Machine-detector interface and beam-induced background studies for a 10 TeV muon collider

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ICFA mini workshop: Beam-Beam Effects in Circular Colliders BB24

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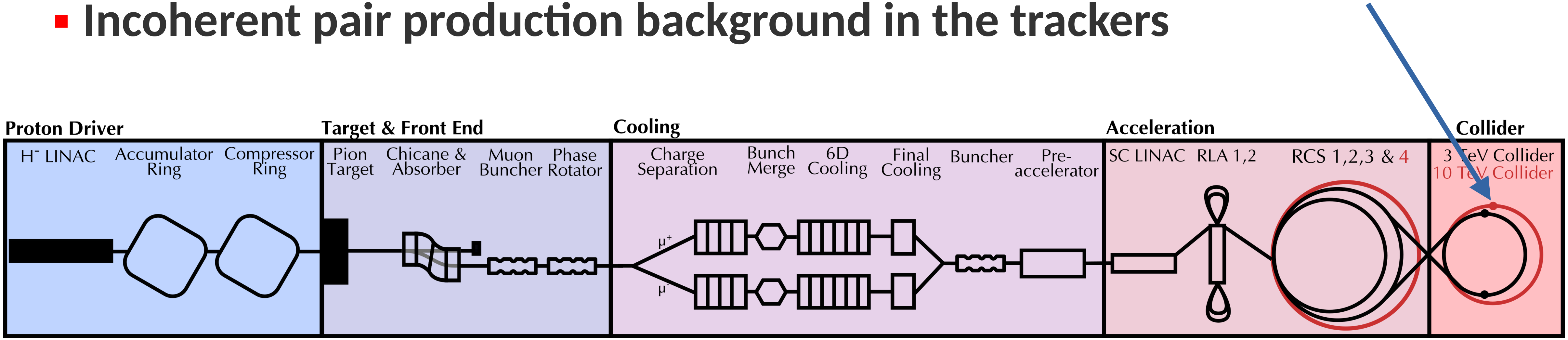
On behalf of the IMCC

Funded by the European Union

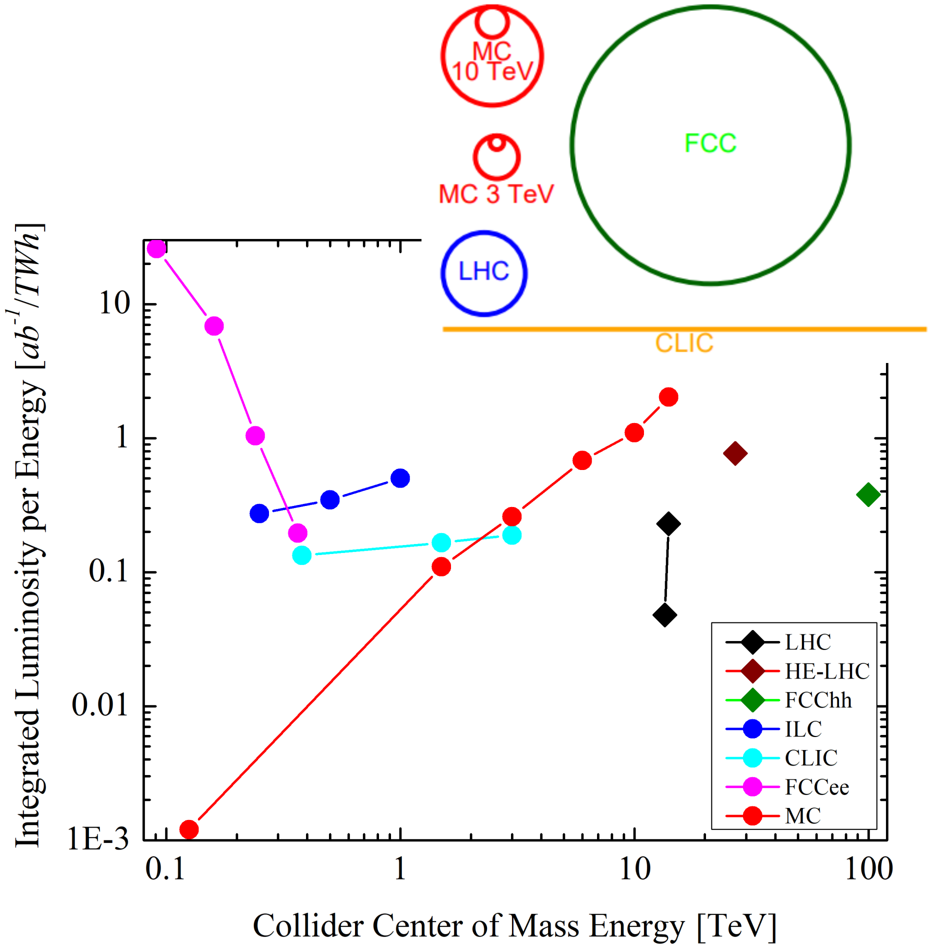
Outline

- Muon collider and MDI overview
- Beam induced background sources
- Current existing lattices
- Decay induced background
- Incoherent pair production background in the trackers

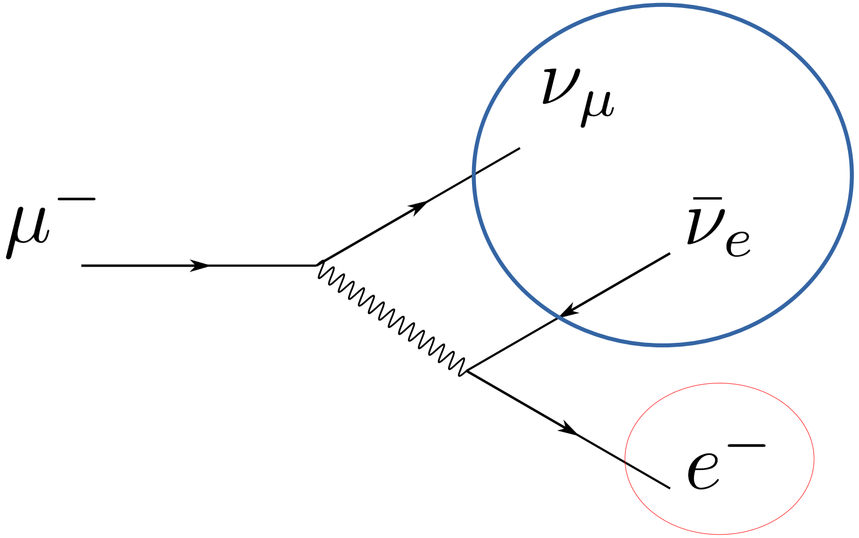


Muon colliders: motivation

- Muon collider are compact and efficient machines. They are **precision** (high luminosity) & **discovery** (high collision energy without partonic effects) machines.
- Extensive work done by the Muon Accelerator Program (MAP)
- (Among the) several challenges to address:
  1) Rapid muon beam production and acceleration
  2) Fast cooling with novel techniques (ionization cooling, final cooling)
  3) **Radiation load & Beam-Induced Background from the muon decay**



Muon colliders: muons decay



Neutrino:
Non relevant for the machine radiation protection or the beam induced background

Electrons:
they are produced at high energy, and are expected to be the most component of the beam-induced background

	HL-LHC		MC (=3 TeV)	MC (=10 TeV)
Main heat source	pp debris	E-cloud	Muon decay	Muon decay
Region	Triplet+D1	Arcs	entire ring	entire ring
Power/meter*	**few 10^{-2} kW/m**	**few 10^{-3} kW/m**	**0.4 kW/m****	**0.5 kW/m****
Magnets	**superconducting**		**superconducting**	**superconducting**

MC = unprecedented power load in a cold machine!

