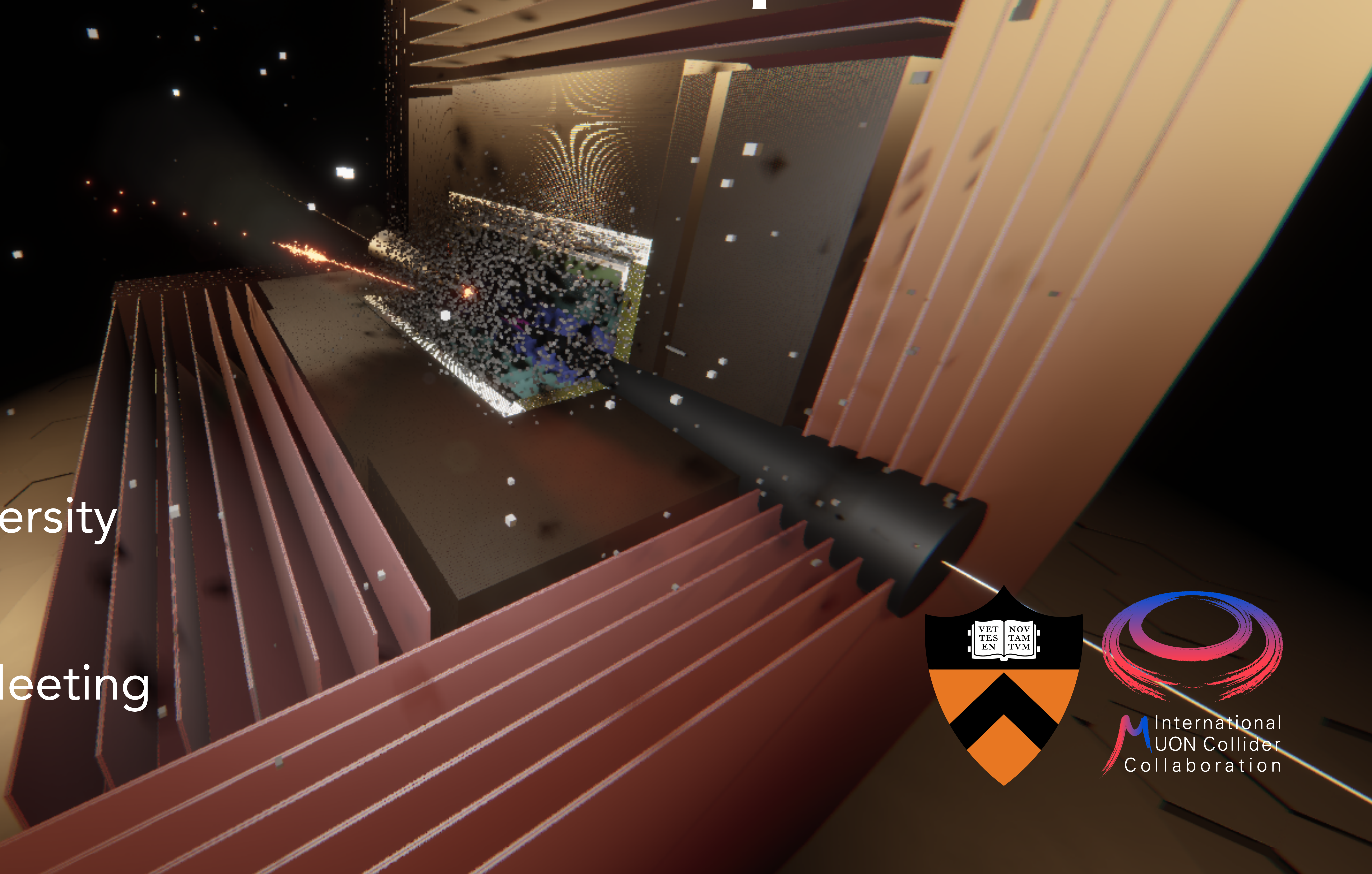
Summary of Recent IMCC MDI and Detector Workshop



Kiley Kennedy, Princeton University

On behalf of many people

Inaugural US Muon Collider Meeting

August 7, 2024

International MUON Collider Collaboration

Introduction

- IMCC Detector and MDI Workshop [Indico]
  - 2-day workshop on June 25-26, 2024 at CERN
  - Aim to establish a configuration for a 10 TeV muon collider
- Participants
  - 47 registered, ~half in-person
  - Variety of research backgrounds: engineers, accelerator physicists, particle physicists
- Scope of Talk
  - KK: Overview of workshop goals, results, and discussion
  - D. Calzolari (next talk): details of implementation

Tuesday, 25 June

14:00 → 18:00 Interaction Region and shielding presentations

14:00	Scope of the workshop Speakers: Anton Lechner (CERN), Donatella Lucchesi (Universita e INFN, Padova (IT))	15m
14:15	Interaction region lattice for the 10 TeV collider (15'+10') Speaker: Marion Vanwelde	25m
14:40	Power deposition and radiation damage in 10 TeV IR magnets (15'+10') Speaker: Daniele Calzolari (Universita e INFN, Padova (IT))	25m
15:05	Beam-induced background at 3 TeV (20'+10') Speaker: Luca Castelli (Sapienza - Università di Roma)	30m
15:35	Coffee break	25m
16:00	Beam-induced background at 10 TeV (20'+10') Speaker: Daniele Calzolari (Universita e INFN, Padova (IT))	30m
16:30	Material considerations for the nozzle (15'+10') Speaker: Andrea Bersani (INFN Genova (IT))	25m

Wednesday, 26 June

09:00 → 09:15	Detector-1 configuration quick overview Speaker: Massimo Casarsa (INFN, Trieste (IT))	15m
09:15 → 09:30	Detector-2 configuration quick overview Speaker: Kiley Elizabeth Kennedy (Princeton University (US))	15m
09:30 → 10:00	Detector effects of beam-induced background Speaker: Davide Zuliani (Universita e INFN, Padova (IT))	30m
10:00 → 10:30	Detector effects of inchoerent pair background Speaker: Federico Meloni (Deutsches Elektronen-Synchrotron (DE))	30m
10:30 → 11:00	Coffee break	30m
11:00 → 11:30	Detector magnet and backround studies	30m
11:30 → 12:00	Magnet, nozzle and cavern dimensions	30m
12:00 → 12:30	Discussion	30m
12:30 → 14:00	Lunch break	1h 30m
14:00 → 14:30	Detector 1 proposal Speaker: Massimo Casarsa (INFN, Trieste (IT))	30m
14:30 → 15:00	Detector 2 proposal	30m
15:00 → 15:30	Discussion	30m
15:30 → 16:30	Write-up of the detector(s) configurations and next steps	1h

Outline

- Part I: Workshop Motivation + Goals
- Part II: Interaction Region + Machine-Detector Interface
- Part III: Detector Concepts
- Part IV: Workshop Outcomes, Outlook + Conclusions

Workshop Motivation + Goals

Context: European Strategy

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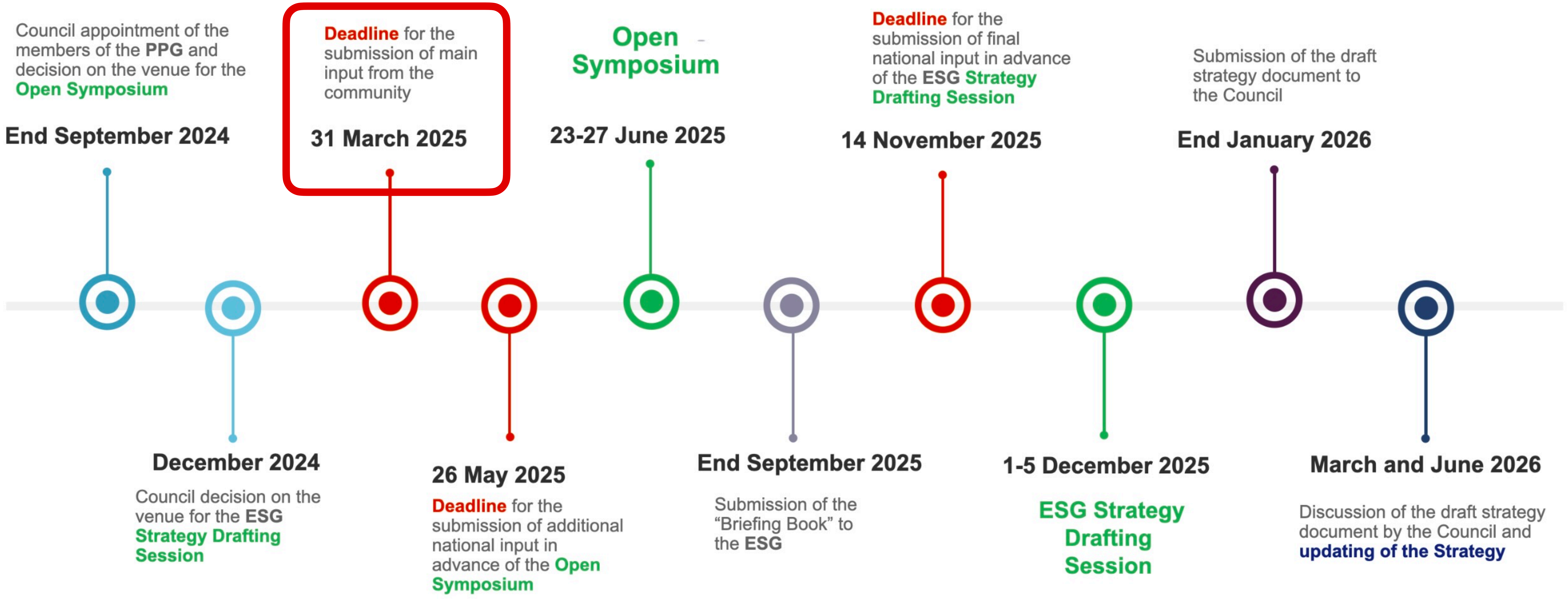
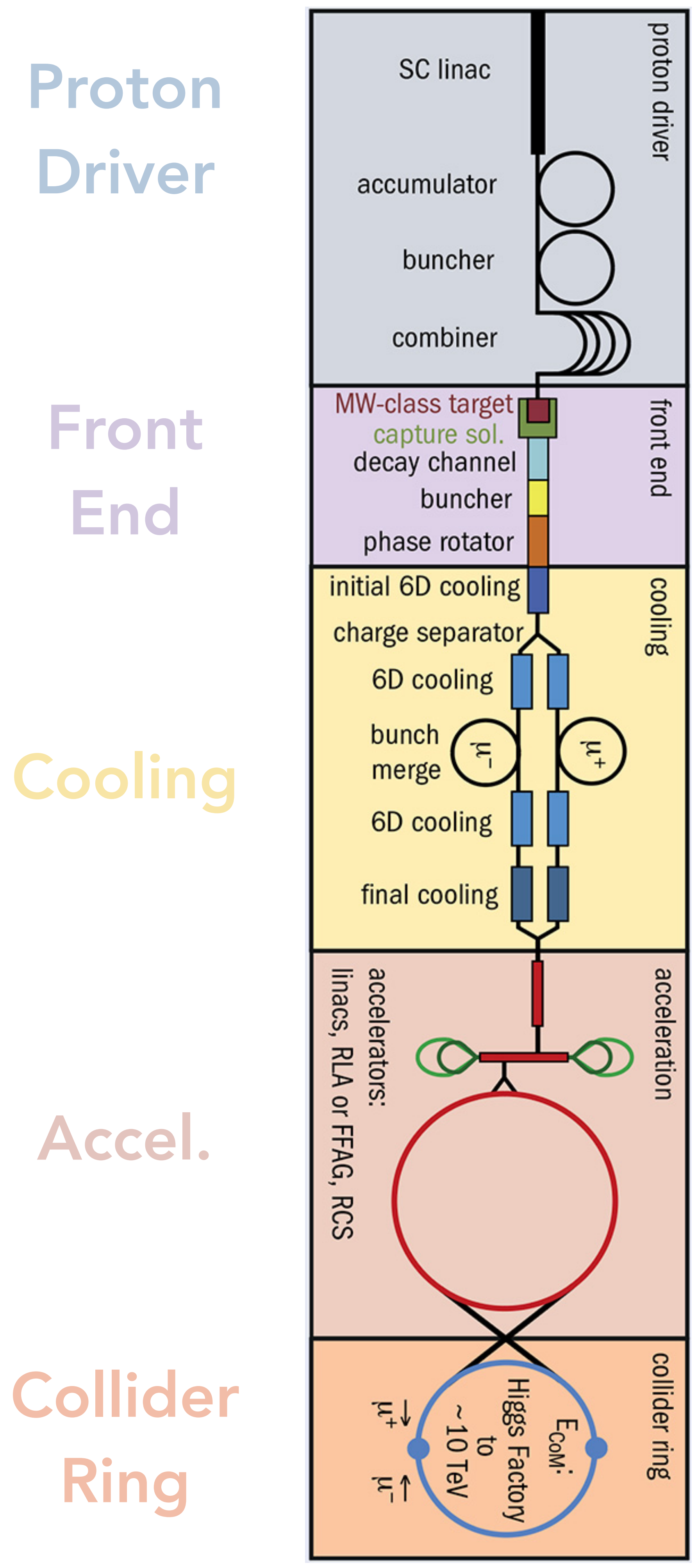
March 2025: Deadline for submission of community input

Must "freeze" 10 TeV reference configurations now to complete studies by submission deadline



Overview of Interaction Region



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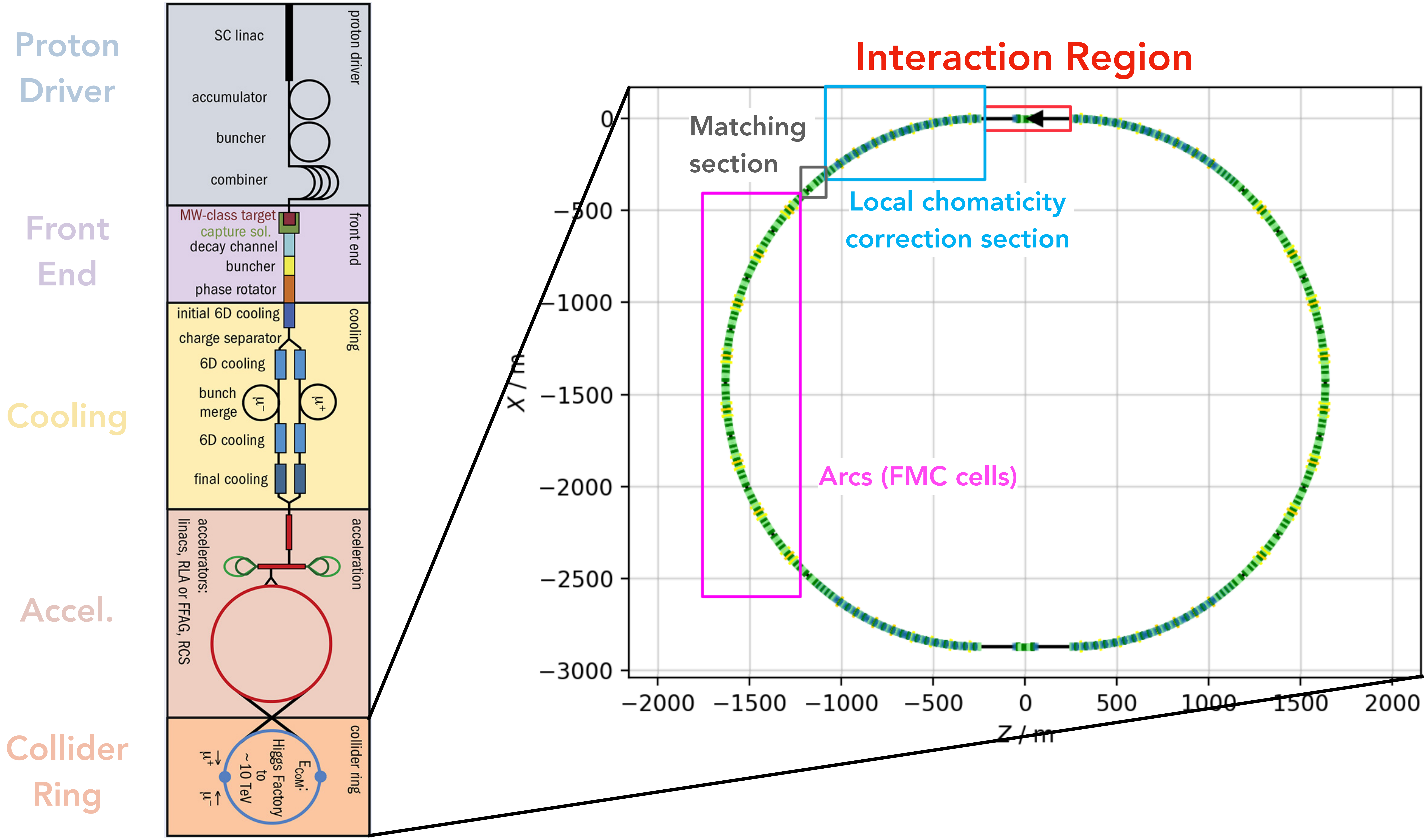

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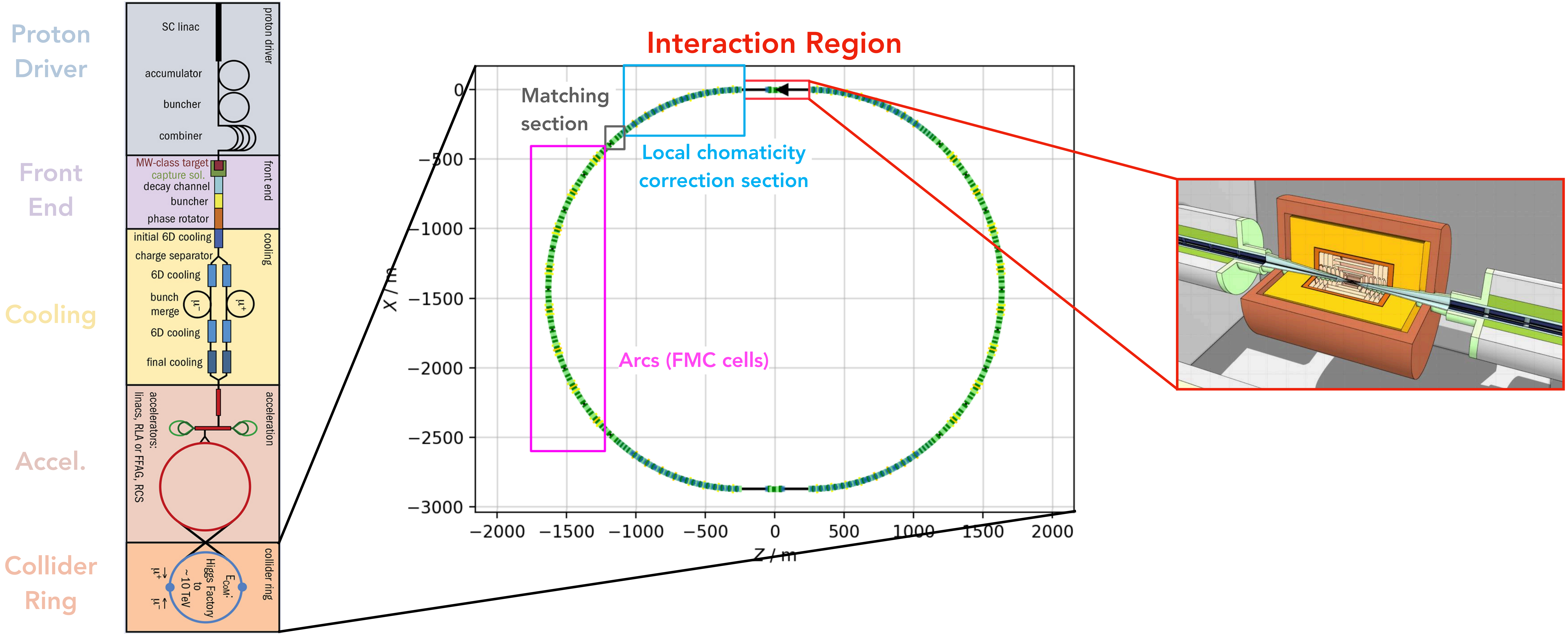
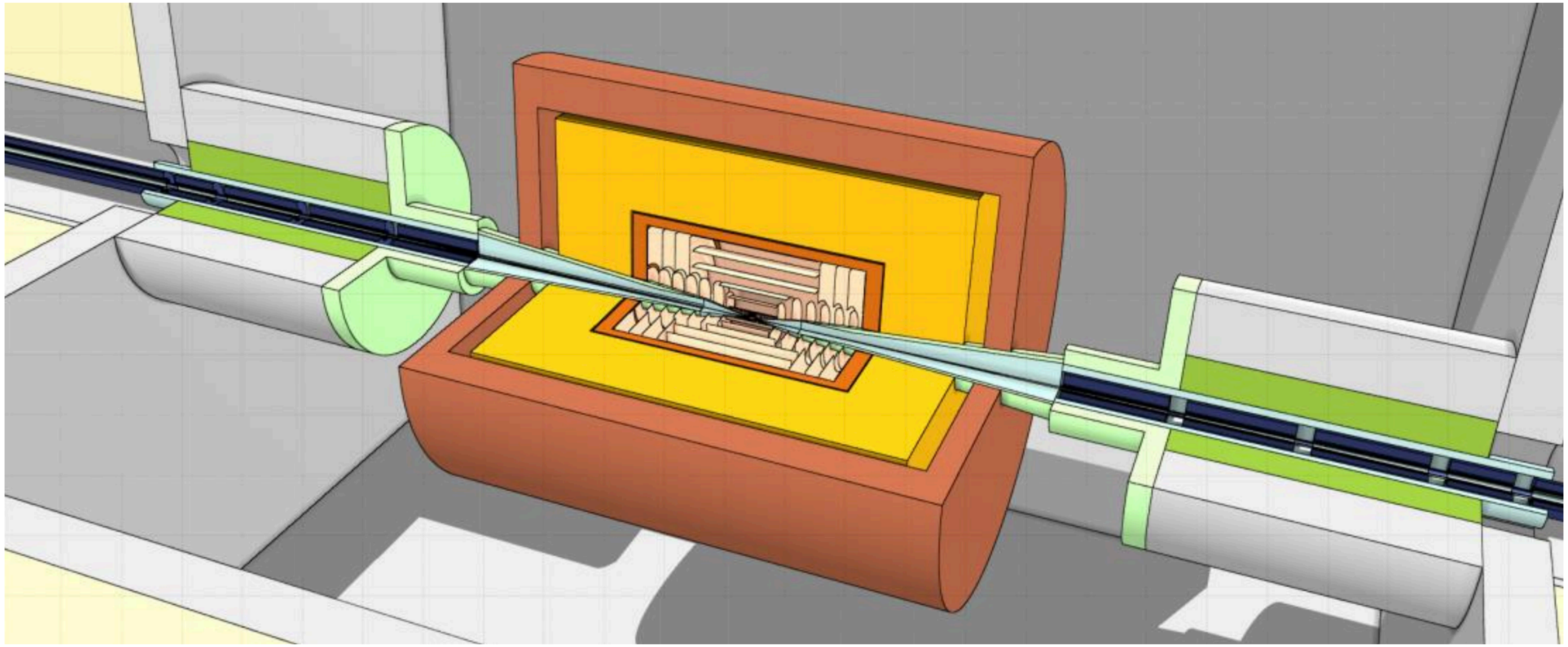


