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International MUON Collider Collaboration

MuCol

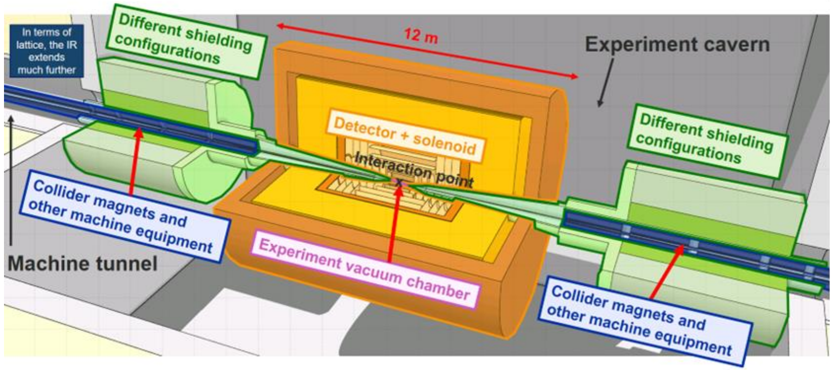
Machine Detector Interface (MDI): challenges and R&D

A. Lechner, D. Calzolari, M. Vanwelde, C. Carli, D. Schulte, D. Lucchesi, L. Castelli, S. Jindariani, B. Caiffi, L. Bottura, S. Mariotto, D. Novelli, A. Bersani, P. Borges De Sousa, and many more

Primary goals of IR and MDI design

(wrt physics performance)

- Achieve the **desired luminosity** (i.e., achieve the desired β*)
- Provide a **sufficiently long drift space** around the interaction point (IP) to house the detector and the detector solenoid
- Enable a **sufficiently large detector acceptance** (in an ideal world 4π) and minimize material budget for the central region
- Sufficiently **mitigate the beam-induced background** and the cumulative radiation damage in the detector and machine



Partially conflicting requirements …

Finding compromises is key!

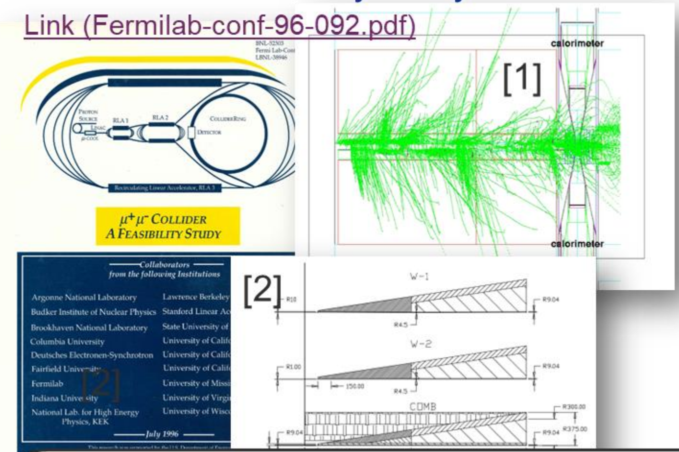
*Artistic illustration of the **decay-induced** background*

History of Muon Collider MDI design studies

Proposal for multi-TeV muon colliders exists since decades → IR and MDI studies since the 1990s

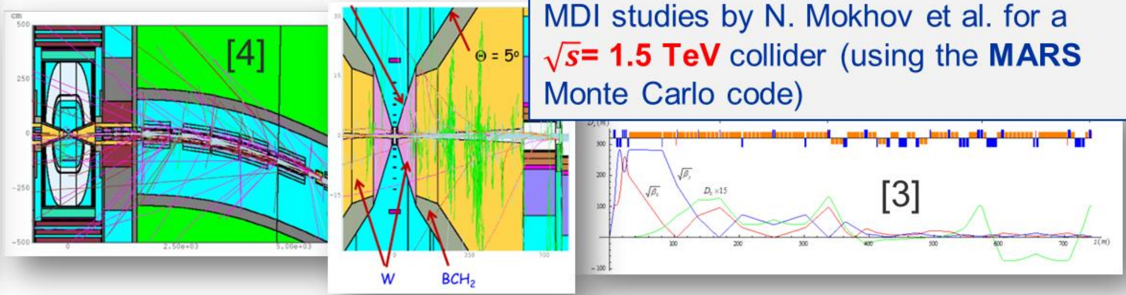
1990-1999: Feasibility Study in the US

Link (Fermilab-conf-96-092.pdf)

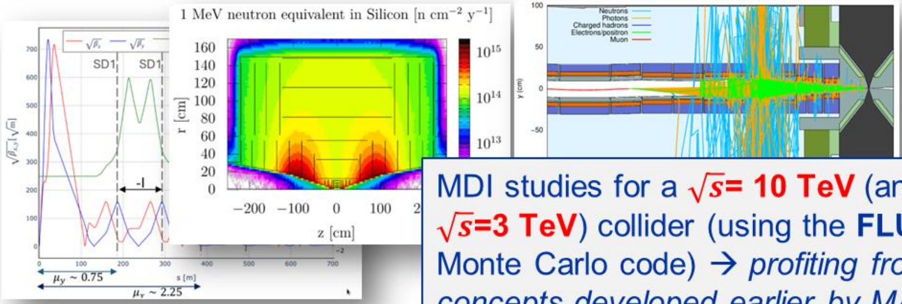


2010-2017: Muon Accelerator Program (**MAP**) in the US

MDI studies by N. Mokhov et al. for a $\sqrt{s}$= **1.5 TeV** collider (using the **MARS** Monte Carlo code)



Since 2022: International Muon Collider Collaboration (**IMCC**)



MDI studies for a $\sqrt{s}$= **10 TeV** (and a $\sqrt{s}$=**3 TeV**) collider (using the **FLUKA** Monte Carlo code) → *profiting from many concepts developed earlier by MAP*

[1] C.M. Ankenbrandt et al., *Status of muon collider research and development and future plans*, PRSTAB 2, 1999.
[2] N.V. Mokhov, S.I. Striganov, *Simulation of backgrounds in detectors and energy deposition in superconducting magnets at μ+μ- colliders*, AIP Conf. Proc. 372, p. 234–256, 1996.
[3] Y.I. Alexahin et. al., *Muon collider interaction region design*, PSRTAB 14, 2011.
[4] N.V. Mokhov, S.I. Striganov, *Detector Backgrounds at Muon Colliders*, Physics Procedia, Volume 37, 2012.

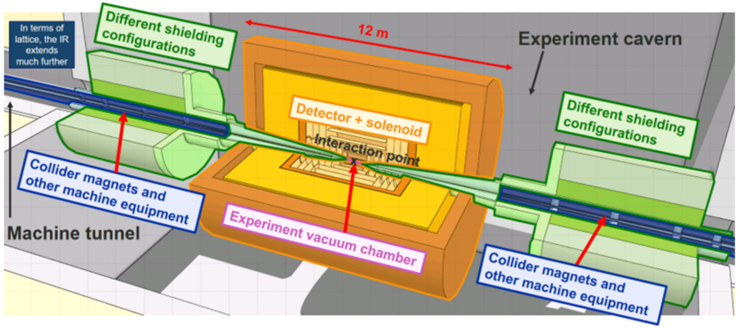
Radiation in the Interaction Region (IR)

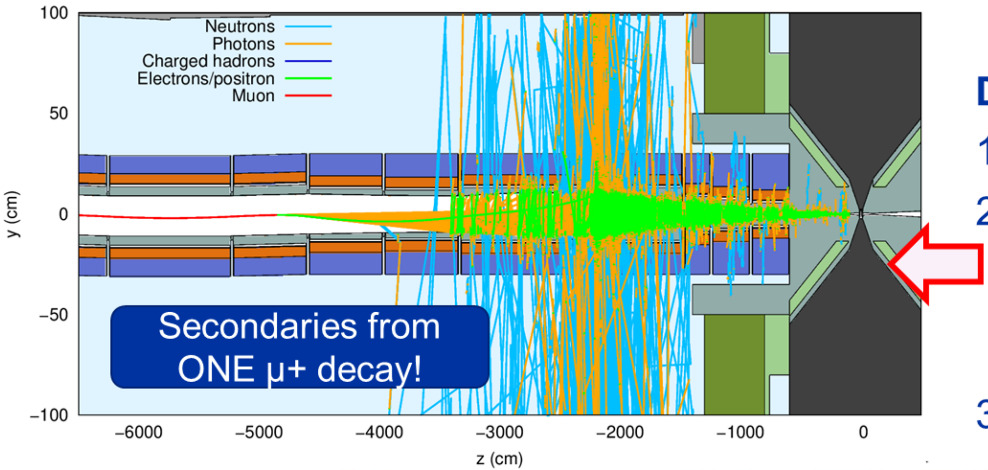
The collider is a hostile radiation environment (mixed radiation fields of leptons, photons and hadrons)

Challenges related to radiation:

Instantaneous effect
1. Heat load in machine equipment
2. Physics background in detector

Cumulative effect (long-term)
3. Radiation-induced ageing of machine and detector components





Design approach:
1. Understand and model radiation sources
2. Simulate radiation transport and secondary particle production in machine and detector (**Monte Carlo simulations**) → quantify effects
3. Develop mitigation measures (shielding etc.)

Radiation sources

	$\sqrt{s}$=3 TeV	$\sqrt{s}$=10 TeV
Muon Energy	1.5 TeV	5 TeV
Bunch intensity at injection	2.2×10^{12}	1.8×10^{12}
Repetition rate (inj. rate)	5 Hz	
Circumference	4.5 km	10 km
Beam revolution time	15.0 μs	33.4 μs
Mean muon lifetime (γτ)	0.031 s	0.104 s
Rel. intensity loss per turn	0.048%	0.032%
Power (decay e-/e+)	400 W/m	500 W/m

*Some radiation sources do **NOT** depend on the presence of the second beam*

Type	Description		Relevance
Muon decay	Decay of stored muons around the collider ring		**Decay e+/e- are the dominating source**
Synchrotron radiation emission by muon beams	Synchrotron radiation emission by the beams in magnets (including IR quads → large transverse beam tails)		**SR photons emitted by muons are a minor source**
Muon beam-gas scattering	Coulomb scattering, Bremsstrahlung emission, e+e- pair production by muons in the Coulomb field of residual gas nuclei		**Emitted e+, e-, γ etc. are expected to be a minor source, muon losses not expected to be a major source**
Beam losses driven by beam dynamics	Beam instabilities, machine imperfections, resonances, …		**Muon losses on aperture can possibly be a significant source**

