beam dynamics requirement: larger apertures and field strengths allows for easier control on the beam shape in the final focus

Conflicting requirement for magnet shielding



Lots of magnet in the forbidden zone. With this configuration we need to increase the HTS material (cost limited)

From: Samuele Mariotto, Barbara Caiffi, Daniel Novelli, Tiina Salmi
https://indico.cern.ch/event/1325963/contributions/5798926/

- Feasibility of the current lattice version still unclear. Possible solutions:
- **Increase β^***:
  this would have immediate consequences in the luminosity, reducing it
- **Decrease the field strength**:
  with a lower field strength the final focusing would require a longer straight section
- **Increase HTS costs**:
  with additional material, higher fields and large bore radii can be achieved (up to a certain extent)

These lattice design choices may have a non negligible impact on the BIB

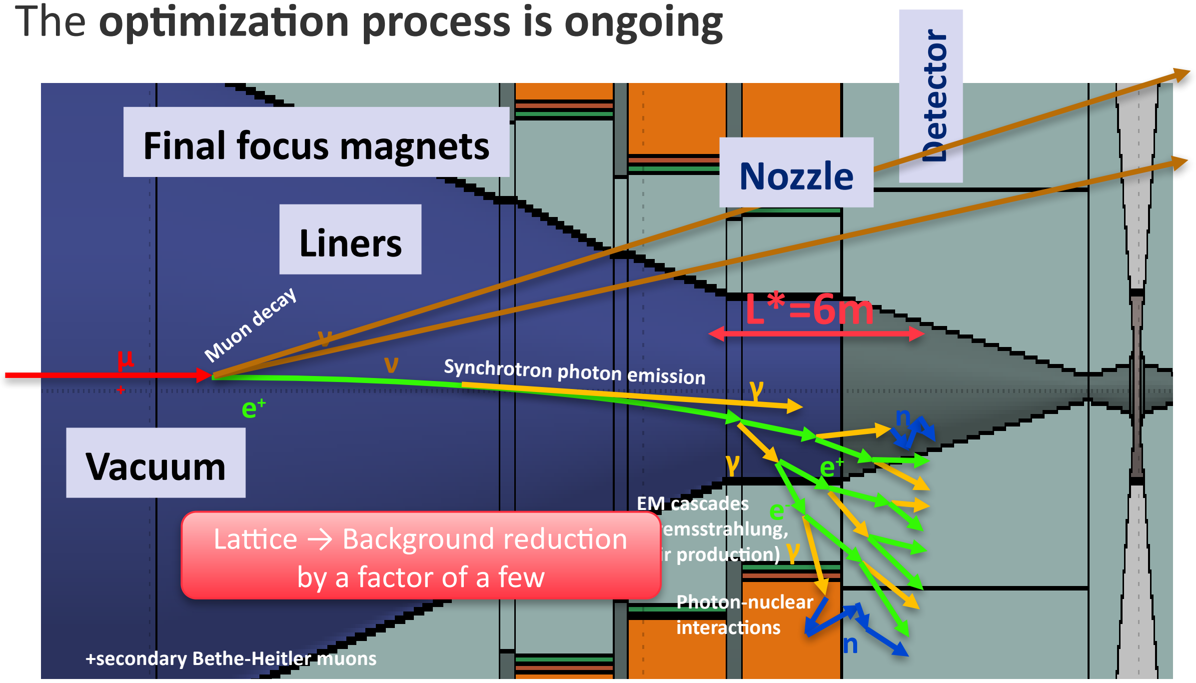
Beam-induced background

	Description	Relevance as background
Muon decay	**Decay of stored muons around the collider ring**	**Dominating source**
Synchrotron radiation by stored muons	Synchrotron radiation emission by the beams in magnets near the IP (including IR quads ⟶ large transverse beam tails)	**Small**
Muon beam losses on the aperture	Halo losses on the machine aperture, can have multiple sources, e.g.: • Beam instabilities • Machine imperfections (e.g. magnet misalignment) • Elastic (Bhabha) μμ scattering • Beam-gas scattering (Coulomb scattering or Bremsstrahlung emission) • Beamstrahlung (deflection of muon in field of opposite bunch)	**Can be significant** (although some of the listed source terms are expected to yield a small contribution like elastic μμ scattering, beam-gas, Beamstrahlung)
Coherent e^-e^+ pair production	Pair creation by real* or virtual photons of the field of the counter-rotating bunch	**Expected to be small** (but should nevertheless be quantified)
Incoherent e^-e^+ pair production	Pair creation through the collision of two real* or virtual photons emitted by muons of counter-rotating bunches	**Significant**