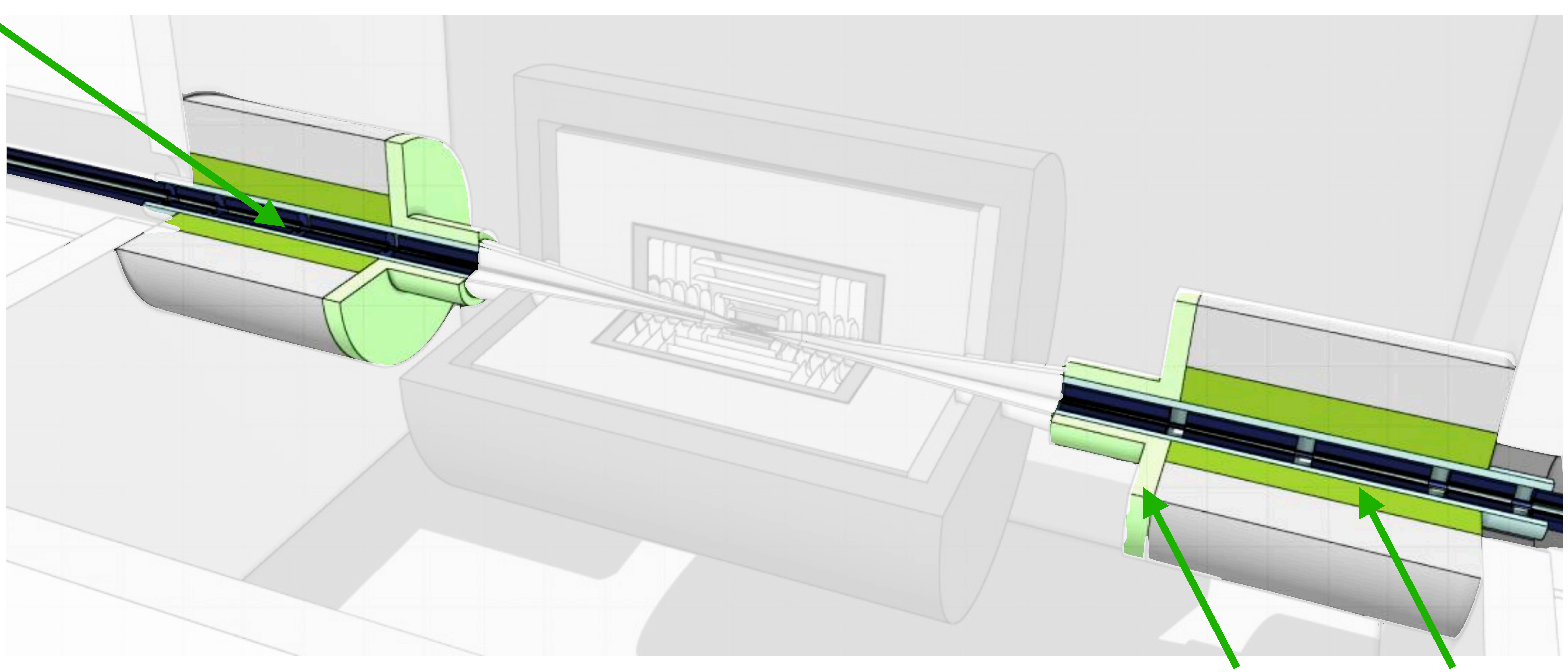
Overview of Machine-Detector Interface



Overview of Machine-Detector Interface

Customized Interaction Region Lattice

Designed to reduce the loss of decay products near the IP



Interaction Region Masks + Liners

Shield the detector from particles lost in final focus region

Overview of Machine-Detector Interface

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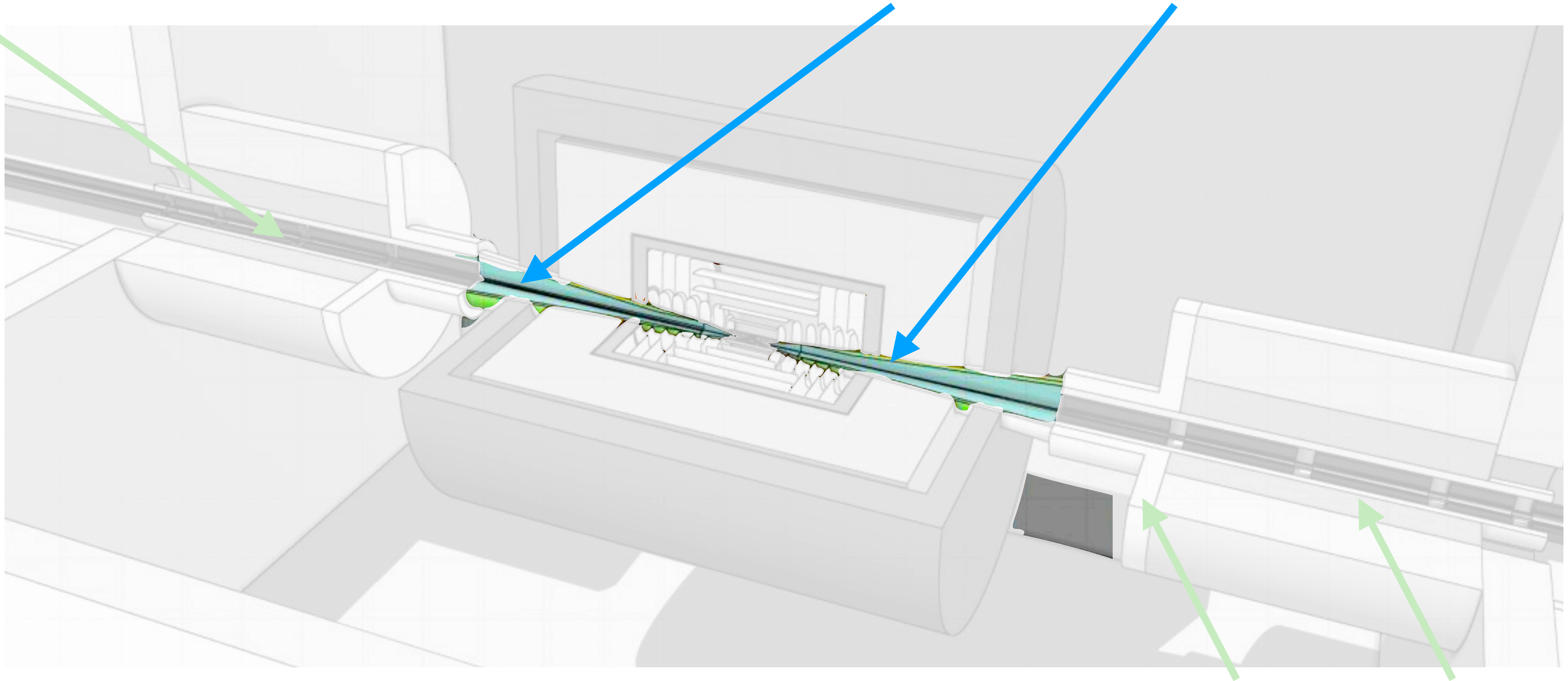
Designed to reduce the loss of decay products near the IP

Nozzles: Conical Absorber Inside Detector

Shield detector from high-energy decay products and halo losses



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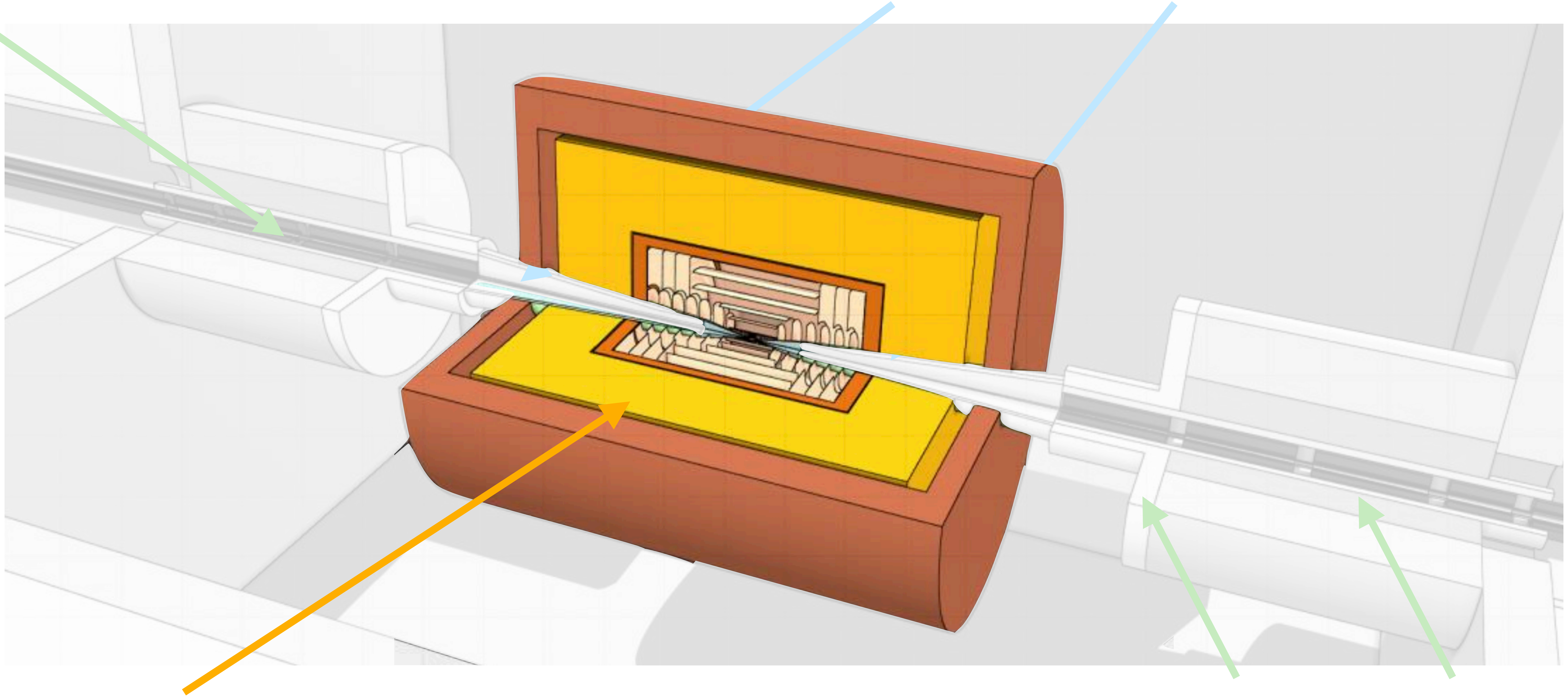

Detector

Measure and discriminate collision products from background

Interaction Region Masks + Liners

Shield the detector from particles lost in final focus region

Workshop Goals: IR + MDI

- Define Reference IR and MDI Configuration
  - IR lattice and magnet apertures
  - Shielding inserts in magnets
  - Nozzle configuration

Is the radiation damage in magnets acceptable?

Are the assumed magnet apertures realistic?

Can we "freeze" the present IR layout for the ESPPU studies or do we need a further iteration?

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Can we "freeze" the present IR layout for the ESPPU studies or do we need a further iteration?

- Further Understand Beam-Induced Background
  - Decay-induced background
  - Incoherent pair production

Are we ready to produce a high statistics reference sample for the detector studies?

Workshop Goals: Detector

- Define Detector Configurations
    - Proceed with one vs. two configurations

Do we proceed with one or two configurations?

Do we have enough people to perform relevant studies?

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  - ECAL and HCAL technology
  - Position of the magnet and return yoke
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- Define Sub-detectors
  - Configuration and technology for tracker
  - ECAL and HCAL technology
  - Position of the magnet and return yoke
  - Muon detector
- Define Software Version(s)
  - Converge on software version to be used for the studies

Interaction Region and Machine-Detector Interface

Collider Lattice + IR Design: Key Challenges

10 TeV Muon Collider Beam Requirements

Parameter	Symbol	$\sqrt{s}$ =10 TeV
Particle energy [GeV]	E	5000
Luminosity [10^{34} cm^{-2} s^{-1}]	$\mathscr{L}$	20
Bunch population [10^{12}]	N_p	1.8
Transverse normalized rms emittance [μm]	ε_n	25
Longitudinal emittance ($4\pi\ \sigma_E\ \sigma_T$) [eVs]	ε_l	0.314
Rms bunch length [mm]	σ_z	1.5
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- Radiation from BIB → magnet shielding

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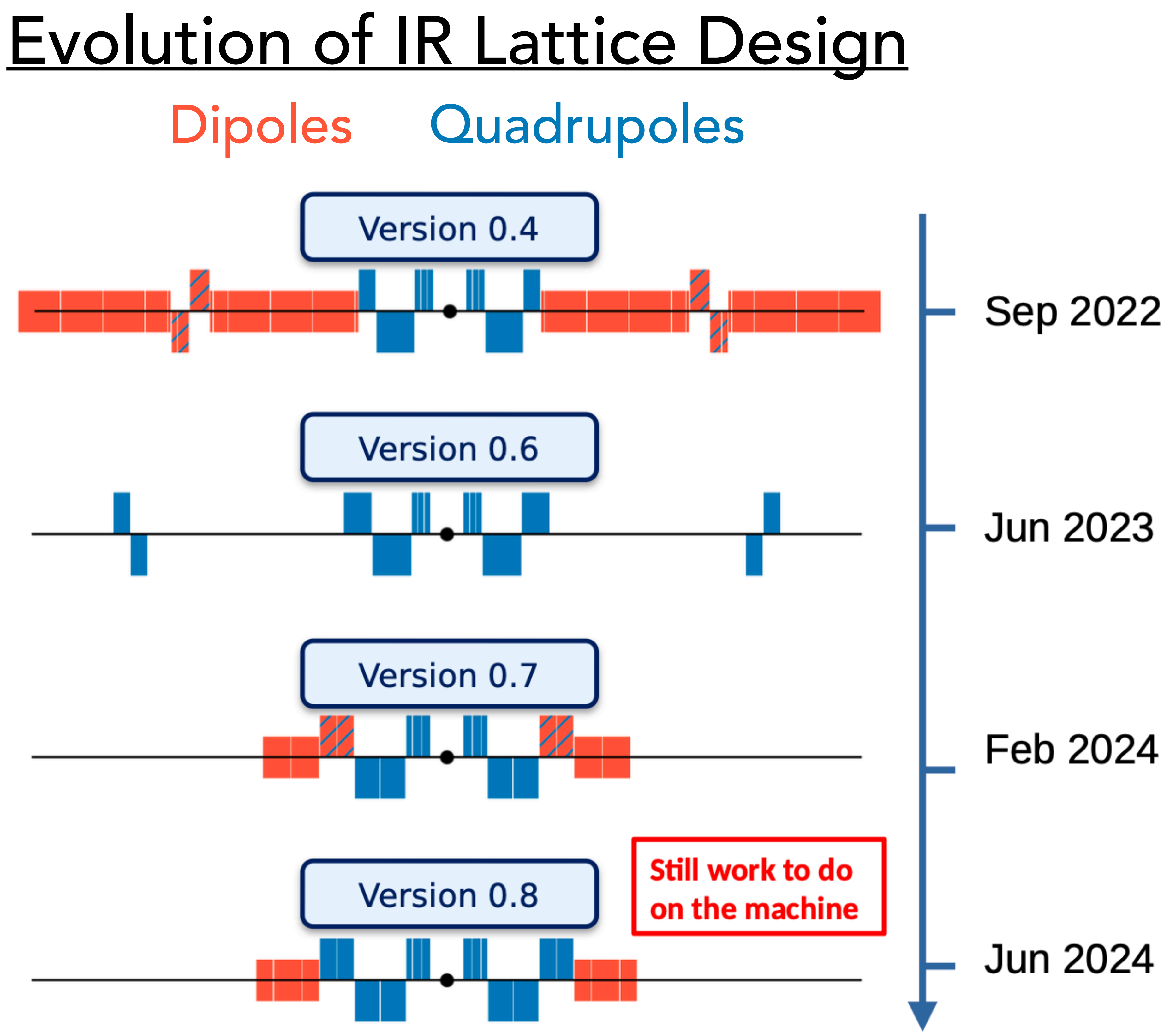
Relatively large aperture

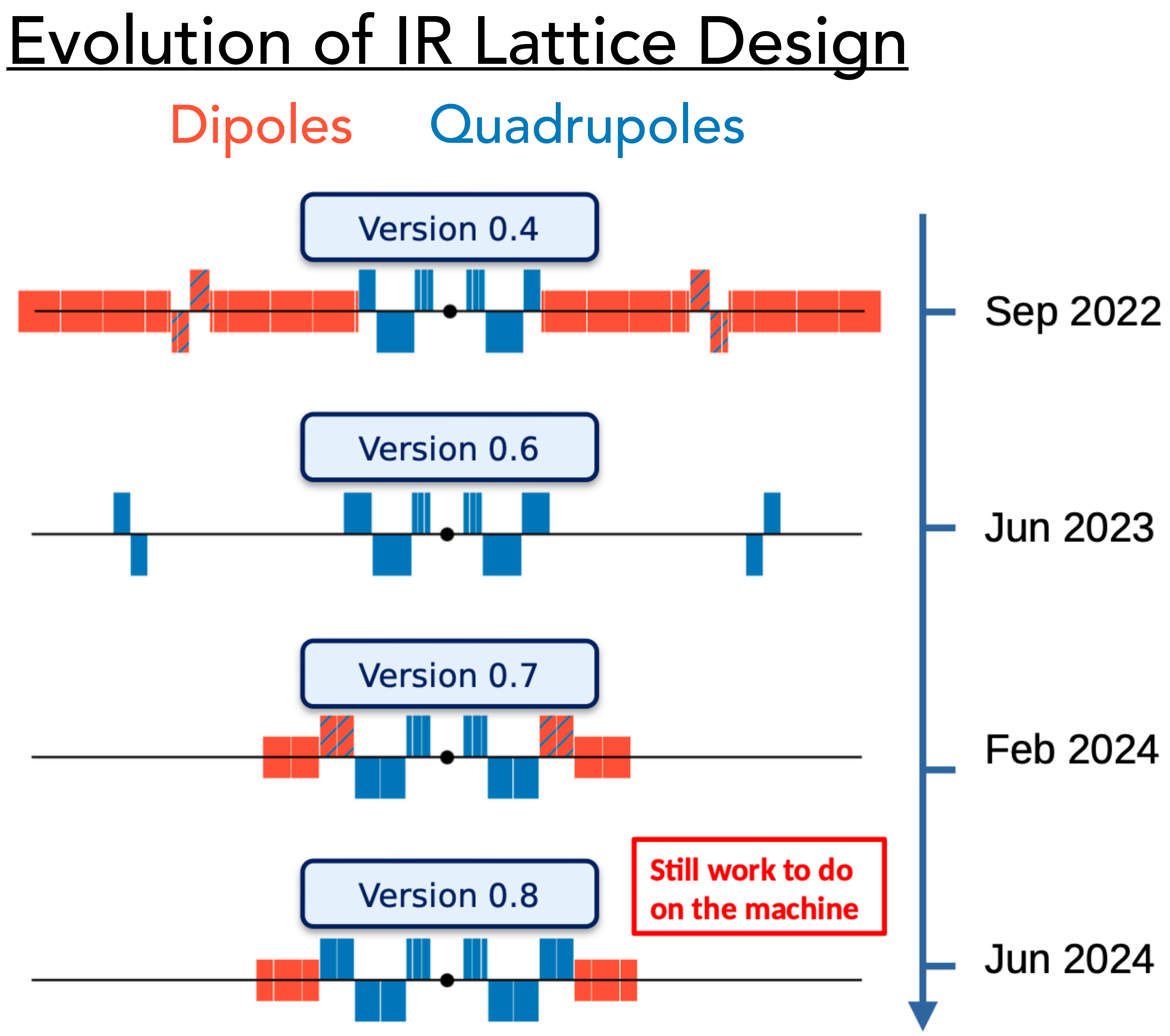
Collider Lattice + IR Design: Current Status

- Several iterations over the past couple of years
  - More recently, added chicane for longitudinal bunch compression



Collider Lattice + IR Design: Current Status

- Several iterations over the past couple of years
  - More recently, added chicane for longitudinal bunch compression
- Radiation load and impact of tungsten shielding:
  - Key metric is total ionizing dose (TID)
  - Dipoles significantly benefit from more shielding: 4 → 6 cm reduces TID by x10
  - With current configuration, collider lifetime ~5-10 years (more details in D. Calzolari's talk)



Nozzle Design: Materials

Tungsten (W)

Mitigate high-energy EM showers

- Critical metrics: mechanical data at low T, machinability, magnetic permeability, cost
- A number of commercially available alloys, but many have limited data
- *(Another potential option: depleted uranium…)*

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Borated Polyethylene

Capture the neutronic component

- Both boron and polyethylene are both highly effective neutron absorbers
- Commercially available material specially designed for nuclear shielding applications

