International MUON Collider Collaboration

MuCol

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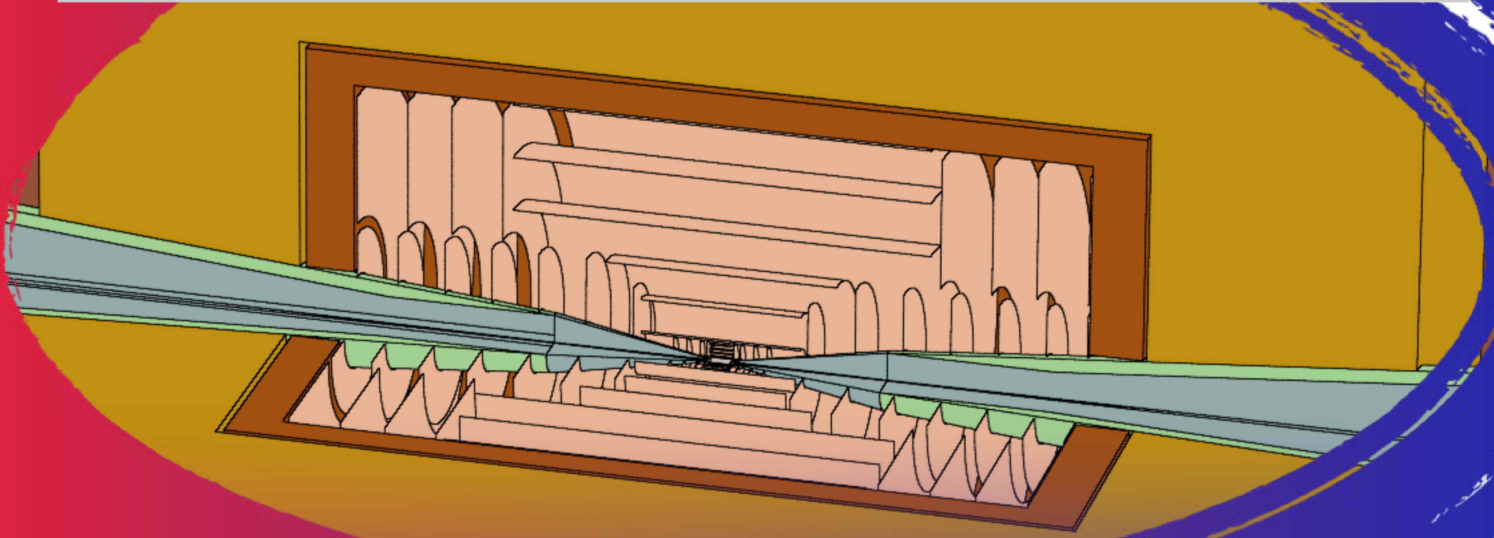
CERN

Muon Collider: Machine-Detector Interface (MDI)

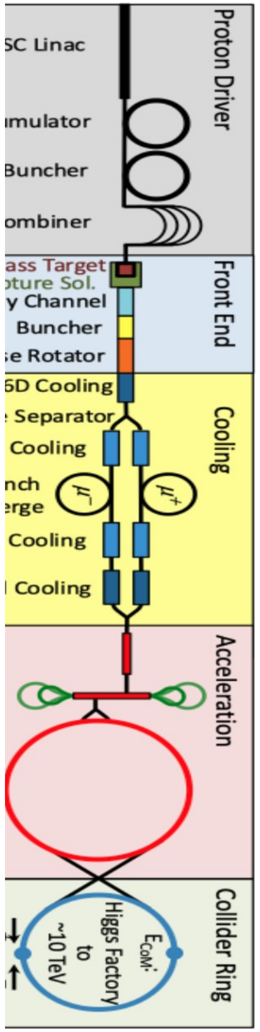


Daniele Calzolari* on behalf of the IMCC & MuCol MDI WG

Workshop on FCC-ee and Lepton Colliders: 22-24 Jan 2025

*CERN (SY-STI-BMI)
INFN sezione di Padova

Introduction



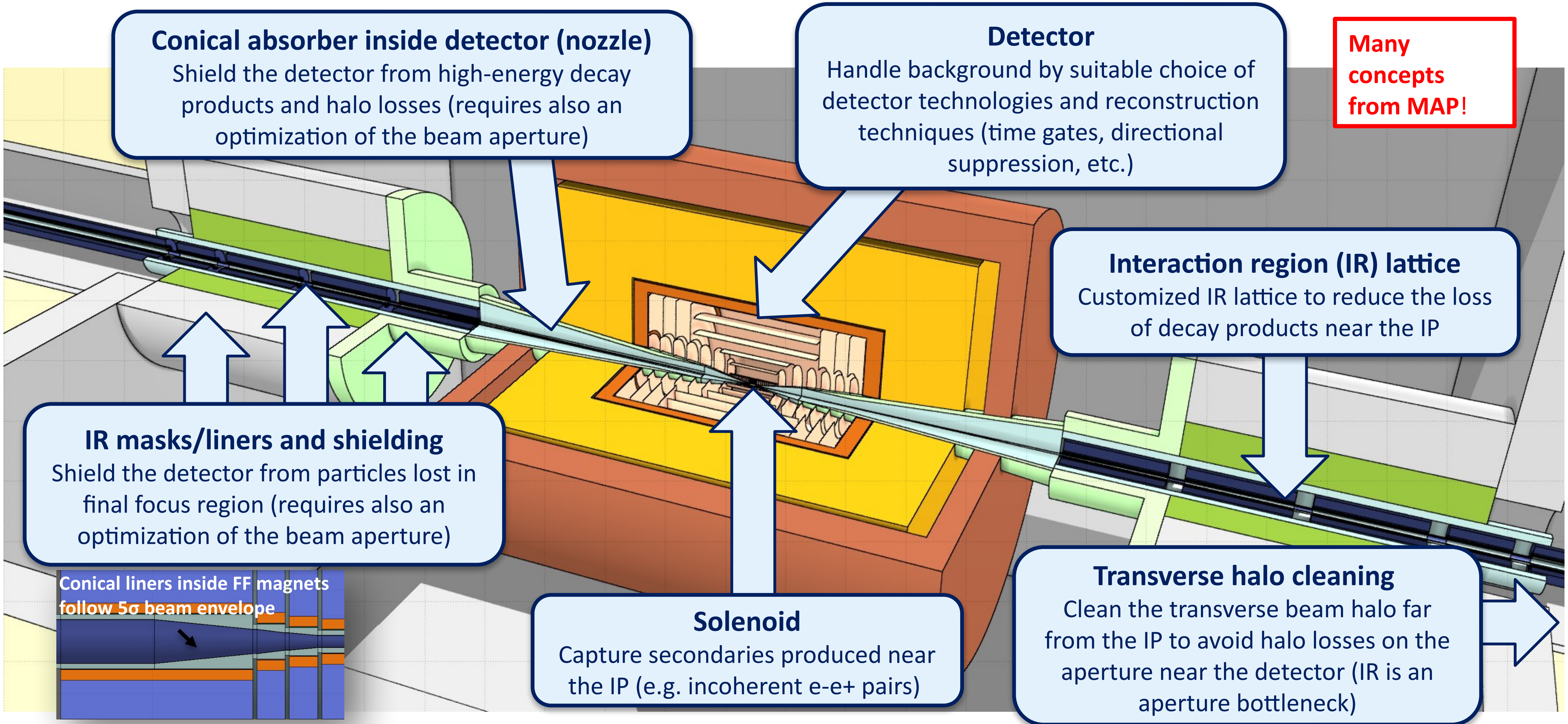
- **Machine-Detector Interface (MDI) objectives:**
  - Study the **beam-induced background (BIB)** and identify mitigation strategies for the **3** and **10(+) TeV** collider options.
  - Develop a credible **interaction region (IR) design** with background levels compatible with detector operations
- Could profit from previous **US MAP** studies (N. Mokhov et al): **MAP design served as starting point.**
- **This presentation:**
  - General introduction to Muon Collider IR and MDI
  - Status and Achievements in view of **ESPPU** stategy update (deadline: March 2025)