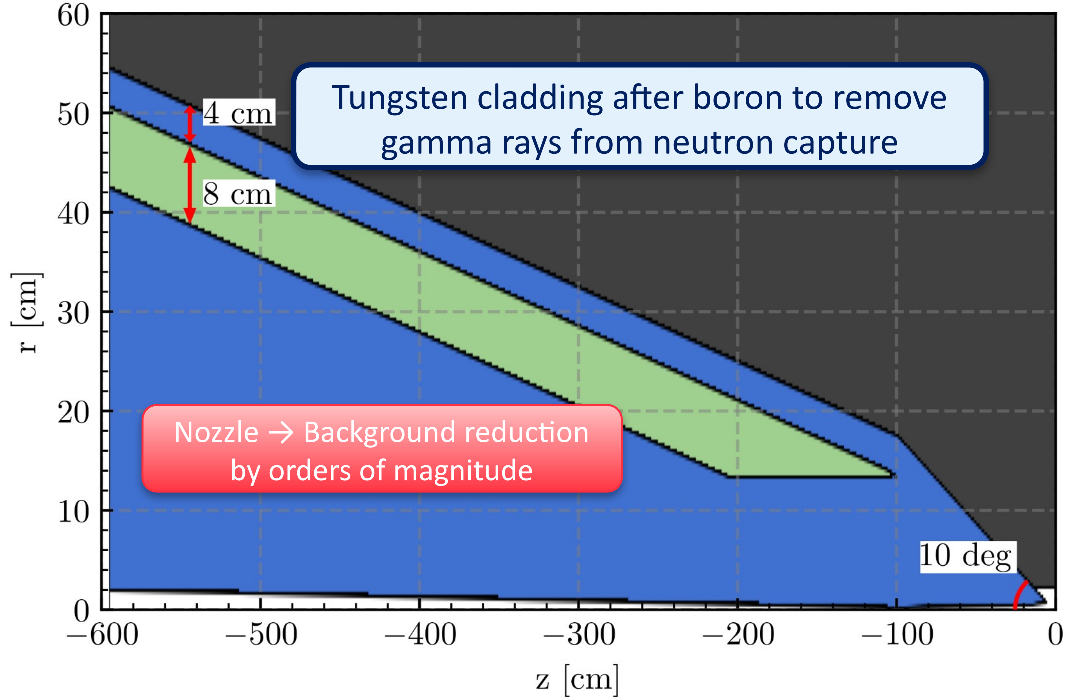
Conical shielding: nozzle

- The **nozzle is the most important element for the shielding** of the background coming from the muon decay.
- Originally taken from **MAP**, with modification for the EU strategy update.
- It reduces the background of several orders of magnitude
- The **optimization process is ongoing**

Component	Density [g/cm3]	Element	Atomic Fraction (mass fraction if negative)
EM Shower Absorber	18	W	-0.95
		Ni	-0.035
		Cu	-0.015
Neutron Absorber	0.918	H	0.5
		C	0.25
		B	0.25



Lattice → Background reduction by a factor of a few



Tungsten cladding after boron to remove gamma rays from neutron capture

Nozzle → Background reduction by orders of magnitude

Workflow in the IMCC

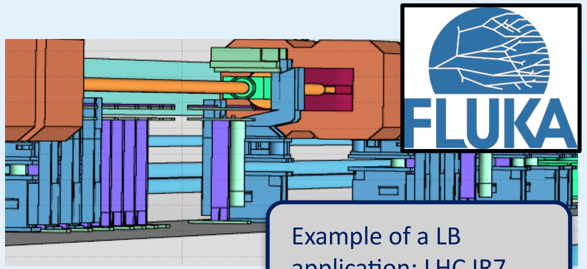
1. Lattice design

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

2-bis. Radiation load simulation

The radiation loads (heat deposition and long term radiation damage) are simulated.

The results needs to guarantee long term survivability of the components

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

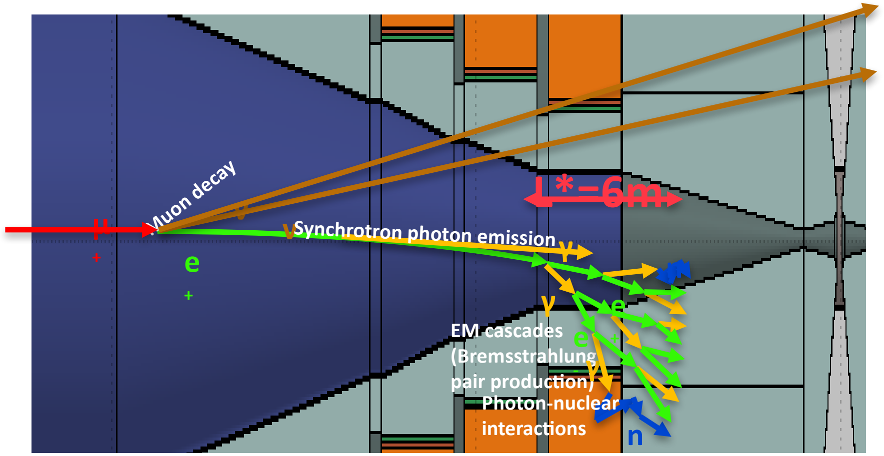
CERN STI/BMI is currently responsible for the geometry built at $\sqrt{s}$ = 3 and 10 TeV

Simulation approaches: 1 vs 2 steps

- To perform Monte Carlo simulations, one could chose to split a simulation in 2 steps, to minimize the computational time required. This is equivalent to a **biasing approach**

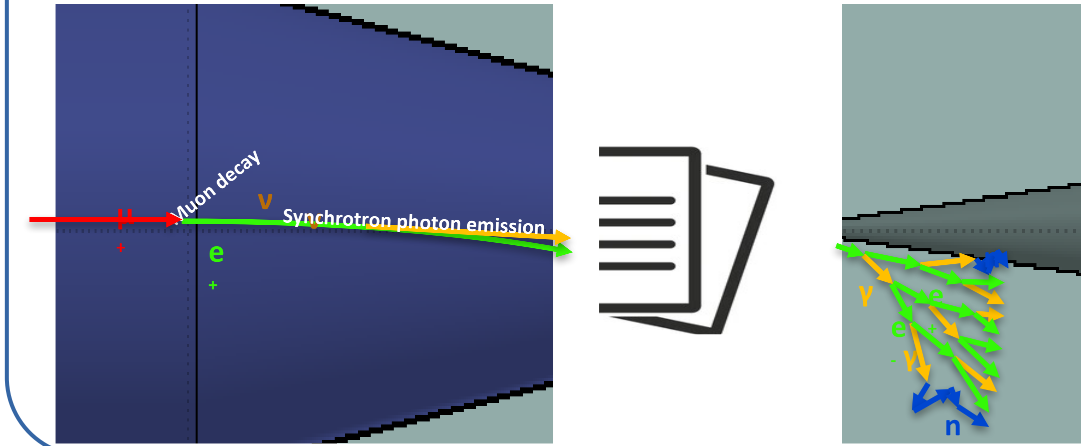
Single step approach

- Starting from the muon decay, all the secondaries are simulated until they enter the detector volume.
- It is possible to **generate pseudo-events from individual muon decays.**



Double step approach

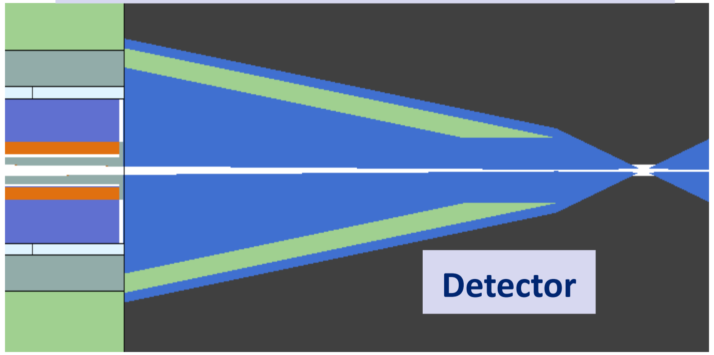
- **First simulation**: the secondaries going in the nozzle area are saved into a file.
- **Second simulation**: randomly sampled particle from the saved file are propagated in the nozzle area.
- Biasing cannot reproduce fluctuation and correlations, but it is mostly fine for radiation damage simulation.