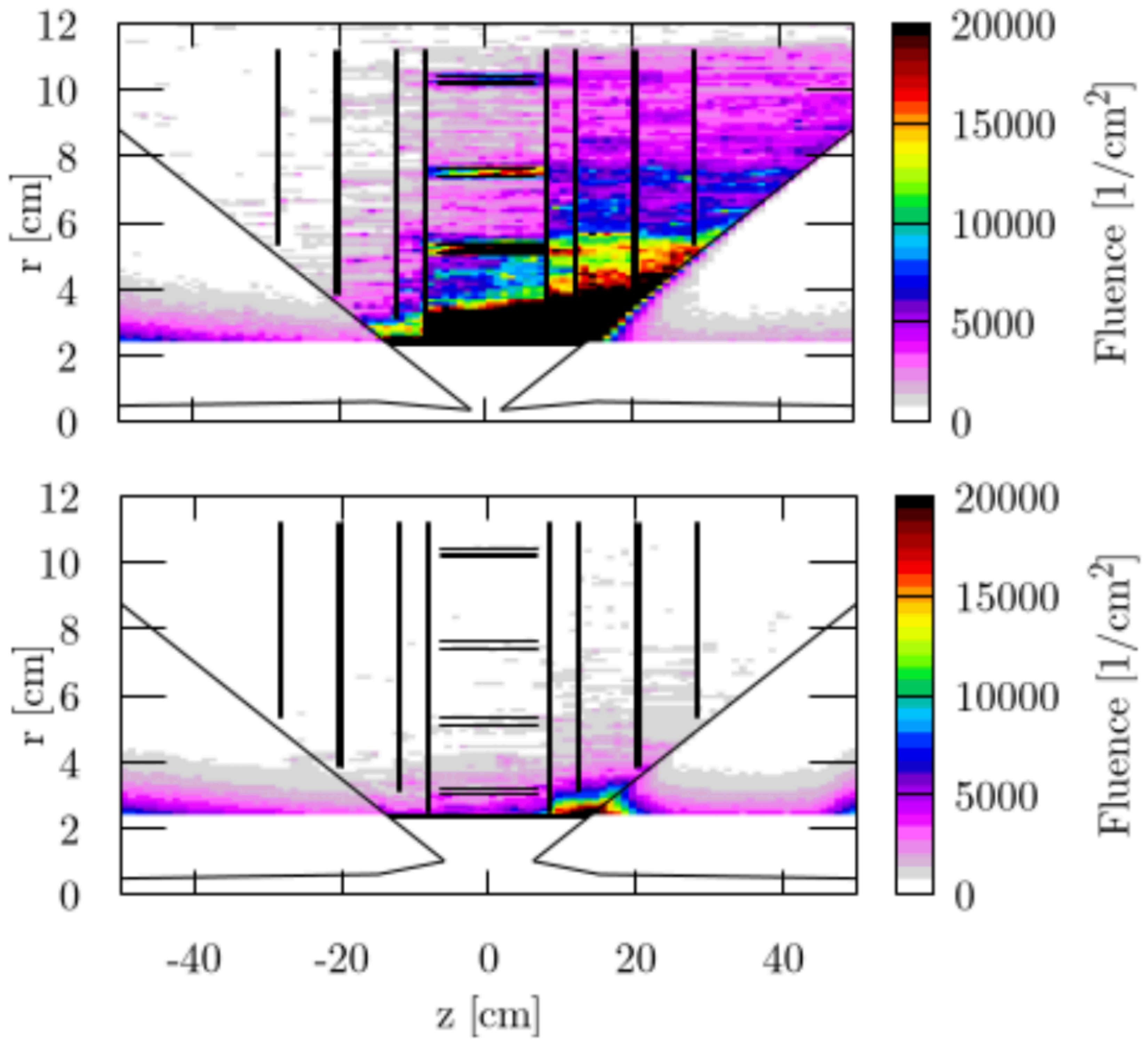
D. Calzolari

Nozzle Design: Distance Optimization

Ongoing studies to optimize nozzle tip distance from IP

Nozzle Tip at 2 cm

Nozzle Tip at 6 cm



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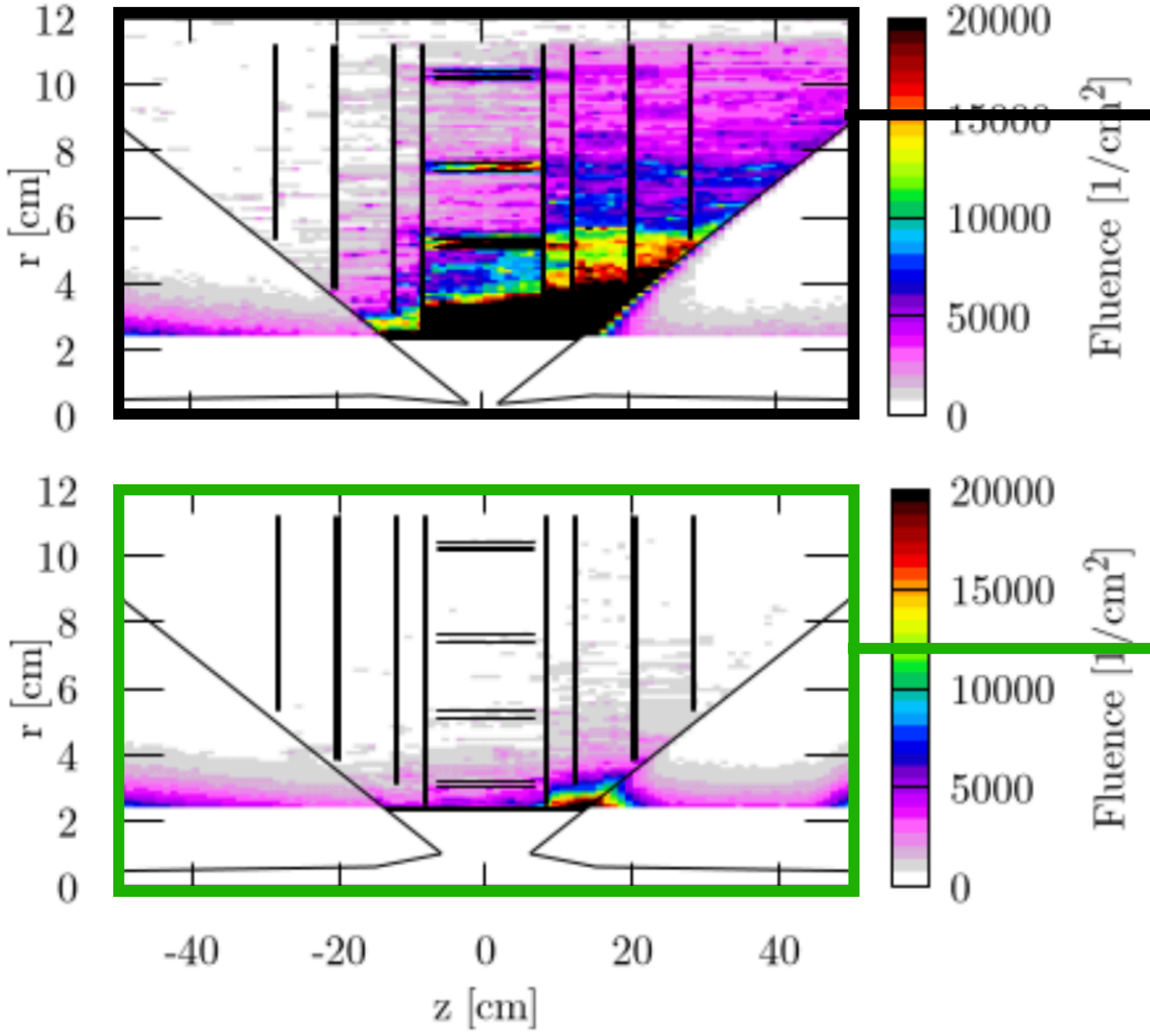
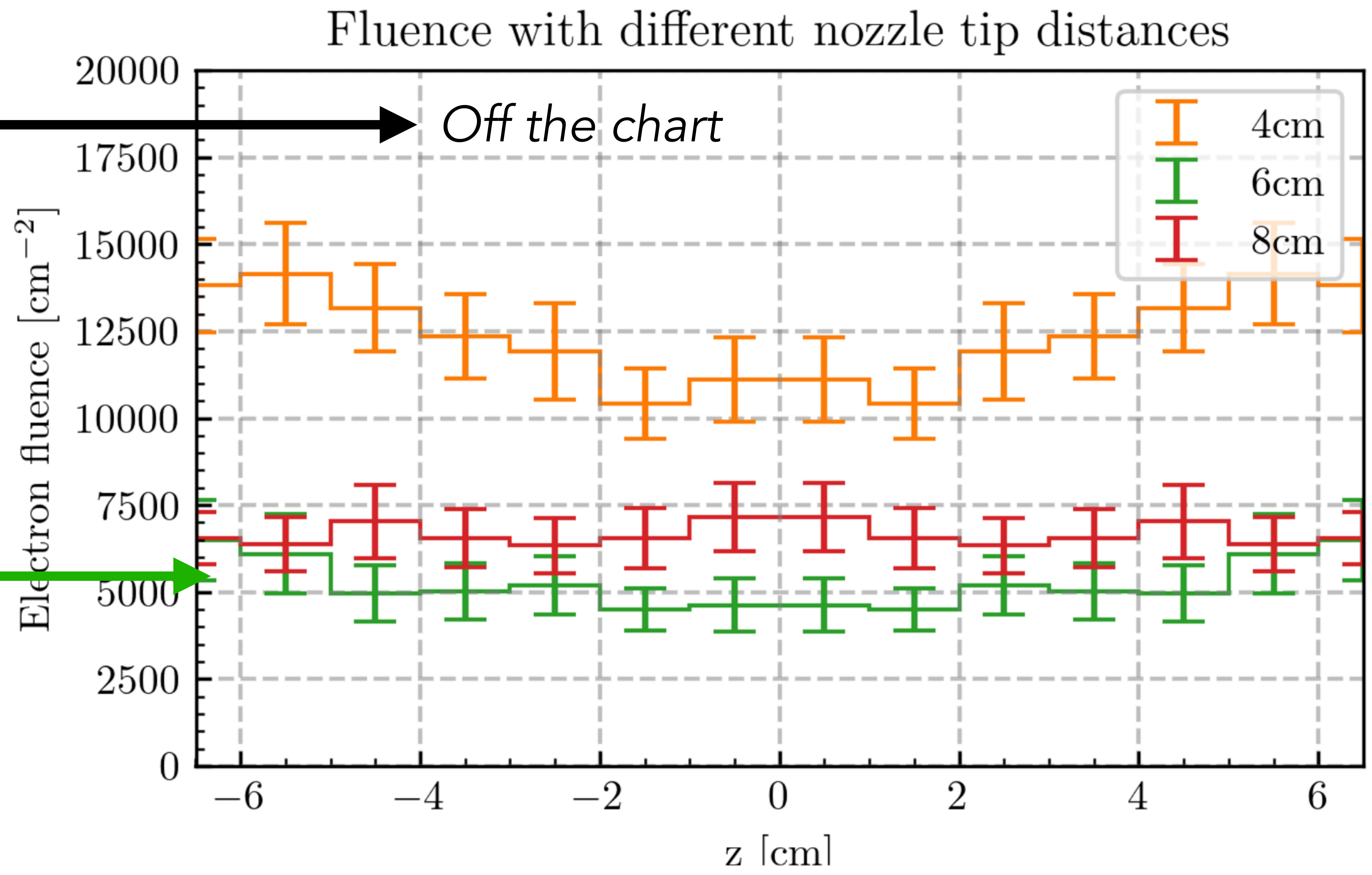




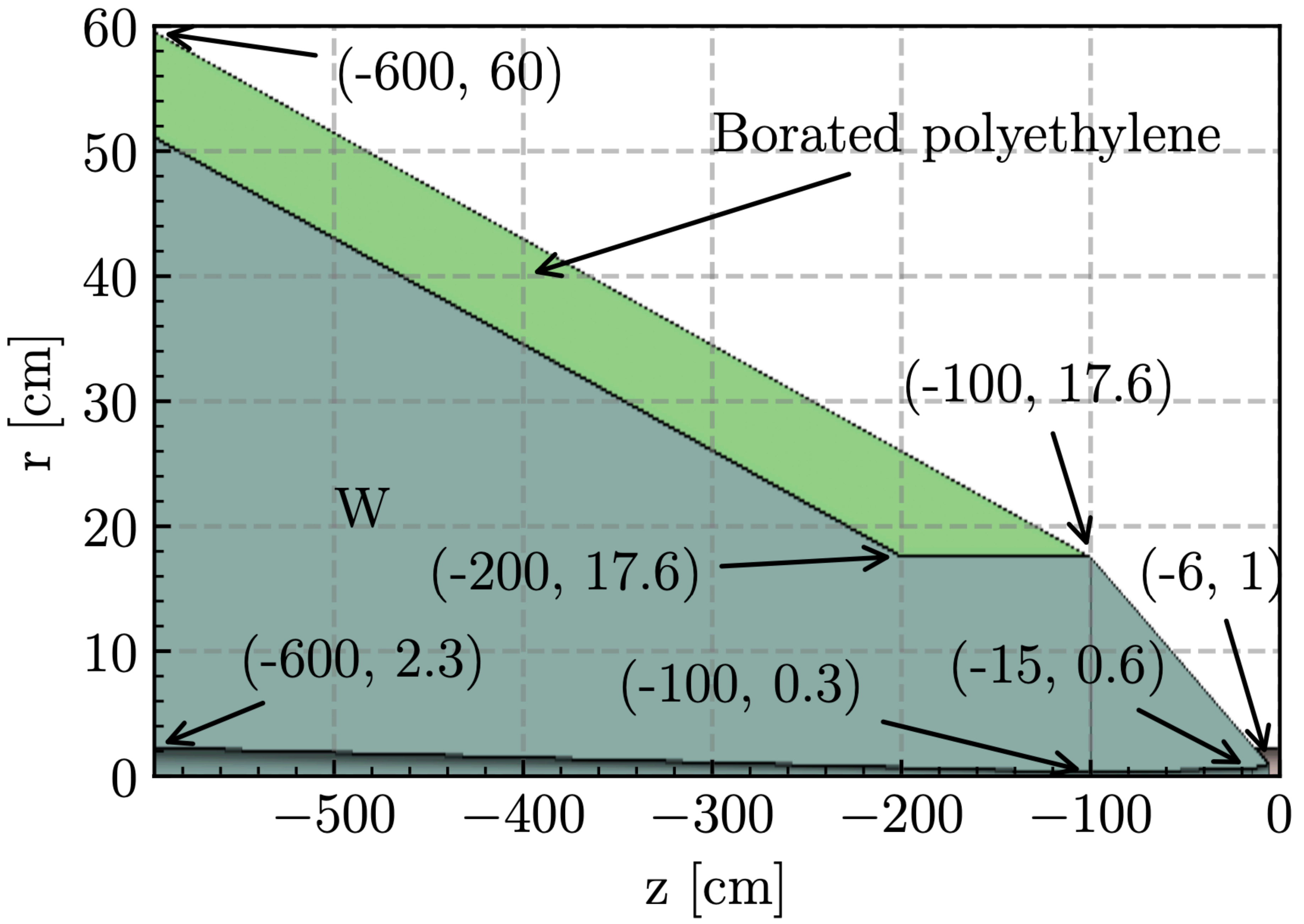
L. Castelli, D. Lucchesi,
D. Calzolari, F. Collamati

Nozzle Design: Shape Optimization

Ongoing studies to optimize nozzle tip shape

Baseline Configuration

From U.S. Muon Accelerator Program, optimized for for 1.5 TeV



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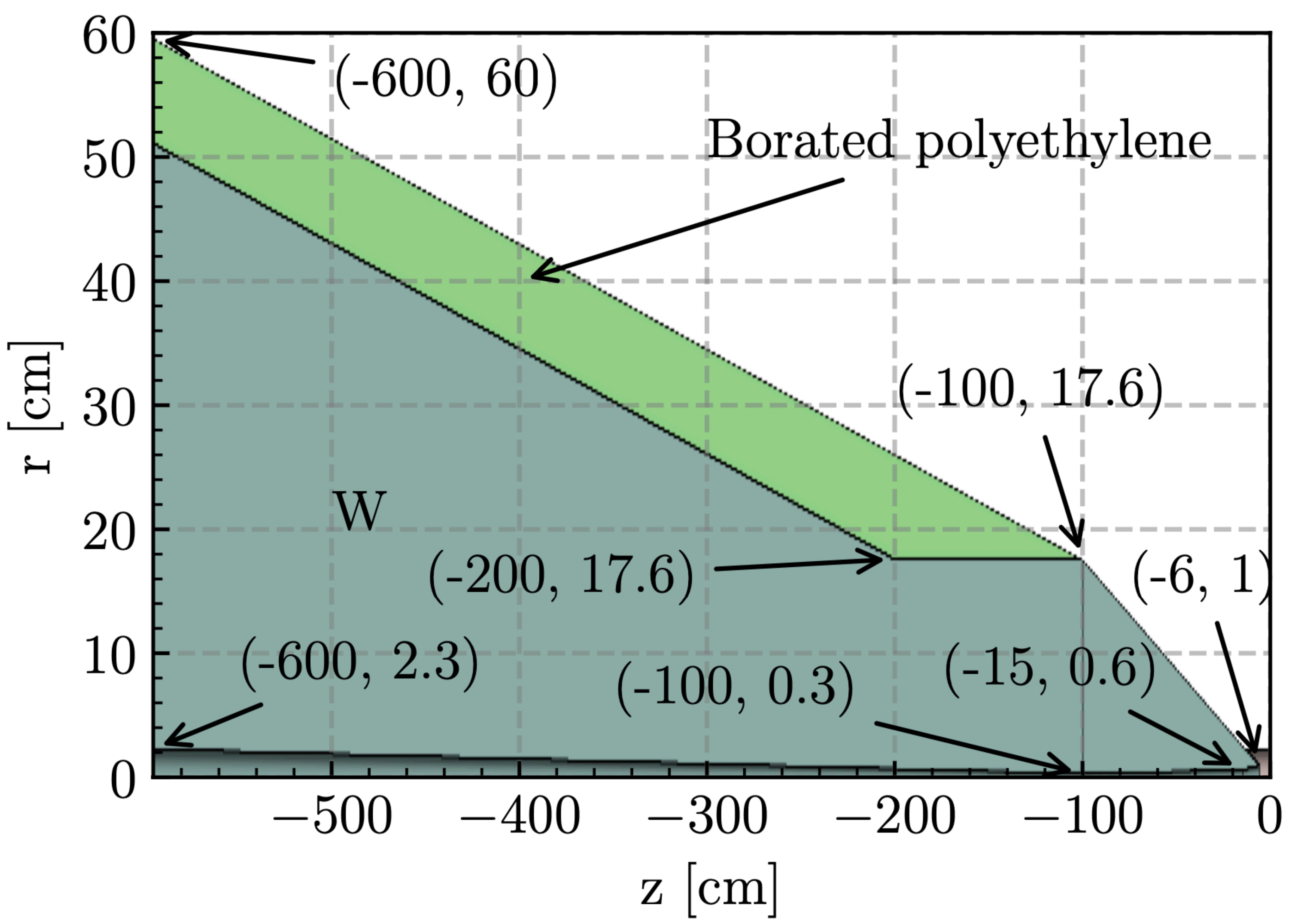
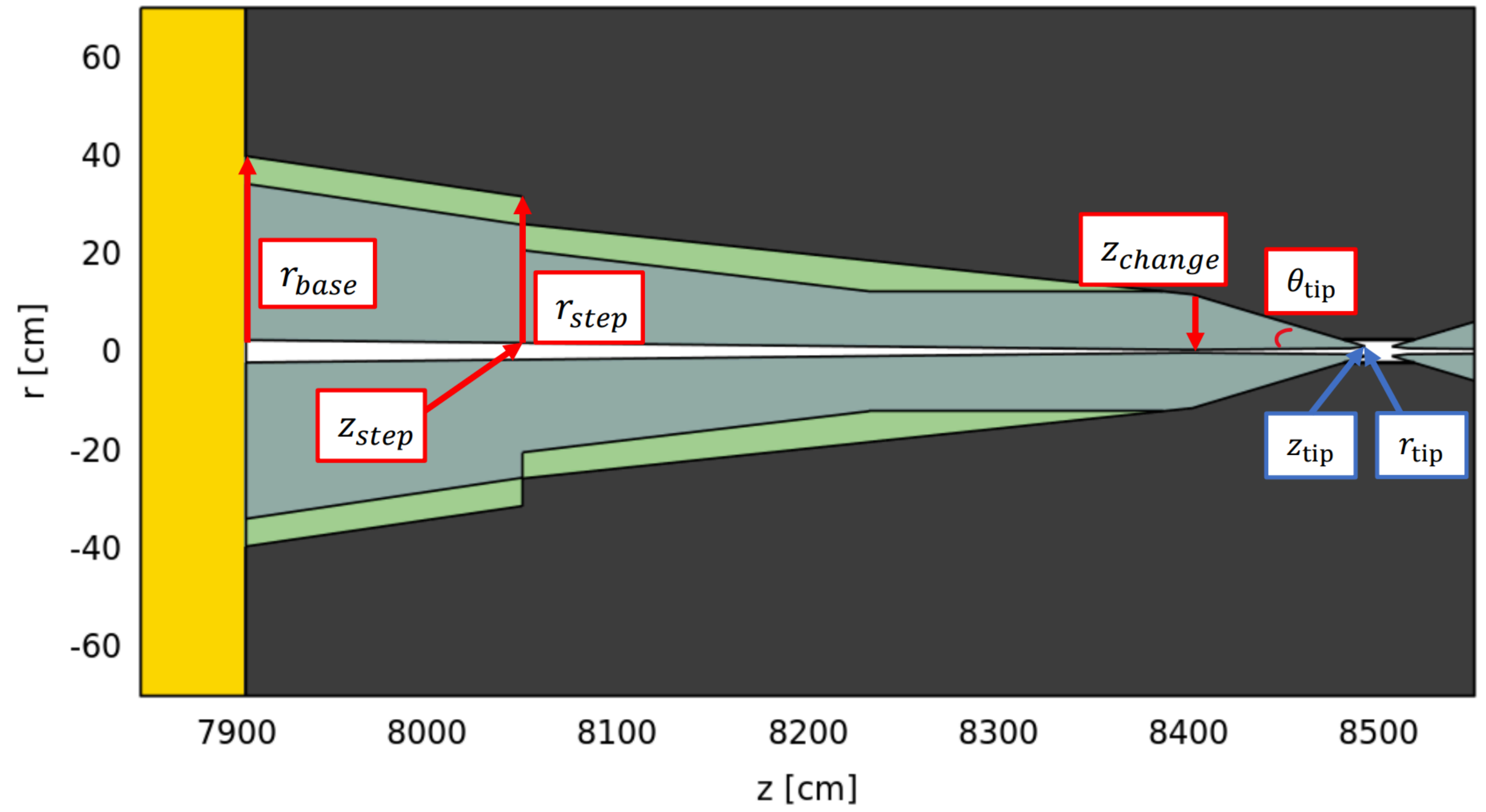
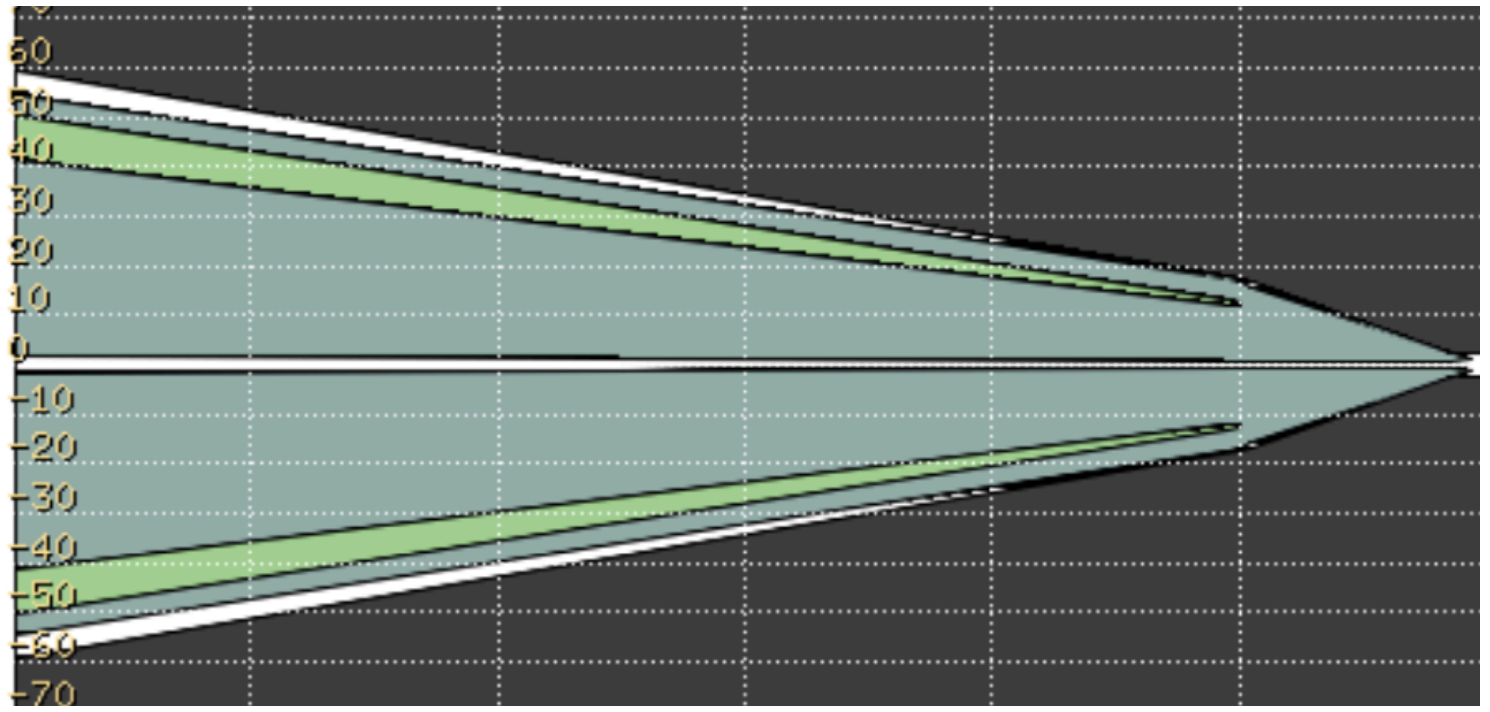