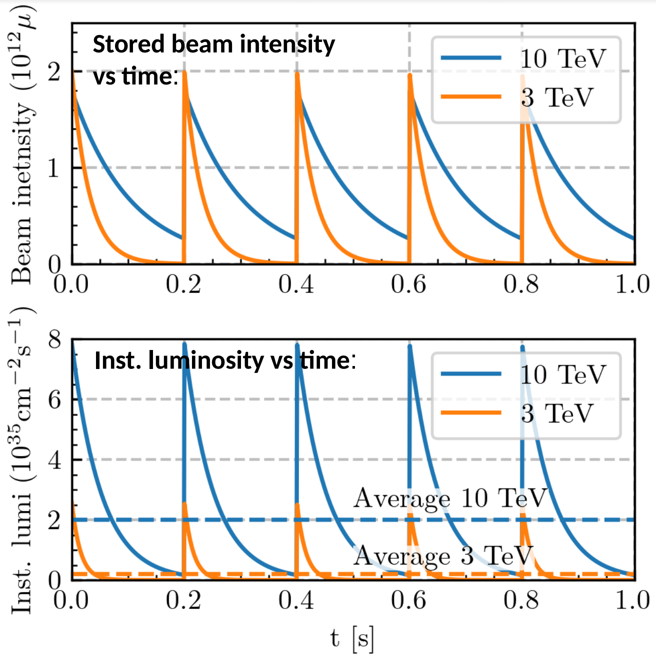
Recap collider parameters

Example as discussion basis numbers will change

	=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.)	2×10^{34} $\text{cm}^{-2}\text{s}^{-1}$ / 1×10^{34} $\text{cm}^{-2}\text{s}^{-1}$	1×10^{35} $\text{cm}^{-2}\text{s}^{-1}$ / 2×10^{35} $\text{cm}^{-2}\text{s}^{-1}$

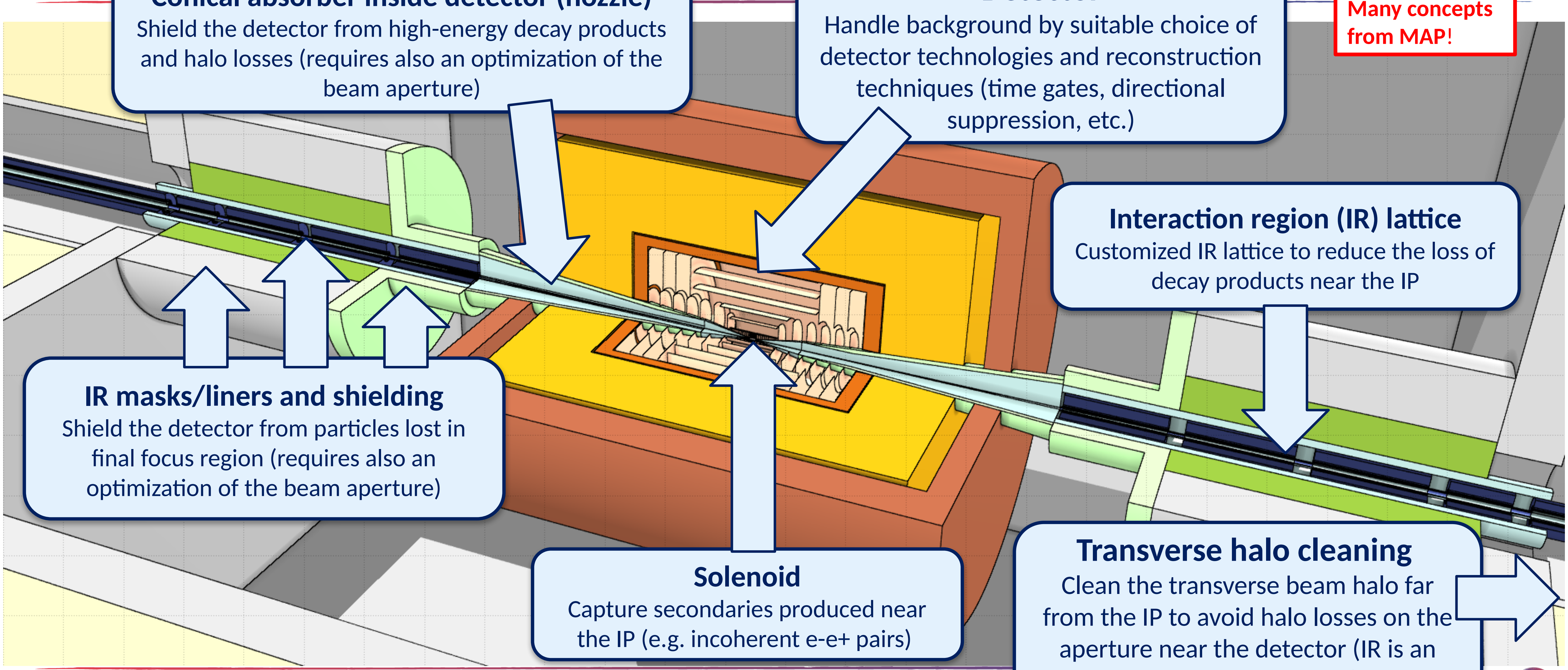
$\tau = 2.2\times10^{-6}$ s

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



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

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)

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

Many concepts from MAP!

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)

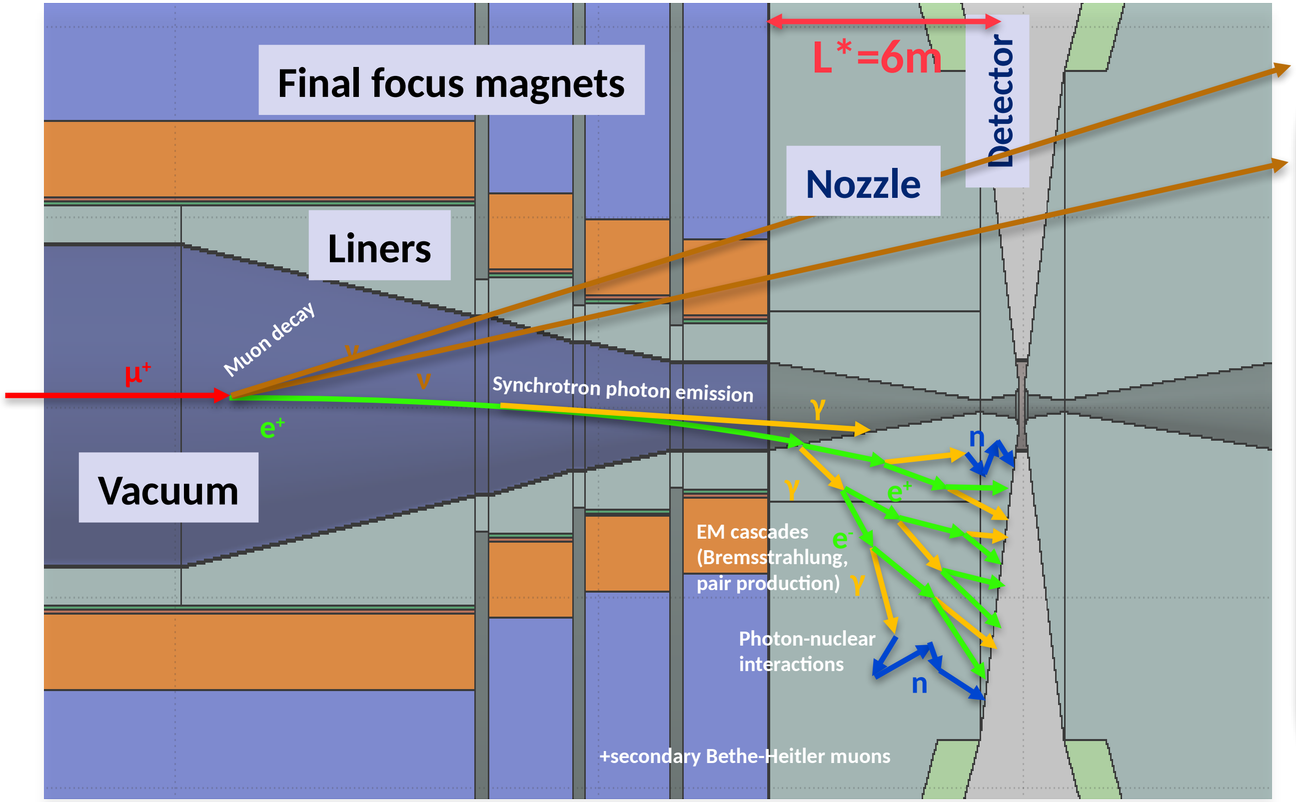
Transverse halo cleaning
Clean the transverse beam halo far from the IP to avoid halo losses on the aperture near the detector (IR is an aperture bottleneck)