*Some radiation sources **DO** depend on the presence of the second beam*

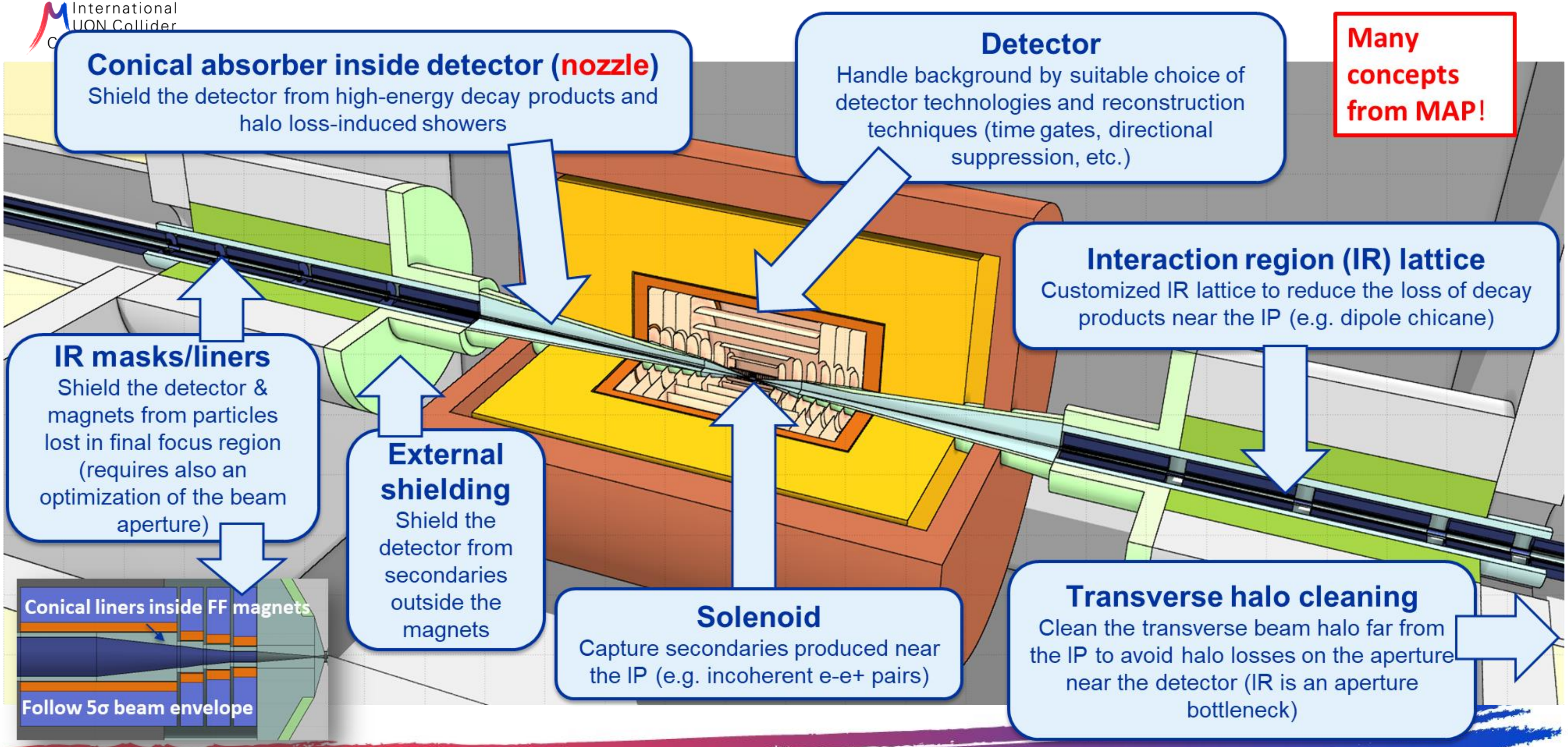
Type	Description		Relevance
Beamstrahlung	Photon emission by muons bent by the collective field of the opposite bunch	Also muons can be lost	**Beamstrahlung photons are a minor source**
Incoherent pair production	Electron-positron pair creation through the collision of real* and/or virtual photons comoving with muons of the counter-rotating bunches		**Incoherent pairs are expected to be a significant source (for the detector)**
Coherent pair production	Electron-positron pair creation by real* or virtual photons in the collective field of the counter-rotating bunch		**Coherent pairs are expected to be a minor source**
Muon-muon collisions			**Expected to be a minor source**

*The real photons come from **beamstrahlung**!

The muon losses due to beam-beam effects and collisions still need further study

- **Muon decay is clearly the dominant radiation source, both for the detector and the machine**
- **Incoherent pair production is a non-negligible source for the detector**
- **Beam halo losses:**
  - Many processes can possibly lead to a formation of a beam halo, including single-beam sources (beam-gas scattering, instabilities, ...) and beam-beam sources.
  - If these particles will be lost or not depends on various factors (e.g. dynamic aperture), but the short muon store time helps
  - For the moment, we do not have quantitative estimates to which extent halo losses are relevant for the 10 TeV detector and machine

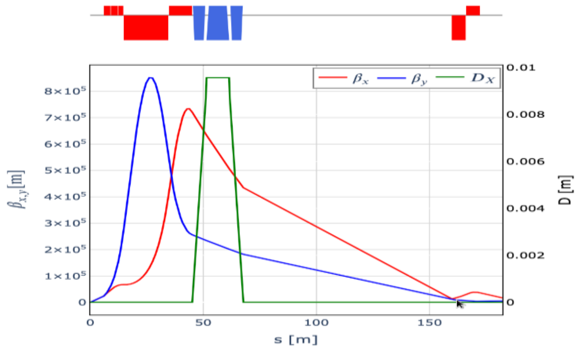
How to cope with rad., in particular physics bkg?



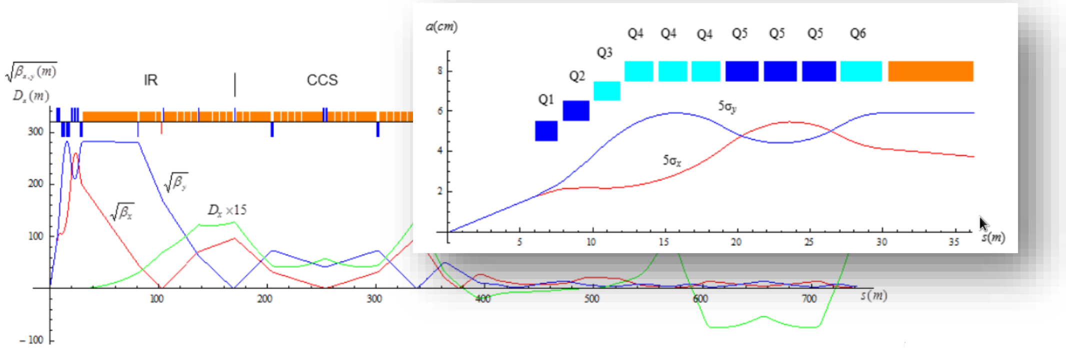
IR lattice design (3 TeV and 10 TeV)

	$\sqrt{s}$=3 TeV	$\sqrt{s}$=10 TeV
Version	US MAP [1]	IMCC (v0.8) [2]
IR layout (final focus)	Quadruplet with dipolar component	Triplet with adjacent chicane
ß*	5 mm	1.5 mm
L*	6 m	6 m
Max. field at inner bore	12 T	20 T

[2]$\sqrt{s}$=10 TeV IMCC lattice – M. Vanwelde, K. Skoufaris, C. Carli:



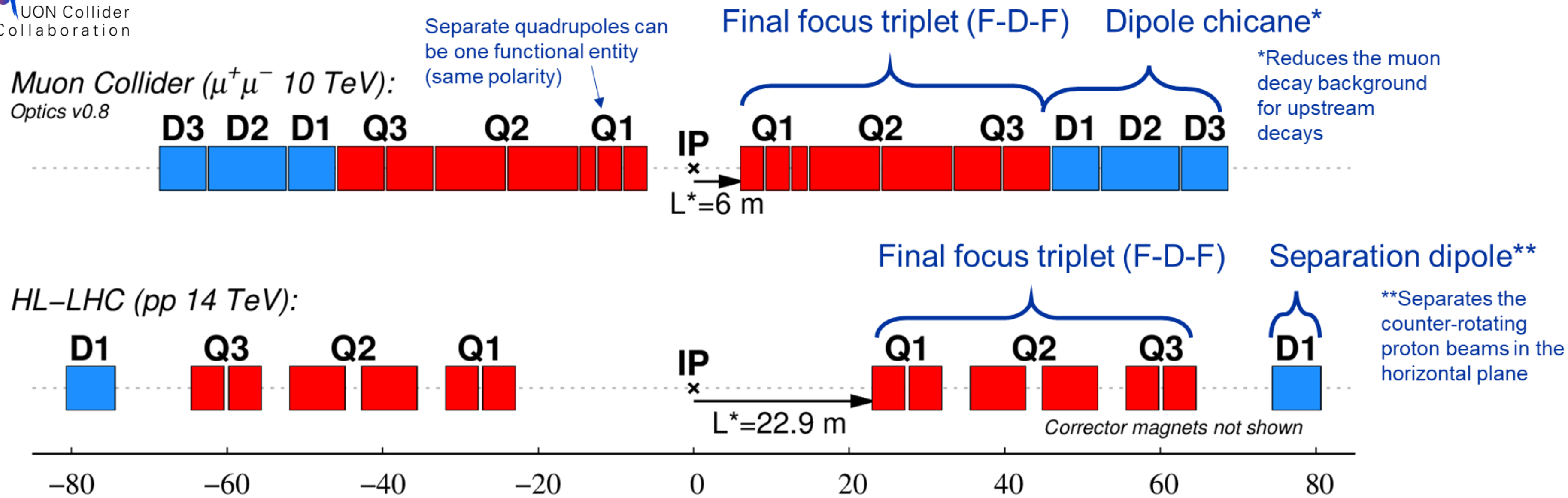
[1]$\sqrt{s}$=3 TeV MAP lattice (quadruplet version) – Y. Aleksahin et al.:



Challenges for IR lattice design:

- small ß*, large ß functions in FF, strong chromatic effects

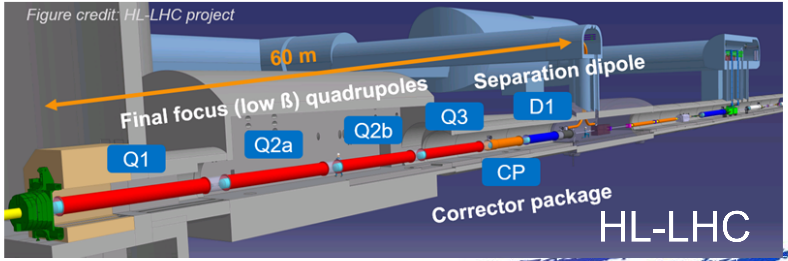
IR layout MuC (10 TeV) vs HL-LHC



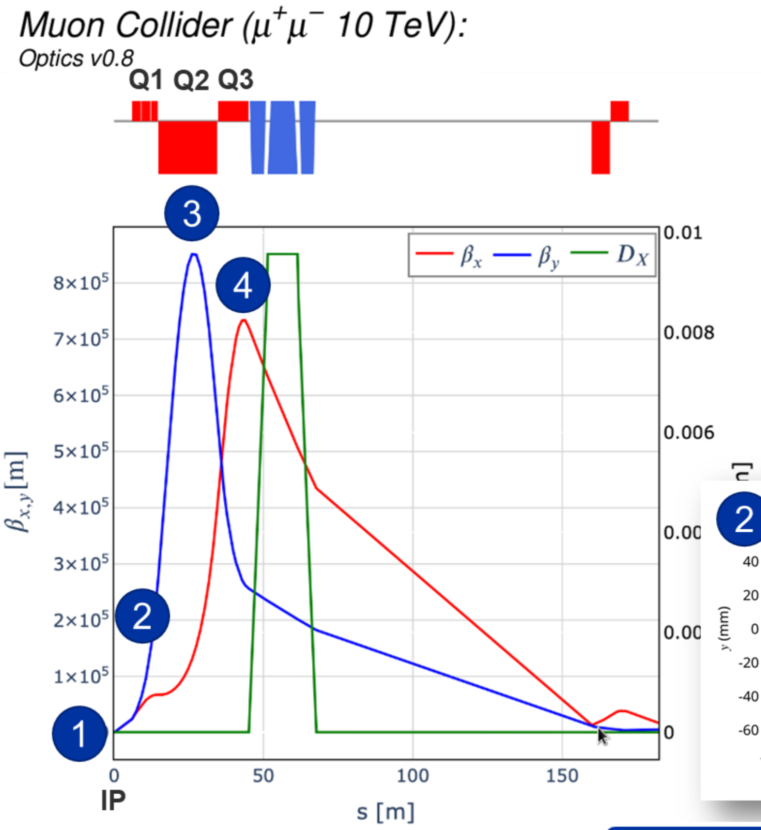
Need much stronger squeeze in MC:

- Small L* (=distance IP to first magnet)
- High-field + large aperture quadrupoles

→ Limits space for detector



IR optics functions (10 TeV)



In the drift around the IP, the β-function increases rapidly:

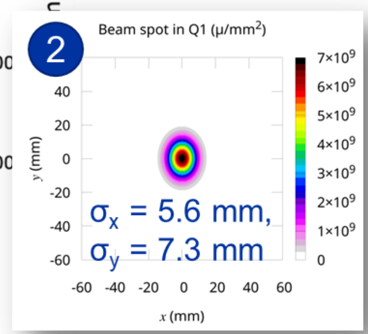
$$\beta(s) = \beta^* + \frac{s^2}{\beta^*}$$

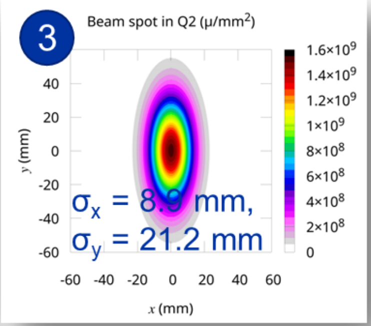
s is the distance from the IP

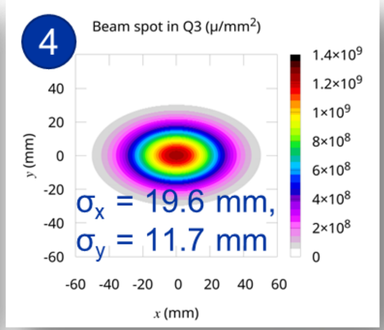
β-function at IP

	β*	β@L*	β_{max}
MC-10TeV (v0.8)	1.5 mm	24 km (L* = 6 m)	**O(1000 km)**
HL-LHC (v1.5)	15 cm	3.5 km (L* = 22.9 m)	21.5 km

1 At the IP: $\sigma_{x,y}$ = **0.9 μm**





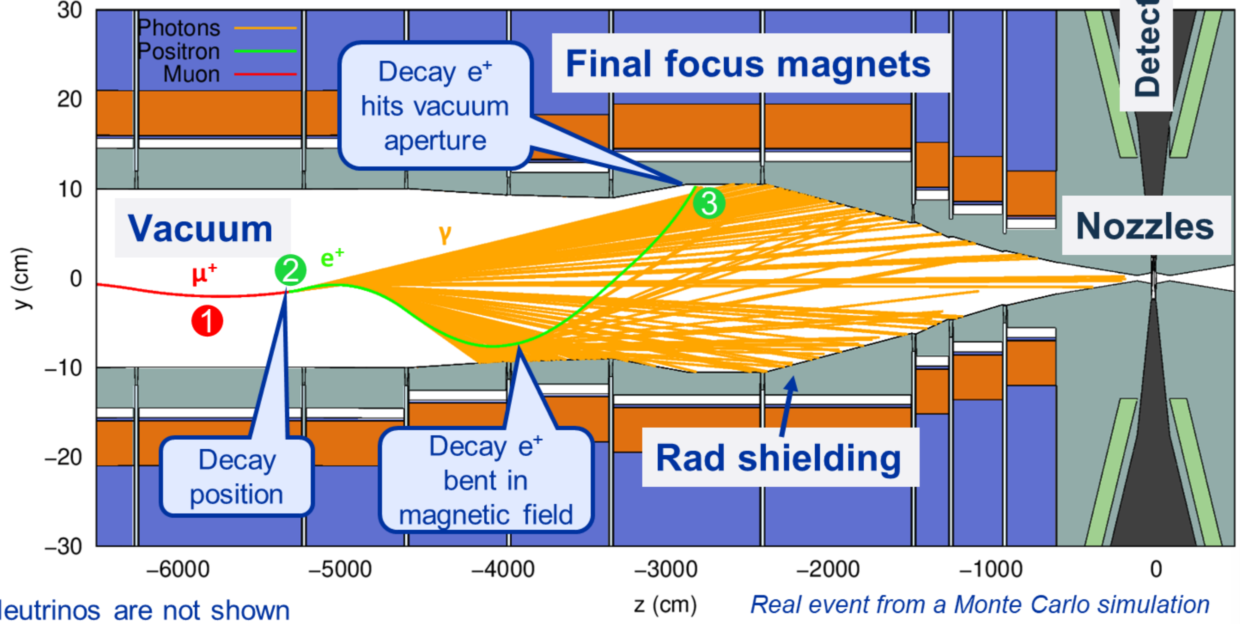


For comparison HL-LHC: @IP: $\sigma_{x,y}$ = 7 μm, max σ in final focus= 2.7 mm

Decay-induced radiation in IR

The lower-energy decay e⁻/e⁺ are overbent by the strong magnetic fields and emit synchrotron radiation (SR)

Squeezed view of the interaction region:



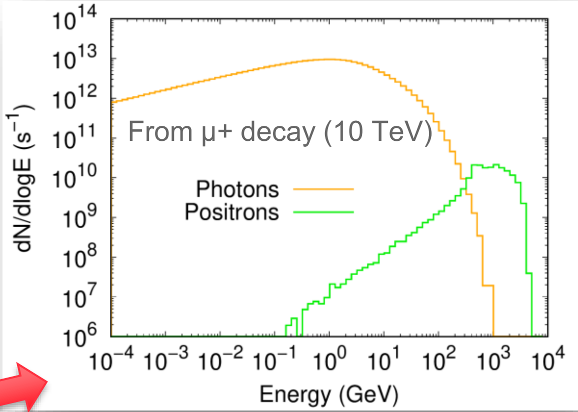
Neutrinos are not shown

Real event from a Monte Carlo simulation

Here:

1. μ^+ (5 TeV)
2. e^+ (1.20 TeV)
3. e^+ (0.45 TeV)

0.75 TeV emitted as SR photons

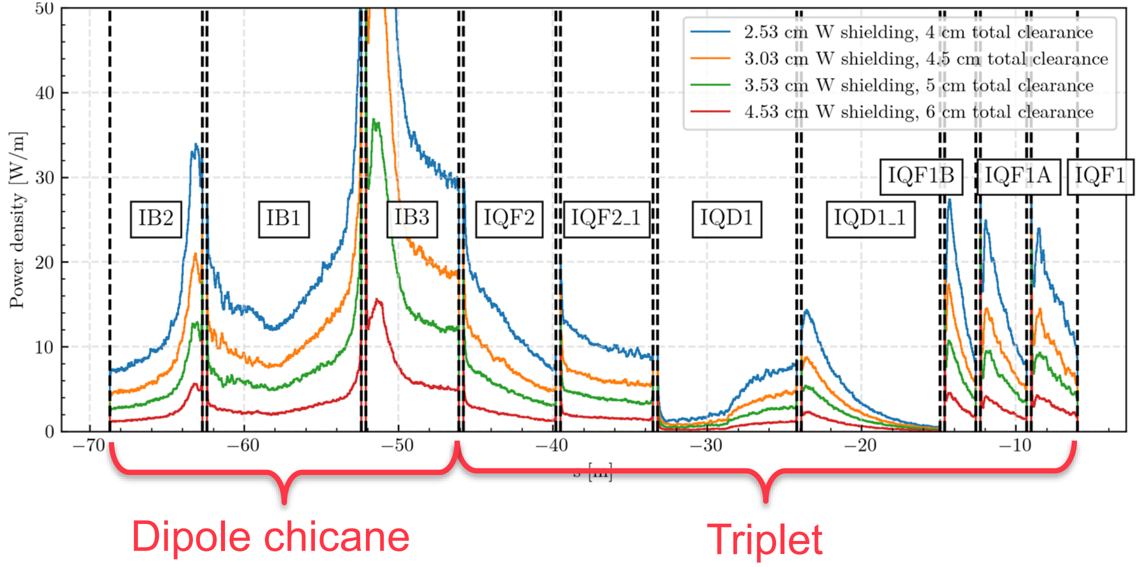


Spectra of decay positrons and SR photons impacting on vacuum aperture within the first 46 m of the IR (final focus and nozzle)

Heat deposition in IR magnets (10 TeV)

Total power in deposition by decay products in 10 TeV straight section (about 300 m): **O(150 kW)**

Muon decay: power deposition (per unit length) in magnet cold masses for different W shielding thicknesses:



→ Chicane magnets intercept significant amount of decay products from upstream drift (need more shielding)

Challenge:

- Heat deposition by decay in cold mass needs of IR magnets to be reduced by two orders of magnitude (to the 1% level)

Need thick W liners (few cm) inside the magnets

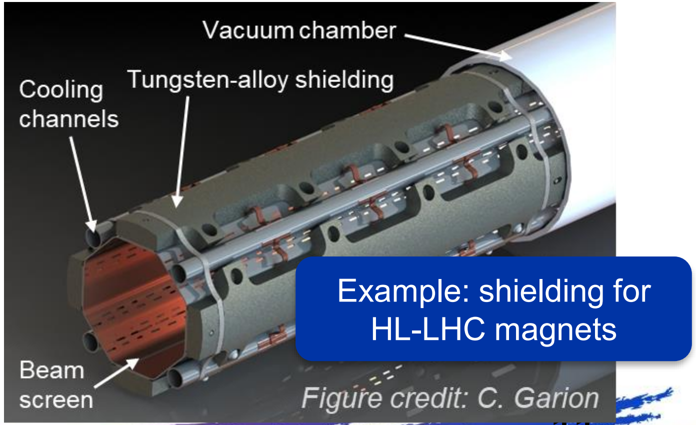


Figure credit: C. Garion

Radiation damage in IR magnets (10 TeV)

Muon decay: annual peak dose in different IR magnets:

Name	L [m]	Shield thickness [cm]	Coil aperture (radius) [cm]	Peak TID [MGy/y]
IB2	6	4.53	16	1.3
IB1	10	4.53	16	3.1
IB3	6	4.53	16	4.9
IQF2	6	2.53	14	7.7
IQF2_1	6	2.53	13.3	4.6
IQD1	9	2.53	14.5	1.1
IQD1_1	9	2.53	14.5	3.7
IQF1B	2	2.53	10.2	6.4
IQF1A	3	2.53	8.6	3.6
IQF1	3	2.53	7	3.5

The thick W liners are also essential for limiting the cumulative ionizing dose in magnet insulation and other radiation-sensitive components

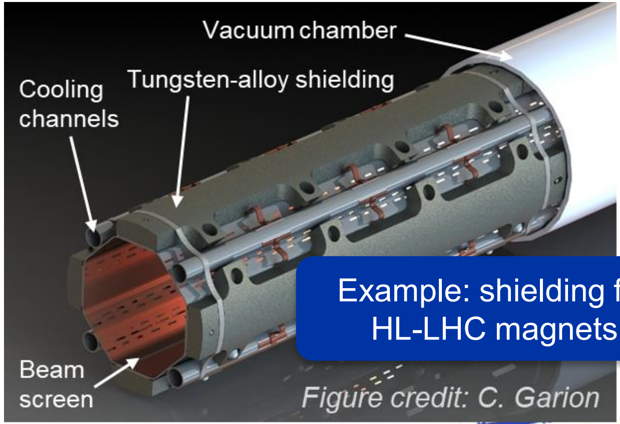


Figure credit: C. Garion

Example: shielding for HL-LHC magnets

IR magnet aperture requirements (10 TeV)