BIB from the muon decay

	Description	Relevance as background
Muon decay	**Decay of stored muons around the collider ring**	**Dominating source**

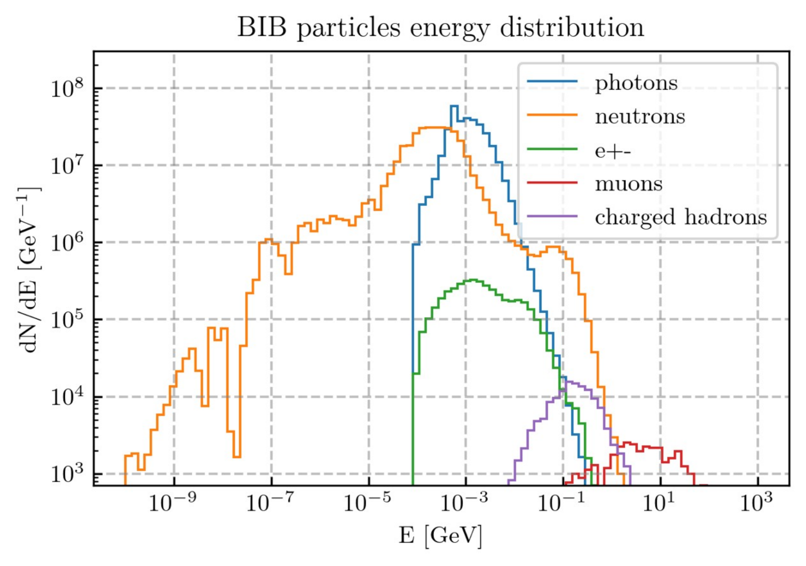
Particles going in the detector area are scored and killed.

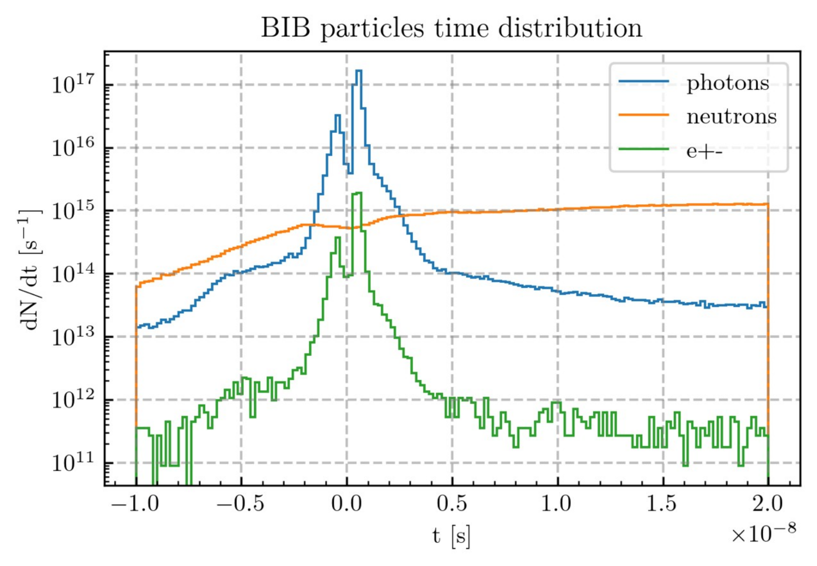


Background particles (from decay) entering detector per bunch crossing (with time cut [-1:15]ns):

- O(10^8) **γ** (>100 keV),
- O(10^7) **n** (>10^{-5} eV)
- O(10^6) **e+ & e-** (>100 keV)

Time and energy spectra





BIB from the muon decay

- Muon **decays** occurring in the **final focus** generate the most relevant part of the background
- The **chicane** removes most of the contribution from the previous straight section
- The different lattices options offer similar performances. Several changes in various aspects of the MDI (nozzle composition, lattice configuration) give results consistent with colliders at different energies.