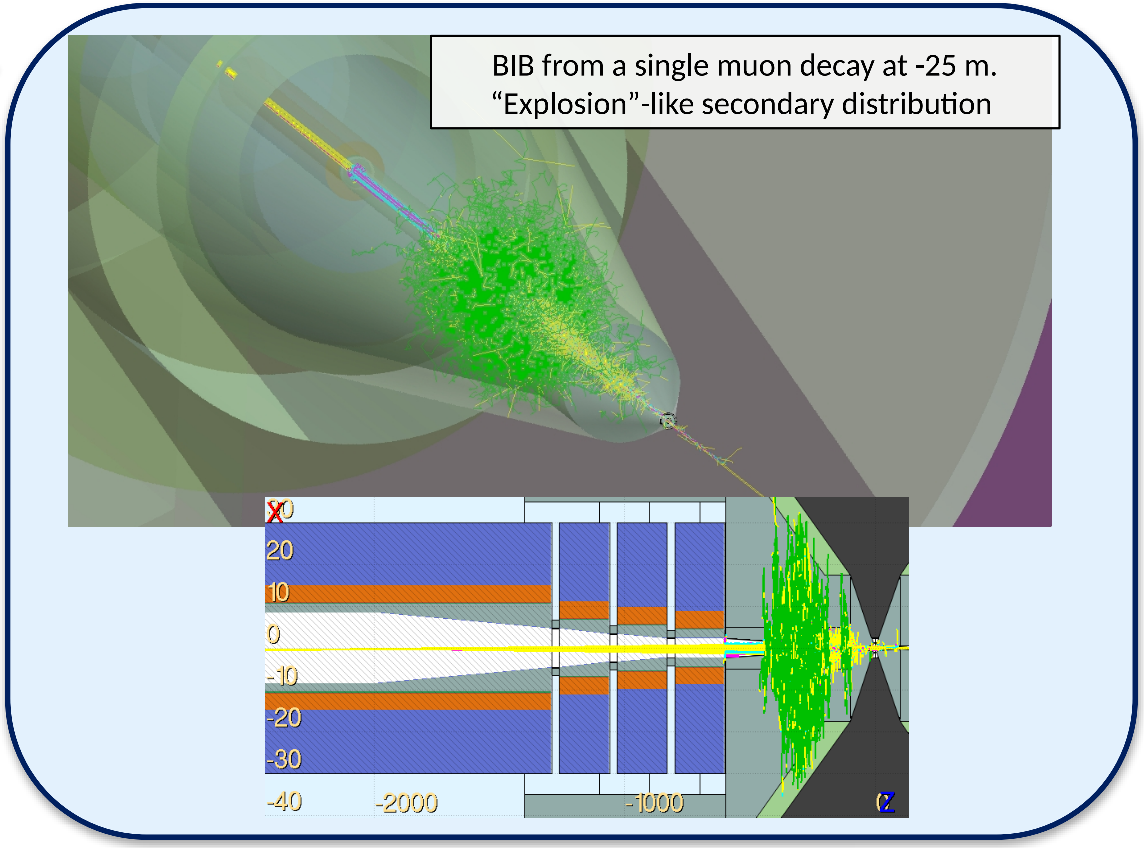
Beam-induced background

	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**

Decay-induced background

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

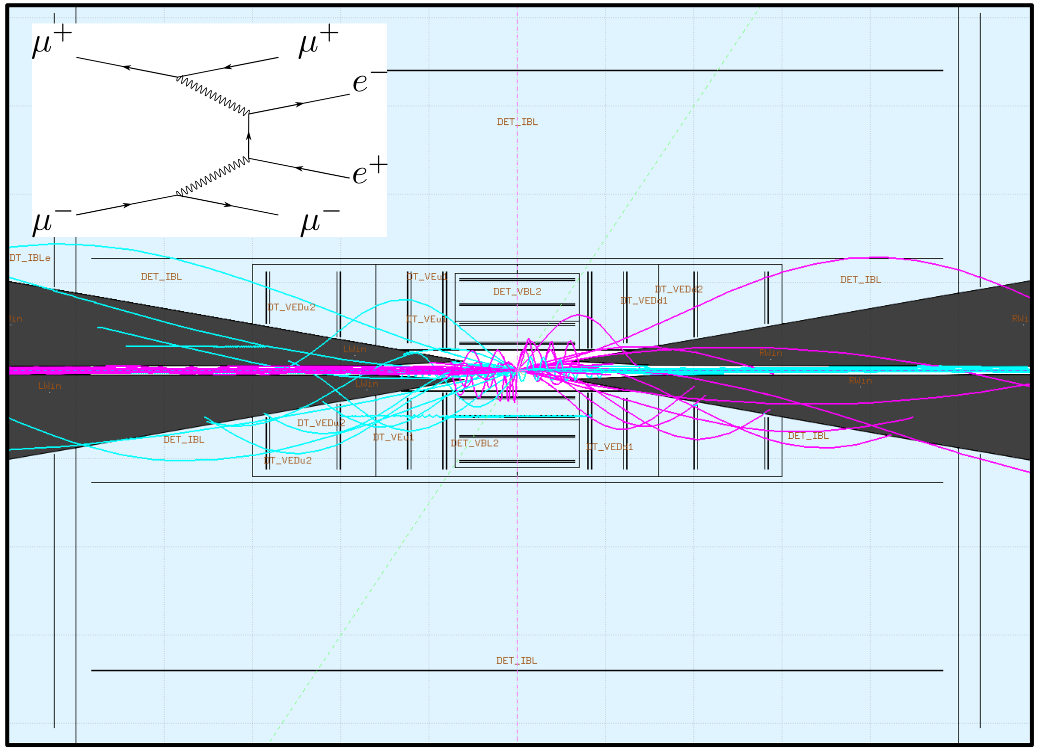



BIB from a single muon decay at -25 m.
"Explosion"-like secondary distribution

Incoherent pair production

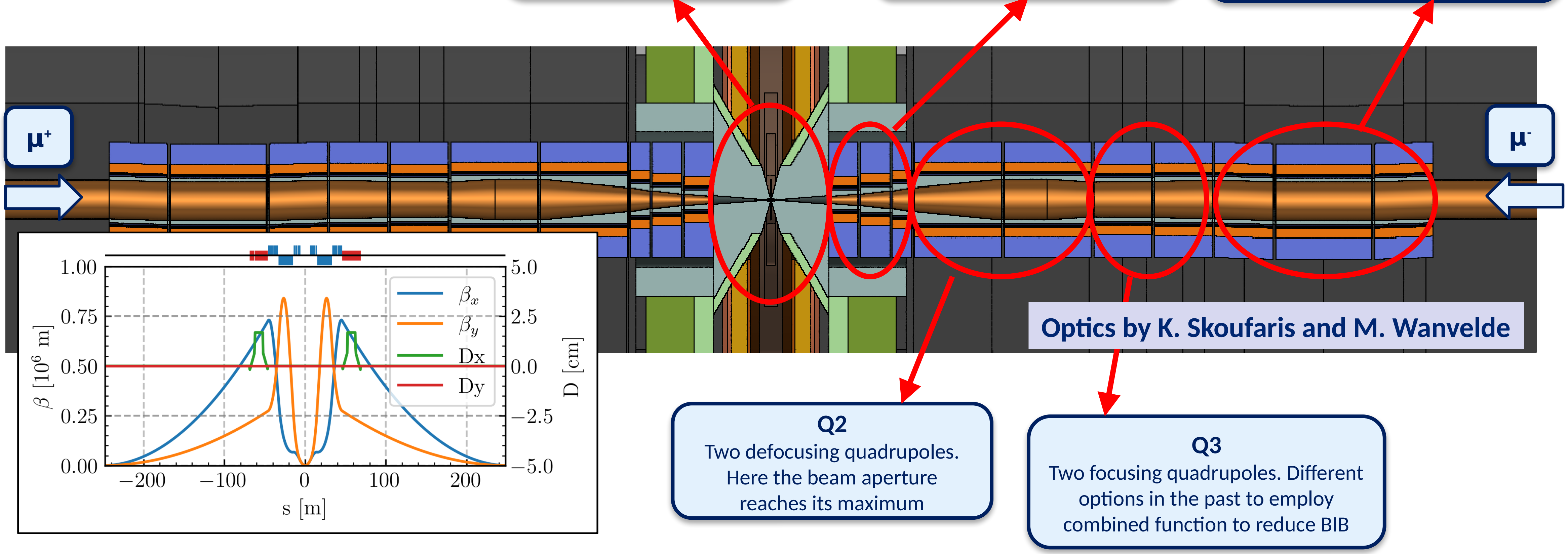
	Description	Relevance as background
Incoherent e^-e^+ pair production	Pair creation through the collision of two real* or virtual photons emitted by muons of counter-rotating bunches	Significant

