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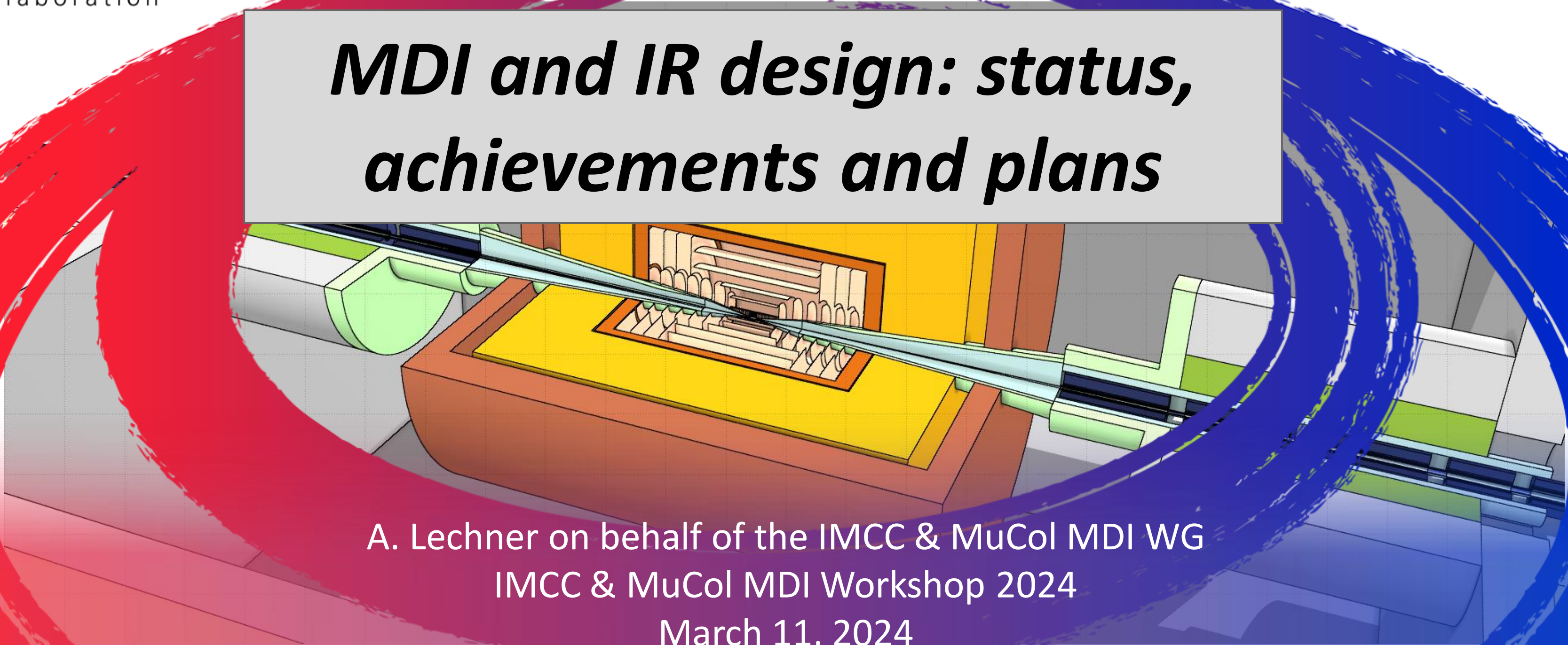
International MUON Collider Collaboration

MuCol

MDI and IR design: status, achievements and plans

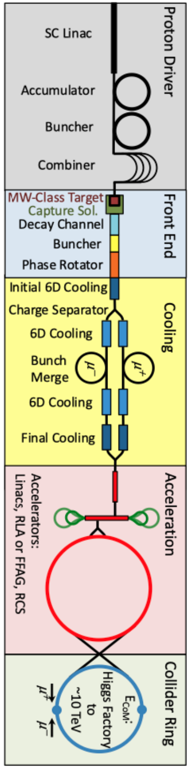


A. Lechner on behalf of the IMCC & MuCol MDI WG

IMCC & MuCol MDI Workshop 2024

March 11, 2024

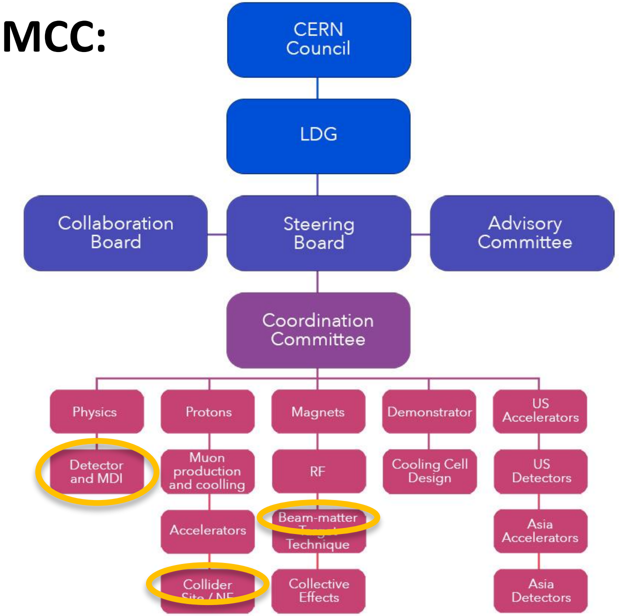
Introduction



- **High-level IMCC objectives for MDI:**
  - Study the **beam-induced background (BIB)** and identify mitigation strategies for the **3 TeV** and **10(+) TeV** collider options.
  - Develop a credible **interaction region (IR) and MDI design** that yields background levels compatible with detector operation
- Could profit significantly from the previous US MAP studies (N. Mokhov *et al*) - **MAP design often served as a starting point**
- **This presentation:**
  - General introduction to Muon Collider MDI and IR
  - Status and Achievements
  - Plans for final ESPPU report (2026)

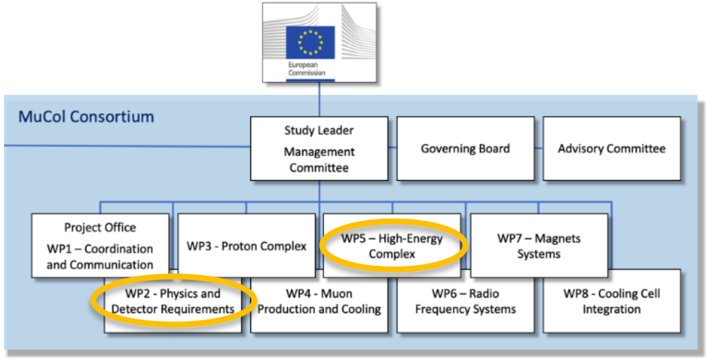
MDI in the IMCC and MuCol (EU study) structure

IMCC:



Detector, MDI and collider design are represented in IMCC coord. committee

MuCol:

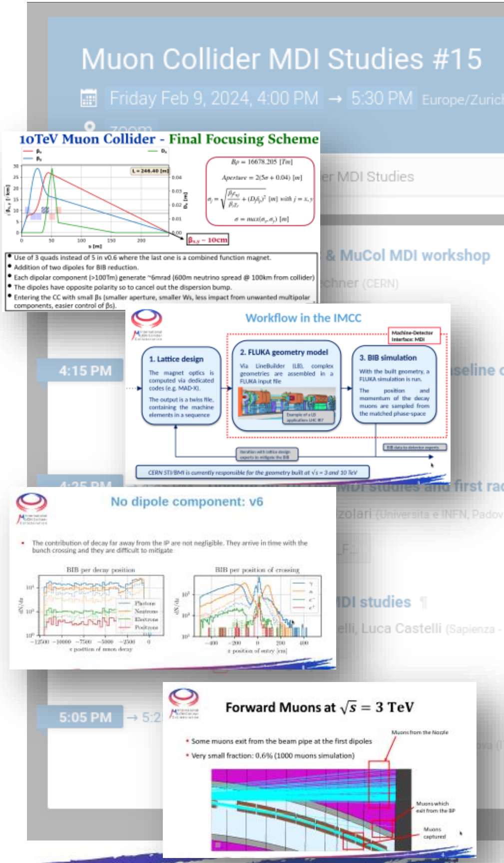


- **WP2** (Physics and Detector Requirements)
  - **MDI – detector studies**
- **WP5** (High-energy complex), **Task 5.1** “Collider design” and **Task 5.4** “MDI design & background to experiments”
  - **MDI – machine studies, IR lattice design, background simulations as input for WP2**

Close collaboration with other WPs (e.g. WP7 magnets)

WG meetings for IMCC and MuCol MDI studies

- **MDI WG (since Nov 2021)** – *machine studies for MDI*
  - Shall bring together expertise from different areas (interaction region design, particle-matter interactions, detector etc.)
  - Meetings every few weeks, usually on Fridays (17h00 CET), see Indico category
  - CERN e-group: **muoncollider-mdi@cern.ch**
- **Physics & Detector WG (since Nov 2020)** – *detector studies for MDI*
  - Meetings on Physics and Detector simulation & Detector performance and MDI
  - Meetings usually on Tuesdays (16h00 CET), see Indico category
  - CERN e-group: **muoncollider-detector-physics@cern.ch**



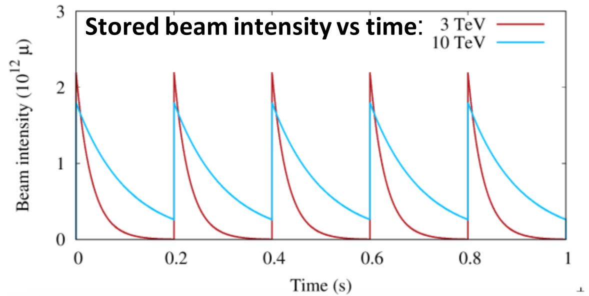
These meetings are open to everyone who is interested to join!

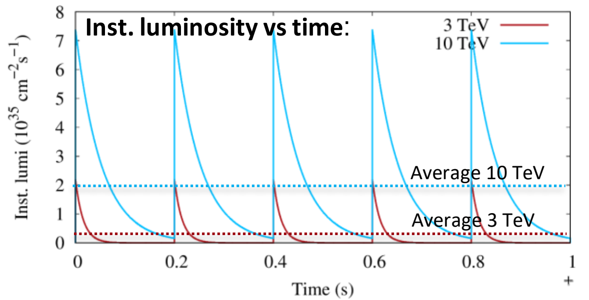
Recap of collider parameters

	$\sqrt{s}$=3 TeV	$\sqrt{s}$=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} $cm^{-2}s^{-1}$ / 1×10^{34} $cm^{-2}s^{-1}$	2×10^{35} $cm^{-2}s^{-1}$ / 1×10^{35} $cm^{-2}s^{-1}$

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

Muon decay	$\sqrt{s}$=3 TeV	$\sqrt{s}$=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

Sources of 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 in 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**

*There are hardly any real photons produced through beamstrahlung

How to deal with the beam-induced background?

Many concepts from MAP!

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

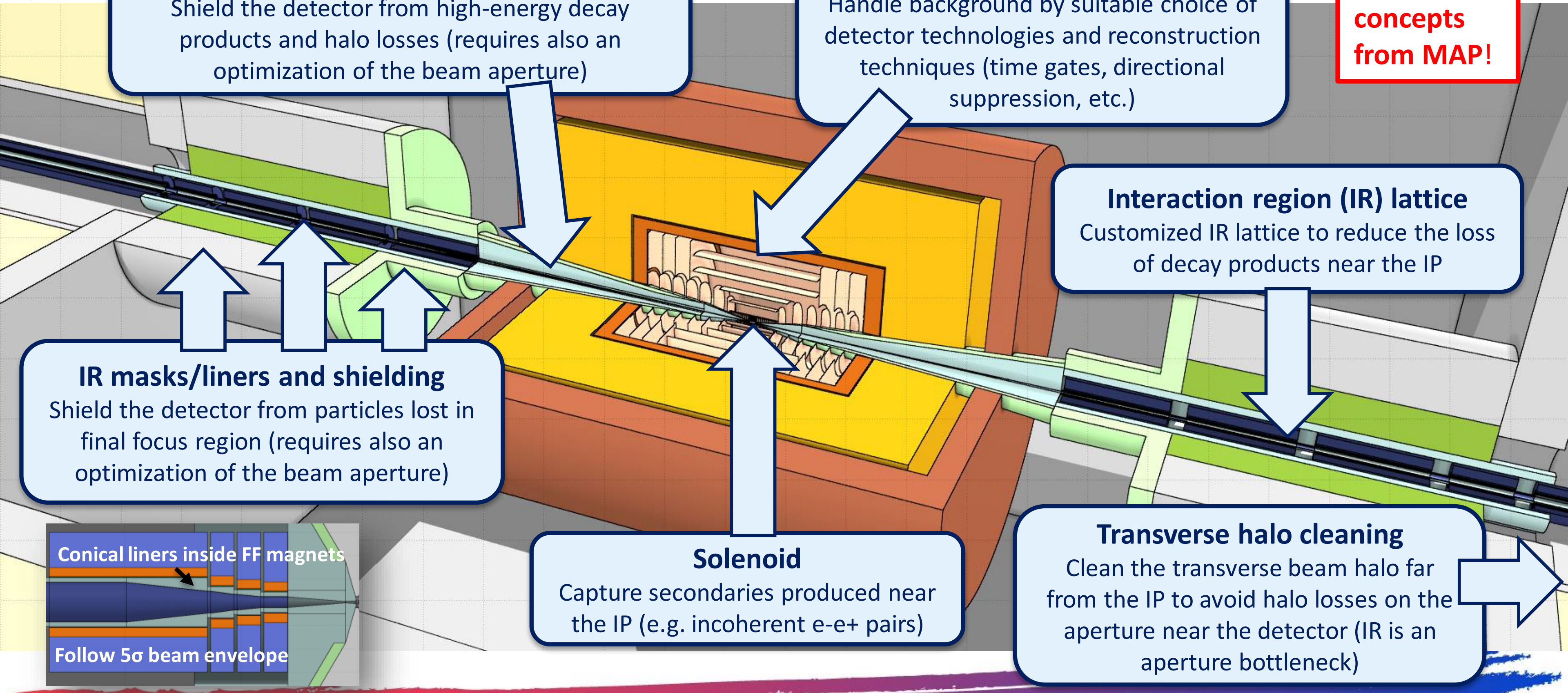
Detector
Handle background by suitable choice of detector technologies and reconstruction techniques (time gates, directional suppression, etc.)