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 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**

*There are hardly any real photons produced through beamstrahlung

How to deal with the beam-induced background?



Interaction region lattices

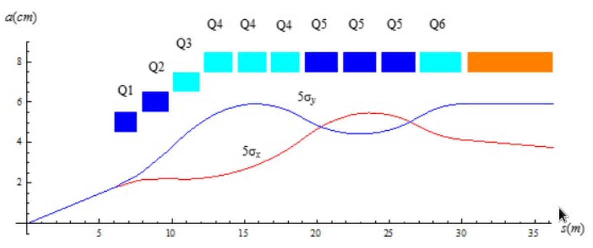
	=3 TeV	=10 TeV
Version	US MAP [1]	IMCC (present vers 0.8) [2]
FF scheme	Quadruplet (with dipolar component)	Triplet (with dipolar component)
ß*	5 mm	1.5 mm
L*	6 m	6 m
Max. field at inner bore	12 T	20 T

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

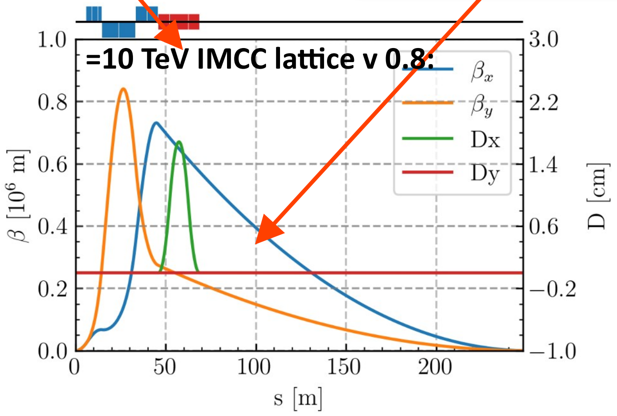
Strong dipoles for background reduction

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

=3 TeV MAP lattice (quadruplet version):

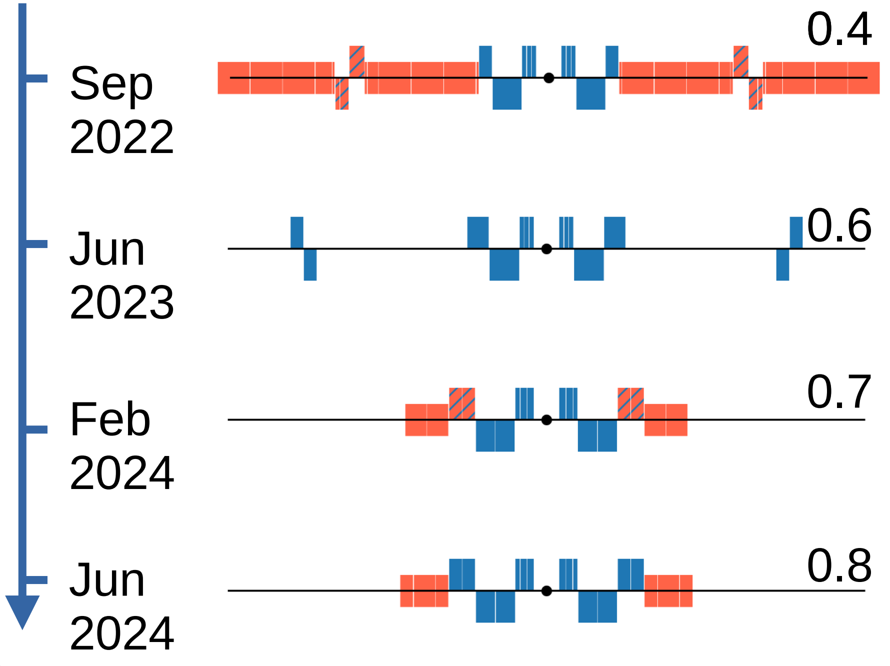


=10 TeV IMCC lattice v 0.8:



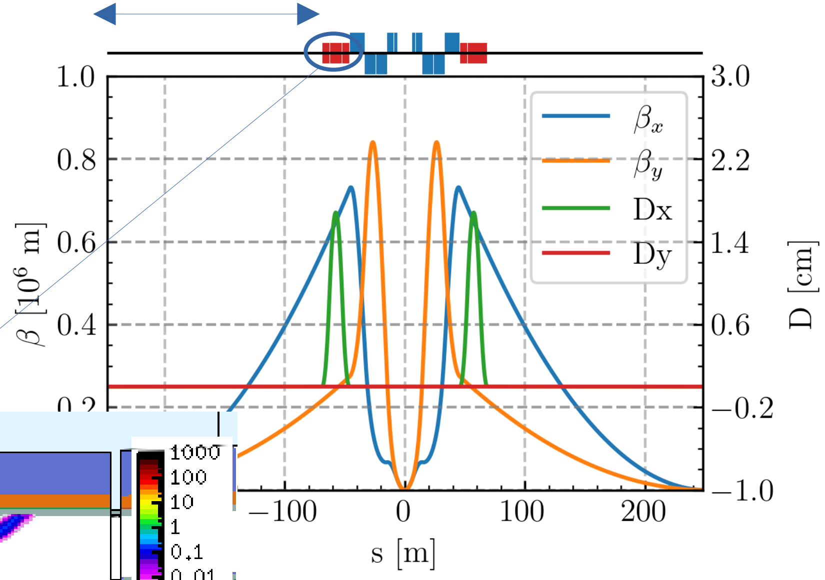
Some of the challenges @ 10 TeV:

- Large ßs in FF magnets, hence large aperture
- High-fields and strong chromatic effects → local chromatic correction scheme