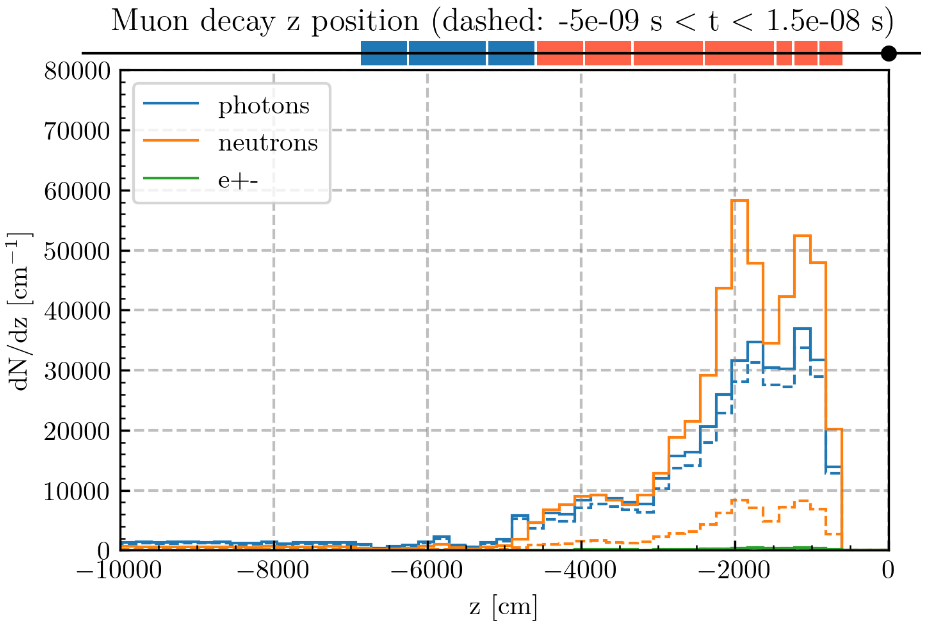


Table: number of particles entering the detector per bunch crossing

Collider energy	1.5 TeV	3 TeV	10 TeV (v 0.4)	10 TeV (v 0.7)	10 TeV (v 0.8)	10 TeV (EU24*)
Photons	7.1E+07	9.6E+07	9.6E+07	1.6E+08	1.6E+08	1.0E+08
Neutron	4.7E+07	5.8E+07	9.2E+07	1.5E+08	1.4E+08	1.1E+08
e+/e-	7.1E+05	9.3E+05	8.3E+05	9.2E+05	8.9E+05	1.2E+06
Ch. hadrons	1.7E+04	2.0E+04	3.0E+04	4.9E+04	5.2E+04	4.0E+04
Muons	3.1E+03	3.3E+03	2.9E+03	5.0E+03	3.3E+03	1.1E+04

Data for 1.5 and 3 TeV options from “Towards a muon collider”

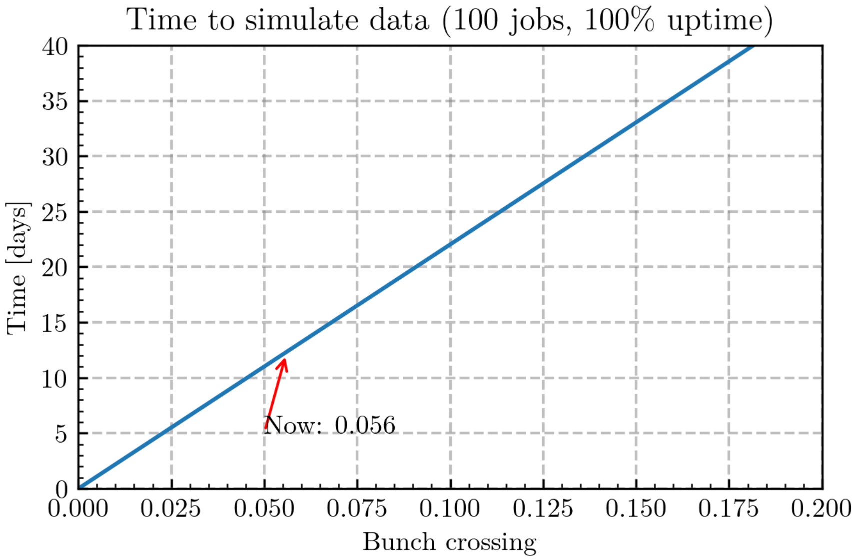
*EU24 considers the lattice v 0.8 with the nozzle shown in the previous slides

BIB from the muon decay

- Simulating the BIB is **expensive**. The simulations parameters are reported in table.

Length of the trajectory [m]	Bunch intensity	Decay per unit length	Total number of decays	Time per primary	Size per primary [MB]
246	1.80E+12	5.78E+04	1.42E+07	1.34E+02	1.36E-03

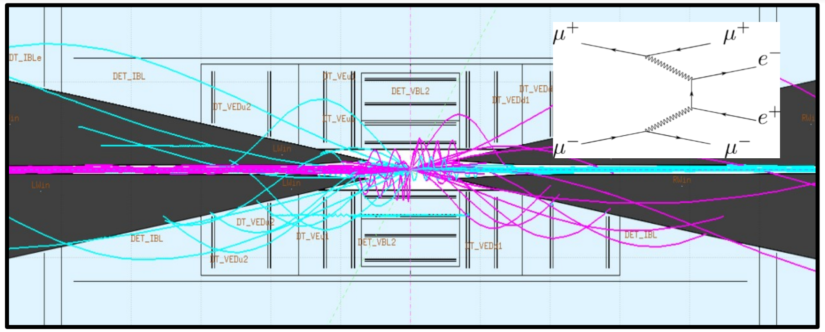
- On a CERN cluster (48 CPUs, 12 cores per socket), a simulation dedicated to the **ESPPU** is run. Up to 100 jobs are running in parallel
- The current objective is to achieve a **satisfactory statistics** before the end of the summer to boost detector reconstruction activities.
- **Missing resources**: for high statistics simulations, additional CPU is needed, or compromise on energy threshold for $e^{+/-}$ and photons

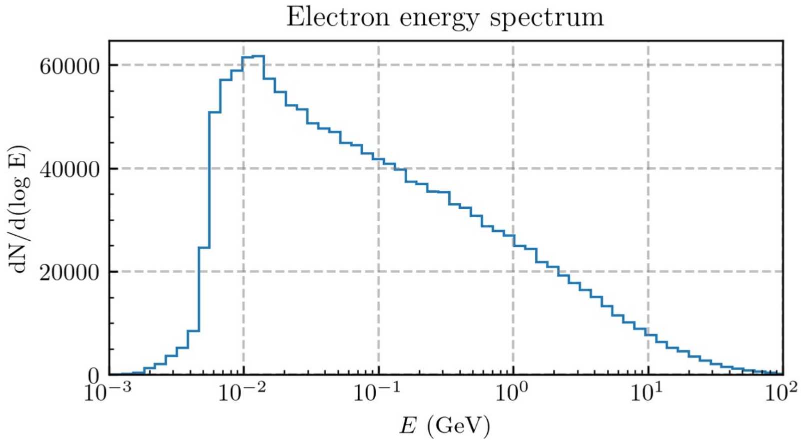


Incoherent pair production

	Description	Relevance as background
Incoherent e⁻e⁺ pair production	Pair creation through the collision of two real or virtual photons emitted by muons of counter-rotating bunches	Significant