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)

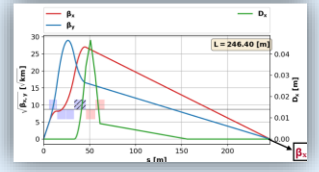
Transverse halo cleaning
Clean the transverse beam halo far from the IP to avoid halo losses on the aperture near the detector (IR is an aperture bottleneck)



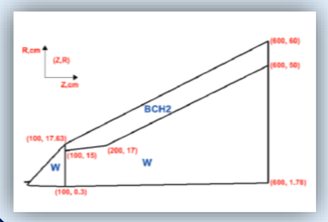
Workflow for background simulations in IMCC & MuCol

Details in the presentations of D. Calzolari and N. Bartosik

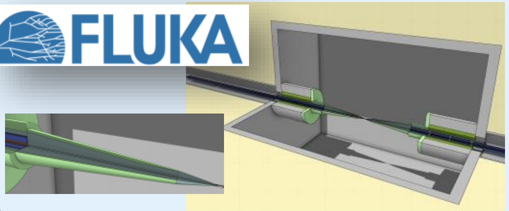
IR layout
Optics (lattice) and apertures



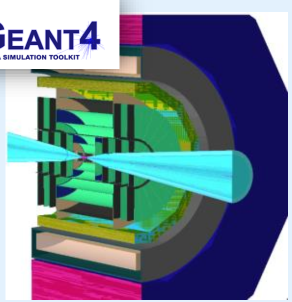
Nozzle & absorber configuration



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!

*BIB=Beam-Induced Background

IMCC & MuCol MDI studies* - roadmap until 2026

International MUON Collider Collaboration

2020/2021
IMCC formed, community meetings

Now
IMCC & MuCol MDI workshop March2024
Interim report completed

2026
Final report for ESPPU

$\sqrt{s}$ = 3 TeV

- MAP $\sqrt{s}$ = 1.5 TeV nozzle → IMCC $\sqrt{s}$ = 3 TeV nozzle
- MAP $\sqrt{s}$ = 3 TeV optics → IMCC $\sqrt{s}$ = 3 TeV optics ???
  - Presently no resources

$\sqrt{s}$ = 10 TeV

- MAP $\sqrt{s}$ = 1.5 TeV nozzle → IMCC $\sqrt{s}$ = 10 TeV nozzle
- IMCC $\sqrt{s}$ = 10 TeV optics

Achievements (selection):

- Development of a 10 TeV IR lattice → impact of lattice design choices on the decay background
- First comparison of decay background for 3 TeV and 10 TeV + first BIB samples for detector studies
- First study of the incoherent pair production background and halo background (10 TeV)
- First estimates of the cumulative radiation damage in the detector (3 TeV and 10 TeV)
- First study of the nozzle optimization potential
- First study of forward muons (10 TeV)

Main goals until 2026:

- Optimization of the nozzle, absorbers, shielding for 3 TeV and 10 TeV, respectively
- Continue 10 TeV IR lattice development
- Engineering considerations for nozzle and integration with detector and solenoid
- Study the permissible halo-induced background in the IR (derive specs for halo cleaning)
- Refinement of incoherent pair production background
- Study radiation damage in IR magnets & detector

***For detector studies, see talk of Donatella**

Lattices presently used for IMCC &MuCol MDI design studies

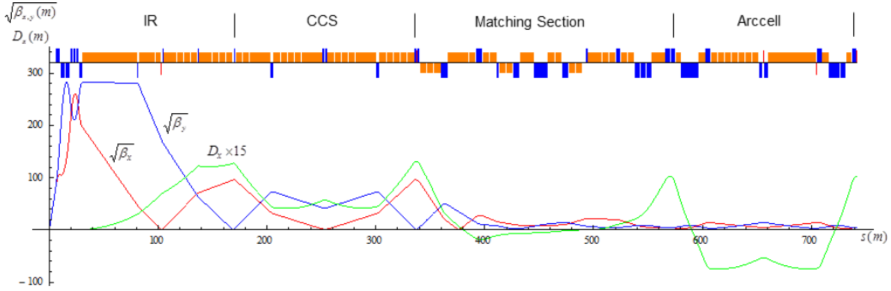
Details in the presentations of
E. Gianfelice-Wendt and K. Skoufaris

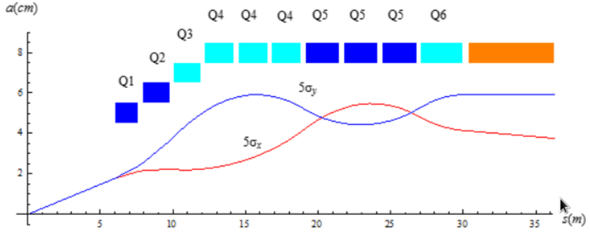
	$\sqrt{s}$=3 TeV	$\sqrt{s}$=10 TeV
Version	US MAP [1]	IMCC (present vers 0.7) [2]
FF scheme	Quadruplet (with dipolar component)	Triplet (with dipolar component)
ß*	5 mm	1.5 mm
L*	6 m	6 m
Max. field at inner bore	12 T	20 T

[1] Y. Alexahin, E. Gianfelice-Wendt, V. Kapin (Fermilab), Y. Alexahin et al 2018 JINST 13 P11002
[2] K. Skoufaris, C. Carli (CERN)

- **Some of the challenges:**
  - Large ßs in FF magnets, hence large aperture
  - High-fields and strong chromatic effects → local chromatic correction scheme