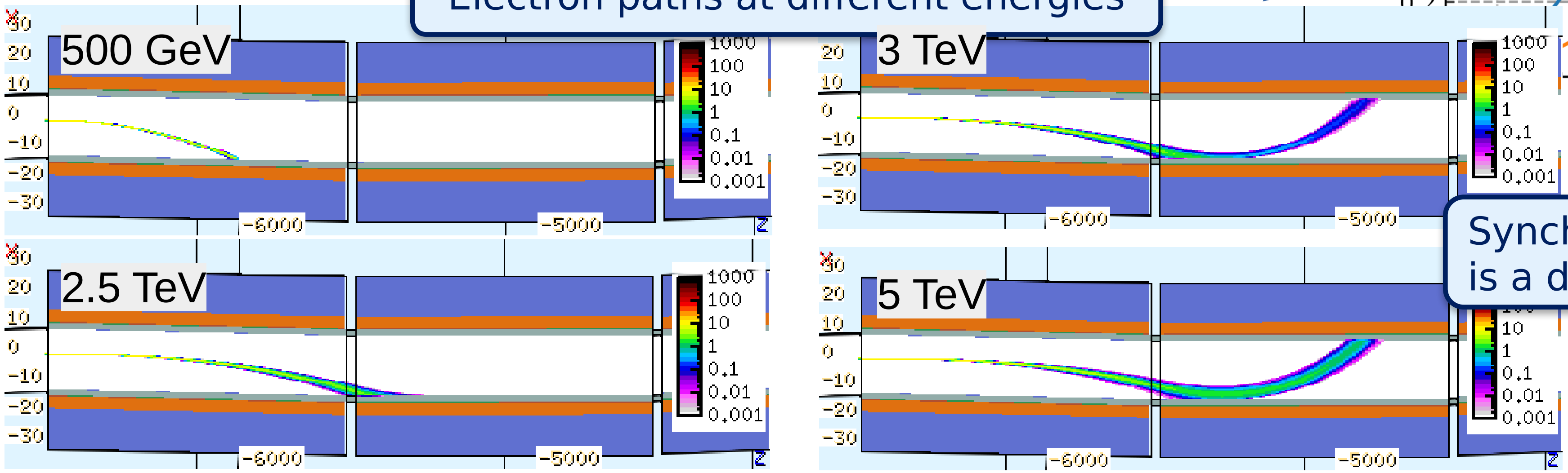


Final focusing region: decay e^+/e^-

- In the interaction region, a long drift collects and accumulates the secondary electrons produced by the muon decay
- The hot-spots in the first dipole magnets require additional shielding



Electron paths at different energies



Synchrotron radiation is a dominant effect!

Radiation load to the final focusing magnets

- 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

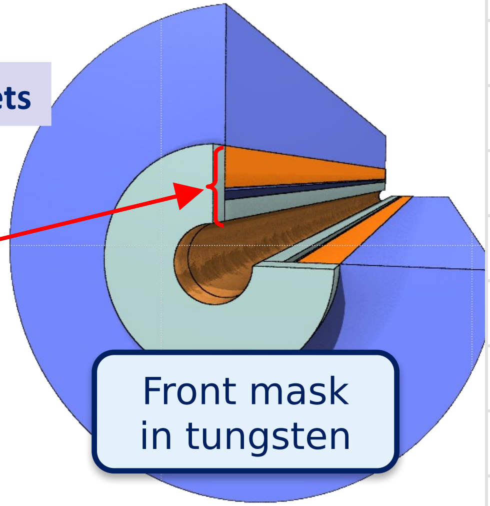
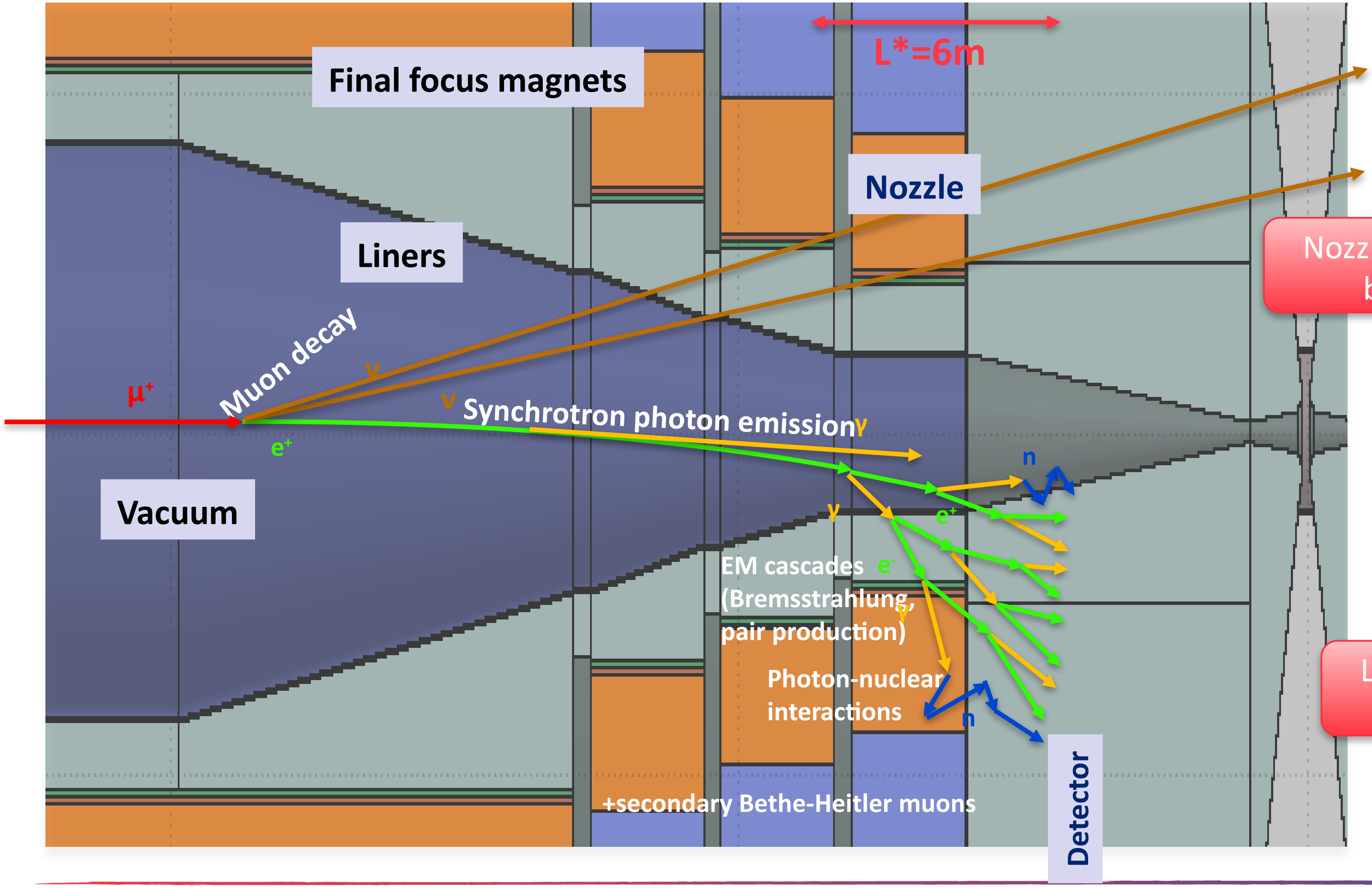