- 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



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

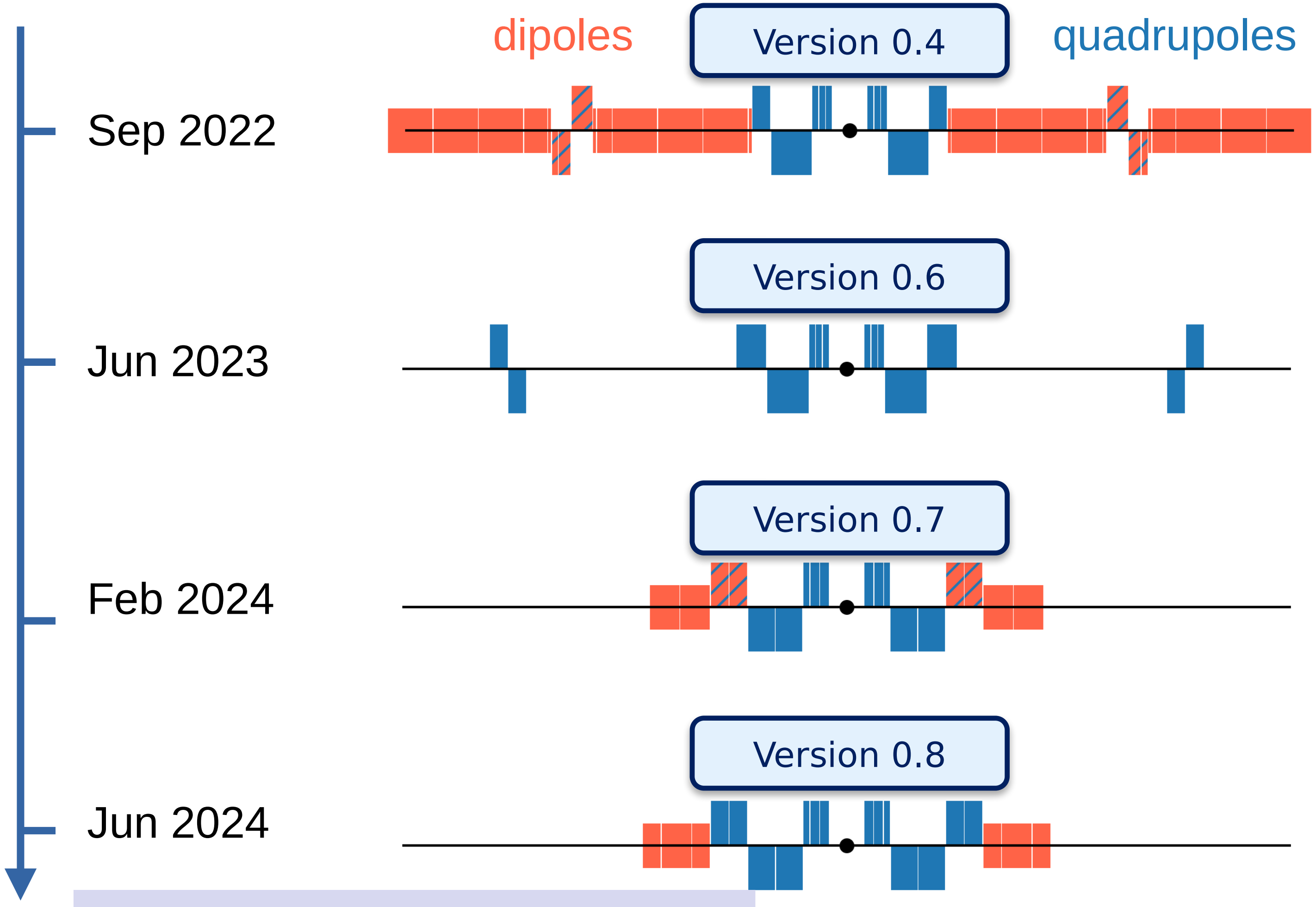
Chicane
Three dipoles that remove the electrons coming from the line

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

Optics by K. Skoufaris and M. Wanvelde

Evolution of the optics



dipoles

quadrupoles

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

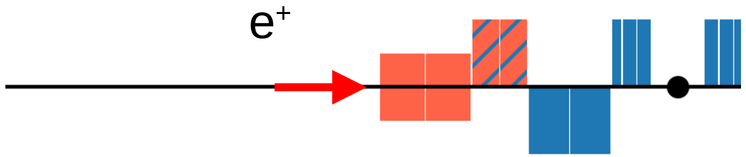
Version 0.8

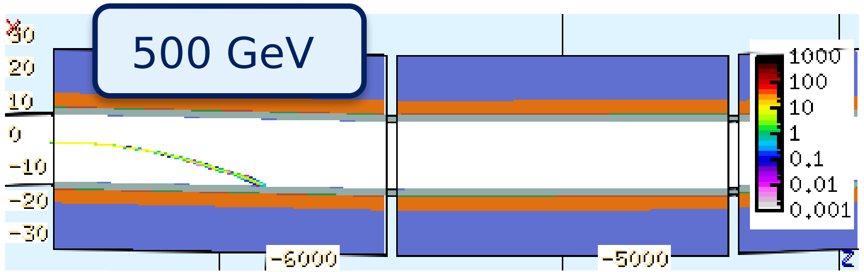
The chicane concludes with 0 angle, and the magnet aperture is increased in the dipoles