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The large beam size + rad shielding translates into very significant aperture requirement for the magnets

Required bore radius of IR magnets:

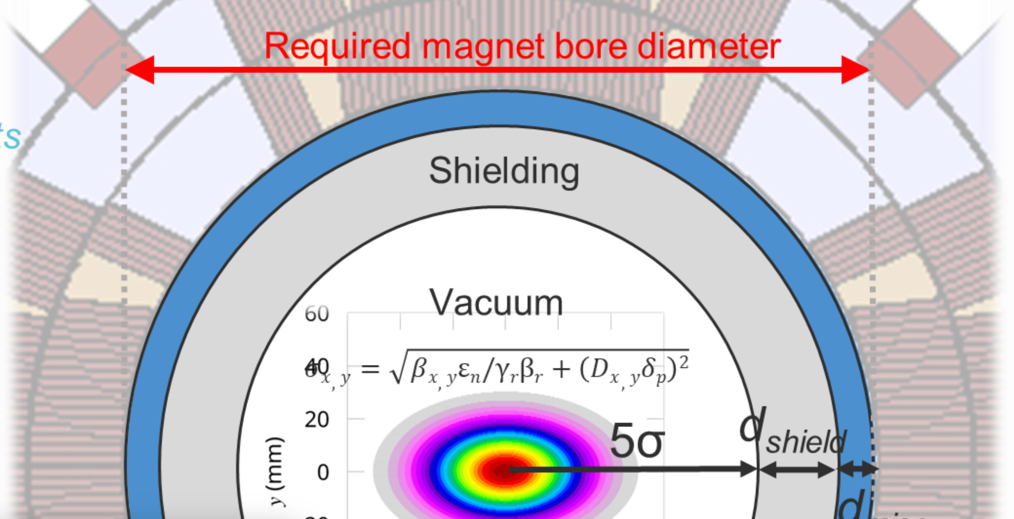
$$R = 5\sigma^{*} + d_{shield} + d_{misc}$$

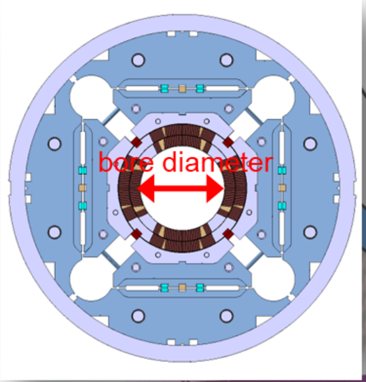
- $5\sigma^{*}$: Required beam clearance (vacuum)
- d_{shield}: Radiation shielding thickness (Q: **2.5 cm**, D: **4 cm**)
- d_{misc}: Vacuum chamber, supports, insulation, etc. (**1.5 cm**)

*Maintained assumption from MAP

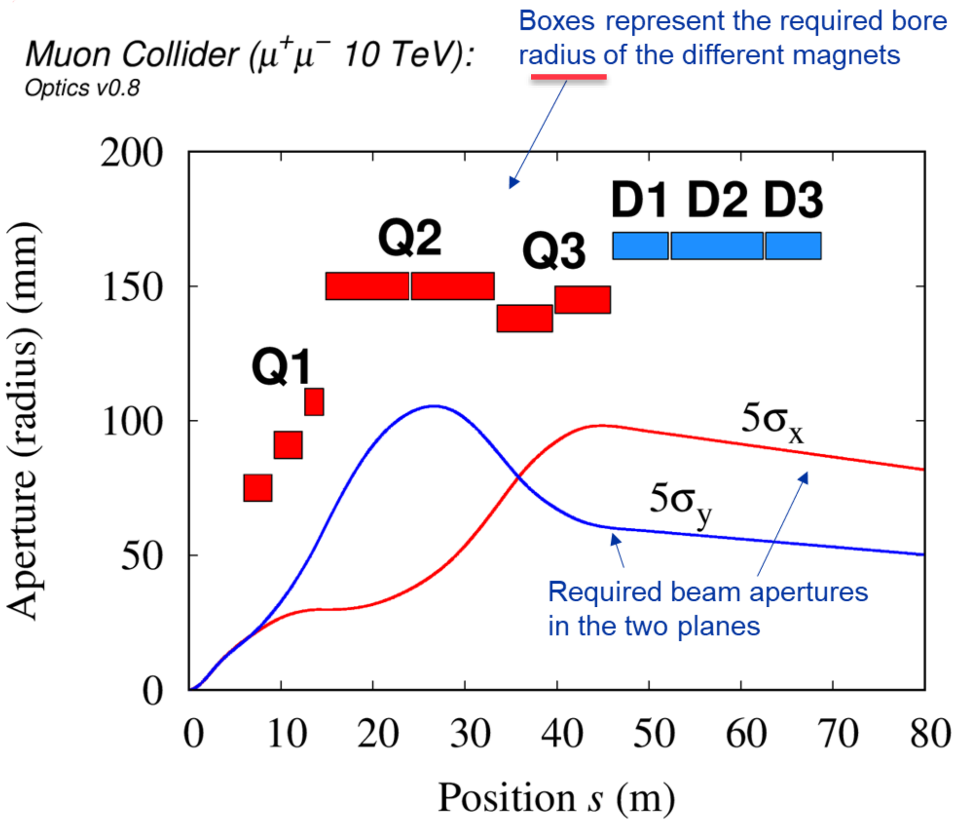
It is assumed that 5σ beam clearance in the IR is sufficient since beams are stored only for a few 1000 turns. Open points to be studied:

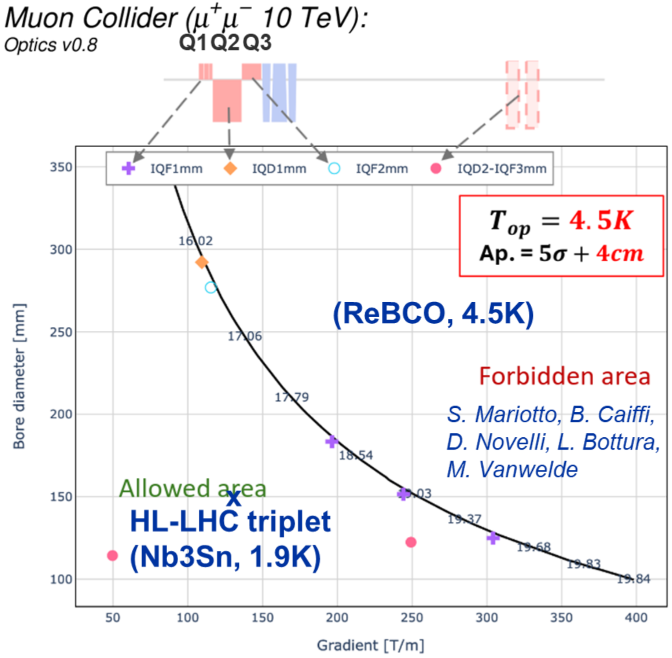
- Halo losses acceptable? (IR is global aperture bottleneck)
- Impedance?





IR magnet aperture requirements (10 TeV)



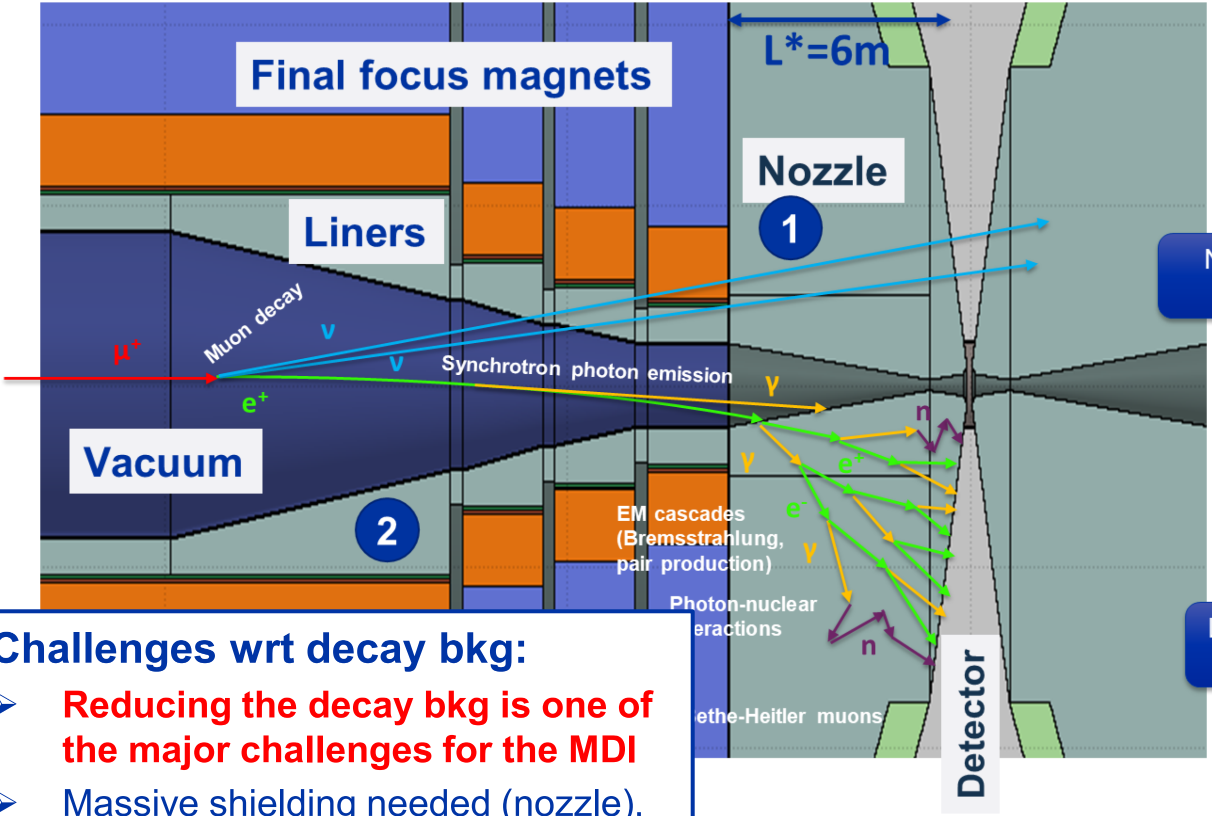


Challenges for IR magnets:

- Very challenging aperture + field requirements
- Large sensitivity to unwanted multipolar components, magnet misalignments, vibrations

Decay-induced bkg in detector

Squeezed view of the interaction region:



1

Nozzle shape and material:
Determines spectra, entry positions and directions of secondaries entering detector

Nozzle → Background reduction by orders of magnitude

2

Lattice and beam aperture:
Determine how many decay products are lost near the IP*, but little influence on secondary spectra and entry positions in detector

Lattice → Background reduction by a factor of a few

* Decay products lost on the inside of nozzle are the most relevant for background