Table: radiation load for each magnet in the final focus

Name	L [m]	Shield thickness [cm]	Coil aperture (radius) [cm]	Peak TID [MGy/y]
IB2	6	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

Anatomy of decay-induced background



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

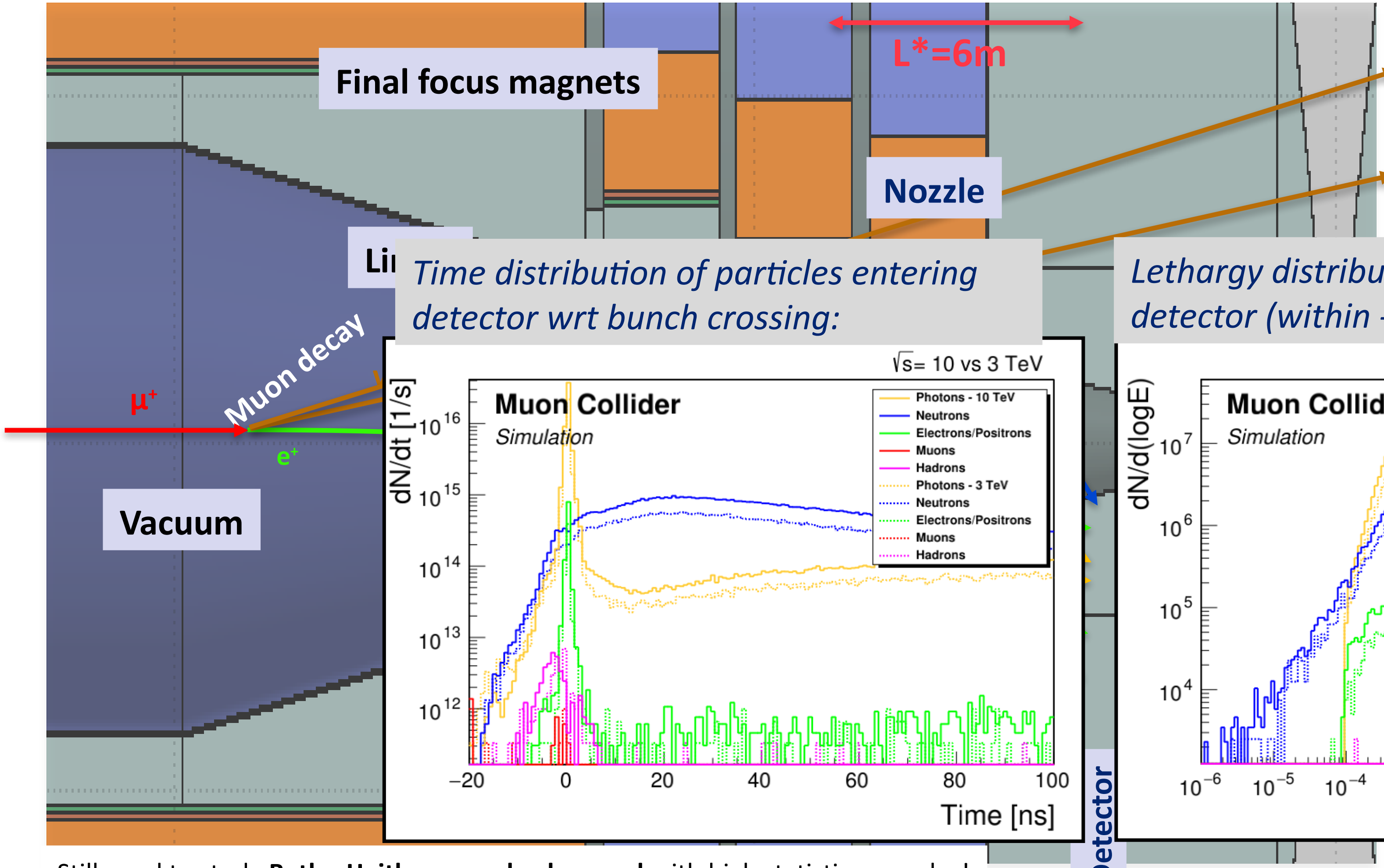
Nozzle → Background reduction by orders of magnitude

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

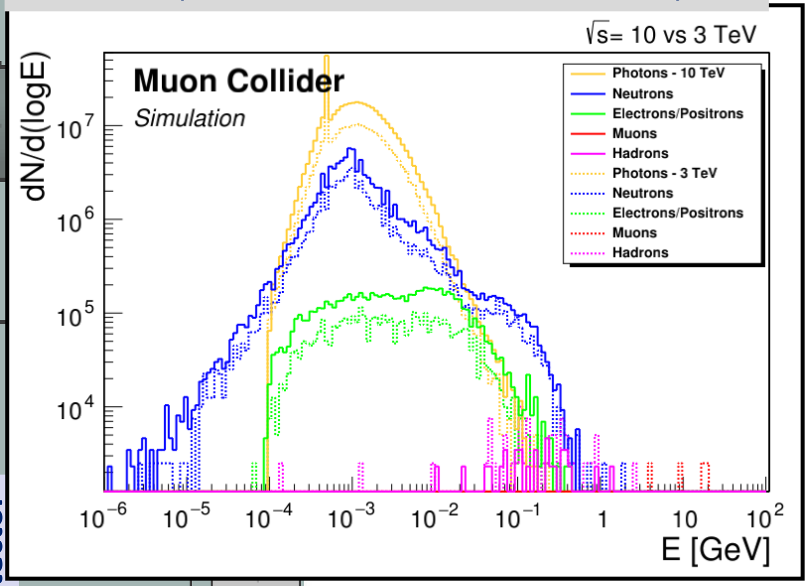


BIB particles (from decay) entering detector per bunch crossing (with time cut [-1:15]ns):

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

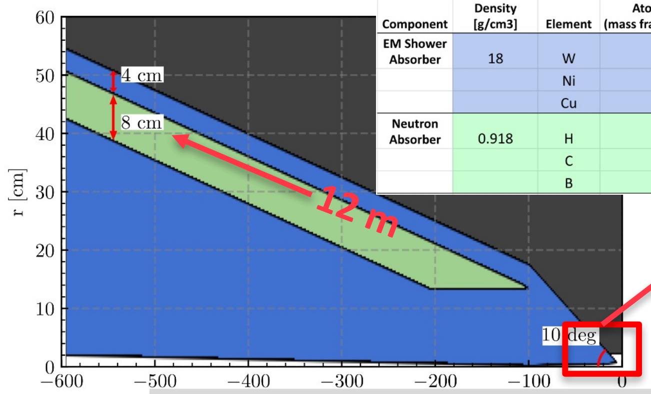
Time distribution of particles entering detector wrt bunch crossing:

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

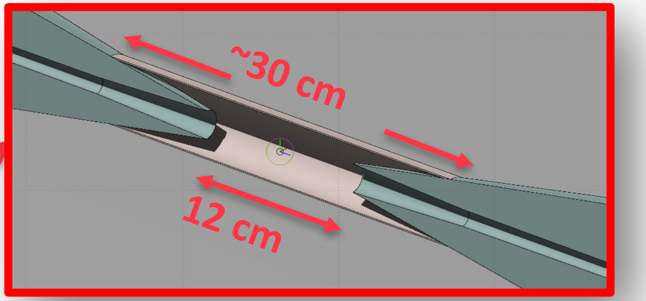


Still need to study **Bethe-Heitler muon background** with high statistics samples!