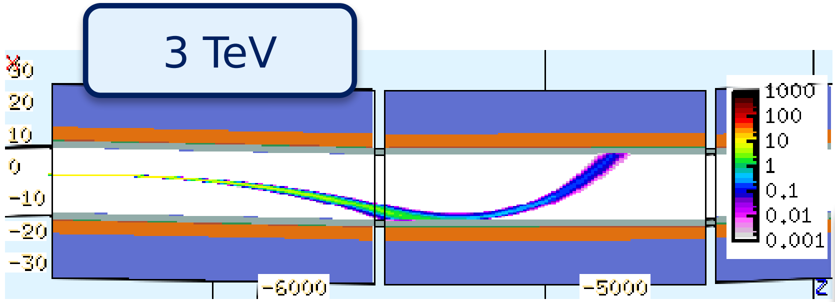
Optics by K. Skoufaris and M. Wanvelde

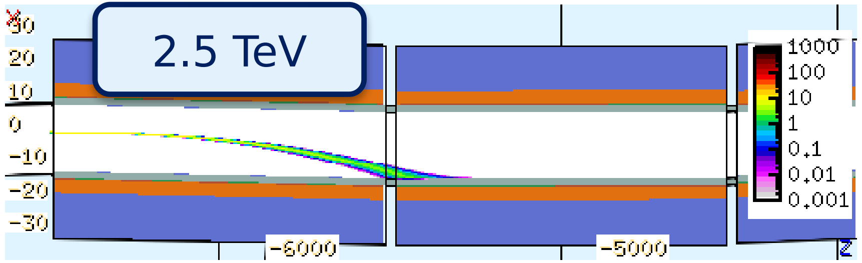
Chicane effect (v 0.7 and 0.8)

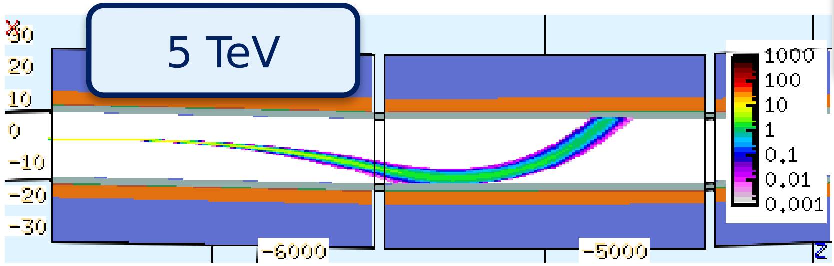
- Considering a pencil beam positrons along the ideal trajectory, the path in the first two magnets is reported.
- Two hotspots are generated in the first and second magnets











Synchrotron radiation is a dominant effect!

Radiation load on the final focus

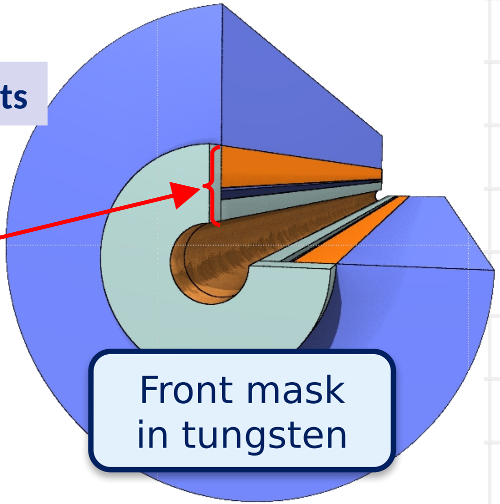
- In all magnets, the limiting quantity is the total **ionizing dose (TID)** in organic materials insulation, spacers etc.)
- The current limitation assumed for the yearly TID is around **5-10 MGy/y** → **50 MGy** during the collider lifetime.
- We assume an **operational time of 1.2E7 second per year**,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

Table: 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

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

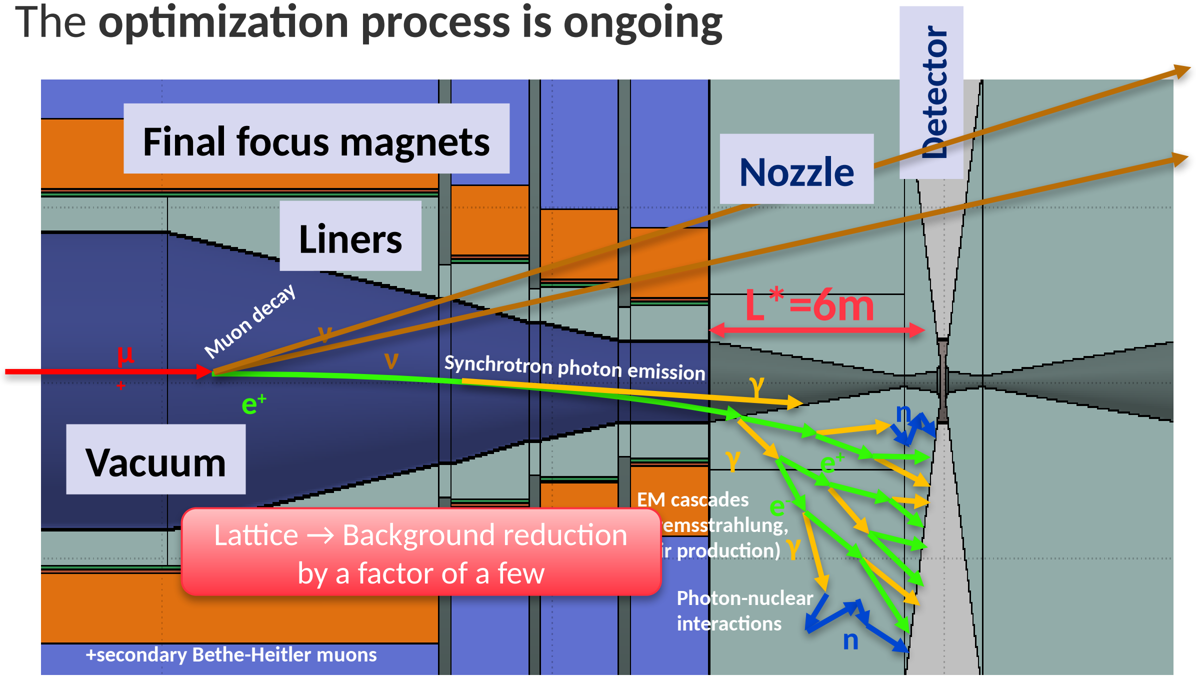


Front mask in tungsten

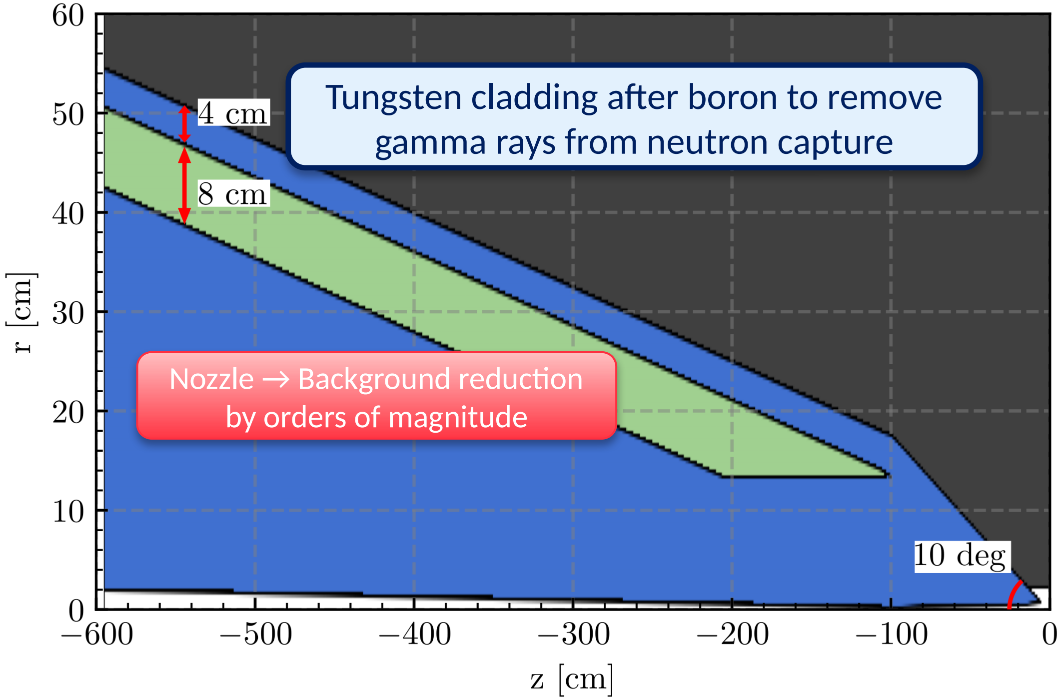
Conical shielding: nozzles

- 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 present nozzle for the 10 TeV muon collider.
- It reduces the background of several order 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