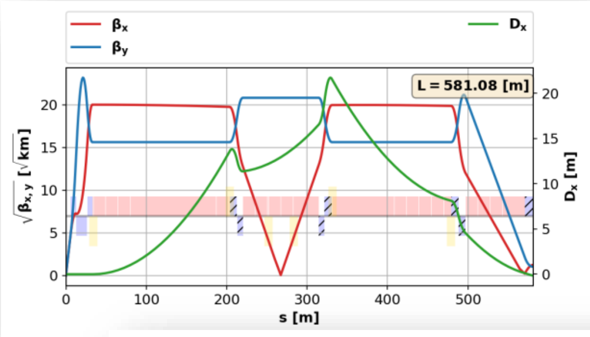
$\sqrt{s}$=3 TeV MAP lattice (quadruplet version):

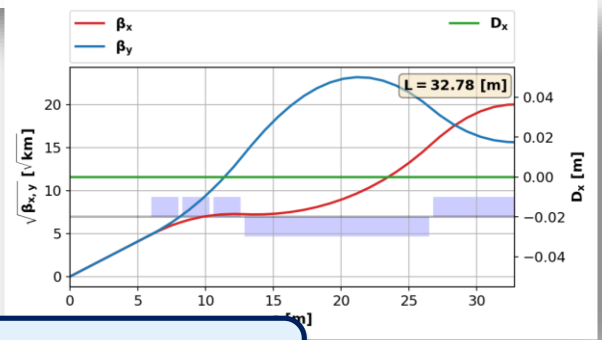




IR lattice iterations for 10 TeV

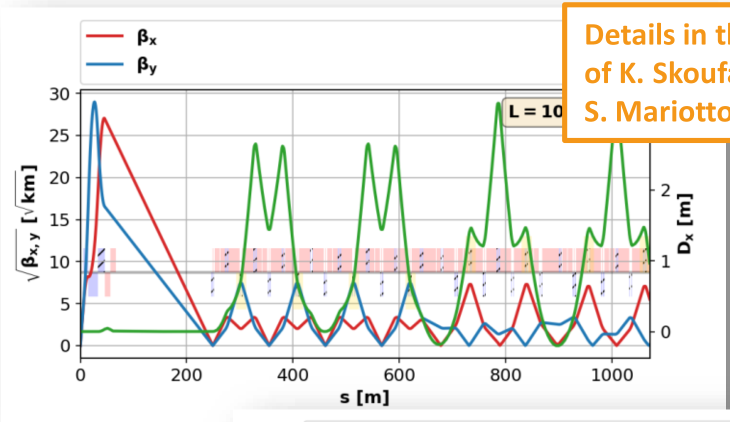
*IMCC lattice **v0.4***





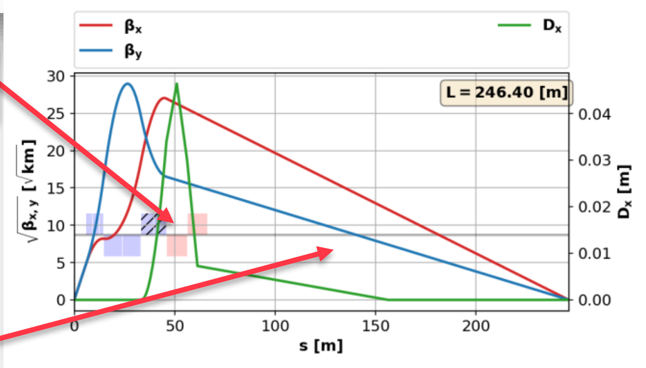
Reference lattice for present 10 TeV BIB sample

*IMCC lattice **v0.7** (present version)*



Details in the presentations of K. Skoufaris (lattice) and S. Mariotto (magnets)

Strong dipoles for background reduction

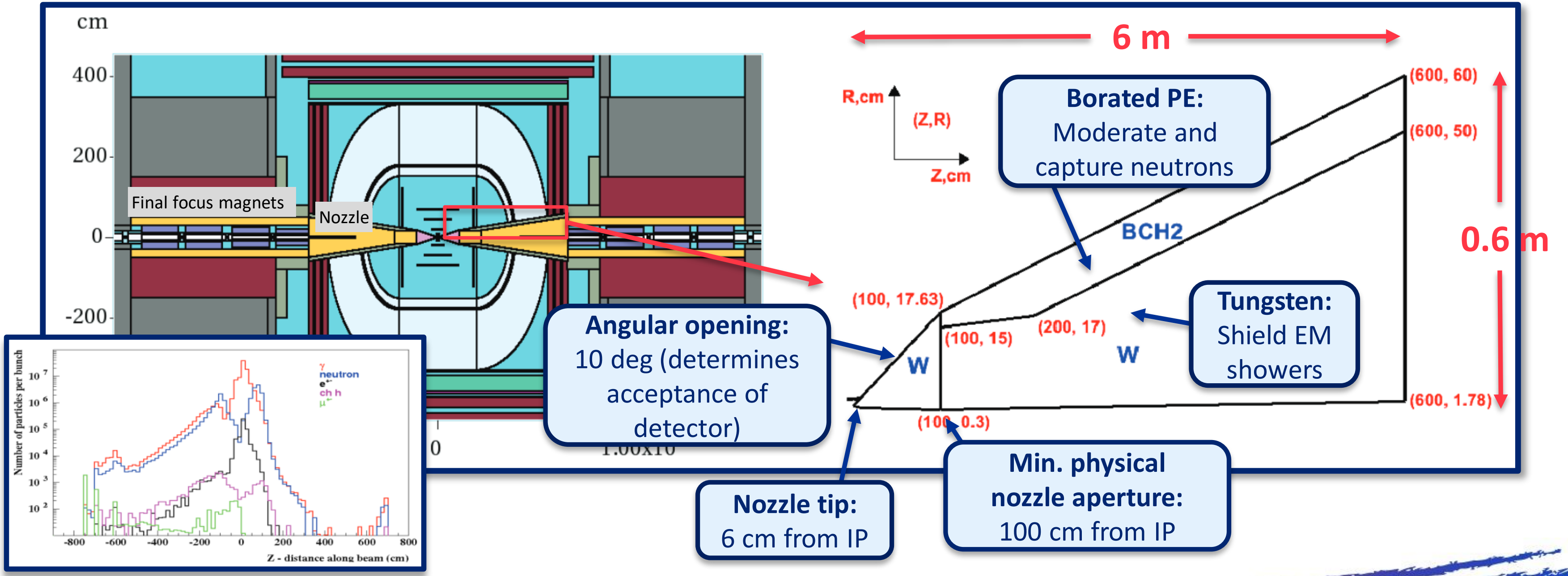


Long drift section for a smoother reduction of the beta values at the end of the FF scheme.