Decay background: towards an optimized nozzle

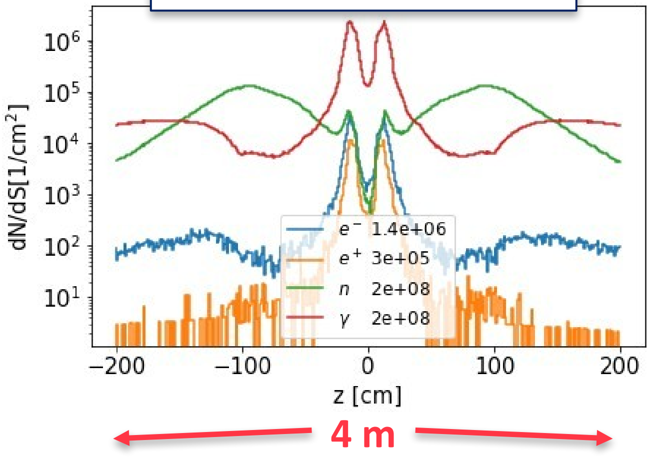


Component	Density [g/cm3]	Element	Atomic Fraction (mass fraction if negative)
EM Shower Absorber	18	W	-0.95
		Ni	-0.035
		Cu	-0.015
Neutron Absorber	0.918	H	0.5
		C	0.25
		B	0.25

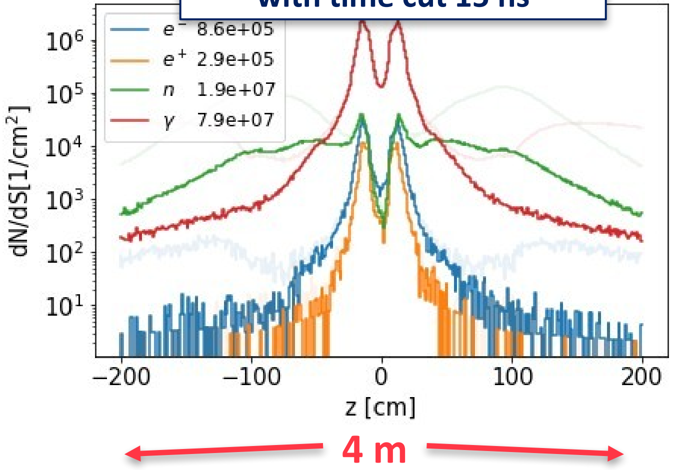


Particle fluence into detector (per bunch crossing) vs longitudinal coordinate:

Muon decay (both beams), no time cut



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

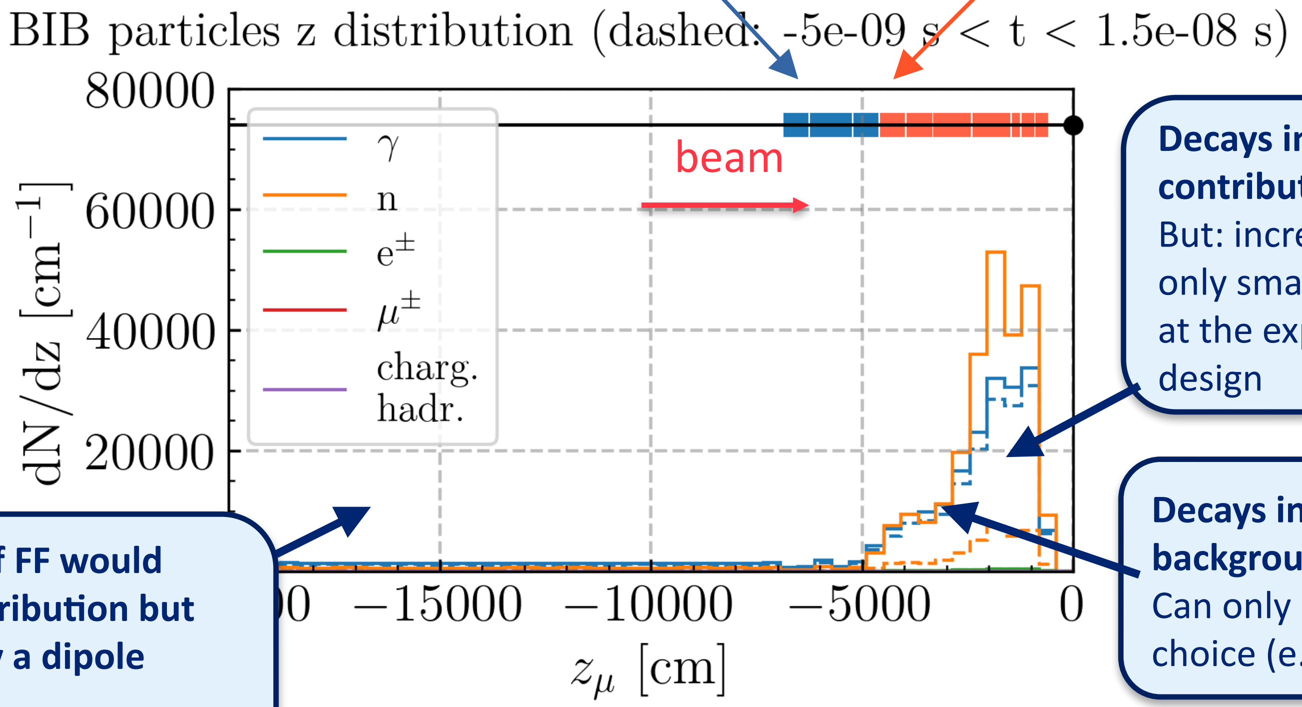


- **Nozzle design**
  - Most results obtained so far were with 1.5 TeV MAP nozzle
  - Preliminary studies show potential to improve nozzle for 3/10 TeV
- **IMCC plans for final ESPPU report:**
  - A sample with an **updated nozzle version** has been provided to the detector community
  - A conceptual optimization is ongoing with scopes beyond the current ESPPU deadline

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 (v0.8)