More Sophisticated Configurations





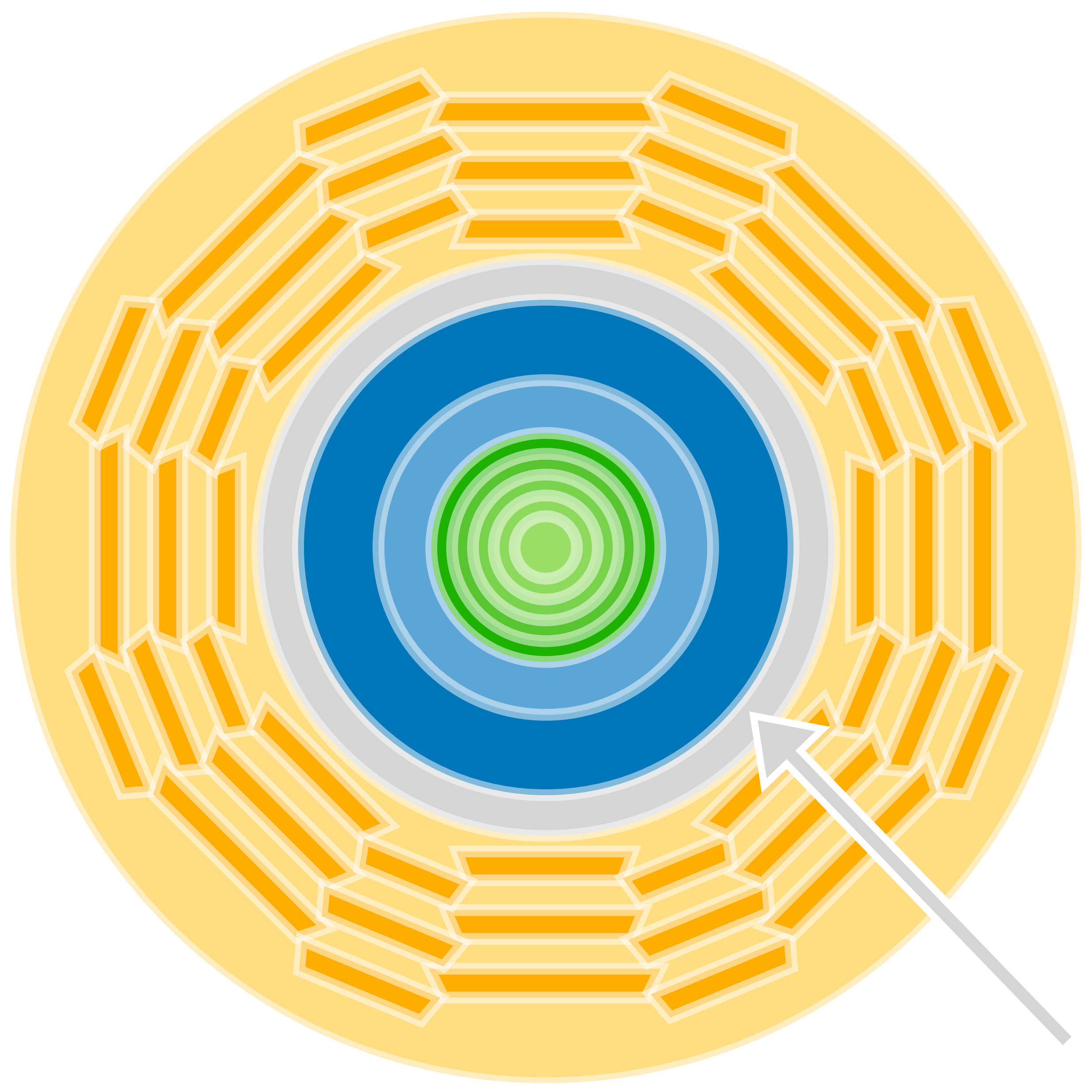
Detector Concepts:
MAIA + MUSIC

Introduced in L. Lee's talk

Overview of 10 TeV Detector Concepts

Starting Point: 3 TeV Detector

Solenoid outside Calorimeters



Nothing is to scale

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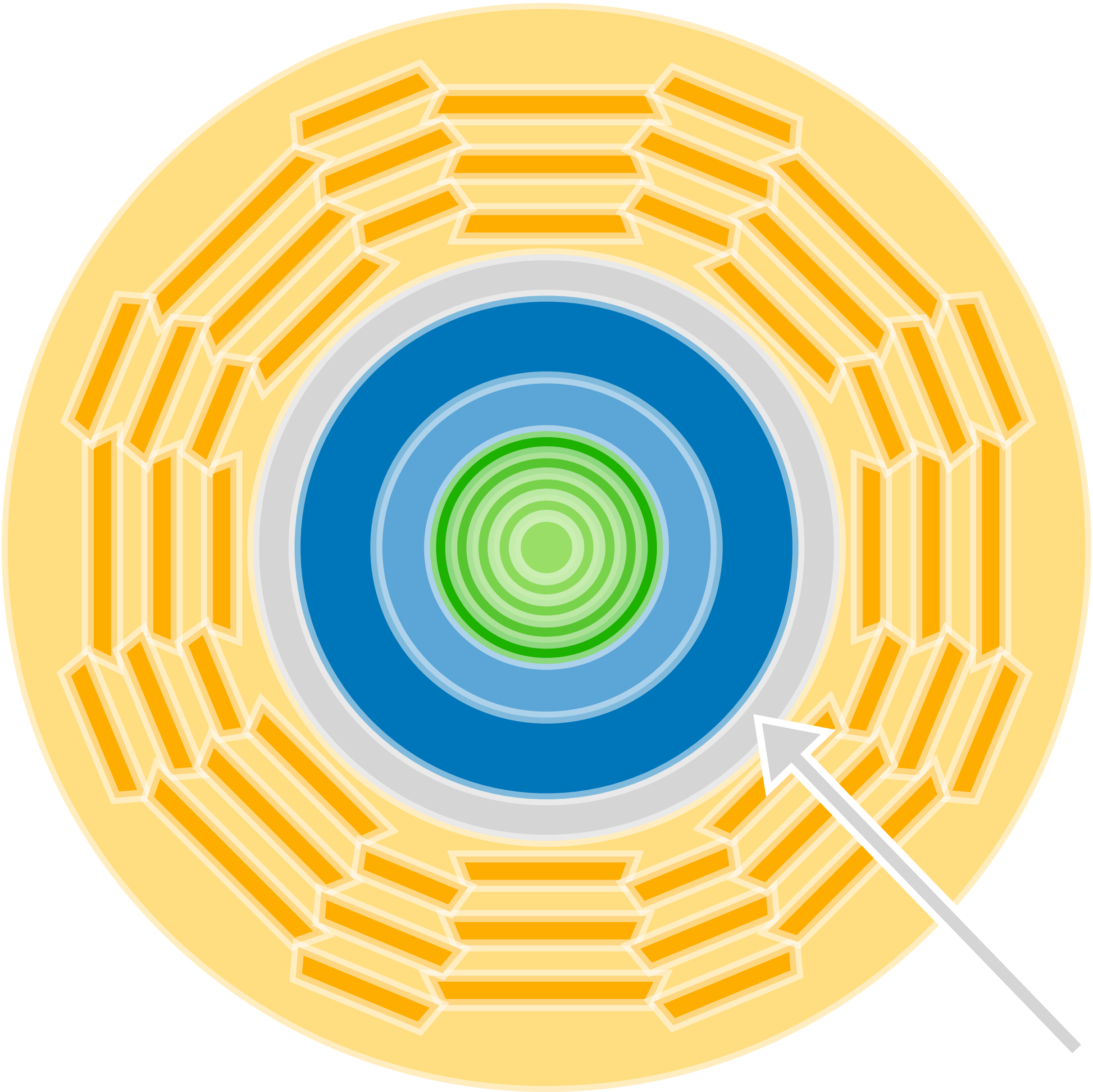
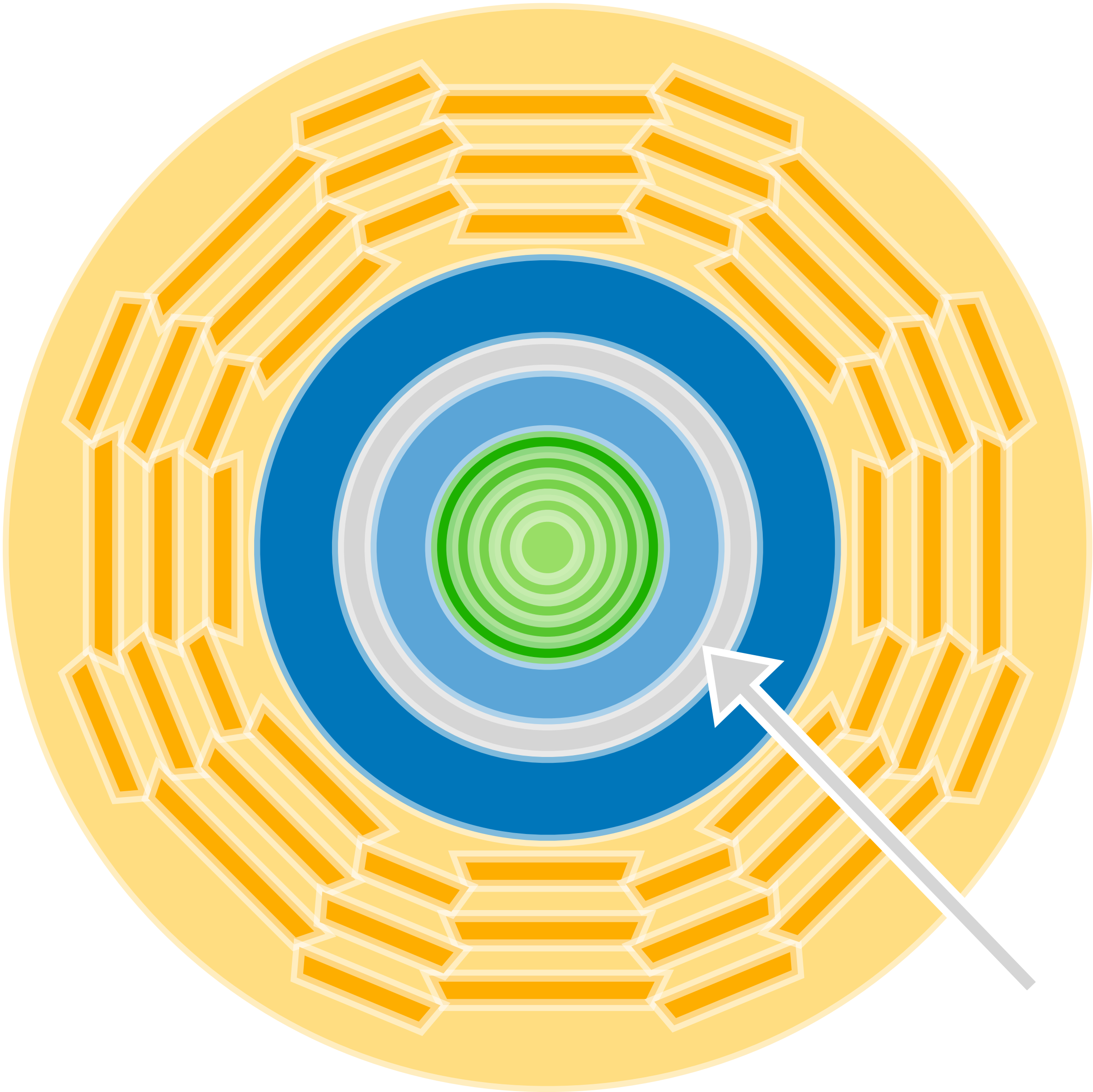


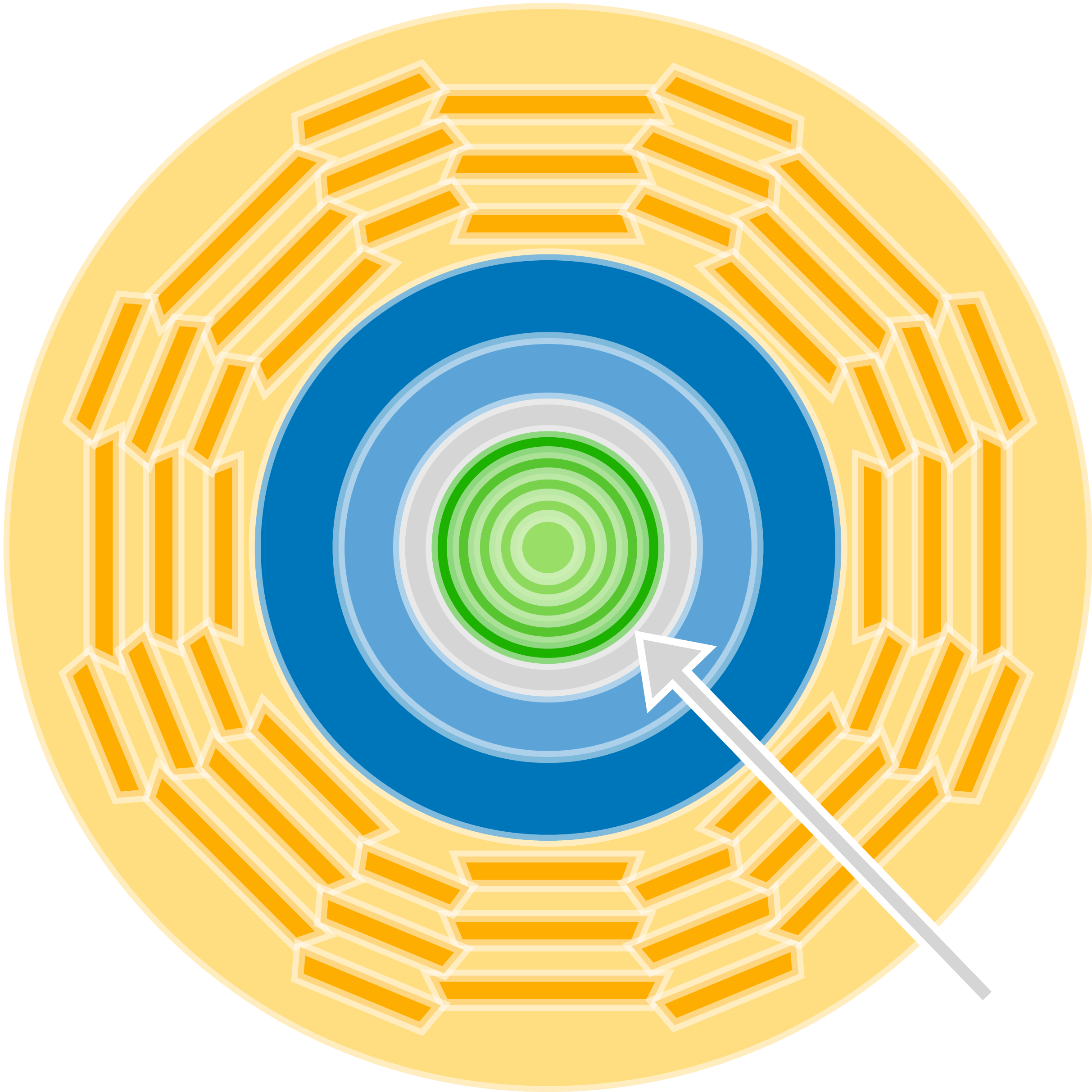
10 TeV MUSIC Detector

Solenoid between ECAL and HCAL



10 TeV MAIA Detector

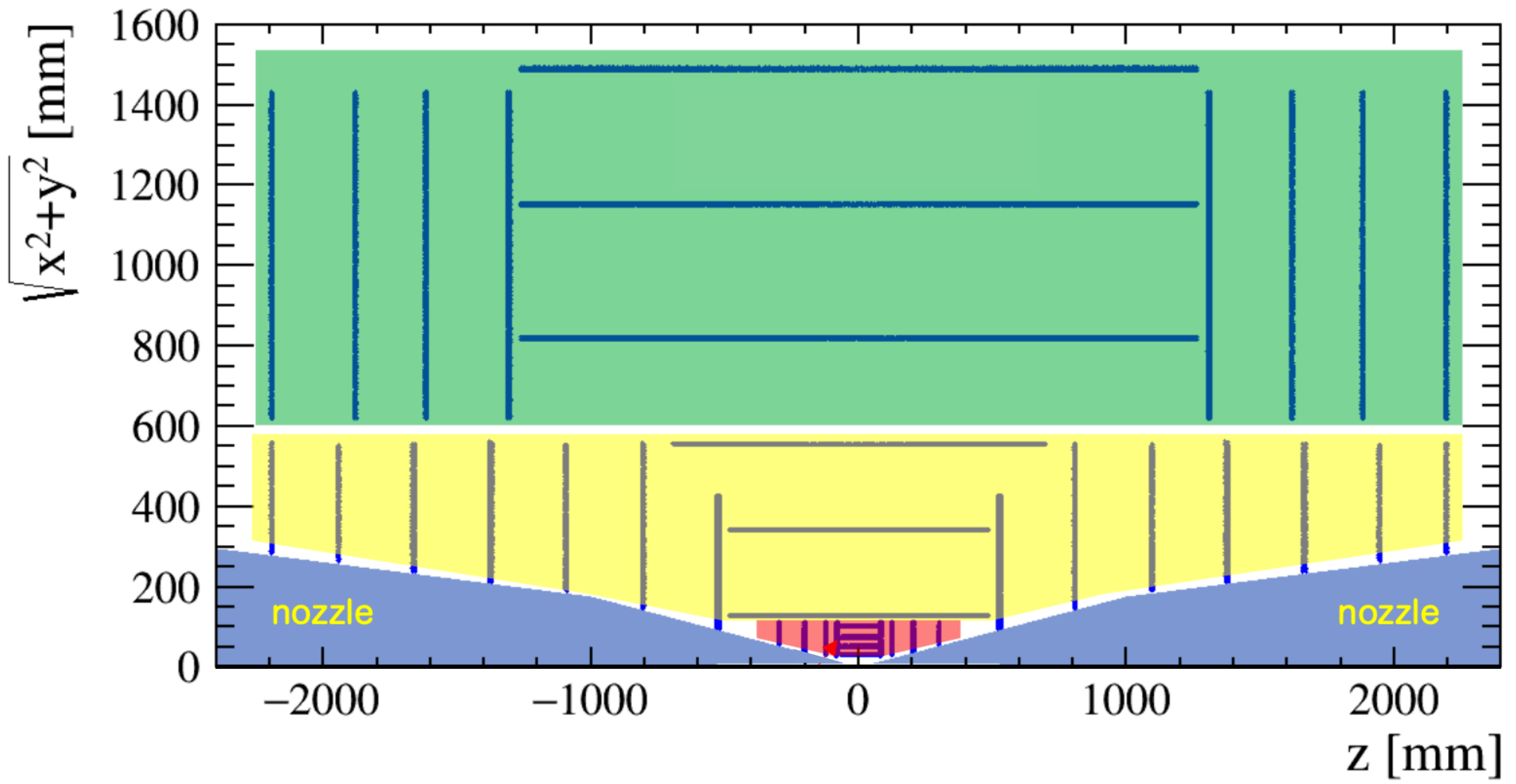
Solenoid inside Calorimeters

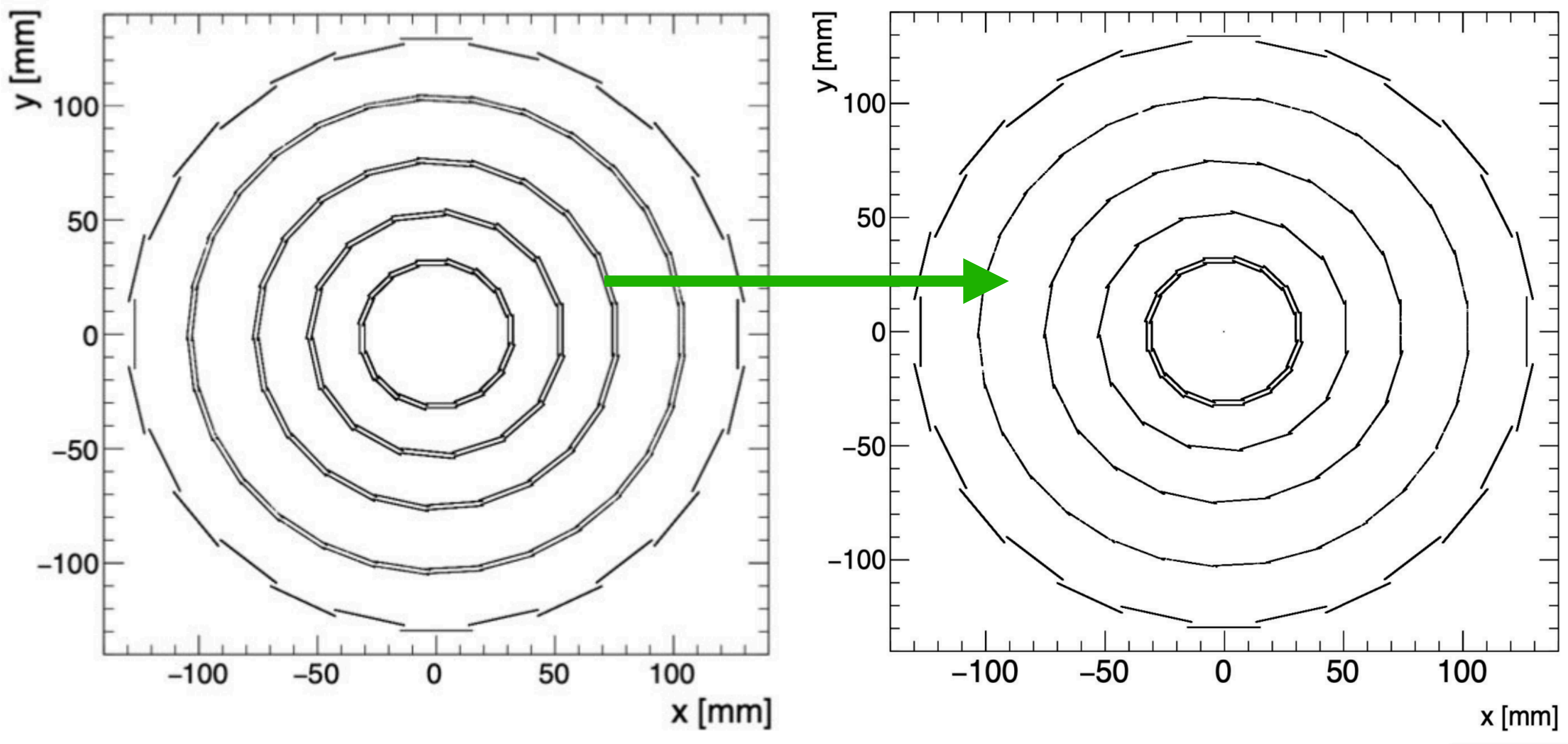


Nothing is to scale

Tracker Design

- Both 10 TeV detectors share a similar design
  - Emphasis on excellent spatial + timing precision, acceptance
- Vertex Detector — Pixels (σ_t ~ 30 ps)
  - Removed most of the doublet layers for stubs in the 3 TeV detector concept *(improved tracking with ACTS)*
- Inner Tracker — Macropixels (σ_t ~ 60 ps)
- Outer Tracker — Macropixels or Microstrips (σ_t ~ 60 ps)
  - Considerations: strip timing; strip availability in ~20+ years; decreasing costs of macropixels
- Further study: layer optimization, especially endcap





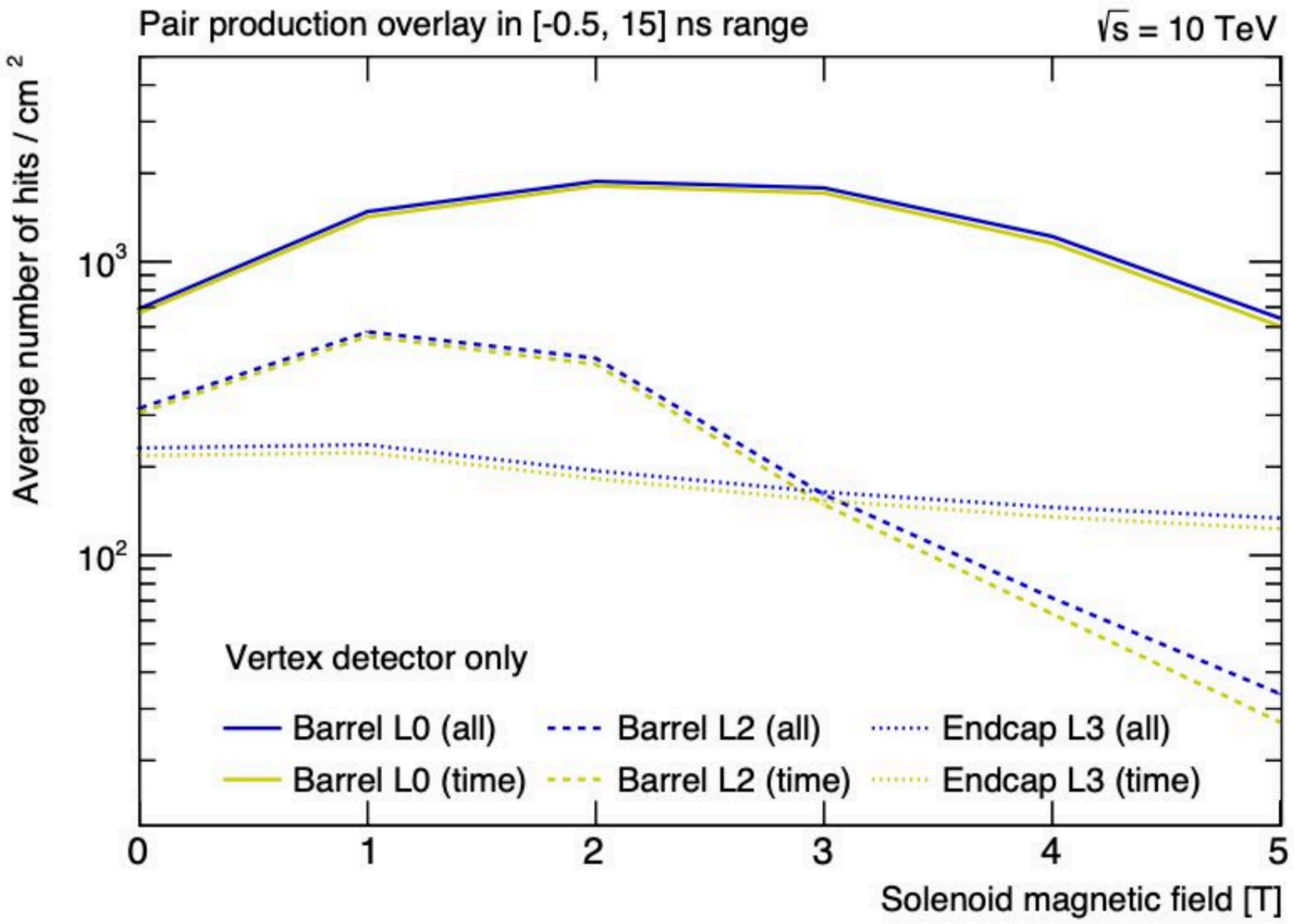
Magnetic Field

- B-field simulation:
  - Currently assumes constant B-field
  - Ongoing: 2D map of magnetic field
- BIB tracker occupancies vary with B-field and radius from the beam line
  - B ≥ 5 T seems desirable with current config
  - Lower B fields may require layer re-optimization
- To evaluate: flavor tagging dependence on B-field strength