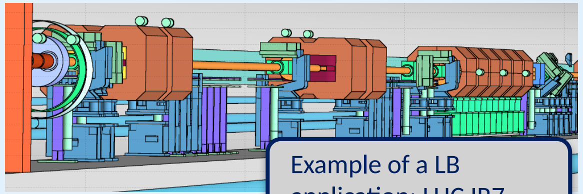
1. Lattice design

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 load (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

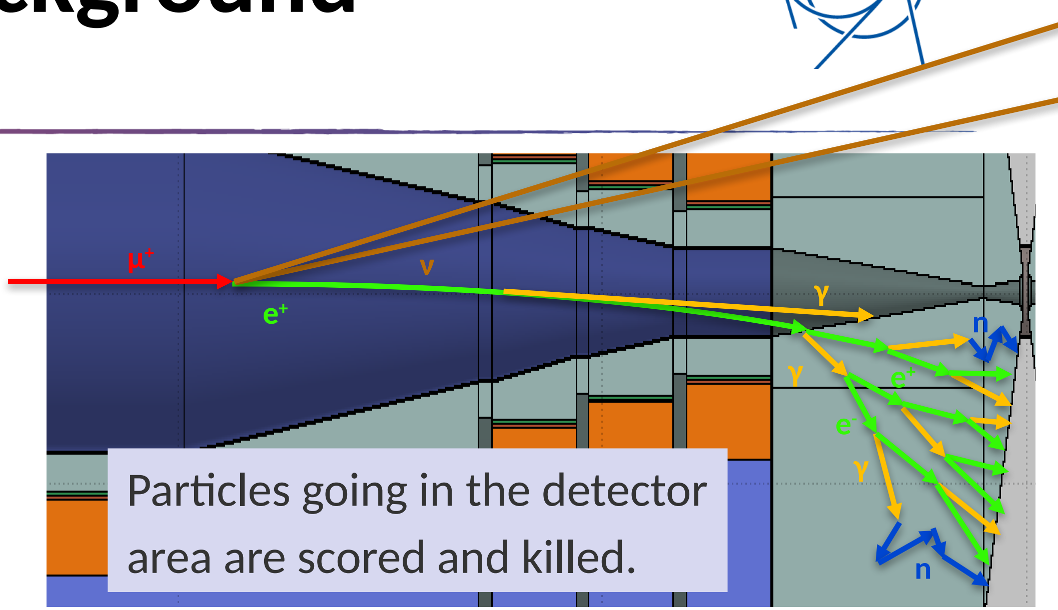
Iteration with lattice design experts to mitigate the BIB

BIB data to detector experts

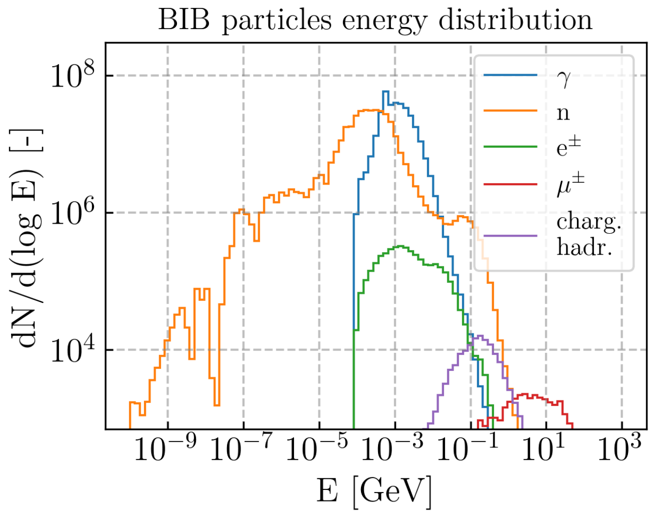
CERN STI/BMI is currently responsible for the geometry built at √s = 3 and 10 TeV

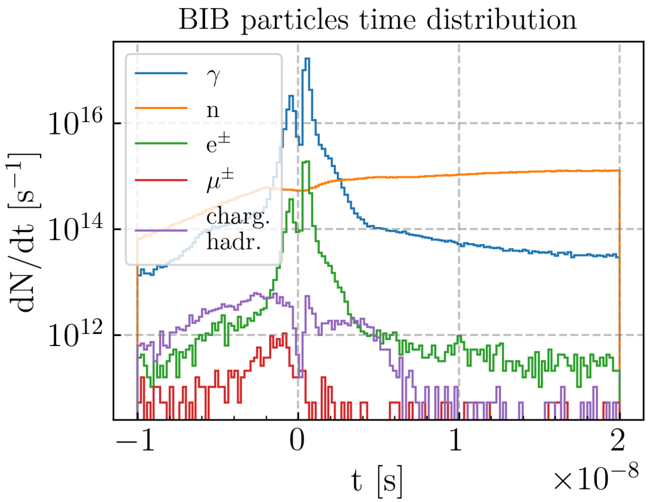
Decay-induced background

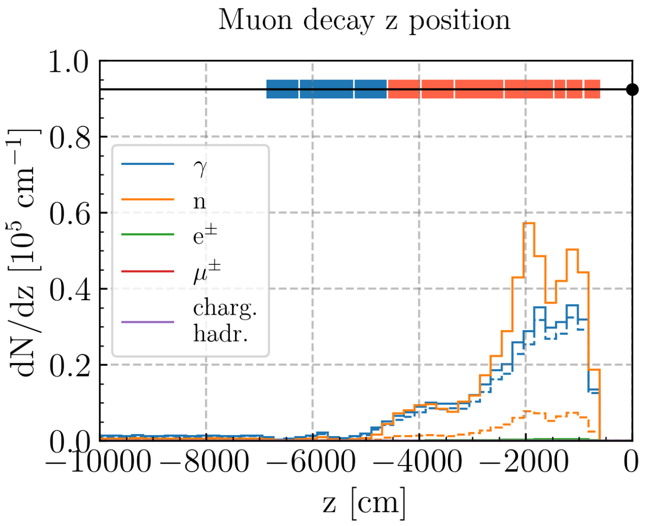
- Background particles (from decay) entering detector per bunch crossing (with time cut [-1:15] ns):
  - O(10^8) **γ** (>100 keV),
  - O(10^7) **n** (>10^{-5} eV)
  - O(10^6) **e+ & e-** (>100 keV)
- The shapes of the energy, time and spatial distribution are partially affected by the lattice, but the nozzle has a dominant effect



Particles going in the detector area are scored and killed.