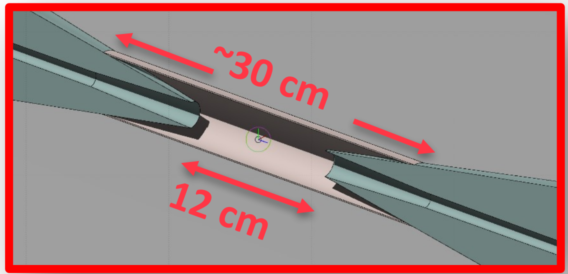
Decays inside nozzle (between IP and L*) contribute very little to the background
But: increasing L* from 6m to 10m yields only small improvement – O(few 10%) – at the expense of a more complex lattice design

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

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

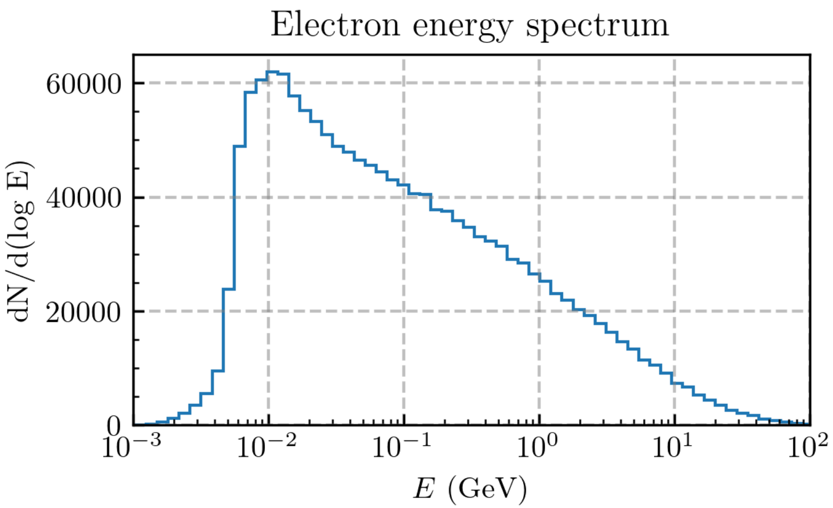
Incoherent e-/e+ pair production

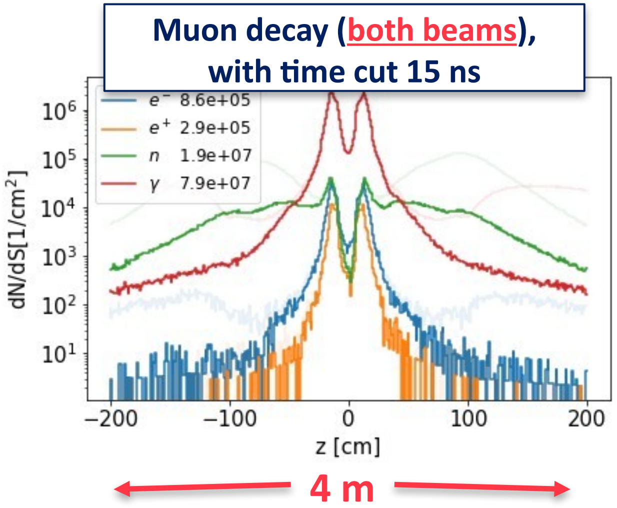
- **Performed a first-order evaluation of incoherent pair production at 10 TeV**
  - Within +/-40 cm from IP, the pair production background contributes a few 10% of the background multiplicity (compared to decay), but the pairs are on average more energetic
- **IMCC plans for final ESPPU report:**
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

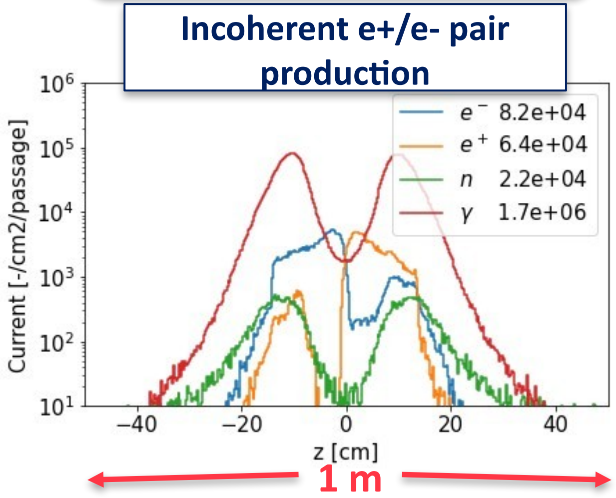


Particle fluence into detector (per bunch crossing) vs longitudinal coordinate:

Pair production: source distribution from GUINEA-PIG

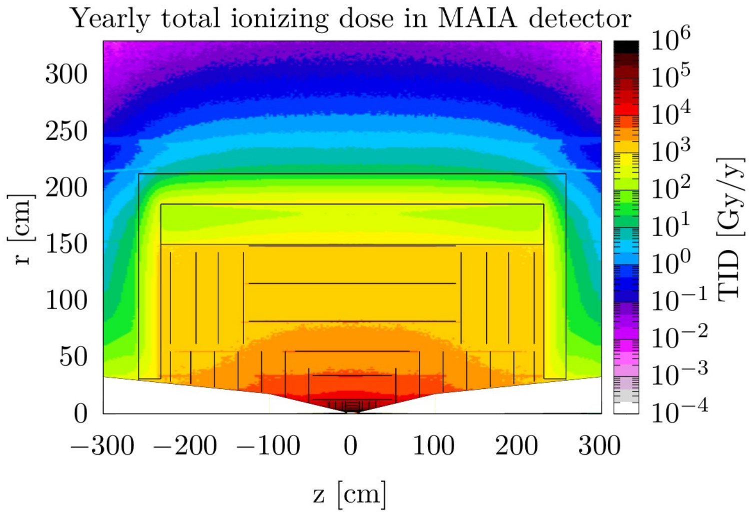


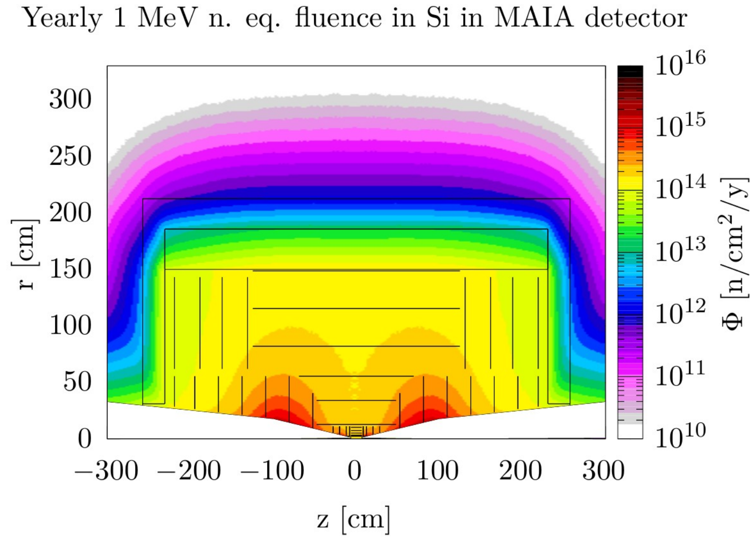




Radiation damage in detector (10 TeV)

Radiation damage estimates for 10 TeV
Includes only contribution of decay-induced background!