Tracker Occupancies vs. B-Field

MAIA Detector Concept
Shown for incoherent pair-production BIB

Fewer curlers ← → *More bending*

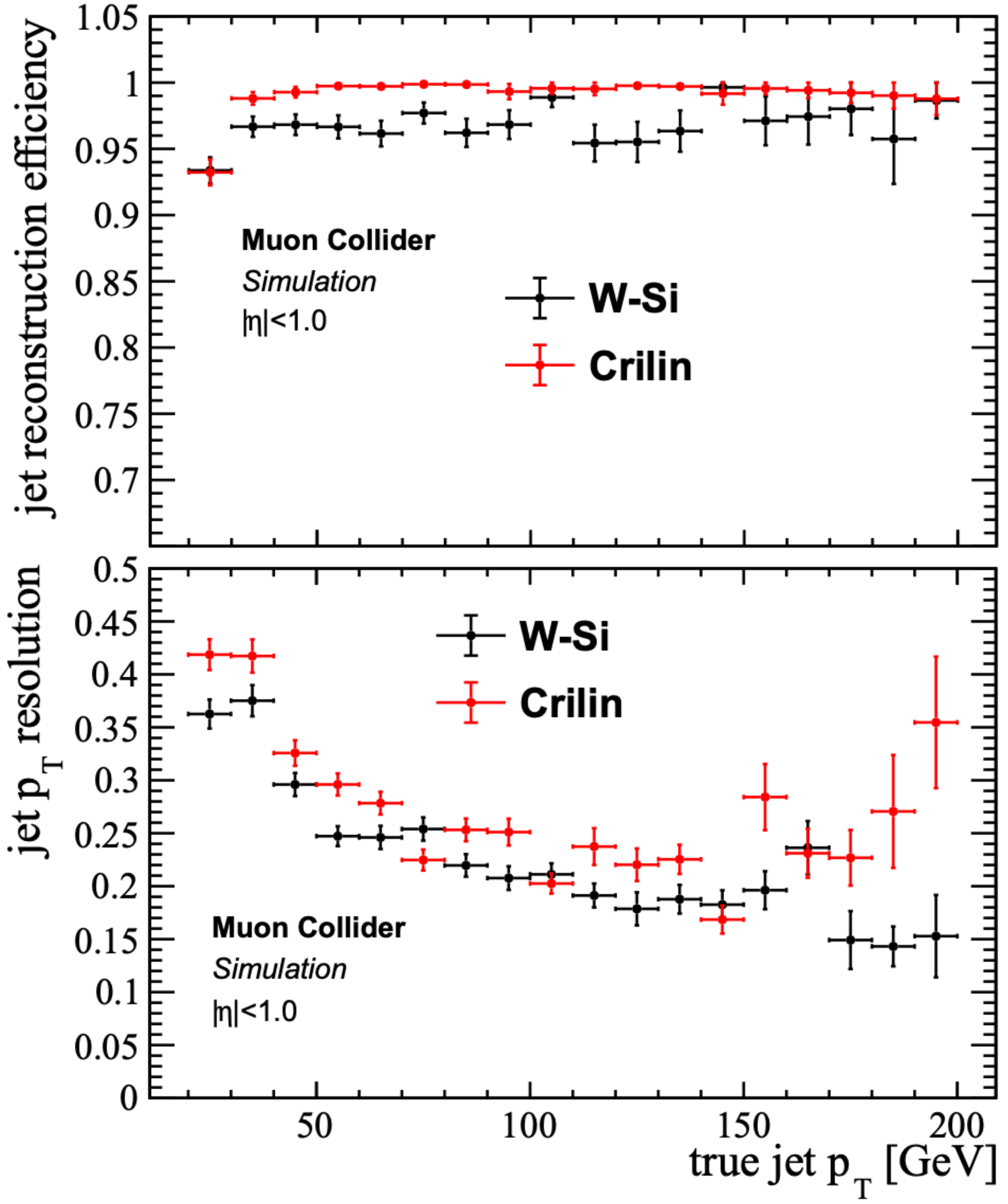


Calorimeter Design

- Challenging BIB environment due to relatively large cell sizes and integration times
  - 5D Calorimetry: high-granularity (eta/phi/depth), excellent timing, good energy resolution
- ECAL: Different technologies for 10 TeV detectors
  - MAIA: W-Si sampling calorimeter
  - MUSIC: Crilin — lead fluoride crystal
- HCAL: Iron+Scintillator (both 10 TeV detectors)
  - Iron as solenoid return yoke
  - To evaluate: make first layer of iron thicker (e.g. 2→20 cm for MAIA) for mechanical stability in B-field

ECAL Technology Comparison

arXiv:2206.05838



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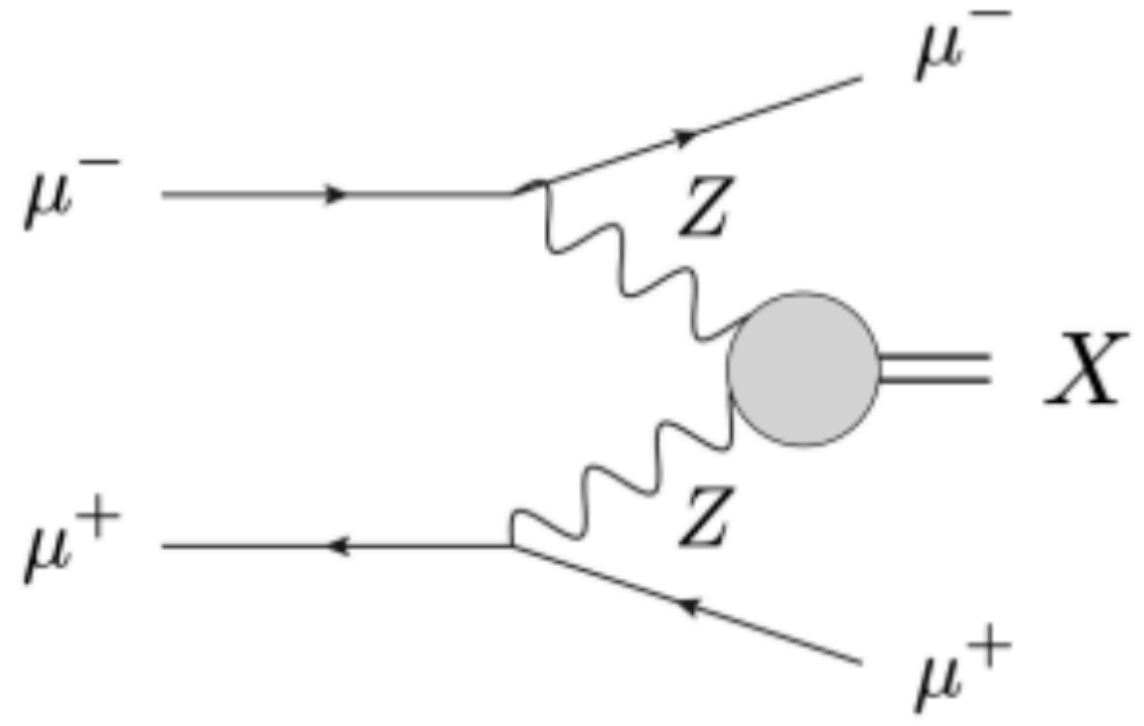
Muon Spectrometer

- **Barrel and Endcap**: least impacted by BIB given shielding from calorimeters
  - Simplified, Air + RPC (both 10 TeV detectors)
  - To potentially replace with scintillator (CERN rule)

- **Forward Region**: challenging given position of nozzle
  - Important physics (VBF) — e.g. Higgs boson width
  - Dedicated forward muon detector candidates



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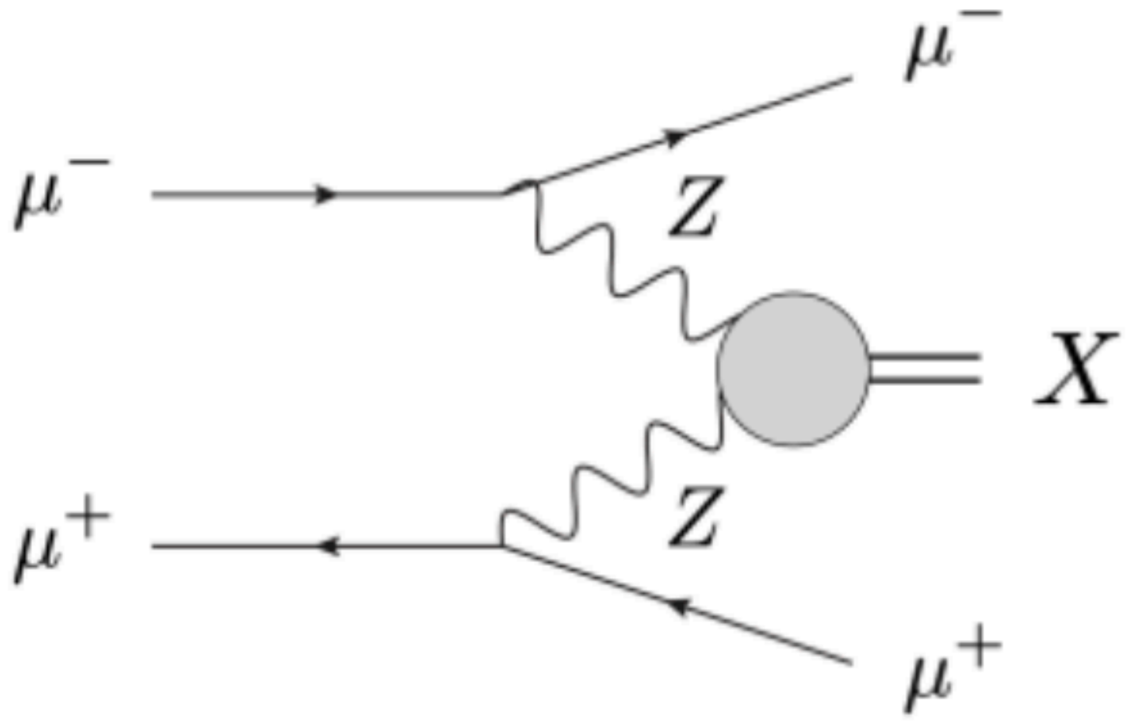
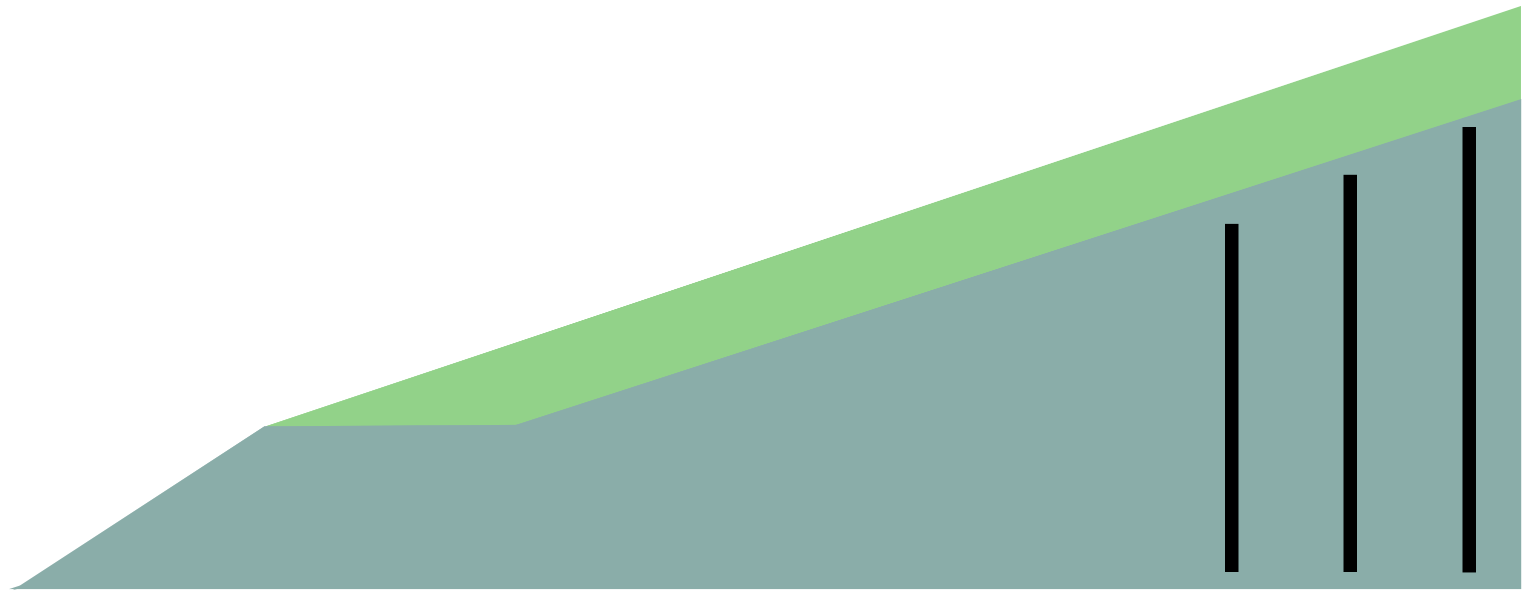


Silicon Layers in the Nozzle

Small detector, high BIB background



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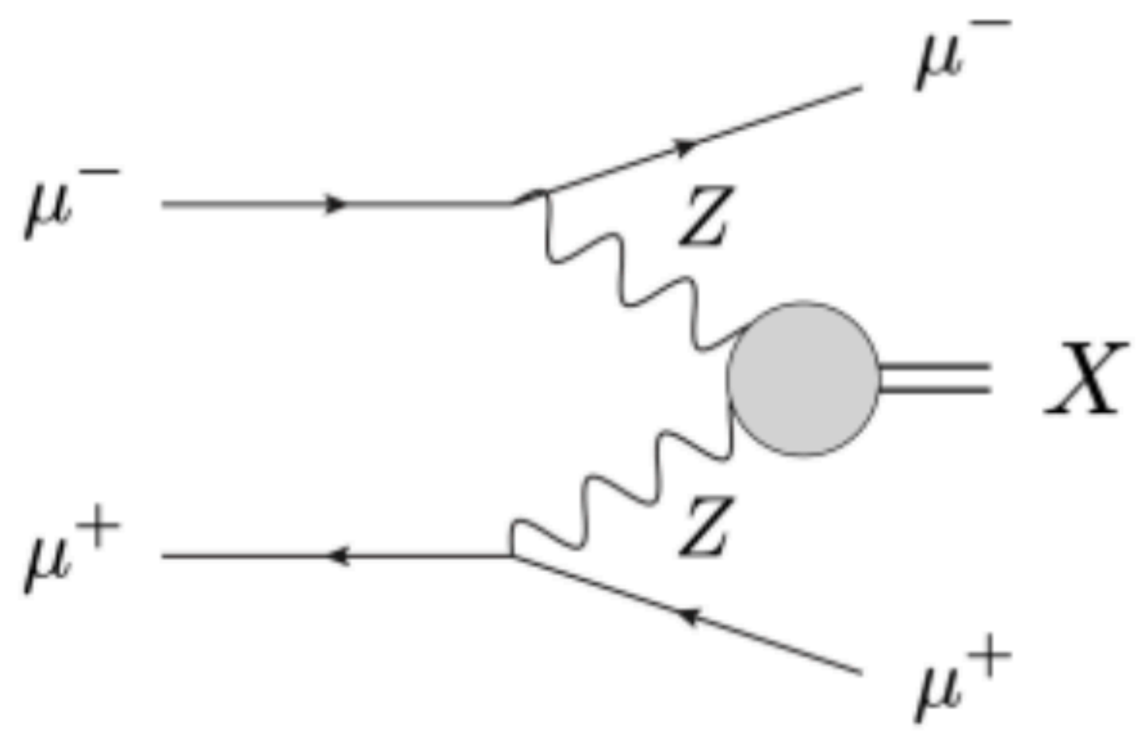

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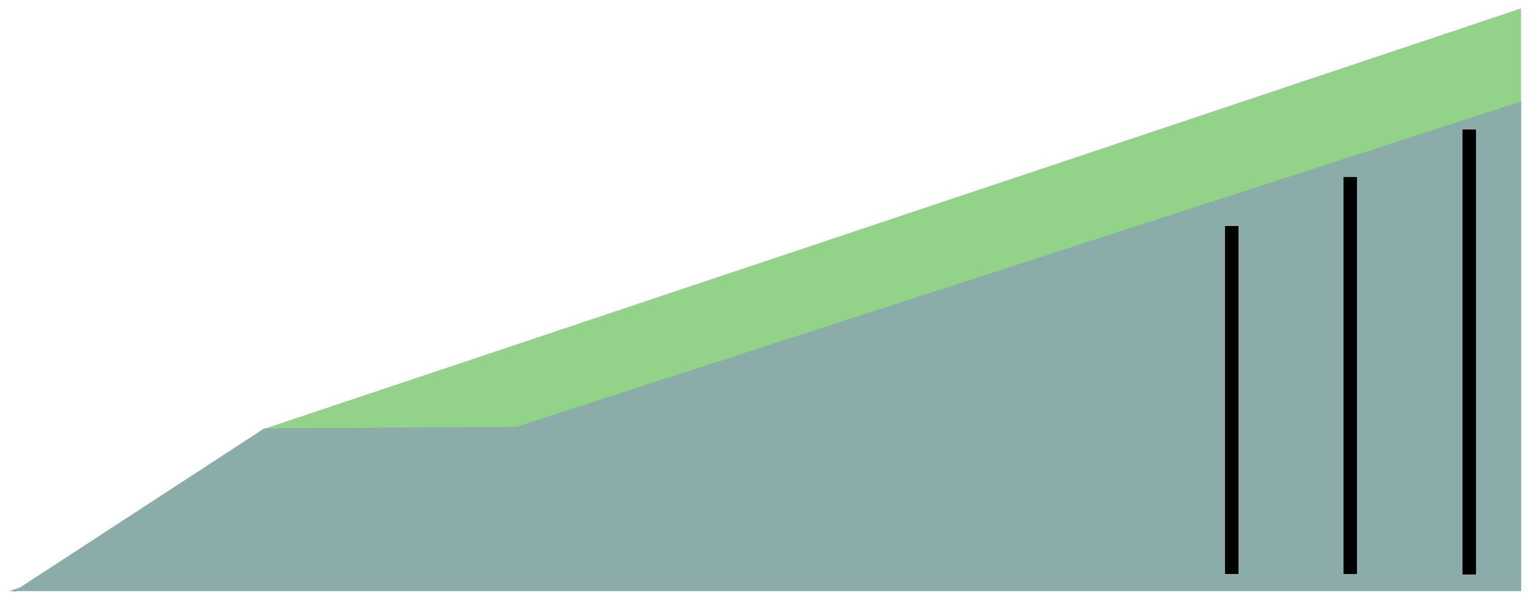
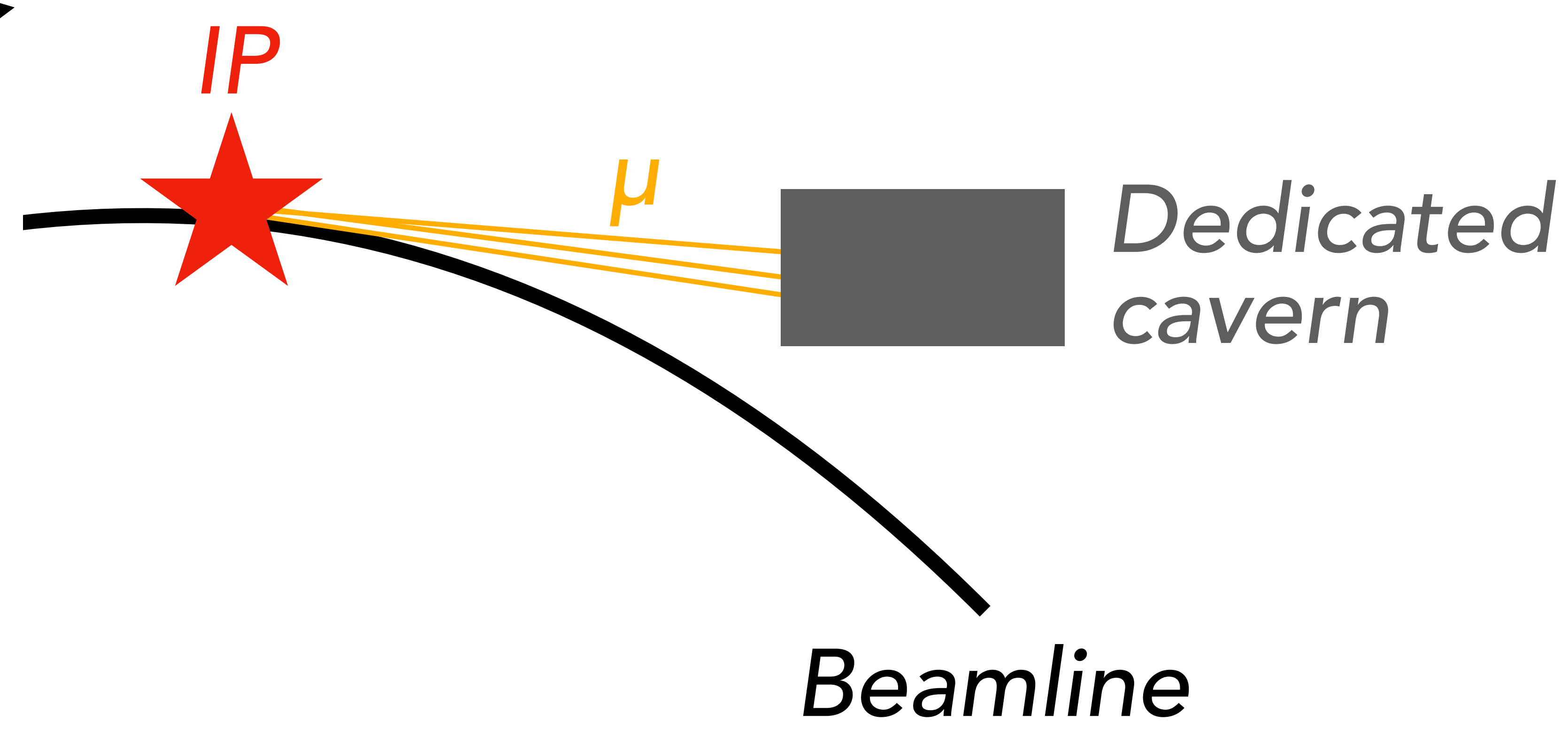


Separate Forward Cavern

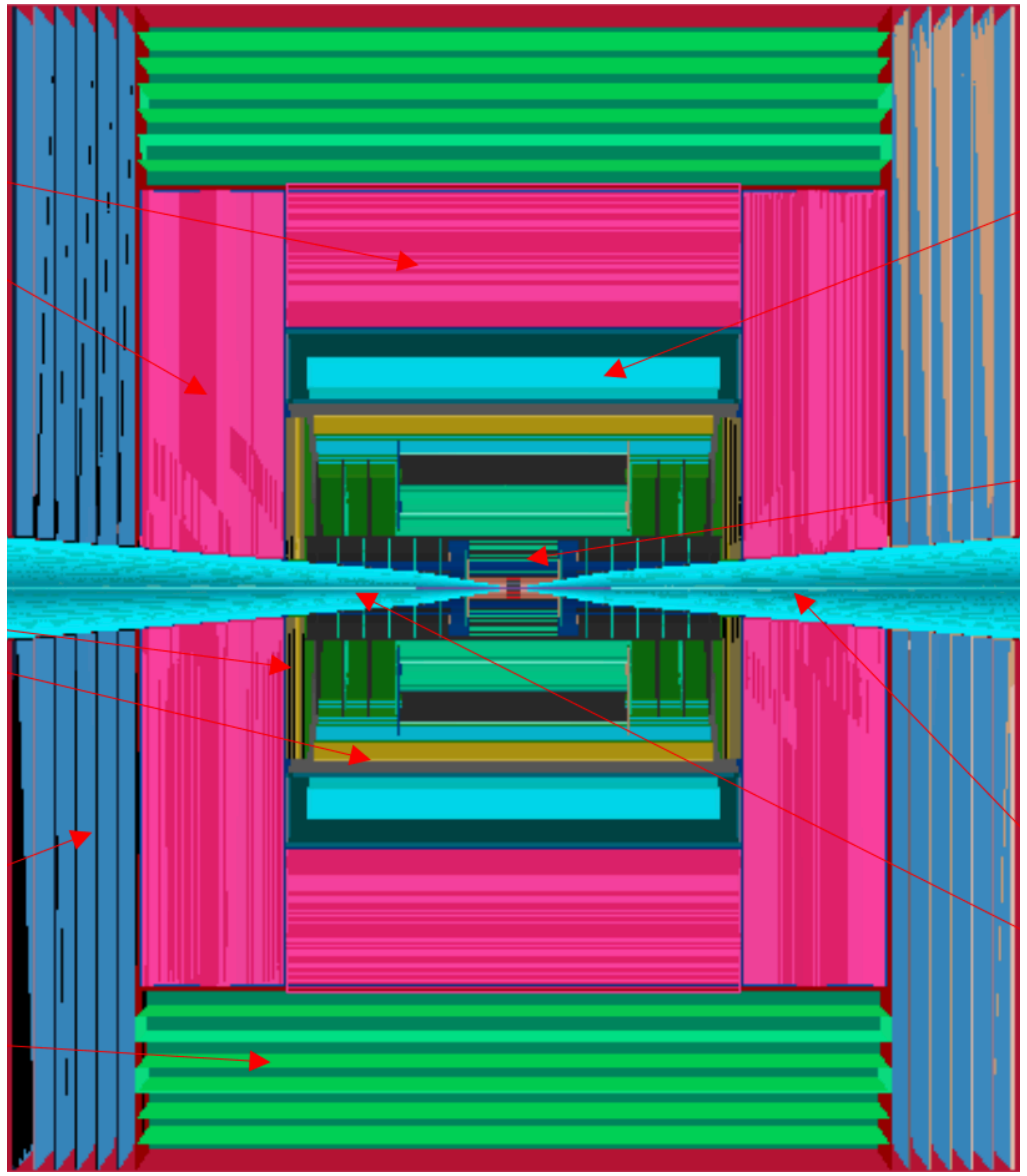
Large detector, low background



Detector Concepts: Further Considerations

- Mechanical Requirements
  - Room for services, cooling, and support infrastructure
  - Physical support for the nozzle

Is the nozzle connected to or independent from detector? How to access the detector?