Comparison lattices

- All different lattices offer consistent performances at 10 TeV. More advanced metrics than the total particle multiplicity should be used

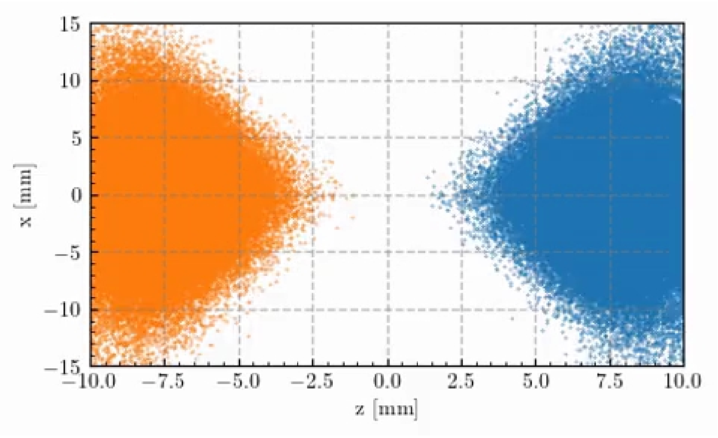
Table: number of particles entering in the detector area per bunch crossing (single bunch)

Collider energy	1.5 TeV	3 TeV	10 TeV (v 0.4)	10 TeV (v 0.7)	10 TeV (v 0.8)
Photons	7.1E+7	9.6E+7	9.6E+7	1.6E+8	1.6E+8
Neutron	4.7E+7	5.8E+7	9.2E+7	1.5E+8	1.4E+8
e^+/e^-	7.1E+5	9.3E+5	8.3E+5	9.2E+5	8.9E+5
Ch. hadrons	1.7E+4	2.0E+4	3.0E+4	4.9E+4	5.2E+4
Muons	3.1E+3	3.3E+3	2.9E+3	5.0E+3	3.3E+3

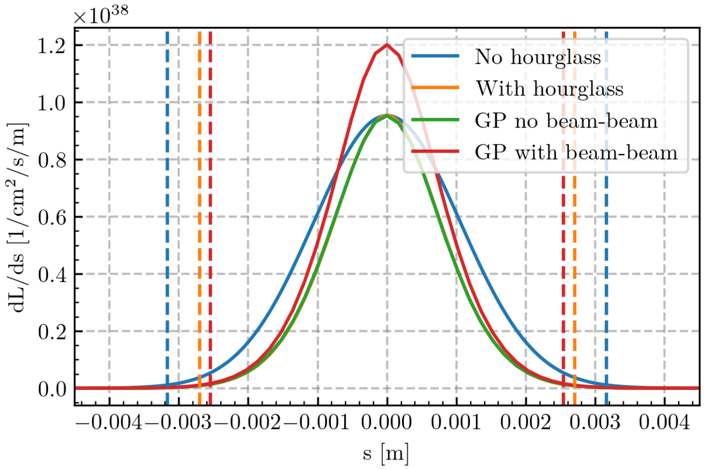
Beam profile in the IP

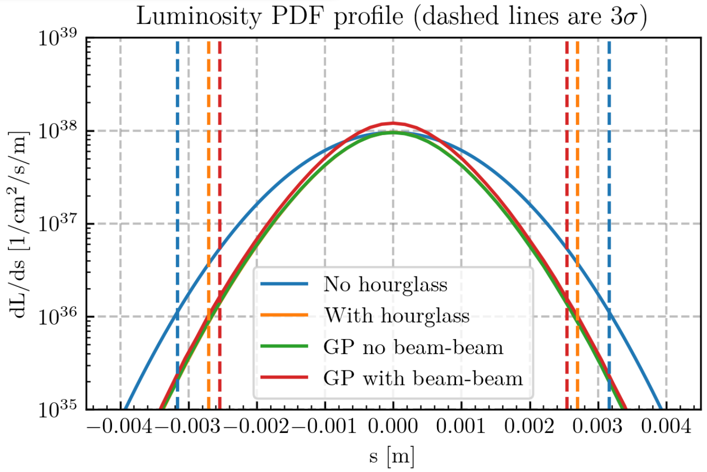
- **The pinch effect** has an influence on the luminosity of the collider. To better understand its magnitude, a realistic model of the beam halo has to be implemented
- I calculated the luminous region with and without beam effects. In all cases, the interactions will occur in the very close proximity of the IP.

Non negligible hourglass effect: β depends on s



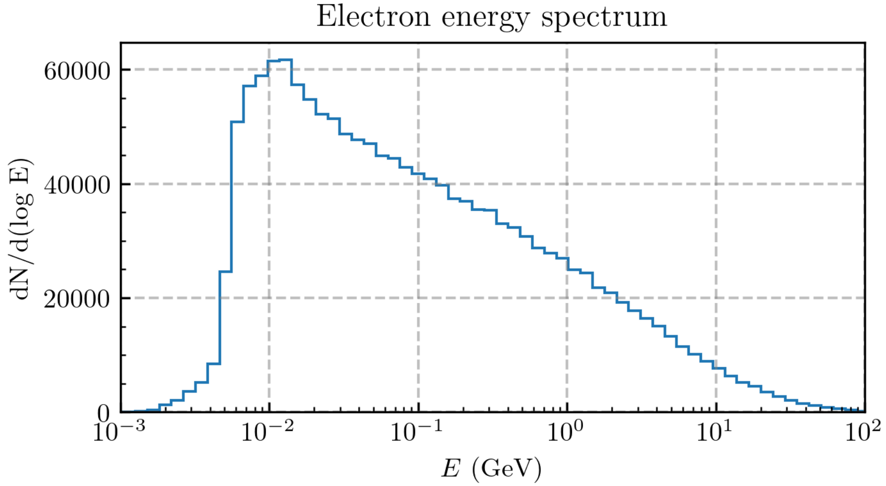
Tiny luminous region:
σ << 1 cm

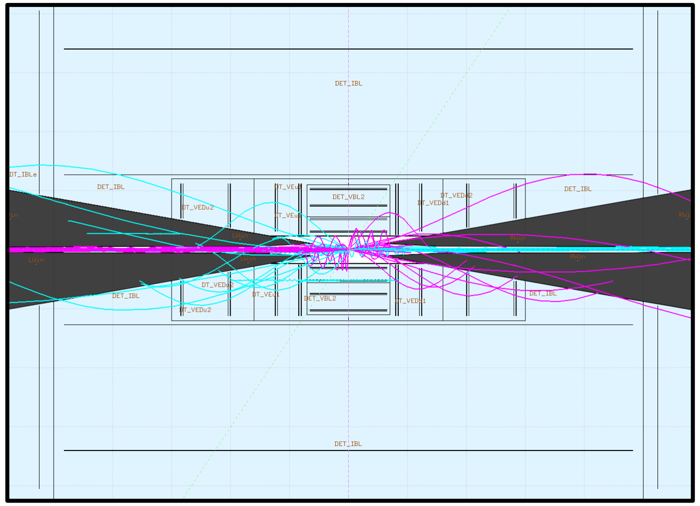




Incoherent pair production background: sample

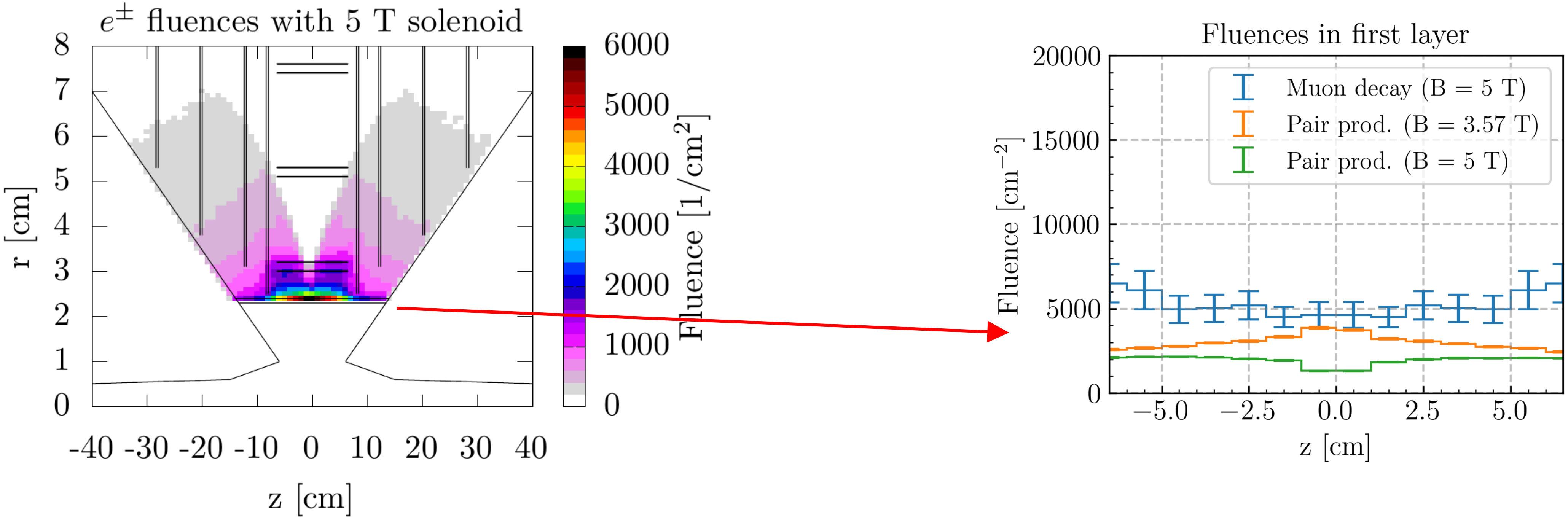
- An updated **Guinea-Pig** version was provided by Daniel Schulte.
- The new software version allows to fully simulate the interaction between **muons**, while in the past the interactions were simulating with a mass scaling of the electrons.
- With higher virtuality, pairs can have more **kinetic energy**.