**For IMCC lattice version v0.8*

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

IMCC plans for final ESPPU report:

- Radiation damage calculation updated with revised nozzle and lattice
- Incoherent pair production is less relevant for the radiation damage in all detector components

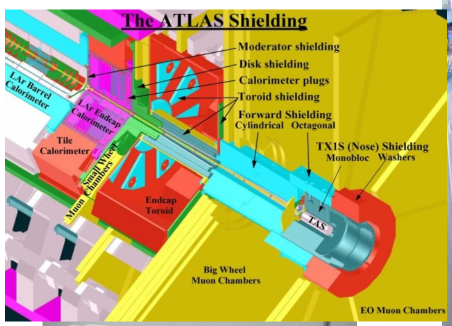
From a conceptual to a technical nozzle design

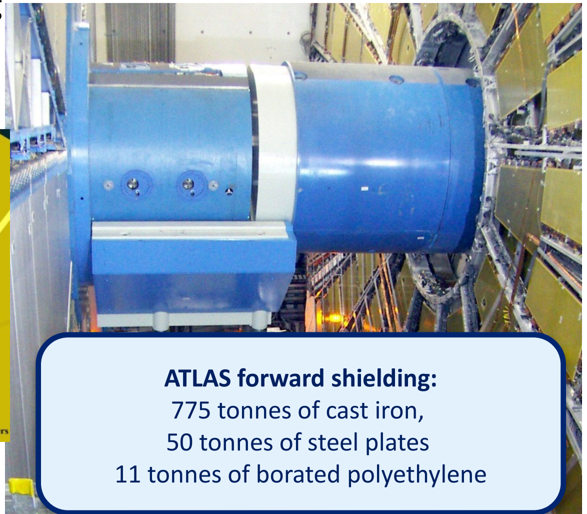
- **Many questions to be addressed for technical nozzle design, for example:**
  - Integration and support inside detector
  - Shielding segmentation and assembly
  - Selection of specific material (tungsten heavy alloy) → machining is an important aspect
  - Heat extraction (cooling)
  - Alignment,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

<u>But:</u> 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

Conclusions

- **Development of a 10 TeV IR lattice** → impact of lattice design choices on the decay background
- IR design ready for a 3 TeV collider
- First comparison of decay background for 3 TeV and 10 TeV + first BIB samples for detector studies
- First study of the incoherent pair production 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**, novel nozzle proposed and adopted
- **Radiation damage in IR magnets estimated**, with the corresponding shielding required

Next steps

- Integration of the IR region and final focusing to cope with strict beam dynamics requirements and severe radiation load.
- Optimization and integration of the nozzle with other components. Moving from a conceptual to a realistic design.

Thank you!

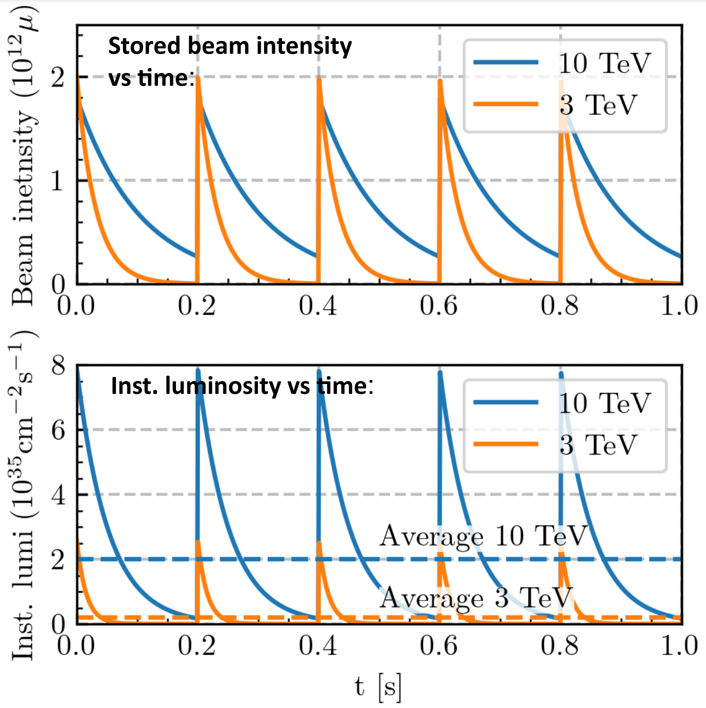
...questions?

Recap of 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} $cm^{-2}s^{-1}$ / 1 x 10^{34} $cm^{-2}s^{-1}$	2 x 10^{35} $cm^{-2}s^{-1}$ / 1 x 10^{35} $cm^{-2}s^{-1}$

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

Workflow in the IMCC

Machine-Detector Interface: MDI

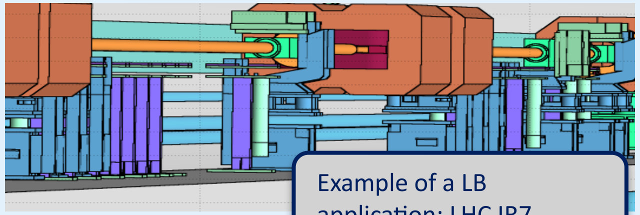
1. Lattice design

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

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

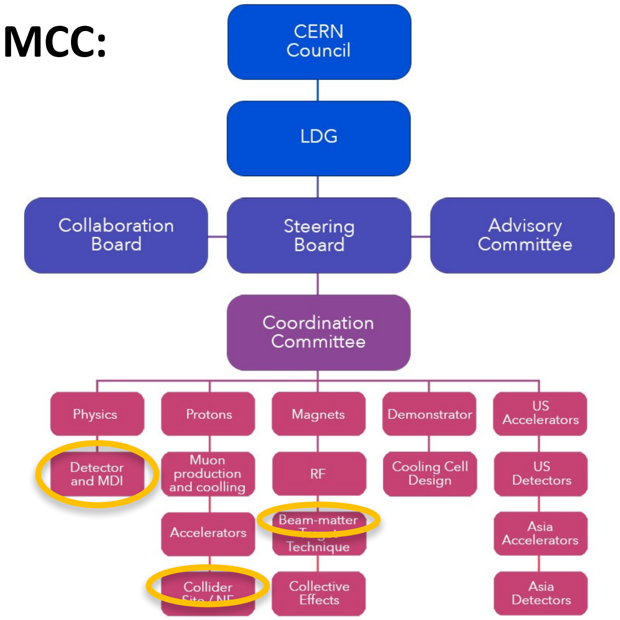
Iteration with lattice design experts to mitigate the BIB