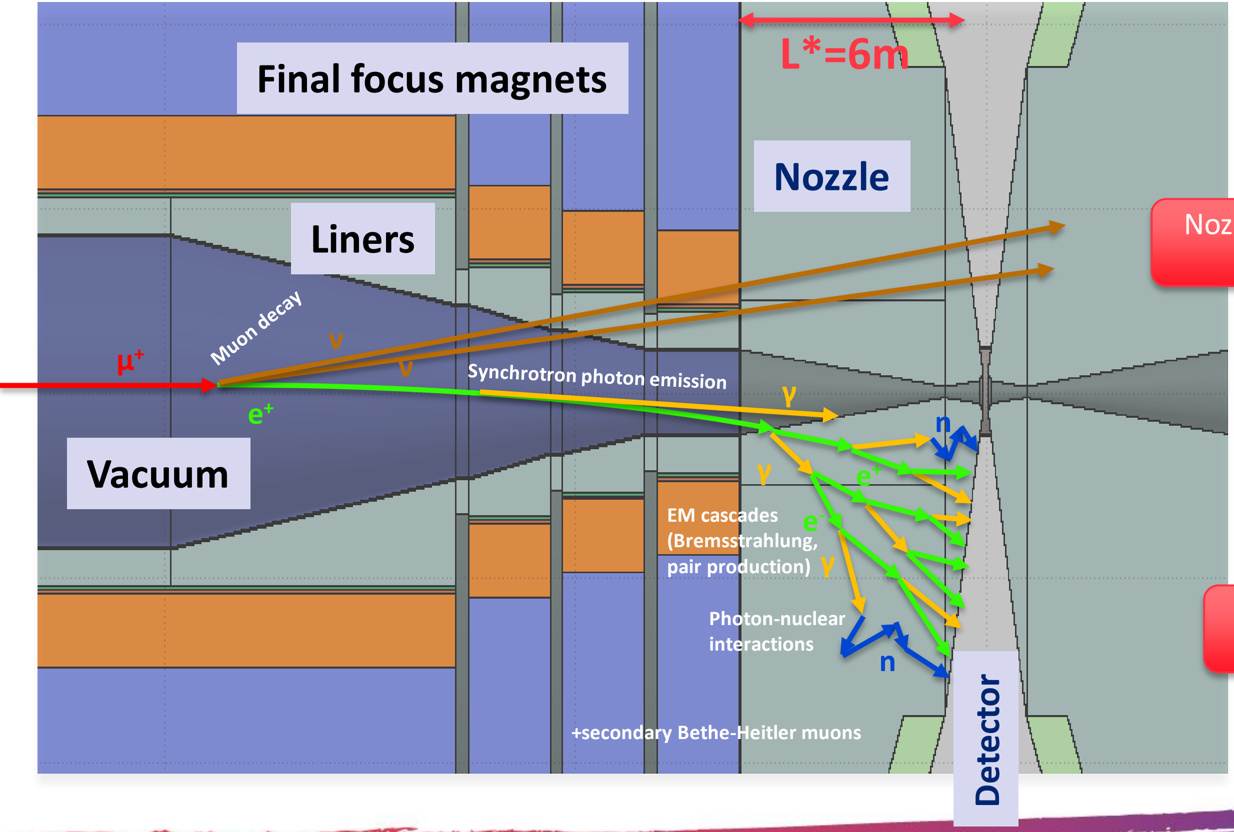
The MAP nozzle for $\sqrt{s}$=1.5 TeV

Detailed studies done by N. Mokhov et al. within US MAP to **optimize nozzle** for a $\sqrt{s}$**= 1.5 TeV** collider (using the MARS Monte Carlo code)

N. V. Mokhov and S.I. Striganov "Detector Backgrounds at Muon Collider", Physics Procedia 37 (2012), link.



Anatomy of decay-induced background



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

Nozzle → Background reduction by orders of magnitude

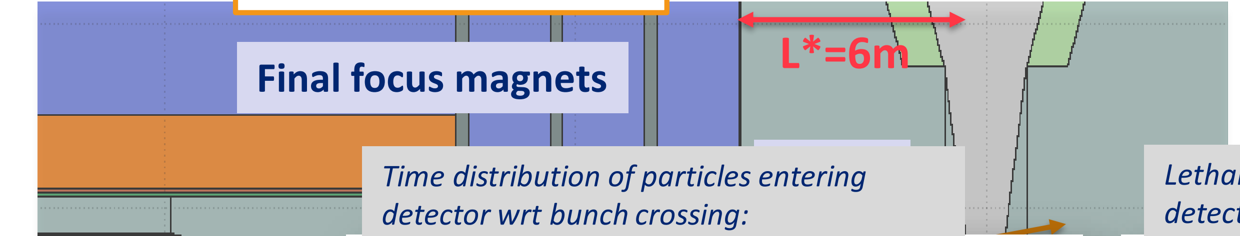
Lattice and beam aperture: Determine how many decay products are lost near the IP*, but little influence on secondary spectra and entry positions in detector

Lattice → Background reduction by a factor of a few

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

Anatomy of decay-induced background

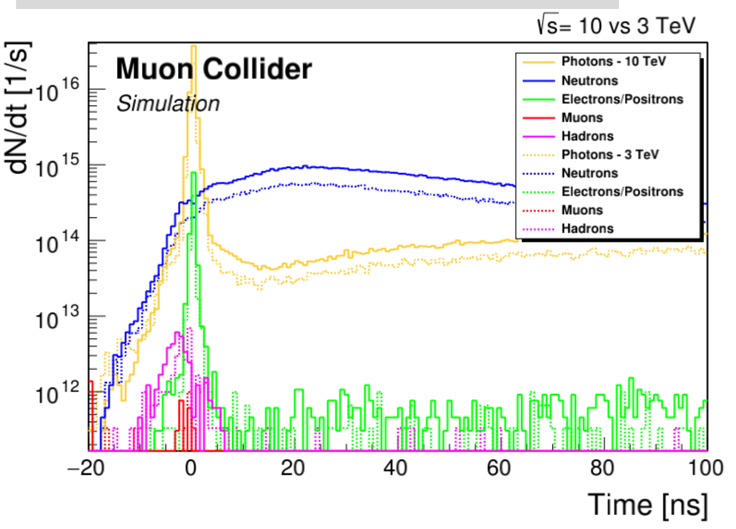
Details in the presentations of D. Calzolari and L. Castelli



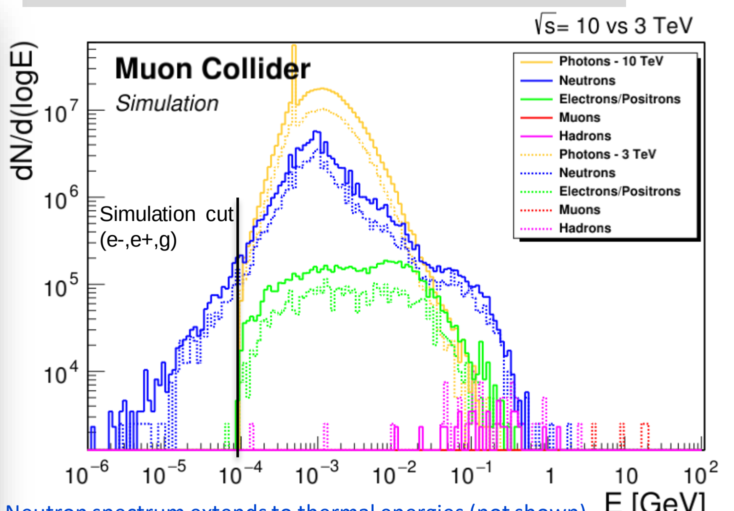
Background particles (from decay) entering detector per bunch crossing (with time cut [-1:15]ns):