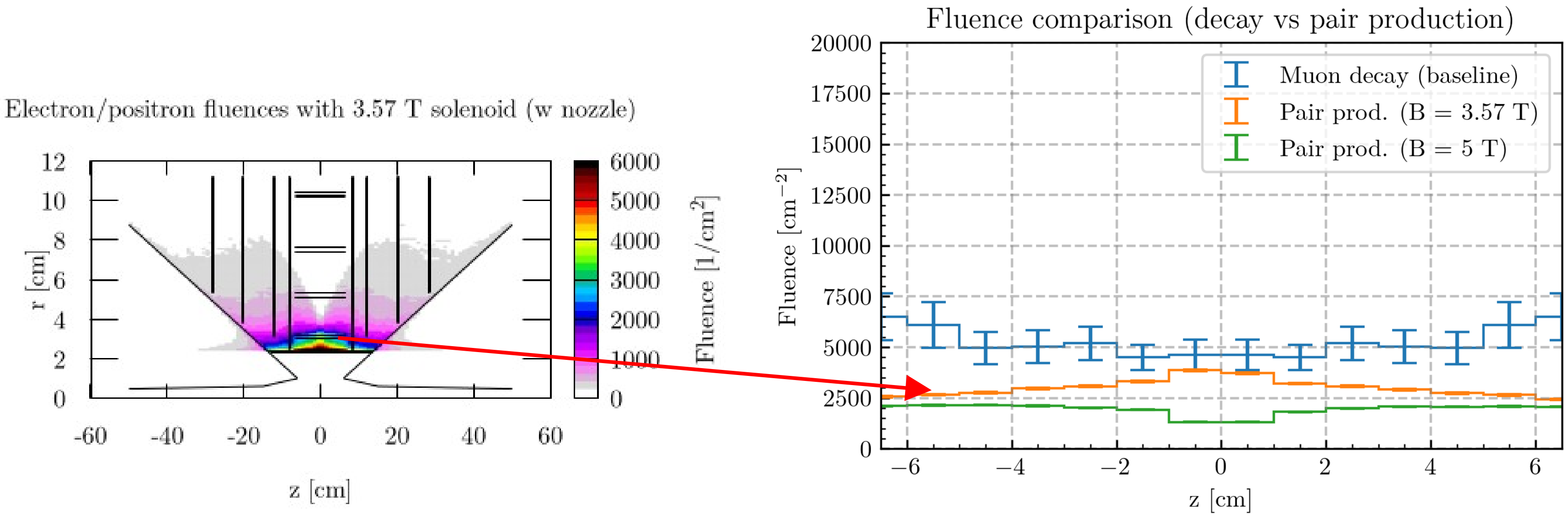
- High energy → non negligible beam-beam effects. The most important phenomenon is due to the **incoherent beam-beam pair production μ+μ- →μ+μ-e+e-**.
  - The incoherent pair production e^+/e^- are provided by D. Schulte and are obtained by a **Guinea-Pig simulation**
- Low total particle multiplicity.
- …**but** the produced **electrons are energetic** and they **impact** directly on the **detectors**, since are generated in the IP





Incoherent pair production background

- **Incoherent e+e- produced at bunch crossing** → difficult to remove with time and directional cuts
- The contribution from these secondary particles is not a dominant factor in the overall background, **but plays a major role in the innermost tracker layers.**
- Dominant sources of hits in the first layers (described in this talk)



Muon halo losses on aperture

- **Muon losses on the aperture are unavoidable**
  - Many processes can contribute to muon losses
  - Liners in final focus and nozzle follow 5σ envelope → aperture bottleneck
  - **Transverse beam cleaning system will be fundamental** to reduce halo-induced background in detector (like in all other high-energy circular colliders)
  - Muon beam halo cleaning is a challenge → need novel ideas (halo extraction instead of collimation)
- **IMCC plans for final ESPPU report:**
  - Refine shower simulations for (generic) halo losses in IR
  - Derive the max. allowed halo loss rate in IR (should stay below decay-background) → **provide specs for halo cleaning system**

***But:* studying a halo removal system until report is not feasible with the present resources**

Previous concepts of halo extraction developed at Fermilab:

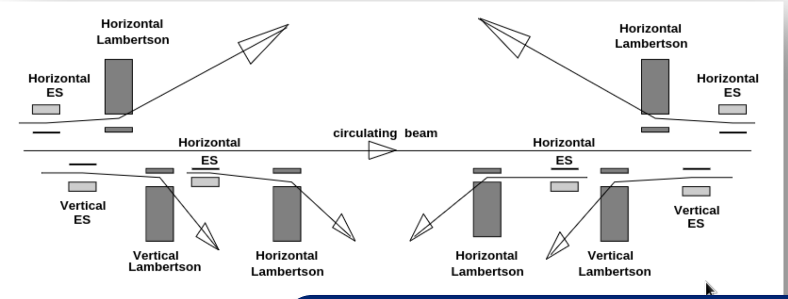
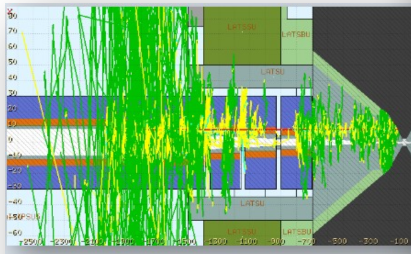


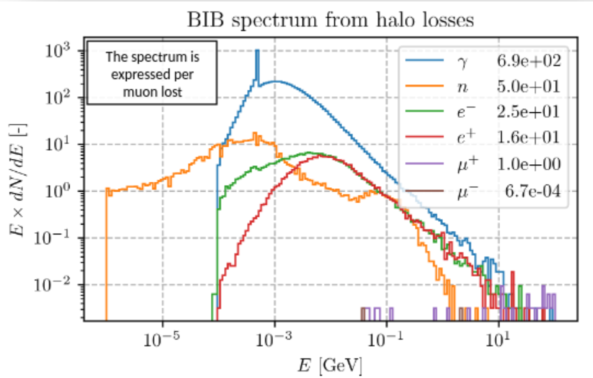
Figure 1: Schematic vi

A. Drozhdin et al., "Scraping beam halo in μ+μ- colliders", AIP Conf. Proc. 441, 242–248 (1998) link

First IMCC halo-induced background studies for 10 TeV:



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

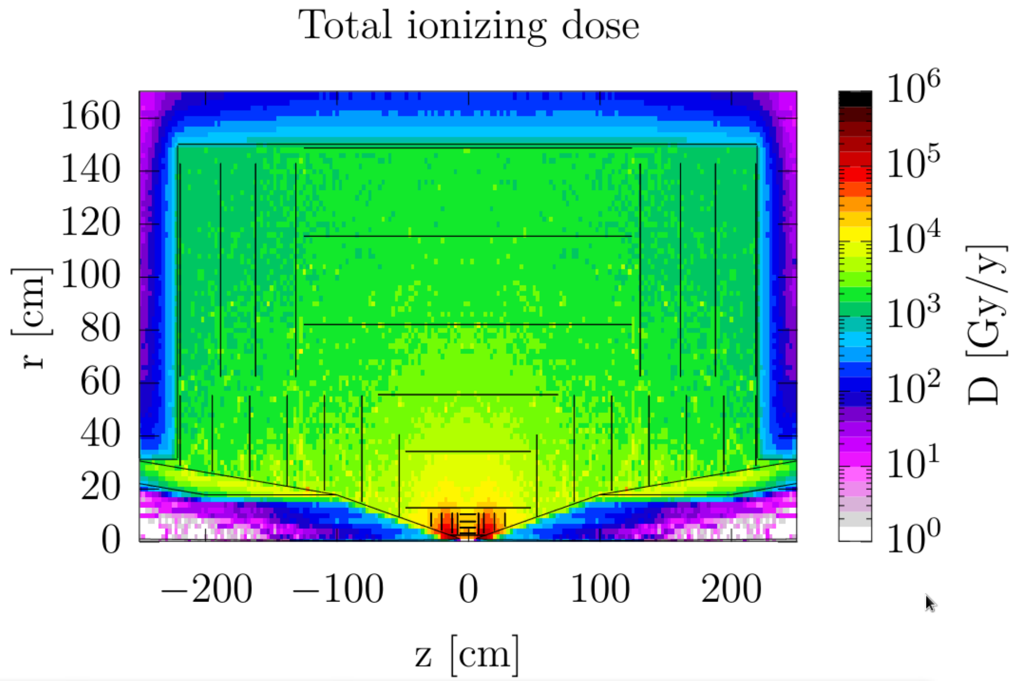


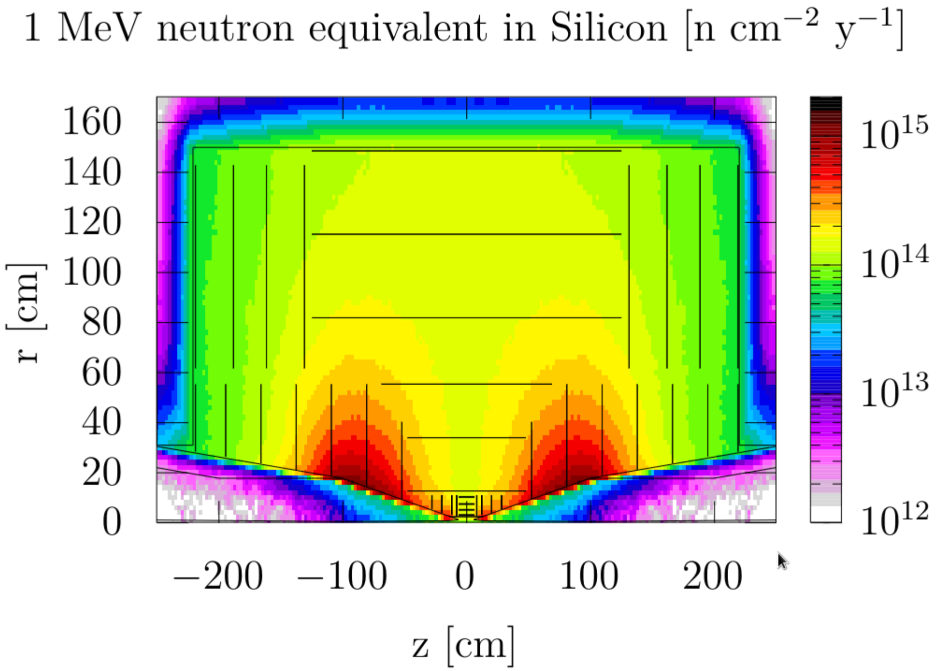
Radiation damage in detectors

For IMCC lattice version v0.4

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

Includes only contribution of decay-induced background!





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

- **IMCC plans for final ESPPU report:**
  - Redo radiation damage calculations with optimized 10 TeV nozzle and lattice (and new detector design)
  - Calculate contribution of other source terms (e.g. incoherent pairs, halo losses)

Conclusions

- Several lattice options for the final focusing of the muon collider have been considered and simulated
- **Final focusing magnets** → shielding design guarantees integrated **radiation load compatible with magnet operations**
- **BIB from muon decay** → assessed with various machine and nozzle configurations. Results used for detector performances studies
- **Nozzle optimization process ongoing**, with aim beyond ESPPU
- **Pair production** background has been assessed. Despite the low counts, those electrons play a dominant role in the **innermost tracker layers**
- The **radiation damage in detectors** assessed with previous lattice versions and expected to be similar also with the latest lattice version.
- **Missing efforts and resources:**
  1) Additional CPU for BIB production: in case of serialized production of very high statistics samples
  2) Engineering studies: integration of the nozzle is vital in the interaction region design
  3) Novel lattice design at 3 TeV
- Non conventional shielding strategies (asymmetric shielding, quasi-nozzleless interaction region etc.) are not currently under study, but could be considered in the future

Thank you

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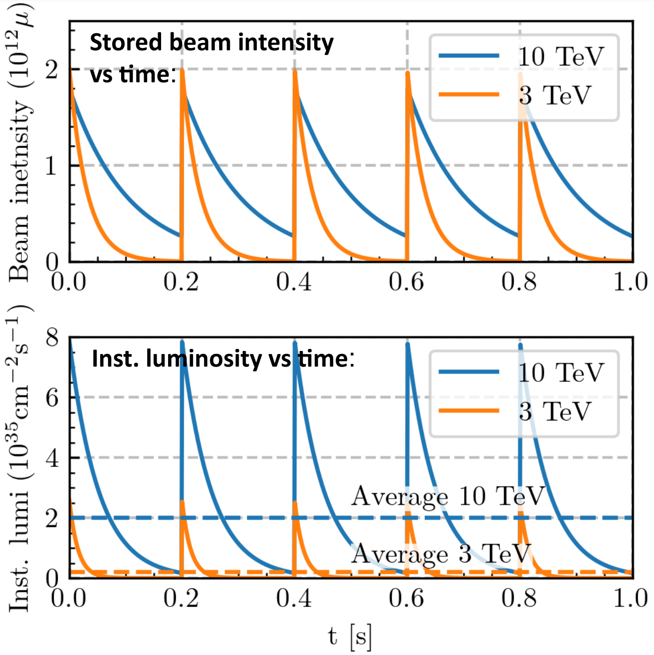
Recap collider parameters