BIB data to detector experts

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

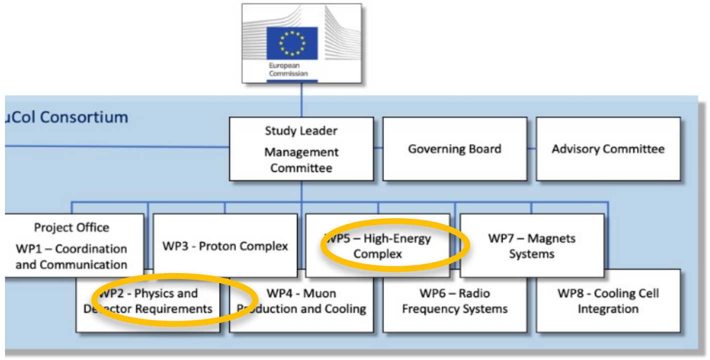
MDI in the IMCC and MuCol (EU study) structure

IMCC:



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

MuCol:



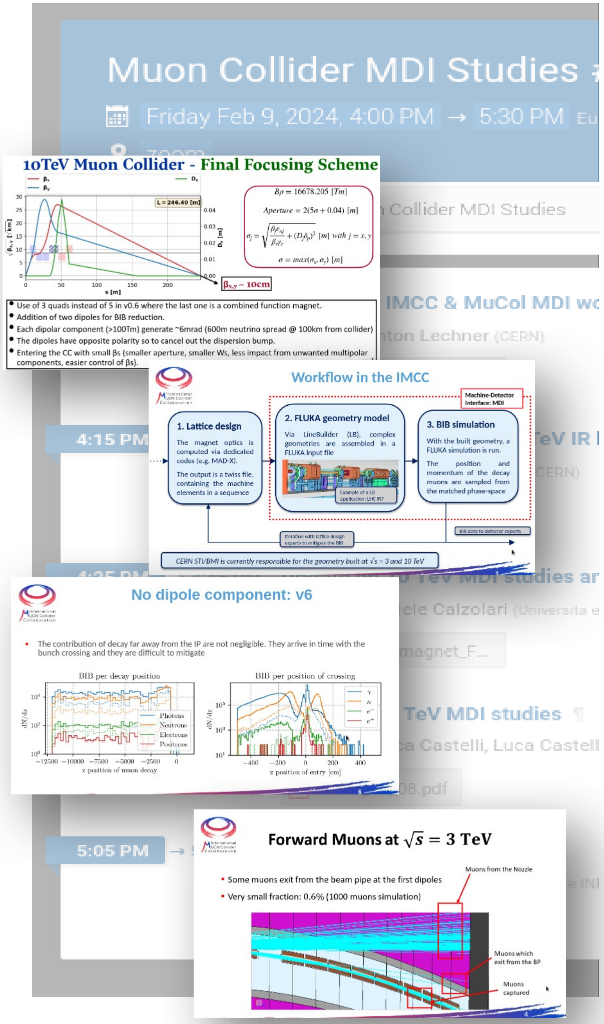
- **WP2** (Physics and Detector Requirements)
  - **MDI – detector studies**
- **WP5** (High-energy complex), **Task 5.1** “Collider design” and **Task 5.4** “MDI design & background to experiments”
  - **MDI – machine studies, IR lattice design, background simulations as input for WP2**

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 <u>open</u> to everyone who is interested to join!



Muon halo losses on the 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:

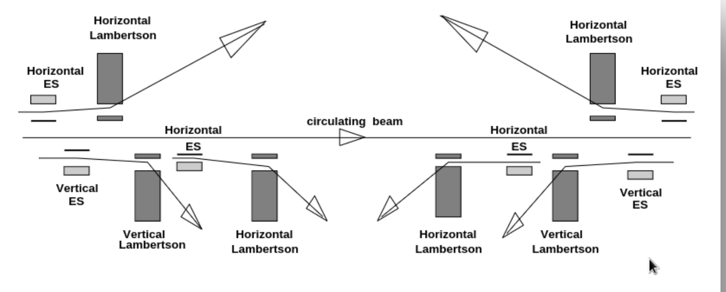
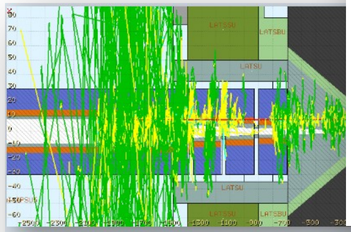


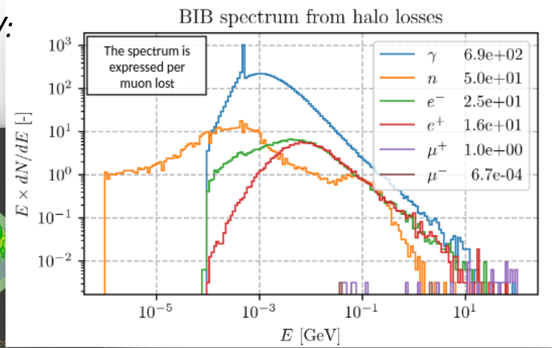
Figure 1: Schematic view of a $\mu^+\mu^-$ collider beam halo extraction.

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

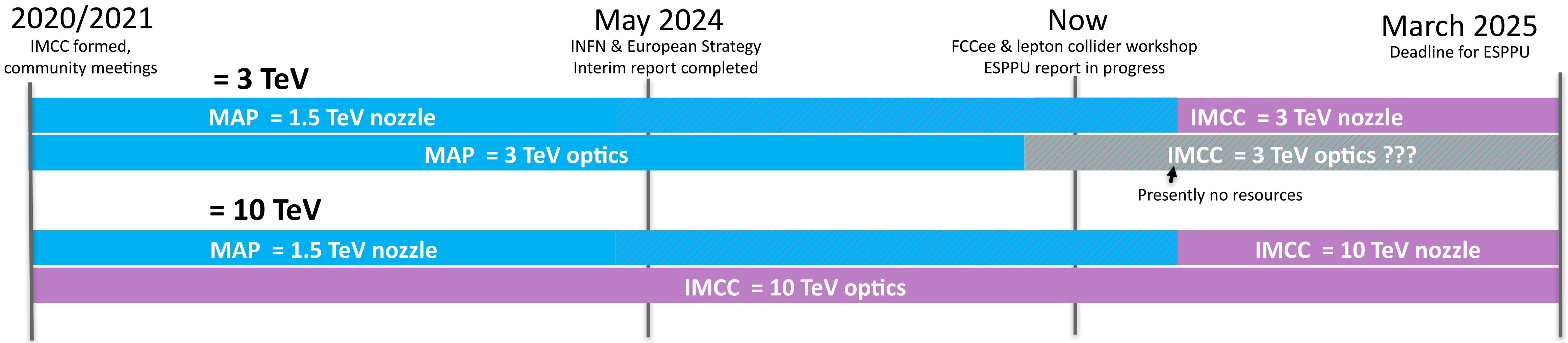
First IMCC halo-induced background studies for 10 TeV:



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



Summary of MDI studies and plans for ESPPU



Main next goals until 2025:

- Further 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)