Detector Concepts: Further Considerations

- Mechanical Requirements
  - Room for services, cooling, and support infrastructure
  - Physical support for the nozzle

- Software Advancements and Current Status
  - ACTS tracking software significantly improved performance
  - Recent transition from MARS to FLUKA for BIB simulation
  - Latest SW release built on key4hep stack
  - Delphes cards available for 3 TeV and 10 TeV

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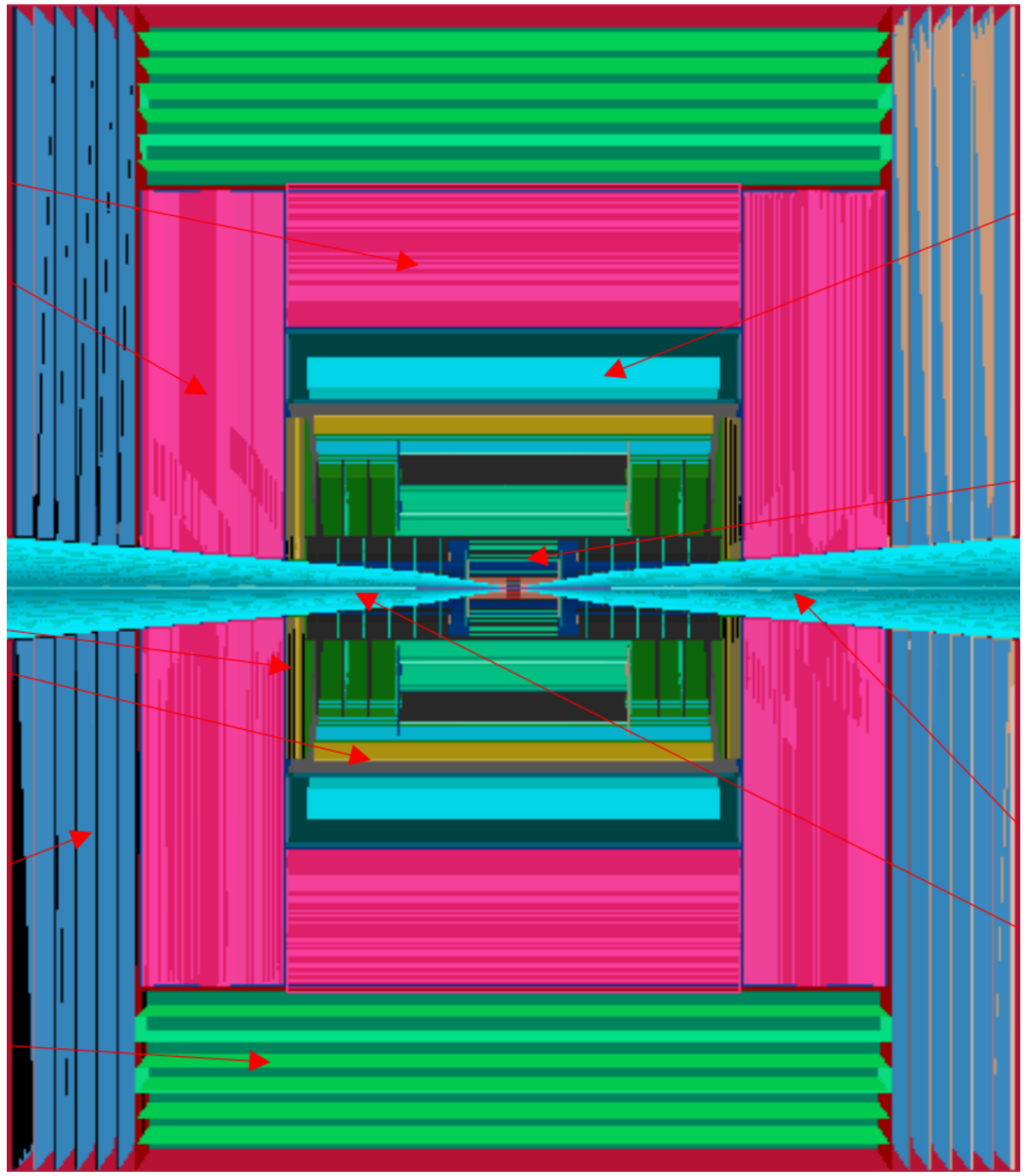

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- Physics Goals
  - Target benchmarks include Higgs performance, high energy NP (e.g. Z′), exotic BSM (e.g. LLP)

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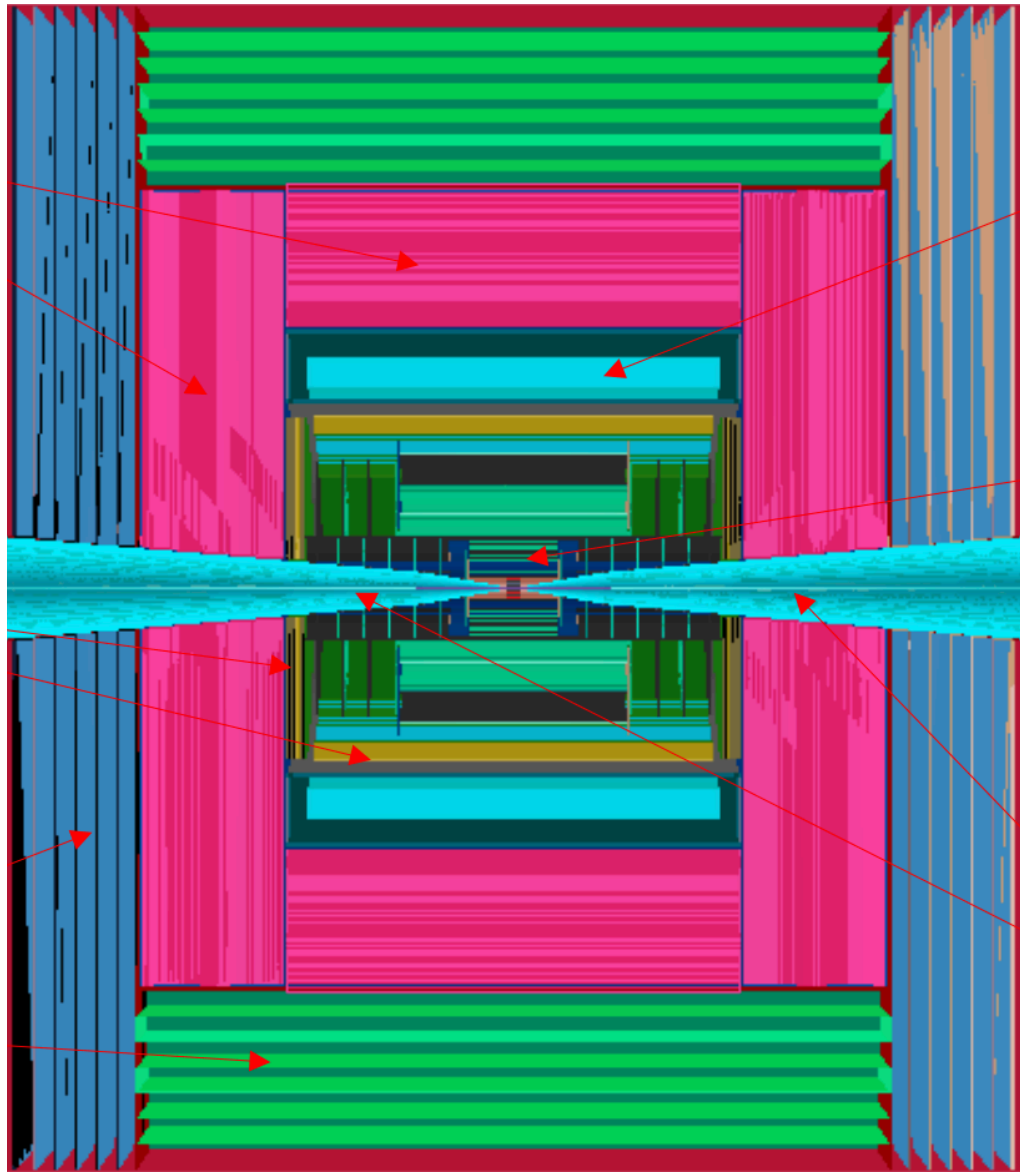

Workshop Outcomes, Outlook, and Conclusions

Workshop Goals, Revisited: IR + MDI

- Define Reference IR and MDI Configuration
  - IR lattice and magnet apertures
  - Shielding inserts in magnets
  - Nozzle configuration
- Further Understand Beam-Induced Background
  - Decay-induced background
  - Incoherent pair production

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  - Decay-induced background
  - Incoherent pair production

Studies presented on BIB from both muon decay and incoherent pair-production

Some work needed before production of high-statistics reference sample

Workshop Goals, Revisited: Detector

- Define Detector Configurations
  - Proceed with one vs. two configurations
- Define Sub-detectors
  - Configuration and technology for tracker
  - ECAL and HCAL technology
  - Position of the magnet and return yoke
  - Muon detector
- Define Software Version(s)
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Two configurations

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Well defined for both detector concepts, with some optimization studies needed in the future

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  - Converge on software version for additional studies

All SW finalized or close to being finalized

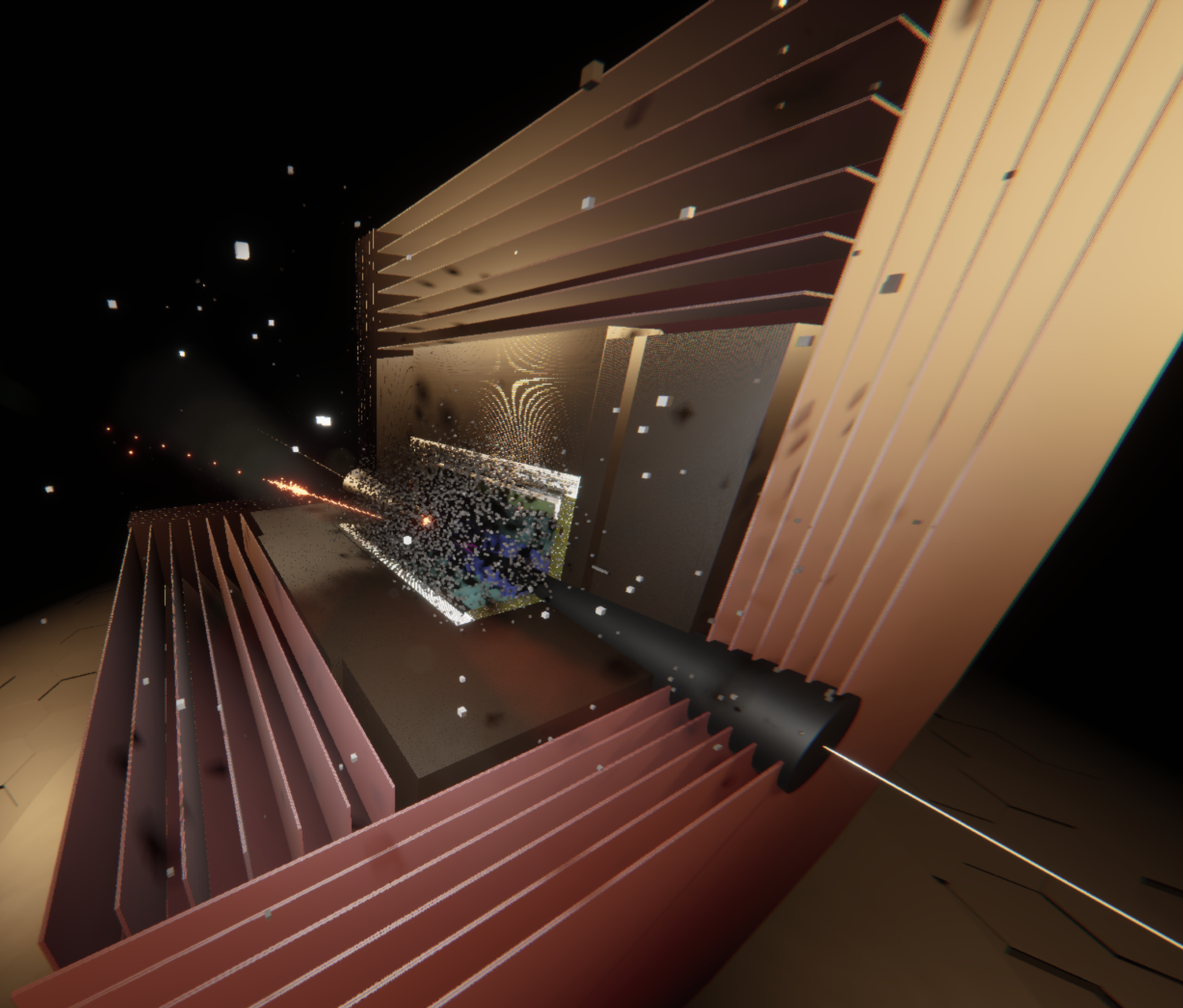
Conclusions + Outlook

- **Conclusions**
  - Workshop established an initial configuration of a 10 TeV muon collider IR and two detector concepts
  - Progress is the result of continuous, iterative changes and improvements by many talented students, engineers, accelerator physicists, particle physicists, and more!

Conclusions + Outlook

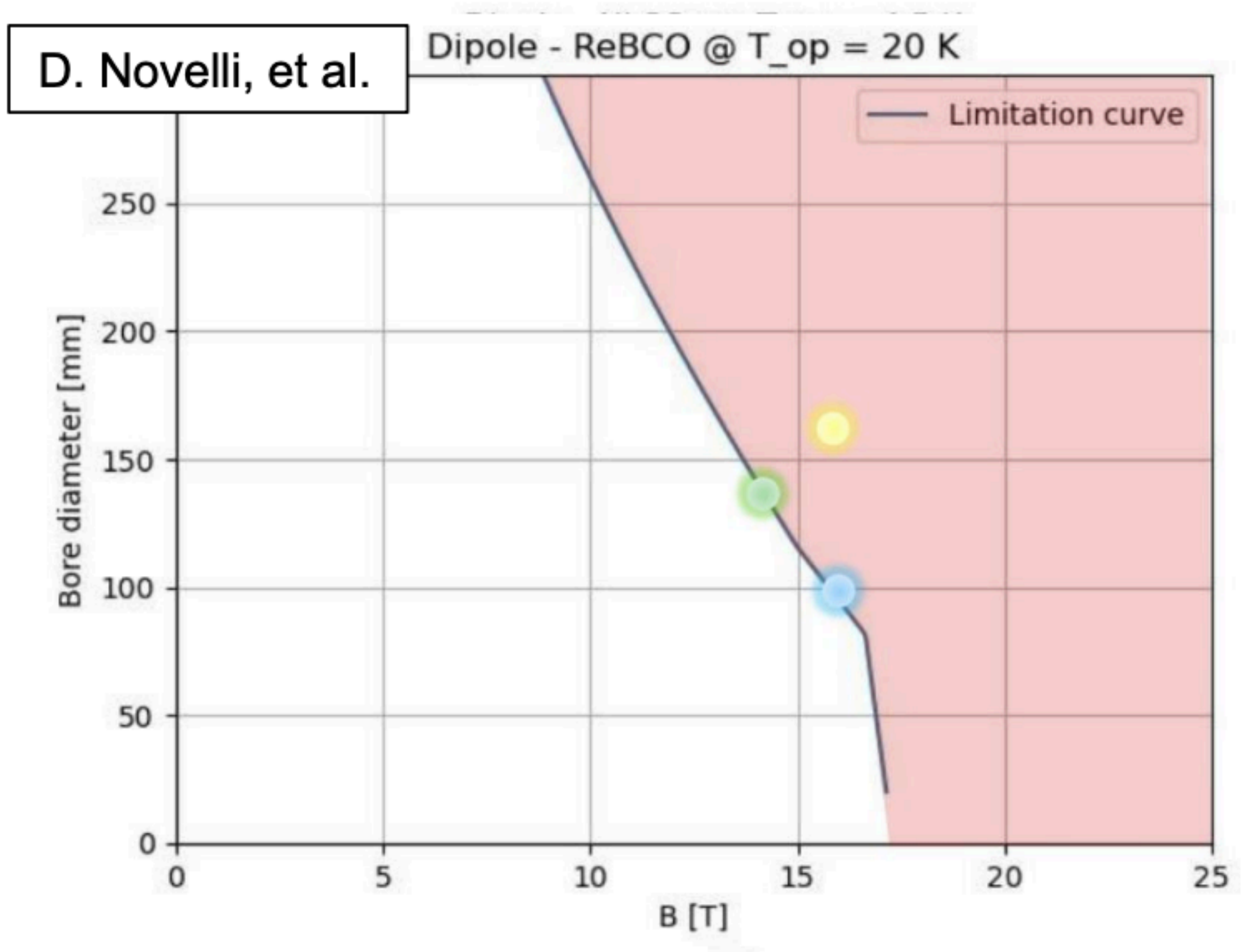
- **Conclusions**
  - Workshop established an initial configuration of a 10 TeV muon collider IR and two detector concepts
  - Progress is the result of continuous, iterative changes and improvements by many talented students, engineers, accelerator physicists, particle physicists, and more!
- **Outlook**
  - Current configurations in very good shape, though there is still room for improvement + optimization
  - Many exciting physics studies to be done by the European Strategy deadline on March 31, 2025!
  - Please reach out if you are interested in getting involved!

Thank You!

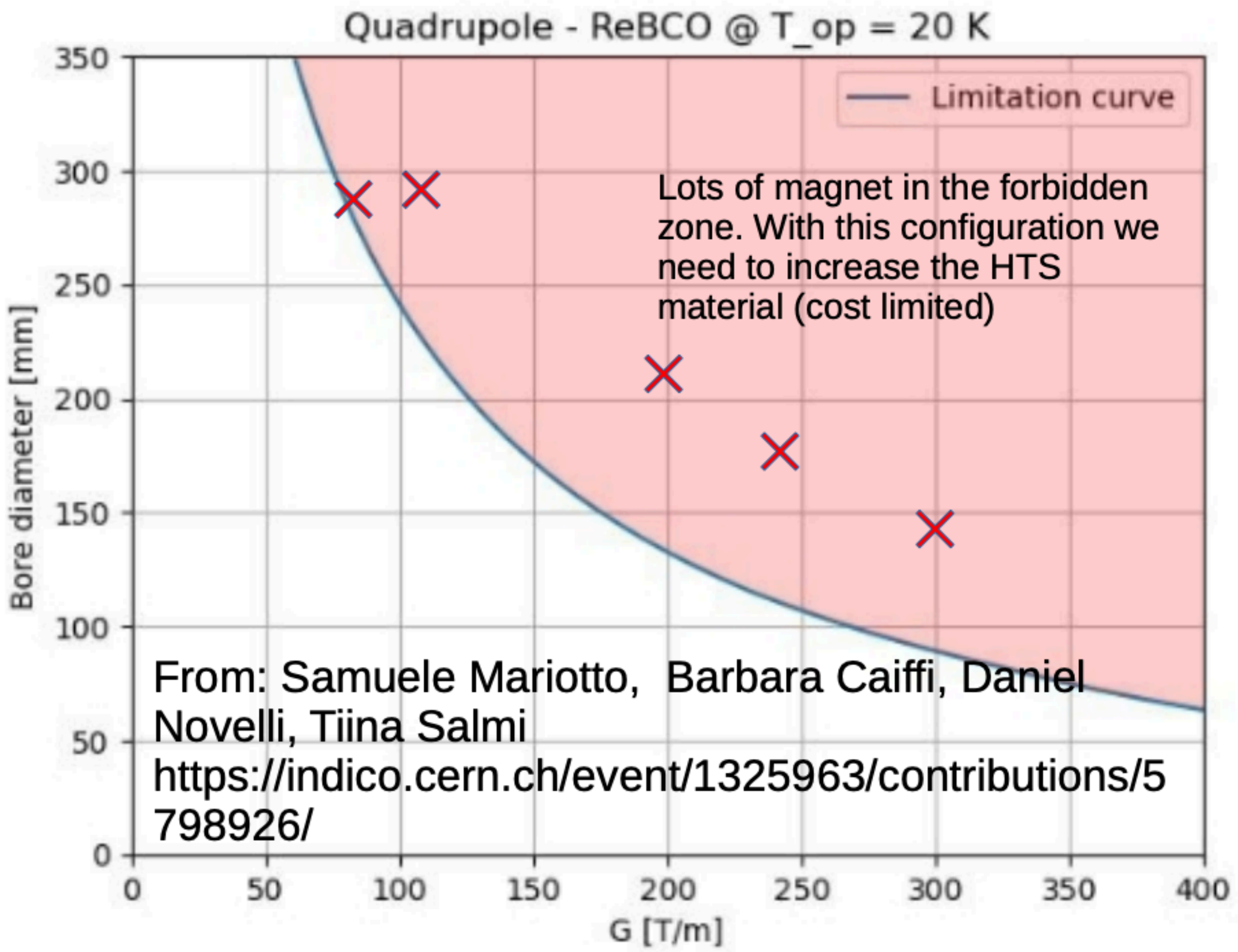


Backup

Magnet Aperture Limitations



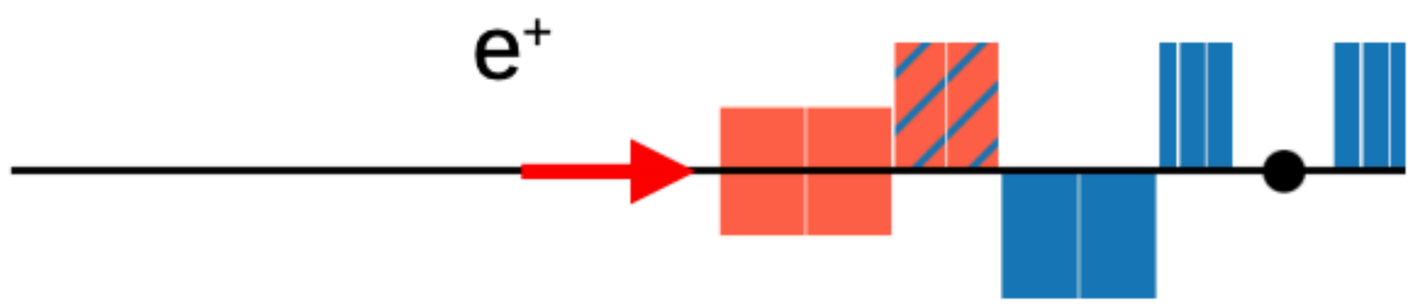
M. Vanwelde, K. Skoufaris and C. Carli

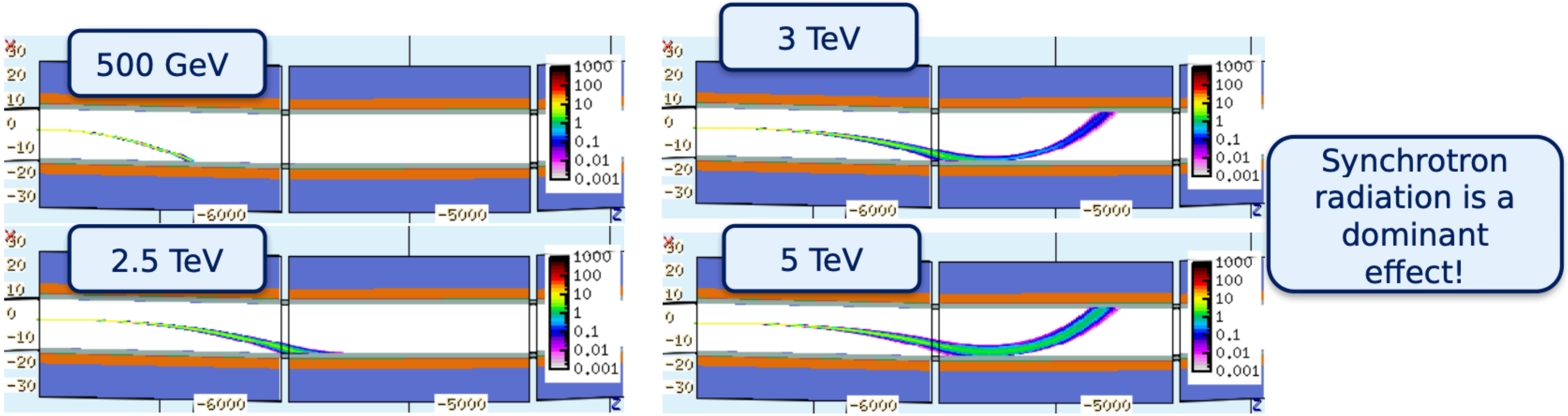


D. Calzolari

Impact of Chicane

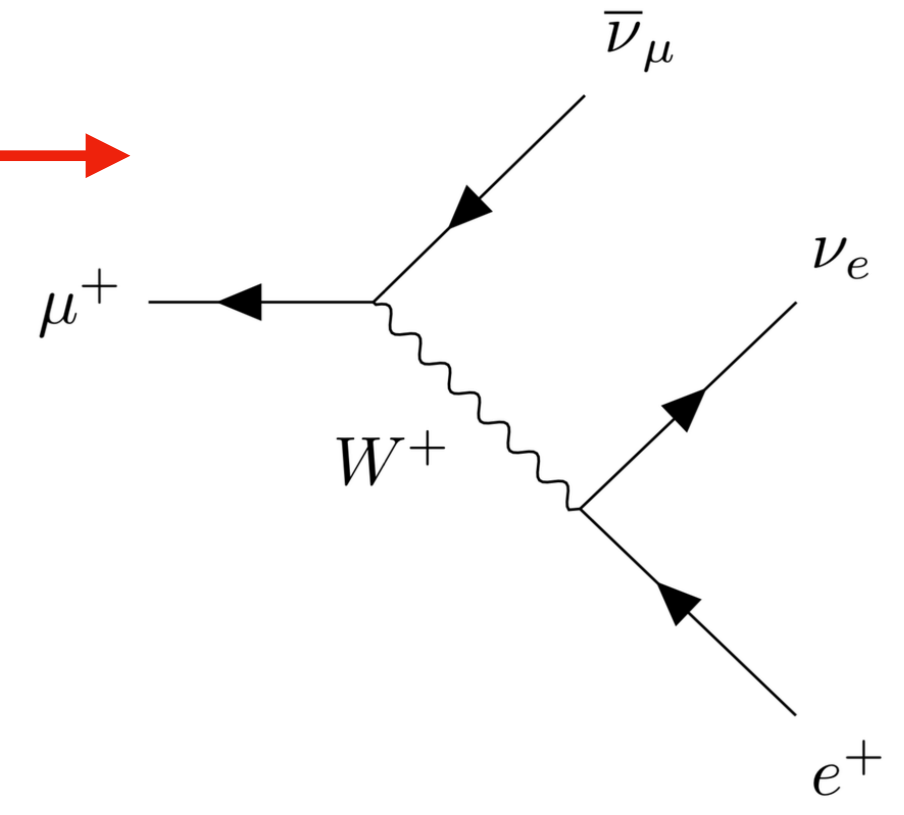
- Considering a pencil beam positrons along the ideal trajectory, the path in the first two magnets is reported.
- Two hotspots are generated in the first and second magnets