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

Time distribution of particles entering detector wrt bunch crossing:



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



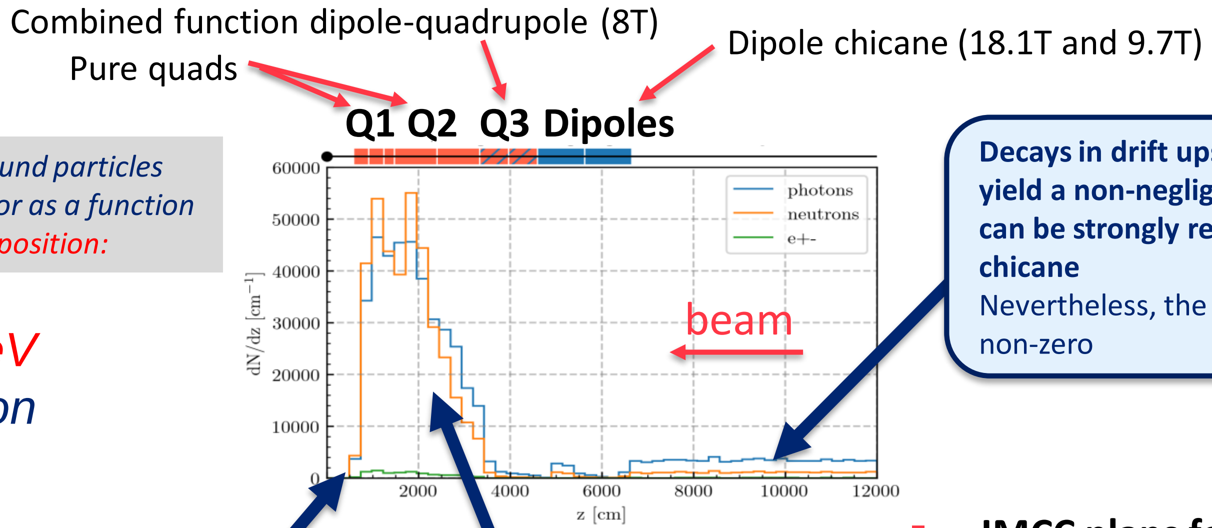
Neutron spectrum extends to thermal energies (not shown)

Still need to study **Bethe-Heitler muon background** with high statistics samples!

Decay background: impact of lattice choices

Number of background particles entering the detector as a function of the muon decay position:

Latest 10 TeV lattice version (v0.7)



Decays in drift upstream of FF would yield a non-negligible contribution but can be strongly reduced by a dipole chicane
Nevertheless, the contribution remains non-zero

Decays inside nozzle (between IP and L*) contribute very little to the background
But: increasing L* from 6m to 10m yields only small improvement – O(few 10%) – at the expense of a more complex lattice design

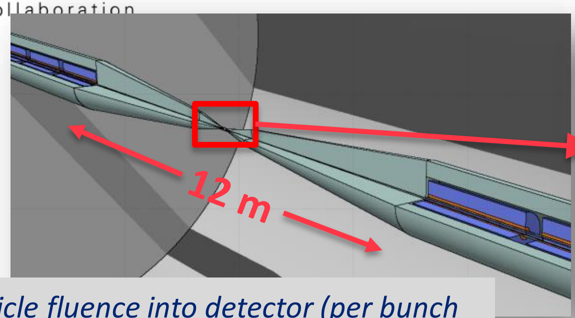
Decays inside triplet dominate background
Can only be partially mitigate by lattice choice (e.g. dipolar component)

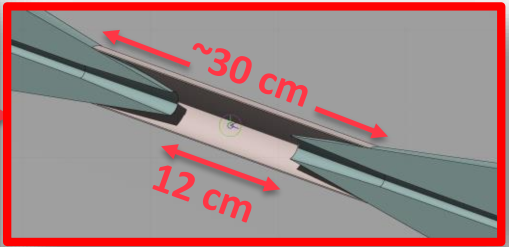
- **IMCC plans for ESPPU report:**
  - Further optimization of lattice in terms of decay background

Details in the presentation of D. Calzolari

Decay background: towards an optimized nozzle for 3 TeV and 10 TeV

Details in the presentations of D. Calzolari and L. Castelli

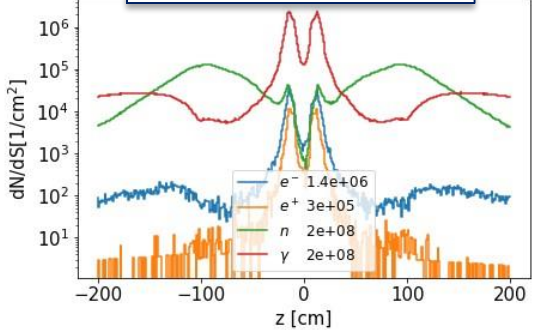




- **Nozzle design**
  - Most results obtained so far were with 1.5 TeV MAP nozzle
  - Preliminary studies show potential to improve nozzle for 3/10 TeV
- **IMCC plans for final ESPPU report:**
  - Optimization of the conceptual nozzle design (shape, material, beam aperture) for 3 TeV and 10 TeV is one of the key priorities
  - Refine the required solenoid field strength

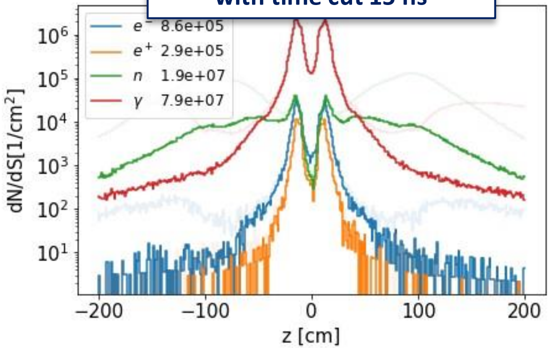
Particle fluence into detector (per bunch crossing) vs longitudinal coordinate:

Muon decay (both beams), no time cut



4 m

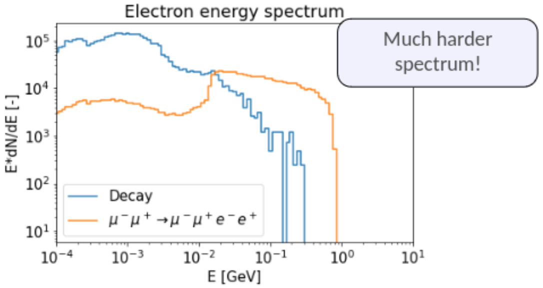
Muon decay (both beams), with time cut 15 ns

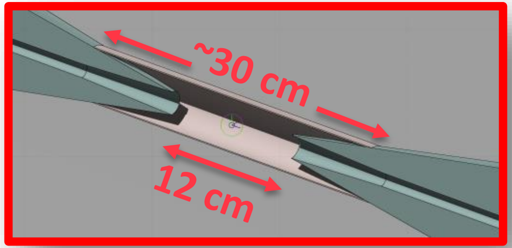


4 m

Incoherent e-/e+ pair production

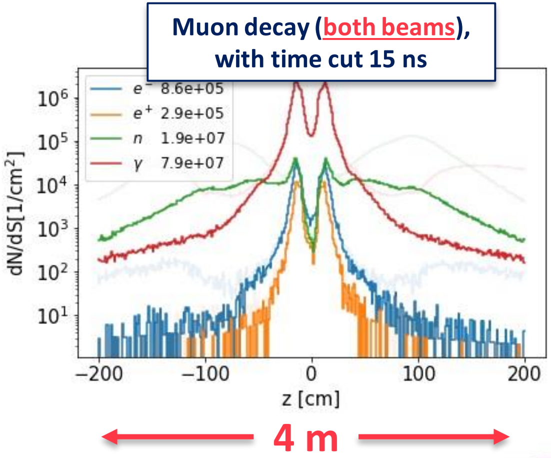
- **Performed a first-order evaluation of incoherent pair production at 10 TeV**
  - Within +/-40 cm from IP, the pair production background contributes a few 10% of the background multiplicity (compared to decay), but the pairs are on average more energetic
- **IMCC plans for final ESPPU report:**
  - Improve description of pair production by muon beams in the GUINEA-PIG event generator

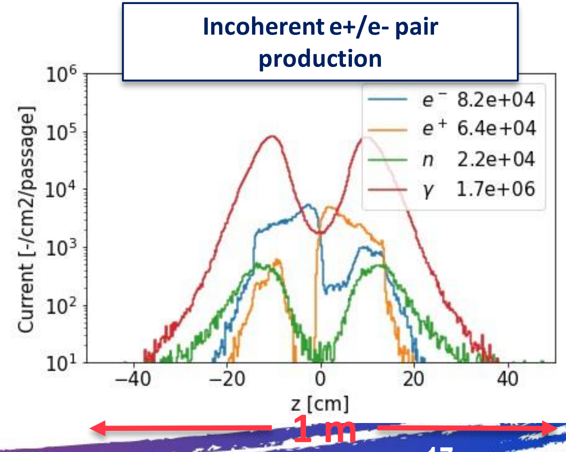




Particle fluence into detector (per bunch crossing) vs longitudinal coordinate:

Pair production: source distribution from GUINEA-PIG





Muon halo losses on the aperture

International MUON Collider Collaboration

- **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:

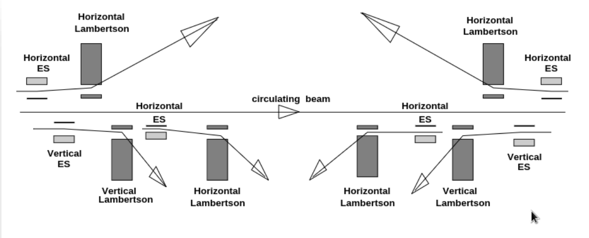
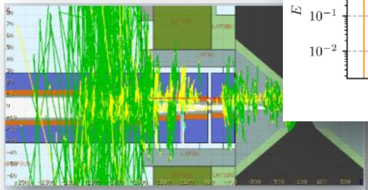


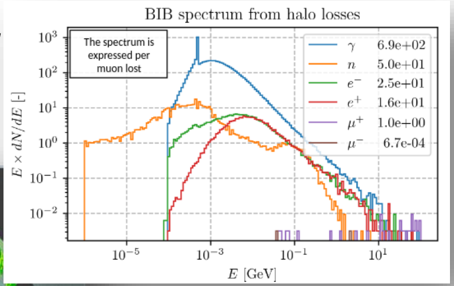
Figure 1: Schematic view of a $\mu^+\mu^-$ collider beam halo extraction.

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

First IMCC halo-induced background studies for 10 TeV:



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



From a conceptual to a technical nozzle design

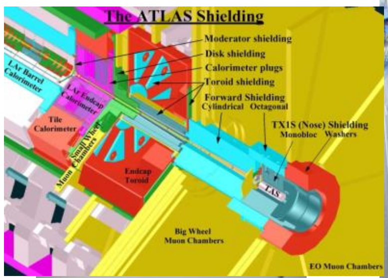
General engineering considerations for shielding: see talks of R. Franqueira Ximenes and B. Miller

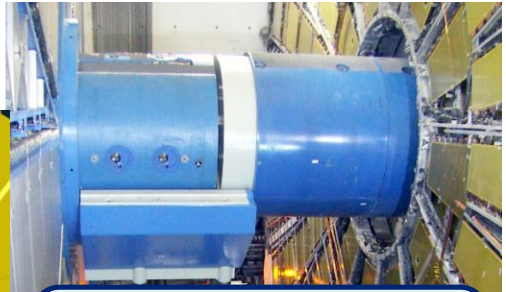
- **Many questions to be addressed for technical nozzle design, for example:**
  - Integration and support inside detector
  - Shielding segmentation and assembly
  - Selection of specific material (tungsten heavy alloy) → machining is an important aspect
  - Heat extraction (cooling)
  - Alignment, vibrations, tolerances, etc.
  - Dedicated vacuum chamber inside nozzle
- **IMCC for final ESPPU report:**
  - First considerations about the nozzle integration inside detector and general technical aspects

    ***But:* do not have resources for detailed technical design studies**

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

Can learn from existing shielding projects, for example ATLAS shielding*:





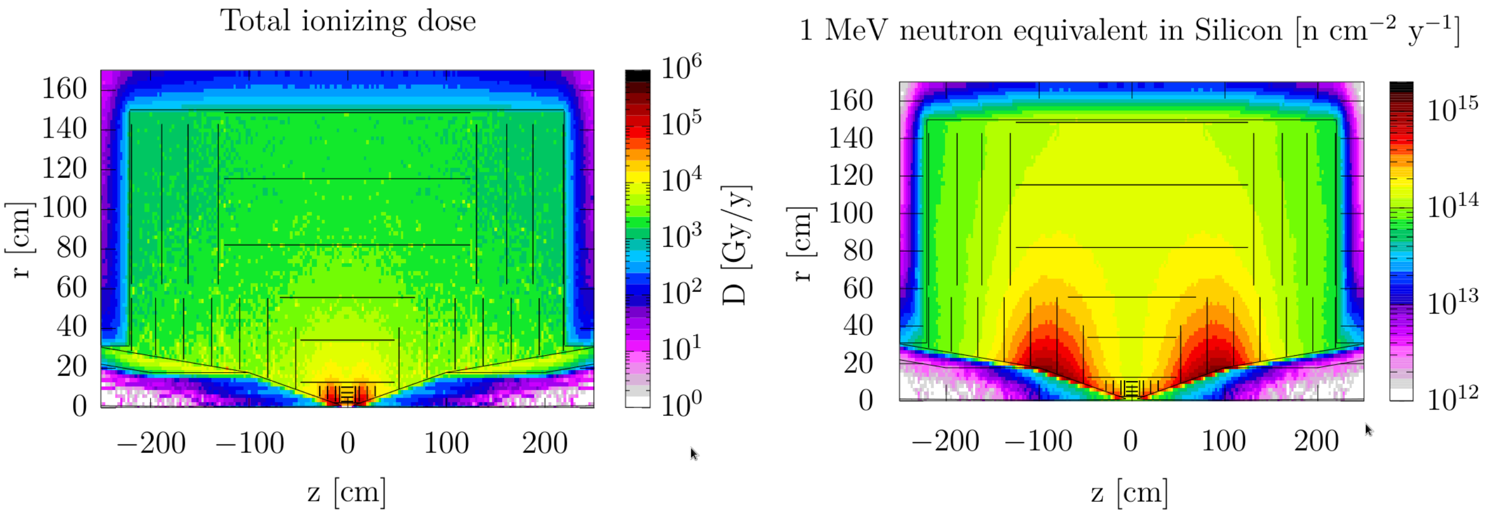
ATLAS forward shielding:
775 tonnes of cast iron,
50 tonnes of steel plates
11 tonnes of borated polyethylene

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

Radiation damage in detector (10 TeV)

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)

Summary of machine-related MDI studies and plans for final ESPPU report

Progress so far (since 2021):

- Development of a 10 TeV IR lattice → impact of lattice design choices on the decay background
- First comparison of decay background for 3 TeV and 10 TeV + first BIB samples for detector studies
- First study of the incoherent pair production background and halo background (10 TeV)
- First estimates of the cumulative radiation damage in the detector (3 TeV and 10 TeV)
- First study of the nozzle optimization potential
- First study of forward muons (10 TeV)

Plans for final ESPPU report (2026):

- Optimization of the nozzle, absorbers, shielding for 3 TeV and 10 TeV, respectively
- Continue 10 TeV IR lattice development
- Engineering considerations for nozzle and integration with detector and solenoid
- Study the permissible halo-induced background in the IR (derive specs for halo cleaning)
- Refinement of incoherent pair production background
- Radiation damage in IR magnets and updated radiation damage studies for detector
- First considerations about luminosity measurements?

International
MUON Collider
Collaboration

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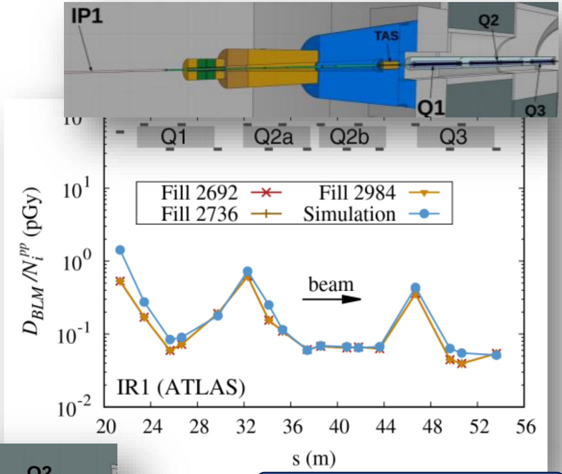
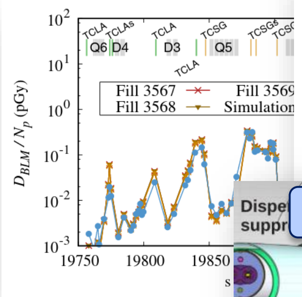
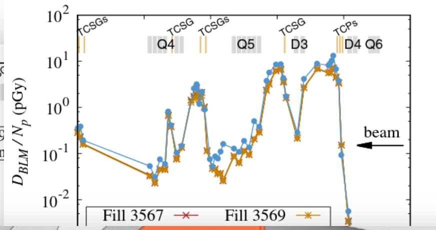
Thank you
for your attention!

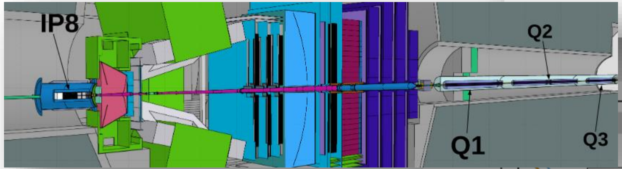
Studying beam losses in colliders – simulation tools

- FLUKA Monte Carlo code is widely used for collider studies (LHC, HL-LHC, FCCee/hh, …)
- Vast experience from LHC operation: agreement with beam loss monitor measurements typically within few 10%

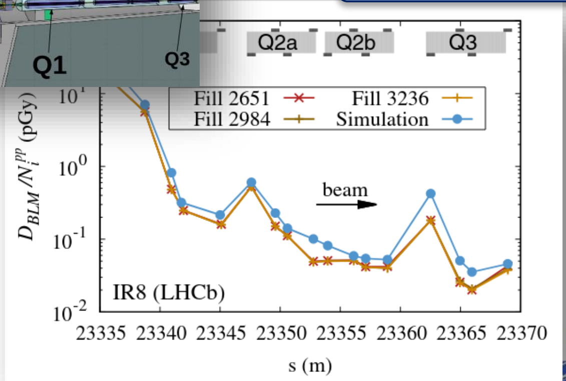


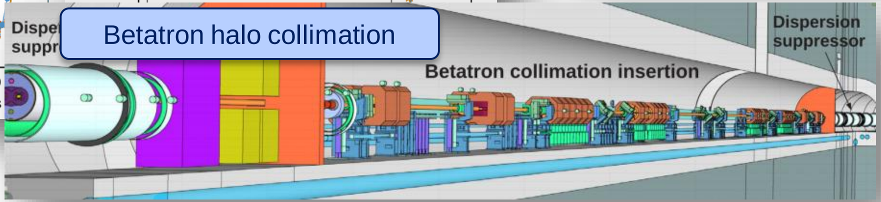






pp collision debris





Betatron halo collimation

A. Lechner et al., Phys. Rev. Accel. Beam (22), 071003, 2019.