Incoherent pair production background: background

- When including the contribution of the interactions with the nozzles, there is an additional fluence of secondary particles.
- The contribution from these secondary particles is not a dominant factor in the overall background, **but could be important in the innermost tracker layers.**



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 feasibly with the present resources

Previous concepts of halo extraction developed at Fermilab:

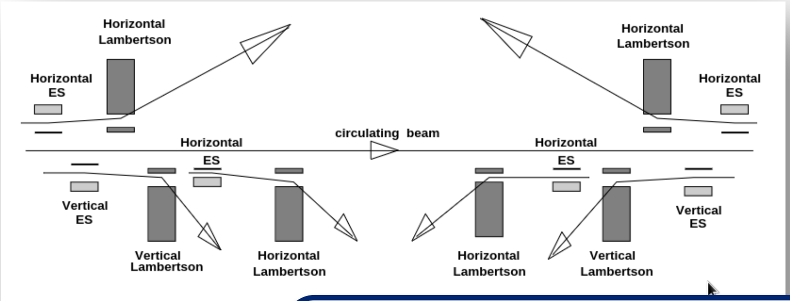
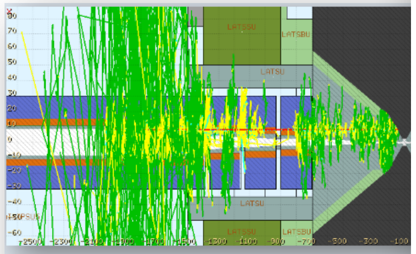


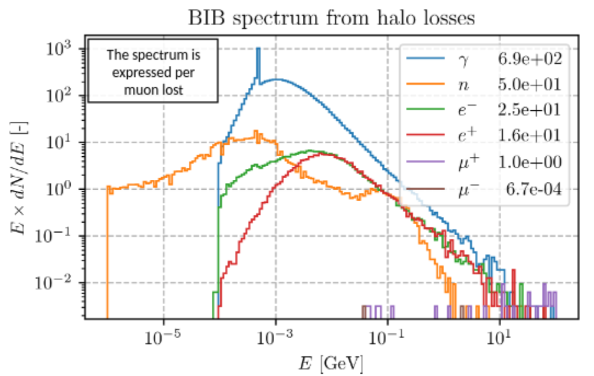
Figure 1: Schematic vi

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.



Conclusions

- Muon decay yields the dominant background in multi-TeV muon colliders
- Massive nozzle-like absorbers are needed to shield the secondary showers
- A chicane helps to suppress the contribution of distant decays in the IR
- Incoherent pair production cannot be neglected since the electrons/positrons can directly impact on the detector

Thank you

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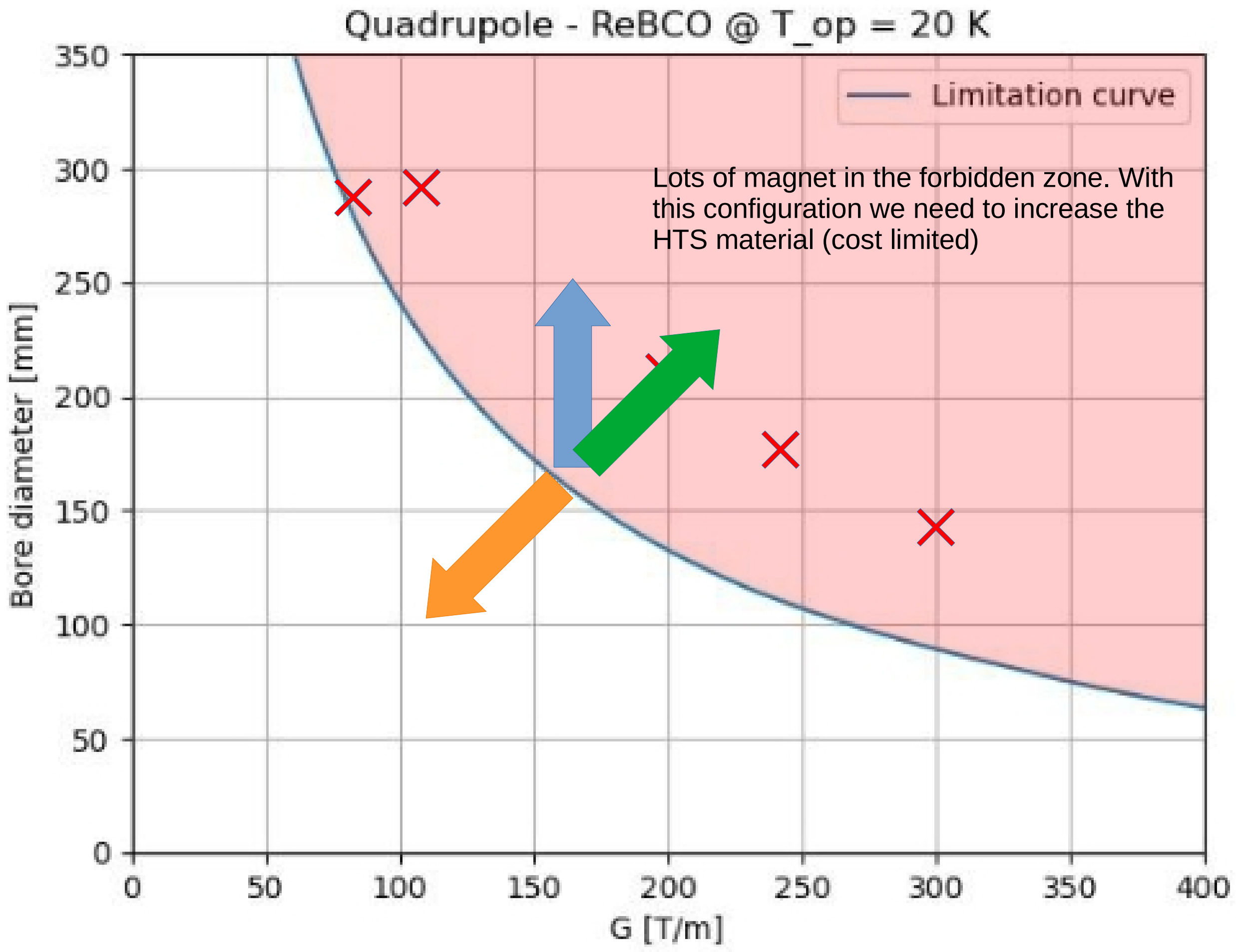
Conflicting requirement for magnet shielding



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 limitation.
- Beam dynamics requirement: larger apertures and field strengths allows for easier control on the beam shape in the final focus

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