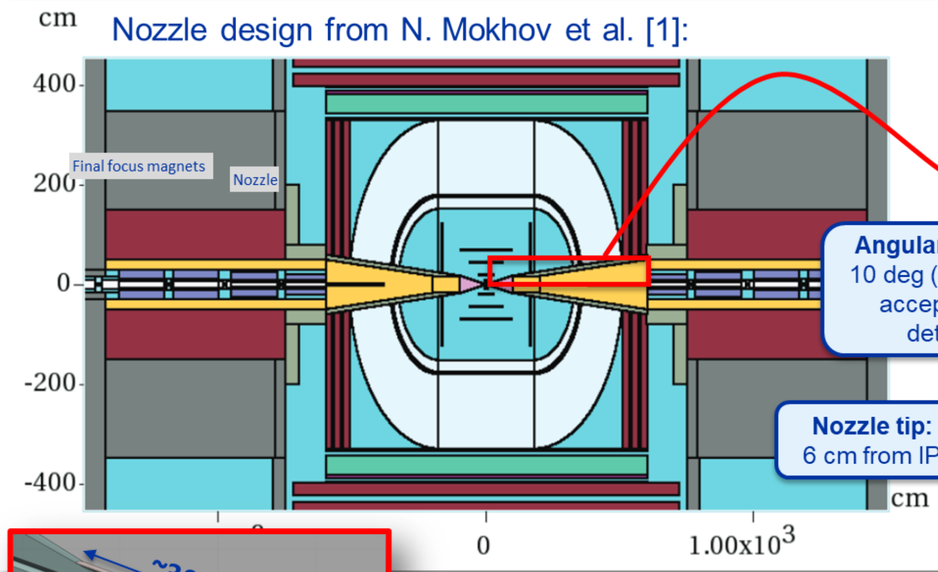
Challenges wrt decay bkg:

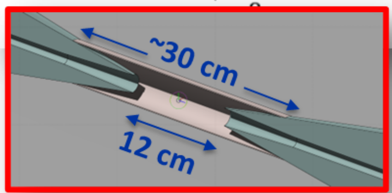
- **Reducing the decay bkg is one of the major challenges for the MDI**
- Massive shielding needed (nozzle), which limits the detector acceptance

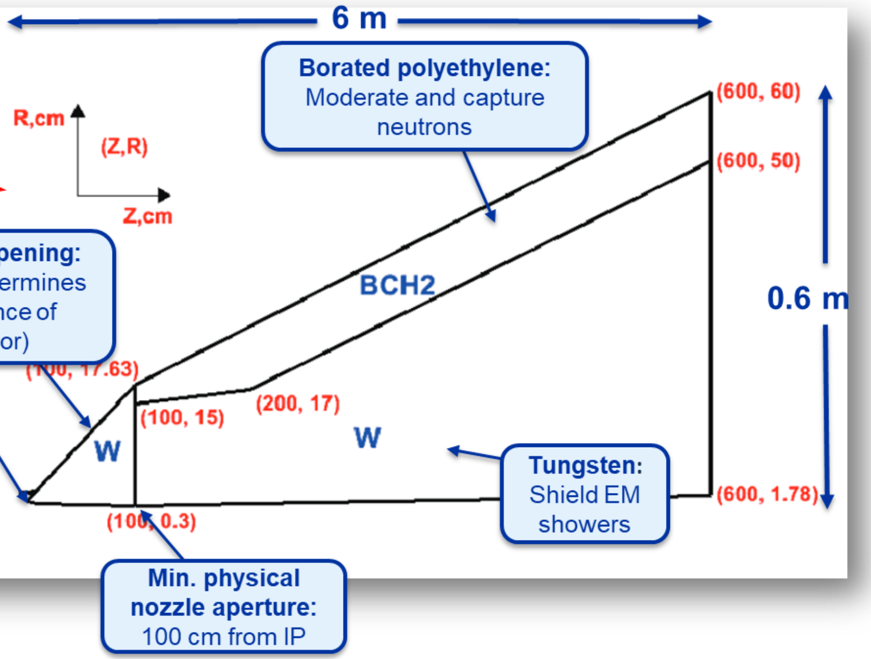
Decay-induced bkg in detector

*The nozzle optimized for a $\sqrt{s}$ = **1.5 TeV Muon Collider** by N. Mokhov et al. (US-MAP studies) works also well for the $\sqrt{s}$ = **10 TeV Muon Collider** (for the moment only small adaptations made)*

Nozzle design from N. Mokhov et al. [1]:

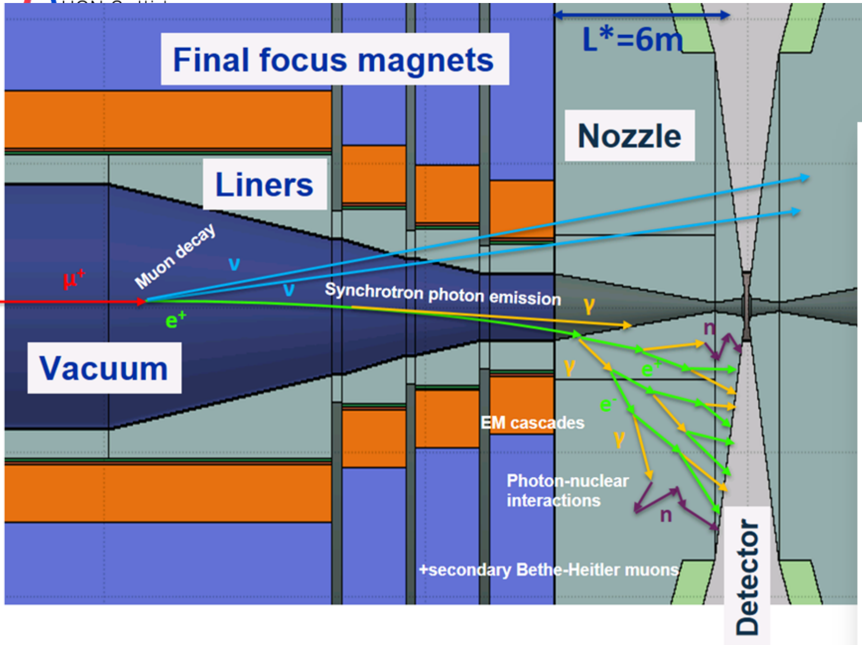




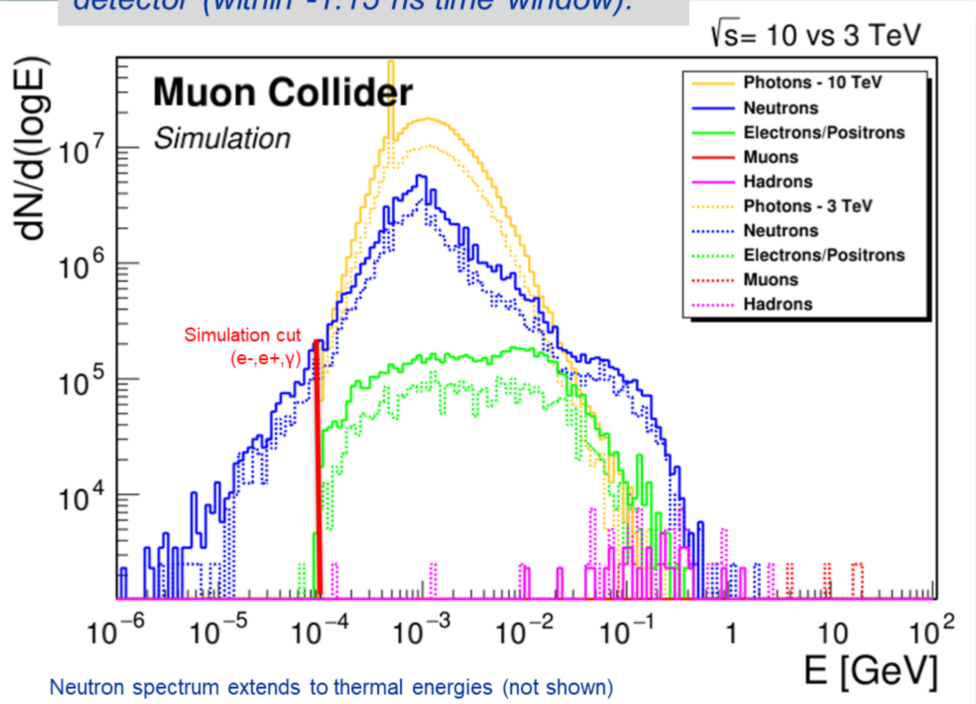


[1] N. V. Mokhov and S.I. Striganov, *Detector Backgrounds at Muon Collider*, Physics Procedia 37, 2012.

Decay-induced bkg in detector



Lethargy distribution of particles entering detector (within -1:15 ns time window):

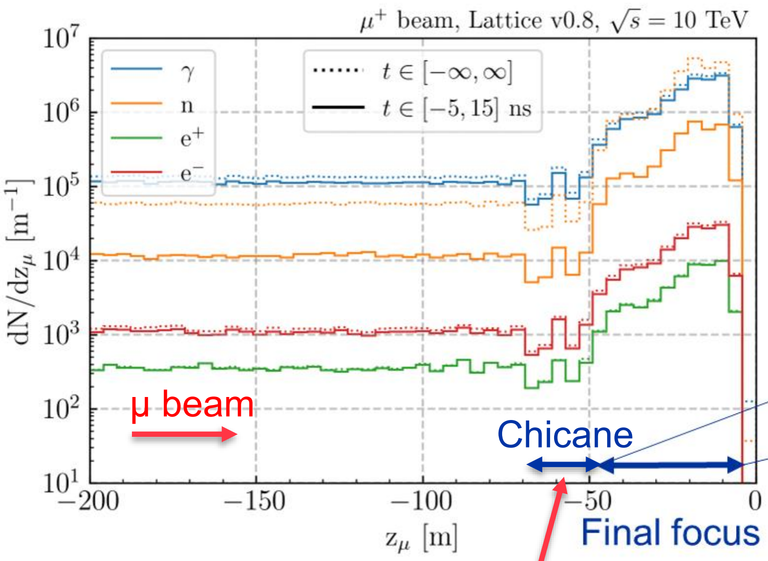


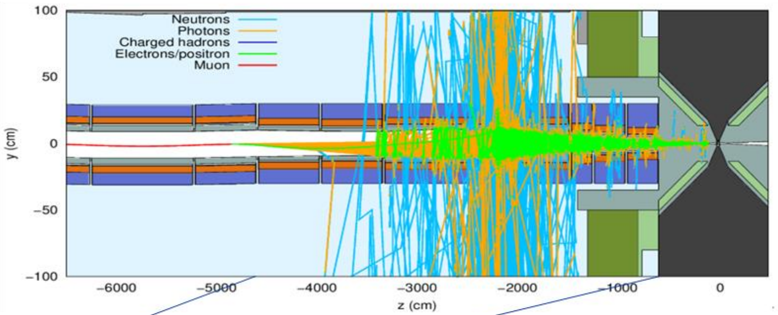
Background particles (from decay) entering detector per bunch crossing (with time cut [-1:15]ns):

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

Decay-induced bkg in detector

Number of particles entering detector envelope vs decay position:

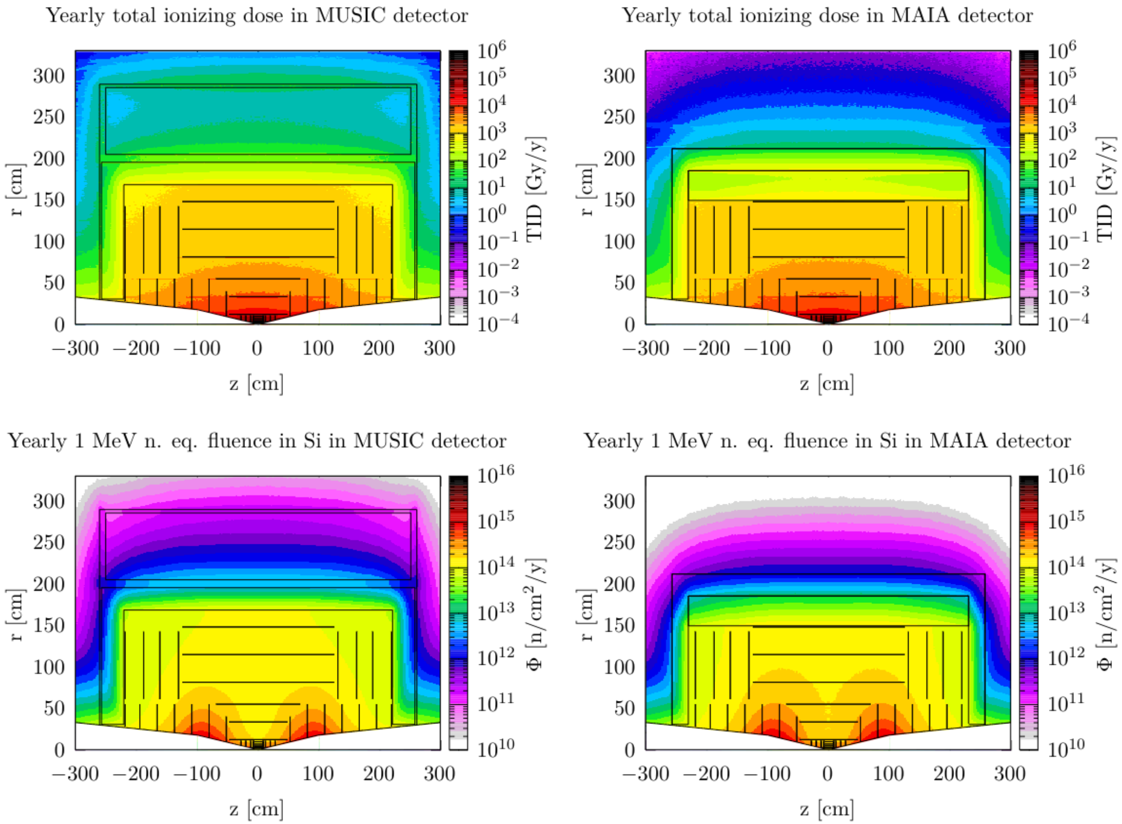




- The muon decay background is mostly due to decays inside the final focus magnets*
- Dipole component helps to reduce contribution of distant decays
- Little contribution from decays inside nozzle (decay products escape on other side)

*Dipole chicane essential for reducing the background contribution due to distant decays in the upstream drift

Decay-induced rad damage in detector



Muon decay products also lead to significant radiation damage in the detector, but thanks to the nozzle the cumulative dose and Si 1 MeV n-eq fluence remain acceptable

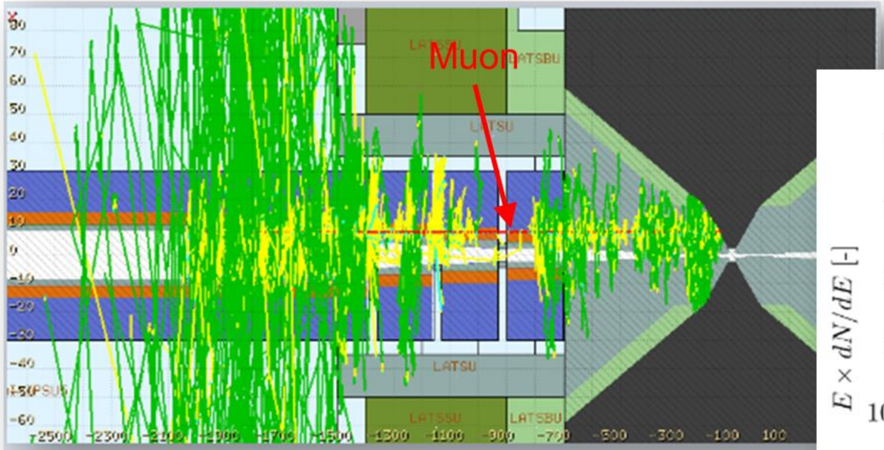
Table 3.2.1: Maximum values of the ionizing dose and the 1 MeV neutron-equivalent fluence (Si) for the two detector options. All values are per year of operation (10 TeV) and include only the contribution of muon decay.

Component	Dose [kGy]		1 MeV neutron-equivalent fluence (Si) [10^{14} n/cm^2]	
	MAIA	MUSIC	MAIA	MUSIC
Vertex (barrel)	1000		2.3	
Vertex (endcaps)	2000		8	
Inner trackers (barrel)	70		4.5	4
Inner trackers (endcaps)	30		11.5	10
ECAL	0.58	1.4	0.15	1

Beam halo-induced bkg in detector

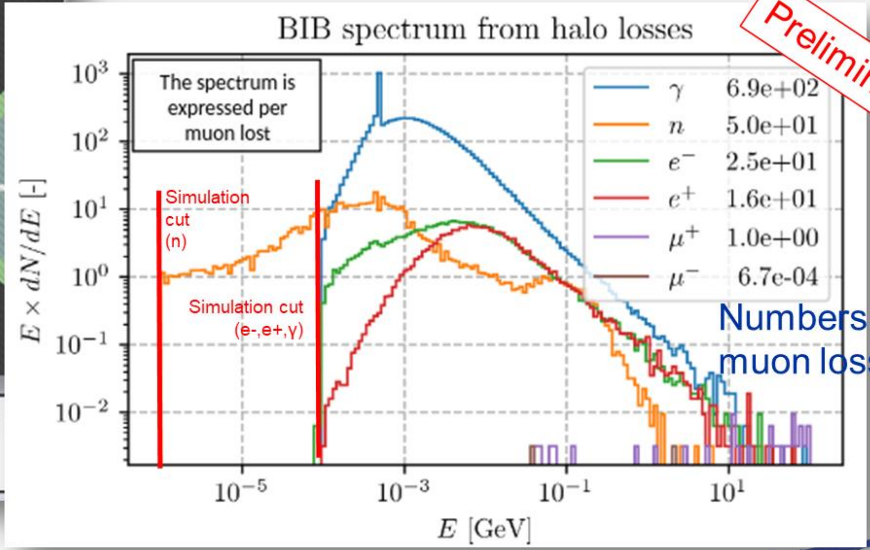
Like the decay products, beam halo losses in the interaction region can create a mixed radiation background (γ, e-, e+, n, etc.) with a wide energy spectrum

Example of muon lost in the interaction region (Monte Carlo simulation):



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

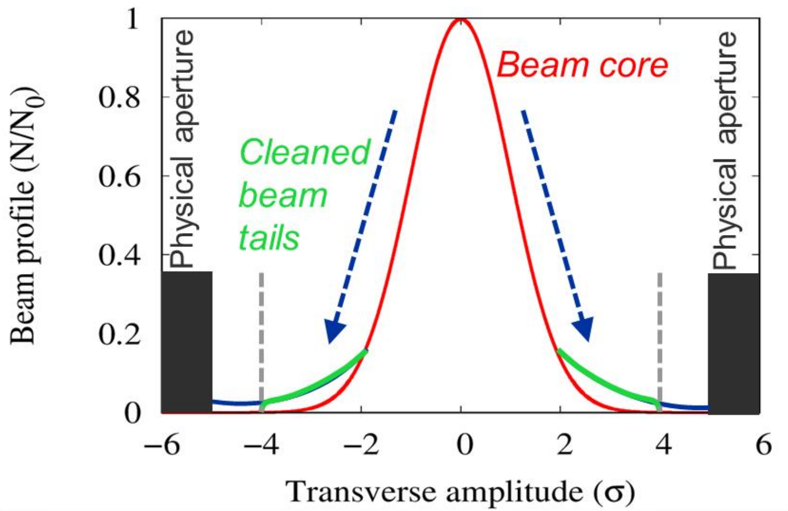
Nozzle helps but muons can also induce showers deep inside nozzle, close to the detector



Numbers depend on muon loss location

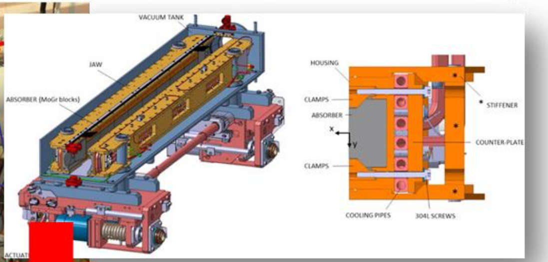
Beam halo-induced bkg in detector

The best mitigation is to remove halo particles in a controlled way far away from the interaction region



- Halo cleaning systems are commonly used for background reduction in high-energy colliders

In most machines, the halo is cleaned with classical collimation systems (material blocks)



Does not work well with TeV muons ...

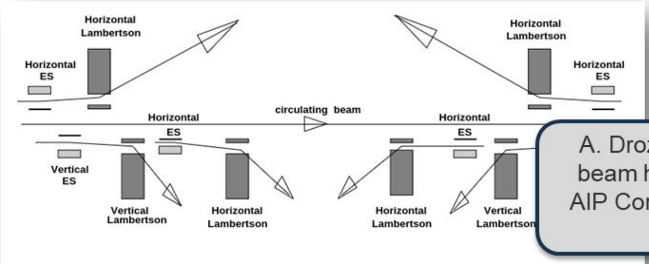


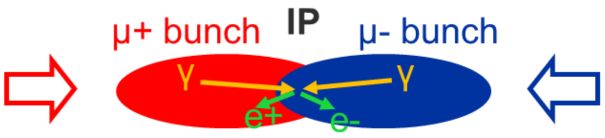
Figure 1: Schematic view of a $\mu^+\mu^-$ collider beam halo extraction.

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

Challenges wrt halo background:

- ➢ Halo formation in muon colliders remains an open topic to be studied (major bkg source?)
- ➢ Muon halo cleaning very challenging

Incoherent e⁺e⁻ pair production as bkg source



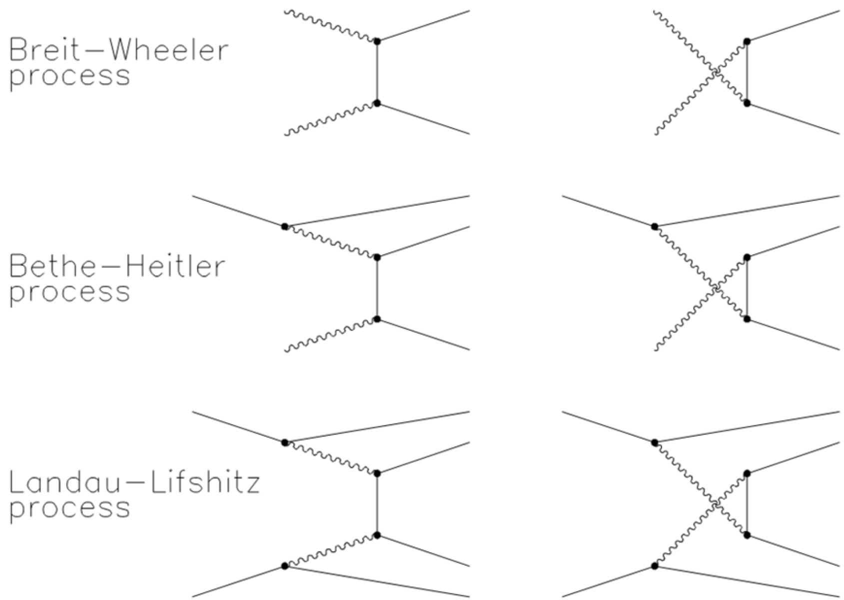
Electron-positron pair creation through the collision of real* and/or virtual photons comoving with muons of the counter-rotating bunches:

- Real-real: Breit-Wheeler process
- Real-virtual: Bethe-Heitler process
- Virtual-virtual: Landau-Lifshitz process

*The real photons come from **beamstrahlung**!