	=3 TeV	=10 TeV
Beam parameters		
Muon energy	1.5 TeV	5 TeV
Bunches/beam	1	
Bunch intensity (at injection)	2.2×10^{12}	1.8×10^{12}
Norm. transverse emittance	25 µm	
Repetition rate (inj. rate)	5 Hz	
Collider ring specs		
Circumference	4.5 km	10 km
Revolution time	15.0 µs	33.4 µs
Luminosity		
Target integrated luminosity	1 ab^{-1}	10 ab^{-1}
Average instantaneous luminosity (5/10 yrs of op.)	2 x 10^{34} $\text{cm}^{-2}\text{s}^{-1}$ / 1 x 10^{34} $\text{cm}^{-2}\text{s}^{-1}$	2 x 10^{35} $\text{cm}^{-2}\text{s}^{-1}$ / 1 x 10^{35} $\text{cm}^{-2}\text{s}^{-1}$

$\tau = 2.2\times10^{-6}$ s

Muon decay	=3 TeV	=10 TeV
Mean muon lifetime in lab system ($\gamma\tau$)	0.031 s	0.104 s
Luminosity lifetime	1039 turns	1558 turns



See also parameter doc: https://cernbox.cern.ch/s/NraNbczzBSXctQ9

Radial build of the magnets

- The radial build of the magnets for the version 0.8 is listed in table
- Still conflicting requirements in terms of field strengths and magnet apertures

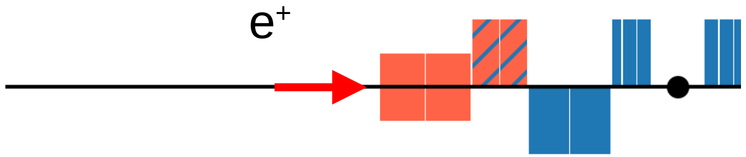
Radial build	Thickness (mm)
beam screen	0.01
shield	2.53
shield support +thermal insulation	1.1
cold bore	0.3
insulation (kapton)	0.05
clearance + liquid helium	0.01
Sum	4

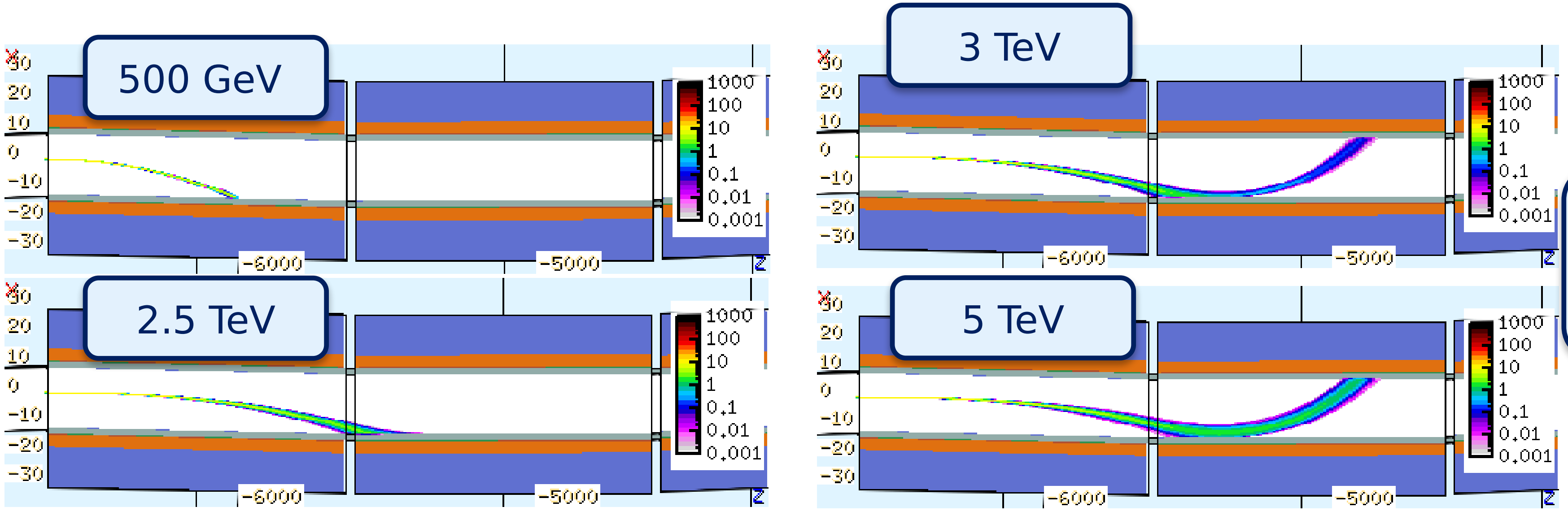
Increased to 4.53 for the dipoles

Name	L	Magnet aperture radius [cm]
IB2	6	16
IB1	10	16
IB3	6	16
IQF2	6	14
IQF2_1	6	13.3
IQD1	9	14.5
IQD1_1	9	14.5
IQF1B	2	10.2
IQF1A	3	8.6
IQF1	3	7

Chicane effect (v 0.7 and 0.8)