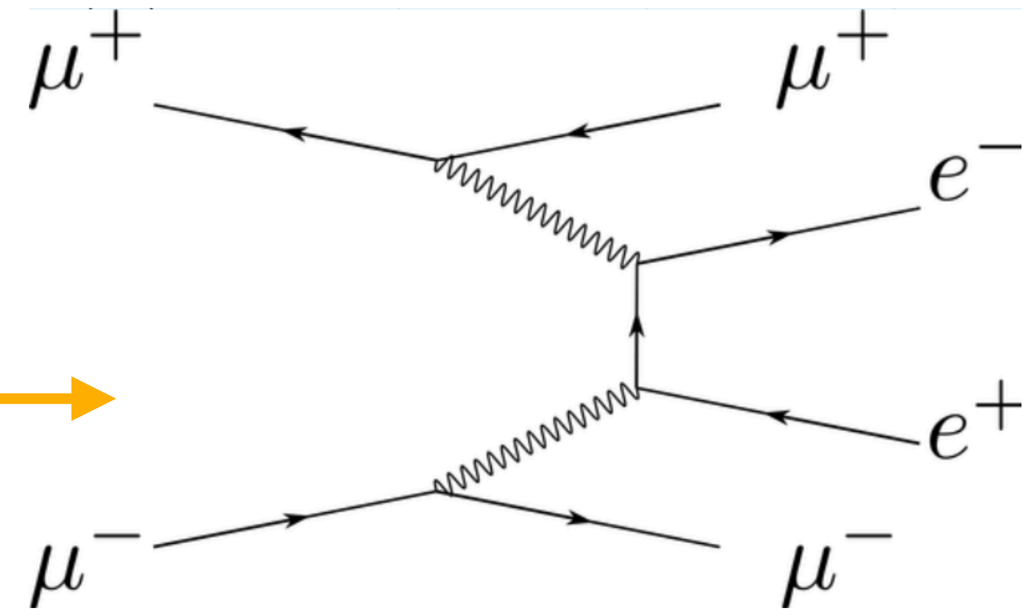




Beam-Induced Background (BIB): Sources

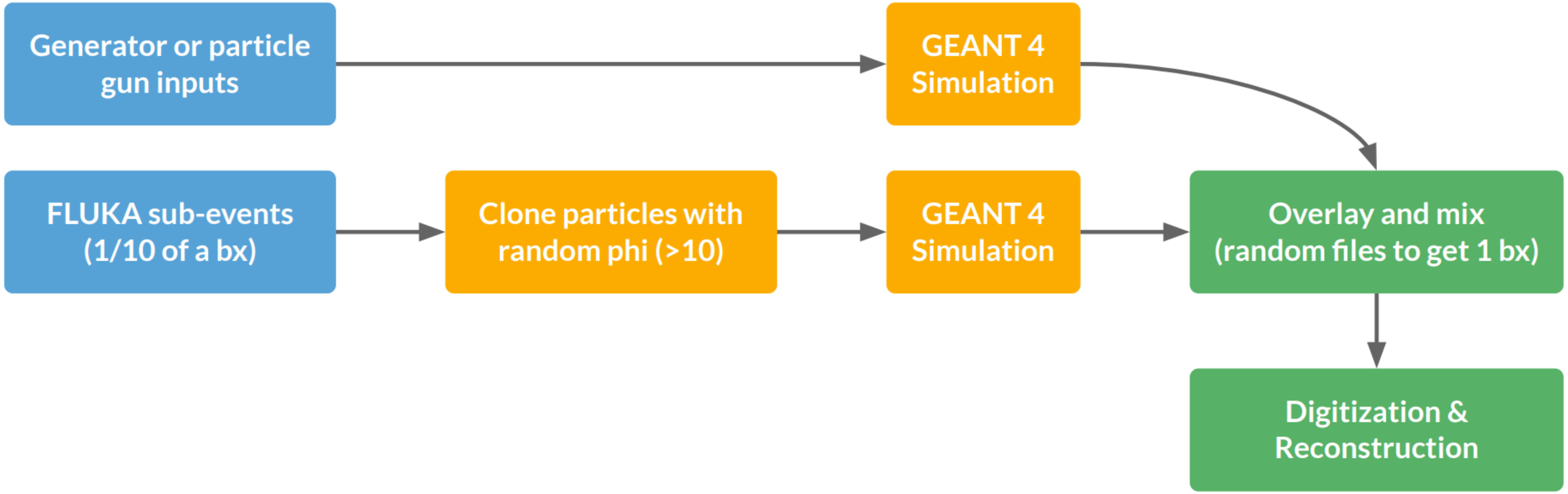
	Description	Relevance as background
Muon decay	**Decay of stored muons around the collider ring**	**Dominating source**
Synchrotron radiation by stored muons	Synchrotron radiation emission by the beams in magnets near the IP (including IR quads → large transverse beam tails)	**Small**
Muon beam losses 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**





BIB Simulation Workflow

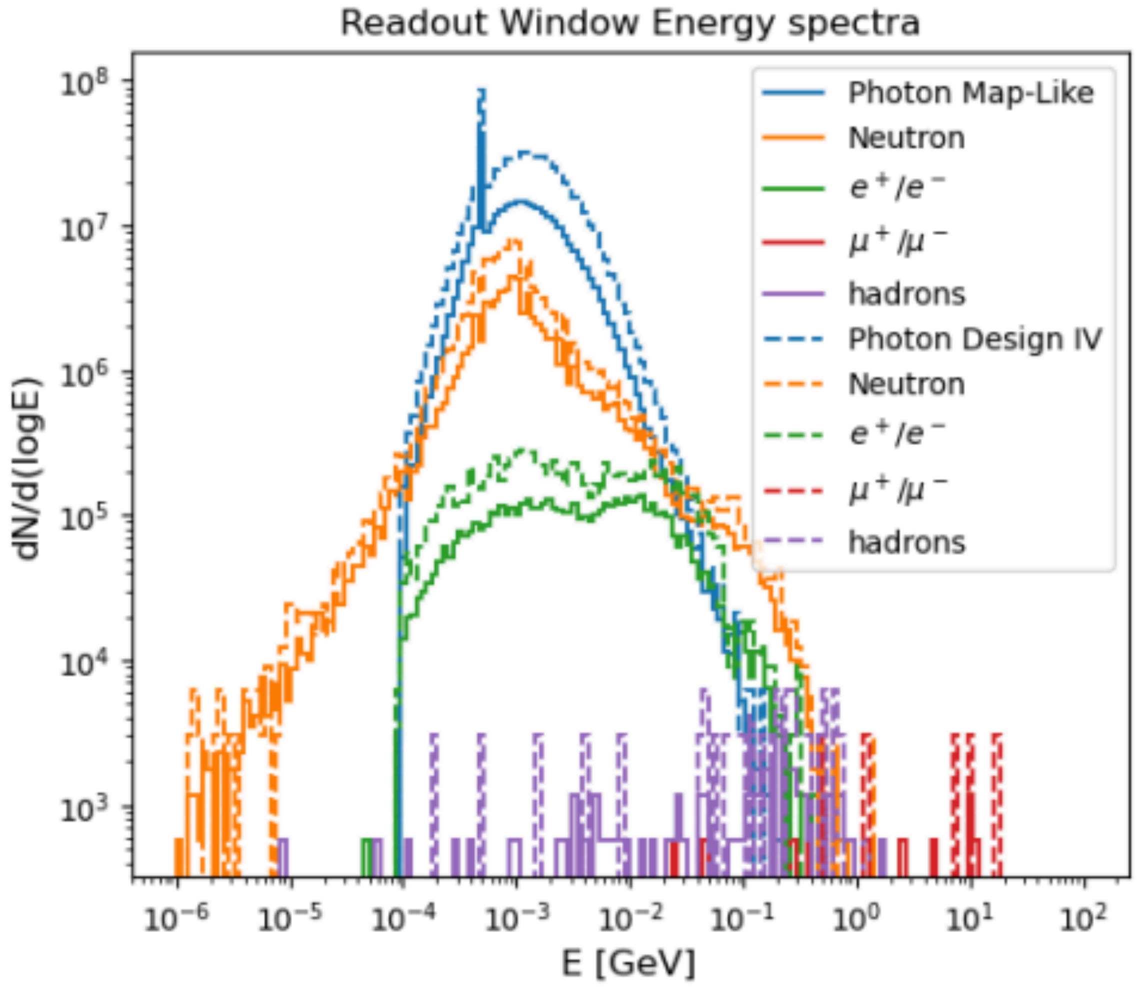
- ➔ Using updated FLUKA 10 TeV BIB
  - ◆ Kinematics look very similar to 3 TeV; but MDI, nozzle optimization extremely important (D. Calzolari)
- ➔ BIB simulation and overlay (N. Bartosik)
  - ◆ Simulating the BIB contributions in FLUKA is computationally expensive, so employ overlay strategy:

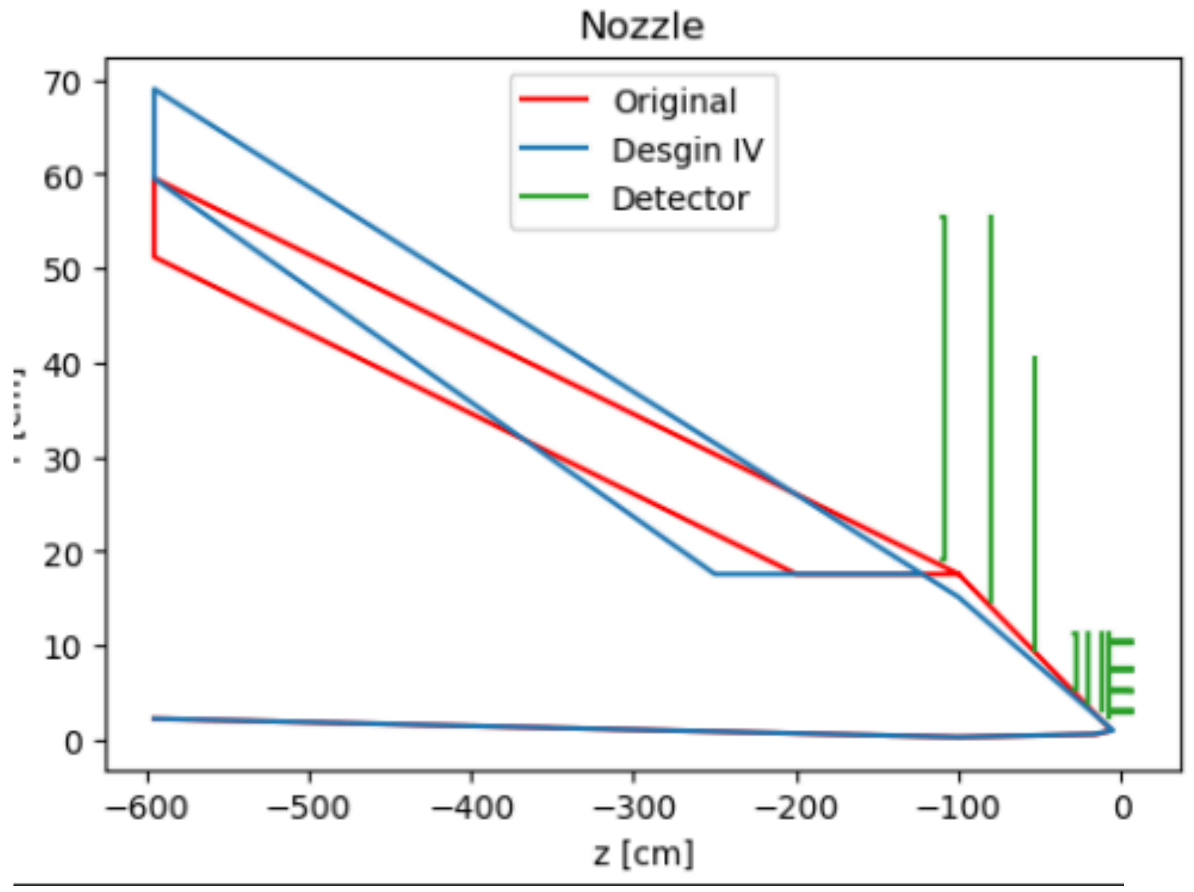


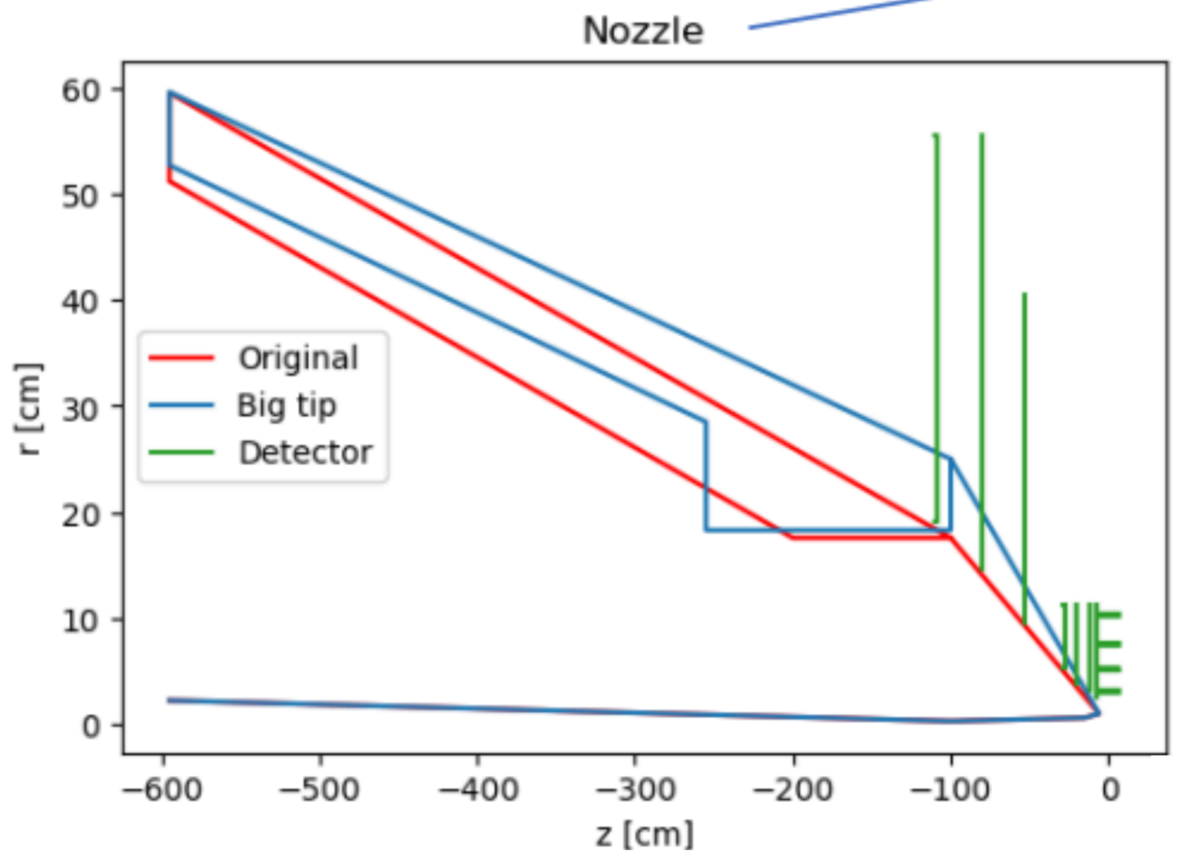
L. Castelli, D. Lucchesi,
D. Calzolari, F. Collamati

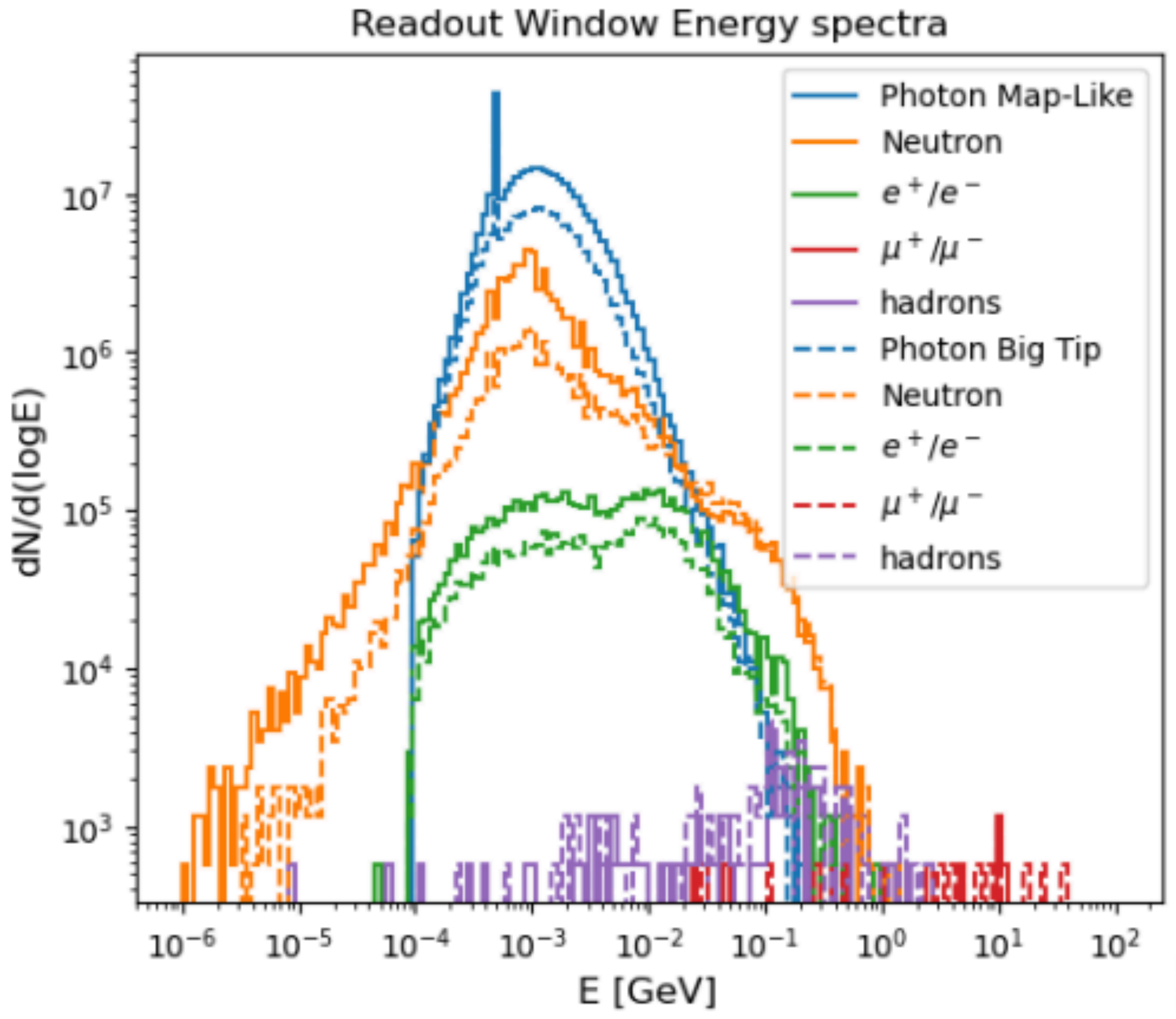
Nozzle Shape Optimization

- Lessons learned:
  - The Beam Pipe cannot be touched
  - Is Boreth layer really effective?
  - Nozzle tip is the critical part $z \in [0, 1]\ m$