See, for example, Refs. [2,3]

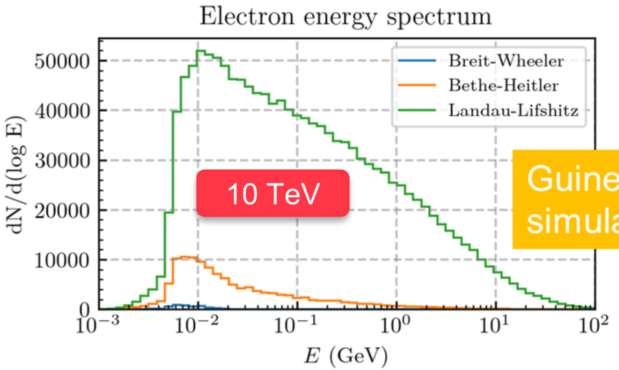
[1]



[1] D. Schulte, PhD thesis.
[2] I.F. Ginzburg, The e+e- pair production at mu+mu-collider, Nuclear Physics B (Proc. Suppl.) 51A (1996) 186-188
[3] P. Chen, Beam-beam interactions in muon colliders, Nuclear Physics B (Proc. Suppl.) 51A (1996) 179-185

Incoherent e^+e^- pair production as bkg source

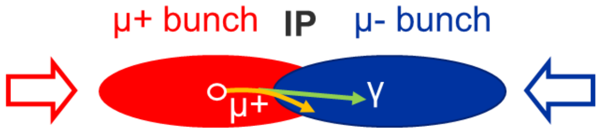
- Beamstrahlung emission small compared to linear e+/e- colliders
- Most incoherent pairs expected from Landau-Lifshitz process



GuineaPig simulations

[1] M. Boscolo, A. Ciarma, Characterization of the beamstrahlung radiation at the future high-energy circular collider, Phys. Rev. Accel. Beams 26, 111002, 2023.
[2] D. Schulte, Beam-beam Effects in Linear Colliders, https://indico.cern.ch/event/457349/attachments/1175828/1699810/Beam-beam2.pdf

Beamstrahlung as a (real) photon source:



Average beamstrahlung parameter (approximation for Gaussian bunches, assuming head on collisions):

$$\langle \Upsilon \rangle = \frac{5}{6}\frac{N_\mu r_\mu^2 \gamma}{\alpha\, \sigma_z(\sigma_x + \sigma_y)}$$

Muons/bunch (N_μ); Classical muon radius (r_μ); Lorentz factor (γ) (47322); Fine structure constant (α); Bunch length (σ_z) (1.5 mm); Transverse bunch size@IP (σ_x, σ_y) (0.9 μm)

Average number of photons emitted per muon and average photon energy (for $\langle \Upsilon \rangle \ll 1$):

$$\langle n_\gamma \rangle = \frac{12}{\pi^{2/3}}\frac{\alpha^2 \sigma_z}{r_\mu \gamma}\frac{6}{5}\langle \Upsilon \rangle$$

$$\langle E_\gamma \rangle = \frac{4\sqrt{3}}{15} E_b \langle \Upsilon \rangle$$

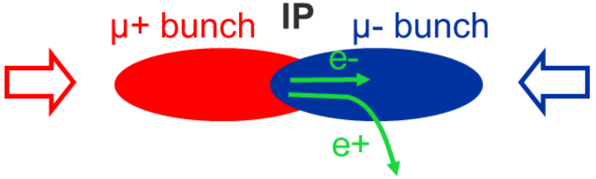
Muon energy (E_b)

Strong focus at IP → high charged particle density → strong EM field seen by muons of other beam

Individual muons can be bent by collective field of the opposite bunch → **Beamstrahlung emission**

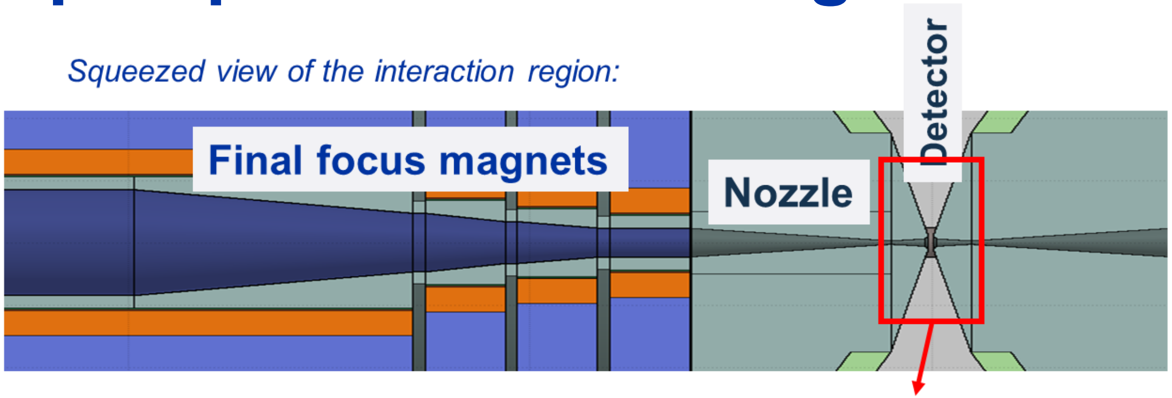
	MuC (10TeV)	FCC-ee Z (91.2 GeV)	CLIC (380 GeV)	CLIC (3 TeV)
$\langle \Upsilon \rangle$	6.6×10^{-7}	1.8×10^{-4}	1.7×10^{-1}	4.9
$\langle n_\gamma \rangle$	0.2		1.5	2.1
$\langle E_\gamma \rangle$	1.6 MeV	2 MeV	8.5 GeV	195 GeV
	For max. bunch int.	[1]	[2]	[2]

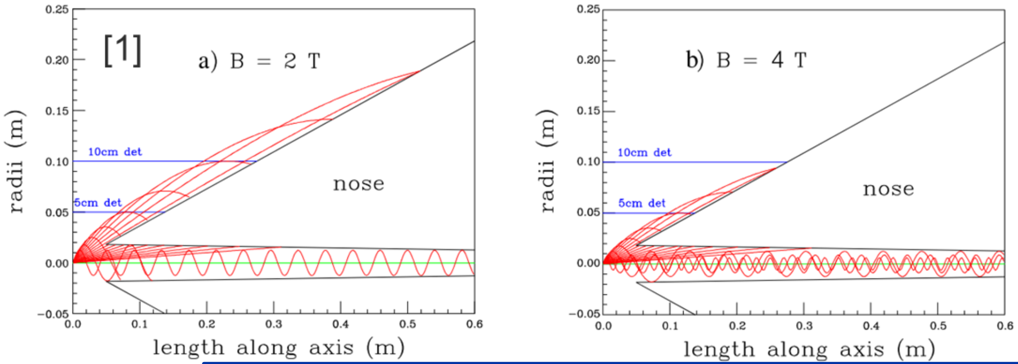
Incoherent e$^+$e$^-$ pair production as bkg source



- The produced e+/e- also receive a kick by the collective field of the bunches
- Furthermore, the e+/e- trajectory is strongly affected by the field of the detector solenoid
- A stronger solenoid field helps to reduce the number of e+/e- which can directly hit the inner tracker

Squeezed view of the interaction region:





$\sqrt{s}$=4 TeV

[1] C.M. Ankenbrandt et al., *Status of muon collider research and development and future plans*, PRSTAB 2,1999.

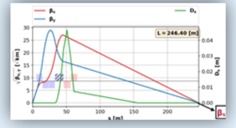
Challenges wrt incoherent pair bkg:

➢ Besides solenoid field, not many handles to reduce pair background

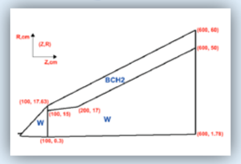
Workflow for background studies

Background studies are based on Monte Carlo radiation transport simulation

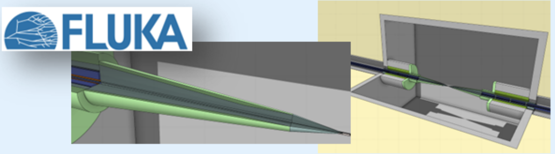
IR layout
Optics (lattice) and apertures



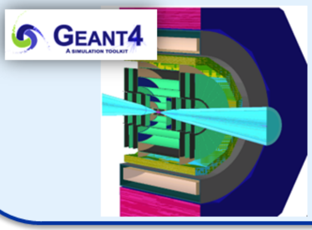
Nozzle & absorber configuration



Background simulations (FLUKA)
*) Realistic geometry model of beam line (magnets), absorbers, nozzle, etc.
*) Sampling of source terms (e.g. muon decay sampling from matched beam phase space distribution)
*) Store distribution of **BIB particles entering the detector envelope**



Detector simulations (Geant4)
*) Simulation of background hits
*) Overlay with physics collision events

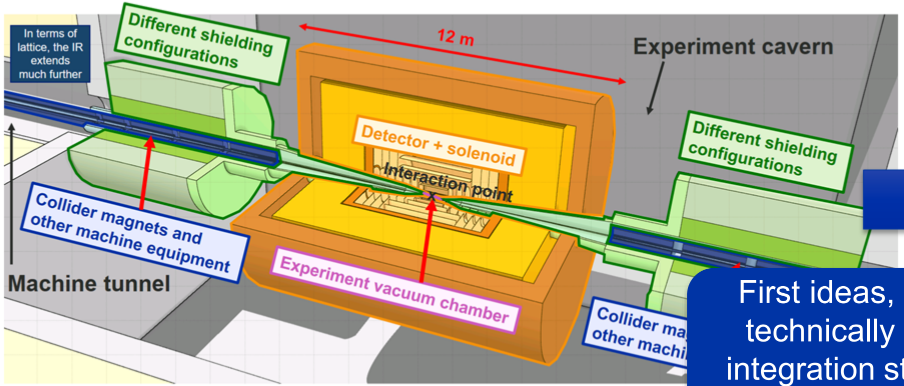


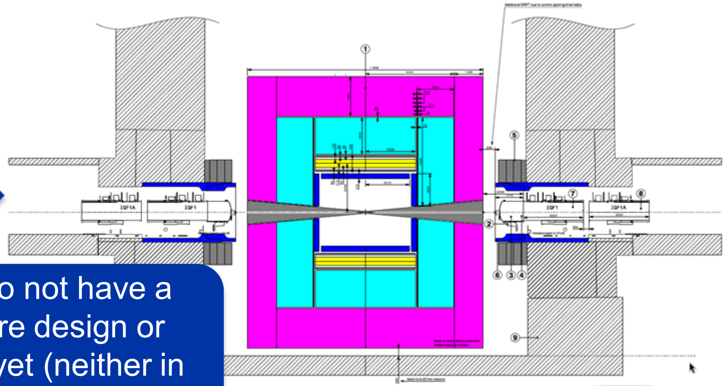
This is of course an **iterative process** to optimize the IR & MDI design!