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

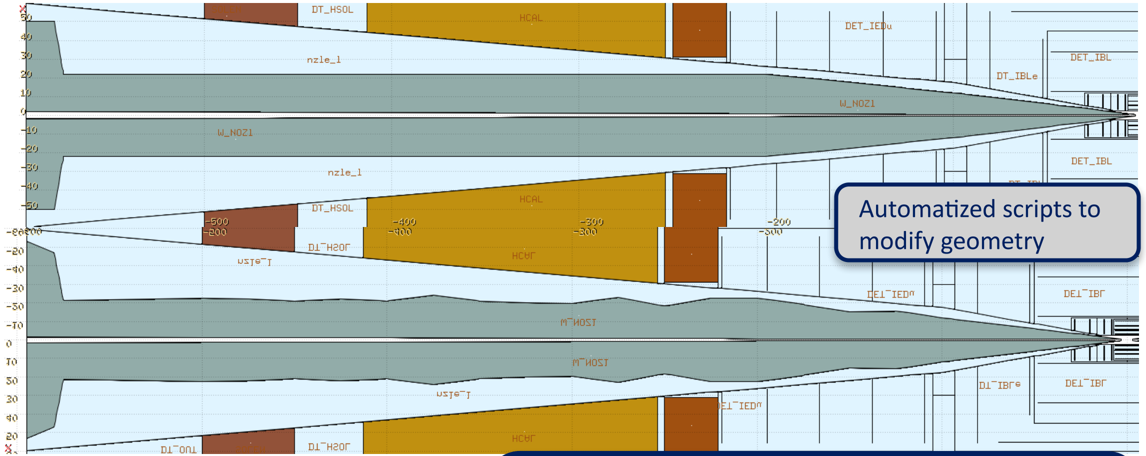




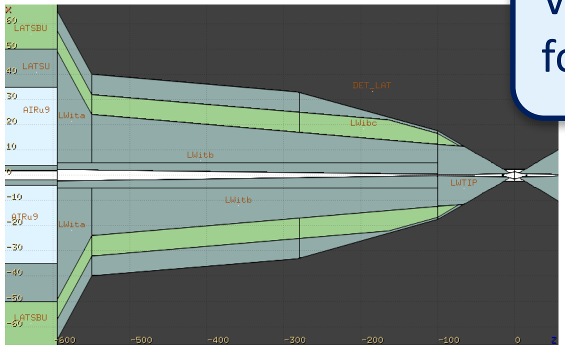
Synchrotron radiation is a dominant effect!

Nozzles optimization process

- The **nozzle optimization** is a **complex problem** with several **conflicting requirements**:
  - Shielding must be feasible from the engineering point of view (for structural support, accessibility, machinability)
  - Minimum amount of blind angle for the detectors
  - Thickness capable of minimizing the amount of background going in the detector area
- Current nozzle configuration developed from MAP one with small adjustment and **froze** for the **European particle strategy.**
- Optimization process will continue in the upcoming months



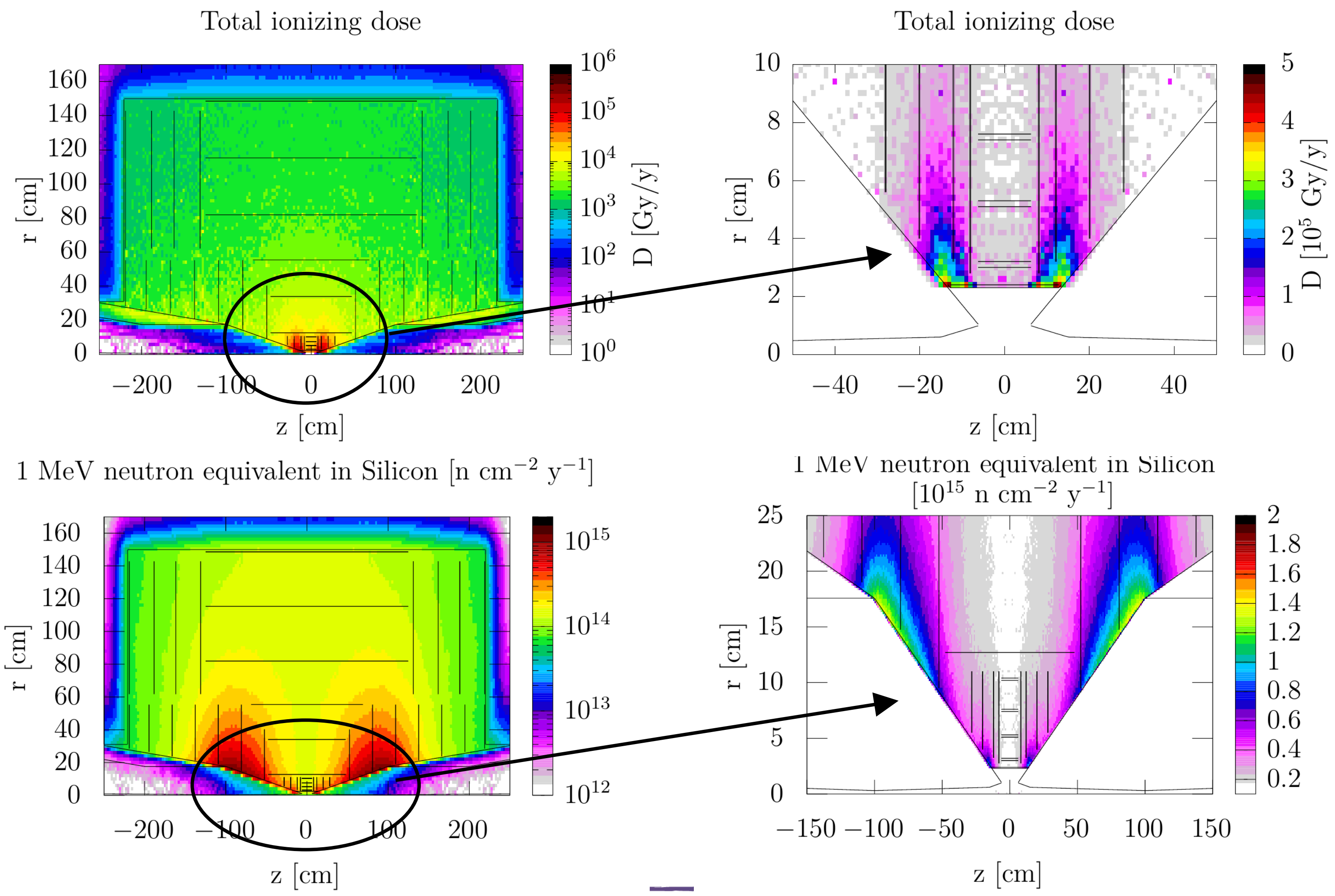
Automatized scripts to modify geometry



Various options and strategies for the nozzle optimization

Radiation damage (v 0.4)

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



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