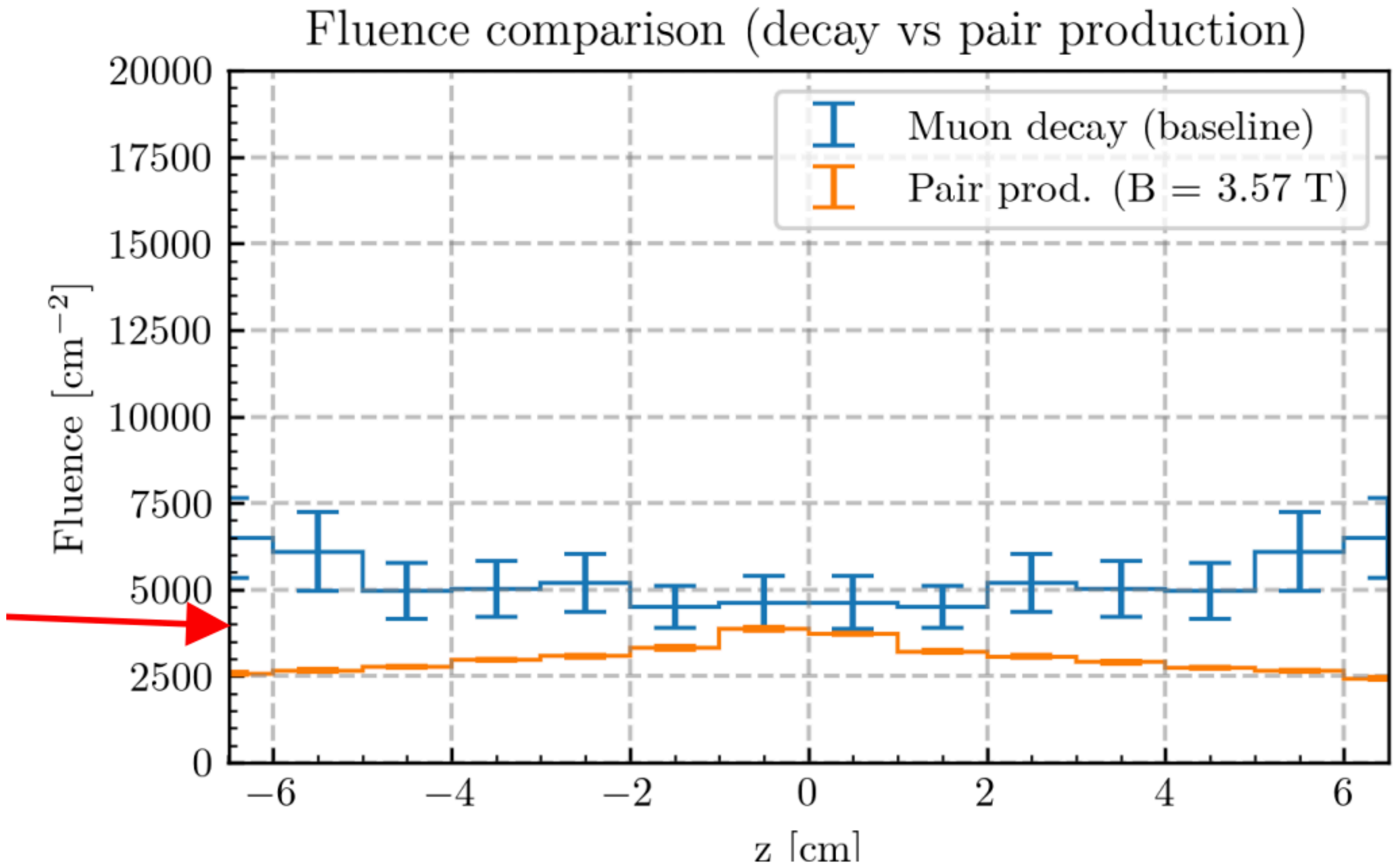


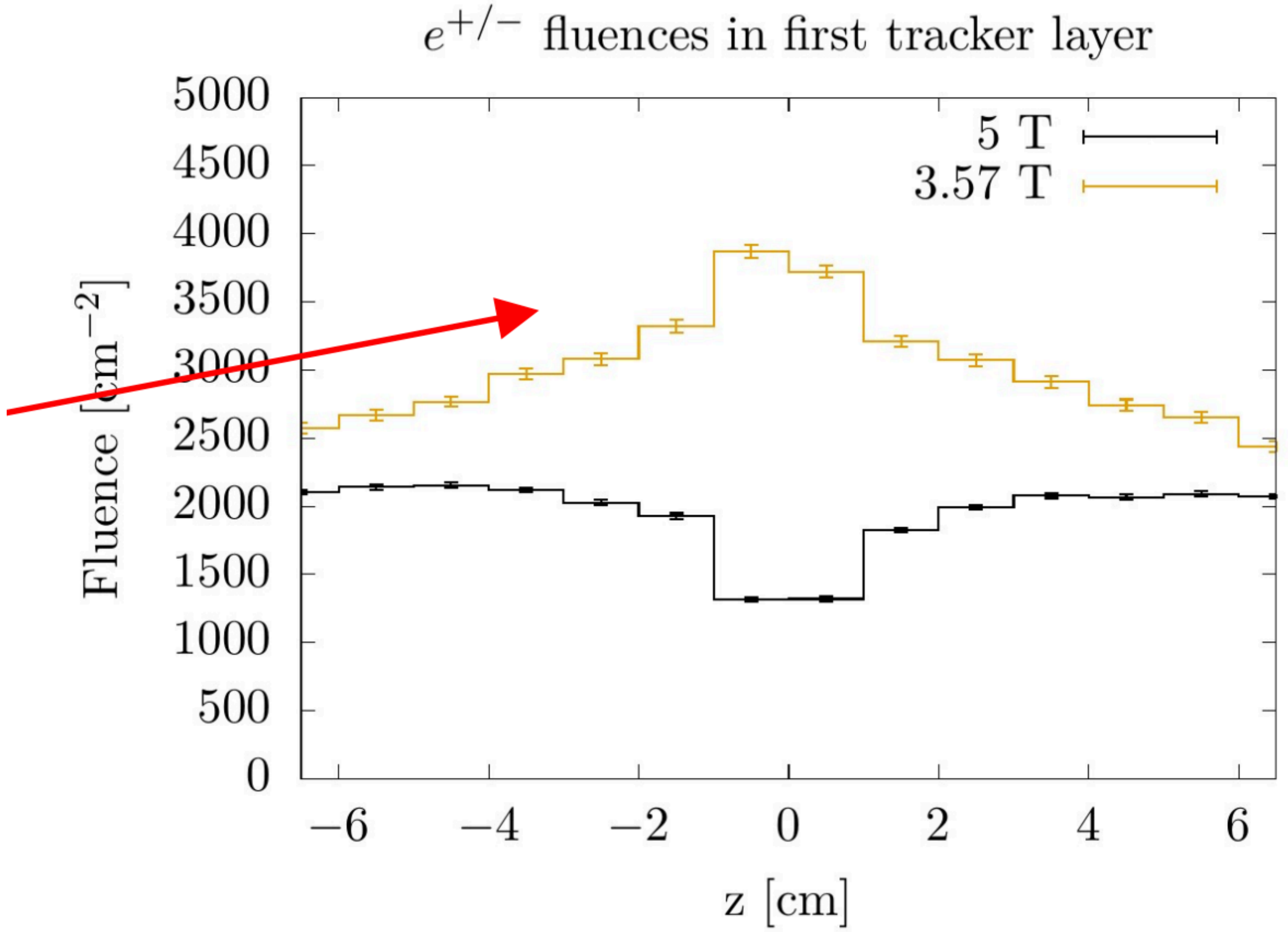






BIB Particle Fluence Measurements





Forward Muon Reconstruction: Silicon in the Nozzle

- Total counts within $\pm 100\ ps$ time window with respect to muons arrival time on layers:

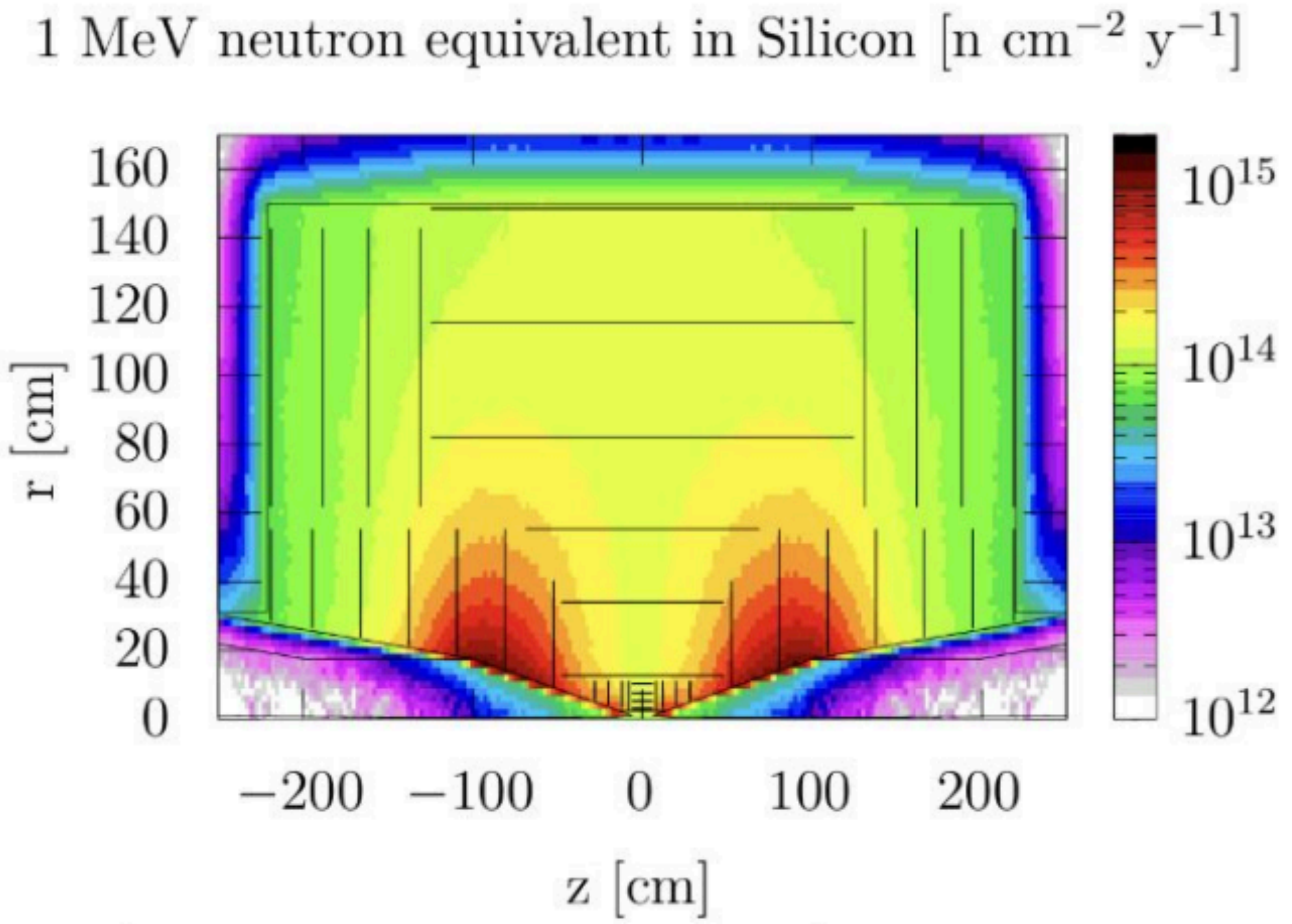
Event	Layer 1	Layer 2	Layer 3
BIB^{*}	$2.5 \cdot 10^{4}$	$2.7 \cdot 10^{4}$	$3.0 \cdot 10^{4}$
$Z\ fusion^{**}$	*3228/6150*	*3232/6150*	*3225/6150*

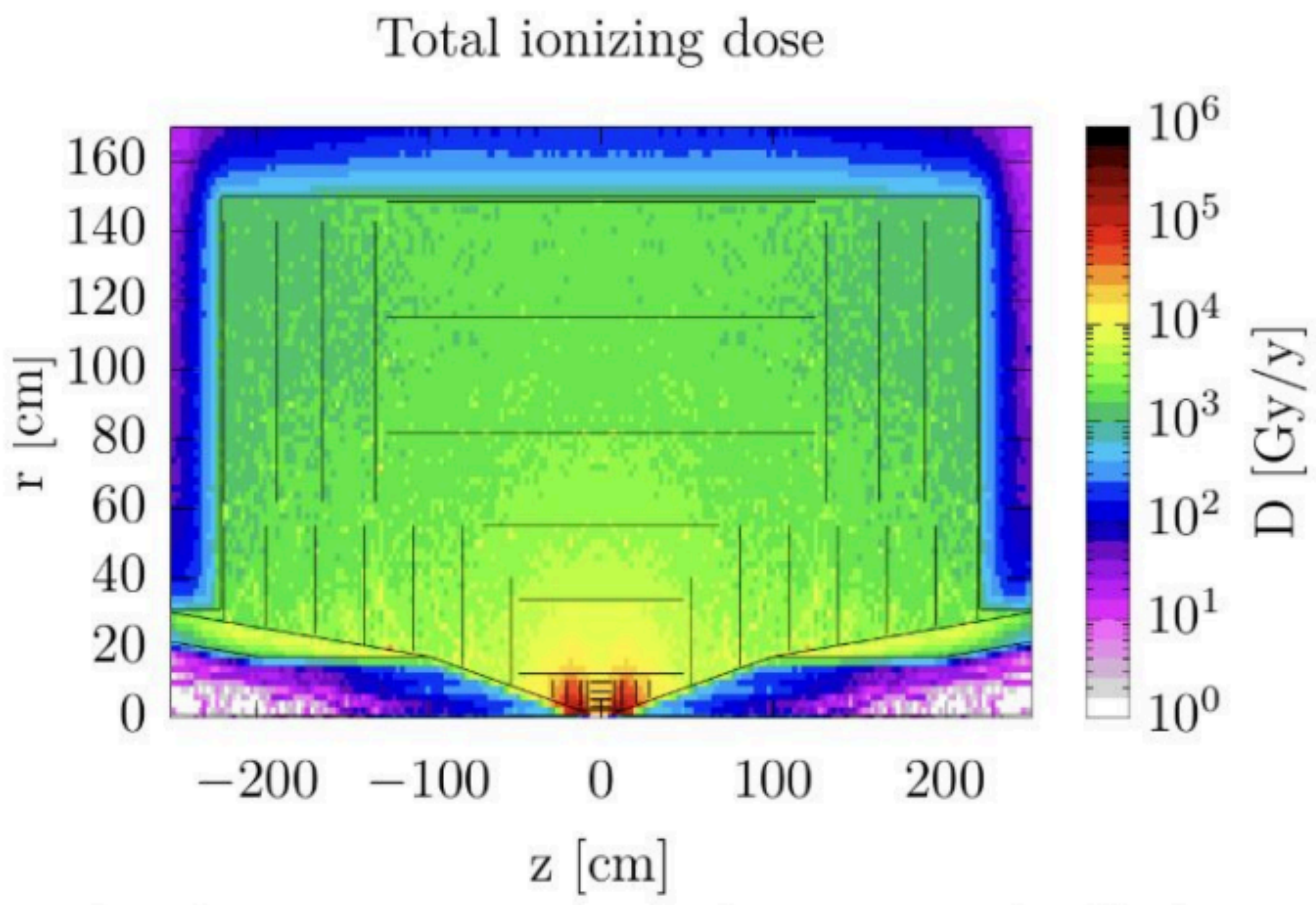
- A rough tracking is performed to discard particles that are not coming from IP:

Event	Global Efficiency [%]	Tracking Efficiency [%]
$BIB^{\#}$	< 0.28	
$Z\ fusion^{\#\#}$	52.5	99.2

Detector Radiation Damage

➔ Radiation at 10 TeV comparable to HL-LHC and previous 3 TeV muon collider studies; much lower than FCC-hh (1018 1 MeV-neq/cm2) (2209.01318, 2105.09116)



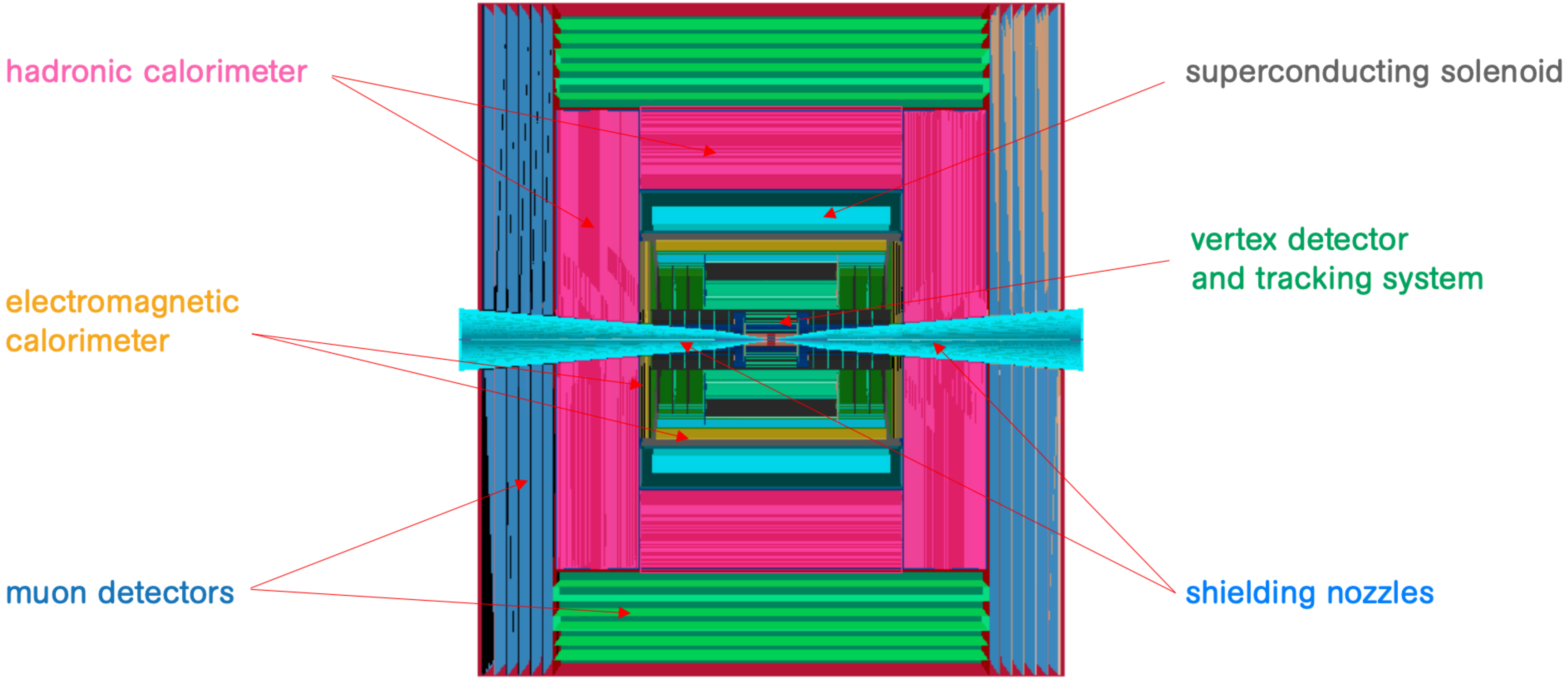


	Maximum Dose (Mrad)		Maximum Fluence (1 MeV-neq/cm^2)	
	R= 22 mm	R= 1500 mm	R= 22 mm	R= 1500 mm
Muon Collider (3 TeV)	10	0.1	10^{15}	10^{14}
HL-LHC	100	0.1	10^{15}	10^{13}
Muon Collider (10 TeV)	20	0.2	3×10^{14}	10^{14}

MAIA Detector Configuration

Subsystem	Region	R dimensions [cm]	|Z| dimensions [cm]	Material
Vertex Detector	Barrel	3.0 – 10.4	65.0	Si
	Endcap	2.5 – 11.2	8.0 – 28.2	Si
Inner Tracker	Barrel	12.7 – 55.4	48.2 – 69.2	Si
	Endcap	40.5 – 55.5	52.4 – 219.0	Si
Outer Tracker	Barrel	81.9 – 148.6	124.9	Si
	Endcap	61.8 – 143.0	131.0 – 219.0	Si
Solenoid	Barrel	150.0 – 185.7	230.7	Al
ECAL	Barrel	185.7 – 212.5	230.7	W + Si
	Endcap	31.0 – 212.5	230.7 – 257.5	W + Si
HCAL	Barrel	212.5 – 411.3	257.5	Fe + PS
	Endcap	30.7 – 411.3	257.5 – 456.2	Fe + PS
Muon Detector	Barrel	415.0 – 715.0	456.5	Air + RPC
	Endcap	44.6 – 715.0	456.5 – 602.5	Air + RPC

MUSIC Detector Concept Schematic



The MUSIC detector (Muon Smasher for Interesting Collisions).

3 TeV Detector Concept

hadronic calorimeter

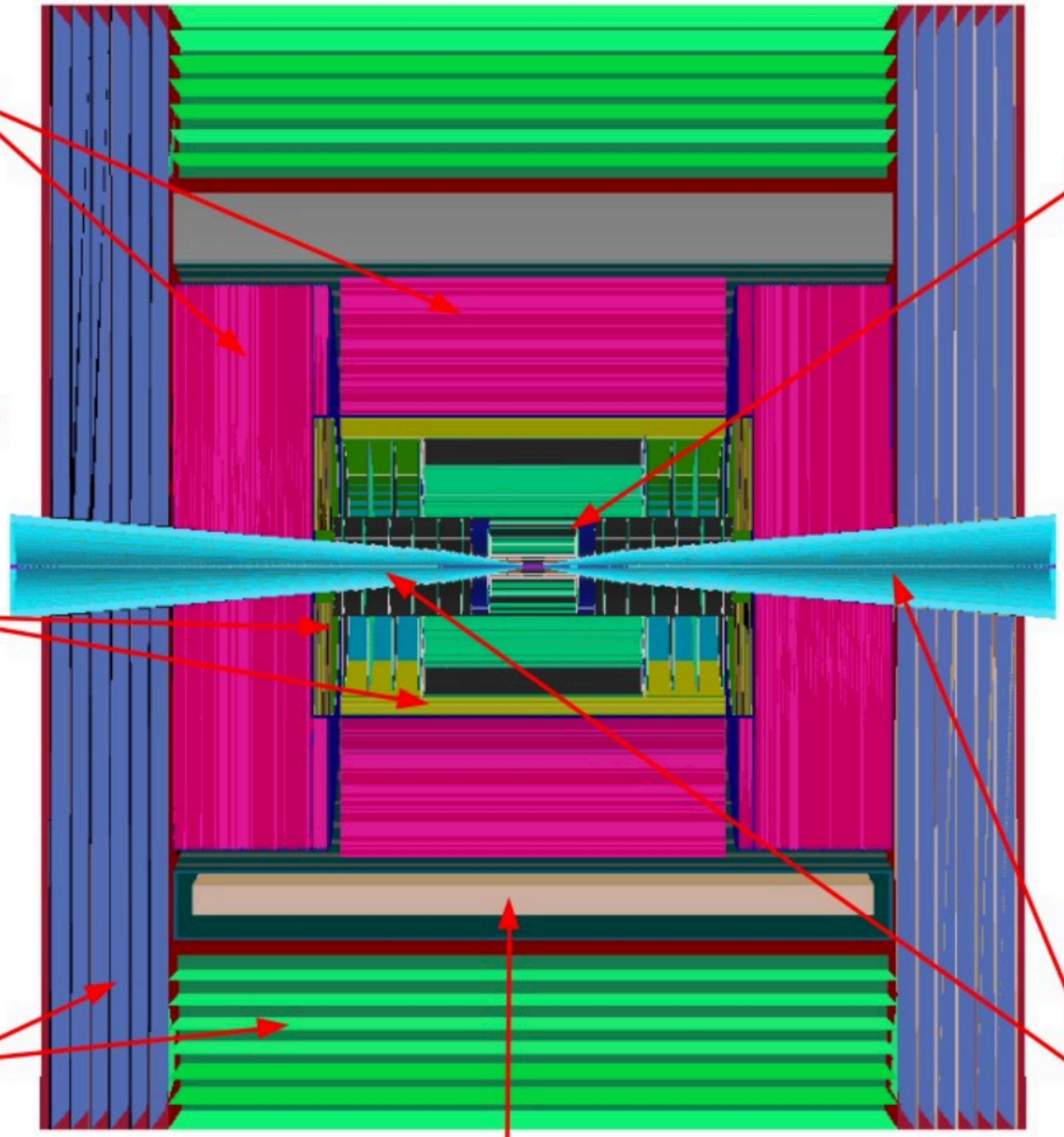
- 60 layers of 19-mm steel absorber + plastic scintillating tiles;
- 30x30 mm^2 cell size;
- 7.5 λ_I.

electromagnetic calorimeter

- 40 layers of 1.9-mm W absorber + silicon pad sensors;
- 5x5 mm^2 cell granularity;
- 22 X_0 + 1 λ_I.

muon detectors

- 7-barrel, 6-endcap RPC layers interleaved in the magnet's iron yoke;
- 30x30 mm^2 cell size.



superconducting solenoid (3.57T)

tracking system

- Vertex Detector:
  - double-sensor layers (4 barrel cylinders and 4+4 endcap disks);
  - 25x25 μm^2 pixel Si sensors.
- Inner Tracker:
  - 3 barrel layers and 7+7 endcap disks;
  - 50 µm x 1 mm macro-pixel Si sensors.
- Outer Tracker:
  - 3 barrel layers and 4+4 endcap disks;
  - 50 µm x 10 mm micro-strip Si sensors.

shielding nozzles

- Tungsten cones + borated polyethylene cladding.

Tungsten Alloy Considerations

- Source: ASTM specification B777-07
- "Machinable, high-density tungsten base metal produced by consolidating metal powder mixtures, the composition of which is mainly tungsten"
- "For purposes of this specification, non-magnetic material is defined as material having a maximum magnetic permeability of 1.05"
- Classification in 4 classes
- Class 4 is not available in non magnetic form

Class	Tungsten nominal weigth (%)	Density (g/cc)	Hardness (Rockwell)
1	90	16.85-17.25	32
2	92.5	17.15-17.85	33
3	95	17.75-18.35	34
4	97	18.25-18.85	35