Towards a realistic MDI design

Still a lot of conceptual and engineering work ahead to reach a technically mature MDI design, for example:

- **Technical design** of key MDI components (nozzle, central vacuum chamber etc.)
- **Integration** of accelerator, shielding, detector, including support structures
- **Strategies for access/maintenance** (how to move detector and shielding, and associated space requirements)
- Definition of required **infrastructure and services** (cryogenics, …)





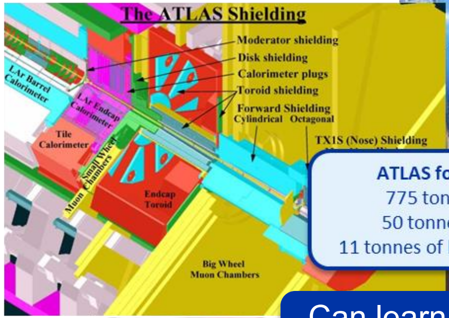
First ideas, but do not have a technically mature design or integration study yet (neither in MAP nor in IMCC)

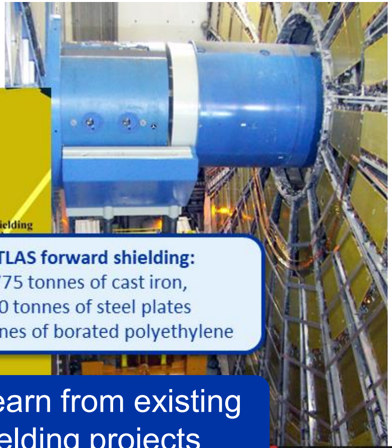
Nozzle engineering design

Key points for technical design of nozzle:

- Shielding segmentation, material choice
- Manufacturing, assembly procedures
- Heat extraction system (cooling)
- Alignment, vibrations, tolerances, etc.
- Integration of shielding assemblies in detector

Example ATLAS shielding*:



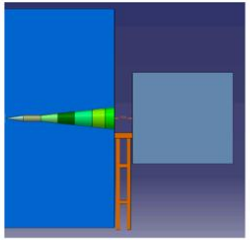


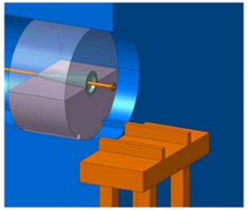
ATLAS forward shielding:
775 tonnes of cast iron,
50 tonnes of steel plates
11 tonnes of borated polyethylene

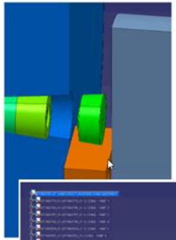
Can learn from existing shielding projects

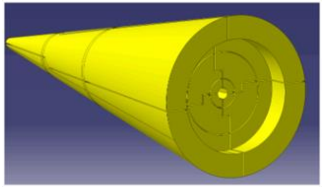
ATLAS toroid shielding:
110 tonnes of cast iron,
2.6 tonnes of borated polyethylene

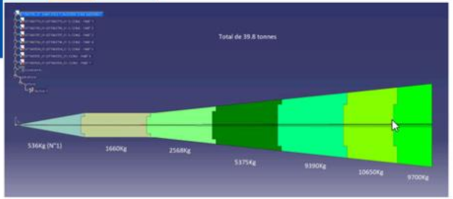
**Pictures/info from: https://atlas-shielding.web.cern.ch*









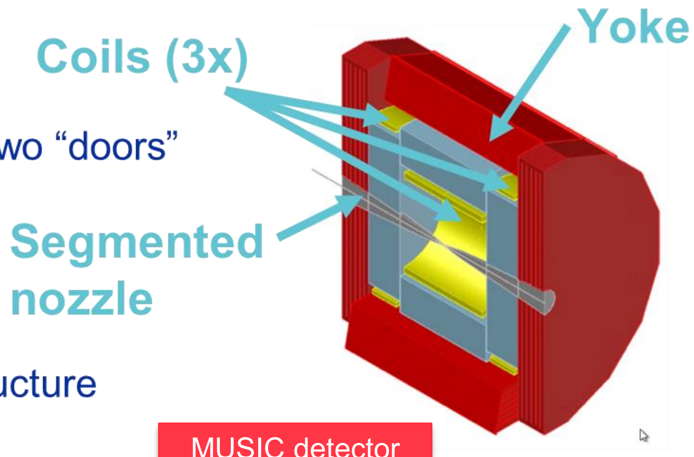


First ideas about nozzle segmentation

Nozzle integration and access to detector

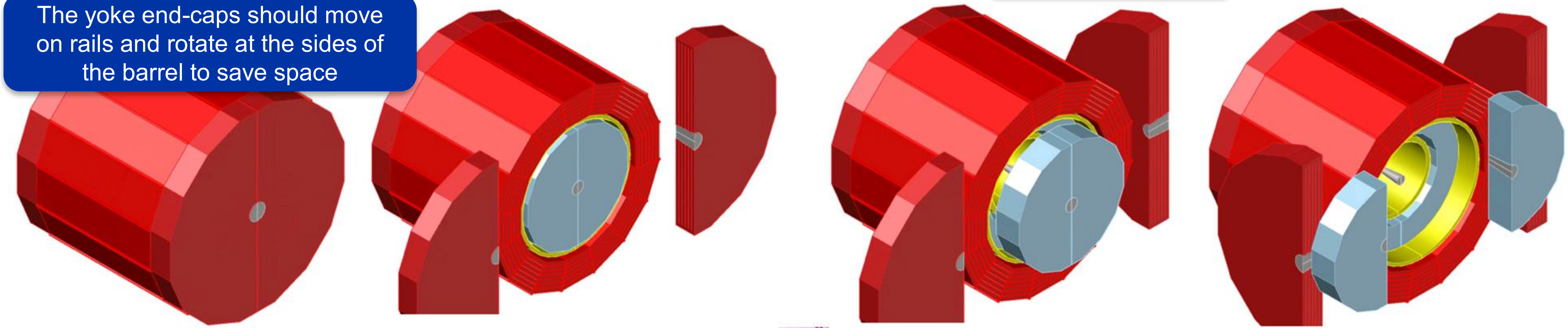
First concept (A. Bersani)

- Yoke slabs to be assembled independently
- Same shape for the end-caps, vertically split into two "doors"
- Tungsten nozzle split into three segments:
  - Two halves integrated in yoke end-caps
  - Two halves integrated in HCAL end-caps
  - Last segment integrated in tracker support structure (including central vacuum chamber)



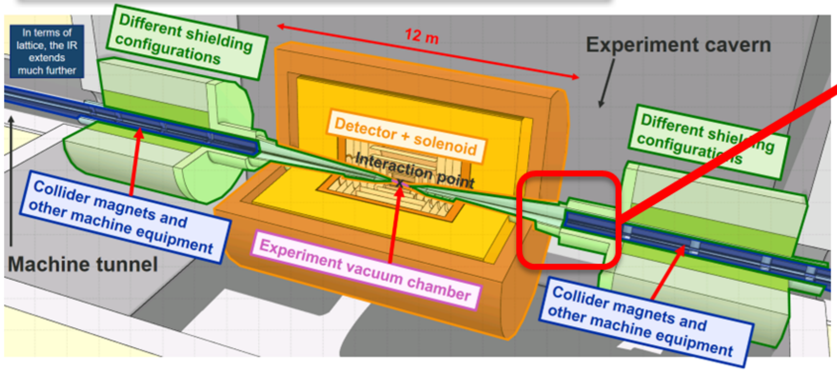
MUSIC detector

The yoke end-caps should move on rails and rotate at the sides of the barrel to save space



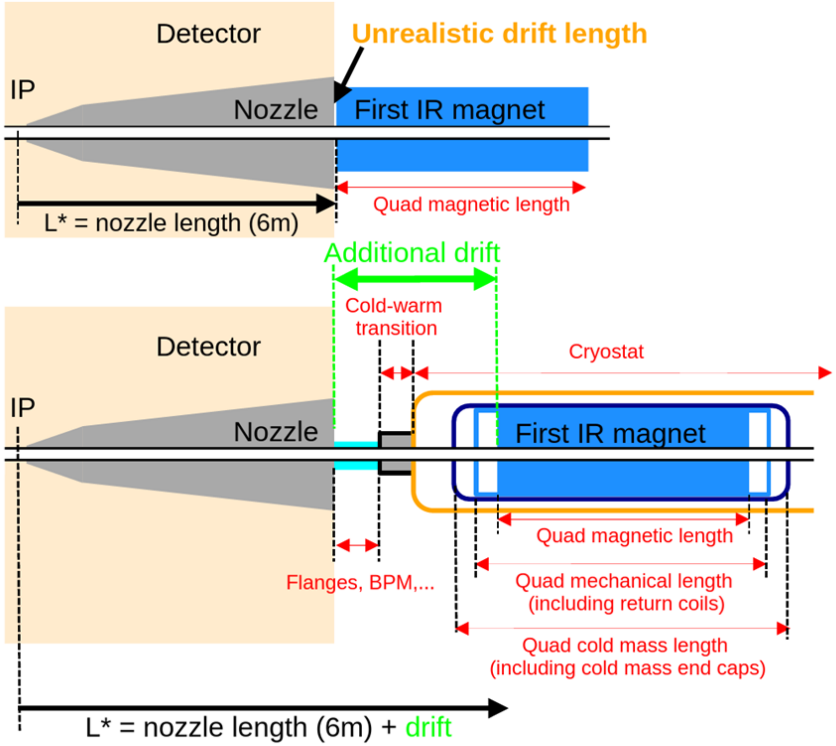
Machine integration

- Realistic machine integration in MDI region still pending
- Need to consider realistic cold mass lengths, cryostats, cold-warm transitions, and other equipment (flanges, BPMs, vacuum pumps etc.)
- Might need to increase L* (challenging for optics design)



Present:

More realistic:



Summary: key topics (1/2)

- Interaction region **lattice** design under consideration of various constraints (heat load, background, technical limits of magnets, interconnect lengths)
  - *Significant challenges due to small β*, for example, β- functions of O(1000 km) in FF*
  - *Key aspects require further iterations (L*, required drift lengths, radiation shielding and apertures of IR magnets, etc.)*
- Mitigation measures for the beam-induced **background**
  - *Nozzle originally developed by US-MAP remains one of the main measures to reduce the decay background (potential for further optimization limited) → detailed studies of decay-induced background for present MDI&IR layout exist (to be continued)*
  - *Limited handle to reduce incoherent pair background (mainly through solenoid field), further studies needed (need to revisit event generator?)*
  - *Halo background remains to be studied (important open questions remain: halo formation? Is a 5σ IR aperture acceptable? Halo removal system far from the IP? What kind of halo removal system?*

Summary: key topics (1/2)

- **Luminosity** monitoring, **forward** detectors
  - *First ideas and preliminary studies, but no concrete proposals yet*
  - *Important to understand if any forward monitor/detector is needed within L* (very difficult integration)*
- **Beam instrumentation** in MDI region, **vacuum system** in the MDI region
  - *Work did not start*
- **Technical design** of key MDI components (nozzle, central vacuum chamber etc.)
  - *Work did not start, different aspects to be addressed (mechanical design, cooling concepts, impedance, supports, etc.),*
- **Integration** of accelerator, shielding, detector, including support structures, infrastructure
  - *About to start first (2D) integration studies, expert input needed (magnets, cryo, vacuum, detector, instrumentation, civil engineering)*
  - *Expect that integration constraints lead to further iterations of the MDI design*